# CHAPTER 2

# LITERATURE REVIEW

The present chapter shows an overview of the literature review regarding the synthesis, development, microstructural, tribological, and mechanical characterizations of composites based on aluminium and its alloy composites. Various authors have developed aluminium and its alloy-based composites by different techniques and reported their results. This chapter is organized in the different sub-categories based on related work and kinds of literature available.

## 2.1 Composites

Composites are the materials formed by combining two or more materials that have different physical and chemical properties, but as a combination, they exhibit properties superior to those of individual materials. Composite classification is done based on the chemical and physical nature of the matrix, e.g. Polymer matrix, metal matrix, and ceramic matrix composites, as shown in **Figure 2.1**. Inter metallic and carbon matrices are also being studied to enhance composite properties [16].

### 2.1.1 Classification of composites

#### 2.1.1.1 Metal Matrix composites (MMCs)

A metal matrix composite (MMCs) is a composite with the minimum of two constituents, one being metal and the other material a ceramic or an organic compound. The matrix usually is a light metal such as aluminium, magnesium, or titanium and becomes compliant reinforcement support.

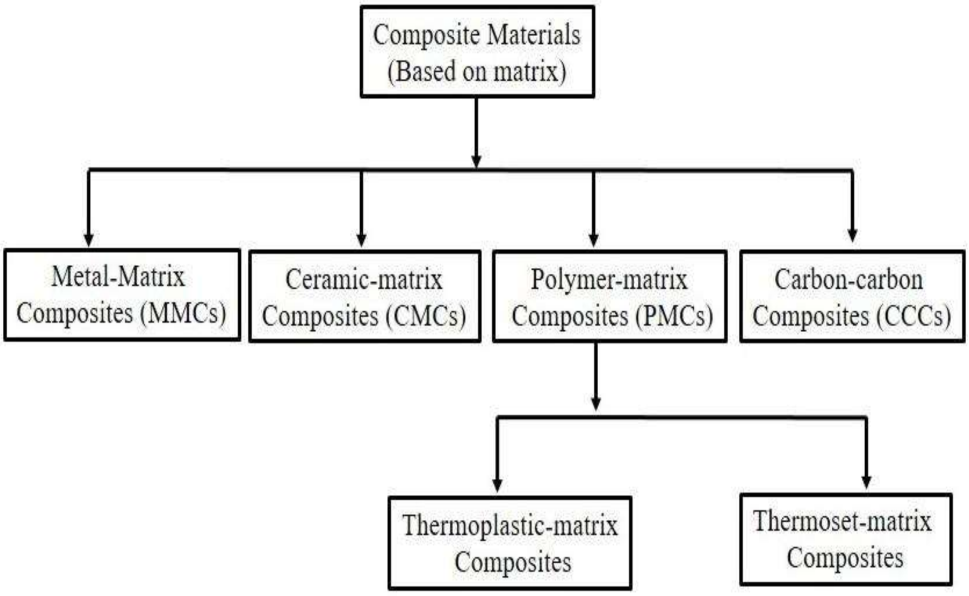


**Figure 2.1:** Classification of composite materials based on the matrix used [16]

### 2.1.1.2 Polymer matrix composites (PMCs)

A polymer matrix composite is a material that consists of a polymer matrix reinforced with a fibrous dispersed phase. The weak mechanical properties of non-reinforced polymers limit their use in structural applications, e.g. tensile strength of one of the high-strength polymer epoxy resins is 140 MPa (20000 psi). Along with low strength, they also possess low impact resistance.

### 2.1.1.3 Ceramic matrix composites (CMCS)

Ceramic matrix composites are a subgroup of composites and technical ceramics as well. They consist of fiber-reinforced ceramic (FRC) material. The fibers may be of different forms, such as short fibers, particles, whiskers, and nanofibers. Its composites are primarily developed for improving the fracture toughness of ceramic materials, but their applications are restricted due to their brittle behavior. Therefore, it can be used in extremely high temperatures and stressful environments.

### 2.1.1.4 Carbon-carbon composites (CCCs)

A new engineering material class consists of carbon fibers reinforced in the carbon matrix. They exhibit brittle to pseudoplastic behavior but are ceramics in nature. It is also known as carbon-fibre-reinforced carbon composite (CFRCC). Carbon matrix reinforced by graphite carbon fibers. Carbon-carbon composites are lightweight materials that can withstand temperatures up to 3000°C [16].

### 2.1.2 Classification based on reinforcement

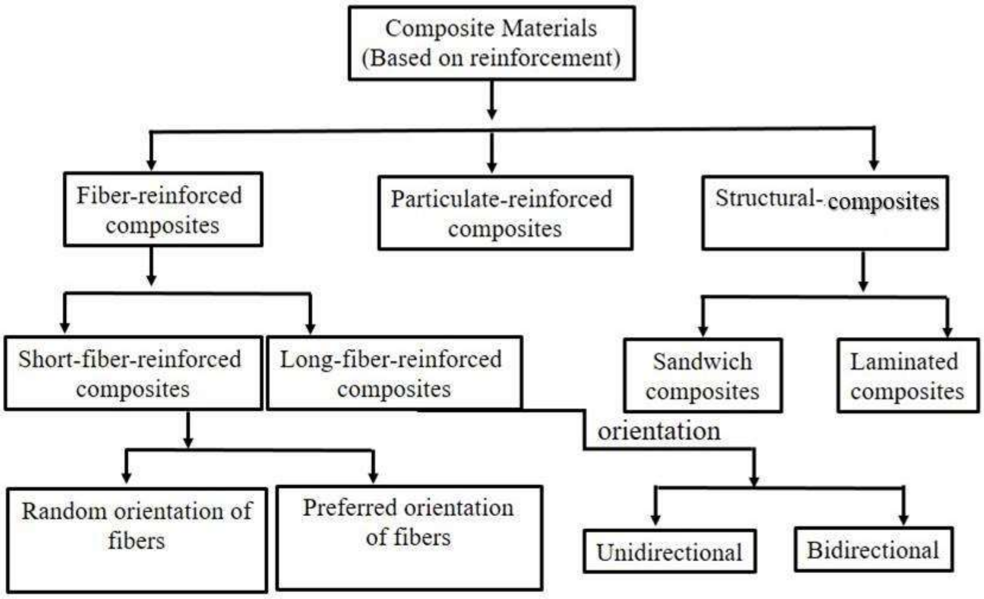


**Figure 2.2:** Classification of composites basis of reinforcement

### 2.1.2.1 Fiber Reinforced

Fiber-reinforced composites include all sorts of fibers, whiskers, and filament, continuous and discontinuous, over the entire range of reinforcement concentration.

#### 2.1.2.2 Particle reinforced

Particle reinforced composite is almost similar to the dispersion-strengthened composite, but the particle size is more significant than 0.1µm, and the volume percentages can be more significant than 25%.

#### 2.1.2.3 Structural composites

In this kind of composite, uniformly distributed fine hard particulates sizes in the range of 0.01 to 0.1 µm and a volume percentage from 1 to 15% are used to enhance the strength and hardness.

**(a) Sandwich composites**

It is a special type of laminated composite in which different materials are bonded together to utilize the properties of each of them for the structural advantage of the whole assembly. A sandwich composite typically consists of three parts: A thick, weak, and light core interface separating two thinner, strong and stiff faces. The faces are bonded to the core with the help of adhesives for load transfer between the layers.

**(b) Laminated composites**

The layers of different materials are used to develop these laminated composites in which the different layers are bonded together with adhesives, to provide additional durability, strength, and other benefits.

## 2.2 Types of reinforcement used in metal matrix composites

The five major categories are as follows:

- Continuous fibers
- Discontinuous fibers
- Whiskers
- Particulates

- Fabric, braid, etc

The above five major categories of reinforcement are shown in **Figure 2.3** . Apart from the metallic wires, ceramics are commonly utilized as reinforcement. The ceramic reinforcements may be nitrides, oxides, and carbides of metals. These ceramic materials are often used as reinforcement with their excellent stiffness and specific strength both at room and elevated temperature. The base metal is affected by each ceramic reinforcements in different ways [17].

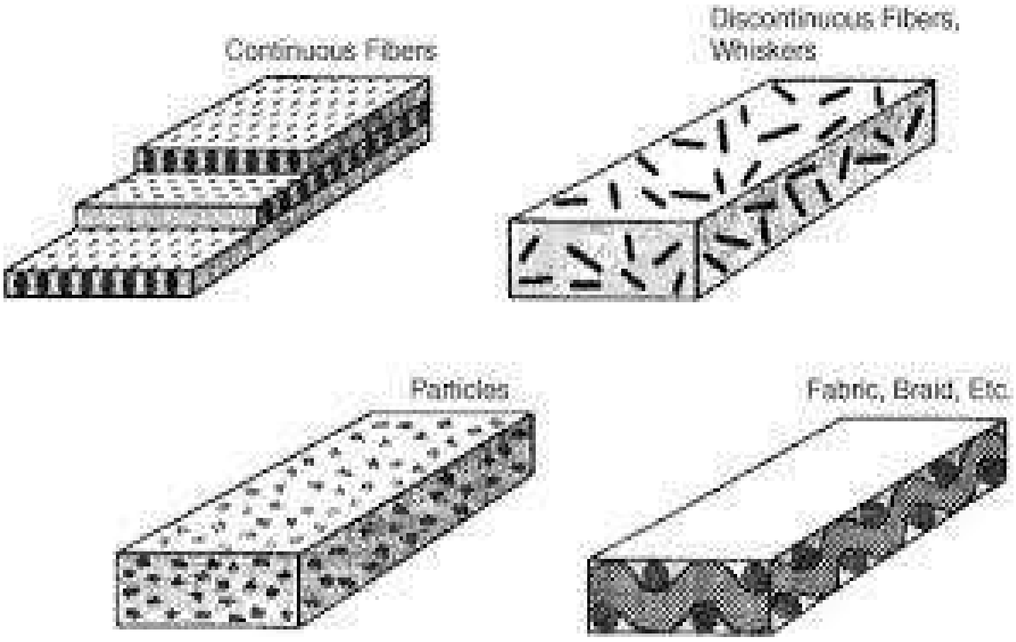


**Figure 2.3:** Type of reinforcements used in MMCs [17]

## 2.3 Metal matrix composites and their importance

Metal matrix composites (MMCs) consist of metal matrix and reinforcement. The matrix is metal in all MMCs, but metals alloys are preferred over pure metals as the matrix. The reinforcement generally used is in the form of particulate, fibers, whiskers, etc. While selecting the matrix for MMCs, high working temperatures, mechanical strength, oxidation and corrosion resistance, etc., are some factors kept in mind. Aluminium [18], Magnesium [19], Titanium [20] and Copper [21] are commonly used matrices in MMCs as of now.

For reinforcement, ceramics are preferred due to stiffness, high elastic modulus, low density, and strength. The few preferred ceramics are SiC, $Al_2O_3$, TiC, $B_4C$, borate whiskers, etc. [22]. The challenge these ceramics face in a metal matrix is that they are thermally unstable and form reaction products at the interface of matrix and reinforcement.

Aluminium has good ductility, thermal, electrical conductivity, and high strength. Along with this, it has good machinability and workability. Corrosion resistance due to $Al_2O_3$ layer formation on its surface also extends its usage in engineering applications. Although low hardness, limited strength, poor tribological properties, and low melting point lead to limited use of aluminium [23]. So aluminium is combined with other elements to enhance its properties, and one such combination is known as aluminium metal matrix composite. Aluminium matrix composites have pure aluminium or its alloy as one of the main constituents that serves as a composite matrix. The reinforcement is non-metallic and usually ceramic such as $Al_2O_3$, SiC, $Mg_2B_2O_5$, $ZrB_2$, and $ZrO_2$. The properties of such composites may be upgraded by varying the reinforcement type and their volume fraction in the matrix. Based on reinforcements, aluminium matrix composites are classified into the following types [24]:

i) Mono-filament reinforced

ii) Short fiber or whisker reinforced

iii) Continuous fiber reinforced

iv) Particulate reinforced

v) Hybrid composites

**(a) Monofilament reinforced aluminium matrix composites (MFAMCs)**

The reinforcements for these composites are produced using the chemical vapor deposition (CVD) technique. The filament size ranges between 100 to 150 µm and is made from silicon or boron by their CVD into carbon or tungsten fibres. The aluminium matrix does the distribution and transfer of load. These composites show lower strength when the direction of load applied is perpendicular to the direction of filament orientation [25].

**(b) Short fiber or whisker reinforced aluminium matrix composites (SFAMCs)**

The whisker-reinforced AMCs are fabricated by hydrolysis or powder metallurgy route. They exhibit properties between CFAMCs and PAMCs. The reinforcements are discontinuous, and their aspect ratio is more than 5μm. The characteristics of SFAMCs lie between PAMCs and CFAMCs. Health hazards restrict the use of such composites.

**(c) Continuous fibre reinforced aluminium matrix composites (CFAMCs)**

This is the most common type of AMC that is being used in various applications. The fibers are continuous with diameters less than 20 μm, e.g. SiC, carbon, or alumina fibers. The commonly used fabrication technique for these composites is the pressure filtration route. Fiber alignment is either pre-woven or parallel and braided before composite production [25].

**(d) Particulate reinforced aluminium matrix composites (PAMCs)**

The reinforcements in such composites are equiaxed ceramics with an aspect ratio less than 5, e.g. $Al_2O_3$, SiC, or $TiB_2$. They are cost-effective, but their properties are inferior to that of CFAMCs and SFAMCs and superior to that of non-reinforced aluminium alloys. They are fabricated using the solid or liquid state method. In secondary forming operations such as forging, extrusion, etc., composites are used [26].

**(e) Hybrid aluminium matrix composites (HAMCs)**

A mixture of the above-mentioned composites forms these types of composites. The processing techniques used to manufacture AMCs are categorized into the following two types:

1) Solid State

2) Liquid State

### Solid-State Processes

Metallurgy routes are adopted for composite manufacturing under this category diffusion bonding and powder category.

#### a) Diffusion bonding

In this technique, the bonding occurs by atomic interdiffusion on the surface of particulate and metal [27]. Although it commonly takes place in metals, ceramic can also join by this process. Uniform distribution of fibers is difficult to achieve through this method. 6061 Al-B fiber composite is manufactured using this method. Monofilament composite fabrication is done using this method.

#### b) Powder metallurgy

In the process of powder metallurgy, the constituents are powdered into small particles, their powder is mixed into the required proportion, then degassing and sintering is carried out at high temperature for pressurizing ceramics into a metal matrix [28].

### Liquid State Processing

Liquid state processing comprises four categories viz. In situ reaction synthesis, spray deposition, infiltration, and stir casting process.

#### (a) In Situ reaction synthesis

In this process, certain chemical reactions between the constituent elements and compounds are carried out to fabricate the reinforcements in the matrix [29]. However, clean interface and uniform reinforcement arrangement are obtained, but the process is restricted by a thermodynamic effect on the nature and composition of reinforcement.

### (b) Two-Phase processes

This technique is used to mix the matrix and ceramic in the phase diagram region where both solid and liquid phases of the matrix exist. This technique is further classified into two categories such as compo-casting/ rheo-casting and spray deposition.

### (c) Compo-casting /rheo-casting

The uniform mixing can be achieved to a greater extent by allowing the melt to cool to a more viscous; two-phase solid-liquid state before stirring. The advantage of the process is that it is easy to mix particles more uniformly in a fluid of lower viscosity than in one of higher viscosity [30].

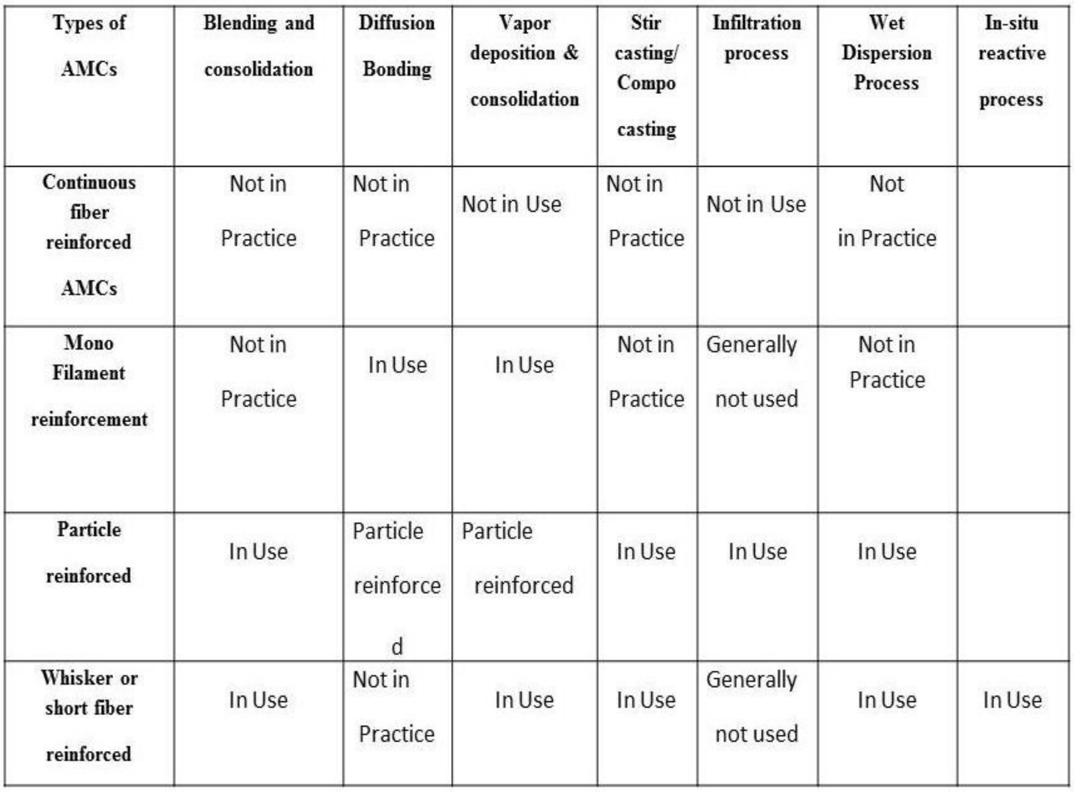
### (d) Spray deposition

This method follows the thermal spraying technique to atomize molten metal; droplets of this molten metal are sprayed into the substrate in a high-velocity gas stream along with the dispersed phase particles supplied from a separate container. This method is the most inexpensive method to produce AMCs. The limitation of this method is non-uniformity in the distribution of reinforcement into the matrix. This process is carried out in two ways, i.e. Thermal spray and osprey process. In the first process, molten metal is used to produce a stream of droplets, and in later, one cold metal is fed into a high-temperature injection zone [31].

### (e) Stir Casting

In this process, the reinforcements are added into the molten metal matrix by stirring, and then this mixture is allowed to solidify. Vortex enables constant stirring. Pre-heated ceramic particles are incorporated into the matrix while it is rotated using a rotating impeller. Segregation of reinforced particles and their settling down is a limitation this method faces. Wetting between the matrix and reinforcement, relative density, and solidification rate are factors that affect the dispersal of particles into the matrix [32].

**Table 2.1** Primary processing routes of AMCs [7]



| Types of AMCs | Blending and consolidation | Diffusion Bonding | Vapor deposition & consolidation | Stir casting/ Compo casting | Infiltration process | Wet Dispersion Process | In-situ reactive process |
|---|---|---|---|---|---|---|---|
| Continuous fiber reinforced AMCs | Not in Practice | Not in Practice | Not in Use | Not in Practice | Not in Use | Not in Practice | |
| Mono Filament reinforcement | Not in Practice | In Use | In Use | Not in Practice | Generally not used | Not in Practice | |
| Particle reinforced | In Use | Particle reinforced | Particle reinforced | In Use | In Use | In Use | |
| Whisker or short fiber reinforced | In Use | Not in Practice | In Use | In Use | Generally not used | In Use | In Use |

## 2.4 A review of aluminium metal matrix composites

### 2.4.1 Silicon carbide reinforced AMC

Improved strength to weight ratio, even more than three times that of mild steel, is obtained by reinforcing SiC in aluminium matrix. Additionally, this composite has high strength, modulus, thermal stability, load-carrying capacity, wear resistance, and less weight [33]. This makes it a promising material for the aerospace industry. The formation of a protective film of silicon oxide coating at 1200°C due to the presence of silicon carbide leads to oxidation and corrosion resistance. The following reaction takes place at the interface

$$4Al + 3SiC \rightarrow Al_4C_3 + 3Si \tag{2.1}$$

$Al_4C_3$ is insoluble and brittle and forms a precipitate or continuous layer on SiC particles. It also improves work hardening, fracture rate, ultimate tensile strength, and average offset yield strength (0.2%) with a slight decrease in ductility. Fracture or crack propagation occurs primarily through decohesion at the interface, when $Al_4C_3$ is absent. A binary alloy Al-Si also forms due to the entry of silicon in the Al matrix [34]. SiC and fly ash reinforced hybrid metal matrix composites were also reported. An increasing percentage of fly-ash and SiC increases dry sliding wear resistance, tensile strength, hardness, impact strength, and compression strength while decreasing density and fluidity.

With the simplicity and ability to produce large quantities, stir casting is the most viable process for particle reinforcement. Another advantage of this method is that, in principle, it allows the use of conventional metal processing routes hence the final cost of the product is reduced. During materials selection, design, and fabrication processes, various important factors like the type of the reinforcing material, its distribution in the matrix, SiC volume fraction, and interfacial reactions, are taken into consideration as it widens the scope of Al-SiC in aerospace industry applications (e.g. fuselage skin) [35-36].

### 2.4.2 Fly ash reinforced AMC

Fly ash consists of $Al_2O_3$, $Fe_2O_3$, $SiO_2$, and CaO. It also contains minerals such as hematite, quartz, mullite, spinel, magnetite, ferrite, alumina, and anhydride. They are obtained from residues, of coal particles and alumino-silicate-based ceramics, generated from furnaces. It also contains iron-rich spheres. By varying, the combustion temperature and cooling rate of the fly ash particle's morphology was controlled. This study observed the size of the particles ranging from less than 1 µm to greater than 200 µm was observed in this study. Most of the particles consisted of solid spheres, ranging from approximately 1 to 100 µm in size. Irregular shape unburnt carbon particles and hollow cenospheres were in the upper end of size distribution. The mixing amount varied for each particle of fly wash, leading to different surface and internal textures. Minor elemental correlations were shown by silicon-rich spheres and aluminium similar to mineral clay matter [37].

The contents in the physical and chemical properties of low calcium fly ash are a mixture of $Al_2O_3$, $Fe_2O_3$, and $SiO_2$ as revealed by X-ray diffraction (XRD) and EDX analysis. Small concentrations of several alkalies and metal oxides were also found. The fly ash had a complex and variable structure and morphology. The cooling rate influenced the particle size, which affected the structure of fly ash and its shape was spherical because of surface tension. The presence of quartz particles was expected in coal which simply passed through with fly ash. Although, from a single source, only small information was obtained on the crystallinity and density variation of fly ash and its constituent phase as a function of particle size. The mechanical properties of fly ash particles and their composites depended on fly ash particles' structure and chemical composition. The average microhardness of fly ash precipitate decreased with an increase in size which was below 100 µm. However, an increase in size led to an increase in hardness of fly ash that was larger than 100 µm, and in the case of less than 100 µm a wide scatter was observed. The porosity also predominates with an increase in particle size [38]. An improvement in hardness, stiffness, damping properties, wear resistance, and lower density was obtained by using fly ash as reinforcement. All these properties make it a promising reinforcement for AMCs. Ultra-light composites with low density are synthesized using cenosphere fly ash, which comprises empty particles. Fly ash composites find applications in the electromechanical industry and automotive parts such as casings, manifolds, shrouds, valve covers, pulleys, pans, etc.

Some authors observed the disadvantages of the liquid metal processing technique as they are susceptible to gravity-aided segregation, composite melt, the large scattering of the interparticle distance between fly ash particles, and higher processing temperature (greater than 1000 K) leads to enhanced interfacial reaction. An improvement in dispersion was observed by preparing Al–5% fly ash composites using semi-solid stir casting process (compo-cast), while casting in metal and graphite molds and solidifying in the crucible, to that by stir casting process. In this process, a highly viscous semi-solid slurry imparts a shear force over the agglomerates and helps in the better separation of dispersoids [39]. More equal distribution was obtained using graphite and metal molds i.e. solidification in crucible provides segregation and wider distribution range, likewise more particles with an interparticle distance between 30-100 µm. The ranges of interparticle distance 30–130 µm and 30–110 µm were obtained, having more than 5% frequency, in composites cast in graphite and metal moulds, respectively. The distribution of particles in composites synthesized using compo casting is better than those produced by stir casting process. In contrast, no severe interfacial reaction is observed in compo casting composites compared to stir casting composites. Compared to matrix alloy, an improvement in compression strength was also observed in Al-fly ash composites fabricated using modified compo casting. But tensile strength was reduced owing to particle fracture and matrix debonding [40].

### 2.4.3 $Al_2O_3$ reinforced AMC

The complex phases formed by $Al_2O_3$ in aluminium matrix improve its hardness and wear resistance, thus making it a suitable material for machine parts. To improve the tribological and mechanical properties in a motor block and crank bearing, these composites show favorable results. When exposed to hot air the aluminium or albite composites come in contact with nitrogen oxide, nitrogen monoxide, carbon dioxide, carbon monoxide, and some trace gases. During cooling, the interfacial region specified by high dislocation density generates due to differential thermal contraction. The dislocations have high strain energy associated with them which enhances the initiation of site oxidation, while specimens get exposed to high temperature [41]. The interface between matrix and $Al_2O_3$ particles enhances oxidation. These sites increase with an increase in reinforcement content, causing more oxidation in a matrix material. At the initial stage, the oxidation process of a matrix (6061Al) is rapid but decreases subsequently as further oxidation is prevented by an oxide layer formed on the surface. However, the cracks present on the brittle layer of oxidation limit the protection. The reinforcement particles of albite provide oxidation sites that further enhance the oxidation. When the temperature exceeds, 600K, oxidation is more severe. Being a soft material, aluminium exhibits poor wear resistance [41].

### 2.4.4 SiC and $Al_2O_3$ reinforced hybrid AMC

It is reported that $Al_2O_3$ and SiC reinforced AMCs are a good substitute for conventional gray cast iron in the automotive industry. As sliding velocity increases, also wear increases and increasing load reduces the wear. With increasing load, the wear mechanism appears to be sub-surface crack and delamination rather than abrasion. This leads to their increased application for piston-cylinder in the aerospace and automotive industry. $Al_2O_3$ is more cost-effective than SiC, thus making this combination a replacement for MMCs. Also SiC (2,800 $kg/mm^2$) is harder than $Al_2O_3$ (1,440 $kg/mm^2$) [42]. The impact of volume fraction and sintering temperature of $Al_2O_3$ on the mechanics of Al. A powder metallurgy technique was used to make the samples. The results show that as the reinforcement content and sintering temperature were increased, the hardness, compressive and tensile strengths also increased. Although, tensile and compressive strengths sharply dropped as sintering temperature, and reinforcement amount reached a certain value [43].

### 2.4.5 Albite reinforced AMC

Albite is an alumino-silicate ($NaAlSi_3O_8$) mineral mainly found in igneous rocks such as granite, also known as feldspar ceramic. The importance of alloy's microstructure in the cracking process was revealed by morphological analysis of the fracture surface. In Al-Si alloys, the morphology and volume fraction of precipitates of Si are influenced by the crack path and decohesion mechanism in alloys of Al-Si. It is noted that the casting conditions affect the alloy structure, yielding a significant change in both ductility and UTS. By adding albite particles in aluminium 356 alloy, an improvement in UTS (along with elongation of 18% and 25%), hardness, and young's modulus were obtained, along with a decrease in ductility. As compared to pure alloys, in MMCs (A356-3% Albite) a relative elastic strain and higher compression yield strength of 37.5% and 17 % respectively were achieved in plastic zones along with a slight increase in compressive strength [44]. The fracture toughness of A-356 alloy improved by 12% with a slight increase in hardness, adding 3% albite ceramic particles, due to albite dispersions in the matrix.

### 2.4.6 Aluminum nitride reinforced AMC

Microelectronic devices mainly find an application of these composites. The thermal conductivity of SiC (250 W/m K), is higher than AlN (175 W/mK), but AlN is more chemically stable than SiC. AlN has good interfacial adherence, thermo-physical properties, and non-reactivity at the interface. Several factors such as sub-structures, grain boundaries, secondary phases, solid solutions, etc. significantly affect metallic materials' mechanical properties. The effect of solid solutions and substructures can be ignored for the present materials. Improvement in hardness, high electrical resistivity, thermal conductivity, specific strength, stiffness, low dielectric constant, and tailorable thermal coefficient of expansion were obtained on grain refinement of reinforcement and matrix that AlN contributed. These properties make it a promising material for electronic packaging [45-46].

The XRD patterns revealed AlNp was stable thermodynamically at 1000°C fabrication temperature. Also, the peaks of AlNp were clear and increased as the AlN content increased while peaks of Al alloy decreased. The microstructural observation suggests that the reinforcement is distributed uniformly without porosity and crack. In optical micrographs, the appearance of single particles contains AlNp clusters. The micrographs clearly showed an interface between the AlNp reinforcement and Al alloy matrix and clusters of AlNp are spherical. The flowability of the Al matrix is resisted and Al alloy matrix ductile content reduces on increasing weight percentage of AlNp. The AlNp refined the grain size of matrix alloy and reduced the ductility [47-48].

### 2.4.7 Carbon nanotube reinforced AMC

Nano-sized reinforcements have drawn attention for MMCs in recent years due to their flexibility, high strength, conductivity, and elastic modulus and other attractive properties. The deposits of coatings of Ni–P-graphite, Ni–P-CNTs, and Ni–P–SiC composites on ring and block specimens. The microstructure of electroless composite coatings of Ni-P-CNTs was amorphous or changed from amorphous to crystalline state as revealed by XRD patterns. Compared to Ni–P-graphite, Ni–P and Ni–P–SiC, and electroless coatings, the Ni–PCNTs composite coating exhibited low friction coefficient and high wear resistance. The central hollow tubes of CNTs with diameters of a few tens of nanometers provide the unique topological structure and super-strong mechanical properties to Ni-P-CNTs composite coating. CNTs served as spacers on the surface when rubbed against another material, thereby decreasing the wear rate and preventing rough contact between the two mating metal surfaces [49]. As the CNTs have a large surface area, their high affinity for agglomeration is the main obstruction faced by their uniform distribution in the metal matrix.

In a metal matrix, the ball milling conditions needed to be optimised to obtain better CNT dispersion, reduce the cold working of a matrix, minimum damage to CNTs, and improved metal/CNT interface [50].

### 2.4.8 Whisker and short fibre-reinforced AMC

Whisker reinforced aluminium matrix composites have been fabricated and studied for decades because of their low density, thermal expansion coefficient, and mechanical properties. However, their applications are still limited by the restraints of secondary forming applications.

## 2.5 Synthesis and characterization methods of ABO whisker by various routes:

The synthesis of uniform diameter single-crystal alumina borate nanowires ($Al_{18}B_4O_{33}$) by a chemical reaction of alumina with boron monoxide in the presence of a supported catalyst was also done in which the TEM analysis of microstructure revealed the nanowire structures were one-dimensional. $Al_4B_2O_9$ nanowires of an average diameter of 17 nm were in significant proportion in TEM specimens. As the mol ratio of $Al(NO_3)_3$ and $H_3BO_3$ ranges from 1:3 to 1:6, the average diameter of $Al_4B_2O_9$ nanowires increased from 7 to 17 nm with the increase in flakes quantity well. This phenomenon can be ascribed to the rise in $B_2O_3$, which resulted in the continuous growth of nanowires for a significant sticking coefficient. These nanowires crystallized, as revealed by their SAED patterns. The length, diameter, and nanowires yield depend upon isolated reaction area at nanometre scale and the abundant local reactants at an appropriate reaction temperature [51].

$Al_{18}B_4O_{33}$, $Al_4B_2O_9$, and alumina borate crystal were synthesized on Pt, and NiB powder coated substrates of Sapphire and Al films. In which the chemical vapour deposition method was used to synthesize $Al_{18}B_4O_{33}$ nanowires and nanotubes at 1000°C using boron trioxide and boric acid ($BI_3/H_3BO_3$) vapour with argon gas as the precursor. In SEM observations, it was found that no nano-structures were formed on bare substrates of sapphire and other kinds of substrates with catalysts, while nanotubes or nanowires were formed on sapphire substrates with catalyst. The diameter and length varied between 10–500 nm and 300 nm–2µm, respectively [52]. The crystal structures of $Al_{18}B_4O_{33}$ and $Al_4B_2O_9$ are very close. While the melting point of $Al_4B_2O_9$ is low (1035°C), $Al_{18}B_4O_{33}$ has a relatively high melting point of 1950°C.

The chemical flux method for the growth of the alumina borate ($Al_{18}B_4O_{33}$) nanowires in high yield was used by some authors. In this method, aluminium powder is added as an additive into boron oxide and aluminium oxide to control the morphology of the final products. This method is adopted to increase the lengths and decrease the diameters of aluminium borate whiskers up to nanoscale. When the aluminium content added is 2% by weight to total reactant precursor, relatively large diameters (120–200 nm) of nanowires common to all were obtained. It was also found that the surface morphology was improved and the diameter also reduced when Al metal powder was added to usually used oxide precursors, and $Al_{18}B_4O_{33}$ nanowires also grew in abundance [53-54].

The well-crystalline $Al_4B_2O_9$ nanorods were synthesized by a low-heating-temperature solid-state precursor method. The use of a metal catalyst or protective gas was not involved in this process. The results showed that the products possessed a large surface area, a single-phase length of up to several micrometres, and narrow size distribution of 20–30 nm. The synthesized precursors have a high reaction activity and large surface area. As a result, at a relatively low temperature and a shorter calcination time, $Al_4B_2O_9$ nanorods were obtained [55]. The morphology of the samples mainly depends on the precursor preparation and the synthetic method. This method does not need any seed, catalyst, or surfactant, which may be promising for low-cost and large-scale production along with high-quality. It might be extended to the synthesis of one-dimension nanostructures of borate.

The ball milling method was adopted for developing single-crystal alumina borate ($Al_4B_2O_9$) nanowhiskers with diameters ranging from 20 to 200 nm on the aluminium powder surface at low temperatures. The growth of the nanowhiskers took place at a relatively low temperature of about 650°C, due to pre-treatment of ball milling. It was found that with increasing temperature, the average diameters of nano-whiskers increased while their lengths were independent of the growth temperatures. The ball milling pretreatment promotes the nano-whisker growth at a relatively lower temperature, during which the dissolution of reactants and the liquid phase formation process are enhanced. To determine nanowhiskers size the calcination temperature is also a key factor [56].

The molten salt process was also used to synthesise single-phase alumina borate ($Al_{18}B_4O_{33}$) whiskers. The growth mechanism followed was a self-catalytic one instead of vapour liquid-solid mechanism. At 1000°C, High crystallized alumina borate whiskers of the orthorhombic structure were obtained. Very clear and straight synthesis products were received at different dosages of $H_3BO_3$, and the granular particles were also scarce. Although, the lengths of whiskers were different for various $H_3BO_3$ dosages.

Longer whiskers were obtained at 0.185g of $H_3BO_3$ dosage, and shorter whiskers were obtained at 0.145g [57]. These results may be because, in the molten state, the supersaturation degree of $B_2O_3$ was limited; at low $H_3BO_3$ dosages. The $Al_{18}B_4O_{33}$ whiskers were 50–150 mm in length and 1.3 mm in diameter, implying a high growth rate.

## 2.6 Aluminum matrix composites reinforced with $Al_{18}B_4O_{33}$ whisker-framework

Aluminium matrix composites were manufactured by squeeze casting using in situ synthesized porous alumina borate ceramic with whisker-framework structure. Compared to SiC whiskers, the method was cost-effective and harmless to humans and the environment. The fatigue behaviour was studied between the temperatures ranging from room temperature to 723 K. The increase in volume fraction of ABO reinforcement led to an increase in fatigue life. It can be seen that the hardness increases by 80% for matrix alloy and 20% whisker reinforced composite by 5%, after the heat treatment. The whiskers provided the strengthening effect of both tensile and fatigue strength at higher temperatures than ambient temperature. The cast defects and primary Si relate to the matrix's fracture [58]. Due to the decrease in the size of the primary Si in composites, there were fewer fractured blocks of primary Si on the fractured surfaces. The cluster of whiskers and cast defects are origins for fracture as exhibited by fatigue and tensile fracture surfaces in the composites at room and high temperatures.

The fracture characteristic of aluminium alloy 6061 reinforced with alumina borate whisker-reinforced was studied. With an increase in the time of T4 treatment, the degree of interfacial reaction increased, with optimal effect on tensile properties. The crack propagation and fracture behaviour of composite corresponds to its mechanical behaviour and degree of interfacial reaction. As interfacial reaction produces more particles of reaction products, the solution treatment makes the interface rougher, as revealed by TEM micrographs of as-cast composite. A fracture model explained that the progression of fracture occurs due to the connection of the main crack and sub crack in its front, which forms due to external stresses but not because of propagation of the main crack itself. The sub cracks on the fracture surface sides changed due to the solution treatment. The sub cracks reduced in size, and the distribution area extended as the treatment went on, and solution time shortened. Also, they become larger as T4 treatment time increases, and the sub cracks become larger near the main crack. These differences led to the peak of the tensile performance of the composites [59].

The fractured surfaces and the effect of interfacial reactions on fractal surfaces in aluminium alloy 6061 composites reinforced with alumina borate whisker were examined. The squeeze-casting technique was used to fabricate composites. The vertical sectioning method was used to measure fractured surfaces in the tensile test. The measuring units ranged between 3 to 15 µm and 1 to 5 µm respectively, were used for fractal phenomena in two plots. The measuring units in fractal dimensions of 3-15 µm were correlated with tensile properties. The degree of interfacial reactions affected the fracture mode, and fractal dimensions increased, leading to an increase in surface roughness. The ultimate tensile strength also improved. It was concluded that composite mechanical properties are not reduced by suitable interfacial reaction and leads to an improvement in the ability of stress transfer of the interface between matrix and whiskers. A better stress transmission from soft matrix to stiff whiskers, which leads to better performance, conduces due to the optimum amount of spinel, also increases surface roughness [60]. The significant brickle reaction produces if the degree of interfacial response is high, making the interface easy to laminate. It will be flat and easy to debond if the degree of interface reaction is low. But the composites give poor performance in both conditions as the mechanical properties depend on the strength of interfaces.

## 2.7 Aluminium metal matrix composites reinforced with coated alumina borate whiskers

Aluminium matrix composites reinforced with ZnO-coated aluminiua borate whiskers, were fabricated by squeeze casting. The study includes coating content effect of on the tensile properties and matrix/whiskers wettability of the composite. It was found that the interfacial wettability increased with increasing coating percentage. The elongation to fracture, ultimate tensile strength, and fracture mechanisms of composites were also studied with respect to coating content. With an increase in coating contents, the tensile strength increases almost linearly; elongation to fracture ($\delta$) of composites depends upon interfacial coating contents. The microcracks and holes decrease the $\delta$ of the composite in the absence of coating content. However, due to the fracture of brittle phases of $Al_2O_3$, a decrease in the $\delta$ of composite takes place, when the coating content at the interface is large. Whiskers slide in the matrix and consume the grinding force during the tensile deformation, only when optimum interfacial coating content [61]. Thus giving a maximum value of $\delta$.

The 2024Al composite reinforced with ZnO-coated alumina borate whiskers was fabricated by squeeze casting. Tensile properties, interfacial microstructures, and fracture mechanisms of as-cast composite and after thermal exposure were investigated. The ZnO coating of the whiskers forms an interface while squeeze casting, reacting with molten 2024 Al and $MgAl_2O_4$. At high temperatures, due to the presence of Mg in the matrix, the thermal stability of composites improved. The discontinuous particles covered the surface of the extracted whiskers from $ABO_w$/2024Al composite, and the whiskers integrity is destroyed. A relatively smooth and thin layer of the continuous product-covered surface of ABO whiskers was extracted from the $ABO_w/ZnO/2024Al$ composite. During squeeze casting, $MgAl_2O_4$ produced at the interface can successfully separate $ABO_w$ from the matrix successfully thus affecting tensile properties after a long exposure to high temperature. As a result, the tensile properties slightly decrease after thermal exposure for 10 h at 490°C [62].

The ZnO coated alumina borate whiskers following the sol-gel method and reinforced 2024Al matrix with these coated whiskers, by squeeze casting, were investigated. Tensile behaviour of composites with respect to aging treatment was studied. The solid solution treatment for 2h at 490°C and aging treatment for 8h at 170°C, resulted in the best tensile properties for the given composite. The aging behaviour of the composites significantly changes due to ZnO coating on aluminium borate whiskers. Many holes and micro-cracks were found in the $ABO_w/2024Al$ composite. This may be due to the matrix and whiskers debonding during tensile deformation or by poor wettability of $ABO_w$ and 2024Al causing unfilled regions of molten aluminium, during squeeze casting. The composites have low tensile properties. However, the interfacial wettability improves in the $ABO_w/ZnO/2024$ Al composite when the ZnO coating of $ABO_w$ reacts with molten 2024Al. The resistance to pull-out of whiskers and the interfacial bonding strength increases, so the composite's UTS and $\delta$ (strain) increased [63].

Aluminium reinforced with $Bi_2O_3$ coated and non-coated alumina borate whiskers fabricated via squeeze casting. The damping measurements with thermal cycling were carried out, to analyse the damping behaviour of composites. The damping mechanism accounted for the strain boundary, dislocation motion, and interfacial slips during thermal cycling. The damping-temperature curves of $Al_{18}B_4O_{33}/Al$ composite with and without coatings of whiskers reflected distinct features. At different frequencies, it was observed that the damping capacities increased for all the composite samples with an increase in temperature. $ABO_w/Al$ composite was observed to have the lowest damping value among all the coated composites. It was noted that with coating contents, the damping values increased, also for coated composites, damping peaks existed, without any change in peak temperatures. The dislocation and damping were affected by the amount and mobility of dislocations as the manufacturing process and volume fraction of all composites are the same so there should not be much difference in their dislocation densities. However, the coefficient of thermal expansion of Al is close to Bi [64]. The presence of free dislocations increases the mobile dislocations density, accounting for the difference in the $ABO_w/Al$ composite and coated composites' damping capacities. The internal low-temperature friction peaks in the coated composites exist due to the interfacial slip and increase of the density of the mobile dislocations between whisker/Bi.

## 2.8 Dry sliding and wear behaviors of aluminum metal matrix composites

Tribology (study of wear, friction, and lubrication) deals with the contact mechanism of surfaces moving each other, which involves energy dissipation. It deals with the science of friction, wear, lubrication and adhesion. The father of modern tribology Leonardo da Vinci credited with pioneering studies on the various subtopics of the tribology such as bearing materials, friction, plain bearing, wear, lubrication system, screw-jacks, rolling-element bearing, and gears.

Wear is the main reason for the material loss, and deteriorating mechanical behaviours and any decrease in wear may result in a significant saving. Wear and dissipation of energy are mainly caused by friction, and any improvement in friction control leads to the substantial saving of energy and materials. It has been evaluated that one-third of the current world's energy resources are utilized to overcome friction [65].

Based on the nature of the movement of the media involved in interaction under load, different types of wear have been classified based on the action involved as follows:

- Wear due to adhesion(Adhesive wear)
- Wear due to abrasion (Abrasive wear)
- Wear due to erosion (Erosion wear)
- Wear due to impact (Impact wear)
- Wear due to fatigue (Fatigue wear)
- Wear due to corrosion (Corrosion wear)

**Adhesive wear** is associated with low sliding velocity, small load and smooth surfaces. This is a universal type of wear that is hard to eliminate; adhesion process involves the contact of asperities on two mating surfaces in relative movement. The asperity contact may join together or develop a bond at the junction when the asperities come into contact and which has higher or develop a bond at the junction when the asperities come into contact and which has higher rupture strength than the yield strength of one of the contacting materials.

**Abrasive wear** occurs when two surfaces, harder and rougher than the other, are in sliding contact. Abrasive wear is the process of removing or displacing materials by ploughing or micro-cutting from one surface by the harder asperities of another surface or by loose harder particles. This type of wear is dangerous because it can occur suddenly with the introduction of a contaminant and may lead to high wear rates and extensive damage to the surface.

**Erosive wear** is the combined process of repeated deformation and cutting. When the action of fluids and particles gradually wears away a solid surface, it is called erosion. Erosion of material can take place under four different conditions:

- Impingent of solid particles against a solid surface
- Impingent of liquid droplets against a solid surface
- The flow of hot gases over a solid surface and
- Cavitation at a solid surface in liquid media

**Impact wear** arises from the repetitive impact of two surfaces, which differ from the impact of solid particles on the surface, causing erosive wear.

**Fatigue wear** refers to the repeated imposition of cyclic loading or stress on the surface of materials, developing a low degree of mechanical damage to the surface and subsurface region with each cyclic loading or stress imposition.

**Corrosive wear** is a process of material degradation where both corrosion wear and wear mechanisms are present. Intense damage material loss takes place as a result of corrosion and wear. When introduced either of these mechanisms alone, the effects can be more damaging. Most commonly in plastic processing, the chemicals and acids produced result in corrosive wear, as these substances attack barrels' and screws' surfaces. Pitting is one of the main characteristics of corrosive wear that takes place in the metering and transition zone's last flights. These pits may also lead to:

- Degradation
- Melting
- Burning

A simple theoretical analysis involving two contacting surfaces sliding over each other under a load normal to the sliding surfaces has carried out by Archard (1953). It was suggested that the communication between the two characters is supposed to happen at the asperities. The true area of contact is equivalent to the summation of the individual asperity. Therefore, from the above definition, the softer materials' hardness, the contact area, Ar, which is the indentation area under the indentations of the harder materials are related by the following expression,

$$A_r = \frac{w}{H} \qquad (2.2)$$

Where, W-applied normal load

H-Softer surface's hardness

The volume of material wearing out for a unit distance of sliding has following relation with real contact area, Ar and the Eq.**2.1** can be written as,

$$Q = KA_r = \frac{KW}{H} \qquad (2.3)$$

The constant K is the coefficient of wear, which is dimensionless and is always less than unity, i.e. in the range of $10^{-5}$ to $10^{-3}$. The dimensionless wear coefficient K is considered by many as an important way of comparing wear processes in various systems.

The resistance offered by any materials may be known as friction force while moving over each other. So, based on this definition of a force of friction, the relative motion can be classified into two important classes ie; sliding and rolling. In both these motions, ideal rolling and sliding, a force in a tangential direction, *F* is required to travel the body over the immobile counterface.

Therefore, the ratio of this tangential force of friction and the applied normal load can be identified as the coefficient of friction generally denoted by character μ:

$$\mu = \frac{F}{W} \tag{2.4}$$

The value of the coefficient of friction conventionally defines the degree of frictional force. For most materials that slide over another surface in the presence of air, the values of μ typically vary in the range of 0.1 to 1.

The laws of friction may be defined as follow:

- The frictional force directly relates to applied load in normal direction.
- The frictional force does not depend on the apparent contact areas.
- The frictional force is independent of the velocity of sliding.

Due to superior wear resistance and high specific strength, much attention and wide acceptance have been gained by aluminium–matrix composites. Many researchers have studied their tribological behaviour because of their application as brushes, bearing material, contact strips, etc. It was also found that on the addition of ceramic particles, as compared to pure alloy, the seizure resistance of composites improved at high temperatures, SiC is more effective than $Al_2O_3$. Compared to other composites, hybrid composites showed better resistance to wear at high temperatures [66].

The as-cast Al-7Si/$TiB_2$ in-situ composite's wear characteristics were studied. It was observed that with an increase in $TiB_2$ particles weight percentage, the composite's abrasive wear rate decreases, and on increasing the load wear resistance decreases. It was also revealed that the volume loss decreases with increasing the weight percentage of $TiB_2$ particles and increases as distance traversed increases [67].

The $SiC_p$ reinforced aluminium matrix composite's abrasive wear behaviour was studied. It was observed that on increasing sliding distance, abrasive size of SiC emery paper, and applied load, the wear rate increased while with a sliding distance of $Al_2O_3$ paper it decreases. It was also concluded that the load is the most important factor affecting the coefficient of friction of hybrid composite along with sliding distance. On increasing the load and sliding distance, the coefficient of friction increases. Compared to pure alloy, the average coefficient of friction of hybrid composite is relatively low [68].

The development of the aluminium matrix composites (AMCs) reinforced with in-situ $AlB_2$ particles using hot rolling, powder metallurgy, and solution treatment was carried out. The formation of in situ albite particles significantly improved the wear resistance of pure aluminium. Likewise, the increased applied load linearly increases the friction coefficient and wear area. However, in this study coefficient of friction is affected by sliding speed, without any regular change. To improve the distribution of reinforcement in the matrix, few authors reported about modified stir casting methods but there is a lack of work on the availability of efficient methods for reinforcements at a nano-level [69-70].