EFFECT OF DEFECTS AND A BUILD PAUSE ON FATIGUE LIFE OF ADDITIVELY MANUFACTURED 316L STAINLESS STEEL

by

Simon Douglas Richardsen
A thesis submitted to the Faculty and the Board of Trustees of the Colorado School of Mines in partial fulfillment of the requirements for the degree of Master of Science (Mechanical Engineering).

Golden, Colorado
Date __________________

Signed: __________________
Simon Douglas Richardsen
Thesis Advisor

Golden, Colorado
Date __________________

Signed: __________________
Dr. Joy Gockel
Professor and Department Head
Mechanical Engineering
ABSTRACT

Build pauses can occur during metal additive manufacturing (AM) with laser beam powder bed fusion (PBF-LB) for a variety of reasons such as power outage, insufficient gas flow, or sensor failure. It is economically desirable to continue a build after the issue is resolved. The effect on part quality, namely microstructure, surface roughness, geometric features, and the impact on the fatigue performance is not well understood. This study considers parts fabricated with a 2-hour build pause in the center of the gauge section. Comparisons of the dimensions, as-printed surface features, microstructure, and fatigue performance are determined. Geometric deviation from part shift during the build pause is significant, however other flaws inherent to AM can also dominate failure depending on severity. A stress intensity factor approach is utilized to determine the influence that the geometric variation and the individual flaws had on the fatigue life. A model is developed to predict and determine part performance after a build pause. Understanding the effect of mechanical changes and geometric shifts from a build pause can help reduce scrap from unintended build interruptions.
# TABLE OF CONTENTS

ABSTRACT .................................................................................................................................................... iii

LIST OF FIGURES ....................................................................................................................................... vi

LIST OF TABLES .......................................................................................................................................... vii

ACKNOWLEDGMENTS ............................................................................................................................... viii

CHAPTER 1  INTRODUCTION ................................................................................................................... 9

1.1 Research Objectives and Questions .................................................................................................... 9

1.2 Thesis Overview .................................................................................................................................. 9

1.3 Additive Manufacturing Introduction ................................................................................................. 10

1.3.1 Metal Additive Manufacturing ...................................................................................................... 10

1.3.2 Laser Powder Bed Fusion .............................................................................................................. 11

1.3.3 Flaws Caused by the PBF-LB Process ......................................................................................... 11

1.4 Stress Concentration ............................................................................................................................ 13

1.5 Stress Intensity in Fatigue .................................................................................................................. 13

1.5.1 Derivation of the Stress Intensity Factor .................................................................................... 14

1.6 Change in Stress State at a Notch ........................................................................................................ 15

1.6.1 Stress Triaxiality ........................................................................................................................... 16

1.7 Fatigue Failure .................................................................................................................................... 16

1.8 Minimum Defect Size to Initiate Failure ........................................................................................... 17

1.8.1 Fatigue Life Models for Defects .................................................................................................. 17

1.9 PBF-LB Flaws and Effect on Fatigue ................................................................................................. 19

1.9.1 Fatigue of Wrought 316L ............................................................................................................ 19

1.9.2 Fatigue of PBF-LB 316L ............................................................................................................. 19

1.9.3 PBF-LB Defects Initiating Failure ............................................................................................. 19

1.9.4 PBF-LB Microstructure ............................................................................................................... 20

1.9.5 Impact of AM Build Interruptions ............................................................................................... 21

1.10 Contributions ...................................................................................................................................... 22

CHAPTER 2  EFFECT OF A BUILD PAUSE ON THE FATIGUE BEHAVIOR OF LASER POWDER BED FUSION 316L STAINLESS STEEL WITH AS-PRINTED SURFACES ........................................................................ 23

2.1 Material and Methods .......................................................................................................................... 23

2.1.1 Material .......................................................................................................................................... 23

2.1.2 Additive Manufacturing Build ..................................................................................................... 23

2.1.3 Build Pause .................................................................................................................................... 24

2.1.4 Fatigue Tests .................................................................................................................................. 25
LIST OF FIGURES

Figure 1.1  A 100MPa uniaxial normal stress compared to the same 100MPa stress, in a triaxial state... 16
Figure 1.2  A Kitagawa-Takahashi diagram with the El-Haddad criterion added................................. 18
Figure 2.1  Fatigue bar print layout from 3DXpert software for the 3D Systems DMP Flex 350.............. 24
Figure 2.2  The S-N curve depicting the fatigue life of all the specimens. All specimens have as-built surface condition. The results from this study are compared against a separate build that did not have a build pause, but still retains the as-built surfaces, acting as a control. ........... 27
Figure 2.3  The build pause location identified with the line. ................................................................. 28
Figure 2.4  A is a schematic of the design. B is the actual visible line on the fatigue specimen. C shows a schematic of the surface shift. D is a filtered edge profile to demonstrate the magnitude of the specimen shift........................................................................................................... 29
Figure 2.5  The individual heights of the failure of each specimen relative to the build pause (indicated by the red line). The red, yellow, green, and blue points referring to decreasing layer shift magnitudes. .......................................................................................................................... 30
Figure 2.6  A variety of defects that resulted in failure imaged on SEM. A and B demonstrate the radial fracture surfaces on a specimen that failed at the build pause. C and D illustrate how defects result in clear fracture initiation sites. ................................................................. 31
Figure 2.7  An SEM image of a specimen with multiple crack initiation locations .............................. 32
Figure 3.1  A surface notch example shown on the fracture surface of a failed fatigue bar from the SEM ...................................................................................................................................... 39
Figure 3.2  Widespread shiny lack of fusion pores on the surface of a specimen that failed earlier than expected................................................................. 40
Figure 3.3  A lack of fusion pore on SEM and individual grains visible on the surface of the metal of an LOF surface notch. ................................................................................................................................. 41
Figure 3.4  The stochastic distribution of pore sizes ................................................................................ 41
Figure 3.5  An example defect area calculation for a surface notch that initiated a crack .................. 42
Figure 3.6  Stress intensity factor of various surface notches................................................................. 43
Figure 3.7  The stress intensity factor vs cycle count for the layer shift approximation ....................... 44
Figure 3.8  A comparison of the two different stress intensity factor approximations........................ 44
Figure 3.9  A modified Kitagawa-Takahashi diagram to predict finite life of flaws.............................. 46
LIST OF TABLES

Table 3.1  Coefficients for shape factor correction [18].......................................................... 36
Table 3.2  Beretta estimates of the max stresses and critical defect area for various life expectancies
for 316L SS .......................................................................................................................... 45
ACKNOWLEDGMENTS

There were a number of contributions from my peers in this thesis. Filtering was assisted by Edwin Glaubitz. EBSD imaging and interpretation was done by Matthew Schreiber. Gideon Crawford helped me with capturing SEM images. My advisor, Dr. Joy Gockel, provided excellent guidance in the research process. This material is based on research sponsored by the U.S. Army DEVCOM Ground Vehicle Systems Center and Air Force Research Laboratory under agreement number FA8650-20-2-5700.
CHAPTER 1 INTRODUCTION

1.1 Research Objectives and Questions

The research objective of this work is to determine the influence of a build pause and other flaws on the fatigue life of an additively manufactured component and to predict part life for a given flaw. This work encountered a layer shift because of a build pause which created a defect that could also cause failure. This paper analyzes the comparative impact of a build pause and other process induced defects on the fatigue life of Laser Beam Powder Bed Fusion (PBF-LB) 316L Stainless Steel (316L SS) produced on a 3D Systems DMP Flex 350. Due to the build pause and the stochastic nature of other defects in PBF-LB additive manufacturing, this research examined the effect of both the build pause and of surface and interior flaws on the initiation of cracks under fatigue loading. The hypothesis of this work is to prove that a stress intensity factor approximation will quantify defects and the layer shift caused by the build pause to predict the influence on fatigue life.

1.2 Thesis Overview

This work seeks to provide a framework for understanding a build pause and the relevant flaw that accompanies it. Fatigue testing was undertaken on a 316L PBF-LB print that was halted part way through the printing process and was resumed after a 2-hour break. The relevant introductory matter is in chapter one to discuss various considerations from literature and mechanics. Chapter two delves into the most critical aspects of the build pause, the methodology of testing and imaging, as well as a full characterization of the layer shift that resulted from the untimely build interruption. Following the fatigue testing, it was determined that the build interruption had a peculiar effect on the specimens in this study as approximately half of the specimens fractured at the very layer where the build interruption took place. This piqued interest in the applicability of developing a model or method to determine the stress intensity or stress concentration at the region. In chapter three, a stress intensity factor approach is described for modeling the layer shift. It is compared against the reputed stress intensity factor model currently used in many additive manufacturing papers. The work pursues a stress-life approximation to understand the meaningful impact of this stress intensity factor approximation for many different stress intensity factors and cycle counts. Ultimately, an adapted finite life Kitagawa-Takahashi approach is shown to effectively model the life of a component with a given stress intensity factor because of multiple different flaw types. This work will quantify the fatigue testing of PBF-LB 316L SS specimens with a visible witness line flaw, determine the relative magnitude of stress intensity factors of process flaws vs witness line under fatigue loading, and predict the usable life of an AM sample with a witness line or another defect.
1.3 Additive Manufacturing Introduction

Additive manufacturing is a growing technology that is rapidly seeing more implementation in a variety of industries including medical, aerospace, and automotive. While this technology has previously been used more for rapid prototyping and conceptual models, it is being used more for the manufacture of loaded components in mechanical systems. [1] This is a challenge for industry adoption because additive manufacturing can produce a variety of defects that may compromise the structural integrity of a part. In aerospace applications with high cycle fatigue life requirements, a large defect in a critical part can result in a decommissioning or recycling of that part. [2] Worse yet, if a printer is to pause as a result of a power outage or print error, the entire build plate will be scrapped for concerns of dimensional or mechanical faults that might result.

Additive manufacturing is a layer-by-layer manufacturing process wherein material is added in slices to create a whole part after some number of layers are completed. Originally, welding could be considered the first additive manufacturing process, but the first process officially designated as such is the stereolithography technology developed by 3D Systems. [3] The process has expanded to different material types and is even in use in structural and biological applications. Industries with complex parts of any type can find utility of some AM process to tackle an otherwise prohibitively complicated component.

1.3.1 Metal Additive Manufacturing

Metal additive manufacturing is a more recent development on additive technologies. Most metal additive processes have a material that is sintered or melted using a heat source over several layers. This iterated two-dimensional process is repeated hundreds if not thousands of times to create gradually changing cross sections, ultimately creating the three-dimensional part. For the most part, three different types of feeding processes exist, wire feed, powder feed, and powder bed, with two different types of thermal processes, either fully melting (fusion) or partial melting (sintering). While partially melted sintered parts will often have lower densities and higher porosity, fully melted parts made via fusion will often have very high density, at optimal processing parameters. [4] [5] [6]

Additive manufacturing can be competitive and superior by some metrics when compared to conventional manufacturing techniques. Additive manufacturing can produce a number of complex three-dimensional designs where other processes like machining and casting have limitations specific to the process. Industry adoption of additive manufacturing is hampered by mechanical unreliability, something that is explored in this research. The development of internal porosity and surface notches are the key elements of additive manufacturing that are under scrutiny as these are elements of the technology that hold it back from weight bearing part applications that interest multiple industries. [7]
1.3.2 Laser Powder Bed Fusion

PBF-LB is a process in which an overhead laser is used to dump light energy into a bed of metal powder in a specific shape. Once the laser scans the cross section, the print bed lowers itself slightly to make room for the next layer. A new layer of fresh powder is deposited on top, and the process begins again. The fresh powder comes from a hopper and the recoater blade moves from one side of the print bed to the other. Each step has several processing parameters key to the efficiency and effectiveness of the process, as well as the mechanical characteristics of the printed part. The melting-based approach of PBF-LB requires a good understanding of the heat transfer and thermal capacity properties of the material in addition to the energy input of the laser. The wavelength of the laser is important due to some of the reflectivities of the constituent powder. The power and speed of the laser is important as this will impact the size and shape of the melt-pool. The layer thickness and hatch spacing are important as these two impact the overlap of heat gradients and the potential for lack of fusion between laser passes. PBF-LB differs from another process called Electron Beam Powder Bed Fusion (PBF-EB). PBF-EB uses an electron gun rather than a laser, and requires a conductive material that is baked and sintered at each layer before the scan can begin, as the electrons need somewhere to go once they reach the powder feed stock, and sintering each layer enables the transfer of electrons and prevents movement of the powder particles. Laser Beam Powder Bed Fusion uses mirrors to direct the laser, while Electron Beam Powder Bed Fusion will usually use electromagnetic lenses to move the electron beam.

PBF-LB has its own specific drawbacks and benefits. The biggest benefit of PBF-LB as it is compared to other metal additive processes is the high ability for detailed structures and the supportive nature of powder that was not melted together. PBF-LB has very small laser spot sizes and small powder particles enabling intricate designs. This, of course, comes at the cost of production speed and timelines. For this reason, PBF-LB is often used for smaller more intricate components that require higher part density and better dimensional accuracy.

1.3.3 Flaws Caused by the PBF-LB Process

Additive manufacturing flaws are under scrutiny from a mechanical standpoint in order to determine the maximum allowable defect size for a part to qualify and survive its end use case. Defects can come in a variety of ways. Two common types of defects seen in PBF-LB style 3D printing are keyhole pores and lack of fusion pores. Keyhole porosity results when too much energy is dumped into the powder bed at one location, resulting in the vaporization of the metal or its constituents, thereby creating a pore underneath the surface. Lack of fusion porosity is caused by the inverse, when too little energy is put into the loose powder. Individual powder particles will not melt fully under these low energy conditions and the final part will be rife with porosity in the non-melted regions between powder particles. These defects will frequently result in part failure.
Porosity is affected by the amount of energy input there is on a layer, as well as the method of inputting the energy in the first place. Different scan strategies exist for a multitude of reasons, but one consideration for scan paths is buildup of thermal energy that could potentially result in excessive porosity at a location. Different process parameters and machine parameters exist in order to prevent excessive or insufficient heat energy in certain locations.

Kurzynowski et al. described some mechanisms of scanning strategies on relative part densities in order to understand how they contribute to the formation of pores independent of laser parameters. [12] First, they found that while maintaining all the processing parameters, but by varying only the scan strategy, there was a decrease in the relative density and an increase in porosity. Some scanning strategies (i.e., chessboard) resulted in a notable decrease in porosity. Additionally, the porosity seen was consistent through each layer indicating it was the scan strategy and the boundaries of the melt pool that were the principal determining factors. The distribution, size, and quantity of these pores was found to be highly dependent on the scan strategy used, as the specimens will develop areas of too little or too much energy resulting in lack of fusion porosity or keyhole porosity. A number of questions could be raised due to the process parameters remaining mostly constant in this study. The study addresses these through the amount of energy deposited in each layer. The variation was not in the laser power, hatch spacing, speed, and layer height; rather the study focused on only the scan strategy implemented. The unchanging machine settings indicate that a lot of porosity might come as a result of too much or too little energy in some locations on each layer forming keyhole or lack of fusion porosity in each layer.

Scan strategy and process parameters are crucial to preventing lack of fusion porosity (LOF). An LOF pore will have a few characteristics that are important to stress consideration. LOF results in an oddly shaped pore due to two key factors. First, the packing of the spherical powder will not allow for round pores at the non-melted sections. Secondly, the irregular overlap of the non-melted sections will result in jagged areas of insufficient thermal energy deposition. These two factors will lead to the oddly shaped, jagged pores where metal is not sufficiently melted. This odd shape will result in a pore with non-uniform and less predictable stress concentration effects, as it could have a much sharper corner in one location that would have a more pronounced effect under load. [8] [13] [14]

A keyhole pore will have a more predictable architecture, as it forms from a more predictable mechanism. When a keyhole pore forms, the powder will melt and vaporize as a result of too much energy input. A small gas bubble will be formed and cut off at the bottom of the vaporized section. As the laser continues to move on, the gas bubble will have been set into the previous layer of the material, resulting in the keyhole pore that will increase the local stress concentration effects and effectively decrease the cross section of the material. This formation mode has been shown in literature. Wang et al. ran Computational Fluid Dynamics models as well as verification by in-situ X-ray imaging which showed two distinct phenomena drive the formation of a keyhole pore in the material. First a bubble is formed
due to keyhole instability. Then a bubble at the base is forced downward due to the high vertical velocity of the molten metal and is captured in the solidification front. [15]

1.4 Stress Concentration

A stress concentration is a region where stress is experienced differently due to a change in the geometry and the loaded cross section of a given part. Some examples of this can include shaft reductions or notches in shafts, as well as large gaps in the center of a cross section. Conventional design principles advise avoiding stress concentrations as they can cause localized weakness in regions of loaded parts. [16]

In ductile materials under static loading, stress concentrations can typically be ignored, as the local plasticity will result in yielding at the stress riser, but the lower stressed material in the bulk of the material will not yield. Once the entire remaining cross section surpasses the yield point in a statically loaded ductile material, the sample will fail. In a brittle material, a stress concentration will have a more substantial effect on the strength of the material. This is because a brittle material does not have a region of local plastic deformation, rather the entire specimen will yield at once. As soon as the stress experienced at the stress concentration surpasses the yield strength of the material, a crack will form that will propagate through the statically loaded brittle specimen. [17]

A stress concentration in a cyclically loaded specimen is different. A crack will grow with cyclic loading at a stress concentration. This results in a different stress concentration factor used in fatigue loading. Notch sensitivity is a value used to determine the corrections applied to estimate the impact of a stress concentration on a dynamically loaded ductile part under cyclic fatigue loading. [16]

1.5 Stress Intensity in Fatigue

Linear Elastic Fracture Mechanics (LEFM) is used to describe how a stress intensity factor is modeled. A stress intensity is a stress field imposed by a sharp crack tip and a stress applied. A stress concentration factor depends on many geometry related factors while a stress intensity factor depends only on the crack length and how it is placed in the overall surroundings. It is assumed that the crack tip is very sharp and not round like a stress concentration. A stress intensity factor is useful in determining the potential for a crack to propagate, as if the stress intensity factor at a crack is below the allowable threshold stress intensity factor, the crack will not propagate. [18] [19] [20]

A stress intensity factor is calculated in a certain fracture mode. Mode I is a crack that is opened and pulled in tension. Mode I fracture is the most common fracture mode reviewed due to the mechanical advantage of a crack opening with displacement orthogonal to the crack face. Mode II crack displacement is loaded in in-plane shear, as the crack face slides over itself. Mode III crack displacement is loaded in
out-of-plane shear. Mode I crack opening is the applicable fracture mode for this research as all specimens were loaded in tension-tension fatigue loading. [17]

Fracture mechanics is applied to a part with a crack and a small zone of yielding when compared to a much larger part cross section. Linear Elastic Fracture Mechanics allows a bulk cross section of a material to perform in accordance with traditional mechanics, while a crack propagates in accordance with a secondary set of equations which can model the stress field around the crack tip. This assumption is good for use with the studies discussed in this thesis as all of the cracks and initial defects are orders of magnitude smaller than the cross section of the specimens.

1.5.1 Derivation of the Stress Intensity Factor

A stress intensity creates a stress field around the crack. Westergaard developed a solution using Airy’s stress function that enables the calculation of the stress field around the stress intensity. Equations 1.1, 1.2, and 1.3, model the stress field around a stress intensity. [21]

\[
\begin{align*}
\sigma_{xx} &= \text{Re} \ Z - y \text{Im} \ Z' \\
\sigma_{yy} &= \text{Re} \ Z + y \text{Im} \ Z' \\
\sigma_{xy} &= \text{Re} \ Z - y \text{Im} \ Z'
\end{align*}
\]  

Where \( Z \) and its derivative \( Z' \) are in terms of stress applied in equations 1.4 and 1.5.

\[
Z(x + iy) = \frac{\sigma_\infty}{\sqrt{1 - (\frac{a}{x + iy})^2}}
\]  

\[
Z'(x + iy) = \frac{-\sigma_\infty a^2}{(x + iy)^3 \left[1 - \left(\frac{a}{x + iy}\right)^2\right]^{2/3}}
\]

As an example, the Westergaard solution develops a stress field in the y direction for a mode I crack shown in equation 6, where crack length (a) is in x dimension.

\[
\sigma_{yy} = \frac{\sigma_\infty}{\sqrt{1 - (\frac{a}{x})^2}}
\]  

Irwin used the Westergaard solution and solved for the \( Z \) and \( Z' \) terms using an equation to convert the imaginary \( x + iy \) term in terms of crack length and crack tip radius. In keeping with a stress
intensity, he used the assumption that the internal radius is too small to be of use and therefore the crack length dominated the stress approximation. This enabled a crack tip solution in equation (1.7) which is directly comparable against and nearly in agreement with the Westergaard solution in equation (1.6). [22]

$$\sigma_{yy} = \frac{\sigma_{\infty}\sqrt{\pi a}}{\sqrt{2\pi r}}$$  

This model from Irwin is just an approximation while the Westergaard solution is exact, but the Irwin approximation enabled the development of the stress intensity factor which is absolutely paramount to fracture mechanics. The stress intensity factor (K) utilizes the term in the numerator of Irwin’s approximation, where a is crack length. [22]

$$K = \sigma_{\infty}\sqrt{\pi a}$$  

A stress intensity can be calculated using a stress intensity factor shown in equation (1.8). This factor is calculated from a shape factor, a crack length, and a stress value. There is no need to look at notch root radius or other geometric factors, as they are all taken into account with the infinitely sharp corner and the shape factor. The shape of the crack and the boundaries of it will form a shape factor approximation Y, which is a primary focus of this work, in order to apply to a variety of crack conditions and locations in equation (1.9). [20]

$$K = Y\sigma_{\infty}\sqrt{\pi a}$$  

1.6 Change in Stress State at a Notch

A stress concentration functions as a stress riser, a localized region where stress is higher and therefore more likely to yield or fracture. A stress intensity has a more dramatic change in stress experienced around a sharp crack. Fatigue loading combined with a stress riser will result in a gradually growing crack front. The change in stress at this corner or crack can be shown on a Mohr’s circle in order to demonstrate the tendency to fail in brittle fracture rather than in ductile yielding, as is typically expected for a ductile material like 316L stainless steel. A Mohr’s circle is a 2-dimensional diagram of a stress transformation for a component, which will incorporate a vertical shear stress axis and a horizontal normal stress axis. The intersection of the circle correlates to the maximum shear and maximum normal stresses experienced.
1.6.1 Stress Triaxiality

Under a uniaxial stress state, without any stress concentration, stress is simply modeled as a force over an area and lacks any consideration of a surface condition. On a Mohr’s circle diagram, the circle intersects at only the origin and at the stress applied, as shown in Figure 1.1a.

![Figure 1.1](image)

Figure 1.1 A 100MPa uniaxial normal stress compared to the same 100MPa stress, in a triaxial state

At a higher applied stress, the Mohr’s circle needs to breach either the yield stress ($\tau$) to begin deforming plastically, or the Mohr’s circle needs to breach the fracture stress ($\sigma$) to experience brittle fracture. For 316L in a uniaxial stress state, this yield stress is lower than the fracture stress and therefore under uniaxial loading, excluding ultra-high strain rates, the specimen is likely to first undergo ductile deformation before experiencing any brittle fracture.

A biaxial stress state is one in which the stress is applied in two orthogonal directions and occurs in all specimens at the sidewall under tensile loading. Triaxial stress states occur at a corner, and this leads to a higher likelihood of brittle failure. As the stress triaxiality increases, the likelihood of brittle fracture increases, and this is the reason for brittle fracture occurring at a region with a crack. The crack changes the stress field near the crack tip. A triaxial stress state increases the normal stress experienced while decreasing the shear stress experienced as shown in Figure 1.1b. This means that a higher degree of stress triaxiality will result in more brittle fracture and less ductility. [23]

1.7 Fatigue Failure

Fatigue failure strength data is derived from several specimens tested at a number of various levels of cyclical stress ranges. This generates a curve of the specimen’s cycle counts and the stress
applied. This allows for the understanding of stress ranges and expected lifetimes for a given material, and this varies from one material to another. A second important consideration is the stress intensity factor range experienced by a material under cyclic loading. [24] As the stress intensity depends on the load applied, as well as the crack length, an increase in either value changes the stress intensity at any given moment. A stress intensity factor range is the difference between the maximum and minimum stress intensity applied. [25]

When a crack attempts to move through a material, it will go through three different crack growth rate regimes. A threshold stress intensity factor is the minimum stress intensity factor required for a crack to begin to propagate. This first regime, where a crack initiates, has a very slow crack growth rate which increases progressively as the stress intensity factor increases due to crack length increases (assuming the cyclic stress applied remains unchanged). The second regime is where a crack grows steadily and is shown as a simple straight line on a crack growth rate plot. Finally, the third regime is where a crack begins to grow at an unstable rate once again and proceeds to a given critical stress intensity factor that ultimately results in fast fracture. [26]

A crack will propagate only above a threshold stress intensity factor and therefore this is an important consideration when there is a defect in a material, as the stress intensity factor will be impacted by both the stress applied and the crack length. Crack growth rate is impacted by the ratio of the applied stress, with a larger mean stress applied resulting in a faster crack growth rate at every stress intensity factor. Additionally, a larger mean stress applied results in a lower stress intensity factor threshold. [16]

1.8 Minimum Defect Size to Initiate Failure

Given the requirements of a stress intensity factor of a single pore to be greater than the stress intensity factor threshold, there exists a minimum acceptable defect size for a material that undergoes a known stress. There also exists a maximum acceptable stress for a material with a pre-existing crack or defect in it. There are various models for how these defects can come to initiate a crack and result in a part failure. [27]

1.8.1 Fatigue Life Models for Defects

The Kitagawa-Takahashi model is an infinite life stress modifier that draws from the idea of a critical defect size. [28] 316L stainless steel has an endurance limit, meaning under some loading conditions, the stress applied will never result in part failure for an ideal specimen free of defects. The Kitagawa-Takahashi diagram is a method of extrapolating upon this principle for finding the stress to achieve infinite life in a part with a flaw. The model states that the stress where the part will not fail is constant up to a certain critical flaw size where the stress will begin to decrease as the flaw size increases. [27] [29]
Following this same theory, El Haddad developed a theory on finding a critical defect length. He based his research on a crack propagating above the threshold stress intensity factor for a material and the rate at which such cracks propagate based on varying crack lengths. Both these theories are shown in Figure 1.2. He found that crack growth rate predictions were unable to accurately determine short crack growth rates, due to the fact that the approximations were fitted to long crack growth data. The crack can be modeled accurately by forming a calculation for $l_0$, the effective crack length, which can be calculated using the endurance limit and the threshold stress intensity factor. This factor is able to be used to determine short crack growth and crack initiation from a flaw as shown in equation 1.10. This is then also able to be used to determine the stress a part with a flaw can endure with infinite part life in equation 1.11.

\[
\Delta K_{th} = \Delta \sigma_{th} \sqrt{\pi (l + l_0)} 
\]

\[
\Delta K_{th} = \Delta \sigma_e \sqrt{\pi l_0} 
\]

Murakami described methods of approximating defect size and determining the influence on fatigue life. Murakami showed that there exists a correlation between infinite fatigue life and defect size by using Vickers hardness, though this model in equation 1.12 is not implemented in this thesis. [32]

\[
\sigma_{wl} = 1.43(HV + 120) / \sqrt{area_{eff max}}^{1/6} 
\]

Murakami also demonstrated the utility of a semi-elliptical area approximation for defects that initiated crack growth as a meaningful method of obtaining the size required to calculate their respective
influence on the fatigue life calculation. This method is critical for determining pore and flaw influence and remains a common way to measure defects in additive manufacturing fatigue literature. [32]

1.9 PBF-LB Flaws and Effect on Fatigue

1.9.1 Fatigue of Wrought 316L

316L Stainless steel has been studied for use in different industries and applications. Fatigue studies of 316L have quantified material properties and common characteristics. Mohammed et al. found that 316L specimens manufactured by machining had a fatigue limit (defined in these studies of 1E7 cycles) of 146 MPa, while Wood has found the fatigue limit to be substantially higher at 400 MPa. [33, 34] The variation comes down to how the processing was done to the material that result in earlier failure and microstructural variations.

1.9.2 Fatigue of PBF-LB 316L

It is challenging to compare PBF-LB results across different studies due to the nature of machines using different processing parameters resulting in very different specimens. Some specimens might have substantially higher porosity and different microstructures due to the differences between primary process parameters as well as different intrinsic machine processing parameters. [12] [35] [36] [37] The general trend, however, is clear. PBF-LB performs below wrought counterparts. Wrought machined 316L Stainless Steel shows greater fatigue life at all stress levels when compared to PBF-LB Stainless Steel specimens. [38] This is thought to be a product of the surface roughness and surface porosity. Rough surfaces and surface pores introduce stress concentrations and stress intensities that will decrease the fatigue life of any specimen. [39] [40] [41] Murakami describes 80-90% of part failures are the result of fatigue loading, and of those fatigue failures, nearly 100% result from a stress concentration at a defect. [32]

The print vs loaded orientation has been shown to play an important role in the fatigue life. [40] Many studies have found horizontally printed specimens to have slightly better fatigue performance when compared to vertically printed specimens. The microstructure also plays an important role in fatigue life, as the columnar grain growth in the build direction commonly seen with PBF-LB specimens resists early crack growth because of the orientation of grain boundaries relative to a mode I crack, when the build direction is the same as the loaded direction.

1.9.3 PBF-LB Defects Initiating Failure

PBF-LB has a number of characteristic defects. Keyhole porosity and lack-of-fusion porosity, as well as the surface roughness and changes at the contour are the largest issues with additive manufacturing that result in impactful defects. [2] Some examples of this have been inadvertently
documented in literature as there have been a number of studies that explore stress concentrations in 3D printed geometries, only to find there was an internal or surface pore that started a crack. [42] Due to the failure prediction methods described above, there exist minimum defect sizes to initiate a fracture and as such, fatigue crack initiation has been shown to be dependent on pores in more defective samples, but in dense specimens, a combination of defect pores and subgrain size influenced the fatigue limit. [43] The grain size and the subgrain size were shown to increase with the volumetric energy density. [44] It has, however, also been shown that in general a larger percent porosity will yield a shorter fatigue life and lower strength. [45, 46] Additionally, [39] demonstrated that surface roughness and defects at the surface result in lower fatigue life and tensile strength. [47] [48] It is often shown that machining the surface off does provide improved fatigue performance. Fatigue life was shown to be lower in specimens with defects at the surface, common in additively manufactured PBF-LB specimens. Additionally, it was found that the majority of defects capable of crack initiation were located within 250 µm of the surface. This is particularly applicable to the work described in this thesis as all of the specimens involved were tested with their as-printed surface condition. [38] [49] [50]

1.9.4 PBF-LB Microstructure

316L Stainless Steel produced by PBF-LB has a widely documented and predictable microstructural evolution. [51] The grains formed during the laser powder bed fusion process form as columnar grains in the print direction. The microstructure has a few impacts on the fatigue crack growth rate of cracks and the ability of cracks to propagate. [52] One way this has been discovered is through analysis of vertically and horizontally printed specimens. Vertically built samples perform differently from horizontally built samples in uniaxial tension fatigue. Yu et al. found that vertically built PBF-LB 316L SS samples exhibited longer fatigue life than horizontally built specimens after about 350 MPa total stress amplitude, but that horizontally built specimens performed slightly better at stress levels above 350 MPa. [53] The researchers reasoned that this was due to the possibility of the high angle grain boundaries of the columnar grains in the vertically built samples providing a barrier to crack propagation. They also found that with their high density PBF-LB parts, the defects within the part caused no discernible impact on the crack growth, rather the microstructure appeared to provide the difference in crack growth. Riemer et al. demonstrated that microstructure following solidification dramatically affected fatigue crack behavior of 316L processed by selective laser melting (SLM). [54] [55] Crack growth rate in the first regime was seen to vary substantially based on the crack growth direction in relation to the long grain axis. HIP was able to provide isotropic crack growth behavior, but the as-built condition demonstrated these anisotropic fatigue crack growth behaviors.
1.9.5 Impact of AM Build Interruptions

A build pause is not a well-documented occurrence and parts are usually just cast aside. The literature regarding a build pause for a PBF-LB process is sparse and contains very little information on characterizing the build pause layer and the influence it has on fatigue, if any. It is clear that a build pause can affect microstructure and mechanical properties of a material. [56] Only 1 study has reviewed specifically PBF-LB 316L SS as it pertains to a build interruption. The build pause was 60 minutes long and at approximately half height, allowing the parts to cool as well as exposing them to the open atmosphere. The restart procedure was done in two batches, the parts were either scanned once before a new powder layer was deposited, or the parts were scanned 3 times before the new powder layer was deposited. Stoll et al. demonstrated that in all circumstances a build interruption did not result in a line or feature that will be identifiable on a polished and etched sample. A tensile sample did show locations on the fracture surface where there were visible laser scan tracks, indicating the layer deposition and scan was disrupted by a factor of the build interruption. It was also found that the build interruption did have some influence on the tensile strength of the specimens as it decreased both the horizontally and vertically printed specimen strength, but it was more pronounced on the vertically printed specimens. They also tested a hybrid bar that was partially made by machining and partially made by printing on the top half of the machined bar, which did not break consistently at the joint of the two different techniques, demonstrating the effectiveness of the PBF machine in that unique application. [57]

Other studies into build pauses have reviewed grain morphologies and mechanical performance of different alloys in the presence of a build pause. Richter et al. produced a study that compared an uninterrupted print with a print that had a 1-hour build pause with atmospheric exposure. Richter found that a build pause had a negligible effect on the tensile properties of PBF-LB AlSi12 and the fatigue testing revealed no substantial cause for concern regarding the build interruption, but the fatigue limit for both high cycle and very high cycle fatigue specimens was slightly lower on the build pause specimens. Richter found melt tracks on the fracture surfaces of the build pause specimens, which broke at the build interruption, possibly related to an oxide forming when the build chamber was exposed to open air. [58] For AlSi10Mg, two studies examine the tensile properties as a result of a build pause. Binder et al. printed several specimens at a preheated 200°C with varying build interruptions. [59] All three batches had an initial print time of 113 minutes at which point the internal recorded temperature using thermocouples was 130°C. The first batch was then only cooled by about 13 degrees before the print continued nearly instantly after the print had paused. The second batch and the third batch shared a 41 minute break without continuous substrate heating and the temperature dropped by 76 °C. The second and third batch differ by the restart procedure, where the second batch was slowly heated and attained a total temperature decrease of 26 °C, while the third batch was quickly restarted without an extensive reheate and had a total temperature drop of 70 °C at time of restart. Binder was able to characterize the
surface as well as the microstructure and it was clear that some degree of remelting had occurred. The surface was shifted and the layer with the build interruption was clearly visible for this print. Binder et al. did not, however, find any substantial difference in the tensile properties unless the build pause was combined with remelting. Hammond et al. produced two batches of samples. The print was pre-heated to 200°C and then printed approximately 41mm of height, before the print was paused, the substrate was removed from the build chamber, all excess powder was cleaned and removed, then the substrate was returned to the build chamber and re-started after a 200°C preheat. The second batch was normally printed tensile bars with the 200°C preheat. Hammond found that while the build interruption had little impact on the tensile strength of the AlSi10Mg specimens, there was a substantial amount of localized failure at the layer where the build interruption occurred. X-ray CT in this study demonstrated no internal voids or flaws at the location of the build pause. [60] Alterations to the material could come from atmospheric or temperature changes. [61] [62]

1.10 Contributions

This research seeks to further develop the understanding of flaws on fatigue properties of 316LSS, based on what is already explored and what has yet to be shown in literature. This document seeks to address the lack of a substantial body of literature of PBF-LB 316LSS with a build pause tested in fatigue. The work performed in this document feeds into a qualification framework that could be used for a layer shift or a flaw. The primary contributions of this work are:

1) Test additively manufactured steel bars with a witness line in fatigue.

2) Determine the relative magnitude of a stress intensity factor of process flaws vs witness line under fatigue loading.

3) Predict the usable life of an AM sample with a witness line or flaw.
CHAPTER 2 EFFECT OF A BUILD PAUSE ON THE FATIGUE BEHAVIOR OF LASER POWDER BED FUSION 316L STAINLESS STEEL WITH AS-PRINTED SURFACES

Build pauses can occur during metal additive manufacturing (AM) with laser power bed fusion (PBF-LB) for a variety of reasons such as power outage, insufficient gas flow, or sensor failure. It is economically desirable to continue a build after the issue is resolved. However, the effect on part quality, such as microstructure, surface roughness and geometric features is not well understood. This study considers parts fabricated with a 2-hour build pause in the center of the gauge section. Quantitative comparisons of the dimensions, as-built surface features, microstructure, and fatigue performance are determined. Geometric deviation from part shift during the build pause location is significant, however other anomalies inherent to AM can still dominate failure. Understanding the effect of material changes from a build pause can help reduce scrap from unintended build interruptions.

2.1 Material and Methods

2.1.1 Material

The specimens were printed from 316L stainless steel powder. The size of the powder was characterized with a mean size of 32.9μm diameter. The lower 10% of the powder was of size 20.3μm, the D50 was 33.47μm, and the D90 was 53.8μm. The powder was in its twelfth re-use. 12 reuses correlates to 942 total hours of printing time.

2.1.2 Additive Manufacturing Build

Forty vertical fatigue bars were printed on a 3D Systems DMP Flex 350 PBF-LB printer. The print layout is shown in Figure 1 and the samples used for this study are labeled 1-30. The processing parameters were laser power (300 Watts), laser speed (900 mm/s), hatch spacing (100 μm) and layer height (60 μm), which are the default processing conditions. The bars were removed from the build plate using electron discharge machining (EDM) and with no additional post processing. The geometry of the printed specimens is shown in Figure 2.1. The large rectangles are tall plates that were printed but not used for this study. The large circles are medallions that extend only slightly above the build platform and were not used for this study. The small circles are the fatigue bars that were used in this study.
2.1.3 Build Pause

The build pause was unplanned but occurred very near the center of the gauge section of the fatigue bar. Approximately halfway through the build, at layer 842 out of 1707 layers in total, the system experienced a pressure error and stopped the print part way through the scan of this layer. The build chamber remained under the inert environment during the build pause. 142 minutes elapsed before the print was restarted, at which point a manual re-coat was performed and the entire layer was re-scanned before continuing the print. This build pause produced a visible witness line on the surface of the fatigue specimens at the pause location.
2.1.4 Fatigue Tests

Force controlled ASTM E466 fatigue testing was performed on a MTS 370.10 Landmark 22.5 kip load frame at 20 Hz over a variety of maximum stress levels between 150 MPa (the point at which a test bypasses the designated runout of $10^7$ for this work) and 450 MPa (the approximate yield stress of the printed material based on previous tests). The stress ratio tested was 0.1 for all samples. Several fatigue tests were completed at each level. All fatigue testing was on the same machine at different times and in a random stress and specimen order. Specimens with larger measured surface shifts were spread throughout the whole range of max stress amplitudes tested. The test would reach a steady state force input and establish a specific range of parameters. As a crack propagated through the specimen, the compliance changes and the machine detects the decrease in the force for a smaller cross section and terminates the test. The initiation location was known due to this test procedure as once the fatigue force dropped below 75% of the steady state testing parameters, the test would conclude and the specimen would be manually pulled apart by an operator leaving a region of overload failure. The region of fatigue crack growth was then noted to be on the opposite end of the fracture surface from the overload failure region.

2.1.5 Material and Surface Characterization

2.1.5.1 Laser Confocal Scanning Microscope Surface Measurement

Every specimen was scanned several times under an Olympus laser scanning confocal microscope. This was done to characterize the layer shift and the specimen surface roughness. The layer shift was to be characterized around the circumference of every cylindrical specimen by taking images at the 12:00, 3:00, 6:00, and 9:00 locations at the same height as the layer shift. This collected light microscope images, laser intensity images, and height data for each side of every specimen. A single surface measurement was taken away from the build pause to serve as a representative data point for the surface condition away from the layer shift.

2.1.5.2 Layer Shift Magnitude Characterization

Each of the images taken was then filtered in OmniSurf3D in order to achieve an understanding of the surfaces. The specimens were first unwrapped (due to their circular cross section) before filtering took place. There were several different band pass filters attempted until the filter was able to effectively extract the profile of the specimen. The filter was different between the circumferential direction and the build direction. The filter in the build direction was a short wave gaussian filter of 0.4mm with a long wave gaussian filter of 25mm in order to capture large magnitudes. The filter in the circumferential direction implemented a short wave gaussian filter of 0.4mm with a long wave gaussian filter of 0.5mm. Each of the images for all the specimens was sorted and worked in a batch process with the filtered $Sz$ (peak to valley) tabulated for each image. The largest layer shift magnitude was taken from each sample.
2.1.5.3 Surface Roughness Characterization

A surface image taken from a part of the specimen away from the build pause was used in a characterization of the surface. There was also a filtering step done to obtain information about the pit depth of the surface. The surface of the sample was unwrapped and fed into a band pass filter with the long wave gaussian filter at 0.6mm and the short wave gaussian filter at 0.015mm to effectively filter the surface without losing the features of interest. A single $S_v$ value (deepest valley below mean) was collected as a characteristic value.

2.1.6 Fractography

The laser scanning confocal microscope and a scanning electron microscope were used to capture high magnification images of defects on the fracture surfaces. The laser images have the highest resolution and best clarity due to the highly reflective surface features at the fracture initiation sites. Defects on the fracture surface were measured and characterized by placing the images into ImageJ and highlighting and calculating the defect area. The images for the surfaces were all taken at 10x or 20x magnification. The working distance for the 10x magnification was 10.4 mm, while the 20x magnification lens had a working distance of 7.4 mm. The images were taken on the standard resolution mode (1024x1024 pixels) and the high-resolution mode (4096x4096 pixels). Scanning electron microscope images were valuable in determining the flaws that resulted in crack initiation. The flaws were similarly identified and measured, but the SEM images were able to provide a better resolution of the correct defect and discerning radial marks. SEM images were taken at a working distance of between 13 and 14 millimeters on a FEI Quanta 600i ESEM using secondary electron detection. The spot size was 5mm with a 20 kV accelerating voltage, using an Everhart Thornley detector.

2.1.7 Microstructure Characterization

One specimen was mounted, ground, and polished to observe the microstructure at the build pause location. The round edge of the fatigue bar near the large step was polished approximately 1 mm into the sample to provide a surface for imaging. Electron backscatter diffraction imaging (EBSD) was used to characterize the grain structure at the build pause and below the build pause to determine if the modification of the thermal history affected the microstructure. The grains were colored according to orientation and the boundaries were highlighted. The EBSD imaging took place on a FESEM – JEOL 7000F and EDAX EBSD camera. The working distance was 20mm and the step size was 3.0 $\mu$m with a 20 kV accelerating voltage.
2.2 Results

2.2.1 Fatigue Testing

![Fatigue Testing Graph](image)

Figure 2.2 The S-N curve depicting the fatigue life of all the specimens. All specimens have as-built surface condition. The results from this study are compared against a separate build that did not have a build pause, but still retains the as-built surfaces, acting as a control.

An S-N curve was developed in order to visualize the results of the fatigue testing. The S-N curve is shown in Figure 2.2. The results of this study are compared against a separate build that did not have a build pause. All specimens from both builds are tested in the as-built surface condition. Specimens failed at the same approximate cycle counts with minimal spread in the data. This indicates that there is a competing effect between the layer shift and other defects in the component that will lead to failure. The build-pause specimens also appeared to perform slightly lower than other literature values for 316L PBF-LB fatigue [63] [64] [65].

2.2.2 Variability in Fatigue Testing

Despite having a very close SN curve, some of the fluctuations in the points could likely be explained by the variation in the test conditions. The fatigue testing was set at a given stress level for each specimen at the R value of 0.1. The stress level was determined from the cross-sectional area measured with flat calipers on the cylinder. With the rough surface, measurement error can play a factor as flat calipers will not perfectly obtain a cross section as it sits on the peaks and measures the extra sintered powder on the edges and the imperfect ridges from the PBF-LB process. This introduces some error, but the consistency in the measurement method should at least retain the precision of the measurement method, if it does not maintain the accuracy.
Some fatigue error could also come from drift in the PID controls background as the feedback loop settles. It was noted on occasion that upon returning to the machine, the force applied had drifted by a few percent (4% at most) on either the top end or the bottom end, but never drifting enough to trigger the 25% force drop condition to stop the test.

2.2.3 Effect of Layer Shift

2.2.3.1 Characterization of Build Pause Layer Shift

Figure 2.3 demonstrates the results of the EBSD scan at the build pause. There is a black line that indicates where the build pause occurred. There was no apparent change to the microstructure at the build pause. The cooling and solidification of the material is therefore similar enough that the grain morphology is the same before and after the build pause. Because of the rapid cooling associated with PBF-LB AM, it is commonly seen in literature for AM microstructures to exhibit these largely columnar and highly oriented grain structures. [5] [7] [66] [67] [68] [69]

The build pause location identified with the line.

The microstructure was also analyzed in additional locations and several depths below the build pause location in order to ensure there were no microstructural changes to lower layers as a result of the build pause. Note that the black spot with unreasonably miniscule grains on Figure 2.3 is area off the specimen and is not representative of a microstructure as it is the mounting media.

2.2.3.2 Magnitude of Each Layer Shift

The original design of the fatigue bars is shown in Figure 2.4A. The fatigue bars each suffered from a visible witness line at the point where the build pause occurred as shown in Figure 2.4B. This surface defect was characterized as a translational shift on the specimen as illustrated in Figure 2.4C. All
of the specimens exhibited a sharp internal corner at the layer shift where the completed layers moved uniformly in one direction. The shape and magnitude of the surface shift was quantified for every specimen. The magnitude of the shifts on each specimen varied between 65 µm and 137 µm and appeared to correlate positively with the distance from the center of the plate, while the specimens furthest from the center exhibited the highest magnitudes of translational shifts. An example of the quantified measurement of the surface shift is shown in Figure 2.4D. Many of the specimens exhibited a small amount of material at the backside of the layer shift. This layer shift was so substantial that it was visible to the naked eye and could be felt with a finger at the surface.

Figure 2.4  A is a schematic of the design. B is the actual visible line on the fatigue specimen. C shows a schematic of the surface shift. D is a filtered edge profile to demonstrate the magnitude of the specimen shift.
Figure 2.5 shows the failure location relative to the build pause, and the dimensional magnitude of the layer shift at the witness line. Over half of the tested specimens failed as a result of the shifted witness line at the build pause. The fracture surfaces for the specimens that did not fail at the witness line are investigated in the following section to determine the failure mechanism.

The fatigue tests also produced inconsistent failure location. Nearly half of the specimens broke at the build pause witness line, while the other specimens broke at varying locations along the gauge length. The failure may have occurred at different places in the gauge section, but this did not result in a drastically different fatigue life. Specimens that broke at the build pause exhibited similar part life as specimens that broke away from the build pause. This indicates that the build pause, or a substantial defect elsewhere in the part results in failure. Applied stress did not appear to have an influence on whether or not the specimen failed at the witness line or at a different location along the gauge section.

It was found that the larger translational steps were more likely to result in failure at the shifted layer than smaller translational steps. Failure occurred at the larger layer shifts in 70% of cases, but only in less than 50% of all other layer shift categories in this study, with the lowest magnitude of layer shift resulting in only 25% of these specimens failing at the layer shift. This is likely due to larger stress intensities at those locations that result in failure. This suggests that just as with the stress intensity factor threshold for crack propagation, there exists a critical defect size for the layer shift.
2.2.4 Fractography

Representative fracture surfaces captured via SEM are shown in Figure 2.6. The fracture surfaces all exhibited features characteristic of brittle failure due to fatigue failure. The specimens that broke at the build pause witness line proved challenging as they did not demonstrate a singular large defect resulting in failure, rather they had a radial fracture morphology normal to the circumference of the cylinder. This is in stark contrast to the specimens that broke away from the witness line, which all exhibited fairly obvious and substantial defects that contributed to the part failure at that location.

Figure 2.6 A variety of defects that resulted in failure imaged on SEM. A and B demonstrate the radial fracture surfaces on a specimen that failed at the build pause. C and D illustrate how defects result in clear fracture initiation sites.

The witness line resulted in fracture in Figure 2.6 A and B, with a few cracks initiating circumferentially around the specimen and moving inward, similar to cracks seen on notched fatigue bars.
These fracture surfaces are characteristic of each of the parts that failed at the build line, indicating the consistency of the fracture morphology on the specimens that failed at the build pause witness line.

The defects that initiated failure away from the build pause have interesting and distinct morphologies. Some appear to be lack of fusion, some are clearly spatter particles that got embedded in the surface, and some are entire sections of contour that were torn out with the fracture. The very noticeable defects that caused failure away from the build pause have example areas shown in Figure 2.6 C and D. The defects can easily be shown to have substantial marks around them, such as radial lines, that demonstrate the origin of failure. A very obvious defect is noted in Figure 2.6 C with a notch in the surface. This large defect was the initiation location of the failure and has characteristic radial lines. In Figure 2.6 D a large void is shown and clearly initiated fracture with the radial lines that move away from it. Figure 2.6 C and D therefore illustrate large defects that caused failure of the specimen. The way that the radial lines and fracture surfaces appeared demonstrated the mechanism of crack initiation.

![An SEM image of a specimen with multiple crack initiation locations](image)

Figure 2.7 An SEM image of a specimen with multiple crack initiation locations

Some specimens exhibited multiple interesting crack initiation locations. One such specimen is shown in Figure 2.7. This is a sample with several crack initiation locations and as a result has two distinct features on the fracture surface where the cracks eventually connected. The resulting fracture surface comes from several cracks initiating at flaws, both of which demonstrate substantial stress intensity factors. The two individual flaws exhibit similar radial lines and can be easily identified. The cracks both initiated independently of one another, one crack did not start because of another one, rather, they likely started around the same time in the fatigue life due to the similar lengths of the crack propagation when they met up. Other samples exhibited multiple cracks, though on different printed
layers, so they did not meet up. For those other samples, there was one clearly dominant crack that resulted in failure.

2.3 Conclusion

This chapter investigated fatigue performance of a PBF-LB print that experienced a pause in the build, resulting in a visible witness line on the surface. This witness line is a dimensional shift at the layer where the build pause occurred. The impact of this build pause on the fatigue life of the specimen appears to be driven by the geometric magnitude of the shift and there is no change in microstructure observed at the build pause.

The layer shift at the build pause location led to failure in more than half of the specimens, likely because of the increased stress concentration at that location. The specimens that failed at the layer shift exhibited substantial radial fatigue growth marks demonstrating that it was not a single point, but rather a notch type of stress concentrator at this location. The magnitude of the layer shift also appears to influence failure, with the larger shifts more often leading to failure at the build pause location.

However even with the presence of this layer shift stress concentrator, other defects inherent to the AM processing, such as surface roughness and porosity, still initiated failure in some specimens. This indicates that there are competing effects from large layer shifts and other large defects for which initiation site will lead to failure.

This work provides insight toward the impact of a witness line on fatigue failure which can inform acceptance criteria for this type of print anomaly and potentially decrease overall scrap rates. A smaller layer shift may be acceptable if the part is in the fully as-built surface state because there are other flaws that would lead to a similar fatigue life with failure occurring in other parts of the specimen.

Because the internal features of these specimens were not affected by the build pause, a post-processing surface treatment could be used to remove the witness line. The next chapter seeks to create a unified framework to determine how dimension of the various flaw categories present in AM PBF-LB material lead to failure. Understanding the influences of flaws on fatigue behavior can provide guidance for post-processing requirements and necessary design guidelines around critical defects. The next chapter works to create a comparison between the flaws and the layer shift, and develops a meaningful way to review the influence they have on part life.
CHAPTER 3 STRESS INTENSITY FACTORS AND FATIGUE LIFE PREDICTION FROM MULTIPLE FLAW TYPES

Fatigue life of a specimen will decrease with a flaw. AM is known to have process induced flaws. These individual flaws are characterized and measured for use in determining their individual stress intensity factors. Some surface flaws were results of spatter, whereas others were apparent lack of fusion. Despite these differences in formation mechanism, they can still be modeled with a stress intensity factor. The build pause resulted in a layer shift that acts as a stress concentration. To compare the build pause layer shift to individual surface flaws, the build pause witness lines are modeled using a stress intensity factor approach. The stress intensity factor of a layer shift can be used in a number of different round bar crack models, as it includes a way to calculate different stress intensity factors with the presence of a stress concentration factor. The stress intensity approximation for both the surface flaws and the layer shift is then used in a model based on the El Haddad model of a non-propagating crack. This specific model presented is tailored for 316L SS manufactured via PBF-LB, as it implements a wrought material condition and modifies the wrought material condition with a defect stress intensity factor criterion from the data in this study. The prediction of the stress-life for parts with various defects is modeled in the context of stress intensity factors and correlates well with the data in this work.

3.1 Methods

3.1.1 Stress Intensity Calculation from Surface and Near-Surface Flaws on Fracture Surfaces

Individual defects were characterized by first reviewing the image for radial lines or any other indicator of fatigue crack growth. Usually, the best method was to search along the edge of the fracture surface on the side where the crack had initiated. For the surface flaws that resulted in failure, an area calculation was undertaken from the fracture surface to determine the size of each individual flaw that initiated a crack. This flaw size was calculated using ImageJ [70] and was used in order to ultimately calculate the approximate stress intensity at this defect on a specific part. These defects were characterized by the method outlined by Murakami. [32] By approximating the abnormally shaped defect to a semi-elliptical defect area, this area can be used in a stress intensity equation to determine the influence of this specific flaw. The calculation is at its root, just a simple stress intensity equation, with a designated shape factor and the defect area given by the semi-elliptical approximation.

The stress intensity factor range from each of these can be modeled by using Equation 3.1.

\[ \Delta K = Y \Delta \sigma \sqrt{\pi \text{area}_{\text{eff}}} \]  

(3.1)
The surface pit depth below mean was utilized in a single stress intensity calculation based on Murakami’s surface roughness approximations. He developed a model for a rough surface and adapted it to several different types. For this particular paper, it is important to note the correct defect calculation. For a surface similar to the highly variable additive manufactured surface, it is assumed to be a periodic rough surface but with the assumption that the deepest surface notch is the point of interest. For deeper and sharper surface cracks, as is appropriate for additive samples, the stress intensity can be modeled by Equation 3.2 where $a$ is the crack length. Equation 3.2 takes a geometric correction factor $F$ which can be approximated by the size and shape of the surface finish. \[ K_I = F\sigma_0\sqrt{\pi a} \] (3.2)

### 3.1.2 Stress Intensity Calculation from the Layer Shift

The layer shift was also characterized by a stress intensity approach, albeit by a more substantial one. The layer shift functions as a stress concentrator and can be modeled as a stress intensity, as described by Pasman. [18] The stress intensity factor approximation was derived from a large number of points for different stress ratios, different geometries, and varying stress concentration magnitudes. This uses a measured crack length at each point and develops a stress intensity model from this. A curve was fitted to this experimental data and a unique shape factor for use in a stress intensity factor equation was formed. This stress intensity factor approximation is in the same form, but the shape factor equation includes a number of constants and inputs.

First, the normalized crack length relative to the diameter of the round bar is used to calculate the shape factor shown in equation 3.3, where $a$ is the crack length and $D$ is the round bar diameter.

\[ \beta = \frac{a}{D} \] (3.3)

This normalized crack depth is fed into equations 3.4 and 3.5. Equation 3.4 represents a constant for the sake of equation simplification, and equation 3.5 is a curve fit for the shape factor. This shape factor, $Y$, depends only on $\beta$, the normalized crack depth, and assumes a perfectly round bar without another geometric stress concentration.

\[ g = 0.92 \left( \frac{2}{\pi} \right) \left[ \frac{\tan\left( \frac{\pi \beta}{2} \right)}{\frac{\pi \beta}{2}} \right]^{0.5} \] \[ \cos\left( \frac{\pi \beta}{2} \right) \] (3.4)
\[ Y(\beta) = g \left[ 0.752 + 2.02 \beta + 0.37 \left( 1 - \sin \left( \frac{\pi \beta}{2} \right) \right)^3 \right] \] (3.5)

The shape factor can be put into a stress intensity factor approximation shown in equation 3.6 for a given normalized crack depth.

\[ \Delta K = Y(\beta)\Delta \sigma \sqrt{\pi a} \] (3.6)

In order to account for a geometric stress concentration at the same region as the crack, a correction factor, \( Y_{corr} \), must be implemented. This geometric correction factor is calculated by equation 3.7, where \( \beta \) is the normalized crack depth, and \( K_t \) is the stress concentration factor of the geometric feature. The coefficients used in this equation are tabulated in Table 3.1.

\[ Y_{corr}(\beta, K_t) = p_{00} + p_{10} \beta + p_{01} K_t + p_{20} \beta^2 + p_{11} \beta K_t + p_{02} K_t^2 + p_{30} \beta^3 + p_{21} \beta^2 K_t + p_{12} \beta K_t^2 + p_{03} K_t^3 + p_{40} \beta^4 + p_{31} \beta^3 K_t + p_{22} \beta^2 K_t^2 + p_{13} \beta K_t^3 + p_{04} K_t^4 \] (3.7)

<table>
<thead>
<tr>
<th>Coefficient</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>p00</td>
<td>0.8864</td>
</tr>
<tr>
<td>p10</td>
<td>-4.495</td>
</tr>
<tr>
<td>p01</td>
<td>0.4676</td>
</tr>
<tr>
<td>p20</td>
<td>27.6</td>
</tr>
<tr>
<td>p11</td>
<td>1.492</td>
</tr>
<tr>
<td>p02</td>
<td>-0.302</td>
</tr>
<tr>
<td>p30</td>
<td>-72.37</td>
</tr>
<tr>
<td>p21</td>
<td>-0.8863</td>
</tr>
<tr>
<td>p12</td>
<td>-0.8267</td>
</tr>
<tr>
<td>p03</td>
<td>0.1137</td>
</tr>
<tr>
<td>p40</td>
<td>72.07</td>
</tr>
<tr>
<td>p31</td>
<td>-4.963</td>
</tr>
<tr>
<td>p22</td>
<td>1.064</td>
</tr>
<tr>
<td>p13</td>
<td>0.05621</td>
</tr>
<tr>
<td>p04</td>
<td>-0.01338</td>
</tr>
</tbody>
</table>

Table 3.1 Coefficients for shape factor correction [18]
The assumptions in this analysis require a correction factor and a modification to the stress ratio. The correction factor is designed to account for a different geometry. For this study, a constant stress concentration factor of 1.5 was generated using an approach from Noda et al. for a shoulder fillet using a Neuber approximation to get from the tensile stress concentration factor to a fatigue stress concentration factor with a notch sensitivity of 0.3mm for 316L. [71] [18]

The stress ratio also necessitated some tailoring be done to the approximation of the layer shift stress intensity. In order to approximate the correct stress intensity factor, the following equation (3.8) was to be implemented.

$$\frac{\Delta K_{eff}}{\Delta K} = 0.55 + 0.33R + 0.12R^2$$

The layer shift was implemented into this approach and calculated in comparison to the other stress intensities at the defects identified.

### 3.1.3 Stress Life Approximation

Following the calculation of the stress intensity factors, it was now pertinent to form the stress life approximation. The basis of this is a modification of a Kitagawa-Takahashi diagram to account for finite life. Beretta et al. have developed a model to form a stress life approximation, given a number of data points from a fatigue stress vs cycles (S-N) curve and a number of data points for defect size. [72] [73] [27]

First, the fatigue S-N data for an “ideal” material condition is obtained and a power trendline is fitted to the data. Second, a plot of stress intensity factors vs cycles is generated. These stress intensity factors are from the defects identified to have resulted in a crack initiation. A trend line is generated for the stress intensity factors. Given these two trend lines are of the form shown in equations 3.9 and 3.10, where A, B, C, D, E, and F represent the constants for each trendline. This allows the selection of a specific number of cycles for which a prediction will take place.

$$\sigma_{max,N_i} = A(N_i)^B + C$$

$$\Delta K_{th,N_i} = D(N_i)^E + F$$

These two equations can be implemented into equation 3.11 to find a characteristic area flaw size for a given chosen number of cycles. This is a constant that is used to understand the way that a single flaw will affect the fatigue life. It is an adaptation of the El-Haddad criterion for non-propagating cracks, adapted specifically for use in elliptical pore approximations.
The area estimate for a given cycle count is fed into the modified El-Haddad stress calculation in equation 3.12 to yield a single point representing the stress that a part can withstand given a specific area, $A$, for a specific cycle count, $N$.

$$\sqrt{A_{0,N_i}} = \frac{\Delta K_{th,N_i}}{(1 - R)\sigma_{max,N_i}} \sqrt{A}$$ \hspace{1cm} (3.11)

This can be iterated for many defect sizes to generate a curve for use on a Kitagawa-Takahashi diagram. By additionally iterating this whole process for different cycle predictions, several curves can be generated in order to generate a spectrum of stress-life prediction curves.

3.2 Descriptions of Flaw Type and Shape

The flaws found in this study all had unique shapes. Some were larger than others, several had very different likely causes, and some were more difficult to characterize and utilize than others. There are several different elements that contributed to each of these. The surface notches were identified as the result of failure in approximately half of the specimens tested with different appearances and types in each of them.

3.2.1 Surface Notches

The first type of flaw more commonly seen was a notch at the surface often resulting in a crack initiation. Surface was obviously very rough but beyond that, defects at the surface resulted in failure more often than anything else. The exposure of a large defect included with the rough surface is what resulted in failure beyond simply the repeated surface roughness causing failure. These were commonly seen to have sintered powder along their edges, defects of irregular shape, and typically existed somewhere in the expected contour pass. The irregular shape insinuates the cause of the defect being one of process irregularity. An example of this is shown in the SEM image in Figure 3.1.
3.2.2 Porosity

The second flaw type was a likely lack-of-fusion pore. These were highly reflective and retained lines that are commonly seen in literature on the top-pass of a PBF-LB print. The lack of fusion pores exhibited highly odd shapes and, in some cases, had evidence of non-melted powder. LOF pores were not a major consideration in this study, but there were a few specimens where LOF pores were very visible on the surface. One specimen failed as a result of widespread LOF pores at some layer away from the build pause, pictured in the laser image in Figure 3.2 where each of the shiny locations are individual LOF pores. This specimen was manufactured in the back corner of the machine, a region that is known for producing problematic specimens for the specific machine these were made on.
Figure 3.2  Widespread shiny lack of fusion pores on the surface of a specimen that failed earlier than expected.

Due to other circumstances with the machine, this could have been expected. The printer suffered from repeated issues in the rear right corner, specifically LOF issues caused by improper gas flow that could result in the laser being blocked. There were other samples that exhibited substantially less LOF porosity, but again, it was mostly uncommon among the dataset. This flaw type is shown in Figure 3.2 and Figure 3.3, which exhibits the melt pool top surface in Figure 3.3A as well as clear and obvious grains visible on the surface of the lack of fusion area in Figure 3.3B.
Figure 3.3  A lack of fusion pore on SEM and individual grains visible on the surface of the metal of an LOF surface notch.

3.3  Results

3.3.1  Sizes of Surface Notches

The various flaws varied greatly in size. A few flaws were much larger than the others. The flaws characterized were assumed to have not been changed substantially by the crack growth as they were assumed to be pre-existing. The characteristic length of these flaws was expressed as a sqrt(area) due to the fact that literature commonly utilizes an elliptical estimate of flaw size due to the mostly circular nature of pore approximation. A sqrt(area) connects very clearly to a diameter or a crack length. The flaws in this study had sqrt(area) between 100-300μm. The spread was fairly large and it appeared bimodally spread between 100 and 300μm, as seen in Figure 3.4.

Figure 3.4  The stochastic distribution of pore sizes
3.3.2 Stress Intensity at Various Flaws

The stress intensities were calculated using the Murakami area from the fracture surface images. The individual larger defects were almost exclusively surface notches and pores. These calculations were done using the semi-elliptical area approximation. An example is shown in Figure using ImageJ to illustrate the area implemented in this calculation.

Figure 3.5 An example defect area calculation for a surface notch that initiated a crack

The area approximation method, in keeping with the Murakami area approximation, is shown in Figure 3.5. This area approximation does visually appear to overestimate the area, but the reason for this is specified by Murakami. [32] The stress intensity factor increases with crack length increases, which scale with area. The effective area calculation shown below is the method for flaws that resemble the flaws in the image. Capturing the largest area will effectively capture the largest length.

These effective areas were fed into the stress intensity factor equation in equation 3.14 to capture the data for the individual defects.

\[
K_I = 0.65\sigma_0\sqrt{\pi \text{area}}
\]  

(3.14)

This approach was used to create a graph that could illustrate some of the stress intensities at different specimen life cycles. Several papers show that given a threshold stress intensity factor is
exceeded which results in failure of a specimen. The stress intensity factor of the individual defects is plotted on Figure 3.6 in order to demonstrate how stress intensity factor affects a specimen life.

![Stress Intensity Factor of Various Surface Notches](image)

Figure 3.6  Stress intensity factor of various surface notches

The trendline for this data is given by equation (3.15). This is the first of two equations that will feed into the stress life prediction.

\[
\Delta K_{th,N_i} = 103.9(N_i)^{-0.247}
\]  

(3.15)

The specimen life was clearly correlated with a decrease in the stress intensity factor of a given defect. Additionally, the data levels off at stress intensities below approximately 2.5-3 MPa m\(^{1/2}\), which supports the utility of the method as this is the approximate stress intensity factor threshold for a PBF-LB 316L SS specimen.

### 3.3.3 Stress Intensity at the Layer Shift

The layer shift specimens had a similar curve that appeared to follow nearly the same trend. This is shown in Figure 3.7 and is promising because the layer shift stress intensity factor approximation was originally developed for crack growth at a shoulder fillet. This approximation appeared to produce an accurate result with a slight underestimation of the stress intensity factor, when compared to the curve of the defects. The stress intensity factors were calculated according to section 3.1.2.
Figure 3.7 The stress intensity factor vs cycle count for the layer shift approximation

It retained a similar amount of spread and had a slightly closer curve fit. The key difference between the two curves is the layer shift approximation being slightly lower across the board, as visible in Figure 3.8.

Figure 3.8 A comparison of the two different stress intensity factor approximations.
3.3.4 Stress life Approximation

By implementing the Beretta approach described in section 3.13, [72] the specimen stress life was able to be approximated. In order to obtain the metric for a critical defect at every stress level, a wrought dataset and a stress intensity factor dataset was used. The wrought dataset came from a separate study and was used to get a baseline for the “ideal” material condition, the trendline for the wrought fatigue SN data is in equation (3.16).

\[
\sigma_{max,N_i} = 1166.8(N_i)^{-0.066}
\] (3.16)

The stress intensity factor data that was used was the flaws that initiated cracks in the components in this study is from Figure 3.6 and denoted earlier in equation (3.15). The two trendlines in equations (3.15) and (3.16) were used in the Beretta approach to determine the critical defect size at each target cycle count. [72]

\[
\sqrt{A_{0,N_i}} = \left(\frac{\Delta K_{th,N_i}}{(1-R)\sigma_{max,N_i}}\right)^2 \frac{1}{\pi}
\] (3.17)

\[
\Delta \sigma_{w,N_i} = (1 - R)\sigma_{max} \frac{\sqrt{A_{0,N_i}}}{\sqrt{A} + \sqrt{A_{0,N_i}}}
\] (3.18)

Table 3.2 Beretta estimates of the max stresses and critical defect area for various life expectancies for 316L SS

<table>
<thead>
<tr>
<th>Cycle</th>
<th>Stress Max (MPa)</th>
<th>Critical Flaw (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000</td>
<td>739.6</td>
<td>255.6</td>
</tr>
<tr>
<td>10000</td>
<td>635.3</td>
<td>111.1</td>
</tr>
<tr>
<td>100000</td>
<td>545.8</td>
<td>48.3</td>
</tr>
<tr>
<td>1000000</td>
<td>468.8</td>
<td>21.0</td>
</tr>
<tr>
<td>10000000</td>
<td>402.7</td>
<td>9.1</td>
</tr>
</tbody>
</table>

This works by generating a table shown in

Table 3.2 of critical flaw sizes at various maximum stress values from the two fitted curves. Each row in the table feeds into equations (3.17) and (3.18), with varying defect sizes, A, in order to form the life-specific Beretta prediction. The critical flaw area is used in an El-Haddad approximation of stress range and therefore yields the criterion for a maximum stress for a given cycle count. This is then calculated for various values of defect area to generate a finite-life approximation for those possible defect areas given the known stress curve fit and the known critical defect size. The defects calculated by this
simple approach can be implemented into a stress intensity factor approximation which can be used for all
defects, not just circular ones. This is the focus of Figure 3.9.

![Figure 3.9](image)

A modified Kitagawa-Takahashi diagram to predict finite life of flaws

Once fed into the equation and with the new values of critical flaw size, this was able to
approximate the life of both the individual defects as well as the layer shift specimens in the context of a
stress intensity factor, not just a defect area. This approximation maintains a good approximation to the
specimens without straying too far out of a boundary. This is a new interpretation of a Kitagawa-
Takahashi diagram that implements a stress intensity on the X axis instead of individual area estimates.
Ultimately this approach can be more useful for defects that are not circular, and applies to certification of
a maximum allowable crack size for a flaw. Certification of a part depends on this sort of interpretation.

3.4 Conclusion

This chapter approximated a shoulder fillet crack stress intensity model in to modelling the layer
shift caused by a build pause. The build pause layer shift acted as a stress concentration and this chapter
focused on interpreting the impact of this process flaw through the lens of a stress intensity factor. This
chapter compared the layer shift model against the Murakami model used to approximate a stress intensity
factor at a surface notch.
Two separate stress intensity factor calculations were done for each of the two types of part failures. The stress intensity factors for the layer shift were plotted against the stress intensity for the surface notches. The shoulder fillet crack stress intensity approximation exhibited a slightly lower stress intensity at every cycle count, though the stress intensity factors for the irregular surface notches had more spread in the data. The spread in the surface notch data likely came from challenges regarding the flaw size and shape estimates. The layer shift model and the surface notch model differed only by about 15% and retained the same shape and trend.

The stress intensities were used in a stress-life approximation in order to attempt to predict part failure. By taking the stress intensity factor data for the surface notches and implementing wrought 316LSS S-N data, a modified El-Haddad model was used to find a number of curves for a given stress-life prediction for 316L SS. The data collected in this research fit within the region of each stress-life curve. The successful implementation of a shoulder fillet stress intensity model to model a layer shift has implications for possible mechanisms of estimating stress intensity factors at a build pause as well as at a flaw. Additionally, the application of a modified Kitagawa-Takahashi diagram improves the backing behind the idea of being able to calculate the finite life of a part produced by additive if defects are known. The application of these elements feeds directly into industries like aerospace where qualification is crucial to get a part certified.
CHAPTER 4  DISCUSSION

4.1 Fractography

In the individual specimen calculations, it was challenging to get a perfect area approximation for defects. There were challenges in obtaining a good surface image due to the highly reflective fracture surface. For this reason, images were taken based on the laser surface reflection and the SEM rather than by a camera or lighted optical microscopy. This led to a more interpretable and ultimately better fracture surface image.

4.2 Defect model

The stress intensity factor curve appeared as expected, but it included some variation likely as a result of the area approximation and stress intensity shape factor, which was a constant 0.65 for each of these points, despite the defects themselves varying widely in their shape. This value of 0.65 came from the Murakami approach. [32] Additionally, there was not a substantial amount of spread on the original SN curve which demonstrates that the SIF approximation was likely fluctuating due to area estimates and shape factor estimates. Further work could be done to develop a more accurate shape factor, given the spread in this data.

It is possible that the difference between the layer shift and the defect stress intensities came about as a result of a slight overestimation of defect areas, as in some experimentation with the values, decreasing the defect area by a small amount brings the defect stress intensity factors down to approximately a similar range as the layer shift stress intensity factors. This needs to be explored further in a new study designed for strange surface notch shapes in order to understand the correct ways to approximate surface flaws more closely.

4.3 Layer shift model

The layer shift stress intensity factor model described in chapter 3 provided a result that very closely resembled the stress intensity factors of the defects measured and calculated. This points to the applicability of the model. There was some variation, however, that came likely as a result of the information used to develop the equations and constants from the source. [18] The primary issue is the bounds that were on the data used in the model. Pasman tested samples in $R = 0.5$ and $R=0.05$ stress ratios, as well as multiple stress concentrations for shoulder fillets. [18] The issue likely arises from the stress ratio, as within the Pasman model, the smaller R ratio proved to have more variation and a worse curve fit in the stress intensity calculation. Due to the work in this paper being tested at $R = 0.1$, the R ratio is likely the greatest source of the 15% lower stress intensity seen in the data.
4.4 Prediction

The data in this study correlated well with the Beretta modified El-Haddad approach described in chapter 3. A number of questions were raised during the development of the model, as there was no perfect dataset from which to approximate a “wrought” or “ideal” material condition. This dataset had to come from literature and varied substantially from study to study. As a result, a study was done to understand the effect of different source data on the prediction. It was found that while there was an influence of different wrought datasets on the Beretta model[72], the variation occurred outside of the bounds of the stress intensity factor and defect area data in this research. Given this, fluctuations in the wrought dataset were not considered to be a large source of error.
CHAPTER 5  CONCLUSIONS

This work investigated fatigue performance of a PBF-LB print that experienced a pause in the build, resulting in a visible witness line on the surface. This witness line is a dimensional shift at the layer where the build pause occurred. The layer shift is not the same for every part, rather each specimen has a unique layer shift with a unique magnitude. The impact of this build pause on the mechanical strength of the specimen appears to be driven by the geometry and not by the microstructure, as there is no change in microstructure observed at the build pause. The layer shift led to failure in more than half of the specimens, because of the increased stress concentration at that location. The specimens that failed at the layer shift exhibited substantial radial fatigue growth marks demonstrating that it was not a single point, but rather a notch type of stress concentrator at this location. The magnitude of the layer shift also influences failure, with the larger shifts more often leading to failure at the build pause location. However, even with the presence of this layer shift stress concentrator, other defects inherent to the AM processing still initiated failure.

A stress intensity factor approximation of the stress concentration was able to be applied to determine the impact of the layer shift on the specimens in this study. This stress intensity factor approximation was shown to be comparable to the known and tested stress intensity factor approximations used at flaws and pores. This work also described and tested an approach to finding how a stress intensity factor of a flaw or layer shift would impact the usable life of a specific part under specific loading conditions and was able to effectively demonstrate the applicability of the methods described. The Murakami stress intensity factor approach based on a semi-elliptical area approximation yielded close values to expected, but differed slightly in some ways and was not perfectly reliable for this data set, likely due to the oddly shaped pores and complexity of the surface exposure.

The stress life predictions are shown on a modified Kitagawa-Takahashi diagram. The model used is based on the El-Haddad model of a non-propagating crack. It is modified once by Beretta to produce an approximation of a non-propagating crack through defect area. This work seeks to modify this approach by categorizing defects in terms of stress intensity factor, making it possible to utilize the model for oddly shaped flaws that are better modeled with a stress intensity factor. In this case, using a stress intensity factor approach to the Beretta modified El Haddad model was able to produce good estimations of the stress-life for a given part given a certain stress intensity factor. This work provides insight toward the impact of a witness line on fatigue failure which can inform acceptance criteria for this print anomaly and potentially decrease overall scrap rates.
CHAPTER 6 FUTURE WORK

This study raises a number of questions regarding layer shifts and stress intensity factors.

1) How can the layer shift approach be made more accurate? Does the stress intensity approach work for even smaller geometric deviations? The layer shift could be produced purposefully and tested in order to try to minimize the influence of any other build-pause related factors.

2) If given a variety of different defects, can they all be modeled on the modified K-T diagram as effectively? An investigation into the effects of shapes and deterministic internal flaws could seek to prove the influence of various types of defects, both in the bulk of the material, near the surface, and at the surface.

3) More data is required for understanding the real effect of a layer shift. The mechanical implications were only tested in tension-tension fatigue in this study, a further investigation into the effects in compressive or bending fatigue could reveal new challenges.

4) A build pause can clearly manifest in different part conditions, as seen in the variability in the build interruption literature review. How does the layer shift actually manifest in the machine, does it require a specific condition? A test of several different restart procedures and machines could deduce some factors that play a role in the mechanism.

5) A full review of how the build pause differs by machine and material is critical to create a useful framework for industry applications.

6) Could a simple machining step remove the build pause symptoms, or are there microstructural impacts not yet seen? Printing various build pause procedures and specimens, then machining off the surface to investigate if they continue to break at the line could deduce the mechanical impact of factors not investigated here.
REFERENCES


