Selection Process, Modified Impact Testing And Failure Analysis Of An Electron-Beam-Melted Ti-6Al-4V 3d Tessellation Based On The Eulerian Path Of The First Stellation Of The Rhombic Dodecahedron Open Unit Cell

Hugo Lopez

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SELECTION PROCESS, MODIFIED IMPACT TESTING AND FAILURE ANALYSIS OF AN ELECTRON-BEAM-MELTED Ti-6Al-4V 3D TESSELLATION BASED ON THE EULERIAN PATH OF THE FIRST STELLATION OF THE RHOMBIC DODECAHEDRON OPEN UNIT CELL

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Dean of the Graduate School
Dedication

The work presented here is dedicated to my beloved grandmother Dr.Irma Herrera Aguilar, an example of intelligence, determination and character. May she rest in peace.
SELECTION PROCESS, MODIFIED IMPACT TESTING AND FAILURE ANALYSIS OF AN ELECTRON-BEAM-MELTED Ti-6Al-4V 3D TESSELLATION BASED ON THE EULERIAN PATH OF THE FIRST STELLATION OF THE RHOMBIC DODECAHEDRON OPEN UNIT CELL

by

HUGO FRANCISCO LÓPEZ LÓPEZ DE CÁRDENAS, B.S.

THESIS

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MASTER OF SCIENCE

Department of Metallurgical And Materials Engineering

THE UNIVERSITY OF TEXAS AT EL PASO

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I would like to thank my grandmother Dr. Irma Herrera Aguilar, an example of intelligence, determination and her ever continuous desire for scientific knowledge even when she was almost 90. I would like to thank you, abuelita, for your financial support in order to continue my master’s studies, and I would like you to be proud of me. I have always done my best. I miss you and I love you.

I would like to thank my dad Dr. Hugo Lopez, for setting an example for me. Dad, not everyone has a dad who starts his Ph.D. at 50 years old and at the end of his studies receives recognition for being the best student in his generation. You have always been a good example and you always stood up for me. Thank you. I’m so proud of you.

I also would like to thank my wife Stephanie for supporting me and tolerating my usual bad temper during difficult times. I love you.

Mama, thank you and do not worry for me. I’m a fighter and I will always do my best of efforts. I love you. To my brother and sister, I love you both.

I would like to express my gratitude and respect to Dr. Stafford, for because of him, professionally, I’m what I am and I’m not a business major. Thanks for believing in me. I also would like to thank all the MME department, special thanks to Dr. Murr, Dave Brown, and Faye.

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Finally, I would like to acknowledge myself for my diligence and discipline even on the most of difficult times. This is not for me, this is for my family. Semper Fi!
Abstract

Ti-6Al-4V lattice block structures manufactured through the electron beam melting (EBM) process are a promising field in design and research due to great advantages that the alloy, the process and the final product offer. Three lattice block structures were manufactured through the electron beam process using an ARCAM A2 machine. The structures were designed using the MATERIALIZE™ software and were designed around different types of unit cells. Compression testing was performed and one unit cell was selected due to its anisotropic behavior for modified impact testing. The same unit cell was used and it was scaled up to add a total of five LBS with different densities while maintaining their truss cross-sectional area. Absorbed impact energy was monitored and a relationship was determined. Finally, a failure analysis comprised of stereomicroscopy, scanning electron microscopy (SEM) and energy dispersive x-ray spectrometry (EDS) was performed to better understand the fracture mechanisms involved on impact testing.
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Chapter 1: Introduction

Geometrical arrangements in nature are the result of millions of years of design fine-tuning. Tree leaves, animals, and deoxyribonucleic acid (DNA) are few examples of the preservation of form and configuration across a point, line, a plane, or hyperplanes. Nature has been successful on applying geometry to simplify complex systems; replication with the minimum amount of information.

![Figure 1: Examples of geometrical arrangements found in nature](image)

Complex systems described in simple terms provide another advantage, and that is that information can be easily transferred. Nature has its way of compacting information, and that is the story of nature’s pursuit of perfect packing. This is nature at its finest.

Man-made lattice block structures (LBS) tend to replicate the crystallographic aspect often found in nature like unit cell crystal features such as an edible grain of salt to an expensive diamond. LBS can be effectively implemented in a wide variety of applications, such as thermal and noise insulation.
chemical and energy transport or catalytic effects\textsuperscript{2}, ultralight structural components\textsuperscript{1}, and impact energy mitigation as they have the highest energy absorption per unit mass of any material\textsuperscript{3}.

The work presented in this thesis combined LBS and electron beam melting (EBM) to design and fabricate structures using Ti-6Al-4V. For the first part of the study, three sets of \textgamma-beamed Ti-6Al-4V LBS were designed using MATERIALIZE\textsuperscript{™} software and built using an ARCAM machine. The specimens then underwent compression testing; and one unit cell was selected to build new samples for impact testing.

The second part of this thesis focused on the selected unit cell; it was scaled up by different factors, to be eventually tested on a modified impact test; in order to monitor their energy absorption capabilities.

A failure analysis study completed this work, comprised of extensive stereomicroscopy, Scanning Electron Microscopy (SEM), and Semiquantitative Energy Dispersive (X-ray) Spectrometric analyses (EDS); to better understand the root causes and mechanisms for failure.
Chapter 2: Background

Packing is an exercise in filling space: tessellation divides it up. The two subjects come together whenever objects are packed so that they fill all space, such as the square tiles of the typical bathroom wall. The following images are a good graphical example of ordered and disordered 2D tessellations:

![Ordered and disordered 2D tessellations, from the pavements of Lisbon](image1)

Figure 2.1: Ordered and disordered 2D tessellations, from the pavements of Lisbon

A tessellation or tiling of the plane is a collection of plane figures that fills the plane with no overlaps and no gaps. Two dimensional tessellations can be constructed by arranging an array of points in a plane, and making these the centers of the tiles (or cells), by including in each tile all points closer to its center than any other. This is what is called a Voronoï construction. The following images show the Voronoï patterns from disordered disk arrangements, and an example of a disorderly 2D tessellation in metallurgy:
Besides tessellating in the 2-dimensional Euclidean plane, it is also possible to tessellate other n-dimensional spaces by filling them with n-dimensional polytopes, for example, filling 3-dimensional Euclidean space with cubes to create a cubic honeycomb. Nature provides us with many examples of successful packing equal-sized spherical objects into the smallest possible space. A good example of packing in nature is pits inside a pomegranate:

Figure 2.3: Pits inside a pomegranate
2.1 Dode-thin’s (Dt) Unit Cell Origin: Kepler’s Rhombic Dodecahedron

In geometry, the rhombic dodecahedron is a convex polyhedron with 12 identical rhombic faces. It is an Archimedean dual solid, or a Catalan solid.\(^7\)

![Figure 2.4: Rhombic dodecahedron\(^7\)](image)

The rhombic dodecahedron can be used to tessellate 3-dimensional space. It can be stacked to fill a space much like hexagons fill a plane:

![Figure 2.5: Rhombic dodecahedron 3D tessellation\(^7\)](image)

Previous tessellation can be seen as the Voronoï tessellation of the FCC lattice. The rhombic dodecahedron also appears in the unit cells of diamond and diamondoids. In these cases four vertices are
absent, but the chemical bonds lie on the remaining edges\textsuperscript{7}. The following sketch is the resulting cellular array or LBS; note how it tessellates space:

![Figure 2.6: The packing of rhombic dodecahedron to fill space\textsuperscript{8}](image)

Although the rhombic dodecahedron space filling is not the least-energy system, it often appears as the basis of the solution to certain minimal problems in nature.\textsuperscript{9}

### 2.2 Dt’s unit cell: Rhombic Dodecahedron’s First Stellation

The stellation process consists on extending the edges of regular polyhedra until they meet at new vertices. The rhombic dodecahedron’s first stellation shown below is an interesting space-filling solid since it is a true space-filling body:
The Dode-thin (Dt) unit cell has been developed in such a way that it closely resembles what in mathematical graph theory has been defined as an Eulerian path, which is a path in a graph which visits each edge exactly once. So, we can affirm that we have the unit cell that follows the Eulerian path of the first stellation of the rhombic dodecahedron.
2.3 Electron-Beam Melting Technology

Electron-Beam Melting (EBM) is a solid freeform fabrication process that builds fully dense metal parts in layerwise fashion.\(^1\) Moreover, the EBM process allows the construction of highly elaborated metallic structures that were previously deemed impossible or too complex to fabricate, such as: small scale meshes and foam arrays. The advantages of this process, to list some are\(^ {11,12} \):

- High beam-material coupling efficiencies (95% efficiency)
- Beam deflection w/o use of moving mirrors
- Vacuum supports processing of reactive metals and alloys
- No casting required
- No welding required
- No molds required

According to the literature distributed by ARCAM, an EBM machine manufacturer, the following are the technical capacities of their A2 machines:

Figure 2.9: ARCAM A2 technical data
The next images show the ARCAM A2 machine, as well as a diagrammatic sketch of the machine configuration:

![ARCAM A2 Machine](image1)

**Figure 2.10:** Left image ARCAM A2, Right image ARCAM’s machine configuration

The flexibility and capacities that this technology offers has gained the interest of National Aeronautics and Space Administration (NASA) and the US Army; to the point that it is considered as one of the critical technologies to dominate for future missions since quality replacement spares can be fabricated in-situ.

2.4 Ti-6Al-4V Extra Low Interstitial Alloy

Titanium is an allotropic element, at room temperature it has an hexagonal-closed packed (HCP) crystal structure or the α phase; at 883 °C the structure transforms to a body-centered cubic (BCC) or β phase. Alloying elements generally can be classified as α or β stabilizers, and the main aim of adding alloying elements to titanium is to improve its mechanical properties. Alloys containing 4% to 6% of
beta stabilizers are called $\alpha + \beta$ alloys according to the classification performed by Finlay and Bradford.\textsuperscript{17}

![Figure 2.11: Crystal structures of pure titanium\textsuperscript{18}]

The alpha phase is similar to that of an unalloyed titanium, but its strengthened by alpha stabilizing additions of oxygen, nitrogen, and carbon, which form interstitial mixed crystals, and aluminum, which dissolves as a substitution mixed crystal, stabilize the $\alpha$ phase. Beta stabilizers such as hydrogen, vanadium and molybdenum, result in stability of the Beta phase at lower temperatures.\textsuperscript{15} An alpha-beta alloy consists of alpha and retained or transformed beta phases at room temperature.\textsuperscript{19}

Besides the effect on transformation temperatures and consequent lattice parameters, impurities also have important effects on the mechanical properties of titanium.\textsuperscript{20} The strength of technical grade titanium is enhanced mainly due to oxygen and, to a lower extent, due to nitrogen, carbon, silicon and iron\textsuperscript{21} while lowering its ductility. In 1952 Larsen reported that small silicon additions were found to be
beneficial in increasing strength and resistance to air and nitrogen at elevated temperatures\textsuperscript{22}; through segregation and therefore reducing the mobility of dislocations.\textsuperscript{23}

Even in small amounts the combined effects of impurities on the mechanical properties of titanium are rather significant. The next table shows average data of the hardening action of alloying elements, used in practical work with titanium alloys.

Table 2.1: Increase of ultimate strength of titanium in MPAs per percent of alloying additive\textsuperscript{21}

<table>
<thead>
<tr>
<th>Element</th>
<th>$\Delta \sigma_b$, MPa</th>
<th>Element</th>
<th>$\Delta \sigma_b$, MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td>50.0</td>
<td>Manganese</td>
<td>75.0</td>
</tr>
<tr>
<td>Tin</td>
<td>25.0</td>
<td>Chromium</td>
<td>65.0</td>
</tr>
<tr>
<td>Zirconium</td>
<td>20.0</td>
<td>Iron</td>
<td>75.0</td>
</tr>
<tr>
<td>Molybdenum</td>
<td>50.0</td>
<td>Cobalt</td>
<td>55.0</td>
</tr>
<tr>
<td>Vanadium</td>
<td>35.0</td>
<td>Silicon</td>
<td>12.0</td>
</tr>
<tr>
<td>Tungsten</td>
<td>35.0</td>
<td>Niobium</td>
<td>15.0</td>
</tr>
</tbody>
</table>

Listed below are the ranges and effects of some of the most important elements used for alloying in titanium. Note that, silicon does not have any effect on either structure because it is considered as neutral in its effect on either phase.\textsuperscript{23}
Table 2.2: Ranges and effects of some alloying elements used in titanium\(^{20}\)

<table>
<thead>
<tr>
<th>Alloying element</th>
<th>Range (approx), wt %</th>
<th>Effect on structure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td>2-7</td>
<td>α stabilizer</td>
</tr>
<tr>
<td>Tin</td>
<td>2-6</td>
<td>α stabilizer</td>
</tr>
<tr>
<td>Vanadium</td>
<td>2-20</td>
<td>β stabilizer</td>
</tr>
<tr>
<td>Molybdenum</td>
<td>2-20</td>
<td>β stabilizer</td>
</tr>
<tr>
<td>Chromium</td>
<td>2-12</td>
<td>β stabilizer</td>
</tr>
<tr>
<td>Copper</td>
<td>2-6</td>
<td>β stabilizer</td>
</tr>
<tr>
<td>Zirconium</td>
<td>2-8</td>
<td>α and β strengthener (see text)</td>
</tr>
<tr>
<td>Silicon</td>
<td>0.05 to 1</td>
<td>Improves creep resistance</td>
</tr>
</tbody>
</table>

Ti-6Al-4V is a very well tested alloy and it is used on a wide range of industries due to its high strength-to-weight ratio, excellent mechanical properties, high corrosion resistance, and high friction coefficient, making it a widely used alloy in the aerospace\(^ {24,25}\), implant biomaterial\(^ {26}\), and defense industries as a weight-effective protection against small-arms projectiles\(^ {27}\).

The specific alloy grade selected for this work was Ti-6Al-4V extra-low interstitial (ELI), since the EBM processing of this alloy system is well understood, and because it has multiple applications in all sorts of industries.

Ti-6Al-4V ELI is the high-purity version of Ti-6Al-4V, having smaller concentrations of carbon and oxygen. This chemical difference, makes the ELI grade superior to its conventional counterpart in terms of damage tolerance, by increasing its fracture toughness, and by reducing its fatigue crack growth.
rate. The next histogram compares side to side some of the mechanical properties of these two material grades:

![Image of a bar chart comparing mechanical properties of commercial Ti-6Al-4V vs. Ti-6Al-4V ELI](image)

**Figure 2.12: Room temperature properties of commercial Ti-6Al-4V vs. Ti-6Al-4V ELI**

The following table compares the mechanical properties of Ti-6Al-4V as stated in the standard specification ASTM F136 with those listed on ARCAM’s datasheet for ARCAM Ti-6Al-4V ELI.

<table>
<thead>
<tr>
<th>Property</th>
<th>ARCAM Ti-6Al-4V ELI *</th>
<th>ASTM F136</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile Strength min (MPAs)</td>
<td>970</td>
<td>860</td>
</tr>
<tr>
<td>Yield Strength (MPAs)</td>
<td>930</td>
<td>795</td>
</tr>
<tr>
<td>Rockwell hardness (HRC)</td>
<td>32</td>
<td>N/A</td>
</tr>
<tr>
<td>Elongation(%)</td>
<td>16</td>
<td>10</td>
</tr>
</tbody>
</table>

*Stated as Typical*
Note how the ELI-grade specifies lower oxygen content than its regular counterpart, which increases the alloy’s fracture toughness. The table below compares chemical composition as specified by ASTM F136 and as stated by ARCAM’s Ti-6Al-4V ELI datasheet:

<table>
<thead>
<tr>
<th>Element</th>
<th>ASTM F136</th>
<th>ARCAM Ti-6Al-4V ELI</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>0.05</td>
<td>0.01</td>
</tr>
<tr>
<td>C</td>
<td>0.08</td>
<td>0.03</td>
</tr>
<tr>
<td>H</td>
<td>0.012^A</td>
<td>&lt;0.003</td>
</tr>
<tr>
<td>Fe</td>
<td>0.25</td>
<td>0.1</td>
</tr>
<tr>
<td>O</td>
<td>0.13</td>
<td>0.1</td>
</tr>
<tr>
<td>Al</td>
<td>5.5 - 6.5</td>
<td>6</td>
</tr>
<tr>
<td>V</td>
<td>3.5 - 4.5</td>
<td>4</td>
</tr>
<tr>
<td>Ti^B</td>
<td>Balance</td>
<td>Balance</td>
</tr>
</tbody>
</table>

^ Material 0.032 in. (0.813 mm) and under may have hydrogen content up to 0.0150 %.
^ The percentage of titanium is determined by difference and need not be determined or certified.

The stated values for ASTM F136 are maximum values unless specified otherwise, while values for ARCAM’s Ti-6Al-4V ELI are stated as “typical.”

### 2.5 Cellular Metal Categories

Evans and Hutchingson\(^1\) have classified cellular metals according to their topological design into basically two families: open cell structures and closed cell structures, and two subdivisions classifies them even further, stochastic and periodic, which make reference to the type of distribution the cells exhibit.
2.6 Open Cell Lattice Block Structures

Lattice block structures are based on repeating building blocks called unit cells. The development of EBM CAD-assisted technology allows the construction of such structures that were previously deemed impossible to fabricate due to (1) the highly elaborated geometry of the unit cell, and (2) the small size of the unit cells.

The structure proposed for this research is an open cell periodic cellular metal, which also can be called as an open cell lattice block structure. Image shown below illustrates the periodicity of LBS, while image on the left shows its unit cell.
2.7 LBS Applications

The applications are numerous where e-beamed Ti-6Al-4V open cell structures can be successfully implemented. These structures prove to be of particular advantage when it comes to high performance functions such as the following:

- Ultra light structures\(^1\), i.e. lattice block structures for missile structural components\(^{31}\) and innovative titanium lattice structures for Off-board surface vessels\(^{32}\)
- Impact absorption and blast wave mitigation\(^3\), e.g., light antiballistic armor\(^{14}\) given the excellent areal density either as an appliqué or integral armor
- Matrix of a metal matrix composite\(^{33}\)
- Thermal and noise insulation\(^1\)
- Chemical and energy transport or catalytic effects\(^2\)
- Functionally graded materials\(^{34}\)

The material by itself is already a good choice, when it comes to impact absorption and blast wave mitigation. The U.S. rolled homogeneous armor (RHA) is the baseline for all conventional ballistic comparisons, and Ti-6Al-4V when compared to it, performs with an almost 2-to-1 figure of merit (Specific Y.S.).
Table 2.5: Ti-6Al-4V ELI Vs. RHA\textsuperscript{35}

<table>
<thead>
<tr>
<th></th>
<th>Ti-6Al-4V ELI</th>
<th>RHA (MIL-A-12560)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hardness (HB)</td>
<td>302-364</td>
<td>241 - 331</td>
</tr>
<tr>
<td>Elongation</td>
<td>&gt;10</td>
<td>11 - 21</td>
</tr>
<tr>
<td>Y.S. min (MPas)</td>
<td>896</td>
<td>794</td>
</tr>
<tr>
<td>ρ (g/cm\textsuperscript{3})</td>
<td>4.43</td>
<td>7.8</td>
</tr>
<tr>
<td>Specific Y.S. (Y.S./ ρ)</td>
<td>202K</td>
<td>102K</td>
</tr>
</tbody>
</table>

Furthermore, a combination of Ti-6Al-4V with LBS can easily mitigate impact shock in all of its modes, since cellular metals have the highest energy absorption per unit mass of any material. Applications can be varied, ranging from liners for super high pressure vessels, to blast protection doors in oil wells or gas processing facilities, to automotive door side bars, to automotive crushable bumpers and special-purpose packaging, and to military purposes.

The following image shows how a shock wave can be mitigated using a sandwich panel and the resultant response to blast loading:
The fact that the EBM machine is interfaced with a CAD-CAM system opens the doors to further innovation. Such grid structure can be e-beamed to fit perfectly any surface after this has been previously scanned with a 3D scanner. A good example of this technological convergence is utilizing these structures to replace human bones.

Figure 2.16: Reconstruction of a human skull using EBM
An interesting design was proposed by Sypeck, where he proposes a multifunctional use of cellular truss core sandwich structures that form a wingskin for hypersonic airplanes. Such wingskin sandwich structure can be easily accomplished with LBS. According to his design a curved truss core sandwich panel, wingskin is integrated with active cooling. The wingskins are multifunctional in the sense that the open cell core supports loads and also serve the function of a heat exchanger.36

![Figure 2.17: Multifunctional hypersonic wingskin](image-url)
Chapter 3: Methodology

3.1 LBS Design

Materialize™ is a software package that is widely used for Rapid Prototyping (RP) and (RM) applications. It comes with a grid function to construct solids based on user-selectable unit cells. The software works the following way: the user defines the dimensions of the final geometry, then after selecting the grid function the unit cell is selected and its dimensions defined by x, y, and z. Drawing of the .stl file is done then exported to into the ARCAM machine and component, whereby its subsequently sintered using the selected powder metal.

![Figure 3.1: From left to right, final solid geometry for compression testing, ‘Dode thin’ unit cell, G7 unit cell and IG7 unit cell](image)

By looking at the unit cell structure it can be noted the resemblance of the unit cell to the Japanese artistic Kagome wire structures.
Bulk Shape geometry and dimensions comply with Ashby’s recommendation for uniaxial compressive specimens of a height-to-thickness ratio exceeding 1.5. Ashby’s recommendation is in accordance with what is considered the ratio to induce the barreling mode in compression deformation.\textsuperscript{37}

![Diagram of deformation modes](image)

**Figure 3.2:** Modes of deformation in compression. (a) Buckling, when L/D > 5. (b) Shearing, when L/D > 2.5. (c) Double barreling, when L/D > 2.0 and friction is present at the contact surfaces. (d) Barreling, when L/D < 2.0 and friction is present at the contact surfaces. (e) Homogenous compression, when L/D < 2.0 and no friction is present at the contact surfaces. (f) Compressive instability due to work-softening material.

According to the literature available\textsuperscript{38,39}, if the smallest size of the sample is more than six times that of pores within the porous body, the size effect will be avoided. Fabricated samples were designed with one extra cell per side at a unit cell size of 3mm, resulting in a bulk size of 24x24x36mm as the following figure shows.
3.2 Compression Testing

Compression testing took place using a calibrated Tinius Olsen tensile/compression testing machine fitted with a 50KN cell, which for machine protection reasons was limited to 45KN. Samples had their tops and bottoms machined in order to remove any excess material that could cause noise in the measurements. Mobil1 synthetic grease was used to reduce friction between the specimen and machine fixtures.

3.3 Impact Testing

Compression testing focused on the Dt unit cell solely; the unit cell for impact testing was scaled up by different factors. Another set of Dt specimens was built specially for this purpose, consisting of unit cells of 3, 4, 5, 6 and 7 millimeters. Due to the fact that it would be impractical (not to say that is impossible) to test a fully scaled up specimen with unit cell size 7mm on the impact tester (final dimensions would be 56x56x84mm) overall size of all the specimens was kept to the same fixed dimensions of 24.5x 24.5x56mm.
Energy absorption can be monitored and measured via impact testing. Conventional impact fracture testing induces as its name implies fracture. According to the “Standard Terminology Relating to Fracture Testing” fracture toughness as a generic term for measures of resistance to extension of a crack. It is performed mainly through two methods, the Charpy and the Izod impact testing. Both tests are usually performed on a pendulum-type machine such as the one shown below:

![Figure 3.4: Pendulum impact machine](image)

Depending on the type of test, the specimen dimensions and its position with respect to the anvil change as it is explained as follows:
A close-up detailed diagram of the striker, specimen and anvil interface is shown below. Please note the specimen dimensions and the shape of the striking edge of the pendulum as this will represent a technical roadblock in testing our samples.

Figure 3.6: Left image General configuration of anvils and specimen in Charpy test, Right image striker profiles for Charpy testing.
The striker is the part of the pendulum that contacts the specimen during the fracture event. The striker is mounted differently on each type of pendulum. The Tinius Olsen machine is equipped with a striker that uses four mounting bolts and is pinned for alignment. The pinned configuration assures that the striker is aligned properly.43

Figure 3.7: “U” Type Machine pendulum designs

The Charpy test is performed with standard-sized specimens (10x10mm) specimens, however smaller specimen sizes are specified.

Table 3.1 Conversion table for subsize Charpy impact test specimen44

<table>
<thead>
<tr>
<th>Size of specimens (a), mm</th>
<th>Minimum average impact strength for three specimens</th>
<th>Minimum impact strength for one specimen or for set of three specimens</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 × 10 (full size)</td>
<td>20.3 J 15.0 ft · lbf</td>
<td>13.6 J 10.0 ft · lbf</td>
</tr>
<tr>
<td>10 × 7.5</td>
<td>16.9 J 12.5 ft · lbf</td>
<td>11.5 J 8.5 ft · lbf</td>
</tr>
<tr>
<td>10 × 5</td>
<td>13.6 J 10.0 ft · lbf</td>
<td>9.5 J 7.0 ft · lbf</td>
</tr>
<tr>
<td>10 × 2.5</td>
<td>6.8 J 5.0 ft · lbf</td>
<td>4.7 J 3.5 ft · lbf</td>
</tr>
</tbody>
</table>

When we try to apply the standardized Charpy test to LBS, several problems arise. The first problem is that the Charpy test usually requires notched specimens, while unnotched specimens are for
plastic, ceramic and malleable metal testing. LBS cannot be notched since it is not a fully solid structure.

The second problem comes from the fact that a minimum of 7 unit cells are required to overcome size effects.\textsuperscript{38,39} The smallest manufacturable unit cell size is 3mm, so it would be needed at least a 21mm sample size to comply with Ashby’s recommendation. The largest specified Charpy is 10mm.

![Charpy V-notch specimen](image)

Figure 3.8: Largest Charpy specimen as specified per ASTM E23

The third and last problem is the striker’s geometry and the anvil’s dimensions. Because of all the technical challenges previously mentioned, Charpy testing was opted-out as the testing method and an alternate method was sought.

A modified impact testing method was developed and used the conventional Izod testing method as a basis, taking into consideration that the Izod test is designed to induce fracture through impact and a stress concentrator (notch). The LBS used for this experiment could not be notched since they were not fully solid structures, and testing would eventually demonstrate that for LBS there is no systematic crack propagation, only energy required for failure. Modifications for testing were required and a special
impact machine striker was designed, built and heat treated to replace the stock component. As-built unnotched specimens were struck one by one and impact data was recorded.

Figure 3.9: Modified impact striker top view

Figure 3.10: Modified impact striker side view
Material selected to manufacture striker was A2 tool steel, and it was hardened to the same hardness of stock striker (58-60 HRC). Upon impact testing completion, macroscopically agglomerated debris was collected and carefully stored for following failure analysis.

### 3.4 Stereomicroscopy

Stereomicroscopy was performed using a Leica M205C stereomicroscope with an apochromatic 20.5:1 zoom and FusionOptics™ technology, fitted with a Leica DFC290 image capturing device.

![Image of Leica M205C stereomicroscope](image)

**Figure 3.11** Leica M205C stereomicroscope

### 3.5 Scanning Electron Microscopy

A Hitachi TM-1000 Tabletop scanning electron microscope using backscattered electron imaging at a fixed accelerating voltage of 15kV was used for observation. SEM was fitted with a SwiftED-TM Energy Dispersive (X-ray) Spectrometer (EDS) system, a silicon drift detector with a detection area of 30mm² for semiquantitative chemical analysis. Preceding chemical analyses of the samples EDX detector was calibrated using copper standard reference tape.
Figure 3.12: Hitachi TM1000 tabletop SEM
Chapter 4: Results and Discussion

The next set of images show the unit cell as well as the finished e-beamed specimens with unit cell size of 3mm.

![Image: Left image Dt unit cell, Right image built specimen](image1)

Figure 4.1: *Left image* Dt unit cell, *Right image* built specimen

![Image: Left image G7 unit cell, Right image built specimen](image2)

Figure 4.2: *Left image* G7 unit cell, *Right image* built specimen
G7 and IG7 share the same unit cell, being the only difference the fact that the unit cell of IG7 has been rotated.

Figure 4.3: *Left image IG7 unit cell, Right image built specimen*

Murr et al. characterized the structures and found that the three structures had similar densities. The measured density for the Dt structure is 1.59 g/cm$^3$, and since G7 and IG7 have the same unit cell their densities are equal (1.83 g/cm$^3$). The next graph shows the compression results of three samples for each geometry, each one with a different unit cell as labeled.
Since D7 and ID7 have the same densities, their differences in compressibility can be only attributed to the unit cell orientation. Density does not seem to play a role for LBS compressive response, at least for small density differences.

During the compression testing, only one structure out of the three mentioned geometries failed at loads under 45KN. This was IG7, and the stresses and strains at failure are next:

Table 4.1: Stresses and strains at failure for IG7

<table>
<thead>
<tr>
<th>Load (N)</th>
<th>Stress (MPAs)</th>
<th>Strain</th>
</tr>
</thead>
<tbody>
<tr>
<td>21000</td>
<td>103</td>
<td>0.03</td>
</tr>
<tr>
<td>24000</td>
<td>119</td>
<td>0.03</td>
</tr>
<tr>
<td>22000</td>
<td>108</td>
<td>0.03</td>
</tr>
</tbody>
</table>
Compression testing data highlighted another important aspect of the structures, and this was that Dt behaved anisotropically when compared to D7 and ID7. Based on this information a conclusion can be made. LBS, unlike stochastic metal foams yield’s stress, do not rely solely on their density but also on their unit cell geometry due to their highly ordered structure.

4.1 Modulus of Resilience ($W_r$)

Resilience or elastic energy is the ability of a material to absorb energy when deformed elastically and then return to its original shape upon release of load. In other words, it is the amount of energy stored in a material when loaded to its elastic limit. It is represented by the area under the stress-strain curve up to the elastic limit (see the shaded areas in next figure), that is:

$$W_r = \frac{\sigma^2}{2E} = 0.5\sigma\epsilon = 0.5\sigma\left(\frac{\sigma}{E}\right)$$

Equation 1: Modulus of resilience

Of materials A and B in next figure, material A has greater resilience because of its higher yield strength and higher modulus of elasticity.
The following histogram was obtained for the G6, IG& and Dt based structures and shows the strain energies at IG7’s yield strain. Note how again Dt remained in between D7 and ID7, which suggests its anisotropic behavior.
4.2 The Particularities of Dt-based Structure

During compression testing most of energy absorption takes place after the yield stress has been reached, that is during plastic deformation. A stiffer material does not necessarily make it tougher. Stiffness is defined as the slope of the stress-strain curve over the elastic region, whereas toughness is defined as the area under the entire stress-strain curve (elastic+plastic) up to fracture, and is therefore also a measure of ductility. A material’s toughness reflects its ability to absorb energy and depends on test conditions (e.g., strain rate) and defects within the specimen (e.g., notches).48
The second part of this thesis focuses on the Dt’s anisotropic behavior. The unit cell was scaled up by different factors and specimens were tested on a modified impact test in order to monitor their energy absorption capabilities. Another set of Dt specimens was built specially for this purpose, consisting of unit cells of 3, 4, 5, 6 and 7mm. Due to the fact that it would be practically impossible to test a fully scaled up specimen with unit cell size 7mm on the impact tester (final dimensions would have been 56x56x84mm), overall size of all the specimens was kept to the same fixed dimensions of 24.5x24.5x56mm.

Scaled-up Dt impact testing specimens were characterized and documented in “Next generation biomedical implants using additive layered manufacturing of complex, cellular and functional mesh arrays,” written by Murr et al.47
Table 4.2: Dode-thin mesh build sequence properties

<table>
<thead>
<tr>
<th>Build Size (cm) (Volume: cm³)</th>
<th>Mass (g)</th>
<th>Density, ρ (g/cm³)</th>
<th>Sturt Size (mm)</th>
<th>Base Channel Size (mm)**</th>
<th>Porosity (%)</th>
<th>Relative Density (ρ/ρ₀)¹</th>
<th>E (GPa)</th>
<th>Resonant Frequency, f (kHz)</th>
<th>Internal Friction (10⁶)</th>
<th>Sturt Hardness HV (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.7x4.7.7.1 (156.84)</td>
<td>122.5</td>
<td>0.78</td>
<td>1.2</td>
<td>2.4</td>
<td>82</td>
<td>0.18</td>
<td>0.92</td>
<td>6.9</td>
<td>3.0</td>
<td>---</td>
</tr>
<tr>
<td>4.1x1.1x5.9 (99.18)</td>
<td>85.7</td>
<td>0.86</td>
<td>1.0</td>
<td>2.0</td>
<td>81</td>
<td>0.19</td>
<td>1.53</td>
<td>7.9</td>
<td>5.0</td>
<td>---</td>
</tr>
<tr>
<td>3.1x3.1x4.4 (51.81)</td>
<td>51.8</td>
<td>1.22</td>
<td>0.8</td>
<td>0.9</td>
<td>72</td>
<td>0.28</td>
<td>2.70</td>
<td>12.9</td>
<td>2.7</td>
<td>---</td>
</tr>
<tr>
<td>2.3x2.3x3.6 (20.74)</td>
<td>33.0</td>
<td>1.59</td>
<td>0.7</td>
<td>0.7</td>
<td>64</td>
<td>0.36</td>
<td>6.15</td>
<td>19.8</td>
<td>5.7</td>
<td>3.7</td>
</tr>
</tbody>
</table>

*Materialize™ Software (materialize.com).
**Base channels are essentially square openings in the build base (see figure 6).
¹ρ₀ = 4.43 g/cm³
²Q

Modified impact testing generated the following data when impacting Dt structures with different densities at room temperature.

![Density Vs. Absorbed Energy](image)

Figure 4.8: Impact test results
Impact data obtained showed that the absorbed energy is directly proportional to the density of the structures.

A figure of merit (FOM) is a way to determine the relative utility of something for a specific application using a known value as a reference. For the work presented in this thesis a FOM was developed as a means to rank performance of the structure in absorbing relative impact energy with respect to its relative density:

Table 4.3: Figure of merit for structures with different unit cell sizes

<table>
<thead>
<tr>
<th>Unit cell size</th>
<th>Energy/Density (J/g/cm³)</th>
<th>FOM</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>189</td>
<td>0.94</td>
</tr>
<tr>
<td>4</td>
<td>200</td>
<td>1.00</td>
</tr>
<tr>
<td>5</td>
<td>183</td>
<td>0.91</td>
</tr>
<tr>
<td>6</td>
<td>163</td>
<td>0.81</td>
</tr>
<tr>
<td>7</td>
<td>144</td>
<td>0.72</td>
</tr>
</tbody>
</table>

It was observed that globally, the Dt structure with unit cell size of 4 mm was the most efficient using this criteria.
L.E. Murr obtained the following relationship between the density of the Dt structures, their dynamic modulus of elasticity and the energy absorbed on impact:
The following relationship was also found by L.E. Murr using also the dynamic modulus of elasticity:

Table 4.10: Density of Dt structures vs. dynamic modulus of elasticity and impact energy

Table 4.11: $E/\rho$ vs. $J/m^2$
4.3 Tear not shear

The follow diagram shows that the trajectory that the striker follows is circular once the pendulum is released:

![Diagram of pendulum trajectory](image)

**Figure 4.12: Trajectory of the pendulum**

As the striker approaches the specimen, the horizontal distance \(dx\) gets smaller, and the vertical distance \(dy\) gets smaller too. At the moment the striker hits the specimen, both \(dx\) and \(dy\) become zero. Immediately after the striker hits the specimen, \(dx\) and \(dy\) start increasing. Conventional Izod and Charpy specimens do not see any effects of the circular motion of the striker, because (1) their thickness (10mm maximum) is insignificant in comparison to the diameter of the path described by the pendulum, (2) the surface of the specimen is relatively smooth, and (3) the striking edge has a radius.
The modified impact test performed on this paper used a sample thickness of 25mm with a very rough surface, and a striker with no striking edge radius at all. If the specimen had undergone shear induced by the striker, the latter would have left a mark (notch) consistent with a homogeneously applied load. Therefore, impact mark would be something similar to what is indicated by the red square:
Instead the marks left on the specimen indicate that the striker did not apply a homogeneously distributed load:

![Impacted specimen](image1)

**Figure 4.15: Impacted specimen**

At the instant of impact the lower portion of the specimen was fixed by the machine’s vise jaw, and the striker was traveling parallel to the ground. After striking, pendulum continued to follow its circular trajectory. Hence, the only way the triangular notch could have been induced was if the specimen suffered a bending moment.

![Bending moment](image2)

**Figure 4.16: Bending moment applied to specimen**
Therefore, it can be inferred what the loading conditions were:

![Impact forces on specimen]

Figure 4.17: Impact forces on specimen

The damage suffered by the lower portion of the specimen indicates that indeed specimen underwent localized compression, and subsequent crushing and densification of the cells.

![Localized densification on specimen’s cells]

Figure 4.18: Localized densification on specimen’s cells
The top portion of specimen also shows localized densification of cells:

Figure 4.19: Localized densification on specimen’s cells

The following set of images show specimens after being impacted:
Figure 4.20: From top left clockwise specimens 3, 4, 5, 6 and 7

Note that specimens 4 and 6 have a prominent ‘notch’ induced by the striker (red arrow). Nevertheless, that was not the fracture’s origin.
4.4 Stereomicroscopical Analyses

Stereomicroscopical fractographs revealed the absence of secondary cracks, and very limited plastic deformation was observed, with very few trusses showing a miniscule shear lip typical of ‘ductile’ fractures. Minimal plastic deformation of trusses adjacent to fracture surfaces was observed, whereas most fractures occurred at the truss-nodule interface. The loss of nodules was minimal.
Figure 4.22: Stereoscopical fractograph of specimen 3 showing flat fracture surfaces. Original Magnification 50X

Figure 4.23: Stereoscopical fractograph of specimen 3 showing a ‘cup’ fracture. Original Magnification 50X
Figure 4.24: Stereoscopical fractograph of specimen 3 showing missing nodule. Original Magnification 50X

Figure 4.25: Stereoscopical fractograph of specimen 4 showing nodule and no trusses. Fracture showing some ‘cup’ behavior. Original Magnification 50X
Figure 4.26: Stereoscopical fractograph of specimen 4 showing nodule with dimples on surface.
Original Magnification 50X

Figure 4.27: Stereoscopical fractograph of specimen 5 showing nodule and no trusses
Original Magnification 50X
Figure 4.28: Stereoscopical fractograph of specimen 5 showing flat fracture surfaces. Original Magnification 50X

Figure 4.29: Stereoscopical fractograph of specimen 6 showing nodule and no trusses. Very limited cup behavior. Original Magnification 50X
Figure 4.30: Stereoscopical fractograph of specimen 6 showing missing nodule.
Original Magnification 50X

Figure 4.31: Stereoscopical fractograph of specimen 7 showing missing nodule.
Original Magnification 50X
4.5 SEM and EDS Analyses

Scanning Electron Microscopy (SEM) confirmed stereomicroscopical observations while shedding new evidence on the nature of the specimen fracture. SEM revealed the widespread presence of spherical shallow dimples, characteristic of Mode I loading (Uniaxial tensile load, uniform strain) and a smaller presence of parabolic tear dimples also characteristic of Mode I loading (Uniaxial tensile load, non-uniform strain, bending or ductile tear). Although parabolic dimples might be indicative of Mode II in shear loading as well, it was discarded as the loading condition due to the fact that macroscopic evidence pointed towards a tearing load.
Figure 4.33: SEM fractograph of specimen 3 showing several fracture surfaces and high density of Boules de Noël. Original Magnification 60X @ 15keV

Figure 4.34: SEM fractograph of specimen 3 showing mostly shallow spherical dimples. Original Magnification 1200X @ 15keV
Figure 4.35: SEM fractograph of specimen 3 showing a shallow dimples and inclusion.  
Original Magnification 5000X @ 15keV

Figure 4.36: EDX of Inclusion on specimen 3
Table 4.4: Elementary composition of inclusion on specimen 3

<table>
<thead>
<tr>
<th>Element</th>
<th>Weight %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td>2.1</td>
</tr>
<tr>
<td>Silicon</td>
<td>2.4</td>
</tr>
<tr>
<td>Titanium</td>
<td>89.9</td>
</tr>
<tr>
<td>Vanadium</td>
<td>5.6</td>
</tr>
</tbody>
</table>

For comparison purposes an EDX was performed on the base metal.

Figure 4.37: EDX of base metal sample 3

Table 4.5: Elementary composition of specimen 3 base metal

<table>
<thead>
<tr>
<th>Element</th>
<th>Weight %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td>5.6</td>
</tr>
<tr>
<td>Silicon</td>
<td>0.9</td>
</tr>
<tr>
<td>Titanium</td>
<td>88.4</td>
</tr>
<tr>
<td>Vanadium</td>
<td>3.9</td>
</tr>
<tr>
<td>Iron</td>
<td>1.1</td>
</tr>
</tbody>
</table>
Next set of images were taken on specimen 4.

Figure 4.38: SEM fractograph of specimen 4 showing TMPSF (yellow arrow) and IMPSF (red arrow) with medium density of Boules de Noël. Original Magnification 60X @ 15keV

Figure 4.39: SEM fractograph of specimen 4 showing mostly shallow spherical dimples. Original Magnification 1200X @ 15keV
Figure 4.40: SEM fractograph of specimen 4 showing dimples and inclusion. Original Magnification 5000X @ 15keV

Figure 4.41: EDX of Inclusion on specimen 4
Table 4.6: Elementary composition of inclusion on specimen 4

<table>
<thead>
<tr>
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Figure 4.42: EDX of sample 4 base metal

Table 4.7: Elementary composition of specimen 4 base metal

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Figure 4.43: SEM fractograph of specimen 4 showing transitional parabolic shallow dimples. Original Magnification 1800X @ 15Kev

Figure 4.44: SEM fractograph of specimen 4 showing TMPFS (yellow arrow) and unmolten particle (blue arrow) at IMPFS (red arrow) with medium density of Boules de Noël. Original Magnification 60X @ 15keV
Figure 4.45: SEM fractograph of specimen 4 showing superficial cracks.
Original Magnification 400X @ 15keV

Figure 4.46: SEM fractograph of specimen 5 with high density of Boules de Noël.
Original Magnification 60X @ 15keV
Figure 4.47: SEM fractograph of specimen 5 showing mostly shallow spherical dimples. Original Magnification 1200X @ 15keV

Figure 4.48: SEM fractograph of specimen 5 showing inclusion. Original Magnification 5000X @ 15keV
Figure 4.49: EDX of inclusion on specimen 5

Table 4.8: Elemental composition of inclusion on specimen 5

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Figure 4.50: EDX of sample 5 base metal
Table 4.9: Elemental composition of sample 5 base metal

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Figure 4.51: SEM fractograph of specimen 6 showing IMPSF with low density of Boules de Noël, and superficial cracks on nodule. Original Magnification 60X @ 15keV
Figure 4.52: SEM fractograph of specimen 6 showing shallow spherical dimples and inclusion. Original Magnification 1200X @ 15keV

Figure 4.53: SEM fractograph of specimen 6 showing inclusion. Original Magnification 5000X @ 15keV
Table 4.10: Elemental composition of inclusion on specimen 6

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Table 4.11: Elemental composition specimen 6 base metal

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Figure 4.56: SEM fractograph of specimen 7.
Original Magnification 60X @ 15keV
Figure 4.57: SEM fractograph of specimen 7 showing shallow spherical dimples and coloration contrast. Original Magnification 1200X @ 15keV

Figure 4.58: SEM fractograph of specimen 7 showing spherical dimples and inclusions. Original Magnification 5000X @ 15keV
Figure 4.59: EDX of Inclusion on specimen 7

Table 4.12: Elemental composition of Inclusion on specimen 7

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Figure 4.60: EDX of sample 7 base metal
Table 4.13: Elemental composition of specimen 7 base metal

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Figure 4.61: SEM fractograph of specimen 7 showing parabolic dimple.
Original Magnification 2500X @ 15keV
Figure 4.62: SEM fractograph of specimen 7 showing parabolic dimples.  
Original Magnification 1200X @ 15keV

Figure 4.63: SEM fractograph of specimen 7 showing ‘black’ and ‘white’ dimples.  
Original Magnification 5000X @ 15keV
Figure 4.64: EDX of white dimples of specimen 7

Table 4.14: Elemental composition of white dimples on specimen 7

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Figure 4.65: EDX of spherical black dimples on sample 7
Table 4.15: Elemental composition of black dimples on specimen 7

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Figure 4.66: SEM fractograph of specimen 7 showing parabolic dimples.
Original Magnification 1200X @ 15keV
4.6 LBS Morphology Characterization

SEM imaging revealed the morphology of the melt, and how connectors are composed of a series of stacked pool melts. Pool melt stacks are concentric and defined by a solid angle with respect to the connector growth direction.
Figure 4.68: SEM photomicrograph showing stacked pool melts with a low density of Boules de Noël (red arrows). Pool melt stack composed of 5-6 pool melts (yellow bracket)

A model that describes the growth of connectors on a nodule is proposed as follows:
Figure 4.69: Diagrammatic proposed model for growth of a truss on a nodule. From top left clockwise, *first sketch* nodule, *second sketch* initial melt pool on nodule, *third sketch* metastable melt pool stack, *fourth sketch* second melt pool stack forming a solid angle with respect to direction of first pool stack, *fifth sketch* direction of second melt pool stack being counterbalanced by next melt pool stack and so on successively until connector reaches desired length and another nodule is formed (*sixth sketch.*)
SEM also revealed what appeared as superficial cracks caused by contraction forces as the melt cooled. It is not believed that the cracks are secondary cracks caused by impact testing because they appear shallow and do not seem to converge radially to a point in common. Instead they follow a tortuous path.

Figure 4.70: SEM photomicrograph showing superficial cracks caused by contraction forces as the melt cooled
SEM imaging showed that there are basically two types of fracture for this sort of construction: transmelt pool stack fracture and intermelt pool stack fracture. The transmelt pool stack fracture (TMPF), characterized by the fact that fracture paths travel across melt pool stacks is an indication of good melt coalescence. The intermelt pool stack fracture (IMPF), characterized by fractures traveling between pool stacks is an indication of lack of melt pool coalescence.

Figure 4.71: SEM fractograph of TMPF

The next image shows melt pool stacks and their concentricity, an IMPSF and an unmolten particle at the fracture surface.
From the previous picture it is clearly visible that as pool melts start piling one on top of another, they reduce their diameter and that is when another melt pool of bigger diameter starts another melt pool stack. The new pool, having greater mass than the last of the pool melts in the previous stack, is hydrodynamically instable and then slides, creating a solid angle while the melt freezes. Another possible explanation for the sequential reduction of melt pool diameters is the Marangoni effect that induces the transfer of mass.

Surface tension is a function of temperature, and since a liquid with a high surface tension pulls more strongly on the surrounding liquid than one with a low surface tension, the presence of a gradient in surface tension will naturally cause the liquid to flow away from regions of low surface tension.50

It is a well known fact that EBM processing induces large thermal gradients in the region where the electron beam intercepts the melt, leading to variations in the surface energy of the melt close to the beam inducing a Marangoni or thermocapillary flow. During the melt processing of many materials, the
Marangoni contribution can dominate the fluid flow, influencing the trajectories of inclusions within the melt and providing a potential mechanism for controlling the removal and/or distribution of inclusions.\textsuperscript{51}

Semiquantitative Energy Dispersive (X-ray) Spectrometric analyses (EDS) measured the chemical composition of fractured and non-fractured surfaces. Non-fractured surfaces revealed the base alloying elements (Ti-Al-V) and an average silicon concentration of 0.8\%. On the other hand, dimpled surfaces revealed an average silicon concentration of up to 3.3\%, suggesting that preferred fracture surfaces developed through microvoid coalescence of silicate inclusions.

Given the silicon concentrations and the meticulous cleaning procedure that preceded EDX examination, it can be safely assumed that silicon was deliberately added by the powder metal manufacturer in order to serve two purposes: (1) as a nucleation agent to catalyze solidification and (2) as an alloying element to increases the ultimate strength of the alloy.\textsuperscript{52,53}

This argument makes perfect sense if we consider the following facts: (1) silicon is regarded as neutral in its effect on either phase\textsuperscript{23}, (2) silicon concentration is not controlled by applicable standard specifications (ASTM F136, ARCAM Ti\textsubscript{6}Al\textsubscript{4}V ELI datasheet); therefore it can be added in any desired concentration and alloy composition will stay within specifications as long as other alloying elements’ concentration is respected (Ti’s concentration stated as balance); and (3) faster cooling rates result in better control of the melt pool diameter which in turn translates into tighter dimensional control.

Moreover, EBM manufacturing is completely the opposite of any other process that requires a mold, and the material is expected to do exactly the opposite as well. In a molded process the material is
constrained volumetrically by the mold, so molten material has to flow and solidify slowly to fill all mold cavities and finally end with a quality product. EBM requires exactly the opposite from any material that deemed for molding since there is no volumetric constraint, and material is required to solidify quickly so it can provide structural support to next layers. The deliberate addition of silicon or any nucleating agent for solidification is necessary for an efficient EBM fabrication.
CHAPTER 5, SUMMARY AND CONCLUSIONS

Geometrical arrangements in nature are the result of millions of years of design fine-tuning. Tree leaves, animals, DNA and the M-theory postulated by Lucasian professor Brian Greene are few examples of the role that geometry plays in nature and its success on simplifying complex systems, such as replication with the minimum amount of information.

Complex systems described in simple terms come with a bonus, as the information can be easily moved back and forth. Nature has its way of compacting information, and that is the story of nature’s pursuit of perfect packing.

Man-made lattice block structures (LBS) tend to replicate the crystallographic aspect often found in nature, from a grain of salt to stalagmites. LBS can be effectively implemented in a wide variety of applications, such as thermal and noise insulation\(^1\), chemical and energy transport or catalytic effects\(^2\), and ultralight structural components among others. This thesis has only focused on the latter while taking into consideration that other applications are not less relevant.

The work presented in this thesis conjugated LBS and electron beam melting (EBM) technology and characterized the final product. EBM is a solid freeform fabrication process that builds fully dense metal parts in layerwise fashion\(^1\). This moldless fabrication process is a very efficient one due to its high scanning speeds, high beam-material coupling efficiencies, and high accuracy\(^2,38\), which allows for the building of complex geometries that were previously deemed impossible or too complex to manufacture.

The first part of this research consisted of designing and characterizing three sets of Electron-Beam Melted (EBM) Ti-6Al-4V LBS designed and constructed with different unit cells. Specimens were named G7, IG7, and Dt in reference to the names assigned to unit cells by the MATERIALIZE™ software used to construct them. All samples were designed with a unit cell size of 3mm, having 8 unit
cells in width, 8 unit cells in length and 12 unit cells in height to avoid the influence of any size effects.\textsuperscript{38,39}

Samples underwent compression testing, and although all samples had approximate densities they behaved differently, with IG7 yielding at approximately 22 KN in compression, Dt and G7 showed no yielding at all even when loaded up to 45KN. The calculated strain energies ($U_\varepsilon$) at 0.03 $\varepsilon$ was of 2132 KPAs for G7, 1913 KPAs for Dt, and the modulus of resilience of IG7 was of 1539 KPAs since it yielded at given strain. Dt’s value closeness to that of IG7 indicated that it could take almost the same mechanical energy without permanent deformation, and led to the conclusion that Dt was behaving anisotropically when compared to D7 and ID7.

The second part of this thesis focused on Dt’s anisotropic behavior. The unit cell was scaled up by different factors and specimens were tested on a modified impact test in order to monitor their energy absorption capabilities. Another set of Dt specimens was built specially for this purpose, consisting of unit cells of 3, 4, 5, 6 and 7 millimeters. Due to the fact that it would be practically impossible to test a fully scaled up specimen with unit cell size 7mm on the impact tester (final dimensions would have been 56x56x84mm), overall size of all the specimens was kept to the same fixed dimensions of 24.5x24.5x56mm.

Impact testing used the conventional Izod testing method as a basis, with the particularity being that the Izod test is designed to induce fracture through impact and a stress concentrator (notch). The LBS used for this experiment cannot be notched since they not a fully solid structure, and therefore modifications for testing were required. A special impact machine striker was designed, built and heat treated to replace the stock component. Specimens were struck one by one and impact data was recorded. After testing macroscopically agglomerated debris was collected and carefully stored for further inspection.
Analyzed impact data obtained showed that the absorbed energy is directly proportional to the density of the structures.

A figure of merit was developed, that is absorbed impact energy/density of specimen and it was used as a mean to rank performance of the structure in absorbing relative impact energy with respect to its relative density. It was observed that globally, the Dt structure with unit cell size of 4 mm was the most efficient using this criteria.

Naked eye inspection suggested that modified impact test had not induced shear, but rather resulted in tearing on the samples, a hypothesis that would be eventually confirmed. Stereomicroscopical fractographs revealed the absence of secondary cracks, and very limited plastic deformation was observed with very few trusses showing a small shear lip typical of “ductile” fractures. Insignificant plastic deformation of trusses adjacent to fracture surfaces was observed, whereas most fractures occurred at the truss-nodule interface. Loss of nodules was minimal.

Scanning Electron Microscopy (SEM) confirmed stereomicroscopical observations while shedding new evidence on the nature of the specimen fracture. SEM revealed the widespread presence of spherical shallow dimples, characteristic of Mode I loading (Uniaxial tensile load, uniform strain) and a smaller presence of parabolic tear dimples, characteristic of Mode I loading (Uniaxial tensile load, non-uniform strain inducing bending or ductile tear). Although parabolic dimples might be indicative of Mode II in shear loading, it was discarded as the loading condition due to the fact that macroscopic evidence pointed towards a tearing load. Evidence of a brittle overload, that is cleavage or quasicleavage, was nonexistent. The presence of inclusions was detected and documented.

Subsequent SEM imaging showed a good quality EBM process with a fully dense fracture surface and transmelt pool stack fractures, which is an indication of good material sintering. Semiquantitative Energy Dispersive (X-ray) Spectrometric analyses (EDS) measured the chemical composition of fractured and non-fractured surfaces. Non-fractured surfaces revealed the base alloying
elements (Ti-Al-V) with an average concentration of silicon of 0.8%, whereas dimpled surfaces revealed silicon an average concentration of 3.3%.

Heterogeneous distribution of Si can be the result of silicon being added in a poorly controlled post-manufacturing process of the powder metal, or the result of a Marangoni flow influencing the trajectories of the inclusions due to the large thermal gradients inherent to the EBM process.\textsuperscript{51}

After collecting and analyzing the evidence, it was concluded that specimens macroscopically failed in a brittle manner, while microscopically, failure was microductile Mode I overload on tension and tear due to the microvoid coalescence of silicate inclusions.

Given the silicon concentrations and the meticulous cleaning procedure that preceded EDS examination, it can be safely assumed that Si was deliberately added by the powder metal manufacturer in order to serve two purposes, (1) as a nucleation agent to catalyze solidification and (2) as an alloying element to increases the ultimate strength of the alloy\textsuperscript{52,53}.

This argument makes perfect sense if we consider the following facts, (1) silicon is regarded as neutral in its effect on either phase\textsuperscript{23}, (2) silicon concentration is not controlled by applicable standard specifications (ASTM F136, ARCAM Ti-6Al-4V ELI datasheet) therefore it can be added in any desired concentration and alloy composition will be within specification as long as other alloying elements’ concentration is respected (titanium’s concentration stated as balance), and (3) faster cooling rates result in better control of the melt pool diameter which in turn translates into tighter dimensional control.
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**Glossary**

*Apochromatic lens.* - is a photographic or other lens that has better correction of chromatic and spherical aberration than the much more common achromat lenses.

*Areal density.* - A measure of the weight of armor material per unit area, usually expressed in pounds per square foot (lb/ft²) or kilograms per square meter (kg/m²) of surface area.⁵⁴

*Apliqué armor.* - Armor that can be easily installed or removed from a weapon system in kit form without adversely affecting its structural integrity or operation.⁵⁴

*Connector.* - Truss, strut of lattice block structures.

*Intermelt pool stack fracture (IMPF).* - Crack propagation along melt pool stack interfaces. Detachment of nodules from connectors takes place through this mechanism.

*Integral armor.* - Armor material used as part of a structure to perform a load-carrying or other operational function, in addition to ballistic protection. Also known as structural armor.⁵⁴

*Melt pool.* - Subsection of melt pool stack. Smallest structural component of a lattice block structure connector. Analog to weld bead

*Melt pool stack.* - Collection of melt pools stacked up concentrically with respect to each other. Truss sub-section of electron beam melted nodule-to-nodule connectors of Lattice block structures. Aligned melt pool pile-up. Analog to stacked weld beads.

*Polytope.* - Geometrical figure bounded by portions of lines, planes or hyperplanes; e.g., in two dimensions it is a polygon, in three a polyhedron.⁵⁵

*Transmelt pool stack fracture (TMPF).* - Crack propagation across pool stacks.

*Boules de Noël.* - Partially melted particles attached to the main LBS structure in EBM process.
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This thesis was typed by Hugo Francisco López López De Cárdenas
Vita

Hugo Francisco López López De Cárdenas was born in Ciudad Juárez the 13th of February of 1976, being the first of three children of Hugo López and Araceli López. He studied in Juárez until he started his bachelor’s in UTEP in the Fall of 1993. While working on his bachelor’s he had various jobs to help himself financially, he worked as a waiter, auto mechanic, engineer assistant at W. Silver, adult education teacher at Languages R US, and research assistant at UTEP. In May 2003 he obtained his bachelor’s degree, and after working as an engineer in México he was offered a job in Paris, France. He married Stéphanie Malterre the 15th of January of 2005 in the Parisian suburb of Créteil. Hugo lived and worked in France until the summer of 2006, when he was offered a job as a material’s designer and failure analyst at Delphi’s MTC in Juárez, México. Hugo’s desire to evolve intellectually pushed him to continue his studies and in January 2008 he started his first semester towards his Master’s degree. Hugo managed to work full time at Delphi and to study full time at UTEP successfully. During the Wall Street meltdown, Delphi cut all scholarships and Hugo was able to continue his studies thanks to the financial support supplied by his recently deceased grandmother. Hugo lost his job at Delphi in winter 2009, and he was able to pay his last semester (spring 2010) thanks to the financial support of his wife and to the quarter time position assigned to him as a research assistant by his advisor Dr. L.E. Murr.

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