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Advances in AMC: A Review of Processing Techniques, Mechanical Performance and Wear Properties

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Abstract
The global utilisation of Al alloy has been significantly increased, and the manufacturing of "aluminium matrix composites (AMCs)" has been a significant source of global revenue and employment, as a result of the inclusion of a variety of reinforcements to Al. This article provides a comprehensive survey of the diverse literature that has been conducted on the progress of "aluminium matrix composites (AMCs)". The review article concluded that the advancements in graphene-reinforced AMCs have significantly enhanced mechanical and tribological properties. Powder metallurgy (PM), particularly the SPS process, proves effective in achieving superior densification and minimizing undesirable phases. Composite performance is enhanced by strengthening processes such as "CTE mismatch, Hall–Petch, Orowan, and load transfer". Reinforcements like SiC, and carbon-based materials refine grains, enhancing "tensile strength, hardness, and wear resistance". The use of nano-reinforcements ensures better structural integrity, while self-lubricating elements improve tribological properties. Additionally, sustainable natural minerals offer economic and environmental benefits. Optimal processing conditions, including controlled atmosphere and stirring time, are crucial for achieving uniformity and superior properties in AMCs.

Keywords: Aluminium matrix composites (AMCs), Mechanical Performance or properties, Wear (tribological) Properties, aluminium (Al) alloy, Powder metallurgy (PM), Metal matrix composites (MMCs), etc.

INTRODUCTION

Large-scale manufacture of "metal matrix composites (MMCs)" with a wide range of applications is made possible by improvements in fabrication techniques and the availability of a variety of reinforcing materials. Metal matrix composites (MMCs) are enhanced in many ways by the addition of ceramic, metallic, or organic compounds to a metal or alloy matrix. These compounds increase "the MMCs' specific strength, stiffness, elastic modulus, resistance to wear and corrosion, thermal conductivity, and many more" [1]. These metals include "Al, Mg, Ti, Cu, Ni, Fe", and others. MMCs are mostly made of magnesium and aluminium. The remarkable qualities of magnesium composites over numerous alloys have led to a significant demand for them. Low ductility, weak fracture resistance, and strong atmospheric reactivity, however, restrict its use in the automobile industry[2]. Aluminium and its alloys are extensively employed in automotive and aerospace applications due to their excellent performance and reduced weight. These materials have excellent properties such "low density, high specific stiffness", robust resistance to wear and corrosion, and high specific strength [3]. The kinds, sizes, and volume proportion of the reinforcing particles might be changed to improve these qualities. In order to provide a range of aerospace parts that need enhanced mechanical properties, wear resistance, and frictional resistance, AMMCs are used [4].

A significant rise in the amount of research conducted in the area of aluminium MMCs has occurred within the last ten years. Mostly used to substitute metallic alloys in aeroplane parts like wings and fuselage and automobile parts like brake discs, drums, and pistons, these amalgamations save production costs [5], [6].

Aluminum-based composites are primarily made using two methods: solid state processing (like powder metallurgy and mechanical alloying) and liquid state processing (like stir casting) [7]. The powder metallurgy technique combines the reinforcement and matrix for compacting, and then sintered the compacted section to make it stronger. In the process of mechanical alloying, components react to create reinforcement. The most common and economical technique for producing aluminium composites is stir casting[8]. Using both the ex-situ and in-situ techniques, ceramic particles consisting of oxides, carbides, nitrides, and borides are used to reinforce aluminium MMCs since it is easier to spread the reinforcement in the aluminium matrix. Moreover, aluminium MMCs have been produced using industrial waste like fly ash and agro-waste materials like rice husk and lemongrass ash[9], [10].

Fabrication methods for aluminum matrix composites

"In-situ fabrication, liquid state fabrication, solid state fabrication, and contemporary methods" are among the manufacturing technologies used to create the AMCs. The qualities of AMCs are largely determined by the composite production techniques used[11]. A thorough summary of the procedures employed in the manufacturing of MMCs is shown in Fig. 1. Each procedure has its own set of benefits, drawbacks, and restrictions. Using high pressure and temperature to shape materials into a solid state is known as solid state fabrication[12]. Materials are treated below their melting point using these techniques. The basic idea behind liquid state manufacturing techniques is to melt the metal matrix, add the reinforcing components, and then solidify the mixture. When using in-situ production techniques, chemical interactions immediately inside the matrix create the reinforcing phase[13]. Using cutting-edge technology and creative approaches, modern manufacturing procedures seek to create high-performance composite materials. The two main fabrication techniques used in the creation of AMCs are stir casting and powder metallurgy. Powder metallurgy is preferred by researchers in this area in particular because of its simple raw material preparation, high tolerance, little secondary processes and material loss, and excellent particle dispersion in the pure alloy[14].

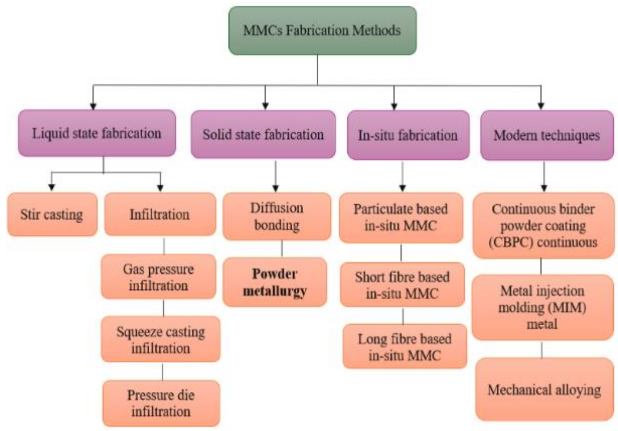

Figure 1 Fabrication methods used for MMCs[14]

Need of aluminum alloys and composites

The four main groups into which lightweight materials for automobiles can be broadly classified as potential replacements for conventional engineering materials (like steel and cast iron) are the high-speed steel (HSS) family (which includes conventional HSSs and advanced high-strength steels), composites (such as Al-based composites or carbon-fiber-reinforced plastics), light alloys (such as aluminium, magnesium, and titanium alloys), and advanced materials (such as mechanical metamaterials) [15]. Since the turn of the century, components composed of these lightweight materials have been extensively used in the automotive industry, including "the dashboard, bumper, engine, body shell, wheel, suspension system, brake, steering system, battery, seat, and gearbox" (Figure 2)[16].

Figure 2 The most common lightweight materials utilised in vehicle components are light alloys [16]

Mechanical characteristics of AMCs

The behaviour of the reinforced element, the porosity among the reinforced element and metal matrix, and the uneven distribution of reinforcing particles may all affect the mechanical characteristics of aluminium MMCs [17]. In the following, we have examined the mechanical properties of the aluminium AMCs.

- **Hardness behavior of AMCs**

The bulk hardness of the material is increased by adding robust ceramic particles to an aluminum-based matrix. "Grain size, dislocation density, micron- or nano-sized reinforcing particles, heat input, porosity, and other" variables all influence the microhardness of an aluminum-based composite, depending on the manufacturing procedures used[18]. Particle size and hardness have an inverse relationship. Hardness is increased when grain size is smaller and decreased when grain size is bigger. Higher porosity proportions decrease the composite's hardness, whereas lower porosity proportions enhance it. Hardness rises because to better distribution of reinforcing particles and base matrix grain refining [19].

- **Tensile behavior of AMCs**

As compared to monolithic aluminium, the tensile strength of aluminium composites reinforced with carbides and graphene has increased dramatically due to a variety of strengthening processes. The current work on the tensile behaviour of composites made of aluminium under various particle conditions is fascinating to read. The AMCs have higher engineering stresses than plain Al. While AMCs' UTS increased to 135% of pure aluminium, AMCs' UTS rose to 292% of pure aluminium. A higher grain boundary density at smaller grains prevents dislocation motion, according to the Hall–Petch connection [19].

Wear behavior of AMCs

Material gradually deteriorates or is destroyed when one or both surfaces are subjected to relative motion (sliding, rolling, or impact action). At asperities, surface contacts are often the source of the wear phenomena. When formulating distinct wear hypotheses, the researcher takes into account the physical condition and physio-mechanical characteristics of the surface[20]. "Holm developed a wear theory in 1938" that was based on atomic mechanics. He also calculated the volume wear loss of the substrate along a unit sliding path. The adhesion theory of wear was developed by "Burwell and Strang (1952), Archard (1953), and Archard and Hirst (1956)", who also provided a theoretical equation that was quite close to Holm's equation. By continually moving a certain quantity of material, sliding weakens and ultimately breaks the material[21]. Aluminium composites are used in braking rotors, brake drums, and brake discs, among other tribological applications. In these kinds of applications, Al MMCs need to be used; however, the factors that influence tribological behaviour must be carefully examined[22]. In the aerospace and automation industries, the wear behaviour of composites is a critical tribological characteristic that must be preserved in robust engineering applications, which is why a number of academicians are intrigued by it. However, it is crucial to consider the material's resistance to attrition before employing it in any engineering applications, despite the fact that numerous researchers have exhaustively investigated the tribological characteristics of various aluminium alloys in both dry and damp conditions [19].

LITERATURE REVIEW

(Akgümüş Gök et al., 2024) [14]have been thoroughly examined. These include the powder metallurgy method's fabrication and characterisation of aluminum-based "composite materials reinforced with Al2O3, SiC, B4C, and MgO powders". When the sintering duration and temperature were increased, aluminum-based composite materials composed of Al2O3, SiC, B4C, and MgO particles typically exhibited higher densities and lower porosities. In general, the density of the material rose and a more uniform structure was produced by raising the compaction pressure. SiC and B4C were shown to have superior strength, hardness, and wear resistance when compared to other materials. As a result, they may be used for high-performance applications, including cutting tools, the automotive, aerospace, and defence industries.

(Samal et al., 2020) [5]Due to their exceptional corrosion resistance, weight, specific modulus, and abrasion resistance, aluminum-based composites are the most potential structural materials across MMCs for aerospace and automotive applications.Aluminium MMCs were made using a variety of fabrication techniques after taking into account various reinforcing particles, including oxides, nitrides, carbides, borides, and their mixtures. The development of stable reinforcement particles in the composites allowed aluminium MMCs to exhibit superior mechanical and wear properties. The recently published review paper examines the most recent advancements in the microstructure, wear, processing, and mechanical characterisation of aluminium composites that have been reinforced with a variety of particulates. The manuscript's conclusion includes a short discussion of these composites' potential applications.

(Alam et al., 2023) [16]discusses the construction processes, mechanical characteristics, and latest developments in "aluminum-based composites reinforced with SiC, TiC, and graphene". Steel and other metals may be reinforced using graphene nanoplatelets since they are lighter and many times stronger than steel. However, the uniform distribution of graphene in metal or aluminium is a challenging issue for material scientists. A comprehensive evaluation is conducted of the methods used to fabricate AMCs in order to achieve a uniform distribution of graphene. We evaluate and analyse the mechanical characteristics of aluminum-based composites, with a focus on microhardness, wear behaviour, and tensile strength. Lastly, a plan for promoting more growth in this field has been explored.

(Ashebir et al., 2022) [23]A study on metal matrix composites (MMC) was carried out, concentrating on "aluminium matrix composites (AMC)". It has been studied how different reinforcing ceramic particles, including graphite (Gr), silicon carbide (SiC), and aluminium oxide (Al2O3), affect the mechanical and metallurgical characteristics of MMC. In order to demonstrate a comprehensive comprehension of the numerous facets of HAMCs, such as "manufacturing, physicomechanical properties, wear, and corrosion properties", a comprehensive analysis of the summary of several different characterisations, such as X-ray diffraction (X-RD) and optical microscopy (OM), has been conducted. This analysis includes testing for hardness, tensile, compressive, and tribological behaviour.

(Teferi et al., 2022) [24]Aluminium matrix composite is widely used to produce improved spare parts for automobiles, aeroplanes, medical equipment, and other machinery. Aluminium metal matrix composites reinforced with silicon carbide particulates comprised the primary focus of this review study. This review paper investigates the aluminium matrix composite's mechanical, chemical, and physical properties, including thermal and electrical conductivity. In addition, different manufacturing methods, process variables, applications, and research gaps for the future were thoroughly examined. Along with related phenomena, the effect of “:silicon carbide particle (SiCp) reinforcement in the aluminium metal matrix” is thoroughly investigated in this work.

(Bhoi et al., 2020) [25]gives a summary of the various reinforcing materials and manufacturing procedures employed in the synthesis of Al-MMCs. In order to emphasise the degree of reinforcement and improvement that took place during processing, the common mechanical parameters (such as compressive strength, tensile, andhardness, etc.) that have been reported by various researchers are fully examined. To identify the possibility of reinforcing particles in Al-MMCs, the operating circumstances that impact the tribological behaviour and the factors that cause it are carefully considered. In order to stimulate future research paths, the many drawbacks and potential future developments of Al-MMCs are finally discussed.

(Singhal et al., 2024) [26]examines how various types of reinforcing particles affect the properties of Al-Si alloy AMCs. In the aerospace and automotive industries, these reinforcements are ideal for high-performance applications since they have been shown to significantly improve wear resistance, reduce friction, and boost the overall strength and toughness of the composites. Furthermore, this paper emphasises the difficulties in creating these composites, including minimising porosity and attaining a uniform particle dispersion. In order to overcome these obstacles, it also talks about the most recent developments in processing methods. The use of natural reinforcements, which lower material prices and support sustainable manufacturing methods, may also have positive economic and environmental effects, as this paper discusses.

(Wazeer et al., 2024) [27]The greater temperature tolerance and better strength-to-weight ratio of "Metal Matrix Composites (MMCs)" have garnered a lot of interest for possible uses in the aerospace and automotive sectors. MMCs are made by integrating a reinforcing material into a metal matrix. Among the greatest engineered structural components are aluminum-based metal matrix composites because of their remarkable strength, stiffness, wear resistance, thermal stability, and a host of other properties that change dependent on the kind and amount of reinforcements utilised. The mechanical properties of "aluminium metal matrix composites" are examined in the section, as well as the advancements that have been made in the field.

CONCLUSION

Recent research on graphene-reinforced aluminum matrix composites (AMCs) highlights significant enhancements in mechanical and tribological properties, primarily attributed to the successful incorporation of graphene and other reinforcements. Powder metallurgy (PM) has proven to be the most effective fabrication method, with spark plasma sintering (SPS) offering superior densification and phase stability. Al–graphene and Al–SiC composites exhibit enhanced performance as a result of strengthening mechanisms that include "Hall–Petch, Orowan, coefficient of thermal expansion (CTE) mismatch, and load transmission". Orowan strengthening is particularly significant at higher reinforcement fractions. Ceramic additives, SiC, are among the reinforcements that provide a substantial increase in abrasion resistance, tensile strength, and hardness. The incorporation of nano-reinforcements enhances structural integrity, while self-lubricating elements like CNTs provide superior wear resistance. For even load distribution and less particle clustering, use fine or dual-size reinforcements in conjunction with stir casting to guarantee a uniform dispersion of reinforcement particles. Heat treatment prior to manufacturing enhances tensile properties. Additionally, natural minerals offer sustainable and cost-effective reinforcement alternatives. Processing conditions, including milling time and inert atmospheres, play a crucial role in uniformity and grain growth. All things considered, improvements in AMC processing methods keep enhancing their tribological and mechanical performance, which makes them ideal for demanding applications.

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