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# A Review on the Manufacturing of Hybrid Aluminum Metal Matrix Composites Reinforced with SiC and $Al_2O_3$

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**ABSTRACT**

Silicon carbide (SiC) and alumina ($Al_2O_3$) reinforced hybrid aluminum metal matrix composites (HAMMCs) are a remarkable development in material engineering because of improved mechanical and thermal characteristics. This review includes a detailed discussion of their production methods, liquid-state processes such as stir casting and solid-state methods such as powder metallurgy. These techniques are discussed with respect to their effects on reinforcement distribution, bonding, and overall composite properties. The potential of the hybrid reinforcement strategy to promote both properties which increase strength, hardness, wear resistance and thermal stability as well as properties which are desirable for lightweight materials needed in many industries is investigated. The issues that arise in processing HAMMC and the importance of uniform reinforcement dispersion and avoiding agglomeration and weak interface bonding are also discussed, as well as recent advancements in technologies such as ultrasonic cast aluminum alloy and frictional stir processing of LM13 aluminum alloy. These developments are intended to overcome the shortcoming in typical fabrication techniques whilst providing enhanced mechanical characteristics and low cost. Uses of HAMMCs have been found in aerospace, automotive, and biomedical fields where the parts need to be light, strong, durable, and withstand wear and tear for use in structural elements or prosthetic limbs, respectively. The review also explores the fabrication and characterization methodologies to assess the mechanical and microstructural characteristics of HAMMCs including tensile tests, hardness test and wear test. Last but not the least, the document discusses future research directions that are more related to use of environmentally friendly reinforcements, modern techniques of manufacturing and sustainability. The escalating demand for high performance and light weight products makes HAMMCs suitable to meet the new challenges in engineering.

## 1. Introduction

### *1.1. Background on Aluminum Metal Matrix Composites*

Aluminum Metal Matrix Composites (AMMCs) are a major step forward in material engineering where Al is reinforced with other materials to improve the characteristics. In the case of composite, aluminum or its alloy plays the role of matrix and besides offering light weight and good ductility, contain reinforcements with enhanced strength and wear resistant such as ceramics like SiC and $Al_2O_3$. AMMCs are to take the advantage of both components as far as mechanical properties of the finished product is concerned, the improvement of which is considered over existing aluminum alloys.

The growing use of lightweight, high strength materials in various industries has created strong interest in AMMCs. They are used in almost all areas of the industry such as

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aerospace, automotive, marine and defence industries because of the enhanced specific strength and resistance to wear. Moreover, the concept of coupling or embedding more than one type of reinforcement is possible within a single matrix that has expanded the understanding of these composites that they can produce far better mechanical performance compared to conventional composites.

Techniques used in the manufacturing of AMMCs include but not limited to stir casting and powder metallurgy. These methods play a major role in controlling the dispersion and interaction of the reinforcements within the matrix which is particularly important in defining the properties of the final material. Therefore, it becomes important to understand how the matrix and reinforcement work in order to achieve overall performance.

One important feature specific to AMMCs is the fact that their design can be tailored to application needs by varying parameters such as reinforcement type, size, the arrangement of morphological features, and the application of specific processing techniques. This has the great advantage of making them highly versatile and thus easily transportable from one discipline to another.

Progressing in the fabrication techniques have made many new pathways for the investigation of hybrid aluminum composites. In view of the growing interests of the industries in searching for new materials for lightweight construction materials with excellent strength and durability, AMMCs can be regarded as some of the promising materials for this application, [1], [3], [4], [6], [11] and [14].

### *1.2. Importance of Hybrid Reinforcement*

Organosilicon/aluminum metal matrix composites are significant to materials science because of the enhanced mechanical properties resulting from synergistic reinforcement interactions of hybrid AMMCs. The inclusion of such reinforcing agents such as silicon carbide (SiC) and alumina ($Al_2O_3$) into an aluminum matrix not only increases the strength and rigidity of the composites but also solves particular performance issues that occur with conventional composites. This combination strategy makes it possible to fine-tune properties of the material to suit demands of various sectors at once.

The idea of hybrid reinforcement is in the sense that it enhances the performance of the composites by developing a multi-material reinforcement structure which has special characteristics. For example, SiC exists as an ultra-hard material with wear resistance and $Al_2O_3$ as a thermal stable and corrosion resistant material. Thus, when choosing the reinforcements with suitable properties, the hybrid AMMCs can possess the entire spectrum of characteristics which cannot be provided by the single-reinforcement approach.

Also, the properties such as increased toughness and reduced brittleness which are very important in cases of loads with high dynamic stresses are also exhibited by hybrid composites. Besides toughness, these improvements also result in safety and reliability of engineering parts. In addition, there is a clear opportunity for weight loss when using these composites; aluminum paired with high strength reinforcements offer attractive lightweighting opportunities especially for industries where weight is at a premium such as aerospace and automotive industries.

Furthermore, it is possible to design the hybrid AMMCs with isotropic characteristics, which could be crucial when it is necessary to achieve similar performance in various directions. This flexibility is quite attractive for numerous engineering applications where particular mechanical characteristics are of paramount importance.

Finally, it can be stated that hybrid reinforcement in aluminum metal matrix composites is crucial to create the tailored material properties along with improved performance in a wide range of applications, [6], [9], [14], [11].

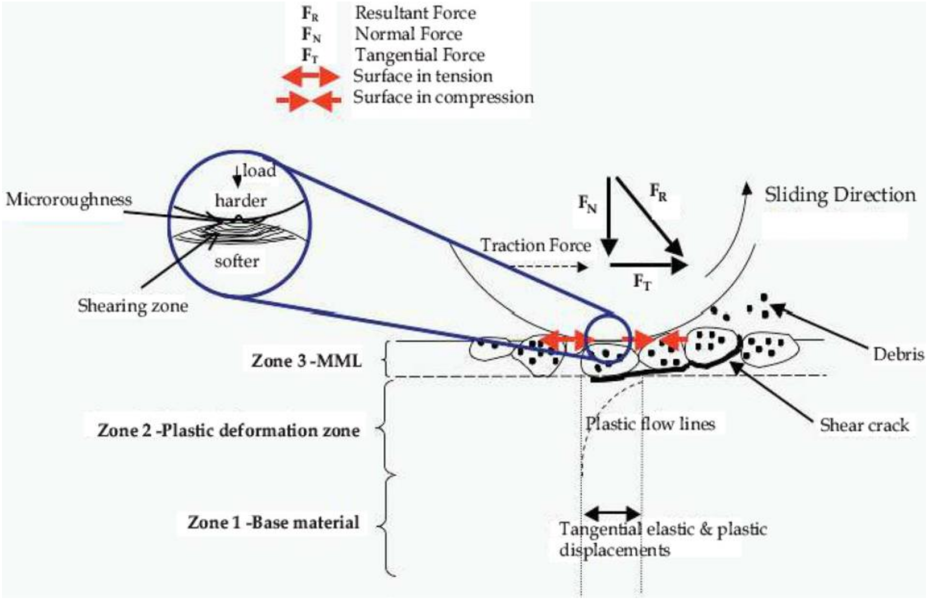


**Figure 1**: MML formation Full size image, [17].

### *1.3. Objectives of the Document*

The primary purpose of this document is to bring out the less understood facets of Hybrid Aluminum Metal Matrix Composites (HAMMCs) and their importance in the development of materials science. This paper aims to provide a comprehensive review of the composite of the aluminum matrices with different reinforcements focusing on SiC and $Al_2O_3$. It focuses on aspects of their application in enhancing mechanical properties including strength, hardness, and wear resistance. A critical review of the contemporary manufacturing processing methods such as, casting and powder metallurgy forms the core objective of this work with the view of pointing out the advancements that facilitate the incorporation of these reinforcements in aluminum matrices.

Furthermore, it is the purpose of this document to discuss the experiences made during the processing of hybrid AMMCs including the problems encountered during the processing and those which pertain to the uniform distribution of reinforcements which are critical determinants of performance. Knowledge of these challenges enables improvement of the manufacturing process and the physical and mechanical properties of the materials. It will also seek to find out how reinforcements and the matrix embed themselves together by understanding bonding processes and the role of interphase layers.

It also encompasses characterization of these composites by mechanical property characterization tests and microstructural characterization methods. Such assessments will form a basis for comparison with the traditional composites and help to establish the prospective durability under various operation conditions. Finally, this work aims at encouraging more studies on hybrid composites by outlining the technologies and market demands that may redefine future application in various sectors, [26], [11], [15], [2], [17], [19], [20], [8] and [28].

## 2. Fabrication Techniques for Hybrid AMMCs

### *2.1. Overview of Fabrication Methods*

The synthesis of hybrid aluminum metal matrix composites (AMMCs) involves a number of processes that affect the characteristics and behaviour of the material. These methods can be classified into methods under the liquid state process and the solid state process and each possesses its own merits and demerits. Stir casting, a liquid-state processing method, is particularly preferred because it is the simplest and least expensive to use on a commercial scale. Here, the matrix is in a molten state and the reinforcements are incorporated in a randomly oriented fashion to form a uniform suspension before the solidification of the aluminum matrix.

Stir casting enables adding different reinforcements, including ceramic materials such as silicon carbide (SiC) and alumina ($Al_2O_3$) that improve the mechanical properties including hardness and tensile strength. Control of conditions such as the stirring speed, thermal control and distribution of reinforcement during this stage is important for avoiding problems such as particle agglomeration and guaranteeing that the matrix and reinforcement phase wet properly.

In this case, solid-state techniques include the powder metallurgical techniques such as hot pressing and cold isostatic pressing. These approaches allow for manufacturing of composites without the requirement for melting of the matrix material. Applying these methods usually leads to reduced porosity and enhanced mechanical characteristics because interface adhesion between the matrix and reinforcement particles is stronger.

Every fabrication process tends to pose certain difficulties in terms of process control including the dispersion of reinforcements in the matrix to the desired distribution, and the mechanical characteristics of the composite. New processing technologies are under constant research to counter these challenges to improve the performance characteristics of hybrid AMMCs and also with due consideration of environmental impact, [16], [4], [3], [13] and [8].

### *2.2. Casting Techniques*

#### 2.2.1. Investment Casting

investment casting, also known as lost-wax casting, is applied universally in the fabrication of intricate forms of hybrid AMMCs. To start with, a wax model of the intended part is made and later covered with ceramic material which on solidification forms a rigid cast. Once the wax is evaporated, there is a cavity into which molten aluminum with ceramic reinforcements or fibers is poured.

Investment casting has its significant capability in delivering high dimensional accuracy and surface finish that are essential for particularly used in aerospace and automotive industries where parts functionality is paramount. The use of this method provides the ability to plan and control reinforcement material deposition accurately in the aluminum matrix to improve other properties such as strength and wear resistance while reducing undesirable characteristics like porosity.

The right material for reinforcement including silicon carbide (SiC) and alumina ($Al_2O_3$) are crucial when it comes to designing for better wear and load carrying capacity. The volume fraction of these reinforcements can be controlled during casting and this enables manufacturers to choose the right mechanical properties of hybrid AMMCs.

Nonetheless, investment casting has its strengths where challenges on the side of process optimisation come into the picture. These factors include pouring temperature, cooling rate and composition of the mold and good adhesion between the matrix and the reinforcement are important for enhanced performance [2], [44], [16], [25] and [29].

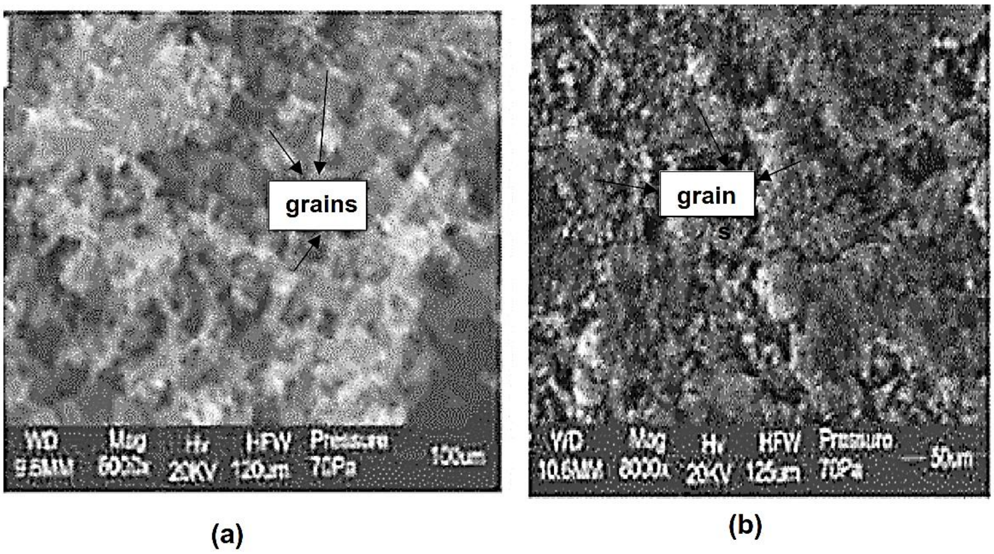


**Figure 2**: (a) A representative microstructure of Al-alloy, (b) microstructure of 7.5 wt% (RHA + CSA) Al-composites, [2].

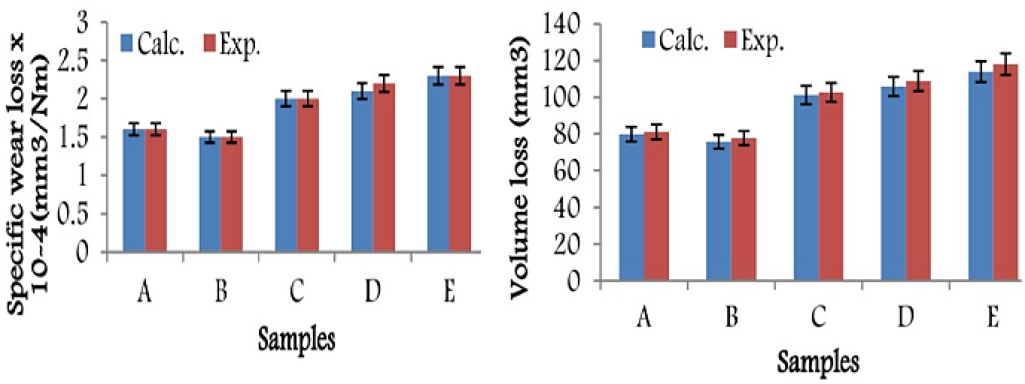


**Figure 3**: Variation of specific wear loss and volume loss for single and hybrid (BLA and silica sand), [2].

2.2.2. Semi-Solid Processing

Thus, semi solid processing has become one of the most important fabrication methods for making hybrid aluminum metal matrix composites (AMMCs). This technique is applied in the semi-solid state of the metal matrix which normally ranges between the solidus and liquidus temperature regimes. The manner in which work is conducted in this semi-solid state is beneficial in various ways as compared to conventional methods of casting. The semi-solid slurry structure provides thixotropic properties that enhance the flowability of the slurry during the mixing of reinforcement particles into the aluminum matrix.

Stirring plays an important role during semi-solid processing so as to encourage the homogenization of the reinforcements like SiC and $Al_2O_3$. Other critical variables including the stirring temperature and time greatly affect the formation of the microstructure and mechanical characteristics of the synthesized composites. The studies show that it is possible to achieve significant enhancements in tensile strength once the stirring temperatures are kept within the range 630 °C to 680 °C. Higher stirring temperatures decrease the viscosity thus improving the flow and mixing.

However, the risk may come at higher temperatures where oxidisation is likely to affect the quality of the material. The potential of mixing is also affected by the balance between time and temperature; when stirring is done intensely, the particles may clump together, or the mixture's viscosity increases. The main activities during this stage involve the dynamic interaction between the reinforcement particles and molten aluminum alloy to obtain composites with enhanced performance characteristics.

The use of nanoceramic reinforcements in this methodology also appears to be effective in increasing strength substantially while retaining adequate elongation characteristics for applications. Continuous innovations in the process control of stirrer speed and pouring temperature are crucial in optimizing the production of techniques that improve the mechanical properties of hybrid AMMCs in various industrial applications. [39], [14], [24] & [7].

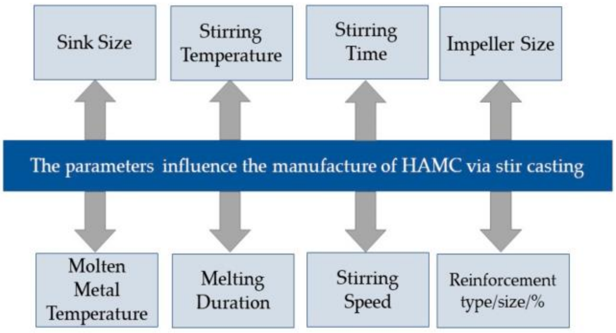


**Figure 4**: Factors that influence the stir casting process, [14].

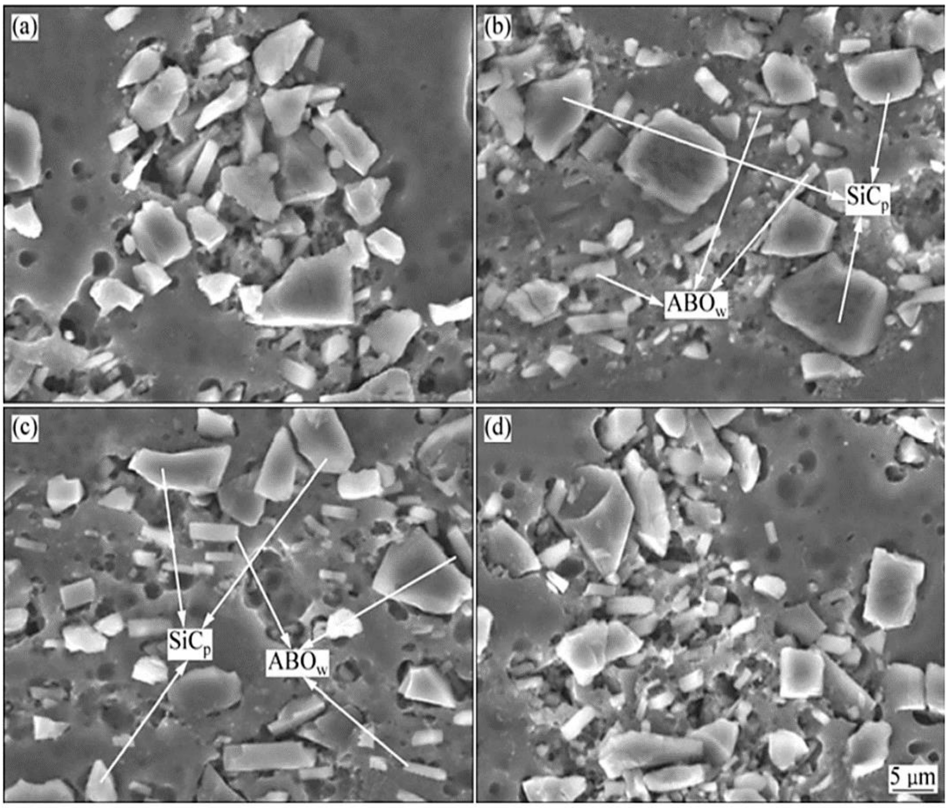


**Figure 5**: Micrographs of (5%ABO w + 15%SiC p)/6061Al composites fabricated at different stirring temperatures for 30 min: (a) 680 $^{o}$C; (b) 650 $^{o}$C; (c) 640 $^{o}$C; (d) 630 $^{o}$C, [14].

**Table 1**: Comparison of various techniques using that MMC can be manufactured, [24].

| Sr. No. | Criteria | Solid State Processing | | Liquid State Processing | | Squeeze Casting | In-Situ Technique |
|---|---|---|---|---|---|---|---|
| | | Friction Stir | Powder | Centrifugal Casting | Stir Casting | | |

| | | Processing | Metallurgy | | | | |
|---|---|---|---|---|---|---|---|
| 1 | The ability to produce composites | Surface composites | Composites in Bulk<br><br>Composites that are functionally graded (FGM) and have a step-by-step structure | Functionally Graded Composites | Bulk Composites | Functionally Graded Composites in Bulk | Bulk Composites |
| 2 | Shape of resulting composites | Plates | Complex shapes can be manufactured, depending on the die and punch. | Hollow shape | Depending on the mold, intricate shapes can be produced. | Complex shapes can be manufactured, depending on the die and punch. | Depending on the mold, intricate shapes can be produced. |
| 3 | Requirement of major equipment | Workpiece holding fixture and vertical milling machine<br><br>Configuration for Friction Stir Welding | Ball milling or melt atomization (for powder preparation)<br><br>For combining powders, use a twin cone screw mixer blade mixture or a rotating drum.<br><br>Press with hydraulics (for compacting)<br><br>(for sintering) furnace | Furnace (for melting matrix and preheating particles)<br><br>A rotating mold that produces centrifugal force | Furnace (for melting matrix and preheating particles)<br><br>A mechanical stirrer (used to mix molten liquids)<br><br>Mould (to obtain the necessary forms) | Furnace (for melting matrix and preheating particles)<br><br>Press with hydraulics (for compacting)<br><br>Die and Punch (used to create intricate forms) | Furnace (for melting matrix and preheating particles)<br><br>Mould (to obtain the necessary forms) |
| 4 | types of flaws that can occur in composites that are made | Pores, cracks, tunnels and voids, fragments, lack of penetration, hooking, flash, kissing bond, and other surface flaws | Poor sintering, micro-laminations, density fluctuations, and ejection cracks | Gas porosity, metallurgical flaws, mold material flaws, pouring metal flaws, cracking or ripping along edges, and shrinkage flaws | Gas porosity, fractures or ripping at edges, metallurgical flaws, mold material flaws, gas porosity, and pouring metal flaws | Metallurgical flaws, gas porosity, mold material flaws, pouring metal flaws, cracking or ripping along edges, and shrinkage flaws | Gas porosity, mold material flaws, pouring metal flaws, cracking or ripping along edges, and metallurgical flaws |
| 5 | Defect level | Microscopic and sometimes Macroscopic | Microscopic and sometimes Macroscopic | Both Microscopic and Macroscopic | Both Microscopic and Macroscopic | Both Microscopic and Macroscopic | Both Microscopic and Macroscopic |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 6 | The incidence of defects in manufactured composites | Moderate | Low | High | High | Moderate | High |
| 7 | Regulating the reinforcement particle content | Controlling the weight or volume percentage of reinforcement is challenging. | Controlling the weight percentage of reinforcing particles is easier. | Controlling the weight and volume percentage of reinforcement particles is simpler. | Controlling the volume percentage and weight of reinforcement particles is simpler. | Controlling the weight or volume percentage of reinforcement is challenging. | Weight or volume percentage of reinforcement is hard to control. |
| 8 | Distribution of reinforcement particles | Homogenous distribution | Step-wise distribution, homogeneous distribution, and varying distribution along the thickness | Varying distribution along the thickness | Homogenous distribution | Heterogeneous or Homogenous distribution | Heterogeneous or Homogenous distribution |
| 9 | Equipment and production cost | Moderate | High | Low | Low | Moderate | Low |
| 10 | Highlighting Feature | Green manufacturing method for microstructure modification | Capacity to mix normally incompatible ingredients into a powder | Composites come in nearly infinite diameters, thicknesses, and lengths. | Cost-effective simplicity, adaptability, and suitability for large-scale manufacturing | Reduce gas compression and solidification shrinkage. | Cheapest method, suitable for large scale production |
| 11 | Limitation | Reduced flexibility, low production rate, and inability to process non-forgeable materials | It is only cost-effective for mass production to create intricate designs. | requires expert labor, the interior diameter of the composites is difficult to manage, and the cast composites' strength is limited. | Poor wettability, thermal mismatch, potential interfacial reactivity, and the need for post-processing methods to address casting flaws and agglomeration | High cycle duration, low flexibility, difficulty maintaining homogeneity, and increased likelihood of matrix-reinforcement reaction | It is impossible to make composites with a higher reinforcing particle content. |

## *2.3. Powder Metallurgy Methods*

### 2.3.1. Hot Pressing

Hot pressing is a well-known fabrication technique for hybrid AMMCs where powder metallurgy is blended with high temperature treatment. This technique combines metal powders and reinforcing agents subjected to high pressure and temperature to help achieve improved particle adhesion and minimized pore formation. The procedure starts with mixing alum powder with reinforcements such as SiC or $Al_2O_3$ to enhance mechanical characteristics of the material.

In hot pressing, the temperatures do not exceed the melting point of aluminum to avoid liquefaction of the matrix material while ensuring that the operation allows solid-state diffusion for interaction between matrix and reinforcements. Pressure application is an important factor contributing to density and such characteristics as strength of structures, which are important for obtaining the necessary mechanical characteristics.

The developed microstructure of AMMCs reveal uniformly distributed reinforcement particles that enhance the strength and tribological properties because of the proper load transfer phenomenon and interfacial adhesion. However, problems such as the control of temperature differential and achieving equal pressure across the mold can cause such flaws as voids or uneven positioning of the reinforcement bar.

Advanced process parameters and changes in design of equipment to tackle these problems are discussed in this paper with regard to the performance characteristics of hybrid AMMCs. In the end, hot pressing can be seen as one of the main techniques to create high-performance AMMCs for use in the most demanding industries, such as aerospace and automotive, [14], [7], [5], [36], [18] and [12].

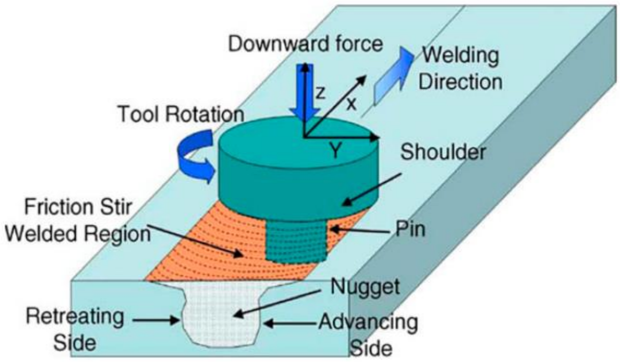


**Figure 6**: The process of FSP, [14].

Table 2: Hardness value of AA6061 reinforced with $Al_2O_3$ and AlN, [14].

| Specimen | Microhardness (HRB) | | | |
|---|---|---|---|---|
| | Base Metal | Average | Stir Zone | Average |
| 1. FSP of AA6061 | B-89 | B-87.33 | B-91 | B-89.33 |
| | B-85 | | B-88 | |
| | B-88 | | B-89 | |
| 2. 75% $Al_2O_3$ & 25% AlN | B-87 | B-87.66 | B-93 | B-91.33 |
| | B-91 | | B-87 | |
| | B-85 | | B-94 | |
| 3. 50% $Al_2O_3$ & 50% AlN | B-89 | B-87 | B-94 | B-93 |
| | B-87 | | B-92 | |
| | B-85 | | B-93 | |
| 4. 25% $Al_2O_3$ & 75% AlN | B-88 | B-88 | B-89 | B-88.66 |
| | B-85 | | B-87 | |
| | B-91 | | B-91 | |

## 2.3.2. Cold Isostatic Pressing

Cold Isostatic Pressing (CIP) is extensively used powder metallurgical process to fabricate hybrid aluminum metal matrix composites (AMMCs). It forms highly dense, uniformly structured materials with well defined and controlled microstructures by exerting uniform hydrostatic pressure on a powder compact, normally aluminum and reinforcements such as silicon carbide or alumina. One of the main benefits of CIP is the generation of near net shape parts which decreases the amount of material used and hence maximizes utilization.

The process starts with the mixing of the aluminum alloy and reinforcement particles and thereafter the particles are placed in a flexible mold and subjected to high pressure in a fluid media such as oil or water. It has been shown that this isotropic pressure enhances the packing of the powders and their compaction. The material is also subjected to sintering at higher temperatures after compaction in order to improve the particle and the mechanical characteristics.

CIP offsets the uniaxial pressing conventional techniques in aspects of die wall friction as well as the uniformity of particle packing. Because it can receive a certain level of geometries without distorting the microstructure, it is ideal for high performance. The subsequent sintering steps may be adjusted to control the interparticle bonding and properties such as hardness as well as strength which makes the hybrid AMMC to exhibit superior mechanical performance for higher end applications in industries. [18], [41] and [24].

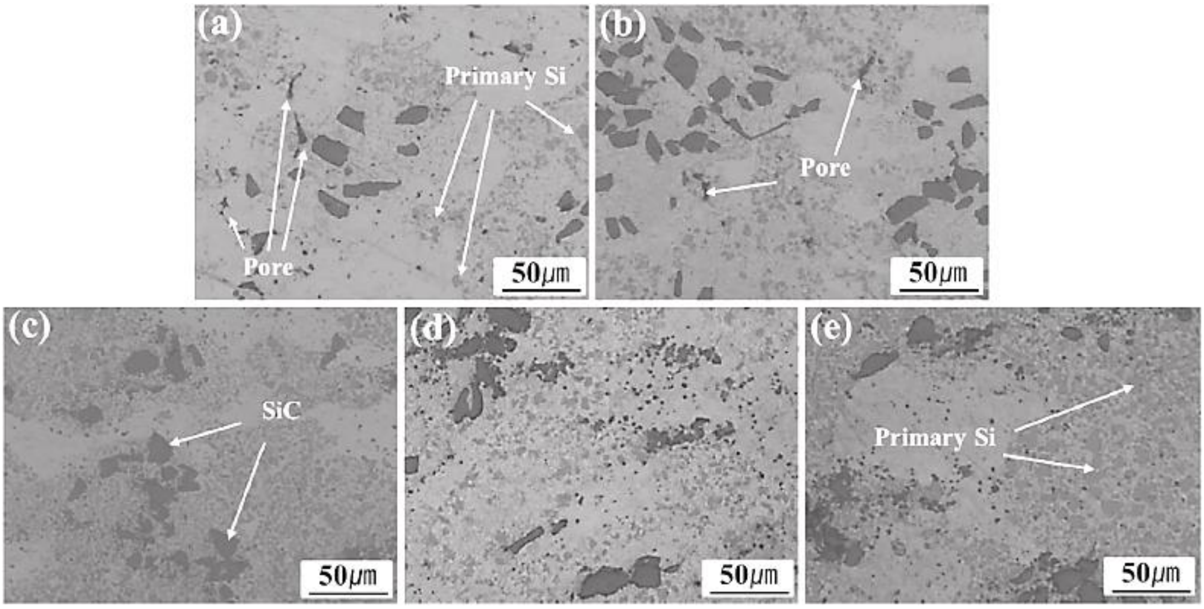


**Figure 7**: Open in a new tab Microstructure of sintered samples manufactured at various sintering temperatures (a) 480 °C (b) 520 °C (c) 560 °C (d) 580 °C (e) 600 °C, [24].

## 3. Reinforcement Materials: SiC and $Al_2O_3$

### *3.1. Properties and Characteristics of SiC*

SiC is a significant reinforcement element in hybrid aluminum metal matrix composites (AMMCs) because of its remarkable physical and mechanical features. SiC is silicon carbide a strong ceramic material, which is used for its hardness, thermal conductivity and abrasion resistance, and is has a density of around 3.1g/cm³ and a melting level of approximately 2730 ⁰C, making it suitable to high temperatures.

For instance, the improved strength to weight ratio of SiC is very useful in applications such as aerospace or automotive, where weight is a very large factor, but strength cannot be compromised. The superior wear resistivity improves the tribological characteristics of the composite material resulting in lower wear rates of engine components and machining tools.

Moreover, SiC enhances the coalescence mechanism of aluminum matrix because of its compatibility with aluminum alloy during processing. However, it was also found that its reinforcement performance depends on the size and distribution of the particles; finer particles are known to improve mechanical properties better than the larger ones due to reasons of increased contact area for bonding.

The addition of SiC greatly enhances the hardness and tensile strength of AMMCs, and even low volume percent increment improves the performance over unreinforced aluminum alloys. However, if the content of SiC is too high, the aggregative phenomenon may happen, which may negatively affect ductility. Therefore, SiC is essential for the improved use of multi-functional high-performance hybrid AMMCs in challenging applications, [17], [34], [33] and [36].

### *3.2. Properties and Characteristics of $Al_2O_3$*

The ceramic material most widely used is Alumina $Al_2O_3$, commonly referred to as Aluminum oxide with superior mechanical and thermal performance, alumina is used extensively as the reinforcement phase in Aluminum metal matrix composites (AMMCs). The use of alumina as a material for being embedded in an aluminum matrix has a number of benefits, the most notable of which is the ability to increase the hardness, strength and wear resistance of the whole composite. Alumina has a density of around 3.69 g/cm³ and therefore supports the light weight of AMMCs but at the same time offers a robust mechanical performance. This property makes these composites suitable for use in high temperature environments because it melts at around 2072 °C.

Geometrically, alumina outperforms other possible matrix materials due to its impeccable chemical stability that matches aluminum's naturally inherent corrosion resistance. This fusion also prolongs the durability of more AMMCs containing alumina in their composites as reinforcements. Generally, the particle size of alumina is in the range of 60 micrometers and thus easily suspend evenly in the aluminum matrix during processes like the stir casting process.

The mechanical properties of $Al_2O_3$ reinforced AMMCs are appreciable; the studies show that the improvements in tensile strength and microhardness can be achieved by the incorporation of alumina particles. For instance, research shows that incorporating of nano-sized $Al_2O_3$ particles raises the yield strength by about 81 % due to enhanced dispersion and decreased agglomeration realized through methods such as ultrasonic treatment in solid mixed casting.

In addition, when $Al_2O_3$ is used in combination with other reinforcements like silicon carbide (SiC), the development of hybrid composites gives better tribological characteristics than conventional materials. The combined impact of these reinforcements improves the wear protection and sweeps the friction coefficients in sliding situations, [17], [8] and [1].

## 4. Mechanisms of Reinforcement Interaction

### *4.1. Bonding Mechanisms between Matrix and Reinforcements*

The interfacial interactions between the aluminum matrix and reinforcement particles such as SiC and $Al_2O_3$ are critical in the behaviour of hybrid aluminum metal matrix composites (AMMCs). These include mechanical interfacial bonding between the reinforcements and the matrix, formation of chemical bonds, and effect of surface treatments to the wettability of the reinforcements. As a result, added ingredients such as SiC get locked up within aluminum when the metal cools, which results in an interlocking of the material that strengthens the composite. Unfortunately, the success of this bond depends on factors such as particle size, spatial distribution and surface properties.

Adequate wettability is critical for the formation of the perfect interfaces for the structures being bonded. It can be enhanced through several approaches, for example, incorporating conducive alloying additions that have affinity with the matrix as well as the reinforcement. For example, the introduction of magnesium can enhance better wetting of the ceramic particles in a heated aluminum environment due to the reduction of interfacial tension. These changes in contact between the matrix and reinforcement are of paramount importance for effective load transfer.

In addition, surface treatments on the reinforcements, for example through coatings or chemical processes, improve the interfacial adhesion greatly. Such treatments optimise chemical interactions within the interfaces by compounding intermetallics or raising interface adhesion with coupling agents. Van der Waals forces are also adduced as influential forces that contribute to the overall bond strength despite being relatively weaker than covalent forces.

Also, the higher degree of control in the dispersion of particles and the lower porosity achieved through advanced processing technologies will go a long way in improving the interfacial bond. Specific solute-solvent interactions during the mixing process, like ultrasonic cavitation, or in stirring methods, like using paddles, have been reported as having the potential of improving the homogeneity in hybrid AMMCs. Knowledge of these bonding mechanisms is highly essential when designing composites with desired property enhancements for specific applications, [19], [43] and [8].

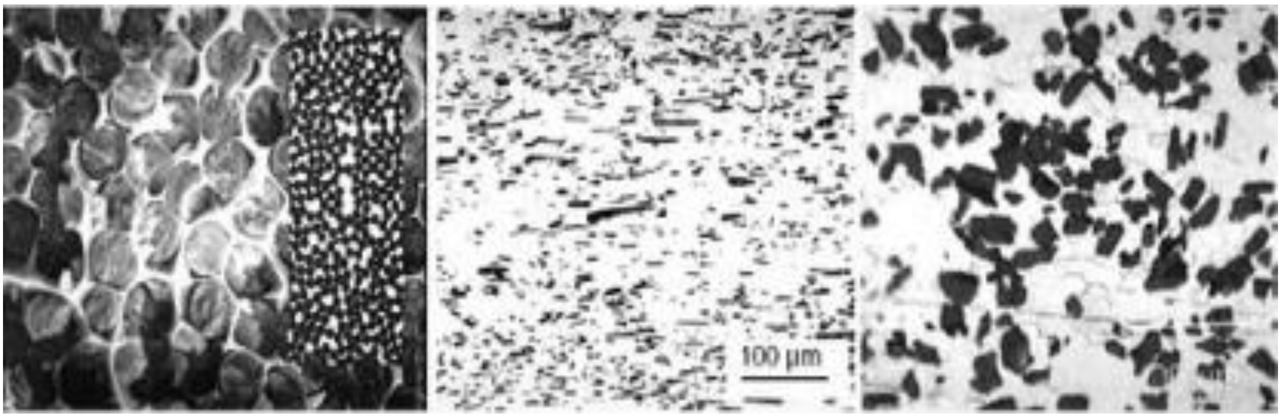


**Figure 8**: Classification of MMCs and their characterizations, [13].

### *4.2. Role of Interfacial Layers in Performance*

In the hybrid AMMCs, the interfacial layers are effective in improving the mechanical property of the material. This strong interfacial layer enhances the load transfer between matrix and reinforcements and also makes the structure stronger and ductile. Some of these include wettability of the reinforcements, surface energy, surface roughness of the aluminum matrix and the alloying elements.

The reinforcements like SiC and $Al_2O_3$ form some kind of interaction at the interface. To the surface of SiC particles it is allowed to apply some treatments or coatings to increase density of aluminum and, hence, increase adhesion. It may be coupling agents or intermetallic formed at the time of solidification of the cladding. Improved wettability enhances the possibility of the particles to get closer to the molten matrix during the fabrication process making the bond stronger.

There is always a need to have good intermolecular interactions at the interfaces in the composites in order to have a high mechanical properties. If it has poor wettability the use of ultrasonic treatment or preheating should be considered as it reduces the gas layers around particles or increases the interaction forces with molten metal respectively.

Furthermore, the development of technology such as in-situ processing ensures the development of stable reinforcement phases in the matrix during fabrication besides enhancing particle distribution, thermal stability and bonding under high temperatures. Finally, the above improved wettability results in better mechanical interlocking and the AMMCs hybrid perform better in [19], [43], [8] and [7].

## 5. Processing Challenges and Innovations

### *5.1. Challenges in Fabrication Processes*

Hybrid Aluminum Metal Matrix Composites (AMMCs) face several issues in the course of their production, which limits their application. Dispersing the reinforcements homogeneously in the metallic matrix, in this case aluminum, is challenging but necessary for the composite's optimum performance. These reinforcement materials may also have some chemical reactivity with the matrix during processing which results in agglomeration or clustering and hence degrading the mechanical properties of the composites. Further, good adhesion between the matrix and reinforcements is another factor that has to be achieved while synthesizing; this should be done without jeopardizing the microstructure properties of the niobium based matrix. Lack of good interaction between these phases can lead to formation of bad interfaces that have detrimental effects on the system.

Another major concern is the control of thermal gradients developed during processing leading to residual stresses and crack formation. These mechanical defects do not only lower the general strength of the mass of the material, but may also cause earlier failure in structural uses. Though the application of sophisticated techniques like Additive Manufacturing has been considered as the probable solutions to these issues, those techniques more often are costly and complex.

This is because the raw materials used to produce hybrid AMMCs' composites are relatively costly and the processing more labor intensive. The absence of a standard format of design data only adds a problem on their commercial applicability, wherein the manufacturers are left with a single question bothering them, about how much property predicting capability is enough for service conditions. Moreover, to achieve a good balance between improved mechanical properties and reasonable ductility, it has been a difficulty: hybrid composites generally exhibit lower ductility than monolithic materials.

However, it has been found that for most of the hybrid AMMCs, post-processing operations are required to achieve the final cross-sectional geometry of the components, which adds to the cost. Hence, future studies should aim at defining new processing techniques that overcome these challenges and at the same time increase efficiency and performance of the materials. [13] & [19].

### *5.2. Innovation in Processing Techniques*

The development of the processing methodologies of the hybrid aluminum metal matrix composites (AMMCs) is important for addressing the manufacturing and performance issues. A new feature is the applications of mixed forms of reinforcements where different types such as SiC and $Al_2O_3$ are incorporated to improve properties such as strength and wear. This approach enhances the functionality and enables properties be tailored to meet the required application.

Advances such as Selective Laser Melting in AM could offer brand-new chances to design advanced AMMCs including enhanced microstructural attributes. Additive manufacturing provides for a good distribution of the reinforcements, a problem seen particularly in batch manufacturing processes. SLM also enables the generation of tough-to-develop topologies that cannot be made using traditional manufacturing processes.

Taking into account the fact that AMMCs require solid-state processing, Friction Stir Processing (FSP) appears as another effective approach for improving their mechanical performance. FSP alters the microstructure during processing, which enhances the interfacial adhesion of the matrix material to the reinforcements while at the same time enhancing the toughness of the material without causing a detrimental effect on ductility.

However, the enhancement of process parameters of the reinforced composite which determines the wettability between the matrix and reinforcements is critical since it determines the distribution and bonding of the reinforcements that influence the final performance of the composite. Further research on improving the ductility coupled with progressive strength and wear resistance is needed through novel processing techniques in the production of AMMC, [12], [24], [28] & sustainable recycling of manufacturing scrap.

## 6. Characterization of Hybrid AMMCs

### *6.1. Mechanical Property Testing Methods*

#### *6.1.1. Tensile Testing*

Tensile testing is therefore a critical technique in the characterization of the mechanical properties of hybrid AMMCs. This process involves subjecting a test piece to uniaxial tensile forces and continuing till it breaks. The data gathered from this test comprises stress and strain; these are employed to develop a stress-strain diagram which explains the nature of the material to forces being applied on it.

It is therefore a large drawback of this testing that one of the most important yield, which is the tensile strength, is the maximum stress that can be placed on a material before failure in tension or while stretching. For hybrid AMMCs, tensile strength is strongly dependent on the type and volume of reinforcements, matrix alloy selection, and the manufacturing technology: Even within the sameFML category (such as SESC), the tensile strength of AMMCs may differ significantly.

For the very purpose of offering good accuracy and precision, specifications such as ASTM E8 or ISO 6892 are normally adopted. They noticed that grain structure and orientation of specimens are well controlled during preparation to avoid such variations. In stir casting or powder metallurgy production steps, the dimensions should be accurately machined to be made uniform hence the accurate testing requirements.

Also, the fibre-matrix interface and the nature of the reinforcement materials have a strong influence with the tensile performance. Good interfacial adhesion decreases the stress concentration and enhances the mechanical properties; however, weak interfacial adhesion can cause failure under tension.

Fractography analysis which is characterization technique complements tensile testing by revealing failure modes. Characteristics of fracture surfaces can be used to gain valuable insights into how reinforcements influence the behavior of materials under stress and how microstructures influence overall performance, [22], [21], [23] and [16].

#### *6.1.2. Hardness Testing Methods*

The most important data measured through hardness testing techniques are the mechanical properties of hybrid aluminum metal matrix composites (HAMMCs) especially with reference to their hardness or resistance to deformation and wear. Two well known tests carried out for this purpose are Vickers and Brinell tests.

The Vickers hardness test involves the use of a diamond indenter applied on the material at a particular load where the indentation area is determined after testing. This method can therefore be applied widely and yield consistent results even in composite samples with different microstructures.

The Brinell test uses a hardened steel or carbide ball as its penetrator, and the indentation left is qualitatively measured by the diameter after the test. This process is useful for mean field correction when the microstructure of the material is coarse and contains substantial local variations in hardness.

As with the previous techniques, the decision as to which of these methods to employ depends on characteristics of the material and the degree of precision needed. When they contain hard reinforcement, for example, silicon carbide (SiC), or alumina ($Al_2O_3$), some extra attention should be paid to prevent wear of the indenter.

The newly developed techniques like nanoindentation can be used to determine hardness at the microscale which is important for analysing HAMMC materials reinforced with nano sized particles. It is important that samples must be prepared properly and the environment which the test is to be conducted must also follow certain settings, [22], [14], [38].

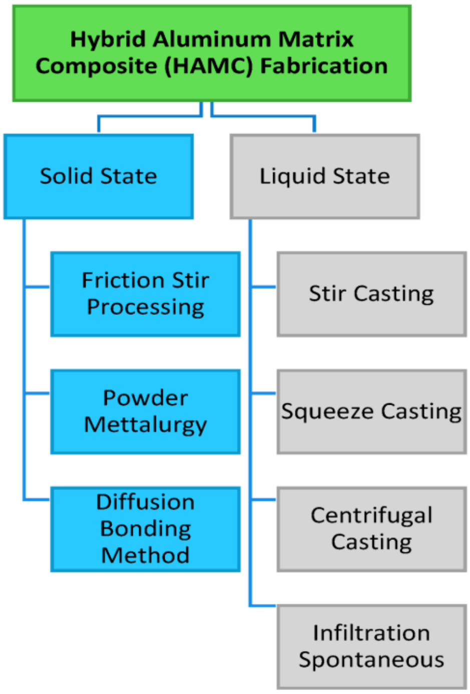


**Figure 9**: Fabrication process on the HAMC, [14].

*6.2. Microstructural Analysis Techniques*

It is necessary to investigate the microstructures in the hybrid aluminium metal matrix composites (AMMCs) for their application and mechanical properties. Several approaches enable this analysis, and they provide the different features of the composite's microstructure. SEM gives a higher resolution image which enables the researchers to study the dispersion of the reinforcement particles such as silicon carbide (SiC) and aluminum oxide ($Al_2O_3$). SEM provides the means of evaluating particle size, particle shape and degree of agglomeration, all of which affect mechanical characteristics.

Optical Microscopy provides lower magnification view of the structure in which the grains and phases can be identified and helps to assess the grain refinement from viewing operations such as stir casting or FSP. Of this technique, one can accurately map microstructural characteristics with process variables.

X-ray Diffraction (XRD) is used to analyze diffraction patterns to identify present phases and their quantity within hybrid AMMCs and relate microstructure characteristics to mechanical properties.

Scanning Electron Microscopy (SEM) provides a macro and microscopic view of the matrix and reinforcement as well as fractography to investigate failure modes while Transmission Electron Microscopy (TEM) reveals in detail the interfacial bonding and the mechanisms of load transfer at the nanoscale.

Finally, Energy Dispersive X-ray Spectroscopy (EDX), used in tandem with SEM or TEM, provides information on the elemental composition that helps to understand the impact of changes in reinforcement content on the microstructure. Integration of these methodologies provides improved characterization of hybrid AMMCs for optimization of fabrication techniques and material properties as indicated in [14], [15], [24], [40] and [13].

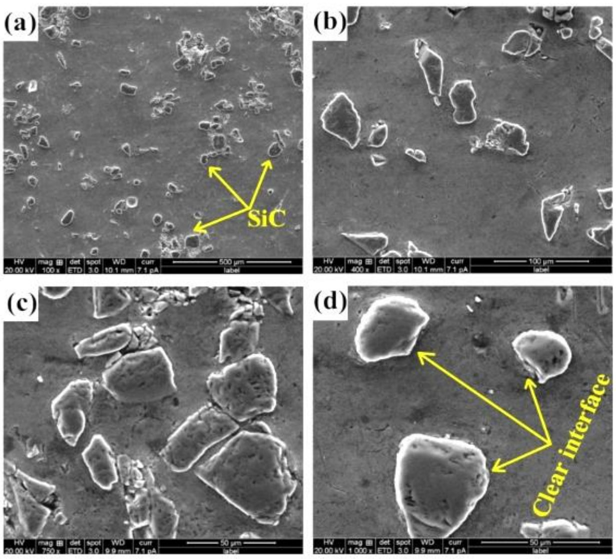


**Figure 10**: Open in a new tab SEM images of AA 6061-15 vol.% SiC at magnification (a) 100×; (b) 400×; (c) 750×; (d) 1000×, [15].

## 7. Performance Evaluation of Hybrid AMMCs

### *7.1. Comparative Studies with Conventional Composites*

The inherent characteristic of aluminum metal matrix composites or AMMCs as compared to traditional composites is the use of multipurpose reinforcements including silicon carbide (SiC) and alumina ($Al_2O_3$). When incorporated strategically, this reinforcement increases mechanical and tribological properties, including tensile strength, hardness and markedly superior wear resistance compared to single-reinforcement and pure aluminum. These findings show that, hard ceramic reinforcements work in increasing both, strength and wear properties as they enhance the uniformity of microstructure and encouraging load to be distributed evenly in the aluminum matrix.

As with all AMMCs, Hybrid AMMCs also display enhanced tensile strength and toughness accompanied by low density. Some of their process allowabilities like the stir casting make it possible to accommodate many kinds of reinforcements with the right particle distribution that is critical for sound performance under pressure in various sectors.

Amid real-world application, such hybrid AMMCs are most useful in field, which demand both light weight and high strength like aerospace and automotive industries. These improved mechanical properties lead to a better fuel economy and lower operating costs in vehicle parts. Moreover, hybrid composites have shown that they possess desirable properties of durability under different types of stresses and improve various defficiencies of the single reinforcement systems. With an upswing in research and development, the hybrid aluminum alloys are expected to revolutionize the material selection criteria in more than one high performance engineering disciplines, [31], [14], [8], [7].

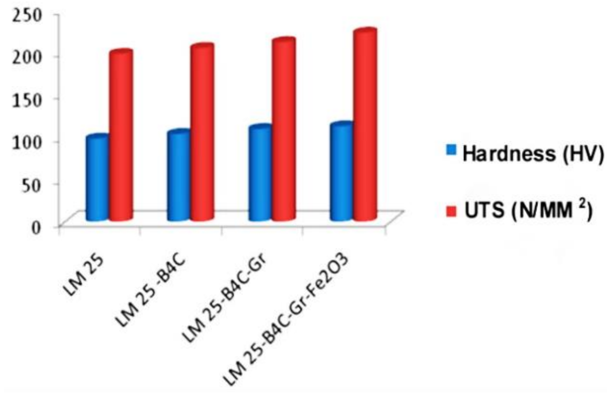


**Figure 11**: Variation of hardness and UTS of the samples, [14].

*7.2. Long-term Durability Assessments under Various Conditions*

The need for determining the extended service life of hybrid AMMCs for their performance in different environmental and mechanical conditions cannot be overstressed. These evaluations mimic practical uses in which a material is exposed to changes in temperature, moisture, and abrasive wear. The incorporation of reinforcements such as silicon carbide (SiC) and alumina ($Al_2O_3$) strongly improves the wear resistance of these composites as compared to aluminum matrices.

Studies show that hybrid reinforcements enhance the wear properties of AMMCs, keeping structures strong under high loads and enabling lower wear rates. It is further revealed that distribution and adhesion of reinforcement particles play a significant role in the improvement of the premature failure such as agglomeration and porosity.

T6 is one of the heat treatments that are helpful in raising tensile strength and hardness, and decreasing fatigue and creep life. Modification of the microstructures due to heat treatment also improves the interfacial adhesion between the matrix and the reinforcements, thus increasing the durability.

Some of the other characterization techniques used in the study of wear include use of scanning electron microcopy to determine wear pattern and surface characteristics after some time. Further future work focuses to enhance the knowledge of long-term behavior of hybrid AMMCs and to investigate new reinforcement hybrid structures and processing methods for high-performance applications in aerospace and automobile industries [15], [7], [42], [32], [17] and [8].

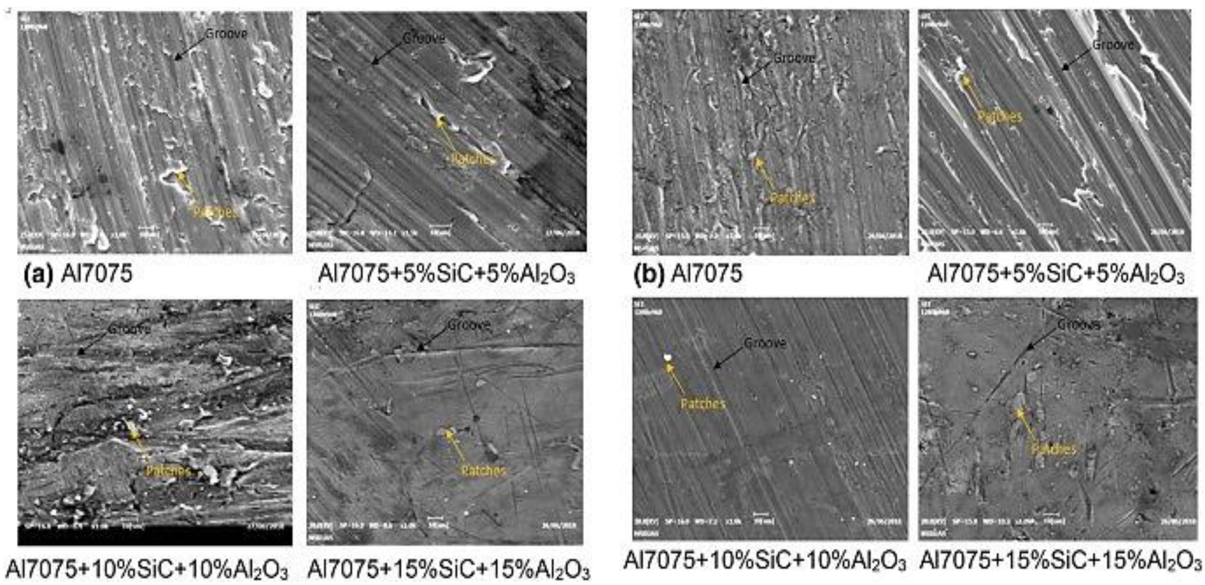


**Figure 12**: Worn surface of HAMMCs (a) as-cast, (b) age hardened Full size image, [17].

## 8. Applications of Hybrid Aluminum Composites

### *8.1. Aerospace Industry Applications*

Hybrid aluminum metal matrix composites are permeating the aerospace industry's supply chain due to these materials' superior characteristics that meet the sector's demands for lightweight design and performance. These composites are popular due to their reduced weight which means lower fuel consumption – an important factor given today's growing fuel prices and increasing environmental concerns. Owing to the use of the reinforcing agents like silicon carbide (SiC) and alumina ($Al_2O_3$), the hybrid AMMCs depict improved mechanical efficiency in terms of strength to weight ratio, stiffness and resistance to wear.

These advanced composites are specifically useful in load bearing areas like the wings and body of the aircraft, as well as on the engines. Not only do they help in weight loss but they are also extremely strong and tough while in use and operation. Also, more advanced manufacturing processes such as stir casting and powder metallurgy have enhanced the particle distribution and at the same time reduced reinforcement agglomeration problems. This uniformity is important since mechanical properties must be uniform when used in aerospace applications.

The emerging studies also suggest that composite reinforcements should enhance material properties more than conventional aluminium alloys. For example, the incorporation of hard ceramic particles improves wear resistance but at the same time retains adequate toughness. It also allows the manufacturers to come up with the design solutions which had not been possible before due to the current constraints of performance and safety.

In addition to the superior performance, the ability to create hybrid AMMCs through scalable methods enable the realisation of low cost manufacturing for aerospace industries. As technologies continue to develop, constant research of these materials in an effort to further enhance these parts of an aircraft is anticipated to provide the industry with more uses of these products to increase sustainability while providing the best performance for as many functions in an aircraft as possible. [14], [30], [37], [31], [10], [45] and [8].

### *8.2. Automotive Industry Applications*

The automotive industry has gradually shifted towards the use of hybrid AMMCs because of their desirable properties that greatly boosts vehicle performance and efficiency. These composites integrate aluminum with diverse reinforcing agents like silicon carbide (SiC) and alumina ($Al_2O_3$) and show significant enhancement in strength-to-weight ratios, strength, and wear threshold – properties ideal for automotive applications where parts need to be light but equally resilient.

The benefit of AMMCs is most noticeable in applications where a single part has to perform both the structural and functional roles such as the engine block, transmission case, or suspension components. These materials are lighter and more fuel-efficient, which directly corresponds with severe environmental standards. Moreover, the thermal management characteristic of hybrid AMMCs also enhances the conductive heat transfer in high operating temperature automotive application prolonging the durability of key engine parts.

Besides, the reinforcement of hybrid AMMCs by integrating eco-friendly reinforcements from agro-industrial byproducts helps in improving the mechanical properties of the composites and to overcome sustainability issue of car manufacturing industry. This approach enables manufacturers to drive down production costs while at the same time also cutting their emissions. In addition, the flexibility of fabrication techniques that have been employed to develop these composites

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like stir casting and powder metallurgy is likely to enhance scalability to meet the demand.

Cross-sectional research have shown that hybrid AMMCs are superior to the original materials in terms of fatigue and corrosion characteristics, which are suitable for fluctuating conditions in automobile uses. The constant application of the new manufacturing technologies extends the scope of these materials and opens opportunities for new, performant and environmentally friendly lightweight vehicle concepts, [2], [30], [8] and [27].

### *8.3. Biomedical Devices Applications*

Nowadays, new generation advanced hybrid Aluminum Metal Matrix Composites (AMMCs) have prospective applications in the biomedical field based on their light weight, high strength and bio-inertness. These are best used in a prosthetic, dental, and orthopedic applications. Both silicon carbide (SiC) and alumina (Al 2 O 3) increase the mechanical functionality of these composites and offer superb wear as well as corrosion qualities, which is crucial for application in biomedical implants.

A critical strength of the hybrid AMMCs is their potential to address problems linked with the conventional implant materials such as titanium and cobalt-based alloys that can lead to stress shielding and ion toxicity. AMMCs can be designed as hybrids with tailored surface topography to enhance implant osteoconduction and mechanical loading – factors critical for the implant's longevity.

Technological improvements in fabrication technology make it possible to fabricate geometric designs according to patient specific anatomy. Powder metallurgy and casting make it possible to produce designs of parts with the required shapes and distribution of reinforcement for further performance under different conditions.

Hybrid orthopedic composites of metals and bioactive ceramics point to the future of material science for orthopedic implants that stimulates bone growth as well as provide sound mechanical properties. Future work on the biodegradable composites should identify the better developments which would help to dissolve these implants after use without other surgeries. The market for the hybrid AMMCs is continuous to grow as new formulation and processing technique are developed, [11], [8], [10] and [4].

## 9. Future Directions and Research Trends

### *9.1. Emerging Technologies in Composites Manufacturing*

The global market of manufacturing the hybrid aluminum metal matrix composites (AMMCs) is still young and rapidly growing, due to the increasing need for high-performance and eco-friendly materials. New technologies are tuning their sights to increasing the fabrication techniques to enhance mechanical characteristics of these composites without compromising on cost and eco-friendliness. One of the most effective strategies comprises the incorporation of environmentally friendly reinforcements that enhance the properties of the composites and at the same time, maintain sustainability. Literature review focuses on enhancing process parameters like stirring speeds in stir casting methods in order to obtain uniform particle distribution and to avoid formation of clusters.

Moreover, the development of the multi-material structures with complex geometries has led to the investigation of use of AM techniques to develop hybrid AMMCs. This strategy enables a better decision-making process on where and how the reinforcements should be positioned in the matrix and may create composites for different uses. Such possibilities as integration of the powder metallurgy with more contemporary methods might suggest new roads in material creation.

They include challenges such as clumping which is a big hindrance or contamination when preparing the nanomaterials during the production process if ignored this denounces the whole intention of using nanomaterials in hybrid composites. New processing techniques to retain the nanostructures while enhancing the interfacial adhesion between particles and matrix are in development. Furthermore, the synergies on going through various academic institutions, industries stakeholders and governmental organizations are anticipated to boost development in this area by продуктов encouraging multi-disciplinary approaches with the aim of tackling existing challenges and improving properties of the materials.

Over the course of a wide range of industries shifting to hybrid AMMCs—especially in aerospace, automotive, and biomedical industries—there is an expected emphasis on creating revolutionary solutions that address the need for enhanced performance and sustainability. This trend reflects a more sustainable development pattern of manufacturing industries that conform to global sustainable development objectives, [11], [2], [12], [13] and [39].

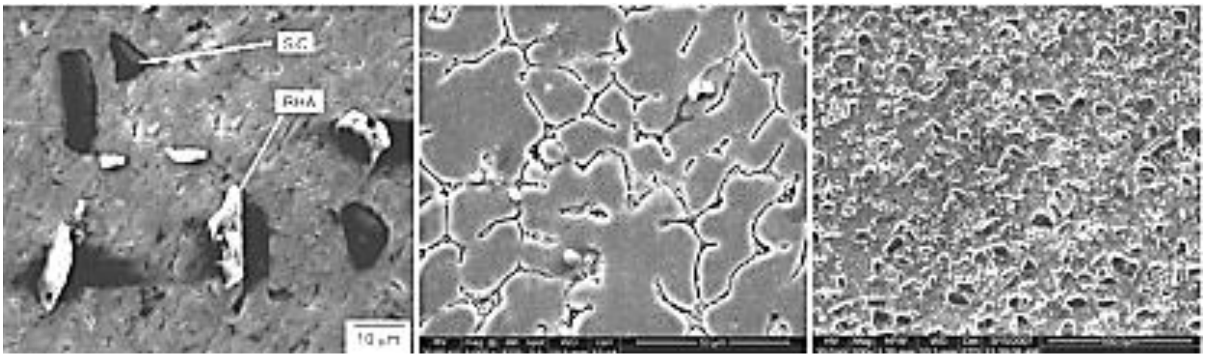

**Figure 13**: Microstructural images of fiber, whiskers, and particulate-reinforced MMCs, [13].

*9.2. Potential Market Needs for Hybrid AMMCs*

The increasing demand for the hybrid aluminum metal matrix composites is because of the enhanced characteristics which makes them suitable for use in aerospace, automobile, and construction industries. These sectors prefer AMMCs for their high strength to weight ratios, resistance to corrosion and high operating temperatures. The automotive industry looks for materials that would make cars lighter in order to improve fuel consumption without compromising strength; the aerospace industry requires strong components that are at the same time lightweight.

Sustainability issues are also driving the market needs by leveraging the use of green components into the hybrid AMMCs. Employing agricultural residues or industrial scrap in fabrication not only solves environmental problems but also reflects new global trends in manufacturing.

There is still a high demand for hybrid AMMCs, and so improvements in manufacturing technology are crucial for their production. Methods that guarantee consistent reinforcement placement and improved mechanical performance are vital for large volume manufacturing at reasonable costs while incorporating advanced technologies such as additive manufacturing combined with conventional processes like stir casting.

The various case studies in the LPSC-MSEAM project will reveal the economic benefits and performance enhancement of hybrid AMMCs through life cycle assessments and cost-benefit analyses applied to industries. University-industry relations are believed to advance research by creating synergies that allow new innovations to be developed to address existing problems and construct new uses pertinent to certain industries. [2], [20], [13], [10].

## 10. Conclusion

### *10.1. Summary of Key Findings*

Lightweight Aluminium metal matrix Composites (AMMCs) are one example of progress in material science that exhibit special combination of properties when reinforced with different particles including; Silicon Carbide (SiC) and Aluminum Oxide ($Al_2O_3$). This integration results in enhanced tensile strength, increased hardness and impact strength as well as increased load carrying capacity. In as much as fabrication techniques are concerned, it is important to look at stir casting and other method such as Friction Stir Processing and their importance in improving the distribution of the reinforcement particles with in the composite.

The relation between the matrix and reinforcements is highly sophisticated because it defines the mechanical characteristics of the composite and its ability to work under different operational conditions. Interfacial bonding and the mechanically mixed layers during wear show that hybrid AMMCs are superior to conventional materials because they decrease wear rates while increasing structure strength.

But there are still problems in the processing of these composites. Solutions to these issues are pursued through new production technologies that consider the mechanical characteristics for particular uses. As the increase in the use of hybrid AMMCs is evident in industries like aerospace, automotive industries, and biomedical fields, more research requirements are needed to enhance the properties of such systems.

New trends in the usage of advanced material depict a rising need of light weight high strength material to fit into various engineering applications. Therefore, the exposure of new processing technologies and reinforcement schedules to achieve the prospective development of hybrid aluminum composites has to be carried out continuously [16], [24], [17], [10], [19], [35] and [23].

### *10.2. Implications for Future Development*

Several noteworthy tendencies and innovations in the scope of materials science and engineering are predicted to reshape the subsequent evolution of hybrid aluminum metal matrix composites (AMMCs). Particular emphasis is placed on optimizing processes like stir casting and powder metallurgy, which are already revealed some upgrades to both the mechanical and thermal characteristics of AMMCs. Sophisticated processes such as ultrasonic assisted stirring and squeeze casting are believed to enhance the particle distribution leading to near perfect composites with few defects.

Furthermore, employing sustainable reinforcements such as agricultural residue, waste ash from industrial processes would point to a route towards really making composites cheaper and environmentally friendly. This trend goes in line with the general enhancing trend of employing environmental friendly products within the construction industry.

These challenges are the most important ones that should be tackled by research activities in the field of hybrid AMMC technology which includes the prediction of material properties, satisfying cost requirements, improvements in recyclability, and a suitable combination of ductility and strength. Standardized protocols for measuring the behavior should be created in order to make improvements to reliability in industrial applications involving such composites.

In addition, the identification of new reinforcement materials, such as ZrO2, in combination with other methods of manufacturing, including friction stir processing, may result in composites with specific characteristics that would be useful in specific high-performance applications in aerospace, automotive, and construction industries. If these hybrids are to be effectively utilized in the future, the microstructural relations inherent in such structures must be clarified by future research.

These advancements show the future prospect of hybrid AMMCs as they move from niche applications to broader market opportunities in weight conscious applications requiring high performance material that can withstand high stress, [11], [15], [24], [2], [10], [13] and [35].

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