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A Comprehensive Review of Magnesium Matrix Composites (MMCs) and Its Manufacturing Techniques

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Abstract

Magnesium matrix composites (MMCs) can overcome the mechanical properties of magnesium alloys by adding reinforcements. These MMCs have properties of hydrogen storage, high specific stiffness and strength, superior dimensional stability, exceptional shock absorption capability, and excellent electromagnetic shielding. No other component can compare with these unique and remarkable capabilities. In recent days, the MMCs have become more attractive in many industries, like aerospace, defense, automotive, electronic packaging and also in the medical field due to their low density and biocompatibility. It appears that a great deal of research has been done recently on the topic of bioresorbable metallic compounds, with a focus on magnesium's potential application in bone implant therapies. MMC is among the most appealing biodegradable materials being investigated at the time for orthopedic skeletal immobilization and substitute joint devices. Numerous manufacturing techniques are used to produce the MMCs like stir casting, powder metallurgy, additive manufacturing, laser cladding etc. This paper reviews the recent advancement of the various techniques with suitable reinforced material to produce the MMC.

Keywords: Magnesium matrix composites, powder metallurgy, Stir casting, additive manufacturing, laser cladding

INTRODUCTION

Magnesium Matrix Composites (MMC) are more widely considered for many developed applications in the modern world, which may be because of their properties and ability to restore the traditional materials that are currently available. However, in the modern engineering world, MMC, which has a density that is around 30% lower than that of aluminum alloy, attracts attention from application fields due to its excellent physical properties and cast ability.The density of MMCis nearly one-fourth of cast iron, and two fifths of titanium alloy. The MMC is regarded as the most suitable green material of the twenty-first century due to its amazing physical and chemical significance, which include good machinability, strong unique strength, good suitable stiffness, minimal density, and biocompatibility [1]. Magnesium Metal Matrix Composite has made significant strides in research, however it is not suitable for use in applications involving higher temperatures where dissipation occurs.Appropriate reinforcing materials can be used to create composites and set the stage for a number of applications in order to resolve such disputes.A structurally less dense material, magnesium has been carefully considered as a potential solution to focus on the aforementioned problems, such as endurance and minimized weight, in multiple

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sectors of industry. Because of its unique qualities, magnesium is essential for many other sectors in addition to technological uses. According to the researcher, there are currently no feasible magnesium-related transplants obtainable in the field of medicine. There is still more clinical research to be done, and the degradable composite made of magnesium alloys will have a prominent place in the medical profession for temporary implants [1-2].

At the moment, adding rare earth elements to magnesium alloy and adding correct reinforcements through compositing are both reasonably successful methods. Rare earth elements (RE) are expensive, which makes manufacturing more expensive and yields fewer benefits. To make magnesium matrix composites (MMCs), they have lower density and superior mixing properties in a range of test factors and many engineering applications.The benefits of magnesium alloy, such as excellent temperature resistance, outstanding impact resistance, good dimensional stability, strong strength, good specific stiffness, great modulus of elasticity, and low density, are still present in MMCs. In addition, MMCs perform strongly in terms of hydrogen storage, electromagnetic shielding, damping, and other domains. Thus, after aluminum matrix composites, MMCs is therefore regarded as yet another extremely significant light metal composite [3]. Metal matrix composites are expected to become the ideal, essential structural and functional composites due to these exceptional properties in the present advanced aerospace engineering, automotive engineering and defense and military product production industries etc. They also have an enormous market for applications and a wide range of potential uses [6].

As a result, the creation of efficient MMC preparation technology has drawn previously unheard-of significance and attention. MMCs are made up of the following structural components: the magnesium matrix, the reinforcement, and the interface area separating the two. From the standpoint associated with composite design theory, the selection of reinforcement is crucial for efficiently enhancing the magnesium matrix's overall mechanical characteristics while preserving its low weight. In general, MMC reinforcement ought to possess the three next attributes: one is excellent mechanical qualities and low density characterizes the reinforcement, the second one is when the magnesium melts during preparation, the reinforcement's structure remains stable and resists harm, and lastly, a strong interface bond can be formed between the magnesium matrix and the reinforcement [7].

In order to enhance the mechanical and many other structural characteristics of the MMCs interface, it is essential. It has the ability to shift the load between the reinforcement to the matrix. The attainment of exceptional mechanical characteristics necessitates the uniform dispersion of reinforcements, as inadequate densification and reinforcement agglomeration and tangling will impair the composites' capabilities [8]. Numerous types of reinforcements have been used in the process of fabricating the metal matrix and these are categorized into various forms, like Aluminum oxide, magnesium oxides, titanium oxide, zirconium oxide, titanium diboride, zirconium boride, carbon fibers and carbon nano tube (CNT) etc. [9].

There have been many different types of MMC manufacturing in recent years. These methods primarily include stir casting, powder metallurgy, friction stir processing, electrophoretic deposition, Additive manufacturing laser cladding and thixomolding etc [10]. These MMCs are made by fusing different fabrication technologies together and offering further techniques of improvement built upon conventional preparation technologies [11]. Thus, additional auxiliary processes including rolling, hot extrusion, open-die hot forging, and high-energy ultrasound are used to optimize the reinforcements dispersion and distribution between the reinforcements and the magnesium matrix [12].

The combination of these multi-step and multi-pass procedures results in a manufacturing process that is more laborious and complex, lengthening the production cycle and raising production costs. In addition to being impractical for mass production, it is challenging to achieve integrated shaping of the intricate and accurate components. It has been seen that the development and implementation of high-performance MMCs are hampered by these constraints. It is important to create more sophisticated, efficient, and straight forward methods for producing high-characteristic metal components, MMCs in order to fulfill the production industry's pressing need for lightweight, high-performance metal components and to broaden the application range of MMCs [13].

Table 1. Various mechanical characteristics of Mg, Al,Ti and steel.

Material	Density (g/cm^3)	Yield strength(N/mm^2)	Elastic modulus(GPA)	Melting points (^0C)	Elongation (%)	References
Mg	1-74 - 1.87	70-215	40-47	450-650	0.8- 10	[3]
Al	2.55 - 2.85	50-350	70 -95	485–690	0.5-10	[3]
Ti	4.5 - 4.9	700-1200	100-120	1485–1690	5-10	[4]
Steel	7.5 – 8	180-1050	190-200	1380–1450	5-70	[5]

VARIOUS MANUFACTURING TECHNIQUES OF MMC

Additive Manufacturing

Additive manufacturing (AM) is an innovative metal part manufacturing technique that offers a advanced technological approach for the production of high-performance components. Additive manufacturing process rapidly solidifies the molten pool at a rate of upto 10^8K/s, a non-equilibrium process [14]. Faster cooling rates can refine grains, prevent segregation, prevent the putting about of alloy elements during the solidification process, and substantially improve the mechanical properties of the components.The additive manufacturing process has seen significant improvements in developing concept, ingredient form, component performance, and other aspects compared to the expensive and time-consuming traditional casting process. This allows AM to process parts with complex structures quickly and efficiently without the need for casting molds or external processing tools. In addition, the resulting components have adequate dimensional precision. Consequently, AM technology has considerable promise for producing high-performance metal parts and is anticipated to minimize the constraints of conventional methods on the formation of magnesium alloys [15].

Additive manufacturing is a process that creates three-dimensional items by layering materials on top of computer-based 3D model data Figure 1. It is also referred to as 3D printing or rapid prototyping techniques.It has developed very quickly and considerably during the last few years, grabbing a lot of people's attention [16].

In comparison between traditional manufacturing techniques and additive manufacturing. The AM generate the finished product with complicated shapes and structures, significantly lowering the number of processing steps and speeding the entire manufacturing cycle. The setup cost is limited in AM technology. This method overcomes the complex geometry product and structure construction significantly and minimizes the processing time. Furthermore, the benefits of AM become increasingly apparent with increasing product complexity, which is produced when stacked components come together, making it simple to construct extremely geometrically complicated objects that would be hard to fabricate employing traditional subtractive or shaping manufacturing procedures[17]. The total manufacturing cost of additive manufacturing (AM) technology is mostly related to material, size of the product, etc. The total manufacturing cost of additive manufacturing (AM) technology is largely unaffected by the design's complexity in conventional manufacturing procedures like injection molding [18]. In comparison to traditional manufacturing techniques, additive manufacturing (AM) offers a higher level of flexibility in design and the technical benefits of highly precision fabrication of complicated parts.The production of medical devices, automobiles, aircraft, and defense applications are all quickly accelerated by this special edge, which offers a practical response to the growing need for faster, lighter, larger, safer, more time- and cost-effective systems.For instance, the automobile industry uses metallic and ceramic flake reinforced MMCs because of their exceptional durability, hardness, and wear resistance.Materials made of carbon like carbon nanotubes and graphene reinforced metal matrix composites possess application in the electrical and aviation areas due to their low heat conductivity and high particular rigidity and other particular strength, respectively [16].Due to their favorable biological characteristics, bioactive ceramics reinforced are utilized in biomedical materials.It has been seen that the use of AM is grow continuously from 2013 to 2019 it grow approximately 3 billion US dollar to 11 billion US dollar.

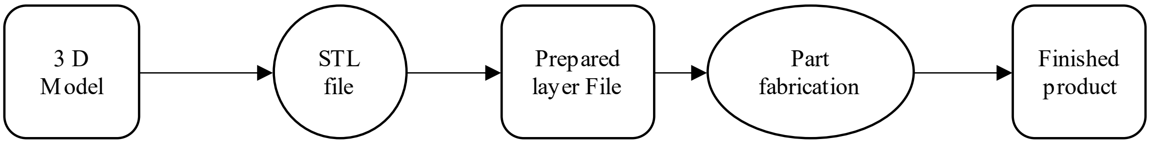

Figure 1. Additive manufacturing process flow diagram.

AM offers enormous potential for use in the automobile industry, as automobile sector hold the biggest percentage of the market of all transportation-related categories.The research and commercialization of outstanding MMCs can be significantly aided by the coupling of the superior highly performance properties of MMCs with the technological benefits of AM techniques, which can manufacture complicated parts for the structure. The recent as well as future growth of AM MMCs is hampered by the under developed state of investigation on AM MMCs, the immaturity of relevant fabrication processes, and the lack of a comprehensive and thorough link between manage, frame work, and performances [17-19].

Laser Cladding

In recent trends modern industries are using laser cladding and alloying manufacturing techniques to modify the surface properties of the material. The laser cladding is a very sophisticated and advanced manufacturing techniques to fabricate the metal matrix composites MMCs. Cladding and alloying is one of the most often utilized surface modification and fabrication process for improving the magnesium alloy's surface characteristics. Laser cladding is most popular surface modification techniques among the other cladding methods like electron beam cladding (EBC), plasma transferred arc (PTA) cladding, and gas tungsten arc (GTA) cladding due to its excellent metallurgical qualities, minimum dilution rate, minimum distortion, quick cooling rate, thermal control, significant energy density, small heat affected zone, and creation of fine and refined microstructure[20-21].Ceramic material, transition material and composites material are commonly used nn cladding and alloying. And rare earth material is also used to enhance the surface properties. Aluminum(Al), titanium (Ti), silicon (Si), cobalt (Co), chromium (Cr), iron (Fe), zinc (Zn), Zirconium (Zr), nickel (Ni), and copper (Cu) etc are used in MMCs in cladding and alloying process [22]. There are many important process variables like material feeding rate, scanning speed, beam size of laser, laser spot size, and rate flow of argon are critical that impact laser cladding and alloying. A hard, wear-resistant material is applied in a way that only causes the substrate's skin to melt the coated layer itself in laser surface cladding.Upto five percent of the coating's dilution level is optimized. Hard coating is produced by laser cladding because it results in fine grain structure, minimal dilution, reduced distortion, and a smaller heat affected zone (HAZ), as well as good metallurgical connection between the coating and substrate. There are the following different categories of laser cladding and alloying [23-24]. Figure 2 shows the Schematic diagram of laser cladding fabrication process.

Preplaced powder approach

The coating powders in the preplaced powder approach were thoroughly mixed with polyvinyl alcohol. This polyvinyl alcohol acts as a binder. The mixing compound is evenly applied to the substrate material's surface to create a pre-coated layer with a consistent thickness. Before applying a laser heat from the source to melt the powder, the pre-coated layer needs to be thoroughly dried [25].

Powder injection approach

In this method of powder injection technique for magnesium alloy surface cladding, blended powders are introduced via the side nozzle in the laser-metal contact area. Powder is heated by the laser beam after it has fallen to the surface.A tip at the connection zone supplies the powder mixer from the side, and a straight vertically dropping laser beam source heats the powder afterwards.The substrate surface is heated vertically by the laser, and powder is introduced through the side nozzle at an angle of roughly 45 degrees. A coated layer on the outside was produced during melting and solidification. Inert gas is simultaneously fed through the side to guard against air contamination. Argon gas is typically employed as a shield [26-27].

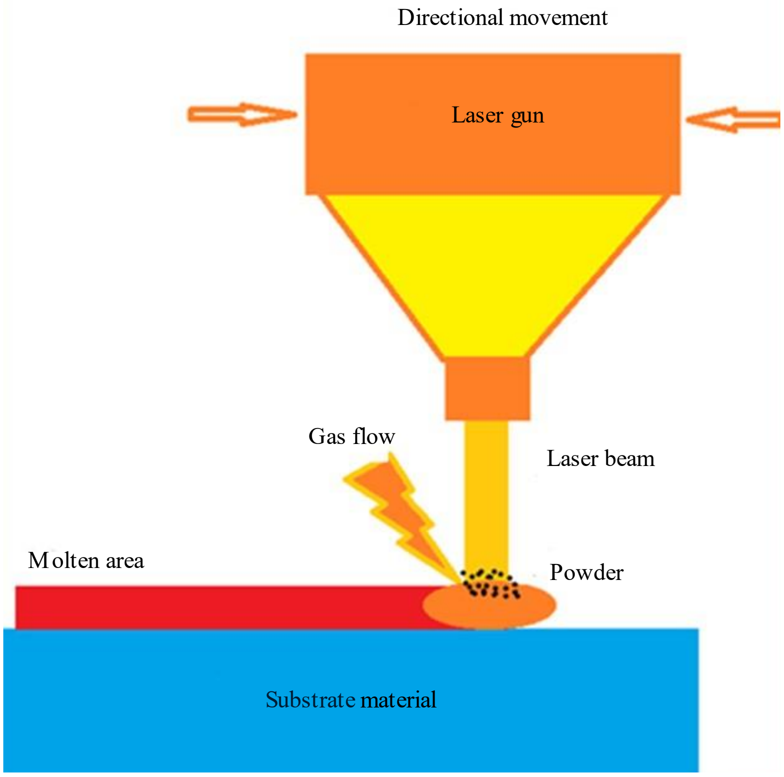

Figure 2. Schematic diagram of laser cladding fabrication process.

Coaxial powder feeding method

By using this technique, a mix of powders settles in the area of contact zone on the substrate's top surface. Later that, the fine powder is melted using a laser heat. The magnesium alloy's surface develops a coated layer upon melting and solidification. Compared to all other laser cladding and alloying processes, this one is very effective [28-29].

Wire feed approach

Wire is employed as the feedstock in this process. The coating material wire in this procedure is fed to the laser wire interaction site at an angle.As turns out that this procedure can only be used for coating metal or alloys. Since composites wires aren't commonly available in marketplaces so this approach can't be used to apply a composite coating[30].

Paste form feeding approach

The powders are utilized as the feedstock in this process. In order to create a paste from the mixture, the substance that coats and a binder are combined.By the side nozzle, the coating material is delivered in the paste form. Because the laser beam heat the interaction zone vertically, paste melts as it comes into contact with the coating zone's surface [31-32].

Stir Casting Process

The stir casting metal fabrication is traditionally and primary use technique in the production of particle reinforced metal matrix composites (PMMC). In this process stirring the reinforcement ingredient element into the molten metal is the primary step in the producing of composites.In the process of stir casting MMCs a chosen matrix material is melted, and then a reinforcement material is added. However, the melt must be decontaminated using a suitable medium before adding the reinforcement material since the molten metal reacts with airborne oxides, oxidizing the base material and reducing its characteristics.To achieve the intended arrangement of the dispersed form in the cast matrix, the melted material substance embedded dispersoids must next solidify under distinct circumstances. The mold is kept moderately below the furnace and has a pouring aperture at the bottom when using the stir casting with bottom pouring technique. This kind of setup speeds up the pouring process and improves particle integration. The composite characteristics are getting closer to improvement because of the shorter pouring time and improved particle introduction into the mold. Figure 3 shows a schematic process diagram of stir casting. A power source (motor) at the stirrer's top is used to start the stirring. A screw system allows the up and down motion of the stirrer. After the proper stirring of matrix material for a pre-determined period of time, reinforcement material is added into this. Pre-heating is essential to prevent the thermally cracking of the composite's material [33-35].

Since most ceramic reinforcement substances are denser than matrix alloy, mixing procedures are employed to introduce and evenly disperse the discontinuous phase; otherwise, if the reinforcement material is not adequately stirred, it could fall at the bottom of the crucible.

The following mixing methods are frequently employed for incorporating ceramic reinforcement into a melt:

- Incorporating particles into a molten alloy that is being violently stirred.
- Using an injection guns, inject the discontinuity phase into the molten form [36].

Stir casting is very attractive method of MMCs because it is the most cost-effective method of producing metal matrix composites among all the alternatives that exist and uses a traditional metal processing process.This method's preparation costs for composite material are roughly one-third to other competing techniques, and for large-scale manufacturing [37].

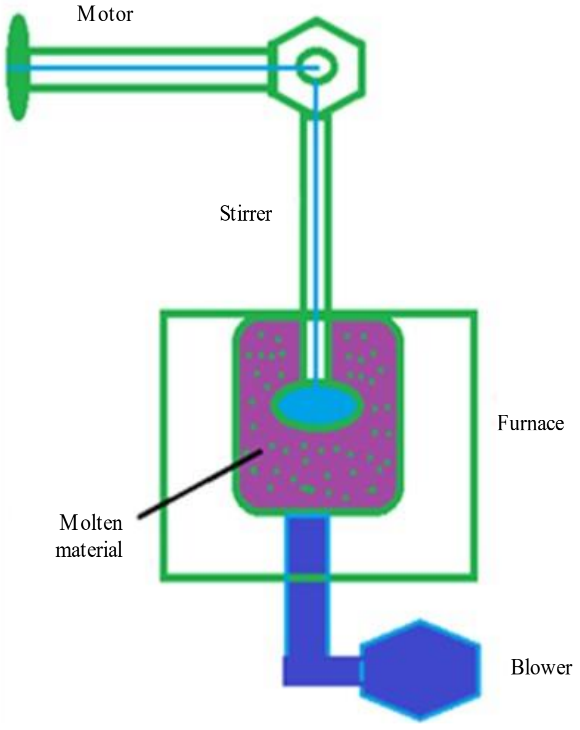

Figure 3. A Schematic diagram of stir casting.

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Powder Metallurgy

In the (PM) powder metallurgy process,the base metal powder and its alloy powder are mixed with the reinforced alloy powder.After mixing, the compacting is done to get required shape by the help of die and punch.Sintering process is required after the compacting.A uniform blend of powders is produced by the ball milling process.By filling a die and punching under load, the mixed powder is transformed into a solid-state.This solid form of the powder is heated below the molten temperature or elevated temperature. This heating process is called as a sintering process.A schematic diagram of powder metallurgy process is showing in Figure 4 [38].

IMPROVEMENT IN MMC BY ADDING VARIOUS REINFORCEMENT WITH DIFFERENT FABRICATIONS TECHNIQUES

Metal Matrix Composites (MMC) are made by mixing two or more distinct base metals to form new metals. This composite new material have excellent characterstics as compared to base metal.By adding the different micro and nano micro sized reinforcement material improve the important mechanical and other various characterstis like strength,wear rate and hardness [39].A right manufacturing techniques are also important to develop the new MMC. In the give table 2 give the out come in MMC by adding different reinforcemen with different manufacturing techniques [30-55].

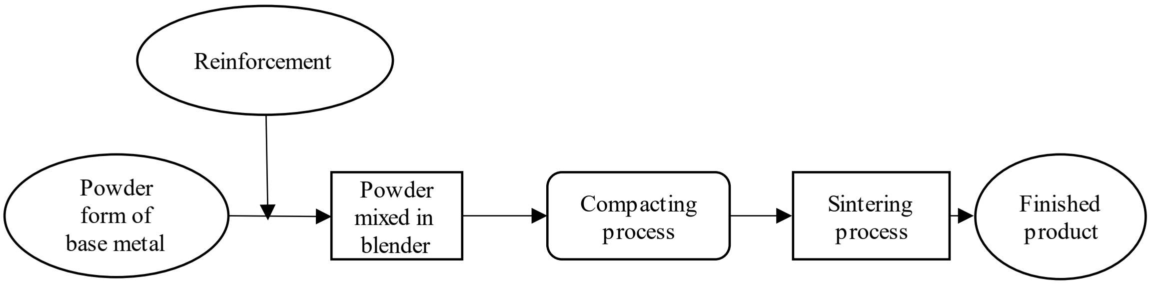

Figure 4. Powder metallurgy process.

Table 2. Observation of Various mechanical properties of MMC and its reinforcement[37-52].

Base material	Reinforced material	Fabrication techniques	Outcomes	References
AZ31B Magnesium matrix	Alumina (Al_2O_3)	Disintegrated melt deposition technique	Mechanical and wear properties increased at three different volume fractions (0.66 vol%, 1.11 vol% and 1.50 vol%) of 50 nm-sized Al_2O_3 particulates.	[40]
Magnesium alloy (AZ91D)	SiC (3%, 6%, and 9%)And BN (3%)	Stirring-squeeze cast method	Hardness,compression strength increased and same time yield strength,corrosion resistance also increased (20%,35% and 80.84%)by adding Sic (0-9% and BN.	[41]
AZ31	0.1 wt.% GO-SnO_2	Situ processing	Yield strength and ultimate tensile strength are increased by 33.5% and 23%.	[42]
AZ91D	Titanium and nickel micro-particulates	Powder metallurgy	Increase the yield strength, compressive strength and ductility values of the matrix alloy.	[43]
Magnesium matrix (AZ91D)	B_4C & $Mg_2B_2O_5$	Squeeze casting	The additions of $Mg_2B_2O_5$w and B_4Cp, can more effectively enhance the mechanical properties of the hybrid composite.	[44]
AZ91D	0.5%, 1%, 1.5% graphene particles	Stir casting	By adding grapheme hardness, tensile strength, impact and ductility increased.	[45]

WE43-T6	SiC and Al_2O_3	EDM	Increased hardness, ultimate strength, and tensile strength and weight reduced 1% by adding 5% reinforced material	[46]
Pure magnesium	Hydroxyapatite	Stir casting	Make the biocompatible alloy and improve the corrosion resistance.	[47]
Magnesium alloy (AZ91)	SiC particles	Ultrasonic vibrations	Mechanical properties of the composite increased at differnd Wt % of SiC.	[48]
AZ31B Magnesium matrix	Alumina (Al_2O_3)	Powder metallurgy	Yield strength decrease by the addition of Al_2O_3.wear rate increased at low speed.	[49]
AZ91	10% quid quill ash particles	Stir casting	Increase hardness, yield strength, and ultimate tensile strength by 32.34%, 18.86%, and 12.34%, wear resistance of the composites reinforced with 5 wt% and 10 wt% of particles is improved by 14.05% and 30.81%.	[50]
Magnesium (mg)	Ni50Ti50	Stir casting	Hardness and strength increased when grain size reducedced at different load.	[51]
AZ91	Yttrium oxide (Y2O3)	Centrifugal casting	composite had a hardness of 106.89 ± 1.25 HV, a tensile strength of 197.39 ± 2 MPa, and a compressive strength of 335.29 ± 5 MPa.	[52]
AM60 Magnesium matrix	Ceramic particles and Al_2O_3 fiber	Squeeze Casting	Increased the hardness value of the composite,Young's Modulus (131%), yield strength (49%), and fracture strain (74%).	[53]
Pure magnesium	Eggshell (ES)	Powder metallurgy	Mg/10 wt% ES composite exhibited the best wear performance	[54]
AZ31	1, 2, and 4 wt% submicron-MgO	Powder metallurgy	Tensile strength of composites is improved to 344.1 MPa, elongation is increased up to 21.5%	[55]

CONCLUSIONS

The characterstics and performance of MMCs is largely depend upon the magnesium matrix and its reinforcement materials. The optimize combination of magnesium matrix and reinforcement is improve the mechanical (strength, hardness), chemical (corrosion), and wear properties.The correct fabrication techniques is also an important parameter for better dispersion of reinforcement with the base metal.In this paper various fabrication techniques like Additive manufacturing, Laser cladding, and Stir casting discussed.

The below conclusions were find from the above study.

- In comparison to traditional manufacturing techniques, additive manufacturing (AM) offers a higher level of flexibility in design and the technical benefits of highly precision fabrication of complicated parts.
- Laser cladding is distinct from other conventional techniques because it uses a powerful laser heat source instead of an arc or gas flame and making the application of thin overlays feasible.
- Stir casting is very attractive method of MMCs due to its low setup cost among all the alternatives that exist.This method's preparation costs for composite material are roughly one-third to other competing techniques, and for large-scale manufacturing.

FUTURE SCOPE

Magnesium-based composites (MMCs) are difficult to fabriacte, however some researchers have succeeded by using the P/M or stir casting processes due to cost effectiveness. By using nanoparticles, they can expand their research even further because the behavior and characterstics of nono particles can be different from those of micro sized particles.

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