STUDIES ON THE PERFORMANCE OF METAL MATRIX COMPOSITES (MMC)

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DOCTOR OF PHILOSOPHY

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By

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Dedication

To my mother

And

In the memory of my father and my father-in-law

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This is to certify that the thesis entitled “**STUDIES ON THE PERFORMANCE OF METAL MATRIX COMPOSITES (MMC).** " submitted by Sri **Sujit Das** who had registered his name on 11/01/2008 for the award of PhD (Engineering) degree of Jadavpur University is absolutely based upon his own work under our guidance and supervision fulfilling the part of the requirement for the award of the degree in Ph.D. (Engineering) of Jadavpur University.

To the best of our knowledge the results contained in this thesis in part or full did not form a basis for the award of any previous degree or diploma or any other academic award anywhere before.

The thesis, in our opinion, has reached the standards fulfilling the requirement for the award of the degree of **Doctor of Philosophy** (Engineering) in accordance with regulations of the Institute.

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ABSTRACT

The role of engineering materials in the development of modern technology need not be emphasized. As the levels of technology have become more and more sophisticated, the materials used also have to be correspondingly made more efficient and effective. The increasing use of Aluminium alloy materials in structural and space applications generated considerable interest for the development of techniques to predict the response under various operational conditions. Metal Matrix Composites (MMC) are relatively new materials and are used extensively in different fields such as automobile, aerospace, etc. Among metal matrix composite materials, particle reinforced MMCs are increased applications due to their very favorable properties, including high mechanical properties and good wear resistance. These composites are potential structural material for aerospace and automotive applications. Silicon Carbide particulate reinforced aluminum (SiCp-Al) composites possess a unique combination of high specific strength, high elastic modulus, good wear resistance and good thermal stability than the corresponding non-reinforced matrix alloy systems. Aluminium silicon carbide reinforced metal matrix composite has tremendous application in automobile, aerospace and other industries due to their excellent properties. Aluminum Metal Matrix Composites initially replaced Cast Iron and Bronze alloys but owing to their poor wear and seizure resistance, they were subjected to many experiments and the wear behavior of these composites were explored to a maximum extent and were reported by number of research scholars for the past decades. The acceptance of particulate Metal Matrix Composites (MMCs) for engineering applications has also been hampered by the high cost involved in producing components. Although several technical challenges exist in the casting technology yet it can be used to overcome this problem. One of the major challenges is the uniform distribution of reinforcement within the matrix, which directly affects the properties and quality of composite material. In the present work a modest effort has been made to develop Aluminium based Silicon Carbide particulate MMCs with two main objectives. i) To develop a low cost technique of producing MMCs. ii) To obtain homogenous dispersion of reinforcement material. To achieve the above said objectives Mechanical alloying method of Powder Metallurgy has been adopted. Powder Metallurgy (P/M) is an ideal method of fabrication for MMCs because of the ability to produce near net shapes and little material waste associated with the process. Mechanical alloying of powders resulted in improvement in hardness and compressive strength of Al-SiCp composites. In this work a 2^3 full factorial design of experiments (DOE) was used to collect experimental data to statistically analyze the effect of the process parameters on the hardness, density, forgeability etc. of the sintered Al-SiCp composites using RSM .Three factors central composite design is employed for carrying out this work. Analysis of variance is used for checking the validity of the model. Optimum conditions for better mechanical properties are determined using desirability function approach. The influences of different parameters in mechanical properties Al-SiCp particulate composite have been analyzed in detail. The predicted values and measured values are fairly close, which indicates that the developed model can be effectively used to predict the better mechanical properties of Al-SiCp. The effect of weight percentage of silicon carbide on hardness of composites was investigated by using Vickers hardness Test. It was observed that the distribution of silicon carbide particles was uniform. Other published work was also compared and found to be in very good correlation with the predicted result.

Keywords: *Metal matrix composites, Response surface method, Design of experiment, Central composite design. Al-SiCp particulate composites, Mechanical characterization, Mechanical alloying, Microstructural analysis, Powder metallurgy.*

Nomenclature

α	Distance from the centre point of the design to a star point (star arm)
B_1	$[\hat{\beta}_o \ \hat{\beta}_1 \ \hat{\beta}_2 \ \hat{\beta}_3 \ \hat{\beta}_{12} \ \hat{\beta}_{13} \ \hat{\beta}_{23} \ \hat{\beta}_{123}]^T$
B_2	$[\hat{\beta}_o \ \hat{\beta}_1 \ \hat{\beta}_2 \ \hat{\beta}_3 \ \hat{\beta}_{11} \ \hat{\beta}_{22} \ \hat{\beta}_{33} \ \hat{\beta}_{12} \ \hat{\beta}_{13} \ \hat{\beta}_{23}]^T$
β_o	Free term of the regression equation
β_i	Regression coefficient of ith process parameter (linear terms)
β_{ij}	Regression coefficient of interaction between ith and jth process parameters (interaction terms)
β_{ii}	Regression coefficient of self interaction of ith process parameter (Quadratic terms)
β_{ijk}	Regression coefficient of interaction among ith, jth and kth process parameters
$\hat{\beta}_o$	Estimated value of β_o
$\hat{\beta}_i$	Estimated value of β_i
$\hat{\beta}_{ij}$	Estimated value of β_{ij}
$\hat{\beta}_{ii}$	Estimated value of β_{ii}
$\hat{\beta}_{ijk}$	Estimated value of β_{ijk}
$E(x)$	Mathematical expectation of the variable x
ε	An error component

$F_{estimated}$	Estimated value of Fisher's F-ratio
$F_{\alpha_s;\nu_1,\nu_2}$	Fisher's F-ratio for ν_1 upper and ν_2 lower degrees of freedom for α_s level of significance
R1	Density of the sintered components
R_{CCD}	Density of the sintered components obtain through central composite design
R_2	Tangential Cutting force
$\overline{R_2}$	(R_2 - ε)= Tangential cutting force excluding error terms
R3	Hardness of sintered components
$R3_{CCD}$	Hardness of the material obtain through central composite design
R_a	Average value of Surface roughness
SRccd	Surface roughness of the sintered machined component obtain through central composite design
k	Number of controllable process parameters
l	Number of levels for each process parameter
m	Number of coefficients in the regression equation
N	Total number of design points = $n_f + n_a + n_c$
n_a	Number of axial points = 2k
n_c	Number of central points
n_f	Number of points used in factorial positions = 2^k
σ_β^2	Variance of regression coefficients

σ_{res}^2	Residual variance
σ_e^2	Estimate of error (replication variance)
$t_{\text{estimated}}$	Estimated t value
$t_{\alpha_s,\nu}$	Value of Students t distribution for α_s level of significance and ν degrees of freedom
$\mathbf{X}$	A matrix formed by column vector $\mathbf{x_0}$, $\mathbf{x_1}$, $\mathbf{x_2}$, $\mathbf{x_3}$,**…..**etc
$\mathbf{X}^{\mathbf{T}}$	Transpose of the matrix $\mathbf{X}$
x_i	Coded value of ith process parameter
$\mathbf{x_o}$	Coloum vector of dummy variable i.e column of 1’ s
$\mathbf{x_i}$	Coloum vector of coded values for process parameter x_i
$\mathbf{x_{ij}}$	Scalar product of column vectors $\mathbf{x_i}$ and $\mathbf{x_j}$
$\mathbf{x_{ijk}}$	Scalar product of column vectors $\mathbf{x_i}$, $\mathbf{x_j}$ and $\mathbf{x_k}$
z_i	Actual value of ith process parameter
z_i^{max}	Maximum actual value of the ith process parameter
z_i^{min}	Minimum actual value of the ith process parameter
z_i^{o}	Centre point of the design or the basic level of the ith process parameter
Δz_i	Unit or interval of variation on the z_i axis for the ith process parameter

CHAPTER 1

INTRODUCTION

INTRODUCTION

Outline of the chapter: 1.1.General Introduction, 1.2.Research Objective and Approach, 1.3.Research Methodology.

1.1. General Introduction:

In the 21st century, high strength, lightweight and energy efficient materials have received extensive attention, since the problems of environment and energy are major threshold areas. In order to fulfil this requirement, engineers and researchers are striving to develop new and better engineering materials. The modern engineering material finds wide application in the aerospace, defence field, engineering industry and automobile and leisure industry. The performance and efficiency for these applications can be increased largely by the application of modern engineering materials: composites. Metal matrix composite (MMC) is one such material developed for several applications. Hence, it is clear that technological developments in various fields depend on the advances made in the field of materials and in a way, it is one of the key factors that ultimately decide the extent of perfection and sophistication achieved by modern technology.

Further, the need of composite for lighter construction materials and more seismic resistant structures has placed high emphasis on the use of new and advanced materials that not only decreases dead weight but also absorbs the shock & vibration through tailored microstructures. Composites are now extensively being used for rehabilitation / strengthening of pre-existing structures that have to be retrofitted to make them seismic resistant, or to repair damage caused by seismic activity. As a result of intensive studies into the fundamental nature of materials and better understanding of their structure property relationship, it has become possible to develop new materials with improved physical and mechanical properties.

Many researchers have reported newer materials that meet these requirements. Composite materials are emerging chiefly in response to unprecedented demands from technology due to rapidly advancing activities in aircrafts, aerospace and automotive industries. The recognition of the potential weight savings that can be achieved by using the advanced composites, which in turn means reduced cost and greater efficiency, was responsible for this growth in the technology of reinforcements, matrices and fabrication of composites.

Composites do not necessarily give higher performance in all the properties used for material selection. In figure 1.1[1], six primary parameters such as strength, toughness, formability, joinability, corrosion resistance, and affordability are considered for material selection. If the values at the circumference are considered as the normalized required property level for a particular application, the shaded areas show values provided by ceramics, metals, and metal–ceramic composites. Clearly, composites show better strength than metals, but lower values for other material selection parameters.

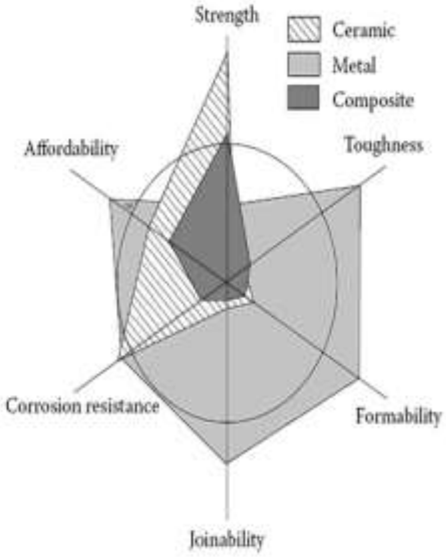


Figure.1.1: Primary material selection parameters for a hypothetical situation for metals, ceramics and metal–ceramic composites.

Metal matrix composites (MMCs) are widely used in industry because of their excellent mechanical properties. Nowadays, there are various products used of MMCs especially for automotive and engineering applications. This is because of their high strength, high elastic modulus, and low co-efficient of thermal expansion, light weight, low thermal shock, good wear resistance and many more advantages. The combinations of these properties are not available in conventional engineering materials such as metals. Metal matrix composites (MMCs) first emerged as a distinct technology in a time when improved performance for advanced military systems provided a primary motivation for material development.

Aluminium metal-matrix composites (AMCs) are such newly developed materials. The mechanical properties also depend on the composite particles for the reinforcement of the aluminium. Most of the alloys that were used as matrices are light alloys, particularly those based on aluminium. Aluminium-based particulate metal matrix composites (PMMCs), offering a unified combination of metallic properties and ceramic properties. Therefore, a lot of research work is essential in manufacturing of MMCs and to improve its properties.

MMCs usually have poor workability compared with non-reinforced metals because of the presence of some amount of non-deformable particles or fibers in the microstructure. In order to fabricate high quality PMMCs with desirable mechanical properties, important factors such as chemical reaction, the poor wettability between the matrix and the reinforcement, and the introduction of porosity during the incorporation of the particles require considerable attention [2, 3]. While some MMC applications were established in this early timeframe, MMCs were still a relatively immature technology by the early1970s, when recession in many developed countries curtailed funding for research and development.

Most of the researches on metal matrix composite (MMCs) in the recent years are focused on the development of high performance continuous fibre-reinforced composites for specialized applications. During the past two decades, a lot of research has been devoted to controlling the size, shape, morphology, and distribution of the grains in ceramics, in order to improve the mechanical properties. In spite of their unique properties, such composites are very expensive. Therefore, development of less-expensive composites for non-critical applications is desirable. Particulate-reinforced MMCs are cost-effective alternatives and have the advantage of being machinable and workable using conventional processing method. AMCs are relatively cheaper compared to other types of MMCs. Therefore, AMCs are always being the first choice of material selection in industrial applications and attracting growing interest. In various industries, particularly the automotives and aerospace/ application of aluminium alloy matrix composites reinforced with phases such as SiC_p or Al_2O_3 are increasing [4].

For production of aluminium based composites, the traditional form of process has not shown to be efficient, due to the oxide layer that covers the particles of the powder. The presence of this layer makes the diffusion process more difficult in a solid state sintering, and also in a liquid phase sintering. It is known that secondary processing of discontinuously reinforced composites can lead to break up of whisker agglomerates, to the reduction and elimination of porosity, as well as improving bonding and its mechanical properties. In this way, this secondary process allows the efficient breakage of the oxide layer in small particles which are dispersed easily in the aluminium matrix [5-7]. Extrusion is used as the most common secondary processing operation because of its excellent preferential axial alignment of discontinuous fibers [8].

Unless an appropriate deformation process design is employed, fractures can occur during the consolidation process, like extrusion or forging. Many researchers have investigated the wettability of reinforcement particles with the matrix [9]. The distribution of the reinforcement particles affected by the process parameters and another factor that has been found to significantly affect the final distribution is the size of the reinforcement particles [10-13]. The high cohesive energy of ultrafine particles gives them a highly agglomerative nature and leads to an increase in the total surface area. Consequently their tendency to clump together for forming agglomerates. However, currently available processing methods often produce composites with clustered particles within the matrix resulting in PMMCs with low ductility [14, 15] and induces an unwanted brittle nature to PMMCs [16, 17]. There is also a processing challenge with PMMCs is to homogeneously distribute the reinforcement in the matrix, which would improve the properties and the quality of the composite. The agglomeration of the reinforcement particles leads to an inhomogeneous response and lower macroscopic mechanical properties. In order to fabricate high quality PMMCs with desirable mechanical properties, important factors such as chemical reaction, the poor wettability between the matrix and the reinforcement, and the introduction of porosity during the incorporation of the particles require considerable attention. While composites have already proven their worth as weight-saving materials, one of the current challenges is to make them cost effective. The efforts to produce economically attractive composite components have resulted in several innovative manufacturing techniques currently being used in the composites industry.

There are three types of production methods in producing the AMCs. It includes liquid-state processing, solid state processing and vapour-state processing. Among the variety of choices particulate reinforced aluminium composites can be processed more easily by powder metallurgy process. Continuous advancements have led to the use of composite materials in more and more diversified applications. Prediction of optimum values of the process parameters and a uniform distribution of the reinforcement may help for better mechanical properties and metallurgical properties of the composites and [18, 19].

1.2. Research Objective and Approach:

Aluminium is the most popular matrix material for the metal matrix composites (MMCs). The Al alloys are quite attractive due to their low density, their capability to be strengthened by precipitation, their good corrosion resistance, high thermal and electrical conductivity, and their high damping capacity. Aluminium matrix composites (AMCs) have been widely studied since the 1920s and are now used in sporting goods, electronic packaging, armours and automotive industries. They offer a large variety of mechanical properties depending on the chemical composition of the Al-matrix. They are very attractive for their isotropic mechanical properties (higher than their unreinforced alloys) and their low costs. Pure aluminium is quite a popular and attractive choice as a matrix material to develop metal matrix composites owing to its excellent casting properties, better formability characteristics, option of modification of strength of composite by employing optimal heat treatment, unique balance between physical mechanical properties.

Particles of silicon carbide possess hardness value of approximately 2700 HV and are commonly used as grinding abrasives. SiC_p becomes more attractive as a reinforcing material due to its substantially lower cost. SiC particles in an aluminium matrix results in a composite that has better mechanical and physical properties than the unreinforced aluminium. Its strength, thermal conductivity, abrasion resistance, creep resistance and dimensional stability are all superior to those of the base metal.

When SiC particles are used as filler in aluminium, it increases the tensile strength and elastic modulus of the matrix, but on the other hand it will bring down the ductility. The aluminium based matrix SiC_p reinforced composites have found extensive applications in the aerospace, military and civil industries as they offer a good combination of high strength, high elastic modulus, increased wear and fatigue resistance. There have been several attempts by researchers to produce high quality Al-SiC_p composites following different fabrication routes.

Most of the study on the aluminium metal matrix composites reported in the literature focuses of stir casting or vortex method for fabrication of MMCs. But, the major drawback of this method is uneven distribution of particulates in the matrix alloy which results in non-homogenous properties of the composite material. And also solidification is often accompanied by severe segregation of alloying elements, causing undesirable consequences such as brittleness and lowered strength. And it is difficult or impossible to incorporate very fine particles and the volume fraction is limited to around 20-30%. The process and the compositions of the alloy and the particles have to be tightly controlled to avoid excessive reaction between particles and the melt. The conventional powder metallurgy relies on sintering at elevated temperatures to achieve consolidation. Bonding between particles is achieved through diffusion which requires both high temperature and long time. This not only makes the process expensive but also tends to destroy any non-equilibrium structures existing in particles. Without any assistance from pressure or liquid, full density is also hard to obtain. It is thus desirable to investigate a consolidation process at much lower temperatures and for much shorter time. One such promising method to consolidate particles into bulk material is back pressure equal channel angular consolidation method, which makes use of severe plastic deformation to achieve consolidation at much lower temperature than the powder metallurgy and vortex method.

In view of the above, the current research work is carried out to fabricate aluminium metal matrix composite using aluminium (99.99% pure, average particle size of 400 mesh, manufacturer LOBA Chemie, Mumbai-400005.) as matrix phase, silicon carbide particle (average particle size of 400 mesh, manufacturer HIMedia Laboratories Pvt. Ltd. Mumbai-400086.) as reinforcing phase and to evaluate their forgeability and mechanical properties.

The research work on pure aluminium - SiC_p metal matrix composites is carried out with the following objectives.

1. Fabrication of composite material containing SiC particles in different wt%, reinforced in pure aluminium matrix phase.

2. The effect of variation of sintering time on density, hardness, forgeability properties and the metallurgical behaviour of Al- SiC_p composites.

3. The effect of variation of compacting pressure on density, hardness, forgeability properties and the metallurgical behaviour of Al- SiC_p composites.

4. The effect of variation of percentage of reinforcement materials on density, hardness, forgeability properties and the metallurgical behaviour of Al- SiC_p composites.

5. To develop mathematical models by using second order Response Surface Method (RSM) with Central Composite Design (CCD) considering the above mentioned process parameters.

1.3. Research Methodology:

The methodology adopted to achieve the objectives is listed below and the same is graphically represented in the figure 1.2.

1. Based on the literature survey and experimentation of prior experimental studies, a methodology was developed to fabricate composite materials using powder metallurgy technique.

2. Experimental tests were carried out to investigate the density, hardness and forgeability properties of the composite material.

3. The effect of parameters such as sintering time, compacting pressure and wt% of reinforcements on the density, hardness and forgeability properties of composite materials were studied.

4. The microstructure, particle distribution of composite material were investigated through Optical microscope, X-ray Diffraction analysis and SEM analysis.

5. The samples were produced by variation of process parameters as per the Design of Experiment (DOE) by using MINITAB software (version 14) and the Response Surface Method (RSM)

6. Statistical analysis was carried out to determine the significant influencing factors and their interactions with density, hardness and forgeability of composite materials.

7. Multiple linear regression models were presented and validated using confirmation tests.

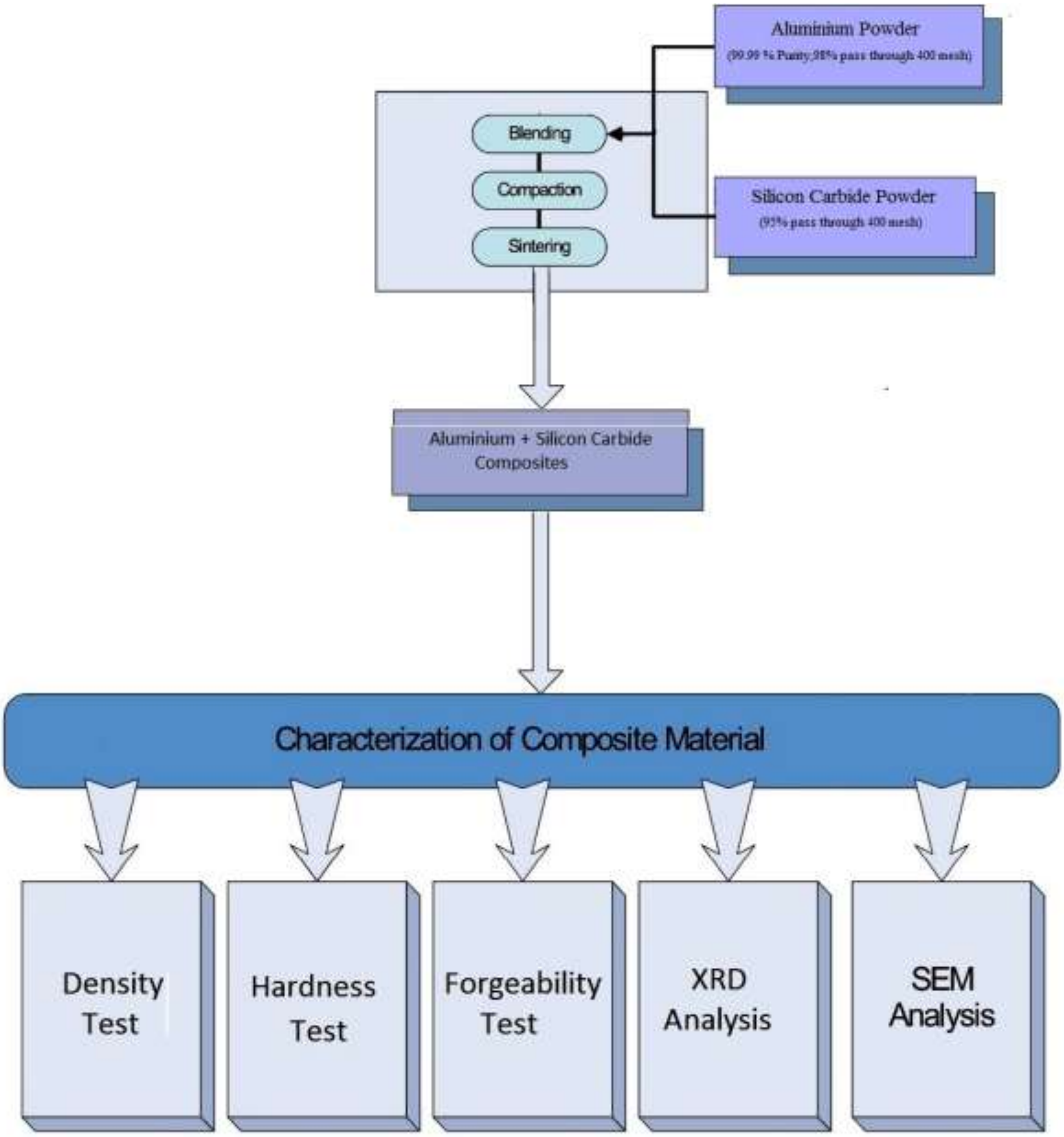


Figure.1.2: Research methodology.

CHAPTER 2

THEORY AND LITERATURE SURVEY

THEORY AND LITERATURE SURVEY

Outline of the chapter: 2.1. Metal Matrix Composites, 2.2. Why Use Composites? 2.3. Characteristics of Composite Materials,2.4. Classification of Composite Materials,2.5. Classification of MMCs.2.6. Comparison of MMCs with other Metals.2.7. Fabrication of MMCs, 2.8. Aluminium Matrix Composites (AMCs), 2.9.Characteristic of Aluminium Metal Matrix Composites, 2.10. Modelling Techniques, 2.11.Test of Significance, 2.12.ANOVA. 2.13. Summary.

2.1. Metal Matrix Composites:

A composite material consisting of two or more physically and chemically distinct parts, which are suitably arranged but mechanically or metallurgically bonded together and having different properties respect to those of the each constituent parts. The constituents are combined at a microscopic level and are insoluble even in the liquid state, or mixtures of metals with non-metallic substances such as oxides and other refractory materials. One constituents is called reinforcing material and in which it is embedded is called the matrix material. The reinforcing material may in the form of the fibres, particles or flakes and the matrix phase's materials are generally continuous. Examples of composite system are concrete reinforcement with steel, epoxy reinforced with graphite fibres etc. Each of the various composites retains its identity in the composite and maintains its characteristic properties such as stiffness, strength, weight, high temperature, corrosion resistance, hardness, and conductivity, which are not possible with the individual components by themselves. Typically, composites are composed of a rigid reinforcement or additive constituent (such as fibers or particles) embedded in a more forgiving matrix. The matrix component is, thus the continuous phase, in which the reinforcing phase is distributed. The reinforcement or additive constituents used for composite materials usually carry most of the load and furnish the dominant properties.

The matrix, on the other hand, serves two very important functions:

(a)It holds the reinforcement phase in place and

(b)Under an applied force it deforms and distributes the stress to the reinforcement constituents.

Example of the traditional composite is brick which consists of clay that mix up with grass and concrete that have mixture of cement and sand. In this example, clay and cement are matrix component while grass and sand are the reinforcement. When the matrix component is metal, we call such a composite a Metal Matrix Composite (MMC). The reinforcement can be in the form of particles, whiskers, short fibers, or continuous fiber. There are three entities that determine the characteristics of a composite which are:

(i) Reinforcement,

(ii) Matrix and

(iii)Interface.

Therefore, any solid material that can be processed so as to embed and adherently grip a reinforcing phase is a potential matrix material (including polymers. metals' and some inorganic materials such as glass, plaster, portland cement, carbon and silicon). In certain Metal Matrix Composites (MMCs), the matrix itself may also be a key strengthening element. There is a wide variety of reinforcement available today. Some are high strength materials such as Kevlar or glass, while others have special properties, such as graphite (lubrication), wood fibers (natural resource). Notably, ceramics particulates, such as silicon carbide (SiC), alumina (Al_2O_3) and boron carbide (B_4C), have become very popular.

This is a very large family of materials whose purpose is to obtain certain property resulting by the combination of the two constituents (matrix and reinforcement), in order to obtain the mechanical characteristics (and sometimes thermal) higher than that it is possible to have with their corresponding matrices. For this reason, about the wide range of new developed materials, composites are certainly those able to comply better the needs of most technologically advanced industries.

2.2. Why Use Composites?

Composite materials are not new. They have been used since antiquity. No record exists as to when people first started using composites. Some of the earliest records of their use date back to the Egyptians, who are credited with the introduction of plywood and the use of straw in mud for strengthening bricks. Similarly, the ancient Inca and Mayan civilizations used plant fibres to strengthen bricks and pottery. Swords and armour were plated to add strength in medieval times. An example is the Samurai sword, which was produced by repeated folding and reshaping to form a multi-layered composite (it is estimated that several million layers could have been used).

Composites have also been used to optimize the performance of some conventional weapons. For example: in the Mongolian arcs, the compressed parts are made of corn, and the stretched parts are made of wood and cow tendons glued together, Japanese swords or sabers have their blades made of steel and soft iron; the steel part is stratified like a sheet of paste, with orientation of defects and impurities in the long direction, then formed into a U shape into which the soft iron is placed. Thus the sword is imparted good resistance for flexure and impact. Composite materials have been in existence for many centuries, Eskimos use moss to strengthen ice in forming igloos. Similarly, it is not uncommon to find horsehair in plaster for enhanced strength. All of these are examples of man-made composite materials. Bamboo, wood, bone, and celery are examples of cellular composites that exist in nature. Wood is a composite system where the lignin matrix is reinforced with cellulose fibres. Bones in which the matrix made of minerals are reinforced with collagen fibres, are also composites. Muscle tissue is multidirectional fibrous laminate. There are numerous other examples of both natural and man-made composite materials.

The structural materials most commonly used in design can be categorized in four primary groups:

(i) Metals,

(ii) Polymers,

(iii) Composites, and

(iv) Ceramics.

These materials have been used to various degrees since the beginning of civilisation. Their relative importance to various societies throughout history has fluctuated. Ashby [20] presents a chronological variation of the relative importance of each group from 10,000 B.C. and extrapolates their importance through the year 2020. The information contained in Ashby's article has been partially reproduced in Figure 2.1. The relative importance of each group of materials is not associated with any specific unit of measure (net tonnage, etc.). As with many advances throughout history, Advancement in material technology (from both manufacturing and analysis viewpoints) subsequently alters many aspects of society. Progress in the development of advanced composites from the days of E glass / Phenolic structures of the early 1940’s to the graphite composites used in the space shuttle orbiter is spectacular. The importance of composites has experienced steady growth since about 1960 and is projected to continue to increase through the next several decades. It has been observed that, the remarkable increase in relative importance of composites as structural materials has been started around 1960, when the race for space dominated many aspects of research and development. Similarly, the Strategic Defence Initiative (SDI) program in the 1980s prompted increased research activities in the development of new material systems.

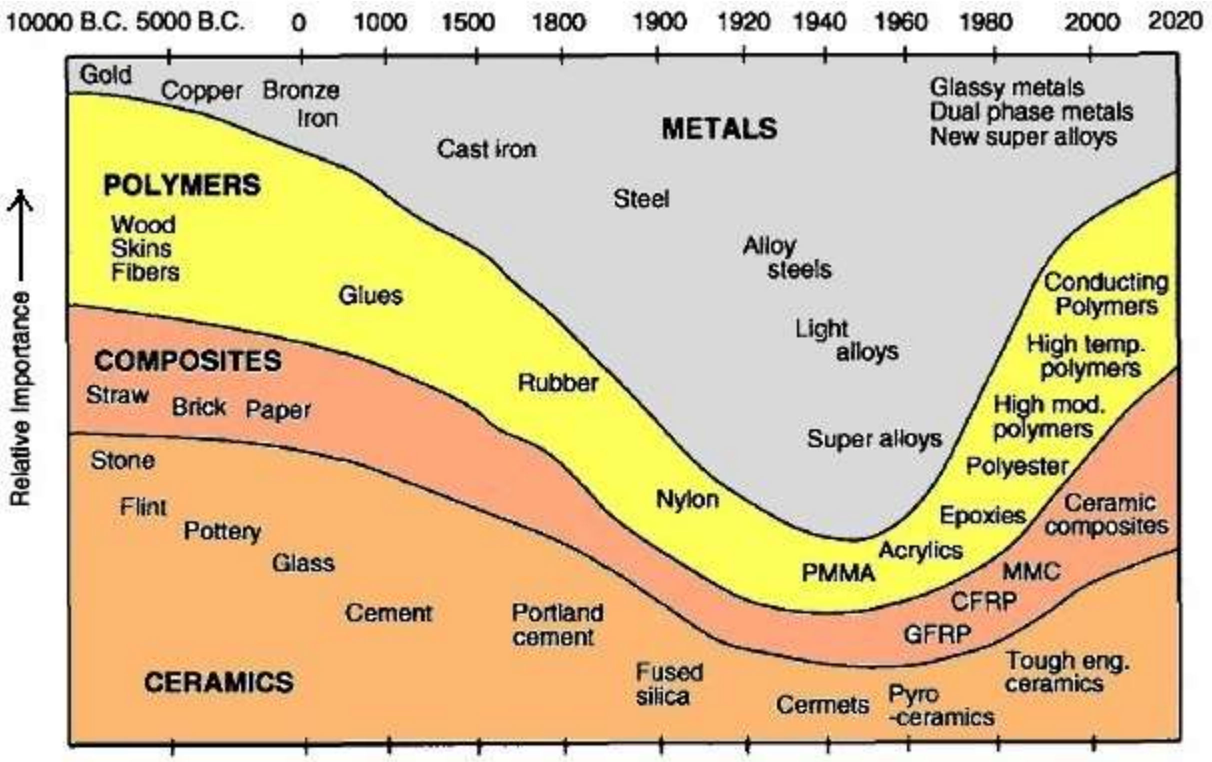


Figure.2.1: Relative importance of material development through history (after Ashby).

Many natural materials may be considered as of composite type; the classic example being wood. A very elementary example of a Ceramic Matrix Composite would be mud mixed with straw; still a very widely used material in the construction of houses. The incorporation of the straw improves the strength, toughness and the thermal insulation properties of this very basic composite. In principle at least, the degree of reinforcement (volume fraction of straw) and the level of alignment of the straw stalks (and their lengths) may be adjusted, so that not only the properties but also their anisotropy may be optimised differently in various parts of the structure. Use of composites will be a clear choice in many instances.

Material selection will depend on factors such as working lifetime requirements, number of items to be produced (run length), complexity of product shape, possible savings in assembly costs and on the experience and skill the designer in tapping the optimum potential of composites. In some instances, best results may be achieved through the use of composites in conjunction with traditional materials. Weight reduction of products / components (made of heavy materials, e.g. steel) has been a long-standing demand of the industries, but all attempts made so far to replace the heavy metal with lighter, e.g. Aluminium, failed to meet the acceptance criterion set for properties like strength, stiffness, wear resistance, machinability, electrical / thermal conductivity and corrosion resistance which are of significant technological importance.

These composite materials have strengths, especially at elevated temperatures which are superior to that of cast and wrought metals of similar basic composition. The composites industry has begun to recognize that the commercial applications of composites promise to offer much larger business opportunities than the aerospace sector due to the sheer size of transportation industry. Thus the shift of composite applications from aircraft to other commercial uses has become prominent in recent years. The various reasons for the use of composites are:

- To reduce weight.
- To reduce cost.
- To increase stiffness, strength and dimensional stability.
- To increase toughness and impact strength.
- To increase heat deflection temperature.

- To increase mechanical damping.
- To reduce permeability to gases and liquids.
- To modify electrical properties.
- To decrease thermal expansion.
- To increase chemical wear and corrosion resistance.
- To maintain strength/stiffness at high temperatures while under strain conditions in a corrosive environment.
- To increase secondary uses and recyclability, and to reduce negative impact on the environment.

The importance of composites as engineering materials is reflected by the fact that out of over 1600 engineering materials available in the market today more than 200 are composites. In some ways this is realistic and gives us a feeling of continuity from former “material-based” ages such as the Stone, Bronze and Iron ages. Certainly, the last 50 years have been associated with some remarkable developments in composite materials.

2.3. Characteristics of Composite Materials:

Metal Matrix Composites are multi-phase materials in which a strong, stiff reinforcing phase, typically a ceramic, is incorporated throughout a softer, ductile metal phase. The constituents of a composite are generally arranged so that one or more discontinuous phases are embedded in a continuous phase. The discontinuous phase is termed the reinforcement and the continuous phase is the matrix. An exception to this is rubber particles suspended in a rigid rubber matrix, which produces a class of materials known as rubber-modified polymers. Therefore, composites may be defined as materials consisting of two or more identifiable constituents deliberately combined to form homogeneous structures with desired or intended properties.

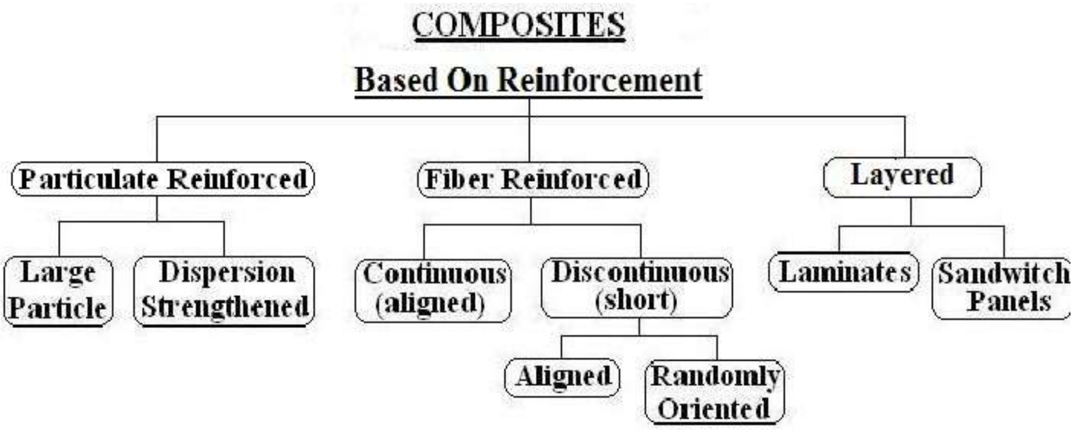
Reinforcements also come in different forms, such as fibers (long and short), whiskers, microspheres or particles. Most importantly, reinforcing materials typicality supply the basic strength of the composites. However, they can also contribute to the improvement of material properties other than simple strength / stiffness (including impact strength, thermal, chemical, electrical and abrasion resistance). The physical and mechanical properties of composites are dependent on the properties, geometry, and concentration of the constituents. Increasing the volume fraction of reinforcements can increase the strength and stiffness of a composite to a point. If the volume fraction of reinforcements is too high there will not be enough matrix to keep them separate, and they can become tangled. Similarly, the geometry of individual reinforcements and their arrangement within the matrix can affect the performance of a composite. The numbers of microscopic flaws that act as fracture initiation sites in bulk materials are reduced when the material is drawn into a thinner section. Therefore, the strength of the fiber is greater than that of the bulk material. Individual fibers are hard to control and form into useable components. The binder (matrix) material must be continuous and surround each fiber so that they are kept distinctly separate from adjacent fibers and the entire material system is easier to handle and work with. Without a binder material fibers are hard to separate and they can become knotted, twisted.

2.4. Classification of Composite Materials:

Composites are generally classified at two distinct levels.

Level I Classification:

The first level of classification is based on reinforcement.



A. Particle Reinforced Composite:

These can be further classified under two subgroups:

(a) Large particle and

(b) Dispersion strengthened composites.

The distinction between these is based upon reinforcement or strengthening mechanism.

(a) Large Particle Composite:

In the case of particle-matrix interactions cannot be treated on the atomic or molecular level. Properties are a combination of those of the components. The rule of mixtures predicts that an upper limit of the elastic modulus of the composite is given in terms of the elastic

moduli of the matrix (E_m) and the particulate (E_p) phases by:

$$E_c = E_m.V_m + E_p.V_p \quad \text{--} \ (2.1)$$

Where, V_m and V_p are the volume fraction of the two phases.

A lower bound is given by:

$$E_c = E_m.E_p / (E_p.V_m + E_m.V_p) \quad \text{---} \ (2.2)$$

Concrete is a familiar example of large-particle composite.

(b) Dispersion Strengthened Composite:

A dispersion strengthened composite contains small particulates or dispersions, which increase the strength of the composite by blocking the movement of dislocations. The dispersed is typically a stable oxide of the original material. Particle-matrix interactions occur on the atomic or molecular level and lead to strengthening. Particles like oxides do not react so the strengthening action is retained at high temperatures. A common example is sintered aluminium powder. Particles for dispersion-strengthened composites are normally much smaller (diameter between 0.01 micrometer and 0.1 micrometer). Dispersion strengthened composites can themselves be divided into two sub-categories:

(i) Dispersion Hardening:

In this case small, 10 nm to 250 nm diameter particles (usually oxides) are dispersed into a metal matrix.

(ii) Precipitation Hardening:

In this case a precipitate is nucleated and grown within the metal matrix.

B. Fiber Reinforced Composites:

In this case strong fibers are imbedded in a softer matrix to produce products with high strength to weight ratios. The load is transmitted from the matrix material to fibers, which absorb the stress. The length-to-diameter, or aspect ratio of the fibers used as reinforcement influences the properties of the composite.

(a) Continuously Reinforced Composite:

They are two types;

(i) Monofilament Composite:

Continuous monofilament reinforcements are large diameter (typically 100μm - 150μm) fibres, usually consisting of SiC_p or boron, which has been deposited (e.g. by chemical vapour deposition) on to a carbon or tungsten wire core [Clyne 2000]. The monofilament fibres are usually aligned in a unidirectional manner within the matrix. These large diameter fibres do not display a high degree of flexibility and are usually used as single fibres.

(ii) Multifilament Composite:

Multifilament reinforcements are small diameter (5μm - 30μm diameter) fibres, which can be woven, knitted, stitched, braided or wound. These fibres have a small bend radius, which improves their flexibility. Because of the flexibility of these fibres they can be incorporated into a matrix in a unidirectional manner, or combined (e. g. woven into a multi directional reinforcement).

(b) Short Fibre Composite:

These consist of a metal matrix with ceramic fibres distributed throughout. The fibres range in diameter from -1μm - 150μm [Hull 1996], with aspect ratios ranging, typically, from 3 to 100. The fibres (e. g. "Saffil", short alumina fibres) are fine grained polycrystalline in structure.

(c) Whisker Reinforced Composite:

These composites are essentially similar to the short fibre type, the exception being that the whiskers are mono crystalline [Levitt 1970] and usually have a diameter < 1μm, with aspect ratios up to several hundred. Their mechanical properties have been found to be superior when compared with polycrystalline short fibres. Higher the aspect ratio, stronger is the composite. Therefore, long, continuous fibers are better than short ones for composite construction. However, continuous fibers are more difficult to produce and place in the matrix. Shorter fibers are easier to place in the matrix but offer poor reinforcement. There are two possible extremes with respect to orientation:

(i) A parallel alignment of the longitudinal axis of the fibers in the single direction, and

(ii) Because of the flexibility of fibres they can be incorporated into a matrix in a unidirectional manner, or combined (e. g. woven into a multi directional reinforcement), a totally random alignment [21].

The different types of fiber-reinforced composites are shown in Figure 2.2.

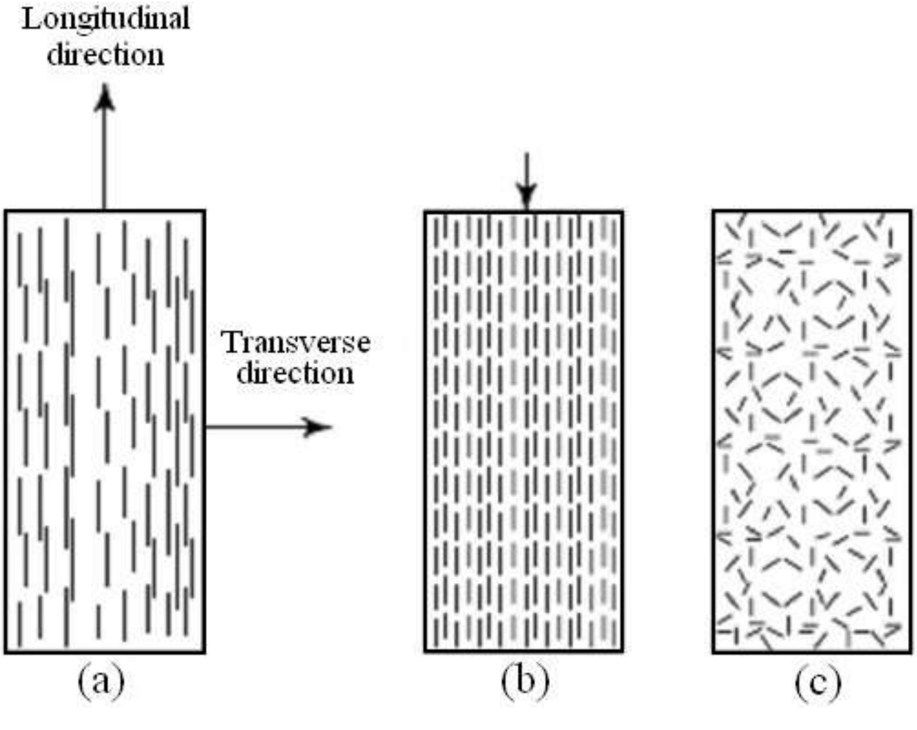


Figure 2.2: Representation of (a) Continuous and aligned fiber composite. (b) Discontinuous and aligned fiber composite. (c) Discontinuous and randomly oriented composite.

C. Layered Composite:

Layered composites consist of alternate layers of, usually, two constituent materials. These composites can contain layers from a few nanometres thickness up to thickness of several centimetres. This category of composites includes coatings and / or film deposition (e. g. ceramic coating of metals to improve wear resistance).

(a) Laminates:

Layers are fastened together one on top of another at different orientations are frequently utilized, shown in Figure.2.3. In this case multidirectional stresses are imposed within a single plane. These are called laminar composites. These are generally designed to provide high strength and low cost at a lighter weight. An example of laminar composite is plywood.

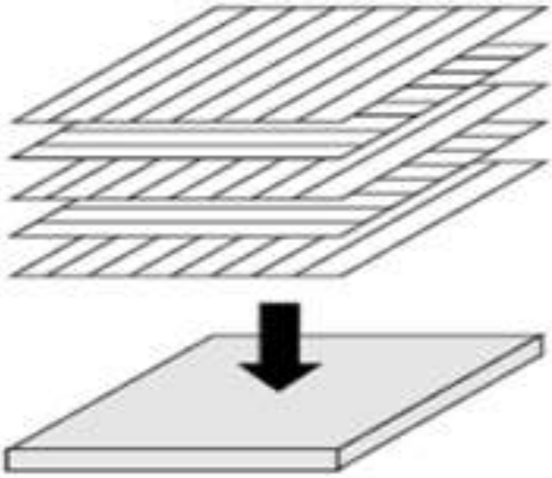


Figure 2.3: Laminar composite.

(b) Sandwich Structures:

Thin layers of facing material over a low density material, or comb core such as a polymer foam or expanded metal structure. In structures of this type, the facing material serves to fix the inner core in place. The core provides the strength. Typical face materials include aluminium alloys, fiber-reinforced plastics, titanium, steel and plywood. The honeycomb structure (Figure 2.4.) is one of the core structure, widely used in industries such as the aircraft industry, where higher strength and lower weight are important factors. The honeycomb structure consists of thin foils that have been formed into interlocking hexagonal cells, with axis oriented perpendicular to the face panels [22-24]. An example of sandwich-structured composite is corrugated cardboard.

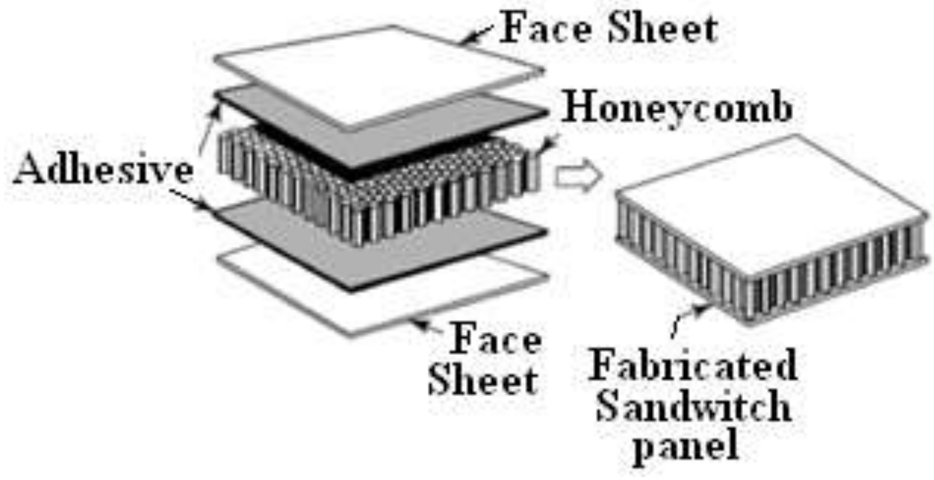
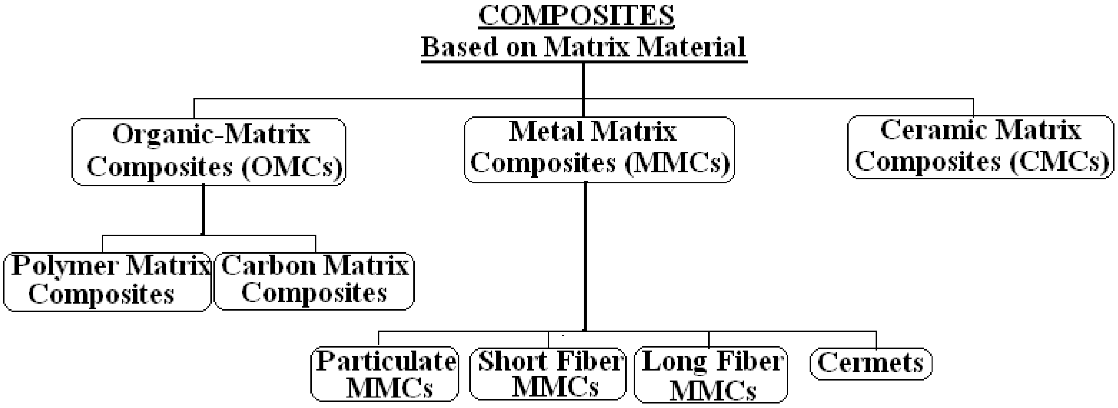


Figure 2.4: Honeycomb structure.

Level II Classification:

The second level of classification is based on the matrix constituent.



A. Organic Matrix Composite (OMC):

The term “Organic Matrix Composite” (OMCs) are generally assumed to include two classes of composites: Polymer Matrix Composites (PMCs) and Carbon Matrix Composites (commonly referred to as carbon-carbon composites). In each of these systems, the matrix is typically a continuous phase throughout the component**.** Polymer Matrix Composites are composed of a matrix from thermoset (Unsaturated Polyester (UP), Epoxy) or thermoplastic (PVC, Nylon, Polystyrene) and embedded glass, carbon, steel or Kevlar fibers (dispersed phase).

B. Ceramic Matrix Composite (CMC):

Ceramic matrix composites are used in very high temperature environments. These materials use a ceramic as the matrix and reinforce it with short fibers, or whiskers such as those made from silicon carbide and boron nitride.

C. Metal Matrix Composite (MMC):

In a composite material, when the matrix is a metal (e,g aluminium, magnesium, iron, cobalt, copper)or its alloy, we have a "Metal Matrix Composite. MMCs are multi-phase materials in which a strong, stiff reinforcing phase, typically a ceramic, is incorporated throughout a softer, ductile metal phase. There is however particular classes of MMC, which are unorthodox, for example, gas as the dispersed phase creating metallic foam. Also the inclusion of graphitic plates, refractory metals, intermetallic or semi-conductors can be used to obtain a specific property or properties. The performance of these materials, i.e. their characteristics in terms of physical and mechanical peculiarity, depend on the nature of the two components (chemical composition, crystalline structure, and in the case of reinforcement, shape and size), the volume fraction of the adopted reinforcement and production technology. In general we can say that metal matrix composites utilize at the same time the properties of the matrix (light weight, good thermal conductivity, ductility) and of the reinforcement, usually ceramic (high stiffness, high wear resistance, low coefficient of thermal expansion). By this way it is possible to obtain a material characterized, if compared to the basic metal component, by high values of specific strength, stiffness, wear resistance, fatigue resistance and creep, corrosion resistance in certain aggressive environments. However, cause to the presence of the ceramic component, ductility, toughness and fracture to the coefficients of thermal expansion and thermal conductivity decrease.

In recent years, the development of Metal Matrix Composite (MMCs) has been receiving worldwide attention on account of their superior strength and stiffness in addition to high wear resistance and creep resistance comparison to their corresponding wrought alloys. The ductile matrix permits the blunting of cracks and stress concentrations by plastic deformation and provides a material with improved fracture toughness. Cast composites, where the volume and shape of phases is governed by phase diagrams, i.e. Cast iron and Aluminium-silicon alloys have been produced by foundries for a long time. The modern composites differ in the sense that any selected volume, shape and size of reinforcement can be introduced into the matrix. The modern composites are non-equilibrium mixtures of metals and ceramics, where there are no thermodynamic restrictions on the relative volume percentages, shapes and size of ceramic phases [25].

The high toughness and impact strength of metals and alloys such as aluminium, titanium, magnesium and nickel-chromium alloys, which undergo plastic deformation under impact, is of interest in many dynamic structural applications of metallic composites. These materials have also been strengthened considerably by means of various strengthened principles (like grain boundary strengthening, cold working, solid solution strengthening, etc.) to improve their properties. But these approaches are often found to affect the toughness and durability at elevated temperatures and / or under dynamic service conditions. One of the important objectives of metal matrix composites, therefore, is to develop a material with a judicious combination of toughness and stiffness so as to decrease the sensitivity to cracks and flaws and at the same time increase the static and dynamic properties. This necessity eventually leads to the efficient reinforcement of metals and metal alloys by unidirectional or multidirectional implantation of whiskers or continuous fibers. The reinforcement effect occurs due to the extraordinary high strength of whiskers and fibers with diameters below a few micrometers. Thus, the field of Metal Matrix Composite (MMCs) began in the mid of 1960’s with the realization that whisker reinforced MMCs can be competitive with continuous fiber reinforced composites [26], from the standpoint of mechanical properties [27].

The complex fabrication routes, limited ability to be fabricated [27, 28] and the small difference in property enhancement between whisker and particulate reinforcement [29] and moreover, the health hazards associated with the handling of SiC whiskers [30, 31] have shifted the emphasis recently more towards particulate or chopped fibers rather than whisker reinforcement of metals. This necessity eventually leads to the efficient reinforcement of metals and metal alloys by unidirectional or multidirectional implantation of whiskers or continuous fibers, especially aluminium, because of its light weight and good wettability with silicon carbide [32]. The important shift in metal matrix composite technology began in the mid 80’s with more and more discontinuous reinforcement taking the place of continuous reinforcement such as carbides, nitrides, oxides and elemental materials like carbon and silicon. While discontinuous whisker reinforced MMCs are still under development for aerospace applications, automotive components fabricated from particulate and discontinuous fiber reinforced MMCs, which exhibit essentially isotropic properties, are already in mass production, led by the introduction of diesel piston by Toyota in 1983 followed more recently by engine and cylinder blocks from Honda [33,34].

The present trend, therefore, seems to be towards the development of discontinuously reinforced metal matrix composites. Which are gaining widespread acceptance primarily because they have recently become available at a relatively low cost compared to unidirectional and multidirectional continuous fiber reinforced MMCs and the availability of standard or near standard metal working methods which can be utilized to form these MMCs [35]. Discontinuously Reinforced Aluminium composites composed of high strength aluminium and its alloys reinforced with silicon carbide particulates or whiskers are subclass of MMCs. The combination of properties and fabricability of aluminium metal matrix composites makes them attractive candidates for many structural components requiring high-stiffness, high strength and low weight [36].

Successful development and deployment of metal matrix composites are critical to reaching the goals of many advanced aerospace propulsion and power development programs. The specific space propulsion and power applications require high temperature, high thermal conductivity and high strength materials. Metal matrix composites either fulfill or have the potential of full filling these requirements [37]. Metal matrix composites also offer considerable promise to help automobile engineers meet the challenges of current and future demands.

It is thus evident from literature that we can successfully reinforce the SiC_p, Al_2O_3, TiB_2, boron and graphite in the Aluminium matrix alloy. The reinforced Aluminium matrix alloys have made significant strides from laboratory towards commercialization. But the factors understanding that influence the physical and mechanical properties of these materials is really a challenge [38] because they are sensitive to the type and nature of reinforcement, the mode of manufacture and the details of fabrication processing of the composite after initial manufacture.

2.5. Classification of MMCs:

Based on the type and nature of the reinforcement, MMCs can be broadly classified into three basic types:

A. Continuously Reinforced MMCs:

a. Monofilament MMCs:

The monofilament fibers are usually aligned in a unidirectional manner within the matrix.

b. Multifilament MMCs:

These fibers have a small bend radius (Table 2.1), which improves their flexibility.

B. Discontinuously Reinforced MMCs:

Discontinuous reinforced composites: containing short fibers, whiskers or particles (Figure 2.1).

C. Short Fiber MMCs:

These consist of a metal matrix with ceramic fibers distributed throughout.

D. Whisker Reinforced MMCs:

Their mechanical properties have been found to be superior when compared with polycrystalline short fibers [39].

E. Particulate MMCs:

This classification can be further divided into two sub-categories [40], dispersion strengthened and large particle (or true-particle) composites. Dispersion strengthened composites can themselves be divided into two sub-categories:

(i) Dispersion hardening - in this case small, 10 nm to 250 nm diameter particles (usually oxides) are dispersed into a metal matrix;

(ii) Precipitation hardening - in this case a precipitate is nucleated and grown within the metal matrix.

Table 2.1

Curvature data for various fibers.

Material	Trade Name	Diameter d (μm)	Fracture Strength σ_f (G Pa)	Maximum Curvature K_{max}(mm^{-1})	Minimum Bend Radius(mm)
SiC Monofilament Continuous	**Sigma (UK)**	**150**	**2.4**	**0.08**	**12,5**
SiC Multifilament Continuous	**Nicalon (Japan)**	**15**	**2.0**	**1.4**	**0.71**
Al_2O_3+ SiO_2 Short Fiber Discontinuous	**Saffil (UK)**	**3**	**2.5**	**5.5**	**0.18**
SiC Whisker Discontinuous	**N/A**	**1**	**5.0**	**22.2**	**0.045**

In dispersion strengthened composites the particles, which usually constitute -1 wt% of the material, must be closely spaced (< -1 μm). This spacing is necessary because of the strengthening process (dislocation obstruction) involved. Due to the mechanism of strengthening, these materials are not considered true composites [41].

Large particle composites consist of a metallic matrix with large diameter (l μm – 50 μm), usually ceramic particles distributed throughout the matrix. The strengthening process here is primarily load transfer between the matrix and the reinforcing particle [41].

The choice of reinforcement is related to the type of application, to the compatibility between the reinforcement and the matrix and to the interfacial resistance matrix/ reinforcement. As already mentioned, the ceramic reinforcement is usually in the form of oxides, carbides and nitrides, i.e. that element with high strength and stiffness both at room temperature and at high temperatures. The common reinforcing elements are silicon carbide (SiC_p), alumina (Al_2O_3), titanium boride (TiB_2), boron and graphite. That particle type is the reinforcement most common and economical.

The continuous reinforcement composites have the possibility to incorporate a mix of properties in the chosen material as the matrix, as better wear resistance, lower coefficient of thermal expansion and higher thermal conductivity. The products are also characterized by high mechanical strength (especially fatigue strength) along the direction of reinforcement, so they are highly anisotropic.

Discontinuous reinforcement has a positive effect on properties as hardness, wear resistance, fatigue resistance, dimensional stability and compression resistance [42]. This material also shows a significant increase in stiffness but to the disadvantage of ductility and fracture toughness. One of the biggest advantages of discontinuously reinforced composites is the possibility (especially in the case of reinforced aluminium alloy) to work with the usual techniques of rolling, extrusion and forging. The addition of the hard second phase however entails a fast tool wear, requiring sometimes diamond tools.

2.6. Comparison of MMCs with other Metals:

The figure 2.5. shows the comparison of metals like Steel & Aluminium with composites, which indicates that in comparison by weight composites are much lighter than other two metals. Similarly in comparison of thermal expansion the composites are low which is good for places where high temperature working is required. In case of stiffness & strength the composites are ahead of the aluminium & steel.

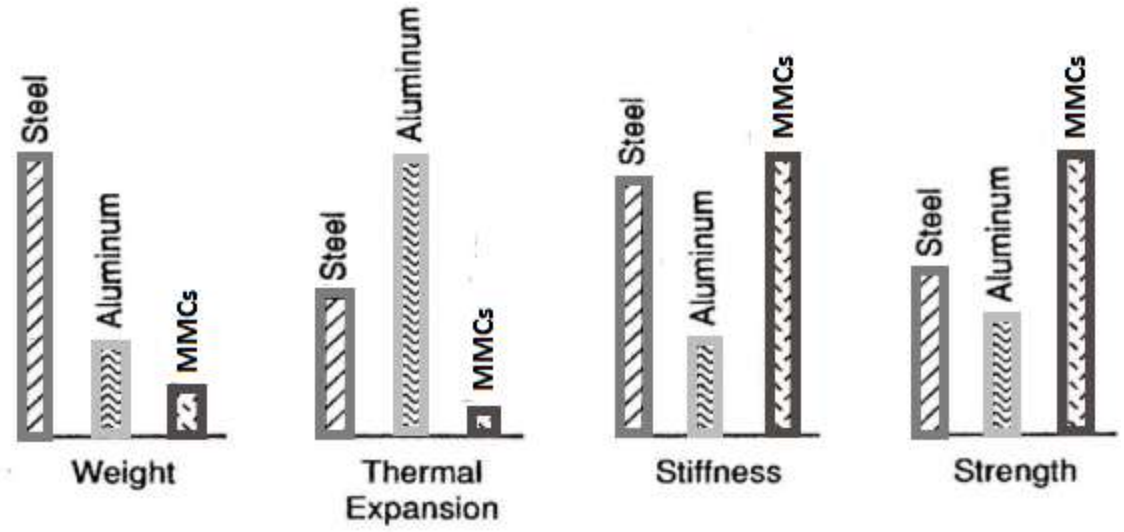


Figure 2.5: Comparison of MMCs with other metals.

Disadvantages of MMC, in comparison to metals and polymer matrix composites, in areas of production and application, are as under:

- Expensive production system.
- Technology still comparatively immature.
- Complexity about the production processes (especially about the long fiber MMC).

Limited experience of services dedicated to production.

2.7. Fabrication of MMCs:

MMCs can be tailored to offer the desirable properties demanded by the application, which makes them advantageous over unreinforced metal alloys.

2.7.1. Selection of Material:

The matrix was considered for a long time simply a means to hold together the fibers or any other type of reinforcement**:** however this speech especially for a polymer matrix composite is effective. Over the years instead it has been increasingly clear that the microstructure of the matrix and consequently its mechanical properties exerts a considerable influence on the overall composite performance. When designing the metal matrix composite, an engineer aims for combining the desirable attributes of the metal and the reinforcing phase. Criteria for materials selection should be the desirable properties the MMC needs to possess and the interaction between metal matrix and reinforcement, exhibited at their interface. To take the maximum advantage of the properties of the metal matrices and enhance them with proper reinforcements, the selection of a matrix should satisfy three basic requirements [43]:

- **(i)** High ductility in order to provide strain accommodation around the brittle reinforcements;
- **(ii)** Low melting point in order to permit liquid-phase fabrication processes without impairing the reinforcements' properties;
- **(iii)** Low density in order to achieve high specific properties.

According to these criteria, aluminium and aluminium alloys are found to be the best selection among metals as matrices for metallic composites, while magnesium and titanium may also be useful for some limited applications.

Among the most metal alloys used as a matrix in MMC, there are aluminium, titanium, magnesium and copper, with intermetallic compounds that are finding growing interest due to their excellent resistance at high temperature. As reduction in weight is a priority for MMC development, the major research has concentrated on light metal alloy matrices e. g. alloys based on Aluminium (Al), Beryllium (Be), Magnesium (Mg) and Titanium (Ti). A comparison of these light alloys result in the following observations [44].

Aluminium

- Long fiber: boron, silicon carbide, alumina, graphite.
- Short fiber: alumina, alumina-silicon.
- Whiskers: silicon carbide.
- Particle: silicon carbide, boron carbide.

Major disadvantage is its limited temperature capability. Age hardened alloys operating at temperatures -1909C can lead to precipitate coarsening and strength loss.

Magnesium

- Long fiber: alumina, graphite.
- Whiskers: silicon carbide.
- Particle: silicon carbide, boron carbide.

Major disadvantages are high chemical reactivity, poor corrosion resistance and high creep rate.

Titanium

- Long fiber: silicon carbide.
- Particle: titanium carbide.

Major disadvantages are chemical reactivity and oxide formation causing problems with powder forming and diffusion bonding.

Copper

- Long fiber: silicon carbide, graphite.
- Particle: titanium carbide, silicon carbide, boron carbide.
- Filament: niobium – titanium.

Super alloys

- Filament: tungsten.

The concentration of effort on aluminium stems also from its unique combination of good corrosion resistance, low density and excellent mechanical properties [45]. Thereby, with the addition of stronger ceramics reinforcements, the usability of these aluminium MMCs has reached another level.

The improvement in material properties and major applications of these aluminium MMCs with different reinforcements in both continuous and discontinuous forms have been highlighted by other researchers [46]. Due to high costs and limited development of appropriate fabrication process, these MMC materials have had limited application. However, since the last few decades, new and less expensive reinforcements (principally in the form of fibres and particles) along with improved manufacturing techniques are fast coming to unlock the potential of MMCs.

2.7.2. Property Development:

The opportunity offered by composite materials to alter the properties of the metal matrix in favour of the intended application is unique. Under ideal MMC production conditions, the principal mechanical, thermal, physical and tribological properties that the composite will exhibit are defined by the rule-of-mixtures [47] which is a method of approach to approximate estimation of composite material properties, based on an assumption that a composite property is the volume weighed average of the phases (matrix and dispersed phase) properties. According to Rule of Mixtures properties of composite materials are estimated as follows:

$$P_c = P_mV_m + P_fV_f \qquad \text{----------} \quad (2.3)$$

Where P_c is the property of the composite material, Pm is the property of the matrix, P_f is the property of the reinforcement, V_m is the volume fraction of the matrix phase, and V_f is the volume fraction of the reinforcement phase. The rule of mixtures gives very good estimates of the properties for continuously reinforced composites.

On the other hand, for particle reinforced MMCs, it is preferable to consider the properties of a two phase composite in terms of a dielectric constant ε_c. The Hashin - Shtrikman bounds [43] predict the range of the effective dielectric constant of an isotropic composite according to:

$$\varepsilon_{1}{+}v_1 = \varepsilon_{2}{}_{+}\, v_{2} \qquad \text{----------} \quad (2.4)$$

Where ε_1 and ε_2 the dielectric constant of each phase, with $\varepsilon_2 > \varepsilon_1$, and v_1, v_2 the volume fraction of each phase. These are the best possible bounds for the dielectric constant of an isotropic, two-phase material when the volume fractions of each phase are known. The properties of an isotropic composite are expected to fall within these two bounds. However, since the mechanical properties are highly sensitive to reinforcement size, volume fraction, distribution, processing defects, brittle reaction zones and the matrix structure [48], it is very common for composite materials to exhibit properties that are lower than those defined by the Hashin – Shtrikman bounds.

One of the major challenges when producing MMCs is to achieve a homogeneous distribution of the reinforcement particles in the matrix. To obtain a specific mechanical/physical property, ideally, the MMC should consist of fine particles distributed uniformly in a ductile matrix, with clean interfaces between particle and matrix. However, the current processing methods often produce agglomerated particles in the ductile matrix and as a result they exhibit extremely low ductility [15, 49]. Clustering leads to a non-homogeneous, anisotropic response and lower macroscopic mechanical properties. Particle clusters act as nucleation sites for crack or de-cohesion at stresses lower than the matrix yield strength, causing the MMC to fail at unpredictable low stress levels [50, 51].

2.7.3. Interface:

Both reinforcement and matrix are also selected on the basis of what will be the interface that unites them. In fact, cause to the fabrication and working conditions to which these materials are submitted, along the interface fiber/matrix special processes develop, capable in this zone of producing compounds and/or phases that can significantly influence the mechanical properties of the composite.

The interface between the matrix and reinforcement has been recognised in the early studies of composites as a very important microstructural feature of composite materials [52]. It is a transition zone where compositional and structural discontinuities can occur over distances varying from an atomic monolayer to over five orders of magnitude in thickness [53]. Interfacial characteristics in metal matrix composites reinforced with ceramic reinforcements play a significant role in determining the mechanical properties, such as strength, ductility, toughness and fatigue resistance.

A weak interface results in a low stiffness and strength but a high resistance to fracture, whereas a strong interface produces high stiffness and strength but often a low resistance to fracture [54]. Reactive solutes in the matrix can attack the reinforcement during processing and/or service and deteriorate the interfacial strength [55]. The addition of alloying elements in the matrix has been found to limit the chemical reaction [56] and more specifically, the addition of silicon (Si) to aluminium and aluminium alloy matrices prevents the formation of Al_4C_3 at the interface in Al-SiC or Al-graphite composites [57].

Wettability plays a key role in interfacial bonding due to adhesion between the reinforcement and the matrix. The contact angle formed by a liquid droplet resting on a solid substrate as seen in Figure 2.6 can be used to describe the wettability [58]. According to the Young-Dupré equation [59], the contact angle θ can be expressed as:

$$\gamma_{lv} \cos\theta = \gamma_{sv} - \gamma_{sl} \qquad \text{---} \quad (2.5)$$

where γ_{sv} is the surface energy of the solid, γ_{sl} the solid liquid interfacial energy and γ_{lv} the surface energy of the liquid and θ the contact angle.

In molten metal and ceramic particle systems, the high surface tension of the metals, of the order of 1000 mJ/m², makes wetting very difficult [60]. Poor wettability results in inadequate bonding between the metal and the reinforcement particles. In practice, to improve wettability between the metal and the ceramic particles, the following actions are recommended:

- Application of a metallic coating on ceramic particulates [61]
- Varying the matrix alloy composition [62]
- Heat treatment of the ceramic particulates [53].

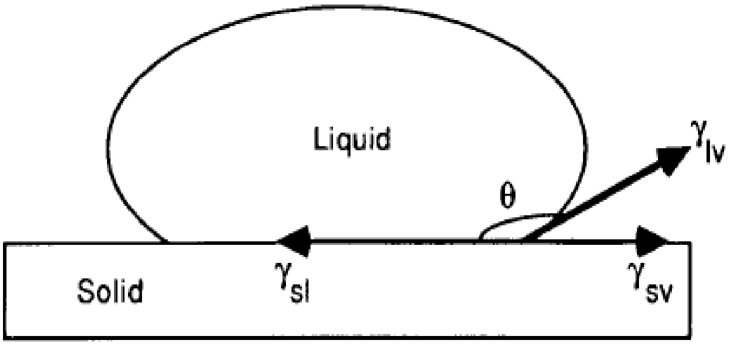


Figure 2.6: Schematic diagram of a liquid drop on a solid surface showing interfacial forces and wetting angle.

This interface can be as a simple zone of chemical bonds (as the interface between the pure aluminium and alumina), but can also occur as a layer composed by reaction matrix/reinforcement products (type carbides produced between light alloy and carbon fibers) or as a real reinforcement coatings. The mechanical and thermal properties of MMC can be summarized by a quantitative way through the following Table 2.2.

In particular, note the fact that the E/ρ value for conventional metals usually is not more than 25. About the possible disadvantages for the MMC production and application, these are based, comparing it to metals and polymer matrix composites, mainly on the following points:

(i) Expensive production system.

(ii) Technology still comparatively

(iii) Complexity about the production processes, especially about the long fiber MMC.

(iv) Limited experience of services dedicated to production.

Table 2.2

Mechanical and thermal properties of MMC.

Density, ρ	2.5-3.1 gm/cm^3
Modulus of elasticity, E/ρ	90-300 Mpa
Specific resistance, E_r	30-60 Ώ-m
Tensile Strength, Ultimate (σ_r)	300-700 Mpa
Thermal Conductivity, k	120-00 W/m.^{o}K
C.T.E.	7-20 µm/^{o}K

Now a day's, research all over the world is focusing mainly on Aluminium because of its unique combination of good corrosion resistance [63], low density and excellent mechanical properties. The unique thermal properties of Aluminium composites such as metallic conductivity with coefficient of expansion that can be tailored down to zero, add to their prospects in aerospace and avionics. Thus, entire families of light weight composites, though considered impossible just a few years ago, are either available now or hovering on the brink of commercialization. For example, a series of Aluminium matrix composites reinforced with silicon carbide particulates have been developed by Duralcan USA, Div. Alcan Aluminium corp., San Diego, California [64]**.** A high temperature creep resistant titanium alloys has been developed as matrix material for the National Aerospace plant by Timet for McDonnell Douglas. Titanium alloy Ti-6Al-4V, reinforced with continuous silicon carbide filaments, is hot isostatically, pressed by Textron for turbine engine shafts [65]**.**

CERAMTEC AG (Germany) currently utilizing matrix material for MMC products are Aluminium and specially the Al-Si_9Cu_3 standard alloy. Apart from being fairly inexpensive in comparison with other light metals (e.g., magnesium and titanium), it has delivered outstanding results in many automotive and aerospace applications and is noted for its uncomplicated processing properties. In practice, the matrix may be constructed of almost any other light alloy or non-ferrous metal, particularly magnesium. They are also developing new ceramic cutting tools, and also superior material for cylinder linings.

Titanium has been used in aero engines mainly for compressor blades and discs due to its higher elevated temperature resistance property [66]. Magnesium is the potential material to fabricate composite for making reciprocating components in motors and for pistons, gudgeon pins, and spring caps [67]. It is also used in aerospace due to its low coefficient of thermal expansion and high stiffness properties combined with low density. The choice of Silicon Carbide as the reinforcement in Aluminium composite is primarily meant to use the composite in missile guidance system replacing certain beryllium components because structural performance is better without special handling in fabrication demanded by latter's toxicity [68, 69]. Recently Aluminium- lithium alloy has been attracting the attention of researches due to its good wettability characteristics [70].

2.7.4. Reinforcements:

Reinforcement increases the strength, stiffness and the temperature resistance capacity and lowers the density of MMC. In order to achieve these properties the selection depends on the type of reinforcement, its method of production and chemical compatibility with the matrix and the following aspects must be considered while selecting the reinforcement material.

- Size – diameter and aspect ratio:
- Shape – Chopped fiber, whisker, spherical or irregular particulate, flake, etc:
- Surface morphology – smooth or corrugated and rough:
- Poly or single crystal:
- Structural defects – voids, occluded material, second phases:
- Surface chemistry – e.g. SiO_2 or C on SiC or other residual films:
- Impurities – Si, Na and Ca in sapphire reinforcement;

Inherent properties strength, modulus and density.

Among the different forms of reinforcement continuously reinforced aluminium MMCs exhibit excellent properties. However, properties between the longitudinal and transverse directions of continuously reinforced metallic composites need to be carefully balanced to achieve a better performance [71, 72]. On the other hand, particulate composites differ from fibrous composite in that the distribution of the additive is discontinuous rather than continuous' The uniform dispersion of the particles within an aluminium matrix results in more isotropic material properties which facilitates the fabrication of the aluminium MMC material. More recently, particulates have become the focus of attention, because these materials represent the cheapest available source of reinforcement and may thus provide the stimulus for wider application of MMC components. Therefore, substantial benefits can be achieved by the use of particulate to reinforce metals, especially where an increase in stiffness over the unreinforced alloys is required at low additional cost.

From the fabrication point of view, it is very attractive that particulate reinforced aluminium alloys can be processed using conventional rolling, forging and extrusion techniques. Ceramics have become the most suitable materials for MMC reinforcements due to their special characteristics not found in traditional metal alloys. Silicon carbide (SiC) particulate, alumina (Al_2O_3) particulate and boron carbide (B_4C) particulate are more commonly used ceramics for aluminium MMCs. One typical example of industrially used particular reinforced aluminium MMC is silicon carbide. Combining SiC particles in an aluminium matrix results in a composite that has better mechanical and physical properties than the unreinforced aluminium: its strength, thermal conductivity' abrasion resistance, creep resistance and dimensional stability are all superior to those of the base metal [73, 74]. Silicon carbide reinforcement can be used in the form of fibre, whisker or particulate; however, the latter two are more popular. The amount of SiC particulate added into the aluminium alloy can be varied from l0 to 50 wt%, depending on what the application requirements are. Silicon carbide incorporated in aluminium at low volume fraction used for structural aluminium MMC

A. Forms of Reinforcements:

Among the different forms of reinforcement shown in the Figure 2.7, excellent properties have been obtained from continuously reinforced aluminium MMCs [43]. However, properties between the longitudinal and transverse directions of continuously reinforced metallic composites need to be carefully balanced to achieve a better performance. Even though such a balance can be obtained by combining fibers or hybrids selection and stacking sequences, matrix alloy selection, with component design, it will involve additional cost. On the other hand, particulate composites differ from fibrous composite in that the distribution of the additive which is more discontinuous rather than continuous. The uniform dispersion of the particles within an aluminium matrix results in more isotropic material properties which facilitates the fabrication of the aluminium MMC material. More recently, particulates have become the focus of attention, because these materials are unquestionably the cheapest available source of reinforcement and may thus provide the stimulus for wider application of MMC components [75]. Therefore, substantial benefits can be achieved by the use of particulate to reinforce metals, especially where an increase in stiffness over the unreinforced alloys is required at low additional cost. Further, from the fabrication point of view, it is very attractive that particulate reinforced aluminium alloys can be processed using conventional rolling, forging and extrusion techniques. Hence, their usage has become more widespread.

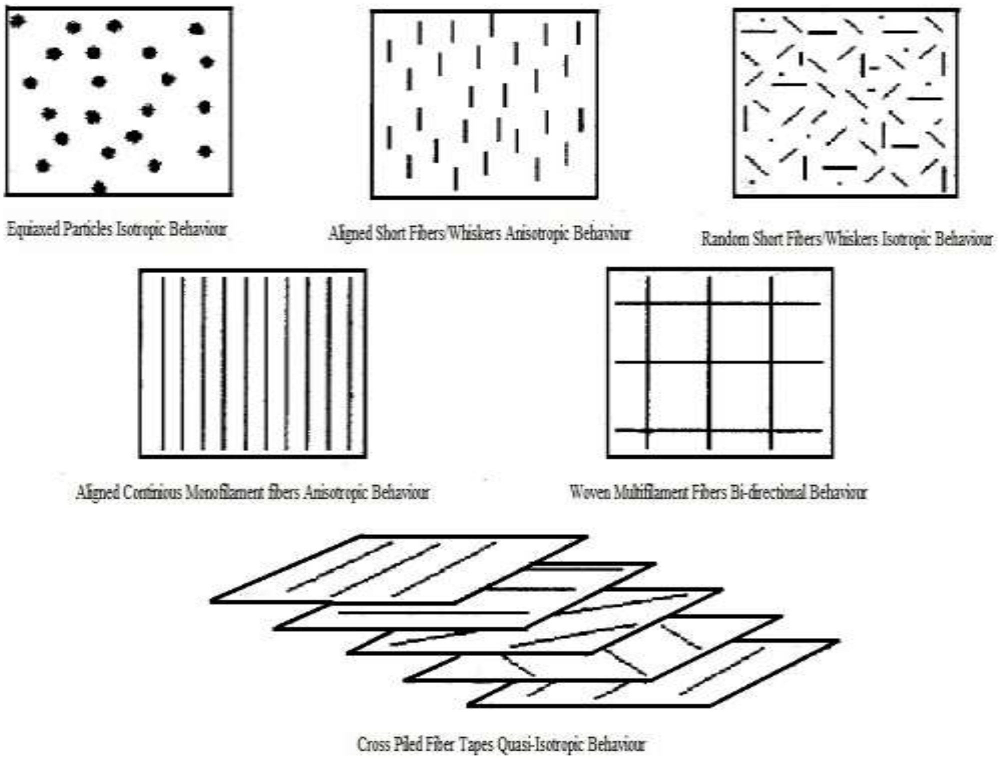


Figure 2.7: Effect of reinforcement orientation on mechanical properties.

One typical example of industrially used particulate reinforced aluminium MMC is silicon carbide incorporated in aluminium at low volume fraction (10-30 vol. %) being used for structural aluminium MMC.

B. Types of Reinforcements:

Ceramics have become the most suitable materials for MMC reinforcements due to their special characteristics not to be found in traditional metal alloys. Silicon carbide (SiC), alumina (Al_2O_3) and boron carbide (B_4C) are most commonly used ceramics for aluminium MMCs. silicon carbide reinforcement can be used in the form of fibre, whisker or particulate; however, the last two are more popular. Alumina is preferably used in the fibre or whisker form, but its particulate or microsphere forms are also available. Boron carbide is normally used in particulate from is used. Among these different types of ceramics, both SiC and Al_2O_3 have been used as the reinforcing materials for most of the MMCs used in past research.

(a) Al_2O_3 reinforced Aluminium MMCs:

Aluminium MMCs may be reinforced with Al_2O_3 in the form of fibers, whiskers or even particulate Al_2O_3 microsphere. The unique Al_2O_3 microsphere-reinforced MMC has been developed by Comalco Aluminium Limited, Australia, using a proprietary liquid metallurgy technique. Such MMCs have displayed superior properties viz tensile strength, ductility, fatigue strength and modulus of elasticity using Al_2O_3 reinforcement at 20 vol. % [76-78].

(b) Graphite reinforced Aluminium MMCs:

The use of graphite reinforcement in a metal matrix has a potential to create a material with a high thermal conductivity, excellent mechanical properties and attractive damping behaviour at elevated temperatures [79]. However, lack of wettability between aluminium and the reinforcement, and susceptibility to oxidation of graphite [80, 81] lead to manufacturing difficulties and cavitations of the material at high temperatures.

(c) SiC reinforced Aluminium MMCs:

Particles of silicon carbide possess hardness value of approximately 2700 HV and are commonly used as grinding abrasives. SiC becomes more attractive as a reinforcing material due to its substantially lower cost. SiC particles in an aluminium matrix results in a composite that has better mechanical and physical properties than the unreinforced aluminium. Its strength, thermal conductivity, abrasion resistance, creep resistance and dimensional stability are all superior to those of the base metal [82]. The amount of SiC particulate added into the aluminium can be varied from l0 to 50 vol. %, depending on what the application demands.

The most commonly used volume fraction is between l0 to 30 vol. %. There is a wide range of matrices and reinforcements that can be combined to produce PMMCs. Of these, the aluminium based matrix SiC reinforced composites have found extensive applications in the aerospace, military and civil industries as they offer a good combination of high strength, high elastic modulus, increased wear and fatigue resistance [83, 84]. Addition of SiC particles should theoritically increase the tensile strength and elastic modulus of the matrix, but on the other hand it will bring down the ductility [15, 85]. There have been several attempts by researchers to produce high quality Al- SiC_p composites following different fabrication routes.

2.7.5. Fabrication Processes:

Fabrication processes result fundamental about the MMCs, to determinate their mechanical and physical properties. Since the technology that concerns them is relatively young, the various manufacturing processes, especially as regards their history, are often customized by individual manufacturers to suit the specific necessity [86]. In general, the most common manufacturing MMC technologies are divided primarily into two main parts: the primary and the secondary, sometimes following from the “preprocessing” phases. About this latter, they are all steps, which precede primary processing (surface treatment of ingredient materials, or preform fabrication for infiltration processing).

The primary processing is the production of composites by combining ingredient materials (powdered metal and loose ceramic particles, or molten metal and fiber performs), but not necessarily to final shape or final microstructure.

The secondary processing follows primary processing, and its aim is to alter the shape or microstructure of the material (shape casting, forging, extrusion, heat-treatment, machining). Secondary processing may change the constituents (phases, shape) of the composite.

The choice of production processes, both primary and secondary, is very much determined by the type of reinforcement and the matrix, their mechanical and thermal properties, the shape, length and fibers packing from them than the matrix.

A basic classification, about the technological methods for MMCs, takes account of the state where the constituents during the primary cycle of production:

A. Liquid metal processing.
B. Vapour state processing.
C. Plasma/spray deposition.
D. In situ processing.
E. Ingot metallurgy (IM).
F. Synthesis by chemical reaction.
G. Solid state processing.

A schematic overview of the situation is well represented in Figure 2.8.

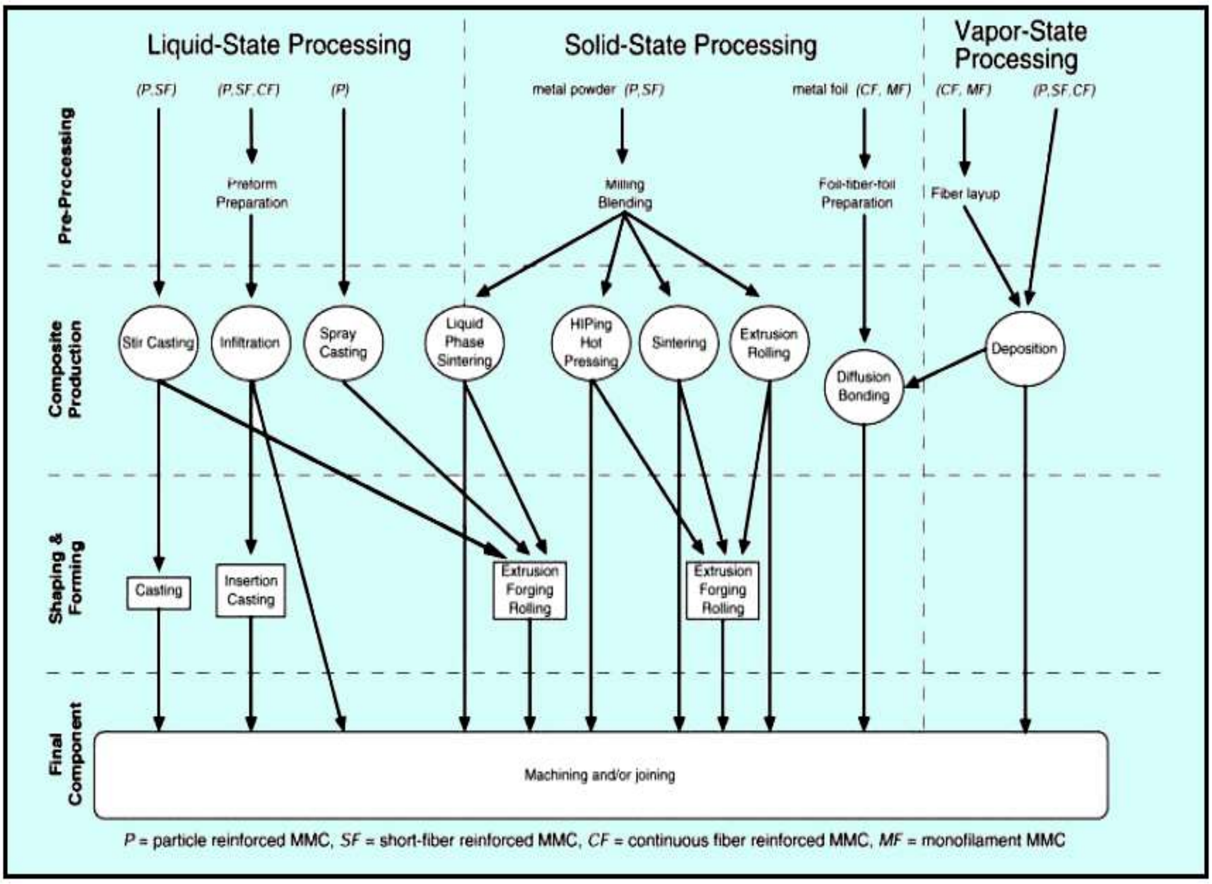


Figure 2.8: Schematic overview of the production processes of MMCs.

A. Liquid Metal Processing:

Many times it is better to have the matrix in liquid form so as to facilitate the flow of filling the interstices and to cover completely the fibers, whatever form they may be. That is the reason because the foundry is one of the techniques more used and less expensive to produce metal matrix composites. In such a situation, using a molten bath, production can be increased considerably: it is not coincidence that it is widely used by industry to produce semi-finished products and for this there are several solutions [87, 88].

Generally in this case technologies are divided between those that provide for the incorporation of ceramic reinforcement into the liquid metal, and that where the cast is infiltrated into a pre-forms of the same reinforcement. The most common are shown below.

(a) Liquid Metal Infiltration:

This process can also be called fiber-tow infiltration. Fibers tows can be infiltrated by passing through a bath of molten metal. Usually the fibers must be coated in line to promote wetting. Once the infiltrated wires are produced, they must be assembled into a preform and given a secondary consolidation process to produce a component.

Secondary consolidation is generally accomplished through diffusion bonding or hot molding in the two-phase liquid and solid region. The fabrication process of MMC by vacuum metal infiltration used by Chapman *et al.* [89] is shown in Figure 2.9.

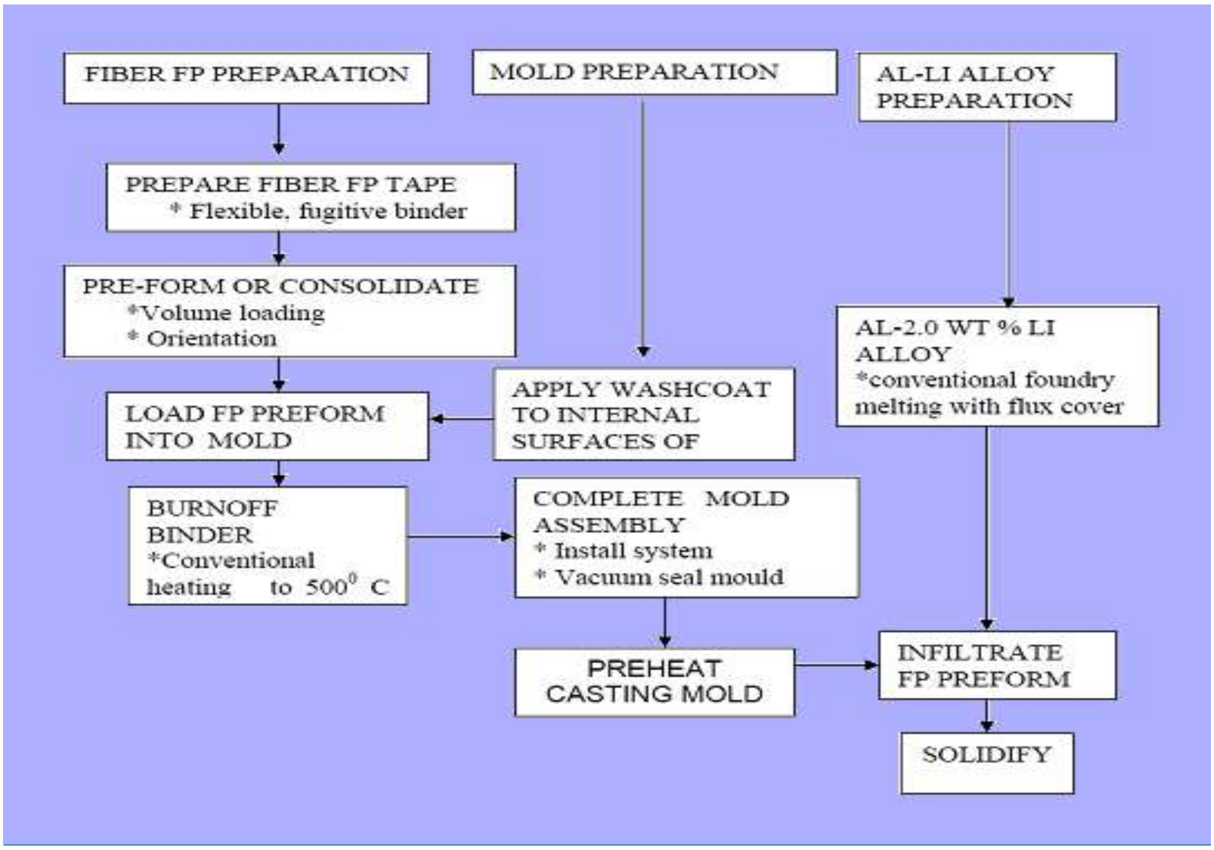


Figure 2.9: Flow chart for FP/Al plate casting.

(b) Squeeze Casting:

Squeeze casting is an important solidification technique in the liquid phase processes. This casting process is a combination of the casting and forging process. Molten metal is poured into a die. As the metal starts solidifying, the die is closed and pressure (50 to 100 MPa) is applied till the material fully solidifies [89]**.** The fabrication process of MMC by squeeze casting is shown in Figure 2.10.

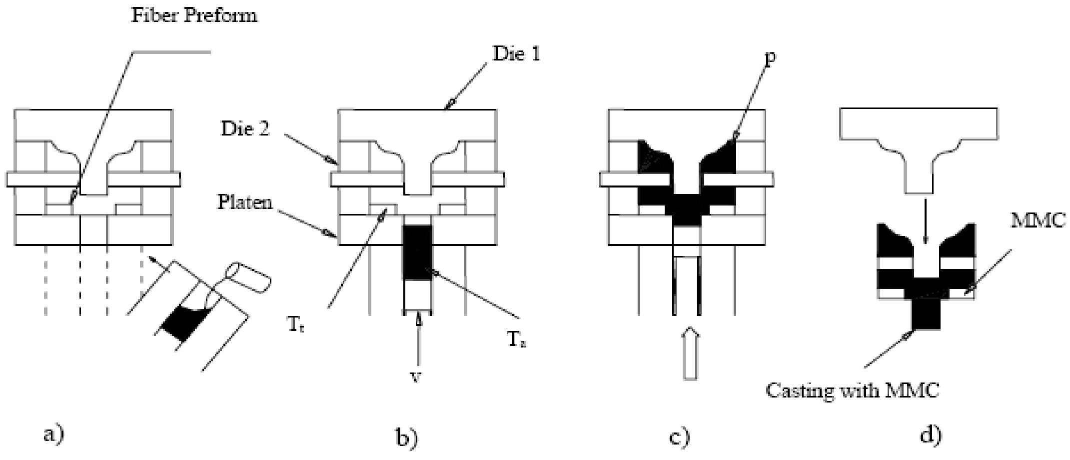


Figure 2.10: Sequences of the Squeeze casting process with a vertical machine.

(a) Pouring, (b) Casting, (c) Squeezing and (d) Ejecting.

(c) Spray Co-Deposition Method:

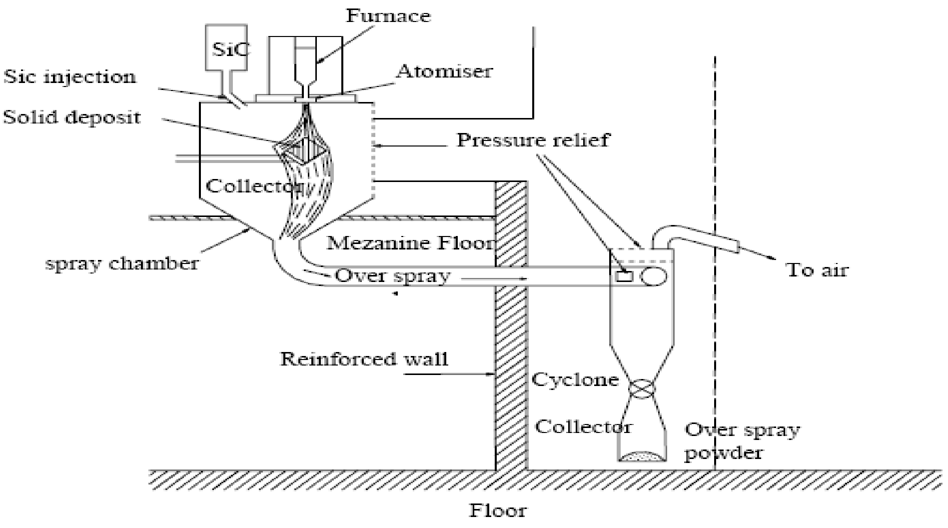


Figure 2.11: Schematic diagram of spray deposition equipment.

Spray-deposition method is an economical method of producing a particulate composite. A schematic of the Alcan spray deposition process is shown in Figure 2.11 [90-93].

(d) Stir Casting:

Stir-casting techniques shown in Figure 2.12 [94] are currently the simplest and most commercial method of production of MMCs. This approach involves mechanical mixing of the reinforcement particulate into a molten metal bath and transferred the mixture directly to a shaped mould prior to complete solidification.

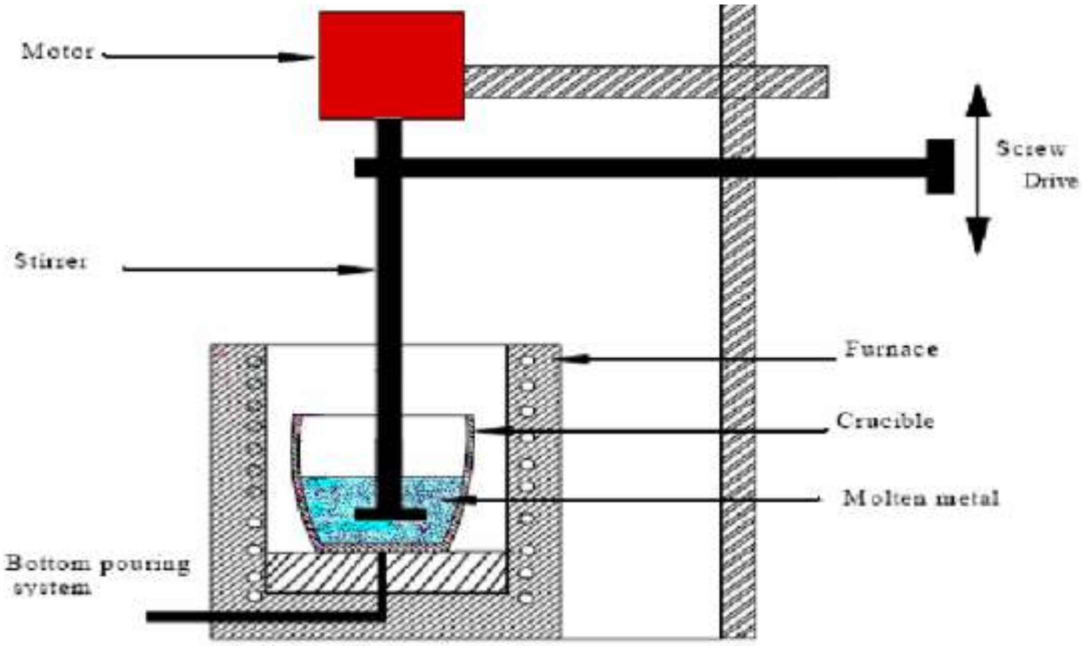


Figure 2.12: MMC produced by casting route through Stir Casting method.

(e) Compo Casting:

Other than P/M, thermal spraying, diffusion bonding and high-pressure squeeze casting, this is the most economical method of fabricating a composite with discontinuous fibers (chopped fiber, whisker and particulate) [94]. A schematic of the compo casting equipment used to fabricate the composites is shown in Figure 2.13.

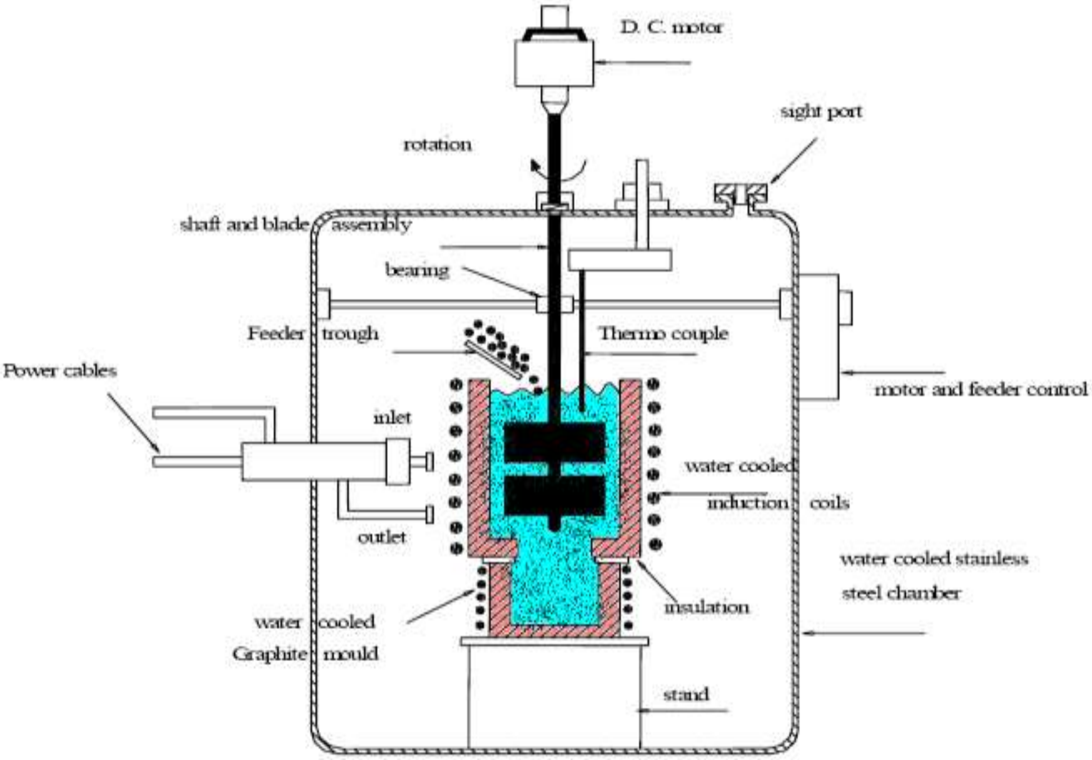


Figure 2.13: Compo casting method (mixing fibers or Particulates with metal).

B. Vapour State Processing:

In this process composites are formed by deposition on the reinforcement of successive layers of matrix. In particular, the PVD (Physical Vapour Deposition) technique is used about the formation of the external fiber coatings whose purpose is to consolidate them than the matrix [94].

Physical Vapour Deposition (PVD):

Many PVD processes used to produce MMC, all generally very slow (the typical deposition are of 5-10 mm/min). There is a continuous passage of fibers through a region in which the metal must be deposited at a vapour pressure of relatively high and where the condensation successes in order to produce a thin coating on the fibers [94].

PVD processes can be divided into two main categories:

(i) Vaporization and deposition techniques using electron beam (EBED):

This process requires the use of a gun which produces the high energy electron beam (EB), which vaporizes the material matrix and produces the metal vapour to condense on the fibers.

(ii) “Sputtering” techniques:

By the “sputtering” techniques instead a piece of coating is bombarded with ions of a processing gas (such as Argon), which breaks off atoms from the work piece, sketching on the fiber.

C. Plasma/Spray Deposition Processing:

The methods spraying of manufacturing are based on the generation of a mixture of metal matrix droplets with ceramic particle, which are then sprayed on a removable substrate. The advantages of such process are mainly about the rapid solidification of the matrix, which involves the addition of a reinforcing phase and a reduction in reaction time between reinforcement and matrix [94]. Moreover, the step of mixing and degassing processes typical of powder metallurgy are virtually gone out.

(a) Spray Forming Process:

In the forming process by spraying drops of molten metal is sprayed with particles of reinforcing phase and collected on an underlying support on which the composite is made solidify [95]. The Figure 2.14 shows the schematic diagram of spray forming technology for metal matrix composites.

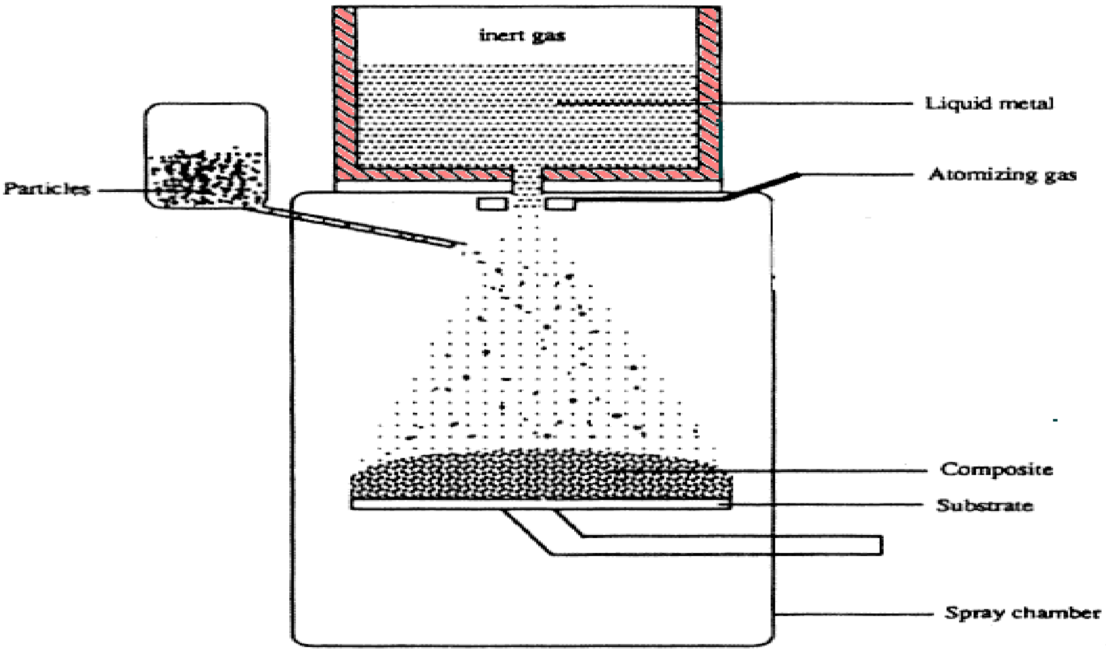


Figure 2.14: Spray forming technology for MMCs.

(b) Low Pressure Plasma Deposition (LPF):

Alloy powder and reinforcement are fed into a low pressure plasma. In the plasma, the matrix is heated above its melting point and accelerated by fast moving plasma gasses. These droplets are then projected on a substrate, together with the reinforcement particles [95]. The production of particle composites by plasma spray facility has shown in Figure 2.15.

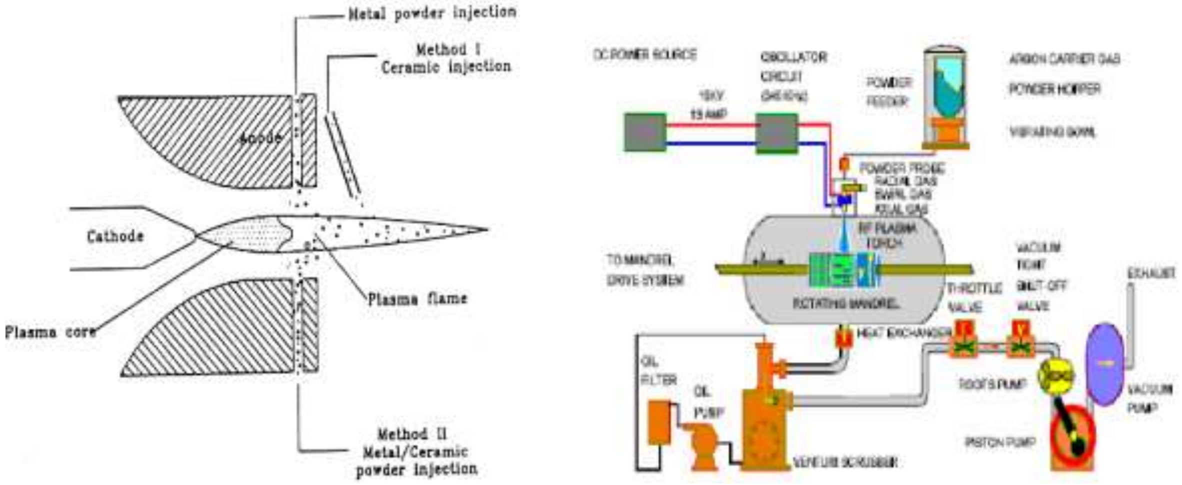


Figure 2.15: Plasma spray facility for the production of particle composites.

(c) Electric Spray Arc Forming:

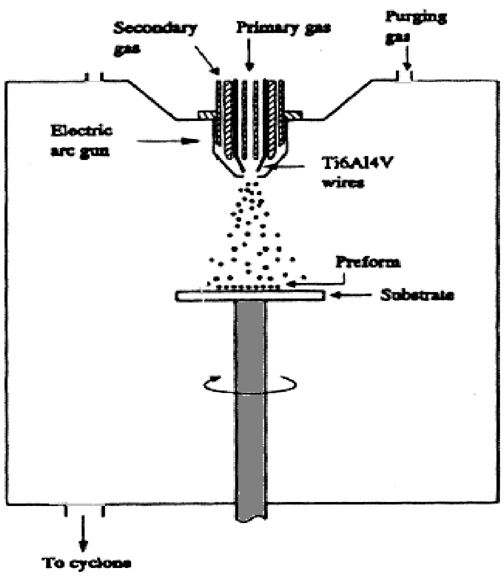


Figure 2.16: Basic function of electric arc spray forming.

In this case is generated by an electric arc by the use of a potential difference between two filaments consisting of metal matrix composite. Then the tip of the wires are melted continuously and are atomized by the one or more inert gas jets and then it is directed to a ceramic fiber pre-forms (Figure 2.16) [95].

D. “In Situ” Production:

The in situ production route of metal matrix composites is highly interesting because it avoids the need for intermediate formation of the reinforcement. Indeed, in this process the reinforcements are formed by reaction in situ in the metal matrix in a single step [96]. A further advantage is that the interfaces between the reinforcement and the matrix are very clean, enabling better wetting and bonding between them and the matrix (no gas adsorption, no oxidation, and no other detrimental interface reactions).ion, costs are reduced, as the handling of the fine particle reinforcement phases are eliminated.

E. Ingot Metallurgy (IM):

This production technique (Figure 2.17) consists of two consequential steps: the first consists of a dispersion process, during which the element that forms the reinforcement ceramic is incorporated, at random and not in default, in the molten metal matrix. Usually the system is mixed to facilitate the dispersion of particles [96].

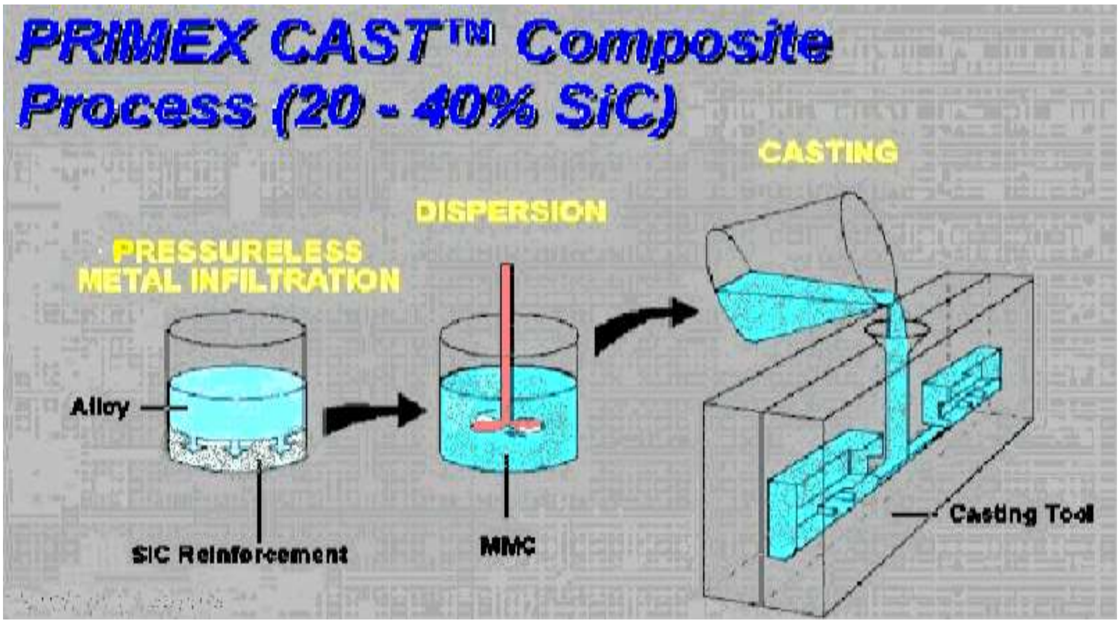


Figure 2.17: IM (Ingot Metallurgy) technology.

F. Synthesis by Chemical Reaction:

In this case composites are obtained by in situ reaction between a liquid and other phase, as a gas or solid, the basic mechanisms are the same chemical reaction (Figure 2.18) [96].

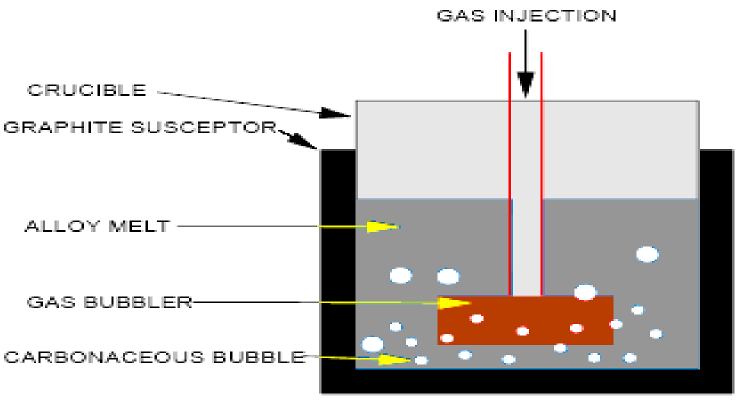


Figure 2.18: Technology of synthesis of MMC by chemical reaction.

One of the most important production technology that is based on the principle of synthesis through chemical reactions regard the process for "Exothermic Dispersion" (XD). The process, patented by Martin Marietta Corporation, provides high temperatures heating of various mixtures so as to activate an exothermic reaction, that diffuse by independent and very fast way, allowing to create very fine dispersion of some pottery independent and very fast way, allowing to create very fine dispersion of some pottery stable phases.

G. Solid State Processing:

About the solid state production reinforcement is embedded in the matrix through diffusion phenomena produced at high pressures and high temperatures. In this case it appears crucial monitoring of the diffusion phenomena to avoid the growth of undesirable phases or compounds species on interfaces. That is why the various steps of processing are usually preceded by a "pre-processing" having the purpose of preparing the surfaces before they are subject to the concerned bonds. Moreover, about the primary process a method is that to reduce the time of this diffusions for example carrying out extrusion of a sandwich fiber/matrix. In these cases a hot-rolling can be also used, but the matrix deformation should be limited to minimize the reinforcement movement and thus the formation of voids. The high temperatures are used to facilitate the flow of reinforcement in the matrix, but the risk of harmful chemical attack must be considered on the fibers, for which generally solid-state processes should be made in a vacuum or inert atmosphere [96].

(a) Diffusion Bonding:

This method is normally used to manufacture fiber reinforced MMC with sheets or foils of matrix material. One of these techniques is such that the “foil-fiber-foil” where alternating sheets of reinforcement (usually a long fiber) and matrix are stacked one over the other, and then be united together, shown in Figure 2.19.

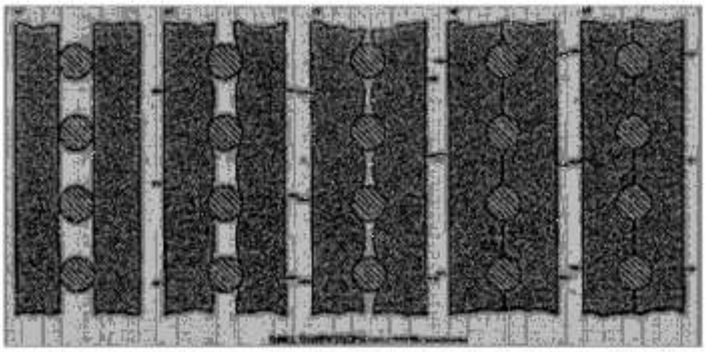


Figure 2.19: Diffusion bonding process and the consolidation steps Foil/Fiber/Foil.

The consolidation of the foil together and with the fiber, with the penetration of the metal among the interlacing of these, happens through a process of sintering, which is implemented by the two main phenomena. Figure 2.20. shows the different steps in fabricating MMC by diffusion bonding [96].

An alternative procedure to produce the composite tape is to spray the matrix directly on fibers using plasma, when they are on the cylinder fasteners. This avoids the use of polymer binders and composite sheets are ready for the step of junction and compaction (Figure 2.21.). Diffusion forming is really a very good method to produce composite with high mechanical properties. The problem is that these processes require high intensity of energy (high pressures and high temperatures). It appears one of the most technological processes used about MMCs, due to the possibility to produce composite for high-strength applications in the medium/high temperatures.

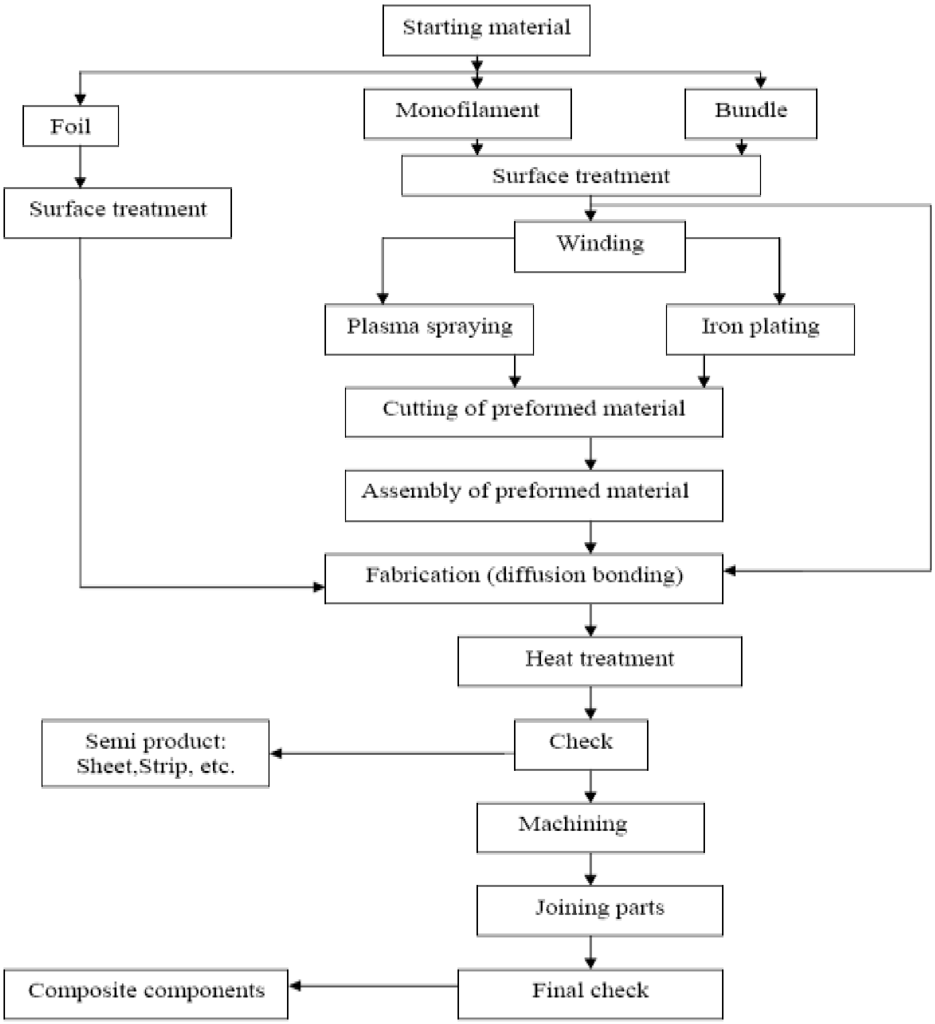


Figure 2.20: Flow chart for composite fabrication by diffusion bonding.

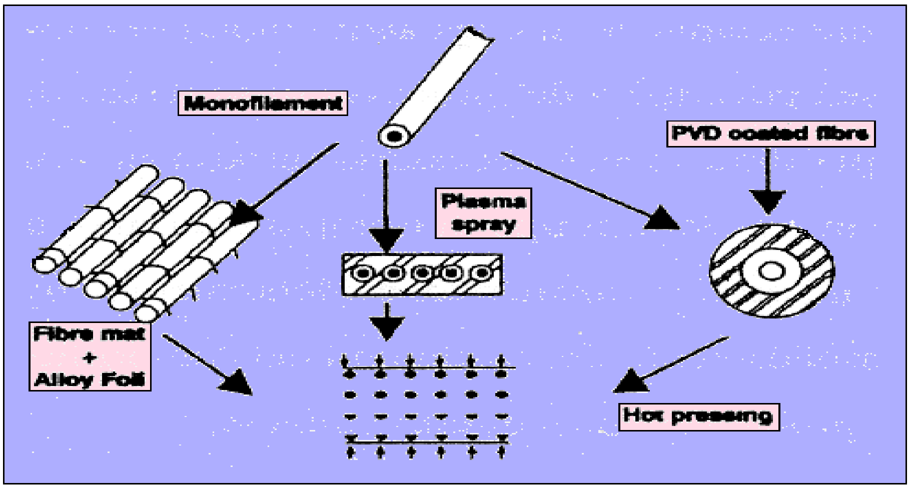


Figure 2.21: Main processes of fibers arrangement.

(b) Powder Metallurgy Process:

The pressing of metal powders to form solid objects of a specific shape is not a recent development and was known to have been used by ancient civilizations [97]. The types of aluminium based powders available fall into two categories elemental and pre-alloyed. Elemental aluminium can be mixed with other metals e. g. copper, to produce an alloy during processing. The powder metallurgy technique shown in Figure 2.22 is the most commonly used method for the preparation of discontinuous reinforced MMCs [98].Powder Metallurgy (P/M) is a highly developed method of manufacturing reliable ferrous and non-ferrous products by mixing elemental or alloy powders, compacting the mixture in a die; the resultant shapes are then heated or “sintered” in a controlled-atmosphere furnace to bond the particles metallurgically. Powder Metallurgy is a continually and rapidly evolving technology embracing most metallic and alloy materials, and a wide variety of shapes.

P/M is used in a wide variety of applications: tungsten or molybdenum filaments in lighting elements, sprockets and pulleys for automotive engines, super-alloy turbine disks used in civil and military aero engines. New commercial aircraft engines contain between 680-2000 kg of P/M per engine ranging from Hard metal and diamond-bonded cutting tools, porous metals and filters, friction linings for clutches and brakes, sintered and bonded powder magnets, and lightweight metallic foams. Powder Metallurgy as an alternative production process is competitive against the conventional process because of its economic advantages and properties/performance advantages.

P/M typically uses more than 97% of the starting raw material in the finished part suited to high volume components production requirements. The parts produced by this process have long-term performance reliability in critical applications. Successful production by powder metallurgy depends on proper selection and control of the following principal steps (Figure 2.23):

(i) Selection of metal powders of suitable degree of fineness.

(ii) Selection of powder characteristics like, purity, particle size & shape, uniform size distribution and the surface texture of the particle.

(iii) Design of compacting tools and dies.

(iv) Selection of compaction load.

(v) Weighing and mixing of the necessary powders (and lubricant) to obtain the composition.

Pressing the powder (mixture) in a suitable mold (of required size and shape) to cause cohesion to occur between the powder particles. Sintering the compacted mass at a temperature high enough to cause diffusion and inter granular crystal growth to occur. Sometimes before sintering pre-sintering is done at a moderate temperature (less than sintering temperature) to develop additional green strength and drives off mixing lubricants and/or moisture. Finishing and selecting the final product for additional one or more heat treatments.

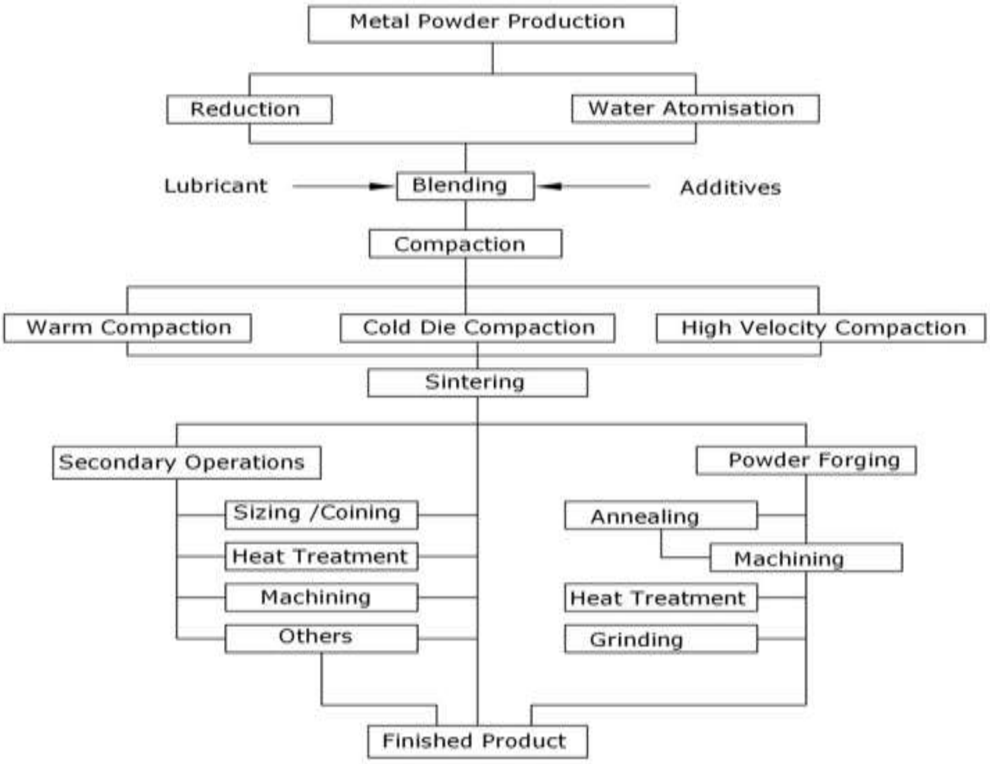


Figure 2.22: Basic steps of the powder metallurgy process.

Particle size in powder metallurgy is of great concern and that has been found to significantly affect the final distribution is the size of the reinforcement particles. It affects compaction, permeability, flow and mixing characteristics and mechanical bonding. The properties of powder metallurgy products are highly dependent on the characteristics of the metal (or material) powders that are used. Some important properties and characteristics include chemistry and purity, particle size, size distribution, particle shape, and the surface texture of the particles. Several process can be used to produce powder material, with each imparting distinct properties and characteristics to the powder and hence to the final product [44].

The particle size of powders falls into a range of 1 to 100μ ($1\mu=10^{-6}$ metre), with the range of 10 to 20μm (micron) being predominant.

The performance of metal powders during processing and the properties of powder metallurgy are highly dependent upon the characteristics of metal powders are used. Powder flow ability is the rate at which a metal powder will flow under gravity. The relative density of the finished product depends on powder size distribution, shape and flow ability. Final material properties also hampers due to powder impurities. Because of the high specific surface of a powder, a large amount of the material is directly exposed to the surroundings during different stages of powder production and processing [64].

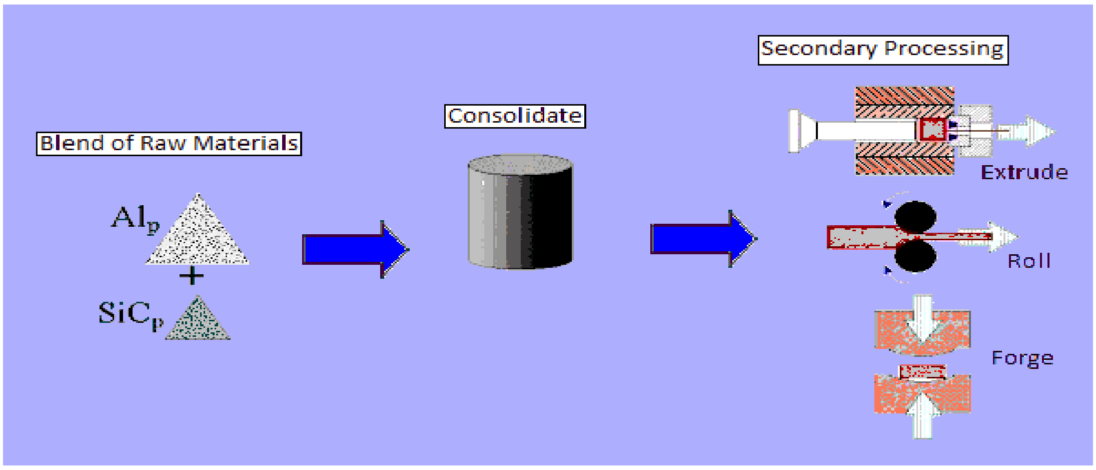


Figure 2.23: Illustration of key steps in a process of production through MMC powder metallurgy.

Powder Mixing and Blending:

The blending (or mixing) of the metal matrix powder and the ceramic reinforcement particulates is an important stage in the preparation of MMCs. In the most cases a single powder will not possess all of the characteristics desired in a given process and product. Most likely, the starting material will be a mixture of various grades or sizes of powder, or powders of composition, with addition of lubricants or binders. The final product chemistry is often obtained by combining pure metal or non-metal powders, rather than using pre-alloyed material [65]. Sufficient diffusion must then occur during the sintering operation to produce a uniform chemistry and structure in the final product. Binder is used to increase the green strength by means of adhesion whereas lubricant improves the flow characteristics. Lubricants such as graphite serve as a lubricant during compacting and improve the flow ability, compressibility at the expense of reduced green strength.It controls the distribution of the reinforcing particles and the green density of the pressed compacts, which, in turn, affects the mechanical properties of the MMC. Many variables have been identified in the powder mixing process [99,100], some which are listed below: -

a) Type of mixer.

b) Geometry of mixer.

c) Constructional material of mixer.

d) Volume of powder before mixing.

e) Volume ratio of component powders.

f) Volume of mixer.

g) Inner surface area of mixer.

h) Surface finish of mixer.

i) Volume of powder after mixing.

j) Characteristics of powders.

k) Rotational speed of mixer.

l) Mixing temperature.

m) Humidity when mixing in air.

n) Mixing time.

o) Mixing medium (gas or liquid).

As the volume of powder for this research are small and to reduce wastage a small scale mixing technique is necessary. Powders must be dried and de agglomerated. The powder size, shape and density all have a part to play in the distribution of the powders. Generally, the larger the particles the better the distribution, larger particles rise to the top with the smaller particles concentrating at the bottom, spherical particles are more easily mixed than irregular shaped particles and heavier particles segregate on the top and lighter particles sink to the bottom [101-102].

Role of Lubricants and Additives:

Prior to compactions, the powders are mixed with lubricants that lower the friction between the powder particles during compaction and between the compact and the die walls, improving compactibility and drastically reducing die wear. Lubricants used are stearates, stearic acid, polytetrafluorethylene, polyvinyl fluoride, and even waxes. The latter are used for the production of P/M steel structural parts, although for complex shapes, Zn-stearate containing lubricants are still necessary. The undesirable residue after decomposition of a lubricant is ‘ash’. The stearates have the highest amount of ash (zinc stearate ~ 14%) and waxes have the lowest (paraffin wax ~ 1%). The addition of a lubricant should be as small as possible, typically 0.5 to 0.8 wt. % being added.

Presence of lubricants and binders are not desirable in the final product and they are removed (volatilized or burned off) in the early stage of sintering, living holes that are reduced in size. Blending or mixing operations can be done either dry or wet, where water or other solvent is used to improve mixing, reduce dusting and lesser explosion hazards [66-71]. Currently, trials with direct spray lubrication of the compacting die (die wall lubrication) are performed which enables significant reduction of the amount of admixed lubricant. Amount of lubricants or additives added depends on the shape of the compact. Complex shape required large amount lubricant/ additives.

Compacting:

Compacting is one of the most critical steps in the P/M process. Cold pressing of the powders usually follows the blending stage. This cold compaction has four major functions [97]:

(1) To create the desired shape;

(2) The control of dimensions;

(3) Control of porosity;

(4) To impart adequate strength for handling.

Two common methods of cold compaction are single and double unidirectional pressing. Powder pressing to form a green billet can take many forms, some of which are listed below [100].

a. Single action unidirectional pressing.

b. Double action unidirectional pressing.

c. Isostatic pressing.

d. Powder rolling.

e. Stepwise pressing.

f. Direct powder extrusion.

g. Canned powder extrusion.

h. Powder swaging.

i. Explosive compacting.

j. Powder forging.

Loose powder is compressed and densified into a shape known as a green compact, usually at room temperature. The main objective for compaction of alloyed powders is to reach the highest possible density with the lowest compaction force and to attain the green strength required for safe handling of the green compacts. The green density depends on the compacting pressure as well as on the physical and technological properties of base iron and / or other powder particles, type and amount of lubricant, the friction between the die wall and the powder. Green strength is dependent on the morphology (specific surface area) of the powder particles. Spherical particles with a relatively low specific surface area results lower green strength. High product density and the uniformity of that density throughout the compact are generally desired characteristics. In addition, the compact should possess sufficient green strength till sintering [87]. In production of structural parts, standard cold pressing, repressing (double pressing), and warm compaction methods are used and new methods are permanently being developed for increasing the density of parts at the lowest pressure.

Compacting parameters are controlled by the metal powder particle properties, mainly by hardness and particle shape and particle size distribution. In industrial practice, the compacting pressures for compacting powder mixes applied were in the range of 20-95 Ton, which has maintained for 5 min to achieve green compacts for all composition of SiC_p composites. A rigid tool set is required, usually consisting of a hard metal die and cold work tool steel punches and core rods (Figure 2.24). Ejection of the green compact from the die is also a critical process. The powder mix properties, compacting pressure employed and the coefficient of friction between the powder and the die affect the ejection force. Repressing (or double pressing) is a cold die compaction operation used for increasing the density of pre-sintered parts (by 5 to 20%) before final sintering in a double pressing and sintering technique.

Compaction pressure and technique also indirectly affects the mechanical properties of sintered components through the resulting density/porosity, which is regarded as a main feature of a P/M part for deteriorating the mechanical properties.

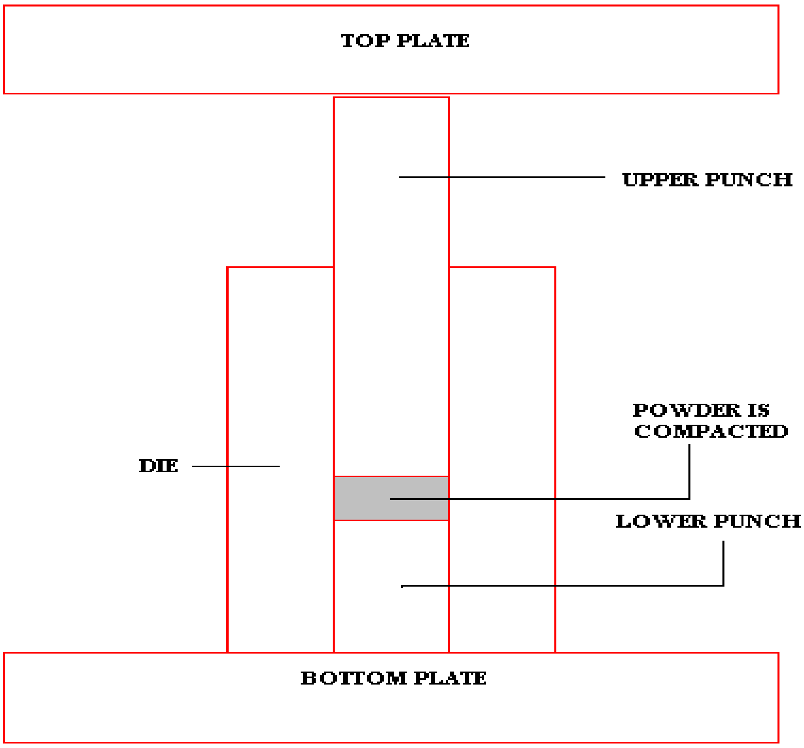


Figure 2.24: Compaction Process.

During compaction a lubricant is usually used, this may be mixed with the powder or applied to the walls of the die. The lubricant is necessary to reduce friction between the powder and the tooling surfaces; this permits higher effective pressures to be transmitted to the powder and thereby results in a higher green density being obtained. The pressure at which the powders are pressed has a large effect on the green density of the material. For aluminium and aluminium alloys relatively low pressures are needed to form a compact green billet as only small plastic deformation of the powder is necessary. Therefore any compacting pressure above the yield strength of the metal will form a coherent compact.

Sintering:

Sintering is a very important active thermal process during which, the dispersed metal body consisting of pressed powder particles, transforms into a metallurgically strong metal body of defined properties. In contrast to other sintered materials such as, hard metals and ceramics, sintered steel components shrink marginally during sintering, the porosity thus being present also in the as-sintered components.

Sintering is the consolidation of small particles (powders) into a solid mass. The driving force for the consolidation is the excess surface free energy in the system. The consolidation of the particles is a diffusion process carried out at high temperature (the temperature being dependent on the material being sintered). The atoms within each particle diffuse to points of contact between powders.

The steps involved for the basic theory of sintering are described below [97, 101].

Step 1. The initial loose powder contact. The loose particles (powder) are brought intimately together, usually by pressing.

Step 2. The powder is brought to a specified elevated temperature, usually below the melting point of the major constituent.

Step 3. Diffusion of atoms is increased at the elevated temperature and a sinter bond forms between powder particles. This initial sinter bond where each bond is separate from the other, (i. e. there is no impinging between bonds) is termed the initial neck.

Step 4. The neck continues to crow, closing interconnecting pore channels.

Step 5. The pores become more rounded in shape.

Step 6. The continued consolidation results in a reduction of pore size.

Step 7. Continued consolidation gives further pore size reduction and leads to densification of the material.

During sintering (Figure 2.25) the particle contacts increase in quality due to formation of bonding between the atoms or ions comparable with the bonding strength of a regular lattice. In pure, single components, sintering takes place completely in the solid state. In multi-components systems a liquid phase may be involved, but only to the extent that the solid skeleton guarantees the geometrical stability of the part. Sintering can be understood as a thermally activated material transport in a powder mass or a porous compact, decreasing the specific surface by growth of particle contracts, shrinkage of pore volume and change of pore geometry. Sintering may be accompanied by shrinkage, leading to densification, especially in fine powders; coarser powders may sinter with almost perfect dimensional stability [86-92], which results from diminution of the specific surface area due to growth (or even initiation) of particle contact areas and decrease in pore volume or the spherodization of the pores. The macroscopic manifestation of the sintering of a compact is its densification which is characterized as a length, volume and porosity decrease or as density increase. Sintering may also be declared as a complex and special heat treatment process requires a special set of sintering conditions, because driving forces and material transport mechanisms associated with the process in particular sintering stages are different. Various mechanisms are taking place in sintering including removal of lubricant / de-binding, reduction of surface oxides, evaporation and condensation and plastic deformation. In the final stage, sintering is responsible for the formation of a new microstructure of sintered products with defined physical and mechanical properties and dimensions.

The determining process variables involved in sintering of a loose powder and/or of a powder compact are temperature, time, and atmosphere. The cooling rate plays an important role in the final microstructure formation of the sintered materials, especially alloyed ones.

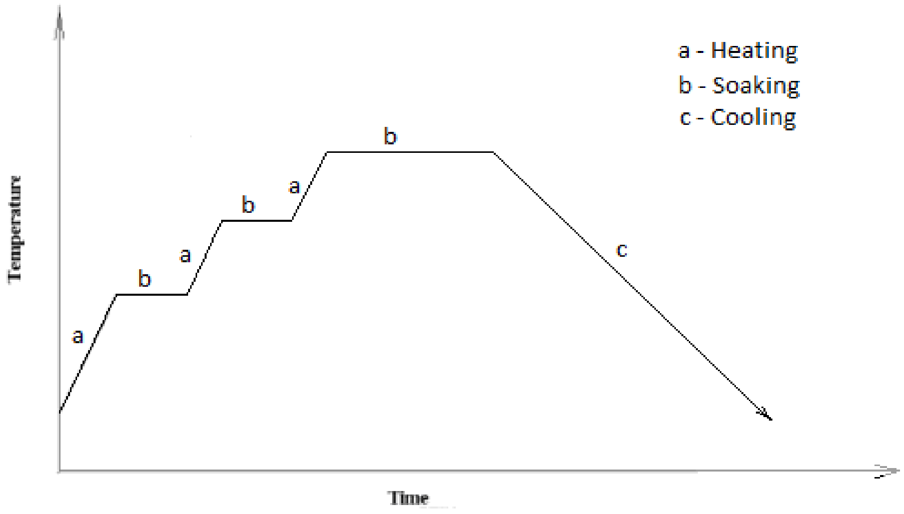


Figure 2.25: Graphical representation of Sintering Process.

Sintering Temperature:

The first stage of sintering and alloying of a metal powder material occur during heating. All sintering stages require an adequate temperature or successful homogeneous formation of a metal body. Main reduction-degassing processes take place during heating.

The common sintering temperature depends on the material systems and the preparation method, especially on alloying and on the required properties.

Sintering Time:

Sintering time is closely related to sintering temperature and varies between 30 and 120 minutes. Soaking period is very vital for successful homogeneous formation of a metal body and it also depends upon the size of the component .There is a trend to shorten sintering time and increase sintering temperature, due to economic reasons.

Sintering Atmosphere:

The sintering atmosphere is a factor that affects the course of all sintering stages involving delubricating, reduction and diffusion, thus strongly influencing the final properties. In general, the sintering atmosphere plays a more important role for the properties of a sintered material.

The sintering atmosphere should be reducing or inert (nitrogen. argon) the furnace atmosphere provides three functions:

- Preventing oxidation,
- Removal of the lubricant or binder,
- Reduction of surface oxide films to form metallic surface.

Some major problems encountered with the furnace atmosphere can be:

- Ineffective lubricant removal,
- Oxidation of open pore surfaces during cooling.
- Alloyed with an element with high oxygen affinity.

Vacuum sintering is used for production of composites through powder metallurgy process mainly under laboratory conditions in stationary furnaces.

Effect of Sintering:

Sintering affect the physical, microstructural and mechanical properties of the product. In particular the alloy element distribution, which is strongly affected by the sintering parameters, can have a pronounced impact on the machinability. The cooling rate of a sintered part in connection with sintering conditions has a significant effect on machinability due to change in hardness. The type of sintering atmosphere used for sintering a material must be considered in relation to the starting oxygen content of powder admixture and the final properties of the material, ultimately to the as-sintered oxygen content. The effect of sintering atmosphere on machinability of P/M products can be perceived in a different mode in some cases.

The sintering of aluminium has its own specific complexities. The formation of an oxide layer on the surface of aluminium particles creates a barrier between the aluminium particles and therefore aluminium is more difficult to sinter than materials, which have no inhibiting barrier coating [102, 103]. To facilitate sintering of aluminium and aluminium alloys the surface coating of the oxide layer must be disrupted to allow metal-to-metal contact. During the pressing stage the oxide layer can be broken to allow the aluminium metal of each particle to be in contact. Gutin states that in slightly oxidized aluminium powders, diffusion of aluminium atoms was found over the whole surface of the particles; however, in severely oxidized powders the diffusion was not uniform and took place only in regions free of oxide [104]. During the initial pressing of the powders, Gutin found cracks to appear in the oxide and the particles seized together in areas containing low oxide formation.

Other researchers have reported the beneficial effect of magnesium during the sintering of aluminium [105, 106]. Lumley states that trace amounts of magnesium has been found to "disrupt the passivating alumina layer through the formation of a spinel phase ". This disruption then allows solid slate sintering and the wetting of the aluminium metal. Kondoh states that the presence of magnesium has a "de-oxidizing effect ". This chemical change of the oxide was found to occur at temperatures above 397°C with holes observed in the oxide layer.

Advantages of Powder Metallurgy:

The dimensional accuracy and surface finish of P/M products are such that subsequent machining operations can be totally eliminated for many applications. Wide variations in compositions are possible. Parts of very high purity can readily be produced. Metals and ceramics can be intimately mixed. In most cases the chemical homogeneity of the product exceeds that of all competing techniques.

Complex shapes can be produced, such as combination gears, cams, and internal keys. Porous parts can be produced that could not be made in any other way. Structure and properties can be controlled more closely than in other fabricating processes. Impossible parts (e.g., super-hard cutting tool bits) can be produced. The use of diamond in industry has been made possible mainly through powder metallurgy [93].

Wide variations in properties are available in this process. Products can range from low-density parts with controlled permeability to high-density parts with properties that equal or exceed those of equivalent wrought counterparts. All steps in the P/M process are simple and automated. Product uniformity, reproducibility and less labour skill results in high production rates. P/M is a cleaner and quieter process, which gives longer life to the components. Control of grain size, relatively much uniform structure and defect free (e.g., voids, blowholes, etc.) components are the characteristic of P/M products. Powder metallurgy is a manufacturing process in which no material is wasted.

Powder metallurgy is free from the limitations imposed by phase diagram. For example, it is difficult to produce copper-lead bearing alloys containing large amounts of lead, since the two metals are insoluble as liquids. However, mixed powders of copper and lead can be successfully shaped by powder metallurgy.

One of the advantages of the P/M route is a higher yield of usable material, and a finer uniform microstructure that confers improved mechanical properties. The P/M process has also allowed the development of new types of materials, Special high-duty alloys having microcrystalline or even amorphous (glass like) structures. The final consolidated product is characterized by very high strength, ductility, and thermal stability. Microcrystalline and amorphous structures can be achieved. Their use in aircraft structures would significantly reduce the weight and increase the payload. Whether by controlling porosity to develop the unique capability of self lubrication as used in ‘sealed for life’ systems or by optimizing the chemistry to provide improved longevity in wear parts P/M has a solution.

Limitations of Powder Metallurgy:

Molten metal can flow through complicated shapes due to its fluidity where powder metallurgy can’t be used. Relatively high die and tool cost is associated with the process. Because of the high pressures and severe abrasion involved in the process, the P/M dies must be made of expensive materials. The size of products (as compared to casting) is limited because of the large presses and expensive tools which would be required for compacting.

Precautions should be taken in handlings pyrolytic powders (e.g. Mg, Th, Zr) to prevent fires or explosions and toxic powders (e.g. U, Be, Th) to minimize health hazards [94,107]. Metal powder cost is quite high. On a unit weight basis, powdered metals are considerably more expensive than wrought or cast product.

2.8. Aluminium Matrix Composites (AMCs):

Aluminium is the most popular matrix for the metal matrix composites (MMCs). In AMCs one of the constituent is aluminium/aluminium alloy, which forms percolating network and is termed as matrix phase. The other constituent is embedded in this aluminium/aluminium alloy matrix and serves as reinforcement, which is usually non-metallic and commonly ceramic such as SiC_p and Al_2O_3. 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
- Improved abrasion and wear resistance
- Control of mass (especially in reciprocating applications)
- Improved damping capabilities.

These advantages can be quantified for better appreciation. For example, elastic modulus of pure aluminium can be enhanced from 70GPa to 240GPa by reinforcing with 60 vol. % continuous aluminium fiber. Similarly, it is possible to process Al-9% Si-20 vol. % SiC_p composites having wear resistance equivalent or better than that of grey cast iron. All these examples illustrate that it is possible to alter several technological properties of aluminium/aluminium alloy by more than two–three orders of magnitude by incorporating appropriate reinforcement in suitable volume fraction.

AMC material systems offer superior combination of properties (profile of properties) in such a manner that today no existing monolithic material can rival. Over the years, AMCs have been tried and used in numerous structural, non-structural and functional applications in different engineering sectors.

Driving force for the utilisation of AMCs in these sectors include performance, economic and environmental benefits. The key benefits of AMCs in transportation sector are lower fuel consumption, less noise and lower airborne emissions. With increasing stringent environmental regulations and emphasis on improved fuel economy, use of AMCs in transport sector will be inevitable and desirable in the coming years.

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 materials in engineering system to be wide spread, there is a compelling need to redesign the whole system to gain additional weight and volume savings. In fact according to the UK Advisory Council on Science and Technology, AMCs can be viewed either 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 utilising near-net shape forming and selective-reinforcement techniques AMCs can offer economically viable solutions for wide variety of commercial applications.

Recent success in commercial and military applications of AMCs is 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 applications of AMCs in everyday societal use. In this article, overview is given on the current state of art on aluminium matrix composites with regard to processing, microstructure, properties and applications of AMCs. Challenges and opportunities for the intense use of AMCs are also outlined [108,109].

Types of AMCs:

AMCs can be classified into four types depending on the type of reinforcement.

(a) Particle Reinforced AMCs (PAMCs).

(b) Whisker or Short Fiber Reinforced AMCs (SFAMCs).

(c) Continuous Fiber Reinforced AMCs (CFAMCs).

(d) Mono Filament Reinforced AMCs (MFAMCs).

Some of the salient features of these four types of AMCs are detailed below.

(a) Particle Reinforced Aluminium Matrix Composites (PAMCs):

These composites generally contain equiaxed ceramic reinforcements with an aspect ratio less than about 5. Ceramic reinforcements are generally oxides or carbides or borides (Al_2O_3 or SiC or TiB_2) and present in volume fraction less than 30% when used for structural and wear resistance applications. However, in electronic packaging applications reinforcement volume fraction could be as high as 70%. In general, PAMCs are manufactured either by solid state (P/M 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 fiber/continuous fiber reinforced AMCs but far superior compared to unreinforced aluminium alloys. These composites are isotropic in nature and can be subjected to a variety of secondary forming operations including extrusion, rolling and forging.

(b) Short Fiber and Whisker Reinforced Aluminium Matrix Composites (SFAMCs):

These contain reinforcements with an aspect ratio of greater than 5, but are not continuous. Short alumina fiber reinforced aluminium matrix composites is one of the first and most popular AMCs to be developed and used in pistons. These were produced by squeeze infiltration process. Whisker reinforced composites are produced by either by P/M processing or by infiltration route. Mechanical properties of whisker reinforced composites are superior compared to particle or short fiber reinforced composites. However, in the recent years usage of whiskers as reinforcements in AMCs is fading due to perceived health hazards and, hence of late commercial exploitation of whisker reinforced composites has been very limited. Short fiber reinforced AMCs display characteristics in between that of continuous fiber and particle reinforced AMCs.

(c) Continuous Fiber Reinforced Aluminium Matrix Composites (CFAMC):

Here, the reinforcements are in the form of continuous fibers (of alumina, SiC_p or carbon) with a diameter less than 20 µm. The fibers can either be parallel or pre woven, braided prior to the production of the composite. AMCs having fiber volume fraction up to

40% are produced by squeeze infiltration technique. More recently 3M^{Tm} corporation has developed 60 vol.% alumina fiber (continuous fiber) reinforced composite having a tensile strength and elastic stiffness of 1500 MPa and 240 GPa respectively. These composites are produced by pressure infiltration route.

Mono Filament Reinforced Aluminium Matrix Composites (MFAMCs):

Monofilaments are large diameter (100 to 150 µm) fibers, usually produced by Chemical Vapour Deposition (CVD) of either SiC or B into a core of carbon fiber or W wire. Bending flexibility of monofilaments is low compared to multifilament. Monofilament reinforced aluminium matrix composites are produced by diffusion bonding techniques, and is limited to super plastic forming aluminium alloy matrices. In CFAMCs and MFAMCs, the reinforcement is the principal load-bearing constituent, and role of the aluminium matrix is to bond the reinforcement and transfer and distribute load. These composites exhibit directionality. Low strength in the direction perpendicular to the fiber orientation is characteristic of CFAMCs and MFAMCs. In particle and whisker reinforced AMCs, the matrix are the major load-bearing constituent. The role of the reinforcement is to strengthen and stiffen the composite by preventing matrix deformation by mechanical restraint [110].

In addition to four types of AMCs described above, another variant of AMCs known as hybrid AMCs have been developed and are in use to some extent. Hybrid AMCs essentially contain more than one type of reinforcement for example, mixture of particle and whisker, or mixture of fiber and particle or mixture of hard and soft reinforcements. Aluminium matrix composite containing mixture of carbon fiber and alumina particles used in cylindrical liner applications is an example of hybrid composite.

Primary Processing of AMCs:

Primary processes for manufacturing of AMCs at industrial scale can be classified into two main groups.

(a) Solid state processes.

   (i) Powder blending and consolidation (P/M processing).

   (ii) Diffusion bonding.

(iii) Physical vapour deposition.

(b) Liquid state processes.

(i) Stir casting.

(ii) Infiltration process.

(iii) Spray deposition.

(iv) In-situ processing (reactive processing).

Powder blending followed by consolidation (P/M processing), diffusion bonding and physical 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 microstructural integrity desired. Table 2.3. provides feasibility of various primary processes for manufacturing different types of AMCs [110,111].

Table 2.3

Primary processing routes of AMCs

Types of AMCs	**Blending And consolidation**	**Diffusion Bonding**	**Vapour deposition and consolidation**	**Stir casting/ slurry casting**	**Infiltration process**	**Spray deposition and consolidation**	***In- situ* reactive process**
Continuous Fiber-reinforced AMCs (CFAMCs)	Not in Practice	Not in Practice	In use	Not in practice	In used	Not in practice	-----
Mono filament-particle Reinforced AMCs (MFAMCs)	Not in Practice	In use	In use	Not in Practice	Generally	In use	Not in use Practice
Particle-reinforced AMCs(PAMCs)	In use	Not in Practice	In use	In use	In use	In use	In use
Whicker or Short fiber Practice Reinforced AMCs(SAMCs)	In use	Not in Practice	In use	Generally not used	Generally not used	In use	Not in use

2.9. Characteristics of Aluminium Metal Matrix Composites:

Some of the salient features about the characteristics of AMCs are detailed below.

2.9.1. Density of Aluminium Metal Matrix Composites:

Reinforcement of MMC also provides some outstanding advantages such as high material utilization, more refined microstructure that provides superior material properties as well as greater microstructure homogeneity. Among others, however, the powder metallurgy (P/M) method has known as a very promising route, which is most attractive due to several reasons. Firstly, in P/M technique micro structural control of the phases is possible. Secondly, the lower temperatures employed during the process accounts for the strict control of interphase kinetics. Poor distribution of reinforcement degrades the composites in terms of its physical and mechanical properties and negates the attractiveness of reinforcement additions [111-115]. Composites combine the characteristics of aluminium and aluminium alloys matrix (low density in comparison with ferrous materials, good corrosion resistance and machinability) with the characteristics of ceramic particles (e.g. SiC_p, TiC_p, B_4C_p, Al_2O_3, SiO_2, etc.) which improve in special mechanical, tribological and thermal expansion characteristics [116-119]. As sintering is a predominant factor for controlling the density of the P/M products, variation of wt% of reinforcing materials, compacting pressure, sintering time, temperature largely affects the density of the P/M components [119-123]. The sintered parts of high density can be steam treated to close the surface pores. It is also observed that the green density and sintered density is a function of powder type and compacting pressure.

2.9.2. Hardness of Aluminium Metal Matrix Composites:

Both theory and experimental work by several authors indicated that the degree of strengthening imparted by the reinforcement increases with the matrix work-hardening rate.

The hardness and yield strength of the composite is changed by the heat treatment procedures. Composites aged to peak hardness have a higher volume fraction of strong precipitates, which act as an obstacle to dislocation movement. This mechanism results in an increase in the dynamic shear stress of the composite during metal cutting. Cutting tests were carried out on silicon carbide particulate reinforced aluminium composites subjected to different heat treatment conditions to find a correlation between matrix hardness and machinability of cast aluminium based composites [124].

The results of the experimentation showed that naturally aged composites were more abrasive and higher tool wear was developed than the artificially aged samples. However, a similar study conducted on 6061 composite showed a reverse trend. The cutting tool wear is highly dependent on the work-hardening properties of the matrix material [124]. The results of investigations carried out to reveal the thermal softening characteristics of the matrix at higher feed rates were a reason for improved tool life. It is mentioned that the increase in feed rates improves the heat conduction from the cutting zone onto the work piece, thus softening the matrix material and at the higher feed rates there is a reduction in contact between the hard ceramic particles and the cutting tool edge and, hence, lower tool wear [125,126].

2.9.3. Forgeability of Aluminium Metal Matrix Composites:

The use of aluminium-based particulate reinforced MMCs for automotive components and aircraft structures have been shown to be highly advantageous over their unreinforced counterparts due to their high specific stiffness. However, the application of these materials is often limited by their poor ductility which is generally associated with inhomogeneous distribution of the reinforcement particles [127,128]. Other causes of poor ductility are oxide/impurity contamination in powder metallurgy (P/M) [129,130] and the formation of large brittle intermetallic compounds as a result of reactions between ceramic reinforcement particles and molten metal in casting. The co-spray deposition process has been reported to be capable of avoiding these problems and thereby producing better mechanical properties [131-135]. However, previous work showed that co-sprayed MMCs have very limited ductility also [136]. Furthermore, the strength of these materials is below those of their unreinforced counterparts.

This is largely due to highly concentrated bands of SiC particles occurring at recurrent intervals which form a disposition known as tree ring structure (TRS) [137]. Also, it was found that forgeability is greatly affected by the TRS which can limit forging as an effective route for manufacturing discrete engineering components. It was shown that the distribution of reinforcement particles in cast and P/M materials can be improved by mechanical working, resulting in an increase in tensile ductility. On other hand redistribution effect of extrusion on forgeability was insignificant [138-140]. As this matter is yet unresolved, it is obvious that further investigation is required to study the effects of mechanical working on fracture related properties. Most work-to-date on the mechanical working of particulate reinforced MMCs has been focused on the effects of extrusion and rolling on mechanical properties and metallurgical structures [141-143].

Cold forging allows net shape or near net shape parts to be obtained with no or very few machining and finishing operations required after deformation. Unfortunately, the extremely high forging pressures considerably lower the die life; furthermore, the low workability of metals at room temperature reduces the shape complexity of the cold-forged parts. Improvements of the material forge ability can be obtained by including in the forging sequence an annealing treatment before deformation. However, if very complex geometries and large deformations are involved, one or more intermediate annealing treatments may also be necessary to counteract the work hardening effect.

It is also studied that, on the microstructure and mechanical properties of an Al/ SiC_p composite cold die forged gear [144]. They have observed that cold forging of SiC_p reinforced Aluminium based metal matrix composites reduce the grain size, defects, and the fracturing of the secondary phase and SiC particulates. Because of a cold plastic deformation, a large crystal distortion occurred resulting in the increase in the dislocation density that enhanced mechanical properties. The minimum isostatic pressure to prevent fracturing during cold die forging has found to be 650 MPa.

It is compared that the mechanical properties of forged and as-cast samples of Al-SiC_p alloy composites with different volume fraction of SiC_p reinforcement [145]. Evaluation of structural properties showed that mechanical properties of forged sample are greater than cast sample. They also concluded that the porosity in the as-cast component increases with increasing reinforcement volume fraction and the increase becomes abrupt after adding SiC_p above 17 vol%. Also, the ductility of composites is decreased with increasing amount of SiC_p. Forging improves ductility and the elongation fracture increases above 10%, in 17vol% SiC_p.

It is studied that, the micro-structure of as-fabricated and forged specimen at room temperature on 2124 alloy with SiC_p reinforced composites [146]. The material exhibited excellent forgeability. They also stated that MMCs can be hot deformed and they may even show super plastic behavior. Their investigation showed the following characteristics of MMCs when forging operation are carried upon. MMCs hot deformation causes micro-defects like voids and cracks, lowering the material strength. Composite forging limit is improved at higher temperature and at lower strain-rates; but it is not suitable from economic point of view MMCs with aluminium matrices, under plastic deformation showed better forgeability than Al- SiC_p foundry matrices. The forged composites showed good mechanical strength and better ductility then HIP as-fabricated material. This is due to the fact that smaller particulate SiC were used then as reported in literature for similar materials.

Finite element techniques coupled with microstructural model for evaluation of particle stress during forging of a metal matrix composite [147]. They used Eshelby equivalent approach to predict particle stresses, strains and temperatures for F3S20S cast stock, an aluminium matrix composite with 20 vol% SiC_p. This model includes both diffusional and time-dependent process and plastic relaxation processes, the model can be used over a very wide range of temperatures and strain-rates. When associated with stress dependent models of damage prediction, the particle stress model can be used to predict the actual levels of damage arising from forging processes.

It is studied that the effects of forging on microstructure and tensile properties at room and high temperature of a particulate reinforced aluminium matrix composite (AA618 alloy), consisting of 20 vol% Al_2O_3 particles [148]. Micro structural analysis of as-cast and heat – treated composite showed large grain size of aluminium alloy matrix and non-homogeneous distribution of reinforcing particles. The forging process led to a noticeable grain refinement, but no significant variation in size and distribution of reinforcing particles was reported by them. Using Voronoi Tessellation method, they evaluated the effect of forging process on distribution of ceramic reinforcement. They also concluded that fracture surface created on forged AA618 alloy component, both at room and high temperature is mainly attributed to particle reinforcement deboning, due to a weak interface, and ductile fracture of the matrix.

It is investigated that, the effects of forging temperature on microstructure and mechanical properties of in situ 2 vol% TiC/Ti-1100 composites [149]. Their work showed that different micro-structures of MMCs can be obtained after the composite is forged in different temperatures range.

It is showed that grains refinement occurred during forging of 10 vol% SiC_p /AZ91 magnesium as-cast composites at 420^0C with 50% reduction and a much finer grain size was obtained when subjected to hot-extrusion. They also pointed that fine SiC particulates restricted the dynamic recrystallized grain growth during hot extrusion leading to improved refine structures of grains. Combination of hot forging and extrusion produced finer grain size (about an average of 2.7µm for SiC_p /AZ91 magnesium matrix composite). SiC_p particles were found to be distributed along boundaries in as-cast components. This was eliminated and much more uniform particle distribution was obtained by two-steps processing with increase in yield strength and ultimate tensile strength. Fractographic analysis revealed that the size of dimples in matrix was smaller in two-steps processing although brittle fracture occurred, indicating that plasticity of SiC_p /AZ91 composite has improved due to extrusion process. The work hardening rate decreased linearly with increasing value of $(\sigma - \sigma_{0.2})$, where σ is true stress and $\sigma_{0.2}$ is yield stress of the specimen.

A new empirical relationship for the determination of the barrel radius based on the circular radius of curvature and compared with experimentally measured value of barrel radius using aluminium or iron P/M composites during cold forging under triaxial condition [150]. A straight line relationship was predicted between the fractional theoretical densities and exponential of strain component, between the fractional theoretical density and the new geometrical shape factor proposed by them, and between the measured and calculated barrel radius with slope taken as 1.0; with different slopes for percentage content and size of iron particles. They observed that greater densification and higher rate of change of barrel ratio with respect to the stress ratio parameter occurred for smaller iron particle size of Al-Fe composites.

It is also conducted a similar analysis on cold forging but using aluminium with alumina powder with same objective and verified the conclusions that they have done for Al-Fe composites [151] . They have put forward the relationship between stress ratio parameter and the barrel radius as the following empirical expression, $R_b = CS^{-m}$, where R_b is the barrel radius, S is the stress ratio value, and C and m are empirically determined constants. They have also indicated that the rate of change of barrel radius with respect to the axial strain depends upon the initial perform density. Other works includes verification of relationship between various stress ratio parameters determined using the measured values of dimensional output, and density measured during cold upsetting of aluminium –alumina composites under triaxial stress state condition.

It is studied that, hot forming behavior of 2168 aluminium alloy reinforced with 20% of Al_2O_3 particles. They have employed both processing maps and microstructural observations for investigating deformation by hot torsion in the temperature and strain-rates ranging 350-500^{0}C and $10^{-3} - 10\ s^{-1}$ respectively. Their analysis of the maps revealed that at 400-500^{0}C temperature and $10^{-3} - 10\ s^{-1}$strain-rates and highest values of efficiency (η

=36%); in such conditions the material exhibits dynamic recrystallization as revealed in TEM observations [152].

It is also evaluated that the influence of hot deformation of Al-5.5% cu composites using homemade, sprayed aluminium powder and electrolytic copper powder to obtain components with a very high density and higher degree of mechanical properties [153]. Hot closed die forging with heat treatment and ageing resulted in high density and influence on mechanical properties. They have also concluded that mechanical properties and hardness of these homemade materials depend on the heat treatment parameters, i.e., the solutioning and ageing. The solution and ageing of the Al-5.5% Cu composites can triple their hardness as compared to components not heat treated. This process of hot deformation has a leading advantage over costlier hot isostatic pressing (HIP) from economic point of view.

An environmental effect related to composites is also studied and it is showed that the chips derived from machining of semi-finished product are difficult to recycle by conventional methods [154]. Hence an alternative method is devised where the chips are cut or milled and converted to final product directly by hot plastic working. This method is simple, consumes very less amount of energy and the final product present is characterized by low porosity and relative density of 98% as compared with metallurgically produced alloys. Comparing the mechanical properties with those of metallurgically produced aluminium and $AlMg_2$ alloy it can be stated that for the Al-base composites the yield strength is greater and ultimate tensile strength is nearly the same as those metallurgically-produced materials and for $AlMg_2$-base composites the yield strength is comparable, but the ultimate tensile stress is lower than those of metallurgically produced materials. For improved properties, tungsten is to be added at higher content and in more granulated form. Environmental impact of the final product is negligible and the components produced can be processed further by other plastic working methods.

It is studied that, the important factors that affect the strength and mechanical properties of powder forged Al-Si alloys which are generally brittle. Results showed that the overall particle size of the alloy powder is to be controlled above 45μm; lesser size will lead to difficulty in obtaining green compact of considerable strength [155]. Nitrogen environment is most suitable in sintering process of green compacts. Lubrication is necessary for mechanical compaction and eliminates the surface cracks on forged products but not in cold isostatic pressing. Strength of the sintered products depends mainly on silicon grain size; larger sizes have more and larger voids, and occur easily under plastic deformation.

It is also investigated that, the formability of aluminium matrix composites reinforced with an Inconel fiber network. They concluded that tensile strength and ductility are decreased with increase in reduction of diameter [156]. Young's modulus of the wires is slightly higher than that of as-cast composites, indicating absence of any porosity in composites after deformation. The result s obtained showed that high ductility of aluminium matrix composites reinforced with Inconel fibers allows good formability. No porosity or defect was detected in composite wires. The fiber fragments rapidly reach a minimum aspect ratio of about 7. The mechanical properties also showed improvement, which the authors have used shear lag model to explain the effects of fragmentation and alignment of fibers.

Although many papers have shown relevant researches being conducted on the behavior of the aluminium composite but still more information is required on certain properties like forgeability, compaction, flow stress curve etc, so that a more appropriate model can be obtained to predict the failures of the components fabricated from aluminium matrix composites and its appropriate utility.

2.9.4. Machinability of Aluminium Metal Matrix Composites:

The term “Machinability” has traditionally referred to the ease with which a material can be machined with acceptable quality under given set of conditions. But machinability is a difficult term to define and quantify because large number of variables are involved in it. Cutting forces, power consumed, tool life, and surface finish are only some of the factors to be considered when referring to machinability. The difficulty arises because of the dependence of these factors on a large number of variables such as work material, tool geometry, cutting conditions, machine tool rigidity. Materials with good machinability require less power to cut but materials with lower machinability require special arrangements for machining. So, the machinability of materials has significant economic impact. On other hand, properties like hardness and stiffness, which make metal matrix composites appealing to industry but can present major challenges during machining? Wide spread application of MMCs will not possible without the solution for the shortened tool life and material sub surface damages encountered during cutting operation. Because the presence of hard ceramic reinforcements in MMCs provide higher wear resistance but are detrimental to cutting tools. This causes premature failure of the cutting tool, leading to higher machining cost. The increase in the wear land of the cutting tool severely affects the quality and integrity of the machined surface. Cutting with a worn tool leads to a higher percentage of particulates being fractured and debonded on the machined surface. Although the latest innovative manufacturing processes can produce near-net shape components to minimize machining, final machining and finishing processes are generally still required to fabricate a MMC component to the final dimensions. The efficient and economic machining of these materials is required for the desired dimensions and surface finish. Therefore, to minimize the processing cost, it is important to know the machinability of machining MMC. However, in view of the growing engineering applications of these materials, a need for detailed and systematic study of their machining characteristics is emphasized.

Several investigations were carried out to study the effect of particulate volume fraction and size on the progression of tool wear rate [157-159]. It has been shown that the particulate sizes together with the cutting speed have a much stronger effect on tool wear rate than the volume fraction of particulates [160]. A critical volume fraction and finer reinforcing particles hold the key for a better tool life [161-163]. Mollard *et al.* [164] showed a reduction in fluidity when 0.15 wt% Ti was added to an Al-4.5wt%Cu alloy, tested with a vacuum fluidity apparatus. Tiryakioglu *et al.* [165] found no effect of grain refinement on the fluidity of an A356 alloy tested in a sand spiral test, adding 0.04 wt% Ti as Al- 5wt%Ti-1wt%B master alloy. Lang [166] found a significant increase in fluidity with boron additions in the range of 0.04-0.07wt% B to Al-Si alloys, tested with a bar die casting. Dahle *et al.* [167] observed a more complex variation of fluidity with successive additions of Al-5wt%Ti-1wt%B in Al-7wt%Si-Mg and Al-11wt%Si-Mg alloys. Fluidity was reduced with grain refinement below 0.12wt% Ti, while it increased with additions above 0.12wt% Ti. The fluidity length decreased 5% with 0.01wt% Ti and up to 9% with a further addition of 0.12wt% Ti [148]. Al-Si alloys grain refined by boron showed the smallest grain size, the largest fraction solid at dendrite coherency and the best fluidity. The fluidity measurements by Dahle *et al.* [167] were assessed using a vacuum fluidity test apparatus of about 7% relative reproducibility. For all alloys the fluidity was lower at the highest grain refiner content than in the unrefined alloy. Kwon and Lee [168] studied the effect of grain refinement on A356 alloy a relation between the densities of the reinforcement and matrix and the tool wear acceleration is also found to exist. It is clearly evident from the literature that most studies on the machining characteristics of MMCs have been based entirely from experimental results. Furthermore, there is still no systematic approach to model the tool flank wear rate during machining metal matrix composites. Thus, the primary objective of this study is to conduct an investigation to understand the influence of various factors and their interactions on the progression of cutting tool wear during intermittent cutting of MMCs. Further, a methodology for analytical modeling of tool wear progression has been developed as a function of cutting tool/matrix/reinforcement material properties and process parameters in orthogonal metal cutting. Agarwala and Dixit [169] observed that the importance of preheating in the incorporation of graphite particles in an aluminium alloy. There was no retention when the graphite particles were not preheated, whereas the particles were retained when preheated. Heating of SiC particles to 900^{O}C assist in removing surface impurities, desorption of gases, and altering the surface composition due to the formation of an oxide layer on the surface[170]. Aluminium plates reinforced with *55%* FP fibers are drilled [164-170]. Soluble oil coolant caused accelerated wear of the drill edges. Abrasive slurry at the cutting edge was the main cause, since the accelerated wear disappeared when compressed air was directed at the drill end. AI-Mg-Si-Cu/Al203 is machined.

Coolant was found to increase the tool wear because the temperature at the chip formation region then remained low, which kept the matrix strength high. Aluminium-based MMCs reinforced with SiC particles, $A1_20_3$, and B_4C are drilled and milled [171-173]. Similar results were found for milling tests. Pure water and pure oil using as coolant and lubricant even worsened the situation. The emery fluid that was produced a mixture of cutting fluid and broken reinforcement, was claimed to be responsible for the higher tool wear. An excellent surface finish comparable to a ground surface was achieved due to lack of build-up-edge (BUE). It is suggested using cutting fluid to flush away the chip, therefore preventing the tool from re-cutting the abrasive chips [174-176].

The BUE, although protecting the tool and reducing its wear rate by over 80% in some cases, could, however, be detached and smeared along the cutting path. Cold forging allows net shape or near net shape parts to be obtained with no or very few machining and finishing operations required after deformation. Unfortunately, the extremely high forging pressures considerably lower the die life; furthermore, the low workability of metals at room temperature reduces the shape complexity of the cold-forged parts. Improvements of the material forgeability can be obtained by including in the forging sequence an annealing treatment before deformation.

However, if very complex geometries and large deformations are involved, one or more intermediate annealing treatments may also be necessary to counteract the work hardening effect. H. So *et al.* [177], compared the mechanical properties of forged and as-cast samples of Al-Si alloy composites with different volume fraction of SiC_p reinforcement. Evaluation of structural properties showed that mechanical properties of forged sample are greater than cast sample. Their experimental results verified that yield strength, Tensile strength and elastic modulus increases with increase in percentage of volume content of SiC particulates. This increase in yield strength and tensile strength is seen with content upto 17 vol% but starts decreasing above that value. They also concluded that the porosity in the as-cast component increases with increasing reinforcement volume fraction and the increase becomes abrupt after adding SiC_p above 17 vol%. Also, the ductility of composites is decreased with increasing amount of SiC_p. Forging improves ductility and the elongation fracture increases above 10%, in 17vol% SiC_p. Badini et al. [178], studied the micro-structure of as-fabricated and forged specimen at room temperature on 2124 alloy with SiC_p reinforced composites. The material exhibited excellent forgeability. They also stated that MMCs can be hot deformed and they may even show super plastic behaviour. Their investigation showed the following characteristics of MMCs when forging operation are carried upon. MMCs hot deformation causes micro-defects like voids and cracks, lowering the material strength. Composite forging limit is improved at higher temperature and at lower strain-rates; but it is not suitable from economic point of view MMCs with aluminium matrices, under plastic deformation showed better forgeability than Al-SiC_p foundry matrices. The forged composites showed good mechanical strength and better ductility then HIP as-fabricated material [179-185]. This is due to the fact that smaller particulate SiC_p were used then as reported in the literature for similar materials.

2.10. Modelling Techniques:

By modelling technique we can establish the mathematical relation between input and output results for many experimental procedures. In the manufacturing of powder metallurgy products, the modelling technique is very much effective because so many input parameters (variables) are responsible for the output results i.e. finished components.

The modelling process can be represented by a schematic diagram as shown in Figure 2.26 [186]. A process transforms the input variables like materials, men, machines, methods, technology and other resources into some outputs that have one or more responses. The measurable and controllable input variables are generally represented by x_1, x_2, x_3 …..x_k. Uncontrollable input variables are generally represented by q_1, q_2,q_3 ….q_n. The output variables (noise) are generally designated by y_1,y_2,y_3,……y_m.

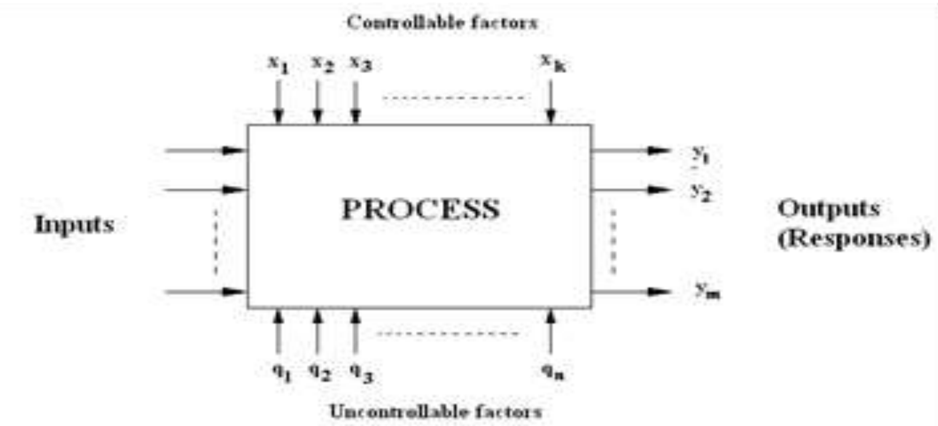


Figure 2.26: A generalized model of a process or system.

The physical quantities associated with a process like temperature, pressure etc. varies with time in a random manner and thus a process can be called as a random process. In a given time interval, a random process takes some specific form unknown in advance which is known as realization of the random process. In a random process there can be an infinite number of such realizations. A random process can be stationery or non-stationery. The stationery random processes are referred in Figure 2.27a can be describe as those which are independent of the choice of zero in the time axis i.e. a time translation of a simple function results in a similar simple function of the random process. Stationery random processes yield the same probability characteristics within any time interval. On the other hand a non-stationery random process as shown in Figure 2.27b are those which depends on the choice of zero on the time axis i.e. a time translation of a sample function will not result in a similar sample function of the random process. Hence, the statistical properties of interest for non-stationery random processes will be different in different observation intervals.

he necessary statistical data require for analysis are gathered by conducting experiment. The experiment may be passive or active. In passive experiments the values of each independent variable are altered from measurement to measurement in term. This procedure can also be used in the normal course of service of the process.

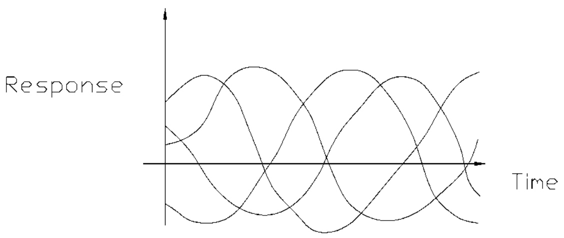


Figure 2.27: a) Stationary random processes.

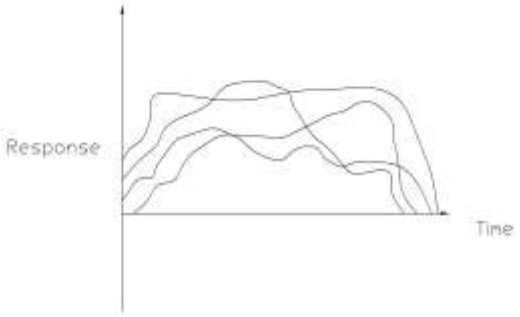


Figure 2.27:b) Non-stationary random processes.

The necessary statistical data require for analysis are gathered by conducting experiment. The experiment may be passive or active. In passive experiments the values of each independent variable are altered from measurement to measurement in term. This procedure can also be used in the normal course of service of the process. The data collected are analyzed by using different statistical methods. An active experiment is conducted according to a predetermined plan or design, known as experimental design. During this experiment, the values of the independent variables are altered all at a time and the amount of experimentation can be cut down substantially. The choice of an experimental design depends on prior information about the process or the planned and objective sought. The process of experimental design was first proposed by R.A.Fisher of U.K in the 1930s. However, further improvement of the process was carried out by Box and Wilson of U.S.A. [187,188]. These methods are now extensively used for various statistical analysis of different engineering processes.

This chapter mainly deals with the theoretical back ground about the statistical method for the process of system optimization. A brief description about stationery and non-stationery random processes, generalized input-output model of a process and design of experiment (DOE) have been explained. An experiment can be conducted to collect data about the process parameter and response variables. Factorial design, full factorial design and the concept of interaction between process parameters have also been discussed here. Various types of regression models have been mentioned and explained how a suitable regression model can be used to analyse the effect of process parameters on the response variables.

2.10.1. Regression Analysis:

Regression analysis is a statistical process for estimating the relationships among variables. It includes many techniques for modelling and analyzing several variables, when the focus is on the relationship between a dependent variable and one or more independent variables. More specifically, regression analysis evaluating the relationship between a given variable (usually called the dependent variable) and one or more other variables (usually known as the independent variables) and helps one understand how the typical value of the dependent variable changes when any one of the independent variables is varied, while the other independent variables are held fixed i.e. most commonly, regression analysis estimates the conditional expectation of the dependent variable given the independent variables – that is, the average value of the dependent variable when the independent variables are fixed. In all cases, the estimation target is a function of the independent variables called the regression function. In regression analysis, it is also of interest to characterize the variation of the dependent variable around the regression function which can be described by a probability distribution.

Regression analysis is widely used for prediction and forecasting. The regression model is used to determine whether two variables are related or not. An empirical equation can be established to relate input-output parameters by utilizing least square method. Firstly, it has to be determined whether there is any relationship between the two variables i.e. the independent variables and dependent variable. This is done by examining the graph or chart of the observed data. This graph is often called scatter diagram. After determining the equation by regression analysis, correlation analysis can be used to find out the degree to which the variables are related. Sometimes the correlation between two variables may be insufficient to determine a reliable estimating equation. In such case the data may be added from more independent variables and may be able to determine and estimating equation that describes the relationship with greater accuracy. This process is called multiple regression and correlation analysis.

Regression analysis can predict the outcome of a given key business indicator (dependent variable) based on the interactions of other related business drivers (explanatory variables). For example, it can predict sales volume based on the amount spent on advertising and the number of sales people one employed. Of course, a real model would need more variables and is much more complex.

The first stage of the process is to identify the variable we want to predict (the dependent variable) and to then carry out multiple regression analysis focusing on the variables we want to use as predictors (explanatory variables). The multiple regression analysis would then identify the relationship between the dependent variable and the explanatory variables – this is then finally presented as a model (formula).

Identification of the Process Control Variables:

The control variables of the process, both inputs and outputs i.e. factors and responses are identified as per related research works. The range of the process control variables are also selected as per earlier research works and the characteristics of the materials. In the present study, initially the list of all factors of the preform manufacturing process including their upper and lower levels of setting, are identified based on the actual experiments. In this experimental work, three process control variables namely compaction load, sintering temperature and sintering time are identified.

A detailed review of each of the factors is done to ensure whether these factors are independent in nature. The range of the process control variables is also selected based on practical experience and design of experiments. The ranges are as follows i.e. weight percentage of SiC_p 2 wt% to 10.045 wt% (in a fixed dia. of 25mm), Compacting pressure from 40 Ton to 93.635 Ton and sintering time from 30 min to 56.817 min and sintering temperature 600 °C in different stages.

Developing the Design of Experiments:

A designed experiment is a test or a series of tests where preplanned changes are made to the controllable variables of a process or system so that the reasons for changes in the response can be observed and identified. Experiments are performed by researchers in all fields of enquiry to discover and predict something reasonable about a particular process or system. Design Of Experiments (DOE) refers to the systematic and scientific methods which are followed for planning the experiments such that the experiments can be performed in the most efficient and economical way to get the required data that will result in valid and objective conclusions. The statistical approach to experimental design is required if we wish to draw meaningful conclusions from the observed data. There are many problems which involve data that are subjected to experimental error. In this situation, statistical methodology is the only objective approach to analysis.

The three basic principles which are followed for experimental design are;

- Replication,
- Randomization and
- Blocking.

Replication means repetition of basic experiments. It has two important properties. Firstly, it allows the experimenter to obtain an estimate the experimental error which is a basic unit of measurement for determining whether the observed differences in the data are really statistically different. Secondly, if the sample mean is used to estimate the effect of a factor, replication permits the experimenter to obtain a more precise estimate of this effect. Randomization is the corner stone underlying the use of statistical methods in the experimental design. It means that both the individual runs or trials of the experiments that are to be performed and the allocation of experimental materials are randomly determined. The Statistical methods require that the observations (or errors) be independently distributed random variables. Randomization makes this assumption valid and also assists in averaging out the effects of extraneous factors that may be present.

2.10.2. Two Level Factorial Experiments:

Two level factorial experiments are factorial experiments in which each factor is investigated at only two levels. The early stages of experimentation usually involve the investigation of a large number of potential factors to discover the important factors. Two level factorial experiments are used during these stages to quickly filter out unwanted effects of the less important process variable, so that attention can then be focused on the important or effective variables one.

2.10.3. Factorial and Full Factorial Designs:

In many experiments, it is necessary to study two or more factors. For such experiments, factorial design is found to be most efficient experimental method. Factorial design means that in each complete replication of the experiment, all possible combinations of the levels of the factors are investigated [189]. As an example, if there are a levels of factor A and b levels of factor B and each replicate contains all ab treatment combination. In such case, factorial design is the most suitable method.

However, there are several cases of the general factorial design and they are used widely in the research works. The most important of these special cases is that of k factor, each at only two levels. These levels may be quantitative such as pressure, temperature and time. However, they may be in qualitative form, such as high and low levels of factor or +1, and -1 respectively. A design with all possible high and low combinations of all the input factors is called a full factorial design in two levels and denoted by 2^k.

Alternatively, this concept can be illustrated by regression model representation for example, both of our design factors are quantitative such as pressure, temperature etc. The 2^k factor factorial experiment can be written as

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_{12} x_{12} + \epsilon \qquad \text{---} \ (2.6)$$

Where, y is the response , β' s are the parameters whose values are to be determined, x_1 is a variable that represent factor A, x_2 is a variable that represent factor B and ϵ is a random error term.

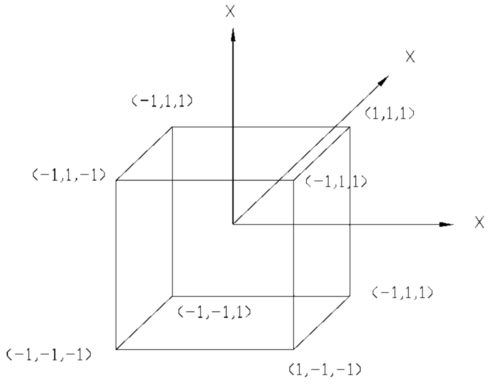


Figure 2.28: Geometrical configuration of a 2^3 (N=8) full factorial design.

The coded full factorial design for three (k=3) parameter process can be represented geometrically as a cube (Figure 2.28) whose eight corners represent the eight experimental points (Table 2.4).

The regression equation $y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_{12} x_{12} + \epsilon$ can be further analyzed for factorial 2 and factorial 3 model.

The experimental matrix given in the above table has a property which is called orthogonality i.e. the scalar product of all column vectors are equal to zero ($\sum_{i=1}^{N} x_{ui}x_{ji} = 0$, for $u \neq j$; $u, j = 1,2,\ldots..k$). This is a very important property which reduces the difficulties in estimating the coefficients of the regression equation because the co-efficient matrix (X^TX) of normal equation becomes diagonal and its diagonal elements are equal to the total number of experiments N in the design matrix.

Table 2.4

Design points for a 2^3 (N=8) full factorial design.

Design Points	**Dummy variable**	**Coded values of process parameters**			**Response (y)**
	X_0	**X_1**	**X_2**	**X_3**	
1	+1	-1	-1	-1	y_1
2	+1	+1	-1	-1	y_2
3	+1	-1	+1	-1	y_3
4	+1	+1	+1	-1	y_4
5	+1	-1	-1	+1	y_5
6	+1	+1	-1	+1	y_6
7	+1	-1	+1	+1	y_7
8	+1	+1	+1	+1	y_8

A regression equation with k degree polynomial can be written as,

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \ldots\ldots + \beta_k x_k + \epsilon = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \varepsilon$$

$$= \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \varepsilon \tag{2.7}$$

and the fitted equation is,

$$\hat{y} = \mathrm{E}\,(y - \varepsilon) = \hat{\beta}_o + \sum_{i=1}^{k} \hat{\beta}_i x_i \tag{2.8}$$

A second degree polynomial regression equation often called second order response surface can be written as,

$$y = \beta 0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k} \beta_{ii} x_i^2 + \sum_{i}^{k} \sum_{j}^{k} \beta_{ij(i<j)} x_i x_j + \varepsilon \tag{2.9}$$

and the fitted equation is represented by

$$\hat{y} = E\,(y - \varepsilon)$$

$$= \hat{\beta}_o + \sum_{i=1}^{k} \hat{\beta}_i x_i + \sum_{i=1}^{k} \hat{\beta}_{ii} x_i^2 + \sum_{i}^{k} \sum_{j}^{k} \hat{\beta}_{ij\,(i<j)} x_i x_j \tag{2.10}$$

However, for evaluating the effects of process parameters (main effects and interactions)

The following regression can be used,

$$y = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i}^{k} \sum_{j}^{k} \beta_{ij(i<j)} x_i x_j + \sum_{i}^{k} \sum_{j}^{k} \sum_{u}^{k} \beta_{iju(i<j<u)} x_i x_j x_u + .. + \beta_{12....k} x_1 x_2 \cdots x_k + \varepsilon \tag{2.11}$$

And the fitted equation can be written as,

$$\hat{y} = \hat{\beta}_o + \sum_{i=1}^{k} \hat{\beta}_i x_i + \sum_{i}^{k} \sum_{j}^{k} \hat{\beta}_{ij\ (i<j)} x_i x_j + \sum_{i}^{k} \sum_{j}^{k} \sum_{u}^{k} \hat{\beta}_{ij\ u(i<j<u)} x_i x_j x_u + \ldots\ldots + \hat{\beta}_{12\ldots\ldots k}\ x_1 x_2 {}^{\cdots\cdots} x_k$$

--------------------------- (2.12)

Using least square method, the coefficients of all the above regression equations can be estimated with the help of the following matrix equation,

$\mathbf{B = (X^T X)^{-1} X^T Y}$ --- (2.13)

The matrix **X** will be different for the different regression equations. **Y** is the column vector of observed responses and **B** is the column vector of estimated coefficients of regression equation.

2.10.4. Development of the Model and Calculation of Regression Coefficients:

The input-output model or analysis matrix under study is obtained by adding an ‘I’ column I s and “X_1* X_2”, X_1* X_3 , X_2 * X_3 , “X_1* X_2 * X_3 ” columns to the matrix of 8 trials for a 2^3 experiment. Table 2.5 shows matrix of the 2^3 full factorial experiments

Table 2.5

Model or analysis matrix of 2^3 full factorial design of experiments.

Trial	Factor X_1	Factor X_2	Factor X_3	Factor X_1* X_2	Factor X_1*X_3	Factor X_1*X_3	Factor X_1* X_2*X_3
1	-1	-1	-1	+1	+1	+1	-1
2	+1	-1	-1	-1	-1	+1	+1
3	-1	+1	-1	-1	+1	-1	+1
4	-1	-1	+1	+1	-1	-1	+1

5	+1	+1	-1	+1	-1	-1	-1
6	+1	-1	+1	-1	+1	-1	-1
7	-1	+1	+1	-1	-1	+1	-1
8	+1	+1	+1	+1	+1	+1	+1

2.10.5. Estimation of Effects of Parameters:

Main Effects:

The main effect of a parameter is determined as the difference between the average response with the parameter set at its high level and average response with the parameter set at its lower level. For example, the main effects of X_1 can be determined as follows (Table 2.5)

Main effect of $X_1 = ¼ (Y_2 + Y_5 + Y_6 + Y_8) – ¼ (Y_1 + Y_3 + Y_4 + Y_7)$

Interaction Effect:

The interaction effect is the combined effect of more than one variable. The level of interaction factor is obtained by multiplying the levels (sign) of the main factors. After multiplying it we get –ve sign then the interaction is set at lower level and if we get +ve sign ,then the interaction is set at higher level. For example, the interaction of factors X_1 and X_2. i.e. X_1X_2 is computed as follows (Table 2.5). Interaction effect $X_1X_2 = =1/4(Y_1+Y_4+Y_5+Y_8)-1/4(Y_2+Y_3+Y_6+Y_7)$

2.10.6. Linear and Non-Linear Models:

A linear model is one in which the independent variable is added or multiplied together with the parameters. A non-linear model has exponents, logarithms, or other complicated functions of the independent variable and parameters. Some non-linear models can be reduced to linear models to make it easier to do the fitting. For example, if the Y values curve upwards like a simple quadratic in relation to the X values, then it might be appropriate to fit $Y= aX_2$. This model can be reduced to a linear one simply by introducing a new variable called S (say), which has the same values as X_2. Then linear model can be fitted Y =aS. Some statistical programs generate these new variables automatically when we fit quadratics, cubes, or other higher order polynomials.

However, most non-linear models cannot be reduced to a simple linear model in this way. But a good statistical program can fit non-linear models in to a linear mathematical form of the model. The statistical program then calculates the values of the parameters that give the best fit to our data. The usual method is to minimize the sum of the squares of the residuals.

2.11. Test of Significance:

A statistical hypothesis test is a method of making statistical decisions using experimental data. In statistics, a result is called statistically significant if it is unlikely to have occurred by chance. The phrase "test of significance" was coined by Ronald Fisher: Critical tests of this kind may be called tests of significance, and when such tests are available we may discover whether a second sample is or is not significantly different from the first one. The t-test is probably the most commonly used Statistical Data Analysis procedure for hypothesis testing.

The amount of evidence required to accept that an event is unlikely to have arisen by chance is known as the significance level or critical p-value: in traditional Fisherian statistical hypothesis testing, the p-value is the probability conditional on the null hypothesis of the observed data or more extreme data. If the obtained p-value is small then it can be said either the null hypothesis is false or an unusual event has occurred. It is worth stressing that p-values do not have any repeat sampling interpretation.

The significance level is usually denoted by the Greek symbol α (lowercase alpha). Popular levels of significance are 5% (0.05), 1% (0.01) and 0.1% (0.001). If a test of significance gives a p-value lowers than the α-level, the null hypothesis is rejected. Such results are informally referred to as 'statistically significant'. The lower the significance level, the stronger the evidence required. Choosing level of significance is an arbitrary task, but for many applications, a level of 5% is chosen, for no better reason than that it is conventional.

2.12. ANOVA (Analysis of Variance):

ANOVA is a test whose goal is to assess the plausibility of the hypothesis stating that the means of these normal distributions are indeed equal. More generally, k groups of observations are known to generate by k independent normal distributions with identical variances and respective means $\mu_1, \mu_2, ..., \mu_k$. The groups need not have the same size.

ANOVA will test:

The null hypothesis H_0 : $\mu 1 = \mu 2 = ... = \mu k$

Against the alternative hypothesis H_1 : at least one of the means is different from the others.

The analyst chooses a significance level α (typically, 0.05 or 0.01). ANOVA produces a p-value. If the p-value is less than α, the hypothesis will be rejected.

Else, the conclusion will be that data is not incompatible (at this significance level) with the hypothesis that all the means are equal (recall that this is not a confirmation that H_0 is true).

So ANOVA may be perceived as a generalization of Student's t test to more than two groups.

An F-test is any statistical test in which the test statistic has an F-distribution under the null hypothesis. It is most often used when comparing statistical models that have been fit to a data set, in order to identify the model that best fits the population from which the data were sampled.

The hypotheses that the means of several normally distributed populations, all having the same standard deviation, are equal. This is perhaps the best known F-test, and plays an important role in the Analysis of Variance (ANOVA).The hypothesis that a proposed regression model fits the data well. A full factorial experimental design (l^k) with six additional central points (n_c) have been considered for performing the statistical analysis. The six additional central points give an estimate of experimental error. Table 2.5 gives the observed data for different settings of process parameters. The data have been considered by conducting the experiments in a random order of run numbers and equation (2.6) has been fitted to the observed data by using MINITAB software (version 14). The coefficients of the fitted equations can be obtained from equation (2.11) given below.

$\mathbf{B_1} = (\mathbf{X}^T \mathbf{X})^{-1} \mathbf{X}^T \mathbf{Y}$, -- (2.14) where,

$\mathbf{B_1} = [\hat{\beta}_0 \quad \hat{\beta}_1 \quad \hat{\beta}_2 \quad \hat{\beta}_3 \quad \hat{\beta}_{12} \quad \hat{\beta}_{13} \quad \hat{\beta}_{23} \quad \hat{\beta}_{123}]^T$,

$\mathrm{X} = [\mathbf{x_0} \quad \mathbf{x_1} \quad \mathbf{x_2} \quad \mathbf{x_3} \quad \mathbf{x_{12}} \quad \mathbf{x_{13}} \quad \mathbf{x_{23}} \quad \mathbf{x_{123}}]$,

$\mathbf{x_0} = [1 \quad 1 \quad 1 \quad 1 \quad 1 \quad 1 \quad 1 \quad 1]^T$,

$\mathbf{x_1} = [-1 \quad 1 \quad -1 \quad 1 \quad -1 \quad 1 \quad -1 \quad 1]^T$,

$\mathbf{x_2} = [-1 \quad -1 \quad 1 \quad 1 \quad -1 \quad -1 \quad 1 \quad 1]^T$,

$\mathbf{x_3} = [-1 \quad -1 \quad -1 \quad -1 \quad 1 \quad 1 \quad 1 \quad 1]^T$

$\mathbf{x_{12}} = [1 \quad -1 \quad -1 \quad 1 \quad 1 \quad -1 \quad -1 \quad 1]^T$,

$\mathbf{x_{13}} = [1 \quad -1 \quad 1 \quad -1 \quad -1 \quad 1 \quad -1 \quad 1]^T$,

$\mathbf{x_{23}} = [1 \quad 1 \quad -1 \quad -1 \quad -1 \quad -1 \quad 1 \quad 1]^T$,

$\mathbf{x_{123}} = [-1 \quad 1 \quad 1 \quad -1 \quad 1 \quad -1 \quad -1 \quad 1]^T$,

Y = Column vector of response

2.13. Summary:

A detailed study was undertaken to pool-up the existing literature on Aluminium based MMCs and efforts were put to understand the basic needs of the growing Composite industry.

- The usability of the aluminium alloy metal matrix composite materials depend upon its mechanical and physical properties.Pure aluminium matrix is preferred to various alloy matrices due to the high temperature stability of the aluminium as compared with aluminium alloys. Lower working temperature's in case of alloy matrices is attributed to lower stability of the alloy matrix and coarsening of the grains. In addition, the load transfer in case of pure aluminium matrix is more effective due to the clean interface.

- There exists a wide range of database in the literature for different types of reinforcements in aluminium metal matrix composites, particulate SiC chosen as reinforcing material.
- It is apparent from the literature that parameters controlling the mechanical properties of particulate reinforced composites are still not understood in any detail. However, some of the important factors are becoming apparent.
- The most important aspect of the microstructure is the distribution of the reinforcing particles, and this depends on the processing and fabrication routes involved. However, if the process parameters are not adequately controlled, the composite shows a non-homogeneous particle distribution and then a deterioration of the mechanical properties [190,191]. Reinforcing particles used in the composites have a varying density. Density of the particles is one of the most important factors determining the distribution of the particles in the matrix metal. Reinforcing particles having higher density than matrix metal can settle at the bottom and particles of lower density can segregate at the top especially in case of liquid method, the reinforcing particle content may vary from one casting to another or even it can vary in the same casting from one region to another but uniform distribution of the reinforcing particles in the matrix is a necessary condition for homogenous microstructure of composite and it greatly affect the properties of composite. More uniform distribution of the reinforcing particles in the matrix by adopting powder metallurgy process. Hence the study of the distribution of the particles in the composite is of great significance [192-197].
- The attractive physical and mechanical properties that can be obtained with metal matrix composites, such as high specific modulus, strength and thermal stability, have been documented extensively [198-200]. The various factors controlling the properties of particulate MMCs and the influence of the

manufacturing route on the MMC properties has also been reviewed by several investigators [201-203]. Improvement in modulus, strength, fatigue, creep and wear resistance has already been demonstrated for a variety of reinforcements [204]. Of these properties; the tensile strength is the most convenient and widely quoted measurement and is of central importance in many applications.

- The liquid state processing is generally less expensive and easier to handle, and the composites can be produced in variable shapes, using techniques already developed in the casting industry for monolithic metals. However the technical difficulties related to liquid state processing include, detrimental interfacial chemical reaction, high localized residual porosity and poor interfacial bonding which degrade the properties. Meanwhile powder metallurgy processing can avoid strong interfacial reaction and also minimize the undesired reaction between the matrix and the reinforcement because generally a lower manufacturing temperature is used in powder metallurgy. The content and distribution of reinforcement, as well as the microstructure of the matrix can be controlled relatively easy. Hence the P/M products normally have superior properties over that of their cast counterparts.

- The strength of particle-reinforced composites is observed to be most strongly dependent on the volume fraction and particle size of the reinforcement.
- Dislocation strengthening will play a more significant role in the MMC than in the unreinforced alloy due to the increased dislocation density.
- Of greatest concern appears to be the introduction of defects and inhomogeneities in the various processing stages, which has been found to result in considerable scatter in the mechanical properties [205].

- Tamer Ozben *et. al.* studied on the Mechanical properties of SiC particle reinforced Al-MMC. They observed that increasing the input of reinforcement element produced better mechanical properties such as impact toughness and hardness [206].

- The priority of this work will be to prepare MMC using SiC_p as reinforcement material and to study its mechanical properties and forgeability.

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CHAPTER 3

EXPERIMENTAL SET UP AND STUDY ON MECHANICAL PROPERTIES

EXPERIMENTAL SET UP AND STUDY ON MECHANICAL PROPERTIES

Outline of the chapter: 3.1 Introduction, 3.2 Fabrication of Al-SiC$_p$ metal matrix composites, 3.3 Micro structural examination and phase analyses, 3.4 Measurement of density, 3.5 Measurement of hardness, 3.6. Measurement of forgeability.

3.1 Introduction:

Metal Matrix Composites (MMCs) are combinations of a tough metallic matrix with a hard ceramic reinforcement to produce composite materials with superior properties to conventional metallic alloys. Addition of ceramic reinforcing phases such as silicon carbide (SiC$_p$) has been shown to produce materials with improved specific properties; it also results in a marked increase in their hardness. Ceramic materials have excellent mechanical properties; namely high hardness, high temperature strength and chemical stability materials in industrial fields. The process lubrication system, such as grease free bearing system for the chemical pumps, is expected to expand the use of ceramics in industrial applications. In particular, uses of aluminium alloys in automotive applications have been limited due to their inferior strength, rigidity and wear resistance, as compared to those of ferrous alloys. Particle reinforced aluminium composites; nevertheless, offers reduced mass, high stiffness and strength and improved wear resistance. MMCs have slowly replaced some of the conventional light weight metallic alloys such as the various grades of aluminium alloys in applications where low weight and energy saving are important considerations and yet without sacrificing the strength of the components. In these MMCs, the good ductility of the metallic alloy as the matrix material is retained while the modulus and strength of the composites are increased as a result of the reinforcement phases. The strength of Al-SiC$_p$ composites increases with an increase in the weight percentage of ceramic phase. The important characteristics of SiC$_p$ AMMCs are low specific gravity, high thermal conductance, and low corrosiveness. Powder blending and consolidation, a solid state method of fabrication, consistently produces superior mechanical properties distributed evenly throughout the material. The increase in strength observed after the sintering process decreases the machinability of the material creating new challenges. P/M techniques are extensively used in the manufacture of particle MMC. Using these techniques, the matrix as well as reinforcement is used in the form of powder. Of all metals, aluminium is most commonly used as a matrix for MMC. The light weight of aluminium allows the production of high strength to weight ratio materials. Heat treatment plays an important role in controlling the wear, hardness; forgeability and machinability properties of a SiC_p reinforced composite material. No information is available in the literature on the comparative property study of Al-SiC_p MMCs with and without heat treatment. Metal matrix composites have generally produced, either by liquid metallurgy or powder metallurgy route. Of these processes, forging is of high technical and economic interest because it avoids problems such as the need for special tools (expensive diamond tipped inserts) during machining, poor mechanical properties because of reactions between some ceramic reinforcements and molten metal in casting, and the porosity in P/M components. In the liquid metallurgy, the particulate phases have mechanically dispersed in the liquid before solidification of the melt. Among others, however, the powder metallurgy (P/M) method has known as a very promising route, which is most attractive due to several reasons. Firstly, in P/M technique microstructural control of the phases is possible (Figure 3.1). Secondly, the lower temperatures employed during the process accounts for the strict control of interphase kinetics. In the P/M method, the starting powders can be elemental or pre-alloyed. However, it is difficult to take advantage of both these requirements because they are prone to cause an inhomogeneous distribution. Poor distribution of reinforcement degrades the composites in terms of its physical and mechanical properties and negates the attractiveness of reinforcement additions. Using elemental powders are not only economical, but also bring an extra advantage to modify the matrix composition easily. The presence of SiC particles accelerated the aging process due to the increased dislocation density, which provides more sites for the nucleation of precipitates. Metal matrix composites reinforced by ceramic particles, with low density, high strength and modulus and flexible fabricating techniques, have received particular attention in the past decades. Meanwhile, the particular preparation techniques of the composites rely on these factors. Poor distribution of reinforcement degrades the composites in terms of its physical and mechanical properties and negates the attractiveness of reinforcement additions. Composites combine the characteristics of aluminium and aluminium alloys matrix (low density in comparison with ferrous materials, good corrosion resistance and machinability) with the characteristics of ceramic particles (e.g. SiC_p, TiC_p, B_4C_p, Al_2O_3, SiO_2, etc.), which improve in special mechanical, tribological and thermal expansion characteristics. As sintering is a predominant factor for controlling the density of the P/M products, variation of wt% of reinforcing materials, compacting pressure, sintering time, temperature largely affects the density of the P/M components. The sintered parts of high density can be steam treated to close the surface pores. It is also observed that the green density and sintered density is a function of powder type and compacting pressure. Present study examines the variation of density (R_1) as a function of process parameters (weight percentage of SiC_p x_1, compacting pressure x_2, and sintering time x_3) of sintered iron P/M components. The samples were produced by changing the process parameters as per the Design of Experiment (DOE) and the Response Surface Methodology (RSM) has been used to plan and analyze the density. The experimental plan adopts the face centred Central Composite Design (CCD). A second order response surface model has been used to develop a predicting equation of density based on the data collected by a statistical design of experiments. The Analysis of Variation (ANOVA) shows that the observed data fits well into the assumed second order RSM model. It is worth mentioning that this model is one of the most widely used methods to solve the optimization problem in manufacturing technology. In the experiment, porosity of the samples, compacted and sintered under different conditions were investigated by the optical microscope. It is found that porosity of the samples decreases with the increase of compacting pressure, weight percentage of SiC_p and sintering time. To develop the SiC_p reinforced AMMC and study the effect of variation of weight percentage of SiC_p, compacting pressure, and sintering time on the hardness, forge ability behaviour, in order to improve the properties in HT composite. This paper present a reliable set of parameters as the result of an experimental investigation that demonstrate versatility, and numerous and diverse range based on experience and technology during the machining of aluminium reinforced silicon carbide metal matrix composite (Al-SiC_p MMC) which will provide valuable guidelines to the manufacturing engineers.

3.2 Fabrication of Al-SiC_p Metal Matrix Composites:

3.2.1. Material Selection:

Air atomized aluminium powder (average particle size of 400 mesh) reinforced with SiC particulates (average size of 400mesh) are used as the test material along with commercially pure aluminium. Aluminium matrix composites having 5, 10, 15 and 20 wt% fraction of SiC particles were used as the test material along with commercially. The above composites and aluminium has fabricated by powder metallurgy technique (Figure 3.1- 3.3).

Figure3.1:Weighing balance.

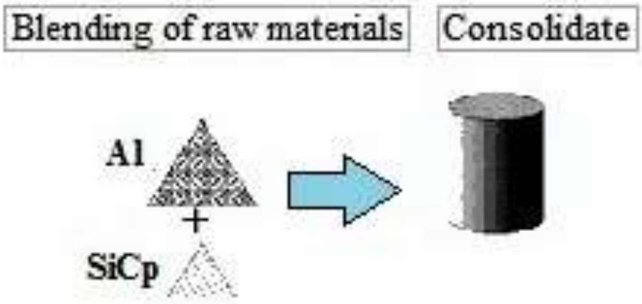


Figure 3.2:Mixing of powder materials.(accuracy±0.1mg.)

3.2.2. Blending:

The metal and ceramic powders were blended in a drum with a cylindrical mixer (diameter 40 mm, height 35 mm), at a constant speed of 1500 r.p.m for 1h. Blending is one of the crucial processes in P/M where the metallic powders have mixed with the ceramic reinforced particles. Good blending produces no agglomeration of both the metallic and ceramic particle powders. To achieve this, several parameters such as particle size, blending speed and duration have taken into consideration to ensure the SiC particles distributing homogeneously in the matrix powders. The powder blending parameters have listed in listed in Table 4.1.

Figure 3.3:Various steps involved in synthesis of Al-SiCp composites in P/M technique.

Figure 3.4:Hydraulic press Make: Lawrence & Mayo.

Figure 3.5:Tubular Vacuum Furnace.

3.2.3. Compacting:

A mixture of the particles and the binder (Zinc Stearate) has poured into a cylindrical die with 110 mm high, 25 mm inner diameter and 75 mm outer diameter (Figure 3.6). After pouring, the powder mixture was cold isopressed with a hydraulic press (Make: Lawrence & Mayo) (Figure 3.4) for 5min to obtain green compacts (Figure 3.7).

Figure 3.6: Metallic Die with punch

Figure 3.7: Green compact.

Figure 3.8: Sintered sample.

Table 3.1

The powder blending steps

Mixture	Filling of mixer	Operation	R.P.M	Time (min)
400 mesh pure Al, 400mesh SiC_p and Binder (Zinc Stearate)	50	Blending	1500	20
	75	Blending	1500	20
	100	Blending	1500	20
		Rest		10
		Blending	1500	20

3.2.4. Sintering:

The green compacts are then subsequently baked at 300˚C and followed by sintering in an induction type floor stand tube vacuum furnace (Figure 3.5) (dia of hot zone 75 mm length of hot zone 150 mm and maximum temp1450˚C). During processing, the matrix powders have exposed to atmosphere, which contains oxygen and moisture also, and it would oxidize at high temperature. Moreover, the moisture would react chemically with the oxide, and such reaction would reduce the bonding force of Al-SiC_p interface and further deteriorate the mechanical properties of the composites. Thus, the degassing should carry out in an environment of elevated temperatures and high vacuum, where the dew point and the oxygen partial pressure are low. The adsorbed compounds will evacuate and further oxidation can suppressed effectively. To avoid the oxidation of Al alloy powders at high temperature and to abbreviate the preparation procedures, the degassing and sintering procedures of the green compacts have incorporated together.

Table 3.2

The sintering steps

Operation	**Temperature**		**Duration**
	From	To	
Heating	Ambient (32˚C)	300˚C	45 min
Soaking	300˚C	300˚C	30 min
Heating	300˚C	500˚C	30 min
Soaking	500˚C	500˚C	30 min
Heating	500˚C	600˚C	30 min
Soaking	600˚C	600˚C	45 min
Cooling in furnace	600˚C	Ambient (32˚C)	

The stepped heating procedures of the degassing and sintering has introduced into the experiment. The sintering parameters have given in the Table 3.2**.** At the low temperature stages, the atmosphere and moisture could extract out, while the crystallized water would evaporate during sintering at the high temperature stages.

Sintering at a normal pressure usually has a little influence on the Al-SiC$_p$ interfacial cohesion due to the presence of an oxide layer on the Al powder surfaces. Therefore, an advanced sintering has carried out at the elevated temperature and high pressure to get the better interfacial cohesion. As it is well known, the matrix alloy will react with SiC particles or the interfacial layer will become thicker at over-elevated temperatures because of the intense atomic diffusion, and the matrix will lose its strength at high temperatures, a suitable temperature for the high pressure sintering should selected in this process.

3.3 Microstructural Examination and Phase Analyses:

The samples have been polished and etched with the etchant (2.5 ml Nitric acid, 15.0 ml Hcl, 1.0 ml HF and 95.0 ml water for microstructure evaluation of the composite. It also helps in determining the grain structure and distribution and alignment of the reinforcement particles in the composite. The gain refinement of metal matrix-based composites reinforced by tough particles can interpret by the increased effective extrusion ratio with increasing volume fraction of incompressible reinforcements. The P/M samples sintered at fixed temperature (530°C) for fixed sintering time (40 mins.) under different compacting pressure, have been prepared and the microstructures (Figure 3.10.1a-e) examined by using microscope (Figure 3.9 Olympus, CK40M).

The white portion of the figure indicates Al Matrix and the black portions indicate SiC_p in the specimen. From the figure it is quite evident that with gradual increase of compacting pressure the porosity of the samples gradually decreases. Similar behaviour is also observed with the variation of sintering time and sinter temperature, the porosity changes (not shown in figure). Decrease in porosity would increase the density. The plastic deformation is beneficial to improve the homogeneity of the reinforcement. Particle matrix debonding and particle agglomerate decohesion are the two mechanisms are of secondary importance when the particles are well distributed and strongly bonded.

Figure 3.9: Optical microscope (Olympus, CK40M).

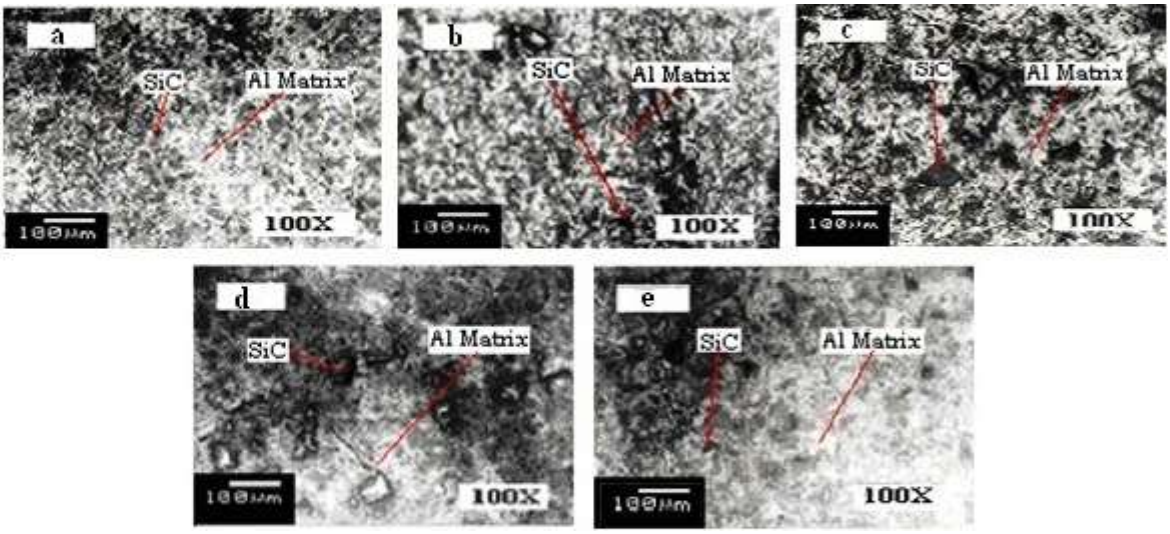


Figure 3.10.1: Microstructure of Al-SiC$_p$ P/M composite specimen at different pressure (a) Compacting pressure 93.63586Ton, Sintering temperature 530°C Sintering time 40 mins; (b) Compacting pressure 80Ton, Sintering temperature 530°C, Sintering time 40 mins; (c) Compacting pressure 60Ton, Sintering temperature 530°C, Sintering time 40 mins; (d) Compacting pressure 40Ton, Sintering temperature 530°C, Sintering time 40 mins. (e) Compacting pressure 26.36414Ton, Sintering temperature 530°C, and Sintering time 40 mins.

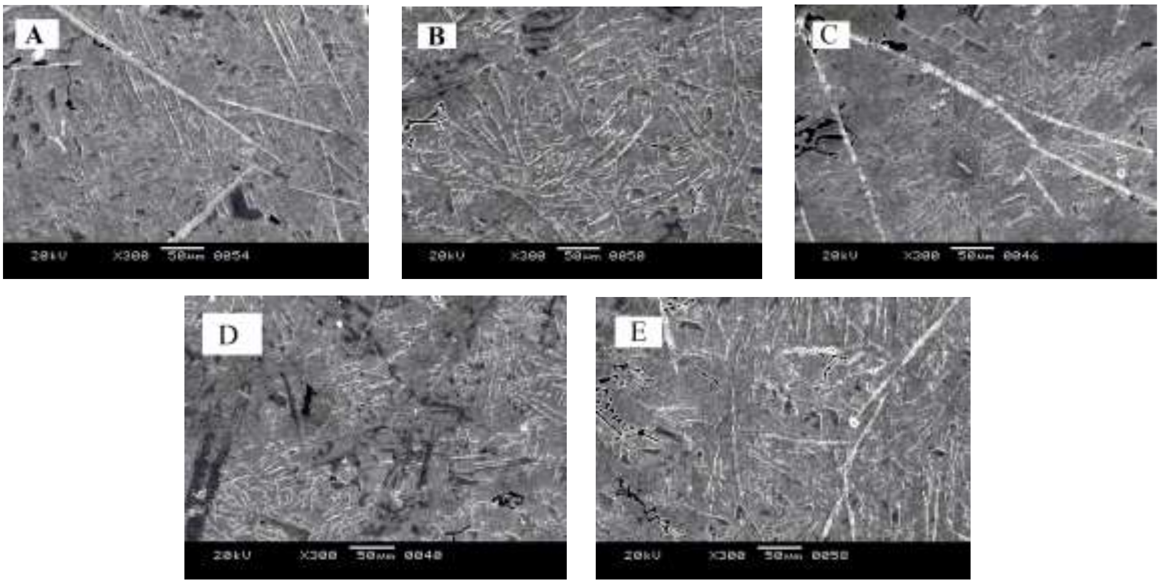


Figure 3.10.2: SEM images of of Al-SiC$_p$ P/M composite specimen at different pressure (A) Compacting pressure 93.63586Ton, Sintering temperature 530°C Sintering time 40 mins; (B) Compacting pressure 80Ton, Sintering temperature 530°C, Sintering time 40 mins; (C) Compacting pressure 60Ton, Sintering temperature 530°C, Sintering time 40 mins; (D) Compacting pressure 40Ton, Sintering temperature 530°C, Sintering time 40 mins. (E) Compacting pressure 26.36414Ton, Sintering temperature 530°C, and Sintering time 40 mins.

A scanning electron microscope (JSM-6360, Japan) is used for this study the microstructure of the prepared composites. Before scanning, samples are cut according to the size of the tray of the machine and polished and etched using proper etchant. Figure 3.10.2A-E shows the SEM micrographs of the composites having different amount of reinforcements. It shows that the composite is compact and SiC particles are almost uniformly distributed in the matrix. The bonding of the material is good resulting in finer grain structure of the composite.

Figure 3.10.3a-e show XRD plots of the specimens. Xray diffraction analyzer (Rigaku, Ultima III) using Cu (40 kV, 30 mA) radiation is used to identify SiC_p phase in the composite. Diffraction peaks are identified through JCPDS software. The plots confirm the presence of aluminum (largest peaks) and SiC_p in the composites. Peak values are collected over the 2θ range of 20◦ -90◦. Peak values are obtained for all the prepared samples and they show varied diffraction peaks. Intensity of aluminum and SiC_p is observed at different peaks.

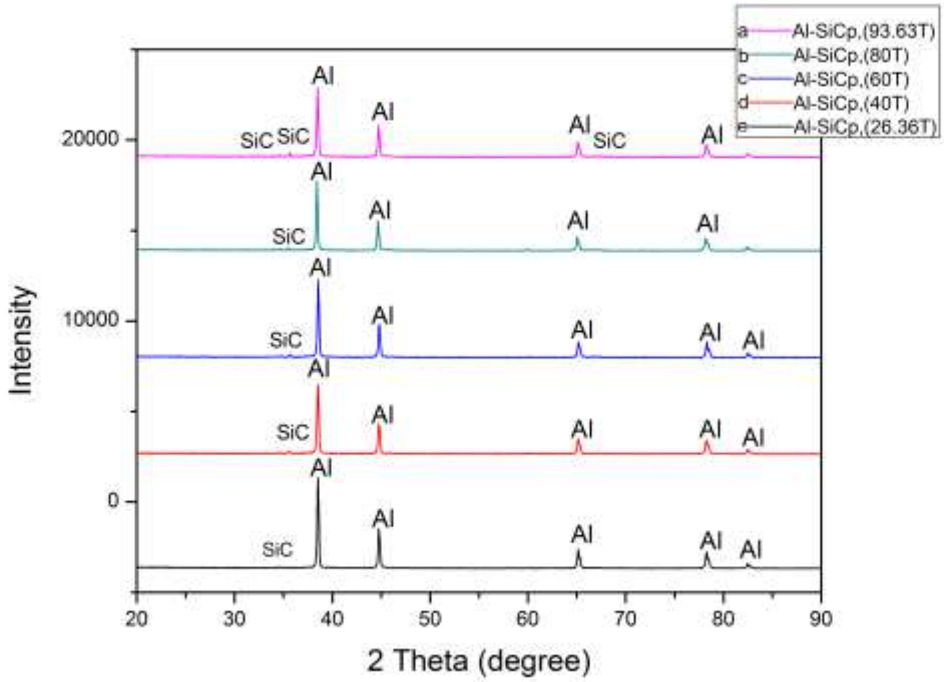


Figure 3.10.3 XRD plots for Al-SiC_p P/M composite specimen at different pressure (a) Compacting pressure 93.63586Ton, Sintering temperature 530°C Sintering time 40 mins; (b) Compacting pressure 80Ton, Sintering temperature 530°C, Sintering time 40 mins; (c) Compacting pressure 60Ton, Sintering temperature 530°C, Sintering time 40 mins; (d) Compacting pressure 40Ton, Sintering temperature 530°C, Sintering time 40 mins. (e) Compacting pressure 26.36414Ton, Sintering temperature 530°C, and Sintering time 40 mins.

The samples were produced by changing the process parameters as per the Design of Experiment (DOE) and the response surface methodology (RSM) has been used to plan and analyse the mechanical properties (density, hardness and forgeability) of aluminium metal matrix composites. The experimental plan adopts the face-centred Central Composite Design (CCD). A second order response surface model has been used to develop a predicting equations based on the data collected by a statistical design of experiments. Present study examines the variation of density (R_1) as a function of process parameters (weight percentage of SiC_p x_1, compacting pressure x_2, and sintering time x_3) of sintered P/M components (Table 3.3). The Analysis of Variation (ANOVA) shows that the observed data fits well into the assumed second order RSM model. It is worth mentioning that this model is one of the most widely used methods to solve the optimization problem in manufacturing technology.

Table 3.3

Symbols, levels and values of process parameters.

Process parameters (Independent variables)	**Symbols**		**Levels**					
	Actual	**Coded**	**Actual**			**Coded**		
Weight percentage of SiC_p	Z_1	X_1	2	5	8	-1	0	+1
Compacting pressure (Ton)	Z_2	X_2	40	60	80	-1	0	+1
Sintering time (Min)	Z_3	X_3	30	40	50	-1	0	+1

3.4 Measurement of Density:

The density of the composites was obtained by the Archimedean principle of weighing the sample first in air and then in water. Then, theoretical density of composite and its alloy has calculated from the chemical analysis data. Then theoretical density of composite and its alloy has calculated from the chemical analysis data. The measured relative density of the compacts was about 81.2%. The gain refinement of metal matrix-based composites reinforced by tough particles can interpret by the increased effective extrusion ratio with increasing volume fraction of incompressible reinforcements (Table 3.4). Since the density of SiC_p (3.215 gm/cm^3) is higher than that of the Aluminium (2.7 gm/cm^3), the addition of SiC_p leads to an increase in the density of the material as long as the reinforcements are uniformly distributed in the matrix and no SiC_p clusters are formed. The measured relative density of the compacts was about 81.2%. The gain refinement of metal matrix-based composites reinforced by tough particles can interpret by the increased effective extrusion ratio with increasing volume fraction of incompressible reinforcement. One of the major objectives of present investigations is to shade light on the density of the compacted sintered samples. In this context 60 different P/M components (diameter 25 mm) were produced according to design of experiment.

3.4.1 Relative Density:

Relative density of the samples was determined by comparing the measured density (by Archimedes principal) of the samples (prepared through sintering) with standard specimen obtained through rolling process. Relative density (R_1) of these samples were measured by hydrostatic weighing method against the variation of controllable process variables like weight percentage of SiC_p (x_1), compacting pressure (x_2), and sintering time (x_3) (Table 3.4).

Table 3.4

Observed Density values for different settings of process parameters based on 2^3 full factorial design.

Std Order	Run Order	Pt Type	Blocks	Wt.% SiCp	Compacting Pressure. (Ton)	Sint.Time (Min)	Rel.Density (gm/cm³)
1	55	1	1	2	40	30	2.712
2	59	1	1	8	40	30	2.892
3	1	1	1	2	80	30	2.702
4	3	1	1	8	80	30	3.02
5	35	1	1	2	40	50	2.7144
6	9	1	1	8	40	50	2.9304
7	4	1	1	2	80	50	2.724
8	19	1	1	8	80	50	3.084
9	27	-1	1	-0.04537849	60	40	2.70027
10	44	-1	1	10.0453785	60	40	3.132
11	13	-1	1	5	26.36414339	40	2.7405
12	2	-1	1	5	93.63585661	40	2.862
13	32	-1	1	5	60	23.18207169	2.76

14	52	-1	1	5	60	56.81792831	2.834
15	15	0	1	5	60	40	2.808
16	54	0	1	5	60	40	2.809
17	58	0	1	5	60	40	2.807
18	29	0	1	5	60	40	2.808
19	47	0	1	5	60	40	2.808
20	21	0	1	5	60	40	2.809
21	14	1	1	2	40	30	2.713
22	38	1	1	8	40	30	2.893
23	25	1	1	2	80	30	2.71
24	10	1	1	8	80	30	3.01
25	41	1	1	2	40	50	2.7145
26	17	1	1	8	40	50	2.9303
27	18	1	1	2	80	50	2.724
28	45	1	1	8	80	50	3.086
29	37	-1	1	-0.04537849	60	40	2.70026
30	23	-1	1	10.0453785	60	40	3.131
31	49	-1	1	5	26.36414339	40	2.74054

32	42	-1	1	5	93.63585661	40	2.863
33	48	-1	1	5	60	23.18207169	2.75
34	6	-1	1	5	60	56.81792831	2.833
35	50	0	1	5	60	40	2.807
36	36	0	1	5	60	40	2.809
37	20	0	1	5	60	40	2.808
38	39	0	1	5	60	40	2.809
39	22	0	1	5	60	40	2.809
40	46	0	1	5	60	40	2.806
41	33	1	1	2	40	30	2.714
42	31	1	1	8	40	30	2.8921
43	12	1	1	2	80	30	2.73
44	16	1	1	8	80	30	3.04
45	40	1	1	2	40	50	2.7115
46	26	1	1	8	40	50	2.9306
47	5	1	1	2	80	50	2.7245
48	7	1	1	8	80	50	3.0845
49	8	-1	1	-0.04537849	60	40	2.70025

50	43	-1	1	10.0453785	60	40	3.132
51	11	-1	1	5	26.36414339	40	2.7405
52	28	-1	1	5	93.63585661	40	2.863
53	56	-1	1	5	60	23.18207169	2.77
54	53	-1	1	5	60	56.81792831	2.834
55	34	0	1	5	60	40	2.809
56	30	0	1	5	60	40	2.808
57	57	0	1	5	60	40	2.807
58	24	0	1	5	60	40	2.807
59	51	0	1	5	60	40	2.806
60	60	0	1	5	60	40	2.808

3.4.2. Mathematical Modelling for Density:

From the results of ANOVA a mathematical model has been proposed for the evaluation of density, RCCD (Density) of the powder metallurgy components. The proposed model is expressed as

$$\text{RCCD (Density)} = -0.820967 + 0.218738\,x1$$

$$+\,0.008407x2 - 0.571286\,x3$$

+ 0.007148x12 – 0.000002x22

+ 0.064705x32 – 0.000333x1x2

– 0.020574x1x3 + 0.000767x2x3

Where, RCCD: response, i.e., density in central composite design.

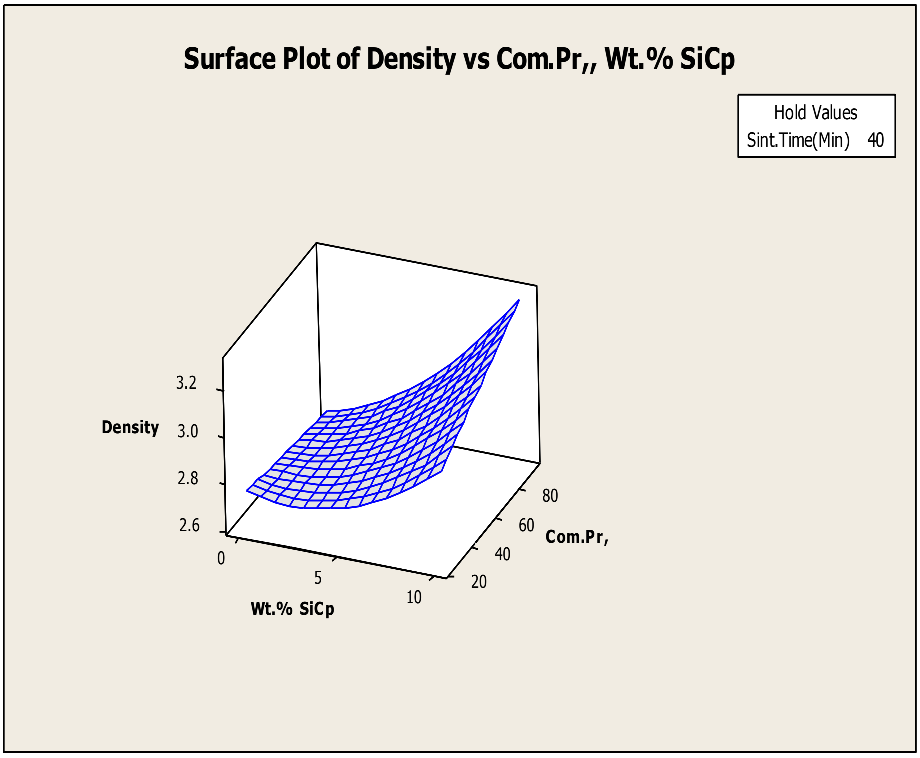


Figure 3.11: Surface Plot of density (R_1) vs. compacting pressure (x_2) and wt% of SiC$_p$ (x_1) for a fixed value of sintering time (x_3).

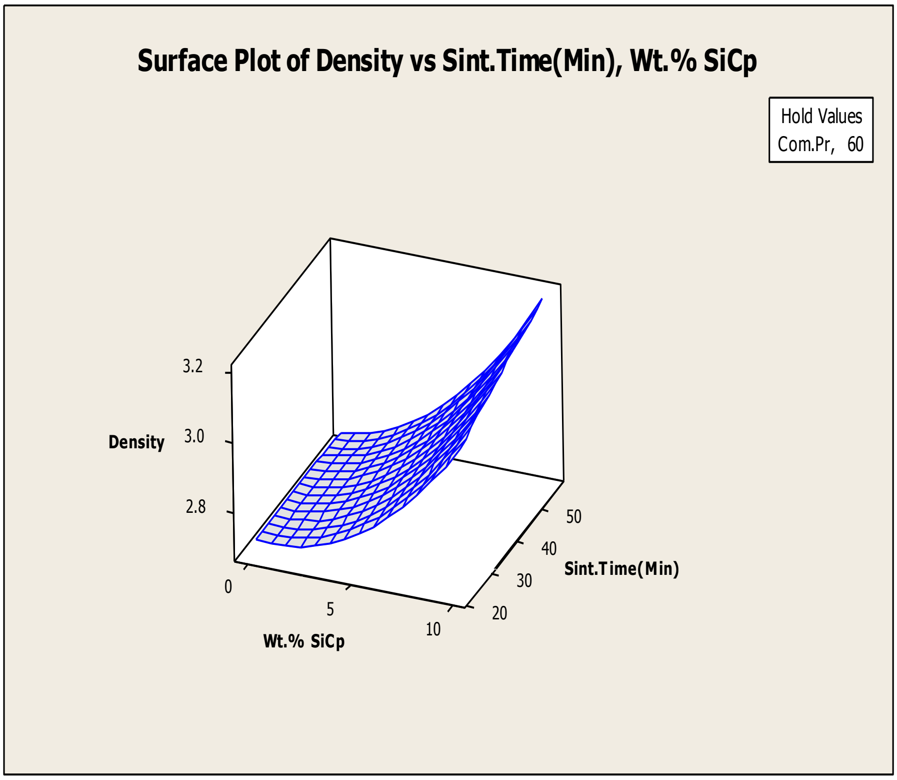


Figure 3.12: Surface Plot of density (R_1) vs. sintering time (x_3) and wt% of SiC$_p$ (x_1) for a fixed value of compacting pressure (x_2).

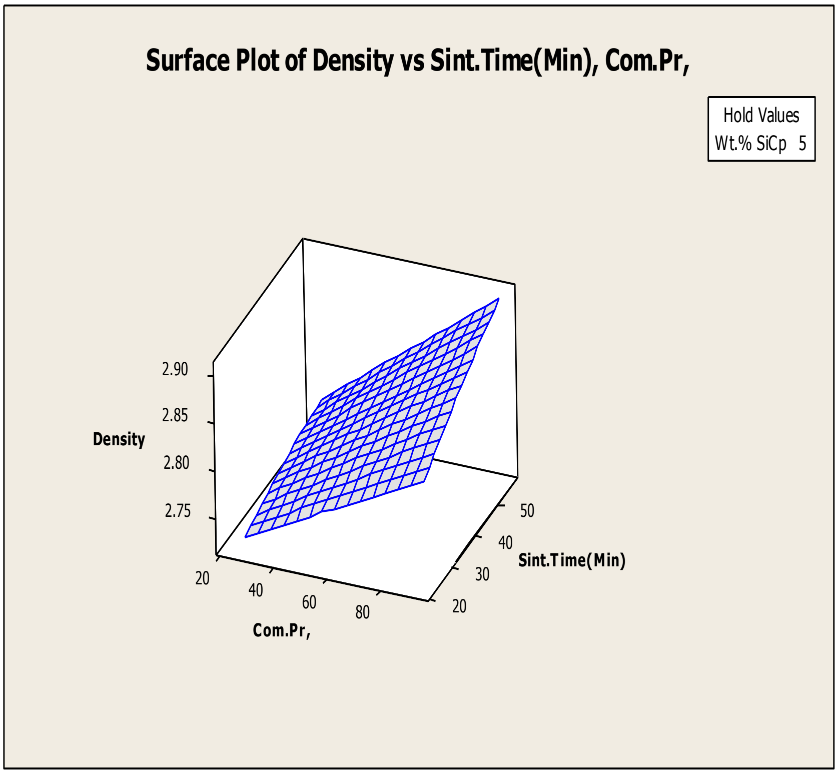


Figure 3.13: Surface Plot of density (R_1) vs. sintering time (x_3) and compacting pressure (x_2) for a fixed value of wt% of SiC$_p$ (x_1).

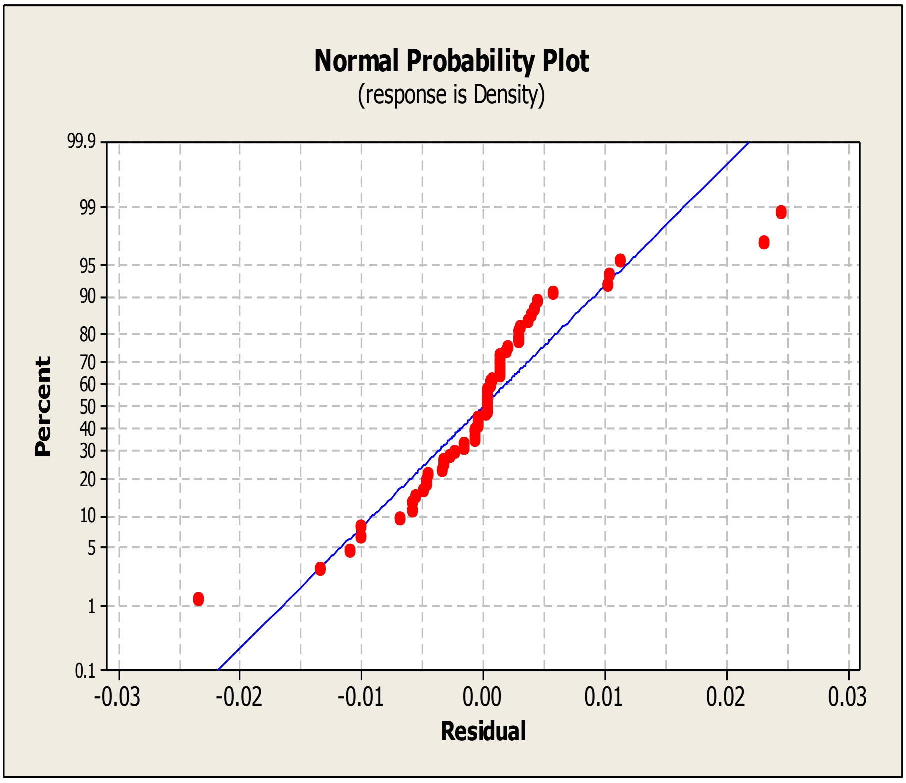


Figure 3.14: Plot between observed density data and predicted density for RSM model.

3.4.3. Result Discussion of Density Test:

Al-SiC$_p$ powder mixtures of different composition are compacted sintered at an inert atmosphere, at a fixed temperature for different time duration. The samples are compacted under different pressure range (40-93.63586 Ton). The total experiment is performed according to the Design of Experiment (DOE). Using the experimental data a mathematical model has been developed to predict the density variations of the using response surface method.

The model shows increase in density due to change in wt% of SiC$_p$ (x_1) and sintering time for compaction load from 40-93.63586 Ton at a fixed sintering time of 40 minutes and for a fixed value of compacting pressure (x_2). The response variable, density (R_1) shows linear increase when it is plotted against sintering time (x_3) and compacting pressure (x_2) for a fixed value of wt% of SiC$_p$ (x_1) and the prediction of density variation from the mathematical model developed in this study matches closely with the observed data (R^2 = 89.8 %).

3.5 Measurement of Hardness:

Hardness is one of the important mechanical properties in case of composite material as the hardness of the matrix metal is very low, which limits its wide application. The hardness of the composites and matrix alloy has measured after polishing to a 6-µm finish. In the experiment the hardness of aluminium alloy composites were measured by Vickers hardness testing machine (Figure 3.15) at different section of the as cast composites.

Figure 3.15: The micro hardness testing machine, for measuring micro hardness of MMCs.

Table 3.5

Observed Hardness values for different settings of process parameters based on 2^3 full factorial design.

Std Order	**Run Order**	**Pt Type**	**Blocks**	**Wt.% SiCp**	**Compacting Pressure.(Ton)**	**Sint.Time (Min)**	**Hardness (VHN)**
1	55	1	1	2	40	30	85.144
2	59	1	1	8	40	30	94.216
3	1	1	1	2	80	30	85.4
4	3	1	1	8	80	30	110.6
5	35	1	1	2	40	50	85.1728
6	9	1	1	8	40	50	96.0592
7	4	1	1	2	80	50	85.48
8	19	1	1	8	80	50	115.72
9	27	-1	1	-0.04537849	60	40	85.00054
10	44	-1	1	10.0453785	60	40	119.56
11	13	-1	1	5	26.36414339	40	85.6075
12	2	-1	1	5	93.63585661	40	94.72
13	32	-1	1	5	60	23.18207169	87.4

14	52	-1	1	5	60	56.81792831	90.36
15	15	0	1	5	60	40	89.31
16	54	0	1	5	60	40	89.36
17	58	0	1	5	60	40	89.32
18	29	0	1	5	60	40	89.34
19	47	0	1	5	60	40	89.35
20	21	0	1	5	60	40	89.38
21	14	1	1	2	40	30	85.134
22	38	1	1	8	40	30	94.216
23	25	1	1	2	80	30	85.44
24	10	1	1	8	80	30	110.62
25	41	1	1	2	40	50	85.1738
26	17	1	1	8	40	50	96.1592
27	18	1	1	2	80	50	85.58
28	45	1	1	8	80	50	115.74
29	37	-1	1	-0.04537849	60	40	85.0154
30	23	-1	1	10.0453785	60	40	119.66
31	49	-1	1	5	26.36414339	40	85.6175

32	42	-1	1	5	93.63585661	40	94.72
33	48	-1	1	5	60	23.18207169	87.34
34	6	-1	1	5	60	56.81792831	90.46
35	50	0	1	5	60	40	89.51
36	36	0	1	5	60	40	89.56
37	20	0	1	5	60	40	89.35
38	39	0	1	5	60	40	89.38
39	22	0	1	5	60	40	89.34
40	46	0	1	5	60	40	89.4
41	33	1	1	2	40	30	85.154
42	31	1	1	8	40	30	94.216
43	12	1	1	2	80	30	85.34
44	16	1	1	8	80	30	111.6
45	40	1	1	2	40	50	85.1728
46	26	1	1	8	40	50	96.0592
47	5	1	1	2	80	50	85.48
48	7	1	1	8	80	50	116.72
49	8	-1	1	-0.04537849	60	40	85.12354

50	43	-1	1	10.0453785	60	40	120.56
51	11	-1	1	5	26.36414339	40	85.6275
52	28	-1	1	5	93.63585661	40	94.92
53	56	-1	1	5	60	23.18207169	87.35
54	53	-1	1	5	60	56.81792831	90.46
55	34	0	1	5	60	40	89.35
56	30	0	1	5	60	40	89.46
57	57	0	1	5	60	40	89.29
58	24	0	1	5	60	40	89.41
59	51	0	1	5	60	40	89.45
60	60	0	1	5	60	40	89.48

3.5.1. Mathematical Modelling for Hardness:

From the results of ANOVA a mathematical model has been proposed for the evaluation of hardness HCCD of the powder metallurgy components. The proposed model is expressed as

HCCD (Hardness) = $89.3690 + 16.5935x1$

$+ 6.4900x2 + 1.5144x3$

+ 13.5038x12 +1.2193x22

– 0.0878x32 + 12.7640x1x2

+2.4209 x1x3+1.1789x2x3

Where HCCD: response, i.e., hardness in central composite design.

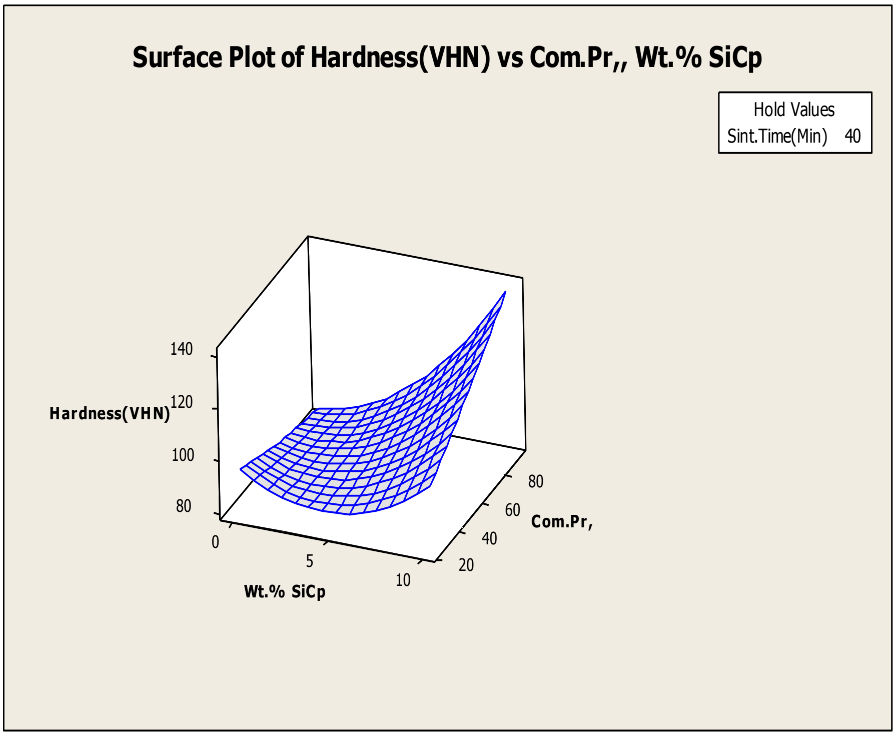


Figure 3.16: Surface Plot of hardness (R_1) vs. compacting pressure (x_2) and wt% of SiC$_p$ (x_1) for a fixed value of sintering time (x_3).

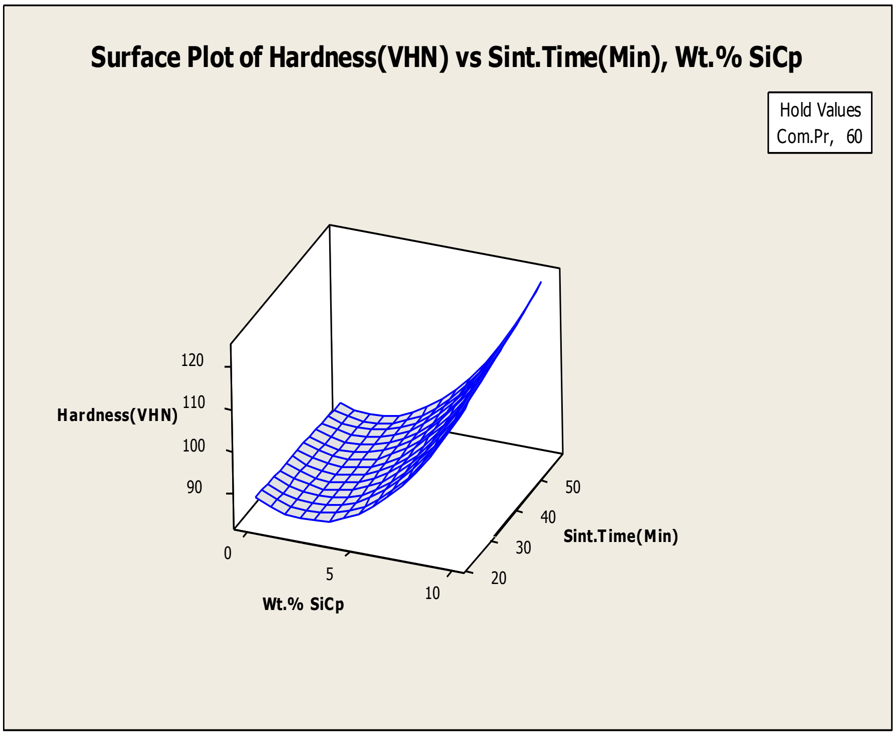


Figure 3.17: Surface Plot of hardness (R_1) vs. sintering time (x_3) and wt% of SiC_p (x_1) for a fixed value of compacting pressure (x_2).

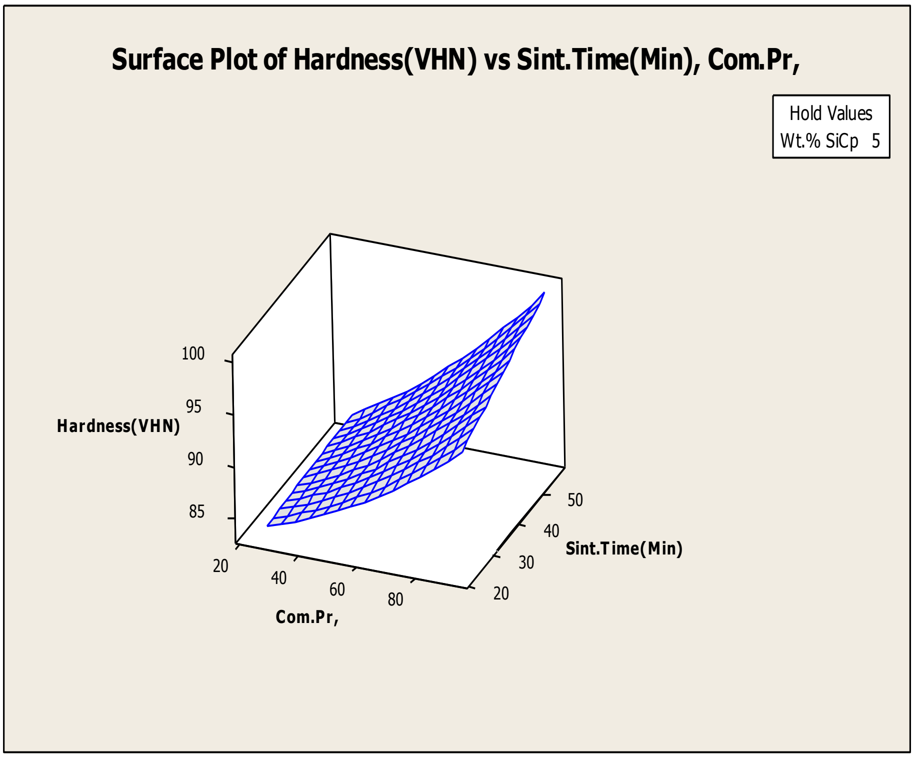


Figure 3.18: Surface Plot of hardness (R_1) vs. sintering time (x_3) and compacting pressure (x_2) for a fixed value of percentage weight of SiC_p (x_1).

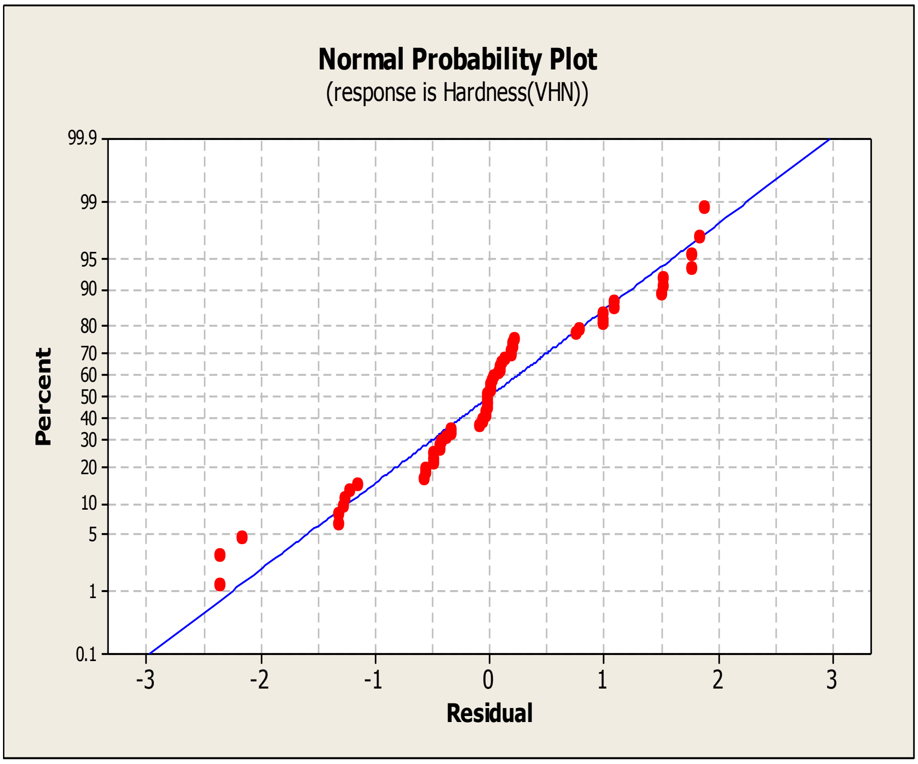


Figure 3.19: Plot between observed hardness data and predicted hardness for RSM model.

3.5.2. Result Discussion of Hardness Test:

Hardness of Silicon carbide particle reinforced aluminium metal matrix composites (Al-SiC$_p$) are influenced by sintering temperature, SiC$_p$ percentage weight and compacting pressure. A mathematical model has been used to predict the hardness variations by response surface method using the experimental data. The model shows increase in density due to change in percentage weight of SiC$_p$ (x_1) and sintering time for a fixed value of compacting pressure (x_2). The response variable, density (R_1) shows linear increase when it is plotted against sintering time (x_3) and compacting pressure (x_2) for a fixed value of wt% of SiC$_p$ (x_1). The prediction of hardness variation from the mathematical model developed in this study matches closely with the observed data (R^2 = 99.12%) which represents a highly reliable design of experiments.

3.6. Measurement of Forgeability:

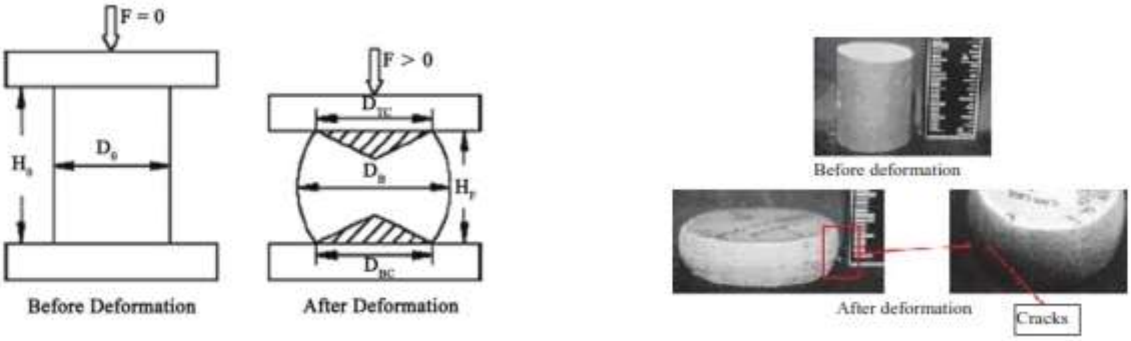
The limit of forgeability is expressed as the critical reduction in height % critical, by the following equation:

$$\% \text{ Critical} = \frac{H_F - H_O}{H_F}$$

where (H_O) is the initial height of the sample and Initial diameter is (D_O) in mm. After each interval of loading dimensional changes in the specimen such as (H_F) is the final height of the sample in mm after deformation top contact diameter (D_{TC}), bottom contact diameter (D_{BC}), bulged diameter (D_B).

Figure 3.20: 20 Ton Hydraulic Press used for upsetting of MMC specimens at room temperature.

Critical reductions under unlubricated conditions only have compared to assess the forgeability of the experimental materials. The impact load was applied at room temperature on samples of different composition (Figure 3.20-3.21). At different load, the percentage of deformation investigated.



(a) (b)

Figure 3.21: (a) Forgeability, (b) Photographs showing performance before and after forgeability test.

Table 3.6

Observed Forgeability values for different settings of process parameters based on 2^3 full factorial design.

Std Order	**Run Order**	**Pt Type**	**Blocks**	**Wt.% SiCp**	**Compacting Pressure.(Ton)**	**Sint. Time (Min)**	**Forgeability (% of deformation)**
1	55	1	1	2	40	30	13.33
2	59	1	1	8	40	30	0.8336
3	1	1	1	2	80	30	8
4	3	1	1	8	80	30	0.5
5	35	1	1	2	40	50	11.11
6	9	1	1	8	40	50	0.6944

7	4	1	1	2	80	50	6.6656
8	19	1	1	8	80	50	0.41664
9	27	-1	1	-0.04537849	60	40	27
10	44	-1	1	10.0453785	60	40	0.37036
11	13	-1	1	5	26.36414339	40	3.9504
12	2	-1	1	5	93.63585661	40	0.9875
13	32	-1	1	5	60	23.18207169	2.6656
14	52	-1	1	5	60	56.81792831	1.19402
15	15	0	1	5	60	40	1.48142
16	54	0	1	5	60	40	1.50142
17	58	0	1	5	60	40	1.47942
18	29	0	1	5	60	40	1.48542
19	47	0	1	5	60	40	1.51142
20	21	0	1	5	60	40	1.48341
21	14	1	1	2	40	30	13.52
22	38	1	1	8	40	30	0.8456
23	25	1	1	2	80	30	8.21
24	10	1	1	8	80	30	0.49

25	41	1	1	2	40	50	11.211
26	17	1	1	8	40	50	0.7044
27	18	1	1	2	80	50	6.6666
28	45	1	1	8	80	50	0.41594
29	37	-1	1	-0.04537849	60	40	28
30	23	-1	1	10.0453785	60	40	0.36536
31	49	-1	1	5	26.36414339	40	3.9552
32	42	-1	1	5	93.63585661	40	0.9869
33	48	-1	1	5	60	23.18207169	2.6556
34	6	-1	1	5	60	56.81792831	1.19435
35	50	0	1	5	60	40	1.48152
36	36	0	1	5	60	40	1.50165
37	20	0	1	5	60	40	1.47973
38	39	0	1	5	60	40	1.48551
39	22	0	1	5	60	40	1.51132
40	46	0	1	5	60	40	1.48345
41	33	1	1	2	40	30	13.44
42	31	1	1	8	40	30	0.8537

43	12	1	1	2	80	30	7.89
44	16	1	1	8	80	30	0.6
45	40	1	1	2	40	50	11.41
46	26	1	1	8	40	50	0.6956
47	5	1	1	2	80	50	6.6336
48	7	1	1	8	80	50	0.41664
49	8	-1	1	-0.04537849	60	40	27.49
50	43	-1	1	10.0453785	60	40	0.36935
51	11	-1	1	5	26.36414339	40	3.9526
52	28	-1	1	5	93.63585661	40	0.9869
53	56	-1	1	5	60	23.18207169	2.6655
54	53	-1	1	5	60	56.81792831	1.19435
55	34	0	1	5	60	40	1.48124
56	30	0	1	5	60	40	1.51457
57	57	0	1	5	60	40	1.47953
58	24	0	1	5	60	40	1.48564
59	51	0	1	5	60	40	1.51153
60	60	0	1	5	60	40	1.48341

3.6.1. Mathematical Modelling for Forgeability:

From the results of ANOVA a mathematical model has been proposed for the evaluation of Forgeability F_{CCD} of the powder metallurgy components. The proposed model is expressed as

F_{CCD} (Forgeability) = $1.5286 - 10.1593\ x1$

$-1.9172\ x2 - 0.7750\ x3$

$+ 11.7495\ x1^2 + 0.2869\ x2^2$

$- 0.2547\ x3^2 + 3.3195\ x1x2$

$+ 1.1684\ x1x3 + 0.2973\ x2x3$

Where F_{CCD}: response, i.e., Forgeability in central composite design.

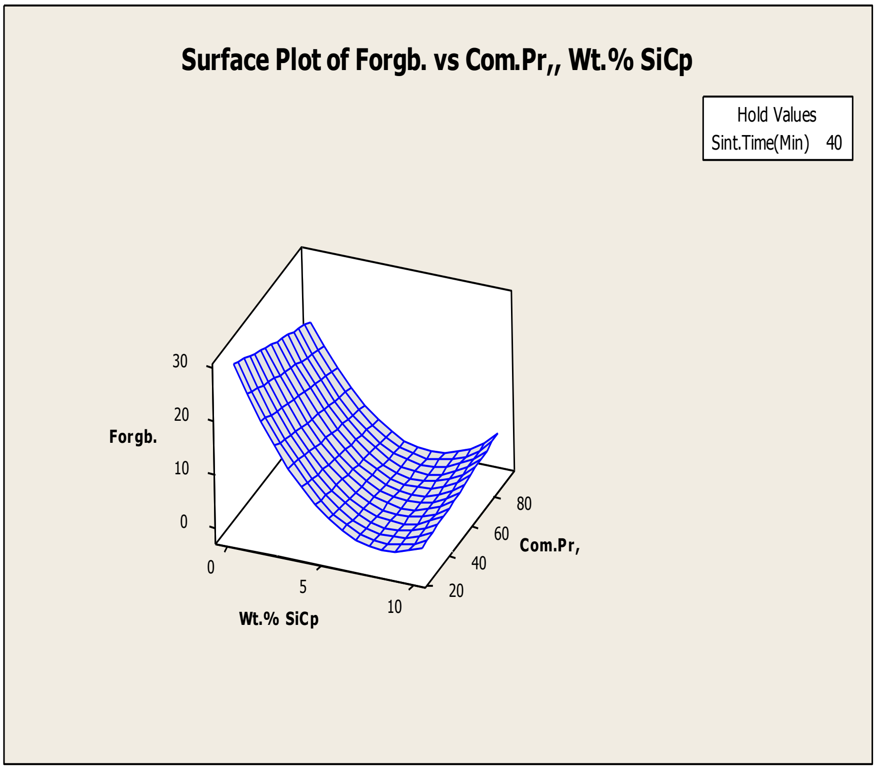


Figure 3.22: Surface Plot of Forgeability (R_1) vs. compacting pressure (x_2) and wt% of SiC_p (x_1) for a fixed value of sintering time (x_3).

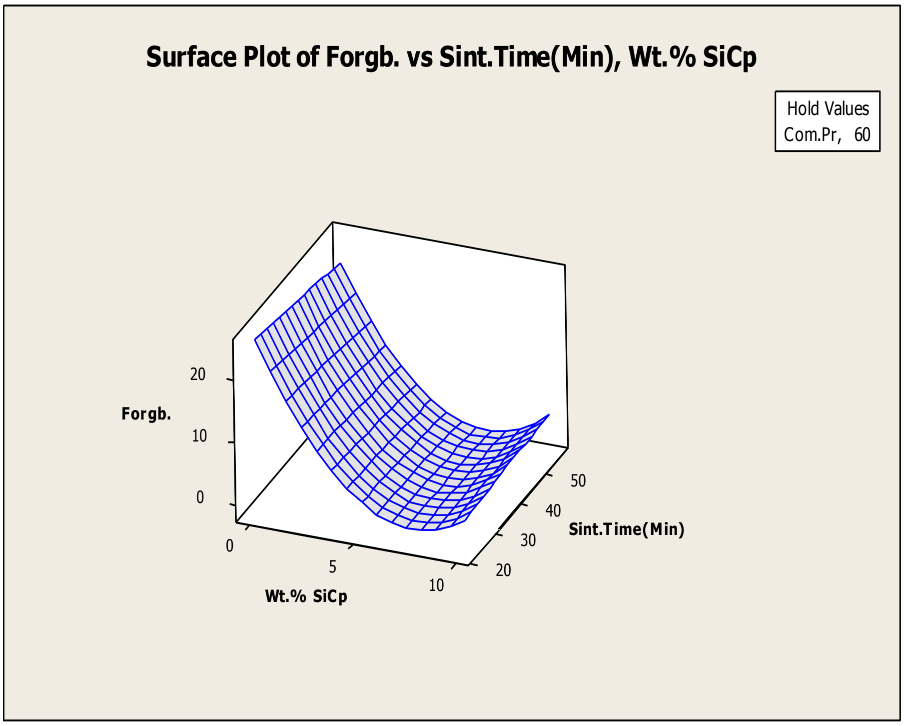


Figure 3.23: Surface Plot of Forgeability (R_1) vs. sintering time (x_3) and wt% of SiC_p (x_1) for a fixed value of compacting pressure (x_2).

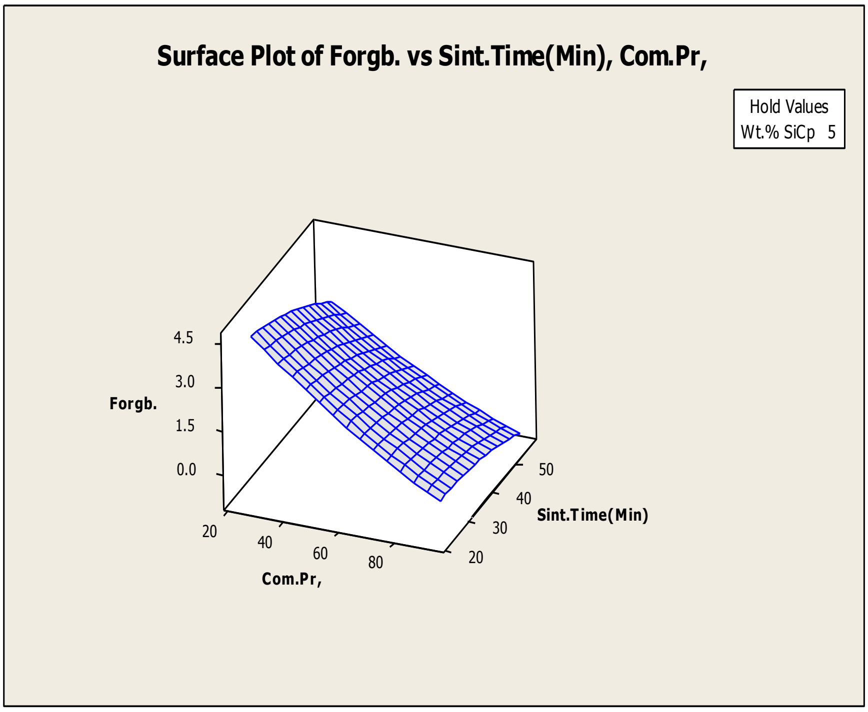


Figure 3.24: Surface Plot of Forgeability (R_1) vs. sintering time (x_3) and compacting pressure (x_2) for a fixed value of wt% of SiC_p (x_1).

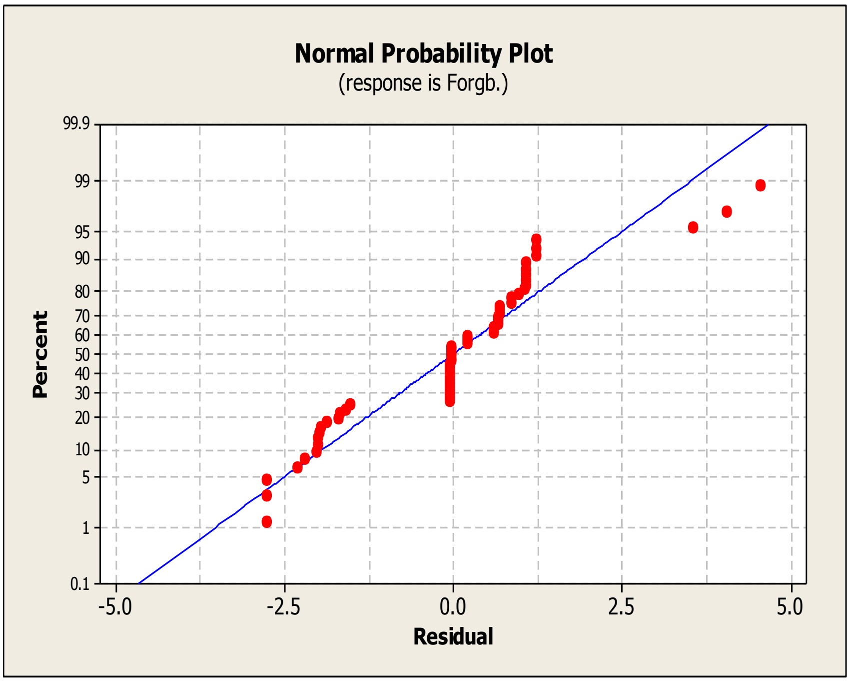


Figure 3.25: Plot between observed Forgeability data and predicted Forgeability for RSM model.

3.6.2. Result Discussion of Forgeability Test:

Forgeability of Al-SiC_p composites are influenced by sintering temperature, wt% of SiC_p and compacting pressure. The forgeability of the MMCs decreases on increasing the wt% of SiC_p in the matrix metal as the brittleness of the composite material increases on increment of wt% of SiC_p in MMCs. The variation of forgeability against wt% of SiC_p (x_1) and compaction load for a fixed value of sintering time (40 minutes) is presented in Figure 7(a), which exhibits a decreasing tendency in forgeability due to increasing in wt% of SiC_p (x_1) and compaction load from 40-93.63586 Ton at a fixed sintering time of 40 minutes. Identical nature of variation is noted in simultaneous increase of sintering time (x_3) and wt% of SiC_p (x_1) for a fixed value of compacting pressure (x_2), which is shown in Figure 7(b). In Figure 7(c) the response variable, forgeability (R_1) shows linear decrease when it is plotted against sintering time (x_3) and compacting pressure (x_2) for a fixed value of wt% of SiC_p (x_1). In this case, the range of variation of the parameters is similar to that of previous two cases. It is worth mentioning that in all the cases the hold values are mean value of the range of variation corresponding to each variable. Average values are preferred because of the inherent nature of the RSM model. This is also evident from the findings that co-efficient of determination (R-Square) value is 94.8 %. Hence, it may be concluded that the prediction made by this developed model corroborates well with the experimental observations.

CHAPTER 4

CONCLUSION

CONCLUSION

In the experimental study, Al-SiC$_p$ metal matrix composites are produced through P/M route. Microstructures, forgeability and mechanical properties were studied in this work. Using the experimental data a mathematical model the variations of properties of Al-SiC$_p$ metal matrix composites has been predicted. The following conclusions can be made:

Different weight fraction of SiC particulates could be introduced to aluminum matrix by traditional powder metallurgy technique.

The microstructural analysis reveals that the composites fabricated by traditional powder metallurgy technique have fairly even distribution of reinforcements in the composite material.

In the case of composites porosity increased with increasing the weight fraction of silicon carbide particle.

The density increased with increasing the weight fraction of silicon carbide particle. The model shows increase in density due to change in wt% of SiC$_p$ (x_1) and sintering time for compaction load from 40-93.63586 Ton at a fixed sintering time and compacting pressure (x_2). The response variable, density (R_1) shows linear increase, when it is plotted against sintering time (x_3) and compacting pressure (x_2) for a fixed value of wt% of SiC$_p$ (x_1) and the prediction of density variation from the mathematical model developed in this study matches closely with the observed data (R^2 = 89.8 %).

Hardness values gradually increase with increasing weight fraction of SiC$_p$ (x_1) in composite specimens. Hardness also increases with sintering time for a fixed value of compacting pressure (x_2). The prediction of hardness variation from the mathematical model developed in this study matches closely with the observed data (R^2 = 99.12%) which represents a highly reliable design of experiments.

Forgeability of the MMCs decreases on increasing the percentage of SiC_p in the matrix metal as the brittleness of the composite material increases on increasing the percentage of SiC_p in MMCs. The mathematical model shows a decreasing tendency in forgeability due to increasing in wt% of SiC_p (x_1) and compaction load from 40-93.63586 Ton at a fixed sintering time of 40 minutes. Identical nature of variation is noted in simultaneous increase of sintering time (x_3) and wt% of SiC_p (x_1) for a fixed value of compacting pressure (x_2). In the response variable, forgeability (R_1) shows linear decrease when it is plotted against sintering time (x_3) and compacting pressure (x_2) for a fixed value of wt% of SiC_p (x_1). This is also evident from the findings that co-efficient of determination (R-Square) value is 94.8 %.

Hence, it may be concluded that the prediction made by this developed model corroborates well with the experimental observations.

It has also concluded that the percentage of deformation increases on increasing the upsetting load.

CHAPTER 5

SCOPE OF FUTURE WORK

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Engineering interest in aluminium alloy based metal matrix composites (AMMCs) has increased, owing to their improved properties and lightweight characteristics compared to traditional materials. Recently, metal matrix composites (MMCs) have emerged as potential alternatives to conventional alloys in high strength and stiffness applications. Particularly, the application of Aluminium based MMCs in automobile and aerospace sector has increased day to day.

The size and percentage of reinforcement particles in the matrix metal plays a vital role and it affects the overall properties of the metal matrix composites.

In this study silicon carbide particles of 400 mesh (average particle size) have been used. This work can be further extended with the help of other particle sizes to study the effect of particle size on mechanical properties, forgeability and machinability of the composite.

The continued growth of aluminium powder metallurgy products in automotive and other engineering applications is largely dependent on the development of higher precision component and improved mechanical, functional and geometrical properties. The final properties of sintered components are determined by various processing variables like powder size, size distribution, powder composition and other alloying elements.

Mechanical properties, forgeability, machinability and hardenability of sintered powders can be improved by addition of elements such as Titanium, Chromium, Molybdenum, Nickel, Manganese and Copper whose machining behaviour need to be studied further for developing better AMMC products by P/M route.

The competitiveness of P/M precision components is enhanced by secondary operations which improve mechanical, functional and geometrical properties. Out of these operations, machining of AMMC components seems to be the most complicated and least understood, even today. The success of machining of conventional materials was achieved by the use of new- cutting tool materials produced by powder metallurgy. Selection of new P/M tool materials can be expected to boost machining of P/M precision parts, both in regard to increased productivity (e.g. through higher cutting speeds) and to reduce overhead cost.

There are various ways to improve the machinability of sintered P/M components of which certain parameters have been considered in the present work. However, improvement of machinability of sintered iron components is a continuous process and there is enough future scope to carry out investigation on other controlling parameters e.g. tool geometry, newer additives and improved sintering conditions.

In future the same study could be done with different reinforcing particles like Alumina, Tungsten Carbide, Boron Carbide etc, and with their micro and nano sized particles.

Therefore, a lot of research work is essential in manufacturing of AMMCs and its properties.