Heat Treatment Control of Residual Stress and Microstructure of 3D-Printed 316L Stainless Steel

A Senior Project
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Bachelor of Science, Materials Engineering

By

Katherine Adelman, Kent Nakano, Hajime Yamanaka
Advisor: Prof. Ryan Smith
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Abstract

One of the major drawbacks of selective laser melting (SLM) as a form additive manufacturing is that it produces parts with severe residual stress that leads to poor mechanical performance due to the thermal cycling of the printing process. In this project, two different heat treatments (high temperature annealing and low temperature annealing) are applied to 316L stainless steel subsized tensile bars fabricated by SLM process to minimize the amount of residual stress in the samples. Residual stress is indirectly measured by X-ray diffraction (XRD), as well as microscopic analysis, hardness testing, and tensile testing are applied to characterize the samples. Unfortunately, the residual stress could not statistically be determined because of large measurement errors even though error corrections were applied. However, the HRB hardness values are determined to be 91.8 HRB for as-built samples, 80.7 HRB for after high temperature annealed samples, and 95.5 HRB for after low temperature annealed samples. The high temperature heat treatment followed by annealing showed a reduction in hardness values, as expected. The low temperature heat treatment appeared to show an increase in hardness. Optical microscopy and scanning electron microscopy (SEM) showed that small dendritic structures, which are ubiquitously seen throughout as-built samples, are gone in the high temperature annealed samples.

Keywords: Selective Laser Melting (SLM), 316L Stainless steel, X-ray Diffraction (XRD), Residual Stress, Scanning Electron Microscopy (SEM), Tensile Testing, Hardness Testing, Materials Engineering
Acknowledgements

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1. **Introduction**

1.1. **Overview**

Additive manufacturing (AM) has more recently been a prominent field of research due to its promising application in rapid prototyping in polymers, metals, and ceramics and capability of manufacturing complex shapes conventional manufacturing methods cannot achieve. The layer-by-layer building technique can be applied in many methods such as stereolithography in polymers to powder bed fusion technologies such as selective laser melting (SLM) in metals. Metals are a promising venue of SLM because the processing may optimize weight and mechanical properties for the aeronautical sector and 316L stainless steel has good corrosion resistance and biocompatibility in biomedical applications\(^1\,^2\). Figure 1 shows some of application of 316L stainless steel fabricated by SLM.

![Figure 1](image)

**Figure 1.** Application of SLM fabrication. (a) gooseneck bracket in aerospace industry, (b) RPD framework in dental industry, and (c) gear box housing in automotive industry\(^3\).

Since the selective laser melting form of additive manufacturing was introduced, the mechanical properties and microstructures have been heavily investigated based on the machine parameters, printing parameters, and different materials\(^2\,^4\). For metals in SLM, the primary variable parameters include laser power, scanning velocity, hatch spacing, and fabrication orientation. Combined, these parameters influence porosity, microstructure, and defect formation. The three inherent solidification defects from SLM are binding defects, gas pores, and voids\(^5\,^6\). It has been proven in 316L stainless steel samples that laser power has the strongest influence on density and that near fully dense (>98% density) parts may have greater ultimate tensile strengths (UTS) and elongation to failure than bulk 316L material\(^2\).
1.2. Powder Information

The composition of 316L stainless powder used in this study is listed in Table I. This information is obtained from the vendor: SLM Solutions Inc.3

Table I: Composition of 316L Stainless Steel Powder

<table>
<thead>
<tr>
<th>Element</th>
<th>Fe</th>
<th>Cr</th>
<th>Ni</th>
<th>Mo</th>
<th>Si</th>
<th>Mn</th>
<th>C</th>
<th>N</th>
<th>P</th>
<th>Si</th>
<th>O</th>
</tr>
</thead>
<tbody>
<tr>
<td>SS316L</td>
<td>Bal.</td>
<td>16.00-18.00</td>
<td>10.00-14.00</td>
<td>2.00-3.00</td>
<td>1.00</td>
<td>2.00</td>
<td>0.030</td>
<td>0.10</td>
<td>0.045</td>
<td>0.030</td>
<td>0.10</td>
</tr>
</tbody>
</table>

The size of powder is a range from 10μm to 45μm. The high chromium content of this austenitic stainless steel results in high corrosion resistant. Although there are different kinds of metal powder provided from the vendor such as titanium alloy powder and aluminum alloy powder, there is a variety of benefits to investigate on SS316L. One of the reasons is due to its wide range of applications in the current industries.

1.3. SLM Process and Inherent Problem

In SLM, a fine laser selectively melts and bonds the surface layers of a powder bed to its substrate, which would be a work plate or previous layers of the build. After each layer is completed another thin layer of powder is deposited; this process continues until the workpiece is complete. Figure 2 shows a schematic of this process. Each time this process repeats, a temperature gradient is generated within the part. The energy put into the metal to melt the powder results in a small, hot, liquid region. Although the liquid cools rapidly, much of its energy is transferred to the surrounding material resulting in a heat affected zone (HAZ). Cooling and solidification contract the uppermost layer more than the subjacent layers, which results in the local formation of alternating tensile and compressive stresses on the part6,7. These local stresses will accumulate and may result in warpage of the workpiece, at times ripping the workpiece from its support structure or the build plate. This warping due to residual stresses is greater on edges of a part and is often more obvious in larger or thinner pieces. However, this does not mean small parts do not have residual stress due to manufacturing. Microscopic residual stress may also form because of phase differences and lattice dislocations7.
Heat treatments are a possible solution to this problem because heat treatments can reduce and resolve residual stresses. Unfortunately, many common heat treatments to reduce stress for 316L are within 600-950˚C and result in the formation of sigma phase.

Literature supports that there are possible heat treatments that could both reduce residual stress without increasing the amount of sigma phase. In fact, one article by Chen, et al. reports that heat treatments at different temperatures changes the amount of a sigma phase content in the samples. Specifically, heat treating samples at 1000˚C for an hour increases the amount of sigma phase and heat treatments at 1100˚C and 1200˚C for a hour each both decrease the amount of sigma phase. The researchers kept track of the delta phase in their research, which has an important role in strengthening the steel. The amounts of sigma and delta phases were calculated in volume fraction from the several Scanning Electron Microscopy (SEM) images by using Image-Pro software.

2. Experimental Procedure

2.1. Sample Fabrication

Samples are first fabricated using the SLM machine located in Cal Poly. There are 3 batches printed for this project. For each batch, 3 different orientations of subsized tensile bars following ASTM E8 are printed. Figure 3 shows the tensile bars of different orientation. The samples fabricated with the flat surface on top will be referred to as X-direction bars (Fig. 3a), the samples fabricated on their side will be referred to as Y-direction bars (Fig. 3b), and the samples fabricated in the vertical direction will be referred to as Z-direction bars (Fig. 3c). Each batch contains two X-direction bars, two Y-direction bars, and three Z-direction bars. In this project, only Z-direction samples were used because of time constraints. The Z-direction samples were
selected because they did not exhibit any obvious warpage after being printed and having their supports removed, thus they were easiest to work with for the rest of the test method.

Figure 3. Printing orientations of the tensile bar samples. (a) X-direction, (b) Y-direction, and (c) Z-direction. Due to print space, the team had two extra Z samples.

The SLM machine parameters used to fabricate those bars were kept the same throughout the batches. The power input for hatching was 190W, the layer thickness was 30μm, the preheat temperature was 150℃, and the recoating time was set to be 30 seconds to make certain that the solidification in each layer was completed before recoating another layer. Finally, the scanning pattern was stripe simply because the coding for the checkerboard pattern was not available.

The two tensile bar samples from each batch were assigned to three different heat treatments: high temperature annealing (HT1), low temperature annealing (HT2), and a combination of high and low temperature annealing (HT3). Figure 4 shows the assignment of each bar in each heat treatment. The bars from the first batch were assigned to HT1 and HT2, the bars from second batch were assigned to HT1 and HT3, and the bars from the third batch were assigned to HT2 and HT3. This assignment was used to control for possible batch differences. A naming system composed of two digits was developed to keep track of the samples. The first digit indicates the batch number. The second digit indicates the heat treatment: 1 corresponding to HT1, 2 corresponding to HT2, and 3 corresponding to HT3.
Figure 4. The assignment of tensile bars from batches to heat treatments. This assignment was used to reduce bias in the batch and heat treatments.

2.2. Pre-Heat Treatment Testings

Before applying heat treatments, several non-destructive tests and some mechanical testing were performed in order to collect data on the as printed parts for later comparison with the heat treated parts. X-ray diffraction (XRD) was used to calculate the residual stress state in the samples. Both optical microscopy and SEM microscopy was done to correlate the mechanical properties and the microstructure. Hardness testing was conducted to provide more data to relate to the strength of the as-build samples.

In XRD measurement, determining lattice strain was necessary to find the associated residual stress in the samples. The sin squared psi ($\sin^2(\psi)$) method was utilized to achieve the goal. In $\sin^2(\psi)$ method, the angle of sample in the XRD was intentionally rotated at certain angles, called psi angles, when measuring the diffracted peaks. The psi angles should be in the range greater than 45°, according to the literature. However, due to the geometry constraint in the XRD chamber, the maximum psi angle in this study was 22.5°. Figure 5 shows the sample in the XRD chamber. In order to measure accurate psi angles, a fixture was designed and printed with acrylonitrile butadiene styrene (ABS). The fixture, illustrated in Figure 6, is 48.06 mm in diameter and 16mm tall so that it can fit in the XRD chamber. The fixture was designed to hold the sub-sized tensile test bars and hold them in five different psi angles: 0°, 5.625°, 11.25°, 16.875°, and 22.5°. The rotation is based about a common focal point at the top surface of the sample so that each XRD scan was on the same point. This fixture was consistently used in all the measurement to reduce the measurement error. The XRD scan parameters consisted of a 2θ range of 35° to 90°, a 0.01° increment, and a scan rate of one second per step. The X-ray source was copper source. The anti-scatter slits used in this XRD measurement was 1mm and the
receiving slit was 0.6mm. These sizes were selected because this configuration provided the best resolution in the peak measurement.

![Figure 5](image1.png)

**Figure 5.** Loaded sample in the XRD chamber. A white ABS fixture was printed and used to make the psi angles.

![Figure 6](image2.png)

**Figure 6.** XRD fixture designed in Solidworks. It holds the subsized tensile test bar at five different angles: 0°, 5.625°, 11.25°, 16.875°, and 22.5°. The rotation is based about a common focal point at the top surface of the sample.

Hardness was determined before applying heat treatments on the samples. The Instron hardness tester was used to measure the hardness values in accordance to ASTM E0018. Three points were selected; two points near what was the bottom of the samples when it was printed and one point on what was the top of the sample when it was printed. The gauge length of the tensile samples was not tested upon so as to avoid influencing later XRD measurements or tensile testing. Another three points of measurement were done after the heat treatment. Figure 7 shows the position of hardness test points.
Finally, the microstructures of samples were observed before the heat treatments were performed. The gauge lengths of the samples were sanded with 4 different grades of sandpaper (240, 360, 480, 600) and polished down to <1μm before etching. The samples were electrochemically etching with a 10% oxalic acid solution for approximately one minute at 0.5A and 6V. Micrographs were taken at 100x, 500x, and 1000x using optical microscopes, and SEM images were also taken of the dendritic microstructure (Fig. 10). The setting for SEM was 20.00 kV, spot size of 4, and high voltage mode.

2.3. Heat Treatments

Three different heat treatments were planned to apply those samples. However, due to the limitation in machine access, only HT1 and HT2 were applied. HT1, the high temperature annealing consisted of holding the samples at 1200℃ for one hour and annealing in the furnace. HT2, the low temperature annealing consisted of holding the samples at 490℃ for five hours and annealing in the furnace. HT1 was based on the study Chen, et al.10 conducted that proved changes in mechanical properties and microstructure would occur. HT2 was designed relative to the sigma phase region and was intended to promote recovery, but not recrystallization and grain growth.

2.4. Post Heat Treatments Testings and Analysis

After heat treatments were applied to the samples, the same non-destructive testings: XRD measurements, hardness testings, and microstructural analysis were performed using consistent measurement settings. SEM images of post heat treatment samples could not be taken due to the time conflict on the SEM machine.

Following the non-destructive testings, the samples were finally tensile tested using an Instron tensile tester in accordance to ASTM E8. By conducting this destructive testing, mechanical properties and performance were directly measured. In the Instron tensile testing, the strain rate of 6mm/minute was used throughout the samples because the heat treated samples were expected to have high ductility. Therefore, a slightly higher strain rate would still output an accurate result. An extensometer was also used to accurately measure the strain in the samples.
XRD data was initially exported as raw file after stripping K alpha peaks. This raw file could not be directly processed on Matlab to analyze the peaks, and therefore, the data was converted to a .xy file with a software called POWDLL. The .xy file stores all the peak positions and the intensities of peaks in two columns: x and y. The corresponding peaks were obtained by using Matlab and the lattice parameters were calculated from the 2θ angles using Bragg’s law. These values were transferred to a statistical software called Minitab. In Minitab, analysis of variance (ANOVA) tests were applied on each calculated lattice parameter value as a function of sin²(ψ) to find the lattice strain in the samples. The lattice strain was obtained from the slope value of the linear fit of the data points corresponding to each heat treatment or batch. The validity of this value is based on several assumptions including isotropic elasticity and no shear stress in the samples. Error corrections was also applied by extrapolation of lattice parameter vs sin²(θ) and peak correction based on several other assumptions such as flat surface. Finally, the lattice strain values were plugged into a simple stress strain equation shown in equation (1):

\[ \sigma_{res} = \left( \frac{E}{1 + \nu} \right) m \quad \ldots \quad eq(1) \]

where m is the lattice strain value obtained from the slope of lattice parameter and the sin²(ψ) graph. E is the young’s modulus, and ν is the poisson ratio. Calculated residual stress with and without error corrections were compared with each other to see the effects from the data correction. The best results from this analysis was picked and reported in the following result section.

3. Results

3.1. Mechanical Testing Result

The results from hardness testing before and after heat treating are listed in Tables II and III, respectively. The average hardness value throughout the samples before heat treatments was 91.8 HRB with error value of ± 3.91 HRB. Compared with this value, HT1 showed a significant drop in hardness by the average of 12.05 HRB. HT2, on the other hand, did not show a significant drop like HT1. Rather, HT2 shows some increase in hardness by the average of 3.3 HRB, which is within the margin for error as built samples.

Table II: Result from Hardness Testing Before Heat Treatment

<table>
<thead>
<tr>
<th>Sample</th>
<th>1-C</th>
<th>1-1</th>
<th>2-1</th>
<th>1-2</th>
<th>3-2</th>
</tr>
</thead>
<tbody>
<tr>
<td>HRB Pt. 1</td>
<td>89.4</td>
<td>90.9</td>
<td>92</td>
<td>90.6</td>
<td>92.4</td>
</tr>
<tr>
<td>HRB Pt. 2</td>
<td>94.4</td>
<td>94.7</td>
<td>94.1</td>
<td>94.8</td>
<td>95.4</td>
</tr>
<tr>
<td>HRB Pt. 3</td>
<td>78.5</td>
<td>91.6</td>
<td>93.1</td>
<td>92.3</td>
<td>87.7</td>
</tr>
<tr>
<td>Average</td>
<td>87.4</td>
<td>92.4</td>
<td>93.1</td>
<td>92.6</td>
<td>91.8</td>
</tr>
<tr>
<td>Total Average</td>
<td>91.8 ± 3.91</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table III: Result from Hardness Testing After Heat Treatment

<table>
<thead>
<tr>
<th>Sample</th>
<th>1-1</th>
<th>2-1</th>
<th>1-2</th>
<th>3-2</th>
</tr>
</thead>
<tbody>
<tr>
<td>HRB Pt. 1</td>
<td>83.3</td>
<td>78</td>
<td>94.3</td>
<td>96.3</td>
</tr>
<tr>
<td>HRB Pt. 2</td>
<td>84.6</td>
<td>77.9</td>
<td>95.7</td>
<td>95.6</td>
</tr>
<tr>
<td>HRB Pt. 3</td>
<td>83.3</td>
<td>77.1</td>
<td>96</td>
<td>95.1</td>
</tr>
<tr>
<td>Average</td>
<td>83.7</td>
<td>77.7</td>
<td>95.3</td>
<td>95.7</td>
</tr>
<tr>
<td>Pre to Post Change</td>
<td>-8.7</td>
<td>-15.4</td>
<td>2.8</td>
<td>3.8</td>
</tr>
</tbody>
</table>

The tensile test graphs are shown in Figure 8 and the mechanical properties are listed in Table IV. It is obvious to see that the HT1 samples, samples 1-1 and 2-1, behaved in similar way in experiencing a reduction in strength and increase in ductility. The 1-2 and 3-2 samples behaved similarly to the control sample, indicating potentially little to no change in mechanical properties. This is also indicated in Table III by the pre to post change being within the margin of error as seen in Table III.

**Figure 7.** Tensile test result for HT1, HT2, and control sample. HT1 altered the mechanical properties significantly, whereas HT2 showed similar behavior with control sample.
Table IV: Tensile Test Mechanical Properties

<table>
<thead>
<tr>
<th>Specimen Label</th>
<th>Yield Strength (0.2% Offset) [MPa]</th>
<th>Tensile Strength [MPa]</th>
<th>% Elongation [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-C</td>
<td>465.7</td>
<td>631.9</td>
<td>41.95</td>
</tr>
<tr>
<td>1-1</td>
<td>300.9</td>
<td>563.9</td>
<td>59.42</td>
</tr>
<tr>
<td>2-1</td>
<td>250.4</td>
<td>554.5</td>
<td>70.20</td>
</tr>
<tr>
<td>1-2</td>
<td>499.9</td>
<td>619.0</td>
<td>43.59</td>
</tr>
<tr>
<td>3-2</td>
<td>513.5</td>
<td>660.8</td>
<td>40.55</td>
</tr>
</tbody>
</table>

3.2. Metallography Result

The images from metallography are shown in the Figure 9. Metallographic images before heat treatments were the same throughout the samples. As is seen in Figure 9 (a) and (b), distinctive layers are observable. Also, there are sub-granular dendrites within the layers. The shape of grains differs because the growth of these cells varies by direction. At layer the boundary, some grains can be seen penetrating through the boundary.

Figure 9. As build micrographs of (a) control sample at 1000x and (b) HT1 sample at 1000x before heat treatment. Distinct boundary layers and cellular growth in different directions are easily seen in both images. Build direction is up the page.
The pre-heat treatment samples were then imaged using the SEM. Figure 10 shows the boundary between two grains, the dendrites are clearly visible in this image. Note the epitaxy at the grain boundary.

![Figure 10](image1.png)

**Figure 10.** SEM image for SLM tensile bar before heat treatment. Note the varying growth directions of the dendrites of different grains, and the epitaxial growth of dendrites at the grain boundary.

The light microscopic images after heat treatments were shown in the Figure 11. It is easy to notice a significant difference in grain size in HT1 sample (Figure 11 (a)). The small grains containing subgrain dendrites are replaced with larger, uniform grains. Annealing twins are also present in the post heat treatment microstructure, indicating that residual stress was present prior to the heat treatment, but not all of this residual stress was resolved. In the Figure 11 (b), post HT2 sample still exhibits a dendritic structure and the distinct layering corresponding to the printing direction.

![Figure 11](image2.png)

**Figure 11.** Post heat treatment micrographs of (a) HT1 at 500x and (b) HT2 at 1000x. (a) depicts recrystallization and grain growth. However, (b) still has some dendritic structure.
3.3. XRD Result

From XRD, there are three different peaks found from each measurement before any kind of heat treatments: (111), (200), and (222) planes from the software called EVA. As explained earlier, several data corrections were applied on these three constructive peaks, but none of them were effective to reduce the error. The lowest error result was from the raw data in (222) plane, and therefore, those data set was investigated further. Figure 12 shows the graph of the lattice parameters calculated from 2θ angles as a function of \(\sin^2(\psi)\) based on the samples. It is obvious that the slopes for samples were not consistent: two slopes were positive and four slopes were negative. Therefore, it is not reasonable to consider all the slopes to be similar. This was confirmed by an ANOVA test of all the samples. The p-value for slopes depending on \(\sin^2(\psi)\) was greater than 5% and therefore it is statistically proven that at least one slope differs from the rest of slopes. However, upon closer examination, Figure 13 illustrates how the slopes from each batch are similar and have the same sign.

![Figure 12. Lattice parameter vs \(\sin^2(\psi)\) for all samples before heat treatments without outliers. The slopes do not have a similar trend.](image-url)
Each batch was then tested with ANOVA and found that the p-value from each batch was lower than 5%. Thus, it is statistically proven that the two slopes in each batch are similar. Because those slopes are similar, the average slope from each batch was used to find the residual stress.

Table V lists the residual stress values for each batch, based off of the raw lattice strain calculations. Compared with the results from tensile testing, the obtained residual stress and error values are unrealistically high.

<table>
<thead>
<tr>
<th>Table IV: Residual Stress Values from Each Batch</th>
</tr>
</thead>
<tbody>
<tr>
<td>Batch 1</td>
</tr>
<tr>
<td>Residual stress</td>
</tr>
</tbody>
</table>

The same procedure was applied on the samples after heat treatments to compare with samples before heat treatments. However, the slopes from each heat treatments were not found to be statistically similar, and therefore, it is not worth finding the average value of different slopes to find the residual stress. This scattered slope inconsistency was found across all samples from each heat treatment. Unfortunately, the residual stress after heat treating could not be determined.

4. Discussion

In the mechanical testing, both yield and tensile strengths of the control and HT2 samples were higher than that of wrought 316L stainless steel\(^{13}\). These mechanical properties could be tied to the metallographic results (Fig. 9a and Fig. 11b). As was in the micrographs from before heat treating (Fig. 9), a large amount of dendritic growth is seen. The finer structure should make the material stronger because small cells have more interfacial area to inhibit dislocation motion. Another reason that the strength would be greater than wrought 316L might be the existence of σ phase which is a brittle and hard phase known well in 316L stainless steel. Even though this σ phase was neither observed in light microscopy nor SEM, it could be one of the reasons. Note that the micrograph obtained in light microscopy (Fig. 9) shows the distinct boundaries of about 30μm thickness. This matches with the layer thickness in the SLM machine, so it was obvious to see the printing process was accurate with the machine settings. There are some portions in the micrographs where some dendritic structure penetrates through boundaries. This could be caused...
by a local uneven distribution of stainless steel powder over the buildplate or from the laser melting more than one layer.

HT1 showed a significant change in properties. The tensile test results in Figure 8 and Table IV, indicate the yield strength dropped by over 150 MPa and increased in ductility more than 20%. The optical micrograph of HT1 in Figure 11a illustrated the drastic change in structure relative to the as built condition seen in Figure 9b. Recrystallization and grain growth are clearly evident due to the lack of dendrites, the formation of annealing twins, and the change in grain shape and size. The grain size in the image is about 100μm, which is almost three times larger than the layer thickness. This increase in grain size and disappearance of dendritic structure can explain the reduction in strength and enhancement in ductility. On the other hand, the micrograph of HT2 (Fig. 11b) did not show a significant difference from the control samples (Fig. 9a). One of the differences in HT2 is that the layer thickness in HT2 seemed to increase by 15μm, and spots of missing dendritic structure can be seen in the material. The lack of microstructural change is represented in mechanical testing because both hardness values and tensile strength did not differ too much from the control sample (Tables II, III, and IV).

Compared with mechanical testing and metallography, the results from XRD measurements turned out to be much more complex than expected. As the results showed, the values listed in Table V were unrealistic and contained huge error values. There are a number of factors that could have contributed these error values and they can be divided into four main categories: machine limitation, sample uniformity, methodological assumptions, and measurement errors.

First of all, the XRD machine used in this study was not designed for residual stress measurement, and therefore, the measurement was not in full range. The maximum psi angle measured in the machine was 22.5° which is half of the required angle for this measurement. Even though there is no standard measurement for residual stress via XRD, it would be the best to measure in full range up to 45° in order to calculate the full stress tensor (normal and shear stresses) in each psi angle\textsuperscript{11}. The full stress tensor would then be used to calculated the residual stress considering the measurement angles and principal stress directions. In order to reduce this error, extrapolation was applied, however, the error values were not reduced. Second of all, lack in sample uniformity could lead to a huge deviation. As seen in the statistical analysis on XRD data sets (Figs. 12 and 13), there seemed to be some differences based on the batches because some trend lines had positive slopes while others were negative. These variations were surprising because the machine settings for printing were exactly the same for all batches. This unexpected sample variability could have led an increase in error value due to variations in geometry, defects, and/or microstructure. Another contributor for huge errors may have been methodological assumptions. In this XRD measurement and its data analysis, the simplest situation was assumed: no shear stress and isotropic elasticity in the material. This assumption was made to make the analysis and calculation simpler. However, these assumptions could not be the right model to reduce the error. Because the SLM process is a complex system, the stress state in the material could also be complex and vary throughout the sample. Also, isotropic elasticity in material may not be true because most of engineering parts are not completely isotropic. Even though the analysis would be much easier to find the residual stress with those assumptions, this could be the main source of error in the residual stress values. Finally, there are a number of improvements that could be made to the XRD measurement process, such as an improved fixturing. The fixture may be incorrectly placed if the fixture is slightly rotated or
translationally shifted, which would could have slightly reduced peak height or lead to some degree of peak shift. This study did, however, show that the measurement itself could be done with the existing XRD machine.

5. Conclusion

In conclusion, there are mainly three conclusions that can be drawn from this study about 316L stainless steel fabricated by SLM.

1. HT1 resulted into a reduction of yield strength, tensile strength, and hardness relative to the as fabricated values. This is most likely due to the microstructural changes.

2. HT2 was not effective to change the mechanical property of SLM samples.

3. There may be batch effects on SLM fabrication process.

Conclusion 1 could be easily drawn by the mechanical testing and microstructure that can explain its behavior. The reduction of about 150 MPa in yield strength and 12 HRB in hardness combined with the observable recrystallization, grain growth, and presence of annealing twins in microstructure could indicate that the HT1 was effective at changing the mechanical properties of the parts produced via SLM. On the other hand, HT2 did not have an obvious effect on mechanical properties. Finally, XRD results (Table V) showed that there might be some inconsistency based on batches considering the unrealistic residual stress values and corresponding error values indicate that there are errors in the measurements and data analysis.

6. Future Work

In order to find better values in residual stress, the following modification and investigation could be done for the future.

1. Redesign the XRD fixture for tensile bars so as to limit all translational and rotational discrepancies that result from fixture placement and include negative psi angles.

2. Specify the error model for the data set to reduce error.

3. Test samples from X and Y print directions and test heat treatment 3.

Even though the fixture used in this study worked well to measure lattice strains in the material by XRD, the design should be improved more to reduce the inconsistency in measurement. An improved design might increase the capable $\psi$ angles which, in turn, could reduce the lattice strain error value because extrapolation is not necessary for that situation. Another problem with the current fixture model is that the fixture may be incorrectly placed if the fixture is slightly rotated or translationally shifted. One of the reasons for error inclusion could be due to the simple assumption in the model selection for the obtained data set. This will make the calculation and analysis much harder, but it is possible to get a reasonable value with more complex corrections. Finally, this study regretfully decided not to investigate on the samples in X and Y directions and HT3 due to time constraints and machine availability constraints.
7. Work Cited


13. ASM Handbooks Online