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(REVIEW ARTICLE)

A review on constituents, applications and processing methods of metal matrix composites

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Abstract

Metal matrix composites (MMCs) exhibit superior mechanical and wear resistant properties, allowing them to be deployed in a variety of manufacturing applications, including structural, automotive, aerospace domains etc. Aluminium as the matrix material has numerous applications due to its high strength-to-weight ratio. The inclusion of hard ceramic particles in aluminium alloys increases overall strength and wear-resistance. It is important to know about different constituents of composite materials. In the present review paper an attempt has been made to highlight important constituents of metal matrix composites and their applications. Also, this review paper covers the various manufacturing techniques of metal composites.

Keywords: Metal Matrix Composites; Constituents; Reinforcements; Processing; Stir Casting

1. Introduction

With the ability to modify their characteristics by adding specific reinforcement, Metal Matrix Composites (MMCs) are gaining popularity as a material for high-tech aerospace applications [1, 2]. Due of its exceptional strength and specific stiffness at both room temperature and extreme temperatures, particle reinforced MMCs have lately garnered a lot of attention [3, 4]. It is widely recognized that the form, size, orientation, distribution, and volume or weight of the reinforcement are micro-structural characteristics that significantly impact the elastic properties of the metal matrix composite [5].

A number of matrix materials have reached the industrial production stage; MMCs manufactured from aluminium and its alloys are among the most common. A wide range of hard and soft reinforcements, including SiC, Al_2O_3, Zircon, Graphite, and Mica, have been developed as part of the major effort towards affordable Al-based MMCs [6, 7]. The fact that graphite, in either its particle or fiber form, is a very strong material with a low density has been known for a long time. A pricey class of materials called as aluminium graphite particulate MMCs made via solidification techniques have several uses, including engineering components, brushes, and bearings [8, 9].

When created, a composite material—defined as an arrangement of two or more components with distinct chemical or physical properties—delivers an entirely new and distinct product with attributes that differ significantly from those of the individual components [10, 11]. Macroscopic fabrication is the norm for material reinforcing. Compared to the

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typical material, the resulting structure is stronger, lighter, and more cost-effective because the individual materials are bonded together. The resultant composite material outperforms its individual components due to its customized qualities [12, 13]. Because of their improved mechanical, thermal, electrical, and environmental characteristics, these composites are often chosen. Metal matrix composites (MMCs), ceramic matrix composites (CMCs), fibre reinforced polymers (FRPs), and concrete are just a few of the many applications that typically call for these materials. Metal matrix composites and ceramic matrix composites are in great demand for a wide variety of construction projects, including but not limited to: boat houses, swimming pool structures, race car components, bath tubs, tanks, and innovative materials used in spacecraft and aviation structures [14, 15]. Sensors, actuators, computing, and communication applications have recently benefited from composites thanks to advancements made by a number of researchers. The terms "smart material" and "robotic material" are interchangeable [16].

The matrix phase of a metal matrix composite (MMC) is typically metal, while the reinforcing phase can be another metal, an organic compound, or even ceramic. You can enhance the properties of MMCs by adding different sized particles, whiskers, or fibers as reinforcements to the matrix [17, 18]. The stiffness, high strength, and fracture toughness of MMCs are important considerations, even if they are not commonly employed as PMCs. One major benefit of MMCs over PMCs is their superior resistance to high temperatures and corrosive environments. The majority of matrix materials are metals or alloys, and these materials have specific requirements for reinforcement: they must be nonreactive and stable at high temperatures. Reinforcements having a high modulus and tensile strength are used to create MMCs with improved strength. Metal matrices include elements such as aluminium, magnesium, titanium, copper, and many more [19, 20]. Reinforcement density is usually more important than base matrices. Renforcing materials typically include carbon, graphite, molybdenum, silicon carbide, titanium carbide, tungsten carbide, boron carbide, and so on. In spite of this, materials like silicon carbide, aluminium oxide, and titanium carbide are not widely employed in industry [21, 22].

Two steps are typically present in MMCs. The first is the reinforcing phase, and the second is the matrix phase, which is typically an alloy of metals. The enhanced qualities of composites and the material properties that cannot be achieved by a single phase are both enhanced by combining the two phases [23, 24]. In an effort to create MMCs with exceptional strength, researchers are devoting more time and energy to reinforcing development. Wear resistance, rigidity, coefficient of thermal expansion, high temperature conduction, and other qualities can be achieved by including reinforcements in the matrix phase [25, 26]]. An important step in creating a high-quality metal matrix composite is choosing the right filler material.

It is possible to create metal matrix composites using a number of different fabrication techniques. The manufacturing method should minimize material cost while maintaining properties like as surface quality, fluidity, thermal conductivity, shrinkage porosity, etc [27].

There is no reaction between the reinforcement and the metal matrix phase since the materials used to make MMCs have distinct physical and chemical characteristics. Processing and application of the created MMC require careful attention to detail because of the regulated reaction required to bring the components into equilibrium and prevent easy fiber pullout [28, 29].

We will go into more detail about how carbides of various types are commonly utilized as reinforcements in metal matrices. The composite's qualities will be improved with the addition of reinforcements at a significantly lower cost than with the traditional monolithic material [30, 31].

2. Constituents of Composite Materials

2.1. Matrix Material

Materials that bind and retain the filler are called a matrix. A possible matrix material can be produced to embed and inherently grip a reinforcing phase in any solid. The chemical compatibility of the matrix material, reinforcement, and any interaction between the two is of the utmost importance [32, 33]. Most often, metals, ceramics, and polymers are used as matrix materials. Matrix is responsible for the following primary functions in a composite:

- Serves as a conduit through which stress from outside sources is transferred and distributed to the reinforcements, with the matrix phase bearing just a small fraction of the total load.
- The stress is transferred from one reinforcement to another, resulting in a thick and completely uniform framework.

- In order to prevent surface damage caused by abrasion or chemical reactions with the environment, matrix shields the individual reinforcement.
- Other functional features like as finish, color, texture, and durability are provided by it.

2.1.1. Metal Matrix

Metals have a lot of strength and durability. In particular, by blocking the microscopic movement of linear faults known as dislocations, they can be plastically deformed and reinforced in a number of ways. Reducing the rate of deformation through obstruction of dislocation motions improves mechanical qualities including tensile and compressive strengths, hardness, toughness, stiffness, and so on. The metal matrix could consist of nickel-based super alloys, magnesium, aluminium, copper, titanium, or any combination thereof. They work well in environments with temperatures between 300 and 500 degrees Celsius.

2.1.2. Ceramic Matrix

Ceramics are manufactured goods that have an inorganic, non-metallic matrix that has been heated to a high temperature throughout the production process. Because of their non-conducting qualities, high hardness, excellent chemical resistance, and high refractoriness, ceramics are utilized as matrix materials. A few examples of the ceramics utilized are silicon carbide, titanium nitride, aluminium oxide, silicon carbide, and silicon nitride.

2.1.3. Polymer Matrix

Metals and ceramics are relatively simple compared to polymers. They are inexpensive and simple to process. Polymer composites are easy to make with the right tools. The polymers have gained widespread acceptance as a matrix material, and reinforced polymers have demonstrated their suitability for structural applications, thanks to the significant improvements made possible by reinforcing them despite their lower strength and modulus. In general, polymers do not perform well as heat or electrical conductors due to their mostly covalent connections. They outperform metals in chemical resistance. From a structural perspective, they resemble enormous chains of molecules held together by covalently bound carbon atoms.

2.2. Reinforcement Materials

The two-phase material's strength comes from the reinforcement material. It makes things better and makes them stiffer. Enhanced mechanical and physical characteristics, including thermal and electrical conductivity, increase a composite's lifespan. They categories reinforcements according to their aspect ratio, which is the ratio of their length to their thickness [34, 35]:

- Fibers
- Whiskers
- Platelets and flakes
- Particulates

2.2.1. Fibers

The longitudinal strength of fibers is higher than that of other materials with very long axis. You may get them in a wide range of diameters and lengths, including continuous, which is versatile because you can use it straight or cut it to size. These are the main components of fiber-reinforced composites, which can have matrices made of polymer, ceramic, or metal, and can be either polycrystalline or amorphous. They contribute the most to the overall load and take up the most space in a composite. Their impact on a composite's following qualities is due to their enormous aspect ratio, which makes them very effective.

- Specific gravity.
- Tensile strength.
- Compressive strength and modulus.
- Fatigue strength and fatigue failure mechanism.
- Modulus.
- Electrical and thermal conductivity.
- Cost

2.2.2. Whiskers

Whiskers are needle-shaped single crystals that are incredibly thin and often have an aspect ratio greater than 10. Their diameter can range from 0.01 to 1.0 µm. They are noncircular in cross-section and have a high surface-to-volume ratio; examples of such shapes are triangles, hexagons, and rhombohedra. The cross-sectional surface area squared is the measure of their diameter. They are efficient due to their wide aspect ratio [36]. The overall whisker/matrix interfacial area is influenced by the whisker's form. In turn, the contact significantly affects the mechanical and physical characteristics of the composites. Whiskers' strength comes from their small dimensions and single crystalline structure, which also accounts for their low defect density.

- The main reasons why metals have whiskers are to increase their stiffness, creep resistance, and wear resistance.
- When reinforced with a ceramic matrix, whisker increases fracture toughness, wear resistance, and creep resistance.
- Whiskers are used in polymer composites to improve thermal and electrical properties.

Some notable whiskers include asbestos, carbon, silicon carbide, silicon nitride, alumina, titanium, titanic borate, titanic nitride, calcium carbonate, silica dioxide, niobium carbide, aluminium nitride, tin oxide, and cadmium oxide [37, 38].

2.2.3. Flakes and Platelets

Aspect ratios ranging from 30 to 120 characterize flakes and platelets. Width typically falls within the 20 to 500 µm range. Ceramic matrix materials are a good match for these reinforcements due to their flat surfaces. Composites that are packed with flake and platelets have a microstructure that is less anisotropic and warping is less likely. Commonly utilized significant platelets include mica, SiC, boron carbide, aluminium, copper, and many more.

2.2.4. Particulates

Particulates are tiny, powdered materials that are both microscopic and foreign. Their aspect ratio is poor. Particulate reinforcements have nearly uniform diameters in all directions. A particle's shape can be round, cubic, plate-like, irregular, or regular in geometry. Particle size, shape, distribution, and volume fraction of dispersion all play a role in how effective the reinforcing particles are. Particulate matter comes in two varieties, each chosen for its unique type of adherence to the matrix phase:

Metallic: It is common practice to enhance a polymer's conducting capability by adding metallic particles to it. It is not possible to dissolve metallic particles in a metallic matrix. Arc rocket propellant, for instance, is a mixture of aluminium powder and polyurethane [39].

Non-Metallic: Graphite, ceramics, conductive carbon black, and other conductive materials are the most common non-metallic particles. Cermet is the name given to the composite that is formed when various elements are mixed together in a matrix; ceramics are among the most common of these materials. Ti-C, TIN, Al_2O_3, AIN, BN, SiC, Si_3N_4, graphite, W, WC, B, TiB_2, glass, ZrC_2, and CaF_2 are among the significant non-metallic particles [40, 41].

3. Advantages of Composites

- Compared to most metals and woods, composites are quite light in weight. For vehicles and planes, for instance, their light weight is a major consideration because less weight equals better fuel economy. Weight is a major consideration for aeroplane designers since lighter aircraft use less fuel and may achieve higher speeds. Composites have largely replaced metal in the construction of several contemporary aircraft, such as the Boeing 787 Dreamliner.
- Composites have the potential to be significantly more robust than metals like steel or aluminium. In any direction, metals have the same amount of strength. The strength of composites, however, can be targeted through engineering and design.
- Strength Correlation with Mass - The ratio of a material's strength to its weight is called its strength-to-weight ratio. Steel, for example, is both heavy and extremely strong. Bamboo poles are one example of a material that is both lightweight and robust. It is possible to create composites that are both lightweight and sturdy. Composites are commonly employed in the construction of aeroplanes due to their exceptional strength-to-weight ratio. It is possible to design a composite such that it does not bend in any particular way. Increasing the thickness of a metal construction in order to achieve a desired degree of strength in a single direction typically

results in a heavier final product. Reinforced composites don't have to be cumbersome. When it comes to modern building materials, composites offer the best strength-to-weight ratio.

- Composites are resistant to corrosion, meaning they won't get damaged by elements like rain or snow, or by strong chemicals that can eat away at other materials. In areas where chemicals are stored or handled, composites are a smart alternative. When left outdoors, they can withstand extreme temperatures and storms.
- The ability to absorb impacts, such as the rapid force of a bullet or the blast from an explosion, is a property of composites that can be strengthened. Composites are utilized in bulletproof jackets and panels, as well as in blast shielding for buildings, aircraft, and military vehicles, because to this characteristic.
- Composites provide greater design flexibility compared to conventional materials, allowing them to be more easily shaped into intricate forms. Because of this, designers can make nearly anything they can imagine. For instance, fiber glass composites are used to construct the majority of recreational boats nowadays. This is due to the fact that these materials can be easily shaped into intricate designs, leading to better boats at a lesser cost. Additionally, composites can have their surfaces shaped to look like any surface, be it smooth or pebbly.
- Part Consolidation - A composite part can stand in for a whole set of metal components. Machines and buildings with fewer parts require less maintenance and run more smoothly over time.
- Regardless of the temperature, humidity, or pressure, the dimensions and size of a composite material do not change. Conversely, changes in humidity cause wood to expand and contract. If you need a snug fit that doesn't change, composites might be the way to go. For instance, they keep the size and form of aeroplane wings from changing when the plane's altitude increases or decreases.
- Composites are not able to carry electrical current since they are not conductive. Electric utility poles and electronic circuit boards are two examples of products that benefit from this quality. You can make some composites conductive if you need them to be.
- Composites do not possess magnetic properties because they do not include any metals. They are safe to use near electrical components that could cause damage. Magnetic resonance imaging (MRI) equipment, which makes use of enormous magnets, works better when there is no magnetic interference. The table and enclosure of the equipment are made of composites. The room's concrete walls and flooring were reinforced with composite rebar during construction at the hospital.
- Radar Transparent - Composites are perfect for use wherever radar equipment is in operation, whether it's on the ground or in the air, because radar signals may travel right through them. Stealth aircraft, like the B-2 stealth bomber flown by the United States Air Force, rely heavily on composites to ensure their near-invisible flight.
- Low Thermal Conductivity - Because of their excellent insulating properties, composites are neither poor heat or cold conductors. Doors, panels, and windows that require additional protection from extreme weather often make use of these materials.
- Durable - Longevity and low maintenance requirements are hallmarks of composite construction. There are still a lot of original composites out there, so we don't have a good idea of how long they last. For fifty years, many composites have served their purpose.

4. Fabrication of Metal Matrix Composites

4.1. Liquid State Processes

4.1.1. Casting or Liquid Infiltration

When a liquid metal is injected into a reinforcing preform that is fibrous or particle, this process is called liquid infiltration as in Fig. 1. The main challenge with liquid-phase infiltration of MMCs is getting the molten metal to wet the ceramic reinforcement. Reactions between the fiber and the molten metal might drastically diminish the fiber's qualities when the infiltration of a fiber preform happens easily. Coatings of fibers placed before infiltration enhance wetting and permit regulation of interfacial reactions. On the other hand, surface oxidation of the coating occurs in this scenario, thus the fiber coatings can't be exposed to air before infiltration. The Duralcan process is the name given to this procedure. Over the range of 600 to 700°C, which is the liquidus temperature, the melt is agitated slightly. Secondary processing, such as extrusion or rolling, may be applied to the solidified ingot. The usage of particles ranging from 8 to 12 μm in the Duralcan technique of creating particulate composites through a liquid metal casting route is essential.

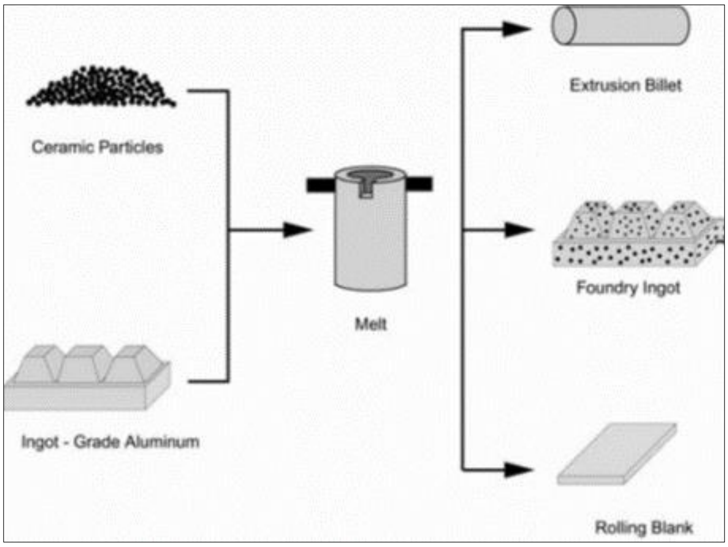

Figure 1 Casting process for particulate or short fiber MMCs [5]

4.1.2. Squeeze casting or Pressure Infiltration

A fibrous or granular preform can be "pushed" into a liquid metal by applying pressure during the infiltration process. The process of solidification is accelerated by applying pressure. By pressing the hot metal into the fibrous preform through its microscopic holes. Due to the short processing time needed, this method of fabricating composites has the advantage of minimizing interaction between the reinforcement and molten metal. Porous and shrinkage cavity-free composites are another hallmark of these materials. An additional variation of the liquid metal infiltration process involves the use of pressurized inert gas to infiltrate a fibrous preform. Using a pressure vessel and relatively high fiber volume fractions, the procedure is carried out in a controlled environment. This method requires heating the fiber preform independently from the matrix alloy in a vacuum-controlled crucible. The fibers are covered with the molten matrix material, which is heated to approximately 100°C above Tm, and at the same time, argon gas is added. The melt, which has additives to help wet the fibers, is forced into the preform by the pressure of argon gas as in Fig. 2.

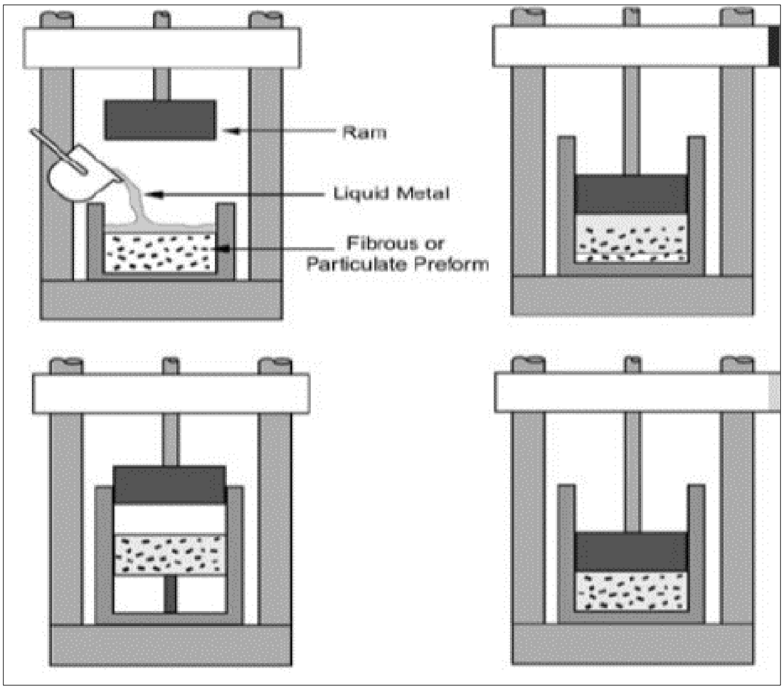

Figure 2 Squeeze casting or pressure infiltration process [5]

4.1.3. Stir Casting Technique

Among the many benefits of the stir casting technique (Fig. 3) which includes a large variety of materials, improved matrix particle bonding, easier control of the matrix structure, simple and inexpensive processing, adaptability to large-quantity production, and excellent productivity for near-net shaped components—it is widely recognized as the most cost-effective method for producing metal matrix composites. The production of AMCs by stir casting is not without its challenges, though. One big issue with this approach is that it has poor wettability and the reinforcing material is not evenly distributed. Reinforcement particles were found to be floating on the surface of the molten matrix when they were added because of their poor wettability in the melt. This indicates that the molten matrix could not wet the surface of the reinforcement particles. The presence of oxide layers on the melt surface and a gas layer on the surface of the ceramic particles, as well as the surface tension, very large specific surface area, and high interfacial energy of the reinforcing particles, all contribute to this. Typically, particles can be mixed into a melt using mechanical stirring. However, when the stirring stops, the particles tend to float back to the surface. This suggests that the gas layers make it difficult for the molten metal to wet the particles.

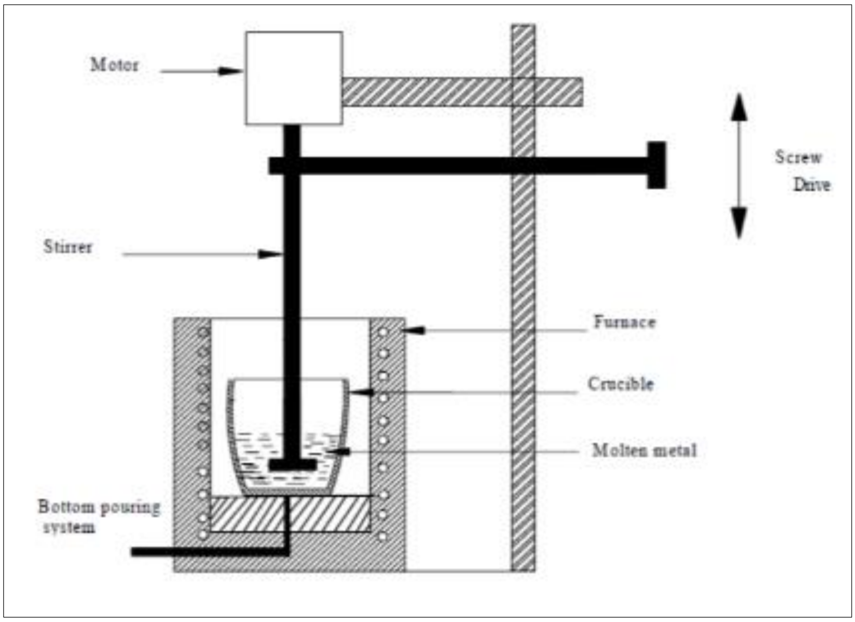

Figure 3 Stir casting method [5]

By removing adsorbed gases from the particle surface and adding surface active elements like magnesium, lithium, calcium, titanium, or zirconium into the matrix, the morphology of the interface can be changed from convex to concave, improving the wettability of the reinforcement particles within the molten matrix alloy. Another method is to heat treat the particles before dispersing them into the melt. Making sure the reinforcing particles are evenly distributed throughout the molten matrix is another challenge. Due to density differences between the matrix alloy melt and the particles used for reinforcement, when the particles are wetted in the metal melt, they have a high propensity to agglomerate and cluster, and their dispersion is not uniform. Mechanical stirring isn't the only method for introducing particles into the matrix; injecting particles into the melt with an inert carrier gas also helps to distribute the reinforcing particles better. As reinforcement particle sizes approach the nanoscale, wettability and distribution become increasingly challenging. The reason behind this is that reinforcement particles tend to clump together more often when nanoparticles' surface areas and surface energies increase. Unsatisfactory casting technology is the root cause of a number of structural flaws, including nanoparticle aggregation, poor wettability, particle clusters, oxide inclusions, and interfacial reactions. In order to enhance the integration and distribution of micro particles within the molten matrix, a new AMC production process is urgently needed.

4.2. Solid State Processes

4.2.1. Diffusion bonding

One popular method for combining metals that are chemically or physically different is diffusion bonding, which is done in the solid state (Fig. 4). Atoms connect when two clean metallic surfaces come into touch at a high enough temperature to cause them inter diffusion. This method's main selling points are its versatility in processing different types of metal matrices and its controllability over fiber orientation and volume percent. Some of the drawbacks include the fact that the process is expensive due to the high temperatures and pressures used, the lengthy processing times involved, and the fact that the intricacy of the shapes that may be made is limited. Diffusion bonding of metal matrix composites relies on vacuum hot pressing.

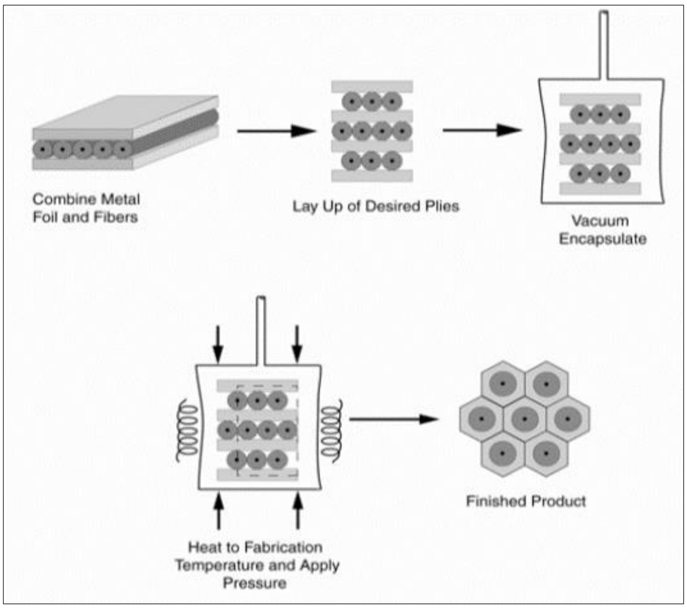

Figure 4 Diffusion bonding process [5]

4.2.2. Deformation Processing

It is also possible to densify and distort the composite material via deformation processing. One phase elongates and becomes fibrous within the other phase during mechanical processing (swaging, extrusion, drawing, or rolling) of a ductile two-phase material, resulting in metal-metal composites. The initial material, typically a cast billet of a two-phase alloy, has a significant impact on the final product's properties when deformation processing is applied. One typical method for creating multilayer laminated composites out of several metals is roll bonding. Plate laminated metal-matrix composites are the proper name for these types of composites. Laminates of Al sheets and discontinuously reinforced MMCs have also been made using roll bonding and hot pressing.

4.2.3. Powder Processing

Compounds reinforced with either short fibers or particles are created using powder processing techniques combined with deformation processing. Producing particle-or whisker-reinforced MMCs usually requires a combination of cold pressing and sintering or hot pressing. For a uniform distribution, the matrix and reinforcing powders are mixed. To make a green body, the mixing and cold pressing stages are repeated. Degassing the cold-pressed green body eliminates any moisture that may have absorbed into the surfaces of the particles before canning it in a sealed container. A completely dense composite is created by hot pressing the material either uni-axially or iso-statically, and then it is extruded.

5. Conclusion

The review paper covers the important constituents of metal matrix composites and various applications of metal composites. Due to high strength to weight ratio these metal composites are widely used for aerospace, marine and automobile applications. There various reinforcements are available to synthesize these metal composites. The most commonly used reinforcements are in form of oxides, nitrides and carbides. The form and shape of reinforcements are fibers, whiskers or particulates. There are several fabrication methods are available to produce metal composites. Two common methods are liquid state processes and solid state methods. In the liquid state method, stir cast or vortex technique is the common process to produce metal composites.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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