Advanced production routes for metal matrix composites

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Abstract

The use of metal matrix composites (MMCs) in a variety of products is significantly increasing with time due to the fact that their properties can be tailored and designed to suit specific applications. However, the future usage of MMC products is very much dependent on their beneficial aspects and hence it is critical to ensure in a robust repeatable manner the superior physical property advantages compared to conventional unreinforced monolithic metal counterparts. Although numerous routes are available for production of MMC products, each of them has their own advantages and disadvantages. This article provides an overview of advanced production routes for MMCs. The discussion also highlights challenges and presents a future prospectus for MMCs. Powder metallurgy and casting routes are still extensively used for production of MMCs. Aluminum alloys are today the most commonly used matrix materials in MMC products. Carbides (eg, SiC, TiC, and B_4C), carbon allotropes (eg, CNTs and graphene), and alumina (Al_2O_3) are currently the most used reinforcement materials. Nevertheless, the use of nano and of hybrid reinforcements are seeing increased usage in niche applications. Additive manufacturing (AM) is discussed as a novel production route for MMC products. This process represents a promising method for the production of MMC products.

KEYWORDS

1 INTRODUCTION

A composite material is an engineered material system made from a combination or mixture of at least two constituent materials with significantly different properties whose combination forms a new material in which its properties differ from the individual constituents. On a microscopic scale the individual constituents of a composite can still be identified distinctly and separate from each other. Composites are multiphase materials which are normally classified as matrix and dispersed/secondary/reinforcing phases, where the matrix phase embeds the dispersed phase and the dispersed phase serves as an underpinning agent for the matrix phase. Therefore, the matrix is continuous whereas the dispersed phase can be either continuous or discontinuous. The main purpose of the dispersed phase is to strength or soft the matrix, while the matrix phase transfers the stresses to the dispersed phase. Efficiency of stress transfer through the interface between the phases plays a critical role in the behavior and performance of composites.[1, 2]

The properties of composite materials are related to the constituent properties and the relative amounts of the individual constituents. The most intuitive and simplest method for predicting the properties of a composite is by using the rule of mixtures. This rule comprises a set of equations derived from basic assumptions such as that both materials are homogeneous, isotropic, and behave in a linear elastic manner. The most widely used equations are the ones that predict the composite density, tensile strength, modulus of elasticity, hardness, and coefficient of thermal expansion. It is important to be aware that the equations differ depending on the preparation technique employed and constituents' physical characteristics. Due to this and also the fact that composites do not always follow the rule of mixtures, some researchers have tailored or developed new numerical models in order to obtain more accurate predictions for the composites properties.[3-15] Numerical methods generally include the boundary element method, finite element method, or finite element analysis, and the finite difference method. The analytical models generally include the principles of elasticity theory, self-consistent model, composite cylinder model, Eshelby model, and other unit-cell models.[16] Table **1** lists examples were such models and theories can be used to predict the behavior and properties of metal matrix composites (MMCs). Additionally, understanding the strengthening mechanisms and hence predicting the yield strength is important for fabricating high performance and quality MMC components. Some of the strengthening mechanisms that can be operative in MMCs are Orowan strengthening, Hall petch strengthening, dislocation strengthening, load transfer strengthening, thermal mismatch strengthening, grain refinement and work hardening.[17-23]

TABLE 1. Various models and theories that have been developed to predict the behavior and properties of metal matrix composites

Model	Composite	Prediction	References
Finite element and modified Halpin–Tsai	A356-SiC(p)	Elastic moduli	24
2D rate-dependent crystal plasticity finite element	Al-graphene	Mechanical behavior under tensile load in a mesoscale	25
An immersed meshfree Galerkin method with stabilized particle integration scheme	Particulate-reinforced composite	3D large strain	26
Finite element with modified Johnson-Cook plasticity model	A2124-SiC(p)	Elastic-plastic properties	27
Mori-Tanaka method	Al2080-SiC(p)	Thermomechanical behavior	28
Neural network multi-layer Perceptron	A332-Al$_2$O$_3$(p) + SiC(p)	Density and tensile strength property	29
Finite element with microstructural models	Al6061-SiC(p)	Microstructure	30
Cohesive finite element based multiscale framework	Al-SiC(p)	Crack propagation	31
Transmission line matrix	Al-SiC(p)	Thermal behavior	32
Finite element and random sequential adsorption algorithm	Particulate-reinforced composite	Microstructure-strength relationships	33
Finite element and Maxwell-Boltzmann's distribution law with Eshelby's stress	Al-SiC(p)	Elastic behavior	34
Modified Clyne model	Particulate-reinforced composite	Strength	35
Finite element based on micromechanical theory	Al-graphene oxide	Elastic properties	36

Composite materials are normally classified according to the matrix material. MMCs consist of a metallic matrix and a dispersed metallic or ceramic phase. Ceramic Matrix Composites consist of a ceramic matrix and a dispersed phase of reinforcing fibers of other ceramic materials or metals. Polymer Matrix Composites consist of a thermoplastic or thermoset matrix and mostly a fibrous reinforcing dispersed phase.

Nowadays there exist numerous techniques for producing composite structures, some of which have been adopted and implemented from traditional manufacturing techniques. However, several of these techniques were developed to satisfy specific manufacturing or design challenges. Selection of a particular manufacturing technique to produce a composite structure is mainly dependent on the structure design, materials and application. As MMCs represent the highest growth area of usage for composite materials, this article provides an overview of MMCs. An extensive study on production routes and materials that are currently in research and development and numerous of successful applications of MMCs components in industry are presented. To help readers in understanding future research areas of focus, the developments, challenges and the prospect for the future of MMCs are also presented.

2 COMPOSITE MARKET

The composite market is exhibiting strong growth across many industry sectors and applications, due to the need for materials that have distinct properties and are environmentally friendly as well as cost effective. The growing of vehicular carbon emission levels across the globe has forced the reform of various policies concerning vehicle emissions. Due to stringent emissions regulations and high production demands, manufactures have implemented incremental improvements in weight reduction and fuel efficiency. This has ignited the automotive composite market in such way that as seen in Figure 1. It is estimated that the

United States of America alone will generate an automotive composite market revenue of almost $1 billion in 2025.37 It is noted at the end of 2018, that the global automotive composite market generated a revenue of $15.7 billion.38 Composites are also becoming increasingly popular in the aerospace industry as they provide good levels of toughness and strength and reduce the overall weight of the aircraft.39 Among many other industry sectors spurring the growth in demand for composite materials, the energy sector represents an enormous source of demand and will soon surpass the aerospace sector as the top user of composite materials.40, 41
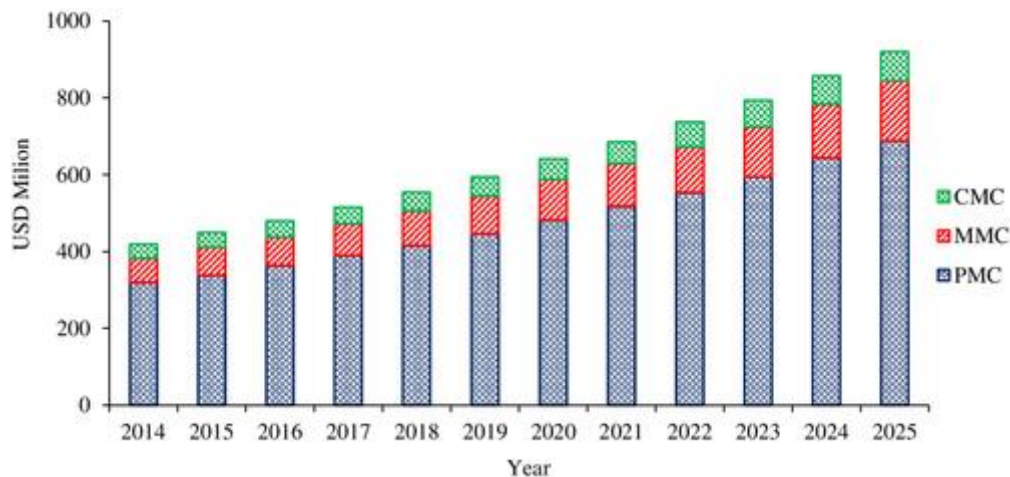

FIGURE 1 Automotive composites market revenue forecast for United States of America. Source: Data extracted from Reference 37

3 BASICS OF MMCs

Metals and their alloys are used in many engineering applications but with recent advancements in MMCs and an endless array of enhancement possibilities are presented. The properties of MMCs can be designed to fulfill requirements that are specific to and dependent on the application.

In MMCs, the matrix material plays an important role as it provides support for the dispersed phase, assists in carrying the loads, and provides stability to the composite structure. Additionally, the matrix material must enable bonding with the dispersed material, withstand the surrounding environment, be able to deform elastically under load and restrict the development and propagation of cracks.42, 43 Density, ductility, and strength retention at elevated temperature are important factors considered when selecting a matrix material. The selection of a suitable matrix material also depends on the type of dispersed material and amenability for production.44

Typically, ceramics (such as carbides, oxides, and nitrides) which are characterized by their excellent strength and stiffness are chosen as dispersed materials in MMCs.45 Reinforcements can be classified into continuous reinforcement and discontinuous reinforcement (short fibers, whiskers, and particles).46 Long fiber reinforced composites typically present anisotropic properties. Also, ceramic fibers are brittle and sensitive to flaws, thus exhibiting the phenomenon of length effect, which means that as their length increases their strength decreases.47 The fiber diameter greatly impacts on the mechanical properties of fiber reinforced MMCs. Large diameter fibers have low strength and tend to fracture at lower levels

stresses.48 Short fibers can be aligned or randomly oriented, this depends on the composite fabrication technique employed. In terms of application, this type of fiber can therefore be used to change specific physical properties of the reinforced compound.48, 49 Whiskers are one of the strongest forms of material developed.2 They are special thin crystals that have diameters in the range of 100 nm and an aspect ratio between 20 and 100.48 Whisker reinforced composites can have extraordinary strengths even higher than particle reinforced composites. This and other properties of composites reinforced with whiskers depend strongly on their orientation.44, 50, 51 A disadvantage of using whisker form of reinforcement is that whiskers tend to become oriented by some processes, such as extrusion and rolling. Sometimes, anisotropy can be a desirable property, but it is a disadvantage if it cannot be controlled precisely in the manufacture of the MMCs.52 Another disadvantage of using whiskers is that they are brittle and easily damaged while handling before integration into the matrix. They tend to break up into shorter lengths during processing, thus affecting their reinforcement efficiency, and are also difficult to densely pack. Particles, on the other hand, are easily packed and thus are possible to obtain higher reinforcement-matrix ratios which enables better mechanical properties.47 Lately, commercial exploitation of whisker reinforced composites have been limited due to health hazards where whiskers can have carcinogenic and toxic effects after inhalation.53, 54 Particles are the most common and least expensive form of reinforcement.44 They are relatively easy to process and compatible with most conventional processing routes. Generally, the distribution of particles in the composite matrix is random. With this, compared to other forms of reinforcement, particulate reinforced MMCs exhibit relatively isotropic properties.55 The main issue with production of particulate reinforced MMCs is the low wettability of the reinforcement with the molten metal matrix. Powder particles may also agglomerate and form clusters, thus preventing them from being homogeneously dispersed throughout the matrix.56 This is the case of nano-reinforcements which are susceptible to agglomeration due to high value of surface energy. In order to overcome these problems an appropriate MMC production route must be selected. In particulate reinforced MMCs, the reinforcing particles are bonded in the matrix and they have the ability to restrict dislocation movement in the matrix material, grain growth and grain boundary slip at high temperatures. Due to this and the combination of their increased physical strength, in effect, the matrix composite is strengthened. The strengthening mechanism depends on particle diameter, inter-particle distance, reinforcement volume fraction, as well as the matrix and reinforcement properties.1, 57, 58 Particulate reinforcement offers numerous desirable properties such as high specific stiffness, good wear resistance and high strength at high temperatures.47 However, the ductility of composites is very often negatively affected by the presence of this second harder phase. Yet, this may be overcome through proactive design of the composite and production routes.59, 60

Aluminum matrix composites (AMCs) are an interesting group of advanced lightweight MMC materials. The use of aluminum and its alloys as matrix material are growing continuously, finding numerous applications in many industries owing to their low density, good strength and ductility, excellent thermal conductivity and corrosion resistance properties.61-63 Rahman et al reported in a study in 2007 a comparison between the usage of numerous matrix and dispersed phase materials by various industries.64 Aluminum was at that time the most used matrix material, followed by iron, titanium and nickel alloys, the latter alloys which hold many useful properties such as high strength capability at high temperature.65-67 The most

commonly used dispersed material is silicon carbide (SiC) and aluminum oxide (Al2O3) followed by titanium carbide (TiC) and carbon (C). In comparison, Al2O3 is slightly denser and has lower wettability characteristics than SiC, but it possesses higher resistance to oxidation and is more chemically stable, even when taking into account that the oxidation behavior of SiC can be controlled to varying levels. Generally, SiC leads to higher mechanical properties.[68-71] TiC exhibits excellent hardness and high temperature stability. Also, it was demonstrated that good wetting and thus adhesion at the interface with metals can be achieved by removing the native oxide film of TiC.[72-74] Carbon-based nanomaterials like carbon nanoparticles, graphene, graphene oxide, and so on, can be found in many different morphologies and configurations. Specific allotropes can be formed which are characterized by their outstanding properties enhancing the formed MMC.[75] Graphene for instance, which consists of only one single layer of atoms arranged in a honeycomb lattice, has been attracting great attention due to its intriguing properties, such as high thermal conductivity, high Young's modulus and high fracture strength.[76, 77] Carbon fiber is used for improving the flexural strength of MMCs. This type of MMC is generally processed using an infiltration-casting route in order to minimize damage to the fibers.[78, 79] The dispersed material plays an important role in MMCs. However, the final properties of composite materials have also strong dependency on the matrix material, fabrication method, uniformity of dispersion of the secondary phase and suitable interfacial bonding.

In comparison to single reinforced composites, hybrid composites incorporate two or more types of dispersed phases (eg, Al2O3 + ZrO2 and B4C + TiB2) within the same matrix. Hybridization promotes synergies between the adopted dispersed phase materials, for this reason hybrid reinforcements can exhibit new structural characteristics (eg, Al2O3-GNS non-continuous network-like structure, carbon allotrope (CNT)-graphene layered structure, CNT-graphite reticulated structure) and additional synergistic properties.[80-85] Hybrid composites can exhibit superior properties compared to those exhibited by composites containing individual reinforcements at the same loading. This is due to a strong synergistic effect on the properties through the usage of hybrid reinforcements.[86] Therefore, hybrid composites are explored for purposes such as of wear resistance, lightweight, chemical stability, and for combining advantages of the dispersed phases based upon the requirements of the application.[87, 88] This type of composite material can find usage in numerous applications such as aviation and automobile.[89, 90] As with single element reinforcement, strategies are needed to reduce some of their deficiencies and improve their advantages.[90, 91] One important aspect to consider under hybrid composites is the use of reinforcement with bimodal or trimodal particle size distributions. It has been reported that large sized ceramics are more capable of producing grain refinement compared to smaller ceramics, while finer particles provide a higher number of barriers per unit volume compared to composites reinforced with larger particles at the same weight percentage.[92, 93]

4 PRODUCTION ROUTES FOR MMCs

4.1 General overview

The selection of a particular production route depends on several factors such as property requirements, envisaged application and the economics of fabrication. Additionally, it is important to take into consideration the fact that different production routes can lead to completely different composite characteristics, even though the same composition and amounts

of the constituents are used.94 The production of MMC can be divided into primary (combining and consolidation) and secondary (shaping or joining) processes. The selection of primary and secondary processes is mainly determined by the matrix and dispersed phases and their respective mechanical and thermal properties and morphology. It is also determined by the chemical properties of each phase and possible evolution of reaction processes establishing the interface between phases. Especially if the composite is exposed to high temperatures, either in processing or service.47 Moreover, the selection of a specific primary process is also dictated by the ability of this process in minimizing dispersed material damage, preserving dispersed material strength and promoting wetting and bonding between the involved phases during processing. Many processes are available for production of MMCs. Where for these, the dispersed phase can be either created in situ or introduced as an ex situ phase. In situ synthesizing is that where the dispersed phase is created within the matrix, typically by the occurrence of a chemical reaction which is often exothermic.95 Differently, ex situ is where the dispersed phase is synthesized separately before its insertion into the matrix.96-98

At present there are several processes of in situ composites. Where, the advantages of in situ tend to be very process and property specific. However, in general, in situ provides more a homogeneous distribution of the dispersed phase particles, the dispersed material surfaces and the dispersed phase-matrix interfaces are more likely to be free of contamination. This route also tends to ensure better bonding between the particle and matrix, and allows the introduction of a large volume fraction and a small size dispersed material. Essentially, in situ processes provide a strong interfacial bonding as the reinforcement-matrix interfaces are clean, resulting in better mechanical properties and less degradation in high temperature applications. The in situ decomposition reaction can be used to obtain strong interfacial bonding. In this matter, using the selective laser melting technique, a study found that this process resulted in diffusion of the Al atoms in Ti_2AlN out of the lattice so that the Al atoms could bond with the matrix forming Zn_7Al.99 Also, due to atom diffusion, Ti atoms separated from the Ti_2AlN. The resulting Zn_7Al-Ti_2AlN composite had besides the main Zn enrich phase, Al enrich phase, and Ti_2AlN phase, two new phases of TiN and $Al_{0.64}Ti_{0.36}$ which were present at the interface and contributed to improved load transfer.99 A disadvantage of in-situ processing of MMCs is that dispersed materials are limited to only those that are thermodynamically stable in a particular matrix. Also, the size and shape of particles are determined by the kinetics of the process during the nucleation and growth activities. Nevertheless, in situ processing of composites is cost effective and scalable, but commercial applications are still limited by the unpredictability of the reactions and the insufficient knowledge concerning its processes.98, 100-104

The properties of ex situ processed composites greatly depend on the volume fraction of the dispersed material, and in terms of processing, ex situ enable production of bulk materials that exhibit isotropic characteristics. For this reason and also because of ease of production and modest production cost, ex situ is widely preferred over in situ. However, ex situ processing has limitations which are mainly due to poor wettability of the dispersed material and reactions of dispersed phase-matrix interfaces. Ex situ processing also imposes difficulties to overcome in terms of homogeneous incorporation of the dispersed material into the matrix. One of the main reasons is because of Van der Waals and electrostatic forces in the liquid mixing process which leads to particle agglomeration and clustering.105-110

Solid state processes use high temperature and pressure to create atomic diffusion between the metal matrix and the dispersed phase. These processes are known for diminishing dispersed phase-matrix wetting issues and for reducing segregation effects and brittle reaction product formation. They also avoid high residual stresses from solidification shrinkage, particularly when contrasted with liquid state processes. Therefore, solid state processes are normally used to obtain the highest mechanical properties. These processes are mainly used for high melting point matrixes. Furthermore, low temperature solid state processing naturally depresses undesirable reactions on the interface between dispersed phase and matrix.111-120

Liquid state processes have been extensively employed in the production of MMCs. These processes are characterized by intimate interfacial bonding, and thus, strong bonding. In these processes, the dispersed material is incorporated into a molten metal matrix, which later undergoes solidification. The quality of the dispersed phase-matrix interfacial bonding determines the mechanical properties of the composite.121 In comparison to solid state processes, liquid state processes are relative simple and cost effective. These processes also permit formation of dense matrices and near net shaped components even in complex geometries, at a considerably fast rate of production.114, 116, 117, 122 Processes such as the conventional casting methods are widely used in liquid state processing. Aluminum is a commonly used material with low melting point, hence requires low energy input from the process. Differently, high melting point matrix materials like titanium alloys are more processed via solid state routes. One problem that can occur with liquid state processes is that high temperature processing can stimulate the development of a brittle interfacial layer between the involved phases, which will then adversely affect the composite properties.113, 121, 123, 124 It can be difficult to provide a uniform distribution of dispersed material without particle floating, sedimenting, or clustering/agglomerating in the molten alloy. The viscosity of the liquid composite changes quickly as the dispersed material is added and during the solidification process. Controlled viscosity during particulate incorporation and solidification is required for successful process resulting in uniform dispersed material distribution. These problems are very common in the stir casting process.56, 117, 121, 125-128 In order to depress adverse reactions and improve wetting, a suitable chemical treatment or coating can be applied to the dispersed material or wetting agents can be added to the melt which will then prevent the formation of oxides, promote positive interfacial reactions and help to reduce the interfacial energy. However, if the coating of the particles is exposed to air prior to infiltration, the coated surface can oxidize, thus negating the positive effects of the coating.57, 115, 118, 121, 129

The most common solid state processes are based on powder metallurgy (PM) production routes. PM is a well-developed technique that involves a small number of energy efficient steps. Its processes are suitable for synthesis of micro- and nano-ceramic reinforced MMCs. In addition, PM routes are extensively used for new composite composition investigation and in industry for part production of MMCs.67, 107, 130-132 An example of PM in industry is Toyota' mass production of titanium matrix composite (TiB_2 reinforced Ti-6.5Al-4.6Sn-4.6Zr-1Nb-1Mo-0.3Si) exhaust valves, in which the valves were specifically designed for mechanical properties at elevated temperatures.133, 134 Liquid state processes such as stir casting, squeeze casting and infiltration have been widely adopted for the production of MMCs.131 Stir casting which is generally used for the production of particulate reinforced MMCs, is currently the most popular commercially practiced route for producing AMCs. It allows large sized and complex designed products to be produced, and is suitable for large volume production.107,

128, 135-138 Stir casting generally involves melting of the matrix material followed by the addition of dispersed material into the molten metal matrix, which is stirred mechanically or electromagnetically creating a vortex that draws the dispersed material into the liquid metal. The stirring is performed until a uniform mixture is formed and then the process is followed by a molding process. Normally, a volume fraction of dispersed material ranging from 10% to 40% is used in this process.107, 139, 140 Duralcan is a series of MMCs commercialized by Rio Tinto Inc. This company is specialized in stir casting and it uses this process as a primary process to manufacture for example A380-SiC gear box components and A359-SiC brake discs. Millennium Materiuals Inc. produces a family of MMC by stir casting called Carolite such as lightweight structural components and advanced media substrates (eg, disks for hard drives).141 Commercially, PM represents a small but important market for MMC production. In contrast, liquid state processes such as stir casting and infiltration account for largest production volumes.140

Production of high modulus iron-based MMCs has been of interest for many researchers. Liquid metallurgical synthesis of low density, high stiffness steels (high modulus steels) containing titanium diboride and titanium oxides mixed with aluminum powder led to a very high titanium diboride yield in the steel, and so the premixture of titanium oxides with aluminum are good candidates for the cost effective production of high modulus steels.142 In addition, the mechanical and physical properties of high modulus steels can be further improved by controlled solidification kinetics and hot rolling followed by annealing above the solidus temperature.143 The addition of nickel to iron-chromium-boron based high modulus steels prepared via casting followed by hot rolling leads to the in situ formation of (Cr,Fe)2B type of borides and changes the matrix from ferritic toward a martensitic and then austenitic structure. The prepared iron-chromium-boron-based composites revealed to be resistant to corrosion in saltspray atmospheres and exhibit a corrosion resistance competitive with conventional stainless steels. In addition, compared to the base material, the composite presented a decrease in stiffness and density but an increase in strength.144 PM represents an alternative to traditional casting processes for the production of wear resistant material. However, to increase the economic efficiency PM processing, supersolidus liquid phase sintering can be used instead. It has been shown with the processing of ultrahigh boron, high carbon gas atomized iron powders that this process leads to fast densification due to low melting and formation of boron rich eutectics.145 Supersolidus liquid phase sintering is also known to enable adjusting the size and shape of the hard phase.146 Usually, for lightweight applications, the focus is improving properties such as stiffness, strength and ductility at low density, which are generally mutually exclusive. In relation to this, bulk metallurgy spray forming enables efficient microstructure refinement through accelerated solidification kinetics. An example for this is the nano-structured steel titanium diboride composites processed in situ through bulk metallurgical spray forming which has mechanical performance of advanced high strength steels and 25% higher stiffness-to-density ratio than any high strength steel, titanium, magnesium, and aluminum alloys. The reason for such improvements are mainly deemed to be due to the nano-sized dispersion of the in situ formed titanium diboride phase.147

High strength zinc-aluminum alloys are very often the first choice to replace brass, cast iron, and aluminum alloys in applications such as bushings, bearings, and other wear resistant applications. A study on compocasting of ZA-27 composites reinforced with short glass fibers showed that the hardness, compressive strength and ultimate tensile strength increases with the

increasing of the glass content. In consideration of improving also the ductility and impact strength of the composites, heat treatment was then performed. However, it led to a degradation of the hardness and ultimate tensile strength.148 Hence, in a such a case, a compromise is needed in deciding the amount of fibers to be incorporated and heat treatment temperature and duration in order to have a composite with better all-around properties.

Magnesium matrix composites is one of the lightest MMCs and is an attractive choice for high performance automotive and aerospace applications. A study into this composite using vacuum stir casted magnesium alloy (AZ91C) plus silicon carbide particles reported that the silicon carbide particles exhibited a homogeneous distribution and were well wetted by the magnesium alloy. The prepared composite presented a lower but close ultimate tensile strength to the unreinforced magnesium alloy. Nevertheless, substantial improvements in elastic modulus and yield strength were achieved. It was underlined that at low processing temperature (700°C) the composite presented no evidence of interfacial reactions. However, when processed at 750°C significant chemical reaction between the magnesium alloy and the silicon carbide interface occurred thus forming complex precipitates containing magnesium, silicon, aluminum, oxygen, and carbon, which were found to deteriorate the fluidity of the composite melt.149

4.2 Progress in MMCs matrix and reinforcing materials

To better understand what processes and materials are utilized nowadays in research for the production of MMCs, 944 of the most recently (published year 2016-2018) published journal articles on MMCs were reviewed. As a result, an extensive database was generated and its data were analyzed for the purpose of this study. The following important high level information was collected from each of the 944 reviewed journal articles: processing routes (here classified into Initial Process, Main Process, and Post Process), matrix material and dispersed material (here classified into Single Reinforcement, Hybrid Reinforcement, and Coated Reinforcement). All of these references are available in the Supplementary Document. Presented here, is a summary of the analysis and a discussion of the related findings from this study.

There are numerous processes and materials that can be used to produce MMCs. Figure 2 shows the material's processing steps involved during the production of any MMC. Depending on the production route, the matrix material can be introduced either within the Initial Process or the Main Process. The reinforcing material is also introduced either within the Initial Process or Main Process. In some cases, the reinforcing material is not required as a secondary phase is formed by precipitation within the matrix elements. On the other hand, agent materials can be introduced where appropriated. Agent materials are defined here as materials (salts, binders, acids, lubricants, gases, and so on) used during processing which are somehow beneficial to the final composite, however they are neither a matrix nor reinforcement material. It is seen in the flowchart that the Post Process step is not always a requirement, this depends on the Initial Process and Main process, materials, and desired final composite characteristics. It is also seen that the final MMC product can be either material feedstock for a subsequent process or the required object itself.
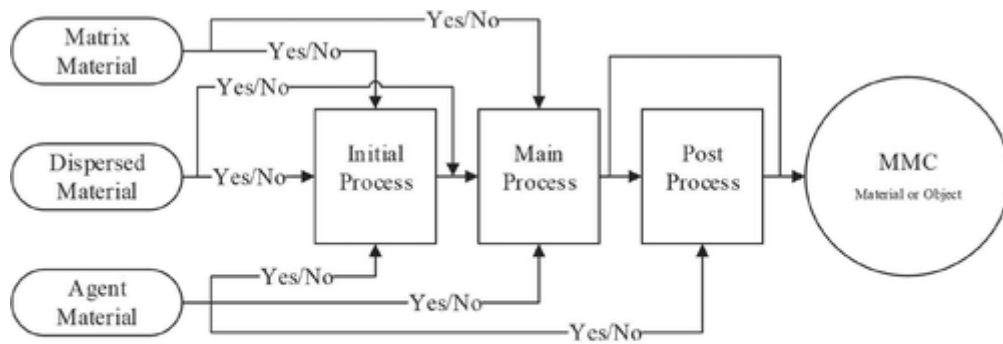
Description:
Initial Process = Process used to blend, treat, coat or make material/s suitable for the Main Process.
Main Process = Process used for composite consolidation.
Post Process = Process used for shaping and forming.
Yes/No = Yes (material is introduced here) and No (material is not introduced here).

FIGURE 2 Overview flowchart of the processing steps involved during production of a MMC

Initial Process	Process Percentage Usage
Dry Synthesis Techniques	26.8%
Wet Synthesis Techniques	16.8%
Electrochemical Deposition techniques	3.8%
Vapor Deposition Techniques	2.9%
Mechanical Alloying	1.7%
Sputtering Techniques	0.5%
Gas Atomisation	0.1%
Main Process	
Powder Metallurgy Techniques	46.2%
Casting Techniques	33.7%
Friction Stir Processing	5.4%
Metal Infiltration Techniques	3.5%
Selective Laser Melting	2.8%
Thermal Spray Techniques	2.2%
Diffusion Bonding Processing	1.7%
Laser Metal Deposition	1.5%
Accumulative Roll Bonding	1.3%
Laser Cladding	1.0%
Equal Channel Angular Pressing	0.3%
Injection Moulding	0.2%
Binder Jetting 3D-printing	0.1%
selective Laser Sintering	0.1%
Ultrasonic Additive Manufacturing	0.1%
Post Process	
Hot Extrusion	8.4%
Hot Rolling	2.3%
Hot Forging	1.4%
Cold Rolling	0.2%
Cold Extrusion	0.2%

FIGURE 3 Extent of process utilization for MMC production research and development

In research and development, as seen in Figure 3, over half of the reviewed journal articles used Initial processes for MMCs preparation. Of these, the dry synthesis techniques are more frequently employed. PM techniques are today the most preferable main process for producing MMCs. PM techniques are encountered in 46.2% of the reviewed journal articles, followed by casting and friction stir processes. Compared to other production routes, PM is an effective and versatile route for production of particle reinforced MMCs. PM is adopted by researchers because it avoids problems encountered by conventional routes and ensures good interfacial bonding between the dispersed phase and matrix, promotes homogeneous distribution of dispersed phase in the matrix and prevents formation of undesirable phases. Additionally, PM techniques work with almost any material and can readily produce good quality composites. The choice of casting for production of MMCs is generally due to the higher usage of this process in industry, as well as processes simplicity, flexibility, and relatively low cost. Differently, friction stir processing is capable of producing surface composites without the necessity of melt processing. Where, the sliding motion of a rotating tool produces severe plastic deformation accompanied by mass material flow. Friction stir processing is being used as an effective technique to modify and refine microstructure for enhancing mechanical and improving chemical and physical properties of materials, making them suitable for many engineering applications.

The other less frequently used processes need research and development where for example they can produce more complicated geometries and have potential to provide unique characteristics within the synthesized composites. Table 1 lists all the processes used by researchers for production of MMCs. New in the MMC world, the AM process has already been examined and offers significant potential for MMC production. AM is of particular interest in the context of MMCs as it promises the production of integrated, very complex, lightweight structures with competitive cost, and reduced lead times. Selective laser melting is an AM technique identified as the most promising route to process MMCs. Its layer-by-layer fashion of manufacturing, freeform fabrication abilities, material melting, and solidification in controlled inert atmosphere and its potential for pointwise control of microstructure and mechanical properties are some of the points that makes this process unique compared to traditional MMC processing routes. Additionally, selective laser melting has the potential to eliminate several issues such as difficult of process control, reinforcement non-uniform distribution, wettability, chemical reaction and porosity, which are commonly within traditional processing routes.150 For production of MMCs, the selective laser melting process uses for example pressure-swirl-gas-atomized powders (the reinforcing nanomaterial is integrated within the matrix powder), gas atomized powders (of matrix and reinforcing material resulting in a composite powder), mechanically mixed powders (containing a mixture of matrix and dispersed powder), chemical vapor deposition treated powders (the matrix powder is coated with another material), and multi-material deposition (powders are mixed in situ by the machine feeder system).151-155

Post processing operations which are normally used for forming and shaping operations were found in over 12% of the reviewed journal articles, on which 8.4% were accounted for Hot Extrusion alone. The post processing techniques shown in Figure 3 were found in the reviewed journal articles. These post processing techniques were found to be used mainly to increase the relative density of composites, improve reinforcement dispersion and rearrangement, improve grain refinement, microstructure and texture evolution, and general composite mechanical

properties enhancement. However, beyond these, they were also found to be used to reduce the amount of machining and other composite post processing requirements.

During the production of MMCs, occasionally two main processes are employed. Table 2 lists all the encountered processing sequences under this classification, the arrows indicate the processing order. Main Process having multi techniques was found in 58 of the reviewed 944 journal articles. PM techniques are well accepted before and after casting techniques, in fact it was encountered in 24 of the reviewed journal articles. Some of the reasons for using two main processes were for example grain refinement, densification, improvement of material wettability, interfacial microstructure modification, and precipitation strengthening.

TABLE 2. List of all of the production routes encountered in the reviewed journal articles

Process	Sub Process			
Diffusion Bonding				
Casting Techniques →	Conventional	Centrifugal	Rheo	Investment
Cold/Hot Rolling	Squeeze	Ultrasonic	Tape	
Hot Forging	Stir	Injection	Compo	
Powder Metallurgy Techniques →	Cold Pressing		Furnace Sintering	
Friction Stirring	Hot Pressing		Spark Plasma Sintering	
Cold/Hot Extrusion				
Laser Metal Deposition	Capillary	Ultrasonic	Vacuum Pressure	
Metal Infiltration Techniques →	Gas Pressure		Liquid Pressing	
Laser Cladding				
Gas Atomisation	Chemical Vapour		Physical Vapour	
Vapour Deposition Techniques →	Deposition		Deposition	
Selective Laser melting				
Electrochemical Deposition Techniques →	Electro Deposition		Electroless Deposition	
Selective Laser Sintering				
Spray Techniques →	Plasma Spray		High Velocity Oxygen Fuel	
Ultrasonic Additive Manufacturing	Cold Spray		Spray Pyrolysis	
Magnetron Sputtering				
Dry Synthesis Techniques →	Grinding	Tumble Mixing	Stir Mixing	
Binder Jetting 3D-printing	Sieving	Manual Mixing	Ball Milling	
Accumulative Roll Bonding				
Equal Channel Angular Pressing	Slurry Mixing	Precipitation	Chemical Reduction	
Wet Synthesis Techniques →	Aqueous	Acid Treatment	Liquid Infiltration	
Mechanical Alloying	Hydrothermal	Molecular Level mixing	Sol-gel	
Injection Moulding				

In terms of materials, researchers explored and developed numerous matrix and dispersed materials. As seen in Figure 4, aluminum and its alloys were the most used matrix materials, with 48% of the reviewed journal articles being on AMCs. It is worth considering what are the reasons for such interest of researchers in aluminum matrix. It is well known that aluminum is a lightweight metal which has high thermal and electrical conductivity, low melting point, and good formability. However, it has high coefficient of thermal expansion and poor mechanical and tribological properties, thus a need and opportunity for improvement via reinforcement for

example is present. The choice of aluminum in research is also influenced by its low energy input requirements which makes it suitable for most of the existing MMCs production routes and high degree of usage within industry. Additionally, its cost is similar or less than other commonly used matrix materials. An extended list of matrix materials (metals, commercial alloys, and developed alloys; 80 in total) encountered in the reviewed journal articles is given in Table 3.
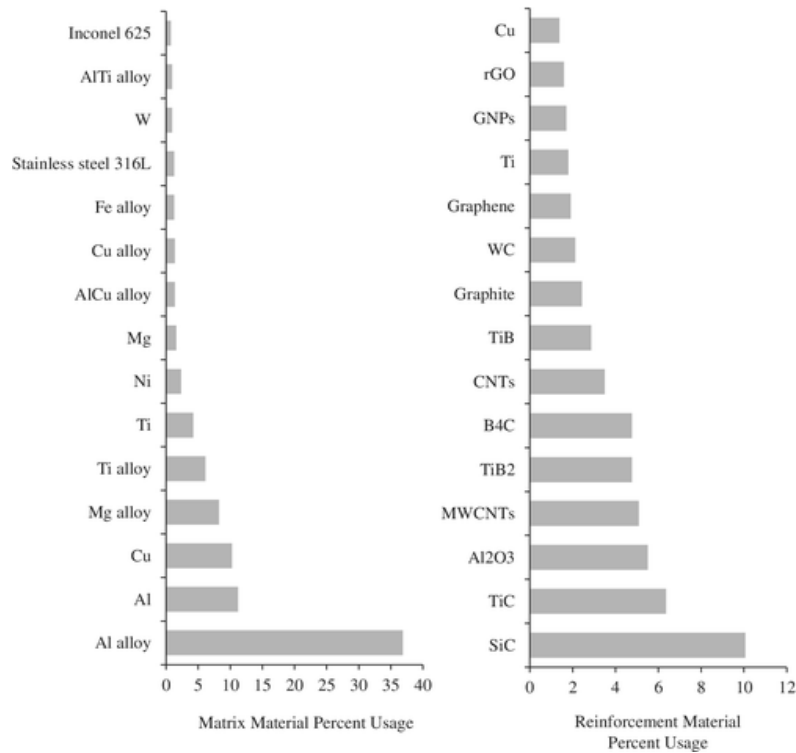

TABLE 3. The main process very often comprises two processes. Presented here are the various cases encountered and their respective occurrence within the reviewed articles. The arrows indicate the processing order

Main process		Occurrence within the 944 reviewed articles
Powder metallurgy techniques	↔ Casting techniques	24
Powder metallurgy techniques	→ Metal infiltration techniques	7
Powder metallurgy techniques	→ Friction stirring processing	5
Casting techniques	→ Friction stirring processing	5
Casting techniques	→ Equal channel angular pressing	5
Powder metallurgy techniques	→ Laser cladding	3
Thermal spray techniques	→ Friction stirring processing	3
Metal infiltration techniques	→ Equal channel angular pressing	1
Powder metallurgy techniques	→ Accumulative roll bonding	1
Thermal spray techniques	→ Powder metallurgy techniques	1
Injection molding	→ Powder metallurgy techniques	1
Powder metallurgy techniques	→ Thermal spray techniques	1
Metal infiltration techniques	→ Thermal spray techniques	1

Regarding dispersed materials, 16% of the reviewed journal articles involved the use of hybrid reinforcements. The main advantage of hybrid composites over conventional composites is that it is possible to design composites with a better all-around combination of properties. Almost 4.5% of the reviewed journal articles employed a coating onto the dispersed material prior the composite synthesis. The coatings were applied onto the dispersed material to aid the bonding of the dispersed phase with the matrix. Figure 4 also ranks the usage comparison of dispersed materials. It is seen that SiC was the dispersed material most used by the researchers, followed by TiC, Al2O3, MWCNTs, TiB2, B4C which were also found in many of the reviewed journal articles. It is good to point out that from the reviewed 944 journal articles, numerous of other dispersed materials were used in MMCs. In fact, 142 different single reinforcements, 120 different hybrid reinforcements, and 32 different coated reinforcements have been examined. The extended list of dispersed materials reviewed in this study is given in Table 4.

It is noted in Table 3 that some metals are listed as dispersed material. Further information on this and references on individual cases can be found in the Supplementary Document. One of the purposes for adding a dispersed phase in a metallic matrix is to use their higher mechanical or/and physical properties. For this purpose, a suitable interface between a matric and interface is required. The literature indicates that by using an ex situ process and as-received dispersed material, a poor interface might be obtained due to impurities and lack of chemical and/or mechanical bonding.[102, 156] Therefore, many researchers, as in the cases seen here, have used an in situ process for the preparation of MMCs. In fact, depending on the process conditions and starting materials, it may have exothermic or endothermic reactions between the two or more starting phases to form new products with a completely different atomic structure and improved interface quality and mechanical or/and physical properties. For example, copper has been previously added to aluminum to prepare in situ intermetallic phases with a completely different atomic structure, thus acting as a dispersed phase for the aluminum matrix.[157] In order to prepare new dispersed phases during the process, mechanically-induced reaction processes like friction stir welding or thermally-induced reaction processes like casting, sintering, and self-propagation high-temperature synthesis have been used. The in situ dispersed phases have a clean interface with the matrix with normally a strong chemical and consequently mechanical bonding. This bonding causes the dispersed phase to help the matrix t load transfer and/or to avoid the movement of dislocations.[158]

Generally, due to a considerable difference between the atomic structure of matrix and dispersed phase, incoherent or semi-coherent interfaces between the phases might be observed. However, depending on the process conditions like temperature and mechanically induced input energy, it is possible to change the quality of interface between the matrix and dispersed phase by formation of a thin reaction layer between a matrix and dispersed phase. This reaction layer has a suitable corresponded interface with the matrix acting as a chemically stable transition for the joining of the two phases.[109, 159]

4.3 Examples of successful applications of MMCs components in industry

Automotive application of MMCs started in 1983 when Toyota placed into commercial production MMC pistons for diesel engines. Squeeze casted pistons composed of aluminum reinforced with ceramic particles and fibers provided a significant improvement in thermal fatigue and wear resistance in comparison to the matrix material on its own

TABLE 4. Extended list of matrix and dispersed materials encountered in the reviewed journal articles

Matrix material			
Al Matrix	Cu	High speed tool steel	TiH_2
Al	Cu alloy	P91 steel	**Mg Matrix**
Al alloy	CuSnTi alloy	TRIP steel	Mg
AlCu alloy	CuTi alloy	Stainless steel 304	Mg alloy
AlTi alloy	Bronze alloy	Stainless steel 440	MgZn alloy
AlSi alloy	CuNiTi alloy	Mild steel	**Mo Matrix**
AlZn alloy	CuO	**Co Matrix**	Mo
AlMg alloy	CuSn alloy	Co	Mo alloy
AlNi alloy	CuW alloy	CoCr alloy	MoNb alloy
AlCuMg alloy	CuZn alloy	CoCrFeMnNi alloy	**Cr Matrix**
AlMgSi alloy	CuNi alloy	CoCrFeNi alloy	CrNiTi alloy
$Al_2CoCrFeNi$ alloy	**Fe Matrix**	CoCrFeNi alloy	CrRe alloy
Al_3Ti alloy	Fe	CoCrNi alloy	**Other Matrices**
AlAgCuLiMgSiZr alloy	Fe alloy	**Ni Matrix**	W
AlCuMgZn alloy	Stainless steel 316 L	Ni	WCu alloy
AlCuMgZnZr alloy	Alloy steel	Ni alloy	Ag
AlCuMnTi alloy	Maraging steel	Inconel 625	AgCu alloy
AlFe alloy	Tool steel	Inconel 718	BCrNiSi alloy
AlFeSi alloy	FeNi alloy	NiTi alloy	Sn
AlLiCu alloy	4130 Alloy Steel	**Ti Matrix**	Zn
AlMoTi alloy	Carbon steel	Ti	
AlNi bronze alloy	Fe_3Al alloy	Ti alloy	
Cu Matrix	Ferritic alloy	Ti_3AlC_2	
Dispersed material—single			
Carbides	Si_3N_4	$NiFe_2O_4$	Ca
SiC	TiN	$Mg_2B_2O_5$	$Ca_2O_7P_2$
TiC	MgGdBN	$ZrMgMo_3O_{12}$	CoCrFeNi
B_4C	Ti_2AlN	ZrW_2O_8	Diamond
WC	AlTiN	Al_2TiO_5	WS_2
Cr_3C_2	CrN	**Others**	W
Ti_3AlC_2	**Borides**	Fe	Sn
Ti_2AlC	TiB	Fe ore	Nb
ZrC	TiB_2	Stainless steel 316 L	Be
TaC	ZrB_2	Medium-carbon steel	Beryl
Al_4C_3	AlB_2	Stainless Steel 2Cr13	Cr
Al_3BC	CaB_6	Stainless steel 304	Si_2Zr_3
Fe_3C	VB	Fe_3Al	Si
Mo_2C	$AlMgB_{14}$	Fe aluminides	Ag
Nb_2AlC	CrB_2	Cu	Zr
NbC	NbB_2	CuAlFe	Ta
Ti_3SiC_2	**Oxides**	γ-Cu_5Zn_8	Gd
Cr_2AlC	Al_2O_3	AlCrFe	Fullerene
VC	SiO_2	Al	Silicate bioceramic

(Continues)

This allowed the use of tighter tolerances which led to higher pressure and improved heat transfer properties. In 1990, Honda started to mass produce squeeze cast cylinder liners and

engine blocks from hybrid preforms consisting of Al2O3 and carbon fibers reinforced aluminum matrix. AMCs promoted a dramatic weight reduction of the engine blocks and superior wear resistance than that of cast iron. Later, AMCs cylinder liners were also incorporated in the Toyota and Porsche engines, and Honda motorcycles were equipped with AMC cylinder liners produced using PM routes. In 1998, the Toyota Altezza 2.0 L engines were equipped with titanium matrix composite (TMC) intake and exhaust valves made from titanium alloy and TiB2 powders via PM routes and an intermediate extrusion step followed by forging. These TMCs valves led to reduction of the engine weight and reduction of cam contact frictional forces. Many automotive manufactures use AMC brake systems in their vehicles. Different casting routes have been used to produce brake discs, pads, and drums from aluminum alloys reinforced with discontinuous dispersed materials such as SiC and Al2O3. Such AMCs are used in brake systems because of their high thermal conductivity and high resistance to wear. As a further example, to increase specific stiffness of drive shafts and to reduce the overall vehicular mass manufactures have opted for AMCs. GMC, Chevrolet, and Ford have successfully used stir casted Al2O3 reinforced Al6061 drive shafts in their vehicles.160 Another example is the hybrid reinforced AMC cylinder liner which was successfully used in the Honda Prelude. Integrally casted with the engine block, the AlSi matrix was reinforced with Al2O3 (12 wt% short fibers for wear resistance) and carbon (9 wt% short fibers for lubricity) had weight savings of 50% compared to the cast iron system and exhibited improved wear and cooling efficiency. Particulate reinforced composites of Al359 reinforced with SiC 20 wt% were cast into brake rotors and drums were used within the Lotus Elise brake system, with the properties of high wear resistant and thermal conductivity. In addition to 60% weight savings compared to the previous cast iron material which was used for these components.161

Large space structures such as antennas, panels, platforms, and booms in use by National Aeronautics and Space Administration (NASA) contain MMC components. Primarily, PM and pressure assisted casting routes were used to process discontinuous reinforced composites. On the other hand, diffusion bonding and casting routes were used to process continuous fibers reinforced composites. Numerous components used in aerospace are AMCs. For example, continuous fibers of boron (B) reinforced aluminum was used for links and struts leading to significant weight reduction of shuttle orbiters. Diffusion-bonded graphite fibers reinforced 6061 aluminum antenna boom offered low coefficient of thermal expansion and the required level of stiffness. Several components encountered in communications satellites have been made from graphite reinforced and SiC reinforced aluminum because they are lighter than just using the metal alloy alone and also because they offer significant cost savings via net shape manufacturing. As a specific example, aluminum 6061-T6 reinforced with either graphite (10%) or SiC (30%) offers an optimized modulus of elasticity to components sensible to vibrational environments such as structures supporting sensitive sensors, cameras, and antennas in space stations and satellites.162

Landing gear components and turbine nozzle actuators of the F-16 and F-22 fighter aircrafts were made with Ti-SiC composites.163 Titanium alloy Ti6AlV4 reinforced with SiC fibers composites were used in gas turbine engines (fan blades) of heavy transporter military planes and boron particles dispersed into Al laminate composites were used on the tail rotor blades of Sikorsky helicopters.164, 165 Specialized in thermal spraying, particularly in HVOF, American Roller successfully produced wear resistant composite coatings. Both, Cr3C2 and

WC reinforced Co or Ni were applied to components to improve their longevity. Ametek Inc. manufactures SiC reinforced aluminum composites via pressure assisted infiltration and then plate them with Ag, Ni, Au, Cu, or Sn for thermal management applications. The company also produces Mo or W reinforced Cu components such as chip mounts, circuit boards, and heat sinks via PM followed by rolling and then machining. Bodycote, a metallurgic service company, uses PM routes in order to reduce interfacial reactions when processing oxides, carbides, silicides, borides, or nitrides reinforced tool steels or aluminum for example. Materion is a company specialized in high performance engineered materials and is a major supplier of beryllium based materials. At Materion, production of BeO reinforced Be and Be reinforced Al are made using gas atomized powders. These powders are processed using PM routes followed by conventional metal processing routes such as extrusion and rolling. Thermal management and structural support in both avionics and aerospace sectors are some of the applications of Be reinforced Al. Made to an electronic grade, BeO reinforced Be composites are classified as E-Materials. Their low density, high strength and modulus, and excellent thermal conductivity and thermal expansion make them especially suitable for electronics and semiconductors applications.141

5 CHALLENGES

MMCs have been successfully used and proven to bring significant benefits to a range of traditional and new engineering applications. However, in order for MMCs to be brought to wider exploitation and increased engineering usage, several challenges must be overcome. The development and processing of low cost MMCs with controlled microstructure and mechanical properties is still very challenging. Uniform and homogeneous dispersion of micro/nano-reinforcement into the matrix material is difficult to achieve. One prospective way to achieve this is via a PM route involving high-energy milling. However, agglomeration and clustering in bulk materials can still be observed. One of the problems with clustering is that the clustered particles significantly reduce the failure strain of the composite. The reaction process between the bonding interfaces is still unclear and also a challenging issue. The interface plays an essential role to exploit the properties of the reinforcement, where weak bonding between reinforcement and matrix results in low mechanical and thermophysical properties of the composite. In comparison to solid state processing, liquid state processing maximizes the reactions between the phases. Over active interfacial reactions reduce the bond strength between these phases. The bonding between the reinforcement and matrix is also influenced by wettability between contact surfaces and this varies from material to material and also is dependent on the process used. In addition, the metal powders oxide state also has an effect on wettability. There is a current lack of detailed knowledge in the literature on how the particle oxide state affects these processes.166, 167 Chemical impurities, porosity, dislocations, and vacancy defects have a severe negative impact on the strength of MMCs.168 AM has entered the MMC world and some of the challenges for processes such as this are to produce as dense as possible a MMC and as well distributed a particulate reinforcement as possible. In addition to other challenges such as mitigation of residual stress and microstructure inconsistency, there are a limited number of materials that have appropriate interaction with a high energy laser beam.169 Some other challenges surrounding the production of MMCs are the control of the distribution of the composite reinforcement, understanding the role of individual reinforcements in hybrid composites, dealing with process limitations with respect to

reinforcement volume fraction, production of geometrically complex composites, transition to high volume and high rate of production, and process modeling.

Quantitative process simulation, process optimization, and process control are important for optimizing the MMC part properties and controlling internal defects. Property improvements particularly in toughness and ductility are still sought. To achieve this, systematic investigations are needed in order to provide full insight into process, microstructure, and property relations. Microstructure optimization of MMCs by heat treatment requires specialized equipment and expertise. In addition, the evaluation of the life cycle and the establishment of recycling strategies are challenging tasks when applied to these materials.

Technological and infrastructural obstacles hinder the full-scale industrialization of MMCs. Complex production routes, higher cost of some material systems, lack of theoretically predicted properties, lack of available design data, lack of standardization in manufacturing technologies, doubted recyclability, and reclamation are a few of the reasons that limit the uses of MMCs in various sectors in spite of their superior properties. Even though the use of a MMC materials are necessary if a special property profile can only be achieved by application of these materials, a cost-effective method for manufacturing composites is essential for expanding their applications. This is because the advantages of MMCs are more clearly recognized when there is a relatively clear cost-performance relationship in the component production.

6 SUSTAINABILITY

The development of viable techniques for the recycling and reclamation of MMCs is crucial to the commercialization of these advanced materials. Therefore, extensive research efforts on the development of ground-breaking more recyclable MMC materials and more efficient separations techniques are still needed. A study on solid-state recycling (direct recycling of scrap metal into bulk material using severe plastic deformation) of AMC concluded that recycled AMC can be used as an alternative high-strength material and as a secondary resource to overcome a shortage of primary resources.170 Another study stated that it is possible to separate molten matrix metals from the reinforcement in the composites using appropriate fluxes. It has been reported that it is possible to achieve 50 vol% matrix metal separation from Al_2O_3 short fiber and 20 vol% metal matrix separation from SiC whisker, from their respective reinforced 6061 alloy MMCs.171 Electrorefining in ionic liquid was also studied to recover aluminum metal from the AMCs. However, the energy consumption was higher compared to remelting with flux or filtration, or to the conventional aluminum recycling process.172 Due to environmental concerns, extensive research has focused on sustainable materials as reinforcements (industrial and agricultural waste) in MMC production. However, developments are still advancing for successful utilization of waste material as partial reinforcement in MMCs.173, 174 Today, virgin MMC material is being used in the production of certain metallic foams for industrial, automotive, aerospace, and defense applications such as heater exchangers, filters, crash absorbers, and solid fuel propellants. However, scrap MMC appears to be suitable also for such applications which would provide an attractive method of recycling.175, 176

7 PRODUCTION COST FOR SELECTED ROUTES

It has been found from this survey that today PM and casting are the top two choices for producing MMCs. It was also seen and briefly discussed above the potential of the disruptive

AM routes for processing MMCs. The cost of the production process has a significant influence on the process selection decision. Figure 5 compares production costs between casting, PM and AM. As illustrated in Figure 5A, the energy consumption per unit mass of AM is high comparing to casting and PM. Where some of the largest contributors to the total energy consumption in AM are laser, motors, pumps, heaters, computers, and system energy losses.177 The energy consumption in casting is normally proportional to the mass of the part produced, because the energy required to melt the material dominates. PM has the lowest energy consumption per unit mass and has a high raw material utilization, over 95%. These energy savings alone contribute considerably to the economic advantage offered by PM.178 It is also important to consider primary material production such as for powders as it can consume more energy than any of the processes mentioned here.179 Therefore, the low energy consumption per unit mass of PM is an encouragement for considering and using this process for processing MMCs. In fact, based on the survey above, this could be one of the reasons why PM is the most commonly used processes when it comes to research and development of MMCs.
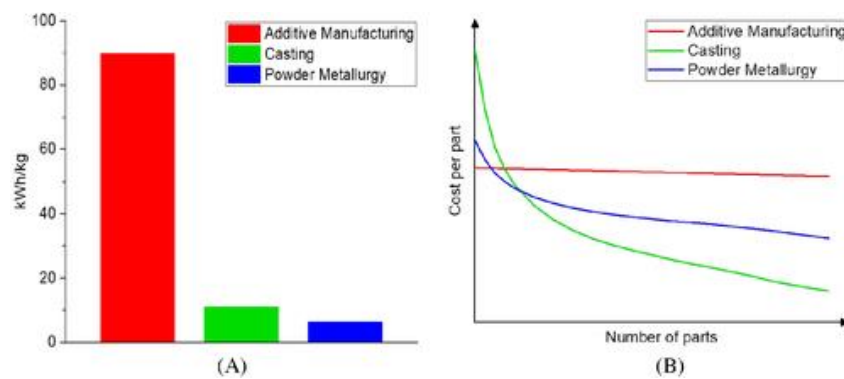

FIGURE 5: Comparison of production cost between casting, powder metallurgy and additive manufacturing route. Energy consumption per unit mass (A) and unit cost trends as a function production volume (B). The chart and plot were generated using information from References181-185 and 180, 186-191

Figure 5B depicts the part unit cost trends as a function production volume. Casting is the most expensive manufacturing route for small volumes due to equipment, tooling, and energy costs. However, as the production volume increases the cost decreases exponentially and after a threshold production volume, the casting route become extremely cost effective. PM is an most economical option than casting for production volumes of up to 20,000 per year.180 However, this may be valid for small and noncomplex parts. In AM, the manufacturing cost remains relatively constant even with an increasing production volume. However, the AM route is more economical when the total production volume is only a few hundred parts. Nevertheless, AM has a major advantage over casting and PM as it can produce small and medium-sized complex functional parts. Furthermore, 3D printer manufacturers are continuously improving their printers (ie, developing printers with industrial scale build volumes, multi-laser scanning and now starting to move toward robotized AM) and it is predicted that the cost of material and printers will gradually decline as AM becomes more popular. Hence, lowering the cost of additively manufactured parts.

8 MANUFACTURING PRODUCTION TRENDS FOR THE UPCOMING YEARS

The Dutch bank ING has estimated that AM will not catch up with conventional manufacturing until 2040 and 2060, Figure 6. Scenario 1 assumes the investment rate in AM machines will double after 5 years and the investment rate in conventional machines to fall back by 33% after 10 years. Scenario

2 assumes that the annual difference in investment rate continues to be 19% on average for coming decades, so that the capital stock and manufacturing production of AM machines will equal that of conventional machines in 2060. The predictions show that, if the current investment rate in AM machines continues, 50% of manufactured products will be additively manufactured by 2060, with this possibly being achieved as early as 2040. Automotive, aerospace, medical/dental devices, industrial machinery, and consumer products are the top industries investors in AM and are large players in word trade. Today, AM is still in its infancy and has very little effect on cross border trade. However, this will change once high speed mass AM production is economically viable. Mass production is not possible yet with most AM routes. However, aerospace companies have additively manufactured parts in series of tens of thousands. AM will increasingly dominate markets which are labor intensive, require customization and for complex shaped products, products that require much assembling, those involving high cost for transportation and inventory, and which generate much waste. AM can be seen is some cases therefore to lead to a lot of cost savings. However, two cost disadvantages are that high speed production is not yet possible and that quality of printed products fall short sometimes of what is required, making conventional manufacturing still required.192
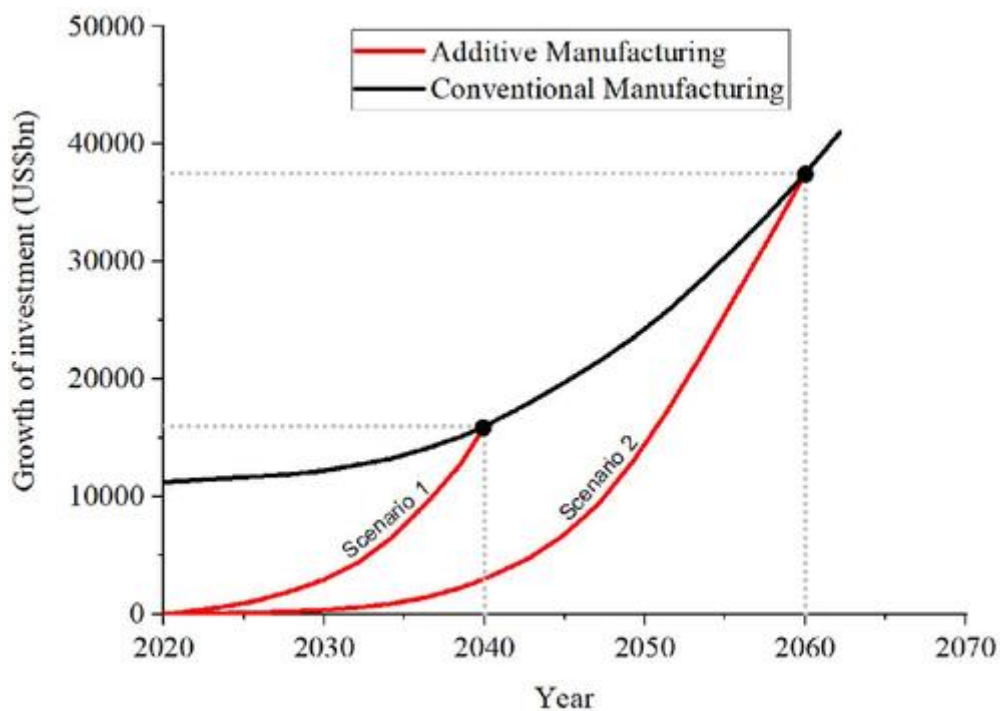

Figure 6: The predicted impact of additive manufacturing on the world manufacturing production.Source:Adapted from Reference192by permission from ING

9 VISION

For the various processes mentioned in this article, each one of them have their own advantages, disadvantages and limitations. Academic researchers have exploited these processes to some extent such that today their feasibility in terms of MMCs production is understood. In industry, many of these processes have been in use for producing MMCs for the last few decades. However, the growth of these processes in terms of usage has not advanced at as high a rate as may have been expected due to many factors such as lack of required trained operator, availability of tailored homogenously mixed materials, processing cost, processes reliability, limitations in composite geometry, reinforcement volume fractions, low production rate, pre/post process requirements, and slow multi-processing steps. AM, a relative new technology also applicable to composites, has clear potential to solve or lessen some of the presented problems in relation to production of MMCs. AM will possibly enable combining and

consolidation operations within the one process, which at the moment is difficult to achieve with the existing MMCs production routes. In the near future, with the re-design of AM machines, it is envisaged that it will be possible to print components having multi materials, matrices, and reinforcements. Also, depending on design creativity and component property needs it will be possible to incorporate tailored features such as a core material within critical regions of printed components. These are just some of many potentials that AM has for MMCs. AM will not solve all the problems currently faced with traditional production routes, but it will certainly change the direction of composites research and development, allowing the introduction of new advantageous characteristics to composite components. Also, as the ability to print MMCs advances it is expected more and more high-end application of MMCs such as those used in the automotive, aerospace, and electronics sectors are being manufactured via AM.

10 CONCLUSION

This paper is based on review of 944 of the most recent papers available which are focused on MMCs. The latest trends and developments in the miniaturization of processes and products as well as the demand of higher quality and multifunctional components has driven the development of new MMC materials. For widespread use and applicability, these materials should be environmental friendly, cost effective, and easy to produce. MMCs offer possibilities for the development of new materials that have a wide range of applications in high-tech manufacturing industries. Particles are the most common and least expensive form of dispersed materials as they are relatively easy to process and compatible with most conventional processing routes. The final properties of the composite materials strongly depend upon the matrix material, dispersed material and type (single, hybrid or coated), and the fabrication method used for MMC production.

Many MMC production routes are used in academia and industry. Minimum damage to dispersed phase, preservation of dispersed phase strength in the matrix, uniform distribution and promotion of wetting, and bonding between the matrix phases are the key factors that dictates the selection of production route for specific matrix and reinforcement materials. Twenty-five advanced production routes were reviewed from the 944 examined studies. However, PM and casting routes are commonly used in academia and industry for production of MMCs due to the ease of the process and the degree afforded of control over the interface between the matrix and dispersed phase. PM, as a solid-state process, ensures good wettability between dispersed phase and matrix, promotes homogeneous distribution of dispersed phase in matrix, and prevents formation of undesirable phases. Casting route for MMC production offers process simplicity, flexibility, and low cost. Aluminum alloys, in both academia and industry, are the most commonly used matrix materials. Beyond their properties, the choice for these materials is influenced by their low energy input requirements which make them suitable for most of the existing production routes. Carbides (SiC, TiC, and B4C), carbon allotropes (CNTs and graphene), and Al2O3 are the most used dispersed materials. Internal defects control, and related ductility and toughness improvements are the on-going challenges for MMCs production process development and implementation.

An increase in the usage of hybrid dispersed materials is noted in recent research studies. Hybrid dispersed materials offer the possibility to design composites that provide better all-around combinations of properties. These allow for more well-defined part properties. In industry, hybrid dispersed materials are successfully employed, bringing significant improvement to the physical, and mechanical properties of the produced composite components.

AM routes for fabrication of MMCs have been investigated more recently via a number of technologies (selective laser melting, laser metal deposition, laser cladding, ultrasonic AM, selective laser sintering, and binder jetting 3D-printing), see Figure 3. This represents 5.6% of the total research activity over

the last couple of years which is a significant emerging effort of international research activity to implement AM for MMC production. It is envisaged that AM could provide a new method for the production of tailored MMCs within a single step production process.

ACKNOWLEDGMENTS