A preliminary investigation on hardness performance of LENS-processed 316 stainless steel (SS)

Sri Sai Kartheek Meka

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The hardness performance of LENS-processed 316 Stainless Steel (SS) is investigated. Hardness performance of LENS-processed 316 SS is important to identify its strength, resistance to wear, quality, failure control, predicting lifetime, determining proper applications and its evaluating performance. Rockwell hardness test was performed at 100kgf load and 150kgf load respectively. A finite element model was developed for the indentation process, and contact radius was obtained and contact pressure was verified with experimental results obtained from white-light interferometry. The Rockwell hardness test was performed according to ASTM E18 - 17e1 test procedure and a tungsten carbide indenter was used for the hardness test of roll-formed 316 SS and additive-manufactured 316 SS. The indentation process was simulated using ANSYS APDL software with different contact models and different loads. It was found that the hardness performance is affected by porosity, which is a key factor in determining the hardness performance of the additive-manufactured samples.
A PRELIMINARY INVESTIGATION ON HARDNESS PERFORMANCE OF LENS-PROCESSED 316 STAINLESS STEEL (SS)

BY

SRI SAI KARTHEEK MEKA
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A THESIS SUBMITTED TO THE GRADUATE SCHOOL
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Thesis Director:
Dr. John Shelton
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Sri Sai Kartheek Meka
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CHAPTER 1
INTRODUCTION

1.1 Hardness

The hardness is a measure of a material’s resistance to permanent deformation. There are many types of hardness testing that are used based on type of application. Rockwell Hardness is one of the macro hardness tests that are used to perform the hardness testing on the materials. Rockwell hardness test is the most widely used hardness testing method because of its least preparation method, simplicity, and it is inexpensive and relatively nondestructive. Hardness testing is widely used in identifying the strength, resistance to wear and the life of the material before failure. Recent advancements in engineering have a huge rise in making new materials to fit the increasing need. Most of these materials are manufactured in a variety of ways; one is additive manufacturing. LENS process in additive-manufacturing has been one of the widely used additive manufacturing techniques for metals. These materials differ in the way they are manufactured. They would be put through different loads, temperatures, and pressures which would cause alteration of the material characteristics. Rockwell hardness test could be used to perform the tests on additive-manufactured materials.

1.2 Hardness Performance for Additive-manufactured Materials

The Rockwell hardness test hasn’t been much widely used in additive-manufactured materials relative to the traditionally produced material. This is because the hardness performance
of the additive materials was not predictable with the existing theories and there was no control over the material characteristics of the additive-manufactured materials. The ability to control the mechanical properties of additive-manufactured materials is critical towards understanding performance characteristics under various operating conditions.

Determining the hardness performance involves a measurement of various parameters, the contact radius, and also the depth of the indentation. Rockwell hardness tests performance for traditional manufacturing methods have been analyzed and conclusions were made on the factors that influence the hardness performance.

1.3 Finite Element Analysis of Rockwell Hardness Tests

Finite element analysis is a great tool to visualize the mechanical indentation process. Building a finite element model involves a lot of considerations that should be accounted for. It also helps us visualize the effect of each input parameter on the final results. So, a finite element model was developed to simulate the Rockwell hardness test and the results obtained at each step of making the model were compared to the experimental values that were obtained from white-light interferometry.

In this study, the Rockwell hardness tests with 100kgf load and 150 kgf load were performed on the samples using a tungsten carbide ball indenter and the indentation was evaluated using white-light interferometry to obtain a key hardness performance parameter contact radius. The FEM model has been developed and the contact radius and pressure that were obtained are compared with the experimental values. The values are in good agreement. A new method has been developed to input the effect of process parameters on the hardness performance of the LENS-processed additive-manufactured samples.
1.4 Directed Energy Deposition- Method of Manufacturing AM Materials

Directed energy deposition (DED) is a kind of AM technique used to add or repair existing components. It has various names like laser-engineered net shaping (LENS), direct metal deposition and 3D cladding. The LENS process can fabricate additive-manufactured parts from 3D CAD solid models and then spraying the metal powder on the molten pool of the bed. The LENS method can manufacture bigger components when compared to other similar types of AM manufacturing. In general, a DED machine has a nozzle which is on a multiaxis arm depositing powder onto the platform and then a laser shines on it, melting it. When compared to the traditional method of material extrusion, DED has the arm movable in multiple directions. It has four or five axes of motion. It is generally used for metals. The spraying of metal and laser beam directly on the powder is done simultaneously, which is shown in Figure 1.

The shape and size of the models are controlled completely by the feed rate and angle from which the powder is deposited on the bed. This process is mainly used for titanium and cobalt chrome and is not suitable for ceramic materials, glass and plastic, which is the reason for its wide application in the aerospace and automotive industry.

![Figure 1: Schematic of the laser-engineered net shaping process [29].](image)

1.5 Other Material Properties Important to Characterization

- Surface Roughness
It is a part of the surface texture. It is quantified by the maximum deviation in the direction of the normal vector. The larger the deviation, the rougher the surface. Roughness is an important parameter to predict a lot of performance characteristics of an object.

- **Yield Strength**

  It is the stress at which material starts to deform plastically, not obeying the Hooke’s law. Any stress beyond the yield strength, the material will not return to its original shape upon the removal of the load.

- **Young's Modulus**

  It is the measure of the mechanical property of stiffness, the ratio of the stress to the strain while the material obeys Hooke’s law.

- **Poisson’s Ratio**

  It is the ratio of decrease in width to the increase in length of an object when forces are within the elastic limit of the material.

- **Shear Modulus**

  It is the Young’s modulus of the body when the force applied is parallel to one of its faces, which are also called the shear forces.
2.1 Steps for Hardness Testing

2.1.1 Sample Preparation

The sample preparation involves the following series of steps, which are shown in Figure 2-4. Figure 5 shows the final specimen ready for hardness testing.
Sectioning and cutting was done using an abrasive cutter to get the sample into required shape, then mounted into the epoxy with Buhler equipment which is also called the mounting machine. Then the sample is ground on 240,320,400,600 grit papers, which is planar grinding, and then rough polished and fine polished to 1 micron level. These samples are prepared as per the ASTM E 384 for micro hardness test, so that it could be even useful for micro hardness testing if needed.

2.2 Hardness testing

Rockwell B hardness test was used to perform indentation on LENS manufacturing sample for checking hardness performance. The load in the Rockwell hardness test B is 100kgf. In addition to the 100kgf load, the 150kgf is also used to perform indentations on the samples. Some Rockwell hardness instruments use dead weights for the load to be applied, whereas some newly built equipment use load cells to apply the loads. We use a traditional Rockwell indenter which uses dead weights to apply load.
2.2.1 Rockwell Hardness B Machine Specifications

- **Maker**: American Chain and Cable Co., Inc.
- **Model**: 4TY
- **Indenter**: 1/16” diameter, tungsten carbide ball
- **Tester No**: 169

\[ HR = N - \frac{d}{s} \]  \hspace{2cm} (1)

where \( N, s \) are scale parameters depending on the indenter. For Rockwell B type of hardness tester, \( N, s \) is 130 and 0.002 mm. The machine used is shown in Figure 6 below.

Figure 6: Rockwell hardness testing machine.

2.3 Hertzian Contact Between Two Surfaces
Hertzian contact is a theory which predicts the contact stress as a function of contact force, radii of curvature and modulus of elasticity. Hertzian contact stress is the stress in the mating parts. Hertzian contact stress is the laying stone for the equations of load bearing and fatigue life in mechanical components such as roller bearings, cams, gears, and many other bodies where their surfaces are in contact. In this theory, no tension force can occur within the area of contact, which means that the bodies can be separated without any adhesion forces and the pictorial representation is shown in Figure 7 below.

![Figure 7: Hertzian contact of a sphere on an elastic half space.](image)

2.3.1 Hertzian Contact – Sphere on Elastic Half Space

Sphere on elastic half space:

\[ a^3 = \frac{3FR}{4E^*} \]

Radius of the circle

(2)
\[ d = \frac{a^2}{R} = \frac{9F^2}{16E^*R} \]  \hspace{1cm} \text{Depth of indentation} \hspace{1cm} (3)

\[ p_0 = \frac{3F}{2\pi a^2} \]  \hspace{1cm} \text{Maximum pressure in an indentation} \hspace{1cm} (4)

\[ \frac{1-v_1^2}{E_1} + \frac{1-v_2^2}{E_2} = \frac{1}{E^*} \]  \hspace{1cm} \text{Equivalent Young's modulus} \hspace{1cm} (5)

\( E_1, E_2 \) are the elastic moduli and \( v_1, v_2 \) are the Poisson's ratio of each body.

\( R \) is the radius of indenting sphere and \( F \) is the applied force.

### 2.4 Theoretical Calculation of Contact Radius and Pressure

The properties that are used for calculation are:

- \( E^* = 1.59 \times 10^5 \text{ N/mm}^2 \)
- \( F = 100 \text{ kgf} = 980.7 \text{ N} \)
- \( F = 150 \text{ kgf} = 1471 \text{ N} \)
- \( R = 1/32'' = 0.7937 \text{ mm} \)
- \( E_1 = 1.9 \times 10^5 \text{ N/mm}^2 \)
- \( v_1 = 0.30 \) (for steel)
- \( E_2 = 6.33 \times 10^5 \text{ N/mm}^2 \)
- \( v_2 = 0.22 \) (for tungsten carbide)

\[ \frac{1}{E^*} = \frac{1-v_1^2}{E_1} + \frac{1-v_2^2}{E_2} \]  \hspace{1cm} (6)

\[ \frac{1}{E^*} = \frac{1-0.3^2}{1.9 \times 10^5} + \frac{1-0.22^2}{6.33 \times 10^5} \]

\[ E^* = 1.59 \times 10^5 \text{ N/mm}^2 \] \hspace{1cm} (7)

**Contact Radius Calculation**

\[ a^3 = \frac{3F \cdot R}{4E^*} \] \hspace{1cm} (8)

\[ a^3 = \frac{3 \times 980.7 \times 0.7937}{4 \times 1.59 \times 100000} \]

\[ a = 0.154 \text{ mm} \] \hspace{1cm} (9)
Contact Pressure Calculation

\[ p_0 = \frac{3F}{2\pi a^2} \]  \hspace{1cm} (10)

\[ p_0 = \frac{3 \times 980.7}{2 \times \pi \times 0.154^2} \]

\[ p_0 = 19692.860 \text{ N/mm}^2 \]  \hspace{1cm} (11)

2.5 Surface Topography Measurement

White-light interferometry is used to measure the indentations that are performed on the traditional materials and additive-manufactured materials. The following are the configurations of the equipment used for measurement.

**Illumination**

Microscope: Mitutoyo – Measuring Microscope – 176-847A

Objective : Magnification 10X, NA 0.3; WD 16 mm;

Depth-of-field: 8.5 µm

**Imaging**

CCD camera Bassler A640f; 1624×1236 pixels

**Software**

Holo-Moire Strain Analyzer

HOLOPLOT MATLAB Code (Dr. Sciammarella)
2.6 Surface Topography of the Indentation:

The indentation measured by software is shown in Figure 8 and Figure 9 for 100-150kgf.

2.6.1 100 kgf Load

![Image of surface topography at 100kgf load]

Figure 8: Surface topography at 100kgf load.

2.6.2 150 kgf Load

![Image of surface topography at 150kgf load]

Figure 9: Surface topography at 150kgf load.
During the measurement of surface topography using white-light interferometry, it has been also observed that adhesion peaks are formed during the indentation process, so the adhesion peaks heights have also been measured, which could serve as a reference for future scope of the study.

Using the images obtained above in MATLAB, the diameter of the indentation was calculated from the data obtained from the graph. These diameters that are obtained using this method are used to compare different samples in this study.

2.7 Indentation of 316 Stainless Steel (Roll Formed)

These indentation images are captured using the interferometer that was mentioned earlier in this chapter. These images which are captured are processed and filtered for noise using Holo-Moire Strain Analyzer that was mentioned earlier. The above-stated method provides us the diameter of the indentations for 100kgf load in Figure 10 and 150kgf load in Figure 11 as 824 µm and 1004 µm respectively.
2.7.1 100 kgf Load

Figure 10: 100kgf load on 316SS (roll formed).
Measured diameter: 824 µm

2.7.2 150 kgf Load

Figure 11: 150kgf load on 316SS (roll formed).
Measured diameter: 1004 µm
2.8 Indentation Test on AM Samples (Scan Rate is 5 in/min)

In a similar method, indentations were performed on additive-manufactured samples of scan rate and different powers initially. The diameters are measured from the images are 737 µm, 780 µm, 796 µm for 475W in Figure 12; 645 W in Figure 13; 875W in Figure 14 respectively.

2.8.1 475 W

Figure 12: Indentation on AM samples of scan rate 5in/min at 475 W. Measured diameter: 737 µm
2.8.2 645 W

Figure 13: Indentation on AM samples of scan rate 5in/min at 645 W. Measured diameter: 780 µm

2.8.3 875 W

Figure 14: Indentation on AM samples of scan rate 5in/min at 875 W. Measured diameter: 796 µm
2.9 Comparison of Experimental Diameter of Indentation for Various Samples

2.9.1 100 kgf

Indentation tests are now performed for different samples with different scan rates, powers and feed rates at 100 kgf load. All of them are plotted in Figure 15 for 100 kgf. It has been observed that for 475 W power, there hasn’t been much difference in the diameter of the indentation.

![Figure 15: Chart showing the comparisons of indentation diameter at 100kgf load.](image)

2.9.2 150 kgf

The indentation test was performed on all the samples that were tested before. But
this time they were tested at 150kgf loads in Figure 16. The data obtained was plotted as a function of the scan rate and the diameter of indentation at different laser powers. It has been observed that the trends in diameters were similar in both the 100kgf and 150kgf loads.

2.10 Comparison of Experimental Diameter of AM Samples at Different Powder Flow Rate

The indentation test data that was obtained earlier is also plotted against the powder flow rate of the LENS process, thereby allowing it to be compared at different powers. The chart in Figure 17 is the comparisons at 100kgf load and the Figure 18 chart shows the similar comparison at 150kgf load.
Figure 17: Chart showing the comparisons of indentation diameter at 100kgf load.
Figure 18: Chart showing the comparisons of indentation diameter at 150kgf load.

2.11 Energy Density of the Additive-Manufactured Samples

These additive-manufactured samples from LENS process are all associated with theoretical energy density. Theoretical energy density is calculated from each sample based on the laser power at which the sample is made. The energy density that is associated with each sample is listed in Table 1 below and the theoretical energy density decreases with increase in scan rate/powder flow rate. These parameters are related to each other, keeping the interaction time to be constant.
Table 1: Energy Densities of Additive-Manufactured Samples

<table>
<thead>
<tr>
<th>Sample</th>
<th>Theoretical Energy Density (J/mm³)</th>
</tr>
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<tbody>
<tr>
<td>475-5</td>
<td>765.49</td>
</tr>
<tr>
<td>475-20</td>
<td>447.28</td>
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<tr>
<td>475-30</td>
<td>214.15</td>
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<tr>
<td>645-5</td>
<td>403.62</td>
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<td>645-20</td>
<td>192.89</td>
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<td>645-30</td>
<td>156.88</td>
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<tr>
<td>875-5</td>
<td>441.47</td>
</tr>
<tr>
<td>875-20</td>
<td>134.40</td>
</tr>
<tr>
<td>875-30</td>
<td>85.86</td>
</tr>
</tbody>
</table>

2.12 Comparison of the Deviations in Contact Radius of the Samples with Roll Formed 316 Stainless Steel

The samples are now compared against the regular 316 SS roll-formed steel. The deviations for different samples have been presented in the bar graphs at different powers for 100kgf load and 150kgf load for each sample. The 475 W, 645 W, 875 W are denoted in Figures 19, 20 and 21 respectively. It was observed that the deviation did not change considerably with increase in scan rate at 475 W, but the 645 W and 875 W had significant change when the scan rate changed. The deviation of experimental data at 150kgf was found to be higher than that of 100kgf load.
Figure 19: Comparison of deviations of 475 W samples.

Figure 20: Comparisons of deviations of 645 W samples.
2.11 Comparison of Adhesion Peaks for Different AM Samples

The adhesion peaks were observed in the samples and measured using the MATLAB data, and the values are presented for different loads and powers and powder flow rates. This data could be used for future work using adhesion to predict the hardness performance of additive-manufactured materials. These values haven’t been used anywhere in this study. Figure 22 represents the peaks at 100kgf and Figure 23 represents peaks at 150kgf. Different adhesive contact theories have also been presented apart from the data obtained.
100 kgf Load

Figure 22: Peak heights comparison at 100kgf.

150 kgf Load

Figure 23: Peak heights comparison at 150kgf.
2.12 Adhesive Hertzian Contact

This theory didn’t come into play until the late 1960 s. When two bodies come close to each other they experience Van-der-Waals force of attraction between each other. They incorporated the adhesion into the Hertzian theory of contact by using the relation balance between the stored elastic energy and the surface energy. This considers pressure and adhesion inside the area of contact. The adhesive contact is presented to serve as a reference for future studies.

2.12.1 JKR Theory

This theory predicts the contact radius “a” and the force “F” using the adhesive energy terms and the interaction term between the two materials.

\[
a_c^3 = \frac{9R^2\Delta \gamma \pi}{8E^*} \tag{12}
\]

\[
d_c = \frac{a_c^2}{R} = \frac{9^{2/3}}{4} \cdot \Delta \gamma^{2/3} \frac{\pi^{2/3}}{E^{*2/3}} \tag{13}
\]

\[
F = -\frac{3}{2} \Delta \gamma \pi R \tag{14}
\]

2.12.2 DMT Model

\[
a_c^3 = \frac{3R}{4E^*}(F+ 2\Delta \gamma \pi R) \tag{15}
\]

\[
\Delta \gamma = \gamma_1 + \gamma_2 - \gamma_{12} \tag{16}
\]

\[
F = -2 \Delta \gamma \pi R \tag{17}
\]

\(\gamma_1\) and \(\gamma_2\) are the adhesive energies of two surfaces and \(\gamma_{12}\) is an interaction term.
CHAPTER 3

FINITE ELEMENT ANALYSIS OF INDENTATION

3.1 Finite Element Model

The finite element model was built using ANSYS 17.1 APDL version. The finite element model consisted of the 8-node quadrilateral Plane 183 elements. The model was meshed using a mapped mesh and a contact model which consisted of the contact and the target elements. Because our model is symmetric in shape and loading conditions, a 2D model can be used for the indentation process. Figure 24 shows the meshed model and Figure 25 shows the contact model of the ANSYS model.

Figure 24: Meshed solid model of the indentation process.
3.2 Properties used for the Finite Element Model

3.2.1 Sample

E: 2.046*10⁵ N/mm² and µ=0.3

3.2.2 Indenter (tungsten carbide); ASTM for Rockwell hardness test (ASTM E18 - 17e1)

E: 6.33*10⁵ N/mm² and µ=0.22

The contact is considered frictionless for the Hertzian model. The indentation can be simulated in two ways; applying a force on the indenter or applying a displacement on the indenter. The force is applied on the indenter to check for the deformation in the material and necessary calculations are made to verify the ANSYS model for regular roll formed 316 SS. The contact radius and contact pressure were obtained from the ANSYS elastic models and are then compared to the values form the experimental results of 316 SS roll formed.

Table 2 has the ANSYS properties that are used in the model.
Table 2: ANSYS Properties of the Finite Element Model

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Analysis type</td>
<td>Structural</td>
</tr>
<tr>
<td>Element type</td>
<td>Plane 183, 4 node quadrilateral element [1,8]</td>
</tr>
<tr>
<td>Material Models</td>
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<tr>
<td>Linear Elastic</td>
<td></td>
</tr>
<tr>
<td>Bilinear Isotropic</td>
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<td>Linear elastic (Indenter-Tungsten carbide)[16]</td>
<td>Young's modulus : $1.9 \times 10^5$ N/mm$^2$ [2,6,7]</td>
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<tr>
<td></td>
<td>Poisson Ratio : 0.3 [2,6,7]</td>
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<tr>
<td></td>
<td>Yield stress: 290 N/mm$^2$ [6,7]</td>
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<tr>
<td></td>
<td>Tangent modulus 1567 N/mm$^2$ [6,7]</td>
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<tr>
<td></td>
<td>Young's modulus : $6.33 \times 10^5$ N/mm$^2$ [1,2]</td>
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<td></td>
<td>Poisson ratio : 0.22[1,2]</td>
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<td>Coefficient of friction at the contact $\mu = 0.1$[1]</td>
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<td></td>
<td>Normal penalty stiffness = 0.1[1]</td>
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<td></td>
<td>Depth of indenter penetration rate FKN =0.1[1]</td>
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<td></td>
<td>Contact stiffness factor FTOLN = 0.1[1]</td>
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<tr>
<td></td>
<td>Solution= Full Newton Raphson’s method [1,4,5]</td>
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<tr>
<td>Loads</td>
<td>Force on the center node of the indenter sphere (node 2083). 980.7 N and 1000N downwards</td>
</tr>
<tr>
<td>Constraints</td>
<td>$U_x = 0$ on Indenter area, Side walls of sample $U_x, U_y = 0$ on the Base of the sample[1]</td>
</tr>
</tbody>
</table>

3.3 Obtaining the plastic properties of 316 SS

The plastic model used involved the use of bilinear approximation from the available material properties shown in Figure 26; which are also listed in [2], [3] and [31] to predict the plastic properties of 316 SS.
Figure 26: Bilinear approximation of strain diagram [2].

The values are calculated using the Ramberg-Osgood curve for 0.2% proof stress.

\[
E_{0.2} = \frac{E_0}{1+0.002n/e} \quad (18)
\]

where \(n,e\) are given by

\[
e = \frac{\sigma_{0.2}}{E_0} \quad (19)
\]

\[
n = \frac{\ln(20)}{\ln(\sigma_{0.2}/\sigma_{0.01})} \quad (20)
\]

\(\sigma_{0.2}\) is the 0.2% proof stress and \(\sigma_{0.01}\) is the 0.01% proof stress.

Using the above equations the yield stress and tangent modulus are calculated for 316 SS, thereby defining the plastic model of 316 Stainless Steel.

3.4 Comparison of the 100kgf and 150kgf Elastic and Plastic Models

The 100kgf model and 150kgf elastic and plastic models have been modelled in ANSYS using the parameters mentioned in Table 1, and the contact radius and the contact pressure were obtained from the models.
The force-time curve is shown in Figure 27, displacement-time in Figure 28 and force-displacement curves in Figure 29 for all the different finite element models that are used.

Figure 27: Force-time for 100kgf and 150kgf elastic and plastic.

Figure 28: Displacement-time for 100 kgf and 150kgf elastic and plastic.
Figure 29: Force-displacement curve for loading and unloading of 100kgf and 150kgf elastic and plastic models.

These graphs show us the clear distinction between each model during its operating conditions that would cause the hardness performance to change from each other. The F-t was given as an input for ANSYS from ASTM E 18-17e1 [12], which represents the loading of Rockwell indentation experiments.

3.5 Comparison of the 100kgf and 150kgf Results

The results are obtained from the finite element models and are tabulated into the tables below. Table 3 shows the comparison at 100kgf and Table 4 shows at 150kgf.
Table 3: Comparison of Results from FEM with Experimental Data of Roll-Formed 316 SS at 100kgf

<table>
<thead>
<tr>
<th></th>
<th>Contact radius</th>
<th>Error</th>
<th>Max. Contact pressure</th>
<th>Hardness</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Hertzian theory</strong></td>
<td>154.27µm</td>
<td>62.6%</td>
<td>19692.86 N/mm²</td>
<td>-</td>
</tr>
<tr>
<td><strong>FEM - Elastic</strong></td>
<td>171.96 µm</td>
<td>58.2%</td>
<td>26351.7 N/mm²</td>
<td>-</td>
</tr>
<tr>
<td><strong>FEM - Plastic</strong></td>
<td>435 µm</td>
<td>5.58%</td>
<td>2929.25 N/mm²</td>
<td>63.5 HRB</td>
</tr>
<tr>
<td><strong>Experimental</strong></td>
<td>412 µm</td>
<td>-</td>
<td>-</td>
<td>70 HRB</td>
</tr>
</tbody>
</table>

Table 4: Comparison of Results from FEM with Experimental Data of Roll-Formed 316 SS at 150kgf

<table>
<thead>
<tr>
<th></th>
<th>Contact radius</th>
<th>Error</th>
<th>Max. Contact pressure</th>
<th>Hardness</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Hertzian theory</strong></td>
<td>176.59 µm</td>
<td>64.8%</td>
<td>22530 N/mm²</td>
<td>-</td>
</tr>
<tr>
<td><strong>FEM - Elastic</strong></td>
<td>198.9 µm</td>
<td>60.3%</td>
<td>31501 N/mm²</td>
<td>-</td>
</tr>
<tr>
<td><strong>FEM - Plastic</strong></td>
<td>500 µm</td>
<td>0.4%</td>
<td>2646.4 N/mm²</td>
<td>d=0.2069mm</td>
</tr>
<tr>
<td><strong>Experimental</strong></td>
<td>502 µm</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
CHAPTER 4
HARDNESS PERFORMANCE OF POROUS MATERIALS

4.1 Effect of Process Parameters on Porosity of AM Materials

Wang et al. [34] has analyzed porosity formation in laser assisted powder deposition process. They used 316 SS powder and analyzed the pores intralayer and interlayer and concluded that interlayer pores relate to higher oxidation kinetics and unmelted powders, whereas intralayer is dependent on stability of powder flow and interaction between the metal powder and laser power; 450W power, 14.8mm/s scan rate yielded pores of smaller diameter than 400W and 17mm/s. The porosity was as low as 1%. The range of porosity observed was 0.5% to 2.2%.

Gurevich.et.al,[36] in 1985 studied the effect of porosity on hardness penetration of powdered steels. For a long time it has been well known that porosity has an effect on the hardness of the material and for additive-manufactured materials, but not a lot of research has been done to predict the hardness performance at macro level of the additive-manufactured materials.

With this, an assumption could be made for initial stages, which is the hypothesis for this study and is also given as

\[ HR = f(\text{porosity}) \]  \hspace{1cm} (21)

which indicates that hardness is considered a function of porosity of the material.
4.2 Effect of Porosity on Finite Element Indentation

It is presented in many papers that porosity has an effect on the material properties of the material. The effect of porosity on Young’s modulus in additive-manufactured materials is given by [32,33]

\[ E_p = (1 - aP)E_0 \]  \hspace{1cm} (22)

where \( E_p \) is the Young’s modulus of porous material, \( P \) is the porosity, “\( a \)” is the constant based on Poisson ratio of the material, \( E_0 \) is the Young's modulus of nonporous body of the same material. This relation currently is applied for Young’s modulus.

The value of \( a \) is given by [33]

\[ a = \frac{3\times(9+5\theta_0)\times(1-\theta_0)}{2\times(7-5\theta_0)} \]  \hspace{1cm} (23)

According to Sayre [32] the same relationship could be applied to derive yield stress, tangent modulus and Poisson ratio. So this relation is used as per the literature for predicting other material properties like the Young’s modulus, yield strength and tangent modulus and are assumed isotropic.

Bahlyuk [35] used this approach in his computational analysis which is a numerical investigation materials produced by powder metallurgy. He studied the effects of porosity dependency of hardness in sinter-hardened material. This paper confirms that materials properties related by the above relations could be used for our finite element modelling to induce porosity.
4.3 Parameters for FEM of Porous Materials

The value of constant “a” is calculated as 2.004 [33] for the 316 Stainless Steel and the input values are listed in Table 5 and the results obtained are listed in Table 6 for 100kgf and Table 7 for 150kgf.

Table 5: Material Properties of the Porous Elements Considered

<table>
<thead>
<tr>
<th>Material Property</th>
<th>1% porous</th>
<th>5% porous</th>
</tr>
</thead>
<tbody>
<tr>
<td>Young’s Modulus</td>
<td>$1.8619 \times 10^5$ N/mm$^2$</td>
<td>$1.7096 \times 10^5$ N/mm$^2$</td>
</tr>
<tr>
<td>Poisson Ratio</td>
<td>0.294</td>
<td>0.27</td>
</tr>
<tr>
<td>Yield stress</td>
<td>$284.188$ N/mm$^2$</td>
<td>$260.94$ N/mm$^2$</td>
</tr>
<tr>
<td>Tangent Modulus</td>
<td>$1535$ N/mm</td>
<td>$1410$ N/mm</td>
</tr>
</tbody>
</table>

Table 6: Contact Radius Results Comparison of Porous Materials at 100kgf

<table>
<thead>
<tr>
<th></th>
<th>100kgf</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Contact radius</td>
</tr>
<tr>
<td>Hertzian theory</td>
<td>154.271 μm</td>
</tr>
<tr>
<td>FEM - Elastic</td>
<td>171.96 μm</td>
</tr>
<tr>
<td>FEM - Plastic</td>
<td>435 μm</td>
</tr>
<tr>
<td>1%</td>
<td>468 μm</td>
</tr>
<tr>
<td>5%</td>
<td>494 μm</td>
</tr>
<tr>
<td>Experimental</td>
<td>412 μm</td>
</tr>
</tbody>
</table>
Table 7: Contact Radius Results Comparison of Porous Materials at 150kgf

<table>
<thead>
<tr>
<th></th>
<th>150kgf</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Contact radius</td>
<td>Error</td>
<td>Max. Contact pressure</td>
<td>Hardness</td>
</tr>
<tr>
<td>Hertzian theory</td>
<td>176.59 µm</td>
<td>64.8 %</td>
<td>22530 N/mm²</td>
<td>-</td>
</tr>
<tr>
<td>FEM - Elastic</td>
<td>198.9 µm</td>
<td>60.3 %</td>
<td>31501 N/mm²</td>
<td>-</td>
</tr>
<tr>
<td>FEM - Plastic</td>
<td>500 µm</td>
<td>0.4%</td>
<td>2646.4 N/mm²</td>
<td>d=0.2069mm</td>
</tr>
<tr>
<td>1%</td>
<td>528 µm</td>
<td>5.17%</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>5%</td>
<td>533 µm</td>
<td>6.17%</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Experimental</td>
<td>502 µm</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

4.4 Comparisons of Experimental AM Material Results with Non-Porous FEM

The contact radius comparisons for 1% and 5% porosity have been presented in the table above; now the experimentally obtained values of contact radius are compared to the finite element results in three stages. The first stage is comparison with nonporous FEM model at different loads for different samples grouped according to the laser power. The 475W, 645, 875 W are compared in Figure 30, Figure 31, and Figure 32 respectively. Similar to the earlier comparisons it was observed that the deviations at 475 W did not differ with increasing scan rate; 645 W and 875W had some deviations.
Figure 30: Comparison of experimental sample value to nonporous FEM model 475 W.
Figure 31: Comparison of experimental sample value to nonporous FEM model 645 W.

Figure 32: Comparison of experimental sample value to nonporous FEM model 875 W.

4.5 Comparisons of Experimental AM Material Results with 1% Porous FEM

The comparisons in contact radius are now compared to 1% porous values from FEM. These also had the same trend mentioned earlier for 475 W. The 475W, 645, 875 W are compared in Figure 33, Figure 34, and Figure 35 respectively. Another observation that was made is that the deviations of the 100kgf load are bigger than that of 150kgf load even though they are compared to their corresponding FEM values. This was the reverse when it was compared with experimental roll-formed stainless steel.
Figure 33: Comparison of experimental sample value to 1% porous FEM model 475 W.
4.6 Comparisons of Experimental AM Material Results with 5% Porous FEM

The comparisons in the third stage are compared to the results that are obtained from 5% porous FEM. The 475W, 645, 875 W are compared in Figure 37, Figure 38, and Figure 39 respectively. A similarity was observed for 475W as in the earlier finite element comparisons and for 645 W and 875W also. It has been also observed that increasing the porosity increased the deviations of my experimental data with respect to the FEM model. This observation would be a crucial one in making conclusions of this study.
Figure 36: Comparison of experimental sample value to 5% porous FEM model 475 W.
Figure 37: Comparison of experimental sample value to 5% porous FEM model 645 W.

Figure 38: Comparison of experimental sample value to 5% porous FEM model 875 W.
CHAPTER 5
CONCLUSIONS

The effect of process parameters on the porosity of the specimen could be predicted with the theory of literature that is available. The effect of porosity on hardness performance is visualized by the finite element model that was developed and verified with experimental results. The model could be used in predicting the penetration depth and contact radius of indentation experiments which would in turn evaluate the hardness performance of the material.

In other words, process parameters affect a key material property called porosity which in turn affects the hardness performance of the additive-manufactured 316 SS samples. So our assumption that was made based on my literature, which is $HR = f(\text{porosity})$ doesn’t stand valid after the results of porous materials were analyzed. Another conclusion can be made from this study:

$$HR = f(\text{porosity, other})$$

(24)

The other properties could be any material properties that are either related directly or indirectly. Further investigation needs to be done to classify effect of others on the hardness performance.
CHAPTER 6
FUTURE WORK

1. Incorporate the effect of adhesion in these additive-manufactured samples to predict hardness performance.

2. Use nano-indentation to predict the effect of indentation on a pore in a porous material.

3. Consider the nonisotropic behavior of the material properties also to be incorporated into the model.
BIBLIOGRAPHY


APPENDIX

ANSYS APDL CODE FOR SOLVING MODELS

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