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EFFECT OF INTER-LAYER TIME INTERVAL ON THE MECHANICAL BEHAVIOR OF DIRECT LASER DEPOSITED TI-6AL-4V

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Abstract

Due to its wide applicability in the biomedical and aerospace fields, where unique and/or difficult to machine geometries are required, Ti-6Al-4V continues to be a strong candidate for additive manufacturing. In this study, the effect of inter-layer time interval on the mechanical behavior of Ti-6Al-4V fabricated via Laser Engineered Net Shaping (LENS™) is investigated. Two sets of specimens were fabricated, each with their own inter-layer time interval, accomplished by depositing either one or two specimens per operation. Tensile tests and fully reversed, strain controlled fatigue tests were conducted on the specimens. Experimental results indicate that specimens fabricated using longer inter-layer time intervals possess a higher ultimate tensile strength, lower ductility, and finer microstructure relative to those fabricated using shorter time intervals. Additionally, specimens fabricated using longer inter-layer time intervals possessed shorter fatigue lives due to presence of more process defects, such as pores and lack of fusion, inherent to additive manufacturing. Such effects are important to consider when producing multi-part assemblies or large parts.

Keywords: Fatigue, Fractography, Tensile properties, Microstructure, Geometry effects

1. Introduction

A promising avenue for manufacturing currently being researched is that of additive manufacturing (AM). Rather than traditional manufacturing, which involves subtractive machining operations, casting, or other methods for material shaping, AM has the ability to create near net shapes through repetitious deposition of material, usually in a layered fashion. While AM can benefit a variety of applications, parts created through AM are susceptible to porosity and other defects [1], which may affect their mechanical and fatigue properties [2-4].

Previous studies indicate that the localized, transient heat transfer and time variant cooling rates inherent to directed energy AM processes, such as Laser Engineered Net Shaping (LENS™), can lead to unique microstructures vastly different from those found in wrought material [5-11].

For Ti-6Al-4V, there is a noted tendency for the LENS material to possess the martensitic phase rather than a stable α+β phase with large lamellar, globular, or bi-modal morphologies, usually found in mill annealed wrought Ti-6Al-4V [5-11]. Some studies have reported coarse α laths, with evidence of prior β grains, near the center of Ti-6Al-4V specimens created using the LENS process [5, 12]. Even changing the inter-layer time interval of additive processes, while holding other process parameters constant, has been shown to produce different microstructural features. Yadollahi et al. [13] found that for stainless steel 316L, varying the time interval between layers for LENS fabrication resulted in different microstructures and mechanical properties. Specimens with longer inter-layer time intervals exhibited finer microstructure, lower elongation to failure, and higher strength. Additionally, the specimens with longer inter-layer time intervals exhibited much higher porosity [13].

Based upon the known differences in microstructure found between additive and wrought material, as well as between additive materials with different inter-layer time intervals, it is clear that an understanding of the effects on mechanical and fatigue properties of altering the inter-layer time interval while holding other process parameters constant is needed. If changing the inter-layer time interval of additive processes significantly impacts the mechanical properties of a part, then doubt is cast upon the ability of small representative specimens to accurately replicate the mechanical and microstructural of the final part with larger dimensions. Therefore, it is vital that the effects of varying the inter-layer time interval be quantified in order to better understand AM property-performance relationships and improve the applicability of test specimen data to the design of parts intended for service.

This study aims to determine the effects of varying time interval during LENS fabrication of Ti-6Al-4V, with emphasis on fatigue behavior. Therefore, two batches of Ti-6Al-4V specimens were manufactured employing different inter-layer time intervals; these specimens were then machined and annealed. Microstructures of the specimens are examined, and mechanical and fatigue properties of the specimens were evaluated. Fractography was conducted in order to determine crack initiation and propagation characteristics, as well as to examine the porosity contained within the specimens.

2. Experimental Setup

For this study, thirty-six cylindrical specimens (110 mm tall, Ø = 11 mm) were fabricated using an Optomec LENS^{TM} 750 equipped with a 1 kW Nd:YAG laser. The specimens were printed in two batches of 18 specimens; one set was printed with an inter-layer time interval of approximately 1 second, while the other set was printed with an inter-layer time interval of approximately 33.5 seconds. This difference in time interval was accomplished by fabricating either one or two specimens at a time; therefore, the specimens with the shorter time interval are referred to as "single built specimens," and the specimens with the longer time interval as "double built specimens." All specimens were built upon 152.4 mm by 152.4 mm, 3.175 mm thick Ti-6Al-4V substrates that have been clamped to the worktable at each corner. Spherical Ti-6Al-4V

Grade 5 Plasma Rotating Electrode Process (PREP) powder with a mesh size of -100/+325, sourced form Phelly Materials Inc., was utilized during the deposition process. All specimens were fabricated in an argon atmosphere, using a laser power of 350 W, a powder feed rate of 0.16 g/sec, and a travel speed of 16.9 mm/sec. Both the layer thickness and hatch spacing were 0.51 mm. In previous research, these parameters were shown to produce nearly fully dense specimens [12]. After the completion of each layer, the hatching orientation used for to-be-deposited tracks was rotated 90° with respect to the previous orientation. Upon the completion of the LENS process, specimens were removed from the substrate, and all but one were machined to the final geometry shown in Figure 1, in accordance with ASTM E606 [14]. Annealing Ti-6Al-4V specimens can relieve residual stresses inherent to the DLD process [15]; therefore, after machining the specimens were annealed for one hour in an argon atmosphere using a tube furnace that was preheated to 704 °C (~1300 °F). The specimens were then air cooled to room temperature via free convection. Figures 2(a) and 2(b) show examples of the specimens after deposition and machining, respectively.

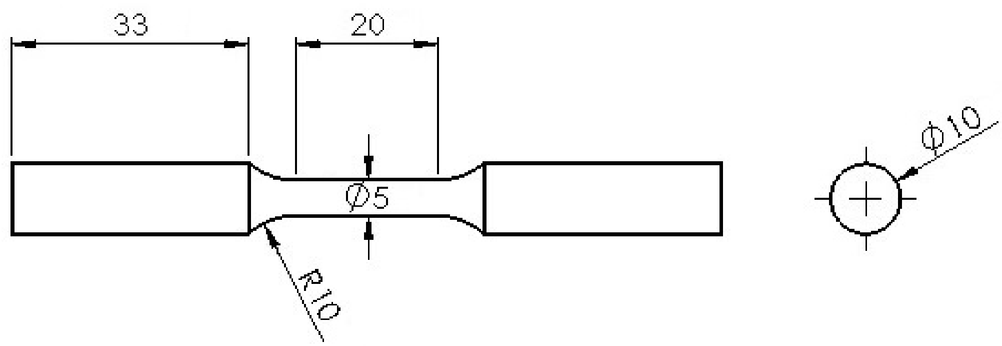


Figure 1. Dimensions of cylindrical tensile fatigue specimens based on ASTM E606 (units in millimeters).

Figure 2. Examples of specimens in the (a) as-built, (b) post-machining, and (c) post-testing state.

In order to investigate the microstructure of the single and double built LENS specimens, an unmachined specimen from each set was sacrificed. Sections were taken from the center of the specimens and subsequently cut along the radial and longitudinal planes. These sections were then hot-mounted in PolyFast and polished. An optical microscope (Zeiss Axiovert 200) equipped with a polarized light source was used to examine the microstructure.

Once machined and heat treated, the gage sections of the specimens were polished to a near mirror finish using sandpaper of progressively finer grits. Tensile tests were conducted at a strain rate of 0.001 s^{-1} using an Instron compression/tension machine, with an Epsilon extensometer. Fully-reversed strain-controlled uniaxial tension-compression fatigue tests were performed using an MTS 810 machine and an Instron Landmark servo-hydraulic test system in conjunction with an MTS extensometer, complying with ASTM E606-92 [14]. Figure 2(c) shows an example of a tested fatigue samples.

3. Experimental Results and Discussion

3.1 Microstructure

The microstructures of the annealed LENS Ti-6Al-4V single and double built specimens are compared in Figure 3. The microstructure from the longitudinal section of the single built specimens, shown in Figure 3(a), consists of predominately Widmanstätten microstructure combined with large α+β colonies (large white and grey features marked by red ellipses) with ultrafine α laths originating from the grain boundary α phases. This type of microstructure exists due to the decomposition of the martensitic (α’ and α”) phases as a result of the cycling heating/cooling of deposited layers during fabrication [16], while residual martensite in LENS Ti-6Al-4V may also be possible [17]. The microstructure of the double built specimen’s longitudinal section, as shown in Figure 3(b), displays the aforementioned Widmanstätten microstructure combined with large α+β colonies and α laths originating from the grain boundary α phases, but with much finer morphologies. The size of the α laths and grain boundary α+β colonies are all smaller for the double built specimens. This change can be attributed to the different cooling rates of the specimens during fabrication; the single built specimens possessed a significantly shorter time interval between layers, leading to heat build-up and a slower cooling rate. The double built specimens, due to the large time interval between layers, cooled to a much greater extent between layers. This in turn led to a greater temperature difference between the previous and current layer during deposition, resulting in a more rapid cooling rate. This finding has also been observed and described in other works [18]. Additionally, while the polished surfaces of the single built specimens exhibited little porosity (Fig. 2(c)), multiple lack of fusion type pores were detected on the double built microstructure specimen surfaces (Fig. 2(d)), suggesting that the double built specimens contain many more defects than the single built specimens. The higher porosity/defects for double built specimens is most likely due to a more poorly developed melt pool being utilized during deposition of the colder layer.

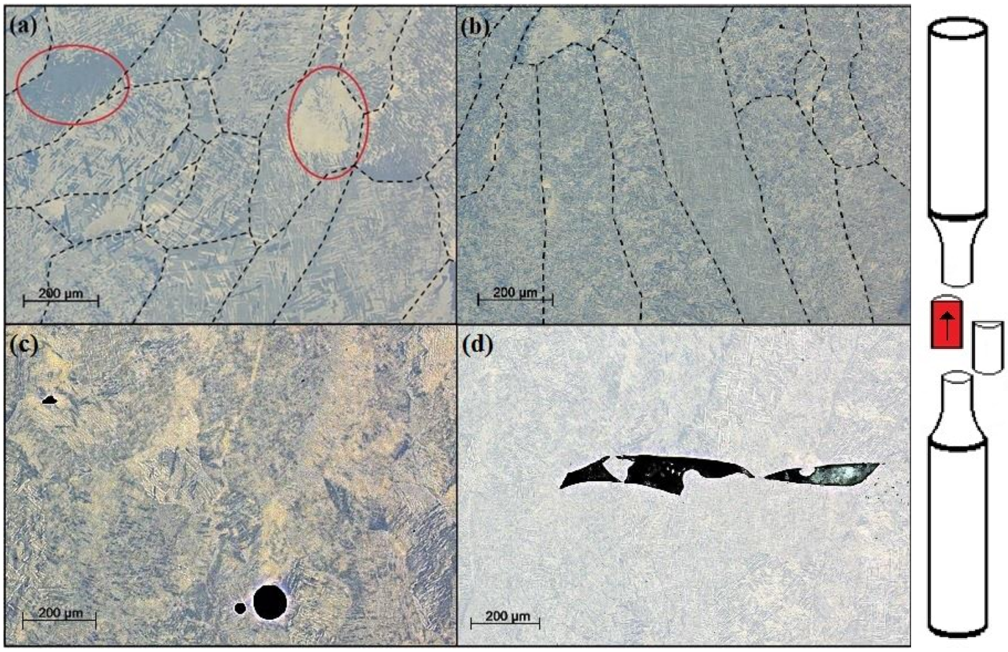


Figure 3. Cross-sectional microstructure of LENS Ti-6Al-4V: (a) single built specimens, (b) double built specimens, and examples of defects found on (c) single built specimens, and (d) double built specimens.

3.2 Monotonic Tensile Behavior

The results of the tensile tests are shown in Figure 4. While all of the specimens exhibited nearly identical behavior in the elastic region, the double built specimens possessed higher yield strengths than the single built specimens due to their finer microstructure. The single built specimens experienced at least triple the elongation to failure than the double built specimens. The single built specimens also experienced much more plastic deformation, as they underwent the majority of the elongation during plastic deformation. In contrast, the double built specimens broke at or just after the yield point, experiencing nearly no plastic deformation. This could be due to the amount and nature of the porosity found in the double built specimens. In addition to small spherical pores similar to those found in the single built specimens (Fig. 3(c)), the double built specimens also contained large lack of fusion pores, with dimensions as large as 1 mm (Fig. 3(d)). Rather than the smooth, uniform surface of the spherical pores, as shown in Figure 5(a), the lack of fusion pores, shown in Figure 5(b), were irregularly shaped, large and flat, giving rise to a much higher stress concentration [19]. These stress concentrations were evidenced by the earlier failure and lack of ductility of the double built specimens; once the material yielded, the pore was large enough to cause rapid specimen failure.

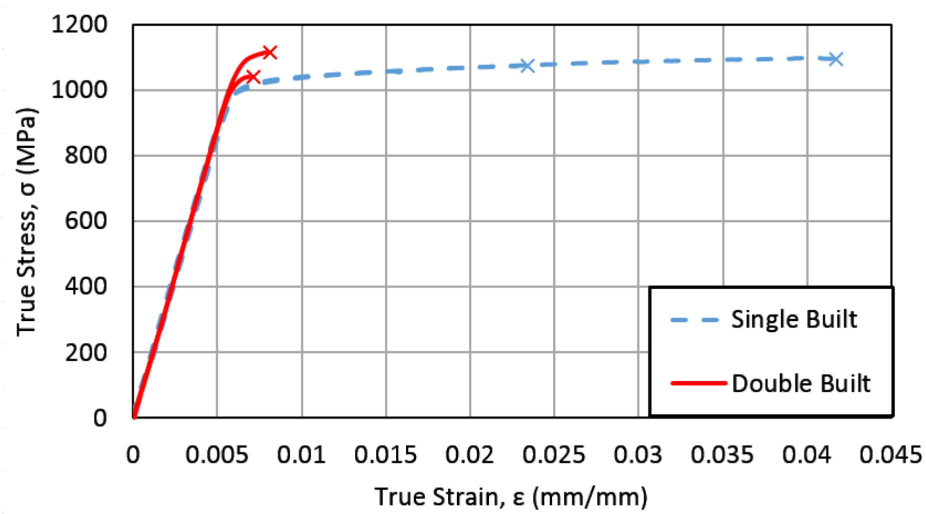
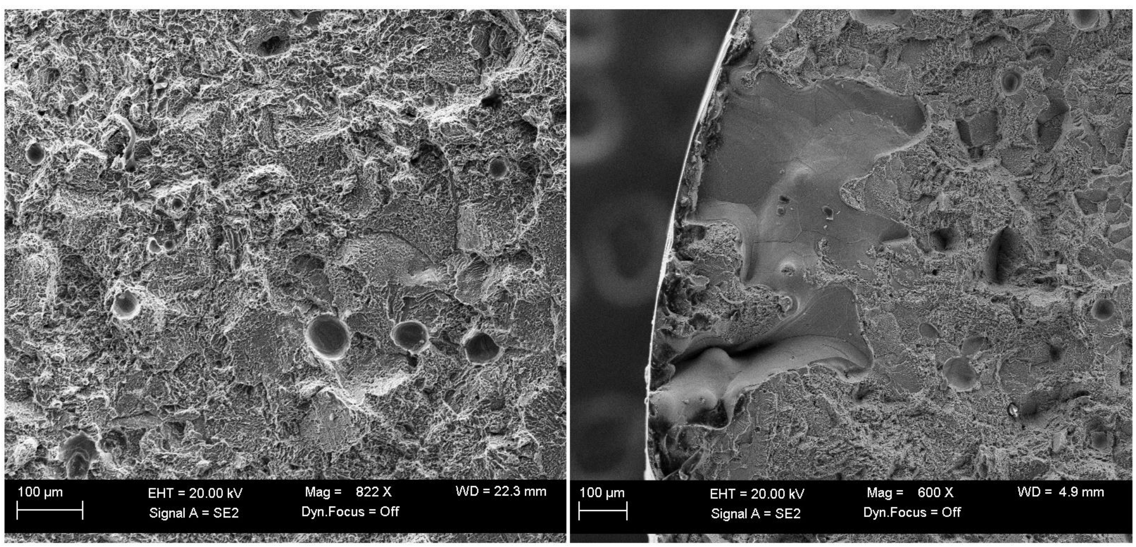


Figure 4. Tensile stress-strain curves for single and double built LENS Ti-6Al-4V.



(a) **(b)**

Figure 5. Pores from tensile fracture surfaces of (a) a single built LENS, and (b) a double built LENS Ti-6Al-4V specimen.

3.3 Fatigue Behavior

Figure 6 provides the strain amplitude versus reversals to failure for the single and double built LENS Ti-6Al-4V specimens. It can be seen that the fatigue lives of the single built specimens are longer than those of the double built specimens by approximately an order of magnitude in the long life regime. Although the fatigue lives are much closer in the short life regime, the single built specimens still exhibit longer fatigue lives. However, it is important to note that there is scatter in the fatigue lives, particularly in the high cycle fatigue (HCF) testing of the single built specimens, due to the existence and distribution of the process defects, such as pores, which play a more dominating role in long life regime [12] .It is interesting to note that the strain-life behavior of the double built specimens contains much less scatter than that of the single built. This could be due to the porosity levels of the specimens; while both sets of specimens contained porosity, the double built specimens contained lack of fusion pores orders of magnitude larger than those found in the single build specimens. Additionally, there was less percent variation in pore size for the double built specimens (~50% mean deviation) than the single built specimens (~90% mean deviation). This can explain the lesser variation in plastic zone size and stress concentration of the double built specimens; corresponding to more consistent fatigue behavior.

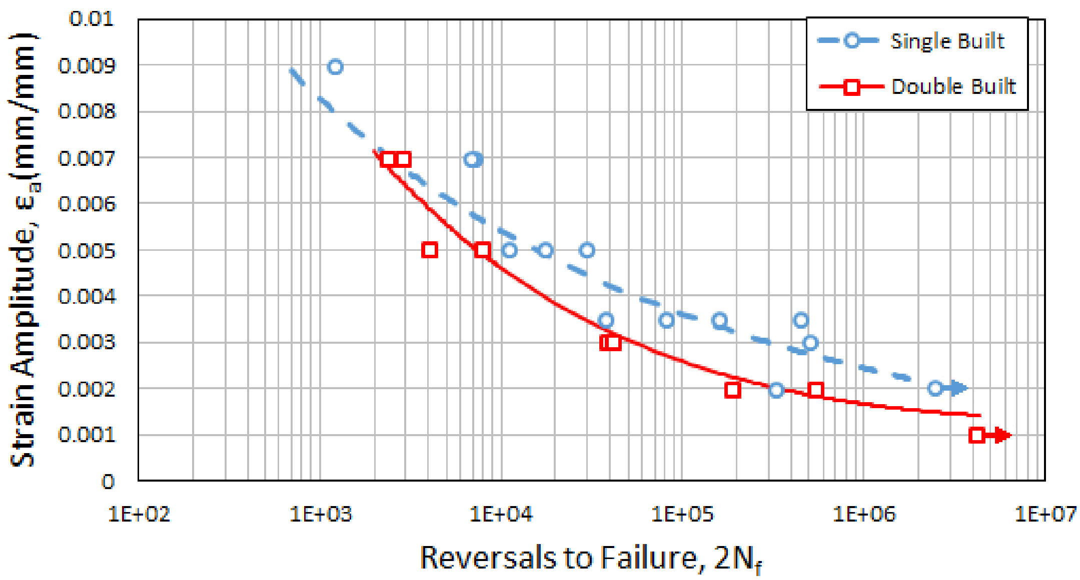


Figure 6. Comparison strain-life fatigue behavior for single and double built LENS Ti-6Al-4V.

Fractography analysis of the LENS specimens demonstrated that both sets displayed fracture surface features significantly different that those found on wrought material. Rather than regions of clearly defined crack initiation, crack propagation, and final fracture, the single built LENS fracture surfaces, as shown in Figure 7(a), were rough and uneven, with small amounts of crack propagation and with pores, usually close to the outer surface of the specimen, serving as crack initiation sites. In contrast, the double built fracture surfaces, shown in Figure 7(b), were smoother, with cracks initiating at large lack of fusion pores, and very little evidence of crack propagation, most likely due to the lack of ductility in these specimens. This supports the argument that the double built specimens possessed much less ductility due to having lack of fusion pores and finer microstructure. Fractography also revealed that the double built specimens possessed large lack of fusion pores and a greater number of spherical pores, with a larger average size, than the single built tests. This supports the observation made during the microstructure investigation that the double built specimens were more porous than the single built specimens. The orientation of these larger pores in relation to the load axis created a larger projected area on the plane normal to the loading axis than those formed by the smaller, spherical pores, leading to greatly increased stress concentrations. Research has shown that these larger projected areas can have more detrimental effects on specimen fatigue life [20]. This larger effective area, along with the finer microstructure, could be the cause of the shorter fatigue lives in the double built specimens. Additionally, there was evidence of multiple crack initiation points on some of the single built fracture surfaces in short life regime, as shown in Figure 7(a). This may be explained by more ductility of single built specimens, and therefore, more plastic deformation in short life regime. This will cause the specimens to spend more time in the crack propagation stage of fatigue; thus, providing more opportunities for other cracks to initiate and grow [21, 22]. It is interesting to note that the large lack of fusion pores in the double built specimens contained multiple partially melted powder, as seen in Figure 7(b).

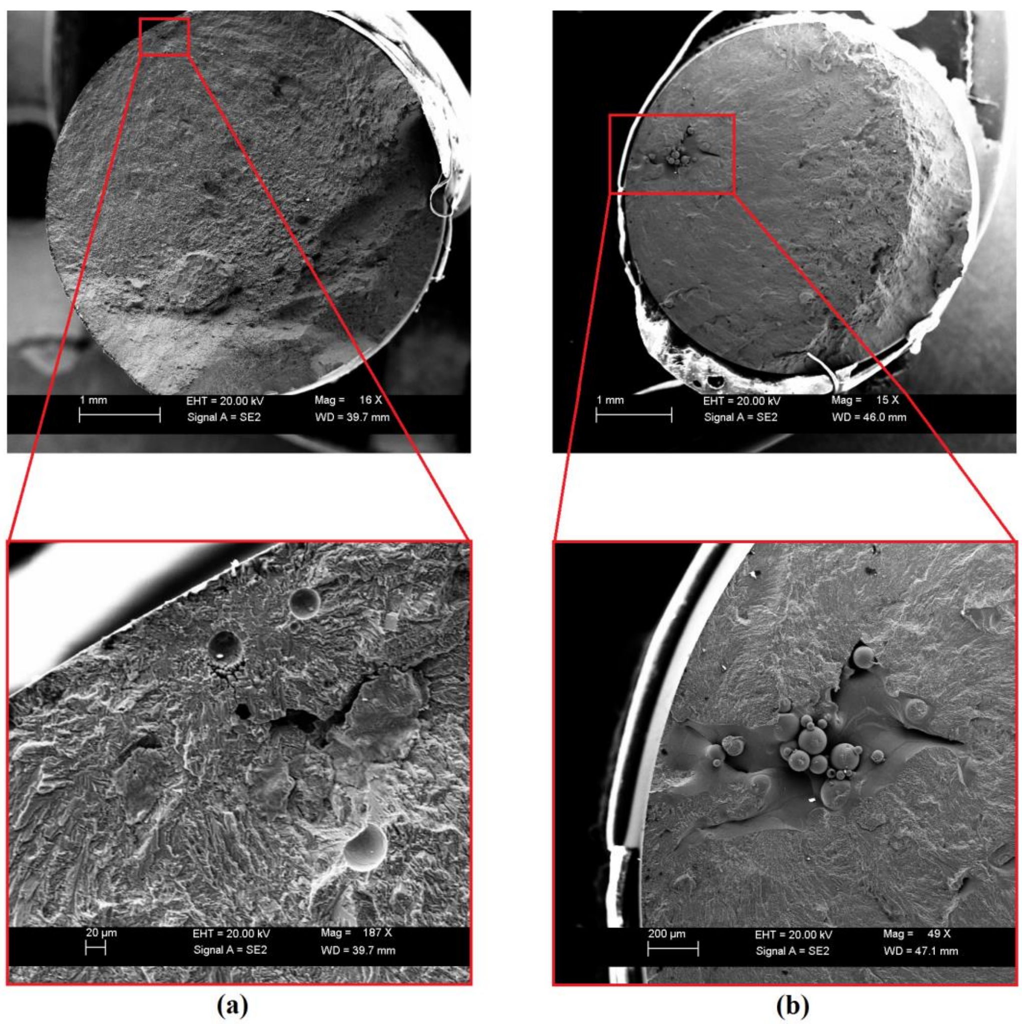


Figure 7. Representative fatigue fracture surfaces for (a) single built and (b) double built LENS Ti-6Al-4V specimens.

4. Conclusions

The goal of this study was to quantify the effects of inter-layer time interval during additive manufacturing on the mechanical behavior of Ti-6Al-4V. It was found that the variation in the inter-layer time interval leads to different microstructures, types (i.e. spherical or lack of fusion) and levels of porosity in the build, which in turn results in different mechanical behavior. In particular, the following conclusions can be made based on this study:

1. Longer inter-layer time intervals create lower bulk part temperatures and higher temperature gradients between layers, leading to higher instantaneous and more sustained/continuous cooling rates. This led to the specimens with longer inter-layer time intervals (double built specimens) possessing higher porosity/defects and finer microstructure in comparison to the single built specimens.
2. Of tested specimens, those with larger inter-layer time intervals possessed higher yield strength and drastically reduced ductility, with failure occurring at or shortly after yielding, due to their finer microstructure and existence of many lack of fusion pores.
3. Specimens produced with an increased inter-layer time interval (double built specimens) exhibited much shorter fatigue lives than those produced with a smaller inter-layer time interval (single built specimens), due to the different microstructure associated with large lack of fusion pores resulting from the different thermal histories.
4. The single built specimens exhibited more scatter in fatigue life than the double built specimens. This appears to be due to the greater relative variation in pore size found in the single built specimens as compared to the double built specimens.
5. Any changes to the inter-layer time interval or geometry employed for a build, without making a corresponding adjustment to the process parameters, can lead to significant variation in specimen porosity, microstructure, and mechanical behavior.

This investigation further demonstrates that one can achieve significantly different microstructural, tensile and fatigue properties in LENS Ti-6Al-4V parts by altering the inter-layer time interval; while maintaining a constant set of process parameters. In other words, changes in manufacturing strategy, i.e. geometry changes or increasing the amount of parts fabricated per build, can result in different, and possibly undesired, mechanical properties, casting doubt upon the representability of specimen properties in relation to the component-level performance (i.e. property-performance relationships). Proper adjustments (i.e. scaling) of processing parameters, such as laser power, scan speed, power feed rate are necessary in order to yield consistent microstructures and mechanical properties for AM parts with different manufacturing strategies.

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