Microstructure and Mechanical Properties of Ti-6Al-4V Parts Fabricated by Laser Engineered Net Shaping Fatigue and Cyclic Deformation of Superelastic and Shape Memory Alloys View project Fatigue of Polymeric materials View project

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MICROSTRUCTURE AND MECHANICAL PROPERTIES OF Ti-6Al-4V PARTS
FABRICATED BY LASER ENGINEERED NET SHAPING

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ABSTRACT

Laser Engineered Net Shaping (LENS®) is a Direct Laser Deposition (DLD) additive manufacturing technology that can be used for directly building complex 3D components from metal powders in a combined deposition/laser-melting process. In this study, the effect of LENS process parameters, such as laser power, powder feed rate and traverse speed, on the resultant microstructure, hardness and tensile strength of Ti-6Al-4V components is experimentally investigated. Optical Microscopy (OM) and Scanning Electron Microscopy (SEM) are used to characterize the microstructure in terms of grain size and morphology. Relationships between process parameters and the microstructural/mechanical properties are provided. Results indicate that the scale of columnar grains increases with slower laser traverse speeds while other process parameters are maintained constant. The size of the α and β laths increases with higher laser powers and slower traverse speeds. The ultimate tensile and yield strengths of the LENS specimens were found to be higher than those of cast and wrought materials, and this can be generally attributed to the different cooling rates inherent to LENS – which impacts grain size. The percent elongation to failure, however, was consistently lower than that of the wrought material.

INTRODUCTION

Titanium alloys have been widely investigated and utilized in a variety of applications, such as aircraft engines, structural components, and bio-applications (e.g. implants). This is a result of their corrosion resistance, low density, high strength at elevated temperatures, and good formability. The primary alloying elements in Ti-6Al-4V are aluminum (Al) and vanadium (V) with trace amounts of oxygen (O) and nitrogen (N). Ti-6Al-4V is a commonly-used titanium alloy with a microstructure that is strongly sensitive to manufacturing process parameters and thermal history. The alloy consists of primary and secondary Hexagonal Close Packed (HCP) α grains along with scattered, stabilized Body Centered Cubic (BCC) β phases. The mechanisms and kinetics differ between these two phases, thus impacting the mechanical behavior of this alloy. Therefore, microstructural identification is essential to better understand and predict the mechanical behavior of many titanium alloys [1].

Laser Engineered Net Shaping (LENS), a commercialized form of Direct Laser Deposition (DLD), is an additive manufacturing technology first developed by Sandia National Laboratories in the late 1990s [2]. The technology allows for the ability to produce and clad complex metallic geometries difficult to manufacture through conventional metal forming techniques. As shown in Fig. 1, during DLD, metal parts are manufactured layer-by-layer from a Computer Aided Design (CAD) solid model by injecting metal powder into a molten pool created by a laser beam. In order to fabricate the desired geometry, a substrate (or build plate) is scanned upon via the laser beam, during which, powder deposition simultaneously occurs. This process is repeated and consecutive layers are sequentially built in the height-wise direction. Due to its cost-saving potential and ability to produce fine microstructures, the DLD process has become a unique means for rapid prototyping/manufacturing and product repair. The DLD process is also appealing for its potential to create functionally-graded compositions [3, 4].

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Many studies have aimed to characterize the mechanical properties of various kinds of titanium alloys manufactured by DLD [5-9]. Such properties include, for example: yield strength, ultimate strength, and hardness, and have been shown to strongly depend on microstructure characteristics such as area fraction, size, distribution, and the morphology of primary and secondary α phases, which are sensitive to the part thermal history. In many cases, any novelty in mechanical properties has been attributed to the fine microstructures produced by the high cooling rates inherent to the DLD process. The influence of laser power and number of passes on the microstructure and hardness has also been evaluated [6]. The results show that the equiaxed α+β microstructure of the parts changes to a mixture of acicular α in β matrix after DLD due to the high cooling rates during the manufacturing process [2]. Furthermore, increasing the energy input increases the thickness of the remelted region. As a result of low cooling rates in this region, the grain size of the alloy may also increase/evolve further.

Kummailil et al. demonstrated that increasing the powder feed rate or laser power increases Ti-6Al-4V layer thickness, while increasing traverse speed decreases layer thickness [4, 10-12]. Brice et al. [6] illustrated the importance of monitoring/controlling the feed rate during DLD fabrication of Ti-6Al-4V. By monitoring/controlling such process parameters, such as laser power, traverse speed, and hatch spacing, higher quality deposits are achievable.

Kobryn et al. investigated the effect of DLD process parameters (laser power and traverse speed) on microstructure, porosity, and build height of Ti-6Al-4V parts. The DLD parts were found to possess a columnar microstructure and a fine Widmanstätten microstructure. Their work demonstrated that increasing the laser power and traverse speed decreases the two types of porosity, namely lack-of-fusion and gas entrainment, in laser-deposited specimens. It was also shown that increasing the traverse speed decreases the build height while laser power has an insignificant effect on build height [7]. Wu et al. [11] also investigated the effects of process parameters on the deposited microstructure of thin-wall Ti-6Al-4V samples. It was found that increasing laser power causes a transition from columnar to mixed/equiaxed morphology in microstructure, while increasing the traverse speed decreases grain size. It was reported that the direction of the solidification heat flux affects the grain morphology of laser-deposited thin-wall Ti-6Al-4V specimens [11].

Kelly and Kampe investigated the microstructure evolution of laser-deposited Ti-6Al-4V samples, using both experimental [12] and modeling approaches [13]. Eighteen layers of a deposited Ti-6Al-4V thin wall, using AeroMet’s laser forming process, were examined in their experimental study [12]. Optical microscopy, hardness, and composition measurements were used to illustrate that the layer-band and gradient morphologies are resultant from the complex thermal history throughout the build direction not as a result of segregation or oxidation.

There have been few studies investigating fatigue behavior of additive manufacturing process, therefore, recent investigations in fatigue behavior of additive manufacturing process and attempts to improve the fatigue life of the fabricated product is becoming another challenge for researchers in this area. For instance, Dong Lin et al. [14] investigated the single layer graphene oxide reinforced metal matrix composites by Laser Sintering. Their investigation proved the improvement in the fatigue life after laser sintering of GO-reinforced iron matrix nanocomposites. In another study, Dong Lin et al. investigated the fundamental mechanism of fatigue performance enhancement during a novel hybrid manufacturing process. Adding the TiN nanoparticles help to further increase the dislocation density by laser shock peening and improved the mechanical properties [15].

In the current study, the evaluation of microstructure variation along the growth direction of the DLD build process is examined and the influence of laser processing parameters: laser output power, traverse speed and powder feed rate on the resultant microstructure of Ti-6Al-4V rod-shaped specimens are investigated. The goal is to further expose the effects of DLD process parameters on the microstructure and mechanical properties of Ti-6Al-4V fabricated and compare with wrought and cast Ti-6Al-4V.

**EXPERIMENTAL PROCEDURE**

The material used for this study was Ti-6Al-4V (AMS 4998C) spherical powder (-100/4+325 mesh). An OPTOMEC LENS® 750 machine with a 1 kW laser source (Nd:YAG) was utilized to fabricate the specimens. Cylindrical specimens with diameter of 7 mm and height of 77 mm were manufactured. The DLD processing chamber was purged with argon to provide for an average oxygen content less than 20 ppm. Microstructural properties along the specimens were invested by employing various combinations of process parameters, such as powder feed rate (0.08 and 0.16 gm/s), traverse speed (0.85, 1.27 and 1.69 cm/s), and laser output power (350 and 400 W).
various combinations of process parameters are shown in Table 1. The layer thickness and hatch spacing were 0.02 mm and the layer orientation alternated between 0º and 90º as shown in Fig. 2.

Table 1. The investigated DLD process parameter combinations

<table>
<thead>
<tr>
<th>Laser Power (W)</th>
<th>Powder Feed Rate (gr/s)</th>
<th>Traverse Speed (cm/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>350</td>
<td>0.156</td>
<td>0.85, 1.27, 1.69</td>
</tr>
<tr>
<td>400</td>
<td>0.076</td>
<td>0.85, 1.27, 1.69</td>
</tr>
<tr>
<td></td>
<td>0.156</td>
<td>0.85, 1.27, 1.69</td>
</tr>
</tbody>
</table>

RESULTS AND DISCUSSIONS

A. MICROSTRUCTURE

The microstructural features, and thus mechanical properties, of DLD specimens are mainly affected by their laser-imposed, volumetric thermal history; consisting of a complex, spatiotemporal temperature field that exists during processing. Prediction of, and designing for, a specimen’s final mechanical properties is a major challenge since each process parameter has a different effect on thermal history.

Experimental results indicate that, for the majority of investigated process parameters, the microstructure of DLD Ti-6Al-4V is predominantly columnar which contains large columnar prior β grains. Prior β grain boundaries are continuous across the multiple layers as shown in Fig. 3.

When the fabrication process starts, the heat rapidly dissipates into the bottom substrate and grains grow counter to the direction of the heat flux, therefore upward, in this case. The addition of each new layer results in re-melting of the top surface columnar grains, which leads to epitaxial growth. These observations are in agreement with the literature, where Kurs et
showed for all their deposited specimens, the microstructure was columnar and parallel to the deposit build direction [16].

During fabrication of the cylinder, a new layer overlaps a previously-deposited perimeter line, causing the outer surface of cylinder to be heated again. The outer edges of the specimen receive approximately twice as much heat input as the rest of the build, causing the perimeter of the cylinder to cool at a slower rate than the interior portion, which results in growth of equiaxed grains; shown in Fig. 4.

![Equiaxed grain structure throughout the top cross-section of cylindrical specimens](image)

Figure 4. Equiaxed grain structure throughout the top cross-section of cylindrical specimens

The microstructure between layers consists of basket-weave Widmanstätten α laths surrounded by retained β grain boundaries. Within the layer, the microstructure exhibits larger colonies of acicular α. The morphology of the layers deposited varies relative to the fully developed microstructure, these layers have experienced different thermal histories relative to previous layers and can be used to capture the intermediate development and evolution of the gradient α morphologies observed in the fully developed underlying layers.

### A.1 Effects of Laser Power

The influence of laser power on the microstructure of DLD Ti-6Al-4V is presented in Fig. 5. The optical morphologies achieved at the same location for each deposited specimen with varying laser power may be seen. The size of columnar grains, β lath, in each sample varies from edge-to-edge and from bottom-to-top. With increasing laser power, the length of the columnar grains decreases and are gradually replaced by large equiaxed grains; α and β lath.

Increased laser power also removes pores resulting in more dense layers. The density of the fabricated specimens were measured using Archimedes’ principle. Higher laser power raises the temperature of deposited layers and this reduces the local cooling rates. In cases with extremely small temperature gradients, the microstructure will be composed primarily of equiaxed grains. Figure 5 illustrates, for any given sample, the size of the α and β laths varies at different locations within the sample. These laths tend to become bigger towards the top of the samples, because the substrate becomes hot at the first layer and the substrate and the build remain hot during subsequent deposition, which leads to the removal of columnar grains, while large equiaxed grains are formed – and this is also reported in the literature [7, 8, 13].

![Effect of Laser Power throw-out the longitudinal cross section of the top of the specimens](image)

Figure 5. Effect of Laser Power throw-out the longitudinal cross section of the top of the specimens, left: 400 W, 0.16 gr/s and 0.85 cm/s, right: 350 W, 0.156 gr/s and 0.85 cm/s

### A.2 Effects of Powder Feed Rate

Figure 6 shows the effect of powder feed rate (0.08 and 0.16 gr/s) on microstructure. For constant laser power and traverse speed, increasing the powder feed rate coarsens the microstructure. If the traverse speed increases, the powder feed rate must also increase proportionally to maintain full density. The microstructure coarsens slightly at the bottom as compared to the middle and top of the sample. However, the difference between the results of the powder feed rates are negligible at the middle and the top of the sample, and this agrees with findings from the literature [3, 4, 12].

![Effect of Powder Feed Rate throw-out the longitudinal cross section of the top of the specimens](image)

Figure 6. Effect of Powder Feed Rate throw-out the longitudinal cross section of the top of the specimens, Left: 0.076 gr/s, 400 W and 0.169 cm/s, Right: 0.156 gr/s, 400 W, and 0.169 cm/s

### A.3 Effects of Traverse Speed

The influence of traverse speed on the morphology is shown in Fig. 7. For the same laser power and powder feed rate, with increasing traverse speed, the grain size decreases.
thickness of the layers further decrease by increasing the traverse speed. When the traverse speed increases, columnar grains become longer and finer due to the decreased energy density to the previously deposited layer. This reduction in energy input is due to the laser and deposition head traveling faster relative to the previously deposited layer, which results in a higher cooling rate. Higher cooling rates do not provide sufficient time for large grain growth. The resulting finer grains serve as nucleation points for the subsequent layers, leading to continued epitaxial grain growth [7, 11-13].

![Figure 7](image1.png)

**Figure 7.** Effect of traverse speed throughout the longitudinal cross section of the top of the specimens, Left: 0.85 cm/s, 400 W and 0.156 gr/s, Right: 0.169 cm/s, 400 W and 0.156 gr/s

### B. MECHANICAL PROPERTIES

#### B.1 Hardness Measurements

Effects of process parameters on specimen hardness are presented in Figure 8. The experimental results clearly indicate that part hardness varies with observed microstructure. It is agreed that high hardness and smaller grain size improve the mechanical properties of Ti-6Al-4V. Results showing that increasing the laser power raises the Vickers Hardness (HV) values, increasing the traverse speed decreases HV, and increasing the powder feed rate does not have a significant effect on hardness. Microhardness tends to be greater at the bottom and top layers than in the middle of a specimen [17, 18]. Distinct microstructure regions with different micro-hardness values have been reported for DLD Ti-6Al-4V [19]. In one regard, the cooling rate of the melt pool and velocity of solidification at the middle part region is slower than the top and bottom regions. In another regard, the middle region is exposed to the cyclic reheating from subsequent layer depositions. The higher cooling rates at the top and bottom regions typically result in a finer microstructure.

![Figure 8](image2.png)

**Figure 8.** Microhardness along radius as a function of traverse speed

#### B.2 Tensile Tests

All the rod specimens were machined to 32 mm gage length, 4 mm gage diameter, 6 mm grip diameter and fillet radius of 30 mm. The tensile loading axis was, therefore, parallel to the built direction. The yield strength and ultimate tensile strength (UTS) are shown in Figs. 9-10 as a function of traverse speed for various combinations of process parameters.

![Figure 9](image3.png)

**Figure 9.** Yielding point as a function of traverse speed

The results indicate that the ultimate tensile strength and yield strength of all specimen fabricated by DLD increased proportionally to the laser power and decreased inversely with powder feed rate. However, there was no significant effect on elongation to failure observed. The traverse speed did not have a significant effect on the ultimate tensile, yield strength, or elongation to failure.
Figure 10. Ultimate Tensile Strength as a function of traverse speed

Tensile properties for DLD Ti-6Al-4V and a comparison with cast, and wrought Ti-6Al-4V are illustrated in Fig. 11. The results show that the UTS and yield strengths for DLD specimens are slightly higher than those for wrought and annealed materials. This may be due to higher cooling rates inherent to DLD, impacting grain size. Fig. 11 is presenting that the UTS and yielding strengths of DLD specimens are lower than SLM and EBM products, as mentioned one of the main reason for answering this phenomena is due to the lower cooling rates of DLD technique compare to the SLM and EBM techniques. The highest values for elongation to failure is related to the EMB method compare to the LENS and SLM, it is showing that using an electron beam as its power source, as opposed to a laser, helping to melt the metal powder better with less porosity and less lack of fusion which have main effects on the elongation to failure rates.

Figure 11. Comparison between DLD, EBM [20], SLM [20], wrought [21] and annealed [21] Ti-6Al-4V specimens

The lack of ductility of DLD samples, compared to different additive manufacturing process, wrought and annealed materials, is generally attributed to the higher cooling rates during fabrication, which cause finer microstructures. In addition, existing micro-porosity and oxide inclusions in the sample can be responsible for this behavior. The elongation to failure for the DLD samples is significantly lower those for cast and wrought materials. Lack of fusion between layers (or lower laser penetration depths) creates voids which can be seen at tensile fracture surface of DLD samples; and these contribute to the lower elongation to failure as shown in Fig. 12.

Figure 12. Tensile fracture surface of DLD Ti-6Al-4V

CONCLUSIONS

This study has investigated the effects of process parameters on microstructure and mechanical characteristics of Ti-6Al-4V fabricated by Laser Engineering Net Shaping (LENS). From this work, the following conclusions are made regarding the Direct Laser Deposition (DLD) of Ti-6Al-4V, in general:

1. Increasing traverse speed, columnar grains become longer and finer due to decreased energy density to the previously deposited layer, therefore the thickness of the layers are decreased. If the traverse speed is increased, the powder feed rate must also increase proportionally to maintain full density.

2. Increasing laser power, the length of the columnar grains decreases and are gradually replaced by large equiaxed grains; α and β lath. Also, it removes pores resulting in more dense layers.

3. The dynamic and repitious temperature gradients/spikes, and sustainable cooling rates, inherent to fabricating DLD Ti-6Al-4V results in the prevelance of columnar
microstructures. It is illustrated that the width of columnar grains decreases by increasing the cooling rates accomplished by higher traverse speeds.

4. Higher ultimate and yield strengths were observed for fabricated specimens than cast and wrought Ti-6Al-4V. Higher cooling rates resulted in finer microstructures, which are mainly responsible for such increases. Occurrence of imperfections (e.g. voids, partially melted powder particles and oxide inclusions) led to lower elongation to failure compared to ones for the cast and wrought material.

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