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Selective electron beam manufactured Ti-6Al-4V lattice structures for orthopedic implant applications: Current status and outstanding challenges

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ABSTRACT

Additively manufactured Ti-6Al-4V lattices display unique mechanical and biological properties by virtue of their engineered structure. These attributes enable the innovative design of patient-specific medical implants that (i) are conformal to the intended surgical geometry, (ii) mimic the mechanical properties of natural bone, and (iii) provide superior biological interaction to traditional implants. Selective electron beam melting (SEBM) is an established metal additive manufacturing (AM) process that has enabled the design and fabrication of a variety of novel intricate lattices for implant applications over the last 15 years. This article reviews the technical and clinical characteristics of SEBM Ti-6Al-4V lattices, including (i) the SEBM process and its capabilities, (ii) the structures of human bones with an exhaustive list of corresponding mechanical properties from literature, (iii) the mechanical properties of SEBM Ti-6Al-4V lattices of various designs and their shortcomings when compared to human bones, (iv) microstructural control of SEBM Ti-6Al-4V lattices for improved performance, (v) the lattice manufacturability and associated geometric errors, and (vi) clinical cases. Existing literature on the mechanical response of SEBM Ti-6Al-4V lattice structures is exhaustively evaluated for documentation quality using established theoretical models. This extensive data-set allows novel insights into the effect of lattice design on mechanical response that is not possible with the individual data; and provides a comprehensive database for those who are actively involved in patient-specific SEBM implant design. On this basis, outstanding challenges and research opportunities for SEBM Ti-6Al-4V lattices in the biomedical domain are identified and discussed.

1. Introduction

Metallic implants help improve the quality of life and longevity of human beings. Among all the applications of metallic implants, the requirements for spinal, hip and knee replacements are significant [1]. The actual clinical application determines the property requirements for implants, e.g., femoral implants call for superior compressive and tensile strengths while dental implants require high fatigue life and wear resistance. In addition, implants are expected to serve a lifetime without failure or revision surgery. One challenge is that the elastic modulus of most current metallic implants is much higher than that of the bone to be replaced, e.g., the elastic modulus of human bone varies from 0.02–40 GPa compared to 110 GPa for commercially pure titanium (CP-Ti), 190–210 GPa for Co-Cr alloys, and 210–253 GPa for 316L stainless steel [2]. This discrepancy can entail serious stress shielding [1].

Lattices can be defined as three-dimensional (3D) open-celled structures formed by the arrangement of a repeating typical unit cell made up of connected struts or plates [3]. The unit cell size can vary from nanometers to centimeters. Lattices should contain no isolated pores while having high porosity (e.g., > 50% or even 70%) [4]. However, additive manufacturing (AM) can produce lower porosity lattices without containing isolated voids. Lattice design provides an effective way of relegating the elastic modulus and strength of a solid material, as well as an innovative biological form of fixation by promoting bone tissue ingrowth into its open-celled structures [2]. In addition, lattice-like open cellular structures are more conductive to inserting antibiotics to eliminate or control infection [5,6].

Table 1 summarizes the 23 most common metallic lattices assessed to date with structural details. The strut of a lattice can be circular, triangular, and hexagonal. Lattices present fundamentally different mechanical and biological behavior from their dense parent materials [51] and have found a variety of applications for light weighting and energy absorption [3,52]. In particular, they have been widely used as bone implants [53–57] because they can enable replication of both the biological and mechanical properties of those naturally occurring

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Nomenclature

AM	additive manufacturing
SEBM	selective electron beam melting
BCC	body centered cubic
SLM	selective laser melting
BCCZ	body centered cubic with vertical struts
FCC	face centered cubic
FCCZ	face centered cubic with vertical struts
FBCCZ	face and body centered cubic with vertical struts
FBCCXYZ	face and body centered cubic with horizontal and vertical struts
ALIF	anterior lumbar interbody fusion
PLIT	posterior lumbar interbody fusion
TLIF	transforaminal lumbar interbody fusion
d	strut diameter
UTS	ultimate tensile strength
TYS	tensile yield strength
UCS	ultimate compressive strength
CYS	compressive yield strength
C, C_1, C_2	constant
E	elastic modulus of the cellular solid
E_s	elastic modulus of the pore-free solid
ρ	density of the cellular solid
ρ_s	density of the pore-free solid
σ	collapse strength of the cellular solid
$\sigma_{y,s}$	yield strength of the pore-free solid

cellular materials. Fig. 1 shows some recent United States (US) Food and Drug Administration (FDA)-approved Ti lattices, of which the Emerging Implant Technologies (EIT) Ti lattice interbody cages have been used in over 10,000 cases in 15 countries [58]. Consistent with the 23 different unit cells illustrated in Table 1, the lattice struts in the implants shown in Fig. 1 were designed and built in a variety of diameters and inclination angles. As will be discussed in Section 6.1 Lattice manufacturability by SEBM, the minimum strut diameter or inclination angle that can be built with high quality reflects the manufacturability of the SEBM process.

As shown in Table 1, research on lattices has focused on Ti alloys and more specifically on Ti-6Al-4V. This is because Ti alloys are the material of choice for most medical and dental applications today [64]. AM allows the cost-effective fabrication of patient-specific lattices. In particular, selective electron beam melting (SEBM) is most suited to the AM of reactive metals such as Ti because of its high vacuum printing chamber [65]. In addition, SEBM offers higher production rates ($80\ cm^3 \cdot h^{-1}$) than selective laser melting (SLM) ($20–40\ cm^3 \cdot h^{-1}$) and more flexibility in powder size selection (up to 180 µm but usually 45–105 µm vs. 20–45 µm for SLM). This difference in size range corresponds to a noticeable difference in affordability for Ti powder. Another important advantage is that owing to the high powder bed temperature, SEBM Ti-6Al-4V lattices or parts do not normally need post stress-relief-annealing [66,67]. In fact, the world's first AM metal (Ti-6Al-4V) acetabula cup, named the Delta-TT Cup, for use in a hip replacement was produced using the SEBM process in 2007 by Lima-Corporate and Arcam and has shown great success after 10 years of surgery [68]. The surface of the Ti-6Al-4V Delta-TT Cup had a lattice-like feature.

This paper provides a comprehensive review of all major aspects of SEBM Ti-6Al-4V lattices for medical applications and identifies research and clinical opportunities that can expand their applications. In addition, available data on the mechanical performance of both SEBM Ti-6Al-4V lattices and human bones are summarized in detail, with a view to providing a database for those who are actively involved in patient-specific implant design.

2. The SEBM process of Ti-6Al-4V lattices

The SEBM process was patented by Arcam AB in 1997 [69]. Today Arcam SEBM systems include Models of S12, A1, A2, A2x, and A2xx (tungsten cathode) and Models of Q10, Q10 plus, Q20, and Q20 plus (LaB_6 cathode) [69]. A typical SEBM process of Ti-6Al-4V lattices consists of four cyclic steps:

(1) Spreading a layer of powder: The first layer of Ti-6Al-4V powder is spread on a stainless steel or titanium platform that is preheated to ~730 °C [70].

(2) Preheating of powder: A defocused electron beam (scanning speed: ~15000 mm/s; beam current: ~40 mA; acceleration voltage: 60 kV) is then used to preheat the entire powder bed (Preheat I) and subsequently the selected area (Preheat II) (Fig. 2a).

(3) Selective melting: a much slower scanning speed (~4500 mm/s) and a smaller beam current (~20 mA) are used for selective melting, where a contour strategy (a Multibeam™ technology) is used to fuse the perimeter of each layer section before a hatching strategy fills in the section area (Fig. 2b) [71]. The Multibeam™ technology allows multi- melt pools to be maintained concurrently in order to improve surface finish [70,72], e.g., 50 melt pools for outer contour and 10 for inner contours [71]. Hatching is used to melt the lattice area using a "snaking" and/or "point" strategy chosen automatically according to the strut diameter (d) (e.g., "snaking" for $d > 1$ mm). To avoid local overheating of the hot region (see Fig. 2b from ② to ③), the hatching track turns on automatically by increasing the beam speed to keep a constant energy. Besides, the hatching speed will increase during melting of the overhanging part to compensate for the insulating effect of the powder bed [73]. In addition, in the hatching process of lattices (Fig. 2b), the line offset is often set to be greater than that used for a bulk part (e.g., 0.2 mm vs. 0.1 mm at the layer thickness of 50 µm). For SEBM of a bulk part, in order to achieve overlap between the hatching lines, the line offset should be smaller than the beam spot size. However, since lattices contain a lot of voids and d is small, the use of a large line offset is more efficient. The beam spot size in the "point" strategy is larger than that used in the "snaking" strategy; as a result the resulting surface finish of the lattice struts is rougher.

(4) Lowering the platform for spreading the next layer of powder: After SEBM of the current layer, the platform is lowered by 50–150 µm for spreading the next layer of Ti-6Al-4V powder.

These four steps are repeated until the entire part is built. A finished part is often cooled in the powder bed to room temperature where air is flooded only at ≤100 °C. It is typically enveloped by a shell of lightly sintered powder particles, most of which can be removed by compressed air for recycling after sieving.

3. Properties of human bones

In order to design a functional lattice implant, it is imperative to comprehend the properties of human bones to be integrated with. Human bones have a varied arrangement of structures at different length scales which work in concert to perform diverse mechanical, biological and chemical functions [75]. In general, human bones are hierarchically structured (Fig. 3 [76]) and they derive their function through such a hierarchical organization. The hierarchical levels are composed of (i) the macrostructure (e.g., cortical and cancellous bone); (ii) the microstructure ranging from 10 µm to 500 µm (e.g., haversian systems, osteons, single trabecular); (iii) the fine-microstructure in the