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Aluminum Metal Matrix Composites

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Abstract: Aluminium metal matrix composites (AMMCs) continue to draw considerable interest from materials researchers because they combine the low density of aluminium with the enhanced stiffness, strength, and wear performance imparted by ceramic or carbon-based reinforcements. This article brings together recent findings on the fabrication, structure, and performance of AMMCs to give readers a consolidated picture of where the field currently stands. The fabrication routes examined include stir casting, powder metallurgy, and infiltration-based processes, together with the process variables that govern how well reinforcement particles disperse within the aluminium matrix. Attention is then given to how reinforcement type, particle size, and volume fraction shape key mechanical and physical outputs such as tensile strength, hardness, and thermal conductivity, as well as how these reinforcements influence grain structure and interfacial bonding. Composites built around alumina, silicon carbide, boron carbide, graphene and carbon nanotubes, and magnesium oxide are compared to show how each reinforcement family affects composite behaviour differently. The discussion extends to where AMMCs are already being applied aerospace, automotive, and electronics components among them and closes by outlining open research questions, including the development of new reinforcement chemistries, refined processing controls, and a better understanding of long-term environmental and performance trade-offs. Taken together, the article is intended as a reference point for researchers seeking a current, integrated view of AMMC development and the directions in which the field is likely to move next.

Keywords: *Aluminum Metal Matrix Composite; Reinforcement; Strength; Stir Casting; Powder Metallurgy.*

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I. INTRODUCTION

Today's era is known as the era of metal matrix composites (MMCs), in which the material has been designed to enhance the stability and mechanical property improvement [1]. Metal matrix composites are special materials made by combining a metal base with one or more other materials, which can be either ceramic or metal, to strengthen and improve their properties. This is mechanical, thermal, and physical properties of the material are improved by the combination of these materials and they can be employed in many applications [2]. To make MMCs, the metal matrix can be strengthened by adding other materials such as ceramics [3], metals, polymers, and so on [4]. A lot of research has been done to improve MMCs [5–9]. As it is evident from the properties of various conventional materials and engineered metals matrix composites shown in Fig. 1, engineered materials have superior properties. The important properties of MMCs are to have ability to hold the high temperature, higher thermal and electrical conductivities, higher transverse strength and stiffness [11]. In addition to this no moisture absorption, MMC have got high resistance to fire and radiations and so MMC is found to be a better alternate for engineer-ing and structural applications [4,12,13]. These materials, therefore, are used by manufac-turers because they have bright, active qualities to produce quality products. Technavio Research by Mahitha-Mallishetty has published a report on the metals and minerals analysts that ‘‘The global metal matrix composites market is expected to grow to 10.8 kilotons by 2021, with a compound annual growth rate" growth-rate of more than 6% in the near future” [14].

Previously there are 15 reports published, about the market situation, one report namely, Grand View Research [15] published in 2014 says, AMMCs are one of the material of largest product segment in the demand with 30% demand. There continues to be a growing demand for strong, but light parts, increasing demand for Aluminum. The demand of aluminium metal matrix composites (AMMC) is expected to rise further till 2023 and will be the preferred over other MMCs. These materials can be used for various purposes such as tool construction, Spacecraft exterior construction, nuclear radiation regulation rod, solar panel production, and aiding chemical reaction as catalyst [15].

The materials that have an Aluminium (Al) base with ceramic particles will have a great hardness and strength with better corrosion resistance and wear resistance [16,17]. This material can have its volume and other properties adjusted for different applications due to its superior control of the mechan-ical properties and microstructure.

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Due to the higher popularity of the reinforcement size, and fraction, particle reinforce-ments are more popular than the fibre type [18]. The resultant properties of AMMC are higher strength, reliability, low ther-mal coefficient of expansion, improved wear characteristics etc are presented in Fig. 2. Carbon, boron, silicon-carbide, gra-phite and alumina, carbon nano tubes, graphene etc can be reinforced into aluminium matrix and produce AMMCs that exhibit strength and rig-idity of 30–40%, when compared to that of bare bones-aluminium [15,19–21]. If the reinforcement is done using nanoparticles that are smaller than 100 nanometers, the resulting composite material is called an aluminum matrix nanocomposite [22]. Aluminum matrix nano composites are also used to deal with the problems of regular engineering materials [23]. It has been found that the equal performance and the versatile property of nano agent as the reinforced agent in aluminium and/or magnesium metal matrix is seen as compared to micro/macro reinforced Aluminium/Magnesium alloy or composite [24 - 27]. But, as the concentration of the ceramic particles is increased, the ductility of metal matrix composites begin to decrease [12,28,29]. Using nano agents helps keep the matrix material flexible without making it less stretchy, even when the material becomes stronger and can handle more force [30]. Also improves resistance to high temperatures creep and to fatigue [31]. These AMMCs have features such as high stiffness, great wear resistance, high specific strength, are lightweight, and have a low density [32,33]. However, these AMMCs are used widely, but the associating fabrication cost [34] restricts their applications. Various processing methods to fabricate the MMNCs are Infil-tration, rapid solidification and mixing of Nano particles through the stirring action. [35].

Until now, study on Aluminium Metal Matrix Compos-ites (AMMCs) is an active research field for past few decades. These materials have already found a variety of uses, from aerospace to auto-mobile and military, due to their outstanding mechan-ical properties including strength, stiffness and wear resistance. Although there is abundant studies on AMMCs, there are some research gap on their characteristics understanding. These gaps are identified and more detailed research work is needed to enhance these properties to use the AMMCs optimally in different industrial applications. In this paper, an effort has been made to thoroughly review the research that has been published on aluminum metal matrix composites. With the mechanical/microstructural properties obtained, the effects of the reinforcements obtained are discussed.

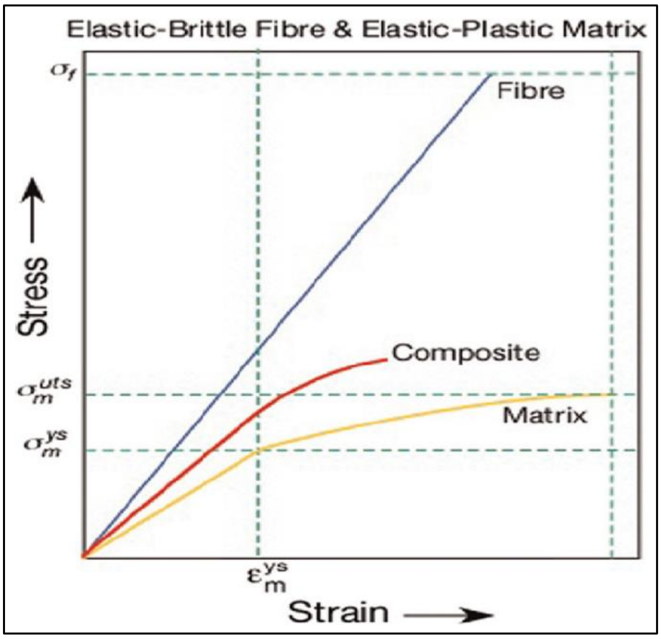

Fig 1 Stress-Strain Diagram for Metal Matrix, Fibres and Synthesis Composites [4].

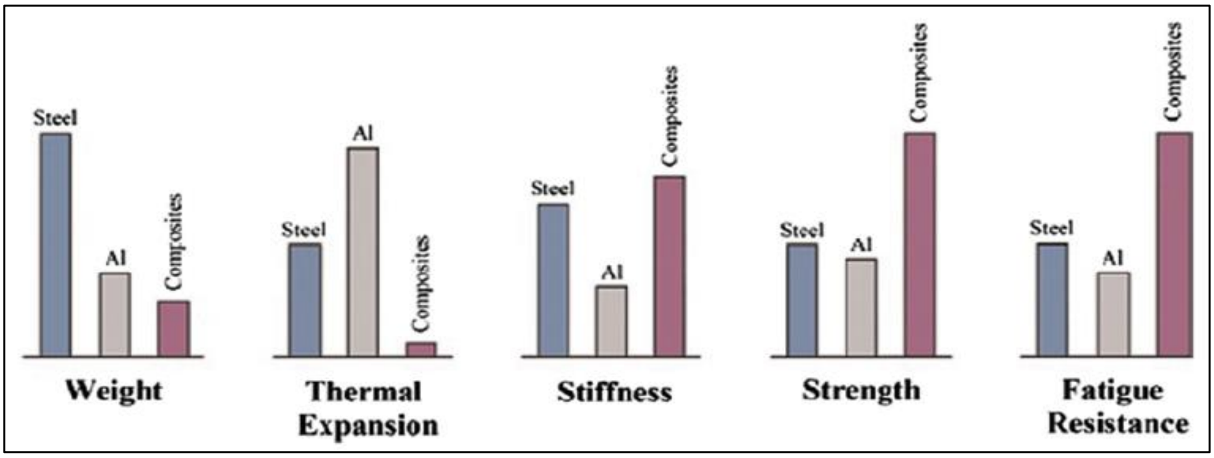

Fig 2 Comparison of Mechanical Properties of Steel, Pure Aluminium and Developed Composites [4].

II. PHYSICAL AND THE MECHANICAL PROPERTIES OF AMMCS

There are composite materials, which are known as Aluminium Metal Matrix Composites (AMMCs) where aluminium is used as matrix along with one or more reinforcing material such as ceramics, metals, fibres or whiskers. The physical and mechanical properties of AMMCs depend on several factors, including the type, size, and amount of the reinforcing materials used, the method used to make the material, and the conditions of heat treatment applied [36]. Fol-The following characteristics are

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seen in AMMCs; Density: The density of AMMCs changes depending on the materials used and how they are made. AMMCs are usually less dense than pure aluminum, but they are still denser than some other types of composite materials like carbon fiber reinforced polymers. Hardness: Hardness of the composite can be increased by adding reinforcing materials to the aluminium. Hardness of AMMCs varies depending on the type of materials used for reinforcement, size and fraction of amount of reinforcement present and it can be measured through hardness testing. Tensile strength: AMMCs

As a result, the amount of reinforcement used will usually be greater than the amount of pure aluminium, which increases the strength of the composite (in terms of its elastic tensile properties) [37]. Young's modulus: Young's modulus of AMMCs is also increased with the stiffening effect provided by the reinforcing materials [38]. Finally, the Youngs modulus of AMMCs are measured by tensile test machine. Thermal conductivity: AMMCs have a lower thermal conductivity than pure aluminium due to the presence of the reinforcing material(s) which is/are insulating. But the thermal conduc-tivity of AMMCs is still relatively high as compared to other composite material. Wear resistance: If mixing with reinforcement materials with aluminum will enhance wear resistance of aluminum composite. The wear resistance of AMMCs is dependent on properties of the reinforced material like nature, size selection and volume fraction of the material and this depends on various test methods. Finally, the physical and mechanical properties of AMMCs are unique and desirable for many applications including aerospace, biomedical and automotive industries. By modifying the composition and manufacturing parameters, the exact characteristics of AMMCs can be modified for each particular application.

- *The Aluminum Metal Matrix Composite (AMMC): The Fabrication Techniques*

Different types of aluminum series have been used to make AMMCs, including 2XXX, 5XXX, 6XXX, and 7XXX series, among others [39]. Different types of aluminium series have varying amounts of alloying elements added to them, and they are used in different ways for various commercial purposes, as shown in the fig.3.

Proteching in literature that various methods are employed to synthesis MMC. Compo-casting and Semisolid forming are liquid–solid processes that are manufactured by the above mentioned processes: Mechanical alloying using high energy milling, the Vortex process, disintegrated melt deposition, powder metallurgy, ultrasonic casting along with ultrasonic treatment, liquid phase or casting methods, pressure-less infiltration, vacuum infiltration, and dispersion techniques. [47]. One of the most popular technique applied to producing particle MMCs is PM.

Using the matrix along with reinforcement in powder form is important for making MMCs through powder metallurgy techniques [49].It is widely used by both researchers and the industry to create MMCs using the powder metallurgy method, which is often combined with cryo-milling.In this process, metals are milled under a very low level of nitrogen atmosphere. temperature around —193 °C (80 K) with a help of steric acid as a process control agent [50–53].

It is noticed that the composite structure gains more strength from the fine grain particles at the nano level. AMMCs have small grains that help make the material stronger, and this can be explained by the Hall-Petch equation [54]. Various mechanisms are responsible for the strengthening of MMCs such as Orowan looping, precipitation strengthen-ing, solid solution strengthening, coefficient of thermal expan-sion and mismatch strengthen-ing [55-59]. The amount of reinforcement is directly proportional to the performance of the mate-rials up to a certain extent (IT' is found). Increase in the concentration will bring brittleness in the overall AMMC and it leads to poor mechanical and electrical properties [60].

- *The Typical use and the Influences of Reinforcements on Mechanical Properties of AMMCs*

The second part added to the first part (matrix) to create a composite material is called the reinforcement. This phase is stronger than the primary phase, and when you combine their effects, the result is better. In general, as the pure metals are modified by alloying their properties are increased at the expense of others. However, through a composite with another material, usually the properties of the output material improves without compromising other properties. Unique examples of this type are the reinforcement of metals with ceramic par-ticles in order to increase some of their properties, e.g. hardness and compressive strength without reducing ductility [61]. The main materials used to strengthen the properties of the substances are silicon carbide, aluminum oxide, silicon dioxide, graphene, and carbon nanotubes, as mentioned in reference [40], and this is illustrated in Figure 4. The properties depend on how much of the reinforcing agents are used and what area they are being applied to.

- *Al-Alumina (Al_2O_3) Composites*

The composites made up of aluminum as a matrix and alumina as a reinforcing material are called as Aluminium Alumina (Al2O3) composites. These are formed by incorporating small quantity of alu-mina in aluminum so that it can better their mechanical and thermal characteristics [62]. The resulting materials are of high strengths, wear resistance and excellent thermal stability [63]. There are multiple methods to make Aluminium-Aluminia composites, including powder metallurgy, hot pressing, and spark plasma sintering. When alumina is added to aluminium it gains the property of.

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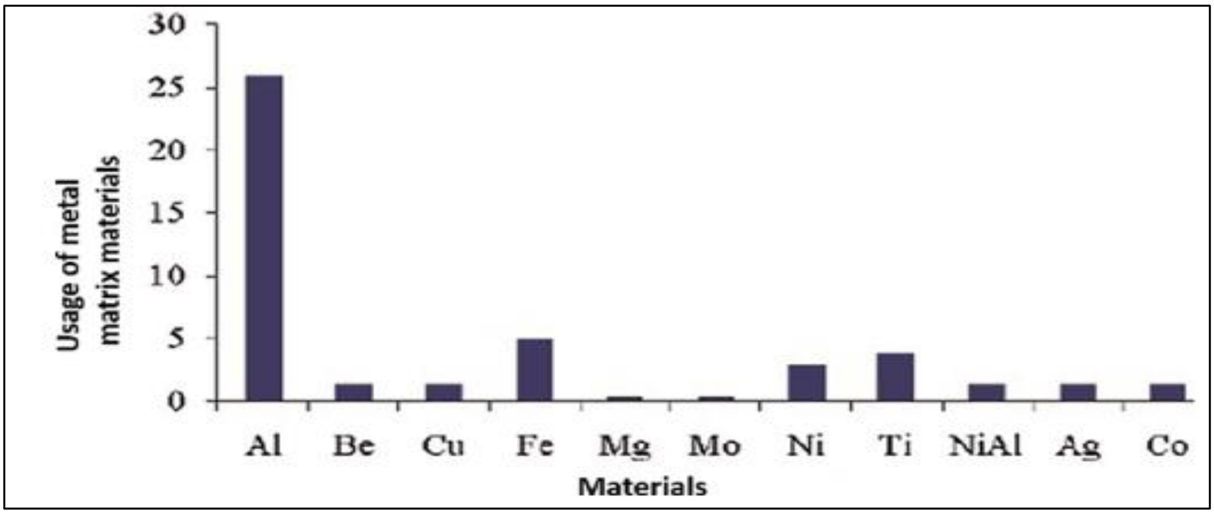

Fig 3 Applications of Metal Matrix in Composite and their Usage [40].

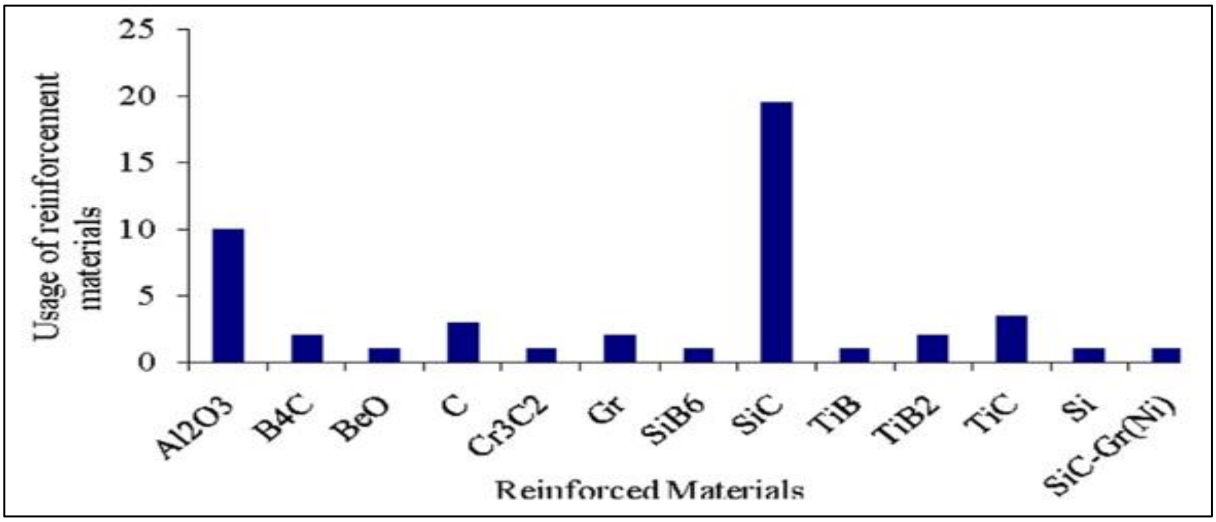

Fig 4 Usage of Reinforcing Agents in MMCs [40].

The material is harder, stronger, and more resistant to wear, making it suitable for use in different applications such as cutting tools, heat sinks, and aerospace parts [4,58]. The properties of aluminum oxide composites can be enhanced even more by adding other materials like silicon carbide or carbon fibers to the composite. They help improve the mechanical properties of the composite and allow it to handle higher stress better. The uses of Aluminum Alumina composites are extensive in the aerospace industry, automotive industry as well as electronics industry. Their proving to be an important material for a wide range of manufacturing processes, they are highly versatility and can be configured to the needs of specific applications. Literature has seen usage of the alumina by various authors for synthe-sising the aluminium metal matrix composites (AMMC) [64]. Clumping together of reinforcing particles is a common issue when making metal matrix composites, which can lead to unwanted changes in the material's strength and internal structure. Solid mixed casting with ultrasonic treatment proved to be appropriate for the synthesis of alu-minium based AMMC, while minimizing the reinforcement particle agglomeration [64]. Su S. et al has developed the AMMC AA2024/ Al2O3 by solid mixed casting with ultra-sonic treatment. It is seen that, when ultrasonic treatment was employed, the drawbacks of cross-section such as agglomeration of particles and non-uniformity of the mixing of reinforcement was overcome and a proper grain refinement was obtained. Induced vibrations, increase the disper-sion of reinforcing agents and reduce the agglomeration as well. When 1 wt% of nano- Al2O3 reinforce-ment is added in the matrix, the yield strength (YS) and UTS can be improved by 81% and 37% respectively, which indicates a good value of the percentage increase ratio. The increased tensile strength and yield strength could be attributed to removing the agglomeration of the particles and uniform distribution of the reinforcement particles caused by the support of ultrasonic.

Powder metallurgy is a usual way to make AMMCs, and it's also often used for creating the composite [65]. An advanced ball milling technique done at room temperature was found to be more cost-effective than cryomilling or high-temperature methods for synthesizing AMMCs, as shown in the fig. 5 [66].

This process will cost less compared to the cryo-milling or high temperature milling method that uses ethanol and then

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low temperature drying. The grain size from milling at room temperature is the same as the grain size from cryo-milling or high temperature milling. Khorshid et al.(2016) [66] used 99% pure aluminum powder as the base material and added aluminum oxide powder in three different amounts—1%, 3%, and 5% by weight—as well as graphene nano platelets as the reinforcing material to create the aluminum metal matrix composites. They saw that the size of the grains in the Al-Al2O3 and Al-GNP final composites didn't change much after annealing, which matched what was found before. However, higher grain size of synthesized Al-GNP is found in comparison to Al-Al2O3. The hardness of the GNP reinforced materials varies relatively less with the annealing in comparison with the pure Nano crystalline (NC) Al and Al/Al2O3 NC AMMCs, where there was a time dependent decrease in the hardness on annealing. No evidence of the sliding of grain boundaries was observed in both AMMCs, Al/Al2O3 and Al/GNP nano crystalline composite. It was observed from the results that the Al-Al2O3 and Al/GNP AMMC produced in this study, the predominant is grain boundary strengthening. The composite obtained higher grain sizes in Al-GNP samples which contributed to the increase in the strength of the composite by solid solution strengthening and grain boundary strengthening of GNP particles.

For synthesising the AMMC, a novel three step mixing method [67] was used, as shown in Fig. 6. In this method heat treatment of two sized 50 nm & 20 mm Al2O3 particles, then injecting the heat treated Al2O3 particles to the molten AA1356 aluminium alloy (AA1356Al) in a controlled atmosphere using argon inert gas and in the last step the melt is stirred by different speeds.

The mechanical properties and the microstructures of the compos-ites are highly influenced by the various parameters such as stirring speed, heat treatment, size of reinforcement particles etc. They found that when introducing nano particles into the aluminium melt directly, they found that there was poor wettability in the melt which resulted in in-homogeneity in the compos-ite. If the heat-treated particles are reinforced, there is a noticeable improvement in wettability and even distribution of the nano particles. The heat treated particles form a matrix structure made up of main α-Al particles and silicon in a eutectic form. Furthermore, other inter-metallic com-pounds (such as Mg2Si, FeSiAl5 and Al4C3) are also present in the eutectic phase. They discovered it's possible to find the best distribution of the reinforcements at a higher stirring speed. Besides, the wettability of the particles is found to be decreasing as the reinforcement concentration increases. It is observed that the hardness and porosity increases with an increase in the wt% of Al2O3 particles and decrease in particle size. Increasing concentration of Al2O3 particles increases the compressive strength. Nano-composites compared with micro-composites, show a higher comp-ression strength.

The statistics from the survey can be summarized as: Dispersion of alumina (Al2O3) particles in the aluminum metal matrix compos-ite (AMMC) is extremely important in determining the properties and performance of the composite. To obtain a highly dispersed Al2O3 particle distribution in the aluminum matrix with uniformity is essential to ensure the effective reinforce-ment as well as better mechanical and physical properties of the composite. Particles size of Al2O3 is one of the factors which affect the dispersion of particles in Al2O3 matrix. The good dispersion results from the high surface area and good bond-ing at interface with matrix due to smaller size. A small PSD range is desired; it will help to give uniformity in all areas of composite where reinforcement is desired. It is expected to obtain a uniform dispersion of Al2O3 particles in the aluminum matrix using different mixing methods. The techniques used are powder metallurgy history techniques such as mechanical mixing, ball milling and high energy milling. These processes are able to de-agglomerate the particles and enhance the dispersion of Al2O3 particles.The dispersion and the interfacial bonding of Al2O3 particles with the alu-minum matrix can be further improved by using surface treatment of the particles. Silane and other chemical methods may be employed to make the surface wetter, and to increase the adhesion of the particles to the matrix. Other materials or particles can be added to help distribute Al2O3 particles uniformly in the aluminum base material. The incorporation of alloying elements or other particles can help in the dispersion of Al2O3 parti-cles in the aluminum matrix. These extra can serve as the nuclei or dispersant making it easier and uniform to disperse the Al2O3 particles and decreasing particle agglomeration. Particles of Al2O3 are affected by parameters in the manufacture like mixing intensity, time and temperature. Controlling these parameters is essential to get even particle distribution to avoid clustering or segregation[70]. Advanced methods like microscopy, such as scanning electron microscopy and transmission electron microscopy, along with X-ray diffraction, can be used to check how well the Al2O3 particles are spread out and mixed in the aluminum material. These methods show how well something is spread out and help improve the settings used in making it. Some other recent studies have looked into materials [111,112], hot rolling and aluminum alloy [113,114,115], heavy metals [116,117], and the micro-structural and mechanical properties of various materials. [118,119,120].

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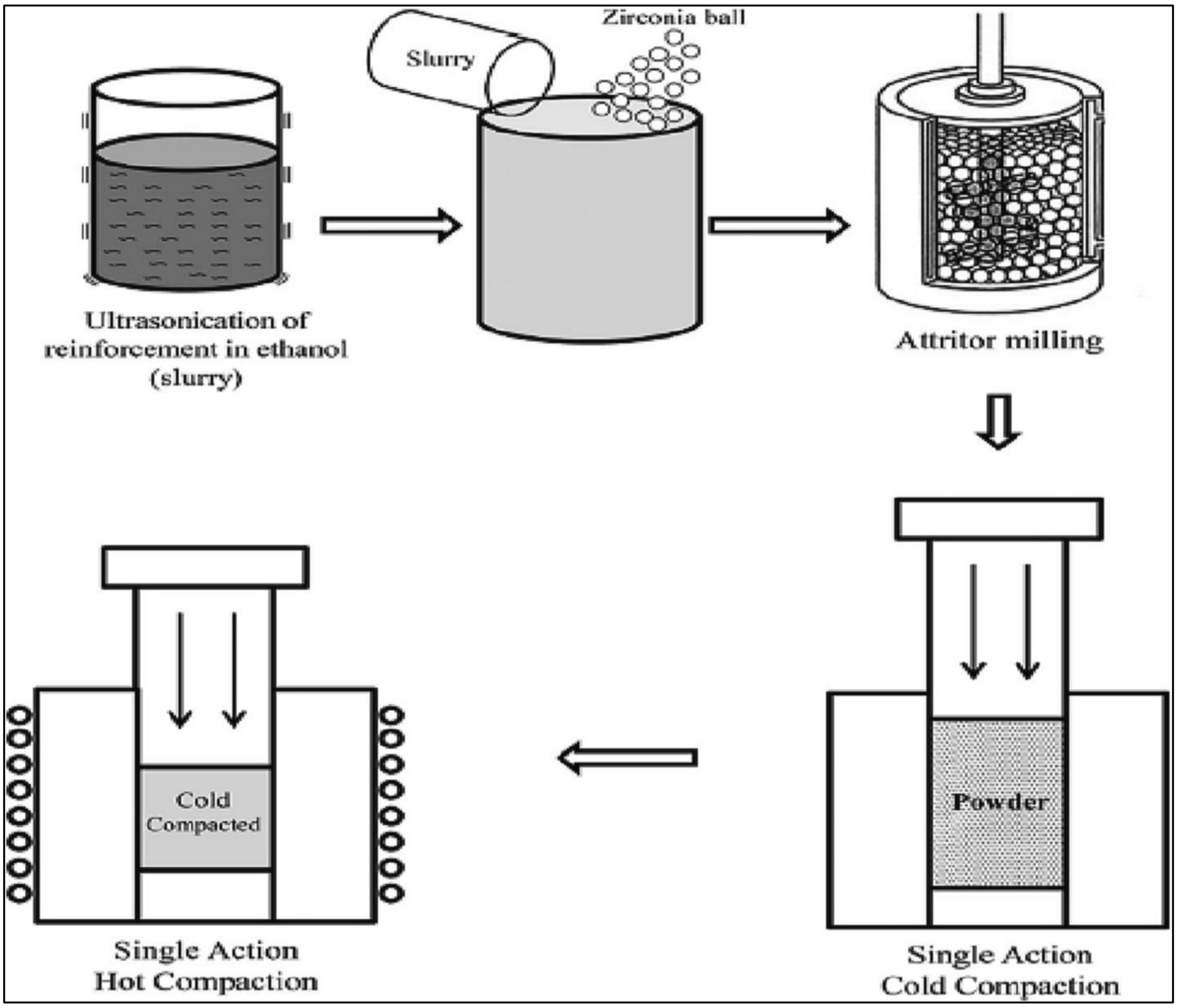

Fig 5 Process of Synthesis AMMCby Powder Metallurgy Route at Room Temperature [66].

- *Al-Silicon Carbide (SiC) Composites*

Al-SiC is one of the important Matrix/Reinforcement combination AMMCs and this combination is ideal for applications in engine and brake parts [71–74]. Using regular machining techniques on Al-SiC composite causes a lot of tool wear, unwanted damage beneath the surface, and cracking [74,75]. Silicon carbide particles are very hard and help make the composite material stronger by raising its melting temperature. Because it is ceramic, it improves the mechanical properties of the made composite. In addition, SiC particles do not react with the matrix at high temperatures and do not form unwanted phases. In addition, SiC particles do not react with the matrix at high temperatures and does not developed undesired phases[76]. The literature reports the various studies pertaining to the fabrication of Al-SiCp MMCs via different routes. The fabricated composite A356/SiC exhibits better wear performance with increasing of the reinforcing level[77]. Hard particles sticking out from the surface can create a protective layer that helps resist wear by blocking the abrasive particles when the part is under wear conditions [78–80]. Most of the wear load is carried by these protruding particles [81-84]. The same enhancement of the wear behavior of the composite A356/B4C compared to the base matrix was observed for all the sliding speed and load conditions [85].

You can see that when you increase the reinforcing material to the best level, the strength goes up.But if you add more reinforcing beyond that best level, the strength starts to go down. Besides, there will be no sharp yield point in the composite as shown in the stress-strain diagram of Fig. 7.The major reason for enhancement in properties may be due to the hindrance in dislocation movement in presence of nano SiC particles in the matrix [86,87]. The same study was carried out with hybrid AMMCs with constant nano-Al2O3 as reinforcement in varying concentration in AA7075-T651 grade Al-alloy as a matrix.

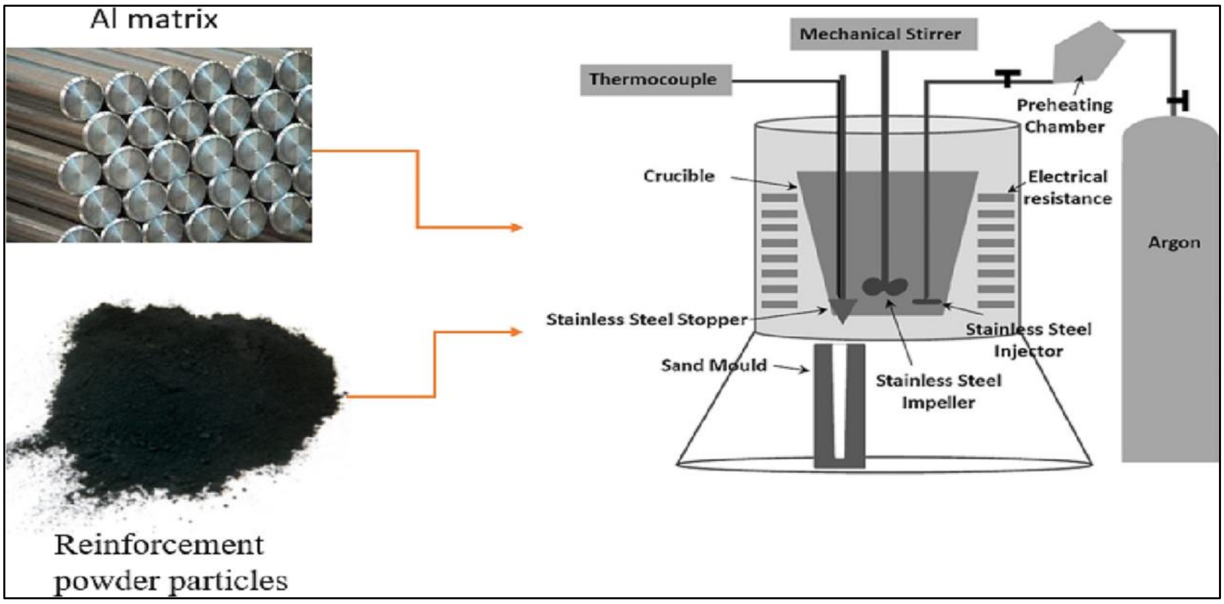

Fig 6 Stir Casting Setup Used to Synthesis AMMCs [67].

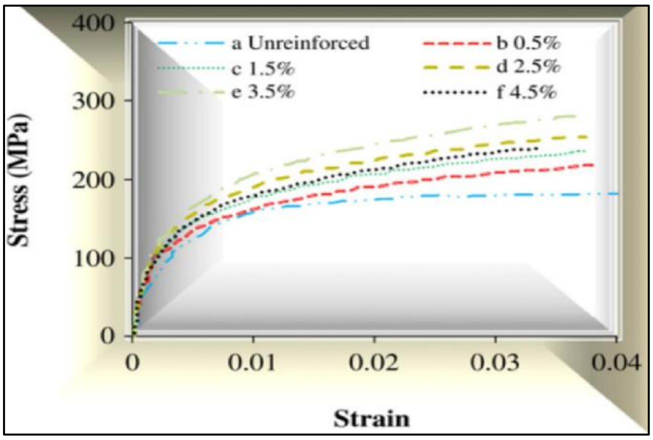

Fig 7 Tensile Strength of Synthesis Composite with Varying SiCwt % Concentration [58].

Of nano-SiC (5%, 10%,15%) using stir casting [88]. Fatigue analysis were performed using 2x106 as standard number of cycles and the resultant fatigue limit values for all the reinforcement levels show that up to a reinforcement of 80%, the limit increases but for higher reinforcements, the fatigue limit decreases. It was found that AMMC-1 (5% SiC) is 4.642%, AMMC-2(10% SiC) is 12.13% and AMMC- Whereas the strength of 3(15% SiC) has 9.82% improvement under fatigue loading compared to the base matrix material. Homogeneous and defect free microstructure of the gives rise to the enhanced fatigue characteristics.

As compared to parent material, I have found the composite to be . . . . It was also observed that the mechanical properties of Al was enhanced by reinforcement of Al2O3 & SiC [89]. It was found that the wear characteristics of the material have been enhanced after reinforcing the Al matrix. Specifically, with casted specimens they exhibited double the wear resistance than the powder metallurgy (PM) specimens, as a result of their more compact structure. The wear resistance of the rein-forcement increases with both an increase of Al2O3 and SiC for both casted and P/M specimen as shown in Fig. 8.

The tensile strength obtained from the specimen casted was determined to be 1.5 to 2 times more than that of the specimen fabricated with P/M method. But the compressive strength and hardness of the P/M and casted samples were found to be about the same. The higher the amount of rein-forcement the harder it will be. But when reinforcement level is increased, the compressive strength and the tensile strength decreases as seen from the Fig. 9(a). However, ductile fracture (for casted specimen) and brittle fracture (for P/M specimen) was observed during the bending and tensile test in 3% Al2O3and 3% SiC as shown in Fig. 9b.

The connection between silicon carbide particles and the aluminum metal matrix in the composite is important to ensure the composite has good mechanical properties and performs well. During the making process, the SiC particles are typically put into the liquid aluminum or mixed with the powder combination. As the matrix solidifies, the SiC particles become trapped in the aluminum, creating a mechanical interlock. This interlocking creates strong physical connections between the SiC particles and the edge of the aluminum matrix, which helps make the composite material stronger overall. The weak intermolecular forces that are the result of temporary fluctuations in electron distribution are van der Waals forces. These The factors which assist the adhesion and bonding of SiC particles to Al matrix are discussed. Though the forces per particle are small, the huge number of SiC particles can be dispersed throughout the matrix, and the strength of the bonding will be enhanced.The chemical bonding between SiC particles and the Al matrix is generally improved by surface treatments or coatings on SiC particles. These treatments include applying coupling agents, or creating inter-metallic compounds at the interface. An important aspect of the wetting of the molten aluminum matrix on the surface of SiC particles is in achieving good bonding. The wetting should be good enough to provide intimate contact and bonding between the matrix and the reinforcement. It should now be noted that there are a variety of bonding mechanisms between SiC and the aluminum matrix that can vary dependent on parameters like particle size, particle distribution, surface treatments, processing technique and the presence of other additions. To obtain effective and uniform bonding between SiC particles and Al, these factors have to be optimized to improve mechanical properties of the AMMC.

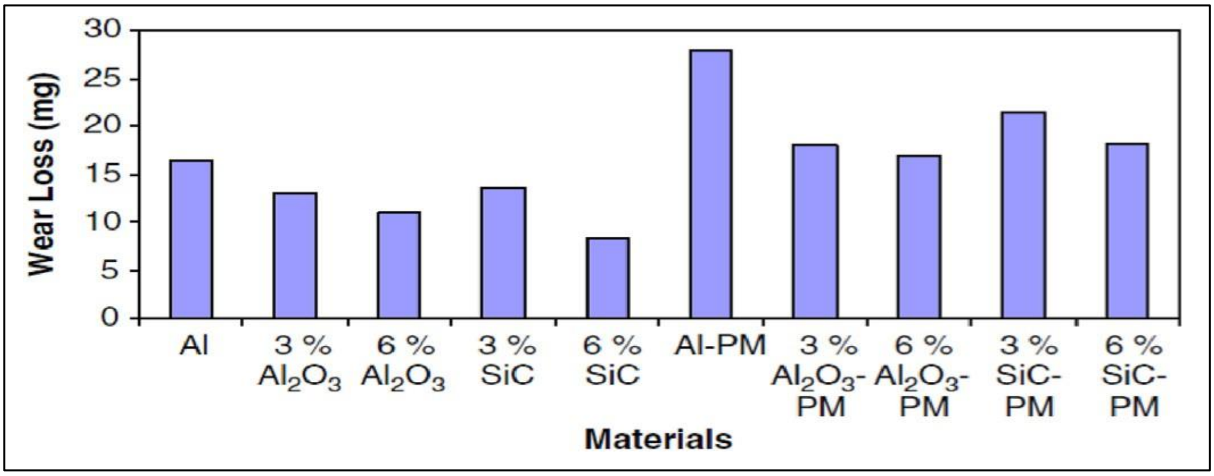

Fig 8 Compare of Wear Losses of AMMC Fabricated by Stir Casting and Powder Metallurgy [89].

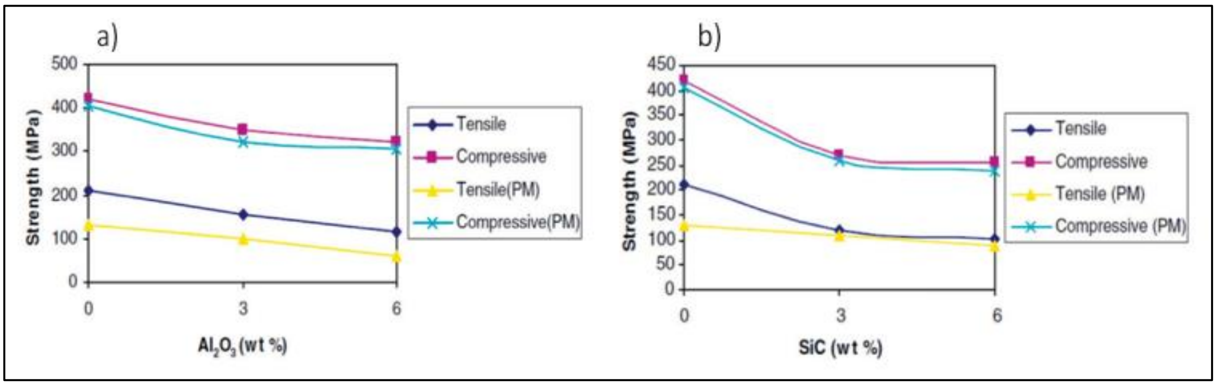

Fig 9 Variation in Tensile and Compressive Strength of AMMC Fabricated by Stir Casting and Powder Metallurgy [89] (a) Strength vs wt % of Al_2O_3 (b) Strength vs wt % of SiC.

- *The Al Boron Carbide (B_4C) Composites*

However, there are some studies on Al/B4C AMMC reported in the liter-ature [91–93]. In this study, Boron carbide (B4C) (a hard with a good mechanical and neutron absorptive property [94]) particles were used as reinforced particles. The mechanical characteristics of pure Al/B4C AMMC with different amount of B4C wt% was studied [91]. It is observed that the tensile properties improve with pure Al/B4C AMMC as compared to matrix material as shown in Fig. 10. The results revealed that as the concentration of reinforcement increases the ultimate tensile strength (UTS) of the composite upto 8 wt% reinforcement and decreases beyond that. The further increment in concentration, UTS decreases. The increase in strength is due to the increase in hindrance to the dislocation motion, by introducing particles of reinforcement. Whereas, at higher reinforcement level encour-ages agglomeration of particles which is the basic cause of the decrease in property of the composite material.

In the case of hardness, positive behaviour is obtained with the increase of reinforce-ment concentration. Improved hardness is the result of improved interface, that is, improved resistance to the motion of dislocations in the composite material. It has also been studied that the nano B4C reinforced product has superior ductility (See Fig. 10 a-b) and hardness as compared to micro reinforced by B4C.

Abdollahi et. al.[93] carried out a study to investigate the tribological behaviour of Al2024/B4C AMMC. Improved mechanical proper-ties of the composited in terms of hardness, wear resistance and strength are reported. Hence, the decrease in the grain size of matrix material and reinforcing material due to mechanical milling leads to increase in the hardness and strength of compos-ite. From then on, the wear rate was found to decrease with increasing hardness of the material [102]. Wear rate of Al2024/B4C nano-AMMC reduced drastically in comparison to the matrix material as presented in Fig. 11. The use of hybrid combination of reinforcing elements SiC and B4C is accompanied by significant improvement of wear characteristics [1].Dispersion can be credited as being the reason for hard ceramic particles throughout it.

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In conclusion, it could be said that Boron carbide (B4C) is one of the hard materials, and the presence of it in the aluminium matrix contributes to the hardness of the composite. The wear resistance of Al–(boron carbide) composite is improved by the addition of boron carbide particles within the aluminium matrix. B4C's hardness and abrasive characteristics are beneficial for reducing the wear and friction between the composite and contacting.

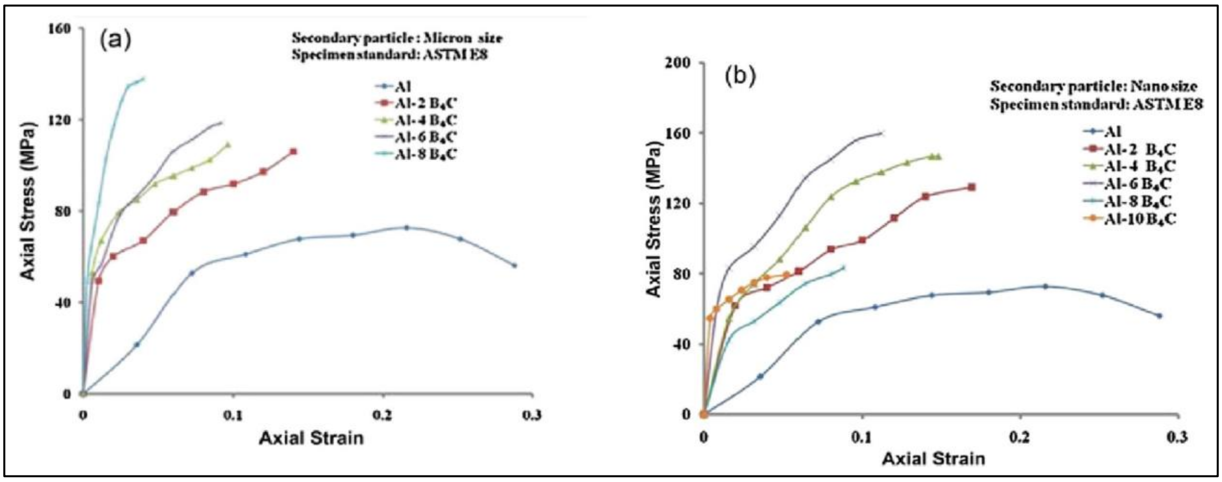

Fig 10 Comparison in Axial Stress–Strain of Al–B4C Composites (a) Micron Size Reinforcement (b) Nano Size Reinforcement [91].

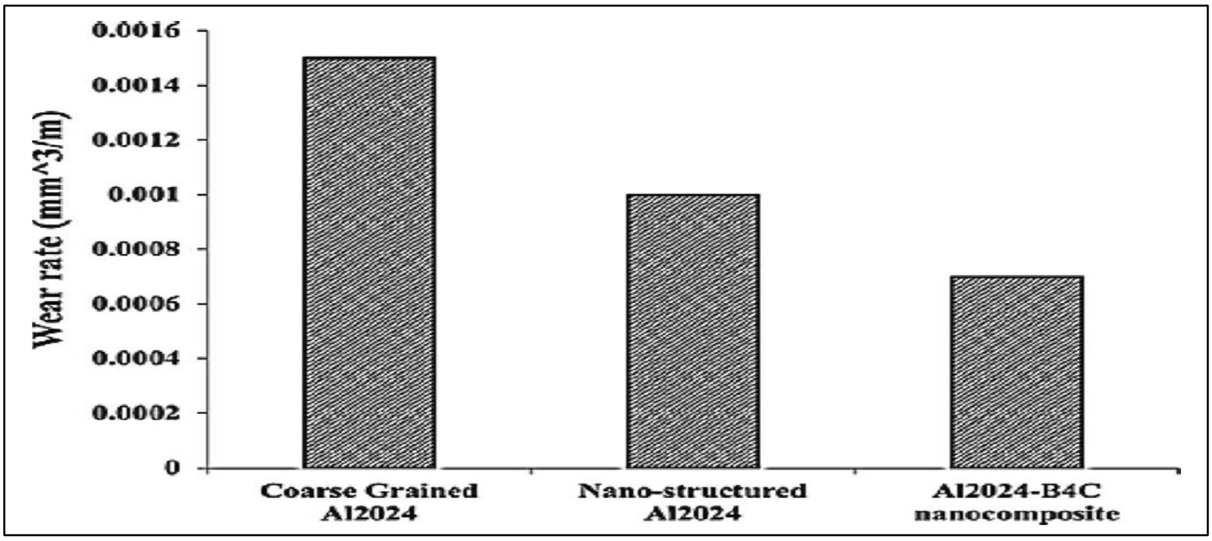

Fig 11 Comparison of Wear Rate of Al2024/B_4C Nano-AMMC with Matrix Material.

Surfaces. Boron carbide is a light weight material which has a high strength and hardness. It is used to reinforce the aluminium matrix as their low density will be desirable. When added to the aluminium matrix, it can offer a barrier to the chances of corrosion of the composite.These properties make them useful in sliding or abrasive wear for applications, or harsh environments.

A summary of the AMMCs that are synthesized and the development of mechanical properties of the corresponding AMMCS with different reinforcement agents is tabulated in Table 1.

- *Al-Graphene and Al-Carbon Nanotubes Composites*

Other than the conventional reinforcements like Al2O3 and SiC, several other reinforcements like graphene, CNT and MgO have been examined for their application in aluminium. Li et al(2015) [52] fabricated the Al/GNFs of different concentration (wt. %) using the method of cryomilling. This Al-GNF interface was not observed to contain any intermetallic compound like Al4C3, which is obtained due to reaction of aluminium and GNF. The results obtained from Anal-ysis represent a great improvement in mechanical properties of the composite reinforced with GNFs. The best improvement in tensile properties is seen when using 1 wt% of GNF.The yield strength increases by 55% and the ultimate strength improves by 68.7%, as shown in fig. 12a and Fig. 12b.

Such improved properties may be attributed to the presence of good GNF particle dispersion, free from reactions, and interfaces. Ductility is increased of Al-0.5 wt%Gr composite as compared to pure matrix material. The ductility decreases when the concentration increased to 1wt%, however. The agglomeration effect of GNF particles

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was the rea-son investigated. The reason for the reduction in properties after reinforcement level 1 wt% is because higher reinforcement level would lead to higher temperature at which the properties are obtained and because of the higher concentration of reinforcement would cause more agglom-eration of the reinforcing particle and hence, weak interface would be formed in the composite, thus affecting the properties that have been obtained. The CNT has been the object of much research interested in its use as the reinforcement for MMCs[5,7,103].The CNT as a reinforce-ment has its drawbacks: issues of dispersion, high number of oriented CNTs and interfaces [6,104,105]. The Al/CNT composite was synthesized with various content of reinforcement (0.5, 1, 2 &5%) by Esawi et al [98] using powder metallurgy route. As seen from the Fig. 13, there is significant increase in the tensile strength (50%) and young's modulus (up to 23%) in the Al/ 2% CNT sample in comparison to matrix sample.

On the contrary, reinforcement concentration increases beyond 2% further show no improvement in tensile strength while their Young's modulus is a little lower than that of Al/2% CNT. This decrease in Young's modulus might be because the CNT particles are clumping together when there is a high amount of reinforcement. Moreover, George et al reported a tensile strength of 138 MPa. The results from [106] for Al/2vol.%CNT clearly show that ball milling plays a role in the preparation of AMMC. However, Kwon et al[107] reported a maximum tensile strength of 194 MPa for the Al-5 vol% CNT composite, but this result did not include ball milling during the preparation of the aluminum metal matrix composite. Besides that, using strain-hardened carbon nanotubes as a way to increase the maximum strength of the carbon nanotube composite. The level to which the CNT particles are graphitized; the overall quality of the CNT particles.

Table 1 Summary of Synthesized AMMCs and Improvements in the Mechanical Properties with Varying Reinforcing Agents.

AA2024 (particle size 80–100 mm with 99% purity) [64]	Al2O3	Diameter of Al2O3 is 95 nm	0.5, 1, 1.5, 2 wt%	Solid-Liquid mixed casting combined with ultrasonic treatment	Tensile Strength: 37% Increase for 1 wt% Yield Strength: 81% increased for 1 wt%
Aluminium powder (99% purity and particle size of 75 mm) [66]	Al2O3 and Graphene nano platelets (GNPs)	Al2O3 -=47 mm. GNPs thickness = 6 mm and platelet dia. = 5 mm.	GNPs (0.1, 0.5, and 1 wt%) Al2O3 (1, 3, and 5 wt%)	Ball Milling at room temperature	Hardness: increase with increasing weight percentage of Al2O3 particles. Other: Porosities were increasing with increasing reinforcement particles.
A356[67]	Al2O3	20 mm and50nm.	20 ms: 1,3,5,10 % 50 nm: 1,2,3%	Al_2O_3 particles are heat treated first then reinforced in the A356 alloy matrix with the help of Argon gas	Load capability of the composite increases as compared to the matrix
Magnesium (AZ91D) [95]	Aluminium Silicate	5 mm and 80 mm.	30 vol%	Squeeze casting	Others: Creep resistance increased with reinforcement concentration
Magnesium[96]	Alumina particles	50 nm.	0.22,0.66and 1.11 vol %	Disintegrated melt deposition technique (DMD)	Hardness: Wear resistance increases as the reinforcement level is increased, till sliding speed of 7 m/s
Aluminium [97]	SiC and CuO	Micro and Nano	–	Sintering	Hardness: Attains maximum value at 2 wt% CuO Others: Density increases from 2.9 kg/ m^3 to 3.06 kg/m^3
A356 [77]	SiC and Al2O3 particles.	SiC = 50 nm & Al_2O_3 = 16 mm	0.5, 1.5, 2.5, 3.5, 4.5 %	Stir casting	Tensile Strength: Max for 3.5% Yield Strength: Increased Hardness: increased Others: wear resistance increased as the reinforcing is increased
AA7075-T651[88]	SiC and Al2O3	–	Nano SiC = 5,10,15 wt% & Al2O3 = 5 wt%	Stir casting	Hardness: Attains maximum value at 2 wt% CuO Others: Increase in reinforcement first increases the fatigue limit and then decrease in the fatigue limit due to agglomeration of particles
Aluminium[91]	Nano and Micro B4C particles	80 nm & 70 mm	2,4,6,8,10 wt%	Ultra-sonic cavitation	Tensile Strength: increases as the reinforcement concentration increases up to 8 wt%. Others: Nano reinforced MMC has more ductility and wear resistance than micro reinforced MMC. Impact energy decreases as the reinforcement level is increased
Aluminium [52]	Graphite nano flakes	–	0.5,1,1.5,2 wt%	Cryo-milling	Tensile Strength: Increased by 68.7% for 1 wt%. Yield Strength: Increased by 55.2% for 1 wt% Hardness: Others: Optimum value of reinforcement is 1 wt% experimentally

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Aluminium [98]	Carbon nano tubes	Length of CNT is 10–20 mm and diameter is 30–50 mm	0.5, 1, 2 & 5%	Ball Milling	Tensile Strength: Increased by 50% for 2 wt% of CNT. Increase in young's modulus by 23% for 2 wt%
Aluminium (99% purity, 10 mm) [89]	Al_2O_3 and SiC	Al_2O_3 = 15–20 mm &SiC = 55–60 mm	0, 3, 6 %	Casting or powder metallurgy	Tensile & Compressive Strength: Decreases as the Al_2O_3 and SiC % is increased for both stir casting and Powder metallurgy (PM) However, Tensile strength & compressive strength for cast composite was more than P/M composites. Hardness: Increases as the as the Al_2O_3 and SiC % is increased for both casting and P/M
Zinc aluminium alloy (ZA-27) [99]	Al2O3	Average particle size of Al_2O_3 is 50 nm.	1,2 and 3 wt%.	Stir casting followed by ultrasonic assisted casting method.	Hardness: Increase in micro hardness as Al_2O_3 % increases
Aluminium 6061 [19]	Boron carbide	50 nm	0,0.5,1.0,1.5,2.0,2.5 vol %	Ultrasonic cavitation	Tensile Strength: Increased by 124% for 2 vol% AMMNC. Increasing Boron carbide amount up to 2 vol%, Hardness: Increases as B_4C% is increased Others: Increases as B_4C% is increased. Increase in wear rate against increasing values of sliding distance, sliding velocity and applied load is more for AA6061 than AMMNC.
Aluminium powder with average particle size of 60 mm and with 99.9% purity [100]	SiC	70 nm,10 mm and 40 mm.	5 and 10 wt% SiC	Powder metallurgy followed by hot extrusion	Tensile Strength: Lower particle size and increasing SiC % yields higher the compressive sterngth. Maximum was 601 MPa for 10 wt% SiC(70 nm) Yield Strength: Hardness: Lower particle size and increasing SiC % yields higher hardness value. Maximum was 72HV for 10 wt % SiC(70 nm) Others: Lower particle size and increasing SiC % yields lower thermal conductivities and density.
Aluminium (99.7% purity) [101]	MWCNTs	dia. = 140 mm length = 7 mm	1, 2.5, 5 wt%	High energy Ball Milling	Increasing wear resistance and decreases in coefficient of friction, as the reinforcement % is increasing. Also, 5 wt% AMMC show high wear resistance at low sliding speed and applied loads.

Other factors, such as the mechanical properties, may also become affected. Moreover, these characteristics of the CNT help to understand the reaction of CNT particles and Al. Further, a higher amount of reinforcing concentration might also have an effect on mechanical properties as a result of formation of aluminium carbide in the composite. Multiwall carbon nano tubes (MWCNT) has appeared to be a superior material for reinforcement, and is now being used to prepare metal composites [8,108].

As shown in Fig. 14[109] it is noticed that, among all the reinforcing elements, CNT and MWCNT shows better improvement on the strength of AMMCs.

Graphene is a two dimensional allotrope of carbon which is being investigated for its potential to be used as reinforcement in Al matrix com-posites. Graphene sheets can be added for improved mechanical strength, electrical conductivity and thermal prop-erties of aluminum..The high hardness value of the graphene and lubricating properties reduce friction and wear between the contacting surfaces and the com-posite. This is a benef-icial characteristic for lubricated applications requiring sliding wear or abrasive wear such as cutting tools and bearings. The density of the composite is also low because graphene has a low density. Such a property is beneficial for applications such as the aerospace and automotive industries where weight reduction is essential to the components yet still a strong structure is desired.

Al – CNT composites have excellent thermal conductivity, high strength and improved mechanical properties [110]. They are used in aerospace, automotive and electronics applications.

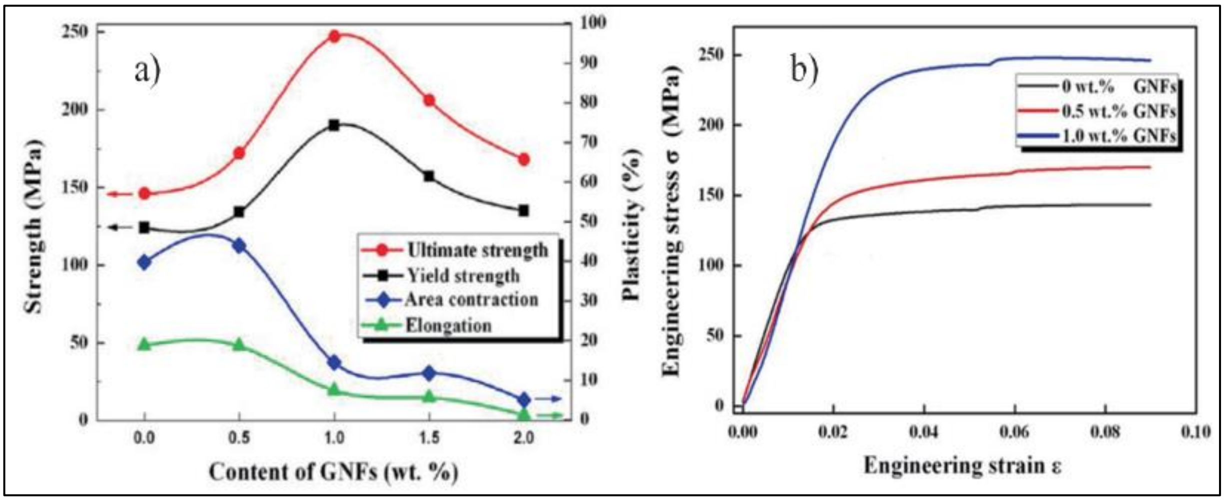

Fig 12 Improved Tensile Properties After the Reinforcement (a) Engineering Stress–Strain Curves and (b) Variation in Tensile Properties of the Al/GNF Composite with Reinforcement Concentration [52].

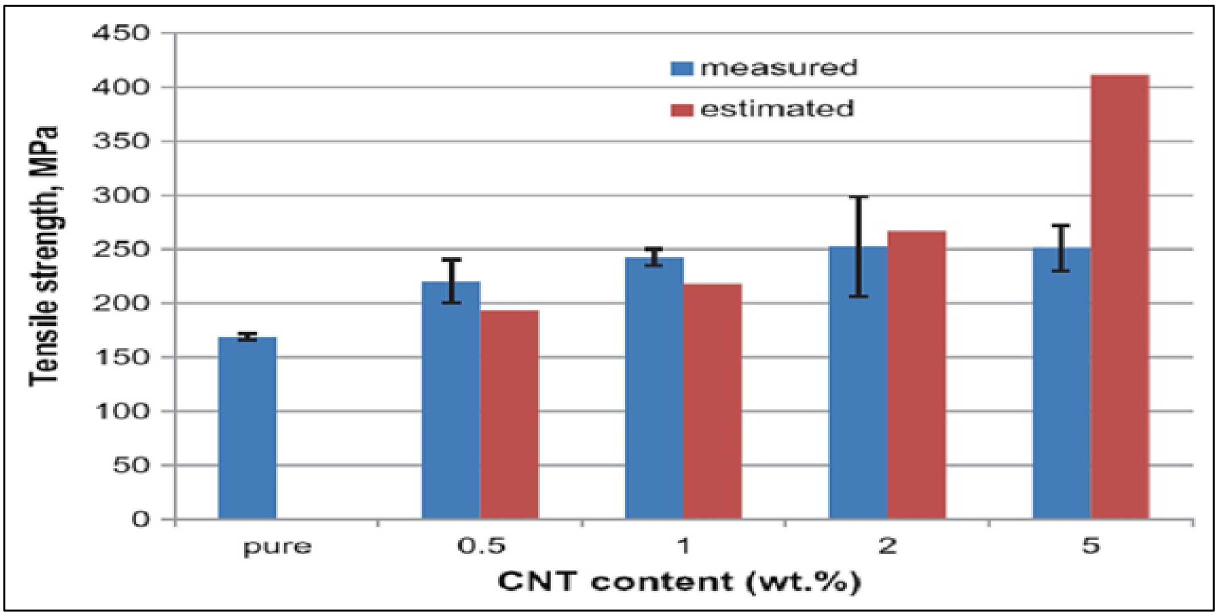

Fig 13Variation in Tensile Strength of Fabricated Al/CNT AMMC Measured and Estimated Based on the Composite Theory with Varying Concentration of Reinforcement [98].

- *Al- Magnesium Oxide (MgO) Composites*

Magnesium oxide, which is a type of magnesium compound, is also used to make AMMCs. Yar et al.(2009) made A356.1/MgO AMMC by stir casting at temperatures of 800 °C, 850 °C, and 950 °C [9]. The density of Al-MgO composite at the casting temperature is found to decrease with increase in reinforce-ment concentration. But, with increased reinforcement level, similarly agglomeration is observed that leads to the decrease in density. With increasing casting temperature, the reinforcement level 1.5 and 2.5%, the density of Al-MgO also decreases. Hence, the temperature is an important factor for determining the "wet-tability," in synthesis composite. Optimum hardness of Al-MgO composite increases as the MgO is added to composite. The composite material obtained with this increase in reinforcement level resulted not only in higher hardness as the respective results displayed but also reinforcement level above 4 vol % did not lead to further increase in hardness. When the temperature goes up, the hardness increases, which is a good thing because higher temperature makes the reinforcement particles easier to wet. It was also said that when the strain stays the same, adding more reinforcement causes the toughness to decrease at 800 degrees Celsius. As the reinforcement level goes up, so does the work hardening, and thus a decrease in the toughness.

III. SUGGESTIONS FOR THE FUTURE RESEARCH

Aluminium metal matrix composite (AMMC) materials have received a lot of attention because they have a special mix of properties like high strength, stiffness, and low weight. Some future research ideas include creating new reinforcement materials.Most aluminum metal matrix composites use ceramic materials such as silicon carbide, alumina, and graphite as the reinforcing components. It's important to do more research on using new materials such as

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carbon nanotubes, graphene, and nanocellulose fibers to enhance the properties of AMMCs. We need to work on better ways to make things in the manufacturing process.Techniques like AMMC, Powder Metallurgy, and Spark Plasma Sintering should be studied more.These methods can help make the production of AMMC better and more efficient. Optimizing the processing settings like temperature, pressure, and time greatly affects the characteristics of the AMMCs. Therefore, optimization.

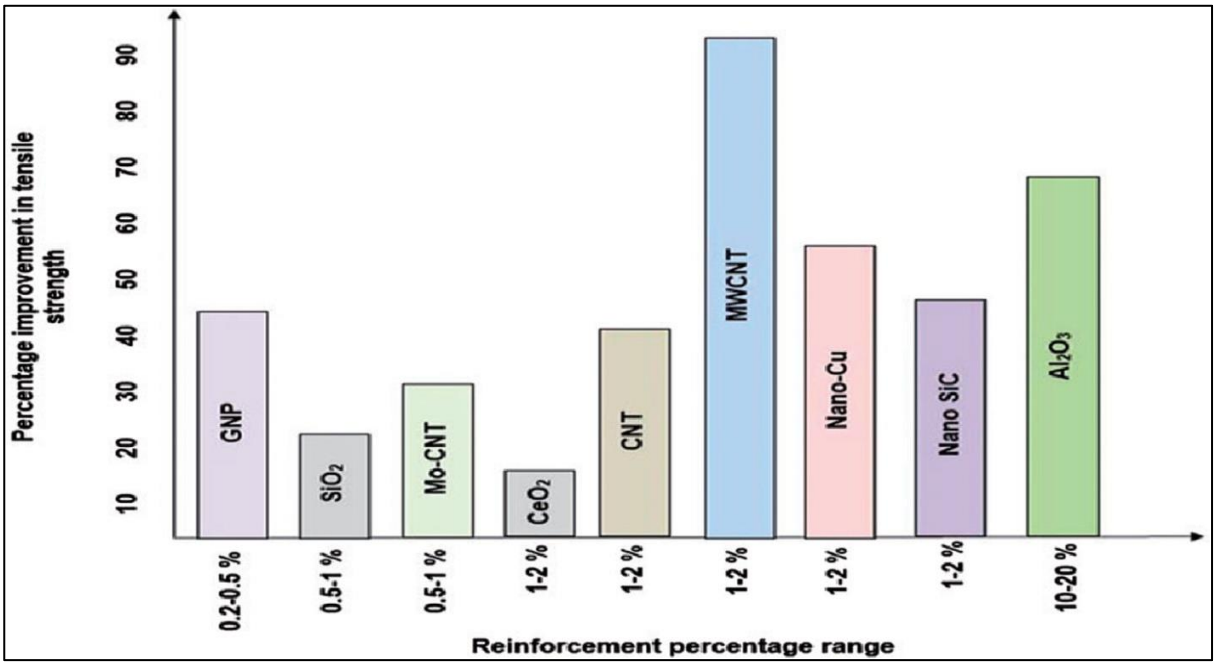

Fig 14 Percentage Improvement in the Tensile Strength of Composite with Type of Reinforcements [109].

To get AMMCs with the right properties, these parameters are important. Characterization techniques are important for understanding the properties and behavior of AMMCs. So, to understand the structure and strength of AMMCs, it's necessary to use advanced techniques such as Scanning electron microcopy (SEM), Transmission electron microscopy (TEM), X-ray diffraction (XRD), and mechanical testing. Modeling and simulation techniques can be used to forecast how AMMCs will act under different types of stress and to improve their performance characteristics. New modeling and simulation tools help predict the properties of AMMCs accurately and are used to improve the design of AMMCs. AMCs can be really good for performance in tough situations, like very high heat or places where there's a lot of corrosive stuff around. Scientists can study how AMMCs work in these situations and create AMMCs that are specially designed for these environments. Applications: AMMCs are promising and their use in different indus-tries is not widespread yet. Future work is needed to investigate the new application of AMMCs in aerospace, automotive and biomedical applications etc. The environmental impact: There may be environmental implications for production and use of AMMCs. Hence, the study of environmental impact of the AMMCs and the development of sustainable way of producing it is needed.

IV. SUMMARY

N recent review articles, the mechanical and microscopic structure features of aluminum metal matrix composites have been covered. The paper explains how different reinforcing materials affect the final composite, and it talks about their importance based on their uses.It also shares knowledge about the various ways the composite gets stronger, how well the parts stick together, its hardness, and its maximum strength, all of which are discussed in the review paper.

- The choice of different reinforcing materials depends on several factors like the cost to make them, the quality of the final product, and what the product is meant to be used for.
- The ability of AMMCs to resist wear can be improved by adding self-lubricating materials such as Graphene, carbon nanotubes (CNT), or multiwalled carbon nanotubes (MWCNT) to them.
- The powder metallurgy method for making AMMCs offers improved movement and interaction at the interfaces. It improves the structure by using quick solidification of fine powder. It also helps reduce the clumping together of the reinforcing elements.
- The stir casting method for producing aluminum metal matrix composites is cost-effective and results in a product that is already in its final shape. But, the application of the nano metal matrix composites is limited due to the phenomenon of "agglomeration" of nano particles of reinforcing.
- It was also found that the structure of the final composite is heavily influenced by the process parameters used, the type of materials added to strengthen it, and how the materials interact at their

boundary.

- When there are reinforcing materials in the composite, the grains will start to form in different places, which helps make the composite stronger and harder.This happens because the smaller grain size makes the material stronger, as explained by the Hall-Petch equation.
- Nano reinforced composites are stronger, harder, and more durable than micro and macro reinforced composites.

V. CONCLUSION

This review has brought together the current understanding of aluminium metal matrix composites, from the routes used to fabricate them through to the mechanical, physical, and microstructural behaviour they exhibit once reinforced. Across the reinforcement systems considered — alumina, silicon carbide, boron carbide, graphene and carbon nanotubes, and magnesium oxide — a consistent picture emerges: composite performance is governed jointly by the choice of reinforcement, its particle size and volume fraction, and the fabrication route used to distribute it through the aluminium matrix. Stir casting remains attractive for its cost and simplicity but is constrained by particle agglomeration at the nanoscale, while powder metallurgy and related sintering routes offer finer control over interfacial bonding at higher processing cost. Grain refinement driven by reinforcement addition, consistent with the Hall–Petch relationship, was identified as a recurring mechanism behind the strength and hardness gains reported across studies. Despite this progress, AMMCs have not yet been adopted as widely as their properties would justify, particularly in aerospace, automotive, and biomedical applications. Closing this gap will depend on further work in novel reinforcement chemistries, tighter process control, more predictive modelling of composite behaviour, and a clearer understanding of the environmental footprint of AMMC production — all of which represent the natural next steps for research in this field.

ABBREVIATIONS

MMNC	Metal Matrix Nano Composites	Al_4C_3	Aluminum Carbide
MMC	Metal Matrix Composites	CuO	Copper Oxide
AMMC	Aluminium Metal Matrix Composite	UTS	Ultimate Tensile Strength
SiC	Silicon Carbide	B_4C	Boron Carbide
Al_2O_3	Aluminium Oxide	GNF	Graphite Nano Flakes
SiO_2	Silicon Oxide	MgO	Magnesium Oxide
CNT	Carbon Nano tubes	$ZrSiO_4$	Zirconium (IV) Silicate
Al	Aluminium	SEM	Scanning Electron Microscope
GNP	Graphene Nano Platelets	TiC	Titanium Carbide
Mg_2Si	Magnesium Silicide	XRD	X-Ray diffraction

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