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## CHAPTER 2

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### LITERATURE REVIEW

#### 2.1 APPLICATION OF Al ALLOYS FOR AUTOMOTIVE COMPONENT

Automotive industries face challenges in improving fuel efficiency, performance of engines due to strict environmental regulations. A most feasible way to enhance the efficiency of an engine is by cutting the vehicle weight. Over the past few decades, Al-Si alloys have been utilised extensively in automobile sector as substitute material to cast iron/steel in manufacturing automotive components owing to its greater stiffness. With this view, Al alloys such as A356, A319 and A390 alloys are frequently utilised in the fabrication of cylinder heads, liners, engine blocks, pistons, etc. The main benefit of Al alloys, besides higher specific strength, is higher thermal conductivity compared to cast iron which allows faster heat extraction. Maximum operating pressure and temperature of engine needs to be increased, particularly in diesel engines to improve the engine efficiency and achieve emission standard requirements.[1, 7, 50]

Despite these advantages, main issue with Al alloys is its inadequate wear resistance for engine block material, cylinder liners and pistons. Thus, fortifying the cylinder wall with suitable technique is essential to meet the required tribological characteristics. Further, Al-Si cylinder block with cast iron liners increases the weight and mismatch of coefficient of thermal expansion and deform liner which reduces the heat extraction leading to increased fuel consumption and emission. Al-Si based engine block without liner improves the thermal conductivity, allowing to reduce the engine size for same power output.

The potent alternative to conventional Al cylinder block fitted with cast iron liner is aluminium matrix composites (AMCs). AMCs can be employed in two ways- either the entire engine block can be made up of monolithic MMCs or only cylinder liner made of MMCs could be placed into a Al–Si alloy cylinder block [39].

Further, sections will discuss various type of composites, fabrication techniques, and their properties such as morphology, mechanical, and tribological properties.

## **2.2 COMPOSITE MATERIALS**

Composite material signifies to a material system composed of distinct constituents dispersed in a continuous phase. The constituents phase called reinforcements and continuous phase is termed as matrix. Composite materials derive distinguished characteristics from the constituent reinforcements and matrix phase due to the geometry of the constituents and interfacial properties [5, 51].

## **2.3 CLASSIFICATION OF COMPOSITE MATERIALS**

Composite materials are categorised based on physical and chemical characteristics of matrix phase: Polymer matrix, ceramic matrix, and metal matrix composite.

### **2.3.1 Polymer matrix composite**

Polymer matrix composite (PMCs) consists of a polymer matrix reinforced with fibres. Various reinforcing materials such as glass fiber, carbon fiber and aramid fibers are used in the PMCs. PMCs are utilised in a range of applications such as aircrafts, automobiles, roofing structures, and interiors because they are lighter, stronger, and stiffer than unreinforced polymers, with the added benefit that their properties and shape can be modified to meet the demands of a given application. PMCs are further classified as thermoplastics and thermosetting polymer composites on the basis of bonding present. The use of thermoplastic based PMCs for engineering application are more common due

to good mechanical properties, outstanding chemical resistance, and lower fabrication cost. Various fabrication methods such as injection molding, compression molding, sheet molding, resin transfer molding prepreg tape lay-up, hand lay-up, pultrusion etc. have been used for production of PMCs. The major drawbacks of using PMCs are generation of hazardous air pollutant during manufacturing and non-bio-degradability after end use [52, 53].

### **2.3.2 Ceramic matrix composite**

Ceramic matrix composites (CMCs) are composed of ceramic fibres or whiskers incorporated in a ceramic matrix. Commonly used reinforcement fibers in CMCs are carbon, SiC, silicon nitride, glass, basalt, and boron. CMCs have excellent characteristics which include low density, high-temperature resistance, high specific strength and modulus, corrosion, and ablation resistance. CMCs are developed mainly focussed on reduction in brittleness with superior toughness. CMCs can be manufactured using Liquid phase route-reactive melt infiltration, hot iso-static pressing, vapour phase route-chemical vapour infiltration solid state route- powder mixture. Although, CMCs have excellent properties but high fabrication cost, high energy requirement and difficult machining restrict the utilization of the CMCs[54, 55].

### **2.3.3 Metal matrix composite**

Metal matrix composites (MMCs) are comprised of a minimum two or more physically distinct and chemically separable phases properly dispersed to impart characteristics that cannot be achieved with the individual phases. In MMCs, a metal or alloy is generally used as matrix phase, and the reinforcement may be metallic or ceramic. They offer great advantages of flexible design, tailor-made materials as per the requirements in an aerospace structure, automotive components, transportation, and

defence [56, 57]. Generally, aluminum, magnesium, copper, titanium, and their alloys are utilised as matrix phase. The reinforcements are generally used as fibers, whiskers and particulates of various metal nitrides, oxides, borides and carbides. Particle reinforced MMCs are preferred over the fibre and whisker reinforced materials due to the lower fabrication cost, easy processing and isotropic properties [58]. High demand with varying properties and requirement of high-performance in automotive and aerospace industry aluminum matrix composite (AMCs) gaining more importance but we require different reinforcements and manufacturing techniques to fulfil these.

AMCs offer superior combination of properties and are used in various structural and functional applications. Performance, economic and environmental advantages are the key factors behind the utilisation of AMCs in these fields. Lesser consumption of fuel and emissions are the main advantages of using AMCs in transportation sector. Application of AMCs in transportation industry will be unavoidable and vital in upcoming years due to stringent environmental regulations and priority on improved fuel economy[5].

The objectives for development of lightweight composites are[8]

- Improvement in tensile strength while preserving ductility and toughness,
- Improvement in Young's modulus,
- Improvement of wear behaviour (sliding contact),
- Enhancement in fatigue strength, specially at higher temperatures,
- Enhancement in creep resistance compared to conventional alloys,
- Improvement of corrosion resistance,
- Reduction of thermal elongation.

## **2.4 FABRICATION PROCESSES OF AMCs**

AMCs can be produced by using insitu route or exsitu route. In exsitu method, reinforcing phase is externally synthesized and added to the matrix, whereas in insitu method reinforcement is produced during the synthesis of composite through controlled reactions. The insitu synthesis of reinforcements results in good wettability, clean interfaces and better bonding with the matrix, thermodynamically stable phase and even dispersion of particles in matrix [16, 20].

Metal matrix composite (MMCs) can be fabricated by several methods. The fabrication route employed is decided on variety of parameters, including type of reinforcement, its dispersion, matrix-particle bonding, microstructure, simple method, and cost-effectiveness. The fabrication technique commonly used to develop AMCs can be categorised into- liquid, semisolid and solid state processes.

### **2.4.1 Liquid state processes**

Liquid-state methods are popular because they are easy, inexpensive, and possibly scalable to large scale. Stir casting, centrifugal casting, infiltration methods, ultrasonic-assisted casting, and disintegrating melt deposition (DMD) technique are among these methods.

#### **2.4.1.1 Stir casting**

Stir casting is the most basic and commonly used method. The introduction of reinforcements into the molten metal/alloy matrix, followed by casting. It is crucial in this process to have adequate wetting between the matrix and reinforcement. Properties of the composite produced using stir casting technique can be changed by varying process variables like stirring speed, stirring duration, processing temperature, pouring temperature, etc[59].

The reinforcement particle can be dispersed homogeneously into the liquid melt by rotating rotor that creates a vortex. The finely distribute melt slurry is shaped by various casting technique such as sand casting, permanent mold casting, pressure die casting or squeeze casting. However, some problems related with the stir casting technique are gas entrapment and slag inclusion in composite, leading to higher porosity and casting defects. Undesired chemical reaction at interface and lower wettability of reinforcement particle increases the particle agglomeration tendency especially in case of nanoparticle reinforcements results in deteriorating material properties[60].

#### **2.4.1.2 Centrifugal casting**

Centrifugal casting is a comparatively low-cost technique that enables excellent reinforcement placement by creating a centrifugal force simultaneously during casting. This method ensures intentional variation of volume fraction of reinforcement across the cross-section in the matrix. Centrifugal casting is used in fabrication of brake rotors, where higher wear resistance is required at rotor face than at the hub. This method reduces the machining of composite which is difficult due to high hardness of the composites [61] [Chawla, 2006].

#### **2.4.1.3 Infiltration process**

Infiltration method includes pressure-assisted injection of molten metal into a porous preform. This method has been extensively utilized to fabricate composites containing reinforcement, for example SiC particles and foams, TiC, glass fiber, Al<sub>2</sub>O<sub>3</sub>, AlN, and Al<sub>4</sub>C<sub>3</sub>. The pressure assisted infiltration method may be employed in two ways: gas infiltration and pressure infiltration. To complete the infiltration of gas, a vacuum or inert gas environment is used. The primary benefits of this process include increased

wettability owing to higher reinforcement activity in vacuum environments, lower porosity, and near net shaped production of components. Disadvantage of this method is segregation of reinforcement particles and reaction between matrix and reinforcements at interface. Recently, pressure less infiltration process has been applied to infiltration of ceramic preform without application of external pressure or vacuum. Merits of this method is lower cost compared with the pressure infiltration technique as it does not need expensive equipment. Limitations of this method are high preform cost, lower wettability and low volume of material can be processed due to longer infiltration time [62]. Zhou et al. adopted similar method to developed CNTs reinforced Al composites, by infiltrating LY12 alloy (Al–Cu–Mg) in CNT–Al–Mg preforms, with 5 h infiltration duration [63].

#### **2.4.1.4 Ultrasonic-assisted casting**

Ultrasonic assisted casting approach is helpful in reducing particle clusters in composites caused by nanoparticle agglomeration and low wettability. Agglomeration of particles generally occurred in conventional stir casting method, whereas, ultrasonic-assisted method uses ultrasonic waves (frequency: 18–20 kHz) treating the melts after addition of reinforcements followed by casting. In liquid melts, high-intensity ultrasonic waves can produce transient cavitation and acoustic streaming. Acoustic streaming in melt generates a pressure gradient that induce stirring effect. Cyclic ultrasonic waves in the liquid phase trigger the development, growth, pulsation, and generation of small bubbles. The trapped air in voids of particle clusters acts as nucleus for cavitation, that breaks the clusters thereby giving uniform dispersion. Although, this method is successful in dispersing nanoparticles and reducing clusters, but scaling up of this method for industrial applications is quite difficult, because the quantity of castings is restrained by the capacity of the ultrasonic source [64].

#### **2.4.1.5 Disintegrated melt deposition (DMD)**

Disintegrated melt deposition (DMD) is a process that combines casting and spray processes. It includes integrating reinforcement phase by agitating the melt with the stirrer when particles are introduced. Then, composite slurry is fragmented by inert gas jet at superheated temperature and placed on the metallic substrate. This method may be used for fabrication of Al and Mg composite but most commonly it is used for Mg nanocomposites because it can overcome various drawbacks of conventional processes of making Mg composites. These drawbacks include oxides in the product because highly oxidizing character of Mg and retention of reinforcements in the crucible owing to differences in density of Mg-matrix and reinforcement. These may introduce the impurities; lower amount of reinforcement and uneven distribution of reinforcement can deteriorate the properties [65].

#### **2.4.2 Solid state processes**

Solid state processes comprise fabrication of composites in solid state condition, for example powder metallurgy, mechanical alloying, diffusion bonding etc.

##### **2.4.2.1 Powder Metallurgy (PM) method**

Powder metallurgy (PM) methods typically include the following steps: mixing reinforcing phase and matrix alloy powders via ball milling or reactive mixing; compacting the blend through cold pressing known as green compacts; degassing the compressed structure to eliminate volatile substances such as lubricants, blending and mixing additives; and green forms then further consolidating via various methods including hot isostatic pressing (HIP), direct sintering, spark plasma sintering etc. [66].

PM techniques may be utilized to produce composite components as well as small components in large volumes. The major advantages of PM techniques are less problems related to wettability, large volume percentage of reinforcements may be added and variety of metal-reinforcement combination can be achieved, which is not possible by conventional liquid state process. Although, PM route has various benefits, however, some drawbacks of this methods are high cost, oxidation of metal powders which requires inert atmosphere, high porosity level in PM components that leads to the poor mechanical properties especially poor ductility[67].

#### **2.4.2.2 Mechanical alloying**

In mechanical alloying (MA), the powder particles are forced to undergo cold welding, fracture, and rewelding, which bonds the matrix and reinforcement together. Refined particle size and the dispersion of nano particles are used to strengthen metallic alloys. The ball-to-powder ratio (BPR), duration, and milling rotational speed are the primary process variables that may affect the properties of composites. Powders are consolidated, degassed, and compacted after milling. Powder contamination must be properly handled throughout the process. Contamination sources include the milling environment, milling tools, and process control agents such as lubricants and surfactants. Impurities may affect grain growth and microstructural development during consolidation, reducing the mechanical characteristics of the resulting composite [67, 68].

#### **2.4.2.3 Diffusion bonding**

Diffusion bonding is a solid-state method applied for fabrication of composites due to inter diffusion of atoms between metallic surfaces. This process is commonly used to produce fiber reinforced Ti composites. AMCs reinforced with mono filament or boron

fibers are also generated through diffusion bonding using foil-fibre-foil technique. This method is not suitable for composites containing high fiber volume fraction, uniform fiber distribution and to produce complex shape components[5].

### **2.4.3 Semisolid processes**

Semisolid casting techniques include moulding a partially solid mixture (slurry) with 20-60% solid fractions and comparatively small globular grains. The advantages of semisolid process are lower processing temperature, non-turbulent filling, lower shrinkage porosity and uniform dispersion of reinforcements. Semisolid casting is broadly classified into two route called thixo-casting and rheo-casting[69].

#### **2.4.3.1 Thixo-casting**

In thixo-casting a solid feedstock with an equiaxed or globular, non-dendritic structure is heated until it partially melts. Thixo-casting is process of forcing the reheated billet into the die by placing it in shot chamber of a die casting equipment [70]. In order to stimulate the production of crystals in the slurry, material is produced by partially solidifying a liquid melt under specific conditions like low superheat and fast cooling. The globular and non-dendritic structure feed stock may be produced by various technique which include mechanical stirring in rheo-casting, magneto-hydrodynamic stirring, and ultrasonic treatment for grain refinement during solidification [71].

#### **2.4.3.2 Rheo-casting**

In rheo-processes, globular or non-dendritic feedstock is not required as in thixo-casting. The semi-solid slurry is formed by cooling the molten metal from its liquid state during the casting process. Rheo-processes are simpler to execute in foundry since they use conventional equipment for melting, transporting, treating, degassing, and handling. There are various approaches in the production of melt slurry but large efforts are made

to produce on demand slurry production capability. A new rheo-casting approach uses cooling slope to produce the melt slurry. In this technique melt at moderate superheat is poured on the cooling plate and large number of small crystals are generated due to high temperature difference and fragmentation of dendrites. These crystals are distributed uniformly into the slurry and act as nuclei which refine the grains. Although many rheo-processes have been used for semisolid metals, However, there has been relatively little investigation into the application of these techniques in the manufacturing of composites.

Since its inception in the early 1970s, many semisolid techniques have been used, such as magnetohydrodynamic stirring, ultrasonic vibration, strain induce melt activation, cooling slope casting process, etc. Cooling slope casting is one of the easiest methods because of its simple design and low cost [72, 73].

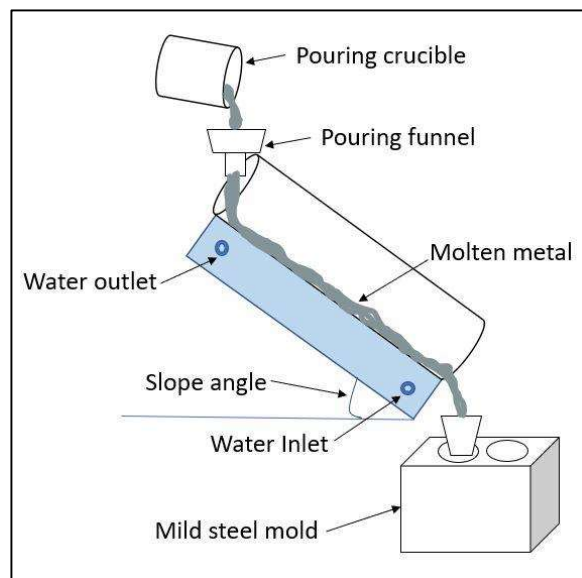
## **2.5 COOLING SLOPE (CS) CASTING**

The CS casting technique includes pouring melt at low superheat over cooling slope plate followed by solidifying in a mould. This method is designed to generate nondendritic feed material for thixo-forming processes. Due to fast heat transfer, many solid nuclei are generated at the contact of melt and slope plate. These nuclei break away from the wall of cooling plate owing to shearing as the melt flowing through the cooling plates. Finally, they are dispersed uniformly in the melt, refining the grains and producing non dendritic and globular microstructure feedstocks [71, 74].

Two processes for the production of non-dendritic and globular microstructures during the flow along CS casting process have been postulated. The first is the dendritic fragmentation mechanism, which is essential for the microstructural evolution of the CS casting process[75]. The fragmentation of dendrites occurs near the contact of melt slurry with the cooling plate because the partially solidified melt collides in flowing slurry under the gravity. The generated crystals are detached from the cooling plate and grow

in the mold. On the other hand, the crystal separation theory is responsible for the generation of nondendritic globular structures in CS casting. As per this theory, granular crystals form and grow on the walls of cooling slope plate and are carried by running slurry. Separation theory implies the mechanism of necking and detachment of these crystals. The major advantages of the CS casting are its simple design and operation, no special equipment required, and it offers low running and maintenance cost. It gives nondendritic and globular microstructure materials desirable for good mechanical properties. The drawbacks of the CS casting process is formation of solidification shell on the cooling slope, oxides and pores may affect the grain morphology and mechanical behaviour of materials [76–79].

The important features of CS casting are the formation of globular microstructure and the thixotropic behavior of the semi-solid slurry that lowers segregation and porosity in the castings. The CS casting also can be a potential process to produce semi-solid feedstock for thixoforming processes. Therefore, it can be utilized for forming near-net shape products in the automobile, aerospace, and other engineering sectors.



**Fig. 2.1** Schematic diagram of cooling slope casting set up

The next section deals with the effect of various processing methods and alloying element on morphology and growth of  $Mg_2Si$ , and mechanical characteristics of Al- $Mg_2Si$  composites.

## **2.6 Al- $Mg_2Si$ INSITU METAL MATRIX COMPOSITE**

The Al-Si-Mg system has been established as a potential system for synthesis of Al based composites having  $Mg_2Si$  intermetallic phase as reinforcement. Early researches on Al alloys revealed the advantages of Mg addition on improvement of corrosion resistance and machinability. Castability is improved by the inclusion of Si with a high latent heat of fusion. Because Si is a eutectic former with Al, there is enough fluidity for shrinkage compensation. The combined additions of Mg and Si at high wt.% forms  $Mg_2Si$  intermetallic phase, emerging a novel class of composites. This Al- $Mg_2Si$  composite is a novel family of superlight materials that is attracting attention for possible aeronautical, automotive, and other technological applications.  $Mg_2Si$  is an intermetallic compound which has high melting temperature of  $1085^\circ C$ , low density of  $1.99 \times 10^3 \text{ kg m}^{-3}$ , low coefficient of thermal expansion (CTE) of  $7.5 \times 10^{-6} \text{ K}^{-1}$ , high hardness of  $4500 \text{ MN m}^{-2}$ , and relatively high elastic modulus of  $120 \text{ GPa}$ .  $Mg_2Si$  is a possible reinforcement for Al-based MMCs due to its unique combination of characteristics.  $Mg_2Si$  and Si have been observed to have similar characteristics and solidification behaviour [46]. Srinivas et al.[80] prepared Al-15% $Mg_2Si$  composite, with excess silicon. They observed that microstructure of Al-15% $Mg_2Si$  composite comprises coarse and hopper like primary  $Mg_2Si$  and primary aluminum around the  $Mg_2Si$  phase. However, addition of refiner Al-Ti-B and Phosphorus refine the  $Mg_2Si$  from  $30 \mu\text{m}$  to  $20 \mu\text{m}$  and distributed evenly in Al matrix.

### **2.6.1 Morphology and growth mechanism of Mg<sub>2</sub>Si**

The shape and size of primary Mg<sub>2</sub>Si particles have considerable effect on the mechanical behaviour of materials. Therefore, understanding the process and controlling the growth of Mg<sub>2</sub>Si is critical. Li et al. [81] studied extensively three-dimensional shapes of primary Mg<sub>2</sub>Si and its growth mechanism in Al–Mg<sub>2</sub>Si composites. The Mg<sub>2</sub>Si phases are found to be in a wide variety of geometric shapes, including octahedrons, truncated octahedrons, hoppers, cubes, and dendrites. However, various shapes tend to establish an equilibrium shape of faceted octahedron in order to minimise surface energy.

Qin et al.[82] has analysed the influence of rate of solidification on primary Mg<sub>2</sub>Si particles morphology. The quick solidification causes a smooth surface cylindrical structure. With decrease in solidification rate the morphology converts into slightly angular features at free surfaces. Further lowering of solidification rate develops typical faceted morphology. They concluded that the growth of Mg<sub>2</sub>Si in hypereutectic Al-Mg<sub>2</sub>Si transforms from faceted to non-faceted type with increase in cooling rate.

### **2.6.2 Influence of different processing routes on the microstructure and properties**

#### **2.6.2.1 Influence of intensive melt shearing**

The influence of intensive melt shearing on particle shape, size and dispersion of primary as well as eutectic Mg<sub>2</sub>Si phases in hypereutectic Al-Mg<sub>2</sub>Si composite has been analysed by Hu-Tian Li et al.[83]. Melt processing by advanced shear technology, a newly developed method for metal melt processing, causes high turbulence and intensive shearing in the liquid alloy. Intensive melt shearing disperses oxide films, intermetallic compounds, etc. and produces even thermal fields and homogeneous composition. It also encourages heterogeneous nucleation sites on these distributed particles, facilitating

refinement of particles. By intensive melt shearing of hypereutectic Al-Mg<sub>2</sub>Si alloy, the coarse dendritic Mg<sub>2</sub>Si are converted to refine compact polyhedral shaped Mg<sub>2</sub>Si. Apart from Mg<sub>2</sub>Si refinement, eutectic phase and lamellar gaps in Al-Mg<sub>2</sub>Si binary eutectic structures are also observed to be reduced. Microstructure refinement of both primary as well as eutectic Mg<sub>2</sub>Si particles can be due to heterogeneous nucleation in Al-Mg<sub>2</sub>-Si alloy melt by shearing action.

#### **2.6.2.2 Influence of melt superheating treatment**

Azmah Nordin et al.[84] analysed the influence of superheating melt temperature and holding duration on morphology of Mg<sub>2</sub>Si phase in Al-2Cu-20Mg<sub>2</sub>Si in situ composite. They found that melt superheating at 950°C with a short holding duration of 15 minutes was discovered to be the most effective parameter to achieve an adequate refinement of Mg<sub>2</sub>Si particles. Microstructure of composite shows smaller polygonal shaped Mg<sub>2</sub>Si particles. These modification and refinement of particles improves the properties of composite.

Q.D. Qin et al.[85] analysed the influence of melt superheating on the microstructure of Al-Si-Cu/Mg<sub>2</sub>Si composite. They observed that as the superheat temperature of melt increased from 720°C to 1020°C, shape of primary Mg<sub>2</sub>Si phase transformed from dendritic to equiaxed, and particle size reduced from 150 µm to around 40 µm. Microstructure of eutectic Mg<sub>2</sub>Si phase altered from coarse flake to needle-like.

#### **2.6.2.3 Semi-solid processing**

Q.D. Qin et al.[86] prepared the Al-Si-Cu/Mg<sub>2</sub>Si insitu composite by CS casting and remelting process. They observed that shape of primary Mg<sub>2</sub>Si becomes globular and doesn't change with increase of isothermal holding time. However, as the holding period is raised from 30 to 600 minutes, average particle size of α-Al grows from 50 to 150 µm

and becomes globular. Shape factor of the particles increases from 0.51 to 0.69 with increase of isothermal holding duration from 30 to 60 min.

Santosh Kumar et al.[73] analysed the influence of pouring temperature on microstructure of Al reinforced with insitu  $Mg_2Si$  composite fabricated by semisolid process cooling slope casting. They noticed that nearly globular shape of primary Al and  $Mg_2Si$  phase has been formed due to the shear force exerted on melt during flow by cooling slope. The mechanism for grain refinement has been grain fragmentation. They have identified that the  $650^\circ C$  has been best pouring temperature for grain refinement and sphericity. H. Saghafian et al.[87] explored the influence of semi-solid process on wear performance of Al-25% $Mg_2Si$  composite fabricated using cooling slope technique. After casting the composite reheated to semi-solid temperature and thixo-formed using hydraulic press. They observed that the thixo-formed sample showing better wear resistance compared to the conventional samples. Cooling slope cast samples has better wear resistance than the as cast samples.

### **2.6.3 Effect of chemical modifications of $Mg_2Si$ particles**

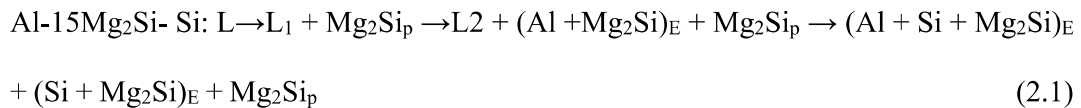
#### **2.6.3.1 Effect of extra silicon addition**

J. Zhang 2000 et al.[88] analysed the evolution of microstructure of an insitu Al- $Mg_2Si$  composite when extra Si was added. They observed that  $Mg_2Si$  particle was refined and globular primary Al phase formed by adding extra Si.

N. Nasiri 2012 et al.[89] examined the influence of adding excess Si on microstructural and mechanical behaviour of Al-15% $Mg_2Si$  composite. They observed that when Si was added up to 2%, particle size of primary  $Mg_2Si$  decreased from  $39\ \mu m$  to  $26\ \mu m$  and increased the  $\alpha$ -Al from 6% to 22%. When the amount of Si increased to 7 wt.%, particle size of primary  $Mg_2Si$  increased, but the proportion of  $\alpha$ -Al phase almost remained unchanged. Addition of up to 2% of Si increased the tensile strength of

composite owing to smaller Mg<sub>2</sub>Si particles but as the Si content increased to 7%, slight effect on ductility of the composite owing to stress concentration sites was observed. Fracture surface showed cleavage fracture of hard phases Si and Mg<sub>2</sub>Si with fine dimples in Al phase.

With increase in amount of Si up to 10%, the equilibrium solidification reaction of the alloy is given in Eq. 2.1:



where the subscript P indicates the primary phase, E indicates eutectic phase.

Chong Li 2009 et al.[90] analysed the effect of excess Si on solidification process and microstructure of hypereutectic Al–Mg<sub>2</sub>Si. The resultant microstructure exhibits a blocky Mg<sub>2</sub>Si phase enclosed by binary eutectic structure of Al-Mg<sub>2</sub>Si, followed by ternary eutectic structure of Al-Mg<sub>2</sub>Si-Si. The primary Mg<sub>2</sub>Si particles have dendritic or polyhedral shapes, but the Al-Mg<sub>2</sub>Si binary eutectic phase exhibits a flake-like shape. Ternary eutectic cells of Al-Mg<sub>2</sub>Si-Si scatter between binary eutectic cells, separating them into somewhat independent "islands."

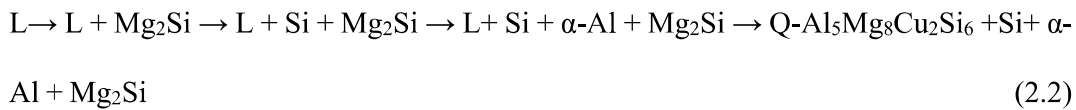
### 2.6.3.2 Effect of extra Mg additions

SC Ram et al.[91] analysed the influence of extra Mg content on microstructure and wear behaviour of A356-Mg<sub>2</sub>Si insitu composites fabricated using centrifugal casting technique. Primary Mg<sub>2</sub>Si phase mostly segregated towards inner zone of the tubular product due to lower density of the phase and action of centrifugal force. Highest hardness was reported in the inner zone decreases gradually towards outer zone due to reduction of Mg<sub>2</sub>Si phase. They observed that with increase of Mg content or Mg<sub>2</sub>Si phase, density of the composite lessens while porosity increases due to large freezing range of composites. The wear characteristics of composite improved with increasing

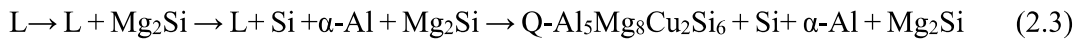
Mg<sub>2</sub>Si content due to better load bearing capacity while formation of protective oxide layer on pin surface and mechanically mixed layer between contact surfaces reduces the metal-to metal contact.

M. Tabib et al.[92] analysed the influence of Mg content on the solidification characteristics of Al-15Si-4Cu-Mg alloy. They observed that amount of Mg content strongly affects phase morphology of Mg<sub>2</sub>Si phase and solidification behaviour of the alloy. The morphology of Mg<sub>2</sub>Si particle was shifted from octahedral to dendritic at 12.5% Mg content. Furthermore, Mg just coarsened the dendrites. The solidification routes in three Mg addition ranges may be classified into three categories given in Eq. 2.2 to 2.4.

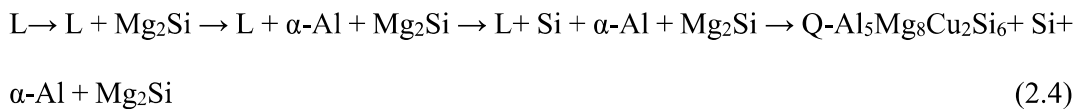
Type I (Mg wt.% ranging from 5.16 to 12.5%):



Type II (Mg wt.% 12.5% eutectic composition):



Type III (Mg wt.% ranging from 12.5 to 15%):



They used Thermocalc software and Scheil calculations to predict the results which are in good agreement of experimental results obtained from microstructural and thermal analysis.

Feng Yan et al.[93] reported that adding extra Mg enhances the mechanical characteristics of Al-Mg<sub>2</sub>Si alloys fabricated by high-pressure die casting (HPDC). The Al-6Mg-8Mg<sub>2</sub>Si alloy provides an outstanding balance of strength and ductility. Adding extra Mg decreases the concentration of eutectic Mg<sub>2</sub>Si, resulting in development of

Mg<sub>2</sub>Si as the predominant phase, which is assumed to be responsible for enhanced mechanical performance.

### **2.6.3.3 Effect of TiB<sub>2</sub> addition**

Various researchers have studied the effect of insitu TiB<sub>2</sub> particles addition on morphology of Mg<sub>2</sub>Si phase in the Al-Mg<sub>2</sub>Si system. Qi Gao et al.[94] have reported that the Mg<sub>2</sub>Si and TiB<sub>2</sub> phases having mutual refinement process. TiB<sub>2</sub> particles serve as the nuclei for Mg<sub>2</sub>Si phase led to refinement of Mg<sub>2</sub>Si phase. The Mg<sub>2</sub>Si phase can wet TiB<sub>2</sub> phase which lessen the segregation of TiB<sub>2</sub> phases. The grain size of Mg<sub>2</sub>Si in the range of 10-15 micron while TiB<sub>2</sub> in sub-micron size about 0.5 microns.

Rui Du et al.[47] reported that the Mg<sub>2</sub>Si particles are a coarse and brittle phase exhibits sharp corners in Al/Mg<sub>2</sub>Si composites that induces stress concentration at edge corner, and leads to crack formation in the composite, ultimately reduces the strength. Thus, they found that the TiB<sub>2</sub> particles modify the morphology of flake-like to polygon shape of the Mg<sub>2</sub>Si phase with reduced size because insitu TiB<sub>2</sub> particles work as the nuclei for Mg<sub>2</sub>Si. Chong Li et al.[38] observed that when Al-Ti-B master alloy and Al-P master alloy are used as grain refiners in Al-12.67Mg-10.33Si alloy, the shape of Mg<sub>2</sub>Si particles changed to polygonal from dendritic, and the particle size reduced from ~100 μm to ~20 μm. TiB<sub>2</sub> particles have a strong lattice-matching coherence relationship and serve as the nuclei for Mg<sub>2</sub>Si phase.

### **2.6.3.4 Modifications of morphology with different alloying elements**

The various elements are used to change and refine the Mg<sub>2</sub>Si phase to enhance the characteristics of composite. Peng Tang et al.[95] analysed the effect of Be on microstructural and mechanical characteristics of Al-8Si/15Mg<sub>2</sub>Si composite. The shape of Mg<sub>2</sub>Si phase changed into regular polygons from dendritic shape and Mg<sub>2</sub>Si phase as

well as eutectic Si was greatly refined with addition of Be. Grain size of primary Al also reduced to 13  $\mu\text{m}$  from 24  $\mu\text{m}$  and nearly spherical  $\text{Mg}_2\text{Si}$  phase and finer eutectic Si was obtained with 1.5% Be. Based on the microstructural characteristics, they proposed that BeO phases were responsible for the change of  $\text{Mg}_2\text{Si}$  phases. BeO can prevent the growth of the oxides which lower the adhesion of  $\text{Mg}_2\text{Si}$ , and refinement of  $\text{Mg}_2\text{Si}$  phase. When heat-treated samples modified with 1.5%Be were compared to unmodified composites, they demonstrated significant enhancements in mechanical and wear characteristics.

M.R. Ghorbani et al.[42] analysed the influence of Mn percentage on microstructure and tensile strength of an Al-15wt.% $\text{Mg}_2\text{Si}$  composite. They observed that adding 1% Mn to the composite altered the  $\text{Mg}_2\text{Si}$  phase morphology into polyhedral from irregular shape.  $\text{Mg}_2\text{Si}$  particle size reduced from 40  $\mu\text{m}$  to 12  $\mu\text{m}$  and just adding 2 wt.% Mn, morphology of the particles become cuboidal. Further, addition of Mn did not have much effect on the particle morphology, while eutectic  $\text{Mg}_2\text{Si}$  phase changes from flake like morphology to stick like morphology. Mechanism involved in transformation of  $\text{Mg}_2\text{Si}$  phase morphology by addition of Mn can be owing to the poisoning effect of Mn on  $\text{Mg}_2\text{Si}$  particles. Optimum Mn content for increasing the tensile and elongation is 2 wt.%. More addition of Mn decreases the tensile properties owing to the development of intermetallic  $\text{Al}_6\text{Mn}$  induced at grain boundaries. Adding 2wt.% of Mn, transforms fracture characteristics of composite from brittle to ductile as fine dimples on fracture surface increases. Chong Li et al.[81] analysed the influence of Ni on eutectic microstructural development of Al-20% $\text{Mg}_2\text{Si}$  fabricated by gravity casting process. With the addition of Ni, eutectic  $\text{NiAl}_3$  forms, transforming the flake-like shape of eutectic  $\text{Mg}_2\text{Si}$  into a rod-like structure. The ternary eutectic phase exhibits a distinct double rod structure with  $\text{Al}_3\text{Ni}$  and  $\text{Mg}_2\text{Si}$  evenly dispersed in Al matrix. Because of

these developed eutectic phases, high-temperature tensile properties of the composite improved by 23%.

Yinling Jin et al.[96] analysed the influence of varying content of Eu addition on primary  $Mg_2Si$  and tensile strength of Al-18 $Mg_2Si$  composites produced by casting and extrusion subsequently subjected to heat treatment. They observed that with increasing Eu content from 0 to 0.1%, primary  $Mg_2Si$  shape changes from dendritic to octahedron, and particle size reduces from  $\sim 90 \mu m$  to  $\sim 16 \mu m$ . T6 treatment spheroidized the sharp edges of  $Mg_2Si$  phase and reduced the  $Mg_2Si$  particle size. There were two modification mechanisms of primary  $Mg_2Si$  phase by adding Eu. It results in diverse nucleation and suppression growth mechanisms. The  $Al_2Si_2Eu$  phase may serve as a heterogeneous nucleus for  $Mg_2Si$  phase, result in refinement of primary  $Mg_2Si$  phase. Second, the segregation or targeted absorption of Eu on facets of  $Mg_2Si$  inhibits the development of  $Mg_2Si$  facets is responsible for  $Mg_2Si$  phase refinement and modification.

Wenqiang Jiang et al.[97] analysed the influence of  $Al_3Sr$  in Al-10 Sr alloy on microstructure and tensile strength of Al-10 $Mg_2Si$  and Al-15 $Mg_2Si$  composites. They observed that following the addition of Sr modifier,  $Mg_2Si$  particle was modified from octahedron morphology to polygon shape and eutectic  $Mg_2Si$  was transformed from Chinese script type to stick like shapes in different processing circumstances such as as-cast, extruded and rolled. Furthermore, the smaller  $Al_4Sr$  phase assisted in refining the primary  $Mg_2Si$  and maintaining consistent distribution. T6 heat treatment process remarkably promoted the globular conversion of eutectic  $Mg_2Si$ . This refinement of  $Mg_2Si$  phase considerably improved the tensile strength and ductility of Al-10 $Mg_2Si$  and Al-15 $Mg_2Si$  in T6 treated condition.

Nur Azmah Nordin et al.[44] used microstructural characteristics and thermal analyses to investigate the influence of Bi, Sb, and Sr additions on nucleation and growth

of  $Mg_2Si$  particles in Al-20%Mg<sub>2</sub>Si composite. They observed that adding these elements lowers the growth of  $Mg_2Si$  phase. The refinement caused by Bi, Sb, and Sr are possibly owing to the action of oxide bi-films available in melt, which function as nucleus for  $Mg_2Si$  particles. Xiao-Feng Wu et al.[98] examined the influence of Sc addition on microstructure, tensile strength and fracture behaviour of Al-11Mg<sub>2</sub>Si alloys. They observed that addition of trace amount of Sc modifies and refine the matrix as well as  $Mg_2Si$  phase in the alloy. Primary Al transformed from dendrite to globular structure and eutectic  $Mg_2Si$  transformed to fine and small fibers from flake morphology. They reported that the development of Al<sub>3</sub>Sc as heterogeneous nuclei, Sc segregation and constitutional supercooling contributed to transformation and refinement of primary Al grains and  $Mg_2Si$  phase morphology. Tensile strength as well as ductility of Al-11Mg<sub>2</sub>Si alloy improved considerably. The refinement and transformation of the matrix and  $Mg_2Si$  phase in Al-11Mg<sub>2</sub>Si resulted in a change in fracture characteristics from brittle to ductile fracture.

Hong-Chen Yu et al.[45] studied the development  $Mg_2Si$  phases in unmodified and modified by Ca-Sb, Al-20Mg<sub>2</sub>Si-4.5Cu composites produced through extrusion and T6 heat treatment. They reported that formation of truncated octahedral primary  $Mg_2Si$  through hot-extrusion and diffusion of Mg and Si atoms by heat treatment was crucial to achieve globular  $Mg_2Si$  particles in Al-20Mg<sub>2</sub>Si-4.5Cu composite. Hardness and tensile strength of composite was considerably enhanced owing to the spherical primary  $Mg_2Si$  phase. R. Hadian et al.[43] analysed the influence of Li addition on microstructure and tensile characteristics of Al-15Mg<sub>2</sub>Si composite. They observed that adding 0.3% Li decreases the  $Mg_2Si$  particle size from ~30  $\mu m$  to ~6  $\mu m$ . The influence of cooling rate was observed using a mold having different sectional test bars. They found that with increase of cooling rates, UTS and ductility of the composite increased. Adding Li in the

composite also enhances UTS and elongation as decohered  $Mg_2Si$  particles reduces in the fracture surfaces.

J. Zhang et al.[88] have analysed the influence of adding mischmetal on microstructural features of insitu Al–15wt.% $Mg_2Si$  composite. Particle size of the  $Mg_2Si$  phase considerably reduced and eutectic  $Mg_2Si$  phase converted from fibrous to flake like morphology as the content of mischmetal increased. A compound  $Al_{11}RE_3$  was formed by adding mischmetal in the composite which influenced the growth of  $Mg_2Si$  phase and may be liable for the transformation and refinement of  $Mg_2Si$  phase. R. Khorshidi et al.[99] explored the effect of 0.5wt%Gd inclusion on microstructural and creep behaviour of Al-15 $Mg_2Si$  composite. The creep behaviour of the composite was investigated using different stress ranges (50-250 MPa) in a temperature range of 473–563 K. Addition of 0.5% Gd in Al–15 $Mg_2Si$  composite form MgGd intermetallic at the grain boundaries that significantly refined the primary as well as eutectic  $Mg_2Si$  phase, transformed the primary  $Mg_2Si$  phase morphology from irregular to polyhedral. During creep test, MgGd intermetallic particles produce a stable barrier that strengthens grain boundaries and inhibits recovery and crystallisation. They stated the predominant creep mechanism in Al-15 $Mg_2Si$ -0.5Gd composites is stress- assisted dislocation climb regulated by lattice self-diffusion.

Guangzhu Bai et al.[100] have analysed the influence of rare earth element lanthanum (La) addition and ultrasonic agitation on microstructure and mechanical characteristics of Al- $Mg_2Si$  composites. Adding 0.4%La significantly altered microstructures of Al- $Mg_2Si$  composites, refining the particles and enhancing globularity of  $Mg_2Si$  particles. Refinement and modification of  $Mg_2Si$  phase are further improved by application of ultrasonic stirring. These modification in microstructure of the composite enhances the mechanical properties. They reported that using ultrasonic stirring with the

addition of minor La in fabrication of Mg<sub>2</sub>Si-Al composite is an effective approach for transforming microstructure and improving the mechanical behaviour for industrial applications. Byungjoo Kim et al.[101] analysed the influence of TiB<sub>2</sub> particle on eutectic Mg<sub>2</sub>Si in Al-8Zn-6Si-4Mg-2Cu alloy. They found that morphologies of eutectic Mg<sub>2</sub>Si converted into small flakes and fine polygonal shape from a Chinese script because TiB<sub>2</sub> particles serve as heterogeneous nuclei for Mg<sub>2</sub>Si.

#### **2.6.4 Effect of solution treatment and ageing**

SC Ram et al.[39] have examined the influence of solution treatment and artificial ageing on microstructure and high temperature mechanical behaviour of centrifugally cast A356-Mg<sub>2</sub>Si composites. Upon solution treatment eutectic Mg<sub>2</sub>Si and Si showed a significant modification in morphology from flake to globular and dot like morphology. Primary Mg<sub>2</sub>Si also refined marginally and sharp edges of the particles become rounded due to diffusion of Mg and Si. Two peaks of hardness observed during ageing, confirm the precipitation sequence. The tensile strength of T6-treated composites at 150°C was substantially higher than as-cast composites. Qin et al.[82] explored the mechanical behaviour of Mg<sub>2</sub>Si-Al composites after modification and ageing. After the composites were modified and aged, primary Mg<sub>2</sub>Si phase transformed from dendritic to polygon, while the eutectic phase changed to fine dot-like morphology. The tensile strength and percentage elongation of modified composites were enhanced by 31.1% and 25%, respectively as compared to unmodified Mg<sub>2</sub>Si-Al composites.

### **2.7 TiB<sub>2</sub> PHASE AS REINFORCEMENT**

Fei Chen et al.[102] investigated the use of insitu ceramic particles as reinforcements such as Al<sub>2</sub>O<sub>3</sub>, TiB<sub>2</sub> and TiC in the fabrication of Al MMCs. TiB<sub>2</sub> is an

attractive strengthening agent for the Al matrix because of its outstanding blend of physical and mechanical characteristics, which include a high melting temperature (3225°C), high hardness (960 HV), high elastic modulus (534 GPa) and excellent corrosion and wear properties. TiB<sub>2</sub> has become increasingly significant for wide variety of applications under erosive, abrasive, corrosive, or high-temperature circumstances owing to its excellent properties. Currently, application of this material is limited in the special purpose in various domains like cutting tools, resilient-to-impact, and wear-resistant coating. Furthermore, TiB<sub>2</sub> does not react with Al melt, to produce any harmful reaction products at the reinforcement-matrix interface. Over the last few decades, researchers have developed innovative production methods for TiB<sub>2</sub> reinforced in situ Al-based MMCs with improved mechanical and wear characteristics.

Mingliang Wang et al.[103] have fabricated A356-TiB<sub>2</sub> composite through salt-metal reaction route. They reported that increasing the content of TiB<sub>2</sub> particles up to 8.37% increased tensile strength and Young's modulus of composites. James Mathews et al.[79] described that in-situ generated TiB<sub>2</sub> particles perform double role as grain refiner and reinforcement responsible for increase in hardness and elastic modulus of Al-4.5Cu-5TiB<sub>2</sub> composite. They observed that the fragmentation of TiB<sub>2</sub> agglomeration due to semisolid forging leads to even dispersion of TiB<sub>2</sub> particles improve the recrystallisation and grain nucleation which increases the dislocation density. Mondal et al. fabricated the Al-4Cu-xTiB<sub>2</sub> composite by reaction of K<sub>2</sub>TiF<sub>6</sub> and KBF<sub>4</sub> with molten Al. They noticed that increasing TiB<sub>2</sub> content tensile strength of composite improves without much loss of ductility. Aging time to achieve peak hardness reduced from 40 h to 6 h with increase of TiB<sub>2</sub> content from 0 to 10%.

The incorporation of combination of micro and nano reinforcements into matrix not impaired ductility and toughness of the composites. Therefore, Al based hybrid

composites are highly promising alternative to conventional composite in which the uniformly distributed reinforcement in the composite is able to improve wear properties. In the next section discusses the microstructural characterisation, mechanical and tribological behaviours of Al based hybrid composites.

## **2.8 AI BASED HYBRID COMPOSITE**

Hybrid composite are the next generation composite system in which two or more reinforcements are incorporated into the matrix to achieve desired properties by selecting suitable combination of particulate reinforcements. Aluminum alloy matrix-based hybrid composites can be fabricated by using combination of reinforcements of micro and nano size.

These next generation composites with two or more particulate reinforcements extend the idea of tailor-making a composite system to meet specific property requirement. Hybrid composite offers greater flexibility compared with single reinforced composite as the properties of hybrid composite depends on the combination and composition of constituent reinforcing elements. The properties of a hybrid composite may be comfortably regulated by combining and composing appropriate reinforcing particles. Hybrid composites have potential to substitute single reinforcement composites owing to low thermal expansion, enhanced wear resistance, high mechanical properties [Zhang (2007), Fei and Wang (2004)].

Aluminum alloy matrix-based hybrid composites can be fabricated by using combination of reinforcements of micro and nano size. Next section discusses the microstructural, mechanical and tribological performance of various hybrid composite systems.

### 2.8.1 Microstructural and mechanical characteristics

In the recent past Al-based composites have shown very promising and attractive results, especially with more than one reinforcement. In this section, microstructural characteristics such as particle size, shape and dispersion of phases and mechanical characteristics have been studied with respect to hardness, tensile strength, ductility etc. of Al-based hybrid composites. Essam A.M. Shalaby et al.[104] studied the fabrication of A359-SiC-Si<sub>3</sub>N<sub>4</sub> using stir casting followed by squeeze casting. They found that squeeze casting process significantly reduces the gas porosity and increases the density of hybrid composite. Microstructural features of composite show uniform distribution of reinforcing phase with good wettability. They reported that reinforcement of SiC and Si<sub>3</sub>N<sub>4</sub> reduces the aging time of the composite from 12hrs to 4hrs. Higher compressive strength of hybrid composite signifies that it may be utilised in automobile and aerospace applications. Jianyu Li et al.[105] analysed the effect of ultrasonic treatment (UT) on microstructure and mechanical characteristics of Al reinforced with 10wt%Mg<sub>2</sub>Si-1wt% nano-sized SiC particles. They observed that eutectic Mg<sub>2</sub>Si is transformed from large flake structure to fine sticks or dots, and dispersed consistently throughout the composite. The agglomerations of SiC particles are removed and evenly dispersed in composites. The SiC particles can act as a heterogeneous nucleus for Mg<sub>2</sub>Si phase, thereby refining the Mg<sub>2</sub>Si phase. The tensile strength and ductility of Mg<sub>2</sub>Si-SiC/Al-Cu hybrid composites have been substantially enhanced. The UTS and ductility of hybrid composites made by UT and squeeze casting are improved by 31.3% and 130.8%, respectively, as compared to composites produced without UT. Aluminium matrix composites have also been prepared with Al<sub>3</sub>Zr and Al<sub>2</sub>O<sub>3</sub> reinforcement by magneto chemistry *insitu* reaction technique using aluminium ingot and Zr (CO<sub>3</sub>)<sub>2</sub> powder[106]. The researcher observed homogeneous distribution of particles in a size range of 0.08–

0.12  $\mu\text{m}$ . Tensile strength was observed to enhance with increasing amount of flux up to a certain wt.% due to Orowan strengthening, whereas, elongation decreased continuously due to increased stress concentration sites.

Zhao et al.[107] employed a magnetochemistry insitu method to generate  $\text{Al}_3\text{Zr}$  and  $\text{ZrB}_2$  particles reinforced aluminum matrix composites and analysed the influence of melt temperature on shape of particles and wear performance of composites. Morphology of  $\text{Al}_3\text{Zr}$  particles transformed from spherical to tetragonal to rod-like and fibers with rise in melt temperature, whereas,  $\text{ZrB}_2$  particles did not exhibit any variation in morphology. They noticed least weight loss under dry sliding conditions for composite with spherical  $\text{Al}_3\text{Zr}$  particles. With similar reinforcement in the aluminium matrix, Zhang et al.[108] examined the microstructural and wear behaviour. They found hexagonal and tetragonal particles of  $\text{Al}_3\text{Zr}$  and  $\text{ZrB}_2$  in a size range of 0.3 to 0.5  $\mu\text{m}$ . They also observed enhancement in wear properties with increasing hard particles. Gaurav Gautam et al.[109] analysed the influence of  $\text{ZrB}_2$  particles on microstructural and mechanical behaviour of AA5052/ $\text{ZrB}_2$ - $\text{Al}_3\text{Zr}$  hybrid composites fabricated by direct melt reaction. They observed that the AA5052Al matrix phase refined with the generation of in-situ  $\text{ZrB}_2$  phase. The hardness of composites continuously improved as  $\text{ZrB}_2$  content in the composite increased. UTS and YS of the composite increased up to 3 vol.% of  $\text{ZrB}_2$  due to increasing strength coefficient. Fractography analysis showed cleavage fracture of  $\text{Al}_3\text{Zr}$  particles and ductile fracture of the matrix, therefore, increasing  $\text{ZrB}_2$  content in the matrix leads to quasi cleavage fracture.

Yang et al.[107] prepared aluminium matrix composites consisting of  $\text{ZrB}_2$ ,  $\text{Al}_2\text{O}_3$ , and  $\text{Al}_3\text{Zr}$  particles by the direct melt reaction technique. They observed hexagonal  $\text{ZrB}_2$  particles of nano size (50 nm), rod shape  $\text{Al}_3\text{Zr}$  particles with the length-diameter ratio of 20, while  $\text{Al}_2\text{O}_3$  particles had rectangular as well as ellipsoidal

morphology. A. Devaraju et al.[110] used friction stir processing (FSP) to produce the hybrid composites by introducing a combination of (SiC - Gr) and (SiC - Al<sub>2</sub>O<sub>3</sub>) particles in aluminium alloy. They found that SiC, Gr and Al<sub>2</sub>O<sub>3</sub> are uniformly distributed. They reported that addition of Gr in composite decreases the microhardness of hybrid composite but increases the wear resistance due to lubricating effect of Gr phase. however, Al-SiC/Al<sub>2</sub>O<sub>3</sub> exhibited better hardness value owing to the presence of hard reinforcing particles.

### **2.8.2 Tribological characteristics**

Before delving into the tribological characteristics of Al-based hybrid composites, it is necessary to first understand the basics of tribology. Wear and friction are concepts used to describe tribological characteristics.

#### **2.8.2.1 Wear**

Wear is the removal of material from one or both mating surfaces when one solid surface slides, rolls, or reciprocates relative to the other. Wear is observed on the mating surface; however, it is dependent on the surface and bulk characteristics of the materials in contact. Material wear is typically regarded as a negative phenomenon; nevertheless, in several circumstances, wear is regarded as a necessary phenomenon. [Bhushan, 1999].

The wear process can be categorized into six types based on surface contact, either mechanical or chemical, including adhesive, abrasive, chemical, fatigue, impact, and electrical-arc-induced wear. However, during sliding motion, the most common types of wear are adhesive, abrasive, and chemical (corrosive), as discussed below.

**Adhesive wear**, as the name implies, adhesive bonds between contacting surfaces are responsible for material transfer/removal during sliding motion. This form of wear is quite prevalent when surfaces of similar materials interact with each other. Contact

between the mating surfaces occurs at the interface due to asperities interaction, which deforms or separates during the sliding motion and generate fragments. These fragments may be moved from one surface to other or removed as wear particles.

**Abrasive wear** occurs, when the hard asperities of one surface or hard particles in the surface or from an external source interact with the soft counter surface. During sliding motion, these hard asperities or particles induce plastic deformation, cracks, and grooves in the soft surface. Material removal caused by plastic deformation can take several forms, including ploughing, cutting, and wedge formation.

**Chemical (corrosive) wear** takes place when interacting surfaces are in sliding motion in a corrosive environment. In the presence of lubricants, such a situation may emerge. Corrosive atmosphere imposed by lubricants and chemicals is enhanced in favorable conditions like high temperature and/or high humidity and chemical wear increases. When test is performed in the presence of air, it is termed as oxidative wear because oxygen in the air acts as a corrosive medium.

### **2.8.2.2 Effect of operating parameters**

The various operating parameters including sliding distance, sliding velocity, applied load, operating temperature, humidity, and other operating conditions affect the wear behavior of materials. The wear rate increases with increasing load owing to surface delamination, third-body wear, groove formation etc. At low loads, the mode of wear is generally mild, and the nature of the debris is mainly oxides; however, at high loads, the nature of the debris changes to severe, with oxidative-metallic debris dominates. However, with the change in sliding velocity, wear behaves differently. Increasing sliding velocity elevates surface temperature, that accelerates the oxidation process. The development of a layer of oxide on the surface decreases metal-to-metal contact reduces the wear rate initially with increasing sliding velocity and subsequently reaches a

minimum value. However, when the sliding velocity increases further, the oxide layer cracks, resulting in excessive material transfer and a significant increase in wear rate is observed.

Weight loss and wear rate are commonly used to examine the wear characteristics of test specimens; however, it is found that the wear coefficient is a better parameter to elaborate wear characteristics of the material. This is due to the wear coefficient taking into consideration not just the wear rate (V/S) and applied load, but also the hardness of the wear pin or counterface, which can greatly affect the wear rate[111]. The wear coefficient is important in various industrial applications as it influences material selection product design, maintenance planning, energy efficiency, safety, and quality assurance. Therefore, predicting and quantifying the wear rate helps engineers to improve the durability and reliability of mechanical components.

The following Archard's wear equation (Eq. 2.5) can be used to determine the wear coefficient [112]:

$$\text{Wear coefficient}(K) = \frac{\Delta W * H}{\rho * L * S} \quad (2.5)$$

where,  $\Delta W$ -weight loss,  $H$ -hardness,  $\rho$ -density,  $L$ -applied load and  $S$ -sliding distance.

### **2.8.2.3 Friction and laws of friction**

Friction is defined as the force that opposes or resists the relative sliding or rolling motion of two surfaces. Physical, chemical, and mechanical characteristics of the materials affect the basic mechanism of friction. At the microscopic level, the mechanism involves adhesive forces between contacting surfaces, asperity interaction, ploughing of one surface by the other harder surface, debris caused by surface fragmentation or fracture of the oxide film, and the surroundings. The fundamental laws of friction are as follows:

- Maximum tangential force is proportional to applied load in static conditions.
- Tangential friction force is proportional to applied load during sliding motion.
- Friction force is independent of sliding speed or area of contact.

#### **2.8.2.4 Stages of Friction**

Initially, continuous welding and surface fracture was considered to be the key mechanisms for sliding friction, but subsequent investigations revealed that plastic deformation is the main mechanism that takes place owing to adhesion of surface asperities. During sliding motion, coefficient of friction (COF) is influenced by number of factors such as adhesion, ploughing, deformation, and third body particle. The friction force does not change much in the initial stage and remains nearly constant. In this region, the ploughing component of friction (plough) is dominant. Because of surface contamination, the adhesive component is of little importance. The friction force increases in second stage because adhesive forces become more significant with time; nevertheless, the friction force increases dramatically in third stage. The higher COF is caused by an increase in the amount of wear particles as well as increased adhesion caused by oxide removal from the contacting surface. Furthermore, surface irregularities may contribute to friction force. The friction force does not change in fourth stage because the amount of wear particles and adhesion stay nearly constant. Friction force reduces in the fifth stage due to reduced ploughing and asperity deformation. This type of state is created as a result of asperity elimination, which results in a mirror smooth surface. Finally, since both surfaces have the same surface finish, the friction force remains constant in the sixth stage. However, because wear particles are always present, mirror smooth surfaces are impossible to produce. The wear particles are entrapped at the

interface during sliding motion between hard and soft surfaces, and there is little change after the fourth stage, and the friction force remains constant.

Various researches on tribological characteristics of Al based hybrid composites have revealed that such type of composites possess excellent tribological characteristics and can replace various conventional alloys and composites. The tribological behaviors of hybrid composites are affected by numerous operational factors such as applied load, sliding velocity, sliding distance, and composite composition, among others. High applied load, velocity, and sliding distance cause significant wear and component failure in many automotive parts where tribological characteristics are critical requirements[24, 26, 113].

Ravinder Kumar et al.[114] investigated the specific wear rate of an Al 7075 reinforced with 7% SiC and 3% graphite. The wear test was conducted at different loads (20-60 N), velocities (2-6 m/s), and sliding distances (2000-4000 m) in dry sliding condition. They stated that the hybrid composite showed lower specific wear rate than the unreinforced Al 7075 alloy at all operational parameters. With increasing load, the specific wear rate demonstrated a rising tendency. However, it reduces until it reaches a sliding velocity of 4 m/s and then begins to increase. The Response Surface Methodology (RSM) was utilised to recognise the most important factor influencing the specific wear rate. They have found that load is the most significant parameter in determining specific wear rates. S.A. Alidokht et al.[115] analysed the wear performance of a friction stir-produced A356-SiC-MoS<sub>2</sub> hybrid composite. They revealed that composites had superior wear resistance than cast alloys. The microstructural investigation demonstrated that the MoS<sub>2</sub> layer formed on surface decreased plastic deformation and material wear substantially. Wear resistance of hybrid composite improved as compared to the alloy specially at higher loads. A. Lakshmikanthan et al.[116] produced A357 alloy reinforced

with SiC having two different particle size. They observed considerable enhancement in the mechanical and wear characteristics of composite as compared to the matrix alloy. V.K. Anand et al.[117] studied the influence of SiC and porcelain on the wear characteristics of A6061 hybrid composite. They found that as the porcelain content in the composite increased it enhanced the wear resistance of hybrid composite. They also noticed that Al6061/5SiC composites with 4.5% porcelain possessed the best wear characteristics. Dev S. et al.[118] developed and evaluated the mechanical and wear characteristics of an Al-Si10Cu3Mg1 alloy reinforced with varying amounts of porcelain containing different metal oxides for piston materials. They noticed that 6wt.% porcelain reinforced composite exhibited the highest wear resistance and could potentially be utilised in automobile components such as pistons.

It is important to precisely predict the wear variables in order to avoid catastrophic and economic loss. Furthermore, the examination of optimal parameters might lead to successful use of MMCs for particular need. The research findings propose a variety of mathematical modelling tools for determining the best parameters. Statistical modelling techniques assist in decreasing iterative processes via optimizing variables with fewer experiments. Several investigations explored the wear performance of Al alloy-based hybrid composite using different statistical techniques such as Taguchi design approach, Factorial design, Response surface methodology (RSM), Regression analysis, Artificial Neural Network (ANN). RSM techniques are widely utilized for a system containing multiple variables, in order to optimize the wear variables for optimal performance of the system [35, 36]. Shoufa Liu et al.[119] examined wear characteristics of Al7075 alloy reinforced by B<sub>4</sub>C and MoS<sub>2</sub>. They noticed that wear properties of hybrid composite improve in comparison to alloy Al7075. R K Mandava et al.[120] explored the wear and friction behaviour of Al7075/FA/SiC hybrid composite. They observed that

the mechanical and wear characteristics of hybrid composites improve as the reinforcing amount increases. They used RSM to identify the optimum wear parameters and noticed that load is the most important variables which affect the wear rate in comparison with sliding distance and speed. K. Umanath et al.[34] examined the wear characteristics of Al6061 alloy reinforced with SiC and Al<sub>2</sub>O<sub>3</sub>. They applied statistical regression analysis and ANOVA to establish relation between input parameters and response. They found that the content of reinforcement is the more influential factor than others which affects the wear of hybrid composite.

Next section, discusses the various work that have been done by researchers on Al-Mg<sub>2</sub>Si-TiB<sub>2</sub> hybrid composite systems.

## **2.9 Al-Mg<sub>2</sub>Si-TiB<sub>2</sub> INSITU HYBRID COMPOSITES**

Al-Mg<sub>2</sub>Si-TiB<sub>2</sub> hybrid composite can be produced by ingot and salt-metal reaction route. Qi Gao 2015. et al.[48] fabricated the 5vol% TiB<sub>2</sub>-10vol%Mg<sub>2</sub>Si/Al composite through salt-metal reaction route and ingot metallurgy. They proposed the mutual refinement mechanism of TiB<sub>2</sub> phase and Mg<sub>2</sub>Si phase. TiB<sub>2</sub> particles serve as the heterogeneous nucleus for Mg<sub>2</sub>Si phase which refine the phase. The Mg<sub>2</sub>Si phase can wet TiB<sub>2</sub> particles which lessen the TiB<sub>2</sub> agglomerations. The particle size of Mg<sub>2</sub>Si was observed to be between 10-15 µm whereas TiB<sub>2</sub> in sub-micron size of about 0.5 µm. They reported that yield strength and ultimate tensile strength of TiB<sub>2</sub>-Mg<sub>2</sub>Si/Al composite were enhanced by 244% and 229% respectively while ductility drastically reduced compared with Al matrix. Rui Du et al.[47] examined the influence of TiB<sub>2</sub> particle on microstructure and mechanical behaviour of Al/Mg<sub>2</sub>Si composite. The Mg<sub>2</sub>Si phase is coarse and brittle, displaying sharp-edge corner that induces stress concentration at sharp edge corner and cracks are formed in such regions and reduces the properties of composite. Thus, controlling the microstructure of Mg<sub>2</sub>Si/Al is critical for improving

ductility and mechanical characteristics. They found that the  $\text{TiB}_2$  particle modify the morphology from flake-like to polygon shape of the  $\text{Mg}_2\text{Si}$  phase and size reduction from about 20 to 10 microns. The  $\text{TiB}_2$  particles in the hybrid composite not just work as the nuclei for  $\text{Mg}_2\text{Si}$ , but they are also an outstanding reinforcement particle that may substantially improve the aluminum matrix, particularly Young's modulus. Young's modulus has great importance in structural design.

Sajjad Amir Khanlou 2017 et al. [121] investigated the Young's modulus of Al-Si-Mg alloy and Al-Si-Mg-Cu/ $\text{Mg}_2\text{Si}$ - $\text{TiB}_2$  composite. They observed that the yield strength and Young's modulus, important material property for structural design, improve with the incorporation of Si, Cu as well as in situ  $\text{Mg}_2\text{Si}$  and  $\text{TiB}_2$  particles.  $\text{Mg}_2\text{Si}$  and  $\text{TiB}_2$  phase uniformly distributed into the matrix and interface between matrix and particles were found clean and well bonded.  $\text{TiB}_2$  particles have hexagonal and cubic prism forms with rounded corners. They applied micromechanics-based model to explain the factors responsible for increase of yield strength and Young's modulus. According to the calculations, the contributions to yield strength of thermal mismatch, Orowan, elastic mismatch, load bearing, and grain boundary strengthening mechanisms are 65.5, 38.3, 26.2, 6.7, and 1.4 MPa, respectively. Fracture surface of composite show the quasi-cleavage fracture composed of cleavage fracture of  $\text{Mg}_2\text{Si}$  phase and ductile fracture of Al phase.