Metal Matrix Composites

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Abstract The chapter introduces the various types of matrix and reinforcements used in metal matrix composites (MMCs) and gives an overview of the types of MMCs, namely fibre reinforced MMCs; particle reinforced MMCs and multi-layer laminates. Standard manufacturing processes for MMCs include Solid-State Processing Methods such as powder metallurgy, mechanical alloying, diffusion bonding and deformation processing, Liquid Processing Methods such as stir casting, melt infiltration, squeeze casting and melt deposition are also presented in Sect. 3. In addition, in situ processes and additive manufacturing of MMCs are also introduced. In Sect. 4, equations are provided to allow the prediction of the properties of MMCs such as density, modulus and strength. Strengthening mechanisms for particle reinforced composites are briefly explained in Sect. 5. A review of various mechanical properties of MMCs produced by different manufacturing techniques is provided in Sect. 6. Lastly, the chapter provides the use of MMCs in various industries.

1 Introduction

This chapter provides an introduction to metal matrix composites. The common types of matrix and reinforcement materials and various manufacturing techniques such as traditional casting and powder metallurgy to modern additive manufacturing processes used in the fabrication of metal matrix composites are provided. Examples of the mechanical properties of MMCs with micron, nano-sized reinforcements are highlighted together with properties of MMCs produced by additive manufacturing techniques.

Materials have always been an essential part of the human civilisation and can be seen from the naming of the ages of civilisations: stone, bronze, iron and steel.

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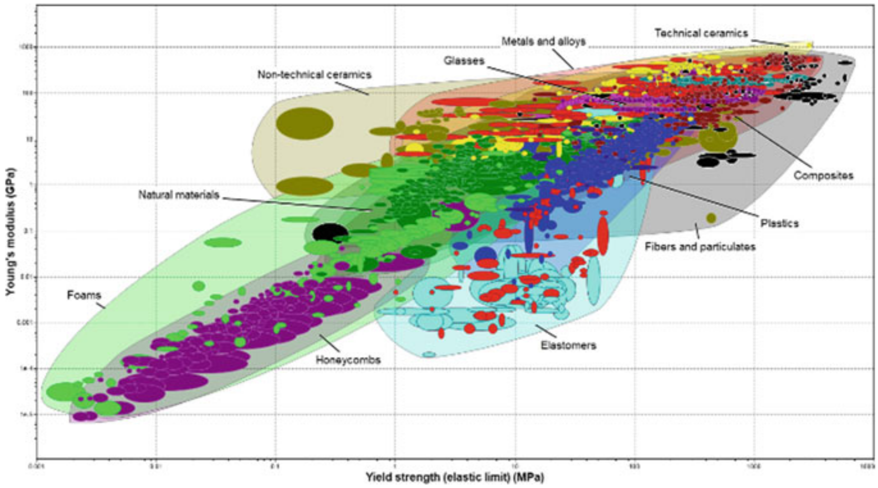

Fig. 1 Illustration of various classes of materials produced using CES Edupack software [3]

In the eighteenth and nineteenth century, iron and steel were used to make steam engines, railway and machines during the first and second industrial revolutions. In the twentieth century, polymers and silicon were ubiquitous in our daily lives. Many types of materials have been developed throughout the centuries from low stiffness and strength materials such as foams and honeycombs to high stiffness and strength materials such as metals and alloys, technical ceramics and composites as shown in Fig. 1.

Early civilisation used natural materials such as loam, mud, sand and straw to make composite bricks for buildings. Composite materials have found increasing applications in recent years. A composite material can be defined as combining two or more distinct materials to attain synergistic or superior properties over the individual constituents. In the aerospace industry, the latest aircrafts such as Airbus A350 and Boeing 787 Dreamliner uses at least 50% of carbon fibre composites in the structure [1]. Wind turbines also use glass-fibre reinforced composites in the turbine blades. However, polymeric composites suffer from low thermal resistance due to the polymer matrix's low melting temperature and low impact resistance with rapid deterioration in mechanical properties due to possible fibre cracking and delamination arising during service.

Metal matrix composites (MMCs) involve the combination of a continuous metallic matrix with reinforcements that typically comprise ceramic material or metallic material. The metallic matrix provides the potential for producing a composite with high mechanical and thermal properties compared to polymer matrix composites. Advantages of MMCs are summarized below [2].

- Higher stiffness and strength with the addition of reinforcements
- Higher service temperature for the metal matrix compared to the polymer matrix
- Higher toughness and ductility over ceramic matrix composites

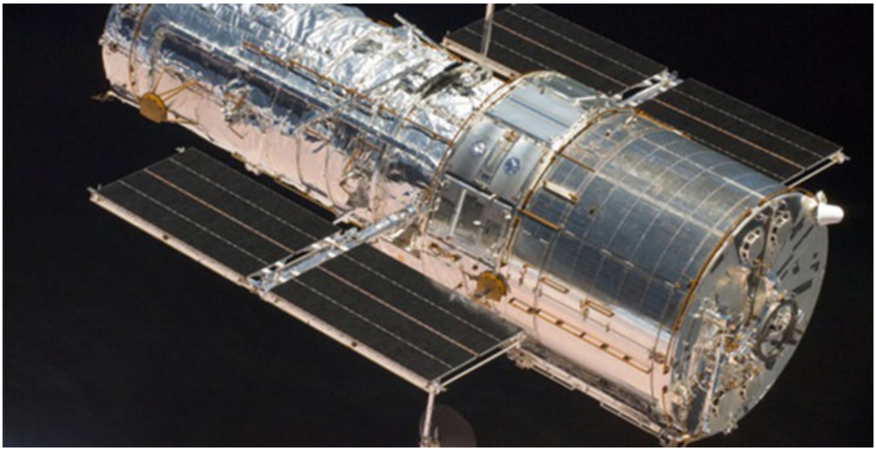

Fig. 2 Hubble space telescope utilises graphite-fibre/aluminium matrix composite for antenna booms. (Photo credit: DARPA)

- Good electrical and thermal conductivity compared to polymer and ceramic matrix
- Improved dimensional stability (e.g., lower thermal expansion with the addition of ceramic reinforcements of low coefficient of thermal expansion)
- Possible weight savings due to higher specific mechanical properties.

The ability to tailor the composites' properties using a combination of matrix and one or more reinforcements (metals or ceramics) makes it attractive for many applications. MMCs are used in various industries such as aerospace, automotive, defence, electronics and sports. For example, aluminium composite is used in the antenna booms for the NASA Hubble Space Telescope, as shown in Fig. 2.

Three entities can determine composite material characteristics: reinforcement, matrix, and interface explained in further details below.

1.1 Matrix

A variety of metals and their alloys are used as the matrix material for MMCs, and most of the research focused on lightweight metals such as aluminium, magnesium and titanium. Aluminium matrix composites are the most researched MMCs due to its low-cost relative to other light structural metals and can be found in aerospace and automotive industries. Magnesium matrix composites offer high specific stiffness and strength but are not widely used due to limited processing such as low extrusion rate and low corrosion resistance. Titanium matrix composites are used in jet engines and military jet landing gears. Other metals used as matrix include steel, copper, solder and nickel-based superalloys. Cobalt metal is also used as a matrix material for carbide reinforcements such as tungsten carbide to make hard metal cutting tools.

Table 1 Mechanical properties of common matrix materials [3]

Metal	Density (g/cm^3)	Modulus (GPa)	Yield strength (MPa)	Elongation (%)
Aluminium	2.67–2.73	69–72	28.5–31.5	37–43
Magnesium	1.73–1.75	44–45.5	65–100	12–20
Titanium	4.51–4.52	100–105	172–240	20–25
Copper	8.94–8.95	120–135	55–340	6–50
Cobalt	8.8–8.9	199–215	295–925	2–20
Iron	7.86–7.88	204–212	110–220	20–55
Nickel	8.85–8.95	190–220	80–795	2–60
Tungsten	19.3–19.4	340–350	1350–1680	10–25

Values of commercial purity metals obtained from CES EduPack software

The matrix's primary purpose is to bind the reinforcements and protect the reinforcements from mechanical and environmental damages. The matrix also allows the transfer of external forces to the reinforcement. Table 1 shows the properties of different metals used in MMCs.

1.2 Reinforcements

Reinforcements are added to improve the performance of the matrix material. The general characteristics of reinforcement are:

- Low density
- High Young's modulus
- High compression and tensile strength
- Good mechanical and chemical compatibility
- Good thermal stability.

The reinforcement can be classified as either continuous or discontinuous (short fibres, whiskers, micron and nano particulates).

Fibres are the most commonly used continuous reinforcement made of either carbon or ceramic. The ceramic types include alumina, silica, boron, alumina-silica, alumina-boria-silica, zirconia, magnesia, mullite, boron nitride, titanium diboride, silicon carbide, and boron carbide. For niche applications such as fighter jet engines, metallic wires made of tungsten are also used as continuous reinforcements for enhanced high-temperature creep resistance.

Fibre reinforced MMCs can provide high stiffness and strength along with the fibre orientation. The fibres are generally brittle and flaw sensitive. To avoid any unwanted reaction with the matrix and improve the bonding and wetting characteristics, the fibres are also often applied with protective coatings. As the fibres exhibit size effects,

Table 2 Types of reinforcements (Table adapted from [2])

Type	Aspect ratio	Diameter	Examples
Particle	1–4	1–25 μm	SiC, Al_2O_3, BN, B_4C, WC
Short fibres (whiskers)	10–1000	1–5 μm	C, SiC, Al_2O_3, Al_2O_3+SiO_2
Continuous fibres	>1000	3–150 μm	SiC, Al_2O_3, C, B, W, Nb-Ti
Nanoparticle	1–4	<100 nm	C, Al_2O_3, SiC
Nanotubes	>1000	<100 nm	C

i.e. the strength of these fibres decreases as the length increases, they can also be classified as either long fibres or short fibres.

As the metallic fibres usually fail due to the high density and the affinity for reaction with the matrix alloy, discontinuous reinforcement like short fibres or whiskers and ceramic particles are preferred for metal matrix composites. Whiskers are more costly than particles but offer higher strength due to their single-crystal structure.

For particle reinforcement, the type, size and distribution of the particles will affect the composite's performance. Classification of the types of reinforcements is shown in Table 2. While the size of particle reinforcement used in MMCs ranges from few nanometres to a few hundred micrometres, they are relatively cost-effective to produce in large quantities compared to continuous fibres. Existing production techniques such as casting or powder metallurgy followed by secondary shaping processing techniques including turning, milling, extrusion, forging and rolling can be applied for discontinuous reinforced MMCs. Also, the particle reinforced composites are known to display more isotropic properties.

Some of the most common particulate reinforcement types are alumina, boron carbide, silicon carbide, titanium carbide, and tungsten carbide. Similarly, whiskers made of silicon carbide, alumina and silicon nitride have also been used in MMCs. Silicon carbide is attractive due to its relatively high modulus, low density, and availability in many forms ranging from whiskers, powders and fibres. Alumina is attractive due to high chemical resistance and oxidation resistance. The properties of different reinforcement materials are shown in Table 3.

1.3 Interfaces

Interfaces refer to the bonding surface between the matrix and the reinforcement. Due to the small size of reinforcements, the bounding surface area occupied by the interface is very large and plays an essential role in determining the composites' final properties. Suitable interfaces free of voids and detrimental interfacial reaction products allow the effective transfer of mechanical forces from the matrix to the reinforcement without failure. Two types of bonding can exist at the MMC interface,

Table 3 Properties of common reinforcement materials [3]

Metal	Density (g/cm^3)	Melting point (°C)	Thermal expansion coefficient (µm/°C)	Modulus (GPa)	Yield strength (MPa)	Price (£/kg)
Al_2O_3	3.94–3.96	2050	7.7–8.5	450–460	1250–1340	25.2–31.5
AlN	3.27–3.33	2400–2510	4.6–4.8	323–348	218–242	78.7–126
B_4C	2.49–2.55	2400–2510	4.41–4.59	362–380	261–289	45.7–67.7
BN	2.2	2280–2380	2–6	48–50	27–30	26.8–39.4
SiC	3.15–3.2	2830–2840	3.9–4.3	450–480	2080–2500	23.6–39.4
Si_3N_4	3.15–3.21	2390–2500	3.23–3.37	288–302	240–270	26.8–40.9
TaC	1.34–1.39	3780–3880	6.6–7.4	360–375	194–250	50.4–75.6
TiB_2	4.45–4.54	2920–3050	6–8	410–430	339–374	14.–20.5
TiC	4.81–5.01	3160–3250	6.6–7.4	420–450	260–330	34.3–52
WC	1.53–1.59	2820–2920	4.5–7.1	600–670	373–530	14.2–22
ZrO_2	6.03–6.16	2550–2700	6–8.8	135–141	125–140	14.2–20.5
Be fibre	1.85–1.86	1280–1290	10.7	304–310	785–795	236–354
B fibre	2.46–2.57	2200	5.5–5.7	395–405	1750–2170	394–504
W fibre	19.4–19.6	3410	4.35–4.5	388–406	2250–2750	40.4–50.7
E glass	2.55–2.6	550–580[a]	4.9–5.1	72–85	1900–2050	1.24–2.48
C fibre (high strength)	1.8–1.84	3690–3830	−2–0.3	225–260	3750–4000	19.1–25.5

Properties are taken from CES EduPack and reflect bulk commercial purity material
[a]Glass transition temperature

namely, mechanical bonding and chemical bonding [2]. Mechanical bonding depends on the surface roughness while chemical bonding generally occurs at high temperature due to diffusion and chemical reaction between the matrix and reinforcement. Weak matrix-reinforcement bonding may lead to inferior mechanical properties of the composites and premature failure. An example of the interfaces between the magnesium matrix and carbon fibres is shown in Fig. 3.

Apart from cost, other limitations that prevent the widespread use of MMCs for engineering components lies in their tendency to fracture easily. The low ductility or brittleness is often caused by micro failure processes that invariably begin at the interfaces. Due to the thermal mismatch between the reinforcement and the matrix, high dislocation density will be generated at the interface. Hence the mechanical properties and overall performance of the MMCs are not limited by bulk properties but by interface properties and toughness. Detailed explanations of the importance of interfaces can be found in various references [1, 2, 4].

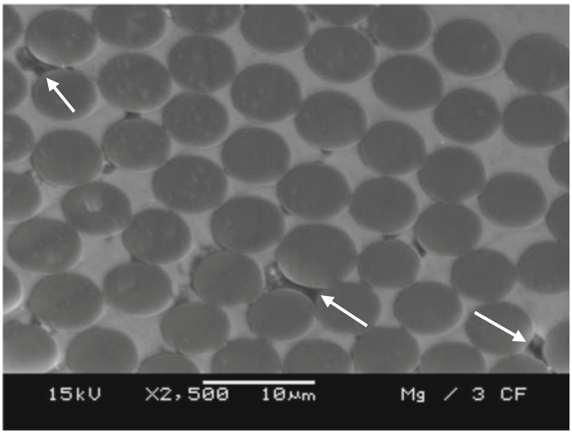

Fig. 3 Magnesium composite reinforced with carbon fibres with some voids marked by arrows

2 Classification of MMCs

Metal matrix composites can be classified in various ways. Depending on the matrix material, MMCs are classified into different categories like:

- Aluminium-based MMCs
- Magnesium-based composites
- Titanium-based composites
- Copper-based composites
- Super alloy-based composites.

Similarly, based on the reinforcement type, MMCs can be classified as fibre reinforced MMCs, particle reinforced MMCs and multi-layer laminates (see Fig. 4). The

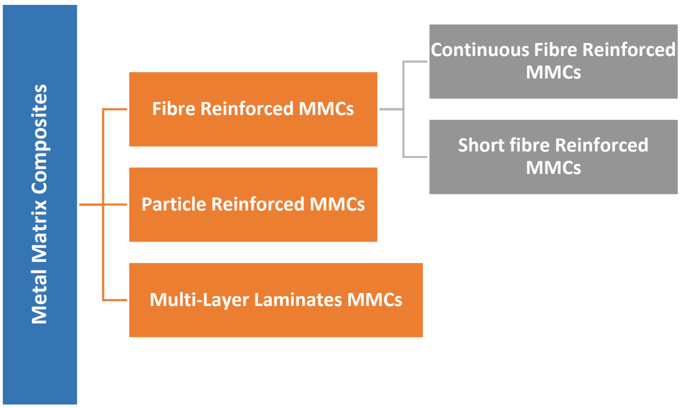

Fig. 4 Classification of metal matrix composites

fibre composites can be further classified as continuous and short (discontinuous) fibre reinforced composites.

2.1 Fibre Reinforced MMCs

The fibre reinforced MMCs can be broadly classified into (i) continuous fibre reinforced composites and (ii) short-fibre reinforced composites.

(i) Continuous fibre reinforced composites consist of a matrix reinforced by a dispersed phase in the form of continuous or long fibres.
(ii) Short-fibre reinforced composites consist of a matrix reinforced by a dispersed phase in the form of discontinuous fibres or whiskers (length < 100 * diameter).

2.2 Particle Reinforced Composites

Particle reinforced composites consist of a matrix reinforced by a dispersed phase in the form of particles. The particle dispersion within the matrix can be either random or with a specific orientation. Particle reinforced composites are relatively cheaper to manufacture due to the lower cost of the reinforcements and possess isotropic properties compared to fibre reinforced composites. An example of an aluminium composite reinforced with silicon carbide particles is shown in Fig. 5.

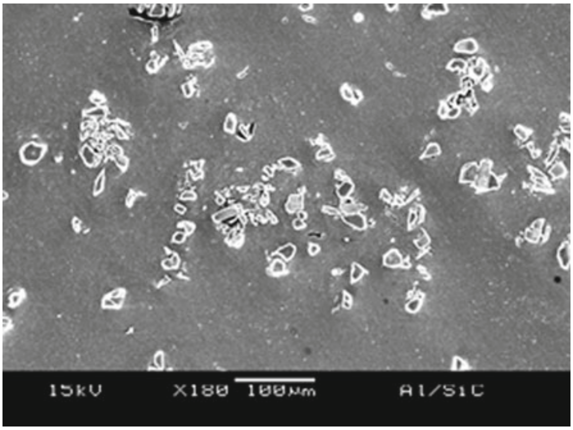

Fig. 5 Aluminium composite reinforced with silicon carbide particles

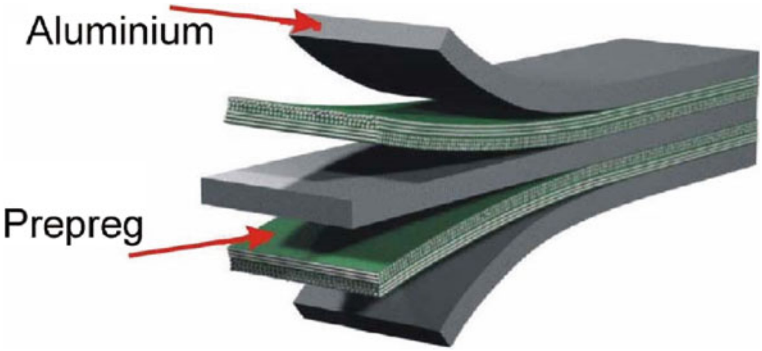

Fig. 6 An example of a cross-ply GLARE laminate, adopted from [6]

2.3 Multi-layer Laminate Composites

In laminated composites, layers of materials are stacked in a specific pattern to obtain a specific set of properties. One of the best known metal laminate composites is Glass laminate aluminium reinforced epoxy (GLARE) used in the aircraft such as Airbus A380 [5]. GLARE comprises alternating layers of thin aluminium sheets and glass fibre prepreg bonded together with epoxy, as shown in Fig. 6. The advantages of using GLARE include high specific strength and stiffness, excellent damage tolerance and impact properties.

3 Manufacturing Techniques of MMCs

Metal matrix composites can be produced using various methods that involve the processing of materials in either liquid, solid and vapour or gaseous state.

3.1 Solid-State Processing Methods

The advantages of using solid-state processing methods include reduced interfacial reactions between matrix and reinforcements due to lower processing temperature than liquid state processing and allowing for a higher volume fraction of reinforcements to be incorporated as the addition of reinforcements lead to an increase in viscosity of the liquid melt making it challenging to achieve a uniform distribution of reinforcement.

There are several solid-state processing techniques used to make particle or whisker reinforced MMCs, and the popular ones include (a) powder metallurgy, (b) mechanical alloying, (c) diffusion bonding, and (d) deformation processing.

a. **Powder metallurgy (PM)**

PM is an established method used for making particulate reinforced composites. In this method, a composite powder blend is prepared by mixing the metal alloy powder with the required amount of reinforcement whiskers or particulates [7]. After blending, the composite mixture is then compacted and sintered. Sintering is typically done in an inert nitrogen or argon atmosphere using electric or resistance heaters. A variant of the sintering is the use of hybrid microwave sintering to consolidate the green compact [8]. Hybrid microwave sintering allows for a significant reduction in sintering time and energy without compromising on the properties of the MMCs [9].

Further consolidation can take place via extrusion to obtain a near dense composite. The extrusion process can improve bonding between the reinforcement particle and matrix by fracturing the oxide film present on the surface of the metal particle. A schematic diagram of the PM process is shown in Fig. 7.

This method has been extensively used to fabricate aluminium and magnesium metal matrix composites with a reinforcement volume fraction of up to 30%. The particle size ratio between metal and reinforcement powders should be comparable to unity for uniform dispersion of reinforcement and avoid clustering [2, 4].

In the case of long continuous fibres, the fibre tows are first infiltrated by dry matrix powder, followed by hot isostatic pressing. However, cold-pressing and sintering are not preferred as the relatively high pressure necessary to achieve the required density can break the fibres. The sintering process can also degrade the fibre quality due to oxidation.

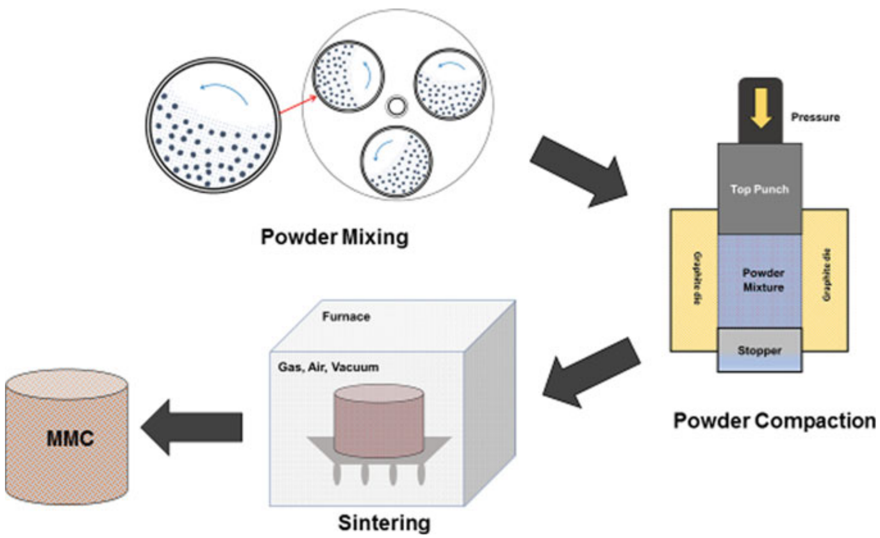

Fig. 7 A schematic showing the flow of powder mixing and consolidation

b. **Mechanical alloying**

Mechanical alloying involves repeated cold welding, fracturing, and re-welding of powder particles in a high energy ball mill. In this process, as shown in Fig. 8, the frictional heat developed at the particle interface results in local melting and consolidation of powder particles and the rapid heat extraction by the cooler particle interior causes rapid solidification. The composite powder mixture obtained is then cold compacted into a green billet that is then canned, degassed and hot-pressed at a temperature closer to the matrix alloy's solidus temperature. Using this method, various high strength equilibrium and non-equilibrium alloys and composites can be synthesised due to the high dislocation density and homogenous distribution of reinforcing constituents.

c. **Diffusion bonding**

Diffusion bonding is a solid-state joining technique used to process a wide variety of metal composites reinforced with continuous/discontinuous fibres. Strands or mats of fibres are sandwiched between metal foils and stacked in the desired order, as shown in Fig. 9. The laminate is then sealed in a can, heated and pressed to full density. Although there are many variants of the diffusion process, the basic principle involves interdiffusion of atoms and bonding between the mating contact surfaces under temperature and pressure. While the fibre orientation and volume fraction can be perfectly controlled, the processing time and cost are relatively high compared to other methods. Only objects of limited size and shape can be produced. Hot roll diffusion bonding is a variant of the diffusion bonding method used to produce sheet laminated metal matrix composites composed of different metals in the sheet

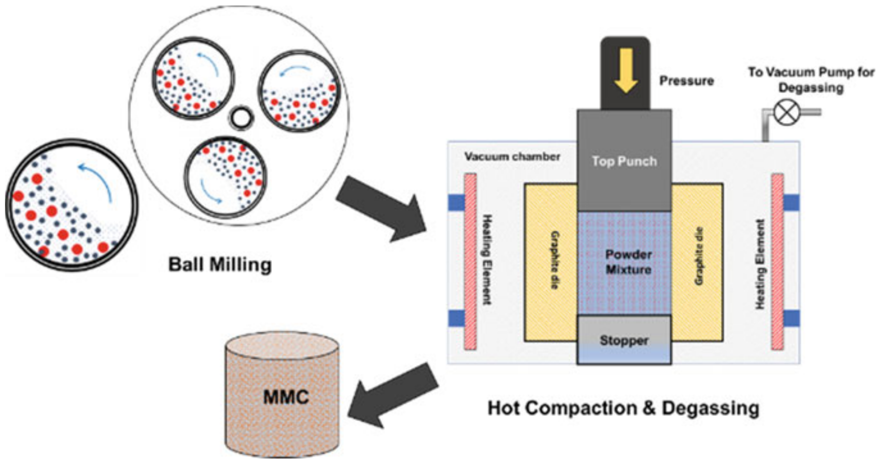

Fig. 8 Mechanical alloying technique

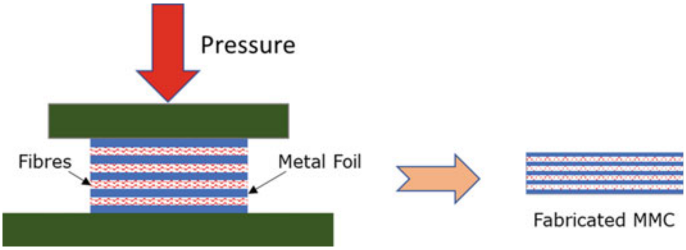

Fig. 9 Schematic of the diffusion bonding process

form. MMCs combinations of B/Al, Gr/Al, Gr/Mg and Gr/Cu have been manufactured using diffusion bonding into parts such as tubes, plates and panels for space applications [10].

d. **Deformation processing**

Mechanical processing methods such as swaging, extrusion, drawing or rolling can produce metallic composite made of a ductile two-phase metal. In this method, a two-phase alloy billet processed by casting or powder consolidation is subjected to mechanical deformation, causing the minor phase to elongate and become fibrous within the matrix. Hence, this method is limited to starting materials in which both phases are ductile and have similar flow stresses so that co-deformation occurs. Large total deformation strains may be employed. Heat treatments are often applied post deformation to promote required microstructural development. This technique is used to manufacture high-temperature superconductor wires comprising ceramic oxide superconductors and silver [1].

3.2 Liquid Processing Methods

Liquid processing methods for MMCs are commonly used due to the relatively lower cost for bulk materials than powder materials for solid-state processing and near net shape processing. In liquid processing methods, the reinforcement material is first dispersed into a molten matrix metal, and the composite slurry is then solidified into the required shape. The reinforcement can be dispersed into the molten matrix material in multiple ways:

- Stir casting—Direct mixing of reinforcement with the molten melt
- Melt infiltration—Infiltration of reinforcement preforms by molten metal
- Squeeze casting
- Melt deposition.

a. **Stir casting**

Stir casting is the most common and cost-effective method of producing composite materials. In this method, the reinforcement phase (short fibre or particles) is mixed with the molten matrix metal employing mechanical stirring or ultrasonic energy under an inert atmosphere. Conventional casting methods then cast the molten composite slurry. The properties of the MMCs produced using stir casting methods will depend on the processing parameters such as the temperature of the melt, stirring speed, stirring duration, and geometry of the stirrer, affecting the distribution of the reinforcements in the matrix. The dispersed phases are often coated with proper wetting agents to achieve better interfacial bonding with the matrix material and avoid any unwanted reaction and dissolution of reinforcement at high temperatures. In case of particulate reinforcement, careful attention must be paid to the particles' dispersion as they tend to form agglomerates for fine powder and segregation in the molten melt due to density difference between reinforcements and liquid melt. In general, the proper selection of processing parameters such as melt temperature, stirring speed, duration, and stirrer geometry, allows for the effective dispersion of particles (in size range 5–100 micrometre) up to 30% by volume. Superheating the molten melt by 50–100 °C is required for the higher volume fraction of particles due to an increase in the molten melt's viscosity. Figure 10 shows the schematic for stir casting where the reinforcement can be dispersed using a blade stirrer or ultrasonic energy.

b. **Melt infiltration**

In melt infiltration, a liquid metal alloy is infiltrated into the porous forms of fibres/whiskers reinforcements. The reinforcement volume can be between 10 and 70% depending upon the level of porosity of the preform.

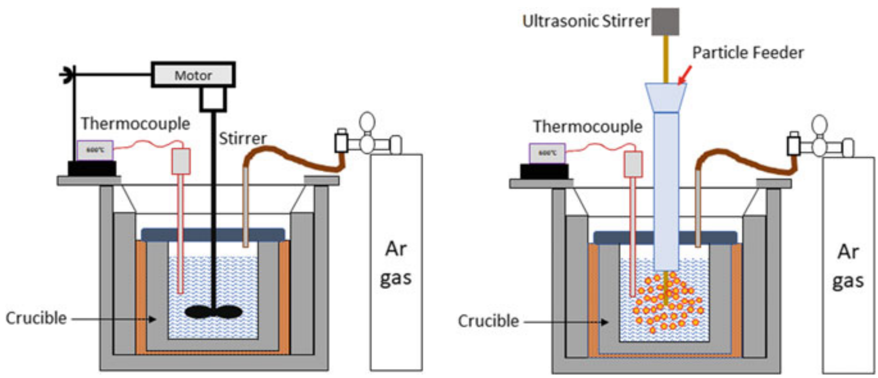

Fig. 10 Schematic diagram of stir casting (left) and application of ultrasonic for dispersion of reinforcements (right)

The infiltration of preforms can be conducted under atmospheric pressure in an inert atmosphere to minimise interfacial reactions between the matrix and reinforcements. However, the pressureless process involves long holding time at a high temperature of approximately 700–1000 °C for aluminium alloys for infiltration of the preform [2]. Infiltration of the preform can also be undertaken employing pressurized inert gas in which the gas pressure can be applied in two ways: (i) application of gas pressure to the melt surface after dipping the preform into the melt for infiltration, (ii) the applied gas first presses the molten metal and then infiltrates into the preform. Since the reaction time in both approaches is relatively short, reactive materials can be processed. However, comparing melt infiltration to squeeze casting, the processing times are relatively longer than in squeeze casting (Fig. 11).

c. **Squeeze casting**

In squeeze casting or pressure infiltration, the molten metal is forced into the preform, and pressure is applied until the solidification is complete. This method can be applied for both the fibres and particles reinforced composites. The prefabricated fibre (short Al_2O_3 fibre, carbon fibre) or particle preforms can be melt infiltrated and solidified under pressure. To avoid damage to the preforms, the melt is first pressed into the preform at low pressure, and then the pressure is increased for solidification. Since the melt solidifies under high pressure of 70–100 MPa, the squeeze cast composites are free from the common casting defects such as porosity and shrinkage cavities. As the infiltration duration is relatively short, the squeeze casting method can also be applied for reactive materials like magnesium and help to minimise interfacial reaction between the reinforcement materials and the matrix. The application of pressure during consolidation also provides the ability to fabricate parts with relatively complex geometry and allow composites with higher reinforcement volume fraction up to 55% to be obtained.

The squeeze casting can be classified into direct and indirect squeeze casting based on the mode of pressure application. In the direct squeeze casting method, the pressure for the infiltration of preforms is applied directly to the melt. However, in the

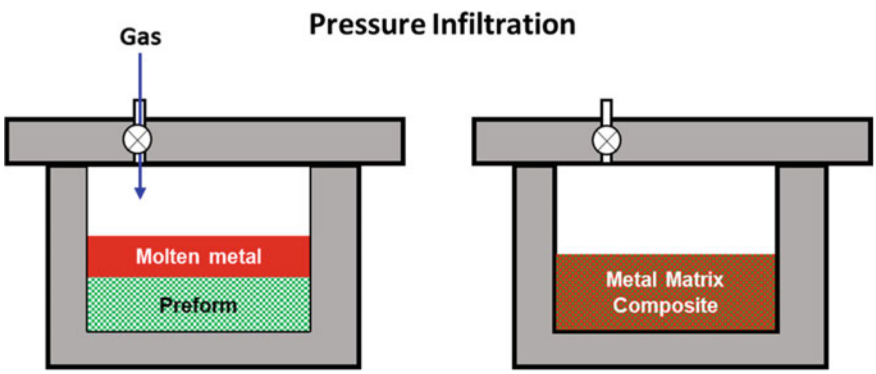

Fig. 11 Melt infiltration using pressurised inert gas

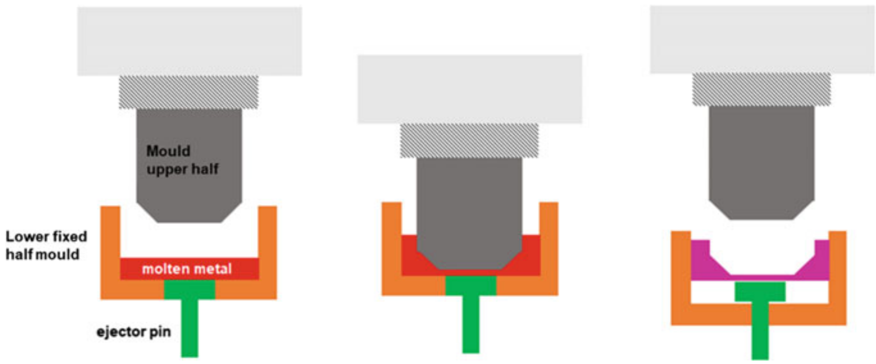

Fig. 12 Schematic diagram of the direct squeeze casting process

indirect squeeze casting, the melt is pressed into the preform through a gate system. Although the tooling is relatively simple for direct squeeze casting, the absence of a gate system necessitates the accurate determination of the melt volume. Another disadvantage is the presence of oxide residue in the composite, which is usually restricted by the indirect squeeze casting gate (Fig. 12).

d. **Melt deposition**

There are several deposition techniques available to produce metal matrix composites. While deposition methods like immersion plating, electroplating, chemical vapour deposition (CVD), physical vapour deposition (PVD) are only used for fibre reinforced MMCs, the spray deposition method can be used for both particle and fibre reinforced composites.

- ***Immersion plating***

This method is applicable for continuous fibre reinforcement which passes through baths of molten metal, slurry, sol, or organometallic precursors.

- ***Electroplating or electrodeposition***

In this method, the matrix metal coating is produced from a solution containing the ion of the desired material in the presence of an electric current. As this process is carried out at moderate temperatures, this method offers less/no damage to the reinforcing fibres. However, processing defects such as poor bonding and porosity are common for MMCs produced using this method. Also, only limited alloy matrices can be processed using this method.

- ***Chemical vapour deposition***

It involves chemical reaction or decomposition of a vaporized component on to the substrate to form a coating. Using this method, amorphous and crystalline (single and polycrystals) coatings of oxide, carbide, nitride or pure metals can be made. When this method is used to deposit the matrix material on the reinforced preforms, it is called chemical vapour infiltration.

- ***Physical vapour deposition***

This method is highly suitable for producing fibre reinforced metal matrix composites in which the vapours of matrix metal were condensed to create coatings on the reinforcement fibres. The coated fibres are then consolidated by hot pressing or hot isostatic pressing. Based on the vapour generation techniques, the PVD processes can be classified into (i) evaporation based, (ii) sputtering and (iii) ion-plating. While the evaporation PVD methods include electron beam/arc evaporation, radiation heating, laser ablation and resistive heating, the sputtering techniques involve vaporization of the coating material from an ionized argon gas molecule via momentum transfer. Similarly, ion plating involves passing the vaporized component through an argon gas glow discharge around the substrate which ionizes and subsequently deposit the vapour onto the substrate. The primary advantage of PVD is the versatility in the coating's compositions and the superior bonding with the substrate. In addition, there are no chemical reaction by-products in these methods. However, PVD methods are relatively complicated and expensive.

- ***Spray deposition***

In spray deposition, reinforcements in the form of particles/whiskers are injected into the spray together with the atomized metal, creating a deposition layer on the substrate [4]. The depositions are then densified by suitable post-processing techniques. Similarly, for continuous fibre reinforcements, the molten matrix metal is sprayed onto the fibres with preferred orientation. In this method, fibre alignment can be easily controlled, and relatively faster solidification rates can be achieved.

- ***Spray-forming of Particle Reinforced MMCs***

It is a promising method for producing particle reinforced MMCs. It involves spray techniques which are used to develop monolithic alloys. Figure 13 shows an example of the spray forming process in which a spray gun is used to atomize the molten matrix metal into which the reinforcement particles are injected. The resulting metal matrix composite (about 97% dense) is then subjected to scalping, consolidation, and secondary finishing processes to produce wrought composites [1]. To facilitate the efficient transfer of particle reinforcement, optimum particle size and shape must be maintained.

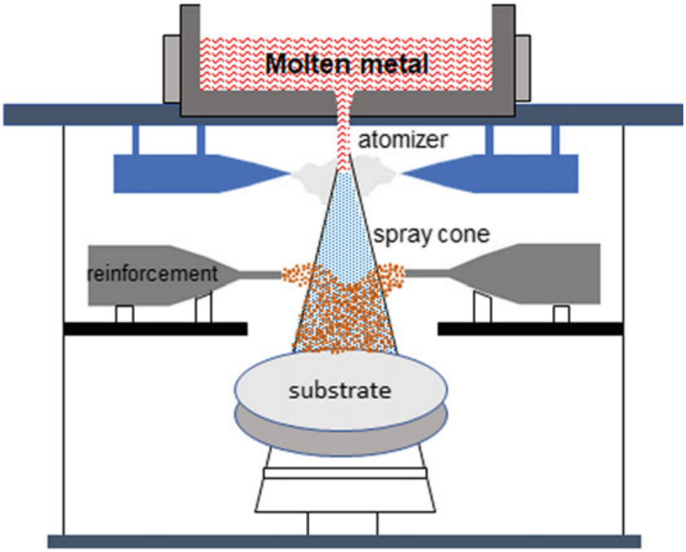

Fig. 13 Schematic diagram of the spray-forming process

3.3 In Situ Processes

In situ processing involves chemical reactions which results in the in situ formation of the reinforcing phase within a metal matrix. One of the classic examples of in situ processing is the controlled unidirectional solidification of a eutectic alloy, resulting in one phase being distributed in the form of fibres or ribbon in the other [2]. As the solidification rate controls the shape and distribution of the in situ reinforcement, better thermodynamic compatibility can be achieved at the matrix reinforcement interface, leaving the reinforcement surfaces free of contamination producing a stronger matrix-dispersion bond. However, in practice, the solidification rate is limited to a range of 1–5 cm/hour because of the need to maintain a stable growth front [2]. The patented XD process developed by Martin Marietta Corporation is an example of an in situ process where molten metal and compounds that will react exothermically come together to form ceramic reinforcement particles with sizes ranging from 0.2 to 10 μm [4]. The typical examples include aluminium MMCs reinforced with TiC and TiB_2, which are formed according to the following reactions:

$$C + Ti + Al \rightarrow TiC + Al$$

$$2B + Ti + Al \rightarrow TiB_2 + Al$$

3.4 Additive Manufacturing

Additive manufacturing (AM) provides new opportunities for manufacturing MMCs with unique microstructure and properties and has been receiving increasing attention in recent years [11, 12]. Most of the research focus on the development of particle reinforced MMCs using AM processes. Both in situ and ex situ processes can manufacture MMCs with unique microstructure, design and mechanical properties. Figure 14 illustrates the AM processes that are employed for manufacturing MMCs. The processes include Powder Bed Fusion (PBF), Direct Energy Deposition (DED), Binder Jetting, Selective Laser Sintering (SLS), Selective Laser Melting (SLM) and Electron Beam Melting (EBM).

4 Predicting Properties of MMCs

Tailoring properties is one of the MMC applications' main advantages. The end properties of composite materials can be controlled by many variables, including reinforcement form, volume fraction, geometry, distribution, matrix/reinforcement interface, void content, and manufacturing process. The following sections will provide equations used in predicting the properties of metal matrix composites from the properties of the matrix and reinforcement.

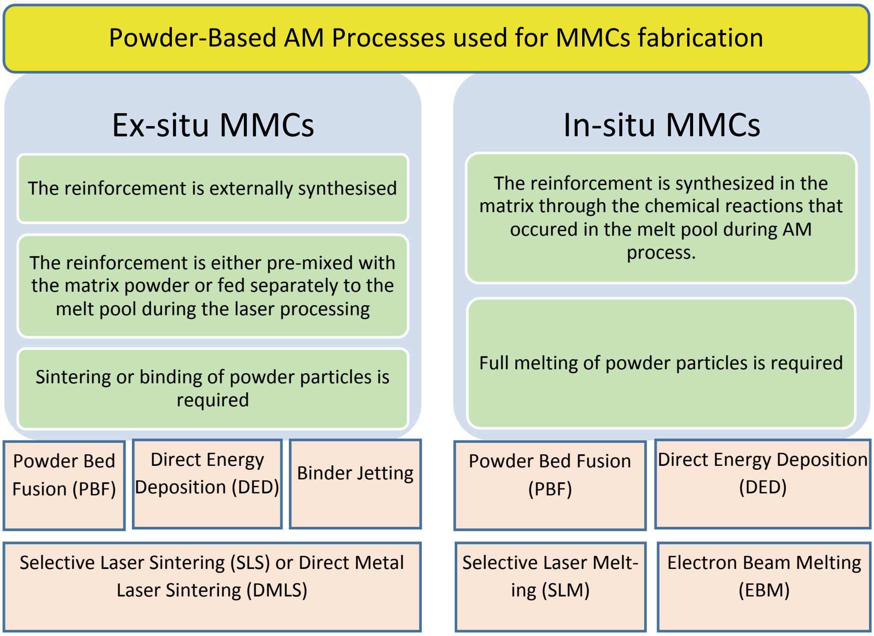

Fig. 14 Powder-based AM processes used for fabrication of MMCs (adapted from [12])

4.1 Volume and Weight Fractions

Based on mixtures' rule, composite materials' properties are the volume-weighted average of the phases (matrix and dispersed phase) properties. Hence, to estimate the mechanical properties of composite material, it is essential to know the relative proportions of matrix and reinforcement. The proportion can be expressed in terms of volume fraction of weight or mass fraction. Weight fractions are commonly used as it is easy to weigh the relative proportions of matrix and reinforcement using an analytical balance. The volume fraction is used in the computation of the properties of the composite. Therefore, knowing the conversion between weight and volume fraction is essential.

The weight fractions can be computed as follows:

$$W_M = \frac{w_M}{w_C} \tag{1}$$

$$W_R = \frac{w_R}{w_C} \tag{2}$$

$$W_M + W_R = 1 \tag{3}$$

where w_M, w_R and w_C are the respective weight of the matrix, reinforcement and composite material.

Similarly, the volume fractions can be computed as follows:

$$V_M = \frac{v_M}{v_C} \tag{4}$$

$$V_R = \frac{v_R}{v_C} \tag{5}$$

$$V_M + V_R = 1 \tag{6}$$

where v_M, v_R and v_C are the respective volumes of the matrix, reinforcement and composite material.

Making use of the relationship between weight, volume and density,

$$w_C = \rho_C v_C \quad w_M = \rho_M v_M \quad w_R = \rho_R v_R$$

where ρ_M, ρ_R, and ρ_C are the densities of the matrix, reinforcement and the composite material.

The relationships between the volume fractions and weight fractions can be expressed as follows:

$$W_M = \frac{w_M}{w_C} = \frac{\rho_M v_M}{\rho_C v_C} = \frac{\rho_M}{\rho_C} V_M$$

where the weight fraction of the matrix can be expressed as

$$W_M = \frac{\rho_M}{\rho_C} V_M \tag{7}$$

and the weight fraction of reinforcement is

$$W_R = \frac{\rho_R}{\rho_C} V_R \tag{8}$$

4.2 Density

The weight and volume fractions can be used to determine the density of the composite material. Using the total weight of the composite material,

$$w_C = w_M + w_R \tag{9}$$

$$\rho_C v_C = \rho_M v_M + \rho_R v_R \tag{10}$$

The density of the composite material can be determined by the volume fractions multiplied by the respective constituents' densities.

$$\rho_C = \rho_M V_M + \rho_R V_R \tag{11}$$

Using the total volume of the composite material, the composite's density can be computed based on the weight fractions divided by the densities of the respective constituents.

$$v_C = v_M + v_R \tag{12}$$

$$\frac{w_C}{\rho_C} = \frac{w_M}{\rho_M} + \frac{w_R}{\rho_R}$$

$$\frac{1}{\rho_C} = \frac{W_M}{\rho_M} + \frac{W_R}{\rho_R}$$

$$\rho_C = \frac{1}{\frac{W_M}{\rho_M} + \frac{W_R}{\rho_R}} \tag{13}$$

4.3 Coefficient of Thermal Expansion (CTE)

Based on the rule of mixtures, the thermal expansion coefficient of composite material can be computed as follows:

$$\boldsymbol{\alpha}_c = \boldsymbol{\alpha}_m V_m + \boldsymbol{\alpha}_r V_r \tag{14}$$

where $_c$, $_m$ and $_r$ refers to the thermal expansion coefficients of the composite, matrix and reinforcement materials.

For particle reinforced MMCs, the coefficient of thermal expansion can also be calculated based on the Turner model as below [1]:

$$\alpha_c = \frac{(\alpha_m V_m K_m + \alpha_r V_r K_r)}{(V_m K_m + V_r K_r)} \tag{15}$$

where K_m and K_r is the bulk modulus of matrix and reinforcement, respectively.

Similarly, for continuous fibre reinforced metal matrix composites, the thermal expansion coefficients along the longitudinal and transverse directions can be calculated as follows:

CTE in the longitudinal direction (along the fibres),

$$\alpha_{cl} = \frac{\alpha_m E_m V_m + \alpha_f E_r V_r}{E_m V_m + E_r V_r} \tag{16}$$

CTE in the transverse direction (perpendicular to the fibres),

$$\alpha_{ct} = (1 + \upsilon_m)\alpha_m V_m + \alpha_f V_r \tag{17}$$

where E_m, E_r are the elastic moduli of the matrix and the fibre reinforcement respectively, and $_m$ refers to the Poisson's ratio.

4.4 Modulus of Elasticity

The elastic behaviour of a composite depends on the type and volume fraction of the reinforcement, and it generally improves with the addition of the reinforcement, as shown below:

$$E_C = E_m V_m + E_r V_r \tag{18}$$

Along the transverse direction,

$$E_{ct} = \frac{1}{\left(\frac{V_m}{E_m} + \frac{V_r}{E_r}\right)} \tag{19}$$

For discontinuous fibres and particle reinforced composites, the elastic modulus can be calculated as follows:

$$E_c = \frac{E_m(1 + 2sqV_r)}{1 - qV_r} \tag{20}$$

where s is the particle aspect ratio and

$$q = \frac{\left(\frac{E_r}{E_m} - 1\right)}{\left(\frac{E_r}{E_m} + 2s\right)} \tag{21}$$

4.5 Tensile Strength

Addition of reinforcements to the matrix alloy generally enhances both yield and ultimate tensile strength. Based on the rule of mixtures, the tensile strength of the composites can be calculated as below:

$$\sigma_c = \sigma_m V_m + \sigma_r V_r \tag{22}$$

where σ_c, σ_m, σ_r refer to the tensile strength of the composite, matrix and the reinforcement, respectively.

However, for short-fibre reinforced composites, the tensile strength is calculated based on the fibre length. i.e. the length of fibre is critical in establishing the relationship.

$$\text{Case I:L} > \text{L}_\text{c};\ \ \sigma_c = \sigma_m V_m + \frac{L\tau_c V_r}{d}; \tag{23}$$

$$\text{Case II:L} < \text{Lc};\ \ \sigma_c = \sigma_m V_m + \sigma_r V_r \left(1 - \frac{L_c}{2L}\right) \tag{24}$$

where c is the shear strength of the bond between the matrix and the reinforcement fibre.

5 Strengthening Mechanisms

MMCs exhibit better strength than their unreinforced matrix metals as they can transfer much of the applied loads to the stronger reinforcement. Some of the common strengthening mechanisms applicable to particle reinforced metal matrix composites are discussed below.

5.1 Dislocation Strengthening

Generally, dislocation density in a composite matrix is higher than in unreinforced metal processed using similar methods. The increased dislocation density in the composites is due to the thermal stresses caused by CTE mismatch between matrix and reinforcement.

$$\Delta\sigma = 12\frac{\Delta\alpha\Delta T V_r}{bd} \tag{25}$$

where $\Delta\sigma$ is the increase in dislocation density, $\Delta\alpha$ is the CTE mismatch, ΔT is the temperature difference, b is Burgers vector, V_r is the reinforcement volume fraction, and d is reinforcement size. Hence, the dislocation density and the matrix strengthening increase with increasing reinforcement volume fraction and decreasing reinforcement size.

5.2 Grain Refinement Strengthening

The matrix grain size of metal matrix composites is usually smaller than that of the unreinforced counterparts. The smaller grain size implies greater grain boundary area and fewer dislocations in the pileups, thus resulting in larger stress requirements to cause yielding. The Hall-Petch equation can be used to explain the strengthening mechanism.

$$\sigma_{Hall-Petch} = \sigma_0 + \frac{k}{\sqrt{d}} \tag{26}$$

5.3 Orowan Strengthening

This strengthening mechanism is vital for dispersion strengthened materials in which the composite strength is improved by restricting the dislocation movement.

However, in other MMCs, the reinforcement particles are too large and too far apart to be considered a practical obstacle to the motion of dislocations. The Orowan-Ashby equation defines the Orowan stress as [13]:

$$\sigma_{Orowan} = \frac{0.13Gb}{\lambda} \ln \frac{d}{2b} \tag{27}$$

6 Review of Mechanical Properties of Developed MMCs

There are many various combinations of MMCs that have been developed by researchers and commercial companies. In recent years, there has been increasing research and development in using nano-size reinforcements. The advantages of using nano-size reinforcements include improvement in both strength and ductility and comparable or superior properties with small volume fraction compared to micron size reinforcement [7]. Examples of the mechanical properties of selected MMCs fabricated using different manufacturing techniques are shown in Table 4.

In addition to the use of nano reinforcements, various additive manufacturing techniques for the fabrication of metal matrix composites have increased exponentially in recent years. Examples of MMCs produced by AM techniques are shown in Table 5.

7 Application of MMCs

Metal matrix composites are used in a range of applications in the automobile, aerospace, power transmission, consumer electronics, and sports sectors. A summary of the various applications of MMCs is provided in Table 6.

The transportation sector has been one of the prime consumers of MMCs, and the applications in this field include drive shafts, pistons, engine and brake components. For example, Toyota introduced squeezed cast Al MMC piston reinforced with chopped fibre for a diesel engine in 1983 [44]. Al–Si matrix composite containing 12% Al_2O_3 and 9% carbon is used in the cylinder liner of Honda Prelude leading to a weight reduction of 20% in the aluminium engine block and improved wear resistance compared to cast iron [44]. Other popular automotive applications of MMC include connecting rod made of SiC-particle-reinforced aluminium–matrix composites to replace steel for lightweight. Duralcan supplied brake rotors of German high-speed train made of SiC particles reinforced AlSi7Mg composite with ~43% weight savings. Since the transportation sector is a high volume and high technology market, the manufacturing cost of MMCs should be as low as possible for their extended applications. Thus, reducing the manufacturing costs of MMC components will significantly aid in the replacement of conventional parts.

Table 4 Mechanical properties of MMCs

Composite	Technique	0.2%YS (MPa)	UTS (MPa)	Elongation (%)	Ref.
Al/13vol.%SiC	Stir casting + extrusion	88	215	9.5	[14]
Al/10wt%Si_3N_4	Stir casting	154	170	4	[15]
Al/5vol.%BN	PM + extrusion	258	377	–	[16]
Al/15vol.%Al_2O_3		260	425	–	
Cu/8wt%WC	Stir casting	–	237	~6	[17]
Al/4.8vol.%SiC	Disintegrated Melt Deposition (DMD) Technique	148	173	10	[18]
Mg/0.63vol.%Mo		123	198	9	[19]
Mg/30vol.%SiC	Stir casting	229	258	2	[20]
Mg/5vol.%Al_2O_3	PM with hybrid microwave sintering	159	214	3	[21]
Mg/10vol.%SiC		140	165	1.5	[22]
AZ91/15vol.%SiC	Stir casting	134	204	1.2	[23]
MMCs with nano reinforcements					
Al/1wt%SiC (as cast)	Stir casting and squeeze casting	203	323	5	[24]
Al4.5Mg/6wt%Al_2O_3	Stir casting	181	204	2	[25]
Al/1wt%CNT	Ultrasonic mixing and ball milling	190	290	5	[26]
Mg/1.3wt%CNT	Disintegrated Melt Deposition (DMD) Technique	140	210	13.5	[27]
Mg/0.97vol.%TiB2		110	173	16	[28]
Mg/0.6vol.%Cu	PM with hybrid microwave sintering	237	286	5.4	[29]
Mg/1.0vol.%SiC		157	203	7.6	[30]
Ti6Al4V + B_4C	Investment casting	954	1029	2.46	[31]
Ti6Al4V/5vol.% (TiB + TiC)	PM and spark plasma sintering	1267	1153	5.1	[32]
Commercially available MMCs					
AL2124/25vol.%SiC	PM using mechanical alloying	400	600	3–4	[33]
Al6061B/20vol.%SIC		410	490	7	
AA2009/25vol.%SiC	PM	448	593	3.4	[34]
AA6092/25vol.%SiC	PM	345	414	3	
AZ91/50%SiC	Squeeze casting	426	503	1.4	[35]
Ti/TiB	Wrought processing	650	810	7	

Table 5 Properties of MMCs fabricated by AM techniques

Composite	Observations	Ref.
AlSi10Mg/1wt%CNT	Fabricated using SLM Density >95%. Highest density 98.53% Hardness of 143.33 HV Tensile strength of 499 MPa and elongation of 7.6%	[36]
Al2024/3%TiB2	Fabricated using solid laser forming The average microhardness of composite is 108.5 HV compared to 75 HV for Al2024 alloy and 62 HV for cast Al2024 Composite achieved higher yield strength (163 MPa), tensile strength (284 MPa) and elongation (18%) compared to Al2024 alloy with 90 MPa yield strength, 202 MPa tensile strength and 7% elongation	[37]
Fe/25wt%WC	Fabricated using SLM Density achieved 98.5% with an average grain size of 0.82 to 1.24 µm Microhardness: 478.5–511.6HV	[38]
316L/3wt%V_8C_7	Fabricated using SLM Density achieved over 97% and the average grain size of ~.5 µm Highest UTS of >1400 MPa and elongation of 18% observed	[39]
Ti6AL4V/1.5%B_4C Ti6AL4V/3%B_4C	Fabricated using direct metal deposition (DMD) In situ formation of TiC and TiB Increased in hardness from 360 $HV_{0.5}$ to 455 $HV_{0.5}$ due to formation of 12vol.% TiB whiskers Improvement in elastic modulus from 115 GPa to 125 GPa For Ti6AL4V/1.5%B_4C composite, UTS is between 1000–1200 MPa in the longitudinal direction and 700 MPa in the transverse direction	[40]
Ti/5wt%B_4C Ti/5wt%BN Ti/2.5wt%B_4C + 2.5wt%BN	Fabricated using Laser engineered net shaping (LENS) Densities achieved range 96.1–97.4% Increase in compressive modulus to more than 152 GPa Highest compressive yield strength of 758 MPa observed in Ti/2.5 wt%B_4C + 2.5 wt%BN	[41]
Inconel 625/graphite Inconel 625/CNT	Fabricated using laser aided additive manufacturing (LAAM) Addition of graphite reinforcement improves yield strength (~688 MPa) and UTS (~970 MPa) but reduces ductility (~13%) compared to pure Inconel 625. Addition of CNT improves yield strength (695 MPa), UTS (~1006 MPa) and ductility (~21%)	[42]

(continued)

Table 5 (continued)

Composite	Observations	Ref.
CoCrFeMnNi HEA/4.8wt% TiN	Fabricated using SLM with remelting SLM built HEA/TiN: average UTS 1059 MPa and average elongation 15.3% Remelted SLM built HEA/TiN: average UTS > 1100 MPa and average elongation 18%	[43]

Table 6 Applications of MMCs

Industry	Applications	Desired properties
Aerospace	Support strut, landing gears, casing, fan and compressor blades, blade sleeve in helicopters	Low density, high strength, high stiffness, high fatigue strength, high fracture toughness
Automotive	Connecting rod, cylinder liner, brake disc, brake callipers, driveshaft, piston	Low density, high strength, high stiffness, high fatigue strength, good wear resistance, good thermal conductivity, good creep resistance
Military	Fins, missile body casings, armour, landing gears, nozzle actuator	Low density, high strength, high stiffness
Electronic	Heat sinks, casings, microprocessor and optoelectronic packaging	High thermal conductivity, low coefficient of thermal expansion
Sports	Bicycle frames, wheel rims, golf club heads, skis, tennis and badminton rackets	High stiffness, high strength, low density

The enhanced stiffness and strength of the MMCs make them highly suitable for military and commercial aircraft applications. For example, the aluminium access doors in the F-16 aircraft have been replaced with SiC particle reinforced MMCs for fatigue life improvement [2]. Similarly, the SiC mono fibre reinforced Ti-composites are used to replace the heavier IN718 and stainless-steel components of the F119 engine in the F-16. MMC has also replaced a CFRP fan-exit guide vane of a Pratt & Whitney engine on a Boeing 777 aircraft. The lower drag brace for the landing gear of F-16 is made of titanium reinforced with SiC fibres allowing a 40% weight reduction compared to the original part, which is made of high strength steel [45].

In the electronics industry, MMCs with controlled thermal expansion coefficients (by controlling the volume fraction of reinforcement and matrix) such as boron/graphite fibres or SiC particles reinforced aluminium composites are used in the new generation advanced integrated circuits to overcome the major concerns related to heat dissipation and thermal fatigue. Continuous Al_2O_3 fibre reinforced Al MMCs with adjustable CTE is also used as electrical conductors for power transmission applications.

The typical sporting applications of MMCs include fishing rods, bicycle frames, golf club heads, and tennis/squash rackets.

8 Review Questions

(1) What are the advantages and disadvantages of MMCs?
(2) Explain the function of the matrix and the reinforcement.
(3) Explain how the interface may affect the properties of MMCs.
(4) What can be done to prevent unwanted reactions between the fibres and the matrix?
(5) Describe the various types of reinforcement.
(6) Provide three examples of fibre reinforcement.
(7) Describe the process of powder metallurgy.
(8) Describe the differences between powder metallurgy and mechanical alloying.
(9) Describe the process of stir casting.
(10) What are the advantages and disadvantages of using squeeze casting over melt infiltration?
(11) How are reinforcements produced during in situ processing of MMCs?
(12) Describe the strengthening mechanisms for composites.
(13) How do the properties of AM manufactured MMCs compared to conventional MMCs produced by liquid or solid processing techniques?
(14) Provide examples of composites used in aerospace and the desired properties.
(15) Explain how it is possible to control the thermal expansion coefficient of MMCs?

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