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Review

A review of powder additive manufacturing processes for metallic biomaterials

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ABSTRACT

Metal additive manufacturing (metal-AM) has undergone a remarkable evolution over the past three decades. It was first used solely as an innovative resource of the prototype. Due to the technology maturity which allows combining various manufacturing processes for the production of a bespoke part that applied complex geometries, additive manufacturing (AM) technology has captured an increasing attention. For the past ten years, it has moved into the mainstream of the industrialised field such as biomedicine. The review covers the recent progress of metal-AM manufacturing technologies, main types of metallic biomaterials, and most common biomedical applications. The direction of the future potential of metal-AM in biomedical research and implementation are further discussed. Selective laser melting (SLM), selective laser sintering (SLS), electron beam melting (EBM), and laser engineered net shaping (LENS) are the most common metal-based additive manufacturing processes employed in the production of the biocompatible parts. The evolution and favourite trend of the metal-AM technologies are highlighted in this review. Additionally, the advancement of metallic biomaterials such as titanium and its alloys, cobalt-based alloys, 316L stainless steel, nickel-titanium, and other metallic biomaterials is also presented since it leads to the transpired of several new studies in the scope of metal-AM in the medical field. The rise of metal-AM in the biomedical industry has also been significant, especially in orthopaedics and dental. The metal-AM is predicted to continue to dominate and further benefit the biomedical industry development.

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1. Introduction

The additive manufacturing (AM) technology is acknowledged as one of the remarkable recent layer-upon-layer material technologies that build 3D object products. The method is relatively different from conventional subtractive and formative manufacturing methods, which produced thousands of component layers. However, the typical drawback of the technology is dealing with each of the layers that potentially faced failure mode. The thin cross-sectional layer of the component typically originates from 3-D solid modelling [1–4]. Correspondingly, the ground has been researched and the use of AM has undergone a remarkable evolution over the past three decades [5,6]. AM was first believed solely as an innovative resource prototype and known as rapid prototyping or solid free-form fabrication [7–9]. However, for the past ten years, it has moved into the mainstream of the industry such as the biomedical sector [10–15]. It has now appeared as a universal need in the manufacturing processes and is believed to hit a tipping point soon. The inherent ability of technology maturity allows the production of unique and complex bespoke part which is not achievable by other manufacturing processes [16–19]. Another benefit of AM includes the potential to produce faster and more cost-effective products, reduce environmental impact, lessen resource-intensive, and shorten lead time [20,21].

At this juncture, AM has become the latest trend of processing technique in fabricating metal and alloys [1,13,18,22]. The current highlights of metal-AM categorised by layer type for biomedical applications are divided into two main categories; powder bed and powder-fed systems. Powder bed fusion system is classified to selective laser melting (SLM), direct metal laser sintered (DMLS), selective laser sintering (SLS), and electron beam melting (EBM) technologies [23–25]. Meanwhile, the powder-fed system involves laser metal deposition (LMD), and laser engineered net shaping (LENS) [26]. The laser process involves the heating of alloy metal powders that form several melt-pools which consolidate through a rapid solidification process [3,25,27,28]. These laser-based manufacturing techniques have shown their capability to achieve required material selection and strictly controlled conditions to achieve further improvement of chemical and mechanical properties, high accuracy, and increase the surface roughness through the argon surface plasma treatment (APT) for biomedical application [29].

The transition of AM from plastics to metals arena can be traced back as early as 1994 when EOS' direct metal laser sintering (DMLS) technology launched its metal powder-based prototype for a commercial system [30,31]. In 1998, the laser-engineered net shaping (LENS) metal powder-based system made into a commercial by Optomec based on the technology was developed at Sandia National Labs [32]. Furthermore, the selective laser melting (SLM) and electron beam melting (EBM) have been made commercially available since 2005 by MCP Tooling Technologies (United Kingdom), which is known as MTT Technologies Group and Arcam AB (Sweden) [32,33]. Subsequently, AM then was adopted as a rising manufacturing method in several industries in 2011. The most important industries are in healthcare and medical-related industries around the world. Strikingly, the mass production of biomedical devices is one of the earliest to adopt AM technology, precisely for hearing aid devices and dental equipment [32,34].

Particularly, metal-AM technology has found extensive applications in the biomedical area including orthopaedics [13,35,36], dental [37–41], and cardiovascular [42] [43,44]. For example, orthopaedic implants should match the anatomical bone defect where the shaping of the implant and assurance of the graft's mechanical stability during the healing period would take protracted time and become more complicated [15]. Since each patient has various anatomies, the technology opted for the print implant as well as other particular biomedical applications with various material properties, external and internal structures, and porosity [45–51]. The technology includes customising products for tissue scaffolds, vessel stent, dental work, and biomedical tools.

The as-cast metals have extensively been used as an implantable material for biomedical devices. Often, these biomedical implantable devices possess unique biological-friendly properties to ensure their capability to respond to complex changes in the human body. In fact, the metals are referred as the adaptation behavioural material to simulate cell response and tissue construction to match the mechanical properties of native tissues, or exhibit suitable surface with favourable tissue response and also as bio-mimic of the multi-level structures [52–54]. Therefore, although most of the biomedical metals influenced a wide range of field, only a few possess suitable clinical biocompatibility processes. Until now, there are different types of powdered metallic biomaterials for metal-AM [11,55–58]. The most common of those are titanium and its alloys [47,59–79], Co-based alloys [41,80–89], and stainless steel [3,90–103]. They have also extensively been utilised due to their excellent mechanical properties. Hence, they only perform a relatively simple function to support, fix, and protect the biomedical devices [104,105].

The study presents the review of a recent trend for metal-AM processing in the last 17 years (years 2001 to 2017) on the processing of various powder metals for biomedical applications. The review begins by outlining the primary attribution of metal-AM in today's technologies; i.e., SLM, EBM, DMLS, SLS, and LENS followed by the discussion on evolution metal-AM technology studies focusing on different types of biocompatible metals. Subsequently, the report describes the emergence of metal-AM technology in diverse biomedical fields. Later, the possible future trend is presented while exclusively highlighting the biocompatible powder metals studies and its applications in biomedical under the light of metal-AM technologies. Finally, the concluding remarks underpin the current studies.