ME-GY-6423-A Fall 2024 Final Report
Additive Manufacturing of Metallic Materials
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Abstract

Through this report, we will explore the mechanical properties and defects in 316L stainless steel parts manufactured via selective laser sintering (SLS), and the impact that the printing angle will have on these properties. This study further investigates how the build orientation influences the mechanical performance and structural integrity of parts. Insights from this study provide a foundation for optimizing the SLS process for applications in high-performance environments. Selective laser sintering uses a high powered laser to sinter together metal powders layer by layer to create 3D objects. 316L stainless steel is a common material used in the additive manufacturing of metallic materials.

Multiple printing angles were printed for analysts, this report will cover the parts printed at a horizontal 90 degree angle. We will test the tensile strength and the impact resistance of the part using a tensile testing machine and Charpy impact test.

After the testing is performed the pieces will be cut and examined through a Scanning Electron Microscopy (SEM) in order to obtain a visual of the microstructure of the part as well as surface or part defects one can not see with a naked eye.

These results will be analyzed to determine the effectiveness of the selective laser sintering printing technique as well as the printing angle and the material used. This report focuses on understanding the relationship between printing orientation and the mechanical performance of 316L stainless steel parts fabricated using **DMLS.** By examining tensile strength and impact resistance, we aim to derive insights for enhancing the reliability and efficiency of this advanced manufacturing technique.

Introduction

For each printing orientation 6 samples were printed, 3 to be used for tensile testing and 3 for impact testing. The printing of these samples took place at LaGuardia Studios lab where they used an XM200G2 metal 3D printer to print and process our parts. The material used is 316L stainless steel. This is one of the most used materials in metal 3D printing due to its low carbon standard which makes it excellent for weldability and also for its corrosion resistance, biocompatibility and high strength and ability to retain its strength even after it is melted. This material comes in powder form ready to be used for printing, metal powders are commonly produced by gas atomization where its size can range from 15 microns to 45 microns. Powders can be expensive to manufacture so most powders are reused for printing.

Properties	**Conventional Methods (Forging/Casting)**	**3D Printing Methods (LMD/SLM)**
Yield Strength (MPa)	~305-350	~480-500 (LMD), ~577 (SLM)
Ultimate Tensile Strength (MPa)	~500-620	~620-641 (LMD), ~800 (SLM)
Elongation (%)	40-55	26-41 (LMD), ~36 (SLM)
Microstructure	Equiaxed grains, larger grain size, presence of twins	Columnar and equiaxed grains, finer sub-structures, fiber and cellular sub-structures, sub-grain boundaries

Printing is achieved by having a sweeper lay a thin layer of powder over the build plate and then having a laser sinter the powder in the shape of the 3D object, after the first layer is done the build plate is lowered and the sweeper lays another layer of powder and the process is repeated until the shape is completed. The part is then allowed to cool in the build chamber and taken out for post processing. The part will then be examined for defects and will be tested to see the physical properties of the part based on the printing angle.

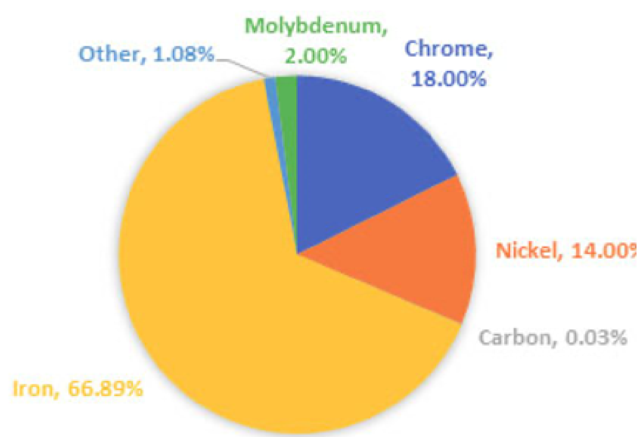
The field of additive manufacturing of metallic materials has revolutionized industries by enabling complex designs, minimal waste, and customized production. Techniques such as Direct Metal Laser Sintering (DMLS) and Selective Laser Melting (SLM) utilize high-powered lasers to fuse powdered metal into precise geometries dictated by CAD files. These methods have gained prominence in aerospace, automotive, and healthcare sectors. However, limitations like build orientation-induced defects and inconsistencies in mechanical properties require deeper analysis.

Material Used:

Because of favorable mechanical properties, excellent corrosion and processability, 316L stainless steels are of great importance in aerospace, marine, gas and chemical industries. Its high strength and corrosion resistance make it highly suitable for nuclear reactor applications.

The chemical composition of 316L stainless steel is:

- Carbon: 0.030% maximum
- Chromium: 16–18%
- Nickel: 10–14%
- Molybdenum: 2–3%
- Manganese: 2%
- Silicon: 0.75%
- Nitrogen: 0.10%
- Phosphorus: 0.045%
- Sulfur: 0.030%



The material used in the project was TruForm 316L SS, a high-quality stainless steel powder ideal for Direct Metal Laser Sintering (DMLS). 20% new powder was used and the remaining 80% recycled powder was mixed from previous prints. This mixture is commonly used in metal additive manufacturing to ensure the material properties meet the necessary requirements for mechanical performance.

Literature Review
2.1 Significance of 316L SS.

2.2 Additive manufacturing techniques for 316L stainless steel
2.2 Effects of build angle on mechanical properties
2.3 Microstructural characteristics of 3D printed 316L stainless steel
2.4 Common defects in 3D printed metal parts

One of the most studied and used materials is the austenitic steel AISI 316L, as demonstrated by the extensive scientific literature [64,65,66,67,68]. The extensive use of this steel for additive manufacturing is due to several factors, such as the high thermal conductivity of AISI 316L, which favors dissipating heat generated during the printing process, preventing excessive thermal gradients, and minimizing thermal stresses.

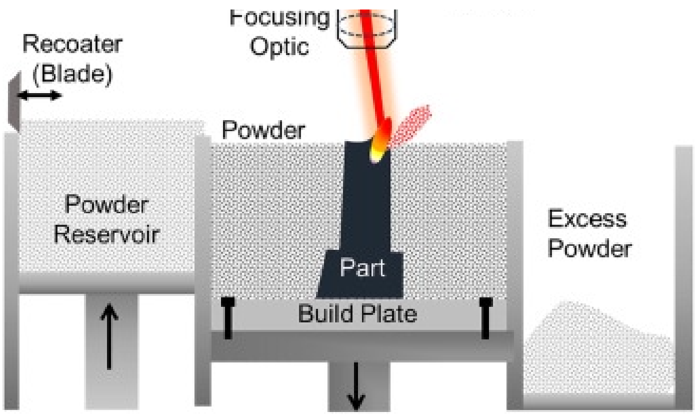
Specimen preparation

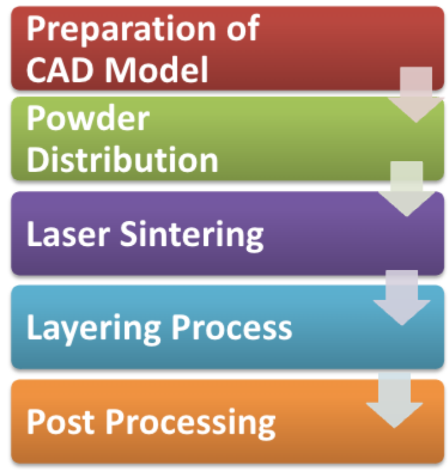
The material used for 3d printing in this project at LaGuardia studios was truForm 316L SS. 316L SS is a high quality stainless steel powder ideal for DLMS. It was sourced from Praxair.

316L Stainless steel is known for its excellent corrosion resistance, mechanical properties and processability, making it an ideal feedstock material for metallic 3D printing.

Understanding DMLS

Direct metal laser sintering (DMLS) is a common 3D printing or additive manufacturing technique that is also referred to as selective laser melting (SLM). In this process, each layer of a part is created by aiming a laser at the powder bed in specific points in space, guided by a digitally produced CAD (computer-aided design) file. Once a layer is printed, the machine spreads more powder over the part and repeats the process. The process is ideal for printing precise, high-resolution parts with complex geometries. DMLS machines use a laser to heat the particulate matter to its melting point in a digital process that eliminates the need for physical molds. The resulting parts are accurate, have excellent surface quality and near-wrought mechanical properties.





Methodology:

Printing process:

Technology used: XACT Metal XM200G2

The printing process was conducted using DMLS at NYU's LaGudaria Studios. A thin layer of 316L stainless steel powder was spread using a recoater blade before selectively fusing it with a laser. Each subsequent layer was built on the previous, following the CAD model until the part's completion. The orientation analyzed in this study involved parts printed vertically, with their width parallel to the build platform.

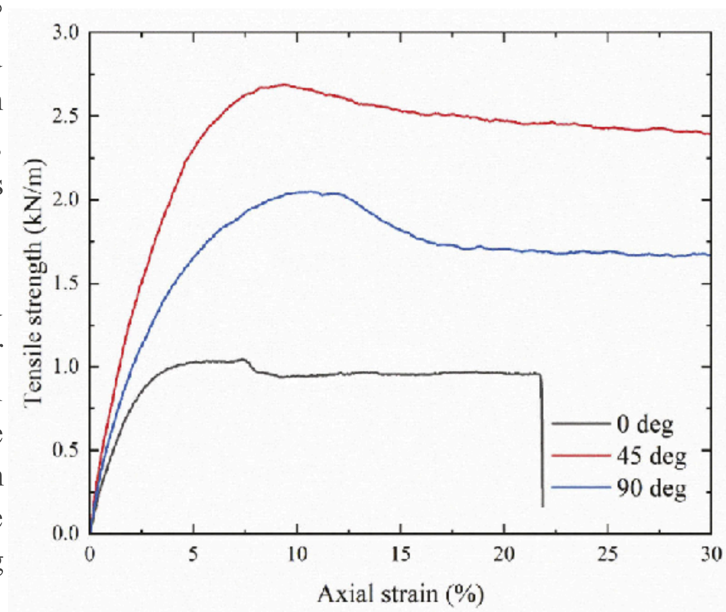
Parameters:

- The printing process employed two beams during the laser sintering process to ensure a faster and more efficient build but we couldn't employ them simultaneously due to laser limitations.
- The beam diameter was set at 0.1 mm, which provides precise laser focusing and accurate sintering of fine metallic powders.
- Laser power was controlled between 50-200 W, enabling optimal energy distribution to melt and fuse the powder layers effectively.

Scanning Type	Laser Speed	Laser Power	Outcome
Up-Skin/ Down Skin	Slow	Low	Improve surface finish and accuracy
In-Skin	Fast	High	Maximize efficiency and strength

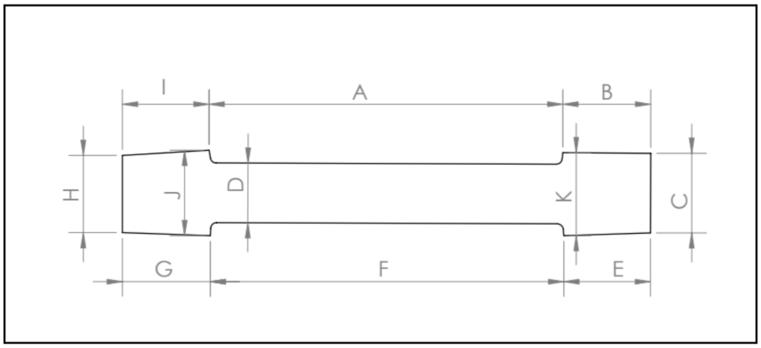
Printing Angle and Considerations:

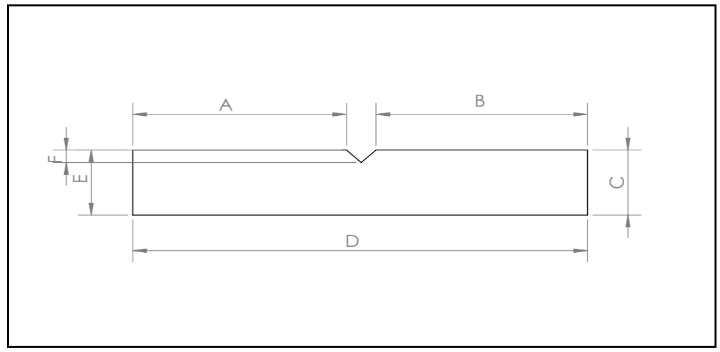
Printing Angle: The printing was done at a 90° vertical orientation, where the parts were aligned perpendicular to the build plate. This orientation was chosen to optimize mechanical strength, reduce thermal distortion, and minimize stress accumulation during the printing process.



The low angle of the printing orientation ensured that the printed parts had a stronger, smoother surface and resulted in higher dimensional accuracy. However, it also made the parts more susceptible to weaker mechanical properties in some areas compared to other orientations. We will observe the mechanical effects of the printing angle in the next sections.

Part detail:





Dimensions:

Tensile Test

A (in)	B (in)	C (in)	D (in)	E (in)	F (in)	G (in)	H (in)	I (in)	J (in)	K (in)	Thickness (in)
2.99	0.75	0.68	0.51	0.74	3	0.75	0.66	0.74	0.71	0.73	0.08
2.99	0.74	0.7	0.51	0.74	2.99	0.74	0.66	0.74	0.7	0.73	0.08
2.99	0.74	0.69	0.5	0.75	3	0.74	0.66	0.74	0.7	0.74	0.08

Impact Test

A (in)	B (in)	C (in)	D (in)	E (in)	F (in)	Thickness (in)
1.01	1	0.36	2.15	0.36	0.07	0.08
1	1.01	0.35	2.15	0.36	0.07	0.08
1.01	1.01	0.36	2.14	0.36	0.07	0.08

These are the dimensions after printing, due to the high heat during printing and the printing angle this causes the parts to warp and slightly alter the dimensions and shape. This can be thought of as a defect and a disadvantage of printing at this orientation.

Mechanical Testing

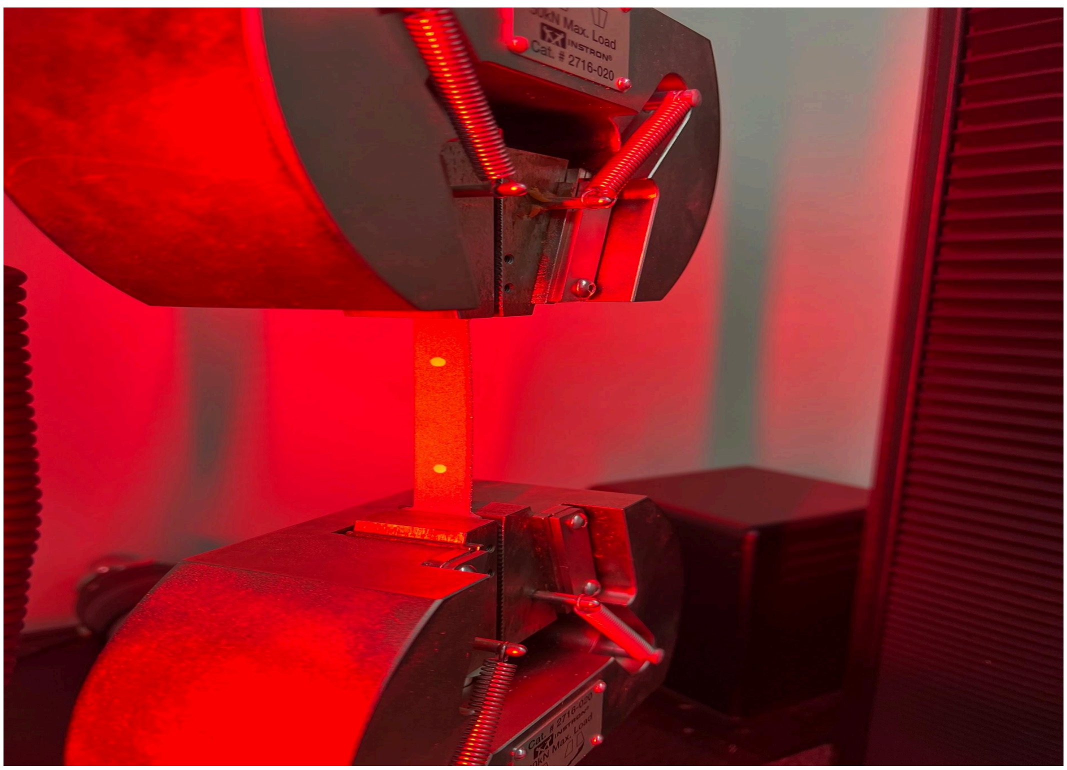
- **Tensile Test:** Standard specimens were tested to failure to determine ultimate tensile strength, yield strength, and elongation.
- **Impact Test:** Charpy impact tests measured the toughness of the specimens under dynamic loading conditions.
- **Defect Analysis:** Scanning Electron Microscopy (SEM) was used to analyze fracture surfaces and identify microstructural defects such as porosity and crack propagation patterns. We were unfortunately unable to perform this due to equipment limitations.
- **Hardness Testing:** Vickers hardness tests were conducted to measure surface hardness and assess localized deformation resistance.

Results and Discussion

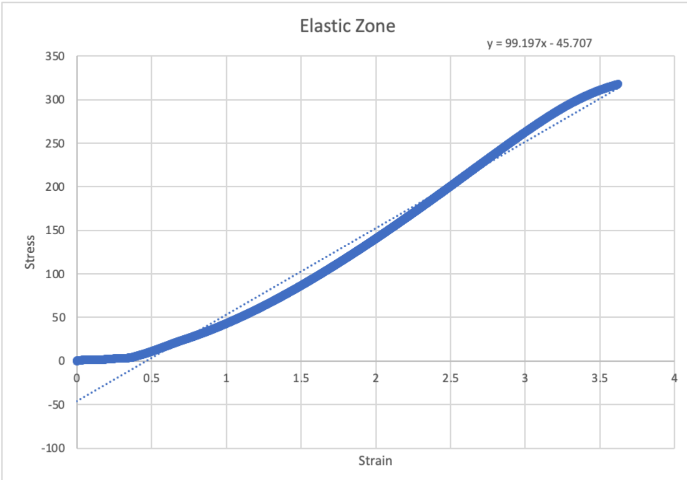
Tensile Properties

Specimens printed vertically exhibited anisotropic properties. The ultimate tensile strength and elongation were observed to decrease compared to horizontally printed counterparts. Microstructural analysis revealed lack-of-fusion defects and uneven grain orientations contributing to these differences. This is in line with what we were expecting for parts printed in the 90° orientation.

Tensile test for part A

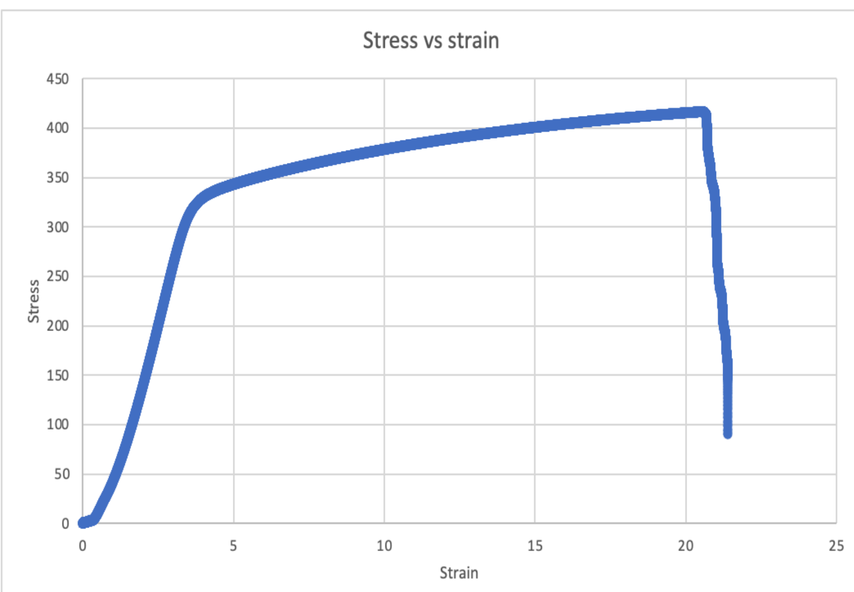


Elastic Zone for part A



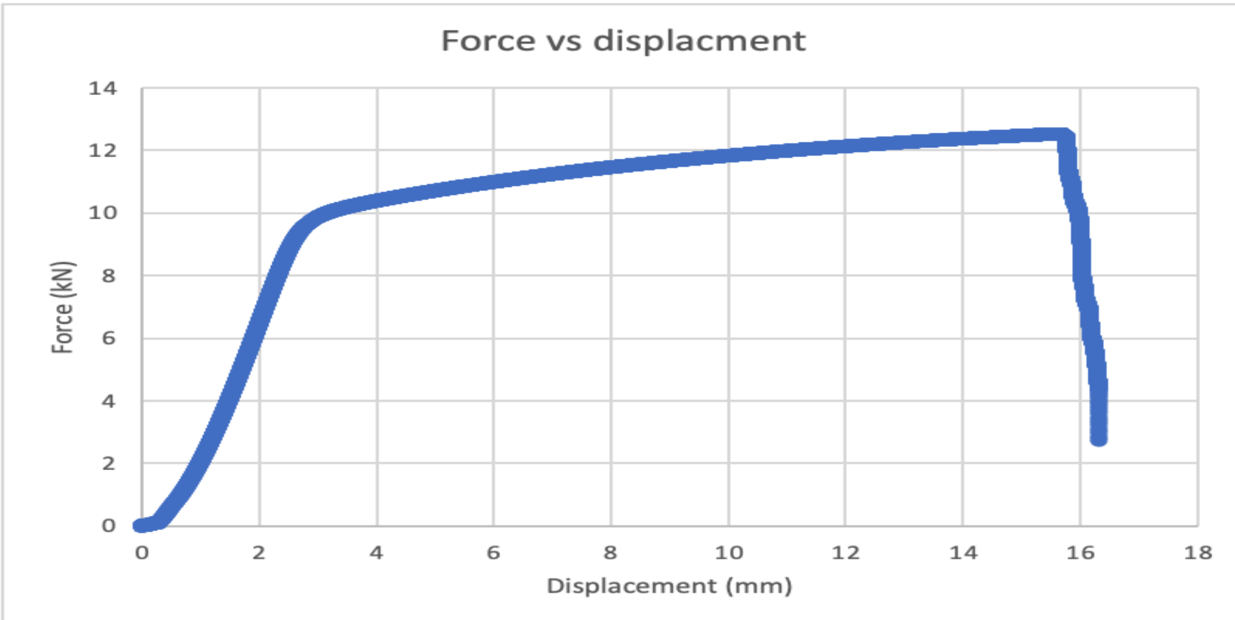
- Elastic Zone: From a stress of 0 up to approximately 325 kN, the material behaves elastically. In this region, the strain increases proportionally to the stress, and the material can return to its original shape once the load is removed. The slope of this curve corresponds to the material's Young's Modulus.
- Taking the slope of this line we can get the modulus of elasticity which in our case is 99.197 GPa

Stress vs strain curve for part A



- Plastic Zone: Between 325 kN and 425 kN, the material enters the plastic zone. In this phase, permanent deformation occurs. The material no longer returns to its original shape once the load is removed, and it deforms plastically. This is indicative of the material reaching its yield point, where it begins to flow under stress.
- Fracture Point: At around 425 kN, the specimen reaches its fracture point, where it fails under the applied stress. The curve shows a rapid drop in stress after this point, signaling material failure.

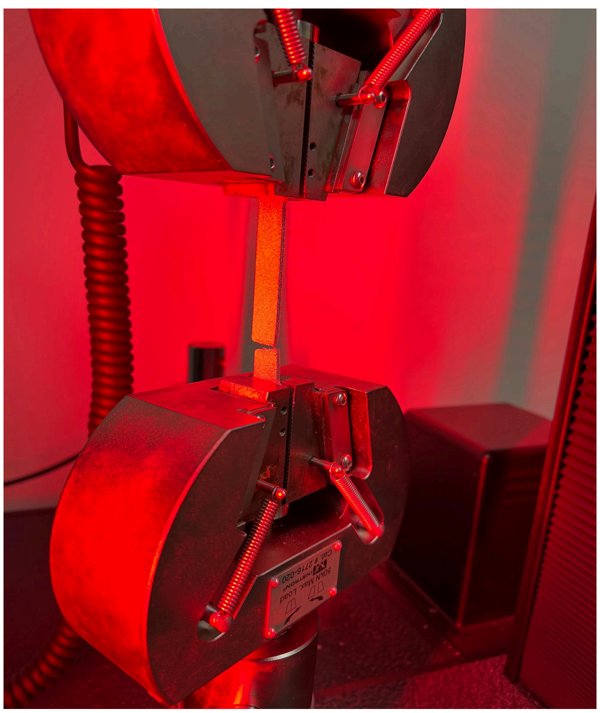
Force vs displacement plot for part A

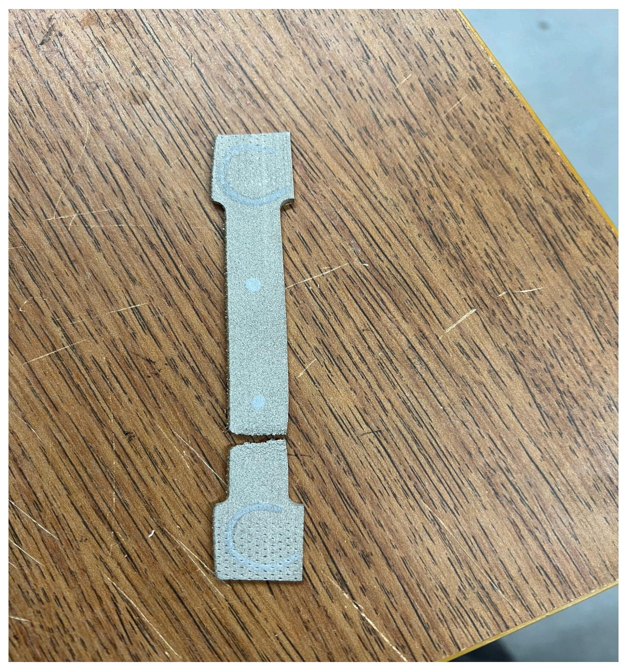


If we plot the force vs displacement we get a similar looking graph as the stress vs strain graph. We can see that the part is in its elastic zone from a force of 0 to 9.5 kN and a displacement of 3mm. The plastic zone is from 9.5 kN to 12.5 at a displacement of 15.8mm where it reaches its fracture point.

Tensile test for part B

Tensile test for part C





Part 3 is an interesting case. During printing it got a micro crack defect. Because of this defect it fractured at a very early stage during testing. Although we don't have the data

Impact Properties

Impact toughness showed a significant drop in vertically printed specimens. The fracture surfaces revealed brittle failure modes attributed to residual stress concentrations and poor inter-layer bonding.

Defects Analysis

SEM images highlighted porosity, unmolten powder particles, and microcracks. These defects were concentrated along layer interfaces, emphasizing the need for optimized laser scanning strategies.

Hardness Properties

The Vickers hardness results indicated significant variability along different orientations. Surface hardness was found to be higher at regions with fewer defects, suggesting an uneven distribution of mechanical properties due to orientation-specific heat transfer dynamics during printing.

Applications

This study's findings are relevant to industries requiring high-performance parts, such as:

- **Aerospace:** Lightweight and durable components for aircraft.
- **Healthcare:** Customized implants with biocompatibility.
- **Automotive:** Corrosion-resistant components in high-temperature environments.
- **Energy:** Components for power plants that require high resistance to corrosion and mechanical stress.

Future Work

1. **Additional Testing**
   - **Fatigue Testing:** Evaluate the performance of DMLS parts under cyclic loading conditions.
   - **Thermal Analysis:** Analyze the thermal stability and heat resistance of printed parts.
   - **Corrosion Testing:** Investigate long-term behavior in harsh environments.
   - **Wear Testing:** Determine the wear resistance for applications requiring high durability.
2. **Data Extraction**
   - **Microstructure Characterization:** Use advanced imaging techniques like X-ray diffraction and 3D tomography to understand grain structure evolution.
   - **Residual Stress Analysis:** Employ non-destructive methods to quantify residual stresses.
   - **Thermal Conductivity Analysis:** Examine the efficiency of heat dissipation in printed parts for thermal-critical applications.
3. **Process Optimization**
   - Develop strategies for reducing defects, such as optimizing laser power, scan speed, and layer thickness.
   - Investigate alternative orientations to balance mechanical properties and minimize defects.
   - Explore the integration of real-time monitoring systems to detect and mitigate defects during the build process.
4. **Broader Scope**
   - Expand the study to other materials such as titanium alloys and Inconel for broader industrial applicability.
   - Explore hybrid additive manufacturing processes that combine DMLS with post-processing techniques like heat treatment or surface polishing.
   - Develop predictive modeling tools using machine learning to optimize printing parameters.

Conclusion

This report looks at the mechanical properties, defects, and performance of 316L stainless steel parts produced using DMLS. Through testing, including tensile, impact, and hardness tests, we identified key factors influencing the mechanical behavior of these parts, including build orientation and microstructural defects.

The findings revealed that printing orientation significantly affects tensile strength, with vertical specimens exhibiting lower strength compared to horizontally printed counterparts. The impact toughness was notably reduced in vertically printed parts, due to residual stress concentrations and poor inter-layer bonding. Defects, such as porosity and un-molten particles, were observed, making us realize the importance of optimizing printing parameters to minimize these flaws.

Hardness testing showed that surface hardness varied based on the orientation and defect distribution, further highlighting the role of print quality in mechanical performance..

In conclusion, optimizing DMLS parameters, such as laser power, scan speed, and layer thickness, is critical for improving the mechanical performance of printed parts. Future research should focus on reducing defects through process adjustments, alongside conducting additional tests like fatigue, thermal stability, and corrosion resistance, to ensure the reliability of DMLS-produced parts for use in high-performance industries such as aerospace, healthcare, and automotive.

This work contributes to a deeper understanding of the complexities of additive manufacturing with 316L stainless steel and lays the groundwork for future advancements in process optimization, which will help broaden the material's application in critical engineering fields.

Acknowledgments

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