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# A METHODOLOGY FOR MEASURING THE COMPRESSION BEHAVIOR OF TI-6AL-4V CELLULAR STRUCTURES FABRICATED BY ELECTRON BEAM MELTING

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**Abstract.** *This work aims to characterize the mechanical behavior in uniaxial compression of two titanium alloy (Ti-6Al-4V) cellular structures, with three different cell sizes each one, fabricated by Electron Beam Melting® (EBM®) additive manufacturing process. Such structures have the potential to be applied in manufacturing stages of metal orthopedic implants with elastic modulus similar to the human bone, reducing the stress-shielding effect and improving osseointegration. Compression tests were carried out in order to find the correlation between mechanical properties and cell geometry. Results showed that for similar porosity, compressive strength increase with the decrease of cell ligament length.*

**Keywords:** *Cellular structures, additive manufacturing, stress-shielding, Electron Beam Melting.*

## 1. INTRODUCTION

Cellular solids are structures with internal pores or channels, distributed throughout component geometry.

Such structures can be found on nature. For instance, honeycomb built by honey bees and on wood and bamboo microstructure (Gibson, 1997).

Engineering applications of cellular solids are in many fields as for example: Thermal-management (Heat exchangers and refrigerators), acoustic absorption, lightweight structures, sandwich panels, impact absorption among others (Ashby, 2000).

Mechanical behavior and therefore the models and constitutive relations for cellular solids may differ for those classical ones applied for fully dense materials (Ashby, 2005). There are many factors which can contribute and affect the mechanical behavior of cellular solids, the most important being the properties of the solid made from (density, Young's modulus, yield strength, etc.), cell shape and component relative density.

Some of the most accepted model for mechanical behavior of cellular solids is the Gibson-Ashby model, which indicates a relationship between relative density (volume fraction of solid) and mechanical properties (Gibson, 1997). This model can be understood by modifying the elastic modulus simultaneously with desired component density, according to Eq. (1).

$$E = E_s \left( \frac{\rho^*}{\rho_s} \right)^n \quad (1)$$

In the equation 1 above,  $E$  is the Young's modulus for an open cell structure with density  $\rho^*$ ,  $E_s$  and  $\rho_s$  are the corresponding values for fully dense solid of the material which the cell is made. The exponent  $n$  in Eq. (1) is assumed to be 2 for metals (Murr *et.al.*,2012). Other properties such as compressive strength also follow similar relationships, dependent on relative density.

### 1.1 Application of Cellular Solids in orthopedic implants

Employment of cellular structures has been cited by several authors (Heinl *et.al.*,2008; Murr *et.al.*,2012) as an alternative for load-bearing orthopedic metal implants manufacturing with elastic modulus ( $E$ ) similar to that of human bone, which may contribute to stress-shielding effect reduction and improvement of osseointegration. Human bone structure can be divided into cortical (dense, with high mechanical strength) and trabecular (porous, with 55-70% void volume). Stress-shielding effect occurs when human bone and metal implant have a considerable stiffness difference, which leads to bone density loss in the correspondent region, impairs healing and in extreme cases, requires corrective surgery. In such situations, cellular solids would allow control of implant relative density and, consequently, bone mechanical properties approximation. In addition, structures with interconnected pores are beneficial for osseointegration as they allow nutrients movement inside the implant (Heinl *et.al.*,2008).

However, regarding metal cellular solids fabrication, challenges in conventional techniques such as Vapor Phase Deposition and Polymeric Foam Replication are due to difficulties to obtain a homogeneous structure and controlled pore size and morphology, besides health risks related to toxic vapor on the former process.

On the other hand, trends of cellular solids application in medical industry are growing recently with the use of additive manufacturing technologies (Cheng, 2012). With such manufacturing process, it is possible to solve some issues related to the conventional methods for fabricating cellular solids as keeping cell size and shape uniformity. Furthermore, feasibility of complex structures and anatomically-matched devices by using a patient's own medical imaging are among these technologies advantages (FDA Staff, 2016). Therefore, being able to fabricate cellular solids by some additive manufacturing process represent enormous prospects as the technology find widespread use.

### 1.2 Electron Beam Melting Additive Manufacturing process

Application of an additive manufacturing technology as Electron Beam Melting®(EBM®) enables (among other well-established advantages as design-freedom) to customize component mechanical properties by changing its cell structure in comparison with a monolithic one. As a result, mechanical properties such as Young's modulus can now be modified. Besides that, the process presents high repeatability, something difficult to achieve in conventional cellular solids fabrication route.

Electron Beam Melting® (EBM®) process, represented at Fig. 01 is based on the construction of parts layer by layer from a CAD model and a raw powder material, which is melted by an electron beam collision scanning in a speed of 8 km/s. Process takes place in a vacuum chamber, as it reduces metal alloy contamination risk due to atmospheric gases. Physical principle is represented in Fig. 1: Electrons are emitted by a tungsten filament, accelerated and directed by electromagnetic lenses against powder particles in a platform. This phenomenon transforms beam kinetic energy into thermal energy with almost 100% efficiency, allowing the fusion of powder layer proportionately to the input energy (Heinl *et.al.*, 2007). With the previous transformation of 3D CAD model into 2D slices, it is possible to scan the beam following the programmed path and to consolidate the construction of parts layer by layer. There is a successive decrease of construction platform for a rake to feed a fresh powder layer. This process uses unmelted powder around the part as support material. However, in unconnected or substantial overhangs geometries, it is necessary to construct supporting structures, which must be removed with postprocessing.

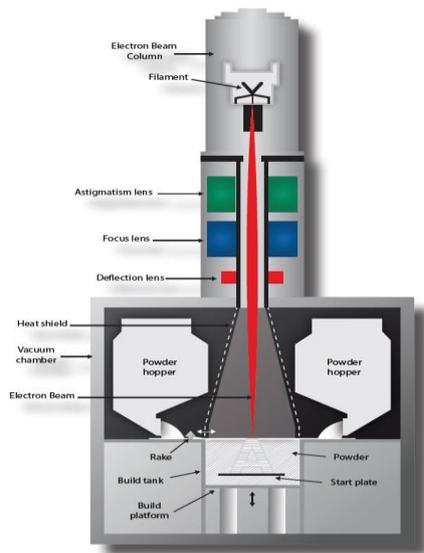


Figure 1 – Schematic representation of Electron Beam Melting process. Source: Available in [www.arcam.com](http://www.arcam.com)

## 2. MATERIALS AND METHODS

Both structures CAD model were generated in Materialize Magics<sup>®</sup> software, a commercial STL files editor, which has a library of common used cellular shapes. Cells geometry were defined as Diamond and Rhombic Dodecahedron, due some available works in literature (Cheng, 2012; Zhao, 2016) which could serve as reference. In cell geometry setting, three lengths (L) of cell trust were defined for each group, according to Table 1. Thickness (t) of the cell edges was scaled proportionally. Relative density was estimated by measures of apparent mass and volume.

Structures were fabricated layer-by-layer using an EBM system (Q10 model - Arcam, AB). Raw material utilized was Ti-6Al-4V (Grade 5) spherical powder with average diameter around 70 $\mu$ m. Metal blasting was the only post-processing performed, but as it is a mandatory step, can be assumed that specimens were compressed as built.

Figure 2 shows macroscopic images of the cellular structures used in this work, where letter D or R refers to the cell shape (either Diamond or Rhombic Dodecahedron) and its respective strut size (in mm), as defined at CAD software.

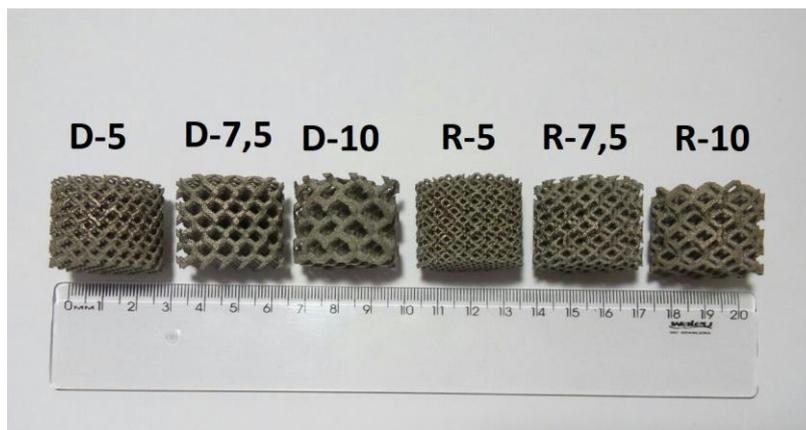


Figure 2 - Lateral view of macroscopic image of Ti-6Al-4V Diamond and Rhombic Dodecahedron cellular structures produced in EBM process. The identification is the same used in Table 1.

Uniaxial compression tests were carried out using an EMIC DL3000 universal machine with a load cell of 30kN capacity. Cylindrical specimen external dimensions were  $\varnothing$  30mm x 25mm, as preconized by ASTM-E9-09 (*Standard Test Methods of Compression Testing of Metallic Materials at Room Temperature*). In order to prevent free-surface effects, spray PTFE was used as lubricant. As a preliminary study, three specimens for each condition were tested.

Aiming at a better understanding of how are the mechanisms by which the cellular structures used in this study deforms, a digital video was recorded during the tests using a GoPro camera.

Scanning electron microscopy (SEM) were employed to analyze the cell structure and size (thickness and ligament length). SEM equipment employed was a Hitachi TM3030 microscope operated at 15kV.

### 3. RESULTS

Results are summarized in Table 1 and Fig. 3. In the Materialize/Magics software, the cell ligament length (strut) was established and cell thickness scaled proportionally, therefore the specimen's relative density are similar (0,167-0,206).

The group with higher compressive strength and Young's modulus were the Diamond-5 (Cell length of 5mm). For this cell geometry, double sizing the cell length and thickness lead to a reduction of ~34% in compressive strength and reduction of ~34% in Young's modulus (see Diamond-10, Table 1).

On the other hand, comparing cell geometry, for most of groups with the same cell ligament length and similar relative density, the Rhombic Dodecahedron structure showed higher compressive strength and Young's modulus than the Diamond type. Further studies are needed to better understand the failure mechanism of each cell and the reasons of such difference in mechanical behavior for structures with similar relative density.

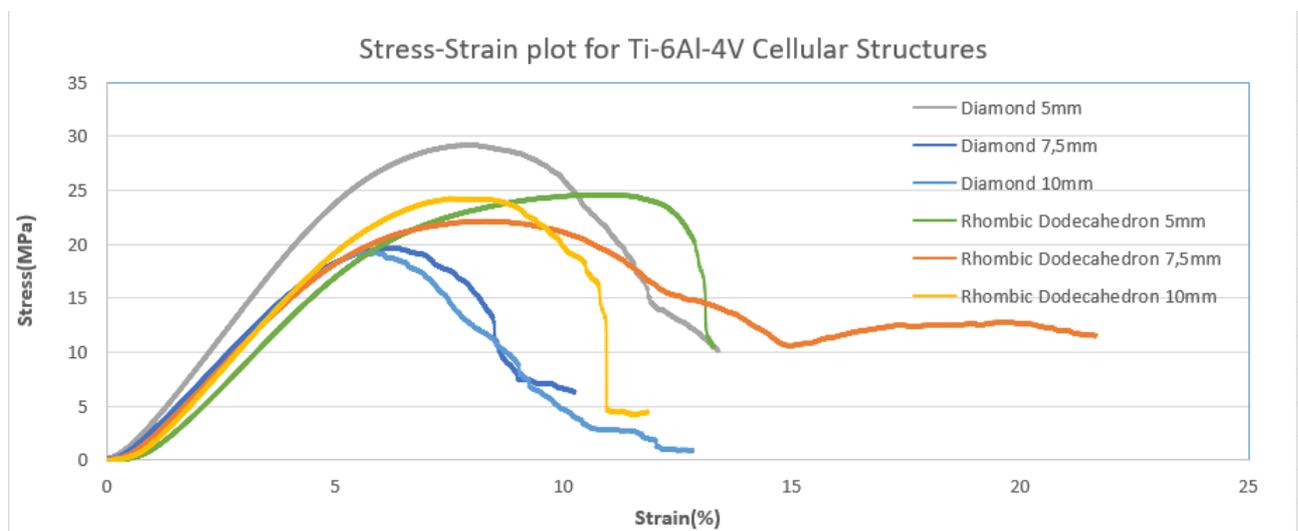


Figure 3-Compression nominal stress-strain curves for cellular structures with similar relative density, modifying cell shape and ligament length.

Table 1. Characteristic of cell structure geometry and mechanical properties of cellular Ti-Al-4V specimens fabricated by Electron Beam Melting

Cell Geometry	Ligament (strut) length (mm)	Ligament(strut) thickness(mm)	Density $\rho^*(\text{kg/m}^3)$	Relative Density (dimensionless)	Porosity (%)	Young's Modulus E (GPa)	Compressive Strength (MPa)
Diamond	$5 \pm 0,5$	$\sim 1,1$	758	0,171	82,89	3,51	29,2
Diamond	$7,5 \pm 0,5$	$\sim 1,6$	725	0,163	83,63	3,21	19,6
Diamond	$10 \pm 0,5$	$\sim 2,2$	744	0,167	83,21	3,38	19,2
Rhombic Dodecahedron	$5 \pm 0,5$	$\sim 0,7$	915	0,206	79,35	5,11	24,6
Rhombic Dodecahedron	$7,5 \pm 0,5$	$\sim 1,15$	763	0,172	82,78	3,56	22,1
Rhombic Dodecahedron	$10 \pm 0,5$	$\sim 1,5$	767,5	0,173	82,68	3,60	24,2

SEM analysis made it possible to measure cell thickness and strut length, thus understanding more about cell geometry and Electron Beam Melting process results itself.

The surface of both Diamond and Rhombic Dodecahedron are extremely rough, which is a well-known characteristic for this additive manufacturing process. Besides that, the structures surface showed several powder particles partially melted and sintered. Such drawback might be a problem in fatigue applications (Li et.al., 2012) due the crack growth potential point. Solutions for the problem would be in process parameters as increasing electron beam

power and/or decreasing powder layer thickness (Cheng et.al.,2012). Figure 4 shows such partially melted particles in some of the Diamond structures. The phenomenon happened in all specimens but with higher intensity at the Diamond-5 group.

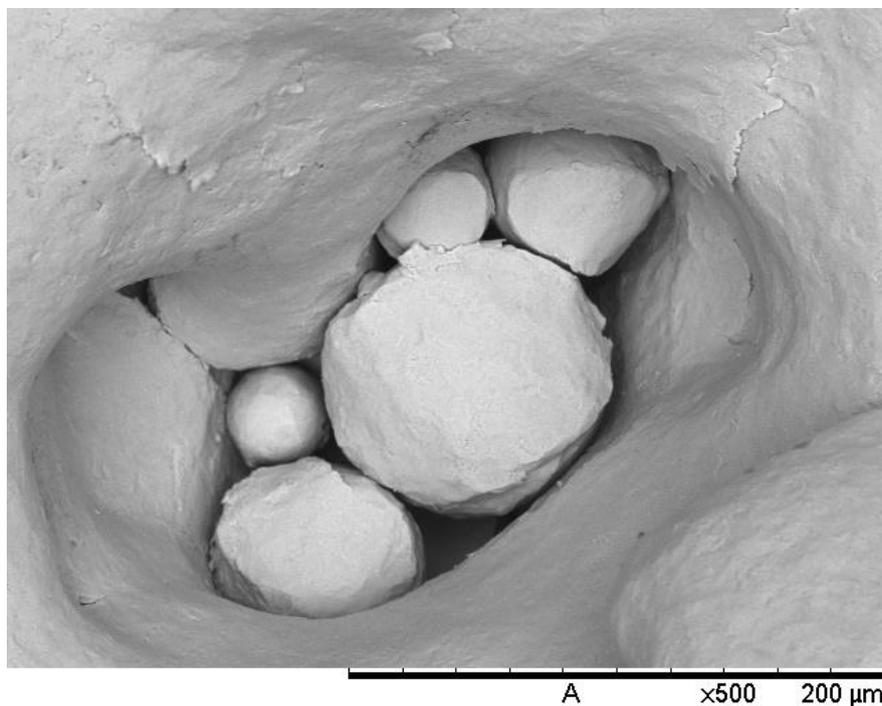


Figure 4 – SEM image of partially melted and sintered particles of Ti-6Al-4V at the surface of the Diamond 10mm structure.

#### 4. CONCLUSION

For similar relative density (0,167-206) and therefore similar porosity (~82%), was possible to fabricated cellular structures with compressive strength between 19,2 and 29,2MPa and Young's moduli in the range of 3,21 to 5,11GPa, which are comparable to those of cortical bone. Thus, the employment of cellular structures fabricated by Electron Beam Melting process would be an alternative for manufacturing orthopedic implants aiming to reduce stress-shielding effects. Additionally, concerns about fatigue need to be investigated more, since stress concentration and possible crack propagation due to the roughness of surfaces and corners are real.

For both cell morphology, sizing the cell ligament length decreased its mechanical properties. The Diamond-5 structure presented higher mechanical properties than the others cell shapes and sizes, however, SEM analyses showed this group had the higher amount of partially melted particles, which might be a challenge in fatigue applications.

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