



Chapter 1

Metal Matrix Composite (MMC) – *An Introduction*

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The present chapter focuses on the overview of composite materials along with various types of composite materials such as Metal Matrix Composite (MMC), Polymer Matrix Composite (PMC) and Ceramic Matrix Composite (CMC) Materials, various techniques for processing MMC products and its wide engineering applications.

1.1 Composite Material

The recent advancements taking place in the field of engineering and technology are quite rapid which has lead towards the development of a new area in the field of engineering materials. One such newly originated area is that of Composite Materials. **Composite materials**, often called as **composites**, are engineered or naturally occurring materials made from two or more constituent materials with significantly different physical and chemical properties which remain separate and distinct at the macroscopic or microscopic scale within the finished structure. Composite materials were developed as alternative materials for obtaining better structural, mechanical and electrochemical properties with special interest for the automobile, aerospace and aeronautical industries.

1.2 Classification of Composite Materials

There are basically three types of composite materials

- (a) Metal Matrix Composite (MMC)
- (b) Polymer Matrix Composite (PMC)
- (c) Ceramic Matrix Composite (CMC)

1.2.1 Metal Matrix Composite (MMC)

A Metal Matrix Composite (MMC) is a composite material with at least two constituent parts; one being a metal as matrix and the other being a ceramic as reinforcement [Chawla and Chawla (2004)]. When at least three materials are present, then it is called as hybrid composite. Therefore, due to the alloying considerations, the MMC materials have higher temperature stability and higher specific strength. The need for composite materials has become a necessity for modern technology due to their improved physical and mechanical properties. Composites have high modulus, fracture and compressive strength. They show improved thermal, wear and corrosion resistance. Easy processing methodology has made MMCs very useful in almost every field of engineering and technology [Torralba et al. (2003)].

Most metals and alloys could be used as matrices and they require reinforcement materials which need to be stable over a range of temperature and are non-reactive too. However, the guiding aspect for the choice depends essentially on the matrix material. The choices for low temperature applications are not many. Only light metals are responsive with their low density proving an advantage. Titanium, aluminium and magnesium are the popular matrix metals which are particularly useful for aircraft applications. High modulus reinforcements are required if metallic matrix materials have to offer high strength. The strength-to-weight ratio of resulting composites will be higher than most of the alloys [Ralph et al. (1997)].

The service temperature of the composites depends upon the melting point, physical and mechanical properties at various temperatures. Most metals, ceramics and compounds can be used with matrices of low melting point alloys. With increase in the melting temperature of matrix materials, the choice of reinforcements becomes more important [Davis et al. (1998)].

The composition of MMCs consist of (a) Matrix and (b) Reinforcement

Matrix

Matrix is the monolithic material into which the reinforcement is embedded and is completely continuous. It provides a compliant support for the reinforcement. The selection of suitable matrix metal or alloys is mainly determined by the intended application of the composite material. In most of the applications, matrix is usually a lighter metal such as aluminium, magnesium and titanium. Light metal matrix composite materials are most easy to process. Therefore, conventionally light metal alloys are used as matrix materials in the development of MMCs for different types of applications. In the high temperature applications, iron, cobalt and cobalt-nickel alloy matrices are common. Conventional cast alloys, conventional wrought alloys and special alloys are also used as matrix materials. In the area of powder metallurgy special alloys can also be applied due to the advantage of fast solidification during the powder production. These systems are free from segregation problems which arise in conventional solidification. Systems with oversaturated or metastable structures are also useful [Kainer (2006)]. Some of the important metals and alloys used as matrix are:

Conventional Cast Alloys

- G-AlSi12CuMgNi
- G-AlSi9Mg
- G-AlSi7 (A356)
- AZ91
- AE42

Conventional Wrought Alloys

- AlMgSiCu (6061)
- AlCuSiMn (2014)
- AlZnMgCu1.5 (7075)
- TiAl6v4

Special Alloys

- Al–Cu–Mg–Ni–Fe-alloy (2618)
- Al–Cu–Mg–Li-alloy (8090)
- AZ91Ca

Reinforcement

Small size reinforcement materials are embedded in the matrix. The reinforcement does not always serve a purely structural task (reinforcing the compound), but is used to change properties such as hardness, wear resistance, friction coefficient, or thermal conductivity [Ram Prabhu T et al. (2014)]. The reinforcement can be either continuous, or discontinuous. Discontinuous MMC's can be isotropic and can be worked with standard metal working techniques such as extrusion, forging or rolling. The most common reinforcing materials in the discontinuous category are alumina and silicon carbide [Kainer (2006)].

Reinforcements for metal matrix composites have a manifold demand profile which is determined by production, processing and by the matrix system of the composite material. The following demands are generally applicable:

- low density,
- mechanical and chemical compatibility,
- thermal stability,
- high young's modulus,
- high compressive and tensile strength,
- good processability and
- economic efficiency.

These demands can be achieved only by using non-metal inorganic reinforcement components. For metal reinforcement ceramic particles, fibers or carbon fibers are often used. Due to the high density and the affinity to react with the matrix alloy the use of metallic fiber usually fails. The materials which are finally used depend on the selected matrix and on the demand profile of the intended application. The

production, processing and type of applications of various reinforcements depend on the processing technique for the composite materials. A combined application of various reinforcements is also possible (hybrid technique).

Each reinforcement has a typical profile which is significant for its effect within the composite material and the resulting profile. The group of discontinuous reinforced metals offers the best conditions for reaching industrial targets. However, the used reinforcement like short fibers, particle and whiskers are mostly cost effective. The production of units in large numbers is also possible. The relatively high isotropy of the properties in comparison to the long-fiber continuous reinforced light metals and the possibility of processing of composites by forming and cutting production engineering is further advantageous [Kainer (2006)].

Binders and lubricants: For processing powdered mixtures consisting of metal powder and ceramic reinforcement by powder metallurgy, lubricants/binders (e.g. stearic acid, zinc stearate, dextrin etc.) are used which perform several functions as given below:

- Lubricants help better flow of powder filling the mould effectively. These reduce die friction resulting in uniform product density. The part is ejected without cracking and die life is increased.
- The main function of binder is to provide green strength to the powder compact. During initial stage of sintering, the binder gets removed thereby leaving voids.

1.2.2 Polymer Matrix Composite (PMC)

Polymer matrix composites (PMCs) are comprised of a variety of short or continuous fibers bound together by an organic polymer matrix. Unlike a ceramic matrix composite (CMC), in which the reinforcement is used primarily to improve the fracture toughness, the reinforcement in a PMC provides high strength and stiffness. The PMC is designed so that the mechanical loads to which the structure is subjected

in service are supported by the reinforcement. The function of the matrix is to bond the fibers together and to transfer loads among them. Polymer matrix composites are often divided into two categories: “reinforced plastics”, and “advanced composites.” The distinction is based on the level of mechanical properties (usually strength and stiffness); however, there is no unambiguous line separating the two. Reinforced plastics, which are relatively inexpensive, typically consist of polyester resins reinforced with low-stiffness glass fibers. Advanced composites, which has been in use for only about 15 years, primarily in the aerospace industry, have superior strength and stiffness and are relatively expensive. Chief advantage of PMCs is their light weight coupled with high stiffness and strength along the direction of the reinforcement. This combination is the basis of their usefulness in aircraft, automobiles and other moving structures. Other desirable properties include superior corrosion and fatigue resistance as compared to metals. Because the matrix decomposes at high temperatures, the applications of current PMCs are limited to service temperatures below about 600°F (316°C). It is evident that the PMCs are widely being used in aerospace industries, military aircrafts, commercial aircrafts, helicopters, automotive industries, reciprocating equipments and naval applications etc.

Aerospace applications of advanced composites account for about 50 percent of current sales. Sporting goods such as golf clubs and tennis rackets account for another 25 percent. The sporting goods market is considered as matured with projected annual growth rate of 3 percent. Automobile and industrial equipment round out the current list of major users of PMCs, with a 25 percent share. The next major challenge for PMCs will be use in the large military and commercial transport aircraft. PMCs currently comprise about 3 percent of the structural weight of commercial aircraft such as the Boeing 757 but would eventually account for more than 65 percent in near future.

The largest volume opportunity for PMCs is in the automobiles. PMCs currently are in limited production in body panels, drive shafts, and leaf springs. By the late 1990s,

PMC unibody structures were introduced in limited production. Additional near-term markets for PMCs include medical implants, reciprocating industrial machinery, storage and transportation of corrosive chemicals and military vehicles and weapons [Bathias (2006)].

1.2.3 Ceramic Matrix Composite (CMC)

Ceramic matrix composites (CMCs) are a subgroup of composite materials as well as a subgroup of technical ceramics. They consist of ceramic fibers embedded in a ceramic matrix, thus forming a ceramic fiber reinforced ceramic (CFRC) material. The matrix and the fibers can consist of any ceramic material, whereby carbon and carbon fibers can also be considered as a ceramic material. The motivation to develop CMCs was to overcome the problems associated with the conventional technical ceramics like alumina, silicon carbide, aluminium nitride, silicon nitride or zirconia is that they fracture easily under mechanical or thermo-mechanical loads because of cracks initiated by small defects or scratches which continue to grow. The crack growth resistance is very low like glasses. To increase the crack resistance or fracture toughness, particles (so-called monocrystalline whiskers or platelets) were embedded into the matrix. However, the improvement was limited and the products have found application only in some ceramic cutting tools. So far only the integration of long multi-strand fibers has drastically increased the crack resistance, elongation and thermal shock resistance and is leading to several new applications.

CMCs are used in many high temperature processes. They have a very high thermal shock and creep resistance which enables designs to sustain large mechanical and thermal loads. As compared to the metallic valves, the service life of the CMC components is much longer and over-compensates their higher purchasing costs. CMC components, used as batch carriers in metal hardening are another example. These C/C-grids have small heat capacity which reduces energy consumption and allows fast heating and cooling cycles. Different from metallic batch carriers, these show no creep deformation providing much longer service life. Other applications of

CMCs in high temperature processes are flame tubes, heat exchangers, protective tiles and various high temperature holders. The high wear resistance and the favorable friction properties of CMCs lead to applications as sliding contact bearings, brakes and clutch-plates. C/SiC brake disk is also used in passenger cars. It has a life time longer than the life time of the car and a much smaller weight than customary brake disks made of cast iron. So, the higher cost of the CMC brake disks are compensated by reduced fuel consumption and elimination of service costs for the renewal of the brake disks [Istomin et al. (2013)].

1.3 Processing Techniques

Various processing techniques used for the fabrication of metal matrix composites are described below [Tjong and Ma (2000)].

1.3.1 Solid State Methods

1- Powder Metallurgy (P/M): Powdered metal and discontinuous reinforcement are mixed and then bonded through a process of compaction, degassing, and thermo-mechanical treatment (possibly via hot isostatic pressing (HIP) or extrusion). Fig. 1.1 shows different steps of powder metallurgy route [Torralba et al. (2003)].

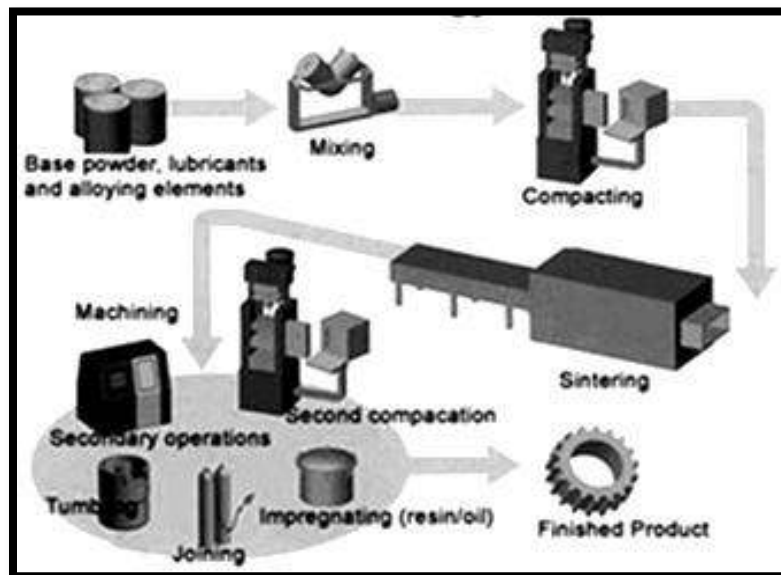


Fig. 1.1 Conventional Powder Metallurgy process

Powder metallurgy is the process of blending fine powdered materials, pressing them into a desired shape (compaction) using a die and then heating the compressed material in a controlled atmosphere to bond the material (sintering). The powder metallurgy process generally consists of four basic steps: (1) powder manufacture, (2) powder mixing and blending, (3) powder compaction and (4) sintering. Recent developments have made it possible to use rapid manufacturing techniques which use the powder as a starting material for the products [Hassani et al. (2014)]. Compaction of the powders is generally performed at room temperature and the elevated-temperature process of sintering is usually conducted under reducing atmosphere. Optional secondary processing is used to obtain special properties or enhanced precision [Bolzoni et al. (2013)].

Sintering can be considered to proceed in three stages. During the first step, neck growth proceeds rapidly but powder particles remain discrete. During the second stage, most densification occurs, the structure recrystallizes and particles diffuse into each other. During the third step, isolated pores tend to become spheroidal and densification continues at a much lower rate. The words Solid State in Solid State Sintering simply refer to the state in which material is in when it bonds.

1.3.2 Liquid state methods

1- Electroplating / Electroforming: The process of electroforming is almost similar to electroplating. It is best described as a process similar to electroplating, but one that is used in manufacturing metallic articles rather than a means of producing surface coatings.

Simply, the difference in most cases is that plating is a coating over a metallic item, it is a thin layer and becomes part of the work piece. Electroforming in most cases is metal built-up over a non-metallic surface. It can be quite thick and it can be separated from the mandrel or work piece as a standalone object. Some of the common uses for electroforming are mold making and reproduction of parts. Fig. 1.2 shows the electroplating/electroforming process.

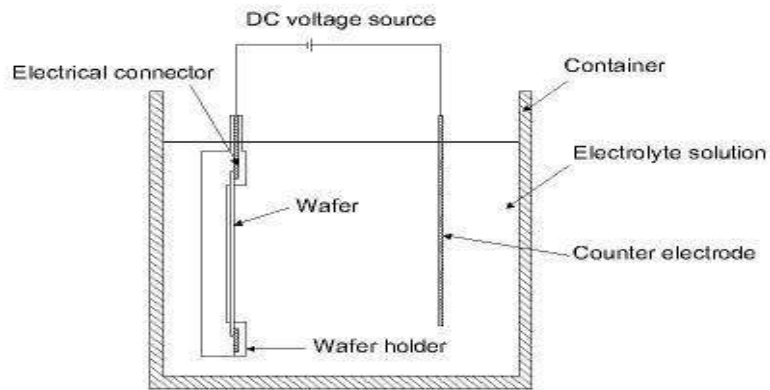


Fig. 1.2 Electroplating / Electroforming process

2- Stir casting: In Stir Casting technique discontinuous reinforcement is stirred into molten metal, which is allowed to solidify [Torralba et al. (2003)]. Fig 1.3 shows stir casting process. Stir Casting is a liquid state method of composite materials fabrication in which a dispersed phase (ceramic particles, short fibers) is mixed with a molten metal matrix by means of mechanical stirring. Stir Casting is the simplest and the most cost effective method of liquid state fabrication [Ezatpour et al. (2013)].

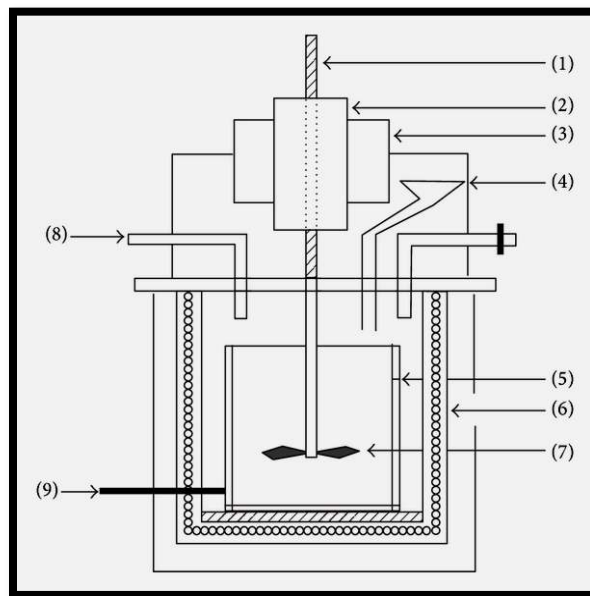


Fig. 1.3 Schematic of stir casting process (1) Stirrer spindle, (2) Sliding mechanism with impeller position control unit, (3) Electric motor, (4) Sprue, (5) Crucible, (6) Electric furnace, (7) Impeller, (8) Argon gas inlet, and (9) Thermocouple

The liquid composite material is cast by conventional casting methods and may also be processed by conventional metal forming technologies. *Stir Casting is characterized by the following features:* Content of dispersed phase is limited (usually not more than 30 vol.%) and distribution of dispersed phase throughout the matrix is not perfectly homogeneous:

1. There are local clouds (clusters) of the dispersed particles (fibers);
2. There may be gravity segregation of the dispersed phase due to a difference in the densities of the dispersed and matrix phase.

The technology is relatively simple and low cost. Distribution of dispersed phase may be improved if the matrix is in semi-solid condition. The method using stirring metal composite materials in semi-solid state is called **Rheocasting**. High viscosity of the semi-solid matrix material enables better mixing of the dispersed phase.

3- Squeeze Casting: Squeeze casting or pressure casting is the most common manufacturing variants for MMCs. In this technique, after a slow mold filling the melt solidifies under very high pressure which leads to a fine-grained structure. In comparison with die-casted parts, the squeeze-casted parts do not contain gas inclusions. This permits thermal treatment of the produced parts. One can also differentiate between direct and indirect squeeze casting. With direct squeeze casting the pressure for the infiltration of the prefabricated preforms is applied directly to the melt. The die is thereby a part of the mold which simplifies the structure of the tools substantially [Seo and Kang (1995)].

However, there is a disadvantage with the direct procedure; in that the volume of the melt must be determined exactly since no gate is present and thus the quantity of the melt determines the size of the cast construction unit. A further disadvantage is the appearance of oxidation products formed in the cast part during dosage. In contrast, in the indirect squeeze casting, where the melt is pressed into the form via a gate system, the residues will remain in this gate.

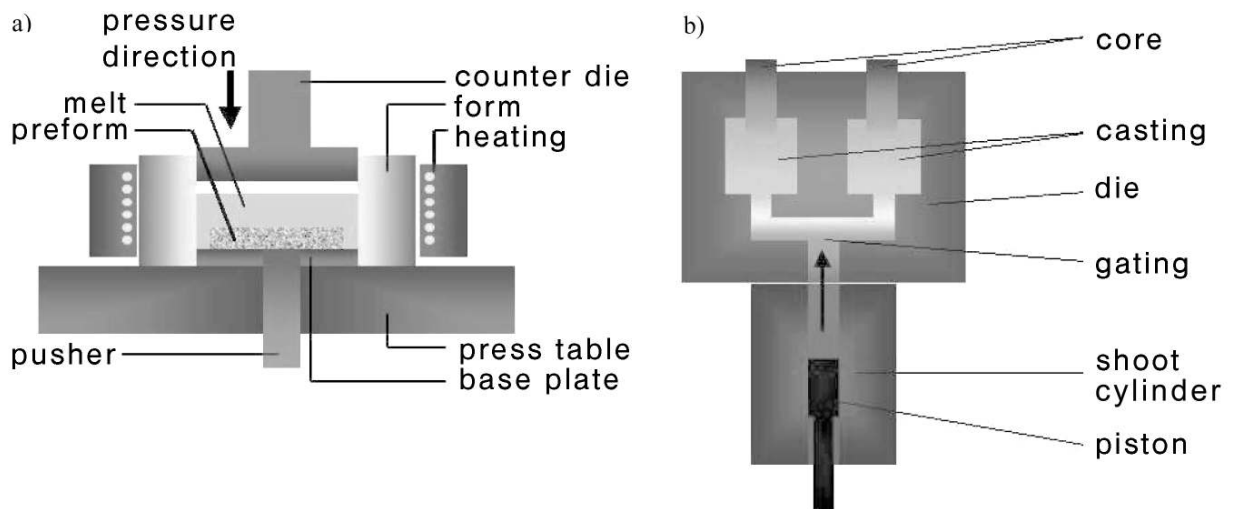


Fig. 1.4 Direct and indirect squeeze casting

The flow rate of the melt through a gate is due to its larger diameter which is substantially less than that in die casting. This results in less turbulent mold filling and gas admission to the melt by turbulences. Both the pressure casting processes make the production of composite materials possible, as prefabricated fiber or particle preforms are infiltrated with melt and solidify under pressure. A two-stage process is often used. In the first stage the melt is pressed into the form at low pressure and then at high pressure for the solidification phase. This prevents damage to the preform by too fast infiltration. The squeeze casting permits the use of relatively reactive materials since the duration of the infiltration and thus the response time are relatively short. A further advantage is the possibility to manufacture difficult shape construction units and to provide partial reinforcement to strengthen those areas which are exposed to a higher stress during service [Zhang et. al (1993)]. Fig. 1.4 shows direct and indirect squeeze casting technique.

4- Spray Deposition: In spray deposition technique, molten metal is gas atomized in the normal way and the spray is caused to impinge while still in the liquid or semi-solid state on a solid former where a layer of dense solid metal of a pre-determined shape is produced. The solid thus produced has a structure similar to that of powder-based material with all the attendant advantages of fine grain, freedom from macro-segregation etc. In common with the P/M process, spray deposition facilitates the

production of alloy compositions that are difficult if not impossible to produce conventionally and in certain cases the benefits that rapid solidification offers can also be obtained. Properties even superior to those of powder-based wrought products have been reported; for example super alloy having a much lower inclusion counts than that of its powder-based equivalent. Fig 1.5 shows Spray Deposition process [Torralba et al. (2003)].

Several deposition techniques which are being used and available are:

- Immersion plating.
- Spray deposition.
- Chemical Vapor Deposition (CVD).
- Physical Vapor Deposition (PVD).
- Spray forming techniques.

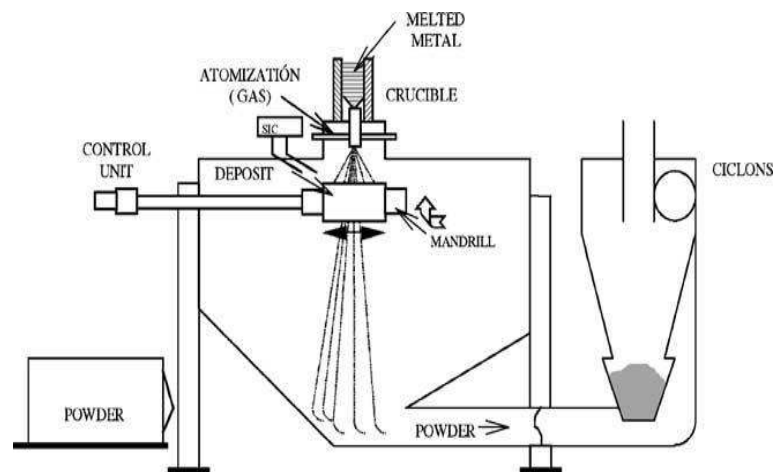


Fig 1.5 Spray Deposition Process [Torralba et al. (2003)]

1.4 Applications of Metal Matrix Composites

Metal matrix composites have large number of applications. A list of few important applications is given below:

- 1) The major applications of aluminium based MMCs are in the automotive sector which includes selectively reinforced pistons for diesel engines, selectively reinforced cylinder bores in engine blocks, intake and exhaust valves, driveshafts and propeller

shafts, brake components (discs, rotors and calipers) and power module components for hybrid and electric cars.

2) Aeronautical MMC applications have been established in the aerostructural, aeropropulsion and in subsystem categories. Aerostructural components include ventral fins and fuel access door covers on aircraft and rotor blade sleeves and swashplates on the helicopters. These components are all produced from P/M billet produced by Al composites. The components are fracture-sensitive and the helicopter rotor blade sleeve is fracture-critical. Aeropropulsion components include fan exit guide vanes for the various engines used on aircraft and continuously reinforced Ti/SiC TMCs produced by FMW composites for nozzle actuator links in the General Electric engine [Rawal (2001)].



Fig. 1.6 Ultra-hard and wear-resistant components manufactured from Fe/TiC MMCs [Miracle (2005)]

3) MMCs for industrial, recreational and infrastructure applications comprise about 6% by mass and about 13% by value of the MMC market. Industrial applications include cemented carbide and cermet materials, electroplated and impregnated diamond tools, Cu and Ag MMCs for electrical contacts, erosion-resistant cladding for the petrochemical industry, Cu-infiltrated steel components and TiC-reinforced Fe and Ni alloys. While most of these materials and markets are established and stable, this last class of MMCs represents a new market of growing importance where exceptional hardness and resistance to wear are of primary importance. These TiC-reinforced Fe and Ni MMCs are used in a wide range of industrial operations such as cutting, rolling, pelletizing, stamping, piercing, warm metal working, drawing, forming and punching. Components include hammers, impact dies, canning tools, crimp rollers, check valves, extruder nipples, bending dies, extrusion dies and hot forging die inserts. Superior performance is provided relative to tool steels and hardened Ni alloys that are conventionally used in these situations.

It is expected that the contents in the present chapter will be useful in understanding the composite materials and the related processing technologies for producing the MMC components. It also highlights the applications of MMCs in industrial and non-industrial areas.

The next chapter 2: Literature Survey presents a detailed discussion of the research work undertaken by various researchers on Metal Matrix Composites (MMCs) during last few decades.