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A Brief Review on Additive Manufacturing Processes for Lightweight Metal Matrix Composites

Recent advances in selection, reinforcement, preparation and processing and their influence on material properties

Abd Baghad*§, Khalil El Mabrouk
Euromed Research Centre, Euromed Polytechnic School, Euromed University of Fez, BP 51, main Fez, Morocco

***Email:** abd.baghad@icam.fr

§Present address: ICAM - Site de Grand Paris Sud, Carré Sénart, 34 Points de Vue, 77127 Lieusaint, France

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Many additive manufacturing (AM) processes have been developed to fabricate lightweight metal matrix composites (LMMCs) from constituent materials. However, the improvement in mechanical properties is significantly affected by the added reinforcing materials in the LMMC compared to metallic materials and their alloys. Recent advances in understanding the selecting criteria and effect of the reinforcement, preparation methods and AM process on the properties of LMMCs are summarised in this review. The preparation methods of particle-reinforced LMMCs include *ex situ* and *in situ* synthesis. The effect of various reinforcement and AM processes such as powder bed fusion (PBF) processes and direct energy deposition (DED) processes on the mechanical properties of LMMC parts are discussed.

1. Introduction

Metal matrix composites (MMCs) have evolved significantly since their appearance in the 1960s. Because of their high price, their applications were initially limited to the aerospace and defence industries. It was not until the 1980s that new applications were investigated, thanks to the development of high-quality, low-cost reinforcements. For their capacity to meet engineering and structural needs, MMCs are currently of interest in the transportation (particularly automobile, rail and marine), construction, electronics and sports industries (1). The unusual and sometimes surprising features of MMCs, significantly superior to metallic alloys, are the basis for this interest.

Generally, lightweight metallic materials, specifically titanium and aluminium, are characterised by poor wear resistance, limiting their further development (2). An effective means of enhancing their resistance is to reinforce them with hard materials: carbides (silicon carbide, titanium carbide and boron carbide), nitrides (silicon nitride, aluminium nitride), carbon allotropes (carbon nanotubes and graphene) and oxides (alumina, silica) are currently the most used reinforcement materials (3, 4). Additionally, as hard materials are not necessarily suitable for stiffness and fatigue resistance, combining two or more materials leads to composites capable of satisfying varying industrial requirements. Moreover, the material properties are highly affected by the operating conditions (stress, temperature, humidity) and the nature of loading (fatigue, impact, fluctuation). Such composite materials allow the user to benefit from different functional properties provided by the light metal matrix and reinforcement. These materials are called LMMCs.

Depending on the distribution of reinforcement and its type (particles or fibres), there are three types of LMMCs: (a) particle-reinforced LMMCs; (b) short fibre- or whisker-reinforced LMMCs; and (c) continuous fibre- or sheet-reinforced LMMCs. The primary industrial methods for manufacturing LMMCs can be roughly divided into three main groups: (a) solid-state processes (i.e. powder metallurgy, mechanical alloying, diffusion bonding and physical vapour deposition); (b) semi-solid processes (i.e. thixoforging and compocasting); and (c) liquid-state processes (stir casting, ultrasonic-assisted casting, pressure infiltration processes and spray deposition). Alternatively, the manufacture of LMMCs can be classified into three main concepts: (a) casting; (b) diffusion bending; and (c) powder metallurgy. Among them, powder metallurgy is the only method used to manufacture LMMCs reinforced by whiskers or particles that exhibit outstanding specific stiffness, strength, isotropic properties and ease of near-net-shape production (5). Liquid-state methods result in inhomogeneous dispersions of reinforcement throughout the LMMCs, resulting in either reinforcement-rich or light-metal-rich regions.

Additionally, traditional methods (i.e. stir casting and powder metallurgy) show many limitations, namely the possible reaction of the reinforcement with the melt or a tendency to settle during casting. The size and morphology of particles (such as spherical or angular particulates, prismatic sections and flat sheets) are the two critical parameters in injection moulding (6). Furthermore, both methods are subject to agglomeration of the reinforcement phase and require post-processing or machining to obtain desired geometry, structure and properties, which is another disadvantage for industrial production. Moreover, the increased tool wear from the reinforcement phase could result in an expensive process. Hence, recent efforts have been made to address these challenges to broaden the application of LMMCs. These efforts have been focused on using metal AM techniques, a recently developed technology that has rapidly become a promising method for fabricating complex-shaped components.

Initially developed in 1986, AM can be defined as assembling materials to fabricate objects using three-dimensional (3D) model data, usually layer by layer, as opposed to subtractive manufacturing methods, such as traditional machining (7). AM provides a processing route to fabricate complex shaped parts with a high level of design accuracy and flexibility while benefiting from the advantages of the AM technique, such as the elimination of the need for post-intermediate tooling. AM, therefore, reduces the manufacturing time, provides opportunities to minimise material waste and energy consumption, and gives the best design for lean production. More companies use LMMC composites to design parts of varying complexity in the AM market. However, even though the term is increasingly used, it is unclear what LMMCs are and how to prepare their parts. In this review, based on the relevant and recent literature, the description of LMMCs, preparation methods of composite powder and metal AM processes for LMMCs (mostly PBF and DED) will be discussed in detail, as depicted in **Figure 1**.

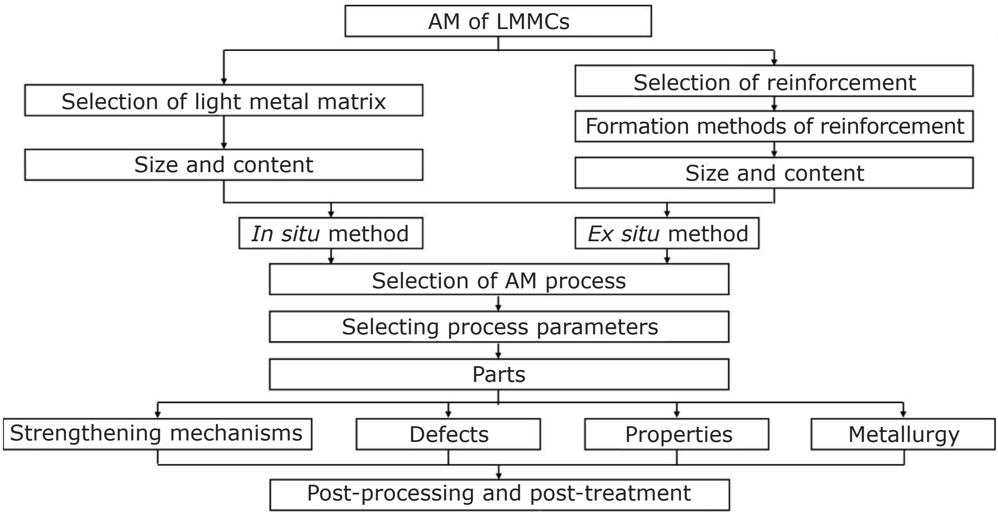


Fig. 1. Design process for the additive manufacturing of particle-reinforced LMMCs

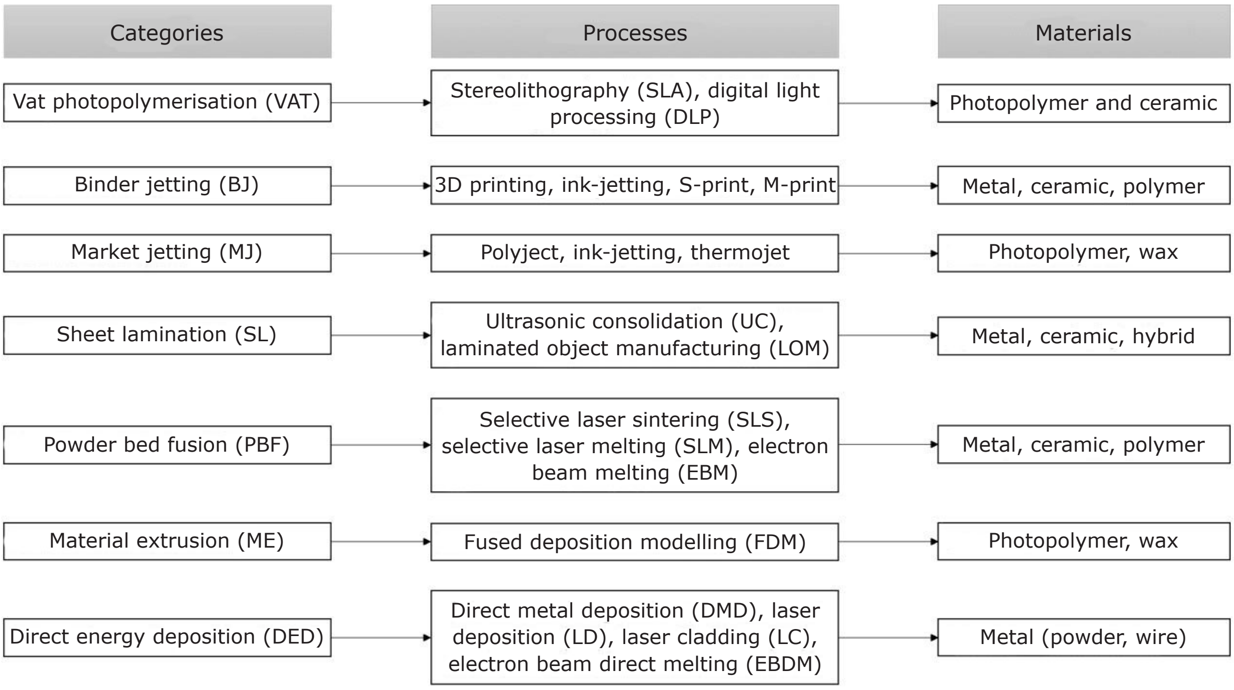
2. Overview of the Metal Additive Manufacturing Processes for Fabricating Lightweight Metal Matrix Composites

According to ASTM F2792-12 (7), AM can be divided into seven categories based on adhesion and bonding techniques. **Figure 2** summarises the categories, the processes and the materials used for each technique. Another classification can be made depending on the state of the raw material (8): liquid processes (i.e. vat photopolymerisation and material jetting); molten or filament processes (i.e. material extrusions); powder processes (i.e. PBF, binder jetting and DED) and solid layer processes (i.e. sheet lamination).

Metal AM can be classified into two main groups: direct and indirect methods. In the case of direct methods, the component is directly fabricated without any additional post-processing; the processes include PBF and DED. In an indirect process such as binder jetting, as a binder is used for shaping, post-processing (debinding and sintering) it is required to consolidate the materials and, therefore, increase the density of the components (9). In general, AM methods have shown the ability to create lightweight metal parts in a clean construction environment with reduced fabrication time and outstanding characteristics. Nevertheless, only a few of them focus on particle-reinforced LMMCs. Metal AM could enable the manufacture of either particle- or fibre-reinforced LMMCs. However, most of the existing literature about LMMCs focuses on particle-reinforced LMMCs. As a result, sheet lamination (SL) might not be applicable for processing LMMC materials with complex geometries (10). In the light of the above, this review focuses on particle-reinforced LMMCs fabricated by powder-based AM processes, namely PBF and DED.

2.1 Powder Bed Fusion Processes

PBF processes were one of the first commercialised AM processes. Originally developed at the University of Texas at Austin, USA, selective laser sintering (SLS) was the first commercially available PBF process. **Figure 3** shows the primary mode of operation of SLS. All other PBF processes derive from them in one or more ways to improve productivity, allow the processing of different materials and avoid specific patented features. Consequently, PBF processes share several essential characteristics, namely: (a) one or multiple heat sources to induce fusion between the powder particles; (b) a method to control the fusion of the powder particles in a predetermined region of each layer; and (c) mechanisms for adding and smoothing the powder layers (11).



Categories	Processes	Materials
Vat photopolymerisation (VAT)	Stereolithography (SLA), digital light processing (DLP)	Photopolymer and ceramic
Binder jetting (BJ)	3D printing, ink-jetting, S-print, M-print	Metal, ceramic, polymer
Market jetting (MJ)	Polyject, ink-jetting, thermojet	Photopolymer, wax
Sheet lamination (SL)	Ultrasonic consolidation (UC), laminated object manufacturing (LOM)	Metal, ceramic, hybrid
Powder bed fusion (PBF)	Selective laser sintering (SLS), selective laser melting (SLM), electron beam melting (EBM)	Metal, ceramic, polymer
Material extrusion (ME)	Fused deposition modelling (FDM)	Photopolymer, wax
Direct energy deposition (DED)	Direct metal deposition (DMD), laser deposition (LD), laser cladding (LC), electron beam direct melting (EBDM)	Metal (powder, wire)

Fig. 2. ASTM international classification of additive manufacturing (5, 7)

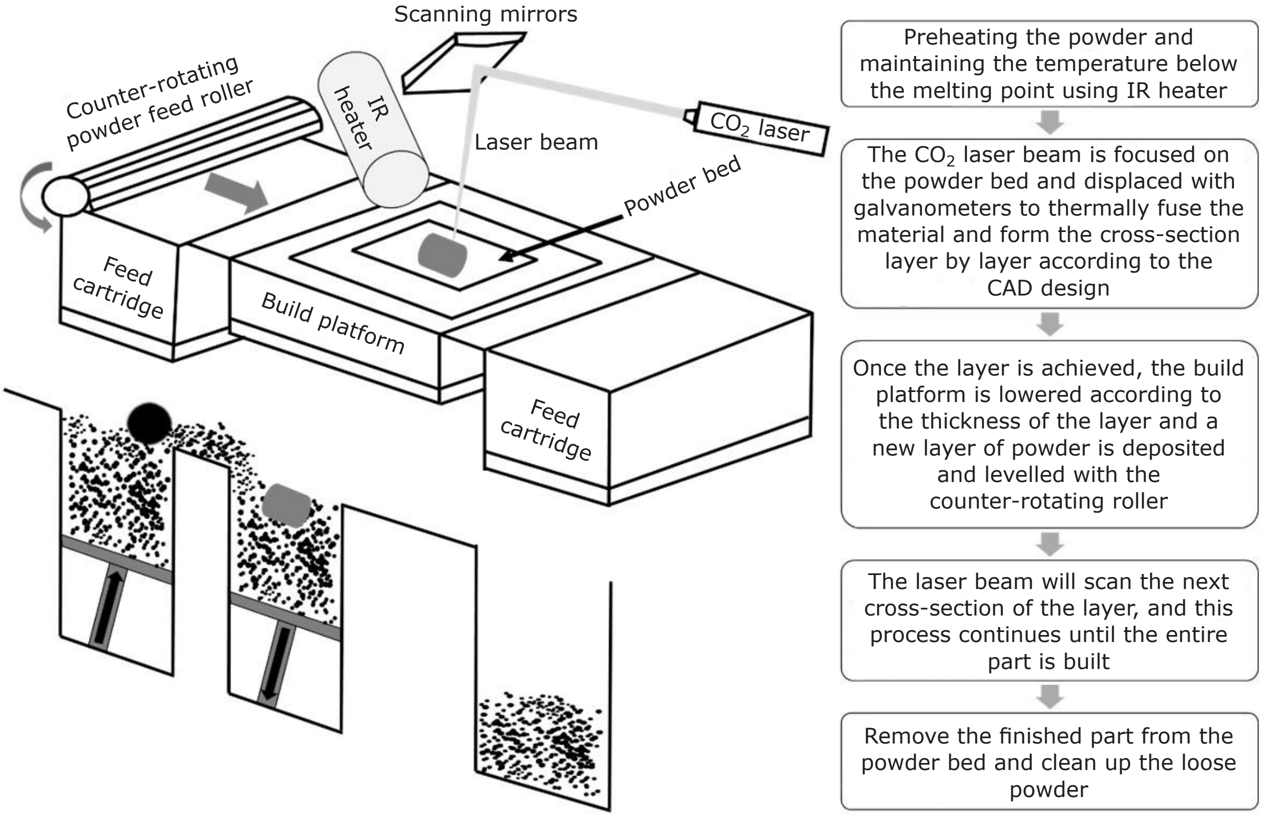


Fig. 3. Selective laser sintering process

PBF processes can be classified depending on the heat sources: thermal fusion (i.e. SLS); laser fusion (i.e. SLS, selective laser melting (SLM) and direct metal laser sintering (DMLS)); electron beam fusion (i.e. electron beam melting (EBM)); and agent or energy fusion (i.e. multi-jet fusion). The two most well-known heat sources are lasers and electron beams. However, as electron beam requires different machine architectures than laser, laser PBF and EBM processes will be addressed separately. **Table I** shows a comparison of the characteristics of these AM processes. Based on these characteristics, SLM and EBM processes offer better surface finish and lower layer thickness compared to DED. Therefore, direct metal deposition (DMD) is more suitable for manufacturing relatively large parts at high processing speeds but with a coarser surface finish, while SLM and EBM are more suitable for manufacturing more precise and complex small objects.

2.1.1 Laser Powder Bed Fusion Processes

In 1994, the company EOS GmbH, Germany, patented its process called DMLS, while in 1996, the Fraunhofer Institute of Laser Technology ILT, Germany, introduced SLM. Although the term DMLS implies sintering as in SLS, it is crucial to understand that metal AM processes are nowadays based on fusion and not on sintering. The difference between sintering and melting is quite simple: melting means the metal goes from solid to liquid due to high temperature. On the other hand, sintering does not allow the metal to melt because the temperature used is not high enough. As a result, the metal particles are agglomerated together, leaving a void and holes.

As previously mentioned, laser powder bed fusion (LPBF) is one of the direct AM processes. A speed-controlled laser scans selected positions in the powder bed and fuse the powder by either partial melting (SLS and DMLS) or complete melting (SLM). The sintering processes result in the production of *ex situ* reinforced LMMCs. In the metal SLS process, composite powder grains consisting of the structural material, binder and reinforcement are used. The low-melt powders (metal matrix) can partially melt during the SLS process and form a bond with the unmelted high-melt powders. The composite powder can be obtained by mechanically alloying a mixture of two or more powders, allowing the powder particles to be repeatedly ground, raked and welded together.

Table I Comparison of the Characteristics of Additive Manufacturing Processes (12–15)

Additive manufacturing processes	Powder bed fusion		Direct energy deposition (DMD)
	Selective laser melting	**Electron beam melting**	
Description	Builds objects by using thermal energy to fuse regions of a powder bed		Build parts using concentrated thermal energy to fuse materials deposited on a substrate
Heat source	Laser beam	Electron beam	Laser, electron beam or gas-tungsten arc
Build envelope	Limited	Limited	Large and flexible
Build capability	Complex geometry, cellular structure, building hollow channels	Complex geometry, cellular structure, building hollow channels	Relatively simpler geometry with less resolution
Beam size, mm	0.1–0.5	0.2–1	2.0–4
Layer thickness, mm	0.05–0.1	0.1	0.5–1
Build rate, $cm^3 h^{-1}$	<50	55–80	16–320
Surface finish	Ra 9/12 μm Rz 35/40 μm	Ra 25/35 μm	Ra 20–50 μm Rz 150–300 μm
Residual stress	High	Minimal	High
Heat treatment	Stress relief required; Hot isostatic pressing (HIP) preferred	Stress relief not required; HIP preferred may or may not be performed	Stress relief required; HIP preferred
Advantages	Surface finish Mechanical strength	Minimal residual stress Mechanical strength Malleability No thermal treatments	Build rate Microstructure control Mechanical strength Footprint Repair tool Coating tool
Disadvantages	Build rate Inert atmosphere Residual stress Stress relief/HIP Malleability	Build rate Powder variety Surface finish Vacuum atmosphere Cost	Surface finish Poor resolution Geometrical complexity Controlled atmosphere Residual stress Metal variety Stress relief/HIP

Even with potential application in several fields, manufacturing is limited in the SLS process because of its products' low dimensional accuracy and surface roughness (16).

DMLS is similar to the SLS process from the perspective of being a powder deposition method. However, the DMLS process does not require any plastic binder mix to hold the composite powder together. Similarly, there is no need for other sintering or infiltration processes to produce LMMC parts for different applications. Nevertheless, the shot-peening process and polishing are secondary finishing operations (17). The shot-peening process controls residual stresses through surface compression, while polishing is used to reduce surface roughness.

SLM is similar to SLS, except it requires more energy because complicated pieces are made at a higher temperature to fuse or melt the powders during the SLM process. However, the SLM process could fabricate *in situ* reinforced LMMCs by activating chemical reactions between the components present in the composite powder. Although the SLM process suffers from limitations caused by the fact that the dimensional accuracy is second-rate, the SLM technique is the most widely used in the literature for the fabrication of LMMCs. The characteristics and properties of the resulting composite powder are of critical importance and significantly determine the quality of the product. When using ceramic particles as reinforcement, each constituent's type, size, morphology and volume fraction may be considered crucial factors for controlling the microstructural homogeneity, laser absorptivity, processability and therefore the mechanical properties of LMMCs fabricated by SLM (18). For instance, according to many attempts, the mixture of ceramics with lower laser absorption using SLM will deteriorate the properties of the part when compared to matrix alloys (18, 19). Recently, Liu *et al*. (20) investigated the effect of process parameters on SLM SiC/AlSi10Mg composites. They demonstrated the highest densities and tensile strength because of silicon and magnesium silicide precipitation hardening, silicon carbide dispersion strengthening and α-alumina solid solution strengthening.

2.1.2 Electron Beam Melting

The EBM system was first commercialised by Arcam AB, Sweden, in 2002. The principle is the same as the SLM process, except that the composite powder is melted with an electron beam instead of a laser source. In the EBM process, a stream of electrons produced by an electron beam is guided with a magnetic field to melt layer upon layer of powdered composite fully and create an object that matches the specifications outlined by a computer aided design model. To avoid oxidation that can compromise highly reactive materials, manufacturing occurs in a vacuum chamber. The EBM process is distinguished by a higher energy density than the LPBF process, enabling the EBM method to have powder layers with a higher thickness (greater than 50 μm). Accordingly, the particle size distribution of the starting composite powder may be within the range of 45–150 μm (larger than LPBF, which is in the range of 15–50 μm) (5). Since the electron beam is wider than the laser beam, EBM can be much faster than LPBF processes, but the latter produces smoother and more accurate parts. The EBM process is more energy-friendly and allows for a more uniform distribution of the thermal field and a much higher throughput (16). In addition, mechanical properties are highly improved using EBM in parallel to reinforcement, which is surely proved by the wear behaviour of $TiC+Ti_3SiC_2+Ti_5Si_3$ reinforced Ti6Al4V alloy, demonstrating an improved microhardness and wear resistance (21).

2.2 Direct Energy Deposition Processes

DED is based on synchronous powder feeding technology, allowing a 3D part to be directly manufactured with very complex geometric features. The composite powder is fed into the printing spot using a nozzle, and an electron beam or a laser will create the molten pool and the melt path. Several DED processes are available today, including direct laser deposition, laser consolidation, laser metal deposition, laser engineered net shaping and laser cladding. In the DED process, deposition begins with a computer aided design model, and printing proceeds layer by layer on a building plate or a substrate part (**Figure 4**). A shielding gas such as argon protects the molten materials from oxidation and ensures better powder flow in the melt. However, unfortunately, it also induces some defects in the structure, such as pores

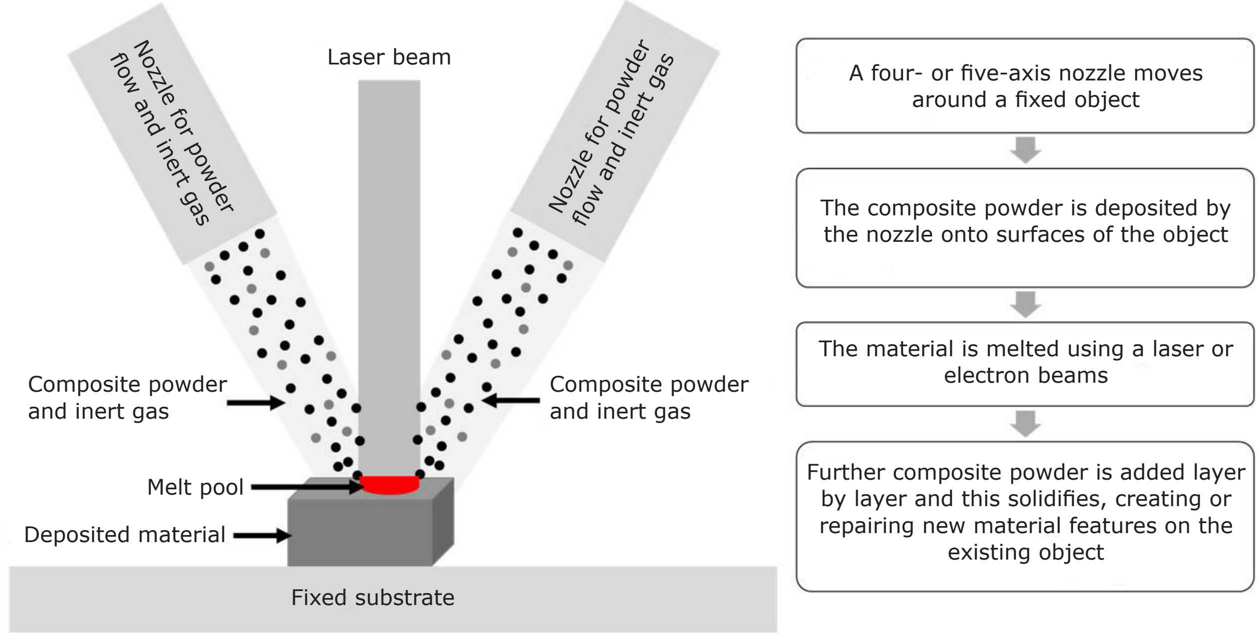


Fig. 4. Direct energy deposition process to produce LMMCs

and layered voids (22). However, an appropriate support structure is required to avoid distortion when manufacturing complex geometries with overhanging features (6). In addition, the cooling rate is very high (10^2~10^5 K s^{-1}), so the resulting microstructure is ultrafine (23).

The DED processes can manufacture both *ex situ* and *in situ* reinforced LMMCs. The DED process is desirable for manufacturing large parts with a lower production cost than other AM methods such as SLM. However, the powders are often larger, requiring a higher energy density, resulting in faster build rates than the PBF processes and poorer surface quality. Even though surface finishing is often a requirement for all metal AM techniques, the surface finish quality is poor in DED compared to PBF. LMMC parts may need to be further treated with additional finishing operations to achieve the desired surface quality. Therefore, DED is a practical approach to preparing LMMCs with high bonding strength because the high energy density of the laser beam will lead to the metallurgical bonding between the light metal matrix and the reinforcement.

3. Lightweight Metal Matrix Composites and their Progress

3.1 Effect of Preparation Methods

Many attempts have been recently made to accelerate the improvement of LMMC properties to meet the growing demand for lightweight structural components with a high stiffness-to-weight ratio in the automotive, aerospace and marine fields. One such attempt is to prepare composites reinforced with hard and stable '*ex situ*' particles. In the *ex situ* technique, the reinforcement is externally synthesised and then pre-mixed with the light metal matrix or introduced separately into the melt pool during manufacturing. Recently, mechanical mixing methods have attracted much attention due to their convenience, speed, cost-effectiveness and applicability to a wide range of materials. Accordingly, regular mixing and ball milling are considered the most widely applied processes for the pretreatment of composite powders. The ball milling method enhances the dispersion of reinforcing particles in micro- or nano-composite powders. The ball milling method can be characterised by the repeated deformation, cold welding and fracture of the powder particles caused by the high-energy impacts of particle/particle and ball/particle collisions.

Regular mixing is based on the same concept as ball milling, except for not using beads. Consequently, there is an absence of decoration of the metal powder particles, which leads to the separation of the different constituents during the powder deposition step, especially in the SLM process (24). For example, Cheng *et al*. (25) used a powder mixture of (TiB_2+TiC)/AlSi10Mg (1.5 wt% and 1.5 wt% of titanium boride and titanium carbide particles, respectively) for SLM, produced by ball milling. They revealed that the composites exhibited very high ultimate tensile strength (552.4 MPa) and excellent ductility (12%), about 1.4% and 2.67% times higher than AlSi10Mg. Highly reinforced aluminium composite powders were fabricated by mechanically alloying AlSi10Mg and titanium boride, whose morphology and composition were adapted to the LPBF process conditions. Graphene/AlSi10Mg composite powder was also produced by ball milling followed by the PBF process (26). Zhang *et al*. (27) reported a powder mixture of silicon carbide particles with AlSi10Mg alloys produced by ball milling and prepared SiC/AlSi10Mg composites by SLM with the highest microhardness (208.5 $HV_{0.1}$), tensile strength (450 MPa), yield strength (408 MPa) and modulus (90 GPa).

Another attempt is to prepare *in situ* reinforced LMMCs, involving the synthesis of reinforcement in the light metal matrix by chemical reactions that melt during the AM process. Compared to the *ex situ* reinforced LMMCs, the *in situ* reinforced LMMCs exhibit higher density. However, this is due to the agglomeration of the reinforced particles, entrapped gas formation and weak interfacial bonding between the light metal matrix and the reinforced particles in the case of *ex situ* reinforced LMMCs (28). Because of the formation of unique intermetallic phases, more stable and finer reinforced particles, stronger interfacial bonding and more homogeneous reinforcement particles, the mechanical properties obtained through *in situ* reinforced LMMCs were superior to those obtained through *ex situ* reinforced LMMCs (28, 29). Regardless of the preparation method, the increase in particle size and applied energy results in the transformation of the aggregation into a uniform dispersion of reinforcements (29). Shi *et al*. (30) successfully prepared *in situ* particle reinforced aluminium matrix composites starting from Fe_2O_3/AlSi12 powder mixture. Pan *et al*. (31) recently prepared Ti6Al4V/TiB_w *via* electrode induction melting gas atomisation as the feedstock for EBM. *In situ* nano-titanium boride reinforced AlSi10Mg composites were also produced by Tang *et al*. (32).

3.2 Effect of Reinforcements on Lightweight Metal Matrix Composites

A reinforcement must respect a certain number of conditions to obtain a quality material. Firstly, the nature of the reinforcement, its morphology and its properties must be considered. In addition, the reinforcement's chemical, physical and mechanical compatibility with the light metal matrix must be carefully analysed. Chemical compatibility issues are related to chemical reactions at phase boundaries and chemical interaction with the environment during the production process. The light metal matrix should have good ductility, compliance and strength to transfer power loads to the reinforcing particles uniformly and continuously to ensure physical compatibility.

Additionally, local stresses in the light metal matrix induced by defects or dislocation should not generate local concentrations on the reinforcing particle. Furthermore, a significant difference in expansion coefficient and melting temperature of the matrix and the reinforcement can create processing problems such as cracks and unwanted reactions (5). A mismatch of thermal expansion between the light metal matrix and the reinforcement leads to the creation of thermally induced stresses, which has implications for the determination of the mechanical properties of LMMCs (33). The component (matrix or reinforcement) with a higher coefficient of expansion will be subject to tensile stresses generated as a consequence of global cooling and heating of the structure, as well as local cooling and heating events when a temperature gradient develops (33). When thermal stresses (or residual tensile stresses) generated are higher than the yield strength of the metal matrix, they induce either a debonding between the reinforcement particles and the matrix, or crack propagation leading to damage accumulation in the light metal matrix (34). Accordingly, the expansion coefficient of the light metal matrix must be higher than that of the reinforcement.

Reinforcements are usually made of hard materials with a compressive strength greater than their tensile strength. An important point to note is that the light metal matrix and the reinforcement need to be in thermodynamic equilibrium or striving to reach it. The thermodynamic equilibrium criterion for solids at constant pressure and temperature is the minimum of the Gibbs energy; the Gibbs energy indicates the change in energy during the chemical reaction and shows the possibility of chemical reactions between the light metal matrix and the reinforcement. Accordingly, the Gibbs energy variation minimum corresponds to a stable equilibrium between the matrix and the reinforcement (35). In addition to selecting reinforcing conditions, a suitable reinforced material should adhere to the composite powder preparation process requirements.

As previously mentioned, most reinforcements are ceramics. **Table II** provides a detailed description of the various properties of Ti6Al4V and AlSi10Mg as a function of reinforcement content. The data were collected from many sources with different reinforcement/Ti6Al4V (or AlSi10Mg) combinations and different AM techniques. A comparison of the performance of the resulting materials shows that the mechanical properties of composites depend on the nature of the reinforcement and its properties. Thus, hydroxyapatite (HA) has poor mechanical properties compared to metals and ceramics, which explains the low ultimate tensile strength and ultimate compressive strength of HA/Ti6Al4V compared to uncharged Ti6Al4V. As ceramics are hard materials, their incorporation as reinforcements leads to reducing deformation at the break of the composites. The same applies to other mechanical properties; the harder and stronger the reinforcement, the better the properties of the resulting composites. For example, changes in titanium carbide content had very profound effects on the hardness and compressive properties of TiC/Ti6Al4V (42, 44).

Strengthening mechanisms have been discussed in a few studies in order to predict the behaviour of the dispersion of the reinforcement in a lightweight metal matrix. For example, Afifa *et al*. (51) in their review suggest that the strengthening mechanisms for graphene-reinforced aluminium matrix include grain refinement, Orowan strengthening mechanism, stress load transfer and thermal expansion mismatch. Improvement of the tensile properties of 1 wt% TiB_2/AlSi10Mg in work by Li *et al*. (52) was attributed to multiple load strengthening, solid solution strengthening and dispersion strengthening. In another study, Li *et al*. (53) improved the mechanical properties of AlSi10Mg by adding titanium boride. The results suggested Hall-Petch, load-bearing and Orowan strengthening mechanisms in this case.

Table II Mechanical Properties of Lightweight Metal Matrix Composites Fabricated *via* Additive Manufacturing Processes

Metal matrix	Reinforcement		Additive manufacturing process	Tensile properties			Compressive properties			Hardness	Reference
	Type	Content		Yield strength (σ_s), MPa	Ultimate strength (σ_u), MPa	Elongation (ε), %	Yield strength (σ_s), MPa	Ultimate strength (σ_u), MPa	Elongation (ε), %		
AlSi10Mg	TiN	2 wt%	SLM	–	–	–	–	–	–	145 HV	(36)
		4 wt%	SLM	315.4	491.2	7.5	–	–	–	156.9HV	(37)
	SiC	–	SLM	–	–	–	–	–	–	218.5 $HV_{0.1}$	(38)
		0–10 wt%	SLM	NS–450	–	–	–	–	–	NS–208.5 $HV_{0.1}$	(27)
	CNT	0 wt%		–	350.0	5.5	–	–	–	–	(39)
		0.5 wt%	SLM	–	420.8	8.87	–	–	8.8	154.12 $HV_{0.2}$	
Ti6Al4V	B_4C	0–1 wt%	SLM	–	–	–	–	1384–1747	14.2–33	375–546 HV	(40)
		0–1.5 wt%, 0–12 vol%	DED	–	1000–1200	–	–	–	–	360–445 $HV_{0.5}$	(41)
	TiC	0–15 vol%	DED	–	–	–	997–1310	1381.0–1636.0	14.1–29.3	39–55 HRC	(42)
		0–35 wt%	EBM	–	850–950	2–7	–	–	–	–	(43)
		0–50 vol%	DED	–	–	–	–	–	–	379.77–736.71 HV	(44)
	HA	0–5 wt%	EBM	–	1110–123	13–5.56	–	1300–875	–	4.1–6.8 GPa	(45)
	CNT	0.8 wt%	DED	1162	1255	3.2	1484	2170	23.8	–	(46)
	TiB_2	0–10 wt%	DED	–	–	–	–	–	–	440–480 HV	(47)
		0–2 wt%	DMLS	–	–	–	–	–	–	383–477 HV	(48)
	TiB_2 whisker	0–5.1 vol%	EBM	838–1039	879–1121	13.1–8.9	–	–	–	–	(31)
	Cu	0–5 vol%	EBM	745–970	906–1126	10.5–3.4	–	–	–	–	(49)
	nYSZ	0–2.5 wt%	LPBF	–	–	–	837–1301	1280–1834	39–10	350–510 HV	(50)

CNT: carbon nanotubes, HA: hydroxyapatite, NS: not stated, nYSZ: nano-yttria-stabilised zirconia

4. Case Study: TiB_2/AlSi10Mg Composites

The AM method adopted in the fabrication plays a crucial role in determining the properties of the final part. Titanium boride reinforcement has attracted much attention in the production of LMMCs (5). Therefore, TiB_2/AlSi10Mg composite was chosen as a case study to investigate the importance and effect of each AM process. A summary of the effect of different AM processes on the mechanical properties of TiB_2/AlSi10Mg composites is listed in **Table III**. Tan *et al*. (54) produced TiB_2/AlSi10Mg composites through the DMD process. They found that macro-agglomeration decreased significantly with decreasing titanium boride content and displacement speed. Moreover, the porosity decreased with the increase of the displacement speed. According to their results, the hardness was significantly enhanced in the presence of titanium boride from 95 $HV_{0.1}$ (AlSi10Mg) to 113 $HV_{0.1}$ (2 wt% titanium boride) and to 125 $HV_{0.1}$ (6 wt% titanium boride), respectively.

However, in research conducted by Lorusso *et al*. (55, 56), the effect of two different compositions (1 wt% of nanosize titanium boride and 10 wt% of microsize titanium boride) on the microstructure evolution, microhardness, nanohardness and elastic modulus of AlSi10Mg produced *via* DMLS was studied. Interestingly, they revealed that the average Vickers hardness and elastic modulus values are quite similar to those of the AlSi10Mg alloy. Thus, the titanium boride microparticles-containing composite showed a higher average microhardness (about 4.8 GPa) and well-defined areas of higher hardness dispersed in the softer lightweight matrix. This was attributed to an agglomeration effect of the reinforcement.

Li *et al*. (52) studied the mechanical characteristics of TiB_2/AlSi10Mg composites fabricated *via* the SLM process. They reported that the microhardness of 1 wt% TiB_2/AlSi10Mg was 120 HV, which was 20.97% higher than that obtained using the DMLS process. It can also be noted that the microhardness of SLM AlSi10Mg composites reinforced with 1 wt% titanium boride is higher than DMD AlSi10Mg composites reinforced with 1 wt% titanium boride (6.19% higher). The increase in microhardness of 1 wt% TiB_2/AlSi10Mg produced *via* SLM was confirmed by Xi *et al*. (57) who found a value of 126 $HV_{0.2}$. However, the composites showed a stabilised microhardness distribution, unlike those obtained using the DMLS process. This indicates that composite manufacturing by SLM gives optimal mechanical properties compared to other processes. Li *et al*. (52) also reported that the ultimate tensile

Table III The Mechanical Properties of TiB_2/AlSi10Mg Composites by Different Additive Manufacturing Technologies

Technology	TiB_2 content	Features	Reference
DMD	2 wt%	Vickers hardness = 113 $HV_{0.1}$	(54)
	6 wt%	Vickers hardness = 125 $HV_{0.1}$	
DMLS	1 wt% nano-TiB_2	Microhardness = 99.2 ± 0.6 HV	(55)
	1 wt% nano-TiB_2	Microhardness = 97.5 ± 1.7 HV Nanohardness = 1.15 ± 0.15 GPa Elastic modulus = 75.5 ± 3.2 GPa	(56)
	10 wt% micro-TiB_2	Microhardness = 97.5 ± 1.7 HV	(55)
	10 wt% micro-TiB_2	Microhardness = 99.2 ± 0.6 HV Nanohardness = 2.40 ± 4.8 GPa Elastic modulus = 78.6 ± 28.8 GPa	(56)
SLM	1 wt%	Microhardness = 120 HV Ultimate tensile strength = 380.0 MPa Yield strength = 250.4 MPa Elongation = 3.43%	(52)
	1 wt%	Hardness = 126 $HV_{0.2}$	(57)
	1.5 wt%	Microhardness = 113.3 $HV_{0.2}$ Ultimate tensile strength = 375 MPa Yield strength = 260 MPa Elongation = 3.1%	(58)
	11.6 wt%	Microhardness = 191 ± 4 $HV_{0.3}$ Tensile strength = 530 ± 16 MPa Ductility = 15.5 ± 1.2%	(53)

strength, yield strength and elongation of 1 wt% TiB_2/AlSi10Mg were 375 MPa, 250.4 MPa and 3.43%, respectively. The improvement in tensile properties compared to AlSi10Mg was attributed to multiple mechanisms, such as load strengthening, solid solution strengthening and dispersion strengthening. Elsewhere, Meng *et al*. (58) showed that the values of microhardness, ultimate tensile strength, yield strength and elongation of 1.5 wt% TiB_2/AlSi10Mg composites are quite similar to the values 1 wt% TiB_2/AlSi10Mg composites (52), although the 1.5 wt% TiB_2/AlSi10Mg composites have slightly higher yield strength.

In another research carried out by Li *et al*. (53), the effect of adding a high content of titanium boride (11.6 wt%) on the mechanical properties of SLM-produced AlSi10Mg composites was investigated. The obtained composites had high tensile strength (530 MPa), excellent ductility (15.5%) and microhardness (191 $HV_{0.3}$). This implies that increased reinforcement content leads to improved mechanical properties. The enhanced strength was mainly attributed to Hall-Petch, load-bearing and Orowan strengthening mechanisms, whereas the enhanced ductility was caused by the modification of grain boundaries by the addition of titanium boride nanoparticles.

5. Summary and Conclusion

Particle-reinforced LMMCs are made of light metals like magnesium, aluminium or titanium. Reinforcement is usually particles. The properties, performance and manufacture of LMMCs usually depend on the reinforcing characteristics. AM technologies offer a high level of flexibility for designing and manufacturing complex geometries and customised products. This review discussed frequently adopted metal AM processes like LPBF and DED to produce LMMCs. The effects of AM processes and reinforcement on the mechanical properties of LMMCs were discussed in detail and the mechanical properties of LMMCs with respect to their preparation method and reinforcement content were also summarised.

New research and development studies are now being undertaken to investigate and improve the properties of LMMC parts and AM technologies, opening up new applications in the automotive, aerospace, construction, rail and marine transport industries. Some future research perspectives and key findings include a variety of ceramic particle reinforcements which have been adopted and continue to be used to improve the properties of various light metal matrices. Scientists need to continue to research new nanoparticles which are not yet widely used as reinforcement. Further studies are also needed to reduce the agglomeration of reinforcements. More emphasis should be placed on 'green' LMMCs that are environmentally friendly and recyclable in nature. Lastly, AM of LMMCs has many challenges. Thus, using the appropriate process and optimal process parameters can minimise the challenges and achieve desirable properties.

Glossary

3D	three-dimensional
AM	additive manufacturing
DED	direct energy deposition
DMD	direct metal deposition
DMLS	direct metal laser sintering
EBM	electron beam melting
LMMCs	lightweight metal matrix composites
LPBF	laser powder bed fusion
MMCs	metal matrix composites
PBF	powder bed fusion
SL	sheet lamination
SLM	selective laser melting
SLS	selective laser sintering

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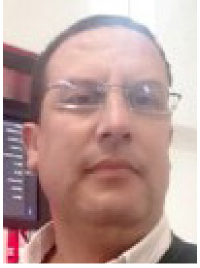
The Authors

Abd Baghad is an Assistant Professor of Materials Science at ICAM, Site de Grand Paris Sud, France. He received his Master of Science and Technology (MST) in Engineering Materials and Processes from the Faculty of Sciences and Technology, Sidi Mohamed Ben Abdellah University, Morocco in 2018. He then obtained his PhD in Materials Science and Processes from the Faculty of Sciences, Ibn Tofail University, Morocco in 2022. His PhD research focused on developing new epoxy/carbon composite materials for use in aeronautics and was supported by grants from Safran Nacelles (France), the Euromed University of Fes (Morocco) and Hassan II Academy of Science and Technology (Morocco). His current research interests include polymers, polymer and metal matrix composites, materials processing and characterisation and applied mechanics.



Khalil El Mabrouk is professor of chemical engineering at the Euromed University of Fez, Morocco, where he is currently the coordinator of Master of Additive Manufacturing (3D printing). His research interests are focused on customised metallic implant with bioceramics coating, 3D additive manufacturing of porous bioceramics for bone regeneration, reinforced thermoplastics implemented by additive manufacturing and autoclave fabrication of composites for aerospace.