

Metal Casting- A General Review

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ABSTRACT

This paper deals about the trends of Al/Al alloys based metal casting . It reviews the historical events of metal matrix composites (MMCs), produced in casting industries. After a brief introduction on properties of metal matrix composites. Processing and the developments of the metal matrix composites have been discussed at length. On the basis of above said subject, the future research needs in metal matrix composites on the basis of applications of the casting in industry was discussed.

Keywords: Metal Casting, Composites, Metal matrix Composites.

INTRODUCTION

Due to the wide choice of materials, today's engineers are posed with a big challenge for the right selection of a material and the right selection of a manufacturing process for an application. There are more than 50,000 materials available to engineers for the design and manufacturing of products for various applications. It is difficult to study all of these materials individually; therefore, a broad classification is necessary for simplification and characterization [1-2].

Types of materials

Materials, depending on their major characteristics (e.g., stiffness, strength, density, and melting temperature), can be broadly divided into four main categories: (1) metals, (2) plastics, (3) ceramics, and (4) composites.

2.1. Metals

Metals have been the dominating materials in the past for structural applications. They provide the largest design and processing history to the engineer. The common metals are iron, aluminum, copper, magnesium, zinc, lead, nickel, and titanium. In structural applications, alloys are more frequently used than pure metals. Alloys are formed by mixing different materials, sometimes including nonmetallic elements. Alloys offer better properties than pure metals. For example, cast iron is brittle and easy to corrode, but the addition of less than 1% carbon in iron makes it tougher, and the addition of chromium makes it corrosion-resistant. Through the principle of alloying, thousands of new metals are created. Metals are, in general, heavy as compared to

plastics and composites. Only aluminum, magnesium, and beryllium provide densities close to plastics. Steel is 4 to 7 times heavier than plastic materials; aluminum is 1.2 to 2 times heavier than plastics[3]. Metals generally require several machining operations to obtain the final product. Metals have high stiffness, strength, thermal stability, and thermal and electrical conductivity. Due to their higher temperature resistance than plastics, they can be used for applications with higher service temperature requirements[4-6].

2.2. *Plastics*

Plastics have become the most common engineering materials over the past decade. In the past 5 years, the production of plastics on a volume basis has exceeded steel production. Due to their light weight, easy process-ability and corrosion resistance, plastics are widely used for automobile parts, aerospace components, and consumer goods. Plastics can be purchased in the form of sheets, rods, bars, powders, pellets, and granules. With the help of a manufacturing process, plastics can be formed into near-net-shape or net-shape parts. They can provide high surface finish and therefore eliminate several machining operations. This feature provides the production of low-cost parts. Plastics are not used for high-temperature applications because of their poor thermal stability. In general, the operating temperature for plastics is less than 100°C. Some plastics can take service temperature in the range of 100 to 200°C without a significant decrease in the performance[7]. Plastics have lower melting temperatures than metals and therefore they are easy to process.

2.3. *Ceramics*

Ceramics have strong covalent bonds and therefore provide great thermal stability and high hardness. They are the most rigid of all materials. The major distinguishing characteristic of ceramics as compared to metals is that they possess almost no ductility. They fail in brittle fashion. Ceramics have the highest melting points of engineering materials. They are generally used for high-temperature and high-wear applications and are resistant to most forms of chemical attack. Ceramics cannot be processed by common metallurgical techniques and require high-temperature equipment for fabrication. Due to their high hardness, ceramics are difficult to machine and therefore require netshape forming to final shape. Ceramics require expensive cutting tools, such as carbide and diamond tools[7-8].

2.4. *Composites*

Composite materials have been utilized to solve technological problems for a long time but only in the 1960s did these materials start capturing the attention of industries with the introduction of polymeric-based composites. Since then, composite materials have become common engineering materials and are designed and manufactured for various applications including automotive components, sporting goods, aerospace parts, consumer goods, and in the marine and oil industries. The growth in composite usage also came about because of increased awareness regarding product performance and increased competition in the global market for lightweight components. Among all materials, composite materials have the potential to replace widely used steel and aluminum/ aluminum alloys and many times with better performance. Replacing steel components with composite components can save 60 to 80% in component weight and 20 to 50% weight by replacing aluminum parts[9-11]. Today, it appears that composites are the materials of choice for many engineering applications.

The properties of a composite depend on the following:

- Properties of constituent phases.
- Relative amounts of constituents.
- Geometry of the dispersed phase (Shape of particles, Particle size, Particle distribution).

- Interfacial reactions between constituents

Several properties of the composites may be assessed by the rule of mixture (ROM), which states that the property of the composite is the sum of products of the property of an individual constituent and its volume fraction in the composite[11].

3. Aluminum/ Al Alloys

Aluminum (Al) had been at the center of a variety of engineering applications since long. It was first of all produced in the laboratory long back in 1825 by reducing aluminum chloride; however, its wide acceptance as an engineering material did not occur till World War II. Aluminum is the most abundant metal in nature around 8% by weight in the earth's crust. The ore from which most aluminum is presently extracted is BAUXITE (Hydrate Aluminum Oxide). About 25% of the total aluminum produced in World is used for Containing and Packaging, about 20% of it is used in architectural applications and about 10% of Al produced is used for electrical conductors. The remainder i.e. 45% is used for durable goods in industry, consumer products, vehicles, and airspace applications[11, 12]. Aluminum is capable of mixing with other metals in liquid state, but solid solubility of alloying elements is typically only up to a few percent. In some cases inter-metallic compounds are formed and become a part in the structure of the aluminum alloy. No element is completely soluble in aluminum in the solid state. The percentage of alloy elements in useful aluminum alloys does not exceed about 15%. A number of other elements in aluminum will also be added because of their roles in fabrication and strengthening. The alloy-designation for Al is based on four digits corresponding to the principal alloying elements. The most important alloying elements in aluminum alloy systems are copper (2xxx), manganese (3xxx), silicon (4xxx),magnesium (5xxx) and zinc (7xxx)[11, 13]. A number of other elements and compounds may also be added to Al for special purposes to have a new class of materials called Metal Matrix Composites (MMCs), which are most important because of their roles in fabric-ability, electrical conductivity, thermal conductivity and strengthening.

4. Some Features of Composites

Composites have been routinely designed and manufactured for applications in which high performance and light weight are needed[13-16].They offer several advantages over traditional engineering materials are discussed as:

- Composite materials provide capabilities for part integration. Several metallic components can be replaced by a single composite component.
- Composite structures provide in-service monitoring or online process monitoring with the help of embedded sensors. This feature is used to monitor fatigue damage in aircraft structures or can be utilized to monitor the resin flow in an RTM (resin transfer molding) process. Materials with embedded sensors are known as "smart" materials.
- Composite materials have a high specific stiffness (stiffness-to-density ratio). Composites offer the stiffness of steel at one fifth the weight and equal the stiffness of aluminum at one half the weights
- The specific strength (strength-to-density ratio) of a composite material is very high. Due to this, airplanes and automobiles move faster and with better fuel efficiency.
- The fatigue strength (endurance limit) is much higher for composite materials. Steel and aluminum alloys exhibit good fatigue strength up to about 50% of their static strength
- Composite materials offer high corrosion resistance. Iron and aluminum/ aluminum alloys corrode in the presence of water and air and require special coatings.
- Composite materials offer increased amounts of design flexibility.

- Net-shape or near-net-shape parts can be produced with composite materials. This feature eliminates several machining operations and thus reduces process cycle time and cost.
- Complex parts, appearance and special contours, which are sometimes not possible with metals, can be fabricated using composite materials without welding or riveting the separate pieces.
- Composite materials offer greater feasibility for employing design for manufacturing (DFM) and design for assembly (DFA) techniques.
- Noise, vibration and harshness (NVH) characteristics are better for composite materials than metals.
- The cost of tooling required for composites processing is much lower than that for metals processing because of lower pressure and temperature requirements.

5. Terminology in Composites

Some of the more prominent terms used with composite materials are defined below. A more detailed list can be found in Tsai, as well as in the Glossary.

Lamina: A lamina is a (or sometimes curved) arrangement of unidirectional (or woven) fibers suspended in a matrix material. A lamina is generally assumed to be orthotropic, and its thickness depends on the material from which it is made. For example, a graphite/epoxy (graphite fibers suspended in an epoxy matrix) lamina may be on the order of 0.005 in (0.127 mm) thick. For the purpose of analysis, a lamina is typically modeled as having one layer of fibers through the thickness. This is only a model and not a true representation of fiber arrangement.



Figure 1: Types of Composites

Reinforcements: Reinforcements are used to make the composite structure or component stronger. The most commonly used reinforcements are boron, glass, graphite (often referred to as simply carbon), and Kevlar, but there are other types of reinforcements such as alumina, aluminum, silicon carbide, silicon nitride, and titanium. It is of two forms firstly FIBERS or WHISKERS and secondly PARTICULATE. Fibers may be continuous or discontinuous in nature[15, 17].

Matrix: The matrix is the binder material that supports, separates, and protects the fibers. It provides a path by which load is both transferred to the fibers and redistributed among the fibers in the event of fiber breakage. The matrix typically has a lower density, stiffness, and strength than the fibers. Matrices can be brittle, ductile, elastic, or plastic. They can have either linear or non-linear stress-strain behavior. In addition, the matrix material must be capable of being forced around the reinforcement during some stage in the manufacture of the composite. Fibers

must often be chemically treated to ensure proper adhesion to the matrix. The most commonly used matrices are carbon, ceramic, glass, metal, and polymeric. Each has special appeal and usefulness, as well as limitations. Richardson presents a comprehensive discussion of matrices, which guided the following presentation[18].

6. Metal Matrix Composites

Metal matrix composites are materials with metals as the base and distinct, typically ceramic phases added to improve the properties. Although it is desired that these phases remain distinct and separate, reactions do occur between them. If this is the case, it affects the processing and final properties of the composites, regardless of which type of reinforcement is used. The Metal Matrix Composites (MMCs), in general, consist of continuous or discontinuous fibers, whiskers or particulate dispersed in a metallic alloy matrix. The reinforcements provide the composite with the properties not achievable in monolithic alloys. Continuous fiber composites have been especially restrained, finding use only in high value parts in the aerospace field. This is due to the difficulty in processing of the materials, forcing manufacturers to offer them at high cost. Discontinuous metal matrix composites, isotropic in nature, have more options and ease of preparation than continuously reinforced types, so that cost is lowered and acceptance is wider. However, even these materials are limited to a few industrial applications. MMCs represent a new generation of engineering materials in which a strong ceramic reinforcement is incorporated into a metal matrix to improve its properties including specific strength, specific stiffness, wear resistance, corrosion resistance and elastic modulus. Thus, they have significant scientific, technological and commercial importance. During the last decade, because of their improved properties, MMCs are being used extensively for high performance applications such as in aircraft engines and more recently in the automotive industries. Aluminium oxide and silicon carbide powders in the form of fibers and particulate are commonly used as reinforcements in MMCs and the addition of these reinforcements to aluminum alloys has been the subject of a considerable amount of research work[17, 19-20].

Among the various types of MMCs, particulate-reinforced composites are the most versatile and economical one. During the past 40 years, materials design has shifted emphasis to pursue lightweight, environment friendliness, low cost, quality, and performance materials. Parallel to this trend, metal-matrix composites have been attracting growing interest. MMCs attributes include alterations in mechanical behavior and physical properties by the reinforced filler phase. Apart from these advantages, MMCs have limitations on thermal fatigue, thermo chemical compatibility, and possess lower transverse creep resistance. In the year 1996, the worldwide composite use was around 2.5 Million Kg and is increased to around 5 Million kg by the year 2007 which might have become manifold by now. Aluminum alloys reinforced with very high volume fractions of ceramic particulate or fibers are evincing much interest for structural applications that require high specific modulus, low thermal expansion coefficient and wear resistance.

However, the development of these materials has been hindered by difficulties in fabrication and shaping them for end user application. MMCs are classified into three categories depending on the aspect ratio of the reinforced phase. Firstly we have unidirectional aligned filaments embedded in a matrix. Mechanical properties like strength and stiffness are higher in the longitudinal direction than those in transverse direction of fibers. Second is a short fiber or whisker reinforced composite. Lastly we have particulate composites in which there are irregular type of particles dispersed in metal matrix[20-21].

7. How MMCs differ from other materials

MMCs differ from other composite materials in several ways. Some of these general distinctions are as follows:

- The matrix phase of an MMCs is either a pure or alloy metal as opposed to a polymer or ceramic.
- MMCs evidence higher ductility and toughness than ceramics or CMCs, although they have lower ductility and toughness than their respective unreinforced metal matrix alloys.
- The role of the reinforcement in MMCs is to increase strength and modulus as is the case with PMCs. Reinforcement in CMCs is generally to provide improved damage tolerance.
- MMCs have a temperature capability generally higher than polymers and PMCs but less than ceramics and CMCs.
- Low to moderately reinforced MMCs are formable by processes normally associated with unreinforced metals.

8. Fabrication Methods

8.1. Solid-State Processes

8.1.1. Deformation processing

It can also be used to deform the composite material. In MMCs mechanical processing (swaging, extrusion, drawing, or rolling) of a ductile two-phase material causes the two phases to co-deform, causing one of the phases to elongate and become fibrous in nature within the other phase. These materials are sometimes referred to as in situ composites. Roll bonding is a common technique used to produce a laminated composite consisting of different metals in layered form. Roll bonding and hot pressing have also been used to make laminates of Al sheets and discontinuously reinforced MMCs. Heat treatments intermediate and/or subsequent to deformation, are conducted to form the desired phase, promote grain inter-connectivity and crystallographic alignment of the oxide, and obtain proper oxygenation.

8.1.2. Powder Metallurgy

This process involves the mixing of two powders in the desired volume ratio followed by compaction. The compacts are then sintered to get the composite. The advantages in this process include the latitude in controlling the volume ratio of the constituents. However, if the difference in the atomic weight of the constituents is large then it is difficult to mix them for liquid phase sintering. Addition of transition metals is a common practice to aid the sintering behavior. This may or may not affect the properties of the resulting composite[22].

8.1.3. Diffusion bonding

It is a common solid-state processing technique for joining similar or dissimilar metals. Inter-diffusion of atoms between clean metallic surfaces, in contact at an elevated temperature, leads to bonding. The principal advantages of this technique are the ability to process a wide variety of metal matrices and control of fiber orientation and volume fraction. Among the disadvantages are long processing times, high processing temperatures and pressures (which makes the process expensive), and a limitation on the complexity of shapes that can be produced. There are many variants of the basic diffusion bonding process, although all of them involve simultaneous application of pressure and high temperature. Matrix alloy foil and fiber arrays (composite wire) or monolayer laminate are stacked in a predetermined order. Vacuum hot pressing is an important step in the diffusion bonding processes for MMCs. Hot isostatic pressing (HIP), instead of uniaxial pressing, can also be used. In HIP, gas pressure against a can consolidates the composite inside the can. With HIP, it is relatively easy to apply high pressures at elevated temperatures with variable geometries[21].

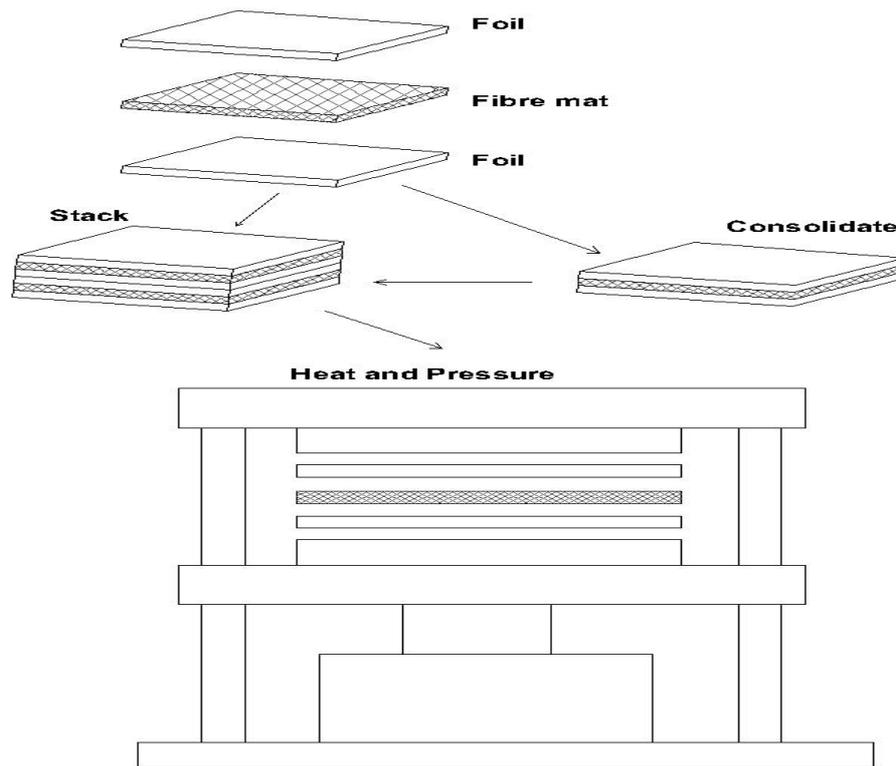


Fig 2. Diffusion Bonding process

8.1.4 *In Situ* Processes:

In these techniques, the reinforcement phase is formed in situ. The composite material is produced in one step from an appropriate starting alloy, thus avoiding the difficulties inherent in combining the separate components as done in a typical composite processing. Controlled unidirectional solidification of a eutectic alloy is a classic example of in situ processing. Unidirectional solidification of a eutectic alloy typically results in one phase being distributed in the form of fibers or ribbon in the matrix phase. Simply controlling the solidification rate can control the relative size and spacing of the reinforcement phase, although the volume fraction of reinforcement will always be constant. The solidification rate in Advanced practice, however, is limited to a range of 1–5 cm/h because of the need to maintain a stable growth front which requires a high temperature gradient.

8.2. Liquid-State Processes

8.2.1. *Liquid Infiltration*

In the infiltration technique, liquid metal is infiltrated through the narrow crevices between the fibers or particulate reinforcements which are arranged in a preform, fixed in space, unlike the stir mixing and casting process where the reinforcements are free to float or settle in the melt due to density differences. As the liquid metal enters between the fibers or particles during infiltration, it cools and then solidifies, producing a composite by three operations: the preform preparation, the infiltration process and the solidification of liquid metal. A transient layer of solidified metal is formed as soon as the liquid metal comes in contact with the cold fiber/reinforcement. Melt infiltration can be achieved with the help of mechanical pressure, inert gas pressure or vacuum. Recently techniques of pressure-less infiltration have also been developed.

8.2.2. *Squeeze casting or pressure infiltration*

It involves forcing a liquid metal into a fibrous or particulate preform. Pressure is applied until solidification is complete. By forcing the molten metal through small pores of the fibrous

preform, this method obtains the requirement of good wettability of the reinforcement by the molten metal. Composites fabricated with this method have the advantage of minimal reaction between the reinforcement and molten metal because of the short processing time involved. Such composites are also typically free from common casting defects such as porosity and shrinkage cavities. Infiltration of a fibrous preform by means of a pressurized inert gas is another variant of the liquid metal infiltration technique. The process is conducted in the controlled environment of a pressure vessel and rather high fiber volume fractions[5][10].

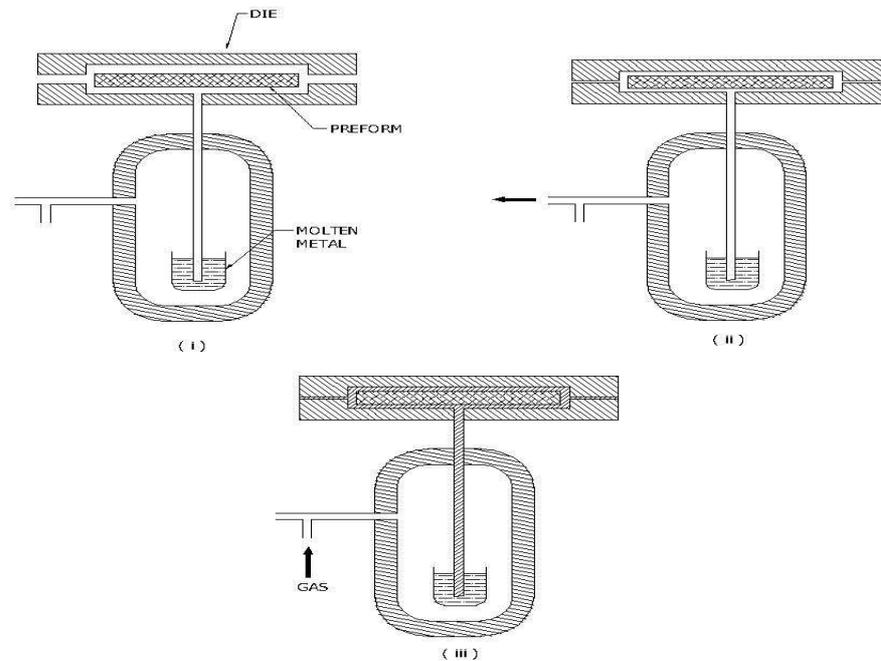


Fig 3. Liquid Infiltration process,(i) insert perform and close die,(ii)evacuate air, (iii) apply gas pressure and maintain during solidification.

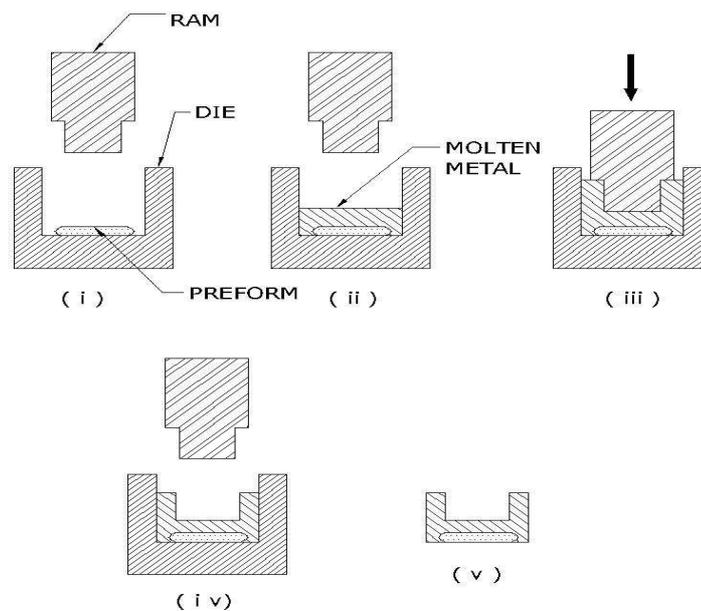


Figure 4. Squeeze casting process (i) insert perform into die cavity, (ii) putting molten metal (iii) close die and apply pressure, (iv) remove ram, (v) extract component.

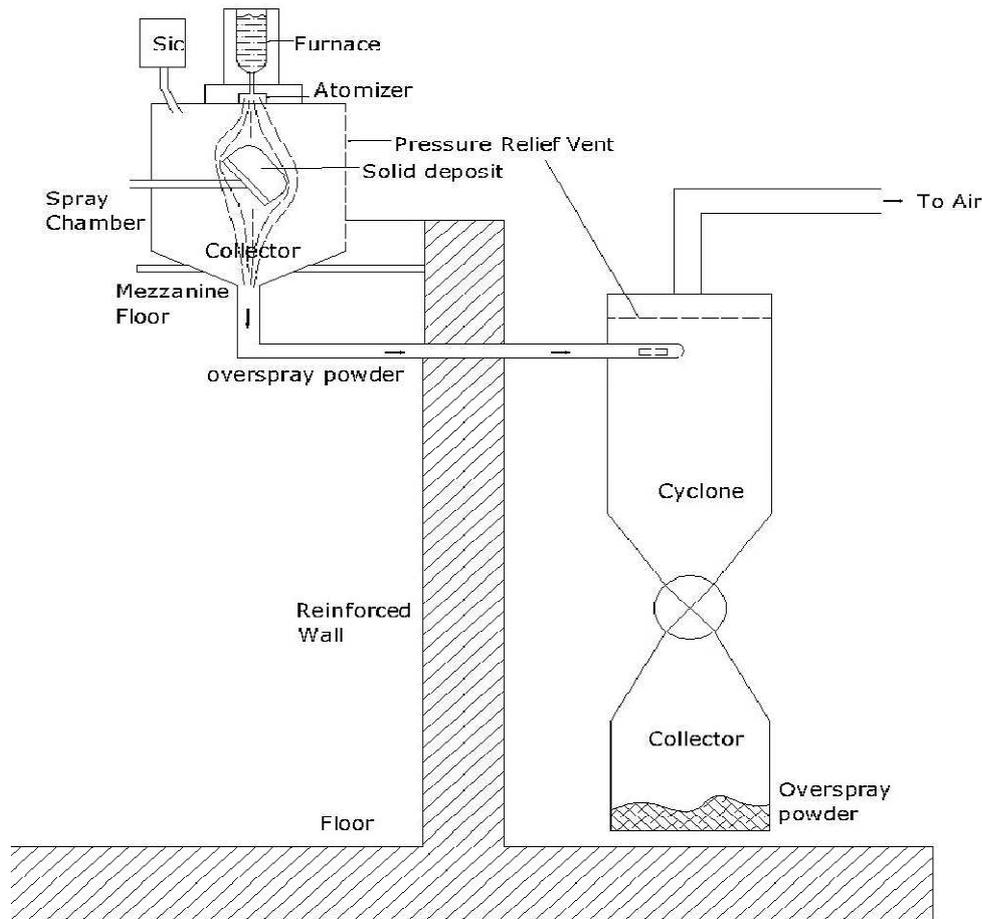


Figure. 5 Spray Casting process

8.3. Spray-Forming of Particulate MMCs

Another process for making particle-reinforced MMCs involves the use of modified spray forming techniques that have been used to produce monolithic alloys for some time. One particular example of this, a co-spray process, uses a spray gun to atomize a molten aluminum alloy matrix, into which heated silicon carbide particles are injected. An optimum particle size is required for efficient transfer, e.g., whiskers are too fine to be transferred. The preform produced is generally quite porous. The cosprayed MMCs is subjected to scalping, consolidation, and secondary finishing processes to form a wrought composite. The formation of deleterious reaction products is generally avoided because the time of flight of the composite particles is extremely short. Silicon carbide particles of an aspect ratio (length/diameter) between 3to4 and volume fractions up to 20% have been incorporated into aluminum alloys. An advantage of the process is the flexibility it provides in making different types of composites, eg, in situ laminates can be made using two sprayers or by selective reinforcement. This process is quite expensive, however, mainly because of the costly capital equipment.

9. Properties of Metal Matrix Composites

Some of the important properties of MMCs are:

- High longitudinal and transverse strengths at normal and elevated temperatures.
- High toughness and impact properties.
- High surface durability and low sensitivity to surface flaws.
- Near-zero coefficients of thermal expansion.
- High electrical and thermal conductivities.

- Excellent antifriction, anti abrasion, damping.
- Excellent machinability properties.
- Reduced wear, anti seizing.
- Lighter in weight.
- Good Specific strength and Specific stiffness.

10. Application of Metal Matrix Composites

There are many reasons for the growth in composite applications, but the primary impetus is that the products fabricated by composites are stronger and lighter. Today, it is difficult to find any industry that does not utilize the benefits of composite materials. Some of the major industries are using MMCs are [12][11][14]:

10.1. The Aerospace industry

The aerospace industry was among the first to realize the benefits of composite materials. Airplanes, rockets, and missiles all fly higher, faster, and farther with the help of composites. MMCs are used as passenger aircrafts, composite gliders, leading edges, ailerons, vertical stabilizers, helicopter blades, propellers, transmission shafts and aircraft brake discs. For space transports, it is used to make rocket boosters, reservoirs, nozzles and shields for atmosphere reentrance.

10.2. The Automotive Industry

Composite materials have been considered the "material of choice" in some applications of the automotive industry by delivering high-quality surface finish, styling details, and processing options. Automotive engineering parts like automotive body parts, wheels, shields, radiator grills, transmission shafts, suspension springs, chassis, suspension arms, casings, highway tankers, isothermal trucks, trailers, wagons, doors, seats, interior panels, and ventilation housings are made from MMCs.

10.3. The Electrical Industry

Some of the important metal matrix composite components are applied and used as insulation materials for electrical construction, supports for circuit breakers and printed circuits, armors, boxes and covers, antennas, radomes, tops of television covers, cable tracks, wind mills, housing cells etc.

10.4. The Sporting Goods Industry

Sports and recreation equipment suppliers are becoming major users of composite materials. The growth in structural composite usage has been greatest in high-performance sporting goods and racing boats. Anyone who has visited a sporting goods store can see products such as golf shafts, tennis rackets, snowskis, fishing rods, etc. made of composite materials. These products are light in weight and provide higher performance, which helps the user in easy handling and increased comfort.

10.5. Marine Industry

Composite materials are used in a variety of marine applications such as passenger ferries, power boats, buoys, fabricate hovercrafts, rescue crafts, patrol boats, trawlers, landing gears, anti-mine ships, racing boats and canoes.

10.6. Consumer Goods

Composite materials are used for a wide variety of consumer good applications, such as sewing machines, doors, bathtubs, tables, chairs, computers, printers, etc. The majority of these

components are short fiber composites made by molding technology such as compression molding, injection molding, RTM, and SRIM.

10.7. Other Industrial Applications

The use of composite materials in various industrial applications is growing. Composites are being used in making industrial rollers and shafts for the printing industry and industrial drive shafts for cooling-tower applications. Filament winding shows good potential for the above applications. Injection molded, short fiber composites are used in bushings, pump and roller bearings, and pistons. Composites are also used for making robot arms and provide improved stiffness, damping, and response time[23][21].

11. Futuristic promises of Metal Matrix Composites

Use of MMCs has recovered and in the long term will continue expand, as a result of technological advancements, both in the area of new methods for producing MMCs, as well as in evaluating MMCs various applications. Though a large number of highly specialized and sophisticated aluminum alloys have been developed in an ongoing effort over the past decades, still there remains urgent need for the development of new or improved Al/Al alloys composites. Aluminum alloys reinforced with very high volume fractions of ceramic particulate or fibers are evincing much interest for structural applications that require high specific modulus, low thermal expansion coefficient and wear resistance. However, the development of these materials has been hindered by difficulties in fabrication and shaping them for end use applications. Aluminium oxide and silicon carbide powders in the form of fibers and particulate are commonly used as reinforcements in MMCs and the addition of these reinforcements to aluminum alloys has been the subject of a considerable amount of research work. Several programs in the U. S. and Japan are looking at composites for future supersonic space vehicles. Japan's ESPR project is developing a Si-Zr-C-O/SiC composite for combustor liners with the goal of reducing CO₂ emissions by 25%. For this project, Kawasaki Heavy Industries has developed a process that involves coating a fiber preform by chemical vapor infiltration, impregnating the preform with a glass powder slurry, and then drying the part.

CONCLUSION

As per their properties, they have significant scientific, technological and commercial importance. During the last decade, because of their improved properties, MMCs are being used extensively for high performance applications such as in aircraft engines and more recently in the automotive industries. MMCs are materials that are attractive for a large range of engineering applications. They are a family of new advanced materials, which are attracting considerable industrial interest and investment worldwide.

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