Chapter

# Novel Applications of Aluminium Metal Matrix Composites

*Francis Nturanabo, Leonard Masu and John Baptist Kirabira*




## Abstract

Advanced materials have offered the materials designer a wide range of options in the specification and selection of materials for various applications. Material properties are continually being improved to meet safety and operational standards in line with prevailing technological developments. Modern technological requirements, together with the consumers' demands for systems and machines that are more energy efficient, stronger, light-weight, cost-effective, etc., dictate that the search for new and advanced materials will remain a subject of interest all the time. The difficulty in designing materials for such stringent specifications cannot be overstated, owing to the conflicting nature of these specifications. Aluminium metal matrix composites (AlMMCs) are a class of materials that have proven successful in meeting most of the rigorous specifications in applications where light-weight, high stiffness and moderate strength are the requisite properties. With a variety of reinforcement materials and flexibility in their primary processing, AlMMCs offer great potential for the development of composites with the desired properties for certain applications. In this review, the development, utilisation and future potential of AlMMCs in various industrial and commercial applications is discussed, together with the existing challenges hindering their full market penetration.


**Keywords:** aluminium, metal matrix composites, novel applications, light-weight, high-temperature



## 1. Introduction

The choice of the right materials is an arduous engineering challenge to the materials engineer and, if done carefully, can be a springboard to the proper and successful implementation and subsequent operation of the design. There are a host of materials available to the designer, and making the right decision is a vital achievement in putting forth a successful design. Materials are required to perform according to the designer's expectations and must possess and retain the right properties in the working environment throughout the working period.

Material selection is in most cases a contradictory decision-making process. Light-weight materials will most likely not possess sufficient strength, and brittle materials will not necessarily be good in fatigue resistance, stiffness or toughness. It is also almost impossible to find a single monolithic material with the required property profile for engineering applications. Moreover, material properties are greatly affected by the working environment (such as temperature, pressure, humidity, etc.) and the nature of loading (gradual, fluctuating, impact, fatigue, etc.). There is need, therefore, to combine two or more materials, as alloys or composites so as to utilise the different useful properties offered by the different materials. Most engineering materials appear in this configuration, and very few applications utilise pure monolithic materials [1]. This is true of aluminium, the most abundant metallic element in the Earth's crust, accounting for 8% of the planet's soil and rocks. Aluminium has been a metal of tremendous importance to the domestic and manufacturing industries from the mediaeval period (fifth–fifteenth century) and played an important role in the early years of the industrial revolution. The successful extraction and the first commercial applications of aluminium took place in the nineteenth century, the period in which the enthusiasm for new materials and their possible uses was immense [2].

The first mention of aluminium as a metal of industrial importance indicated the metal was first utilised in the manufacture of household and ornamental items before becoming an important material in the construction of large industrial structures and machine components. With the advent of alloying technology, the use of aluminium was developed farther and positioned aluminium as the most utilised industrial metal for decades. The popularity of aluminium grew due to its good attributes related to its unique properties, mainly of light-weight combined with good thermal/electrical conduction and reasonably good strength and resistance to corrosion. With alloying, aluminium has found more applications than previously envisioned, making aluminium a serious competitor with (and sometimes a preferred alternative to) the traditional "strong" metals iron and steel [3].

Aluminium alloys and composites have, in most applications, exhibited superior performance compared to their rival metals. The choice of aluminium alloys and composites derives from one important attribute of aluminium metal—light-weight. Light-weight translates into many important outcomes in engineering applications. In the automotive industry, it means less dead weight, lower fuel consumption, lower emissions, increased payload (for passengers and cargo) and easier handling. In the aerospace and aircraft industry, it translates into more payload (cargo), less fuel and lower emissions. There are similar advantages in all areas where aluminium is utilised—marine, rail, packaging, thermal management, building and construction, sports and recreation, etc. Aluminium's good electrical and thermal conductivity have seen its increased use in electrical conductors, electronic packaging and thermal management. Nowadays, aluminium is viewed as an important material for energy conservation and environmental protection [4].

Modern technology aims at meeting the market whose standards are ever appreciating. The market demands faster, more comfortable and hassle-free transport, more compact and lighter machines and tools, more efficient methods of power generation, etc. Most engineered materials can easily meet or surpass design specifications that would not have been envisaged a few years back. Today's materials are subjected to more critical loads, more stresses and more severe operating conditions in an environment never experienced before. In a spacecraft, for example, the operating conditions experienced are quite unique and require special types of materials to withstand the severe stresses imposed on the spacecraft during take-off and maintenance in the orbiting space. Traditional materials have been found wanting in meeting these operating conditions and hence the need to intensify research and development (R&D) efforts in new and advanced materials for specific applications and efficiency improvement. Among the advanced materials on the R&D, the menu is the metal matrix micro- and nano-composites. Metal matrix composites (MMCs) are metals or metal alloys that incorporate particles, whiskers, fibres or hollow microballoons made of a different material and offer unique opportunities to tailor materials to specific design needs [5]. In automotive applications, for example, these materials can be tailored to be light-weight and with various other useful properties including high specific strength and specific stiffness, high hardness and wear resistance, high thermal conductivity, high energy absorption and a damping capacity and low coefficients of friction and thermal expansion.

MMCs, therefore, offer more possibilities for wider applications of materials by manipulating their processing to suit the requisite properties under different working environments. The design of composite materials with specific properties can, moreover, be accomplished with the use of finite element modelling techniques. It is possible to predict the properties of a certain material of specified composition by using these techniques. In the same way, it is possible to design materials to offer specified properties by the use of these techniques [1].

## 2. Types of metal matrix composites and their methods of production

### 2.1 An overview of metal matrix composites

A composite is a mixture of two or more constituents or phases which are chemically distinct on a microscopic scale, separated by a distinct interface, and can easily be specified. In addition, other criteria are normally satisfied before a material can be called a composite. The constituents have to be present in reasonable proportions, and the constituent phases should have distinctly different properties, such that the properties of the composite are noticeably different from the properties of the constituents [4]. The constituent which is continuous and in most cases available in larger quantities is termed the *matrix*. It is commonly viewed that it is the properties of the matrix that are improved upon in the process of producing a composite. The second constituent is known as the reinforcing phase, or *reinforcement*, as it enhances or reinforces the mechanical properties of the matrix. In most cases the reinforcement is harder, stronger and stiffer than the matrix, although there are some exceptions. The matrix may be in form of a ceramic material, metallic or polymeric, with each of these three classes of materials having considerably different /unique mechanical properties. Generally, polymers have low Young's moduli and strengths; ceramics are strong, stiff and brittle; and metals have intermediate moduli, strengths and good ductility [6].

Composite materials are usually classified according to the physical or chemical nature of the matrix, e.g. metal matrix, polymer matrix and ceramic composites. Additionally, the emergence of the intermetallic matrix and carbon matrix composites as reported by [7] has broadened the scope of composites. Intermetallic compounds are metal-based systems centred on the fixed atomic compositions occurring in metallic systems of aluminium with nickel (Ni), titanium (Ti) and niobium (Nb), such as $Ni_3Al$, $Ti_3Al$, TiAl and $Nb_3Al$. Intermetallic compounds are of interest because they often exhibit higher melting points and less ease of deformation due to the lattice arrangement of their atoms [8].

In certain applications, metal matrix composite materials, formed by combining two or more materials—one of which is a metal—exhibit a primary advantage over their counterpart organic matrix composites in regard to the maximum operating temperature. To support this point, [9] reports that the boron/aluminium composite offers useful mechanical properties up to a temperature of 510°C, whereas an equivalent boron/epoxy composite is limited to about 190°C. Furthermore, composites of graphite/aluminium, graphite/copper and graphite/magnesium exhibit higher thermal conductivity due to the significant contribution from the metallic matrix. A metal matrix composite retains the desirable properties of both the matrix and the reinforcement by combining the strength of its reinforcement with the ductility of its matrix [10]. The reinforcing constituent may be a particle, platelet, short fibre or continuous fibre and may range from sub-micrometre to millimetre in size. There is a difference between metal matrix composites and multiphase metallic alloys as the concept of MMCs introduces additional degrees of freedom into designing the microstructure. Materials with desirable properties not obtainable by conventional alloying and heat treatment can be created compositing. This can be achieved by altering the reinforcement type (metallic, ceramic or polymeric), content (volume fraction), size, shape, distribution and orientation [11].

In the early development of MMCs, continuous ceramic fibres and single-crystal ceramic whiskers were the preferred reinforcements as they provided the most remarkable increase in strength and stiffness. Later, particulate and discontinuously reinforced MMCs then followed, registering substantial progress on many fronts especially in composites with aluminium as the metal matrix. In aluminium metal matrix composites (AlMMCs), aluminium or its alloy forms a percolating network and is the matrix phase, while the other constituent, which is embedded in this matrix, is the reinforcement. The reinforcement is usually ceramic such as silicon carbide (SiC) or aluminium oxide ($Al_2O_3$). The properties of AlMMCs can be varied by varying the nature of the constituent phases and their volume fractions [4].

Although the MMCs have been in existence since the 1960s, they have not been put to full commercial use due to their higher production costs and lack of proper understanding of their high-temperature behaviour [12]. The higher costs are mainly attributed to the machining processes requiring tool materials to have very high wear resistance because of the reinforcement component being extremely abrasive [13]. However, with the invention of functionally graded materials (FGMs), it is now possible to reduce the cost of secondary processing. FGMs are an emerging category of advanced materials that exhibit gradual microstructural transitions and/or the composition in a specific direction and hence different functional performances within a part [14, 15].

The rapid growth and development of AlMMCs happened in the years after the launch of the Aluminium Metal Matrix Composites Roadmap 2002, a policy document produced by the Aluminium Metal Matrix Composites Consortium with support from the Technology Research Corporation (TRC) of the United States and other stakeholders. The document spelt out a pathway for the AlMMCs' growth in 20 years from 2002 and asserted the industry's vision to position AlMMCs as the material of choice in a broad range of structural and nonstructural applications. This vision was to be achieved by addressing three strategic goals, namely:

i. To reduce the cost of discontinuously reinforced AlMMCs to be comparable to existing alternatives by 2010

ii. To develop the necessary infrastructure to provide design confidence for AlMMCs

iii. To increase the market size for AlMMCs

By that time, AlMMCs had proved their potential in such applications as aerospace, automotive, electronic packaging, commercial and industrial markets. The market was projected to grow at a 14% overall rate to $173 million by 2004. The industry believed then that there was much greater unrealised potential for growth [16].

### 2.2 Classification of metal matrix composites

Metal matrix composites can be classified into several distinct classes, generally defined with reference to the type, shape and method of their reinforcements. The following classification is relevant to MMCs with aluminium as the matrix metal as explained in [4] and [11]. Typical microstructures are shown in **Figures 1** and **2**.

*Particle-reinforced MMCs*: Invariably known as particulate-reinforced MMCs, these composites generally contain equi-axed ceramic reinforcements, mainly oxides (e.g. alumina, $Al_2O_3$), carbides (e.g. silicon carbide, SiC) or borides (e.g. titanium bromide, $TiB_2$), with an aspect ratio less than 5 and present in volume fraction less than 30%. They can be produced by blending metal and the ceramic powders, followed by solid-state sintering or by liquid-metal techniques such as stir casting, squeeze infiltration and in situ processes.

*Continuous fibre-reinforced MMCs*: These contain either relatively fine continuous fibres, usually of $Al_2O_3$, SiC or carbon, with a diameter below 20 μm, or coarser fibres or monofilaments. The former can be either parallel or pre-woven prior to infiltration to form a composite, while the bending flexibility of the latter limits the range of shapes that can be produced. Monofilaments are large diameter (100–150 μm) fibres, usually produced by chemical vapour deposition (CVD) of either SiC or boron (B) into a core of carbon fibre or tungsten (W).

*Whisker- and short-fibre-reinforced MMCs*: These contain reinforcements with an aspect ratio of greater than 5 but are not continuous. Short $Al_2O_3$ fibre-reinforced MMCs have been dominantly used in pistons. Whisker-reinforced composites, produced by either powder metallurgy or squeeze infiltration into a fibre preform, are generally produced to net/near-net shape. However, usage of whiskers as reinforcements is being restricted due to perceived health hazards.

*Hybrid MMCs*: Hybrid MMCs essentially contain more than one type of reinforcement, for example, a mixture of particle and whisker, a mixture of fibre and particle or a mixture of hard and soft reinforcements. With the discovery of carbon nanotubes (CNT), composites with superior mechanical properties over those of carbon have been produced [19].

Other MMCs with variety of matrices other than aluminium include: *Cemented carbides* (*cermets*)—which are made by powder blending of a high proportion (60–75%) of ceramic or titanium carbide (TiC) with a metal such as cobalt, followed by holding for a short period at a temperature sufficient to melt the metallic constituent (liquid-phase sintering). In situ composites—in which directional solidification is used to form relatively fine aligned two-phase fibre or lamellar structures, resulting in an intermetallic reinforcement with high stiffness and strength. *Co-deformed composites* - in which immiscible metals are co-deformed such that filaments of the second phase with very large aspect ratio are formed within the matrix material. Typical examples include Cu-Cr and Cu-Nb systems. Cermets have outstanding high-temperature strength and are widely used for tool bits [11].

### 2.3 Methods of production of AlMMCs

Primary compositing processes for manufacturing of AlMMCs at industrial scale can be classified into two main groups, namely, (1) liquid-state processes and (2) solid-state processes [4]. The liquid-state processes are further classified into liquid-metal-mixing processes and liquid-metal-infiltration processes. Specifically, liquid-metal mixing is the primary compositing route for producing materials

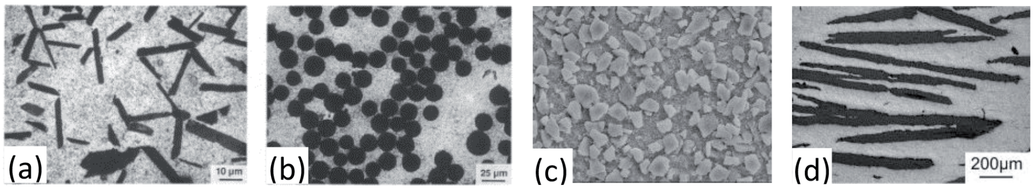


**Figure 1.**
*Typical microstructures of AlMMCs. (a) Al/$Al_2O_3$ platelets. (b) Al/$Al_2O_3$ continuous fibres. (c) Al/$SiC_p$. (d) Al/graphite with 20 vol.% graphite flakes taken along the basal plane (source: [17, 18]).*

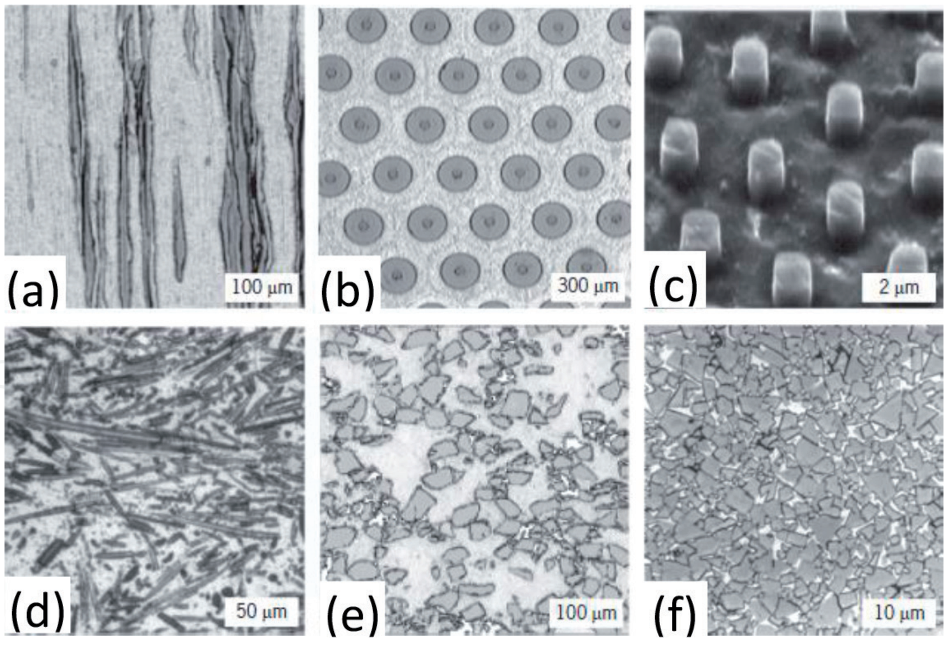


**Figure 2.**
*Typical microstructures of MMCs. (a) Cu/Cr co-deformed composite. (b) Ti-6Al-4 V/SiC monofilament. (c) NiAl/Mo in situ composite. (d) Mg/$Al_2O_3$ short-fibre composite. (e) Al/SiC particulate composite. (f) Co/WC cermet (source: [11]).*

considered for high-volume automotive applications, liquid-metal infiltration for high-volume electronic packaging applications and solid-state processing for high-performance aerospace applications [20].

### *2.3.1 Liquid-metal-mixing processes*

The liquid-metal-mixing process involves the incorporation of reinforcement particles or short fibres into a molten or semi-solid aluminium matrix through a stirring process. In stir casting technique, the process involves the incorporating of ceramic particulate into liquid aluminium melt and allowing the mixture to solidify. It is crucial to ensure that good wettability between the particulate reinforcement and the liquid aluminium alloy melt is achieved. Generally it is possible to incorporate up to 30% ceramic particles in the size range from 5 to 100 μm in a variety of molten aluminium alloys [16]. Surappa [4] identifies another variation of the stir casting process, called *compo-casting*, in which ceramic particles are incorporated into the alloy in the semi-solid state.

Particulate-reinforced AlMMCs have been commercially available in significant quantities since the 1990s. The interest in these MMCs was driven by the combination of improved mechanical and physical properties imparted by the reinforcement while still maintaining the favourable metalworking characteristics and predominantly metal-like behaviour. A second motivating factor was the ability to tailor the mechanical and physical properties through selection of the reinforcement composition along with the matrix alloy.

### *2.3.2 Liquid-metal-infiltration processes*

In the liquid-metal-infiltration process, the molten aluminium or its alloy is moved into a preform of the reinforcement, either as a packed bed or a rigid, free-standing structure. In order for the preform to retain its integrity and shape, it is often necessary to use silica- and alumina-based mixtures as a binder. Some degree of pressure is needed to overcome the wetting and capillary resistance, and this can vary from atmospheric to thousands of *Pascal*. In this process, the concept was to take advantage of the excellent reinforcement properties in a product that was essentially formed to net shape by the casting process. This process can produce materials with a range of reinforcement volume fraction but is especially well suited for reinforcement levels above 50% and in some cases approaching 80%. As a result, the materials produced by this process are well suited for electronic packaging [19, 21].

Other variations of this technique include *spray deposition* and *in situ (reactive) processing*. In spray deposition techniques, the droplet stream may either be produced from a molten bath (Osprey process) or by continuous feeding of cold metal into a zone of rapid heat injection (thermal spray process). This process has been extensively explored for the production of AlMMCs by injecting a ceramic reinforcement into the spray. The AlMMC processed by spray deposition technique is relatively inexpensive with a cost that is usually intermediate between stir cast and P/M processes. *In situ processing* applies to several different processes, which include liquid-solid, liquid-liquid, liquid-gas and mixed salt reactions. These processes lead to the formation of a refractory reinforcement in the aluminium alloy matrix. For example, in the directional oxidation of aluminium (the DIMOX process) [4], the alloy of Al-Mg is placed in a crucible on top of a ceramic preform and the entire assembly heated to a suitable temperature in an atmosphere of free-flowing nitrogen-carrying gas mixture. The molten Al-Mg alloy then infiltrates into the preform—forming the composite [22].

The liquid-metal-infiltration process was first successfully demonstrated in the production of the Toyota piston in which a discontinuous fibre preform was infiltrated by squeeze casting to provide a local improvement in wear resistance in the piston ring land area. The technology has since been adopted for the manufacture of several automotive and military powertrain and suspension components [20].

#### 2.3.3 Solid-state processes

Solid-state processes involve the mixing of reinforcement (particles or whiskers) into a solid-state matrix. Historically, these methods employed solid-state-based processes, such as powder metallurgy (P/M), to produce AlMMCs with the highest combinations of properties. Therefore, these materials are primarily employed in higher-performance applications, especially in the aerospace and automotive markets, where these materials are used in high-performance components, mostly those dominated by fatigue. Initially, ceramic-whisker materials were produced, and subsequently, ceramic-particulate-reinforced materials followed. These materials, while expensive both in terms of the reinforcement and processing costs, developed dramatically improved properties over the base metal and were used in a number of high-performance applications, both military and commercial. However, due to the health risks posed by whisker-reinforced MMCs, particulate-reinforced MMCs have replaced them in many applications, leaving the whisker-reinforced MMCs for specialised military applications [23]. Particulate reinforcement, besides being of lower cost, also exhibited improvements in strength and stiffness almost as high as those obtained in whisker-reinforced materials.

Variations in solid-state processing have been identified (see, e.g. [4]):

*Powder blending and consolidation (P/M processing):* Blending of aluminium alloy powder with ceramic short fibre/whisker is a versatile technique for the production of AlMMCs. Blending is usually followed by cold compaction, canning, degassing and high-temperature consolidation stages such as hot isostatic pressing (HIP) or extrusion. Depending on processing conditions, AlMMCs processed through the P/M route may contain oxide particles in volume fractions ranging from 0.05 to 0.5 and in the form of platelets of few tens of *nanometres* in thickness.

*Diffusion bonding*: Monofilament-reinforced AlMMCs are mainly produced by the diffusion bonding route or by evaporation of relatively thick layers of aluminium on the fibre surface. The 6061 Al-boron fibre composites have been produced by this process. The process is more commonly used in production of Ti-based fibre-reinforced composites. However, it is a cumbersome process and is not suitable for production of complex shapes.

*Physical vapour deposition*: In this process, the continuous passage of fibre is passed continuously through a region of high partial pressure of the metal to be deposited. Here condensation takes place, producing a relatively thick coating on the fibre. Vapour deposition is then accomplished by directing a high-power electron beam onto the end of a solid bar feedstock. Typically, deposition rates per minute are in the range of 5–10 μm. Composites with volume fraction as high as 80% can be produced by this technique.

## 2.4 Properties of AlMMCs and resulting end uses

### *2.4.1 Properties of aluminium and AlMMCs*

Generally, aluminium has derived its importance in industrial and commercial applications due to the following attributes, most of which are imparted to its alloys and/or composites:

i. Aluminium is light; its density is only one-third that of steel.

ii. Aluminium is resistant to weather, common atmospheric gases and a wide range of corrosive liquids.

iii. Aluminium is safe and can be used in contact with a wide range of foodstuffs.

iv. Due to its high reflectivity, aluminium is usually employed in a number of decorative applications.

v. The strength of aluminium alloys can equal (and sometimes exceed) the strength of normal construction steel.

vi. Aluminium is highly elastic, a property which qualifies it to be employed in structures subjected to shock loads.

vii. Aluminium has a unique behaviour of maintaining its toughness down to very low temperatures, unlike carbon steels which would otherwise suffer embrittlement.

viii. Aluminium exhibits ease of workability and formability and can easily be rolled to very thin gauges.

ix. Aluminium conducts electricity and heat nearly as well as copper.

With alloying and compositing, these attributes are enhanced, and the shortcomings of the base aluminium metal are improved tremendously. The major improvements in the properties of AlMMCs are manifested in form of greater strength and improved stiffness, reduced density, improved abrasion and wear resistance, improved high-temperature properties, better control of thermal expansion coefficient, better thermal/heat management, enhanced and tailored electrical performance, better control of reciprocating mass and improved damping capabilities.

The above advantages have been quantified for a better appreciation. For example, [4] reports that the elastic modulus of pure aluminium can be enhanced from 70 to 240 GPa by reinforcing with 60 vol% continuous alumina fibre. Also, a decrease in the coefficient of thermal expansion from 24 to 7 ppm/$^{o}$C can be achieved by incorporation of 60 vol% alumina fibre in pure aluminium.

With the advent of nanostructured materials, new materials have been developed with exceptional properties exceeding those expected for monolithic alloys or composites. For example, carbon nanotubes have ultrahigh strength and modulus; when included in a matrix, they could impart significant property improvements to the resulting nanocomposite [5]. Jun and co-workers [24] present quantifiable results to the effect that incorporating only 10 vol% of 50 nm alumina particles to an aluminium alloy matrix using the powder metallurgy process increased yield strength to 515 MPa—which is 15 times stronger than the base alloy and over 1.5 times stronger than AISI 304 stainless steel.

### *2.4.2 AlMMCs end uses*

Aluminium metal matrix composites are increasingly registering success as “high-tech” materials in various applications. Significant performance-related benefits and economic as well as environmental benefits have been realised as a result of utilisation of AlMMCs. Notable among them are improved properties, increased component lifetime, improved productivity, energy savings, lower maintenance costs and environmental benefits such as lower noise levels and fewer airborne emissions. These composites can replace monolithic materials that include ferrous alloys, aluminium and titanium alloys and polymer-based composites in many applications. For widespread replacement, the whole system may be redesigned in order to gain additional weight and volume savings. Ideally, AlMMCs can be viewed not only as a replacement for existing materials but also as a means of enabling radical changes to the product or system design [4].

Engineering viability of AlMMCs in a number of applications has been well-documented. AlMMCs having a different type of reinforcements and produced both by solid-state and liquid-state processing have been used in many engineering applications. Some of the newer and visible applications of different types of AlMMCs are detailed below.

*Particle-reinforced aluminium metal matrix composites* produced by P/M stir cast/melt infiltration/spraying/in situ processing techniques at industrial level with particulate reinforcements of SiC, $Al_2O_3$, TiC, $TiB_2$ and $B_4C$ have been successfully used in the manufacture of automotive and aerospace components and thermal management. In the gas turbine engine, particle-reinforced AlMMCs have been used in fabrication of fan exit guide vanes (FEGV). They are also used as rotating blade sleeves in helicopters and as ventral fins and fuel access cover doors in military aircraft [25]. Flight control hydraulic manifolds made of particulate silicon carbide (about 40 vol%) reinforced AlMMCs have been successfully used. On a high-volume basis, applications of particle-reinforced AlMMCs have been reported in braking systems of trains and automobiles. Presently AlMMC brake discs are extensively used in European railways and certain models of passenger cars in the United States. Other applications in the automotive industry include valves, crankshafts, gear parts and suspension arms. In recreation and sports, particle-reinforced AlMMCs are used in production of a variety of products including golf club shaft and head, skating shoe, baseball shafts, horseshoes and bicycle frames. Aluminium metal matrix composites containing high volume fractions of ceramic particles are used as microprocessor lids and integrated heat sinks in electronic packaging. They are also in use as carrier plates and microwave housing.

*Whisker- and short-fibre-reinforced aluminium metal matrix composites*: In the wake of greater health risks associated with the handling of ceramic whiskers, production of whisker-reinforced aluminium composites has been limited to specialised use such as the production of track shoes in advanced military tanks. Short-fibre-reinforced AlMMCs are being used in piston and cylinder liner applications [26].

*Continuous fibre-reinforced aluminium matrix composites*: Carbon fibre-reinforced AlMMCs have been used as antenna waveguides for the Hubble Space Telescope for their ability to provide high dimensional accuracy and high thermal and electrical conductivity with no outgassing oxidation resistance. The 6061 Al-boron continuous fibre composites have been used as struts in the main cargo bay of space shuttles. The 3M™ company developed continuous fibre AlMMCs which offer strength equivalent to that of high-strength steel at less than half the density and which retain their strength beyond 300°C [4]. These composites possess four times the electrical conductivity of steel (or half that of pure aluminium) and have been targeting various functional applications, such as (a) core of overhead electrical conductors, (b) automotive push rods, (c) energy storage flywheels, (d) retainer rings for high-speed motors and (e) automotive brake callipers. Aluminium metal matrix composites enable the use of smaller flywheels compared to polymer composites. Thin-walled retainer rings of AlMMCs provide excellent advantages in high-speed motors and can resist very high rotational speeds and still maintain their precise shape. Compared to cast iron, AlMMCs brake callipers made of continuous fibre reinforcement offer such benefits as increased damping, reduced unsprung weight, increased fuel efficiency and improved performance, handling and ride.

Detailed applications and the current state of utilisation are covered in Chapter 3.

## 3. The current state of applications of AlMMCs in various industries

### 3.1 AlMMCs in innovative light-weight designs

#### *3.1.1 Automotive industry*

The automotive market represents the largest current market for AlMMCs on a volume basis. The potential for AlMMCs in this area is barely tapped, however, and represents a great opportunity for substantial growth. Through R&D, lighter, engineered materials are being developed which offer better performance than the existing materials. Replacement of steel and cast iron in internal combustion engine applications as well as in unsprung weight components, such as the brake system, is judged the most promising for the near term.

Aluminium metal matrix composites are suitable replacements, not only for steel but also for aluminium alloys in various automotive systems and components. There are many ways to achieve light-weight without compromising the strength and safety requirements. Ideally, it is common practice to completely replace the existing structural material with the material of higher yield strength, with a possible reduction in section dimensions. The other way of achieving weight saving is to selectively replace conventional steel at specific areas with the lighter materials. By applying the mass reduction techniques, the mass of vehicles can be reduced independent of vehicle size, functionality, class or model [1]. In most of these techniques, lower density aluminium composites continue to replace the carbon steels. Aluminium-based engine blocks, suspension components, body panels and frame members are increasingly becoming common [27]. Most cylinder heads are aluminium-based, and by 2005, engine blocks made from aluminium in the US light-duty vehicles passed the 50% mark, surpassing steel in this area for the first time [28]. However, engine blocks typically require cast iron cylinder liners due to the inferior wear properties of aluminium—a shortcoming that has attracted considerable research and development (R&D) efforts, leading to some positive results. For example, [5] reports about the progress made in the development of aluminium alloy cylinder liners containing dispersed graphite particles that provide solid lubrication. Aluminium alloys and composites are also competing to replace many various traditional steel components in vehicles, such as valve covers, torque converter and transmission housings, crankcase, control arms, cradles, suspension links, door frames, steering wheels, dashboards, sheet panels and beams are also being replaced by alloy aluminium alloys and composites [29]. New areas are being explored for aluminium-based materials, and these include "all aluminium" bodies, bumpers, crash management systems and unibody construction [30].

The automotive breaking system components, such as the disc brakes and callipers, are another area where significant weight savings can be realised by utilising AlMMCs. Most modern vehicle models including Lotus Elise, General Motors EV1, Chrysler Prowler, Volkswagen Lupo 3 L and Toyota RAV4 EV have used SiC-reinforced aluminium brake rotors [31]. Regarding the chassis, the requirements for vehicle performance and survivability of occupants in severe crashes dictate that chassis materials should possess adequate strength and toughness. Aluminium-fly ash (a waste by-product of coal power plants) cenosphere syntactic foams can be used to reinforce box or tubular frame sections in crumple zones to increase torsional rigidity and energy absorption upon vehicle impact [32]. Further cost/weight savings can be realised by incorporating fly ash in the aluminium matrix for components that do not experience extreme loading. In the suspension system, the use of aluminium-based materials has led to reduction in the unsprung weight, consequently, improving vehicle dynamics. Control arms and wheel hubs made of SiC-reinforced aluminium nanocomposites have exhibited improved strength characteristics similar to cast iron while using less material than aluminium. Self-lubricating graphite-reinforced aluminium bushings can also be incorporated into control arm castings to allow for service-free components [5].

Apart from the core body frame structure, weight saving technology features in other areas can add up to substantial secondary weight reductions elsewhere. Lighter roof panels, side panels and beams are being offered by different vehicle manufacturers with thinner gauge high-strength steel (HSS), aluminium and some limited magnesium [33]. Significant weight reductions are being registered within the suspension and chassis system by utilising "alloy" (i.e. aluminium alloy) wheels and redesigned braking systems. In addition, many suspension and chassis parts can realise secondary weight savings from reduction in their size that result from weight reductions elsewhere on the vehicle [1].

There is a limit to the savings made. Although primary weight savings also enable downsizing many of the other vehicle systems, a study sponsored by the National Highway Traffic Safety Administration (NHTSA) evaluated the maximum weight reductions possible for some car models. Using Honda Accord as the study sample, it was found out that the baseline body-in-white (BIW) mass, which was 48% HSS, could be reduced by 22% with advanced high-strength steel (AHSS) and by up to 35% with an aluminium-intensive design [1, 34]. In another study conducted by IKA, University of Aachen (Germany), it was observed that it was possible to obtain a weight reduction of their "alumaximised" model car from 1229 to 785 kg, after primary and maximum secondary weight savings [35].

Weight reduction has been driven to higher heights by new and advanced technologies and concepts. The new concept of "multi-material designs", used mainly for high-volume production, is an alternative to the "all-aluminium" designs of BIW. The concept consists of mixing various materials to benefit from their individual advantages. To this end, it is possible to use aluminium together with high- and ultrahigh-strength steels, magnesium and plastics or composites, where applicable [1]. The driving force behind this concept is to use the "best and most suitable" material for the appropriate functions in order to achieve an overall cost-efficient light-weight design. This concept has been championed by some European car manufacturers, notably, BMW, in their 5 E60 series which utilises 20% as deep-drawing steels, 42% as higher-strength steels, 20% as ultrahigh-strength steels and 18% aluminium alloys. The front-end substructure consists of 16.4 kg steel, and 29.4 kg is made of 86 aluminium-based parts (stamped sheet, extrusions, high-pressure die castings and hydroformed tubes) [35, 36].

The multi-material design concept was adopted and further developed by the SuperLIGHT-CAR (SLC) project. Under the umbrella of the European Council for Automotive Research (EUCAR), the European Commission (EC) in the year 2005 co-funded the 4-year collaborative SLC project, whose overall objective was to develop truly light-weight multi-material car concepts up to 50% lighter than the high-volume cars produced in the year 2004. The SLC project, recognising the importance of weight reduction as one of the most effective ways of reducing fuel consumption and $CO_2$ emissions in the road transport sector, embarked on developing the integrated knowledge and technological capabilities needed to design and manufacture multi-material car bodies with reduced raw material consumption of up to 30% [37]. This was achieved by an ingenious mix of metals headed by aluminium. The multi-material concept consequently exceeded the initial target and yielded a 35% (or an equivalent of 101 kg) weight reduction compared to the reference 2004 benchmark of a VW Golf V [38].

Lutsey [27] reports that reductions are more likely to be registered in manufacturing costs for vehicle mass reduction options up to about 20% for the light-duty vehicles in the 2009 fleet. Quoting the IMPACT Ford F150 project as an example, it is reported that the vehicle designs that reduced the pickup's mass by 19% were achieved at net-zero manufacturing cost, whereas the full 25% mass reduction package came with a $ 500 per vehicle cost increase. Other studies involving aluminium-intensive designs also showed the potential for minimal net-vehicle costs with substantial mass reductions. The SLC multi-material design also shows the feasibility of a unibody structure of aluminium, magnesium and composites that delivers up to a 39% body mass reduction and with costs that are less than €10/kg-saved. The Lotus High Development vehicle study [39] found out that a 33% mass reduction is achievable at a 3% cost increase, which would roughly correspond to a $ 400–600 per vehicle increase in manufacturing cost. All these studies attest to the fact that it is possible to register significant cost reductions by increasingly making use of AlMMCs.

### *3.1.2 Aerospace and aircraft industry*

Aluminium alloys and composites have played a big role in the advancement of aircraft and rocket technology. Right from the Wright brothers' utilisation of aluminium in the engine of their first biplane to NASA's use of an aluminium-lithium alloy in the spacecraft, aluminium has created and enhanced the mankind's potential to fly around the Earth and into the outer space.

Aluminium alloys and/or composites are the favoured choice for the fuselage, wing and supporting structures of commercial airliners and military or cargo aircraft. The airframe of a typical modern commercial transport aircraft is composed of 80% aluminium by weight. Attention is now focused towards aluminium casting technology, which offers lower manufacturing costs, the ability to form complex shapes and the flexibility to incorporate innovative design concepts.

Aluminium metal matrix composites have been the material of choice for space structures of all types ever since the launch of Sputnik 1 (October 4, 1957). Chosen for their light-weight and their ability to withstand the stresses that occur during launch and operation in space, AlMMCs and alloys have been used on Apollo spacecraft, the Skylab, the space shuttles and the International Space Station. Aluminium alloys/composites consistently exceed other metals in such areas as mechanical stability, dampening, thermal management and reduced weight [40].

#### *3.1.3 Rail transport*

Aluminium railroad cars were pioneered for the railroad industry in the late 1950s and are still the material of choice for this mode of transportation. Rail cars, designed with aluminium-based extrusions, require one-third the number of components, have reduced welding needs and are two-thirds the weight of comparable steel cars. The higher carrying capacity of aluminium repays its higher initial cost in less than 2 years, and the life-cycle fuel costs are lower due to the lighter weight of the car [41]. Aluminium-based materials offer excellent resistance to corrosion and high salvage value.

Designing with aluminium results in light-weight cars that retain the strength of steel cars but can carry greater loads, hence saving money in increased freight and reduced fuel costs. The third generation of the French TGV Duplex high-speed train is a good example in this case. The train converted from steel to aluminium-based materials, resulting in a 20% weight saving, while at the same time converting to two decks and keeping the axle load below 17 tons. Similarly, the Japanese high-speed "bullet" train and the Washington DC Metro trains are also made with aluminium-based materials.

The durability of aluminium makes it a suitable material for the railroad environment. Extensive shaking tests and decades of use offer testimony to aluminium's superiority for this application. A recent study shows that after 20 years of service, there is a negligible loss of metal thickness or surface defects on cars used to ship different materials an average of 110,000 miles per year. Metal loss on floors and sidewalls from corrosion and wear measured approximately 25% less than comparable steel cars [42].

#### *3.1.4 Marine transport*

Marine transport has also been revolutionised with the use of aluminium alloys and composites. The use of these materials has enabled an increase in the speed and size of boats, yachts, ferries and ships while improving their fuel efficiency, seaworthiness, safety and reliability and reducing maintenance costs. By substituting aluminium for steel, weight savings of 35–45% in hulls and 55–65% in superstructures can be achieved [42]. Higher vessel speeds and load capacities translate into extra traffic volume and profits for a ship or boat operator.

It is also possible to increase vessel volume and height without loss of stability. Passenger compartments can be larger, and more cabins can be located above sea level. The use of aluminium-based materials also ensures increased manoeuvrability and access to shallow draught ports.

Aluminium-intensive cargo ships with load capacities up to 3000 metric tons have been designed to operate at up to 60 knots, crossing the Atlantic in under

60 hours. Military requirements seek smaller, more agile vessel designs with a lower radar cross section and capable of 60–80 knots or more—another excellent fit for aluminium, which is made possible due to advances in manufacturing methods, such as friction-stir welding and structural bonding.

Aluminium-based materials satisfy the requirements of the International Maritime Organization high-speed code for vessel design, safety and control of fire risk. Compared to steel, aluminium performs better in handling the torsional, flexural, compression and impact loads of high-speed water travel [42].

### *3.1.5 Building and construction industry*

In 2009 the building and construction market constituted the third largest North American market for aluminium. Strength and stiffness are the two most important characteristics for structural applications of aluminium-based materials. The composites of aluminium such as the fibre-reinforced alloys of aluminium, discontinuously reinforced aluminium (DRA) and the conventional metals and graphite/epoxy composites provide the good uniaxial specific stiffness and specific strength and hence are the materials of choice for applications where maximum structural efficiency is the primary selection criterion [43].

Aluminium was first used in large quantities for building and construction in the 1920s, with the applications primarily oriented towards decorative detailing and art deco structures. Nowadays, aluminium-based materials are recognised as some of the most energy efficient and sustainable construction materials. Moreover, an estimated 85% of the aluminium used in modern buildings comes from recycled material. Bridge decks made from aluminium-based materials need minimal maintenance, are corrosion-resistant, require no painting and, unlike concrete, require no extension framework or cure time. Advanced aluminium alloys and composites can easily support the weight of heavy glass spans, thus maximising the building's capability for using natural sunlight.

Aluminium has, over time, been viewed as a vital component of sustainable buildings since the metal is easily recycled and loses none of its properties during recycling. Moreover, the recycling process reduces energy consumption by more than 90% compared to the energy required to produce new aluminium [44]. Aluminium and its alloys are infinitely recyclable. More than 75% of all aluminium produced is still in use today.

### *3.1.6 Offshore applications*

Offshore platforms, helidecks and seawalls are other possible areas where aluminium-based materials can be effectively utilised. In water depths of 400 feet, a 1 ton weight saving in platform superstructure means weight savings of 6 tons in the supporting structure [42].

Aluminium-based materials are often used in the construction of helicopter decks (helidecks) for resupply of oil rigs. Here, marine-grade aluminium alloys offer maintenance-free service with remarkable corrosion resistance. Using aluminium components reduces handling and offshore lifting costs and speeds the task of assembly. Aluminium is safe to use as it does not burn and presents no thermite sparking risks. It requires minimal maintenance. Even in salty water applications, little or no protective coatings are required for aluminium seawalls.

Marine-grade aluminium alloys are used for helidecks, telescoping bridges, accommodation modules, stair towers, cable ladders, fire walls, mud mats, gratings and many other applications. Aluminium structures weigh 40–70% less than equivalent steel structures. Handling is made easier since larger, lighter aluminium structures can be handled and lifted with smaller, less expensive equipment. In marine environments, properly selected aluminium alloys/composites require no painting and require little or no maintenance.

Aluminium seawall shapes are generally extruded, achieving the most strength with the least material. Aluminium is easy to extrude and fabricate; hence, retrofitting of the offshore platforms and customisation become cost-effective. Installation is also easy since designers can create either a single-piece component, bolted connections or interlocking sections for fast and simple fit-up on site. Various proven mechanical methods joining can be applied to aluminium. Its weldability is good as it can be welded three times faster than steel, using inexpensive MIG machines. Aluminium offers excellent safety advantages as it is non-combustible and gives off no flammable vapour when heated—an important consideration when choosing materials for offshore applications such as helidecks [42].

### 3.2 High-temperature applications

#### *3.2.1 Automotive industry*

The high-temperature applications in the automotive industry are mainly concerned with the engine, transmission and braking components. These experience temperatures up to about 300°C. The AlMMCs suitable for use under these circumstances must be able to retain the desired properties of the part/component operating under these conditions [1].

The major automotive components that have been successfully manufactured from AlMMCs are the following:

*Pistons and cylinder liners.* The University of Wisconsin-Milwaukee (UWM) reportedly developed aluminium alloy pistons and cylinder liners containing dispersed graphite particles that provide solid lubrication [5]. The graphite-containing aluminium has a lower friction coefficient and wear rate and does not seize under boundary lubrication. Aluminium/graphite pistons and liners were tested in gas and diesel engines and in race cars, and the results showed reduced friction coefficients and wear rates. The friction coefficient of Al-graphite composites was measured and found to be as low as 0.2 [45]. This makes it a suitable material for cylinder liners in light-weight aluminium-engine blocks, for its ability to enable engines reach operating temperatures more quickly while providing superior wear resistance, improved cold start emissions and reduced weight [46]. Aluminium-based composite liners can be cast in situ using conventional methods, including sand, permanent mould, die casting and centrifugal casting.

*Main bearings.* Lead-free aluminium or copper matrix composites containing graphite particles, as developed at UWM [5], can replace the copper-lead bearings used in crankshaft main-bearing caps. The bearings also improve wear characteristics because deformation of the graphite particles results in the formation of a continuous graphite film, which provides self-lubrication of the component, allowing for improved component longevity. Virtually all journal bearings in the power train could benefit from these materials. Selectively reinforced functionally gradient bearings of aluminium-graphite and copper-graphite alloys can be manufactured in a single step by centrifugal casting of metal-graphite suspensions [47].

*Connecting rods.* For components requiring high strength at high temperatures, such as connecting rods, cast aluminium matrix nanocomposites may be ideal to produce near-net-shape components to replace steel, forged aluminium and titanium components while reducing reciprocating mass.

*Accessories.* For components not exposed to extreme loading, further cost and weight reductions can be realised by incorporating fly ash in the aluminium matrix.

Components such as A/C pump brackets, timing belt/chain covers, alternator housings, transmission housing, valve covers and intake manifolds can be replaced with aluminium-fly ash composites, reducing the vehicle cost and weight, thereby improving emissions and saving energy. Adding fly ash to aluminium also reduces its coefficient of thermal expansion and increases its wear resistance along with making lighter and less expensive material [46].

*Suspension.* Although many automakers use aluminium and light gauge steel for suspension components to reduce unsprung weight and improve vehicle dynamics, a big number of components are still being made from cast iron. Components such as control arms or wheel hubs made of strong silicon carbide (SiC)-reinforced aluminium or aluminium nanocomposites can further improve aluminium alloy designs by enhancing strength while using less material than similar aluminium arms [31].

*Brakes.* Automotive disc brakes and brake callipers, typically made of cast iron, are an area where significant weight reduction can be realised. SiC-reinforced aluminium brake rotors have been embraced by a number of prominent vehicle manufacturers [47]. High cost and machinability issues need to be addressed for widespread use of aluminium composite brake rotors. UWM developed aluminium-silicon carbide-graphite composites, aluminium alumina-graphite and hypereutectic aluminium-silicon graphite alloys with reduced silicon carbide to help overcome cost and machinability barriers. Aluminium-fly ash composites developed at UWM have been explored to make prototype brake rotors in Australia [31]. Strength improvements seen in aluminium nanocomposites being developed at UWM can provide significant improvements in component rigidity without adding a significant amount of material, resulting in lower-weight components.

#### *3.2.2 Applications in aerospace and aircraft industry*

Aerospace propulsion and power systems are ever placing increasing demands on load bearing materials. The quest to propel bigger payloads into space and provide electrical power for space experiments while at the same time meeting the demands of manned and unmanned spacecraft flying at hypersonic velocities requires the right materials. The materials must be light-weight and be able to withstand high temperatures for long periods of time in hostile environments.

Metal matrix composites have the potential to meet the wide variety of these requirements. By selection of the proper high-temperature fibre and combining the fibres with an appropriate matrix, a high temperature, light-weight MMC can be produced. Extensive research is needed on advanced fibres and matrices. Since the fibres provide the characteristics that dominate the strength, stiffness and conductivity of a composite, superior fibres need to be developed. Fibres having high melting points and coefficients of thermal expansion matching those of the matrices need to be evaluated for high-temperature strength, modulus and compatibility with various matrices. In case of matrices, intermetallic compounds offer higher melting points, light-weight and (in the case of aluminides and silicides) good oxidation resistance for aerospace propulsion systems [48].

### 3.3 Other novel applications of AlMMCs

#### *3.3.1 Electronic packaging and thermal management*

Heat sinks play two key roles in electronic packaging: thermal management and mechanical support. Heat sinks support electronic devices and provide a path for heat dissipation. They are used in packages and with printed circuit boards

(PCBs). Traditional heat sinks were primarily aluminium, copper or unalloyed blends of two metals, such as copper-tungsten or copper-molybdenum. The traditional heat sinks have exhibited a number of shortcomings, which has necessitated designing of new improved materials, primarily composites reinforced with fibres and particles. The new materials exhibit better properties including high thermal conductivities; low, controllable coefficients of thermal expansion; weight reductions; high strength and stiffness; and availability of net-shape fabrication processes.

The packaging density is ever on the increase, which has resulted in the demand for materials with high thermal conductivities. In addition, to minimise thermal stresses that can cause component or solder failure, it is desirable that the packaging material should have a coefficient of thermal expansion (CTE) matching that of the ceramic component it supports. Utilisation of composite materials is not a new phenomenon in electronic packaging. For example, polymer matrix composites (PMCs) in the form of E-glass fibre-reinforced polymer PCBs are well-established packaging materials.

Aluminium metal matrix composites with the high volume fraction of reinforcement are attractive materials for thermal management. This is in view of the possibility to further enhance the thermal conductivity (TC) of the composite material by the use of high TC reinforcements and the flexibility to adjust the CTE by controlling the volume fraction of the reinforcement. Aluminium and copper were usually used as matrices due to their high TCs, and the reinforcements involved SiC, carbon and diamond. However, owing to the fact that the specific thermal conductivity of aluminium-based composites was higher than that of Cu-based composites, aluminium-based composites are more desirable in avionic applications where light-weight is demanded [49].

### *3.3.2 Packaging and containerisation*

In 2009, containers and packaging regained their position as the top market for aluminium-based materials. The aluminium industry shipped 4.73 billion pounds for packaging applications or 26.5% of all shipments [42]. Aluminium-based materials are used in products such as beverage cans and bottles, food containers and household and institutional foil. Manufacturers and consumers appreciate foil for its impermeability to light, water and air—making it a preferred packaging material for food, beverage and pharmaceutical products. Moreover, aluminium's light-weight gives it a competitive advantage over other materials with regard to shipping costs and volume.

Regarding containerisation, it is difficult to discuss rail transport of freight and commercial goods without reference to the ubiquitous container. The cargo can be packed into large containers and conveniently shipped to their destinations interchangeably by rail, road, sea or air. The container has greatly simplified the transport of goods and has been adapted to the different modes of transport. With a backbone of aluminium extrusions and with considerable use of aluminium-based sheet material, the growth of containerisation has greatly facilitated the transportation industry.

### *3.3.3 Electrical transmission*

Aluminium-based materials have many advantages for electrical applications. Properties such as light-weight, strength, corrosion resistance and high efficiency in electrical conduction (aluminium has twice the conductivity of copper) render these materials the best choice for transmitting power from generating stations to homes and businesses. Their ease of recyclability makes them a perfect fit for today's environment.

In 2010, electrical market applications rose by 13.1%, and shipments of aluminium conductor steel-reinforced (ACSR) cable, bare cable, insulated wire and cable products soared to 631 million pounds, an increase of 11 million pounds from the previous year. The North American electrical market was the fourth largest for aluminium worldwide, accounting for 7.3% of all aluminium shipments during the year [42].

#### *3.3.4 Sports and recreation*

The sporting goods industry is not left behind as far as utilisation of AlMMCs is concerned. Aluminium metal matrix composites are very attractive as materials for sporting goods applications. The material used generally consists of an aluminium matrix reinforced with particles of silicone carbide or boron carbide. The specific strength and modulus of these materials can offer design advantages not possible with steel or carbon/epoxy composites. In addition, they have a tremendous marketing appeal for the high-end sporting goods consumer as they are a new phenomenon [50]. Recreational products, including those used in golf, cycling, baseball, skiing and other leisure as well as competitive sporting activities, have always offered profitable opportunities for high-performance materials due to the focus on performance over cost. Although AlMMCs have been used in niche applications, more widespread opportunities are available if an improved combination of performance, manufacturability and cost can be achieved through specific R&D activities.

Finally, AlMMCs have been considered for specialised applications in which the combination of properties makes them especially well suited. Examples of these applications include robotics, medical, biomedical and nuclear shielding. These applications may require specific R&D activities to be carried out and technical problems solved before substantial use can occur but may represent high-value market opportunities for the industry if successful [16].

## 4. Challenges and barriers in the development of AlMMCs

Several challenges must be overcome in order to intensify the engineering usage of AlMMCs. Design, research and product development efforts and business development skills are required to overcome these challenges. Surappa [4] emphasised the need to address the following issues:

i. A more and thorough understanding of the science of primary processing, especially the factors affecting the microstructural integrity including agglomerates in AlMMCs.

ii. Need to improve the damage tolerant properties particularly fracture toughness and ductility in AlMMCs.

iii. Need for work to be done towards the production of high-quality and low-cost reinforcements from industrial wastes and by-products.

iv. An urgent need to develop simple, economical and portable non-destructive kits to quantify undesirable defects in AlMMCs.

v. Work in developing less expensive secondary processing tools for machining and cutting AlMMCs.

vi. Work must be done to develop recycling technology for AlMMCs.

The challenges and barriers listed above are echoed by [16]. Further penetration of AlMMCs will largely depend on their primary production processes and secondary machining processes being affordable. Generally, the cost of aluminium is around 4–5 times that of steel. In addition, the manufacturability of these composites is cumbersome. These challenges are being addressed through R&D activities. In early development of AlMMCs, the industry was modelled on the roadmap drawn by the Aluminium Metal Matrix Composites Roadmap 2002, which spelt out a pathway for the AlMMCs growth in 20 years from 2002 and asserted the industry's vision to position AlMMCs as the material of choice in a broad range of structural and nonstructural applications [1]. During the workshop that gave birth to the AlMMCs Roadmap 2002, a number of critical barriers hampering the market penetration of AlMMCs were identified, and common themes agreed on how to mitigate these barriers and realise their vision [16].

## 5. Conclusion

AlMMCs present a great opportunity and a host of possibilities for the materials/design engineer. There are now many possibilities for manipulation of properties/property combinations to suit specific requirements of material and component properties in order to enhance performance and reliability. New and emerging technological developments point to increased utilisation of AlMMCs in current and future industrial developments. Some of the existing barriers and challenges are being addressed through various R&D efforts to find a lasting solution.

From the foregoing review, it is evident that the future of AlMMCs in various industrial and commercial applications is very bright. Advanced technological developments in primary and secondary processing of AlMMCs will continue to give them a competitive edge over the alternative materials such as Mg, AHSS and polymer composites. The main challenges and barriers that have been identified include lack of property modelling (especially the high-temperature behaviour of AlMMCs), lack of design data and high costs of primary and secondary processes. However, there are promising signs of technological breakthroughs by various research efforts dedicated to finding solutions to these challenges. New developments in CNT and nanotechnology have, for example, offered possibilities of production of AlMMCs with enhanced properties for high-temperature applications and improved wear and corrosion resistance. Other developments such as the novel rheocasting process of semi-solid alloys [e.g. see [51]] and FGMs have also offered new possibilities of cost reduction in primary production and secondary processing of AlMMCs, respectively. New alloys of aluminium have been developed for application in such areas as crash management (crash alloy)—an area previously dominated by steel. These alloys offer new R&D opportunities for further development of AlMMCs and will redefine new roles and potential of AlMMCs in automotive applications. Various researchers are also coming up with innovative cost-reduction techniques to bring down the cost of replacing conventional ferrous materials with aluminium metal matrix composites.

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## Conflict of interest

The authors envisage no conflict of interest.

## Author details

Francis Nturanabo[1,2]*, Leonard Masu[1] and John Baptist Kirabira[2]

1 Department of Mechanical Engineering, Vaal University of Technology, Andries Potgieter Boulevard, Vanderbijlpark, South Africa

2 Department of Mechanical Engineering, College of Engineering, Design, Art and Technology, Makerere University, Kampala, Uganda

*Address all correspondence to: fmpazi@yahoo.com

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