A Retrospective Investigation on Hybrid Metal Matrix Composites: Materials, Processing Methods, and Properties of Composites

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ABSTRACT: *Hybrid MMCs are a new class of materials that exhibit superior characteristics and functional response when compared to monolithic alloys and mono-reinforced MMCs, and thus have tremendous potential for widespread application in modern industrial and engineering applications. Since the manufacturing fraternity is proliferating, a cyclic evaluation of understanding the behavior of hybrid MMCs and their evolution is needed. Therefore, to address this necessity, this paper presents a detailed review of hybrid MMC manufacturing methods, materials (matrix and reinforcement) used, physicomechanical, tribological, and corrosion properties, and challenges associated with hybrid MMCs. This retrospective investigation presents the state of the art of hybrid MMC materials in the categories involving matrix materials and their alloys, ceramics reinforcements and secondary reinforcements, and the applications and formation of microstructures. This paper also discussed the overview and the status of various matrix and reinforcement materials in manufacturing hybrid MMCs using different fabrication methods. Further, the significant challenges associated with the fabrication of hybrid MMCs using different manufacturing methods, such as distribution of reinforcement, wettability, and other common limitations identified in the literature, are presented. This paper provides a broad-spectrum attitude on hybrid MMCs techniques, challenges, and future research directions.*

Keywords: *Hybrid MMCs; Processing methods; Physico-mechanical; Tribological and Corrosion properties.*

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1021-9986/2023/6/1842-1870 29/$/7.02

INTRODUCTION

Modern industries are developing novel manufacturing processes and reinforcing materials to address the challenging and competitive criteria, specific material qualities, and obsolescence of high-strength-lightweight materials. In this unique circumstance, metal matrix composites are lightweight, high-strength materials generated by diverse technical manufacturing processes such as liquid, solid, and vapor state processing [1–3]. In terms of wear resistance, specific strength, stiffness, specific elastic modulus, thermal conductivity, and creep resistance, MMCs outperform monolithic materials [4]. Adding a high-performance material as a reinforcement phase to a traditional engineering material produces a composite material with unique properties that cannot attain with a monolithic material.

Fundamentally, MMCs are a newer class of well-established engineering materials composed of a ductile metallic alloy impregnated with strong particles, fibres, or whiskers such as Gr, SiC, boron, and Al_2O_3, TiB_2, and other refractory metals [5]. Fig. 1 shows the classification of MMCs and their qualities, whilst Fig. 2 shows microstructural pictures of fibres, whiskers, and particle-enhanced MMCs. Due to reinforced particles in ductile metal composites, MMCs offer inescapable applications in aviation, auto, military, sports, bicycle frames, ground transportation, marine, electronics, and infrastructure industries [6–9].

Over the last four decades, tremendous research on MMCs has been taking place to address significant challenges such as cost-effective manufacturing, constituent compositions, characterization, and control of the interface between matrix and reinforcement phases. The widespread use of MMCs has possibly sparked more significant research into further advancements in the element's composition of composites. Because traditional MMCs with mono-reinforced materials such as micron-sized particulates or fibers can attain good mechanical and physical properties at high reinforcement content, their ductility and toughness properties deteriorate dramatically with increasing reinforcement content.

Recent research has shown that adding nano-reinforcements can significantly improve matrix alloys' mechanical and physical properties without impairing their ductility and toughness [10, 11]. Due to the grain size strengthening, adding nano TiC particles to Al alloys improves elongation and hardness but not tensile strength [12]. A similar effect in an Al-Si casting alloy impregnated with WC nanoparticles was seen [13]. Due to the grain-size strengthening mechanism, grain boundaries obstruct dislocation movement in the lattice. In the case of the carbon nanotubes impregnated with copper alloy, the CNTs were mechanochemically treated with copper powder to prevent them from floating on the melt surface due to their low density [14]. Similarly, in the case of polymer nanocomposites, nanometal oxides (Al_2O_3, TiC, and TiO_2) in the polymer matrix could also improve the thermal stability of the composite. This characteristic is due to the stereochemical differences between the constitutes of nano polymer composites [15].

However, *Zhou et al.* noted that dispersing nanoparticles at a greater volume percent in MMCs was extremely challenging due to the impact of strong van der Waals forces and the inherent incompatibility of the matrix alloys and nano reinforcement particles [9]. As a result, in all classes of MMCs, the lower percent of nanoparticles consistently exhibits lower strength. Much research has been taking place to address this bottleneck for MMCs and develop the next generation of materials for MMCs.

The key concept behind the new generation is to infuse hybrid reinforcements into matrix alloys, a revolutionary way to make advanced metal matrix composites. Hybrid-reinforced metal matrix composites are a sophisticated family of composite materials that combine good mechanical, physical, thermal, electrical, and structural properties. Hybrid MMCs are the most promising materials for protecting the human body and semiconductor electronics against radials. In advanced applications, hybrid MMCs can replace traditional materials and mono-reinforced MMCs [17–19].

In contrast with mono-reinforced MMCs, infusing hybrid reinforcement material into bulk MMCs is more convenient and promising because the desired rated performance depends on the material, application, and hybrid reinforcement ratio. Thus, the same procedures used to develop mono-reinforced MMCs are utilized for fabricating the hybrid MMCs, thereby expanding the application spectrum of MMCs. Despite their higher production costs than monolithic alloys, MMCs have a longer service life than monolithic alloys. Fig. 3 illustrates the hybrid metal matrix composite microstructure. This article

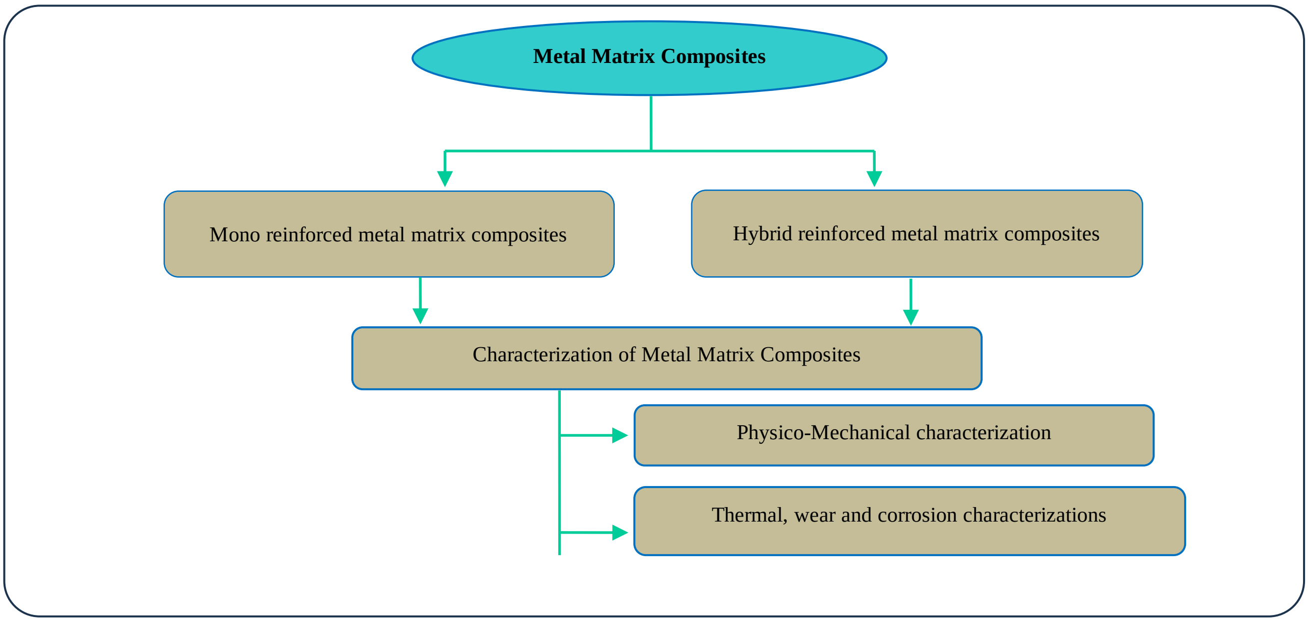

Fig. 1: Classification of MMCs and their characterizations.

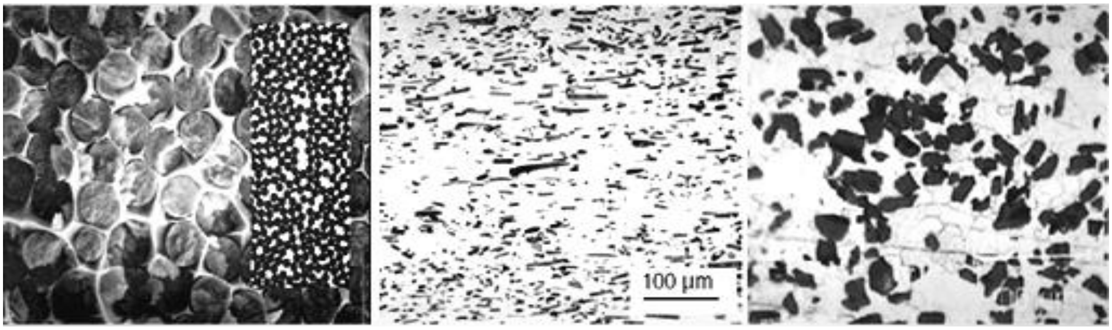

Fig. 2: Microstructural images of fiber, whiskers, and particulate-reinforced MMCs [16].

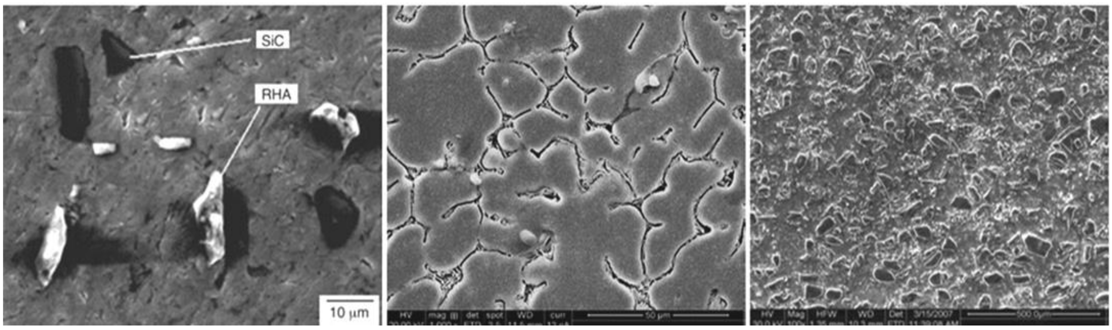

Fig. 3. Hybrid MMC microstructure [10].

reports on retrospective research of hybrid metal matrix composites. These include looking back at the materials, production processes, and mechanical, physical, wear, and corrosion properties of hybrid metal matrix composites.

LITERATURE REVIEW, PREVIOUS RESEARCH

Materials for hybrid MMCs

This section summarises the literature review on the materials (matrix and reinforcement phases) used to fabricate hybrid reinforced MMCs. The properties of hybrid MMCs depend on the choice of composing phases; therefore, selecting base material and reinforcement materials is critical to improving matrix alloy qualities.

MMC matrix materials

Many studies have been taking place to ascertain the MMC matrix and reinforcing materials [20]. As a result, the most common materials used to produce MMCs are aluminium, titanium, magnesium, copper, nickel, cobalt, and its alloys [21]. Among them, aluminium and its alloys were the most suitable material for manufacturing MMCs due to their low density, high thermal and electrical conductivity, and increased corrosion resistance [22]. The 6xxx alloy offers excellent machinability, thermal conductivity, extrudability, and corrosion resistance [23]. To improve the mechanical, thermal, and seizure resistance of mono-reinforced MMCs, B_4C and SiC particles are preferred reinforcement materials [24–26]. In the case of hybrid reinforced MMCs, TiB_2 helps improve the composites' wear resistance [27].

However, adding dual reinforcing components to the matrix alloy increased mechanical qualities while lowering production costs and weight [28]. Table 1 summarises the fundamental properties of various matrix alloys with varying reinforcement and casting processes. The choice of matrix and reinforcing materials for hybrid MMCs is crucial for engineering demands [29, 30]. Typically, hybrid MMCs consist of at least three ingredient compositions: a metallic alloy and two reinforcements in various forms bonded at the atomic level in the composite [31].

Hybrid reinforcements for MMCs

The most prevalent hybrid MMC reinforcing materials are split into two categories: continuous and discontinuous. Al_2O_3, SiC, and carbon fibres are commonly used in hybrid Continuous Reinforced MMCs (CRMMCs). However, hybrid CRMMCs have limited uses due to high production costs and mechanical anisotropy. Compared to hybrid CRMMCs, hybrid DRMMCs showed a considerable gain in mechanical isotropy at a lower cost. These hybrid DRMMCs are further categorised into three groups according to the size of the hybrid reinforcements: Micron-scale Hybrid Discontinuous Reinforcements (MHDRs), Nano-scale Hybrid Discontinuous Reinforcements (NHDRs), and Multi-Scale Hybrid Discontinuous Reinforcements (MSHDRs).

The most commonly employed hybrid micron reinforcements in hybrid DRMMCs are micron-sized hybrid SiC and Al_2O_3 particles [48]. The nanohybrid DRMMCs are reinforced with two or more discontinuous nano-materials, such as hybrid CNT and graphite nano-platelets or hybrid CNT and nano-size SiC particles [49]. Adding hybrid micron and nano-scale reinforcements to hybrid DRMMCs produces multi-scale hybrid DRMMCs [50, 51].

The customized material properties of multi-scale hybrid DRMMCs can be realized by selecting various combinations of matrix alloys and hybrid reinforced particles. The ability of MSHDRs to balance ductility and strength in MMCs has also been demonstrated in previous work [52]. Carbon-based reinforcing components such as graphite particles, carbon nanotubes, and graphene nanoparticles have self-lubricating capabilities that improve the physico-mechanical, wear, and corrosion properties of hybrid MMCs [53]. The processing techniques required to produce various hybrid MMCs by reinforcing different hybrid reinforcement materials will be addressed in detail in the following sections.

Hybrid MMC processing techniques

Hybrid MMC processing techniques can be categorized into two categories: primary processing and secondary processing. Primary processing refers to the series of operations fabricating hybrid MMCs to turn their raw materials into hybrid composites. It primarily entails incorporating hybrid reinforcements into the matrix alloy at the suitable content and achieving proper bonding between the constituents of hybrid MMCs. Secondary processing of hybrid MMCs refers to the additional steps required to transform the primary processing composite into the desired shape, size, and microstructure.

Primary processing techniques for hybrid MMCs

The physico-mechanical, thermal, wear, and corrosion properties are fundamental and most desirable comprehensive characteristics of hybrid MMCs. To attain all these characteristics, achieving a homogenous distribution of hybrid reinforcements, interfacial bonding between the matrix phase and reinforcement phase, and

Table 1: Significant findings on various matrix alloys with different reinforcement and casting methods.

Composite constituents	Size	Processes	Significant findings	References
AA7075/SiC/Al_2O_3 hybrid MMCs	-	Stir casting	The results indicate that increasing the string speed to 550 rpm and the temperature to 800^{0}C overcomes the wettability and non-homogeneous dispersion issues while adding hard reinforcements increases the composite's strength and hardness but not its impact strength.	[32]
Pure Mg/SiC/Al_2O_3 hybrid MMCs	16-100 grit size	Powder metallurgy	The density of hybrid composites increased before and during the sintering process when adding the higher density reinforcing materials.	[33]
AZ31/Al_2O_3/SiC	-	Powder metallurgy	Aluminium oxide and silicon carbide were added to the matrix alloy to enhance hardness and used 2% stearic acid (CH3 (CH2) 16COOH) to generate magnesium MMC green compacts.	[34]
AA6061/B_4C	10 µm	Stir casting	Due to the low wettability of B_4C with Al matrix, the addition of K2TiF6 flux enhanced the wettability. The hard surface area of B_4C particles provides more excellent resistance to plastic deformation, increasing the hardness of composites.	[35]
Magnesium/TiC/MoS_2 hybrid MMCs	55 µm 25–35 µm 10–20 µm	Powder Metallurgy	The magnesium hybrid composite containing 10% TiC and 5% MoS_2 showed the most remarkable improvement in tribological behaviour.	[36]
AA 7075 / SiC / Al_2O_3 / fly ash	53 µm 53-106 µm	Stir casting	Porosity scales in hybrid MMCs occur due to air bubbles in liquid metal, particle feeding time, and surface area interaction with the atmosphere.	[37]
Mg/SiC/Gr hybrid MMCs	35-40 µm 20-25 µm	Powder Metallurgy	CoF was reduced due to Gr's solid lubricant feature and increased with SiC particles. Moreover, Gr solid lubricant content in matrix alloy should not exceed 5%.	[38]
Mg/Ceric Ammonium Nitrate (CAN) based MMCs	-	in situ	In-situ reinforcements of ceramic particles in Mg alloy improved the mechanical properties of Mg-based MMC.	[39]
Mg/SiC/Al_2O_3 hybrid MMC	20 µm	Stir casting, FSP	FSP improved the mechanical and wear properties of Mg-based hybrid MMC than stir cast hybrid composites.	[40]
Al/TiC composites	325 mesh size (Al powder) 10 µm (TiC)	Hot consolidation technique	The mechanical properties of Al/TiC MMCs were enhanced, and the resulting composite was suitable for structural and industrial use.	[41]
Al-TiC MMC	-	In-situ: stir casting	The carbon-bearing activated charcoal powder was added to the Al-Ti melt at 1200^{0}C to form TiC particles. The wear rate of Al/TiC MMC decreased with TiC % increased.	[42]
Cu/Al_2O_3 surface composites	20 µm	FSP	Adding Al_2O_3 particles raises the copper matrix's recrystallization temperature and the mechanical characteristics of CASCs.	[43]
Al6061/SiC/B_4C	100 µm (Al 6061) SiC & B_4C (8 µm & 10 µm)	Powder metallurgy	The PM processing method could not achieve homogenous dispersion of reinforced particles, and the agglomeration of reinforced particles was visible in hybrid composites, as seen in Fig. 4.	[44]
Ti/B_4C MMC	75-180 µm (Titanium Grade 1 powder) & 45-75 µm (B_4C)	Additive layer manufacturing	The author found that Ti-based MMCs processed with ALM have better strength and young's modulus than pure Ti alloys.	[45]
AA2024/Al_2O_3/SiC hybrid MMC	10 µm, 20 µm and 40 µm	Squeeze casting technique	The mechanical properties and seizure resistance of 10 µm hybrid SiC and Al_2O_3 particles were significantly improved.	[46]
Ti-6Al-4V/ TiB_2 powder MMC	100 µm (Ti-6Al-4V) 10 µm (TiB_2)	Direct energy deposition method	Based on mechanical qualities and SEM images, the author showed that direct energy deposition is a promising additive manufacturing process for creating MMC with homogenous reinforcement dispersion.	[47]

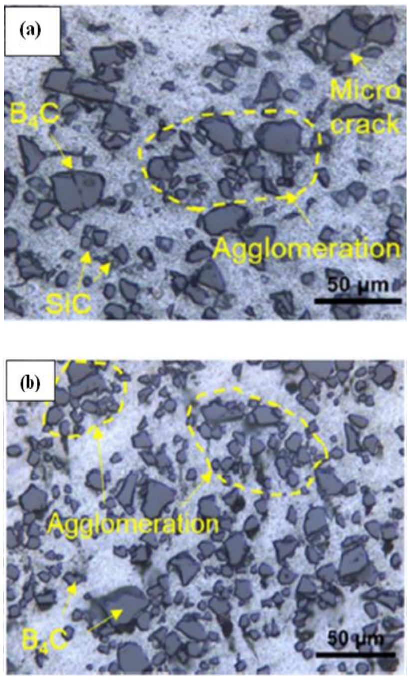

Fig. 4. Agglomeration of reinforced particles in hybrid MMC [44].

structural integrity of hybrid reinforcements is likely to be an essential aspect in fabricating hybrid MMCs. As a result, many manufacturing procedures have been developed over the decades to fabricate hybrid MMCs. As per the methods available to incorporate the hybrid reinforcements into the matrix alloy, primary processing methods are categorized into ex-situ and in-situ processing routes, as indicated in Fig. 5. In addition, a revolutionary processing technology called additive manufacturing is becoming more critical in today's industries for producing hybrid MMCs, as mentioned in the following sections.

Ex-situ processing route

In the ex-situ technique, the reinforcements are prepared separately and then added to the metal matrix, with no chemical reaction between the reinforcing phase and the matrix phase. At the same time, in the in-situ technique, the reinforcement phase is formed through a chemical reaction within the metal matrix [54]. Ex-situ synthesis is the most preferred method for large-scale industrial applications over in-situ processing [55]. The processing routes available in the ex-situ technique are also suitable for most of the in-situ processing routes.

The processing methods such as infiltration, squeezing, and stir casting are most frequently and commonly utilized in liquid-state processing techniques [56, 57], whereas, in solid-state processing, diffusion bonding, powder metallurgy, and FSP are viable processes. In the solid-state processing method, the development of MMCs is due to the mutual diffusion of the matrix and dispersed phase under adequate pressure at high temperatures.

(a) Squeeze casting

Squeeze casting is an ex-situ liquid-state processing technology designed to overcome the limitations of classical casting. It combines forging and a typical casting process to fabricate MMCs. The development of this process is to provide pressure-induced liquid metal solidification, removing casting defects like porosity while maximizing heat flow rate.

It is the most widely used efficient production process for Al and Mg-based MMCs in the fabrication of automotive parts. As seen in Fig. 6, combining the reinforcement and matrix phases with pressure involve four processes.

In order to produce high-quality composites, the following process parameters must be controlled: mold and die temperatures, squeezing pressure time, melt pouring temperature, and melt pouring speed. So far, there have been no optimal process parameter settings to control composite quality [58, 59]. In this process, the base material and reinforcement phase can react chemically, which makes it challenging to create a uniform distribution of reinforcement phases.

However, many authors documented the fabrication of MMCs using the squeezing casting process to assess the characteristics of squeeze-cast MMCs. For example, Zhang XN et al. used the squeeze cast process to fabricate Al-based hybrid SiC whiskers and nano SiC particle composites with high strength and elastic modulus. Similarly, *Muraliraja R et al.* showed the distribution of reinforcement and casting faults in squeeze-cast MMCs [61]. Fig. 7 shows the squeeze cast AA-based mono and hybrid reinforced MMC.

(b) Infiltration method

It is the most widely used liquid-state processing method for hybrid Al/Mg-based MMCs [64]. This approach has two primary stages: making a porous

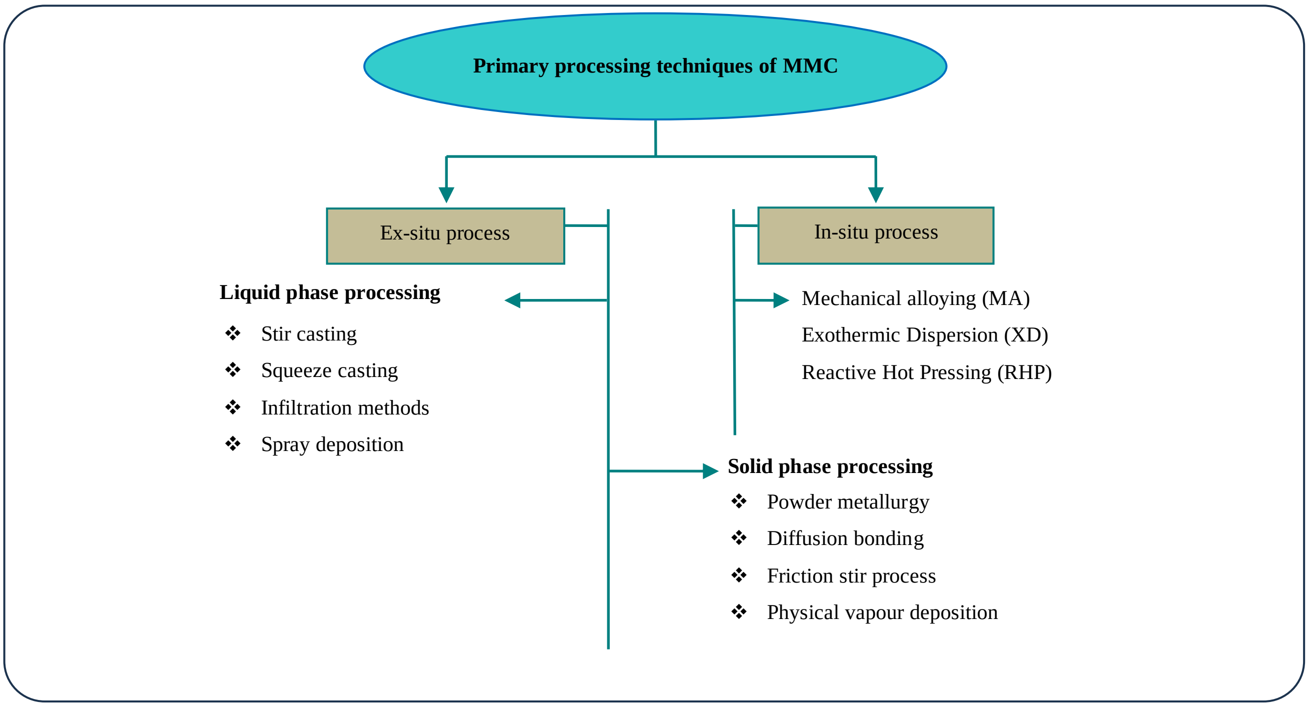

***Fig. 5:** Classification of hybrid MMC fabrication methods.*

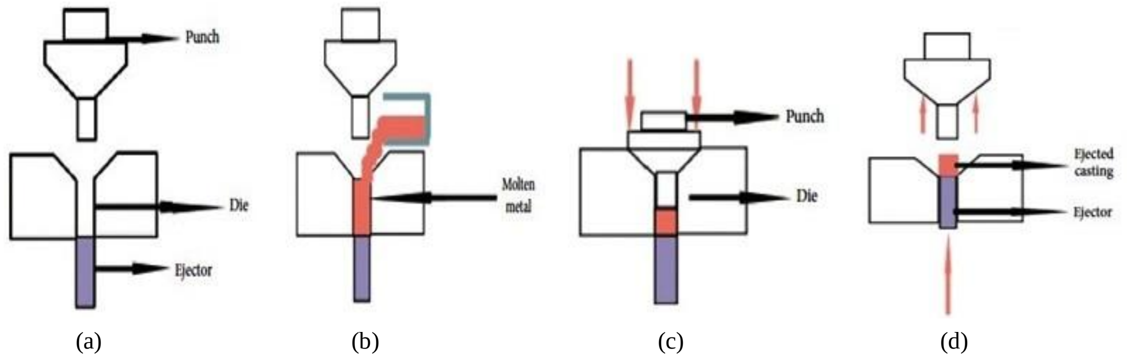

***Fig. 6:** Squeeze casting process (a) 1st step, preheat the die set (b) 2nd step, pouring the molten metal into die cavity (c) 3rd step, solidify molten metal under pressure and (d) 4th step, ejection of casting [60].*

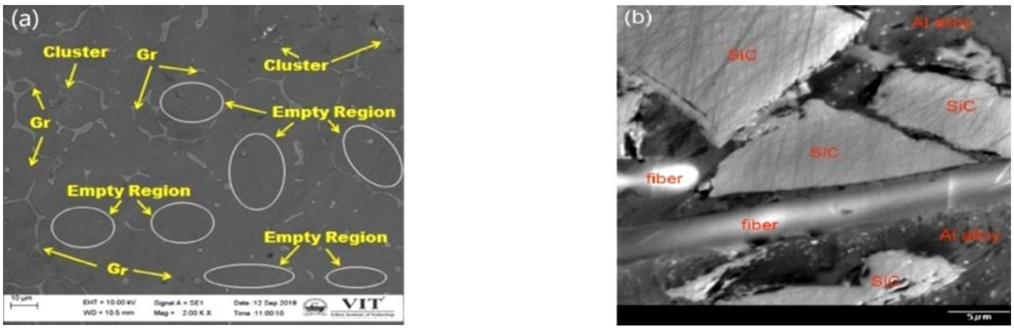

***Fig. 7:** SEM micrographs of squeeze cast composites (a) AA 2024/Gr MMC[62] (b) A319/AZS fibre/SiC hybrid MMC [63].*

pre-form of hybrid reinforcements and infiltrating molten alloy into the pre-forms to produce hybrid composites. This process is classified into three types based on the source of external forces: gravity infiltration, pressure infiltration, and vacuum infiltration [65]. This technique's fundamental strategy is overcoming the poor wetting property of molten metal and the hybrid pre-formed phase [66]. However, this approach has a lower ductility in prepared MMCs [67] due to the increased reinforcement additions.

(c) Stir casting route

Stir casting is the most suited traditional and economical technology for fabricating particle reinforced MMCs [68–70] due to its simplicity, flexibility, proven procedure, low manufacturing cost, and mass production application. In stir casting, mechanical stirring is used at the liquidus state to reduce the sedimentation of reinforced particles by their higher density and increase the reinforced particles' dispersion [71]. In general, non-homogeneous particle dispersion is one of the most challenging aspects of casting metal matrix composites.

A mechanical stirrer was used to stir the melt in order to tackle the difficulties of non-homogeneous particle distribution and surface energy barriers. The stirring speed, stirring time, pouring temperature, wetting elements, reinforcement preheat temperature, and mould are critical process factors in the stir casting route [72–74]. However, proper coating on hybrid reinforcement particles led to attain adequate wetting and uniform distribution of hybrid particles in liquid metal because stir cast process parameters are insufficient to improve the impression of hybrid particles in the liquid metal and the mechanical properties [75].

Further, the production technique and reinforcement size also affect composite properties [76]. Thus, this method has been successfully used to manufacture hybrid reinforced MMCs based on aluminium [77], Mg [78] and Cu [79]. For example, Boppana SB et al. discovered that increasing the amount of hybrid reinforce particles increased the ultimate strength, yield strength, hardness, and elongation property of hybrid MMCs [80]. Similarly, *Sozhamannan GG et al*. found that 750^{0}C to 800^{0}C at 20 minutes holding time was the best parameter for achieving sufficient wetting and homogeneous dispersion of the ceramic particles [81]. Additionally, adding 1.5 % magnesium as a wetting agent to Al/SiC/fly ash hybrid MMCs [82] improves the bond strength of hybrid reinforcements with aluminium alloy. Fig. 8 depicts the SEM, and optical microstructures of a SiC/RHA/Fly ash/Al_2O_3/Gr reinforced Al-MMC.

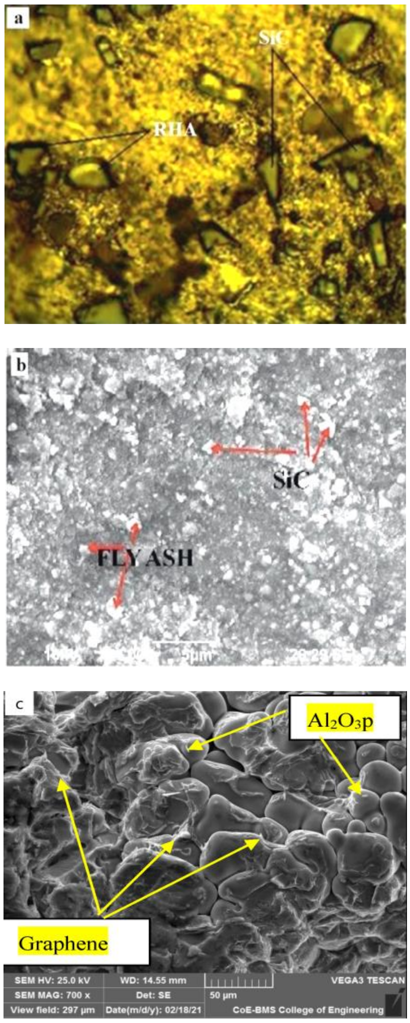

Fig. 8. (a) OM image A356.2/SiC/RHA hybrid composite [83] (b) SEM image of Al6061/SiC/fly ash hybrid composite [84] (c) SEM image of Al6061/Al_2O_3/Graphene hybrid composite [80].

(d) Diffusion bonding

In solid-state processing techniques, it is a widely used fabrication method for long fibre or sandwich composites. When sufficient heat and pressure are applied, MMCs are formed by the diffusion of components, causing them to adhere securely together. The main advantage of this processing technology is the ability to process a wide range of materials and have extensive control over fibre

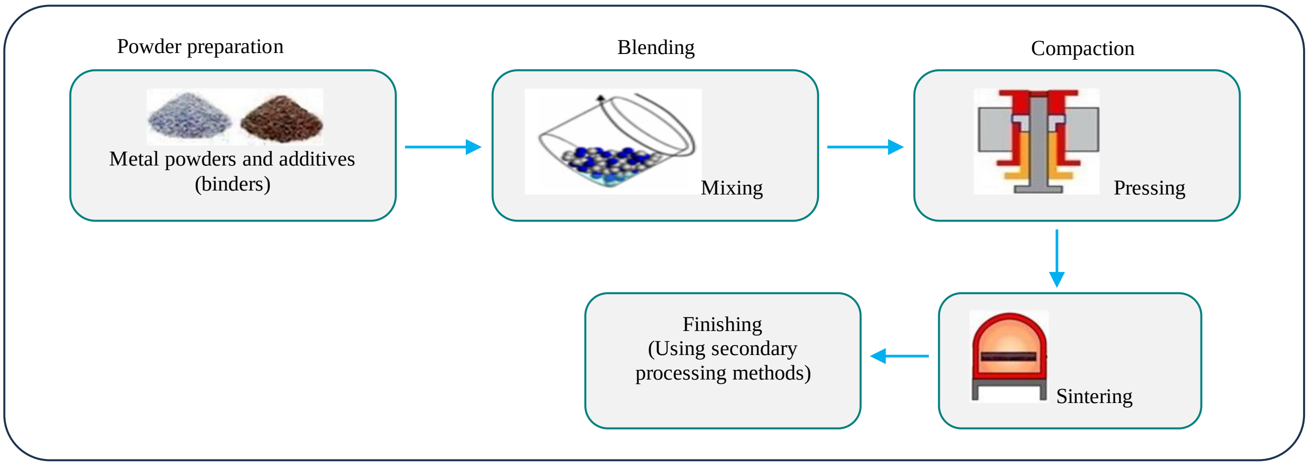

Fig. 9: Process steps involved in powder metallurgy route.

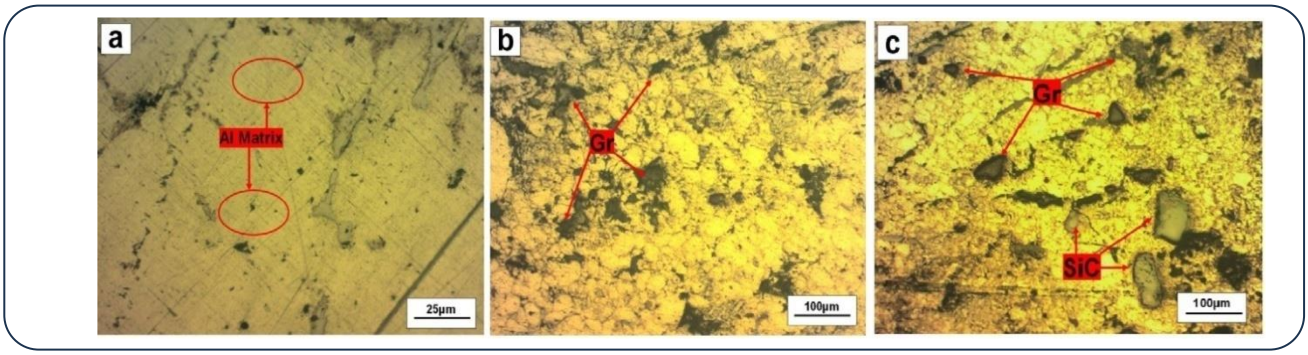

Fig. 10: Hybrid graphite (Gr) and SiC particles reinforced Al based MMC.

material's orientation and volume content in the matrix phase. The combination of controlled process parameters allows excellent bonding between the matrix and dispersed phases [85].

(e) Powder metallurgy

Powder metallurgy is the study of synthesising MMCs from alloyed powders with or without the introduction of ceramic elements, in which powder materials are blended, compacted, and sintered to bond the surfaces [33]. It is the most extensively used and preferred method, particularly in the fabrication of hybrid MMCs, due to its simplicity, adaptability, and flexibility. As shown in Fig. 9, this process requires three phases to fabricate a composite [86–88].

The primary benefit of the PM route is that there is no chemical reaction between the constituents of MMC powders. It produces products with the highest degree of dimensional accuracy. In some instances, secondary processing techniques such as rolling, polishing, and grinding may be required to create completed hybrid MMC products. However, due to the chemical hazardous of powders [89], this route is limited to use for large-scale production. Fig. 10 shows the SEM image of a fabricated hybrid MMC using the PM route. In addition, *Megahed et al.* stated that the extrusion process reduced the porosity defect in PM route after the cold compaction and sintering process [90]. Compaction pressure, sintering duration, and sintering temperature are crucial process parameters in the production of sound composite [91, 92].

(f) Friction stir process

The friction stir process is a unique method of severe plastic deformation that was created as a scrap-free advanced green manufacturing approach with numerous metallurgical and environmental advantages over orthodox manufacturing methods [94]. The FSP method uses tool rotation to disperse hybrid reinforcement particles in matrix alloy uniformly. FSP, in particular, is a solid-state processing method evolved from the modified friction stir welding method [95]. Furthermore, the FSP approach is better for fabricating particle-reinforced surface composites. Fig. 11 shows a schematic design

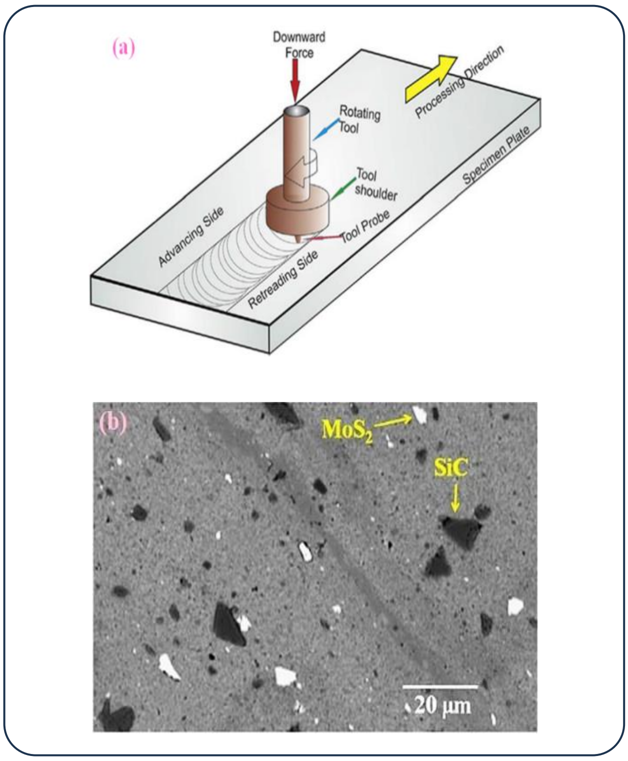

Fig. 11: (a) Friction stir processing method [96] (b) A356 hybrid composite developed by using FSP method [97].

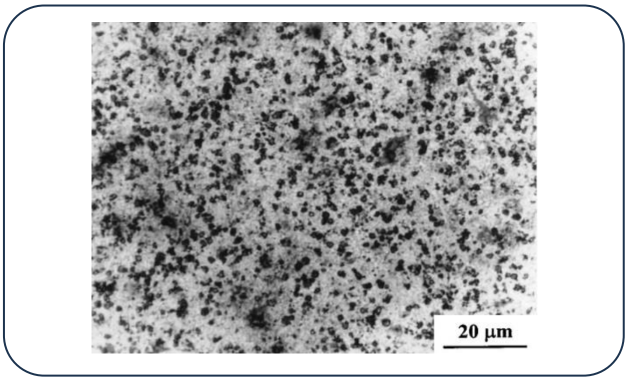

Fig. 12: Optical image of composite prepared by using RHP in-situ method [104].

of the FSP approach and an SEM image of a produced hybrid composite.

For many years, a lot of research works on the development of hybrid MMCs using the FSP method have been chronicled by many authors. For example, particle agglomeration's tendency to produce composites can be significantly reduced by selecting an appropriate FSP tool shoulder diameter [98]. To provide a homogeneous distribution of reinforced particles in composite manufacturing, drilling holes in matrix alloys yields effective results and eliminates the possibility of particle agglomerations [99].

In-situ processing route

The in-situ preparation of hybrid MMCs uses mainly the chemical reaction between the elements to form hybrid reinforcements within the matrix alloy. For preparing hybrid MMCs, in-situ methods have three distinct advantages over ex-situ methods, including:

(i) the process is thermodynamically stable at the interfaces of the composite constituents.

(ii) the process achieves good interfacial bonding between in-situ reinforcements and matrix phase; and

(iii) the process achieves a more homogeneous distribution of hybrid reinforcements when compared to ex-situ reinforcements.

Therefore, due to these benefits, the in-situ hybrid MMCs exhibit superior mechanical characteristics, are free of contaminations in reinforcement surfaces and have the excellent ability for vast applications. The in-situ reinforcement process can be classified into three techniques [100] such as Mechanical Alloying (MA) [101], Exothermic Dispersion (XD) [102] and Reactive Hot Pressing (RHP) [103]. The optical image of the prepared composite using the RHP in-situ method is shown in Fig. 12. In addition to the above ex-situ and in-situ techniques, a unique method for fabricating hybrid reinforced MMCs has been developed, such as additive manufacturing.

Additive manufacturing

The Additive Manufacturing (AM) technology for producing hybrid MMCs has recently gained a lot of interest in the current engineering sectors [105, 106]. Additive manufacturing, also referred to as 3D printing, is a process that converts a three-dimensional design into a physical object. Once the 3D design file has been cut into thin layers, the design is sent to an additive manufacturing machine to manufacture a three-dimensional object. Once a very thin layer of metal powder is dispersed on the platform, the manufacturing process begins. The first layer of 3D design is melted in a powder bed using a laser or electron beam. The platform has been loaded, and another layer of metal powder has been spread across it. The layering and lancing process is thermal until the part is finished. The metallic powder melts, revealing the physical object beneath.

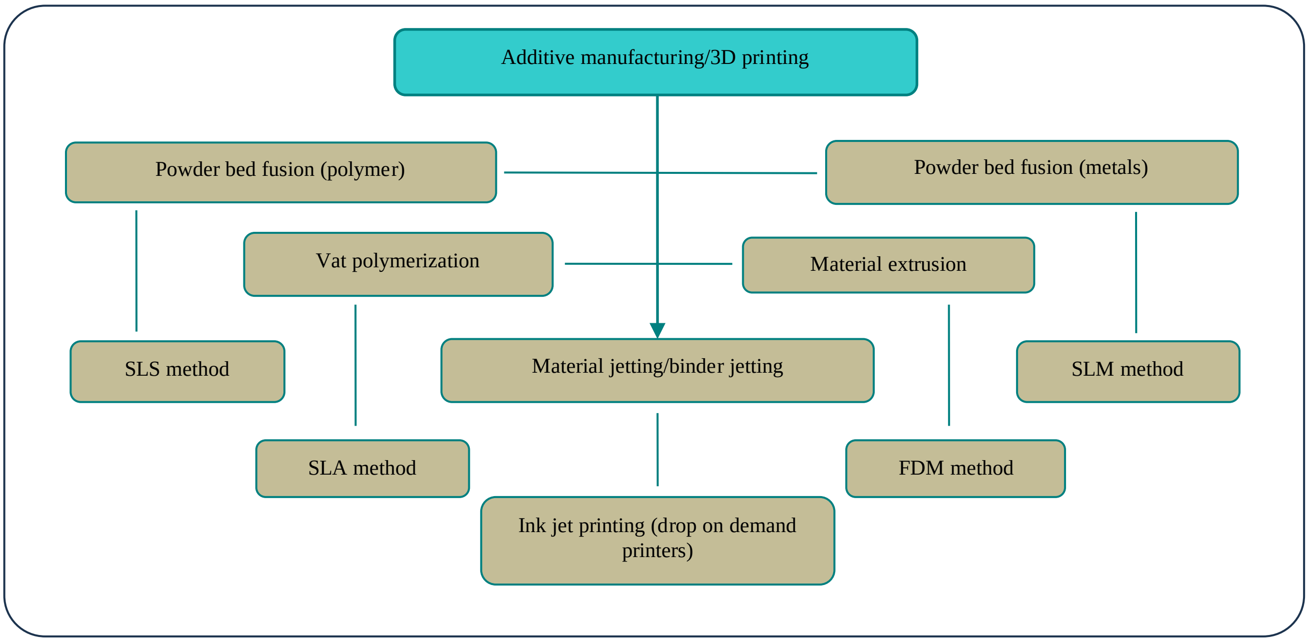

Fig. 13: Classification of AM processes.

Additive manufacturing is primarily used to create parts that are lighter, stronger, and have a more complicated shape than typically manufactured parts [107]. AM is revolutionising industrial production due to benefits such as high design flexibility, high customisation, energy savings, reduced inventory stock and material waste, no need for moulds, and the ability to precise features without increasing cost [108, 109]. The ASTM 52900 standard defines AM procedures based on material type, deposition technique, and material fusion or solidification [110, 111].

As shown in Fig. 13, five basic working principles [112–114] are commonly used to describe AM processes. These includes Selective Laser Sintering (SLS), Selective Laser Melting (SLM) [115], Laser-Melting Deposition (LMD) [116], Fused Deposition Method (FDM) [117, 118], Stereolithography (SLA), Direct Inkjet Printing (DIP), Layer-wise Slurry Deposition (LSD) and Laminated Object Manufacturing (LOM) [119–122] methods. According to Behera MP et al. [123], selective laser melting was the most promising method for fabricating MMCs with higher corrosion, fatigue, and wear resistance [124]. Similarly, author *Li J et al.* suggested a new technology called Ultrasonic Additive Manufacturing to produce multifunctional metal matrix composite structures with embedded printed electrical components [125].

Physico-mechanical, tribological and corrosion properties of hybrid MMCs

The physico-mechanical, tribological and corrosion behavior of hybrid MMCs may be anticipated based on the type, orientation, size, and form of the reinforcements in the matrix alloys. In determining the characteristics of MMCs, the intrinsic qualities of constituents, structural arrangement, and the contact between the constituents would all play a significant role. Apart from these characteristics, a few more significant parameters strongly influence the properties of hybrid MMCs, such as volume per cent and homogeneity of reinforcement, as well as the microstructure of the system.

In many engineering applications, there is a long list of attributes acquired in materials for satisfying the current demands: tensile and impact strengths, hardness, compressive strengths, thermal, seizure and corrosion resistance. Therefore, many previous publications have been analyzed to determine the effect of various reinforcements on different matrix alloys for enhancing the hybrid MMCs properties. The major contributions of various reinforcements on tribo and physico-mechanical and corrosion properties of different matrix alloys are summarised in Table 2 and Table 3.

Aluminium alloys and aluminium-based composites are the most widely used materials [126–129] due to their corrosion and metallurgical qualities and recycling potential for high-performance industries. The volumetric range of reinforcing elements in aluminium MMCs was up to 70% to improve alloy properties. While magnesium alloys and composites have also proven to be appealing as a new class of engineering material due to their lightweight, high strength, improved corrosion resistance, and low thermal coefficient of expansion. Due to these attributes, magnesium composites are also used in the automotive industries and achieve lower CO_2 emissions [130]. Furthermore, if it is used for low-weight airframe structures in aerospace sectors, it would become an innovative technology [131, 132]. In addition, reinforcement of CNTs in the magnesium alloys improved the wettability and bonding strength of the composites [133].

Regarding physical qualities, density and porosity were often utilized parameters for material selection. Thus, the density of composites can be computed using the rule of the mixture and the Archimedes principle [134]. The mechanical qualities of any material are usually determined by its relative density and porosity. In casting, porosity is assessed by comparing theoretical and actual densities [135]. The non-wettability, shrinkage, long particle feeding, poring time, temperature and pressure, gas entrapment, clustering of particles and hydrogen evolution are the reasons to cause porosity defects in hybrid composites [83]. In addition, the density of hybrid MMCs would also depend upon the volume content, nature, form and size of the reinforcement particles [136]. In generally, hardness measurements of hybrid MMCs have been performed in two different positions to test the potential effect of an indenter on the firmer elements, with an average of two results [137].

According to *Kumar K.R. et al*., the higher resistance to dislocation movement and lower density coarse particles in the matrix alloy has increased the tensile strength, hardness, and density of A380 reinforced with fly ash MMC [138]. This inference can be observed in Fig.14 (a, b & c). Similarly, *Mittal P et al.* [139] reported that introducing graphite particles in addition to Al_2O_3 particles in copper-based hybrid MMCs reduces the density and hardness qualities because graphite acts as a solid lubricant, softening the matrix alloy. Another possible reason for the decrease in density is the substantial density difference between graphite and copper alloy. In the case of density and porosity of hybrid rice husk ash and SiC

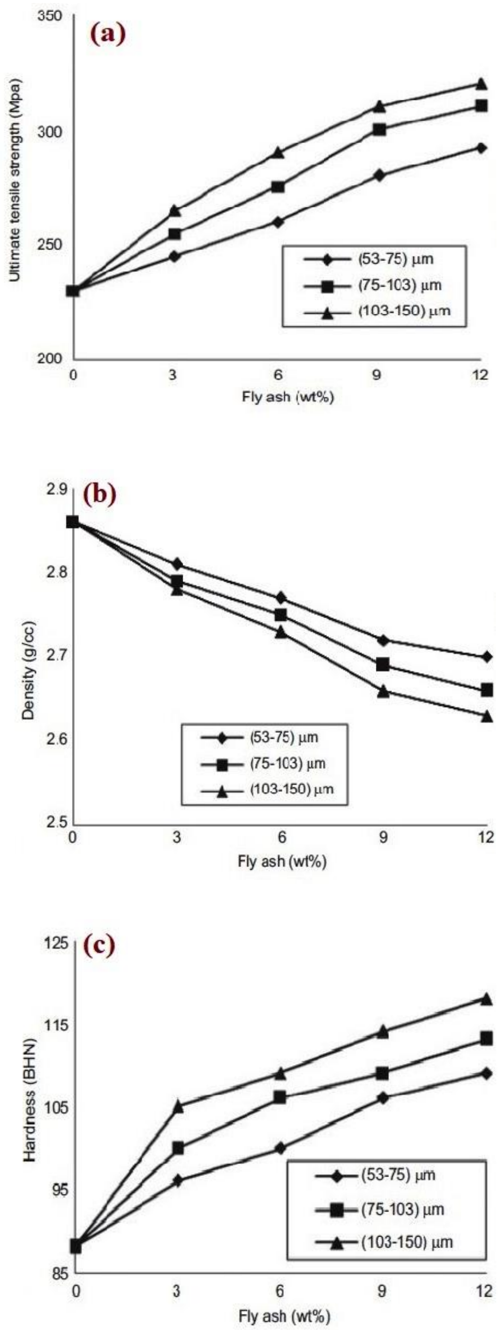

Fig. 14: Mechanical characteristics of fly ash reinforced composites [14].

particulate reinforced MMCs, the decreasing density was mainly due to the presence of low-density rice husk ash and SiC particulates in aluminium alloy. The gas entrapment during mixing, hydrogen evolution and air bubbles entering the slurry are the reasons to increase porosity, and this inference may be seen in Fig. 15a.

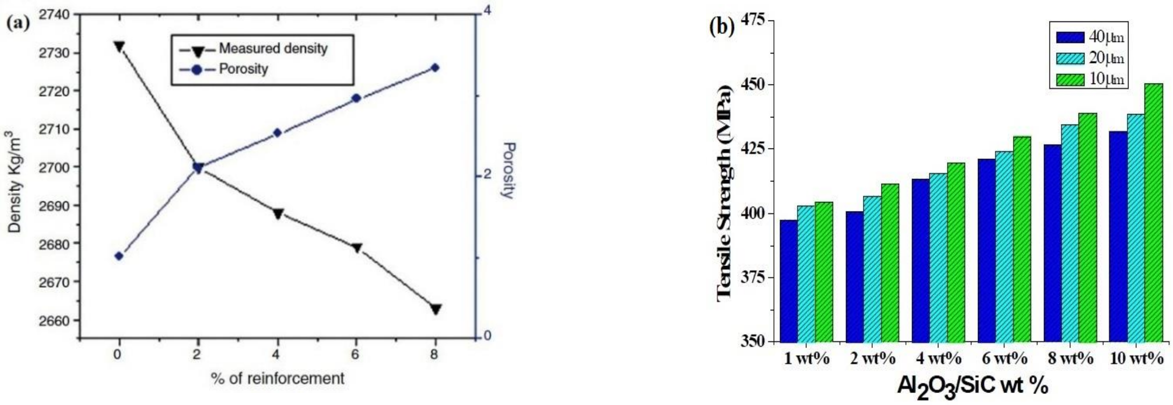

Fig. 15: Effect of hybrid reinforcements (a) density-porosity of hybrid MMCs [83] and (b) tensile strength of hybrid MMCs [46].

As we all know, primary reinforcements such as ceramic particles are extremely hard in nature, less dense, and temperature resistant. As a result, it has no deformation behaviour at high temperatures and pressures. In contrast, secondary reinforcements such as fly ash, rice husk ash, copper, and graphite, among others, can easily deform. According to Fig. 15b, the tensile strength of hybrid MMCs increased with increasing reinforcement content and decreasing particle size. It is simply due to the addition of hard ceramic particles to the ductile matrix alloy, but it dramatically reduces the ductility and elongation per cent of hybrid MMCs [46]. Similarly, including alumina, SiC, and B_4C particles improved aluminium alloy's hardness, yield strength, and tensile strength properties while decreasing ductility.

Furthermore, adding SiC to the ductile matrix creates a strong interface bond with the matrix, improving hybrid composites' mechanical properties [140]. The inclusion of hard ceramic particles/fibres into a ductile titanium matrix considerably increases its hardness, related to the volume percentage of ceramic reinforcement [141]. Furthermore, *Ma X. et al*. [142] found that tensile stress can efficiently transfer to reinforcement materials because of the atomic bonding surfaces between the reinforcement phase and matrix phase. Therefore, the Al/AlNp Metal Matrix Composite (Al/AlNp MMC) can sustain extreme stress without developing a crack. However, *Reddy P.V. et al*. [143] observed that with the limited interface in hybrid composites, the toughness of the composite decreased without affecting the wear and hardness properties. Furthermore, infusing MWCNT and micron-sized SiC particles into magnesium hybrid MMC improves the mechanical properties [144].

Additionally, *Griffiths R.J. et al.* [145] presented an additive friction stir procedure, also known as MELD manufacturing process in additive manufacturing, for enhancing the characteristics and minimising porosity and non-homogeneous dispersion of reinforced particles in MMCs. According to the review findings, *Das D.K. et al*. concluded that the compressive strength of ceramic reinforced aluminium composites improved as the reinforcement per cent and strain rate during compression increased [146].

However, as the fly ash percentage of stir cast composites increases, the problems of agglomeration and flaws rapidly increase [147]. Adding hybrid fly ash and alumina to matrix material significantly enhances the mechanical characteristics while maintaining density reduction [148]. According to *Senapati M.R.*, over 90 mt of fly ash is generated annually in India, which is significantly responsible for environmental degradation [149]. Even though fly ash is pollution, it is a critical raw material for various purposes. The efficient use of fly ash in several industries can contribute significantly to developing new technologies [150]. However, by incorporating fly ash as a reinforcement material into aluminium alloys, the energy content, material content, cost, and weight of chosen industrial components are reduced, while the selected qualities are increased.

Today, tribological and corrosion properties are critical for material application, as wear occurs due to relative motion between two surfaces under various service conditions. In contrast, corrosion occurs due to material dissolution, leaching, and chemical reaction with the environment. There are various types of wear processes

Table 2: Influence of various reinforcing materials on physio-mechanical properties.

Composite constituents	Size	Significant findings (Mechanical and physical properties)	References
A356/fly ash/Al_2O_3	100 µm	Hybrid reinforcements have improved mechanical and density qualities. Using of fly ash as a single reinforcement reduced the density and enhanced the mechanical properties.	[151]
AA 6082/SiCp /Al_2O_3/flyash	53 µm, 53-106 µm	The mechanical and physical properties of hybrid MMCs were improved by mixing hard ceramic particles with fly ash.	[152]
A356.2/RHA/SiC	25 µm (RHA) 35 µm (SiC)	Increasing the reinforcing percentage reduces density but increases the porosity and hardness of the hybrid composite.	[83]
Al6061/Al_2O_3/MoS_2	-	Increasing the alumina particle weight %, improved the mechanical qualities of hybrid composites.	[153]
Al-4%Cu-2.5%Mg matrix/SiC/Al_2O_3	18 µm–40 µm	The Al_2O_3 reinforced composite has higher elongation than the SiC reinforced composite. Adding SiC and alumina reinforcements further enhances the material's proof stress, tensile strength, elastic modulus, and hardness while preserving low porosity.	[154]
AA5083/Fly ash/SiCp	400 µm & 6 µm	Adding fly ash and SiCp reinforcement particles increases composite mechanical and tribological characteristics.	[155]
Aluminum alloy/SiC/Al_2O_3/fly ash	53 µm 53-106 µm	Adding SiC, Al_2O_3, and fly ash particles to aluminium hybrid MMCs improves their mechanical and physical properties.	[156, 157]
Al6061/WC/fly ash hybrid MMCs	2-3 µm	Liquid metal was degassed with dry hexachloroethane. Also, TiC reinforcement material has a more substantial effect on the mechanical properties of hybrid MMCs than fly ash reinforcement material.	[158]
Al356/fly ash/ Al_2O_3 hybrid MMCs	-	It is critical to pay close attention to the following aspects while fabricating MMC using the stir casting process: • Achieve homogeneous reinforcement distribution • Ensure wettability of composite constituents. • Reduce porosity in cast MMC • Avoid chemical reactions between the constituents.	[148]
Al6061-SiC/Graphite hybrid composites	37 µm (SiC) 1 µm (Gr)	The density of hybrid composites has decreased due to the inclusion of graphite particles, and the author has concluded that hybrid composites have higher tensile strength than mono reinforced composites.	[159]
Al7075/SiC/TiO_2 hybrid MMCs	50 µm	They concluded that SiC is the most influential parameter for achieving maximum possible values in tensile, hardness and impact properties.	[160]
Al7075/TiB_2/Gr hybrid composites	2-10 µm (TiB_2) 30-50 µm (Gr)	Incorporating TiB_2 and Gr particles into an aluminium alloy results in a brittle material with low ductility. Increasing the amount of graphite in the aluminium matrix also increases the hardness.	[161]
TiC/AlSi10 Mg nano MMC	-	The material's micro hardness and tensile strength qualities were improved using a selective laser melting technique without the casting errors that traditional processing routes created.	[162]
AZ31/SiC reinforced composites	53 µm	The inclusion of SiC reinforcement not only boosts the load-bearing capability of magnesium alloy but also minimises matrix deformation by limiting dislocation movement.	[163]

that can be classified according to the conditions under which they occur, including adhesive wear, abrasive wear, delamination wear, erosive wear, fretting wear, fatigue wear, and oxidative wear [53, 164]. The primary mechanism for higher loads and high sliding speeds is delamination, which shifts to abrasion when the wear situation changes to lower loads and low sliding speeds.

Usually, hybrid MMCs have a substantially higher wear resistance than their monolithic materials and mono MMCs. It is important to note that the wear loss of hybrid MMCs is highly dependent on intrinsic material properties and extrinsic wear testing circumstances. The intrinsic material properties are type of ductile matrix and reinforcements used, distribution state and size of reinforcements, as well as the matrix and reinforcement interfacial bonding and the extrinsic wear testing circumstances are applied loads and sliding speeds [165].

Furthermore, the presence of fly ash particles in hybrid MMCs reduces wear rate by forming pits surrounding the particles and increasing bulk hardness [166]. The addition of fly ash particles in mono MMCs reduces wear rate by limiting the deformation of the matrix alloy [138]. Similarly, the inclusion of graphite decreases the hardness and frictional coefficient of aluminium MMCs [167]. In addition, incorporating carbon-based materials into a ductile matrix can form a self-lubricating film during the sliding process, preventing direct contact between the sliding surfaces and reducing the ploughing effect of hard asperities, lowering the coefficient of friction and improving wear resistance [168].

In hybrid SiC and Al_2O_3 particle reinforced MMCs [169], wear parameters such as sliding distance and sliding speed have the largest impact on the wear rate. In wear behaviour analysis of hybrid composites, increasing the applied load increases the real contact area, which raises the wear rate and frictional coefficient of composites [170]. More precisely, the inclusion of ceramic particles in magnesium alloys can improve the wear resistance and frictional coefficient (CoF) of magnesium-based MMCs [171]. Most of the time, the hybrid reinforcing material acts as a barrier between the surface of the composite and corrosive media [172]. In general, galvanic corrosion between the composite constituents governs the corrosion behaviour of MMCs [173]. As regards the role of the fibre and carbon, results indicate that the most electrically conducting fibre and carbon produced the most marked galvanic effect, with corrosion occurring preferentially at the fibre-matrix interface.

CHALLENGES AND OPPORTUNITIES

There are many conflicts over the fabrication, capability, and usage of hybrid MMCs in present-day industries. Furthermore, there is serious concern about production cost, property prediction, and unavailability of design data, recyclability, reclamation, secondary processing capability, compromised ductility and toughness properties, as well as the enhancement of superior behaviours. Therefore, these are the few characteristics that limit the widespread adoption of hybrid MMCs.

- In order to achieve the homogeneous dispersion of hybrid reinforcements, atomic interfacial bonding, desirable properties and improved wettability between matrix phase and hybrid reinforcement phase without damaging any metallurgical characteristics, adequate emphasis has to be paid towards the understanding of mechanisms involved in various processing methods, control of process parameters, reinforcements role and development of new processing techniques [192]. Thus, there is a chance to produce hybrid MMCs without any compromising ductility, hardness, wear and toughness properties.
- Hybrid composite performances mainly depend on the shape, size, nature, orientation and volume per cent of reinforcements. Therefore, sufficient work must be done to fabricate lower-cost reinforcements and alloys to produce cost-effective hybrid MMCs with desired qualities.
- The corrosion behaviour of hybrid MMCs would be the main criteria for selecting these composites in many applications at elevated conditions over the mono reinforced alloys. The main reason for lowering the corrosion resistance in hybrid MMCs is due to the chemical degradation of reinforcement interface with matrix alloys and this can be avoidable through controlling the processing parameters and interactions between the interfaces.
- In addition to the above challenges, production of hybrid MMCs by reinforcing the industrial and agro wastes like fly ash, red mud, rice husk, sugarcane bagasse, palm oil fuel ash and coconut husk has attracted significant attention because disposal of these wastes has a biggest problem to the environment and human health. Therefore,

Table 3. Influence of various reinforcing materials on wear and corrosive properties.

Composite constituents	Size	Significant findings	References
FSPed AA6082/CaCO3	10–12 µm	Wear rate and CoF are directly proportional to each other, and the formation of a tribo mixed solid lubricant CaCO3 layer at the sliding surface has considerably reduced wear rate.	[174]
LM25/B_4C/Gr	25-75 µm	The addition of B_4C - Gr particles to the alloy improves hardness and wear resistance.	[175]
Al–Mg–Si alloy matrix/rice husk ash/SiC	50 µm 28 µm (SiC)	The addition of RHA and SiC hybrid reinforcement increased the corrosion and wear resistance of hybrid composites.	[176]
Al/Mg-based hybrid MMCs	-	Concluded that pin-on-disc tribometer and stir casting techniques were the best wear test analysis and fabrication methods for Al/Mg-based hybrid MMCs.	[177]
Al6061/SiC MMCs	150 µm	The SiC reinforced MMCs outperformed the matrix alloy wear resistance, density, and mechanical characteristics.	[178]
Al6061/SiC & Al7075/Al_2O_3 MMCs	20 µm	Al6061/SiC MMCs exhibit superior mechanical and tribological properties than the Al7075/Al_2O_3 MMCs.	[179]
Al2219/TiC particulate MMC	50-60 µm	Adding TiC particles to the matrix alloy improves MMC wear resistance and decreases wear rate compared to Al 2219 alloy.	[180]
Al6061/B_4C/Mica Hybrid Composites	70 µm & 3-10 µm (mica)	During the wear test, the secondary reinforcement, such as mica particles, acts as a solid lubricant between the two meeting surfaces, reducing the frictional coefficient.	[181]
Al/SiC/Mo reinforced MMCs	67 µm (SiC) 74 µm (Mo)	Mixing hard SiC and Mo particles into the matrix alloy increased the proposed hybrid MMC's wear resistance. In terms of wear resistance, hybrid composites surpass matrix alloy and SiC-reinforced composites.	[182]
Al/SiC/FA	53 µm (SiC) 53-106 µm (FA)	When a substantial load was applied to the aluminium hybrid MMC, a solid lubricating coating generated by fly ash material reduced wear loss and frictional coefficient.	[183]
Alumina-Al MMCs and SiC-Al MMCs	-	As a result of the stable inner oxide layer formed by Al2O3, SiC composites had deeper pits than alumina composites.	[184]
Al6065/SiC/graphite hybrid MMCs	-	Hybrid composites have better corrosion resistance than base alloys when tested using potentiodynamic polarisation and impedance methods.	[185]
Al/SiC MMCs	Al powder (60 µm) SiC (3, 6, 11 µm)	It was concluded that increasing the volume fraction and decreasing the size of the SiC particles improved the corrosion resistance of the Al/SiC composites.	[186]
AA7178/ZrB_2 MMCs	-	Adding ZrB_2 particles in Al alloy greatly enhances the corrosion resistance of MMCs through an accumulation of reinforcement particles.	[187]
A356/RHA/Al_2O_3 hybrid MMCs	100 µm (Al_2O_3) 75 µm (RHA)	Due to the inclusion of hybrid reinforcements, the corrosion resistance of A356 alloy has improved.	[188]
Al 7075/Al_2O_3/Gr hybrid MMCs	20-30 µm	In the corrosion study of proposed hybrid MMCs, Al2O3 particles serve as a physical barrier to the formation of corrosion pits, reducing the corrosion rate as well as the potential.	[189]
Cu/SiC/Gr hybrid MMCs	400 mesh (SiC) 60 mesh (Gr)	The additions of SiC and graphite particles to copper alloy increases the corrosion and wear resistance of hybrid MMCs because graphite particles provide a lubricating film and SiC particles cover the defect regions and prevent electrolytic solution attack on the specimen surface.	[136]
Al7075/mica/E-glass fibers hybrid MMC	-	The number of interfaces increased with mica, graphite, and E-glass fibre composition. Interfaces are the main cause of corrosion in composites. Composites, however, have more corrosion pits due to the increased number of interactions.	[190]
Cu/HSSS/WC hybrid composites	-	Stated that the proposed composite attains the improved hardness, tensile strength, and corrosion resistance due to the addition of HSSS reinforcements.	[191]

more researches must be done on recycling and using these wastes for the production of eco-friendly and low-cost hybrid MMCs [193].

• Along with the above challenges, the machinability of hybrid MMCs was a severe problem. Thus, the boundaries of hybrid MMCs have restricted to use of their capabilities in many engineering applications. Therefore, to overcome these challenges, new manufacturing methods must be discovered further to sustain the durability, reliability and machinability qualities of hybrid MMCs.

CONCLUSIONS

In this comprehensive review, the materials used for producing hybrid MMCs, processing techniques, and the Physico-mechanical, tribological and corrosion properties of the hybrid MMCs are all discussed in detail and summarised precisely. Based on the many research studies conducted for this review, inferences are drawn and listed in a set of consolidated tables. The following are some of the findings from the review study done on various aspects of hybrid MMCs:

(i) Among the various matrix alloys, extensive research has been conducted on aluminium alloys for the purpose of improving the fundamental properties of aluminium-based metal matrix composites, while very little research has been conducted on magnesium, copper, and titanium-based metal matrix composites.

(ii) Due to the impact of strong van der Waals forces and the inherent incompatibility of matrix alloys and nano reinforcement particles, it has been found that adding a smaller volume percent of nano particles always results in decreased strength in all classes of MMCs[9].

(iii) In majority of the discussions about hybrid reinforcements in MMCs, mono reinforcements were employed to improve the characteristics of matrix alloys. Regarding hybrid reinforcements, the multi-scale hybrid discontinuous reinforcing materials have been discovered to be identical reinforcing materials for increasing physico-mechanical, tribological and corrosion properties, as well as balancing ductility and strength in hybrid MMCs.

(iv) In terms of tribological and corrosion properties, secondary reinforcements such as graphite, fly ash, rice husk ash, and others improved the properties and behaviours of matrix alloys regardless of matrix material type and nature.

(v) After reviewing various fabrication works, two important manufacturing aspects can be highlighted: the powder metallurgy process is the most cost-effective process for manufacturing Mg/Ti alloy-based hybrid MMCs by maintaining a controlled level of porosity, whereas the stir casting process is also economical in mass production and more suitable for Al as well as Mg alloys.

(vi) It has been found that the stirrer material, stirring speed, and stirring time must be precisely selected during the stir casting process because it is difficult to achieve uniform particle dispersion in the matrix alloy.

(vii) In this conceptual review, it has been found that various studies have been performed on the preparation of hybrid MMCs through various conventional routes, including ex-situ and in-situ techniques, but hitherto very fewer studies have been published on the fabrication of hybrid MMCs by using additive manufacturing methods.

(viii) Based on the review related to the fabrication of hybrid MMCs, the following issues have been identified:

• Achieving more homogeneous or well-defined reinforcement dispersions, improving interfacial bonding, reducing residual stresses, avoiding crack formation at interfaces, dislocations, thermal mismatches between composing phases, and potential variations in the metal matrix were all ongoing research priorities.

• In classical processes such as stir casting and powder metallurgy, there is a chance of secondary phase reactivity with the melt or a tendency for settling during casting.

• Moreover, during solid and liquid state processes, the formation of reinforced phase agglomeration in the matrix must be prevented.

• In most cases, post-processing operations is required to achieve the final size and shape of the component, which increases the component production costs.

(i) As a result of all of these challenges and needs, it has been determined that additive manufacturing can be a suitable process to overcome many limitations imposed by traditional MMC processing methods.

A review of materials used, processing techniques available, and tribo-mechanical and corrosion properties of hybrid MMCs have been carried out in this journal. This review will define the scope and direction of research into developing hybrid MMCs for a specific application using multiple production techniques at low cost and with better attributes.

Nomenclatures

µm	Microns
^0C	Degree centigrade
$A1_2O_3$	Aliminium oxide
AA	Aluminium alloy
Al	Aluminium
ALM	Additive layer manufacturing
Al-Si	Aluminium-silicon
AM	Additive manufacturing
B_4C	Boron carbide
$CaCO_3$	Calcium carbonate
CAN	Ceric ammonium nitrate
CASCs	Copper-Alumina Surface Composites
CNTs	Carbon nano tubes
CoF	Coefficient of friction
CRMMCs	Continuous Reinforced MMCs
Cu	Copper
DIP	Direct inkjet printing
DRMMCs	Discontinuous reinforced MMCs
FA	Fly ash
FDM	Fused deposition method
FSP	Friction stir processing
Gr	Graphite
HSSS	Highly strained stainless steel
Hybrid MMCs	Hybrid metal matrix composites
K_2TiF_6	Dipotassium titanium hexafluoride
LMD	Laser-melting deposition
LOM	Laminated object manufacturing
LSD	Layer-wise slurry deposition
Mg	Magnesium
MHDRs	Micron-scale hybrid discontinuous reinforcements
Mo	Molybdenum
MoS_2	Molybdenum disulfide
MSHDRs	Multi-scale hybrid discontinuous reinforcements
mt	Million tones
NHDRs	Nano-scale hybrid discontinuous reinforcements
Physico	Physical
PM	Powder metallurgy
RHA	Rice Husk Ash
rpm	Revolution Per Minute
SEM	Scanning electron microscopy
SiC	Silicon carbide
SLA	Stereolithography
SLM	Selective laser melting
SLS	Selective laser sintering
TiB_2	Titanium diboride
TiC	Titanium carbide
TiO_2	Titanium dioxide
Tribo	Tribology
WC	Tungsten carbide
ZrB_2	Zirconium di-boride

Received : ; Accepted :

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