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In-situ metal matrix composites development for additive manufacturing: a perspective

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ABSTRACT

Purpose: This paper presents an overview on some ceramic materials capable of achieving in-situ reinforcements in Al/Al-alloy metal matrix composites (MMCs) during laser processing. It also presents perspective on further exploitation of the in-situ reinforcement capabilities for high quality MMCs feedstock material development.

Design/methodology/approach: The approach utilized in writing this paper encompasses the review of relevant literature on additive manufacturing (AM) of MMCs.

Findings: It is widely accepted that the in-situ reinforcement approach has proven to be more advantageous than the ex-situ approach. Though there are still some challenges like the formation of detremental phases and the evaporation of low melting temperature elements, the in-situ reinforcement approach can be used to tailor design composite powder feedstock materials for the AM of MMCs. The preprocessing or tailor-designing in-situ metal matrix composite powder before laser melting into desired components holds more promises for metal additive manufacturing.

Practical implications: The need for the development of MMCs powder feedstock that can be directly fabricated using suitable AM technique without prior powder processing like blending or mechanical alloying has not yet been addressed Therefore, having a pre-processed in-situ reinforced MMC feedstock powder can encourage easy fabrication of MMC and other advantages of AM technologies powder recycling.

Originality/value: The idea explained in this article is relevant to materials development for AM processing of metal matrix composite. This paper has pointed out future trends for MMCs materials feedstock powder development and new ideas for further exploitation of MMCs and AM technologies. The advantages of tailor-designing composite powders other than merely mixing them has been emphasized.

Keywords: Metal matrix composites, In-situ reinforcement, AM materials, SLM, Direct printing

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MANUFACTURING AND PROCESSING

1. Introduction

The numerous advancement in additive manufacturing (AM) technologies has added vasetility to the development of metal matrix composites (MMCs) than witnessed in the conventional manufacturing processes. MMCs are composite materials manufactured from metallic powders (the matrix) and mostly ceramic powders as the reinforcement [1,2]. MMCs combine the tenacity of the matrix (metals) with the rigidity of the reinforcement (ceramics or intermetallic) to give unique composite materials with outstanding properties and potentials [2-4]. Figure 1 presents a schematics of AM fabricated MMCs processing steps.

Besides the excellent properties that lead to weight savings, improved energy efficiency, high specific stiffness and strength, high elastic modulus, excellent wear resistance and higher fatigue resistance, the capability of tailoring properties at an affordable cost is one advantage of MMCs that is of interest to researchers and industries [6]. This lead to their use in many applications such as turbine blades, brake disks, aerospace, cutting tools and high-temperature components [7]. Brake pads, piston rings and pins, connecting rods, disc and cast automobile components are some of the successful applications of Aluminum MMCs in the automotive industry [8]. Coupled with the additional technological and materials properties advantages, The development of this advanced materials using the different metal additive manufacturing technologies (laser melting deposition (LMD), laser powder bed fusion (LPBF), etc.) has received a great boast in recent time [2,9].

Additive manufacturing technology brought numerous advantages to MMCs processing over conventional manufacturing methods. The capability of controlling the microstructure of MMCs due to the controllable processing parameters (energy density, hatch spacing, laser power, powder feed rate, scanning speed and strategy, etc.) in Laser Additive Manufacturing (LAM) processing techniques holds more opportunities for the optimization of MMCs desired properties [6]. However, additive manufacturing of MMCs has met with many challenges and calls for more researches. Most of the drawback of MMCs processing include weak interfacial bonding between the reinforcement and matrix, defects (cracks, residual stresses, thermal mismatch induced work-hardening and dislocations formation of deleterious phases) which may be amplified by the inhomogeneous dispersions of the reinforcement material present [5,10]. Another issue with the presence of a matrix-reinforcement interface is the fact that it can serve as points where cracks can easily develop from and encourage other defects in the MMCs parts [11].

Different researchers have attempted to develop MMCs using AM technologies with most of the researches focused on Al-based MMCs because of their excellent properties [12,13]; and Al-Si alloys (casting alloys with good weldability) as matrix material due to their mechanical properties like high strength to weight ratio and improved hardness, and less tendency for thermal crack [6,9]. Most of the materials often used as reinforcements include carbides (e.g., SiC, B_4C), nitrides (e.g., Si_3N_4, AlN) and oxides (e.g., Al_2O_3, SiO_2) [2,9]. Carbon and carbon nanotube (CNT) has also been the reinforcement material of choice in recent time [12,14]. However, the potentials of AM technologies are still not adequately exploited for the development and processing of in-situ MMCs, which offer better microstructural and mechanical properties than ex-situ MMCs [10].

This article review some of the ceramic materials capable of forming in-situ reinforcement with Al/Al-alloy and seek to present a perspectives on which the in-situ reinforcement capability can be further exploited for high quality AM processed MMCs development. The following section presents a brief classification of the types of MMCs based on the manner in which the reinforcement is achieved. Section three gives an overview of the reinforcement

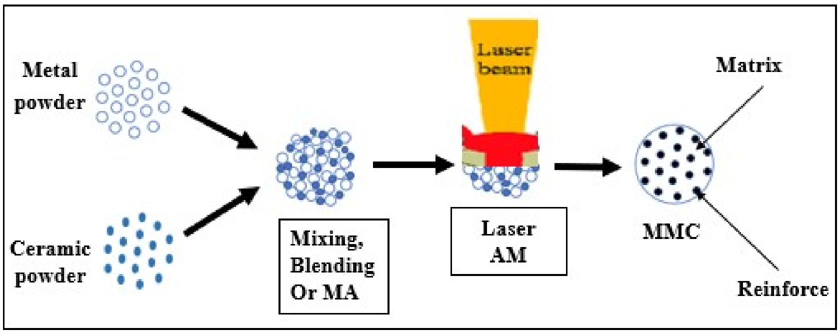

Fig. 1. A schematic of fabricated MMC and its processing steps [5]

materials for in-situ Al-MMCs fabrication. While the section four of this article give a perspective for further exploitation of the in-situ reinforced capability in AM processed MMCs development. Though approaches like mechanical alloying [15], the conventional metallurgy-gas atomization approach [16], or the yet to be implemented matrix-coating-approach suggested by [5]; the need for the development of MMCs powder feedstock material that can be dirrectly printed into parts without prior powder processing step has not been addressed. Hence the perspective given in this article.

2. Classification of MMCs based on method of attaining the reinforcement mechanism

Composites can be classified based on matrix type (metal, ceramic or polymer) or on the structure of reinforcement material (particulate, fibrous or laminate). MMCs can be classified using the shape of reinforcements into particle reinforced, whisker (or short fibre reinforced), continuous fibre-reinforced or monofilament reinforced. However, MMCs are predominantly classified based on whether the reinforcement materials are synthesized externally and added to the matrix (ex-situ MMCs) or internally (in-situ MMCs) during composite fabrication, irrespective of whether the reinforcements are particulate, fibrous or laminate. Each of these MMCs has its advantages and disadvantages [10,11]. The chart in Figure 2 Depicts a broad classification of MMCs as modified from [17], while Figure 3 shows a schematic representation of ex-situ and in-situ MMC.

2.1. Ex-situ MMCs

Ex-situ MMCs have their reinforcement remaining in their original forms. The reinforcement material, in this case, is externally formed before composite fabrication and added into the matrix material under molten or powder form [10]. Infiltration and powder processing are secondary processes often used to insert the reinforcing phases into the matrix.

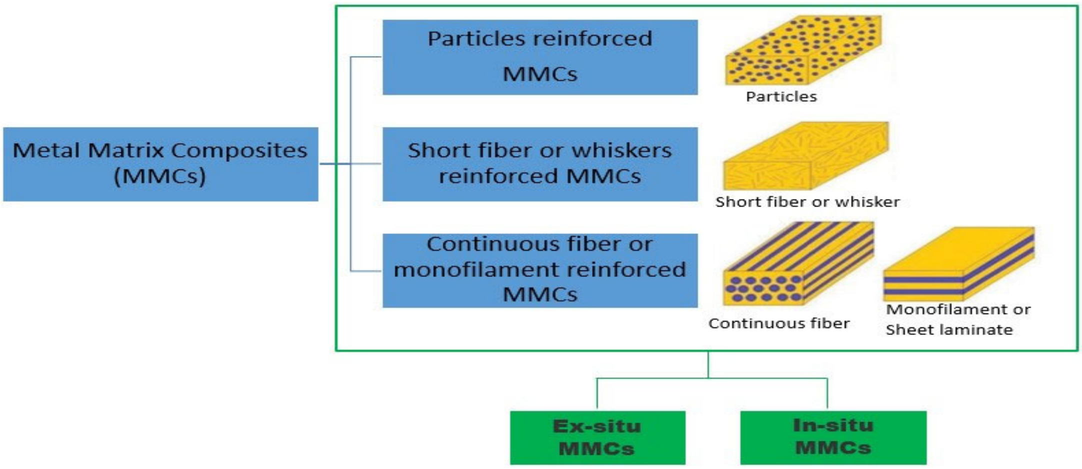

Fig. 2. A broad classification of metal matrix composites [17]

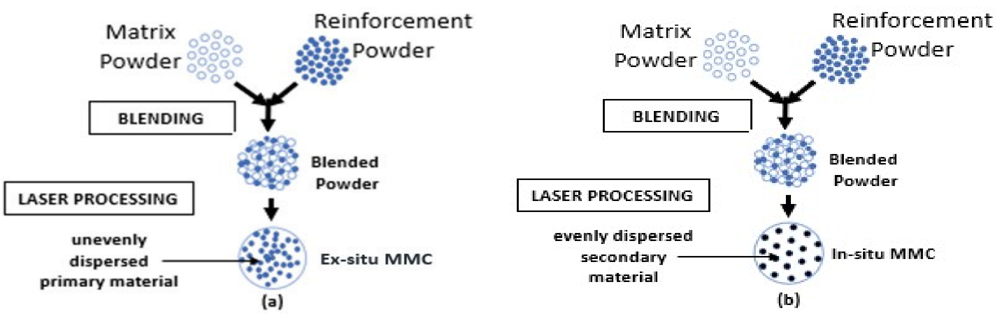

Fig. 3. A schematic representation of (a) ex-situ MMCs, (b) in-situ MMCs

The reinforcement is considered cold welded to the matrix material as there are no reinforcement-matrix interfacial reaction or the formation of new phases during the laser processing of MMCs. The fabricated ex-situ MMCs possess heterogeneous and non-uniform microstructure [2,18]. Some of the limitations of ex-situ MMCs include matrix-reinforcement interfacial reaction, poor wettability of the reinforcement, and the fact that the reinforcement particle sizes always remain as added (depending solely on the particle sizes of the starting powder) [10,11,19]. Such a situation implies a lack of room for grain size refinement and further strengthening mechanism in ex-situ MMCs [11]. Deffects like residual stress and microcracks can also be amplified by the thermophysical properties difference between the matrix and reinforcement material in ex-situ MMCs [19].

2.2. In-situ MMCs

In-situ MMCs are multiphase MMCs in which the reinforcement, in the form of precipitates, are synthesized in the matrix by a chemical interaction between the matrix and reinforcement during the composite fabrication. There are two major types of the in-situ process: (i) reactive and (ii) non-reactive process. The reactive type process consists of two elements, which react exothermically to form the reinforcing phase. However, in the non-reactive type process, monotectic and eutectic phases of alloys form the reinforcement and matrix [17] during fabrication.

Different methods, including merely mixing or mechanical alloying, are employed in preprocessing the starting reinforcement and matrix material into what is often referred to as the primary material before laser processing. In in-situ reinforced MMCs, as opposed to ex-situ and hybrid ex-situ/in-situ reinforced MMCs, the primarily reinforcement particles are fully consumed and transformed into new or secondary phase(s) during the laser processing; with the in-situ reaction greatly depending on the AM process parameters employed [9,11,20].

The in-situ synthesis of MMCs allows for better wetting and cohesion of reinforcement materials with the metallic matrix while resulting in a fine and uniform distribution of the reinforcing phases [21]. It has been widely accepted that in-situ MMCs exhibit more advantages (thermodynamical stable evenly dispersed reinforcement particle, with no tendency for interfacial reaction with the bulk matrix) compared to those produced by ex-situ MMCs [10]. However, the formation of deleterious intermetallics that could be detremental to the properties of the MMCs and the limited control over the in-situ reaction are the main challenge in in-situ MMCs fabrication approach [9,10]. In addition, the evaporation of low melting temperature elements as the constituent powders transform into in-situ phases can lead to metallurgical defects [9]. However, since the in-situ MMCs possess materials different from the starting materials that reportedly offer desirable mechanical and micro-structural properties [2], exploiting these unique materials as raw materials for the additive manufacturing MMCs may result in numerous benefits and breakthroughs in high quality MMCs development.

It is necessary to note that depending on the material nature of the primary reinforcement (ceramic material), the size distribution of the reinforcement powder particles, and the AM processing parameters employed, some of the reinforcement particle do remain as added while some get melted or partially melted. This situation often result in hybrid reinforced MMCs (ex-situ and in-situ reinforced MMCs) [11,20].

3. Reinforcement materials for in-situ MMCs

Whether in the conventional or AM fabrication methods, the reinforcement materials for MMCs ranges from carbides (e.g., SiC, B_4C), nitrides (e.g., Si_3N_4, AlN) or oxides (e.g., Al_2O_3, SiO_2) to elemental materials (e.g., C, Si, etc.) [2,22]. The choice of primary materials for in-situ reinforcements requires materials that will form particles thermodynamically stable within a particular matrix. This section presents an overview of some of the ceramic reinforcement materials for Aluminum that will likely induce in-situ reinforcement in the matrix.

<u>Ceramic reinforcement for Al/Al-alloys</u>

SiC, TiC and B_4C are good reinforcement materials for Al-MMCs because of their chemical stability combined with high hardness, explaining their selection for improving wear resistance of MMCs [18]. Silicon carbide will however dissolve progressively in molten Al to form intermediates influenced by temperature. While Al_4C_3 are formed between 940 K and 1620 K, formation of ternary Al_4SiC_4 happens at 1670 K [18]. Formation of the deleterious phase Al_4C_3 as the final reinforcement particle is undesirable because they are extremely brittle and susceptible to hydrolysis in a humid environment. Temperatures above 1670 K are therefore more suitable for processing SiC reinforced Al-MMCs [23,24]. In the case of AlSi10Mg MMC reinforced with nano-TiC particles, the TiC reacts with the Al matrix to form Al_9Si and Mg_2Si, and significantly lowers the coefficient of friction (COF) and wear rate of the MMC [23]. Though tungsten carbides (WC) show a strong tendency to dissolve in Al alloys as SiC and TiC, it often results in the formation of the intermetallic and deleterious Al_4C_3 phase. Compared to SiC and TiC, TiC is less reactive than WC while WC is less reactive than SiC in Al. But TiC exhibits the least rate of reactivity with Al among the three carbides, and its dissolution rate in Al is far lower than that of SiC and WC [25]. The work of Anandkumar, Almeida and Vilar [26] pointed out that TiB_2 does not show any sign of dissolution or interfacial reaction with the Al matrix during laser processing, while offering only ex-situ reinforcement in Al-12 wt.% Si alloy. However, an in-situ formed TiB_2 in AlSi10Mg matrix has been reported [27], with the in-situ formed TiB_2 having particle morphology different from that of the primary TiB_2 powder particles [11].

In considering the behaviours of the different ceramic reinforcement materials during laser processing, carbides are the most popular reinforcement for a wide range of metallic materials. But the formation of deleterious phases, such as Al_4C_3 in Al-MCs (brittle and susceptible to hydrolysis in a humid environment) often calls for the careful optimization of processing parameters for achieving successful LAM processing. On the other hand, the formation of oxide film on the surface of built layer remains an issue when reinforcing with oxides that often needs careful consideration of the processing parameters employed [9,18]. Nitrides and borides, with their excellent chemical stability and mechanical properties, have been projected as viable alternatives to carbides. Rare earth oxides nano-particles have also been projected as potent microstructural refiner with beneficial effects on the mechanical and corrosion properties of the MMCs [18].

4. A perspective on in-situ MMC powder materials redesign

The fact that the dispersed phases of in-situ MMCs are often different from the starting ceramic powder means that their bulk properties are significantly different from those of the starting materials. In the search for novel materials for additive manufacturing, it may be apt to take a closer look at the phases formed during in-situ processes.

Though the advantages of the in-situ MMCs over the ex-situ MMCs [2,9,10], an uneven dispersion of the primary reinforcement material prior to laser consolidation can prove detrimental to in-situ MMCs [5,6,15]. Since a chemical reaction is the reason for the new phase (precipitate) between the matrix and reinforcement, exploiting this new phase as a material of interest may result in a landmark breakthrough in developing materials for additive manufacturing.

Two different possibilities envisioned for this perspective are highlighted as follows. It could be possible to obtain the new phase (precipitate) formed in the matrix during in-situ processing as a raw material for further fabrication of MMCs with novel and superior properties. In this case, the laser processed MMCs can be re-melted into parts or re-melted and turned into powder through the gas atomization technique. This processing route can be approached as explained schematically in Figure 4. Tthe cost implication and the long processes involved may be the major drawback to this approach.

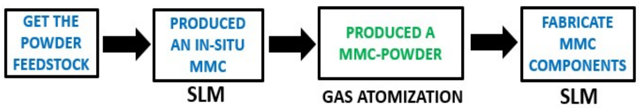

Fig. 4. SLM-SLM processing route for in-situ MMC material development

However, a more promising route could be producing a tailored designed metal matrix composite powder from the powder feedstock, using the induction plasma process. Figure 5 presents a schematic representation of this approach. Plasma systems is capable of producing powder particles with desirable, satellite free, good internal structure, exceptional particles size distribution, and optimal flow properties suitable for AM processes. The plasma can serve as a chemical reactor as well as an enthalpy source [28].

Fig. 5. The inductively coupled plasma approach for in-situ MMC material development

By controlling the chemical reaction during plasma processing, the possibility of manufacturing metal matrix composite powder such as Ti/TiC, Ti/TiN, or Ti-Al-V materials with TiC or TiN reinforcement using plasma system have been reported [29,30]. The capability for the development of composite powders whose particles are by themselves metal matrix composites projected by the plasma technology holds many promises to overcoming some of the difficulties and complexity in producing high quality MMCs parts in Additive Manufacturing. One advantage in successfully developing such powder feedstock using the plasma process is the greater reusability of the MMCs powder feedstock, especially in the powder bed fussion

(PBF) AM processes. In PBF (laser based or electron beam melting) process, the unmelted powder that serves as the support structure are often reused to avoid wastage and encourage sustainability. Such approach is far cheaper and less problematic for monolythic material powders than for MMCs feedstock powder where even dispersion of the matrix-reinforcement particles is of utmost importance for high quality part fabrication. Hecnce, having a feedstock powder where even dispersion of constituent materials is guaranteed even prior to AM processing will be of much benefit to high quality MMCs parts fabrication.

5. Conclusion and recommendation

An overview of different ceramic matetials capable of encouraging in-situ reinforcement in AM processed Al-MMCs have been given in this article. Researches on the AM fabrication of in-situ MMCs have been predominantly focused on Al and Al-alloy base MMCs owing to their numerous advantages over other material. A wide range of ceramic materials have been explored as reinforcements in MMCs. However, carbides are well noted for the formation of deliterous phases or intermetallics in Al/Al-alloys. Also, oxides (especially Fe_2O_3) are noted for the formation of oxide films as they form a wide range of in-situ reinforcements and intermetallics in MMCs. However, careful optimization of AM processing parameters has been widely accepted to allow for the development of desirable in-situ reinforcement in Al and Al-alloys. A perspective on in-situ MMCs feedstock material redesign has also been given in this article. Since numerous advantages will come from AM fabrication of a tailored designed MMCs powder feedstock, further exploitation of the in-situ reinforcement approach to develop high quality feedstock powder via the use of the plasma system has been highly recommended.

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