CHAPTER 2

LITERATURE SURVEY

2.0 INTRODUCTION

Aluminium and its alloys play a significant role in all aerospace, automobile, construction, food processing, decorative article production and other industries. In most of the cases aluminium sheets / strips are in use. [7]. The traditional method of producing aluminium sheets through sheet rolling is expensive energy intensive and large amount of facilities are required. To overcome the drawbacks many new processes for making aluminium sheets are experimented. One such significant process is twin roll casting or Direct Strip Casting. In the present literature survey the basic methods of manufacture of thin metal strips and sheets is presented. It is followed by the second part where in the various aluminium alloys used for making of sheet production is presented. Then the most recent advancement in tailor made aluminium alloy namely metal matrix composites is shown. The last part of literature survey is directed towards the available information on properties and microstructure of normal aluminium sheets as well as twin rolled cast aluminium sheets are given.

2.1 CONTINUOUS CASTING PROCESS FOR ALUMINIUM STRIP

The idea of the continuous strip casting process was proposed by Sir Henry Bessemer [8] and it was patented in the year 1846. Though it was patented in the mid years of 19th century, the process was not extended to aluminium alloys until forties of the twentieth century. The reason for development of the twin roll casting process for the aluminium alloys is competition in the material producing market, rapid development of
new technologies, and increasing demand in the usage of aluminium alloys in the industries. The continuous development of the strip casting process is purely on the practice while the developments in understanding the theory are little understood. There are some attempts to explain the theory behind the strip casting process by some researchers; an increasing attention is being paid to study the basic principles. The strip is produced by popular techniques using wheel and belt machines, twin belt casters and twin roll casters are commonly adopted. These are the continuous casting processes used for producing aluminium slab or strip directly from molten metal and are diagrammatically depicted in Fig. 2.1. These techniques are based on moving the mould in contrast to the fixed mould walls. [9]

2.1.1 Wheel and Belt Machines

The drawback of casters with the fixed mould walls, which cause the friction effects, had hindered the development of the continuous strip casting process for a long time as explained by Lewis [10]. In the year 1882, Lyman [11] came out with a new idea of wrapping a thin metal belt over part of the periphery of a wheel containing a groove in its rim to form a mould with no relative motion between itself and the casting. This is done to overcome the frictional effects of the fixed mould walls. Later Daniels [12] built a machine similar to Lyman [11], but both could not find success commercially and it remained unexploited until the year 1948. In that year the work of Properzi became popular. The outline sketch of the Properzi design is shown in Fig. 2.2 and also the later developments by Rigamonti [10] and the aluminium Laboratories [10]. The Properzi machine was used to produce the electrical conductor wire rod from aluminium [10,13,
Figure 2.1 Types of moving-mould casting machine.
(a) and (b) wheel and belt casters, (c) and (d) twin belt caster, (e) and (f) twin roll caster. (after Emley [9])
Figure 2.2 The basic layout of wheel and belt type casting machines.
(a) Properzi, (b) Rigamonti, and (c) Aluminium Laboratories.
(after Lewis (10))
14]. The machines developed by Rigamonti and the aluminium laboratories are used to cast the flat strip made out of aluminium.

These machines consist of a water cooled steel wheel, a grooved wheel and a tensioned wheel belt. The grooved wheel and the tensioned wheel belt form a mould cavity. When the molten metal is delivered to the water cooled steel wheel, it gets solidified in the mould cavity and leaves the wheel in the form of a strip, rod or wire as the case may be. A major drawback of the Rigamonti machine is that the cast strip forms a closed loop with the belt and it is difficult to deflect the belt to one side so that it does not form the closed loop with the belt. Due to this reason the width of the strip that can be cast is limited. The Rigamonti machine could produce the widths up to 150 mm whereas the modified Porterfield-Coors machine [10] could produce widths up to 300 mm.

2.1.2 Twin Belt Casters

Herrmann [13,15], Day [16] and Schwarzmarie [17] documented a large number of machines based on the twin-belt principle. But many of the machines listed by Herrmann [13,15], Day [16] and Schwarzmarie [17] did not find the commercial success except the ones developed by Hazelett (Alcan belt caster) and Hunter-Douglas. Alcan belt caster consists mainly of flat endless steel belts which form the top and bottom mould faces as shown in Fig. 2.3. The Hunter-Douglas employed two endless chains of mating blocks as shown in Fig. 2.4. These two designs eliminate the drawback of difficult in deflecting the solidified strip as witnessed in the Rigamonti machine. The twin belt casters do usually consist of a long and narrow mould into which the molten metal is supplied horizontally or at a small angle to the horizontal plane. The molten metal is distributed via a special launder to give the correct distribution over the width of mould
Figure 2.3 Schematic arrangement of the Hazelett machine. (after Hamer [18])
Figure 2.4 Schematic diagram of the Hunter-Douglas machine. (after Lewis [10])
cavity. By this, one can produce a long strip of the order 600 to 1200 mm length and 25 mm thick [10]. One drawback in using this machine is it produces center line porosity but this weld up during the subsequent rolling provided hydrogen content in the material is less. Also, the turbulence while introducing the molten metal plays a major role in the quality of the strip produced.

2.1.3 Twin Roll Casters

Bessemer's invention [8,19,20] during the 20th century represents the earliest designs of the twin roll casting processes. But it could not find the commercial success due to the formation of the defects in the cast strip until 1951 when the Hunter aluminium caster [21,22] was first used. The Bessemer caster uses a downward delivery system in which the molten metal is fed downwards into the V-shaped cavity between the rolls, whereas the molten metal is fed upwards in the Hunter caster which is claimed to make the delivery more even and controllable. Davy McKee (Poole) Ltd designed an other type of twin roll caster [23] in which molten metal is fed horizontally to the roll bite as shown in Fig. 2.5. The overall principal of the process is shown in fig. 2.6. Molten metal is fed to a pair of water cooled rotating steel rolls by means of a refractory feeding tip. When the molten metal touches the chilled rolls, cooling starts and the solidification proceeds from the roll surface to the center of the strip. Hot rolling happens when the center of the strip gets enough strength to support the load. The amount of deformation is largely dependent on the casting velocity, casting gauge and the alloy composition. Since the twin roll casters combines two operations namely continuous casting and the hot rolling into one, the capital expenditure required is very less compared to other techniques. But, due to low productivity, its application to the production of strips of various alloys is very limited and is popular only to the aluminium alloys.
Figure 2.5 General arrangement of the twin-roll caster. [23]
Figure 2.6 The overall principle of the twin roll casting process.
2.1.4 Continuous casting process

Continuous casting of aluminium is entering a new era of development, not only with respect to its increasing application in the production process, but also in its own evolution as a process and its interaction with other processes in aluminium manufacture. Continuous casting output has shown an accelerating growth curve. More than 50% of the current world aluminium production is continuously cast, and continuous casting in Japan exceeds 80%. The description of the process, along with its developments and current challenges for improvement, are given below.

The purpose of continuous casting is to bypass conventional ingot casting and to cast to a form that is directly rolled on finishing mills. The use of this process results in improvement in yield, surface condition and internal quality of product when compared to material obtained from ingot.

**Continuous casting involves the following sequence of operations:**

1. Delivery of molten metal to the casting strand.
2. Flow of metal through a distributor or tundish into the casting mould.
3. Formation of cast section in a water-cooled copper mould.
4. Continuous withdrawal of cast metal from the mould.
5. Further heat removal to solidify the liquid core from the casting by spraying water beyond the mould.
6. Cutting to length and removing the cast sections.

A diagram showing the main components of a continuous casting machine is presented in fig. 2.7 [24]. Molten aluminium in a ladle is delivered to reservoir above the continuous casting machine called a tundish. The flow of aluminium from the tundish into one or more open-ended, water-cooled copper molds is controlled by a stopper rod-nozzle or a slide gate valve arrangement. To initiate a cast, a starter, or dummy bar, is inserted
Figure 2.7 Main components of a continuous casting strand [24]
into the mold and sealed so that the initial flow of steel is contained in the mold and a solid skin is formed. After the mold has been filled to the desired height, the dummy bar is gradually withdrawn at the same rate that molten aluminium is added to the mold.

The initial liquid aluminium freezes onto a suitable attachment of the dummy bar so that the cast strand can be withdrawn down through the machine. Solidification of a shell begins immediately at the surface of the copper mold. The length of the mold and the casting speed are such that the shell thickness is capable of withstanding the pressures of the molten metal core upon exiting from the copper mold. To prevent sticking of the frozen shell to the copper mold, the mold is normally oscillated during the casting operation and a lubricant is added to the mold. The steel strand is mechanically supported by rolls below the mold where secondary cooling is achieved by spraying cooling water onto the strand surface to complete the solidification process. After the strand has fully solidified, it is sectioned into desired lengths by a cut off torch or shear. This final portion of the continuous casting machine also has provision for disengagement and storage of the dummy bar.

Several arrangements are now in commercial use for the continuous casting of aluminium. The types of continuous casting machines in use include vertical, vertical with bending, curved or S-strand with either straight or curved mold, curved strand with continuous bending and horizontal.

Most of the original continuous casting machines for aluminium were vertical machines. Vertical machines with bending and curved strand machines although more complicated in their construction were developed to minimize the height of the machine and allow installation in existing plants without modification of crane height.
2.2 ALUMINIUM AND ITS ALLOYS

Aluminium is the second most plentiful metal on earth but, until the late 1800's, was expensive and difficult to produce. Development of electrical power and hall - heroult process for electrolytically reducing Al₂O₃ to liquid metal allowed aluminium to become one of the most widely used and low cost engineering materials. Application number in millions including beverage cans, household applications, chemical processing equipment, electrical power transmission, automotive components, aerospace parts and structures.

Pure aluminium is soft, ductile and atmospheric corrosion resistant and has a high electrical conductivity. As a consequence it is widely used as foils in food industries and conductor cables. However alloying with other elements is necessary to provide higher strengths needed for other applications. The main alloying elements are copper, zinc, magnesium, silicon, manganese and lithium. Aluminium is alloyed with a large number of elements.

2.2.1 Metallurgy of Aluminium Alloys

Aluminium is one of the lightest of the engineering materials with a high thermal conductivity and excellent corrosion resistance in some common environments. It is known that aluminium when solidified below 660 °C generates an FCC crystal structure. Unlike iron aluminium does not undergo any allotropic transformations and the degree of structural refinement that is achievable after casting is limited unless some thermo-mechanical processing can be carried out during downstream processing. Nevertheless a large number of alloys are heat treatable i.e. age hardenable, which allows for a substantial improvement in their mechanical properties.
2.2.2 Alloying Elements in Aluminium

High purity aluminium is rarely used due to very low strength and the metal is generally alloyed with various elements to generate a very large range of useful grades that are extensively used as engineering alloys. Alloying additions to aluminium vary widely and their use is often governed by the extent of solubility in fcc lattice. Table 2.1 shows the solubility of some important alloying elements and it is clear that some elements (Cu, Mg, Li and Zn) are very soluble at the invariant reaction temperature while solubility of many elements is very low at room temperature. A notable feature of some elements particularly Fe, Mn, and Si, is the strong tendency to form intermetallic compounds during solidification.

Table 2.1 [25] shows that alloying additions generate phase diagrams containing either eutectic or peritectic transformations. The addition of several types of alloying elements allows the alloy to undergo a series of precipitation reactions after cooling through the solvus in a manner similar to low carbon alloys. This can result in considerable age hardening during secondary processing.

There is considerable scope for developing new strip-cast aluminium alloys exhibiting improved or novel properties due to the effect of high speed cooling on as-cast microstructure. Since solidification rates of direct strip casting are up to two orders of magnitude higher than Direct Chill Casting alloys may be produced with extended solubility of certain alloying elements, different types and morphology of intermetallic phases and far-from-equilibrium crystalline or amorphous phases.

2.2.3 Classification and key Aluminium Grades

Aluminium alloys are generally classified as wrought or casting alloys. The later are not amenable to Direct Strip Casting and will not be discussed further but detailed
<table>
<thead>
<tr>
<th>Element</th>
<th>Maximum Solubility (wt.%)</th>
<th>Temperature (°C)</th>
<th>Solubility at 20 °C (wt.%)</th>
<th>Type of binary phase diagram</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cu</td>
<td>5.65</td>
<td>548</td>
<td>&lt;0.1</td>
<td>Eutectic</td>
</tr>
<tr>
<td>Fe</td>
<td>0.05</td>
<td>655</td>
<td>&lt;0.1</td>
<td>Eutectic</td>
</tr>
<tr>
<td>Li</td>
<td>4.2</td>
<td>600</td>
<td>0.1-0.2</td>
<td>Eutectic</td>
</tr>
<tr>
<td>Mn</td>
<td>1.82</td>
<td>658</td>
<td>&lt;0.1</td>
<td>Eutectic</td>
</tr>
<tr>
<td>Mg</td>
<td>17.4</td>
<td>450</td>
<td>&lt;2.0</td>
<td>Eutectic</td>
</tr>
<tr>
<td>Si</td>
<td>1.65</td>
<td>577</td>
<td>&lt;0.1</td>
<td>Eutectic</td>
</tr>
<tr>
<td>Ti</td>
<td>1.3</td>
<td>665</td>
<td>&lt;0.1</td>
<td>Peritectic</td>
</tr>
<tr>
<td>Zn</td>
<td>70</td>
<td>443</td>
<td>&lt;0.1</td>
<td>Peritectic</td>
</tr>
<tr>
<td>Zr</td>
<td>0.28</td>
<td>660</td>
<td>&lt;0.1</td>
<td>Peritectic</td>
</tr>
</tbody>
</table>
information is available elsewhere. The former are divided into several subclasses depending on the type of principle alloying addition and these are divided into heat treatable and non heat treatable alloys. There are seven major alloying elements in wrought aluminium alloys and these generate a range of aluminium grades (table 2.2). Notable examples of alloys belonging to a particular grade and typical applications are also given. It is pertinent to note that wrought alloys given in table are a small group of a much wider range of alloys that contain, in addition to one or two major alloying elements, upto five other elements as either an intentional addition or as a consequence of the casting process.

2.2.4 Alloys Amenable to Direct Strip Casting

There are three major processes for producing low grade aluminium strip; direct chill casting (DCC), thin slab casting (TSC) and direct strip casting (DSC). Both strip quality and alloy castability is important factors for determining the scope of DSC in aluminium industry. Commercially proven alloys generally contain low solute level as in AA1XXX aluminium alloy [26]. Where final surface quality is not critical. The restricted range of alloys is due to the compositional and operational window required for producing high quality cast strip. Highly alloyed aluminium alloys are more difficult to cast due to their affinity for hydrogen, poor oxidation resistance and inherent metallurgical characteristics. The main obstacle is the freezing range of aluminium alloys as shown in (fig. 2.8 [27]) for AA1XXX, 3XXX and 5XXX alloys. As the Mg level is increased there is corresponding increase in freezing range to over 100 °C, increased tendency for hydrogen porosity and oxidation of the melt. These problems are also found in AA2XXX and 7XXX alloys where copper and zinc levels are high. Despite these limitations, there is a substantial research into the prospects of TRC AA3XXX, 5XXX.
Table 2.2 Classification of wrought aluminium alloys [26]

<table>
<thead>
<tr>
<th>Alloying addition</th>
<th>Designation system*</th>
<th>Typical types</th>
<th>Age hardening</th>
<th>Typical applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al(&gt;99%)</td>
<td>1XXX</td>
<td>105,011,001,200</td>
<td>NO</td>
<td>Foil, tubing, electrical Conductors, fittings.</td>
</tr>
<tr>
<td>Cu</td>
<td>2XXX</td>
<td>201,420,242,168</td>
<td>YES</td>
<td>Aircraft fittings, aircraft structures, truck wheels</td>
</tr>
<tr>
<td>Mn</td>
<td>3XXX</td>
<td>300,330,043,103</td>
<td>NO</td>
<td>Beverage cans, roofing</td>
</tr>
<tr>
<td>Si</td>
<td>4XXX</td>
<td>403,240,434,047</td>
<td>NO</td>
<td>Sheet, cooking utensils</td>
</tr>
<tr>
<td>Mg</td>
<td>5XXX</td>
<td>500,551,525,083</td>
<td>NO</td>
<td>Brazing alloys on cladded products</td>
</tr>
<tr>
<td>Mg+Si</td>
<td>6XXX</td>
<td>606,060,616,063</td>
<td>YES</td>
<td>Pressure vessels, marine applications.</td>
</tr>
<tr>
<td>Zn</td>
<td>7XXX</td>
<td>700,570,207,075</td>
<td>YES</td>
<td>Automotive panels and architecture</td>
</tr>
<tr>
<td>Others</td>
<td>8XXX,9XXX</td>
<td>800,681,118,090</td>
<td>VARIES</td>
<td>Aircraft components and sheet, forgings</td>
</tr>
</tbody>
</table>

*Based on the aluminium association Inc. (AA) system
Figure 2.8 Commercial Al-Mg alloys and their associated freezing range, adopted from Merchant et al [27].
2.3 GENERAL PROPERTIES OF ALUMINIUM

2.3.1 Density

Light weight is perhaps the aluminium's best known characteristic and with a density of $2.7 \times 10^3$ kg/m$^3$ is approximately one third the density of steel. Aluminium is being light is extensively used in airframe structures thereby increasing pay load. This feature together with other characteristics such as corrosion resistance and tensile strength has lead to replacing steel in many automotive applications in a demand for improved fuel efficiency. Aluminium is often used when weight is an important factor, as in aircraft and automotive applications. The relationship between the density of an alloy and its composition usually approaches linearity closely enough to justify calculating density as the sum of the density contributions of each element present.

2.3.2 Corrosion Resistance

Aluminium has a good corrosion resistance, which is attributable to thin oxide films which always form and protects the underlying metal from further oxidation. Unless and otherwise used in situations which destroys this protective, coating the corrosion resistance remains unaltered. Aluminium is highly resistant to weathering, even in industrial atmospheres which often corrode other metals. Aluminium is not attacked by nitric acid while it has varying corrosion resistance with all other mineral acids. General direct contact with alkaline substances should be avoided as this attacks the oxide skin and are less resistant to corrosion than others. Such alloys can be further protected by a variety of surface treatments or by cladding the exposed surface with a thin layer of an appropriate aluminium alloy.
2.3.3 Electrical Conductivity

Aluminium is one of the common metals having an electrical conductivity high enough for use as an electrical conductor. The electrical receptivity of the aluminium is approximately 2.6548E-8 Ωm. Specific conductivity of aluminium is more than that of copper and it has less than one third the density of copper. All known metallic additions to aluminium reduce its electrical conductivity. Metals in solid solution depress the conductivity to a greater extent than when out of solution.

2.3.4 Specific heat

Aluminium has a relatively high specific heat when compared with other metals on weight basis. Specific heat of aluminium increases approximately linear from room temperature to its melting point. The specific heat of aluminium containing additions that form insoluble constituents would not be influenced appreciably by thermal condition. The dependence of the specific heat of aluminium and its alloy on temperature shows that aluminium contracts or expands more with changes in temperature than most other common metals. This should be adequately provided in design.

2.3.5 Tensile Strength

Commercial pure Aluminium has a tensile strength of approximately 90 MPa and can be improved to around 180 MPa by cold working. The heat treatable grades can develop a tensile strength of around 570 MPa and even higher in some alloys namely 7xxx series. It is interesting to note that aluminium alloys increase in strength without loss of ductility or brittle failures. It is interesting to note that the strength of aluminium alloys yield high strengths without appreciable loss of ductility.
2.3.6 Low Temperature Toughness

Low temperature toughness especially in the presence of notches and flaws is an important factor in metal selection for cryogenic service. Catastrophic failures have also been resulted. Storage tanks for cryogenic fluids illustrate the potential problems and show why aluminium alloys are chosen to ensure maximum safety.

2.4 ALUMINIUM ALLOYS AND STRIP CASTING

With the developments in the technology, like wheel and belt casters, twin belt process and twin roll caster process, to produce the aluminium strips directly from the molten metals, the demand for the aluminium strips increases and it has become an important area in the aluminium industry. Table 2.3 provides the list of aluminium alloys produced in the form of strips produced using various processes along with the approximate production rates. Fig. 2.9 shows the relationship between the investment cost and the productivity of aluminium strip via different processes. From the Fig. 2.7 it can be concluded that when the annual output is below 30,000 tons the lowest investment cost is achieved by the thin strip caster method. However these figures may be outdated because of developments in the thin strip. The twin roll casting process offers low operating and low capital cost, consumes low energy and generates low scrap [28]. It also improves the mechanical properties of the strip due to the finer microstructure. However, there are certain drawbacks like low productivity, limited alloy capability which needs to be overcome if the twin roll casting process is chosen. Some attempts were made by Bagshaw etc Al. [29] and Browne and Hunt in collaboration with Davy McKee (Poole) Ltd [23] to improve the twin roll casting process by predicting the major defects like heat lines mathematically. It has been realized that the effect of the thickness of the strip on the productivity is significant, but the results available from different researchers [23,30]
Table 2.3 Continuous Casting Process Employing Moving Mould (after Emley [9], Lewis [10] and Browne [23])

<table>
<thead>
<tr>
<th>processes</th>
<th>Alloy</th>
<th>Strip Thickness in mm</th>
<th>Production Rate in Tonne/hr/m width</th>
<th>Maximum Mg in Al-Mg alloy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wheel and belt Rigamonti coors</td>
<td>Commercial pure Al</td>
<td>18 – 25</td>
<td>17</td>
<td></td>
</tr>
<tr>
<td>Rigamonti coors</td>
<td>AA2024</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rigamonti coors</td>
<td>AA2117</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rotary strip casting</td>
<td>AA3003</td>
<td>12.5</td>
<td>...</td>
<td></td>
</tr>
<tr>
<td>Peshiney-Lobeck</td>
<td>AA4043</td>
<td>12.5 – 25</td>
<td>...</td>
<td></td>
</tr>
<tr>
<td>Peshiney-Lobeck</td>
<td>AA4047</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peshiney-Lobeck</td>
<td>AA5052</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peshiney-Lobeck</td>
<td>AA5005</td>
<td>18 – 25</td>
<td>...</td>
<td></td>
</tr>
<tr>
<td>Peshiney-Lobeck</td>
<td>AA6061</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Twin-belt Hazelett Hunter-Doughlas</td>
<td>Common grade composition</td>
<td>6 – 40</td>
<td>20</td>
<td>≤ 4.5</td>
</tr>
<tr>
<td>Hunter-Doughlas</td>
<td>AA3003</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hunter-Doughlas</td>
<td>AA5182</td>
<td>25 – 38</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Twin-roll Hunter Davy Mckee</td>
<td>Commercial pure Al</td>
<td>3 – 7</td>
<td>0.6 – 1.1</td>
<td>2</td>
</tr>
<tr>
<td>Twin-roll Hunter Davy Mckee</td>
<td>AA3003</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Twin-roll Hunter Davy Mckee</td>
<td>AA3004</td>
<td>6</td>
<td>1.95</td>
<td></td>
</tr>
<tr>
<td>Twin-roll Hunter Davy Mckee</td>
<td>AA1145</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Figure 2.9 Estimated total investment costs (1970) for plants producing 7mm strip by conventional and strip-cast routes. (after Bloch and Thym [28])
are inconsistent. The productivity of the twin roll casting process is related to the speed of the rolls. The higher the speed of rolls, higher the productivity, but shorter the time available for the process. But the time available of the solidification of the molten metal is too less at higher speeds resulting in the higher rate of defects. In short span of time, in less than one or two seconds, all phenomena like liquid metal flow, heat extraction, solidification and hot rolling has to occur. In a very small time interval the heat has to transfer resulting in a temperature drop of hundreds of degrees. Due to this reason the productivity and the application to various alloys is limited.

2.5 SOLIDIFICATION IN THE TWIN ROLL CASTING PROCESS

Twin roll casting process is a combination of the metal feeding and solidification. Also there will be hot rolling during or after the solidification. It is important to understand the behavior of the solidification to determine the microstructure and properties of the strip. This will also help to minimize the number of casting defects. Therefore the principles of solidification should be applied to study the solidification in the twin roll casting process. It is also important to consider the effect of the moving mold, rolls in this case, in the study of the solidification.

Since much of this work is related to the effects of the operational parameters on the solidification process as well as on the formation of the associated casting defects, a review of the theories of solid-liquid interface structure, under cooling and instability of a planar interface, cellular and dendritic growth and microstructure of roll-cast aluminium strip is necessary. In the next paragraphs, the basic interface structure theories, description of the under cooling, instability of planar interfaces, cellular and dendritic growth, and finally the examination of the microstructure of aluminium cast strip is explained as much as possible.
2.5.1 Cellular and Dendritic Growth

Cellular and dendritic growth are the most common forms found under twin roll casting conditions, especially for pure or low alloy aluminium. Work in the past on cellular and dendritic growth has been concentrated on cell spacing, dendritic arm spacing, cellular and dendritic tip temperature and compositions and the transitions from planar to cellular and cellular to dendritic growth.

A number of approximate models have been proposed for cellular and dendritic array growth [31-39]. Although these models have improved our understanding of cellular and dendritic growth, criticism exists because of arbitrary assumptions that are made. A very recent achievement by Lu and Hunt [40] predicted correctly the absolute stability limit and the onset of constitutional super cooling. Cells were found to be present at low and very high velocities with dendrites at intermediate velocities.

2.5.2 Microstructure of Aluminium Cast Strip

The microstructure of aluminium strip cast by twin roll casting process is governed as the discussion above implies, by heat flow, growth of the interface, alloy composition, grain refinement, casting velocity, strip thickness, hot rolling and so on. The rapid solidification of the metal and the deformation by hot rolling in the cast strip generate a microstructure considerably different to that obtained from conventional routes. Fig 2.10 is a typical example showing the as cast microstructure of Al-Mn alloy strip under polarized light and at low magnification. Fig. 2.10a and 2.10b are the transverse and longitudinal sections respectively of the not refined twin roll cast structure and Fig. 2.10 c the longitudinal section after optimum grain refinement to an average 50 microns grain size. It is clear that a lot of grains are columnar, elongated along the heat flow direction and some what bent during hot rolling in the caster roll gap. The grain
refinement produces more equiaxed grains. This aspect ratio of the grains, however, can be controlled to some extent by judicious grain refinement. Feathery growth of aluminium is also found sometimes in twin roll casting according to D. Allepone [41] and is discussed by Fredriksson et al. [42]. The dendritic cell structure, one of the most important micro-structural aspects, depends strongly on the local cooling conditions [43-46].

Fig. 2.11 summarizes the general relationship between cooling rate and dendrite arm spacing. The fine cell size caused by high cooling rate in twin roll casting suggests that there could be an improvement in the mechanical properties of the cast strip. The distribution of cell spacing also important in the quality of casting. A plot of cell spacing against distance given by Westengen and Nes [48] suggests that the final cells appear at the surface of strip and the coarsest cells in the center (Fig. 2.12). The distribution of cell spacing across the cast strip section, however, may not be as simple if grain refinement is involved. Other microstructural aspects, such as segregation, will be discussed in relevant sections.

2.6 HOT ROLLING IN THE TWIN ROLL CASTING PROCESS

In the twin roll casting a sticking problem may occur due to hot rolling, especially when aluminium alloys are cast. A better understanding of the hot rolling component in the process will certainly be helpful to eliminate or reduce sticking. Unfortunately, up to now there appear to be only two references [49,50] directly related to the study of hot rolling in the twin roll casting process, owing to the complex thermo-mechanical nature of the process and the difficulties of direct measurements, and also due to it is not a major commercial problem. However, hot rolling can, to some extent, be separated from solidification because it occurs after, or near the completion of, solidification. Hence, the
Figure 2.10 The as-cast green structure of Al-Mn alloy strip of $\frac{1}{4}$ inch thick. (a) and (b) not refined, transverse and longitudinal, (c) refined, longitudinal (after merchant et al [47])

Figure 2.11 Freezing rate/ dendrite arm spacing relationship for 3004 and Al-4.5%, cu-2.0%Mn alloys and for several casting processes. (after Miki et al and Merchant et al [47])
Figure 2.12 Variation in cell spacing across the strip thickness. Alloy Al-0.5wt% Fe-0.2wt% Si. (after Westengen and Nes [48])
conventional theories of metal working [51-56] can help in the understanding of mechanism of hot rolling in the process. Of the many parameters in the hot rolling operation the forces acting in the region of contact between materials and the rolls [51], the interface friction, the forward and backward slip [56], the stress distribution [50,54,57] and deformation [47,50,54,58-60] are probably the most important ones.

2.6.1 The Forces Acting in the Region of Contact between the Material and the Rolls

Consider a dual driven roll system as shown in Fig. 2.13. \( P_r \) is the interface pressure distributed along the arc of contact, while \( P_k \) is the radial force acting on unit width, which equals \( P_r R_d \). The tangential friction force, \( F \), can be expressed as

\[
F = \mu P_r
\]

Where \( \mu \) is the coefficient of external friction, in other words, the friction between the surface of the rolls and material rolled. In conventional theoretical analysis, for simplicity, the coefficient of interface friction is usually assumed constant throughout the arc of contact, which leads to a constant interface friction force and pressure. However, this assumption may not be valid, because with the variation of the rubbing velocity between the rolls and the strip, and the possible change in the surface condition of the rolls and the strip from point to point, \( \mu \) may vary very appreciably along the arc of contact. It is also usually assumed that the material does not spread laterally and does not change appreciably in volume during rolling, therefore the velocity \( V_2 \), with which the material leaves the rolls, will be greater than velocity \( V_1 \) with which it enters.

The neutral point, or no-slip point, is defined as the point in the surface of contact between the rolls and the material at which the peripheral velocity of the rolls and the surface velocity of the strip are identical, based on the fact that \( F \) and \( P_k \) may change due
Figure 2.13 Forces acting between the rolls and the material. [51]
to different $\mu$, the position of the neutral point (which could be expanded to neutral zone, when sticking) may be greatly affected by interface friction.

2.6.2 Forward Slip and Backward Slip

Forward and Backward slip are defined as the ratio of $(V_2 - V) / V$ and $(V_1 - V) / V$, respectively, where $V_1$ and $V_2$ are defined as above in Fig. 2.12, and $V$ is the peripheral speed of the roll. The forward slip can be experimentally determined by measuring the distance between two indenters attached on the surface of a roll and the distance between their imprints on the surface of the rolled strip.

The importance of forward slip is that it is the most obvious and easily measured manifestation of external friction in rolling. From it, valuable information on the magnitude and variation of the mean coefficient of external friction can be deduced by comparing empirical relationship between the slip and other quantities with those predicted by theory based on assumptions.

Forcing the experimental and predicted roll torque and strip exit speed (which can be converted to forward slip) into agreement at a single reference roll speed, O'Malley et al [49] obtained the values for the coefficient of friction and the interface heat transfer. These were 0.18 for the friction coefficient 0.025 BTU/hr.in².F for the heat transfer coefficient. Their result for $\mu$ is higher than ones with kerosene lubricant, 0.10 - 0.15, and lower than ones without lubrication, 0.20 - 0.30, measured in the cold rolling experiments carried out by Rokotian [56]. Considering the fact that twin-roll casting is involved in the both rapid solidification and hot rolling, these low values for the friction coefficient and the heat transfer coefficient are doubt.
2.6.3 Stress Distribution

The stresses generated in rolling are so complex that the mathematical treatment becomes possible only if a number of simplifying assumptions are made. The yield properties of the rolled material, geometry of the roll pass and interface friction have been recognized as the most important controlling factors. In rolling operations interface stresses $P$ developed by major active force can reach a multiple of the uniaxial yield stress $\sigma_0$. In contrast, the tangential shear stress $\tau$ can never be larger than the yield stress of the workpiece material in shear, $\tau_0$, as shown in Fig. 2.14 (a). Once this value is reached, movement along the interface stops and deformation continues by subsurface flow, or shear, in the rolled material. This situation is described as sticking, and the sticking friction coefficient is then defined. As a consequence, the calculated maximum possible friction coefficient decreases with increasing mean interface pressure (Fig. 2.14(b)).

Tselikov [54] calculated the contact stress for metal slip with constant friction coefficient under different conditions. The result he obtained is illustrated in Fig. 2.15. The peaks indicate the uneven distribution stress and the possibility of sticking. It is obvious that the higher the friction coefficient and rolling reduction, and the larger the roll, the higher the contact stress. The analysis of contact stress in three-dimensional deformations gives similar results which can be simplified as in Fig. 2.16.

In two-dimensional rolling:

a) Effect of interface friction coefficient

b) Effect of reduction

The values and distribution of the stress and the friction coefficient along the contact length have such an influence on performance that they have attracted much attention by researchers not only from the field of rolling but also from the field of twin-roll casting. Andersson et al. [50] presented a semi-schematic picture of the temperature field in
Figure 2.14 Example of the variation of frictional stress with normal Pressure: (a) Variation of shear stress, and (b) Coefficient of friction. (after Schey [57]).
Figure 2.15 theoretical diagram of distribution of the contact stress over the contact arc.

Figure 2.16 Distribution of the contact stress in three-dimensional deformation.[54]

   c) Effect of roll diameter [54]
the twin-roll casting of strip (Fig. 2.17), together with the contours of flow stress which lie closely parallel to the isotherms because the hot rolling stress is dependent on the logarithm of the zener-Holloman parameter. The method they used was to examine evidence of the deformation found in the micro-structure of the cast strip, i.e taking the heterogeneous deformation of individual grains as slip bands and comparing this with the effect of compressive strain on grain size and the information from crystallographic texture. However, the accuracy and reproducibility of the stress field predicted by using this indirect method remains uncertain.

2.6.4 Deformation

Deformation is usually defined as the ratio of \((h_1-h_2) / h_2\) in rolling theory, where \(h_1\) and \(h_2\) is the strip at the entry and exit, respectively. Deformation can be measured experimentally in cold or hot rolling [51-56,60], but it is hard to measure in the twin-roll casting process, owing to uncertainty in the position of the first solid plane normal to the casting direction on the entry side. Theoretically the strip thickness at the front of the solidification sump is the one needed. It is believed that deformation in the twin-roll casting process depends on various factors, including: casting velocity, strip thickness, superheat, heat transfer coefficients between the roll and the cast material, interface friction, alloy composition and thermo mechanical properties of the alloy. Low casting velocity and low superheat, high heat transfer coefficient and high interface friction, thick strip and soft alloys will result in an increase in the deformation. In other words, anything bringing the solidification sumps backwards at constant contact length, or increasing the friction force, or reducing the resistance of the metal to deformation, will favor deformation.
Figure 2.17 The through-gap temperature and stress fields for a medium-strength aluminium alloy cast with large setback. [50]
In practice, by simply changing casting velocity, a range of deformation from zero to very high values can be gained. From the point of view of productivity the less the deformation the higher the productivity will be, and contrary to this, the more the deformation (within certain limits) the better the strip surface quality and sounder the strip structure. Usually 10 to 50% deformation is used in commercial of twin-roll casters.

2.7 TWIN ROLL CASTING DEFECTS AND STRIP CASTABILITY

The twin roll casting process is, as discussed above, characterized by high cooling rate and hot rolling. Any defects associated with heat transfer, solidification and hot rolling are therefore, likely to occur if sufficient care is not taken. In practice centerline segregation, heat lines and sticking are often found under different roll casting conditions. These significantly affect the strip castability of aluminium alloys.

2.7.1 Center Line Segregation

Center line segregation in twin roll casting process regarded as a type of grain boundary segregation resulting from the impingement of two interfaces moving with a growth component normal to each other, together with the rolling pressure which squeezes the liquid with high solute concentration through the mushy zone towards the center of the strip. This center line segregation in twin roll cast strip can develop into channel segregation [62]. However, the interaction of heat transfer, solidification and rolling in the twin roll casting process and their effect on the formation of center line segregation remains unclear. Jin et al. [63] reported that center line segregation is mainly comprised of eutectic colonies with some metastable phases. Fig. 2.18 show the work of Merchant et al. [47] on the center line segregation in a grain refined Al-Mg-Mn alloy. The thinner the strip and the higher the magnesium content in the alloy, the greater the
Figure 2.18 The centerline segregation in green refined twin roll cast Al-Mg-Mn alloy strip, 200X. (after Merchant et al [47])
risk of forming center line segregates. Further investigation of the formation mechanism of center line segregation is essential in order to produce high quality strip in a wider range of aluminium alloys.

2.7.2. Heat Lines

Heat lines are generally described as semi-continuous longitudinal defects, usually a few centimeters wide, where the cast material leaves the roll bite partially molten, as shown in Fig. 2.19. The formation of defects is related to casting velocity, super heat, interface heat transfer coefficients and alloy composition [23, 29, 62]. The tendency to form heat lines increases with an increase in superheat and casting velocity, and a decrease in the heat transfer coefficients. Mathematically, two parameters, casting velocity and the position of solidification sump in the strip, have been used to predict when heat lines take place.

The numerical modeling work of Bagshaw et al. [29] produced a hysteresis loop in the plot of the strip exit temperature against casting velocity under steady state conditions (see Fig. 2.20), where beyond a critical velocity a catastrophic increase in strip temperature occurs. Berovici's work [64], on the other hand, defines a critical sump length beyond which casting cannot remain stable, i.e. an unstable condition occurs once stable heat transfer from the metal to roll has broken down [65]. These two models of formation mechanism of heat lines are, in principle, similar. However, the latter one is more strict in the accuracy of simulation of the physical problem than the former one, because the shape and position of the solidification front is obtained on fine scale.

Another cause of the formation of the heat lines, reported by Zhou [66], is due to insufficient feeding of liquid metal into mushy zone to compensate for solidification shrinkage. However, this possibility of forming a gap between the rolls and the cast material in twin roll casing caused by the solidification shrinkage may not exist, owing to
Figure 2.19 Heat lines formation in a commercial aluminium alloy. (after Bagshaw [62])
Figure 2.20 Sketch of strip exit temperature as a function of casting speed. (after Bagshaw [62]).
the metallostatic pressure on the liquid metal and the sharp decrease in the shape of the roll bite. The study of heat lines has, so far, not included in the effect of strip thickness. A single geometrical change in strip thickness, say thinner than 2 mm, can be expected to have a large influence on the formation and pattern of heat lines.

2.7.3. Sticking

Although the sticking problem in the hot rolling process has been analyzed by many people [53-56], there are few publications dealing with problem in twin roll casting process. The reason for this is probably that sticking is not encountered before the formations of other defects in the normal operating regions of existing commercial twin roll casters. The general basis for sticking is that it occurs whenever the tangential shear stress ($\tau = \mu p$) reaches yield strength of the rolled material in shear. Hence, anything affecting the interface friction ($\mu$) and the yield properties of the material will affect sticking formation. Of variables in the twin roll casting process, alloy composition, surface condition of rolls, casing velocity, lubrication and strip thickness could be the most important ones.

2.7.4 Strip Castability

Strip castability can be interpreted as the ability to cast alloys with acceptable quality. The twin roll casting process can, as discussed above, produce high quality strip with good profile and surface finish, but the productivity is low and the alloy range is limited. Theoretically, the limit of casting velocity which is then converted to productivity is the one at which the strip exit temperature is close to the solidus of the cast alloy [29]. In practice the actual strip exit temperature in commercial twin roll casting is only about 300°C for a large range of aluminium alloys, which is long way from their solidus, for
instance, 660 °C in pure aluminium (Fig. 2.21). Also 5% Mg in Al-Mg alloys, or 55 °C in freezing range, is considered the upper limit for concentrated aluminium alloys [9] so as to locate the mushy zone within the contact length [67]. The limited heat removal over a short contact length (usually 30-60 mm) and the resulting formation of heat lines and/or sticking make the stable operation of the twin roll casting process very difficult at high casting velocity. Using high thermal conductivity as a roll shell [68] or larger rolls [69,70], improving the efficiency of internal cooling system, applying external cooling, reducing super heat in the molten metal, and employing a high metallostatic head are the many solutions attempted to increase productivity. According to reports of Caron et al. [71], Masounave et al. [72] and Essadiqi et al. [73], the more important ways may be to increase tip set back and to reduce strip thickness without enlarging the cast rolls. In this case productivity was found to increase proportionally with increase of tip setback and exponentially with decrease of strip thickness.

2.8 HISTORY OF COMPOSITES

The development of MMCs first originated in 1950’s and early 1960’s. The need for the requirement of MMCs in industrial application was due to dramatically extend the structural efficiency of metallic materials while retaining their advantages, including high chemical inertness, high shear strength, and good property retention at high temperatures. Early work included the usage of sintered aluminium powder as a precursor in discontinuously reinforced MMC’s. In 1960’s and 1970’s, the major breakthrough was the development of high strength monofilaments-first boron and silicon carbide (SiC). During late 1970’s efforts were renewed in the field of discontinuously reinforced whisker reinforcements. The concept of particulate reinforcements came due to the high cost of whiskers and difficulty in controlling damage during consolidation. During 1980’s
Alloys Used:
- AA-1100
- AA-8006
- AA-5052
- AA-5182
- AA-6061

Figure 2.21 Plot of strip exit temperature against casting speed for various commercial aluminium alloys. (after Bagshaw [29])
major efforts included particle reinforced, whisker reinforced, and tow based MMC's of aluminium, magnesium, iron, and copper for applications in automotive, thermal management, tribological and aeronautical industries. Significant improvements in performance and material quality were achieved by increasing number of mostly small businesses that specialized in production of MMC components for target markets. The full impact of MMC technology was not widely appreciated due to insufficient publicity given to the advantages of using MMCs though the applications of MMCs increased over a period of time.

By the broadest definition, a composite material is one in which two or more materials that are different are combined to form a single structure with an identifiable interface. The properties of that new structure are dependant upon properties of the constituent materials as well as the properties of the interface. In the more familiar world of metals, the mixing of different materials typically form bonds at the atomic level (alloys), composites typically form molecular bonds in which the original materials retain their identity and mechanical properties.

T.W.Clyen [74] defines composites as a material which is a combination of two or more materials (reinforcing elements, filler and composite matrix binder), differing in form or composition on a macroscale. The constituents retain their identities, that is, they do not dissolve or merge completely into one another although they act in concert. Normally, the components can be physically identified exhibit an interface between one another. Examples are cermets and metal-matrix composites.

Van Suchetele [75] explains composites materials as heterogeneous materials consisting of two or more solid phases, which are in intimate contact with each other on a microscopic scale. They can also be considered as homogenous materials on a macroscopic scale in the sense that any portion of it will have the same physical property.
A. Needleman [76] define a composite is a product made with a minimum of two material- one being a solid material and other a binding material (or matrix) which holds together both materials. There are many composite products with more than two raw materials. Those materials are not miscible together and are of a different nature.

Hibbard [77] defines composite as a material system consisting of mixture of two or more micro-constituents insoluble in each other and differing in form and/ or material composition.

The main objective in developing composites is to provide enhanced performance characteristic and properties beyond the established properties of currently available materials. An alloy is a two phase microstructure produced by solidification of a homogenous melt and subjected to subsequent heat treatment. To further enhance the alloy properties, ceramic particulates are mixed with alloy, when the alloy is in molten state and on solidification, produced a material called composites.

The earliest example of man-made composite is the straw-reinforced clay, which molded the civilization since prehistoric times. Egyptians several hundred years earlier to B.C were know to reinforce the clay-like deposits of the Nile Valley with grass plant fibers to make sun backed mud bricks that were used in making temple walls, tombs and houses. The watchtowers of the far western Great Wall of China were supposed to have been built with straw reinforced bricks during the Han Dynasty [78] (around 200 years B.C). Even today the natural fiber reinforced clay, continues to be one of the primary housing materials in the rural areas of many third world countries. The other classic examples are the laminated wood furniture used by early Egyptians (1500B.C), in which high quality wood veneers are bonded to the surfaces of cheaper woods. The origin of paper, which made use of pant fibers, can be traced back to china (1200A.D) were
believed to be made with the adhesive bonded laminates consisting of buffalo or antelope horns, woods, silk and ox-neck tendons [79,80].

The twentieth century has witnessed the birth and proliferation of a whole gamut of new materials that have further consolidated the foundation of modern composites. Many synthetic resins alloys and ceramics matrices with superior physical, thermal and mechanical properties have been developed.

Composites due to their heterogeneous composition allow unlimited possibilities of deriving any characteristic material behavior. This unique flexibility in design tailoring plus other attributes like ease of manufacturing, especially molding to any shape with polymer composites reparability, corrosion resistance, durability, adaptability, cost effectiveness, etc., have attracted the attention of many users in several engineering and other areas. Every other industry is now vying with each other to make the best use of composites. One can notice the application of composites in many disciplines starting from sports goods to space vehicles. This world wide interest during the last three decades has led to all round advancement in the field of composite materials and structures. Several high performance polymers have now been developed. Substantial progress has been made in the development of stronger and stiffer fibers, metals and ceramic matrix composites manufacturing and machining processes, quality control and non destructive evaluation techniques, test methods as well as design and analysis methodology. The modern man-made composite have now firmly established as the future material and are destined to dominate scenario right through the twenty first century.

The major research and efforts are put in the aerospace industry. One of the primary requirements of aerospace structural materials is that they should have low density and at the same time, should be very stiff and strong. Early biplanes used wood
for frameworks and fabrics for wing surfaces. The fuselage of World War 1, famous biplane fighter named Vieux Charles was built with wire braced wood framework. The monoplane, Le Monocoque, had an unusually smooth aerodynamic design and its fuselage was made with laminated tulipwood. Almost all biplanes and monoplanes with a very few exception were built of wood during the first quarter of twenty first century. Lighter woods like balsa, poplar, spruce, tulip, etc., were more popular. Soaring planes in those days also had highly polished thin plywood fuselages. [81]

The ‘thirties’ and ‘forties’ noticed a gradual shift from wood to aluminium for airplane construction. With the increase in the size and speed of airplanes, the strength and stiffness requirements for a given weight could not be met from wooden construction. The trends continued till fifties, by which almost all types of airplanes were of all metal design.

However, the limitation of aluminium alloys could be accessed as early as fifties with the speed of the aircraft increasing sharply (significantly more than the speed of sound), the demand for a more weight optimized performance, fuel efficient design and so on. The aluminium metal usage was stretched to its maximum limit. The search for newer and better materials was the only alternative.

The switchover from aluminium and GFRP to advanced composites in airframe constructions was however very slow at the initial stage. It started with the design and development of a few composite control panels. In course of time, several structural parts such as horizontal stabilizer, vertical polygon, tail cone, canopies fuselage, floor board, rotor hub and landing gears were developed with various composites, which later culminated in the development of several all composites aircraft and helicopters. Today the material menu of almost all aerospace vehicles including rockets, missiles, satellite, etc. are highly composites biased. The composite application in the aerospace industries is
a process of continuous development in which newer and more improved materials systems are being utilized to meet critical design and flight worthiness requirements.

Fiber reinforced composites introduced the anisotropy (directional preference) to thermo-mechanical properties, which although eventually complicates in the design/analysis methodologies, is a desirable feature for design optimization. In the case of thin or moderately thick laminated composite structure, for example wing skins, the lamina anisotropy can be effectively utilized to tailor the design. In the case of three-dimensional structural bodies, such as combustion chambers or rocket nozzle throats, fibre reinforcement can be provided in any arbitrary direction in a 3D space to resist forces along specific directions. Multi directional reinforcement leads to increased toughness and damage resistance. It is therefore, no wonder that fiber reinforced composites are widely employed in aerospace systems, and the major thrust is directed to design/analysis methodologies, fabrication processes and testing, the evaluation for fibre reinforced composites.

Dispersing ceramic particles generates a composite and in a dispersion medium alloy is generally called matrix material and the dispersoid (ceramic material) is usually referred to as reinforcement. Since the primary constituent being a metal alloy, it is referred to as metal matrix composite. It is convenient to describe a composite as being composed of a metal material to which one or more reinforcements or filler materials are added. This permits classification according to the type of matrix material employed as metallic, polymeric, glass and ceramic composite.

2.8.1 General Aspects of Composites

The synergy between the reinforcement, the matrix and the geometry of reinforcement are the deciding factors of the strength and stiffness of the composites. The
random dispersion strengthened metals are a kind of composites in which only the concentration of the strengthening particles is controlled, not their dimension or orientation. In general, a hard dispersoid when used as reinforcement in soft matrix reduces the impact strength of the matrix and at the same time improves other mechanical properties impact strength and adversely affects other properties.

Since the load is transferred from the matrix to the reinforcement by means of shear forces acting on their surface, their surface area must be larger in relation to their cross-sectional area. An efficient reinforcing element will be much longer in one dimension than it is in the other two.

2.8.2 Matrix

It is well known that the composites have two or more chemically distinct phases on a microscopic scale separated by distinct interface and it is important to be able to specify these constituents. The normal view is that, it is the property of the matrix that is improved on incorporating another constituent to produce a composite.

Matrix is a phase that grips or holds the reinforcement of the composite together and permits fabrication into designed engineering structure and it also transfers the load on to the reinforcement. Although the general requirements that the matrix be ductile provides some guidance for choosing a matrix material, the most common determinant of choice is the range of the temperature of the composite that it should face in its intended use.

Composites exposed to a temperature up to 200 °C usually have a polymer matrix. The temperatures high enough to melt or degrade a polymer matrix call for another kind of matrix material, often a metal. Along with the temperature resistance, a metal matrix offers other benefits. Its high strength supplements that of the reinforcement and its ductility lends toughness to the composites.
Related to ceramic matrix composites in character but distinctive in manufacture is a composite in which both the matrix and the reinforcement consist of element carbon. Carbon-carbon composite retains much of its strength even at 2500 °C.

2.8.3 Reinforcement

In a composite of two constituent, the first constituent is referred to as the matrix and the other is referred to as reinforcing phase or reinforcement, which enhances the mechanical properties of the matrix. In almost all the cases the reinforcement is harder, stronger and stiffer than the matrix. Although there are some exceptions for example, ductile metal reinforcement in a ceramic matrix and rubber like reinforcement in a brittle polymer matrix. The geometry of the reinforcement is one of the major parameters in determining the effectiveness of the reinforcement, in other words the mechanical properties of composite are a function of the shape and dimensions of the reinforcement.

The reinforcing phase may either be fibrous or particulate. Particulate reinforcements have dimensions that are approximately equal in all directions. The shape of the reinforcing particle may be spherical, cubical, platelet or any regular or irregular geometry. The arrangement of particulate reinforcement may be random or with a preferred orientation. In the majority of particulate reinforced composites, it is considered for all practical purposes to be random. Its length being much greater than its cross sectional dimension known as the aspect ratio can vary considerably. In single layer composites long fibers with high aspect ratios give what are called continuous fibers reinforced composites, whereas discontinuous fibers may be random or preferred. The frequently encountered preferred orientation in the case of continuous fiber composite is termed unidirectional and the corresponding random situation can be approximated to bi-
directional woven reinforcement. The extensively used ceramic reinforcement in Aluminium Metal Matrix is listed along with their properties in table 2.4.

2.9 METAL MATRIX COMPOSITES (MMCs)

The technology and evolution of metal matrix composite systems has been developed over the past few decades, with primary support from and emphasis on aerospace and airframe requirements and more recently, automotive and electronic applications. At present, a wide variety of composite materials and discontinuously reinforced concepts, including particulate, chopped fiber, and whisker reinforcements are used to create isotropic composites. Primary matrix metals being used are aluminium, magnesium, copper, titanium and more recently, "super alloy" system. Among the important MMCs, one can include the following:

1. Boron/Aluminium
2. Carbon/Aluminium
3. Al₂O₃/Al and Al₂O₃/Mg
4. SiC/Al
5. Eutectic or in situ composites

These MMCs provide high specific modulus plus a service temperature capability much higher than that of polymer matrix composites. Potentially, the excellent toughness and good environmental resistance of metallic matrices can result in quite superior MMC products.

Metal matrix composites are composed of a reinforcement surrounded by a metal matrix. The matrix is a continuous phase which provides a binding support for the reinforcement. Continuous fibers embedded in the metal matrix create an anisotropic
Table 2.4 Mechanical and physical properties of various ceramic particulate reinforcement commonly used in the manufacture of modern discontinuously reinforced metal-matrix composites [82]

<table>
<thead>
<tr>
<th>Ceramic</th>
<th>Density g/cm³</th>
<th>Elastic Modulus</th>
<th>Knoop Hardness</th>
<th>Compressive Strength</th>
<th>Thermal Conductivity</th>
<th>Coefficient of thermal expansion</th>
<th>Specific thermal conductivity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>GPa 10⁶psi</td>
<td></td>
<td>MPa ksi</td>
<td>W/m.K Btu.ft/ft².⁰F</td>
<td>10⁻⁶/K 10⁻⁶/°F</td>
<td>W.m²/kg.K</td>
</tr>
<tr>
<td>SiC</td>
<td>3.21</td>
<td>430 62.4</td>
<td>2480</td>
<td>2800 406.1</td>
<td>132 76.6</td>
<td>3.4 6.1</td>
<td>41.1</td>
</tr>
<tr>
<td>B₄C</td>
<td>2.52</td>
<td>450 65.3</td>
<td>2800</td>
<td>3000 435.1</td>
<td>29 16.8</td>
<td>5.0 9.0</td>
<td>11.5</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>3.92</td>
<td>350 50.8</td>
<td>2000</td>
<td>2500 362.6</td>
<td>32.6 18.9</td>
<td>6.8 12.2</td>
<td>8.3</td>
</tr>
<tr>
<td>TiC</td>
<td>4.93</td>
<td>345 50.0</td>
<td>2150</td>
<td>2500 362.6</td>
<td>20.5 11.9</td>
<td>7.4 13.3</td>
<td>4.2</td>
</tr>
</tbody>
</table>
composite on which alignment affects the strength of the structure in different directions. MMCs exhibit extremely good thermal stability associated with high strength, ductility and toughness at higher temperatures. These characteristic features of MMCs are most desirable for design applications in aero-gas turbine engines. The efficiency of an aero-engine depends upon the turbine entry temperature (TET) of the gas stream, overall pressure ratio and gas path geometry under varying conditions of temperature and load as the aircraft takes off, cruise and touches down. Thus, the engine materials have to undergo combined effects of high temperature and severe stresses during engine operation. The primary requirement of a material, during such an arduous operation is to maintain high temperature strength and stiffness without failing and/or excessively deforming so as to change the component geometry and thereby affecting the engine performance. Polymer based composites cannot be utilized for engine parts due to limitation of their applications at temperatures higher than 450-500 K. MMCs are suitable alternatives with aluminium, titanium and nickel alloys as one of the matrix materials and Al₂O₃, B, carbon fibers, SiC and SiO₂ as one of the reinforcements. Aluminium alloys can be used to TET of 650 K.

2.9.1 Properties of MMCs

Rule of mixtures provide an approximation of the desired properties of the composites such as thermal conductive, thermal expansion and density in certain cases. Mechanical properties such as strength, stiffness, toughness, ductility and wear resistance cannot be easily predicted. In these cases, the rule of mixture prediction can usually provide reasonable estimate of the strength and stiffness in continues and high aspect discontinuous MMCs. However these are exceptions as several complications exist.
Matrix-reinforcement reaction can lead to degradation of the matrix and the reinforcement, leading to deterioration of the mechanical properties. Residual stresses present in the MMCs provide an extra enhancement in mechanical properties. The presence of reinforcements produces changes in the microstructure of the matrix and corresponding changes in the contribution of the matrix to the overall properties of the MMCs. The attractive physical and mechanical properties that can be obtained with metal matrix composites (MMCs), such as high specific modulus, strength and thermal stability have been documented extensively [83, 84, 85]. MMCs combine metallic properties (high strength and high modulus), leading to greater strength in shear and compression and higher service temperature capabilities. Interest in MMCs for aerospace, automatic and other structural application has increased over last fifteen years as a result of availability of relative inexpensive reinforcements, and the development of various processing routes which result in reproducible microstructure and properties [86]. In aerospace application reduction in structural weights can be effected, not only by reducing the alloy density, but also by increasing its weights. [87]

2.9.2 Prospects of Commercialization of MMCs

Two main trends are evident in MMCs development [88]:

1. The production of cheap discontinuous MMCs

2. The production of high performance continuous MMCs

A significant improvement made in MMCs has indicated the advantages they possess over conventional alloys. The main hurdle in the commercialization of MMCs is the high cost factors. Increased consumption in industries can reduce these costs significantly. Such an increase in production however can only be justified with researchers and industrial establishments work in conjunction.
A US based firm business communication company has stated that the metal matrix composites has been adopted in certain applications where ceramic, carbon and polymer based composites were predominantly used but still much more improvements have been successfully used in aerospace applications. They have proved their enhanced capabilities successfully over conventional metals. They have been adopted in the fabrication of advanced aircraft and new generation of satellite launch vehicles. MMCs have been used for structural members of the aircraft, rotating components of an aircraft engine, and for vital parts of the landing gear components also. MMCs have been effectively used for automotive component in medical applications and sporting equipment.

It must be recognized that full characterization of materials is required before they are put into service. It is also important to recognize the highly interactive and multidisciplinary nature of development work in the MMC area. The major steps involved are as follows:

- Development of special reinforcements for MMCs.
- Availability of high volume production of such reinforcements at low cost routes to MMC processing.
- Optimization of matrix metallurgy for MMCs.
- Development of design criteria specific to MMCs.
- Development of testing procedure for MMCs properties relevant to envisaged engineering applications.
- Generation of a database of MMC properties relevant to advanced engineering application.

The primary motive behind the development of MMCs is the attainment of higher strength and stiffness, by suitable combination of filler materials in metallic matrices.
Other important parameters, such as damping capacity, component weight, wear resistance, thermal expansion and high temperature capabilities can be achieved with ease of fabrication, ductility, high thermal and electrical conductivity should preferably be maintained are a few desirable properties at the same time. Further more there is a need to obtain the desired combination of properties at minimum cost.

With all this steps to be completed, it is not surprising that the age of MMCs is still not arrived at. It is also clear that a substantial and long term commitment to MMC development is necessary if their true potential is to be realized. Composite materials are usually classified on the basis of the physical or chemical nature of the matrix phase, e.g., polymer matrix, metal matrix and ceramic composites. In addition, there are some reports to indicate the emergence of inter metallic-matrix and carbon-matrix composites. The present work is concerned with metal matrix composites and more specifically on the aluminium matrix composites (AMCs). In AMCs one of the constituent is aluminium/aluminium alloy, which forms percolating network and is termed as matrix phase. The other constituents are embedded in this aluminium/aluminium alloy matrix and serve as reinforcement, which is usually non-metallic and commonly ceramic such as SiC and Al₂O₃. Properties of AMCs can be tailored by varying the nature of constituents and their volume fraction.

The major advantages of AMCs compared to unreinforced materials are as follows:

- Greater strength
- Improved stiffness
- Reduced density (weight)
- Improved high temperature properties
- Controlled thermal expansion coefficient
- Thermal/heat management
• Enhanced and tailored electrical performance
• Control of mass (especially in reciprocating application)
• Improved damping capabilities.

**AMCs compared to polymer matrix composites are as follows:**

- Higher transverse strength
- Higher toughness
- Better damage tolerance
- Improved environment resistance
- Higher thermal and electrical conductivity
- Higher temperature capability

**AMCs compared to ceramic matrix composites are as follows:**

- Higher toughness and ductility
- Ease of fabrication
- Lower cost

These advantages can be quantified for better appreciation. It is possible to process Al-9%Si-20%vol%SiC composites having wear resistance equivalent or better than that of gray cast iron. These examples illustrate that it is possible to alter several technological properties of aluminium/aluminium alloy by more than two or three orders of magnitude by incorporating appropriate reinforcement in suitable volume fraction [89].

AMCs offer superior combination of properties in such a manner that today no existing monolithic material can compete. Over the year, AMCs have been tried and used in numerous structural, non structural and functional applications in different engineering sectors. **Driving force for the utilization of AMCs in these sector include performance, economic and environmental benefits.** The key benefits of AMCs in transportation sector are lower fuel consumption, less noise and lower air borne emissions. With increasing
stringent environmental regulation and emphasis on improved fuel economy use of AMCs in transport sector will be inevitable and desirable in future. AMCs are intended to substitute monolithic materials including aluminium alloys, ferrous alloys, titanium alloys and polymer based composites in several applications. It is now recognized that in order AMCs substitution for monolithic material in engineering application to be widespread, there is a compelling need to redesign the whole system to gain additional weight and volume savings. In fact according to UK advisory council on science and technology, AMCs can be achieved as a replacement for existing materials, but with superior properties, or as a means of enabling radical changes in system or product design. Moreover, by utilizing near-net shape forming and selective-reinforcement techniques AMCs can offer economically viable solution for wide variety of commercial applications. Recent successes in commercial and military applications of AMCs are based partly on such innovative changes made in the component design. Lack of knowledge and information about utilization possibilities, service properties and material producers have hindered the wider usage of AMCs. Recognizing these peripheral and extraneous difficulties, AMCs community in USA and Europe are pursuing consortium and networking approaches to implement the application of AMCs in everyday societal use. Challenges and opportunities for the intense use of AMCs are increasing.

2.9.3 Particle Reinforced Aluminium Matrix Composites (PAMCs)

These composites generally contain equiaxed ceramic reinforcements with an aspect ratio less then about 5. Ceramic reinforcement are generally oxides or carbides or borides (Al₂O₃ or SiC or TiB₂) and present in volume fraction less than 30% when used for structural and wear resistance application. However, in electronic packaging applications reinforcement volume fraction could be as high as 70%. In general, PAMCs •
are manufactured either by solid state (PM processing) or liquid state (stir casting, infiltration and in-situ) processes. PAMCs are less expensive compared to CFAMCs. Mechanical properties of PAMCs are inferior compared to whisker/short fibre/cotinous fiber reinforced AMCs but far superior compared to unreinforced aluminium alloys. These composites are isotropic in nature and can be subjected to variety of secondary forming operation including extrusion, rolling and forging.

Reinforcement materials include carbides (e.g., SiC, B4C), oxides (e.g., Al2O3, SiO2) as well as elemental materials (e.g., C, Si); carbon and silicon are being used in magnesium- magnesium, copper- matrix composites [90-94].

The problem associated with fabrication of continuously reinforced MMCs such as fiber damage, microstructure non-uniformity, and fiber to fiber contact and extensively interfacial reaction can be avoided with discontinuous reinforcements [95]. In application where extreme loading or thermal condition, such as in automotive components, discontinuously reinforced MMCs are demonstrated to offer essentially isotropic properties with substantial improvements in properties compared to unreinforced materials.[96]

2.10 EVALUATION OF PROPERTIES OF AMCs

2.10.1 Mechanical Properties

Material can be subjected to many different loading scenarios and a materials performance is dependent on the loading conditions. There are five fundamental loading conditions: tension, compression, bending, shear, and torsion. Tension is the type of loading in which the two sections of material on either side of a plane tend to be pulled apart or elongate. Compression is the reverse of tensile loading and involves compressing the material. If a material is subjected to a constant force, it is called static loading. If the
loading of the material is not constant but instead fluctuates, it is called dynamic or cyclic loading. The way a material is loaded greatly affects its mechanical properties and largely determines how, or if, a component will fail; and whether it will show warning signs before failure actually occurs. The tensile test is the experimental test method mostly widely employed to characterize the mechanical properties of materials. From the test record, one can obtain important information concerning the material's elastic properties, the character and extent of plastic deformation, yield and ultimate tensile strength and young's modulus. That so much information can be obtained from one test justifies its extensive use in engineering materials research. The main product of a tensile test is a load versus elongation curve which is then converted into a stress versus strain curve.

With most materials there is a general transition from elastic to plastic behavior, and the exact point at which plastic deformation begins to occur is hard to determine. Therefore various criteria for the initiation of yielding are used depending on the sensitivity of the strain measurement and the intended use of the data. For most engineering design and specific application, the yield strength is used. The yield strength is defined as the stress required to produce a small amount of plastic deformation. The offset yield strength is the stress corresponding to the intersection of the stress-strain curve and a line parallel to the elastic part of the curve offset by a specific strain. The ductility of a material is a measure of the extent to which a material will deform before fracture. The amount of ductility is an important factor when considering forming operation such as rolling and extrusion. It also provides an indication of how visible overload damage to a component might become before the component fractures. Ductility is also used as a quality control measure to assess the level of impurities and proper processing of a material.
2.10.2 Coefficient of Thermal Expansion

When heat is added to most materials, the average amplitude of the atoms vibrating within the material increases. This, in turn, increases the separation between the atoms causing the material to expand. If the material does not go through a phase change, the expansion can be easily related to the temperature change. The linear coefficient of thermal expansion describes the relative change in length of a material per degree temperature change. The change in component’s length can be calculated for each degree of temperature change. This effect also works in reverse. That is to say, if energy is removed from a material then the object’s temperature will decrease causing the object to contract.

The dimensional change of aluminium and its alloys with a change of temperature is roughly twice that of the ferrous metals. Aluminium alloys are affected by the presence of silicon and copper, which reduce expansion, and magnesium, which increase it. Its high expansion should be considered when aluminium is used with other materials, especially in rigid structure, although the stresses developed are moderated by the low elastic modulus of aluminium. If dimensions are very large, as for example in a light alloy superstructure on a steel ship or where large pieces of aluminium are set on a steel framework or in masonry then, slip joints, plastic caulking and other stress-relieving devices are usually needed.

2.10.3 Corrosion

Corrosion is the destructive result of chemical reaction between a metal or metal alloy and its environment. Metal atoms in nature are present in chemical compounds i.e. in the form of minerals. The same amounts of energy needed to extract metals from their minerals are emitted during the chemical reactions that produce corrosion. Corrosion
returns the metal to its combined state in chemical compounds that are similar or even identical to the minerals from which the metals were extracted. Many nonmetallic materials, such as ceramics consist of metals that have their chemical reactive satisfied by the formation of bonds with other reactive ions, such as oxides and silicates. Thus such materials are chemically uncreative and they degrade by physical breakdown at high temperature or by mechanical wear or erosion. Study of corrosion behavior represents the design and application of methods to prevent corrosion. Ideally, science should be embedded to engineering to invent new and better methods of preventing corrosion and apply existing methods more intelligently and effectively. Methods of exposure testing for corrosion measurements are fundamental in corrosion engineering. The emphasis is on measurement of uniform corrosion rates by weight loss of coupon specimens. However exposure methods to determine localized attack are essentially the same, differing only in the form of the specimen and method of evaluation.

Aluminium is a relative metal that owes its corrosion resistance to a thin, protective, barrier oxide surface layer. Corrosion resistance of aluminium alloys varies widely depending on the alloying components that are present. Most of the alloying elements in aluminium decrease corrosion resistance and are added to improve mechanical properties by solid solution strengthening or age hardening. Heat treatment or tempering affects corrosion resistance and mechanical strength by controlling the distribution of alloying element between solid solution and insoluble precipitates.

The 6xxx alloys are age hardenable by precipitation of Mg2Si, which does not behave electrochemically much differently then the aluminium-rich matrix phase. Thus, these alloys retain good corrosion resistance with improved strength [97]. Excess magnesium over that required to form the precipitate increases susceptibility to intergranular attack.
2.11 OVERVIEW OF MMCs PROCESSING METHODS

During the last few decades many researchers [98,99] tried different processing techniques in an effort to optimize the structure and properties of particulate reinforced MMCs. Materials design has shifted emphasis to pursue lightweight, environment friendliness, low cost, quality and performance. Parallel to this trend, metal matrix composites (MMCs) drew the attention of scientific community [100-103]. MMCs attributes include alterations in mechanical behavior (e.g., tensile and compressive properties, creep, notch resistance, and tribology) and physical properties (e.g., moderate density, thermal expansion, and thermal diffusivity) by dispersoid/reinforcements; the material limitations are thermal fatigue, thermo chemical compatibility and low transverse creep resistance. To date, much of the research has focused on the high-performance lightweight needs of the aerospace industry, where the unique needs of defence and advanced research organizations render cost as minor factor and reductions in structural weight are affected by reducing the alloy density and increasing its modulus. New and expensive 2224 extrusion and 2324 plate, which combine high damage tolerance with relatively high strength, have been developed to replace the current 7000 aluminium alloy series for lower wing panel/spar cap aircraft applications [104]. The common candidate materials are Al, Mg, Li and Ti alloy composites as component manufactures aiming at improving the limiting properties of the conventional aluminium alloys for weight reduction and elevated temperature applications such as (e.g., for brake disks, drums, and cylinder blocks), modulus of elasticity (e.g., for driveshaft).

For applications in the automotive, transportation, construction and manufacturing sport goods industries, affordable cost is also an essential factor. Apart from the emerging economical processing techniques that combine quality and ease of operations [105,106] researchers are, at the same time, turning to particulate-reinforced aluminium MMCs
because of their relatively low cost and isotropic properties [107,108] especially in those applications not requiring extreme loading or thermal conditions. Also, the processing problems and commercial difficulties associated with continuously reinforced aluminium MMCs [109,110] are contributory to the recent interest in their particulate counterparts; the use of aluminium alloys for the matrix is preferred because of its comparative advantages [111] including low cost and ease of handling.

The particulate reinforcements have been classified as the by-products from other technologies (e.g., SiC, SiO2, Al2O3, aluminosilicates, graphite and fly ash) and are either readily available or are naturally renewable at affordable cost (e.g., coconut shell char, mica, palm-kernel shell char, and zircon). Further, the potential nature of these filler materials is attractive. For example, SiC has good thermal and chemical stability, both during synthesis and under severe service conditions, strength, cost and availability. The specific applications of these composites include engine blocks, pistons, brake system components, seals, solid lubricants, wear and abrasion resistant structures, electro-mechanic contacts and chassis components.

In the past five years, emerging synthesis techniques have improved the array of fabrication methods for particulate composites with differing reproducible structures and properties [112-114]. The most cost-effective methods are casting [115] and powder metallurgy routes [116-117]. Since the introduction of aluminium MMCs in commercially available quantities, both methods, as well as new techniques, are refocusing directly on netshape products [118-120]. Most of the work in this emerging front has used aluminium alloys as the base material, most commonly hypereutectic, and A356 alloys [121].

Aluminium alloy is a well known casting alloy with high wear resistance, low thermal expansion coefficient, good corrosion resistance, and improved mechanical
properties at a wide range of temperatures. These improvements are significant not only when the silicon phase undergoes structural modifications or a grain refinement is achieved through solute additions, mechanical pressure, or sub-fusion consolidation measures, but also when the silicon particles are finely distributed in the matrix phase. With improved fineness and distribution of the silicon particles, the machinability of the hypereutectic-alloy composites is accentuated. These properties led to the application of aluminium alloys in the automotive industry, especially for cylinder blocks, cylinder heads, pistons, and valve lifters. They are extensively used in tribological ends, but their poor resistance to seizure makes them vulnerable under poor lubricating conditions. The addition of ceramic particulate to these alloys increases stiffness, high-temperature strength, and wear resistance at ambient temperature [122] while the use of graphite and mica lend it to reduced friction applications such as bearings, solid lubricants, and braking components [123-125].

Several investigators have reviewed the synthesis of MMCs [126-127] and especially, AMCs [128-129]. Traditional molten processing (MP) involves a variety of methods, including mixing/vortex, infiltration, and rheocasting; some of these MP routes are currently being extended to a secondary processing stage such as extrusion. Methods other than the MP route include powder metallurgy (P/M), spray atomization/codeposition (SD), and in-situ production. Primary processes for manufacturing of aluminium matrix composites (AMCs) at industrial scale can be classified into two main groups.

(1) Solid state processes

(2) Liquid state processes

Powder blending followed by consolidation (PM processing), diffusion bonding and vapour deposition techniques come under solid state processing. Liquid state
processes include stir casting or compo casting, infiltration, spray casting and in situ (reactive) processing. The selection of the processing route depends on many factors including type and level of reinforcement loading and the degree of micro structural integrity desired. It is possible to manufacture AMC of specific formulation (having the same matrix and reinforcement combination) by more than one route.

2.11.1 Solid State Processing

2.11.1a Powder blending and consolidation (PM processing): Blending of aluminium alloy powder with ceramic short fiber/whisker particle is versatile technique for the production of AMCs. Blending can be carried out in dry or in liquid suspension. Blending is usually followed by cold compaction, canning, degassing and high temperature consolidation stage such as isostatic pressing (HIP) or extrusion. PM processed AMCs, contain oxide particles in the form of plate-like particles of few tens of nm thick and in volume fractions ranging from 0.05 to 0.5 depending on powder history and processing conditions [130]. These fine oxide particles tends to act as a dispersion-strengthening agent and often has strong influence on the matrix properties particularly during heat treatment.

P/M is used in the production of both AMCs and ceramic-matrix composites through the relatively low-cost methods of single compaction, double compaction, and mechanical deformation following hot pressing as well as through high-cost hydrostatic and isostatic compaction, hot dynamic compaction, or explosive compaction methods. In these solid state techniques, subfusion temperature regimes are normally attained in consolidation for optimum results. Depending on the morphology of the reinforcement or the desirable properties, further processing by mechanical-deformation mechanisms are applied.
Alcoa, DWA Composite Specialties, Ceracon, and the Advanced Composite Materials Corporation are using this method in some of their commercial operations [131]. Through the cold compaction of a pretreated elemental matrix blend and particulate mix followed by optimum consolidation conditions by sintering, highly wear-resistant zircon/Al-Si composites have been recently reported by J.U.Ejiofor et al [100]. Another recent study has also produced wear-resistant Al-Si-Mg composites with 0.02 Vf via reaction sintering K.K.Chawla, P.K.Liaw, and S.G.Fishman [132] used the explosive compaction to fabricate SiC-reinforcement 7093 AMCs. During explosive consolidation, a strong shock hardening behavior of the matrix alloy was found.

Similar to P/M is the solid-phase synthesis of particulate AMCs by rapidly quenching the metal powders and fine ceramic particulate using high (mechanical or electrical) energy sources to consolidate the mixture in as short a time as possible. It is a high energy, high-rate process. The short time at temperature benefits phase-transformation control and reduces the chance of degeneration into coarse microstructure. The P/M process has been successfully applied in the manufacture of both Al-SiC and SiC/Ti3Al+Nb composites [133].

2.11.1b Diffusion bonding: Mono filament-reinforced AMCs are mainly produced by the diffusion bonding (foil-fibre-foil) route or by the evaporation of relatively thick layers of aluminium on the surface of the fibre. 6061 Al-boron fibre composites have been produced by diffusion bonding via the foil-fibre-foil process. However, the process is more commonly used to produce Ti based fibre reinforced composites. The process is cumbersome and obtaining high fibre volume fraction and homogeneous fibre distribution is difficult. The process is not suitable to produce complex shapes and components.
2.11.1c Physical vapour deposition: The process involves continuous passage of fibre through a region of high partial pressure of the metal to be deposited, where condensation takes so as to produce a relatively thick coating on the fibre. The vapour is produced by directing a high power electron beam onto the end of a solid bar feed stock. Typical deposition rates are 5-10 μm per minute. Composite fabrication is usually completed by assembling the coated with uniform distribution of fibre and volume fraction is as high as 80% can be produced by this technique.

2.11.2 Liquid state processing

2.11.2a Mixing/Vortex: In the mixing/vortex method, the pretreated and prepared filler phase is introduced in a continuously stirred molten matrix and then cast. The use of an inert atmosphere or vacuum other than air is essential to avoid the entrapment of gases. Mixing can be affected ultrasonically or by reciprocating rods, centrifuging, or zero gravity processing that utilizes an ultra high vacuum and high temperatures for long periods of time. A method of inertial injection has been developed for this process [134]. Difficulties, such as the segregation/settling of secondary phases in the matrix, agglomeration of ceramic particulate, particulate fracture during agitation and extensive interfacial reactions are often encountered. The DURAL process, which incorporates SiC and Al₂O₃ particles into molten aluminium, makes use of this method [135]. The simplest and most commercially used technique is known as vortex technique or stir-casting technique. The vortex technique involves the introduction of pre-treated ceramic particles into the vortex of molten alloy created by the rotating impeller. Lloyd [136] reports that vortex-mixing technique for the preparation of ceramic particle dispersed aluminium matrix composites was originally developed by Surappa & Rohatgi [137] at the Indian
Institute of Science. Subsequently several aluminium companies further refined and modified the process which are currently employed to manufacture a variety of AMCs on commercial scale.

2.11.2b Infiltration process: In infiltration, the molten metal penetrates a pretreated, formed and prepared particulate bed or pre-form with pressure or without pressure (pressure-less infiltration). In the latter case, however, the molten alloy infiltrates the reinforcement by percolation. This method is normally carried out in air, inert gas, or evacuated atmosphere. Mortensen et al [138] associated this technique with such disadvantages as reinforcement-reinforcement contact, structural distortion of the pre-form, large grain size, and undesirable interfacial reactions that culminate into microstructural in homogeneity. Depending on the nature of reinforcement, and its volume fraction, pre-form can be infiltrated, with or without the application of pressure or vacuum. AMCs having reinforcement volume fraction ranging from 10 to 70% can be produced using a variety of infiltration techniques. In order for the pre-form to retain its integrity and shape, it is often necessary to use silica and alumina based mixtures as binder. Some level of porosity and local variations in the volume fractions of the reinforcement are often noticed in the AMCs processed by infiltration technique. The process is widely used to produce aluminium matrix composites having particle/whisker/short fibre/continuous fibre as reinforcement.

The first commercial application was the fabrication of aluminium-alloy diesel pistons containing alumina short fibers by Toyota Motor Corporation [139,140]. Squeeze casting was the primary manufacturing mode. Aluminium-alloy melt was poured into a porous alumina short-fiber pre-form inserted into a preheated die, and a squeeze pressure
was applied in a hydraulic press. The composite aluminium pistons possessed better performance attributes than the unreinforced ones.

The Lanxide process, which is a melt oxidation process, is another infiltration route in the synthesis of AMCs. In fact, Lanxide and Alcan have jointly produced an Al₂O₃/Al alloy composite of exceptional low erosive wear rate through this process [141]. It involves the infiltration of a final-product-shape ceramic pre-form by a molten alloy. The pre-form is normally formed by pressing, slip casting, joining, or injection molding. In air or under a preferred gas, the molten alloy slips through the pre-form and oxidizes or chemically reacts with the pre-form material. The final composite phases consist of the oxidation (or reaction) products and the remaining matrix material. By this method, a dense composite shape is usually achieved.

2.11.2c Rheocasting: Rheocasting (or compocasting) permits the introduction of the pretreated particulate or short fibers into the solidifying, highly viscous, and thixotropic dendritic slurry of the molten matrix by agitation. This mechanically entraps the ceramic reinforcements and prevents any form of segregation. Continued stirring then reduces the viscous mass to low-viscous, fine, non-dendritic slurry. This results in a mutual interaction between the matrix melt and the filler phase, which enhances wetting and bonding between the two phases. Pressure is usually used to effects of a sound casting [142] especially when the volume fraction (Vf) of the particulate material is greater than 0.3 or 0.15, in the case of short fibers. This is because the composite viscosities increase as Vf increases, which is limiting at lower volume fractions. Fiber damage/degradation due to vigorous agitation is another difficulty.

Owing to these effects, rheocasting lends itself only to particulate composites with a very low Vf of low to medium density particulates [143]. A fundamental characteristic
of this technique is that the matrix alloy is isothermally held within the freezing range of
the alloy and together with the reinforcement is mechanically stirred. Stirring and
agitation help to break the solid phases into smaller forms, releasing any particulate
clusters that also break down in the process. New particle-matrix bonding can then take
place through which particulate agglomeration and gravity-induced settling is eliminated.

2.11.2d Spray Atomization/Code position: Spray deposition (SD) is gaining recognition
in the synthesis of discontinuously reinforced MMCs [144,145]. The process involves the
incorporation of fine ceramic particulates in inert-gas atomized droplets of the molten
matrix such that the matrix contains both liquid and solid phases. The matrix material is
usually finely dispersed in droplets by the high velocity spray of the inert-gas jets.

The materials and structural-design advantage of this process is that desired
multiphase matrix materials or discontinuous reinforcement while entrained in a gas jet,
could be incorporated at localized portion. Unwanted reactions are avoided because the
contact time and the thermal exposure between the particulate and the partially solidified
matrix phases are reduced.

The Osprey deposition technique, a two-phase process that has found application
in Alcan productions, is a rare technique. Here, the molten-metal-alloy matrix on which
the reinforcement particulate is injected is atomized by spray jets of inert gas. The solid
mixture can then be collected on a non-wetting substrate in the form of a consolidated
reinforced composite mass. A recent report on this practice [146] has reaffirmed that
spray atomized products are not only free from microsegregation and low in gas contents,
but also exhibit certain characteristics that are associated with rapid solidification. Other
process benefits over ingot metallurgy include low capital costs (less equipment required),
low operating costs (low energy consumption and high material yields), and low overhead
costs (less stock and work-in-progress). Al-Si alloy extrusion billets with excellent dimensional tolerances were recently produced via the Osprey deposition technique [147].

The spray process has been extensively explored for the production of AMCs by injecting ceramic particle/whisker/short fiber into the spray. AMCs produced in this way often exhibit inhomogeneous distribution of ceramic particles. Porosity in the as sprayed state is typically about 5-10%. Depositions of this type are typically consolidated to full density by subsequent processing. Spray process also permit the production of continuous fiber reinforced aluminium matrix composites. For this, fibers are wrapped around a mandrel with controlled inter fibre spacing, and the matrix metal is sprayed onto the fibers. A composite monotype is thus formed; bulk composites are formed by hot pressing of composite monotypes. Fibre volume fraction and distribution is controlled by adjusting the fibre spacing and the number of fibre layers. AMCs processed by spray deposition technique are relatively inexpensive with cost that is usually intermediate between stir cast and PM processes.

2.11.2e In-Situ processing (Reactive processing): Another emerging route that is attracting a number of researchers is the in-situ production of reinforcement particles in the matrix. Many of these researchers [148-149] have reported intrinsic uniformity in the distribution of the reinforcing phases. Many processes can be used to produce these in-situ reinforcements, including the formation of compounds and their decompositions, redox reactions, phase changes, nucleation, growth and recrystallization.

These processes usually produce periodic microstructural changes that account for the uniformly distributed phases achieved. In this production route, particles are obtained in the solvent (which can exist in any three states of matter) due to chemical reaction or diffusion which usually occur under isothermal conditions.
In these processes, refractory reinforcement are created in the aluminium alloy matrix. One of the examples is directional oxidation of aluminium, also known as DIMOX process. In this process, the alloy of Al-Mg is placed on the top of ceramic pre-form in a crucible. The entire assembly is heated to a suitable temperature in the atmosphere of free flowing nitrogen carrier gas mixture. Al-Mg alloy, soon after melting, infiltrates into the pre-form and composite is formed.

Martin-Marietta's exothermic dispersion process or the XD™ process is another in-situ technique for composite processing. XD™ process is used to produce TiB₂ reinforced aluminium matrix composites. The process is flexible and permits formation of both hard and soft phases of various sizes and morphologies that includes viscous, particles and platelets in aluminium alloy matrices.

Gas-liquid reaction is also utilized to produce TiC reinforced aluminium matrix composites. For example, by bubbling carbonaceous gas like methane into Al-Ti melt kept at elevated temperature it is possible to produce Al-TiCp composites. London and Scandinavian Metallurgical Company has developed an in-situ technique which utilizes reaction between mixed salts to produce a dispersion of fine TiB₂ particles in an aluminium matrix. A major limitation of in-situ technique is related to the thermodynamic restrictions on the composition and nature of the reinforcement phase that can form in a given system, and the kinetic restrictions on the shape, size and volume fraction of the reinforcement that can be achieved through chemical reactions under a given set of test conditions.

Chen and Chung [150] have applied a new stir-casting technique to fabricate in-situ AMCs containing approximately 5 vol% TiAl₃ particles. The method involved the stir casting in air of slurry consisting of molten aluminium, TiO₂ particles, and Na₃AlF₆.
particles. According to their report, the composites demonstrated higher tensile strength and ductility than the SiC-reinforced aluminium composites.

2.11.2f Pallet method: Graphite can be introduced into the melt in the form of a pallet consisting of coated graphite powder and base alloy powder to produce cast Al-graphite particle composite [151]. The pallets are made by pressing mixtures of nickel or copper coated graphite particles and aluminium powders together. For the most efficient recovery graphite in the castings, the pallets should be made from a mixture of 67 wt% of 80 μm copper or nickel coated powder and 33 wt% of 400 μm size aluminium powder. When aluminium alloys are melted at a temperature 750-850 °C, the pallets are plunged into alloy melts using refractory coated mild steel cups that are withdrawn after a few seconds. The melts were then stirred manually and cast into permanent moulds.

The pallet method has the advantage of greater reproducibility and flexibility. However, one of the potential disadvantages of the pallet technique is that the pallet contains a layer of oxide on the aluminium powder, which gets dispersed in the melt.

2.11.2g Centrifugal method: Centrifuging during solidification of an axis symmetric part can be used effectively to segregate heavy or light non-metallic additions to the outside and inside extremities of the part prior to solidification. Using the centrifugal method, a casting with particle reinforced outer layer has been produced [152].

Al-11% Si alloys, graphite particle and Al₂O₃ particle were placed in a crucible used as a mould. After the aluminium alloy melts, the crucible was placed in a centrifugal casting device. The melt solidifies under the centrifugal force, embedding the particles in the outer layer of the centrifugal casting.
2.12 APPLICATIONS OF COMPOSITES

Advanced materials are being developed to an increasing extent. Among these advanced materials, one finds metal matrix composites. The first MMCs were developed during the 1960s, but because of the problems associated with the manufacturing processes, and finding suitable reinforcement that could be compatible with the matrix, less attention was paid to these materials. The costs were relatively high. It is mainly during the 1980s [153] that the MMCs have been developed more intensely. The space industry was the first sector interested in the usage of these materials. The next sector of even greater economic importance for the development of new MMC material is the automotive sector.

The ceramic fiber reinforced metal matrix composites have considerable importance for providing lightweight components exhibiting high specific strength, high specific stiffness, and excellent wear resistance, low thermal expansion and improved high temperature properties compared to the conventional materials. The application of the MMCs is offering new approaches to designers to achieve high performance and lightweight of aircraft, motor vehicles and industrial machines.

i. Military applications:

Continuous fiber reinforced metal matrix composites are used to make fins, missile body casting. The composite has been used in missile guidance systems replacing certain beryllium components because structural performance is better without special handling in fabrication demanded by the latter’s toxicity.

ii. Aerospace applications:

Short fiber and whisker reinforced composites are used to make support struts,
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telescope truss, compressor blades, launch tubes, etc. Particulate reinforced composites are used to make metal matrix optics, satellite, solar reflectors, wing panels and precision composites. Carbon – reinforced Copper was used in the combustion chamber of rockets, SiC – reinforced copper was used in nozzles, Al₂O₃ – reinforced aluminium was used in the fuselage, and SiC – reinforced aluminium was used for wings and blades. Aluminium composites are used in the fan exit guide vanes.

iii. Sports applications:

MMCs are used to make tennis racket, skies, bicycle frames, wheel rims and golf club heads. MMCs such as Duralcan (Al reinforced with 10% Al₂O₃ particulates) and Al reinforced with 20% SiC particulars are used in bicycle frames for lightweight, high strength, very expensive mountain bikes.

iv. Automotive applications:

MMCs are used to make diesel engine piston, shock absorber cylinder, piston crown, combustion bowl, connecting rods bearings, cylinder liners, brake-callipers. Automotive applications include cast aluminium composite brake drums and rotors, driveshaft for the Corvette and GM S/T truck, and tire studs.

v. Structural applications:

Graphite aluminium is also used in applications for stable instrument platforms, electronics and thermal control devices such as heat pipes. Stiffness to weight is high since the material is 30 percent stiffer than aluminium with no thermal expansion [154]. Continuous fiber reinforced aluminium was used in space shuttle and Hubble space telescope. Another exciting area of application for aluminium composites is in the fast-
growing electronics packaging market, primarily for thermal management applications in which the ability to match the co-efficient of thermal expansion of the electronic materials is a key attribute.