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Recent developments and opportunities in additive manufacturing of titanium-based matrix composites: A review

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ABSTRACT

Titanium-based materials are widely used in various areas due to their unique combination of outstanding characteristics. Properties such as stiffness, strength and wear resistance of conventional titanium alloys can be further enhanced through development of titanium-based matrix composites (TMCs). Additive manufacturing (AM) technology provides a promising platform for highly efficient fabrication of complex-shaped titanium parts. Although AM of titanium and titanium alloys are increasingly being investigated, far less attention has been paid to AM of TMCs due to their additional processing complications. This study aims to review the current state-of-the-art in AM of TMCs as well as key aspects and research trends for the design, fabrication, and further development of high-performance TMCs. The review highlights the promising outlook for AM of TMCs. However, it also draws attention to critical aspects that require further investigation such as optimization of the processing parameters and additional understanding of melting/consolidating of matrix and reinforcement for AM of defect-free TMC components.

1. Introduction and significance of the study

Titanium (Ti) and Ti-based materials are of increasing importance in various areas such as the biomedical, aerospace and automotive industries and in other specialized applications [1–3]. However, there are substantial prospects for greater application of Ti-based materials if their properties can be improved to levels beyond that afforded by current Ti alloys and processing technologies. They can potentially replace other metallic materials if they can be produced more competitively in terms of performance and cost. This has led to the exploration of Ti-based matrix composites (TMCs) offering superior properties and performance [4].

Ti-based components are generally fabricated by conventional techniques such as casting, forging and powder metallurgy [5,6]. In addition, they usually require some forms of post-fabrication processing such as surface and heat treatments to enhance properties, and machining to achieve the desired shape and dimensional tolerances for the product. However, the fabrication of Ti-based materials is complicated by issues such as their relatively low thermal conductivity and high levels of chemical affinity which can lead to unwanted chemical reactions and particularly impacts on machinability [7]. In the case of TMCs, the differing chemical and physical properties of the matrix and reinforcement can also affect processing and care must be taken to avoid unwanted chemical reactions. Thus, traditional manufacturing approaches typically involve considerable material, energy and time expenditure to fabricate quality parts and this therefore makes fabrication of Ti-based materials tedious and costly.

In recent years, metal 3D printing, based on a layer-upon-layer (additive manufacturing) approach has been extensively applied for a variety of Ti-based materials. This advanced technology can produce complex, near net shape components in a highly efficient manner directly from powders with minimal post processing, offering great potential to simplify and speed up manufacturing process. Most additive manufacturing (AM) methods employ a powerful energy source, typically in the form of a laser to bond the metal powders during layer-by-layer deposition. AM technology for the fabrication of metallic components is generally grouped according to the powder deposition method (e.g. powder-bed and blown-powder systems), laser/powder interaction and metallurgical mechanisms involved in consolidation (partial melting vs. full melting) into the classifications of laser sintering, laser melting and laser metal deposition [8].

The purpose of this work is to present an overview of the current state-of-the-art in AM of TMCs as well as to discuss key issues and research trends to design, fabricate and further develop high-performance

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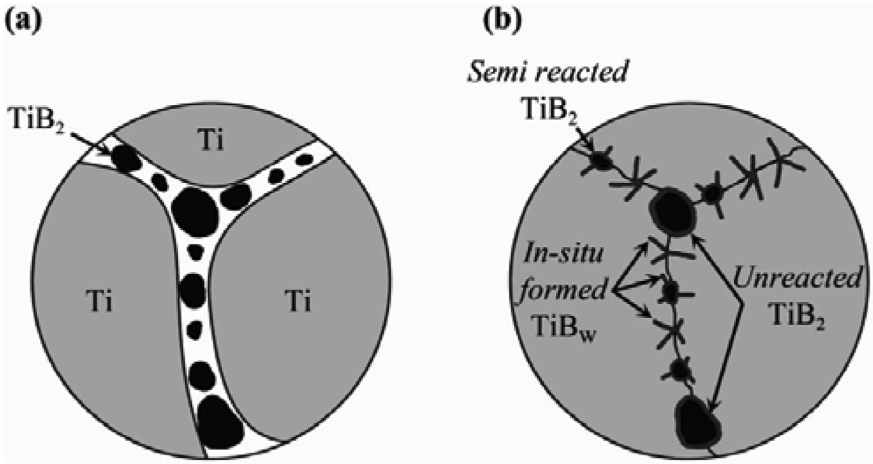

Fig. 1. Schematic representation of the formation of the TiB phase through *in-situ* reaction between Ti and TiB_2: (a) Starting powder mixture showing the fine distribution of TiB_2 particles surrounding the larger Ti powders before sintering and (b) *In-situ* formed needle-shaped TiB as well as semi-formed TiB, and unreacted TiB_2 particles during sintering [23].

TMC components. It commences with a concise introduction to Ti-based materials and their important characteristics with a focus on TMCs. This is followed by an overview of AM methods and their applications for Ti alloys, especially those which have been applied to TMCs. The article subsequently presents a detailed review on the recent developments of AM of TMCs focusing on important aspects such as processing parameters and their impacts on densifications, phases and microstructures as well as mechanical and wear properties. Opportunities, challenges and outlook are also discussed at the end of this work.

2. Ti-based materials and their important characteristics

Ti and Ti alloys are widely used in industrial and commercial applications including aerospace, chemical engineering, surgical implantation, food processing, electrochemical and marine areas. Their success in these applications is due to an outstanding combination of high specific strength (strength-to-weight ratio) which is maintained at high temperatures, excellent mechanical properties, outstanding corrosion resistance and high biocompatibility [7,9–12].

Ti alloys are generally classified into three main groups, known as α, α + β and β, based on the predominant phase composition related to alloying. The alloying elements generally used for Ti are categorized as α-stabilizers (such as Al), β-stabilizers (such as Mo and Mn) and neutral elements (such as Sn and Zr) [2]. Different crystal structures play an important role in determining the properties of Ti alloys. Generally, increasing the α-phase fraction causes an improvement in creep strength, high-temperature strength and weldability. In contrast, increasing the β-phase fraction increases room temperature strength, enhances heat treatability and improves forming capabilities [13]. β alloys are also ideal for orthopaedic implant applications as proper combinations of β stabilizing elements can improve their biomechanical compatibility with adjacent bone tissues [14–16]. Among Ti-based materials, commercially pure titanium (CP-Ti) is the most commonly used within the α group and Ti6Al4V is the most widespread alloy within α+β group. Titanium intermetallic compounds are another promising Ti-based material which have been primarily developed for high-temperature applications due to their good oxidation and creep resistances. However, their inherent low ductility and fracture toughness are regarded as a major drawback and can hinder their practical applications. TiAl-based alloys and Ti_5Si_3 are two common titanium intermetallic materials generally applied to aircraft and structural applications, respectively [17,18].

3. Ti-based matrix composites (TMCs)

Over the past decades, research has focused on the development of metal matrix composites (MMCs) which are stronger, stiffer and show greater temperature-durability properties than their metal alloy counterparts [19]. MMCs can be generally classified into two main categories, known as continuously and discontinuously reinforced MMCs. Discontinuous MMCs generally include particulates, whiskers or short fibers [19,20]. Two general fabrication routes have been established for the fabrication of MMCs, known as *ex-situ* and *in-situ* processing, depending on the method of incorporation of the reinforcement into the matrix. *In-situ* MMCs offer significant advantages over conventional *ex-situ* MMCs and these include a higher thermodynamic stability of the reinforcements in the matrix, enhanced interfacial bonding between the reinforcement and matrix, and typically the *in-situ* formed reinforcing particles are distributed uniformly within the matrix, leading to better mechanical properties [19].

Commonly used compounds which provide effective reinforcement for the fabrication of titanium matrix composites (TMCs) include Cr_3C_2, TiC, TiN, TiO_2, Si_3N_4, SiC, TiB_2, TiB, Al_2O_3 and Ti_5Si_3 [21]. Boron particles and carbon nanoparticles, nanotubes and fibres have been also used as effective elemental additions to produce reinforcing compounds [21]. Some compounds such as TiC and TiB are considered in the *ex-situ* category [21], while some compounds such as TiB_2 and SiC react substantively with the titanium matrix for *in-situ* formation of the reinforcement phases during production of TMCs through methods such as powder metallurgy and ingot metallurgy [22]. A schematic of the process for *in-situ* chemical formation of TiB from the reaction between Ti and TiB_2 during sintering of a TMC is depicted in Fig. 1.

Although several types of reinforcements are considered suitable for fabrication of TMCs, boron, carbon and their compounds have attracted the greatest research interest. Typical properties of some reinforcements as well as those for commercially used matrix materials, pure Ti and Ti6Al4V alloy, are presented in Table 1. TiB particles have been reported to form a good bond and clean interfaces with the Ti matrix

Table 1
Comparison of the properties of reinforcing materials with pure Ti and Ti6Al4V alloy [25,26].

Material	Young's modulus (GPa)	Coefficient of thermal expansion ($\times 10^{-6}$/K)
Pure Ti	105	8.8
Ti6Al4V	110	8.8
TiB	550	8.6
TiB_2	529–540	6.2–6.4
TiC	460	7.4
TiN	250	9.3
SiC	420	4.3
Si_3N_4	320	3.2
B_4C	449	4.5
Al_2O_3	350	8.1