ADDITIVE MANUFACTURING OF METAStABLE BETA TITANiUM ALLOYS

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Additive manufacturing processes of many alloys are known to develop texture during the deposition process due to the rapid reheating and the directionality of the dissipation of heat. Titanium alloys and with respect to this study beta titanium alloys are especially susceptible to these effects. This work examines Ti-20wt%V and Ti-12wt%Mo deposited under normal additive manufacturing process parameters to examine the texture of these beta-stabilized alloys. Both microstructures contained columnar prior beta grains 1-2 mm in length beginning at the substrate with no visible equiaxed grains. This microstructure remained constant in the vanadium system throughout the build. The microstructure of the alloy containing molybdenum changed from a columnar to an equiaxed structure as the build height increased. Eighteen additional samples of the Ti-Mo system were created under different processing parameters to identify what role laser power and travel speed have on the microstructure. There appears to be a correlation in alpha lath size and power density. The two binary alloys were again deposited under the same conditions with the addition of 0.5wt% boron to investigate the effects an insoluble interstitial alloying element would have on the microstructure. The size of the prior beta grains in these two alloys were reduced with the addition of boron by approximately 50 (V) and 100 (Mo) times.
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By

Christopher J. Yannetta
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# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>ACKNOWLEDGMENTS</th>
<th>iii</th>
</tr>
</thead>
<tbody>
<tr>
<td>LIST OF TABLES</td>
<td>vi</td>
</tr>
<tr>
<td>LIST OF FIGURES</td>
<td>vii</td>
</tr>
<tr>
<td>CHAPTER 1. INTRODUCTION</td>
<td>1</td>
</tr>
<tr>
<td>1.1 Advantages of Additive Manufacturing</td>
<td>1</td>
</tr>
<tr>
<td>1.2 Disadvantages of Additive Manufacturing</td>
<td>2</td>
</tr>
<tr>
<td>1.3 Microstructure</td>
<td>2</td>
</tr>
<tr>
<td>CHAPTER 2. LITERATURE REVIEW</td>
<td>4</td>
</tr>
<tr>
<td>2.1 Additive Manufacturing</td>
<td>4</td>
</tr>
<tr>
<td>2.1.1 Energy Source</td>
<td>4</td>
</tr>
<tr>
<td>2.1.2 Feedstock Material</td>
<td>5</td>
</tr>
<tr>
<td>2.2 Titanium Metallurgy</td>
<td>7</td>
</tr>
<tr>
<td>2.2.1 Effects of Alloying Elements</td>
<td>7</td>
</tr>
<tr>
<td>2.3 Laser Engineered Net Shaping (LENS™)</td>
<td>8</td>
</tr>
<tr>
<td>CHAPTER 3. EXPERIMENTAL PROCEDURE</td>
<td>9</td>
</tr>
<tr>
<td>3.1 Introduction</td>
<td>9</td>
</tr>
<tr>
<td>3.2 Laser Engineered Net Shaping (LENS™)</td>
<td>9</td>
</tr>
<tr>
<td>3.2.1 Deposition Parameters</td>
<td>11</td>
</tr>
<tr>
<td>3.3 Sample Preparation</td>
<td>15</td>
</tr>
<tr>
<td>3.3.1 Ti-12wt%Mn Sample Sectioning</td>
<td>15</td>
</tr>
<tr>
<td>3.3.2 Electron Discharge Machining (EDM)</td>
<td>16</td>
</tr>
<tr>
<td>3.3.3 Surface Refinement</td>
<td>17</td>
</tr>
<tr>
<td>3.4 Characterization Equipment</td>
<td>17</td>
</tr>
<tr>
<td>3.4.1 Nova NanoSEM 230</td>
<td>17</td>
</tr>
<tr>
<td>3.4.2 High Resolution X-ray Diffraction (XRD)</td>
<td>18</td>
</tr>
<tr>
<td>3.4.3 ImageJ Software</td>
<td>18</td>
</tr>
</tbody>
</table>
LIST OF TABLES

Table 3.1: Input parameters used to slice the CAD files. ............................................................. 12

Table 3.2: Motor control parameters kept fixed for all samples included in this work. ............. 12

Table 3.3: Individual power densities converted to J/cm³ resulting from varying travel speeds and laser powers. ................................................................................................................................. 13

Table 5.1: Five Ti-Mo samples retained from the original matrix of 18. Area fraction and number of particles were obtained using ImageJ software. The sample number is the laser power in watts followed by the travel speed in inches per minute................................................................. 37
LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.1</td>
<td>Schematic of LENS™ system.</td>
<td>9</td>
</tr>
<tr>
<td>3.2</td>
<td>Change in spot size resulting from under-building and over-building. [11]</td>
<td>10</td>
</tr>
<tr>
<td>3.3</td>
<td>Ti-12wt%Mo just after deposition. A) Samples produced at 40ipm; B) samples produced at 30ipm; C) samples produced at 20ipm. The highest laser power of 620W is on the right side of each section and reduces as moving left to the lowest laser power of 340W.</td>
<td>14</td>
</tr>
<tr>
<td>4.1</td>
<td>Titanium-vanadium phase diagram.</td>
<td>19</td>
</tr>
<tr>
<td>4.2</td>
<td>a) Distorted illustration of the build geometry highlighting regions studied; b) SEM images of the five regions studied.</td>
<td>21</td>
</tr>
<tr>
<td>4.3</td>
<td>a) Inverse pole figure (IPF) maps of five regions of the T-20V build with region 1 at the base and region 5 at the top; b) Texture maps of the corresponding five regions.</td>
<td>22</td>
</tr>
<tr>
<td>4.4</td>
<td>a) Distorted illustration of the build geometry highlighting five regions investigated; b) low and high magnification SEM images of said five regions.</td>
<td>24</td>
</tr>
<tr>
<td>4.5</td>
<td>a) IPF of the five regions in the Ti-Mo system; b) texture maps of said five regions.</td>
<td>25</td>
</tr>
<tr>
<td>4.6</td>
<td>Post processed backscattered SEM images of five regions in the Ti-Mo build. The alpha particles have been assigned random colors for visual purposes.</td>
<td>26</td>
</tr>
<tr>
<td>4.7</td>
<td>MIPARTM data of the five regions studied. a) Number of laths per square micron; b) area fraction; and c) equivalent diameter.</td>
<td>27</td>
</tr>
<tr>
<td>4.8</td>
<td>Titanium and molybdenum phase diagram. The composition used in this section and the temperature of the phase boundaries are highlighted in red.</td>
<td>28</td>
</tr>
<tr>
<td>4.9</td>
<td>EBSD IPF maps of a) Ti-20wt%V and b) Ti-12wt%Mo.</td>
<td>28</td>
</tr>
<tr>
<td>4.10</td>
<td>Mosaic EBSD IPF maps of the Ti-20wt%V system. a) Three images stitched together illustrating a region perpendicular to the build direction and b) three images stitched together representing a region parallel to the build direction.</td>
<td>29</td>
</tr>
<tr>
<td>4.11</td>
<td>Ti-20wt%V data of two positions perpendicular to the build direction indicating strong texturing.</td>
<td>30</td>
</tr>
<tr>
<td>5.1</td>
<td>Examples of defects in Ti-Mo matrix LENS™ builds. a) Large cavity within the sample. b) Un-melted molybdenum particles and non-homogeneous matrix.</td>
<td>32</td>
</tr>
<tr>
<td>5.2</td>
<td>SEM images at 250x magnification of sample 460-40 from bottom to top used for ImageJ analysis. The area fraction of molybdenum particles is 3.23 percent.</td>
<td>33</td>
</tr>
</tbody>
</table>
Figure 5.3: SEM images at 250x magnification of sample 620-20 from bottom to top used for ImageJ analysis. The area fraction of molybdenum particles is 0.17 percent. .............................. 33

Figure 5.4: Image taken from sample 460-40 approximately 1.5mm from the base of the build at 250x magnification. The 254 μm (0.01 inch) scale bar spans one deposition layer.................. 34

Figure 5.5: Image taken from sample 620-20 approximately 3mm from the base of the build at 250x magnification. The 254 μm (0.01 inch) scale bar spans one deposition layer............. 35

Figure 5.6: Ti-Mo matrix plot used to identify samples that would be further studied. The red line represents the cut off point for area percentage of particles at 0.5 percent. ....................... 36

Figure 5.7: The base of sample 520-20 at 250x magnification. a) Original images and b) processed to highlight grain boundaries. ...................................................................................... 38

Figure 5.8: The top of sample 520-20 at 250x magnification. a) Original images and b) processed to highlight grain boundaries. ....................................................................................................... 39

Figure 5.9: SEM micrographs taken at 1000x magnification of sample 580-30. The images are not continuous but taken within each 250x image that make up the mosaic. Image 1 of 11 represents the base of the sample and is located in the bottom left. Image 11 of 11 represents the top of the build and is located in the top right. ............................................................................. 40

Figure 5.10: Side by side comparison of three points in samples 580-30 and 620-20. SEM images were taken at 1000x magnification................................................................. 41

Figure 5.11: Left is sample 580-30, right is sample 620-20, and center overlay is sample 620-30. Each sample includes a 1000x magnification micrograph taken at the base, center, and top of the build. ............................................................................................................................................ 43

Figure 6.1: Backscattered SEM images of a) Ti-20V, b) Ti-12Mo, c) Ti-20V-0.5B, and d) Ti-12-0.5B with higher magnification images inset into b, c, and d............................... 46

Figure 6.2: EBSD IPF maps of a) Ti-20V, b) Ti-12Mo, c) Ti20V-0.5B, and d) Ti12-Mo-0.5B all in wt%. ......................................................................................................................... 47

Figure 6.3: Texture maps highlighting the difference in the two systems with and without boron. a) Ti-20V, b) Ti-20V-0.5B, c) Ti-12Mo, and d) Ti-12Mo-0.5B. ............................................................... 49

Figure 6.4: Ti-Mo and Ti-Mo-B systems.............................................................................................................. 50
CHAPTER 1
INTRODUCTION

Additive manufacturing (AM) is sometimes referred to as 3-D printing, free form fabrication, rapid prototyping, and a few others, that fall under the category of solid free form fabrication (SFF). The multitude of names is representative of growing interest in the SFF field. Prototypes can be developed using basic CAD software and produced relatively quickly into a near net shape requiring minimal machining to achieve a finished product. In the case of AM, it is the ability to precisely control and change microstructure throughout the part that is the primary focus of ongoing research and the method discussed in this body of work.

The SFF process known as laser engineered net-shaping (LENS™) was developed at the Sandia National Laboratories and made commercially available by the Optomec Corporation in New Mexico. [1] The LENS process uses a focused laser to melt metallic powder to create the 3-D shape required. These components may have complex geometries including interior sealed cavities and require little to no machining after the build process. The metallic powder feedstock is introduced via an argon flow power feed system.

1.1 Advantages of Additive Manufacturing

Traditional manufacturing of precision components can be considered to primarily be a material removal process e.g. gears are machined from a rod of feed stock. The AM process in many cases begins with a designer creating the component as a CAD file which is then converted to a stereolithography (STL) file which is used to produce the component in a layer by layer deposition. Multiple components with design tolerances as high as 0.002” to 0.015” can be made in a single run. [2] Expensive components that have been scratched or cracked can be repaired
using a powder feed system by directly implanting the elemental powders into the part at the melt pool. This method is used by the U.S. military which deploys mobile LENS™ stations to repair components such as turbine blades in overseas operations which greatly reduces the amount of equipment and spare parts needed to support an operation. The use of elemental and/or pre-alloyed powders allows for very precise composition control in AM components and when using a powder feed system with multiple feed hoppers the composition can be changed throughout the part.

1.2 Disadvantages of Additive Manufacturing

While AM allows for precise composition control its very nature allows for little to no control of the morphology of the microstructure. The process begins by melting the metallic powder which solidifies at a rate of 200 to 6000 Ks⁻¹ with the heat being transferred from the build in multiple directions directly into the build. [3] The flow of heat becomes increasingly aligns with the build direction as the component grows in height.

1.3 Microstructure

Additive manufacturing, as stated before produces a microstructure that is heavily affected by heat flow. The AM method used in this body of work is Laser Engineered Net Shaping (LENS™), which is a powder feed laser welding method. The development of texture during the deposition process in various AM processes and the effects it has on the materials properties is one of the other biggest challenges in terms of achieving the desired properties required of a specific component. [4] [5] In titanium alloys, when building a component in an AM process the laser or electron beam interacts with the previously deposited layer and the incoming powder which then transform into the beta phase field. [6] Upon solidification the beta grains grow epitaxially parallel
to the path of heat conduction. [6] The initial formation of the beta grains is dictated by the grains in the substrate. When the substrate is comprised of randomly oriented grains the components grains are selected by competitive grain growth in one of the six <100> preferred cubic growth directions. [7] The purpose of this work is to explore the question “Can the manipulation of process parameters and/or small compositional changes provide greater control over the development of a systems’ microstructure?”
CHAPTER 2
LITERATURE REVIEW

2.1 Additive Manufacturing

American Society for Testing and Materials International (ASTM) defines AM (ASTM F2792) as “a process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies. Synonyms: additive fabrication, additive processes, additive techniques, additive layer manufacturing, layer manufacturing, and freeform fabrication.” While the LENS™ uses this process to create metal components, the definition also includes other material classes.

2.1.1 Energy Source

Additive manufacturing requires a focused tunable energy source to fuse the material feedstock once it has been introduced. The two main energy sources currently dominating the field of AM are electron and laser beams. [8] [2]

2.1.1.1 Electron Beam

Karl-Hienz Steigerwald designed and built the first electron beam welding machine in 1958. [9] The process works by focusing a high-velocity of electron beam into the area to be welded and upon impact the kinetic energy is transformed into thermal energy. The electron beam is highly susceptible to atmospheric interference and is normally operated under vacuum conditions. The materials used for the cathode tip are normally tungsten or titanium because there are so few materials that can meet the requirements. The cathode tip must not be sensitive to any remaining atmosphere in the deposition chamber. To achieve high power densities the cathode is
operated at high temperatures to increase the number of electrons with sufficient kinetic energy to overcome the potential barrier and move into the conduction zone and escape the lattice. While operating at elevated temperatures and under vacuum conditions the cathode material must have a low enough vapor pressure to ensure an acceptable tool life. Operating under vacuum limits the delivery options of feedstock material and many electron beam systems use pre-alloyed wire feed stock for this reason. [9]

2.1.1.2 Laser Beams

Laser beams are a more common choice for AM processes because they do not require a vacuum to operate. The laser is transmitted from the source to the weld head via fiber, reflective lenses, or a combination of the two. Once the laser beam reaches the enclosure it is then directed downward to the weld head and through a final focusing lens. The final focus is done at the weld head to keep the focal point fixed in relation to the component being built as its height increases. The laser source and cooling system can be split to operate multiple deposition chambers, which also allows them to be located away from the manufacturing floor in a secure location.

2.1.2 Feedstock Material

Additive manufacturing feedstock delivery systems are generally divided into the following three categories: Powder feed systems, powder bed systems, and wire feed systems. Each of these systems as you might expect has its advantages and disadvantages.

2.1.2.1 Wire Feed Systems

This delivery option requires a spool of pre-alloyed wire be fed into the deposition chamber
to interact with the energy source. The need for pre-alloyed wire can limit the number of systems produced via wire feed in terms of cost as small batches of uncommon alloys are for more expensive than regular bulk purchases. The wire feed delivery system when coupled with the electron beam energy source has the fastest deposition rate of the three options discussed here. The wire feed system has the largest hatch spacing of the three delivery options discussed in this work which consequently increases the post processing machine time relative to the two powder systems. [10]

2.1.2.2 Powder Bed Systems

Powder bed systems allow relatively more compositional freedom when compared to the wire feed delivery method. The powder bed can be filled with a blend of elemental and/or pre-alloyed powders producing a component with very precise compositional control. The powder blend is raked into position and the electron beam or laser source is focused on the surface of the bed while a single layer of the design is executed by the motor control system. The source is shut down or blocked by a shutter. The stage then moves away from the source a distance of one build layer and the process begins again with fresh powder being raked into position.

2.1.2.3 Powder Feed Systems

The powder feed delivery option is the method used in the body of this work. The powder feed system also allows the designer the freedom to choose a mixture of elemental and/or pre-alloyed powders to achieve a relatively high level of compositional control. The powder feed system begins with the powder hopper or hoppers. Additive manufacturing systems may be equipped with two or more powder hoppers; the system used here has four. The powdered material
feedstock is lifted by an auger into a stream of inert gas, commonly argon, and subsequently delivered to the weld head. The powder feed system provides a unique capability when compared to the other delivery systems discussed here. The composition of a part can be changed at any time during the deposition process allowing the designer to produce a component with various material properties at specific points. This is accomplished through the use of multiple powder hoppers. In many compositionally graded components produced with a two powder hopper system the composition is changed by varying the flow rate of the hoppers which contain different blends of feedstock. Every additional powder hopper added to the system essentially increases the degrees of freedom by one.

2.2 Titanium Metallurgy

Titanium readily forms substitutional solid solutions with transition metals. Titanium exists as a hexagonal close packed (HCP) crystal structure at low temperatures referred to as $\alpha$-Ti and as a body centered cubic (BCC) crystal structure at high temperatures referred to as $\beta$-Ti. Pure titanium transforms from alpha to beta at 882°C.

2.2.1 Effects of Alloying Elements

The physical and mechanical properties of titanium can be greatly influenced with the introduction of certain alloying elements. The beta transus line can effectively be moved to favor the stabilization of the alpha or beta phase through the addition of alloying elements. Alpha stabilizing elements such as oxygen which takes up an interstitial position in the lattice can have negative effects on the material properties. In the case of oxygen interstitials the effect is the embrittlement of the titanium matrix. Alloying elements such as vanadium and molybdenum,
which are discussed in this work act as beta stabilizers. Zirconium is an example of an alloying element that does little to affect the transformation temperature but does increase the strength of the alpha phase considerably when added in significant amounts.

2.3 Laser Engineered Net Shaping (LENS™)

The LENS™ process is a result of a joint effort by Sandia National Laboratories and United Technologies who originally paired an Nd:YAG laser with a powder delivery system. [2] This process was made commercially available by Optomec® in Albuquerque New Mexico in 1998. The LENS™ system provided to the University of North Texas which was used to complete this work can be categorized as three main components. These components are all free standing units and include a Nd:YAG laser produced by the US Laser corporation, a gas handling system provided by Radar Technology Incorporated, and a glove box manufactured by Optomec®. These three components were paired to deliver feed stock in an inert atmosphere to a weld head and stage operating under precise DMC file control.
CHAPTER 3
EXPERIMENTAL PROCEDURE

3.1 Introduction

This chapter outlines the equipment used to create, prepare, and characterize the material systems studied in this work.

3.2 Laser Engineered Net Shaping (LENS™)

The LENS™ 750 system by Optomec® was used to create every material discussed in this paper. This is a powder feed system originally equipped with two powder feeders, a 500W Nd:YAG laser manufactured by the US Laser Corporation, and an Argon control system from RTI Products. The 500W Nd-YAG laser has been replaced with a 1500W Ytterbium Laser which produces a near-infrared laser radiation of 1.064 μm and was used for all alloys in this work. The powder feeder panel has been upgraded to include four hoppers. The basic components of the LENS™ can be seen in Figure 3.1.

![Figure 3.1: Schematic of LENS™ system.](image-url)
The powder feed LENS™ process begins with a CAD file which is transferred to the Optomec® system which is then sliced into layers of the desired height. The CAD file is then converted into a stereo-lithography file and parameters such as hatch spacing and layer rotation is set at this time. The file is then converted to a motor control file and the travel speed is set at this point. Once the DMC file is loaded into the work station, the laser power set, and the powder feeders set the process can begin. Elemental powders can have varying geometries as a result of how they are produced. Titanium powder of this size (-150 mesh) is consistently close to spherical while refractory metals such as molybdenum tend to be more irregular in shape. The variation in size and shape between elemental powders has a direct effect on the powder’s ability to flow from the powder feeders to the tool head. For this reason considerable time is spent when working with a new system to insure the feed rate and travel speed are in agreement and the proper working distance is maintained. The laser is focused at 0.305 mm above the deposition plane. [11] When the surface of the build moves out of this position the part is said to be under-building or over-building which is illustrated in Figure 3.2.

Figure 3.2: Change in spot size resulting from under-building and over-building. [11]
The primary reason a build surface moves out of the alignment plain is the powder flow rate is not properly set for the travel speed. Under-building occurs when not enough powder is provided to the tool head and as the distance increases the size of the melt pool decreases as seen in Figure 3.2. The smaller melt pool then captures less powder increasing the rate at which the part moves away from the alignment plain resulting in a runaway process and ultimate failure of the build. As one might imagine, providing an excessive amount of powder to the tool head will result in the opposite process. The melt pool will steadily increase in size capturing more powder until the build fails or the part contacts the tool head damaging the equipment and possibly redirecting the laser outward. Once the powder feed rate for the elemental blend and travel speed is determined the build can begin.

The deposition process takes place in an argon filled glove box maintained at a positive pressure. The oxygen level is continuously monitored and kept below 8ppm. The deposition stage is equipped with a half inch copper plate attached to a network of copper tubing that can circulate chilled water (~25°C) which was active for all builds in this work.

3.2.1 Deposition Parameters

The sample depositions included in this work were all 0.5” x 0.5” cylinders designed using AutoCAD 2016 and exported as a STL file. Optomec® uses the standard system of measurements in their PartPrep® and motor control software and for the purpose of this work standard units are only used when describing the build dimensions. The STL file was then converted to a slice file (SLI) using the PartPrep® software provided by Optomec®. The fixed parameters are given in Table 3.1.
The SLI file is then converted into a motor control file (DMC) using the LENS™ workstation control program and the constant parameters are listed in Table 3.2.

Table 3.1: Input parameters used to slice the CAD files.

<table>
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<td>Hatch 1</td>
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<tr>
<td>Line or Beam Width</td>
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<td>Hatch 2</td>
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<tr>
<td>Slicing Algorithm</td>
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<td>Keep Outside Contours</td>
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<td>Start Location</td>
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Table 3.2: Motor control parameters kept fixed for all samples included in this work.

<table>
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<td>Laser OFF Feedrate (in/min)</td>
<td>50</td>
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<tr>
<td>Deceleration (counts/min/min)</td>
<td>60000</td>
<td>Shutter OFF Delay (ms)</td>
<td>20</td>
</tr>
</tbody>
</table>

3.2.1.1 Ti-12wt% Mo

Spherical titanium powder of 99.9% purity and -150 mesh was obtained from Alfa Aesar. Molybdenum powder of 99.8% purity and -100+325 mesh was obtained from Atlantic Equipment Engineers. These powders were mixed at 88wt% titanium and 12wt% molybdenum and loaded into a single powder feeder. The deposition was made on a Ti-6Al-4V substrate with the cooling water circulating. The SLI and DMC files were created using the fixed parameters given in Tables 3.1 and 3.2 respectively. The DMC file was created with a travel speed of 40ipm and the laser power set to 600W resulting in a power density of 36.6 MJ/m³. Power density calculations will be discussed later in this chapter.
3.2.1.2 Ti-20wt% V

Ti-20wt% V was deposited using 99.8% pure vanadium powder of -100+325 mesh that was obtained from Atlantic Equipment Engineers and the previously mentioned titanium powder from Alfa Aesar. A cylinder 0.5 x 0.5 inches was deposited using the LENS™ system. The deposition was made on a Ti-6Al-4V substrate with the cooling water circulating. The SLI and DMC files were created using the fixed parameters given in Tables 3.1 and 3.2 respectively. The DMC file was created with a travel speed of 40ipm and the laser power set to 600W resulting in a power density of 36.6 MJ/m³.

3.2.1.3 Ti-12wt% Mo Matrix

The matrix detailed in Table 3.3 was devised to investigate the role if any that the LENS™ processing parameters play in the development of the microstructure.

Table 3.3: Individual power densities converted to J/cm³ resulting from varying travel speeds and laser powers.

<table>
<thead>
<tr>
<th>Travel Speed</th>
<th>Laser Power (Joules per second)</th>
</tr>
</thead>
<tbody>
<tr>
<td>cm/s</td>
<td>620</td>
</tr>
<tr>
<td>in/min</td>
<td></td>
</tr>
<tr>
<td>1.69</td>
<td>0.379</td>
</tr>
<tr>
<td>1.27</td>
<td>0.504</td>
</tr>
<tr>
<td>0.85</td>
<td>0.754</td>
</tr>
</tbody>
</table>

The matrix consists of six laser power settings versus three travel speeds given in watts and inches per minute (ipm), respectively. The values given in the table are the power densities for each sample deposited given in MJ/m³ which was calculated using Equation 3.1 and then converted to SI units.

$$\text{Equation 3.1} \quad \rho = \frac{\text{Laser Power (Watts)}}{1,000,000(\text{TS} \times \text{HS} \times \text{LT})} \quad [2]$$

\(\rho\) = Power Density  
TS = Travel Speed  
HS = Hatch spacing  
LT = Layer Thickness
The processing parameters held constant in the SLI and DMC conversions are again those outlined in Tables 3.1 and 3.2, respectively. It can be seen in Equation 3.1 that a given power density can be achieved with different laser power values if the travel speed is altered to balance the equation. Although this was not the purpose of producing this matrix the ten highlighted cells represent pairs of processing parameters that result in similar power densities. The before mentioned spherical titanium and molybdenum powders were mixed to create eighteen samples at 90wt% titanium and 12wt% molybdenum and loaded into a single powder feeder. The deposits were made in one continuous run onto a Ti-6Al-4V substrate, with the cooling system active, in two rows to expedite their removal from the substrate. The completed deposition can be seen in Figure 3.3.

Figure 3.3: Ti-12wt%Mo just after deposition. A) Samples produced at 40ipm; B) samples produced at 30ipm; C) samples produced at 20ipm. The highest laser power of 620W is on the right side of each section and reduces as moving left to the lowest laser power of 340W.
The two deposits in the black rectangle labeled “Bad” in Figure 3.3 were not excluded due to a LENS™ issue, but rather a communication issue. These two samples were removed and are not studied in this work.

The samples were split down the middle of the z-axis and separated from the substrate using a Bridgeport high speed saw. The cuts were made using an abrasive blade under a mist of synthetic coolant to minimize heat affects. Samples were then prepared for SEM characterization using standard procedures.

3.2.1.4 Ti-20V-0.5B and Ti-12Mo-0.5B (all in wt%)

Two additional samples were created with the addition of 0.5 wt% boron using the aforementioned titanium, molybdenum, and vanadium powders. The boron powder was obtained from Alfa Aesar at 99.9% purity and -150 mesh. The powders were mixed and each composition placed in an individual powder feeder. The two depositions were made again using the fixed parameters for the SLI and DMC conversion given in Tables 3.1 and 3.2, respectively. The additional processing parameters are once again a laser power of 600W and travel speed of 40ipm. The builds were made on a Ti-6Al-4V substrate with the water cooling system active.

3.3 Sample Preparation

3.3.1 Ti-12wt%Mo Sample Sectioning

A Bridgeport EZ Track 3-axis CNC mill was used to section and remove the Ti-12wt%Mo samples from the Ti-6Al-4V substrate. The machine was retrofitted with a silicon carbide cut-off blade from Allied High Tech Products Inc. This is a rubber bond, non-ferrous, abrasive blade of the dimensions 8” x 0.03” x 0.5”. The blade was mounted in the vertical position for the first two
cuts that split each sample down the z-axis at a rate of 3ipm with a spindle speed of 2750rpm. Special care was taken to adjust the depth of the cut to counteract the consumption of the blade. The blade was then repositioned in the horizontal position to remove the samples from the substrate at the same federate and spindle speed. Samples were collected and placed in labeled storage as they fell from the substrate. A synthetic based metalworking coolant was applied as a steady mist to mitigate any heat treatment they be caused by the cutting process.

3.3.2 Electron Discharge Machining (EDM)

The remaining compositions were processed with a Mitsubishi FX-10 wire-cut EDM system. This is a 5-axis EDM capable of producing three dimensional components to high degree of accuracy. The geometry of the component to be cut is written in general (G) and machine (M) CNC codes. The material to be cut and tool piece is submerged in deionized water which flushes away the removed material and acts a coolant for the process. Wire feed EDMs work by continuously passing wire from the upper to lower section of the tool piece while applying high voltage. In this work brass wire with a diameter of 0.25mm provided by Consumable Products Group was used in all EDM machining. The wire never actually touches the material but causes the material to erode when sparks jump from the wire to the material. The lack of cutting forces and heat treatment makes the EDM ideal for precision milling without adding residual stress to the material. This particular model has a variety materials stored in memory which allow the user to quickly set all the processing parameters, in this case the titanium alloy preset was used with a federate of 1.5mm per minute.
3.3.3 Surface Refinement

Allied High Tech silicon carbide polishing papers ranging from 400 to 1200 grit were used with water for the initial polishing of all material in this work. Felt pads also provided by Allied High Tech were used with colloidal silica of 1 micron refinement followed by colloidal silica of 0.04 micron refinement. The samples were then left overnight on a Buehler VibroMet™ 2 polisher loaded with 0.04 micron colloidal silica. Samples were cleaned using standard alloy procedures.

3.4 Characterization Equipment

3.4.1 Nova NanoSEM 230

3.4.1.1 Electron Optics

- High resolution field emission-SEM column
  - Monopole magnetic field immersion final lens
  - Through-the-lens differential pumping
  - High stability Schottky field emission gun
- Resolution at optimum WD (high vacuum)
  - 1.0 nm at 15kV (TLD-SE)
  - 1.6 nm at 1 kV (TLD-Se)
- Beam landing energy: 50V – 30kV
- Probe current: 0.6 pA – 100nA continuously adjustable

3.4.1.2 Detectors

- In-lens SE detector (TLD-SE)
- In-lens BSE detector (TLD-BSE)
• EDAX Apollo X Silicon Drift Detector (SDD), Genesis software
• TSL Digiview III Electron Backscatter Diffraction (EBSD) detector, OIM™ software

3.4.2 High Resolution X-ray Diffraction (XRD)

3.4.2.1 X-ray Generator
• Maximum rated output 3 kW
• Rated tube voltage 20 – 60 kV
• Rated tube current 2 – 60 mA
• Target: Cu
• Focus size 0.4 x 12 mm

3.4.2.2 Detectors
• Scintillation counter
• D/teX-25 fast position sensitive detector (up to 160° 2θ /minute)

3.4.3 ImageJ Software

ImageJ is a Java-based image processing program that was used to determine the area fraction of un-melted particles in the Ti-12wt%Mo matrix. Images of the eighteen samples were taken from top to bottom relative to the build direction at a magnification of 250x, HV 20.0 kV, and a spot size of 6.0. Every image was processed and analyzed using ImageJ to determine the area fraction of un-melted particles molybdenum as well as the number and size distribution. This data was processed using Microsoft Excel and will be discussed in chapter 5 of this work.
CHAPTER 4
Ti-20wt% V & Ti-12wt%Mo

4.1 Introduction Binary Titanium Alloys

Titanium alloys have become trusted structural materials due to the ability to manipulate the wide variety of microstructural features. These microstructural features include high specific strength and ductility, corrosion resistance, good fatigue performance, and excellent hardenability. For these reasons titanium alloys have found their way into the biomedical, automotive, and aerospace industries. [12] [13] [14] [15]

Figure 4.1: Titanium-vanadium phase diagram.

The titanium alloys discussed in this work are classified as $\beta$ systems with the $\alpha$-phase being stable at lower temperatures and the $\beta$-phase at higher temperatures. These alloys when
processed via AM experience rapid thermo-cycling causing the system to cross the \( \beta \)-transus line multiple times resulting in a \( \alpha \)-phase system following prior \( \beta \)-grains. The titanium-vanadium phase diagram seen in Figure 4.1 is an example of an \( \alpha \)-\( \beta \) system.

4.2 Microstructure Evolution of Ti-20wt%V

A cylinder of 0.5 x 0.5 inches composed of Ti-20wt%V was deposited via LENS\textsuperscript{TM} using the parameters outlined in Tables 3.1 and 3.2 with a laser power of 600W and a travel speed of 40ipm to investigate the microstructural evolution as a function of position in the build. The geometry of the sample has been distorted for the purposes of illustration in Figure 4.2a below. Five regions have been highlighted in Figure 4.2a, selected at regular intervals to be studied. Figure 4.2b contains SEM images of each region.

The overall microstructure does not substantially change across the five regions seen in Figure 4.2b. Columnar prior beta grains with relatively few equiaxed grains can be seen in region 1 at the bottom of the build but steadily transition to an equiaxed structure as the build progresses to region 5. It is expected that the structures would resemble a directionally solidified microstructure as a result of the LENS\textsuperscript{TM} process. As mentioned previously the rapid thermal-cycling caused by the laser’s raster pattern is melting previously deposited layers near the current position as well as heat treating those layers further down. This columnar nature of the grains may be acceptable or desired in some applications but would need to be broken up through post processing to be useful in many other applications.
Figure 4.2: a) Distorted illustration of the build geometry highlighting regions studied; b) SEM images of the five regions studied.

The inverse pole figure (IPF) maps shown in Figure 4.3a clearly show columnar grains at the bottom of the build, region 1 and equiaxed grains at the top, region 5. Regions 2 thru 4 show the transition from columnar to equiaxed grains. The five regions characterized in this alloy show
a strong (001)β texture as seen in Figure 4.3b. When considering the texture maps and the grain sizes of 2-3 mm and 400-600 microns for the columnar and equiaxed grains, respectively, it can be said that epitaxial growth along the (001)β takes place from the substrate to the top of the build. Simonelli et al [6] has shown that the transformation texture is affected by the grain size such that the transformation texture of large columnar grains tends to be greater than that of equiaxed smaller grains. It is also possible that the larger grains provide a more favorable heat flow path across the solid-liquid interface. [16]

Figure 4.3: a) Inverse pole figure (IPF) maps of five regions of the T-20V build with region 1 at the base and region 5 at the top; b) Texture maps of the corresponding five regions.
4.3 Microstructural Evolution of Ti-12wt%Mo

A cylinder of Ti-12wt%Mo was deposited with the same dimensions and processing parameters as the T-20wt%V from the previous section. Five regions at regular intervals from the base to the top of the build were again chosen for characterization. The build and the regions investigated can be seen in Figure 4.4a, and both low and high magnification SEM images of said regions can be seen in Figure 4.4b. Ti-12wt%Mo is less beta stabilized than the T-20wt%V system discussed in the previous section which can be seen in the SEM images that reveal alpha precipitates within the beta matrix. The changes in morphology from regions 1 to 5 will be discussed more in the following paragraph. In order to compare the grain growth of the two systems the IPF maps in Figure 4.5a have excluded the alpha phase. As in the T-20wt%V system columnar grains of sizes up to 2-3 mm appear in the Ti-12wt% Mo system but with distinction that no equiaxed grains were seen. The texture maps seen in Figure 4.5b also indicate a strong (001)\(\beta\) texture in all five regions. In both beta titanium system regardless of the alloying element the grain growth is primarily columnar and takes place epitaxially along (001)\(\beta\) direction parallel to the build direction.
Figure 4.4: a) Distorted illustration of the build geometry highlighting five regions investigated; b) low and high magnification SEM images of said five regions.
The changes seen in Regions 1 through 5 in terms of morphology, volume fraction, and density of the alpha phase were quantified using the image analysis software MIPAR™. The image analysis was done by taking six backscattered SEM images from random locations within each of the five regions and averaging the data. The processed images of the five regions can be seen in Figure 4.6 were the alpha precipitates were given random colors to help distinguish them as individual particles.
Figure 4.6: Post processed backscattered SEM images of five regions in the Ti-Mo build. The alpha particles have been assigned random colors for visual purposes.

These images are representative of all the 30 images taken and processed. From these images, MIPAR™ calculated the number density and area fraction of the particles as well as the equivalent diameter. In this case, the equivalent diameter is that of a circle that has the same volume as the oblong alpha precipitate. These average values can be seen in the three plots shown in Figure 4.7. It can be seen form these plots that as the distance from the base increases moving from region 1 to region 5 that the number density and area fraction of the alpha particles decreases and the size of the particles increases. A single build of constant composition measuring only a half inch saw a reduction in number density from 0.39 laths per square micron to 0.05 laths per square micron as well an area fraction from 54% to 16%. The equivalent diameter of the laths increased from approximately 1.2 to 1.8 microns as the build moved from the base to the top.
These morphological changes are likely due to a combination of the induced stress inherent to AM processes as well as the rapid thermal-cycling taking place. The equilibrium temperatures of the Ti-12wt% Mo system can be seen in the phase diagram given in Figure 4.8. The alpha phase is stable below approximately 695°C and the beta phase is stable from this point up to the liquidus line at approximately 1725°C. The layer by layer deposition inherent to AM processes causes previously deposited sections to cross the liquidus line and rapidly solidify. The number of previous layers to melt multiple times is dependent on the power density, build geometry, and the composition being deposited. Beyond the group of layer’s that are melting during the build will include an area of a finite number of layers that are thermal-cycling within the stable beta region portion of the phase diagram, in regards to the Ti-12wt% Mo system. If the build is large enough there will be a number of layers further away from the heat source that will cross the alpha-beta line multiple times and beyond that the build will continue to experience rapid heat treatments in the alpha-stable region.
Figure 4.8: Titanium and molybdenum phase diagram. The composition used in this section and the temperature of the phase boundaries are highlighted in red.

This gradation of thermal cycles along the build direction and the temperature range at which these cycles took place has a direct effect on the morphology.

4.3.1 Grain Size and Texturing

The grain size and texture were further investigated through EBSD scans. The IPF maps of the Ti-20V and Ti-12Mo can be seen below in Figure 4.9 a and b, respectively.

Figure 4.9: EBSD IPF maps of a) Ti-20wt%V and b) Ti-12wt%Mo.
The EBSD scans were carried out over the various regions of the entire sample and the size of the beta grains (>2mm) and the morphology virtually the same throughout. The size and morphology is better illustrated in Figure 4.10 a and b. Given the size of the beta grains (1-2 mm) in the two binary systems X-ray diffraction was performed on the Ti-V system to verify the texturing. The Ti-V system was chosen for this test because it appears to be a single phase system.

![Ti-20V EBSD Maps](image)

Figure 4.10: Mosaic EBSD IPF maps of the Ti-20wt%V system. a) Three images stitched together illustrating a region perpendicular to the build direction and b) three images stitched together representing a region parallel to the build direction.

The Ti-V system was sectioned perpendicular to the build direction near the bottom and top and then scanned with EBSD and X-ray using HL slit size of 10mm and a divergent slit size of 6mm. The EBSD IPF maps seen in Figure 4.11 a and b are of the top and bottom sections of the Ti-20V sample, respectively and indicate a grain size of approximately 500 microns. The XRD data shown
in Figure 4.11 e and f is in agreement with the EBSD texture maps as both regions have a single (200)β peak.

Figure 4.11: Ti-20wt%V data of two positions perpendicular to the build direction indicating strong texturing.
5.1 Introduction

Although additive manufacturing (AM) has been around for more than thirty years it is not yet been widely accepted by industry. While AM allows the designer very precise control of elemental composition and the ability to create near net shape parts they are limited in their control of the microstructure. The acceptance of AM depends in part on the ability to produce components with a consistent microstructure that can be tailored to fit specific needs. The microstructure developed during the AM process typically develops a texture in the direction of heat conduction. In the case of β titanium alloys the β grains grow epitaxially, typically along the build direction and when coupled with the repeated heat treatments α colonies form and retain the prior β grain boundaries.

5.2 Ti-12wt%Mo

In an attempt to identify how process parameters effect the microstructure of AM components eighteen samples of identical composition and geometry were created via LENS™ process. Of the four variables that equate to power density shown in Equation 3.1 only the laser power and travel speed were varied. The matrix given in Table 3.3 details the six laser powers and three travel speeds used and highlights five pairs of samples with approximately the same power density.

5.2.1 Sample Disqualification

The samples were initially characterized in SEM at relatively low magnification with the
intention of removing samples based on porosity, cracks, and nonhomogeneous microstructure e.g. un-melted particles, which of course are features not desired by industry. In total thirteen of the eighteen samples were disqualified and examples of these can be seen in Figure 5.1. None of the six samples produced with the lower three laser powers achieved a homogeneous microstructure, but it is worth noting that samples 460-20 and 400-20 had power densities of 48.8 and 56.1 J/m³, respectively which is in the range of the samples retained for further study. The three higher laser powers that produced homogenous structures only did so at 20 and 30ipm and showed a significant increase in particle area fraction in the 40ipm cases.

![Figure 5.1: Examples of defects in Ti-Mo matrix LENS™ builds. a) Large cavity within the sample. b) Un-melted molybdenum particles and non-homogeneous matrix.](image)

The eighteen samples were bisected parallel to the build direction and SEM images were taken at 250x magnification from top to bottom along the center of each sample. These images were processed using ImageJ software to obtain the area fraction of molybdenum particles as well as the average size to determine which processing parameters would be further investigated. Sample 460-40 seen in Figure 5.2 is an example of a system removed from the study and sample 620-20 as seen in Figure 5.3 was kept.
Figure 5.2: SEM images at 250x magnification of sample 460-40 from bottom to top used for ImageJ analysis. The area fraction of molybdenum particles is 3.23 percent.

Figure 5.3: SEM images at 250x magnification of sample 620-20 from bottom to top used for ImageJ analysis. The area fraction of molybdenum particles is 0.17 percent.

The molybdenum particles seen in sample 460-40 are a result of the lower power density (28MJ/m³) used during that build but it is also worth noting that the build layers appear to be poorly mixed. The second position from the base of sample 460-40 in Figure 5.2 is enlarged below in Figure 5.4.
Figure 5.4: Image taken from sample 460-40 approximately 1.5mm from the base of the build at 250x magnification. The 254 μm (0.01 inch) scale bar spans one deposition layer.

The wave like patterns seen in the SEM image are the individual deposition layers which were set to 0.01 inches (254 μm) when creating the SLI file. The nonhomogeneous merging of layers is indicative of a high travel speed. These layers can also be seen below in sample 620-40 Figure 5.5.
Figure 5.5: Image taken from sample 620-20 approximately 3mm from the base of the build at 250x magnification. The 254 μm (0.01 inch) scale bar spans one deposition layer.

The power densities used to build samples 460-40 and 620-40 were 28 and 38 MJ/m³, respectively and the travel speed used to build both at 40ipm. The area fraction of the molybdenum particles is 3.23 and 1.03 percent for samples 460-40 and 620-40, respectively but they both show nonhomogeneous merging of build layers. Further work is needed to determine if a travel speed of 40ipm at a higher power density can achieve a homogenous structure in this system. The data obtained from ImageJ was plotted as area percentage of particles versus power density to see if a trend was apparent as well as a quantitative means to consider a sample as a pass for further study as every sample contained some amount of un-melted molybdenum. This plot can be seen below in Figure 5.6.
The number of molybdenum particles that did not melt into the titanium matrix follows the trend of increasing as the power density decreases. It may be worth noting that 5 of the 6 depositions that contained the most amount of molybdenum particles occurred at 40ipm.

5.2.2 Microstructure of the Five Retained Samples

The five samples retained for further study are listed in Table 5.1 below. The laser power and travel speed are given in the sample number e.g. 620-20 was built with a power of 620W and a travel speed of 20ipm.
Table 5.1: Five Ti-Mo samples retained from the original matrix of 18. Area fraction and number of particles were obtained using ImageJ software. The sample number is the laser power in watts followed by the travel speed in inches per minute.

<table>
<thead>
<tr>
<th>Sample number</th>
<th>Power density J/m³</th>
<th>Number of particles</th>
<th>% Area Fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>520-20</td>
<td>63.46</td>
<td>9</td>
<td>0.13</td>
</tr>
<tr>
<td>580-20</td>
<td>70.79</td>
<td>20</td>
<td>0.15</td>
</tr>
<tr>
<td>580-30</td>
<td>47.19</td>
<td>23</td>
<td>0.36</td>
</tr>
<tr>
<td>620-20</td>
<td>75.61</td>
<td>11</td>
<td>0.17</td>
</tr>
<tr>
<td>620-30</td>
<td>50.45</td>
<td>12</td>
<td>0.19</td>
</tr>
</tbody>
</table>

5.2.2.1 Sample 520-20

The Ti-12wt%Mo produced in the matrix is not unlike the Ti-12wt%Mo discussed in chapter 4 in terms of grain morphology. EBSD scans will need to be performed in the future to confirm that the system is composed of primarily columnar prior beta grains. Figures 5.7 and 5.8 are the base and top, respectively of sample 520-20. The three images on the left are the original SEM micrographs taken to exclude samples based on molybdenum particles, cracks, and porosity while the images on the right have been digitally enhanced to make the individual grains easier to see.

Some of the columnar grains in sample 520-20 extend 4-5 mm and can be clearly seen to change direction with each deposition layer. The top of this sample as seen in Figures 5.7 and 5.8 appears to be free of equiaxed grains as the Ti-12wt% Mo discussed in chapter 4, again EBSD scans will need to be done to confirm this. The columns of SEM micrographs in Figures 5.7 and 5.8 are composed of three images each representing ten total images taken along the build direction. The four in the middle region are not shown here because they are consistent with the top and bottom sections.
Figure 5.7: The base of sample 520-20 at 250x magnification. a) Original images and b) processed to highlight grain boundaries.
Figure 5.8: The top of sample 520-20 at 250x magnification. a) Original images and b) processed to highlight grain boundaries.
5.2.2.2 Sample 580-30

Columnar prior beta grains can also be seen in the base of sample 580-30 under low magnification conditions but become less clear as you move up the build axis. EBSD work will need to be done in the future to determine the morphology as well as the growth direction. The prior beta grains are visible in the higher magnification micrographs but these images are not continuous so a comparison of grain size for sample 580-30 and the four other conditions is not possible at this time. The micrographs in Figure 5.9 were taken at 1000x magnification within the area captured by the low magnification mosaic and are presented relative to the position within the sample.

Figure 5.9: SEM micrographs taken at 1000x magnification of sample 580-30. The images are not continuous but taken within each 250x image that make up the mosaic. Image 1 of 11 represents the base of the sample and is located in the bottom left. Image 11 of 11 represents the top of the build and is located in the top right.
Figure 5.10: Side by side comparison of three points in samples 580-30 and 620-20. SEM images were taken at 1000x magnification.

The four columns in Figure 5.9 represent eleven regions of sample 580-20. The base of the sample is at the bottom of the leftmost column. The build axis moves up a column and continues at the bottom of the next one to the right. Fine scale alpha can be seen at the base of the sample and it steadily coarsens as the build height increases. One interesting difference in sample 580-30 is the alpha laths reach a maximum size in the build around 5mm from the base and from
this point the ratio of alpha to beta appears to decrease while the size of the laths remains relatively constant. The system appears to be purely beta within the last 2-2.5mm from the top. EBSD scans and higher magnification micrographs need to be taken to verify this.

5.2.2.3 Sample 620-20

Large columnar prior beta grains can also be seen in sample 620-20 and again EBSD scans will need to be done in the future to determine if the system contains equiaxed grains. The alpha laths seen in sample 620-20 follow the same pattern as sample 580-30 in terms of alpha coarsening as the build height increases. Interestingly though the alpha is much finer in every stage of the 620-20 build than the 580-30 build as seen in Figure 5.10. The two samples are similar in the fact that the alpha laths reaches a maximum size in each build just before the alpha to beta phase ratio starts decreasing.

5.2.2.4 Sample 620-30

Once again sample 620-30 appears to be primarily prior columnar beta grains with no visible equiaxed grains found but will need to be verified in future work. When comparing 620-30 with 580-30 and 620-20 we see the same trends as far as the coarsening of alpha laths as the build height increases up to a certain point and again the size of the alpha laths peaks before the ratio of alpha to beta begins to decrease. This does not appear to be the case for the 520-20 and 580-20 samples but higher magnification images as well as EBSD scans will need to be taken to confirm this. The power density used to create samples 580-30, 620-30, and 620-20 were 47, 50, and 75 MJ/m³, respectively. When looking at Figure 5.11 there appears to be a correlation between power density and alpha lath size.
Figure 5.11: Left is sample 580-30, right is sample 620-20, and center overlay is sample 620-30. Each sample includes a 1000x magnification micrograph taken at the base, center, and top of the build.

The three micrographs seen in red laid over the images used in the previous figure are taken at the base, middle, and top of sample 620-30 for comparison of the alpha laths in the three different build conditions. It can be seen that in each region of the three different builds the lath size appears to decrease as the power density increases.
CHAPTER 6
THE ADDITION OF BORON IN $\beta$-Ti ALLOYS

6.1 Introduction

The development of texture during the deposition process in various AM processes and the effects it has on the materials properties is one of the biggest challenges in terms of achieving the desired properties required of a specific component. [4] [5] When building a component in an AM process the laser or electron beam interacts with the previously deposited layer and the incoming powder which then transform into the beta phase field. [6] Upon solidification the beta grains solidify and grow epitaxially parallel to the path of heat conduction. [6] The initial formation of the beta grains is dictated by the grains in the substrate. When the substrate is comprised of randomly oriented grains the components grains are selected by competitive grain growth in one of the six $<100>$ preferred cubic growth directions. [7] It has been shown that very small additions of boron into $\alpha/\beta$ titanium alloys can reduce grain size by an order of magnitude in the as-cast condition. [17] [18] Boron is almost insoluble in titanium unlike oxygen and therefor does not embrittle the lattice. [19]

6.2 Materials and Procedures

Two samples composed of Ti-20V-0.5wt%B and Ti-12Mo-0.5wt%B were made via LENS$^\text{TM}$ process using the same parameters found in Tables 3.1 and 3.2. The laser power and travel speed of 600W and 40ipm used in the Ti-20V and Ti-12Mo discussed in chapter 4 were also used to create the samples covered in this chapter. The systems discussed in this chapter were also 0.5 x 0.5 inch cylinders deposited onto a Ti-64 substrate with the cooling system active.
Once the depositions were complete the samples were split down the middle parallel to the build direction and prepared for characterization using standard polishing procedures before being finished in the Buehler Vibromet2 with 0.05-micron colloidal silica. SEM, EDS, and EBSD characterization was carried out using the FEI Nova NanoSEM.

6.3 Results and Discussion

Backscattered SEM images of the T-20wt%V and the Ti-12wt% Mo systems discussed in chapter 4 as well as the T-20wt%V -B and Ti-12Mo -0.5Bwt% systems introduced here can be seen in Figure 6.1(a-d). The prior beta grains and the alpha precipitates can be clearly seen in the Ti-12wt% Mo system while only the beta is observed in the T-20wt%V system. When comparing the Ti-12wt% Mo and Ti-12Mo-0.5Bwt% systems you can see that the addition of boron has clearly altered the microstructure. The alpha found in the T-Mo system is primarily lath-like with an observed length of approximately 5-10 microns. The addition of boron produced a microstructure of equiaxed alpha. Fine scale alpha laths of 1-2 microns in size can also be seen in the Ti-12Mo-B system in the upper inset of Figure 6.1 d. Within the lower inset of Figure 6.1 d titanium borides (TiB) can be seen and were found throughout the beta matrix close to alpha precipitates. It has been shown by Nandwana et al that (TiB) precipitates serve as nucleation sites for equiaxed alpha. [16]

The TiB precipitates have a dramatic effect on the T-20wt%V system as well. With the addition of boron it appears that alpha precipitates along the grain boundary with some equiaxed alpha forming within the grains.
Figure 6.1: Backscattered SEM images of a) Ti-20V, b) Ti-12Mo, c) Ti-20V-0.5B, and d) Ti-12-0.5B with higher magnification images inset into b, c, and d.
The effect boron has made on the microstructure can be clearly seen in the IPF maps of the Ti-20V-0.5B and Ti12M0-0.5B systems seen in Figure 6.2 c and d, respectively. It should be noted that only the beta grains were scanned so that the comparison of beta morphology of the with- and without-boron systems can be easily compared. EBSD IPF maps show the grain size with the addition of boron to be reduced when compared to the boron free system by almost 50
times. The EBSD IPF maps show a reduction in grain size in the Ti-12wt%Mo system by nearly 100 times with the addition of 0.5wt% boron. The grain size was approximately 1-2mm in both the Ti-20V and the Ti-12Mo systems and has been reduced to 35-40 microns and 10-20 microns, respectively with the addition of boron. The addition of 0.5wt% boron to Ti64 and Ti-6242S has been reported to reduce the grain size by an order of magnitude. [17] [18]. Mahbooba et al [20] also reported in 2016 the effect of boron on the beta grain size of Ti-64 but noted that the system remained columnar, which is not the case in these systems.

To evaluate the effect if any the addition of boron may have had on the texturing normally developed during the AM processes [6] texture maps excluding alpha of the boron inclusive systems were taken for comparison with the two binary (boron exclusive) systems as seen below in Figure 6.3. As discussed in chapter 4 the T-20wt%V and Ti-12wt% Mo have a maximum texture intensity of approximately 36 and 35, respectively and show a strong (001)β columnar grain texture [5] [6] parallel to the build direction. Figure 6.3 b and d represent the texture maps of the two systems with the addition of boron. Both systems lose the strong (001)β texturing and have developed a random texture which is supported by a huge drop in intensity in both cases.
Figure 6.3: Texture maps highlighting the difference in the two systems with and without boron. a) Ti-20V, b) Ti-20V-0.5B, c) Ti-12Mo, and d) Ti-12Mo-0.5B.

To investigate what effect if any the addition of boron has on the morphology of the alpha precipitates comparison is made of the EBSD IPF maps and discrete plots of the Ti-12Mo system with and without boron as seen in Figure 6.4. Figure 6.4 a and b clearly illustrates the change in alpha precipitates with the addition of boron in terms of size, shape, and volume fraction.
The grain refinement observed in these microstructures due to the addition of boron is not yet clearly understood. While Zhu et al [21] attributed the microstructural refinement to titanium-boride particles within the molten pool; for the present condition (hypo-eutectic composition) it is clear, from the phase diagram, that this is not the case and that the $\beta$ grains form first. [22] Cheng [23] postulated that the refinement was caused due to a constitutionally supercooled zone ahead of the solidification front. As boron is insoluble in the $\beta$ phase, it is continuously rejected during the formation of these $\beta$ grains. This supercooling phenomenon along with the formation of borides
and, the nucleation ahead of the front lead to the refinement. Adding to this, Tamirisakandala et al [22], in their paper invoked the effect of the growth restriction factor (Q), which was originally proposed by Maxwell et al. [24]. The growth restriction factor talks about the influence of solute elements on the grain refinement and characterizes the degree of growth restriction. For a multicomponent system, it has been shown that overall Q is summation of the Q values for the individual solutes. Thus Q is given by Equation 2.

\[
Q = m(k - 1)Co
\]

Where m is the slope of the liquidus, k is the partition coefficient (CS/CL), and Co is the solute content. The growth restriction factor was calculated for the Ti-Mo system in order to see the effect of boron addition. The binary Ti-12 wt. % Mo has a Q value of 29. With the addition of 0.5wt. % B, the Q value goes up to 67. Similar trends were observed in the case of the Ti-V system, wherein the addition of B leads to an increase in the growth restriction factor, Q, subsequently leading to a refinement of the grains. The coupling of the growth restriction factor (Q) together with the effect of the constitutional supercooling caused by the boron rejection is likely to be the underlying reason behind grain refinement in these laser additively processed alloys.

6.4 Conclusions

To summarize, an additive manufacturing technique, LENS™, was used to deposit samples with different compositions: with and without addition of boron. A dramatic change was observed in the microstructures after the addition of only 0.5wt% boron. SEM+EBSD analysis shows that while the grain size comes down by 100 times in the Ti-Mo system, it goes down by almost 40 times in the Ti-V system. The change in \(\alpha\) morphology in the Ti-Mo system due to the addition of boron is also noted, wherein, it goes from being lath-like to more equiaxed in nature.
CHAPTER 7

CONCLUSIONS

This work demonstrates that additive manufacturing of binary titanium alloys, in this case the LENS™ process, produces a component with a microstructure highly influenced by the directionality of heat flow. The addition of beta stabilizing elements has been shown to affect the microstructure at different points in the build. While the Ti-12wt%Mo system microstructure was columnar prior beta grains throughout the deposit the Ti-20wt%V system microstructure at the base of the build was made up of primarily columnar prior beta grains but did contain some equiaxed grains. The vanadium system progressed to a completely equiaxed microstructure as the build height increased.

The microstructure that develops in a binary titanium alloy produced via the LENS™ process cannot simply be predicted by the value of the power density used for the deposition. The individual variables play a role in achieving a homogeneous microstructure. The five samples deemed closest to a homogeneous microstructure that may be acceptable for industrial purposes were among the seven greatest power densities used in the deposition of the eighteen samples. The two high power density samples that were rejected were built at the lowest travel speed suggesting that Ti-12wt%Mo systems cannot be built with a laser power at or below 400 W. Every laser power used failed to produce an homogeneous structure with the highest travel speed of 40ipm. These statements are considering the other process parameters fixed. The effect the fixed parameters play will need to be studied in the future. There is a small but noticeable difference in the microstructural features that requires further investigation. There appears to be a correlation between the power density and alpha lath size throughout the build.
The addition of 0.5wt% boron has been shown to have a dramatic effect on the microstructure of both the molybdenum and vanadium containing systems. A drastic reduction in grain size was seen in both systems, 100 times in the Ti-Mo and 50 times in the Ti-V. The addition of boron to the Ti-Mo system has also been shown to change the nature of the alpha particles from a lath like to a more equiaxed structure. Three-dimensional APT analysis further confirmed the presence of borides via composition analysis. The boride phase retains a small amount of Mo. The change in the grain size has been attributed to a combined effect of constitutional supercooling, caused by boron rejection from the growing β grains, and the growth restriction factor (Q) of the grains caused by the solute elements.
CHAPTER 8
FUTURE WORK NEEDED

8.1 Processing Parameters

The samples produced using the power density matrix discussed in chapter 5 should have
Higher magnification SEM micrographs taken to quantify the size and morphology of the alpha
to investigate any correlation there may be with the power density used. EBSD scans should
also be made to investigate the texture. Another Ti-Mo matrix should be competed with the
three higher laser powers and two lower travel speeds while altering the layer thickness and the
hatch spacing. I would also like to build a few samples with different raster patterns to
investigate how the directionality of the heat flow from the moving melt pull interacts with the
heat flow down the build axis.

8.2 Build Height

Future work needs to be done to examine what role the size of the component may have
on transition point in the Ti-Mo systems from columnar to equiaxed prior beta grains. The
influence of the microstructure found in the substrate used on the development of the grains
needs to be investigated. Can a substrate be designed to act as a seed for the desired
microstructure?
WORKS CITED


