

The Use of Optical In-Situ Data of Tensile Samples to Model  
Porosity for Part Qualification of AM 316L

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## ABSTRACT

Additively manufactured parts often contain porosity that forms during the building process. These defects can affect the part quality and make individual part qualification difficult. In this study, pores were purposefully designed within tensile samples in combinations of three diameters (200 $\mu\text{m}$ , 350 $\mu\text{m}$ , and 500 $\mu\text{m}$ ) and three volume percentages (1%, 3%, and 5%) for a total of nine combinations. Each combination was built twice in order to compare the ability of hot isostatic pressing (HIP) and solution annealing (SA) to mitigate pore effects and produce a part that achieves acceptable tensile properties. Two control samples with no purposeful porosity included were also built to compare the tensile results within the build to an ideal case for both the HIP/SA and as-built conditions. In-situ optical data was collected during the build in order to detect, analyze, and model the as-built internal porosity. This internal porosity from optical data was compared to XCT data to validate the porosity detection method. The optical data was used to model internal porosity for finite element simulations, although these simulations became too complex for practical computation due to the highly irregular pore shapes in large amounts. The optical in-situ data was also analyzed statistically, and correlation was observed between clusters of large pores and the location of fracture during tensile testing. The HIP/SA process was shown to successfully reduce tensile property scatter and achieve acceptable standards for all pore sizes and amounts.

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## CHAPTER 1: INTRODUCTION

Additive manufacturing (AM) methods have introduced the ability to generate parts with complex geometries quickly while decreasing waste produced and time to market [1]. While these methods are constantly improving, there is still a large amount of scatter in part quality and performance that makes many code and regulatory agencies skeptical about adopting these methods into industry. For instance, two identically-designed parts can be built using the same equipment and build parameters but still vary in properties due to differences in thermal signatures caused by everything from laser power to scan length [2]–[5]. This scatter makes part certification very challenging, and there is currently no clear standard for part or process-based qualification. Currently, parts are often certified by building multiples and destructively testing one in order to qualify the other. However, this method is insufficient and does not account for the individual differences that can arise during the AM process. Much research has been conducted towards monitoring parts in-situ with the intention of qualifying parts rapidly and nondestructively, although there are still many areas of this field to be examined [6], [7]. In this study, tensile bars were designed and built containing purposeful, engineered pores in varying sizes and amounts. Each combination of pore size and amount was built twice in order to test the ability of a heat treatment process to mitigate the effects of porosity on tensile properties. The tensile samples were monitored using an optical in-situ data collection system

which recorded layer-by-layer information. The goal of this research was twofold: to use optical in-situ data to identify defects to predict possible tensile failure locations, and to present and validate a process-based qualification method for laser powder bed fusion (L-BPF) parts. The optical in-situ data was used to model identified porosity and to identify possible tensile fracture locations based on porosity location and size information. This goal was pursued with the intention of furthering understanding of the effect on porosity for possible future part-based qualification. The second goal of process-based qualification was pursued by applying the proposed heat treatment process to tensile bars with exaggerated porosity in order to validate the ability of the process to produce an acceptable part despite large defects. Although this was a singular experiment, the tensile bars in this study were purposefully designed such that they could be compared to the results of previous experiments conducted by industry partners within this project. The results of this experiment confirmed that the proposed heat treatment process mitigated scatter across multiple machines, designs, and porosity amounts. The optical in-situ data was used to locate and analyze porosity to compare to fracture location in order to further development on a part-based quality analysis methodology. The process-based qualification method was verified through tensile test results of AM parts in this experiment alongside those conducted previously and extensively by project collaborators and was used to support a submission to ASME for a new qualification standard.

## **CHAPTER 2: LITERATURE REVIEW AND BACKGROUND**

This chapter will discuss relevant literature in the field of additive manufacturing.

Section 2.1 will provide an overview of the laser powder bed fusion process.

Section 2.2 will give a brief explanation of stress concentrations and their effect on ductile fracture. Porosity in additively manufactured parts will be detailed in Section 2.3, and previous work on porosity monitoring and detection will be detailed in Section 2.4.

### **2.1 Metal AM Process**

While there are many metal AM processes, this work will focus exclusively on laser powder bed fusion (L-PBF) [8]. A computer-aided design (CAD) model for a part is designed and sliced to define layer-by-layer geometries which are then melted by laser from a bed of metal powder. A schematic illustration of this process can be found in Figure 2-1 [9]. After a layer has been finished, the part is lowered in the build chamber for un-melted powder to be spread evenly by a rake in preparation for melting the next layer. Successive layers are bonded together by re-melting, and layer thickness is generally in the range of 10-50  $\mu\text{m}$  [10]. The laser is controlled by mirrors and lenses, and melts by either a continuous or “spot-melt” exposure as the laser path covers the melt area in a designated scan pattern. The melt pools generated by the laser are affected by input parameters and heat transfer conditions. Variations in melt pool shape and size during a

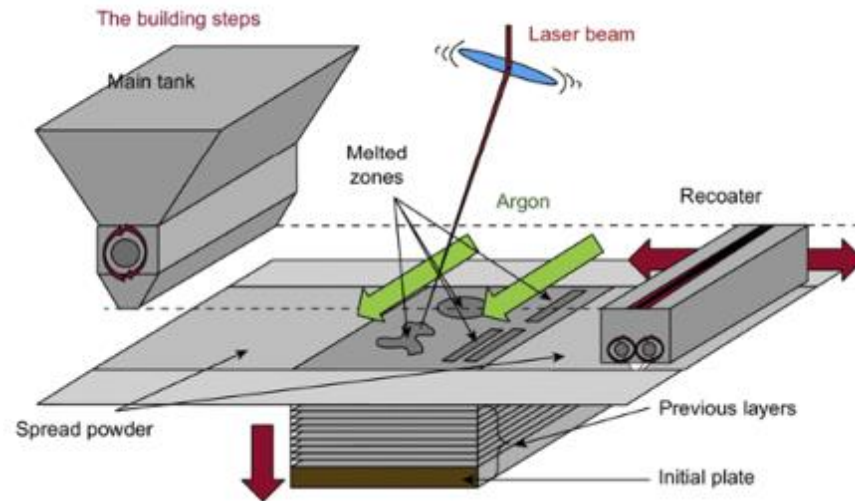


Figure 2-1: An illustration of the L-PBF process build chamber. [9]

build signify variations in thermal conditions within the part, which can often lead to porosity formation.

## **2.2 Stress Concentrations**

Any geometrical discontinuity in a body under stress will result in a nonuniform stress distribution around the discontinuity, causing what is known as a stress concentration [11]. Porosity defects often occur in AM parts, and these voids within the part create discontinuities that cause high stress concentrations [12]. Much research has been conducted into understanding the behavior of different stress raisers. For instance, cracks loaded by tensile stress have infinite stress concentrations at their tips, as shown by C. E. Inglis in 1913 [13]. Irregular pores may have many sharp edges and corners, resulting in high stress concentrations. These stress concentrations can interact and have a subsequent effect on ductile fracture. In particular, it has been shown that voids coalesce through localized plastic flow as the inter-void ligaments experience necking and then fracture [14] (Figure 2-2). The localized plastic zone around pores reaches high stress states and the surrounding areas take on higher stress values, which is a characteristic of ductile fracture. As these stresses reach a critical point, the material yields.

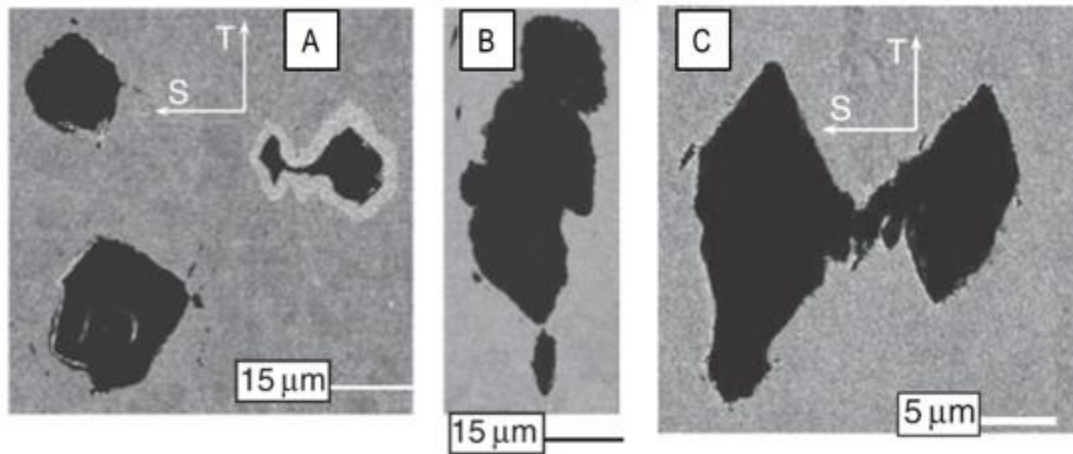


Figure 2-2: (A) Void growth and coalescence in C-Mn steel. (B) Necking of an intervoid ligament. Figures taken from Benzerga, et al. (2010).

How these voids interact with each other has been shown to affect failure. Void size, shape, and location are all factors of importance in this interaction. In a study of 3D voids in compression, Davis, et al. found that diagonal and horizontal interactions increased stress concentrations at the void sides [15]. This was attributed to the confluence of tensile cracks (which initiate at the void poles) and shear fracture at the void sides. A crack propagates between these voids in diagonal bands as the shear fracture of each individual pore drives the local stress above the material yield stress and surrounding material fails. An example of these fractures around a cylindrical void in a plaster material is shown in Figure 2-3. Although the material and stress direction are different, this image illustrates well how the hoop stress (at the void sides) causes local failure and crack formation. The relative location of these pores to each other in horizontal or diagonal configurations places these pores close to this location of local failure and in the path of crack propagation.

## **2.3 Porosity in Additively Manufactured Parts**

Process parameters have significant effects on porosity formation in L-PBF processes [3], [16]. Energy density affects the melt pool size and shape, which in turn creates conditions for pores to form. However, these parameters are often optimized based on builds with simple geometries such as cubes that do not have much (if any) variance in scan length, laser exposure time, or melt area.

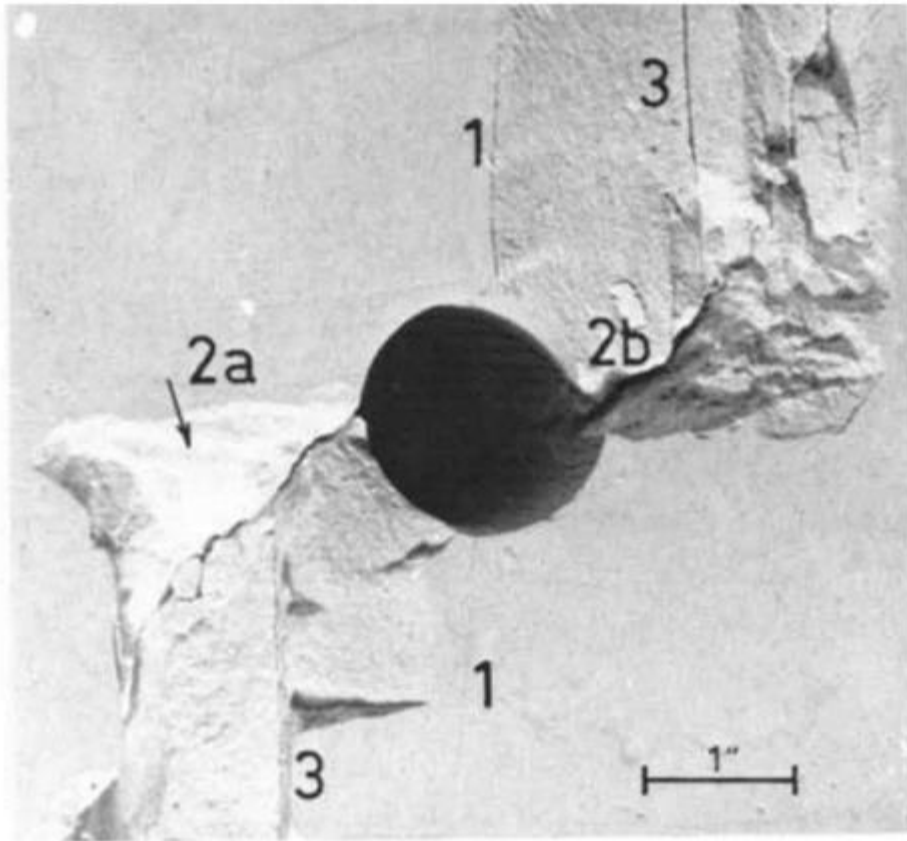


Figure 2-3: Material failure around a cylindrical void under compression in plaster. The labels indicate the order of fracture initiation. 1: tensile cracking. 2a and 2b: shear fracture and crack propagation. 3: additional fracture formed under higher compressive stresses. [15]

Because the parameters are optimized based on a simple geometry, they are not necessarily the optimum parameters for a more complex geometry. This difference is due to changing layer time, scan lengths, and overall heat transfer conditions which lead to varying thermal signatures within a more complex build that do not exist in a simple cube build. These parameters and heat transfer conditions are important to optimize in order to reduce the likelihood of defects within a build. Even for a simple build with little to no variation in geometry, there may be part quality variation. A study which compares different locations on a single build plate showed varying properties even for the same parameter set [17]. In this study, rectangular parts built at the same time but at different locations within a build chamber were found to contain vastly different quantities of porosity. This was attributed to a soot buildup on the mirror used to focus and direct the laser that had accumulated over a long build time, and the researcher performing this experiment had noticed the unusual amount of soot buildup while walking by the build chamber. Micrographs of parts from different build plate locations in this study are shown in Figure 2-4. Lack of fusion porosity is often the result of insufficient melt pool overlap [18], which results in pores containing non-melted powder trapped within a solid part. Yoder, et al. found that a large accumulation of pores resulted in premature failure of a bracket part [19]. The accumulation of porosity was attributed to changing geometry, which created an abrupt change in thermal signature within the part. In this particular study, it was

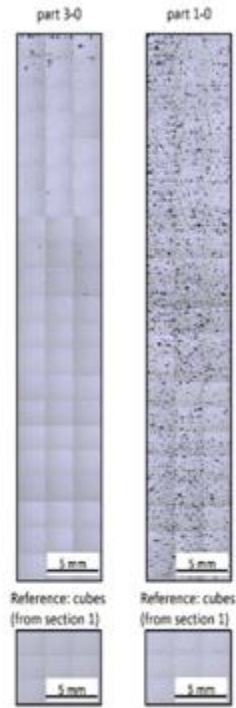


Figure 2-4: Micrographs from sections of two large builds (top) located in different locations on the build plate [17].

not speculated whether the individual sizes or proximity of multiple pores may have been to blame, rather just an unusual amount of porosity in general.

## **2.4 Previous Work on Porosity Detection and Modeling**

Melt pool characteristics have often been used to detect or predict porosity within additive manufacturing processes. The temperature distribution, size, and shape of a melt pool all have influence over part quality. A smaller temperature gradient leads to higher quality in parts [20], but changing geometry and varying energy absorption in AM processes often result in large temperature distributions [21]. This effect is due to the residual stresses induced by large thermal gradients, as well as over or undermelting of areas in comparison to surrounding material that result in porosity defect formation. Because defects may be formed upon remelting, the defect is not always directly observable. This leads to the necessity of detecting melt pool changes which may be caused by underlying defects. Two main methods for in-situ porosity detection are optical and thermal cameras. Infrared (IR) or near-infrared (NIR) cameras are used to monitor the temperature of the melt pool during a build.

### ***Thermal In-Situ Monitoring***

The driving assumption for defect detection in thermal imaging of this type is that pores will be visible as “hot spots” in a temperature distribution due to the insulative nature of unmelted metal powder and its relative low emissivity

compared with melted metal. A study by Boone, et al. used geometry conditions likely to cause porosity formation and a NIR camera to capture the melt pool, and they were able to detect lack of fusion porosity [22]. Porosity was detected in this and many other studies by noting “hot spots” where the temperature appears hotter to the NIR camera due to the pore. Trapped unmelted powder has a higher emissivity value and lower conductivity than melted material, so the powder both appears hotter immediately and cools more slowly than surrounding melted material. While these hot spots are good indications of where a pore might be located, correcting for emissivity is challenging because it relies on an ability of the analysis methodology to distinguish unmelted from melted material. The melting process can happen very quickly, and the temporal and spatial resolutions of the data collection system must be appropriately small in order to determine the transition point from powder to molten to solid metal. The exact time this process takes is highly dependent on individual build parameters, which again complicates this calibration. The study by Boone, et al. applied an emissivity value to each pixel by comparing using a melt pool tracking mask which detected the melt pool in each frame and assumed the entire material within the melt pool was “melted” and every pixel external to the melt pool was not [22]. This method relies on slower cooling due to lower thermal conductivity to produce “hot spots” and indicate porosity and does not account for possible

emissivity differences within a determined melt pool area. Other disadvantages of IR and NIR systems include costly equipment and large data sets.

### ***Optical In-Situ Monitoring***

Optical in-situ systems utilize high speed cameras to detect changes in the melt pool that suggest defects. One such study by Barua et al. correlates RGB values captured by an optical in-situ system to temperature in order to detect an interruption in heat flow, with the region around defects showing an apparent increase in temperature compared with surrounding areas [23]. The “pores” in this study were engineered by drilling holes in a finished part and filling the voids with powder, then depositing material over known “pore” locations. For both optical and thermal in-situ defect detection systems, large amounts of noise due to spatter (in temperature data) and lighting and surface effects (in optical data) present a challenge and require additional processing in order to extract the necessary information from the raw data. While detecting porosity presents many challenges, assessing the effects of porosity presents several more. Many studies have been conducted which model single or pairs of pores in order to evaluate the stress concentrations around these defects [24]–[26]. However, most of these studies calculate average porosity values and do not characterize features of distribution such as combinations of multiple or irregular pores, varying sizes of pores, and varying locations of pores as would occur in AM builds of complex geometries.

### ***FEA Modeling***

One of the goals of this research was to better understand the relationship between porosity features and part failure through the use of finite element modeling. Earlier studies exist which examine problems such as stresses in a plate caused by cracks [13], stresses in a plate caused by two unequal holes [27], and stresses in three dimensions caused by individual or paired holes of varying shapes and distances from one another within an infinite medium [15]. Few studies have been conducted which model porosity with more irregular, nonuniform shapes and varying relative locations as would be more realistic to the formed within an additively manufactured part. One such study examines cast steel tensile samples using film radiography to measure and map representative porosity fields onto finite element simulations [28]. However, in almost all cases the simulation overpredicted the performance of the samples. This was attributed to the limitations of this method of porosity measurement and reconstruction, and the researchers recommended the use of a more detailed porosity reconstruction method to obtain accurate simulation results (suggesting the use of tomography). In the following work, X-ray computed tomography (XCT) was used to better capture the irregular structure of internal porosity within L-PBF 316L stainless steel tensile bars with the intention of using finite element simulations to predict part failure.

## CHAPTER 3: EXPERIMENTAL PROCEDURE

This chapter will discuss the experimental procedure followed in this study.

Section 3.1 will detail the geometry and parameters for the engineered porosity tensile bar build. Section 3.2 will explain the post-processing conducted on the tensile samples. Section 3.3 will describe the testing parameters followed for the tensile tests.

### 3.1 Geometry and Parameters

The following section will address the geometry and parameters for engineered porosity tensile bars built in this study, as well as the parameters used for heat treatment and non-destructive pore detection.

#### ***Tensile Bar Build***

This build provided data to support an ASME Data Package for proposing a new process-based part qualifying standard for additively manufactured parts.

Second, a goal of this experiment was to observe the effect of HIP/SA on large pores in varying amounts. The hypothesis was that large pores might reopen under strain. A third goal was to use optical in-situ data from this build to correlate failure location to defects. The geometry was designed to include engineered porosity within a gauge section, and cylindrical bars were built in a Renishaw® AM250 using standard parameters for 316L. These tensile bars were

later machined to ASTM E8 [29] standard size cylindrical tensile bars. In order to place the engineered porosity within the gauge lengths, ABAQUS was used to take a CAD model of a tensile bar, section it to isolate only the gauge section, and create a mesh of cubic elements. The mesh element size was varied to match desired pore size (200 $\mu\text{m}$ , 350 $\mu\text{m}$ , and 500 $\mu\text{m}$ ), which ABAQUS then automatically numbered and wrote to an input file. The input file was then accessed so the element set for the gauge length could be exported and manipulated to select a desired amount of elements randomly. Those chosen elements were then imported back into the input file as a new set and removed from the model to create voids. This process was completed with the stipulation that all voids be internal, so a single element layer was left unaltered at the surface of the tensile bars to ensure no pores would be located externally. Because the surface layer was the only layer in which the cubic elements were modified to fit into a circular cross-section, the elements used to create voids were all cubic and of equal size throughout the gauge section. Images of a tensile bar model designed in this way can be seen in Figure 3-1. Once the bars were designed with pores of three separate sizes (200 $\mu\text{m}$ , 350 $\mu\text{m}$ , and 500 $\mu\text{m}$  cubic pores) and three different porosity volume densities (1%, 3%, and 5%), the models were exported and sliced into layers in order to create build files. Because the pores were designed holes within the parts, they were formed when the laser purposefully skipped the pore geometry.

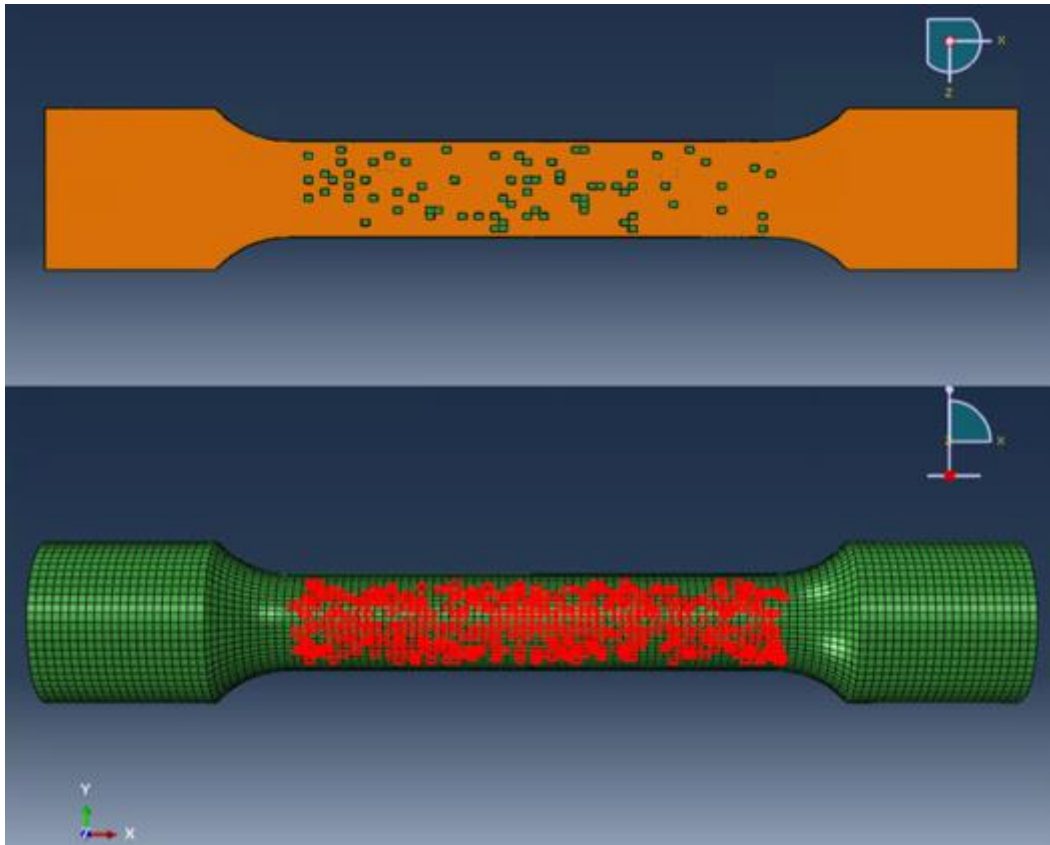


Figure 3-1: Images from ABAQUS software showing internal porosity design for (top) a single slice and (bottom) the entire tensile bar.

Engineered pores built in this way most closely compare to lack of fusion porosity. Two parts of each combination of size and volume density were fabricated in order to test one part in as-built condition and the second part—identical in design—after HIP/SA. Because the pores were placed within what would become the gauge section of the tensile bars, it was important that the tensile bars were centered properly around these internal features. An external ring was therefore designed in the center of each sample for accurately locating the internal porosity during later machining. The build was monitored using the optical in-situ data collection system. The entire build of 20 tensile samples took about 18 hours to complete. Figure 3-2 shows photographs of the completed build and

Table 3-1 details the each part included.

## 3.2 Post Processing

### *Heat Treatment*

Half of the sample bars were subjected to hot isostatic pressing (HIP) and then solution annealing (SA) with water quenching in order to examine the possible effects of these treatments on porosity closure, microstructure, and tensile behavior as compared to samples of the same design without heat treatment.

First, the samples underwent HIP treatment by being brought to a high temperature and pressure for 2 hours, being held at this temperature of 1121 °C

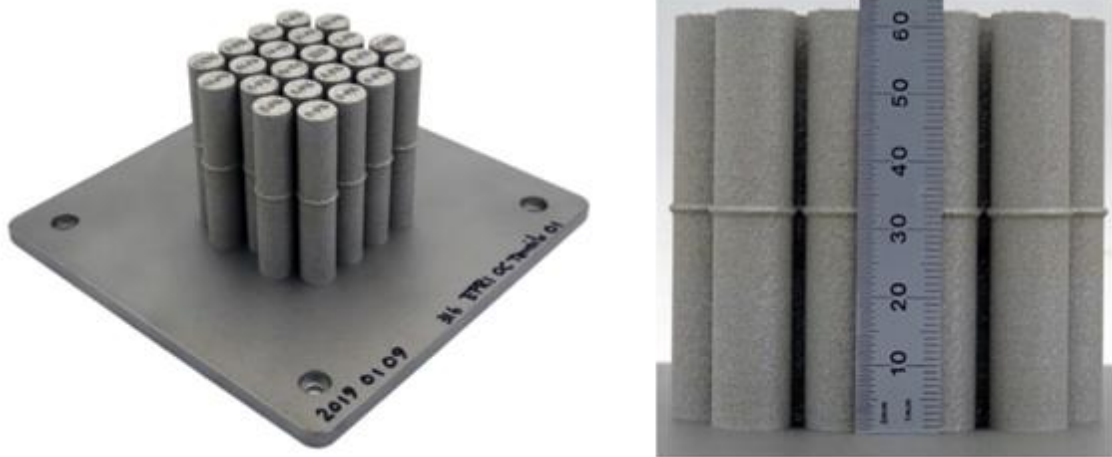


Figure 3-2: Photographs showing the completed bars for the Tensile Bar build in as-fabricated condition with the external ring.

Table 3-1. Part descriptions for Tensile Bar build.

| <b>Design</b> | <b>Label</b> | <b># of bars</b> | <b>Defect Size</b> | <b>Volume<br/>Density (%)</b> |
|---------------|--------------|------------------|--------------------|-------------------------------|
| 200μm-1%      | 2-1%         | 2                | 200μm              | 1                             |
| 200μm-3%      | 2-3%         | 2                | 200μm              | 3                             |
| 200μm-5%      | 2-5%         | 2                | 200μm              | 5                             |
| 350μm-1%      | 35-1%        | 2                | 350μm              | 1                             |
| 350μm-3%      | 35-3%        | 2                | 350μm              | 3                             |
| 350μm-5%      | 35-5%        | 2                | 350μm              | 5                             |
| 500μm-1%      | 5-1%         | 2                | 500μm              | 1                             |
| 500μm-3%      | 5-3%         | 2                | 500μm              | 3                             |
| 500μm-5%      | 5-5%         | 2                | 500μm              | 5                             |
| Optical Cal.  | OpCal        | 1                | NA                 | NA                            |
| Rube Gberg    | RG           | 1                | NA                 | NA                            |
| Control       | CON          | 2                | NA                 | ~0                            |

and pressure of 26,000 psi for 2 hours, and then gradually cooling over 2 more hours to return to room temperature. This process is summarized in Figure 3-3. This procedure followed the standard outlined in a Code Case for the Powder Metallurgy/Hot Isostatic Pressing (PM-HIP) process specifically for Type 316L Stainless Steel submitted by EPRI. This process was performed on the engineered porosity cylindrical samples prior to being machined down to standard size tensile bars. Following HIP, the tensile bars selected for heat treatment were solution annealed. A furnace containing half of the tensile samples was heated to 2050 F for 2 hours and then rapidly water quenched. This procedure was performed by the Materials Science department at the University of Tennessee according to the standards proposed as part of the process-based qualification for this project. Solution annealing with water quenching was performed after the HIP process to ensure a fully austenitic part (see Figure 3-4).

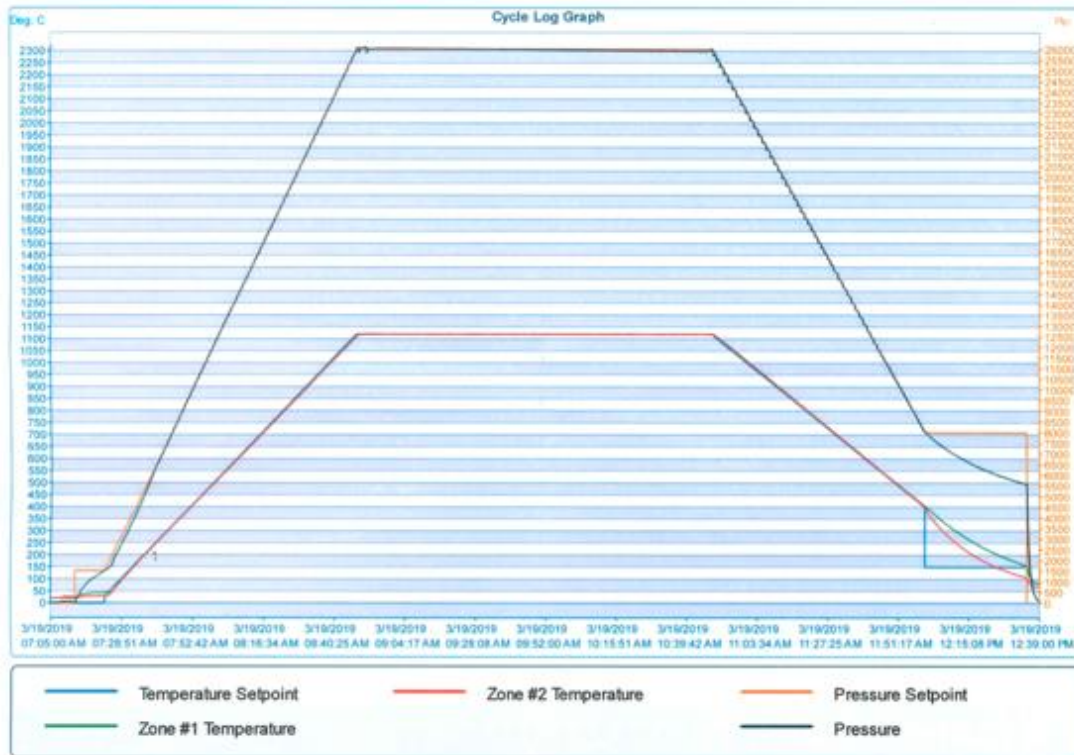


Figure 3-3: Log file showing temperature and pressure during the HIP process for engineered porosity samples.

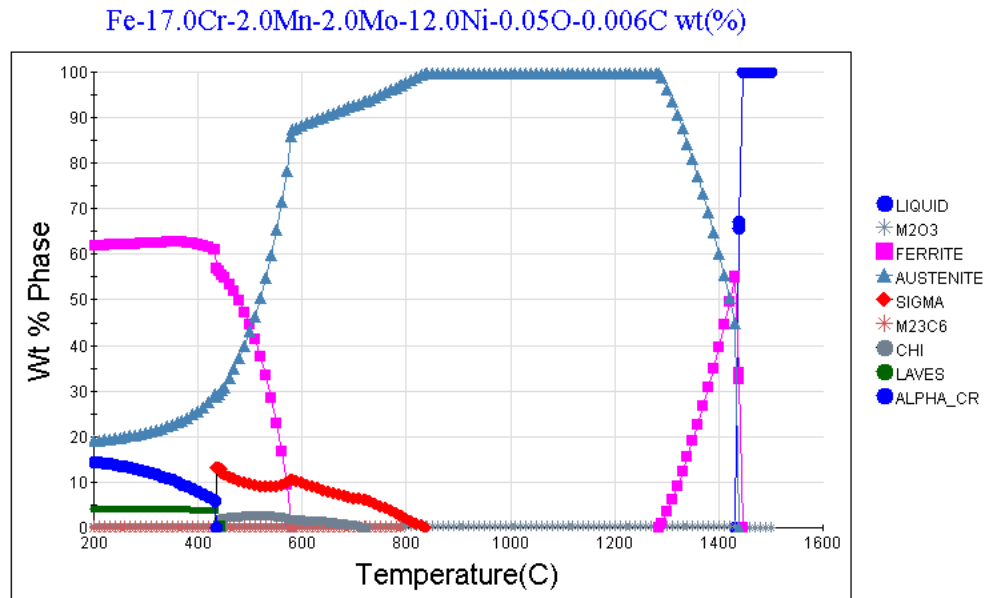


Figure 3-4: WT % phases of 316L with respect to temperature highlighting that austenite is the only phase present once solution annealed at 1100 C and rapidly water quenched.

## ***XCT***

The tensile bars with internal engineered porosities were evaluated nondestructively with X-ray computer tomography (XCT) by North Star Imaging. XCT was performed with the intent of gaining ground truth data for the internal engineered porosity in order to compare the as-built geometry to both optical in-situ data and the original CAD design. This XCT data was used also to validate the methodology of the HIP/SA process as well as quantify the ability of this process to repair engineered porosity. Figure 3-5 shows representative slices from the tensile samples with the largest pore size and greatest volume percentage of porosity (500 $\mu$ m-5%) before and after HIP, highlighting the successful closure of porosity. The minimal spatial resolution of this XCT data was 40 $\mu$ m, and no pores are apparent in the XCT after HIP. Therefore, the pores were closed to at least below 40 $\mu$ m.

## ***Optical Data Processing***

Optical data for in-situ build monitoring results in a much smaller data set than for IR data for builds of the same length while also requiring less initial cost and capturing a larger area (8.3 GB of optical data for all 23 tensile bars compared to 1 TB of IR data for the equivalent area of less than 2 tensile bars). In the case of defect detection, this is more desirable compared to infrared methods due to reduced processing time and greatly increased area of collected data.



Figure 3-5: XCT data highlighting closure of pores after HIP/SA in two representative slices.

One eventual goal of in-situ data monitoring is to identify, locate, and correct defects during a build, and achieving this goal will require a large area of detection and quick processing. The total processing time for all 20 tensile samples was about 10 minutes. Another eventual goal is the ability to qualify a part based on individual build data, which could inform analysis of potential part performance. As a result, being able to quickly process data for as much of a part geometry as possible is important. For the tensile bar build with engineered porosity, the camera used was a Pixelink PL7715cu-T which was programmed to capture two images for each layer of a build. The first image was taken just after powder was raked across the previously melted layer with the purpose of checking powder coverage. The second image was taken after that layer had been melted according to the build file and resulted in an image of the part's cross section in that particular location. It was this second image for each layer that was analyzed for internal defects. Within the build chamber was a single light source, although the view window of the machine also allowed light into the chamber. The camera was placed at a 20 degree angle to the build plate, which means that the images must be corrected for skew. This skew was corrected in post-processing by choosing four points on each tensile bar and defining the physical distance between these points. Through this process, pixel width and height are set manually by dividing a known distance value the number of pixels that span this distance. Samples closest to the center of the build plate (and

therefore closest to the camera's focal point) were less skewed than parts located further from the center. By setting the scale individually for each tensile bar instead of setting the scale for the entire build at once, the effect of this skew due to the distance from the camera focal point was minimized. Following skew and scale corrections, the contrast of the image stack was increased, a smoothing filter was applied, and the images was binarized to define pores. This processed is summarized in Figure 3-6.

### **3.3 Destructive Testing**

The additively manufactured cylindrical bars with internal engineered porosity were machined to ASTM E8 standard cylindrical tensile samples and tested at Metcut Research Inc.. At the beginning of the tensile test, the displacement rate was 0.005 in/min. After the 0.2% yield was attained, the displacement rate was increased 0.063 in/min. This was the common procedure followed by Metcut Research Inc. and was in accordance with ASTM E8.

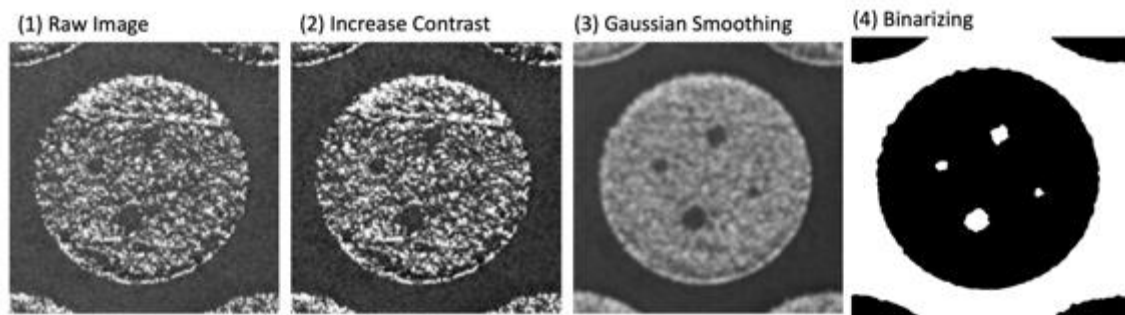


Figure 3-6: Illustration of the optical data processing steps for analyzing porosity.

## **CHAPTER 4: RESULTS AND DISCUSSION**

This chapter will present the results and discussion from the engineered porosity tensile bar experiments. This will include the results from optical in-situ data statistical analysis, as well as the finite element analysis from this optical data and the physical tensile test results.

### **4.1 Evaluation of Internal Porosity Data**

Optical in-situ data was collected for the duration of the build in order to evaluate the engineered internal porosity within the part. Of the two images taken for each layer (one image post-melt and one image post-powder coverage), the post-melting images for each layer were collected in a stack and analyzed for porosity.

#### ***Comparison to XCT data***

The three dimensional reconstruction of internal porosity was compared with XCT data for the optical calibration bar in order to evaluate the ability of the optical data to capture actual porosity of differing sizes and locations. The optical calibration bar was designed with engineered pores in the gauge section varying in diameter from 100 $\mu\text{m}$  to 500 $\mu\text{m}$  in 100 $\mu\text{m}$  increments in order to test the build design and the resolution of the optical in-situ data, as shown in Figure 4-1. Most of the 100 $\mu\text{m}$  pores were not visible in the XCT data, although this may have been a result of pore remelting during the build as well as a limit of camera resolution.

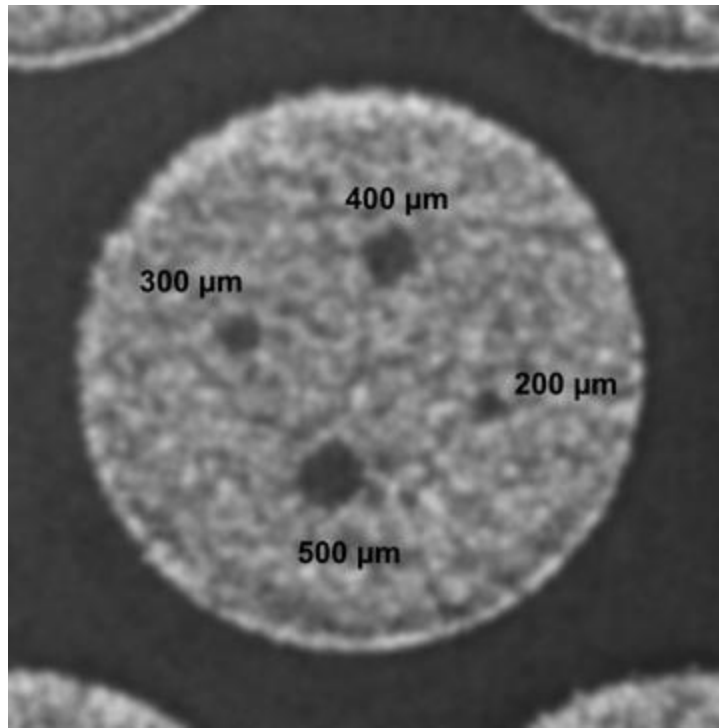


Figure 4-1: Slice view showing internal pores for the optical calibration bar. A 100μm pore was also designed in the center but is not visible in this slice.

Because engineered pores are designed into the build purposefully, the laser skips a designated area to form the pore. On a subsequent raster pass of the laser, it is possible for residual melting to occur close enough to the designed pore that the unmelted powder becomes melted and the pore may be partially or completely closed unintentionally. In comparison, many of the 100 $\mu$ m pores were visible in the optical data. Because the XCT data was used as a ground truth for the engineered porosity, it was concluded that the optical data detection method overestimated the true size of porosity. The exact amount of this overestimation was not determined, as the data collection methods and resolution differences of the XCT data and optical data caused difficulty in matching particular pores without manually lining up specific layers. The optical data was a stack of 2 dimensional images that was extrapolated in the z direction, while the XCT data was created from the averages of 3 dimensional voxels. Any direct comparison of layers was done by hand and lined up visually. With the exception of these 100 $\mu$ m pores, porosity as a whole was very accurately captured when compared to the XCT data (Figure 4-2). Six successive layers from this optical calibration bar were selected and manually lined up, and these layers are shown in Figure 4-3 to better compare individual pores as captured by XCT and optical data. The colors for the comparison are as follows: green is shown where the XC and optical data both show porosity, red is where optical data shows porosity and XCT does not, and purple is where XCT data shows porosity but optical data

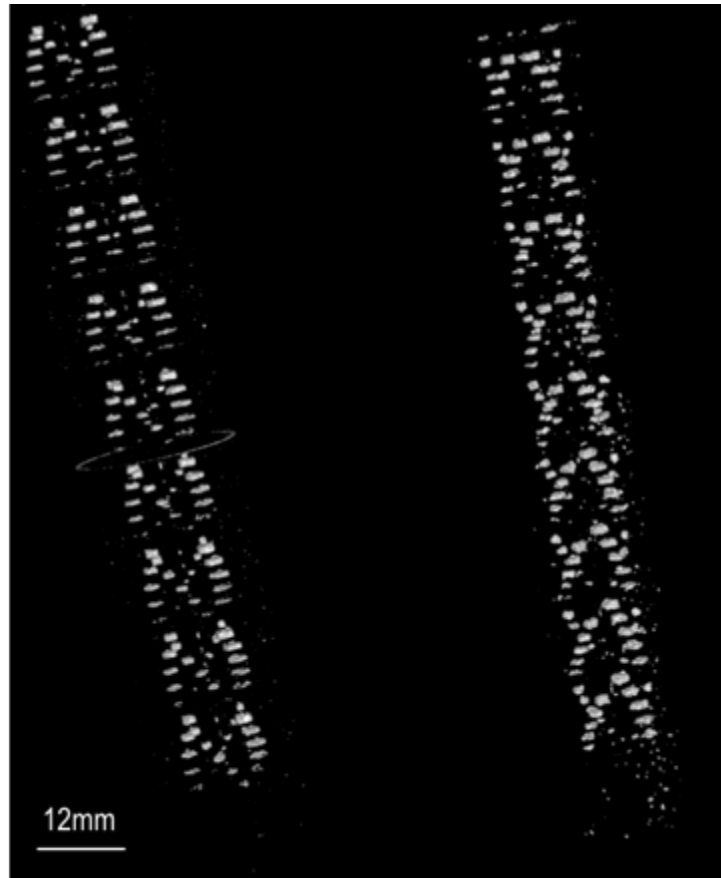


Figure 4-2: (left) Optical data captures even the 100µm pores, which can be seen down the center of the helix pattern. (right) The XCT data closely compares with the optical as a whole, but the 100µm pores in the center were largely not detected.

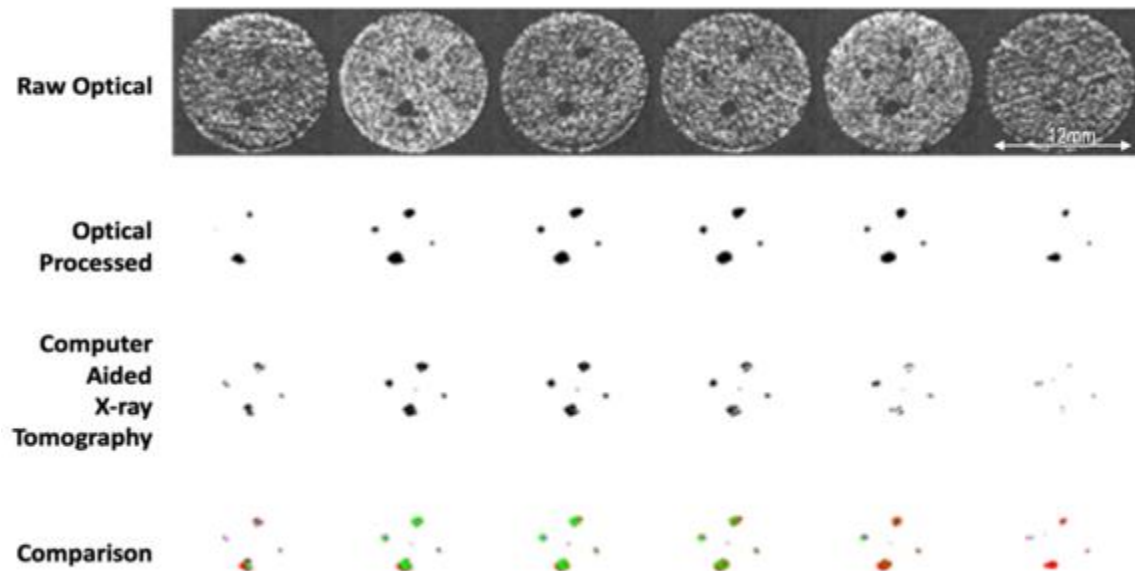


Figure 4-3: Six successive layers of the optical calibration bar are compared for in-situ and XCT data. Green is where the data matches, red is where optical data reports a pore that optical data does, and purple is where X-ray captures a pore not seen in optical data.

does not. This comparison highlights the ability of the optical data to accurately capture porosity, but it is worth noting that the optical data represents the pore as larger than the XCT data does. For instance, in Figure 4-3, the pores as shown by optical data are larger and more defined in the first, fifth, and sixth layers than the pores as captured by XCT data. This was concluded to be a result of remelting that occurs in successive layers during the build. Because the optical data captures porosity after each layer has just been melted, there is no ability for optical in-situ data to account for remelting that occurs when the next layer is built on top of the previous one. This is a well-known effect in L-BPF builds, as it is the way individual layers adhere into one singular part; a layer is bonded to the previous layer by remelting. Because of this fundamental effect of L-PBF, this overestimation of pore edges was expected.

### ***Non-engineered porosity detection***

It is interesting to note that the optical in-situ system was able to capture non-engineered porosity, as well. Figure 4-4 shows a pore that was located by optical in-situ data outside of the gauge length, placing it well outside the area of the build containing purposeful porosity. The optical data again overestimates the size of the pore, but the existence of this non-engineered pore is confirmed by XCT. While the pore may be overestimated by optical in-situ data, the location is accurately detected. This is an important discovery, as the goal of optical in-situ pore detection is to detect pores in normal builds that do not usually contain

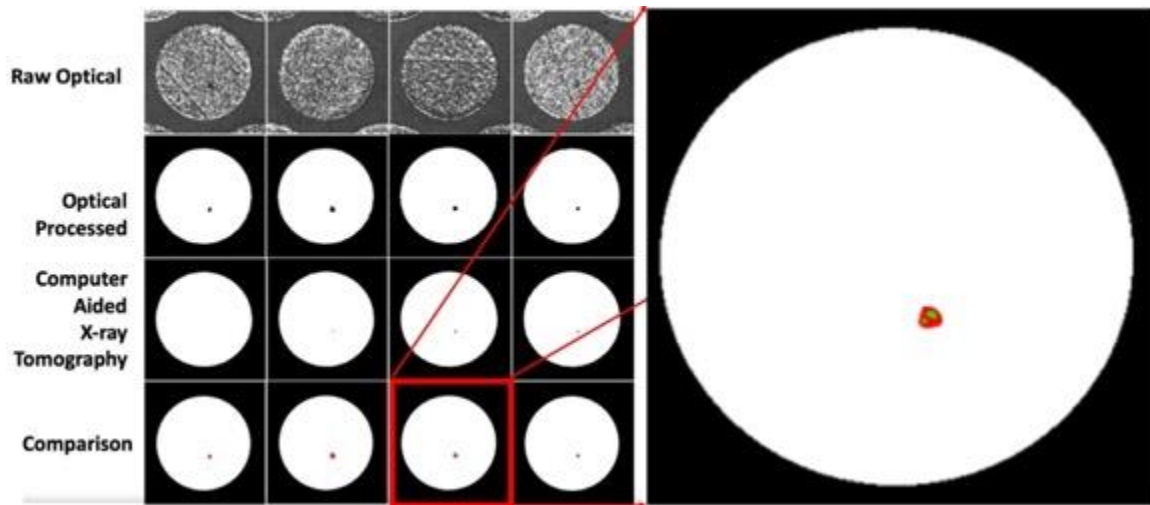


Figure 4-4: A non-engineered pore was detected by optical in-situ data outside the gauge length in one of the samples and confirmed by XCT.

purposeful porosity. This non-engineered pore, which was detected by the optical in-situ data and analysis methodology, proves that this system is able to capture true pores.

### ***Connecting porosity to tensile failure using optical data***

In addition to the ability of the optical in-situ system to detect porosity, it was a goal of this study to evaluate the ability of this data to inform tensile performance. The tensile tests were recorded using DIC software in order to examine local strain effects and compare this data to porosity data. The optical in-situ data reports many statistics for each layer of the build, including number of individual pores detected in a single layer and their areas. The total area of porosity per layer was calculated by adding the areas of individual pores within a single layer. When this quantity was plotted for each layer, no close correlation was observed to layers with the highest amount of total porosity and the location of tensile fracture. However, the individual pore area was also plotted with respect to layer, and this data visualization showed several large pores clustered together near the location where the tensile bar fractured, which was estimated between layers 700 and 750. This is shown for the 500 $\mu$ m-5% as-built sample in Figure 4-5.

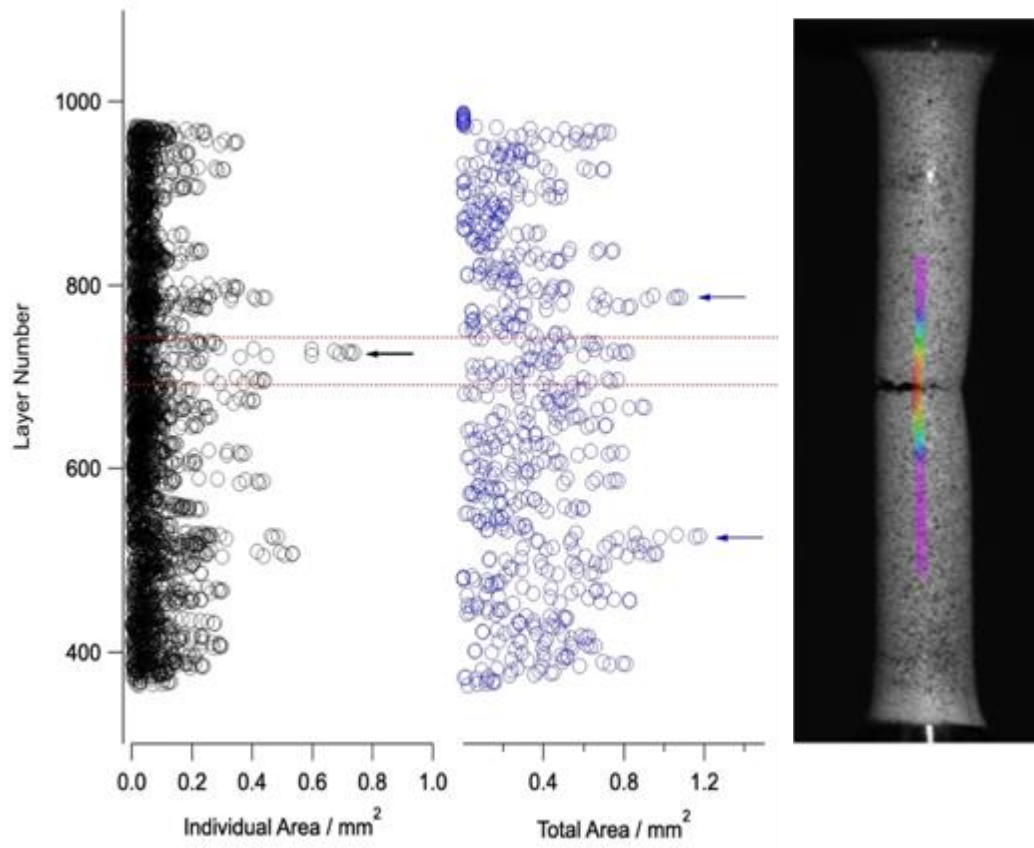


Figure 4-5: A cluster of large pores was detected near the location of tensile fracture. Total pore area in a layer did not seem to predict this location.

Following analysis of the pore area (both individual and total) of the internal porosity, pore proximity to surface was calculated. The hypothesis behind this analysis was that pores which were closer to the surface would have greater influence on fracture location than pores which were closer to the center of the tensile bar. The closer a pore is to the surface, the less area there is to take the additional stress cause by the pore. This results in localized plastic flow in these regions. Because the optical data analysis provides statistics on pore centroids, it is then simple to evaluate the distance of each pore from the surface of the tensile bar. For each tensile sample, the average distance of pores from the surface was calculated and compared to every pore. The number of pores whose centroids were closer than this average to the surface were counted within a set interval of layers. This interval was varied to examine the sensitivity and an interval of 25 (1.25 mm) was chosen in order to observe a correlation between this analysis and fracture location because smaller intervals showed little change in the overall shape of the data. When these intervals are reference in the three following figures, horizontal axis labels indicate the last layer of each interval (i.e. label 525 indicates the interval of layers 500 to 525.) The 500 $\mu$ m-5% bar had a concentration of pores which were close to the surface around the layers 625-650 (Figure 4-6). This was observed to be very near the location of fracture of this tensile bar, and closer to fracture than the cluster of large individual pores which were previously observed.

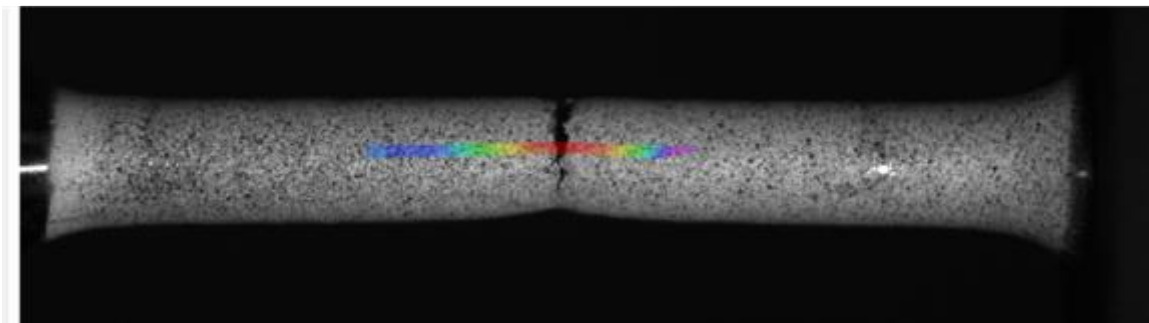
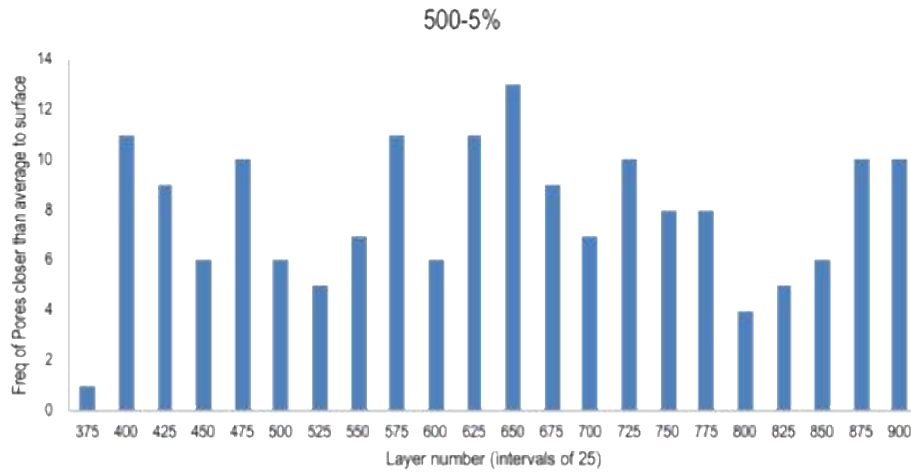


Figure 4-6: The fracture location on the 500 $\mu$ m-5% tensile bar compared with the number of internal pores closer than average to the surface of the bar.

The 350 $\mu$ m-5% tensile bar data is shown in Figure 4-7 and it was noted that there were internal pores closer to the surface only in the layers before the center of the gauge length. This was a distinctly different distribution than that of the 500 $\mu$ m-5% bar, but the fracture location of this bar again occurred near the location of an above average amount of pores close to the surface. The same comparison was then performed for the 200 $\mu$ m-5% and is shown in Figure 4-8. Again it was observed that there was a heavy skew in the amount of pores closer to surface of the part near the location of fracture. It is important to note that because the tensile bars were cut from the base plate and there are no external locator marks, correlating exact layers to their location on DIC images must be done by eye and is therefore an approximation. The center layer was located in the optical data and then the start and end layers for the known gauge length were calculated based on the center layer. Although the exact layers of the gauge length can be determined in the optical data, matching the location of layer to the DIC is not exact due to the lack of an external locator on the machined tensile bar. Only the gauge length of each tensile bar was included in the DIC images due to the nature of DIC data collection: the area of interest must be painted with black and white paint for contrast and the camera must be closely focused on this area. Because of this, all comparisons of DIC images to optical data were assumed to be close but not exact. Although these comparisons are not exact, it was observed that pore location relative to other

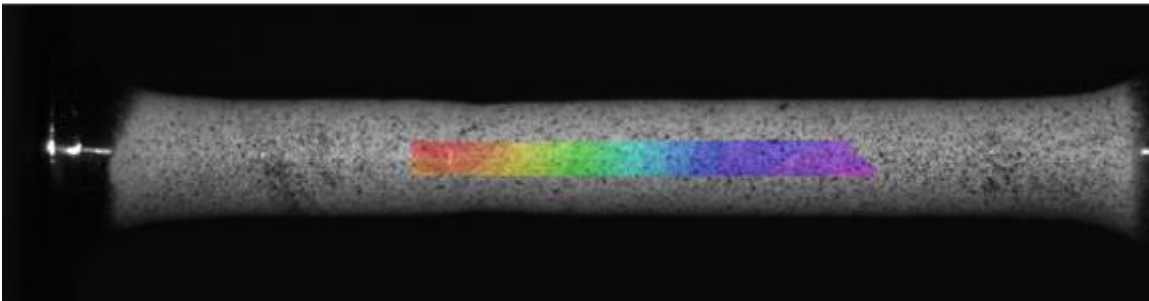
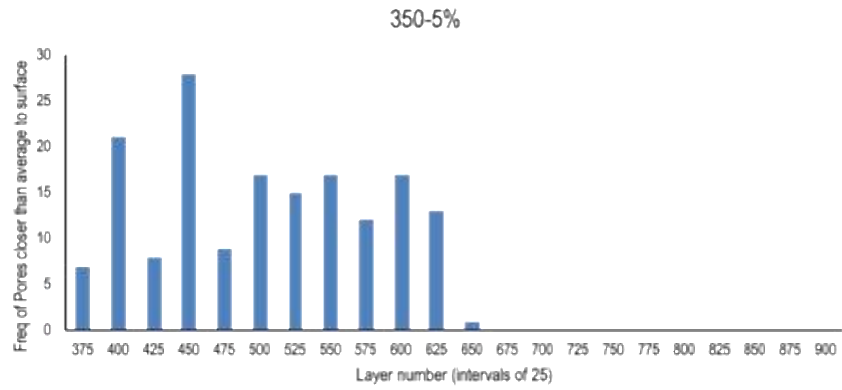


Figure 4-7: The fracture location for the 350 $\mu$ m-5% bar (the red zone) is compared with the number of internal pores closer than average to the surface.

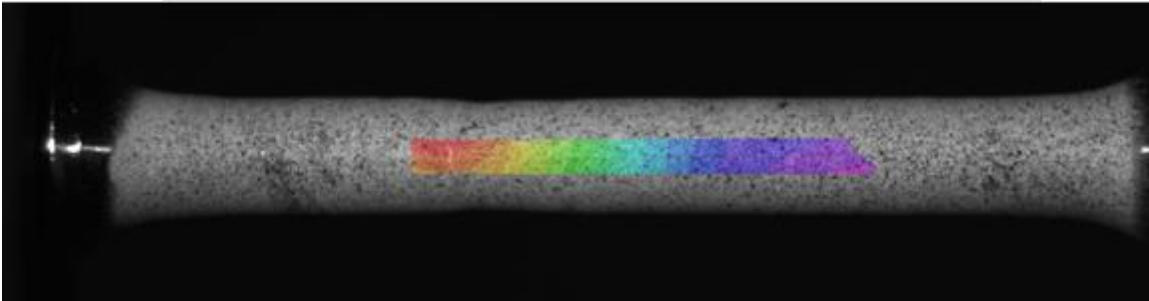
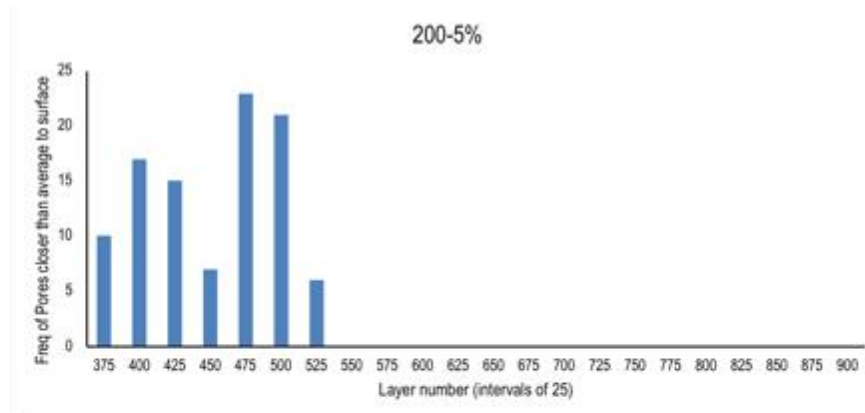


Figure 4-8: The fracture location for the 200μm-5% bar (the red zone) is compared with the number of internal pores closer than average to the surface.

pores (particularly with large pores) and to the surface of the part likely had an effect on fracture location. More work is needed in order to more accurately examine and quantify this effect.

## **4.2 Finite Element Modeling**

This section will be used to explain the motivation, method, setbacks, and results for FEA work. The goal of FEA modeling for this data was to use optical in-situ data to create a CAD part of the tensile bar with embedded porosity. This is theoretically possible by taking the three-dimensional representation of the optical data, which is created by the ImageJ program FIJI [30], and importing this part into CAD software to perform a Boolean operation to remove the reconstructed pores from a solid tensile bar model. In this way, the pores would be placed within a tensile bar model in their as-built condition as recorded by the optical in-situ system.

### ***Importing into ABAQUS***

Optical in-situ data was exported as stereolithography file (STL) , which approximates the surface of an object using triangles. This is not an ideal file format for CAD representation, as it does not contain any information about volume. However, this file format is the only available export option for the 3D reconstruction performed by FIJI [30]. After this file is imported into ABAQUS [31], it appears as an empty mesh with no volume. The 3D reconstruction and

subsequent part representation may be observed in Figure 4-9. The empty mesh within ABAQUS also imports with a few problems: several of the triangular elements have flipped normal vectors, and several triangular elements are not connected to their neighbors and therefore create discontinuities on the surface of the porosity representation. Ideally, this STL file would be imported and then converted to a solid by using an ABAQUS 3d mesh-to-geometry plugin [32]. However, these issues with the STL import prevent the ABAQUS plugin from completing this conversion successfully. The empty mesh is able to convert to a geometry, but the geometry appears with no volume and manifests as a vast amount of surfaces (greater than 3 million) rather than either a solid part or multiple solid parts.

### ***Three Dimensional Sectioning Modeling***

In order to test the capability of the methodology for a smaller data set, the porosity reconstruction was sectioned. A selection of porosity 8 mm long in the center of the gauge section was isolated and analyzed. It was imported successfully into ABAQUS from an STL file, and converted into a surface geometry using the plug-in. The converted geometry was comprised of mostly surface bodies, which were then converted from surfaces bodies to solid pores with volume. Unlike the full geometry, this smaller data set was able to complete this step.

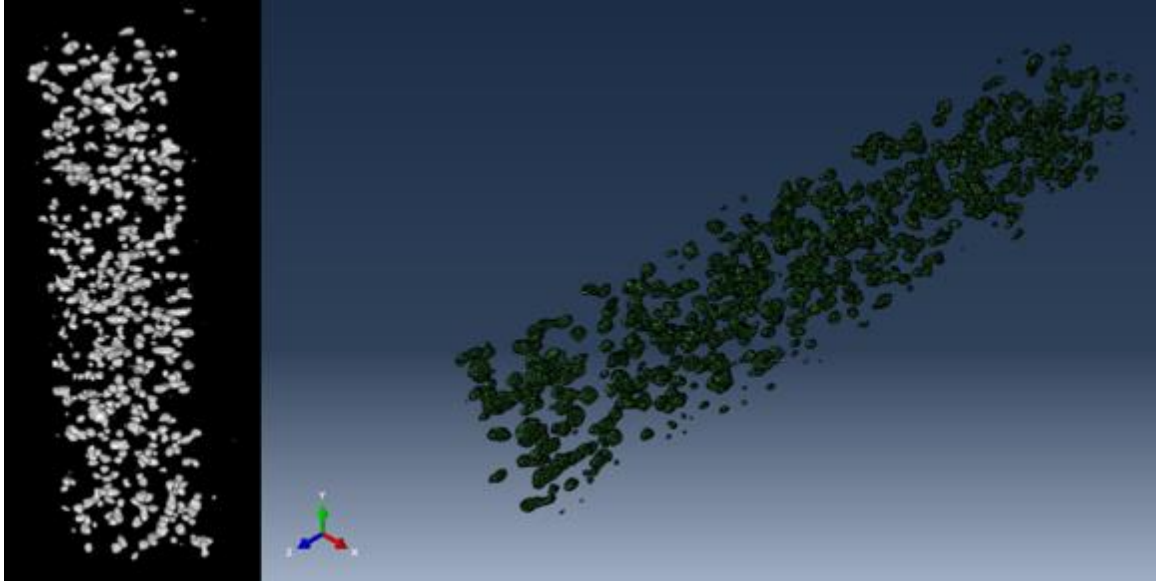


Figure 4-9: (left) Three-dimensional reconstruction of optical data using FIJI and (right) porosity reconstruction imported to ABAQUS software as .stl file.

Next, the Boolean operation was also successful and is shown in Figure 4-10. However, this step resulted in over 3 million interior free surfaces due to the triangular surface approximation of the STL file (Figure 4-11). The resulting sharp corners and points pose a challenge for mesh resolution because the mesh must be fine enough to accurately represent the complex stress distributions at these locations. As such, this geometry contained very complex interior free surfaces made resolution practically very difficult.

### ***Two Dimensional Slice Modeling***

Another approach to simulating the represented porosity was an analysis of the randomly distributed pores on a flat plate. The goal of this attempt was to test the ability of ABAQUS to capture pore interaction and illustrate the complex nature of such a large volume percentage of irregularly shaped pores. There is literature to the effects of single or two interacting pores of circular or ellipsoidal geometries, but this analysis sought to understand the stress distribution caused by pores with varying sizes, shapes, and relative distances. In order to examine the effect of interacting pores in the plane of tension, the gauge section of the tensile bar model (which was reconstructed by extruding the optical in-situ two dimensional XY data) was sliced parallel to the Z direction. This yielded a thin rectangular plate with all the porosity for the Z direction at a particular X or Y location, an example of which can be found in Figure 4-12. This boundary conditions for this model were set to match those of the experimental tensile test and a plane strain

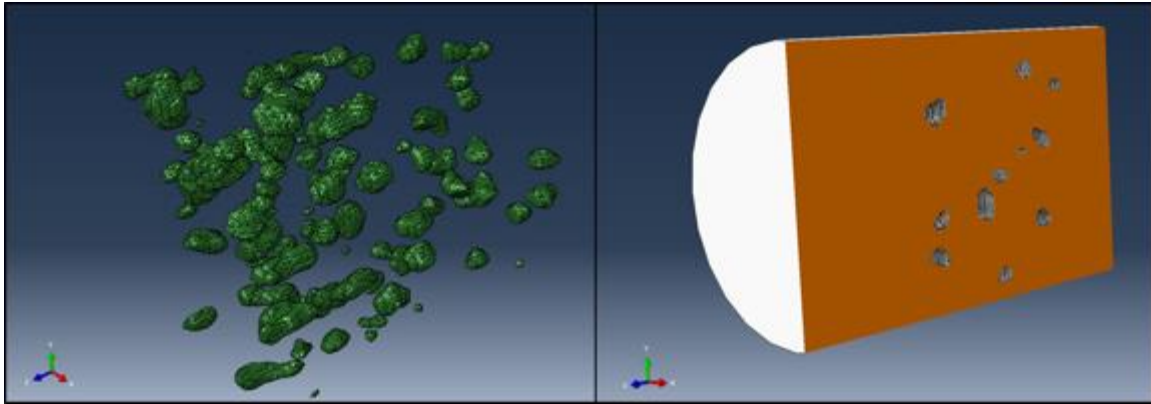


Figure 4-10: (left) a section of the reconstructed optical data was isolated to investigate feasibility of the methodology and (right) was successfully removed from a solid gauge section to create a single part negative of the optical data.

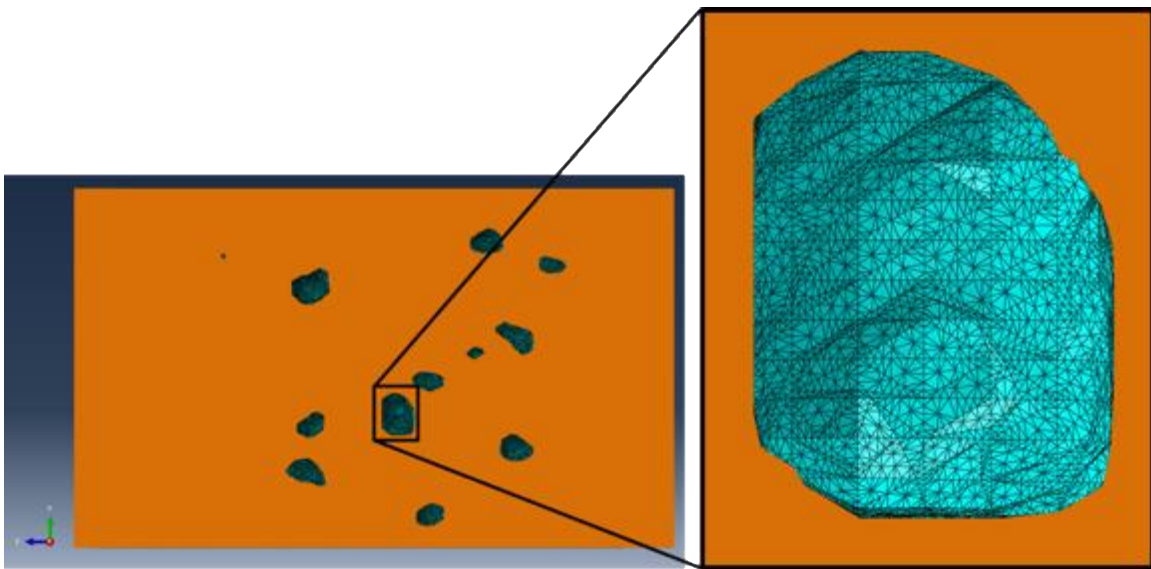


Figure 4-11: Although a solid part was achieved, the irregular and complex shape of the pores created over 3 million interior free surfaces.

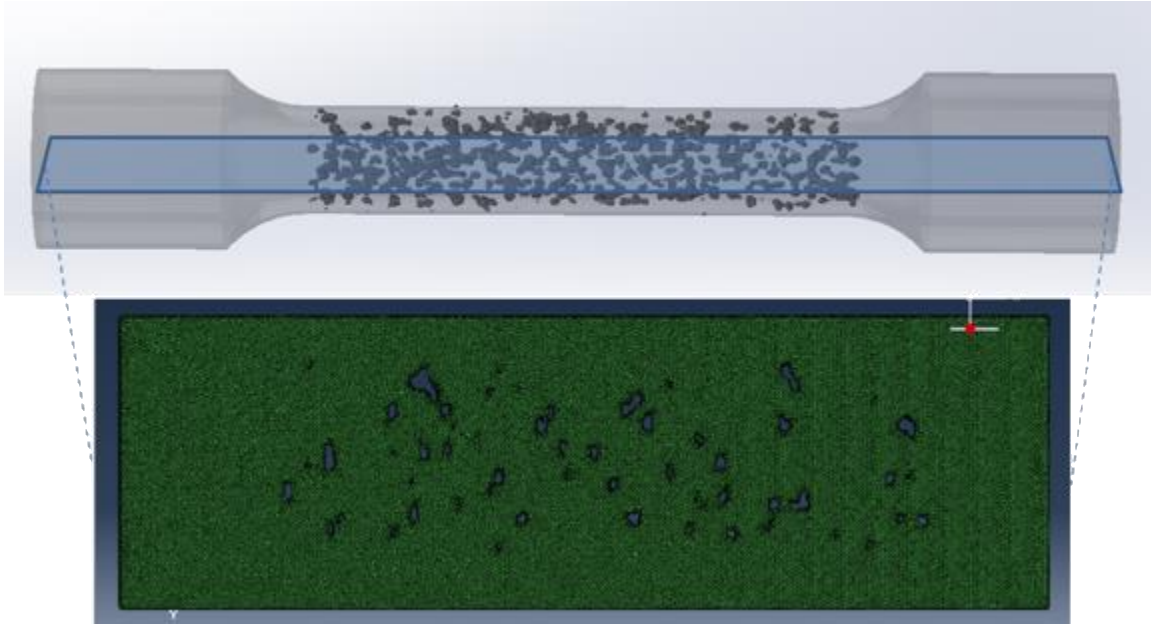


Figure 4-12: A 2D slice was taken long the length of the tensile bar porosity reconstruction to evaluate the porosity interactions on a 2D plate under uniaxial tension.

simulation was chosen, as previous literature has shown that plane strain simulations are able to accurately represent tensile tests [33]. This condition stipulated that all strains are in-plane, which is true for a uniaxial tensile test, but allows stresses in out-of-plane directions. The pore edges in this method are still highly irregular, and as such resulted in tetrahedral elements in this mesh. The results of this analysis are shown in Figure 4-13. It is important to note that while this simulation resulted in a helpful visualization of the interacting stress concentrations due to varying pore sizes and relative locations, the von Mises stress values were not quite accurate. Because the elements of this mesh were tetrahedral (which take on constant stress values) this mesh was not able to accurately capture the high stress values at the sharp stress concentration sites. In order to use different mesh elements, the geometry could be remeshed. However, this step is practically difficult due to the time and computational power necessary to perform the remeshing in three dimensions and may still not be resolvable due to the many discontinuities caused by irregular pores [34], [35].

### **4.3 Tensile Testing Results**

In all cases, the ASTM E8 tensile bars that had been HIP/SA had lower yield strength and higher ductility than their as-built condition twins. This was expected, as HIP is well known to increase ductility at the expense of yield strength. However, there was variation in the effect of porosity on the tensile properties of as-built condition tensile samples. The performance of the tensile

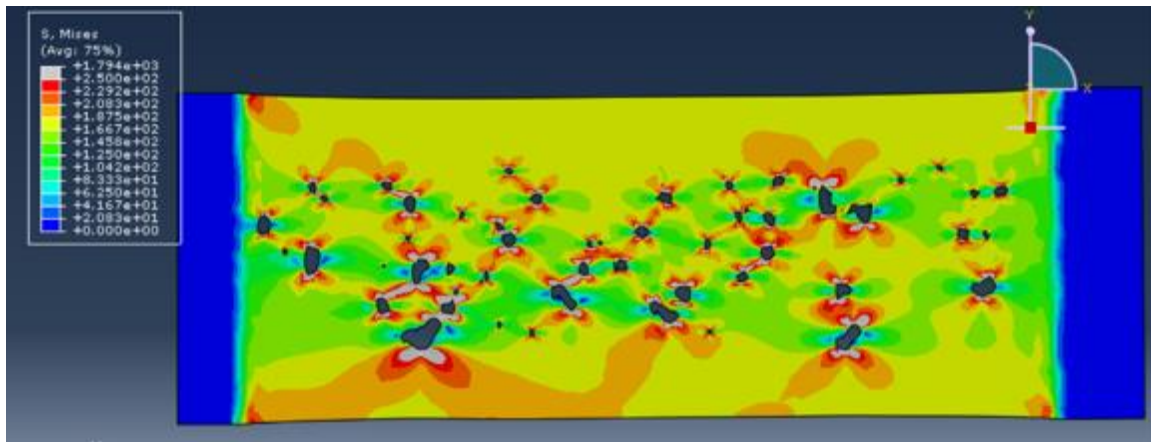


Figure 4-13: Von Mises strain results for the 2D plate representation of pores from optical data shows interacting stress fields forming bands of high stress between pores.

samples with reference to control samples and industry standards will be examined in this section.

### ***Stress-Strain Results***

The stress-strain results from each sample are compared to a control (no intended defects) sample with the same post-processing conditions, meaning that there is an as-built control and a HIP/SA control sample. This was done in order to examine the effect of the varying pore sizes and volume percentages. Overall, the results of tensile testing highlight the ability of the HIP/SA process to mitigate the effects of porosity, even with large pores in large quantities. A comparison of the location of failure in the tensile bars is shown in Figure 4-14. Of interest in this photograph is the difference in the failure location between the HIP/SA and as-built samples for the same pore size and amount variation. It was assumed that the internal porosity was effectively the same for these two bars before heat treating because they were based on identical CAD files. While there may have been slight variations in the final products due to remelting or differing

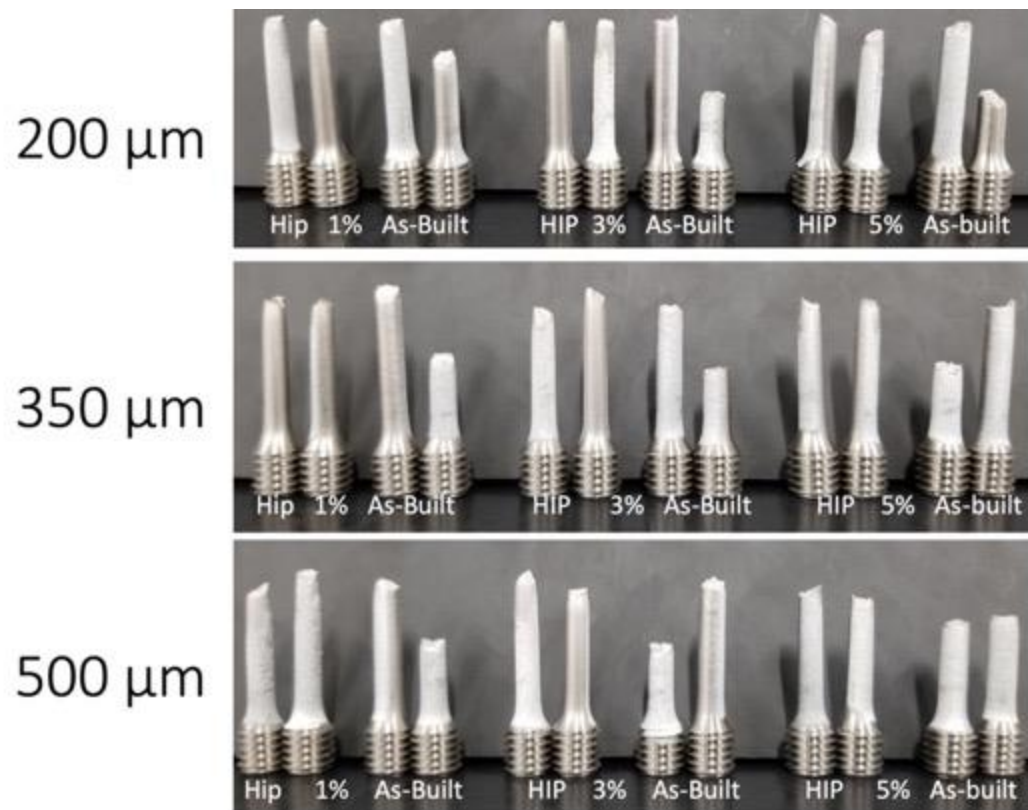


Figure 4-14: Photograph of all tensile samples after tensile testing has been performed.

build plate locations, the engineered porosity should be qualitatively equal in both samples of each size and volume percentage pair. This assumption was visibly confirmed by observing the optical in-situ data for each bar. Almost all tensile bars in the as-built condition failed off-center, with the exception of the 500 $\mu$ m-5% as-built sample. In comparison, each HIP/SA sample fails near the center of the gauge length. This supports the conclusion that the HIP/SA process was able to repair the internal engineered porosity.

### ***Tensile results for 200 $\mu$ m pore size samples***

Results from the 200 $\mu$ m samples for all three different volume percentages are compared for as-built and HIP/SA samples in Figure 4-15. The as-built control sample achieved a 0.2% YS of 58.5 ksi, a UTS of 85.5 ksi, and elongation of 51%. The HIP/SA control sample resulted in a 0.2% YS 40.7 ksi, a UTS of 83 ksi, and elongation of 67%. It was noted that all HIP/SA very closely compared to the results of the control HIP/SA sample, suggesting that the post-processing methods used successfully repaired the 200 $\mu$ m size porosity in all volume percentages. For the as-built samples, yield stress and elongation performance became increasingly less than the as-built control sample as the volume percentage of porosity increased. However, the 200 $\mu$ m-1% as-built sample, which is the “best case” as-built porosity sample in this study with the smallest pores in the least amount, was much closer to the yield stress and elongation of the control sample than the 3% and 5% porosity samples. This 200 $\mu$ m-1% had a

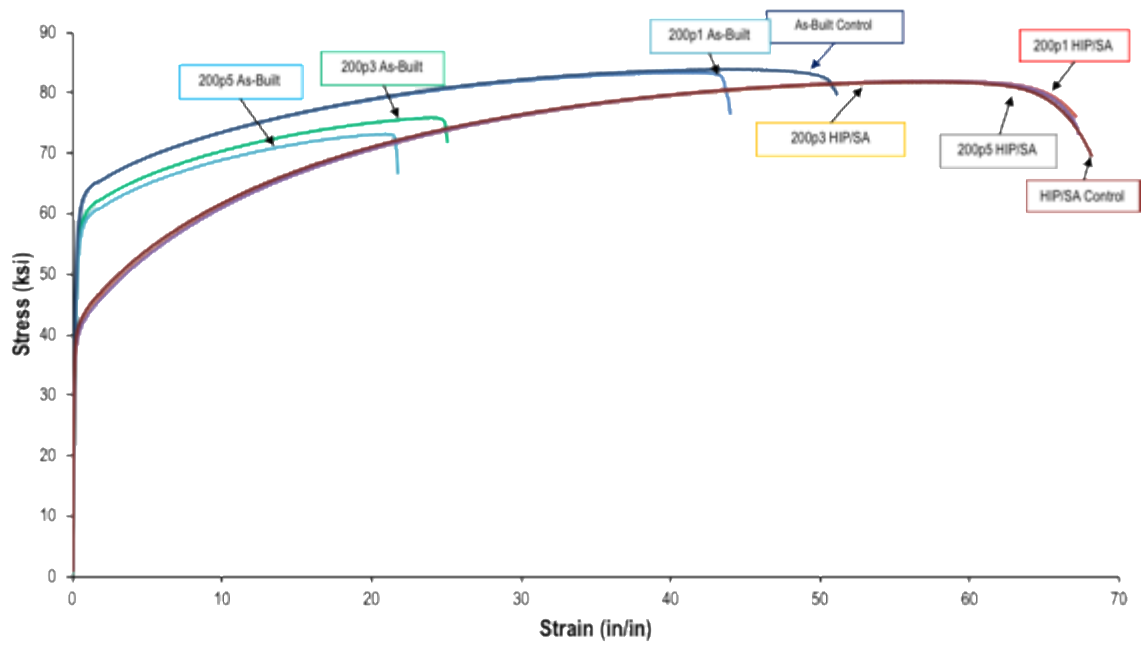


Figure 4-15: Stress-strain curves for all tensile bars with 200µm pores comparing as-built condition results with HIP/SA results.

YS of just 0.5 ksi below the control, a UTS of 0.5 ksi above the as-built control, and elongation of 44% compared with the as-built control's 51%. This suggests that there may be some threshold of porosity size and amount that achieves acceptable performance without additional post-processing heat treatments. It is worth noting that this could also be attributed to normal fluctuations during tensile testing, and there is no way to establish if this is within acceptable error because only one sample of each type was tested.

### ***Tensile results for 350 $\mu$ m pore size samples***

All tensile bars with 350 $\mu$ m pores were compared with the as-built and HIP/SA control samples. The stress-strain results for these samples are presented in Figure 4-16. The results again cluster in two groups: as-built and HIP/SA. All volume percentages in the HIP/SA condition achieved a 0.2% offset yield strength within 2 ksi of the control sample. However, even with this small difference, the HIP/SA samples showed a linear decrease from the control YS with increasing porosity amounts (Figure 4-17). These HIP/SA tensile results are still acceptable even at 5%, although the small decrease in yield strength with initial porosity values suggest lingering effects of the porosity even after the pores are closed by the HIP process.

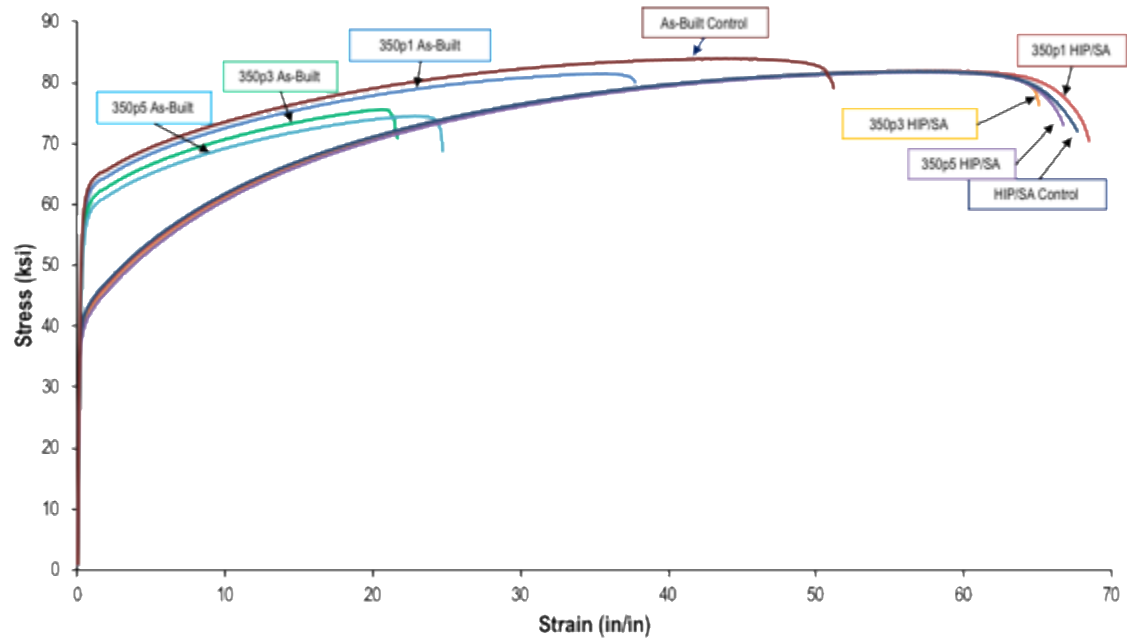


Figure 4-16: Stress-strain curves for all tensile bars with 350µm pores comparing as-built condition results with HIP/SA results.

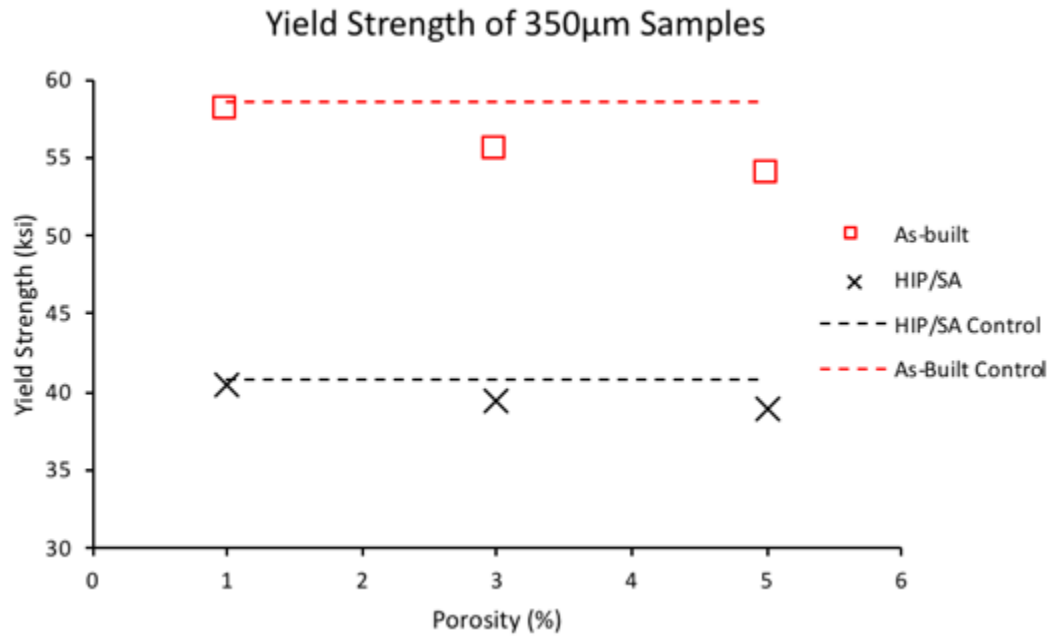


Figure 4-17: The 0.2% offset yield strength results for all 350m samples are compared with the control sample results for both HIP/SA and as-built conditions.

### ***Tensile results for 500 $\mu$ m pore size samples***

For the tensile bars with 500 $\mu$ m pores, once again the HIP/SA samples achieved yield stress and elongation results very similar to that of the control HIP/SA sample, although there was more scatter in elongation for these samples than was observed in the 200 $\mu$ m or 350 $\mu$ m pore size samples (see Figure 4-18). The variation may be the effect of pore reopening and again suggests that there are lingering effects of large pores even after HIP/SA treatment. The deviation of elongation and yield strength with increasing porosity volume percentage is further illustrated in Figure 4-19. It is interesting to note that although the 500 $\mu$ m HIP/SA samples varied from the control sample more than tensile bars with smaller pore sizes in general, the difference between the HIP/SA control sample results and the results of the HIP/SA 500 $\mu$ m engineered porosity samples increased with increasing volume percentages. This suggests that the HIP/SA treatment is either less effective for closing such large pores initially or that there are weakening effects under tension that smaller pores do not incur. All tensile tests were also recorded using digital image correlation software for additional strain analysis. The video from the 500 $\mu$ m-5% HIP/SA tensile sample showed slightly different failure behavior compared to the other samples, which failed quickly once rupture began and exhibited the cup-cone features typical in ductile failure. Images from this recording are shown in Figure 4-20. Although this sample did undergo HIP and solution annealing processes, the failure fractured

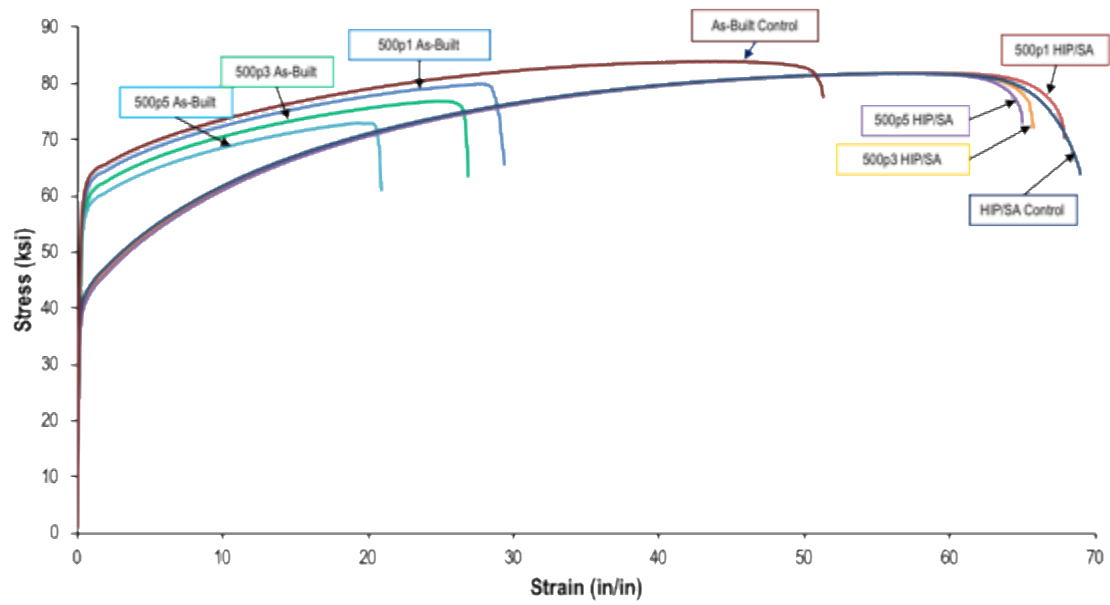


Figure 4-18: Stress-strain curves for all tensile bars with 500µm pores comparing as-built condition results with HIP/SA results.

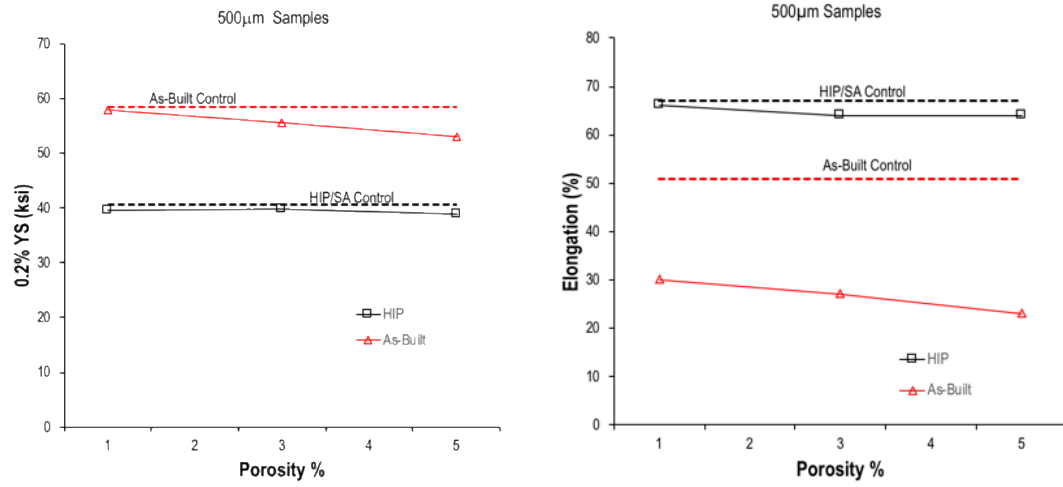


Figure 4-19: The yield strengths and elongations of all 500µm samples are compared graphically.

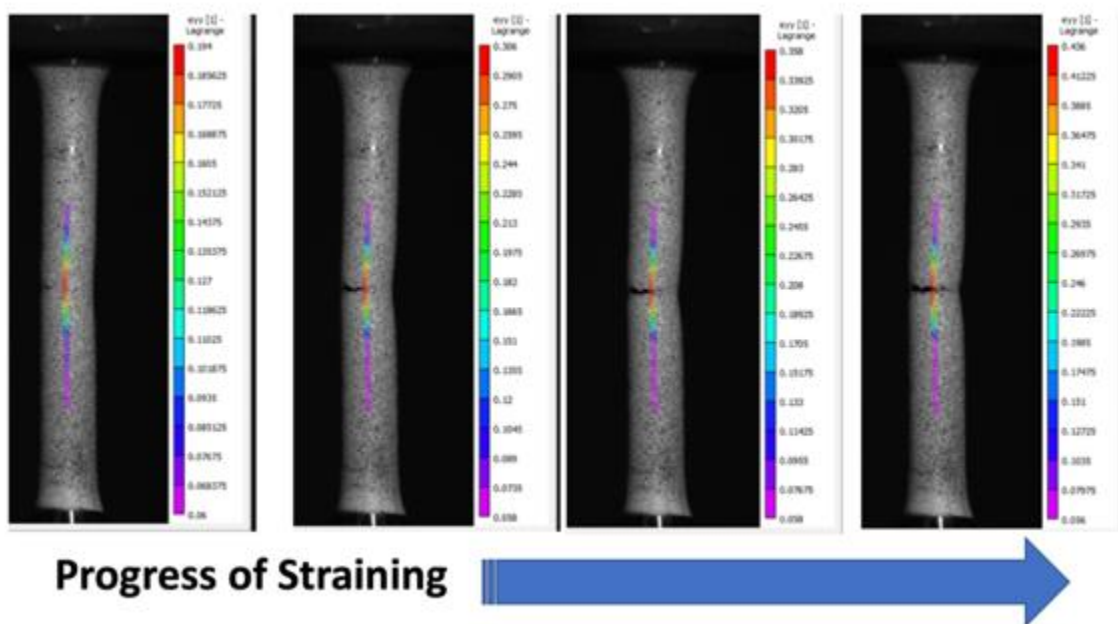


Figure 4-20: Images from DIC video showing fracture of the 500 $\mu$ m-5% HIP/SA tensile sample.

more slowly across the gauge length. It was concluded that there was a lingering effect from large pores at a high volume percentage, particularly because this decreasing result trend with increased porosity amount was observed consistently for the HIP/SA samples of all pore sizes. Further work is necessary to understand the sensitivity of these effects to varying pore sizes and amounts.

### ***Tensile results comparison for all HIP/SA and as-built samples***

The results for 0.2% YS and elongation showed the most variation between samples, and these results are compared with the control results for both as-built samples and HIP/SA samples in Figure 4-21 and Figure 4-22. The ultimate tensile strengths for all samples are plotted in Figure 4-23. The difference in the as-built and HIP/SA UTS was only 2.5 ksi, and the HIP/SA engineered porosity samples did not show much scatter in results. For comparison, the minimum required tensile properties for 316L stainless steel for powder metallurgy (P/M) parts, powder metallurgy hot isostatically pressed (PM-HIP) parts, and wrought parts are compared with the 5% volume percent cases for tensile bar samples with 200 $\mu$ m, 350 $\mu$ m, and 500 $\mu$ m in Table 4-1. These requirements were taken from the ASM Metals Handbook for P/M and wrought parts [36] and from the PM-HIP Data Package submitted to ASTM by EPRI in support of a Code Case for Type 316L stainless steel. It was observed that the HIP/SA process for all samples reduced scatter in all measures tensile properties, while the as-built results performed worse with increasing porosity amounts and sizes. This was

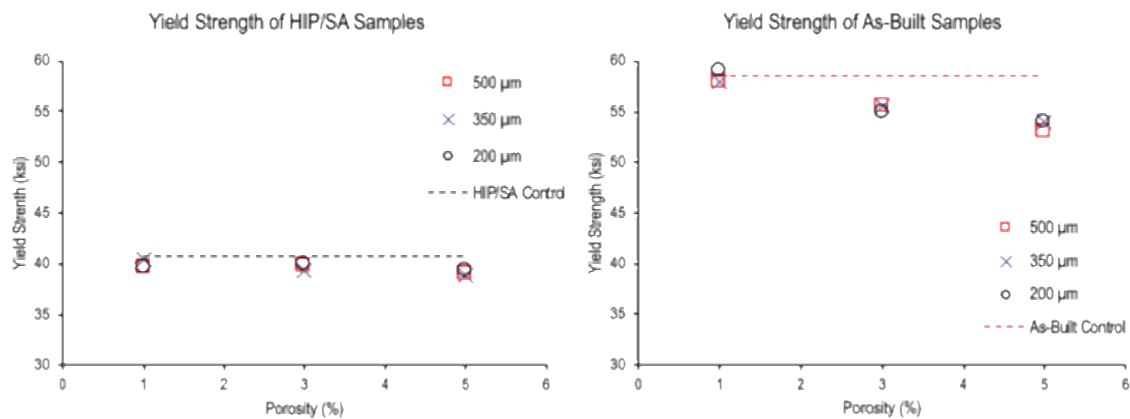


Figure 4-21: Yield strength results are compared for all HIP/SA samples and all as-built samples.

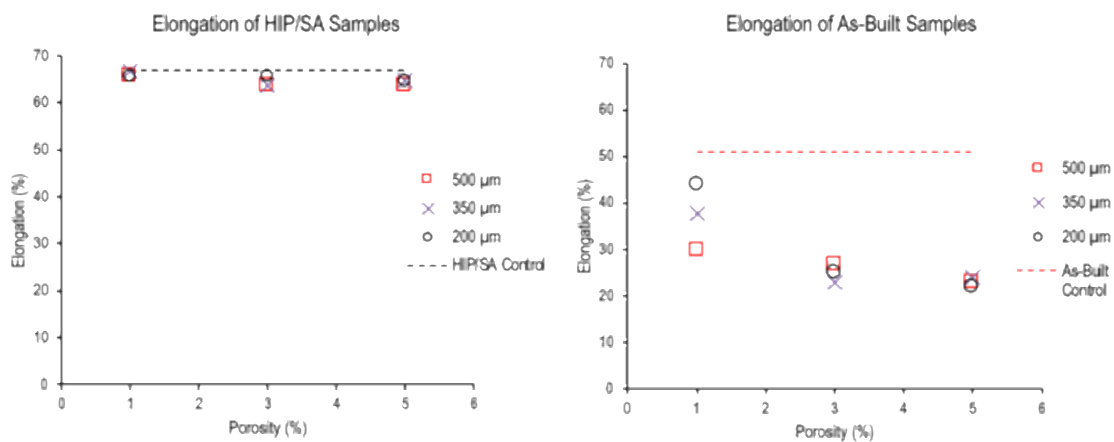


Figure 4-22: Elongation results are compared for all HIP/SA samples and all as-built samples.

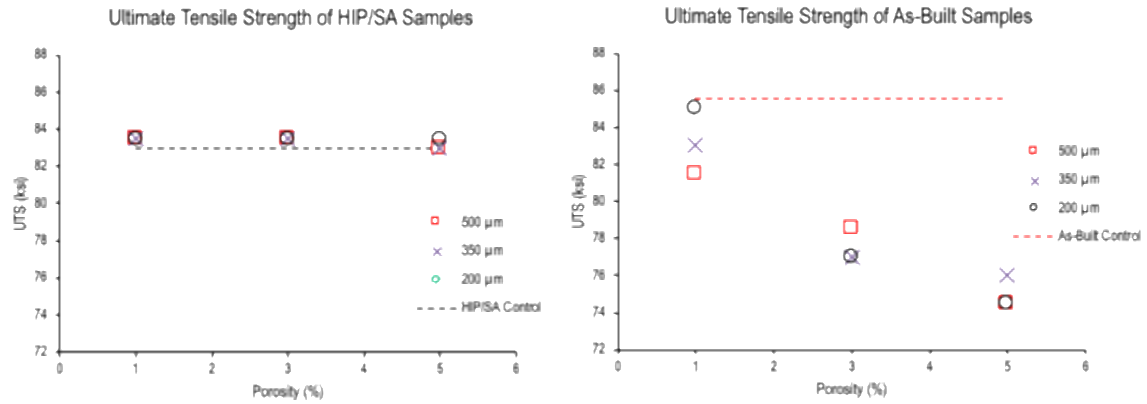


Figure 4-23: Ultimate tensile strength results are compared for all HIP/SA samples and all as-built samples.

Table 4-1: Comparison of tensile results for 5% volume percentages of all pore sizes with the wrought, P/M, and PM-HIP minimum requirements.

| <b>Designation</b>    | <b>UTS (ksi)</b> | <b>0.2% offset yield strength (ksi)</b> | <b>Elongation in 25 mm (%)</b> |
|-----------------------|------------------|-----------------------------------------|--------------------------------|
| P/M 316L              | 57               | 30                                      | 21                             |
| PM-HIP 316L           | 70               | 25                                      | 30                             |
| Wrought 316L          | 70               | 25                                      | 40                             |
| 200 $\mu$ m-5% HIP/SA | 83.5             | 39.4                                    | 65                             |
| 350 $\mu$ m-5% HIP/SA | 83               | 38.9                                    | 65                             |
| 500 $\mu$ m-5% HIP/SA | 83               | 39                                      | 64                             |

expected, but provided important confirmation that the heat treatment procedure successfully resulted in a qualified part. It is important to note that each tensile sample in this experiment was singular, therefore the scatter in results of a single design could not be assessed. Scatter as mentioned above refers to the overall variation in the tensile properties following heat treatment. While it was not ideal that each part design was represented by a singular part, this experiment was limited on time and resources due to the schedule and material availability for the additive manufacturing system used, and these results will be used in comparison to upcoming experiments built in a separate system but using the exact design and specifications.

### ***Comparison of HIP/SA Tensile Results to Complex Builds***

A previous study was conducted during this project which built more complex parts in order to examine the effects of layer time on part quality. While the results of that study are not fully included in this report, tensile samples from those complex parts were heat treated and tested following the same process as the engineered porosity tensile bars. The tensile bars in this study were purposefully machined to the same specifications as the bars taken from complex geometry builds so that a more direct comparison could be made across two builds. The results of these two studies were compared in order to justify the process-based qualification method. Partners on this project using separate manufacturing facilities will be conducting the same tensile bar experiment in

another machine to provide supporting evidence that this process-based qualification method is accurate and repeatable. The parts used here for comparison were part of a layer time experiment (LTE) build contained several variations of a pipe geometry with solid sections and support material added at varying locations in order to examine the effect of layer build times and scan lengths on defect formation. These pipe parts are shown in Figure 4-24. Despite being built separately and having vastly different build times and geometries, the engineered porosity tensile bars and tensile bars cut from the LTE pipe builds yielded very similar 0.2% yield strength and ultimate tensile strength (UTS) results. The yield strengths for all tensile samples hovered around 40ksi, while all samples (with the exception of a single sample from the LTE build, which is suspected to have been an anomaly) achieved above 80ksi in UTS. These results are compared in Figure 4-25. These results support the conclusion that the HIP/SA process proposed for process-based qualification reduces part scatter and achieves acceptable tensile properties even in separate builds with vastly different geometries.

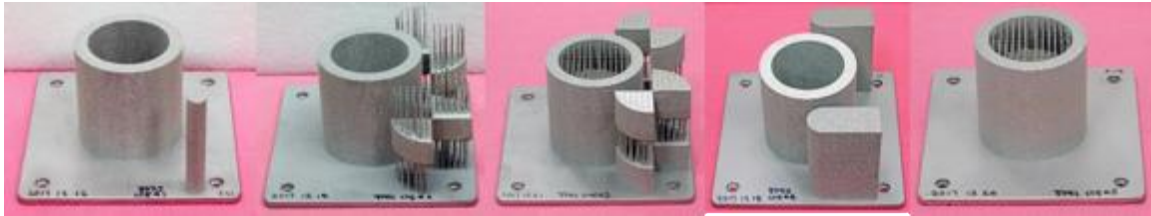


Figure 4-24: LTE pipe builds

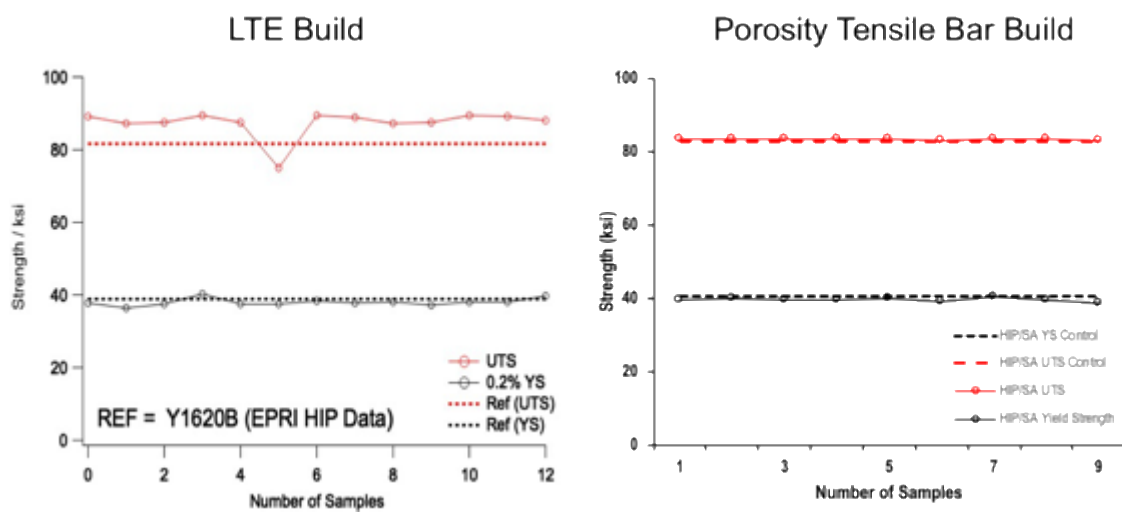


Figure 4-25: Comparison of yield and ultimate tensile strengths for the LTE tensile samples and engineered porosity HIP/SA samples.

## **CHAPTER 5: SUMMARY AND CONCLUSIONS**

The optical in-situ data collection and processing method successfully identified porosity and was confirmed by XCT data. The optical data analysis methodology was able to accurately capture the existence and location of porosity compared with the pore existence and locations indicated by XCT data, although the optical data does overestimate the size of the ground truth pore data as established by XCT. This was attributed to possible remelting effects and was expected. The exact amount of total overestimation was not determined due to variations in data collection and processing methods between XCT and optical data. This optical data was analyzed, and it was determined that important characteristics such as pore size and relative location to other pores and the surface of a part were indicative of fracture location and may be used to identify problem areas for further analysis. Further work is necessary to understand the ability of porosity distribution data to predict fracture location and quantify the accuracy of the comparison between optical layer data and digital images. This optical in-situ data was also used to reconstruct a geometry by extruding layer-by-layer data into a three dimensional representation of the as-built porosity within tensile samples with the intention of using finite element methods to predict part performance. Although several different variations of finite element analyses were attempted, none were completely successful in predicting the performance of the samples based on the in-situ data. More work is necessary to resolve the

problems associated with modeling such complex structures in a three-dimensional part. Tensile results from each variation of size and amount of porosity used in this study achieved industry acceptable standards of yield strength (25 ksi), UTS (70 ksi), and elongation (30%) after a HIP/SA process. Therefore, it was concluded that this process-based qualification method was successful in mitigating porosity effects for additively manufactured 316L up to pores of 500 $\mu$ m size at 5% volume. This conclusion supports an upcoming data package submission to ASME for a new process-based qualification standard for AM parts.

### ***Future Work***

Further work will be performed by industry partners which will repeat the porosity tensile bar experiment using different additive machines and parameters. This will provide additional data points for each tensile bar result in order to examine the validity and repeatability of these results. In addition to verifying the process-based qualification conclusion, these partners will also use optical in-situ data to monitor the builds. This data will be used to compare the fracture locations of identically designed but separately manufactured builds, which will be used to support the validity of the results of this study. Ultimately, it is the hope of these researchers that a methodology may be developed which can use optical in-situ data to identify part defects by providing an internal defect report for each additively manufactured part. This would support a more individual part

qualification method which may be necessary in parts that do not fall under the purview of a process-based qualification, or for parts that will not be HIP/SA following production. Although that is the long term goal for specific part qualification, this work is currently part of an ongoing effort to compile an extensive data package in support of a code case submission to ASME for process-based qualification for additively manufactured 316L.

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## **VITA**

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