CHAPTER 1

INTRODUCTION

1.1 COMPOSITE MATERIALS

The term ‘composite material’ generally referred to heterogeneous mixtures, which are combination of two or more dissimilar materials which are mechanically or metallurgically bonded together, to achieve a definite goal for specific purpose. The concept of a composite material, in general is to synergize certain properties of its constituents, that is, the reinforcement and the bulk material is called the matrix, and to suppress the shortcomings of each of the constituents (Srivatsan et al 1995). This combination can result in a newly synthesized material that has unique and useful properties for a spectrum of structural applications. Interest in the use of reinforcement in a continuous matrix phase, dating back to the early 1960s, was due to the limitations associated with conventional ingot metallurgy, coupled with a critical need for newer generation materials, to meet the growing demands of the aerospace and automotive industries, which required a radical new approach to material synthesis and preparation. The properties of composites are the function of the reinforcement phases of their relative amounts, the geometry of the dispersed phase. Dispersed phase geometry, in this context means the shape of the particles and the particle size, their distribution.

A large majority of these composite materials are metallic matrixes reinforced with high strength, high modulus and often brittle second phases which can be either continuous or discontinuous in the form of a fiber or discontinuous in form of a whisker, platelet and particulate reinforcement in a metal matrix. The incorporation of ceramic reinforcement in a metal matrix has been shown, in some cases, to offer improvement in elastic modulus, wear resistance, strength, structural efficiency, reliability and control of physical
properties such as density and co-efficient of thermal expansion, thereby predicting improved mechanical performance in comparison to the unreinforced matrix. Metal matrix composites (MMCs) are quite attractive in the aerospace, automotive and other industries due to their low density, their capability to be strengthened by precipitation, their good corrosion resistance, high thermal and electrical conductivity, and high damping capacity (Stefanos 1996). MMCs are very attractive for their isotropic or anisotropic mechanical properties. The major drawback of the composites is a drop in the ductility and toughness (Romero and Arsenault 1995).

1.2 CLASSIFICATION OF COMPOSITES

In a wider context composites can be divided into two groups. They are:

- Natural composites
- Man-made composites

Many in natural occurring materials can be regarded as composites, the classic example being wood, bone, muscles, skin, husk of coconut etc. Man-made composites have been used for thousands of years, e.g. laminated woods. In the last century, the uses of composites have been extended after the appearance of the pneumatic type for vehicles and reinforced concrete. The next step was the development of glass fiber reinforced plastics during the Second World War. In the 1970s and 1980s, new type of composite, such as polymer matrix, metal matrix and ceramic matrix composites have been designed and fabricated by man for specific applications (Brian et al 1997). Today, most common man-made composites are widely used in many industries.
1.3 CLASSIFICATION OF COMPOSITES BASED ON MATRIX CONSTITUENT

Composites are commonly classified based on the type of the matrix materials used. The first level of classification is usually made with respect to the matrix constituent, which can be classified as (Surrappa 1997; Baradie 1990):

1. Polymer Matrix Composite (PMC)
2. Metal Matrix Composite (MMC)
3. Ceramic Matrix Composite (CMC)

1.3.1 Polymer Matrix Composites

Polymer matrix composites may involve thermoplastics or thermosetting polymer matrix materials and the reinforcement may be in the form of relatively equiax particles or whisker or continues fiber (Brian et al 1997). The fiber possesses high specific strength and modulus. Since, most fibers are brittle, abrasive and poor in toughness, their structural value is very poor. However, when combined with polymer, in the form of a composite, the resulting material possesses the advantages of plastic viz. toughness, high strength, modulus and low density. Polymer matrix composites have the advantage of large fabrication, low cost, low densities. However, most advanced resins cannot be used above 30°C for prolonged period.

1.3.2 Metal Matrix Composites

Metal Matrix Composites (MMCs) are defined as materials consisting of any combination of fibers, metal wires, whiskers and particles embedded in metallic matrix. MMCs are advanced materials which are generally reinforced with SiC or Al₂O₃ in the form of continuous or discontinuous fibers, whiskers or particulates. The matrix can be any suitable
metal, but aluminum, magnesium, titanium and some super alloys are the most popular. MMCs were developed to meet the ever increasing need for high specific strength and modulus in structural materials. MMCs with unique properties, such as low coefficient of thermal expansion and high thermal conductivity are in increasing demand, and an outstanding characteristic of MMCs is their ability to tailor mechanical and physical properties over much larger ranges that can be obtained with monolithic materials.

1.3.3 Ceramic Matrix Composites

Ceramic matrix composites combine a ceramic matrix material with a reinforcing phase of different composition (such as alumina and silicon carbide) or the same composition (alumina/alumina or silicon carbide/silicon carbide). They are promising thermo-structural materials for in-service high temperature applications. CMCs maintain a good mechanical performance up to 1500°C even in oxidant and erosive environments, as they occur in the "hot parts" of high technology fields such as aerospace and nuclear plants.

However, their main disadvantages are:

1. Low strain to failure, which limits the stress in the fiber at low levels.
2. Relatively high modulus and lack of densities, which prevent the accommodation of thermal stresses from any metal in thermal expansion

CMCs in particular, carbon fiber reinforced SiC matrix composites (C/SiC) are currently used as brake disks in sports cars. SiC fiber reinforced SiC matrix composites (SiC/SiC) are promising materials in nuclear fusion reactors, because of SiC's low activation properties.
1.4 CLASSIFICATION OF COMPOSITE MATERIAL BASED ON THE GEOMETRY OF REINFORCEMENT

In general, composites are classified into three categories according to the aspect ratio of reinforcement: (Kainer 2003 and Surrappa 2003)

1. Particulate reinforced composite materials
2. Whisker reinforced composite materials
3. Fiber reinforced composite materials

1.4.1 Particulate Reinforced Metal Matrix Composites

Particulate reinforced composite materials have hard particles surrounded by a soft matrix. The composite is characterized by the dispersion of particles greater than 1.0 micron in diameter roughly, with a low aspect ratio 1-5 and a dispersion concentration in excess of 10%. In order to provide a useful increase in properties, there must generally be a substantial volume fraction (10% to 40%) of reinforcement. Particulates reinforced composites are must preferred choice for several critical applications, because they offer the isotropic properties. They provide 10 to 30% increase in strength; 30-100% increase in stiffness strength and superior wear resistance compared to unreinforced matrix alloys. Figure 1.1(a) illustrates particle reinforced composites. Nowadays, various kinds of ceramic particles (Oxide, carbide and nitride) are used as reinforcement. Silicon carbide particles reinforced aluminium matrix composites have a good potential for use as wear resistant materials. The particles lead to favorable effects on properties such as hardness, wear resistance, and composite strength. The other particles used as reinforcement in the aluminium matrix composites are graphite, TiC, ZrO₂, B₄C, TiO₂, Al₂O₃.
Figure 1.1 Classification the composite materials based on the geometry of reinforcement, (a) Particulate, (b) Whisker, (c) Fiber reinforced composite materials

1.4.2 Whisker Type of Reinforced Metal Matrix Composites

The aspect ratio of reinforcement is in the range of 1-10. Whisker reinforced metal matrix composites are used in structural and non-structural applications. They also exhibit isotropic and anisotropic properties and they depend mainly on the orientation of fibers. These mechanical properties are superior to those of particulate composite materials. Figure 1.1(b) illustrates a whisker reinforced composite.

1.4.3 Fiber Reinforced Metal Matrix Composites

Continuous fiber-reinforced composites contain reinforcements having lengths much greater than their cross sectional dimensions. The aspect ratio of reinforcement is in the range of 1-100, and mainly diameter of mainly fiber ranges from a fraction of a micron to several millimeters. Figure 1.1(c)
illustrates a continuous fiber reinforced composite. Over the years, a large number of fibers have been investigated as possible reinforcement for metals. The most important during the mid 1990s were alumina, boron, carbon and silicon carbide fibers. Fibers are expected to effect better improvements in rigidity and tensile strength (Frank et al 1987). In composite materials a fiber-matrix interface plays a crucial role and influences both local stresses and the effective properties of composites. Fiber reinforced matrix composites are mainly used in structural applications. They exhibit anisotropic properties. The continuous fiber reinforced composite materials provide more strength and modulus strength coupled with a low density of matrix.

1.5 PROCESSING OF METAL MATRIX COMPOSITE

The emergence of newer processing technologies has made many sophisticated fabrication processes to be adopted with greater control, and this has led to several routes commonly used for the production of discontinuously reinforced metal matrix composites. Due to the choice of matrix material and reinforcement, and geometry of reinforcement, manufacturing methods can vary considerably. Accordingly the processes can be classified into three categories: (Ibrahim et al 1991; Huda et al 1993; Naher et al 2004).

1. Liquid state processing
2. Solid state processing
3. Vapour state processing

1.5.1 Liquid State Processing

This process involves combining the desirable attribution of metals and ceramics. The advantages of liquid state processing are that it is a simple, economical process, and has high performance which tends to offer more flexibility, these allowing very large sized components to be fabricated
(Surrappa 1997; Fevzi bedir 2007). The liquid state process is widely used in many industries owing to fact that the composite materials can be produced net or near net shape. However, many problems are encountered in this process such as the distribution of particles into the liquid matrix, extensive chemical reaction and formation of porosity. The properties of the composite can be improved, by carefully controlling the relative amount and distribution of the ingredients of a composite as well as the processing conditions.

In recent times, several methods are used to combine the solid reinforcement and the liquid matrix phase. These methods are (i) Stir casting, (ii) In-Situ casting and (iii) Infiltration. This liquid state process is more beneficial than solid state techniques.

1.5.2 Solid State Processing

In solid-state processes, both the reinforcement and matrix are combined in the solid state condition. The solid state process is generally used to obtain the best mechanical properties, particularly in the particulate reinforced composite materials. This is because particles are distributed uniformly in the matrix, and formation of intermetallic compounds at the interface due to the chemical reaction between the matrix and the reinforcement is less compared to that in the liquid state process (Amirizad et al 2006; Hailong Wang et al 2008). Powder metallurgy is the most common method to fabricate composite materials. But, PM techniques are complex and different operation steps are needed to fabricate the composites such as mixing, and blending of pre-alloyed powder and reinforcement powder, and degassing under vacuum consolidation (Fevzi bedir 2007).
1.5.3 Vapour State Processing

In vapour state processes, droplets of molten metal are sprayed together with the reinforcing phase and collected on a substrate where the metal solidification is completed. The vapour state process is most the economical process. The matrix microstructure has a very fine grain size and low segregation but it has the drawback of discontinuous reinforcement whereby the product shape is limited.

1.6 PROPERTIES OF METAL MATRIX COMPOSITES

1.6.1 Strength

There are numerous factors influencing the strength of MMCs. In general, there are relatively few applications where the main attraction of using the MMCs stems from the greater strength offered, especially at room temperature while the presence of ceramic particles improves the modulus at higher temperatures. The comparison of Tables 1.1 and 1.2 shows the enhancement of strength in the MMCs due to the addition of ceramic particles considerably. The tensile strength of the MMCs is dependent on the volume of reinforcement in the matrix. The tensile strength decreases, while 0.2% offset yield strength increases on reinforcing Al alloy with different volume fractions of reinforcement. Heat treatment also affects the transition from elastic to plastic behaviour, hence peak-aged MMCs exhibit a slightly greater amount of elastic strain, yield strength and ultimate strength values than those in the as-fabricated condition.
Table 1.1 Some typical properties of unreinforced alloys (Lloyd 1994)

<table>
<thead>
<tr>
<th>Alloy</th>
<th>Yield strength (MPa)</th>
<th>Ultimate strength (MPa)</th>
<th>Elongation (%)</th>
<th>Young’s modulus (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6061(T6)</td>
<td>275</td>
<td>310</td>
<td>20</td>
<td>69</td>
</tr>
<tr>
<td>2014(T6)</td>
<td>476</td>
<td>524</td>
<td>13</td>
<td>73</td>
</tr>
<tr>
<td>2124(T6)</td>
<td>325</td>
<td>470</td>
<td>12</td>
<td>72</td>
</tr>
<tr>
<td>2618(T6)</td>
<td>370</td>
<td>470</td>
<td>9</td>
<td>74</td>
</tr>
<tr>
<td>7075(T6)</td>
<td>505</td>
<td>570</td>
<td>10</td>
<td>72</td>
</tr>
<tr>
<td>8090(T6)</td>
<td>415</td>
<td>485</td>
<td>7</td>
<td>80</td>
</tr>
<tr>
<td>A356(T6)</td>
<td>205</td>
<td>280</td>
<td>6</td>
<td>76</td>
</tr>
<tr>
<td>A380(F)</td>
<td>160</td>
<td>320</td>
<td>3.5</td>
<td>72</td>
</tr>
<tr>
<td>AZ91</td>
<td>168</td>
<td>311</td>
<td>21</td>
<td>49</td>
</tr>
<tr>
<td>AZ61</td>
<td>157</td>
<td>198</td>
<td>3.0</td>
<td>38</td>
</tr>
</tbody>
</table>

Table 1.2 Some typical properties of composite materials (Lloyd 1994)

<table>
<thead>
<tr>
<th>Composites Wrought</th>
<th>Yield strength (MPa)</th>
<th>Ultimate strength (MPa)</th>
<th>Elongation (%)</th>
<th>Young’s modulus (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6061/Al₂O₃/10p(T6)</td>
<td>296</td>
<td>338</td>
<td>7.5</td>
<td>81</td>
</tr>
<tr>
<td>6061/Al₂O₃/15p(T6)</td>
<td>317</td>
<td>359</td>
<td>5.4</td>
<td>87</td>
</tr>
<tr>
<td>6061/Al₂O₃/20p(T6)</td>
<td>359</td>
<td>379</td>
<td>2.1</td>
<td>98</td>
</tr>
<tr>
<td>6061/SiC/15p(T6)</td>
<td>342</td>
<td>364</td>
<td>3.2</td>
<td>91</td>
</tr>
<tr>
<td>6061/SiC/15p(T4)</td>
<td>405</td>
<td>460</td>
<td>7.0</td>
<td>98</td>
</tr>
<tr>
<td>6061/SiC/20p(T4)</td>
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<td>500</td>
<td>5.0</td>
<td>105</td>
</tr>
<tr>
<td>6061/SiC/25p(T4)</td>
<td>430</td>
<td>515</td>
<td>4.0</td>
<td>115</td>
</tr>
<tr>
<td>2014/Al₂O₃/10p(T6)</td>
<td>483</td>
<td>517</td>
<td>3.3</td>
<td>84</td>
</tr>
<tr>
<td>2014/Al₂O₃/15(T6)</td>
<td>476</td>
<td>503</td>
<td>2.3</td>
<td>92</td>
</tr>
<tr>
<td>2014/Al₂O₃/20p(T6)</td>
<td>483</td>
<td>503</td>
<td>2.0</td>
<td>101</td>
</tr>
<tr>
<td>356/SiC/10p(T6)</td>
<td>287</td>
<td>308</td>
<td>0.6</td>
<td>82</td>
</tr>
<tr>
<td>7075/SiC/10p(T6)</td>
<td>556</td>
<td>601</td>
<td>3.0</td>
<td>95</td>
</tr>
<tr>
<td>8090/SiC/13p(T4)</td>
<td>455</td>
<td>520</td>
<td>4.0</td>
<td>101</td>
</tr>
<tr>
<td>8090/SiC/13p(T6)</td>
<td>499</td>
<td>547</td>
<td>3.0</td>
<td>101</td>
</tr>
<tr>
<td>356/SiC/15p(T6)</td>
<td>329</td>
<td>336</td>
<td>0.3</td>
<td>91</td>
</tr>
<tr>
<td>AZ91/SiC/9.4P</td>
<td>191</td>
<td>236</td>
<td>2.0</td>
<td>47</td>
</tr>
<tr>
<td>AZ91/SiC/15.1P</td>
<td>208</td>
<td>236</td>
<td>1.0</td>
<td>54</td>
</tr>
<tr>
<td>380/SiC/10p(F)</td>
<td>245</td>
<td>332</td>
<td>1.0</td>
<td>95</td>
</tr>
<tr>
<td>380/SiC/20p(F)</td>
<td>308</td>
<td>356</td>
<td>0.4</td>
<td>114</td>
</tr>
</tbody>
</table>
1.6.2 Ductility

Limited ductility is a major drawback of the composites. It can be seen from a comparison of Tables 1.1 and 1.2, that a major limitation in the engineering properties of particle-reinforced MMCs is the rather low ductility (as quantified by percent elongation). The tensile elongation decreases with increasing particle content. It has been demonstrated that composite failures are associated with particle cracking and void formation in the matrix within the cluster of particles. Particle fracture is more prevalent in coarser particles. This is because the coarser particles will be loaded more by conventional loading mechanisms. In addition the coarser ceramic particles will have a high probability of containing fracture initiating defects.

1.6.3 Modulus of Elasticity

This is an important property of MMCs which is significantly influenced by the addition of ceramic particles to a metallic alloy. The enhancement of stiffness achieved by the addition of the reinforcement is retained at high temperatures, and this is of great benefit in the design of rotating parts, support members, and structural body work. Elastic modulus (Tensile modulus) which is also called stiffness, is an anisotropic property in the long and short fiber reinforced MMCs, due to the geometric and material properties of the reinforcements. The stiffness of the reinforced metal matrix composite is determined by the elastosonic method and also calculated using the simple rule of mixture theory: (Jayamathi et al 2004)

\[ E_{\text{composite}} = E_m V_m + E_f V_f \]  

(1.1)

where \( E_{\text{composite}} \) is young’s modulus of composite, \( E_m \) is young’s modules of matrix, \( E_f \) is young’s modulus of fiber, \( V_m \) and \( V_f \) is the volume fraction of the matrix and the fiber. In the case of particulate MMCs, there is a near isotropic situation, where the stiffness in the longitudinal and transverse directions will be the same.
The elastic modulus of the composite is increased with an increasing amount of the reinforcement. The quantitative value of the elastic modulus is somewhat dependent on the method of measurement, and some difficulties are due to the presence of thermal residual stresses caused by the difference in the co-efficient of thermal expansion (CTE) between the matrix and the ceramic particles, and also the in homogeneity of the reinforcement distribution in the composites.

To predict the properties of the MMCs from a study of the properties of the individual components, numerous mathematical models have been formulated. Among these models, the simplest is the rule of mixture (ROM) approximation, in which the CTE, density, strength, modulus, or any other desired property of the MMCs can be calculated from the weighted average of the individual components.

\[
\alpha_c = \alpha_m V_m + \alpha_p V_r
\]

(1.2)

where \( \alpha \) are the property of composites, \( V \) the volume fraction and the subscripts c, m and r refer to the composite, matrix and reinforcement respectively. Laminations to the ROM approximation are due to the non-isotropic properties of high aspect ratio reinforcements and the effects of thermal barriers at the interfaces.

### 1.6.4 Toughness

Toughness can be regarded as a measure of the energy absorbed during the process of fracture, or more specifically as the resistance to crack propagation. The toughness of the MMCs depends on the following factors (Chawala 2006):

1. The matrix alloy composition and microstructure
2. The reinforcement size, type and orientation
3. Processing, as it affects microstructural variables.
1.6.5 Wear Resistance

Another important attribute of the metal matrix composites is their improved resistance to wear and abrasion. Although different wear applications require different reinforcement types to achieve optimal wear rate reduction, there are many situations where the wear rates are reduced by factors leading to the introduction of the reinforcement into the matrix. This makes the MMCs very attractive for bearings, bushes, cylinder liners, and brake rotors. In some cases, it is advantageous to control the distribution of reinforcement so as to provide a material of high Wear resistance in selected surface areas, while other regions are suitably tough, strong, or thermally conducting (Ikechukwu and Oguocha 1999).

The increased resistance to abrasion and wear of the MMCs compared to that of unreinforced metals makes these materials very attractive in tribological applications but also renders their machining much more challenging than that of conventional unreinforced metals. The wear resistance of particulate reinforced metal matrix composites is higher than that of whisker or fiber reinforced composite materials

1.6.6 Resistance to Wet Corrosion

Resistance to wet-corrosion, for example, can significantly decrease in some systems, such as carbon-fiber-reinforced magnesium where high corrosion rates result from galvanic coupling between the matrix and the reinforcement. Environmental stability at elevated temperatures may be impaired, for example, in SiC-filament-reinforced titanium or intermetallics due to the presence of a carbon-rich layer at the interface between the fiber and the matrix, this layer being essential for composite strength and subject to oxidative attack.
1.7 INTERFACE OF MMCs

The interface (or interphase) is the zone of transition separating the matrix from the reinforcement, with thermal, physical and mechanical properties that can be different from those of the reinforcement and the matrix. The role of the interface is very critical to the performance of the composites (Ananth et al 1998). The interface between the matrix and the reinforcement plays a crucial role in determining the properties of the metal matrix composites (MMCs). The load transfer on the matrix has to be transferred to the reinforcement via the interface. Thus, the reinforcement must be strongly bonded to the matrix if their high strength and stiffness are to be imparted to the composites.

A weak interface reduces the stress concentration near the interface zone and causes a reduction in the maximum plastic strain. However, debonding in the broken fiber increases the load in the adjacent matrix, creating a diffused plastic zone (Ananth et al 1998). The fracture behavior is also dependent on the strength of the interface. A weak interface results in low stiffness and strength but high resistance to fracture whereas a strong interface produces high stiffness and strength but often low resistance to fracture i.e. brittle behavior.

The interface between the matrix and the reinforcement is a critical region that is affected during fabrication. If this interface is not tailored properly it can lead to the degradation of the properties of the composites. The problems associated with the interface are due to chemical reactions, lack of wettability etc. Hence, it is a very difficult exercise to design optimized interfaces common and suitable to all systems. Some of the methods are used to obtain better interfaces are the modification of the matrix composition, coating of the reinforcement and control of process parameters.
The interface is important in all composite systems whether the reinforcement is in the form of a continuous fiber, a short fiber or whiskers or a particle although the exact role of the interface may differ with the type of reinforcement. In some cases a distinct phase, produced by a reaction between the matrix and the reinforcement, exists at the reinforcement-matrix interface. In other instances, the interface can be viewed as a planar region of only a few atoms in thickness, across which there is a change in the properties from those of the matrix to those of the reinforcement. The nature of the interface bond has a strong influence over the properties of the metal matrix composites. Strengthening of the composites by the reinforcement is dependent on the strength of the interfacial bond between the matrix and the reinforcement.

The mechanical properties of the MMCs are controlled to a large extent, by the structure and properties of the reinforcement-matrix interface. It is believed that a strong interface permits the transfer and distribution of the load from the matrix to the reinforcement. From the point of view of the metallurgical structure the desired interfacial region in a composite relies on several factors.

- An intimate contact between the reinforcement and the matrix to establish satisfactory wetting of the reinforcement by the matrix.
- A very low rate of chemical reaction at the interface and little or no inter-diffusion between the component phases, so that the reinforcement is not degraded (Hashim et al 2001).

The interfacial, considering actual strength and toughness desired for the final MMC depends on the physical and chemical properties of the matrix and the reinforcement, and hence a compromise has to be achieved often balancing several conflicting requirements. In the case of Continuous
Fiber Reinforced Metals (CFRM), high strength is achieved by preventing chemical reactions between the matrix and the inorganic fibers, while a weak interface is desirable to enhance the longitudinal strength and toughness. A strong interface is desirable to achieve good transverse properties in the CFRM.

The interface (or interphase) is the zone of transition separating the matrix from reinforcement, with thermal, physical and mechanical properties that can be different from those of the reinforcement and the matrix. The role of the interface is very critical to the performance of the composites (Ananth et al 1998).

Interfacial bonding affects the fracture behavior of ceramic matrix and metal matrix composites. A strong interfacial bond will not impede an oncoming crack and the composite will fail in a brittle manner. But, in the case of a weak bond, it will lead to debonding at the interface, followed by crack deflection, crack bridging, fiber fracture etc. (Chawala 2004).

Interface bonding can be achieved either by a mechanical or a chemical bond. A mechanical bond can be attained using mechanical interlocking or frictional effects from the thermal contraction of the matrix on the reinforcement. The mechanical bond is the weakest bond however, some sort of additional chemical bond is usually preferred. The chemical bond is characterized by the formation of a new chemical compound at the interface by one or more chemical reactions. These bonds can be covalent, ionic, metallic, etc., and all are usually very strong. However, it is often observed that the reaction is inadvertent or too strong, and has detrimental effects by forming brittle reaction products.
1.8 APPLICATION OF COMPOSITE MATERIALS

Metal matrix composites are a promising new class of materials and their engineering applications continue to grow. Their benefits include a high strength to weight ratio for structural applications, a tailor-able thermal expansion co-efficient for electronic application, and improved elevated temperature strength aerospace applications (Mogilevsky et al 1995). The aluminium based metal matrix composites possess a number of mechanical and physical properties that make them suitable for many automotive applications: low density, good resistance to corrosion, low thermal expansion, and established casting techniques for mass production (Prasad et al 2004). The initial needs for the development of aluminium based metal matrix composites were in aerospace, automotive and defense applications, where high performance materials were required in relatively low volumes, thus justifying high costs. Whilst this fields of application continues to be a great interest, there have been strong moves in recent years to introduce the concept into higher volume applications, notably the automotive fields where larger volume production and lower materials cost are required. In addition, various other more specialized applications exist. Particulate reinforced metal matrix composites are already attracting the attention of material producers and end users owing to their outstanding mechanical and physical properties. The MMC gives more benefits compared to conventional metals, these are given below:

1. Potentially increased design flexibility
2. Better damage tolerance
3. Increased impact resistance
4. Increased fracture toughness
5. Greater scuff resistance
6. Better corrosion resistance
7. High specific strength and stiffness
8. Low thermal coefficient of expansion
9. Better fatigue resistance

The differential advantages of the SiC reinforced with aluminium have been demonstrated in many commercial product forms. Business Communications Company, Inc. estimates that the global MMC market will rise from 3.6 million kg in 2005 to 4.9 million kg by 2010, reflecting an average annual growth rate of about 6.3%. Figure 1.2 shows the usage of the MMCs per year, with the market segment break up (i.e., automotive, aerospace, consumer products, etc.). They offer many attractive features to engineers and designers, especially in the automotive and other ground transportation industries. The high strength-to-weight ratio, enhanced their mechanical and thermal properties over those of conventional materials. The high strength-to-weight ratio is particularly important to reduce fuel consumption and increase fuel economy (Chawla 2006).

![Figure 1.2 Use of the MMCs in different market sectors (Chawala et al 2006)](image)

For aerospace use, MMCs have been the primary materials as they offer a number of potential benefits to the aerospace industry, for the last few
decades. Good performance characteristics, known fabrication costs, design experience, and established manufacturing methods and facilities, are just a few of the reasons for the continued confidence in aluminum alloys that will ensure their use in significant quantities for the rest of this century. The composites have several unique properties that make them attractive for high-temperature space applications.

The high strength and stiffness, and low density of the MMCs generated significant interest in Aerospace industries. Their high compressive and bearing strength, good fracture toughness, and enhanced elevated temperature performance translate directly into reduced flight vehicle weight. For example, carbon - carbon composites are attractive for spacecraft structure because they have relatively low density, and also it have resistant to thermal shock, stable to very high temperatures, and have low thermal expansion and good thermal conductivity.

For automotive use, there is a broad range of opportunities for employing metal matrix composites in automotive power trains, chassis, body structures, and reduction in mass especially in engine parts. It is highly desirable to improve the fuel consumption rate by a reduction in the total weight of the vehicle. Improved material properties, particularly stiffness and strength, are either providing increased component durability or permitting more extreme service conditions. In recent years, research and development has been carried out to substitute the conventional cast iron brake rotor by an aluminium brake rotor (Hiroaki et al 2002).

Many metallic parts of automotive components are made of ferrous and aluminium alloy matrix composites. Efforts are on to replace these with lighter and eco-friendly materials. For example, the Al-graphite composition in diesel engines resulted in lesser wear of the piston and rings reduced the loss of frictional horse power, and showed no seizure under adverse
lubrication conditions. Another example, Toyota has used ceramic fiber reinforced aluminium alloys for the top ring groove in diesel engine piston since 1982 (Mogilevsky et al 1995).

Drive shafts are made of silicon carbide-titanium composites. These are generally for the core of an engine, requiring increased specific stiffness to reduce the unsupported length between bearings, and to increase critical vibratory speed ranges. In 1989, a new MMC technology was applied to a gas-engine cylinder block, and Honda introduced engines using the technology in the United States and Japan. The cylinder block was made from aluminum and aluminum-based MMCs (Varuzan and Kevorkijan 1999).

1.9 FUTURE DIRECTION

Research and development programs point the way to a number of future MMC applications, high temperature engine and airframe components, thermal management, electronic packaging and mechanical devices, such as pumps, electrical generators and actuators.

Leading high temperature fibers are silicon carbide, aluminium oxide and carbon. High temperature matrices under investigation include titanium and nickel aluminides, titanium and niobium. Where high thermal conductivity is also a requirement, copper is under consideration.

Future composites used in thermal management and electronic packaging are likely to use reinforcements such as carbon fibers made from pitch precursors and by chemical vapour deposition. High purity silicon carbide, berllia and diamond particles are other candidates. Key matrices are aluminium, magnesium, copper and beryllium.

The high specific stiffness of MMCs consisting of magnesium and aluminium reinforced with particles such as silicon carbide and boron carbide
combined with the ability to use these materials in low cost processes such as casting, make these materials the leading candidates for mechanical system components.

1.10 SIGNIFICANCE OF ALUMINIUM METAL MATRIX COMPOSITES

Nowadays the main focus is given to aluminium matrix because of its unique combination of good corrosion resistance, low density and excellent mechanical properties (Huda et al 1993). Aluminium matrix composites (AMC) are usually reinforced by aluminium oxide (Al$_2$O$_3$), Silicon Carbide (SiC) and Carbon (C). The reinforcements are in the form of flakes, particulates and fibers. In general, the alloys were considered for their intrinsic characteristics and above all their processing ability (e.g. powder metallurgy, casting, forging, rolling). Al matrices are in general Al-Si, Al-Cu, 2xxx, 6xxx, 7xxx alloys.

7xxx Aluminium alloy exhibits the best combination of strength and toughness for aerospace application. 2xxx aluminium alloy composite is used widely for aerospace application. The 2xxx, 6xxx and 7xxx aluminium alloy have been used widely as matrix material for making composite. Increasing knowledge of reinforcement–matrix wetting and interface reaction has permitted the adjustment of matrix composition with respect to the reinforcement type. In that way the addition of alloying element (e.g. Magnesium (Mg), Copper (Cu), Lithium (Li)) gives an example of how a liquid aluminium matrix can be adapted for use with particles, fibers and whiskers in order to improve chemical compatibility. The addition of Mg and Si gives rise to better dispersion of reinforcement in the liquid (Girot et al 1987). Generally Titanium (Ti), Mg, Nickel (Ni), Cu, Plumbum (Pb), Ferrous (Fe), Argentum (Ag), Zinc (Zn), Stannum (Sn) and Silica (Si) are used as alloying element in Aluminium (Huda et al 1993).
1.11 NEED FOR THE UNDERSTANDING INTERFACE IN A METAL MATRIX COMPOSITE

A detailed understanding of the interface and interface region in a composite material is of vital importance for many manufacturing industries. Information on the interface region is a key factor region in metal-matrix composite materials, because the interface has a significant influence on the properties of the final product. In addition, interface plays a key role in the improvement of reliability during the application of these materials. Therefore, the region of material interfaces has been studied widely in the field of MMCs.

However, approaches to overcome the problems associated with the interface vary between research groups depending on their point of view. Generally, most research activities are focused on the processing of composites with macro-level properties. Recently, a development in analytical equipment has allowed researchers to study and to understand interface behavior at the atomic level. The interface behavior measured may vary, since it is easily affected by experimental conditions and the microstructure of the solid’s surface.

Therefore, the results obtained by many research groups do not always agree well with one another. Thus, it is not surprising to know that much of the research in the mechanism of composite materials has focused on the interface, but due to the complexity of this subject, many issues still remain unclear and unsolved.

1.12 SIGNIFICANCE OF MATRIX-CERAMIC BONDING

In composite materials, the matrix-ceramic bonding plays a crucial role and influences both the local stresses and the effective properties of
composites. The strength and stiffness of a composite depend on the load transfer across the interface and ductility is influenced by the relaxation of high stress near the interface. As far as the matrix-ceramic interface bond in composites is concerned, open literature data are still scarce and contradictory. An essential aspect, in particular, still needs to be clarified, regarding the nature of the bonding between matrix and ceramic. However, a complete and comprehensive investigation of the dissolution, diffusion and chemical reaction phenomena taking place in the interfacial area during the processing of composites. The most important is that the mechanical properties of MMCs depends on the interface bond between the matrix and the reinforcement.

Now a days the main focus is given to the aluminium based metal matrix composites because of the unique combination of the physio-mechanical properties such as low weight, high specific strength and stiffness. Increasing knowledge of reinforcement-matrix wetting and interface reaction has permitted the adjustment of matrix composition with respect to the reinforcement type.

The formation of the interface bond between the matrix and the reinforcing phase has a substantial influence on the production and characteristics of the metallic composite materials. The bond between both phases is usually determined by the interaction between them during the production of the metal matrix composites.

In recent years, there has been an increased interest in analyzing the transition joints of commercial aluminium and silicon carbide. This combination of materials finds widespread applications in many industries. When joining the liquid aluminium with the solid silicon carbide, a number of intermetallics are frequently formed in the interface region, which results in embrittlement at the interface.

Si and C are two elements which exhibit a number of intermetallic phases at the interface of Al-SiC. The direct bonding between Al-SiC at
higher temperatures influences the formation of intermetallics such as Al₄C₃, AlMgSi, and SiO₂. The influences of the formation of intermetallics like Al₄C₃, AlMgSi and Al-Si eutectic phases and their growth have also been studied. The existing literature reports that, a higher bonding temperature results in an increase in the inter-diffusion and better coalescence of the joining surfaces. However, increasing bonding temperature also promotes the growth of brittle intermetallics, which in turn, affect the bond strength adversely.

1.13 SCOPE OF WORK

The purpose of this study is to understand the influence of process parameters such as the processing temperature and holding time on the distribution of particles in the matrix, and the resultant mechanical properties of metal matrix composites. In order to demonstrate the influence of processing temperature and holding time on the effective distribution of the particles in the matrix, Al-11.12 Si / 10% SiCp composite materials were fabricated through the stir casting process, with different processing temperatures and different holding times. The basic parameters that affect the distribution of particles in the aluminium based metal matrix composite are: (i) Processing temperature (ii) Holding time. The processing temperature refers the actual processing temperatures at the time of stirring, and the holding time refers the actual time period during which the SiC particles contact with the liquid matrix materials.

The present study also investigates the phenomena of the matrix-ceramic interfaces at different temperatures and different holding times, through the joining process. The basic processing parameters such as process temperatures and holding times affect the formation of a good interface between the matrix and the reinforcement. This research work focuses on clear-cut interface measurements for several systems. Moreover, it proposes a
general concept on the interface of the Al/SiC, and studies the presence of the intermetallic element at the interface and also how it influences the formation of a strong interface bonding. The processing parameters were selected based on the literature and also from preliminary experimental studies.

In the present study, the Al-SiC were joined under different processing conditions to understand the influence of the process parameters on the interface bond and the resultant mechanical properties. Our solution to the problems associated with interface behavior will certainly be relevant to practical applications, such as the production of advanced composite materials. The results obtained from this research will have a great impact on the development of advanced composite materials and many manufacturing industries, as well as on the expanding technologically important field of interface science.

Interface bonding was evaluated by the microstructure analysis, and the SEM analysis, and the interface bonding strength was evaluated by the tensile test. Further, the hardness measurements are used to study the improvement at the interface due to the formation of intermetallics. The significance of change in chemical composition at the interface was discussed with the EDS testing results. The diffusions of the Si and the C atoms across interface regions were also discussed.

In order to understand the interface bond strength on the micromechanical behavior of the MMCs, a new approach called ‘Microstructure-based Modeling’ was used. This model is used to predict the failure mode such as particle fracture, interface decohesion, and matrix yielding in Al-SiC metal matrix composites. The models were verified and the results compared with the experimentally determined stress-strain values.
1.14 NEED FOR THIS STUDY

Aluminum based particulate reinforced matrix composites are attractive, since significant improvements in stiffness, strength, wear resistance and low density, in addition to high-temperature capability, have already been established. However, the industrial development of these materials has remained limited, although PRMMCs have elicited a great deal of interest in the automotive industry for which large scale production might be expected. Two major reasons have impeded the development of PRMMCs:
(i) Particles distribution in the matrix. Especially, liquids state of processing.
(ii) Formations of strong interface bonding between matrix and reinforcement.

The distribution of ceramics particles in the matrix materials provides the high specific strength, high specific modulus and high stiffness (Hashim 1999). The homogeneous particles distribution is important concern to enhance the mechanical properties. These properties are depends mainly on the behaviour of interface region between matrix and reinforcement. The interface is the region that establishes the bond between the two dissimilarly structured materials viz., the matrix alloy and the reinforcement. Interface is the region that lies between the matrix and the reinforcement. It plays a crucial role in determining the composite properties. The function of interface is transfer the applied load from matrix into reinforcement because the reinforcements are stiff and strong. Therefore, the properties of composites depend on strong interface bonding between matrix and reinforcement.

The individual study not reported in detail but reported the performances of the reinforcements, the composition of the aluminum alloys, the fabrication methods, the mechanical behavior and the characteristics, the areas of application, and the finally the theoretical models allowing prediction of properties. The purpose of this study, demonstrates the influence of process
parameters such as processing temperatures, hold time and composition of matrix in the particle distribution and formation of interface bond between aluminium and Silicon Carbide.

1.15 OBJECTIVES

There has been only minimum literature on the influence of process parameters during stir casting on the homogeneous distribution of particles; it is one of the research areas. Also it is necessary to study the influence of the interface behaviour on the mechanical properties, so as to optimize the performance of the composite. The formation of such interfaces and their influence on the mechanical properties has not been studied. The mechanical as well as physical properties are depends mainly on the behavior of mainly interface in composite materials. From the literature review, it was found that only a few authors have concentrated in addressing critical issues pertaining to the interface region.

An adequate bond could be achieved with suitable bonding parameters, such as processing temperature, holding time and initial pressure. In addition, each process is interrelated and thus has an effect on the other. The processing temperature will aid the inter-diffusion of intermetallic elements across the interface, that reduces the interfacial reaction between the matrix and the reinforcement, and assist the formation of a good interface bond. The interface reactions in the composite depend on the processing temperature and holding time. Hence, the holding time should be optimized to achieve a strong interface bonding between aluminium and silicon carbide.

Hence, it is necessary to study the influence of the process parameters on the distribution of particles, and the formation of the interface bond between the matrix and the reinforcement. Experimental and analytical methods are needed to characterize the interface bonding strength of
aluminium with silicon carbide. Based on the literature review and above the discussion, the important objectives of this research work are listed below:

1. To study the influence of the Stir casting process parameters such as processing temperatures (700°C, 750°C, 800°C, 850°C, 900°C) and holding time (10 Min., 20 Min., 30 Min.), on the distribution of particles and mechanical properties, such as tensile strength, hardness and impact behaviour.

2. To study the effect of the viscosity of matrix at different processing temperatures by the numerical method.

3. To develop the interface bond between aluminium and silicon carbide by the joining process: By using the two parameters, such as different process temperatures and holding times.

4. To analyse the intermetallic compounds at the interface of the Al /SiC: by scanning electron microscope attached with energy dispersive spectroscopy.

5. To study the diffusion of the Silicons at the interface in the matrix by the Herrihanous equation.

6. To correlate the experimental test results with the numerical test results: by microstructure based FEA.

7. To predict the thermal residual stress at the interface at different processing conditions by FEA.

1.16 OUTLINE OF THE THESIS

This research work involves a study of the interface bonding characteristics of aluminium and silicon carbide. This thesis is divided into three main parts. The first part deals with the processing parameters of the stir casting process such as processing temperature and holding time on properties
of Aluminium and silicon carbide composites. The second part presents the chemical reaction between aluminum and silicon carbide at different temperatures and different holding times. The third part deals with the correlation of experimental results with the finite element analysis. The finite element analyses were carried out based on the microstructure modeling.

**Chapter 1** - This chapter describes the significance of composite materials in engineering applications and the need for interface bonding on aluminium and silicon carbide. The interface region plays a vital role in the reliability of composite. The main objective of the present study is to analyse interface bonding strength between the matrix and the reinforcement. These objectives are elaborated in this chapter.

**Chapter 2** - In this chapter, the recent literatures have been reviewed. The mechanical properties, interface bonding characteristics and recent development in composites have been reviewed. The chemical reactions and the segregation of interface compounds are discussed in this chapter. The Finite element analysis to characterize the MMC and the failure analysis and recent models developed are also reviewed in this chapter.

**Chapter 3** - In this chapter the influence of the stir casting process parameters on the effective distribution of the SiC particles in the Al/SiC<sub>p</sub> composites is analyzed. The experimental procedure and conditions involved in the processing of the MMC are presented in this chapter. The evolution of SiC particle distribution in the matrix by means of the microstructure, hardness and density tests are analyzed in this chapter. The mechanical properties of Al/SiC<sub>p</sub> composite processed in different conditions were also analyzed.

**Chapter 4** - In this chapter the influence of processing the temperature and holding time on the interface bonding of the Al/SiC is
determined experimentally. The interface bonding between reinforcement and matrix is discussed with the microstructure and SEM photographs. The chemical reaction between the reinforcement and the matrix is also discussed in this chapter.

**Chapter 5** - The interface bonding strength is modeled using the finite element analysis in this chapter. The failures of interface bonding are carried out with the finite element analysis by SEM based microstructures. Failure mechanisms such as interface decohesion, matrix yielding and particle fracture are also analyzed.

**Chapter 6** - The conclusion on the interface bonding characteristics of Al/SiC is presented in this chapter. The suggestion for the future study on this work is also presented this chapter.

The organization of the research work is given in Figure 1.3.
Studies on the influence of the interface characteristics on the stir cast Al/SiCp and diffusion bonded Al/SiC

Process parameters:
1. Different temperature (700°C, 750°C, 800°C, 850°C, 900°C)
2. Different Holding time (10, 20, 30 minutes)

Materials selection:
- Al alloys (Al-11.12Si)
- Silicon carbide

Interface analysis:
- SEM analysis
- EDS analysis

Mechanical properties:
- Tensile test
- Microhardness test
- SEM analysis
- EDS analysis

Results and discussion

Conclusion

Figure 1.3 Work Methodology