The Comparison of Microstructure and Mechanical Behavior of Stainless Steel 316L Using Near Net Shaped and Fully Embedded Methodologies Using DED Metal Advanced Manufacturing

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Abstract. The objective of this research is to compare the microstructure and mechanical behavior of 3D printed SS 316L using near net shaped and fully embedded manufacturing extraction techniques. Research findings will allow us to determine if two different manufacturing extraction methodologies of a 3D printed stainless steel part will affect the overall performance of test specimens. Research will implement advanced manufacturing, part designing, part modeling, part simulation, part production, CT X-ray scanning, material characterization, and material testing. Printing of test specimens will be done with an Optomec Lens 3D Hybrid Machine Tool Direct Energy Deposition (DED) metal printer. The DED metal printer will be used for prototype printing and printing test samples. The areas of study will also include modeling and design using SolidWorks CAD software. A comparison of printing orientation/configuration, internal composition, and testing of material structure in the areas of stress to complete failure of test specimens. The internal structure analysis will observe the porosity effects of 3D metal printing with near net shaped and cocoon style print parameters. The study will also address the amount of time, production, strength, composition, and overall performance of SS 316L printed material.

1. Project Overview
The objective of this project is to compare the microstructure and mechanical behavior SS 316L using near net shaped and fully embedded manufacturing extraction techniques. The types of printing methods were used, a near net shaped and cocoon style printing. Near Net shaped printing as shown in Figure 1 has a closer tolerance of material around the samples gauge length area. This style of printing adds and additional 2 to 3 mm of material to the gauge length area. Cocoon style printing as shown in Figure 2 adds more tolerance around the samples gauge length area. This style of printing will allow the part to cool slower, adding an extra 5 to 6 mm of material to the gauge length area [1-5].

Figure 1. Near Net Style Print.
2. **SS 316L Powder**

Stainless steel 316L was used for this research due to its resistance to corrosion, its chemical resistance, it has good weldability, it is widely available. Delcrome 316L welding powder was manufactured by Kennametal. Micron size of this powder ranged from 45 to 150 microns in spherical shape, has a metallic appearance with a melting point of 965-1040°C / 1770-1900°F. Ingredient percentage for Kennametal powder are in concentration of weight percentages. Ingredient percentages were, iron (Fe) plus 50 percent, chromium (Cr) 10-25 percent, nickel (Ni) 10-25 percent, molybdenum (Mo) 2.5-3 percent, silicon metal (Si) 1-2.5 percent, and manganese (Mn) at 0.1-1 percent. Exact percentages of powder concentration are withheld due to trade secrets by the manufacturer. Exact percentages of powder concentration are withheld due to trade secrets by the manufacturer.

3. **Additive Manufacturing Printing Process**

A Optomec Lens 3D Hybrid metal printer was used to print samples for this project as shown in Figure 3. The Optomec printer has four powder nozzles, two powder feeders, an Ultra Light laser, and prints within a controlled atmosphere with argon gas. Printing parameters used to print test samples were a laser power of 300W, hatch spacing of 0.015 mm, layer resolution of 0.015 mm. at a speed of 20in./min. on a 1 inch SS build plate.

4. **Subtractive Manufacturing**

A Makino U6, a electrical discharge machine (EDM) was used to perform extraction methods of test samples. The EDM utilizes a copper wire that is 0.2 mm in diameter that was factored into the modeling and designing of the CAD model dimensions. Printed part geometry measurements were collected using a FARO Arm and saved as an iges file. The iges file was uploaded into Solidiworks, a CAD model was created lines and saved as a dxf file. A dxf file is a drawing exchange file extension that is used for importing and exporting CAD files for the EDM. Profile cuts were programmed in inches, unwanted lines were trimmed and removed with the Visi software. EDM setup took up to one hour to mount the build plate in alignment with the orientation of the (0,0) x and y axis created with the Visi software.
5. CT X-RAY Scanning
A North Star Imaging X3000 computed tomography machine was used to perform non-destructive image analysis of the internal and external print qualities of samples. CT scanning was performed on 24 test samples, 12 to be used for tensile testing and 12 for material surface characterization. Radiographs were reconstructed with the use of the Efx CT View software. The first scan of the part is used to set your scanning parameters, and the gains for scans. Gains will adjust contrasting, penetration, noise, pixels within radiographs. Efx CT view software was used to reconstruct the radiographs of samples. Steps that were completed for reconstruction are auto-contrasting, beam hardening, referencing, and reconstruction. All samples need the x-rays reconstructed before uploading the NSI file into Volume Graphics for porosity analysis. See Table 1 for parameter settings.

| Table 1. CT Scanning Parameters. |
|----------------------------------|
| **Fixture** | Tall_base_ext3_holder |
| **Filter**  | 0.02 copper |
|             | 1000 |
| **Frames**  | 4 |
| **Voltage** | 140kV (penetration) |
| **Current** | 100 µA (contrast) |
| **Duration** | 48 minutes |
| **ROI**     | 636x1880+450+20 |

6. Porosity Analysis
Porosity analysis was performed using Volume Graphics software. A NSI format file was uploaded of each sample into the Volume Graphics software. A surface determination was created for each sample and a porosity analysis completed. Porosity volume diameter was set at 2.00 mm per mm³ diameters. Porosity volume was analyzed within the 25 mm gauge length area of all samples as shown in Figure 4. Porosity levels were calculated overall between cocoon and near net shaped samples. Near net samples showed to have higher levels of porosity within the 25 mm gauge length areas than the cocoon printed samples.

![Figure 4. Porosity within 25 mm Gauge Length Area.](image)

7. Microscopy
Grinding, polishing and etching allowed the surface crystal structures to be inspected under the 3D Keyence microscope. Laser path directions were inspected, hatch diameters and spacing were measured. Surface characteristics that were documented were columnar dendrites, equiaxed dendrites, heat affected zones (HAZ), laser directions, and unmelted powders. Columnar dendrites grew in the opposite direction...
of the laser direction, growing towards the areas that were cooler. Columnar dendrites were visually noticeable under the 3D microscope with the near net shaped printed samples.

8. Material Testing
Material testing of samples were performed on the Instron 5982 Tensile Machine. Tensile testing was set to be measured in MPa, with a 2% offset. The modulus of elasticity of sample NN3-3 was noticeably higher than all other samples. This higher level of modulus of elasticity was due to the thickness of the part being thinner in thickest to the other samples. The nominal thickness of samples was 3.00 mm in thickness. Sample NN3-3 had a thickness of 1.89 mm resulting in the higher modulus of elasticity results. A Aramis digital imaging correlation system (DIC) was used as a digital extensometer to take surface and displacement measurements.

9. Conclusion
Test results showed the total modulus of elasticity of cocoon printed samples to be 41979 Mpa, and near net shaped samples to be 46992 MPa as shown in Figure 5. The total yield strength for cocoon printed samples was 529 MPa, and near net shaped samples was 540 MPa as shown in Figure 6. The total tensile strength for cocoon printed samples was 417 MPa, and near net shaped samples was 418 MPa as shown in Figure 7. The conclusion of test results shows the near net shaped printed samples had higher modulus of elasticity, higher yield strength and higher tensile strength.

![Modulus of Elasticity - Near Net & Cocoon Parts.](image)

**Figure 5.** Modulus of Elasticity - Near Net & Cocoon Parts.
Figure 6. Yield Strength - Near Net & Cocoon Parts.

Figure 7. Tensile Strength - Near Net & Cocoon Parts.
References

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