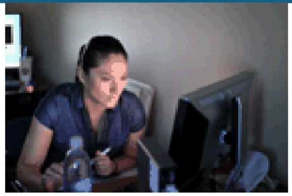
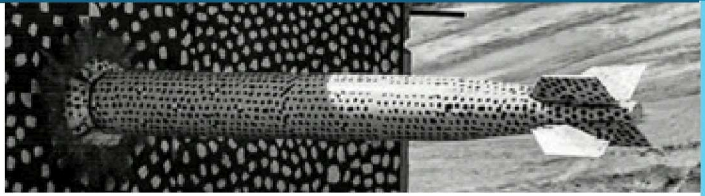
SAND2019-9351PE

NW SPRINT Summer 2019

Project Mishipeshu
NW SPRINT
Sandia National Laboratories

PRESENTED BY

Rebecca Cooper, Michael “1” White, Michael “2” Cui, Mitchell Gosma, & Andy Swanson

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Project Charter

- **Project Scope** – Develop and demonstrate a qualification approach for an additively manufactured metallic housing for delivery to an SNL weapon system, which can also be applied to other components or applications
- **Project Purpose** – To study the questionable reliability and repeatable performance of metallurgically additive manufactured parts, so the advantages of AM can be capitalized upon and a reduction in design cycle time can be achieved
- **Team Goals**
  - Design a metallic housing that effectively meets design requirements
  - Define a comprehensive qualification plan for general AM parts
  - Understand the relationship between print settings and materials to part quality.
- **Customers**
  - NW SPRINT Stakeholders
  - NTESS
  - NNSA
  - DOE
  - DOD

Background for Metal AM

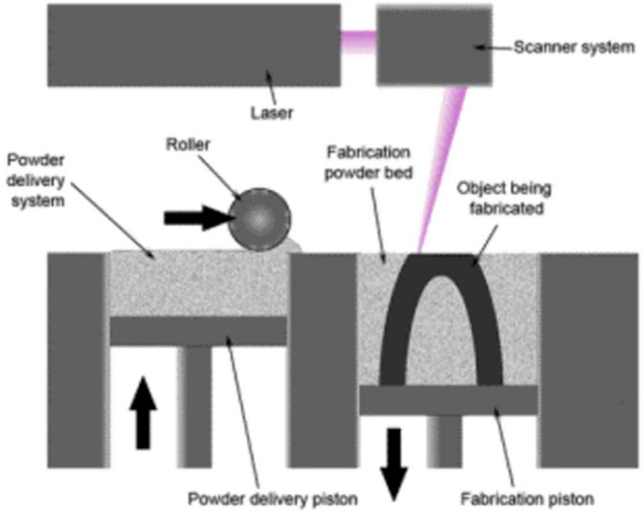


Figure 1: Selective Laser Sintering for Powder Bed Fusion

- Can print parts that are not manufacturable by other means
- Better for printing single use parts (for NW applications)
- Material differences from wrought material
  - Lack of fusion voids
  - Gas porosity
  - Poor surface finish
- Printer Setting Affect Print Quality
  - Laser power, laser speed, powder characteristics, position on the build plate, height off build plate, hatching spacing
  - Processing plateau
    - As seen in testing results
  - In future, can customize settings to improve certain characteristics

Initial Approach

Meeting with Relevant Sandians and Asking Questions

	A	B	C	D
1	Question	Answer		
2	How to model stress concentration factor of pores?	You don't, experimental data is the best way to tell material property		
3	It says online there's a void identification algorithm to measure porosity on surfaces but does that mean it can only be done by destroying the part?	time to do x-ray, CT IS EXPENSIVE BUT EXPLICIT (ours is implicit)		
4	Methods of removing surface crust?	Tumble-polishing		
5	How do unsintered particles getting stuck in voids (especially artificially created ones) affect the product?	Make sure there is a mm sized opening to get 20 micron powder size out		
6	Are we allowed to remove the crust on t-bars or on our final part?	they do it for us		
7	Tolerancing of AM metal parts?	5 thou for small, increases by a couple thou per inch (~10 thou for our part)		
8	Residual stresses in AM parts due to thermal history?	alright because they're small, shift is in xy plane, perpindicular to our build and the loading direction (is in xy plane)		
9	How do each affect the part: laser power, scan pattern, scan velocity, part feature size, geometry?	BRADLEY IS SENDING US		
10	What is max overhang, min thickness, ect?	45 degree overhang, 45 mm (check) bridge, 5 mm diameter arches, 3 mm holes		
11	Do we need insulation or pathways to release heat?	No		
12	Direction of the force relative to the board?	Board is parallel to ground		
13	What is actual test apparatus?	Compressive force on 6" plates		
14	How enclosed does it need to be?	Shouldn't be able to hit it or touch it from the outside		
15	What does contact that makes it fail mean? It's already in contact?	No damage		
16	What's the surface roughness after post-processing?	~10 microns anyway		
17	What post processing are we allowed to do?	Can do but normally get 10 micron surface roughness anyway		
18	What qualification testing do they normally do?	powder sample data, charpy and tensile, hardness, density, DIC, cut them up		
19	How big does the flat point of contact need to be?	No requirements		
20	Microstructure of Lattice?	very fine grain!!!!		Bradley Jared
21	Min size of lattice and overhang that works well?	5 mm max		Andy Brewer
22	"Ease of manufacturing"	support needed, unique qualifications needed or post processing		Mara/Clarification
23	Machine to measure surface roughness	Keyence 3200		Shaun Whetten
24	What is changing between lots	Only 1 parameter is changing between lots		
25	How does hole req work for lattice?	No hole req for lattice		
26	Tolerance on board?	5 thou		
27	Note: Sig Figs on numbers in requirements dictate tolerance!			
28	<2"	Only need to change it by tolerance on the machine		
29	We can do other qualification tests if we want			
30	Say what heat treatments, ect you WOULD have been good and JUSTIFY them, say what qualification would do if had time and money (micro CT)			
31	What do you look for in a test artifact?	hypothesis-->how to test--> how to do control variables to test that, what are controlled and uncontrolled variables		
32		Charpy-->print and get multiple tests out of it (can see if something went wrong), doesn't cover full build plate,4-5 properties with one specimen, if only use 1 sample can get rare defects, needs to have relevance to parts you're printing (needs to test req somehow-->dim tolerance, fatigue, skin effects, microstructure,ect)		
33	It says in a paper that Bradley Jared sent us that tensile testing with dogbones isn't good because it has nominal stress and no stress concentrations, why do you want this?	It means that you don't know where the tensile bars fail because they have no stress concentration and don't know where they will break so you have to analyze the whole thing		
34	What statistical approach do you use to design AM parts?	QMU, margin to worst part, figure out where part will fail and how		
35	Point-based qualification?	point-based=product based qualification, it's important to AM because so many variables		
36	What are the data points in the CDF plots?			
37	How many samples do you actually need in a test artifact for high throughput testing?			
38	Feature sizes of parts you normally print?			
39	What factor of safety is the standard?			
40	Readings on microstructures?			
41	What size should a test article occupy on the build plate?	approximately 1", should be quarter inch away from corners		
42	Difference in external and internal grain structure?			
43	How do you currently qualify components?	for AM, destructive testing is still important, testing in different operational environments		
44	What kinds of qualification will be important for our project?	figure out which quantities are important and which sets you could use based on this, need to understand variability		
45	How do you specify more qualitative results for qualification analysis?			
46	Anything else we should look for in Keyence?	Lack of fusion voids, gas porosity, surface finish		
47	Is it good to have a test artifact that can be used for multiple tests? Should it be destructive?	should be able to be used for multiple tests before any destructive testing		
48	Should the test artifact be to be printed with every print or printed to test capabilities?	every print		
49	Need to know use for factor of safety			
50	Why is ductility best for the second best lot? Why does it look like the reverse for the impact test?	Skin effects with tensile bars--> possible result of ductility discrepancy, PROCESSING PLATEAU--> there's a range of process parameters that are best but will get different characteristics at different ends of plateau		
51	What is WHR and UNFelg?			
52	Look at SAND Reports in A.Brewer's presentation (AM Qualification Roadmap, approacj to elab of attributes)			

To Do | People to Contact | **Questions** | Questions for Mara | Decision Matrix | Qualification Tests

	B	C	D	E	F
1					
2	Status	Description	Person	Started/To Start	Completed/To Complete
3	Completed	Team Name	All		
4	Completed	Team Logo	Rebecca	5-Jun	5-Jun
5	Completed	Dog bone test (Test, Analysis)	All	17-Jun	17-Jun
6	In Progress	Contact list of people		After Testing	
7	Completed	CAD the Housing (CREO)	Mitchell, Rebecca	43627	43630
8	Completed	Prototype Initial CAD		43627	43630
9	Completed	Topological Optimization (ANSYS)	Andy, Michael	43627	43630
10	Completed	Learn CREO	All	Done	
11	Completed	Learn ANSYS	All	Done	
12	Completed	Download Necessary Software Tools	All	Done	
13	Completed	Download and Learn Makerbot Software		Done	
14	Completed	Print Test Article (Team Logo, calibration)		Done	
15	Completed	Make Team Shirts		10-Jun	27-Jun
16	Completed	Input Density Data	Andy	18-Jun	18-Jun
17	Completed	Analyze Density Data for Lots (and density vs strength)	Rebecca, Mitchell	18-Jun	19-Jun
18	Completed	Analyze Hardness Data for Lots	Rebecca	18-Jun	20-Jun
19	Completed	Analyze impact data for lots	Rebecca	18-Jun	20-Jun
20	Completed	Analyze distribution of stress and strain	Andy, Michael	18-Jun	24-Jun
21	Upcoming	Probe samples	Andy, Michael		
22	Upcoming	Analyze porosity of samples (Keyence)	Rebecca, Mitchell		
23	Completed	Finalize CAD designs, TO, structural analysis	All	20-Jun	28-Jun
24	Completed	Decision Matrix		20-Jun	20-Jun
25	Completed	Brainstorming Qualification Testing Plans			1-Jul
26	Upcoming	Researching Qualification Testing Plans			
27	Completed	Finish Statistics	Andy, Michael		8-Jul
28	Upcoming	Finalize Torque Breakaway with Correct Stats			
29	Upcoming	Email Todd Huber about Strain Gauges			

Scheduling Our Time

Takeaways from Meetings

Bradley Jared

- Machine limitations and tolerances in design

Andy Brewer

- Current AM qualification capabilities
- Traceability!
- What qualities are important to our requirements and how do we test them?

Mara Schindelholz

- Traceable answers about project scope

Laura Swiler

- Statistical approach to AM

Shaun Whetten

- What makes a good test artifact

Phil New

- Performance qualification plan

Todd Huber and Mark Stavig

- Testing capabilities
- Test artifact feedback

Measure AM Performance

- Testing artifacts (dogbones + charpy bars) were printed at 3 different laser power, laser speed, and hatching spacing settings
- Various destructive mechanical tests were performed to mechanical properties of the three lots:
  - Density – Archimedes' Test
  - Rockwell Hardness Test
  - Charpy Impact Test
  - Rapid Tensile Testing

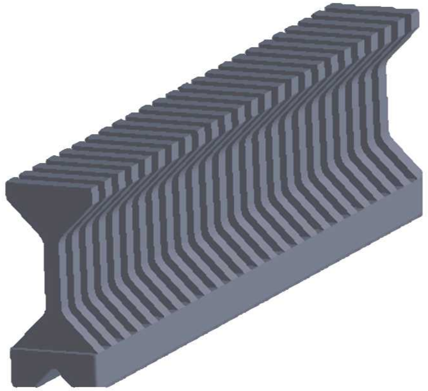


Figure 2: Tensile Bars

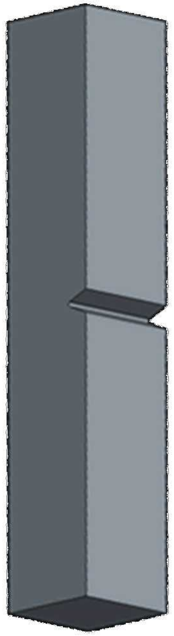


Figure 3: Notched Charpy Impact Bars

Figure 4: Hardness Testing Apparatus

Figure 5: Archimedes Density Testing

Keyence Analysis

- Keyence Machines were used to analyze dimensional accuracy, fracture surfaces, surface roughness, and porosity.
- Lower quality parts in general showed brittle fractures, high surface roughness, and high porosity.
- Dimensions were found to be accurate for all lots, well within the recommended .005-.01 inch tolerancing.

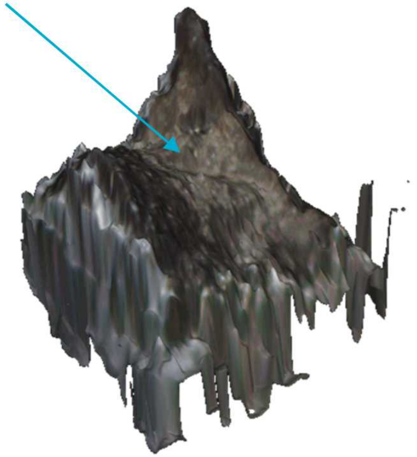


Figure 6: 3D Imagining of a fracture surface from a "good" material lot

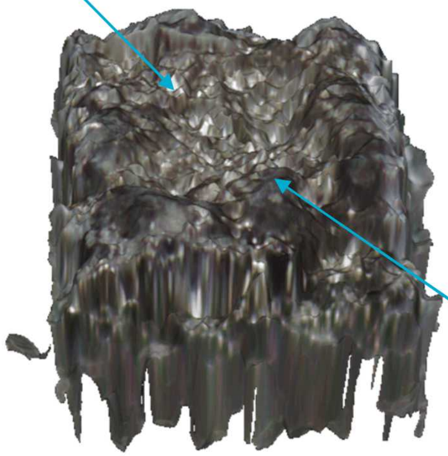


Figure 7: 3D Imaging of a fracture surface from a "bad" material lot

Lot Qualities	Good	Okay	Bad
Dimensional Error (1/1000 in)	1.998	1.831	1.427

Table 1: Dimensional Verification of Charpy Specimens

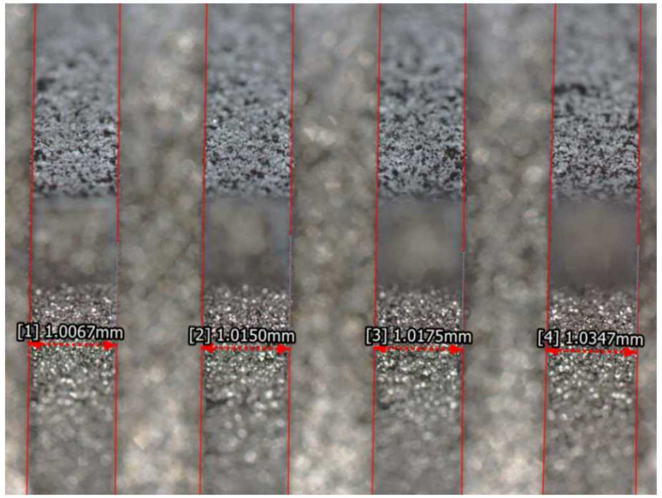
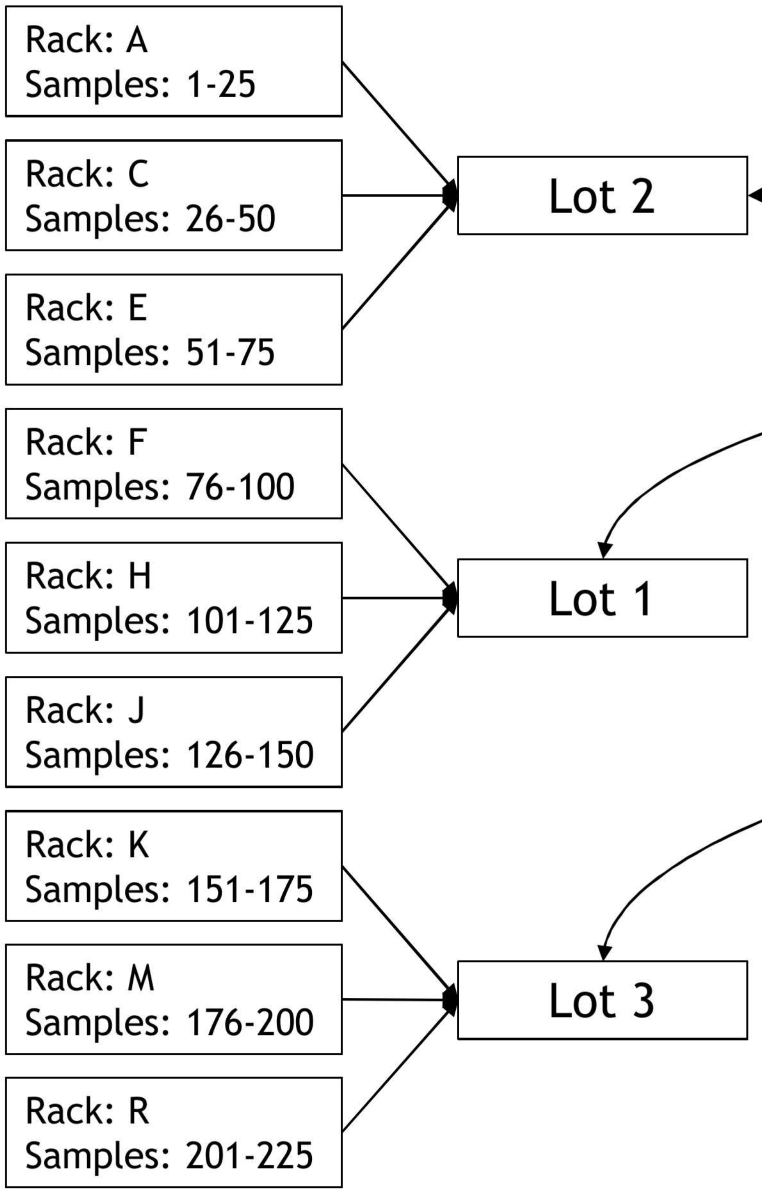


Figure 8: Dimensional verification of tensile specimens

Initial Testing Analysis: Tensile Bars



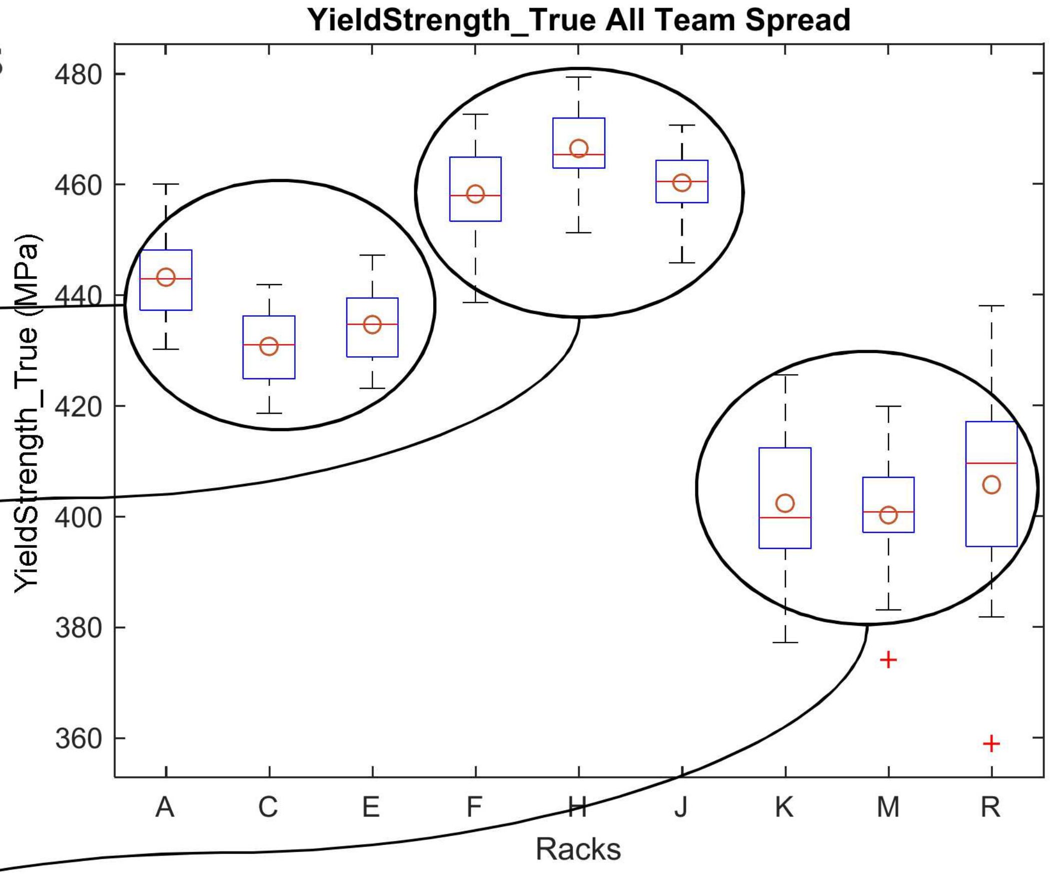


Fig 9: Box Plot: Yield Strength all Teams

Most of our data comes form Tensile Bars:
Lot ≈ Printer Setting
1 Rack ≈ Sample for 1 team
Rack = 25 Tensile Bars

One-Way ANOVA Test:

One-way ANOVA Test: Compares the variation within each group and the variation among the groups using **mean**.

Result: Null hypothesis rejected for most samples.

One-Way ANOVA Test			
	Lot 1 P value	Lot 2 P value	Lot 3 P value
Yield Strength (MPa)	0.0006	0	0.3513
Elastic Modulus (MPa)	0	0	0.0074
Yield Strain (mm/mm)	0.4735	0.0029	0.01
Fracture Strain (mm/mm)	0.0024	0.1788	0.0004
Ultimate Tensile Strength (MPa)	0	0.016	0.0003

Table 2: One-Way ANOVA Result P values

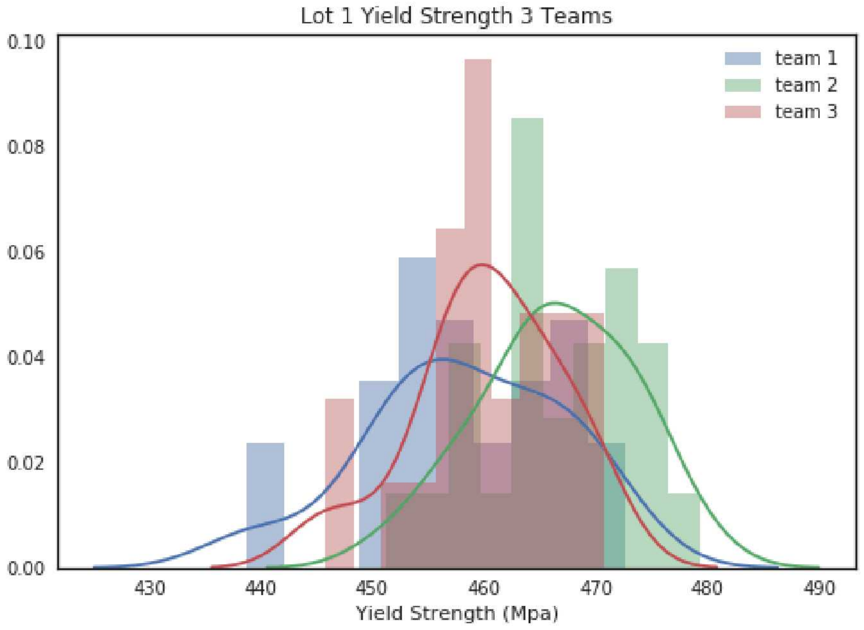


Fig 10: KDE and Distribution failing ANOVA Test

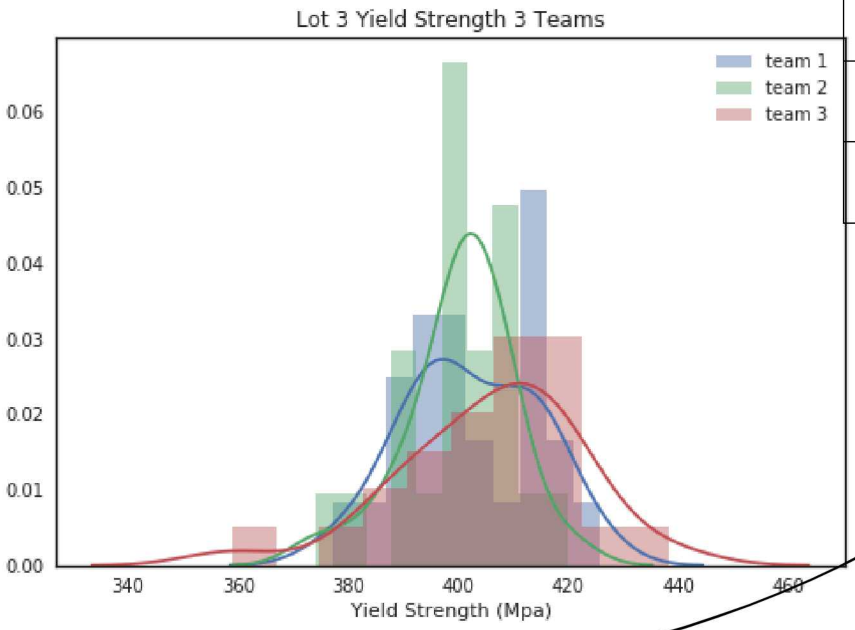


Fig 11: KDE and Distribution passing ANOVA Test

K-Means Data Clustering Machine Learning Algorithm

- 3 Clusters

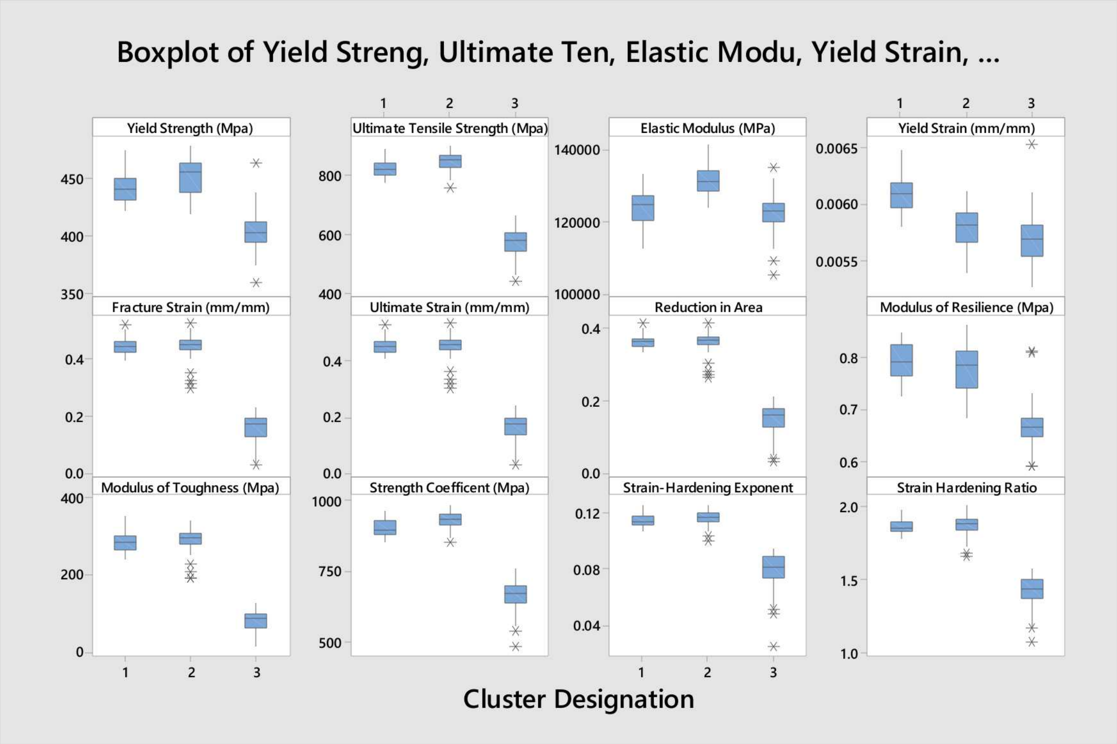


Figure 12: Cluster Parameters with respect to cluster designation box-plots

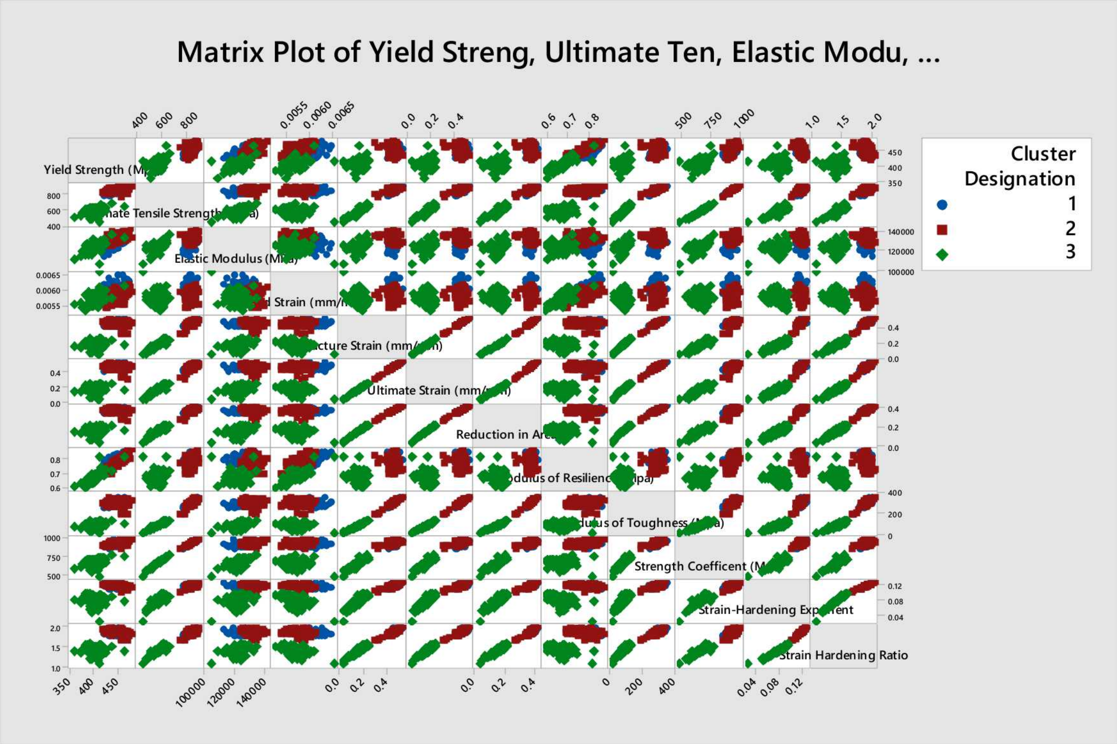


Figure 13: Cluster Designation Matrix graph

Cluster Analysis using Radar Plc

Method: Normalized values through the total means for each of the cluster
Conclusion: Cluster 1&2 and nearly identical in comparison to Cluster 3

Correlation Matrix	Yield Strength (Mpa)	Ultimate Tensile Strength (Mpa)	Elastic Modulus (MPa)	Yield Strain (mm/mm)	Fracture Strain (mm/mm)	Ultimate Strain (mm/mm)	Reduction in Area	Modulus of Resilience (Mpa)	Modulu Toughn (Mpa)		
Yield Strength (Mpa)	1										
Ultimate Tensile Strength (Mpa)	0.87	1									
Elastic Modulus (Mpa)	0.72	0.63	1								
Yield Strain (mm/mm)	0.51	0.38	-0.04	1							
Fracture Strain (mm/mm)	0.78	0.98	0.54	0.37	1						
Ultimate Strain (mm/mm)	0.78	0.98	0.54	0.37	1	1					
Reduction in Area	0.78	0.98	0.54	0.36	1	1	1				
Modulus of Resilience (Mpa)	0.93	0.8	0.4	0.69	0.74	0.74	0.74	1			
Modulus of Toughness (Mpa)	0.82	0.99	0.56	0.39	1	1	0.99	0.77			
Strength Coefficent (Mpa)	0.87	1	0.64	0.36	0.97	0.97	0.98	0.79	[illegible]		
Strain-Hardening Exponent	0.69	0.95	0.53	0.23	0.96	0.96	0.97	0.62	0.95	0.96	1
Strain-Hardening Ratio	0.73	0.97	0.53	0.29	0.99	0.99	0.99	0.68	0.98	0.97	0.99

Table 3: Correlation Matrix (Highlight for Strong Correlation r > .95)

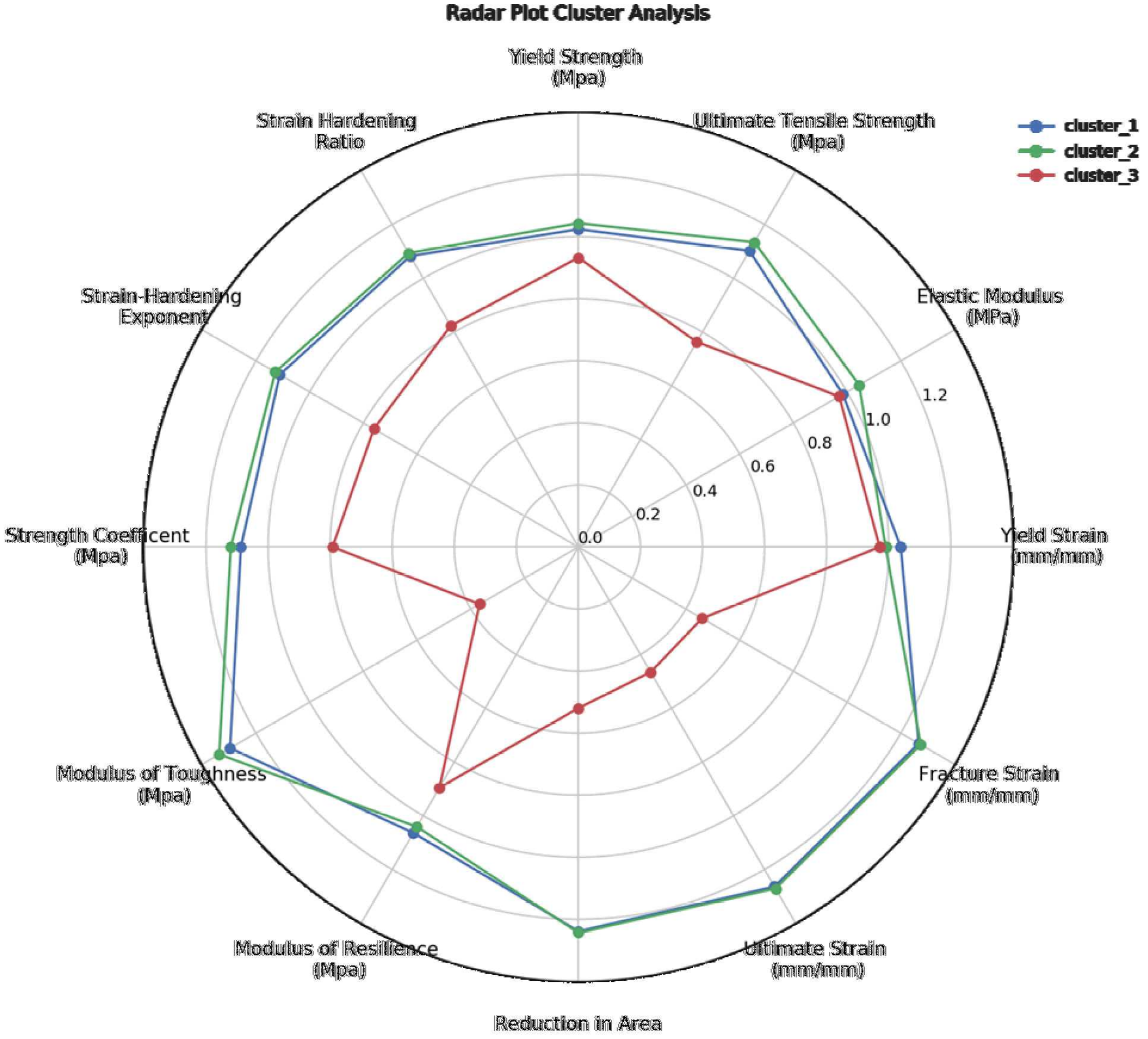


Figure 14: Radar Plot of the 3 Clusters

Updated K Means & Cross-Validation

- 2 Clusters/Validation

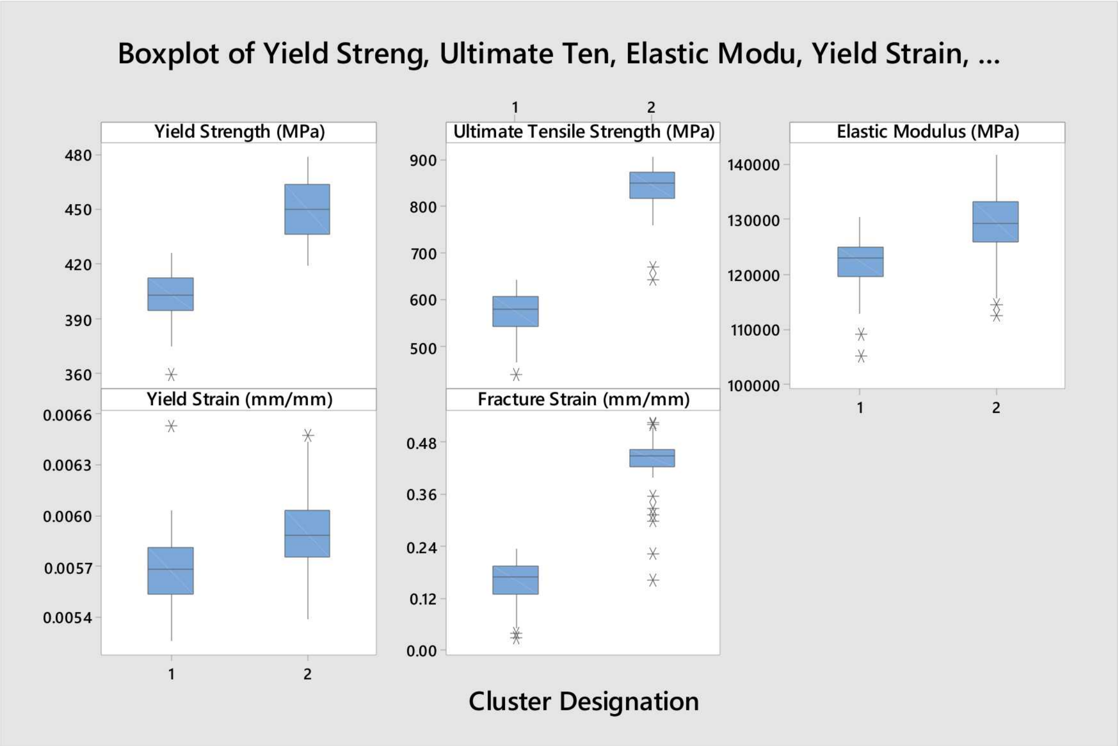


Figure 15: Cluster Parameters with respect to cluster designation box-plots

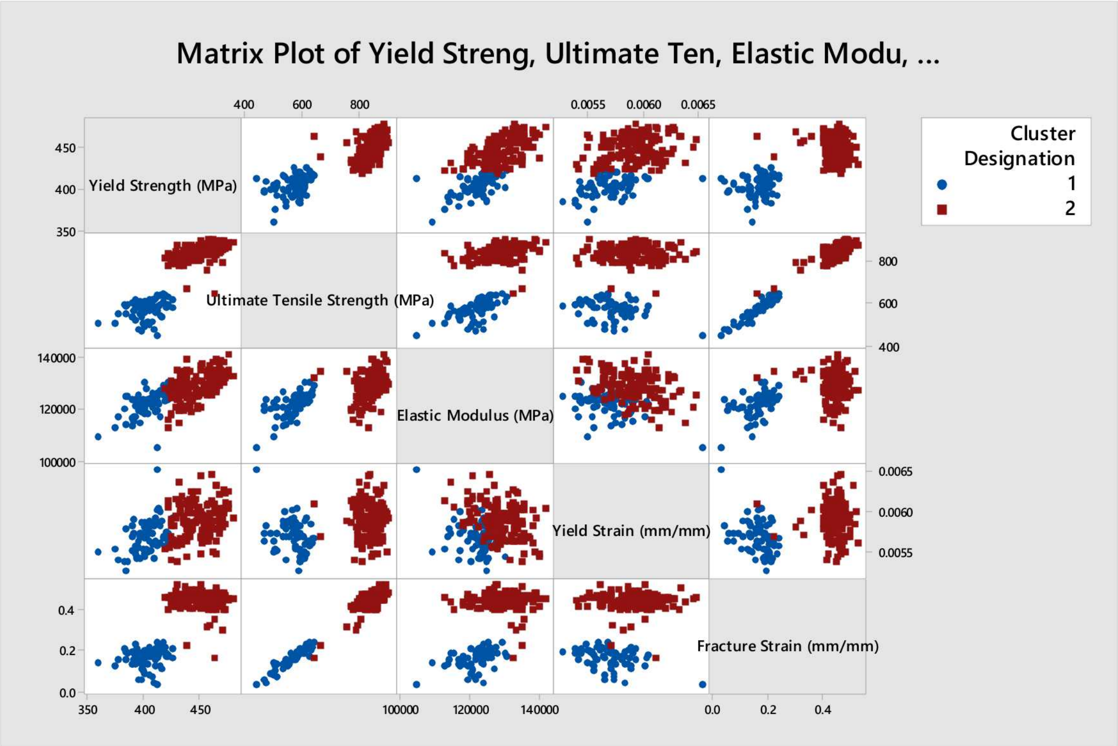


Figure 16: Cluster Designation Matrix graph

Updated Cluster Analysis

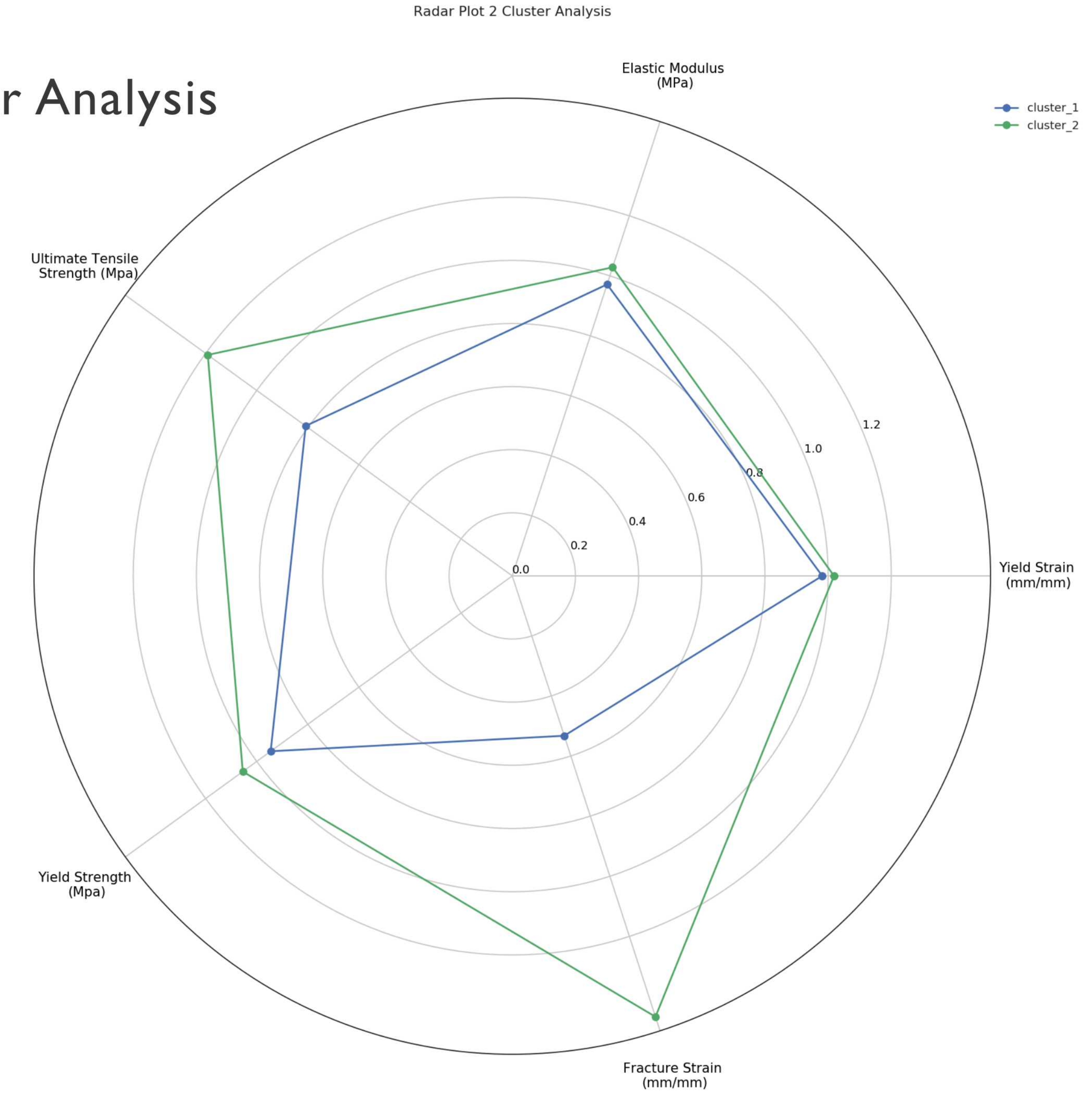


Figure 17: Updated Radar Plot 2 Clusters

Bootstrapping Clusters

Bootstrapping: Resampling from a single original sample with replacements & loosely based on law of large numbers

Result: Resampled 10,000 times

$$\bar{X} \pm Z\frac{s}{\sqrt{n}}$$

Equation 1: Confidence Interval Equation

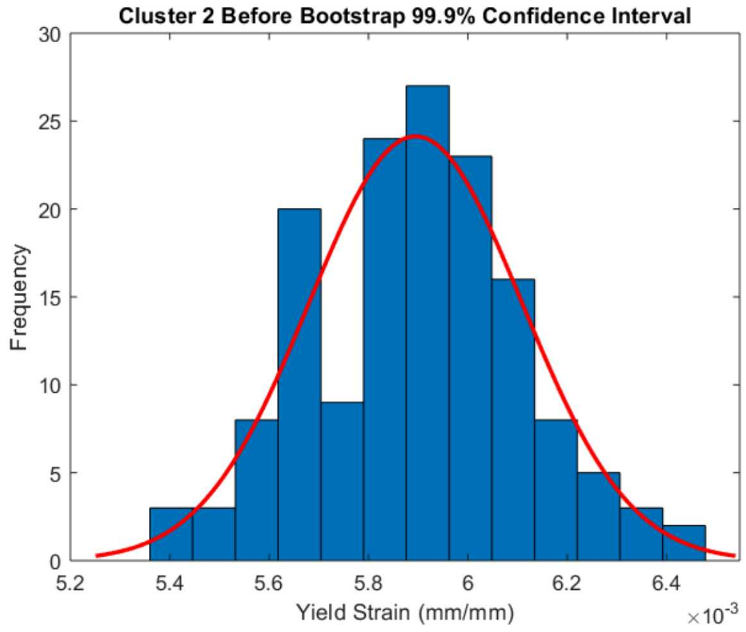


Figure 18: Before Bootstrapping: Cluster 2 Yield Strain

Bootstrapping

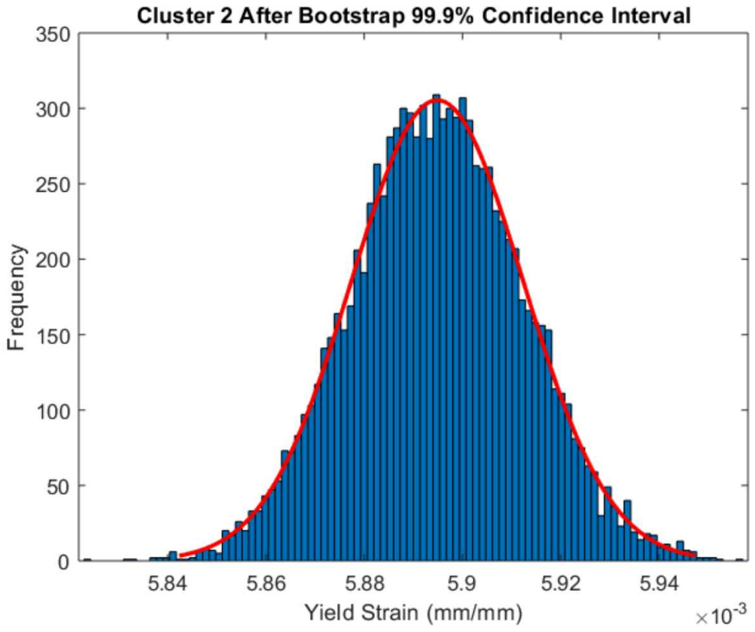


Figure 19: After Bootstrapping: Cluster 2 Yield Strain

ANSYS Material Model

- Used the Ramberg-Osgood relationship to describe the non-linear relation between stress and strain
- Values Obtained used to create an elastic-plastic material model in ANSYS for future FEA

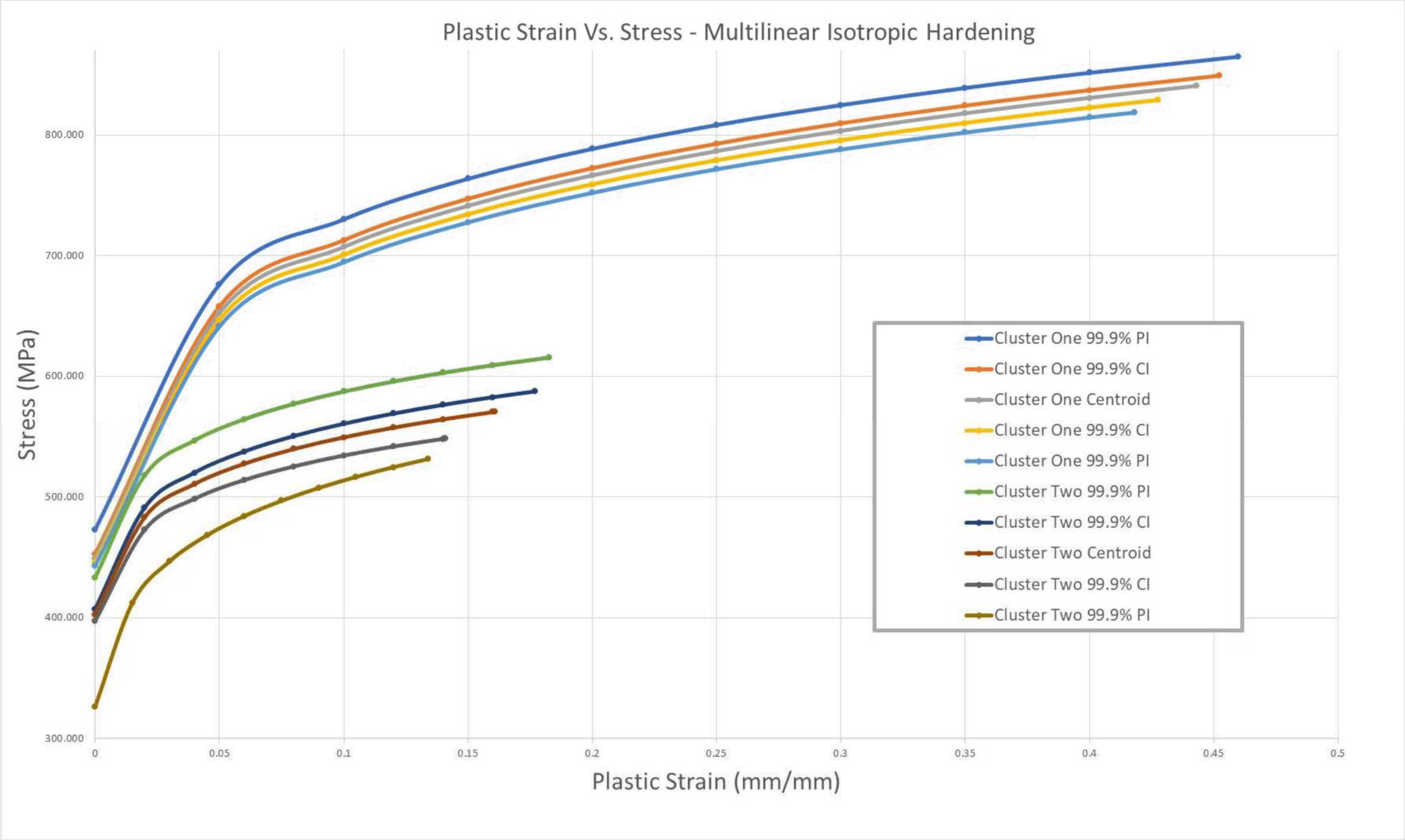


Figure 20: ANSYS Multilinear Isotropic Hardening Model

Accepted Test Article Values to Qualify Part

Material Property Ranges	Cluster One (Acceptable Performance)		Cluster Two (Unacceptable Performance)	
Material Property	99.9% PI Upper	99.9% PI Lower	99.9% PI Upper	99.9% PI Lower
Yield Strength (Mpa)	472.5	442.7	432.7	326.9
Ultimate Tensile Strength (Mpa)	864.9	818.8	615.3	548.1
Elastic Modulus (Gpa)	130.5	127.0	124.0	120.1
Yield Strain (mm/mm)	0.0065	0.0058	0.0057	0.0050
Fracture Strain (mm/mm)	0.46	0.42	0.18	0.14
Density (kg/m^3)	7930.0	7820.0	7440.0	7300.0
Hardness (Rockwell B)	93	90	82	79

Table 4: Table of Cluster Prediction Values

Housing Requirements

- Maximum diameter is 2" and maximum height is 2".
- Surface roughness of at least 10 μm.
- Part has to enclose a 1.75"x1.75"x0.063" (±0.005" on all dimensions) board. Five sides of the board must be enclosed by the housing. Any features on the board are within the dimensions stated.
- Maximum weight is 0.2lb (3.2oz) without the board.
- There must be finger access or some way of easily inserting the board into the housing through one end.
  - At least one end must remain open to insert the housing. The other end can be closed/open.
- No additional materials can be used to mount the board within the housing.
- The sole function of the housing is to protect the board against an applied load of 100 lb. The load will be applied to the housing with the board in the orientation shown to the right (conceptual image showing direction of force only, no other requirements indicated). The orientation of the board within the housing is your choice, but the housing will be positioned in the load frame to have the board in this orientation.
- The compressive load will be applied evenly distributed across 6" square plates below and above the part.
- The part cannot fail, with failure defined as any visual indication of damage to the board with an applied load of 100 lb.

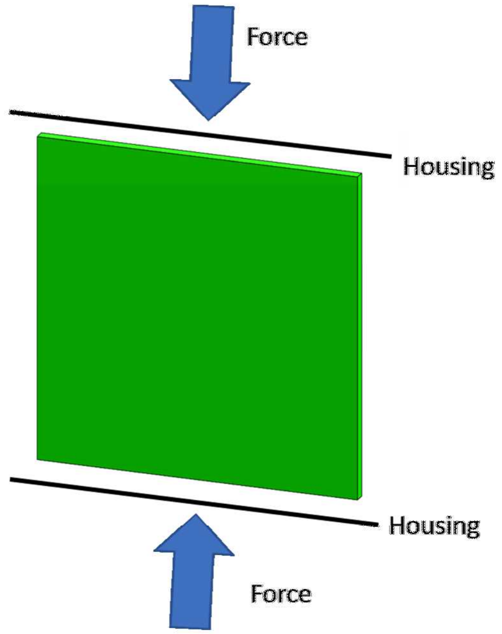


Figure 21: Provided Loading Direction Diagram Relative to Circuit Board

Printer Design Limitations

- Tolerancing:
  - 5 thou for small parts, increases by a couple thou per inch (~10 thou for our part)
  - 5 thou on board
- Max Overhang:
  - 45 degrees
  - 5 mm bridge
  - 5 mm diameter arches
  - 3 mm holes
- Test articles and design must be ¼" away from all corners
- Tumble Polishing for surface roughness
  - Gives ~10 micron surface roughness
- ~5 mm Lattice Cell Size Maximum
- Tolerancing confirmed via dimensional analysis

Housing Design Process – FEA and CAD Software

Creo/Pro-Engineer

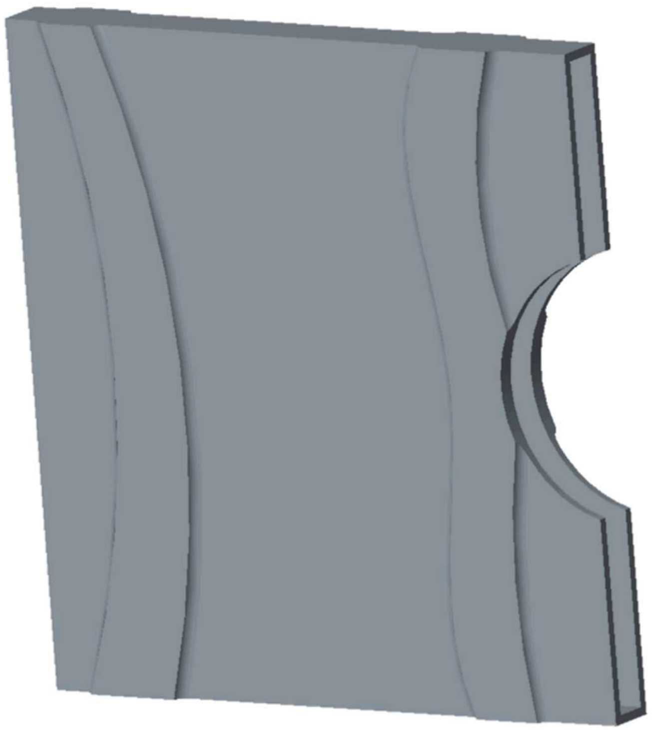


Figure 22: Example of a housing design produced in Creo

ANSYS

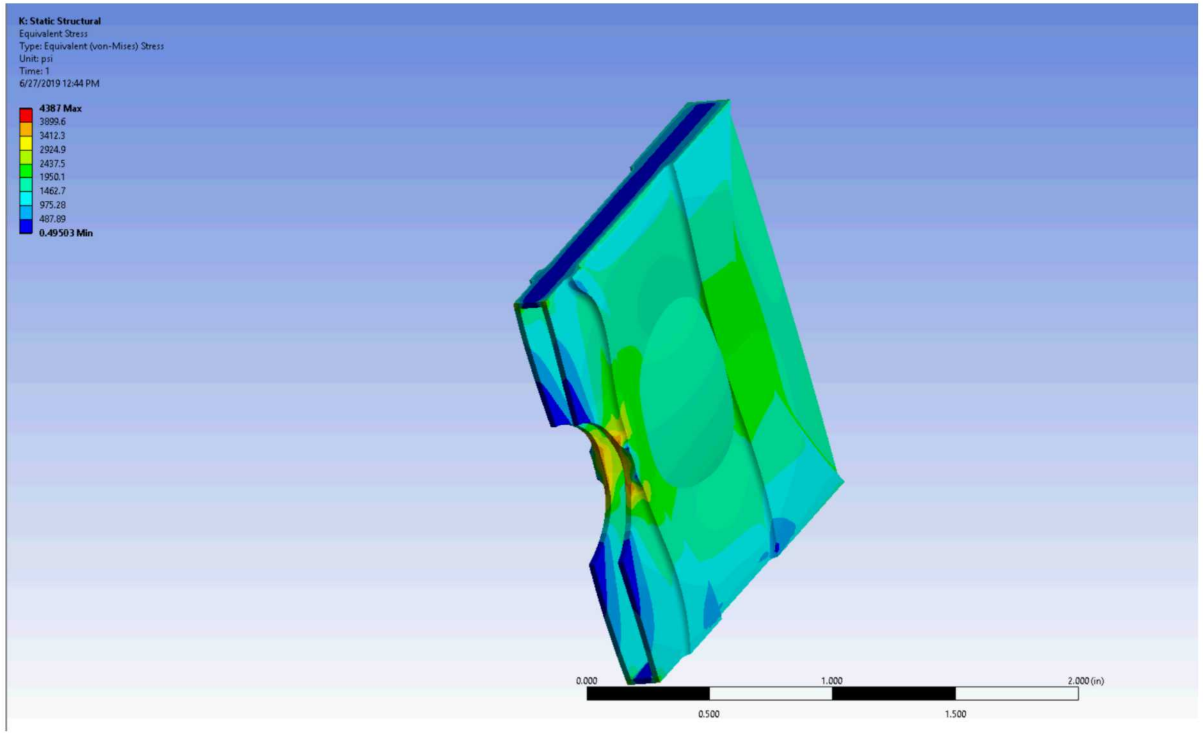


Figure 23: Example of a housing design tested in ANSYS

Housing Design Process - Topology Optimization

- New technology made possible through additive manufacturing.
- Expected forces are applied onto part, then ANSYS software recommends unnecessary material to be removed.
- Unusual geometry would be difficult to dimension and manufacture using traditional techniques.

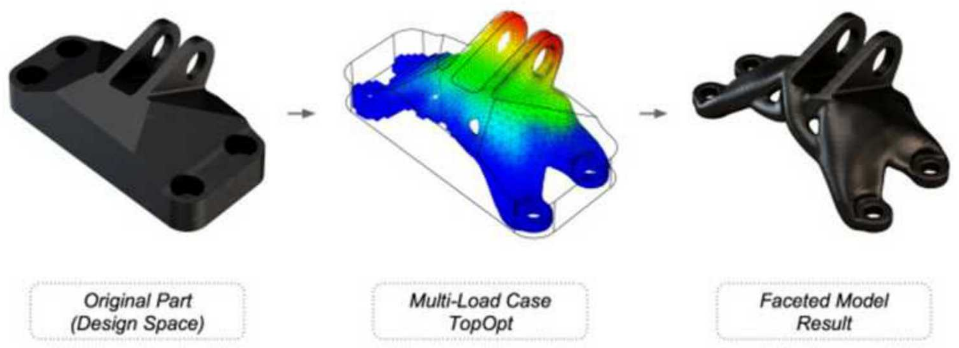


Figure 24: Stages of topology optimization design process

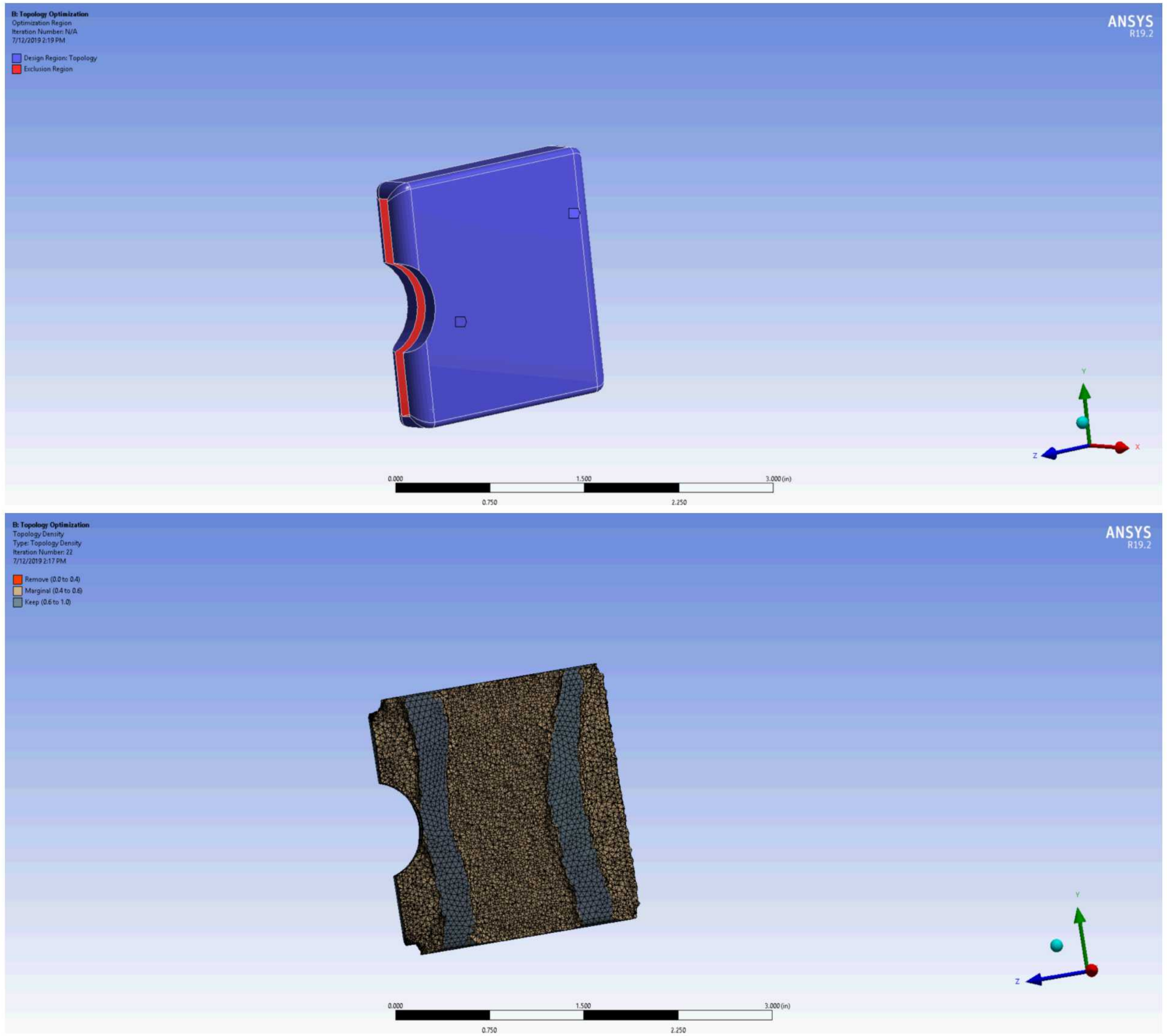


Figure 25: Before (top) and after (bottom) topology optimization

Design 1 – Topology Optimized Casing

- Original Case was designed in Creo, then underwent multiple iterations of topology optimization in ANSYS
- Suggested mass reduction was implemented in Creo
- FEA analysis shows a 26:1 factor of safety over design requirements.
- Estimated Mass: 0.065 lbs

Figure 26: Topology Optimization Iterations

Design 2 - “It’s The Future of Lasagna Technology” –Todd Huber

- Gyroid
- $f(x, y, z) = \cos(x)\sin(y) + \cos(y)\sin(z) + \cos(z)\sin(x) = t$
- Infinitely connected minimal surface with no straight lines
- Currently very popular because of strange properties
  - Even distribution of stress and strain
  - Increased fracture toughness
  - Increased Strength
- Factor of safety: 27:1
- Estimated Mass: 0.17 lbs

Figure 27: Gosma Gyroid Test

Figure 28: The gyroid housing design rendering

Analysis of Design Options

	Mass	Strength	Simplicity	Manufacturability	Creativity	Final Score
Weights	2	3	1	2	5	
Corrugated	2.2	3.3	4.5	3.1	2.0	**54**
Gyroid	0.6	4.1	0.9	2.2	5.0	**67**
Top Op	3.4	4.0	4.5	1.7	3.0	**64**
Schwarz P	0.3	1.2	1.3	2.0	4.5	**50**

Table 5: Decision Matrix

Figure 29: Corrugated Design

Figure 30: Gyroid Design

Figure 31: Topology Optimization Design

Figure 32: Schwarz P Lattice Design

Qualification Requirements

- How comprehensive is the approach – the relationships between material, property, and performance are cohesively conveyed
  - How well the approach can be applied to other components or applications
  - How well the approach is documented

- Conceptual design of the new test structure – stretch goal, fabrication and testing
  - Structure provides some indication of performance
  - Characterization approach used to test the structure specified
  - Ease of test approach proposed
  - Connectivity between microstructure/property to overall performance

Qualification Approach – SIPOC AM Diagram

Suppliers

- Materials Vendor
- Printer Manufacturer

Inputs

- Powder Metal
- Laser Power
- Laser Speed
- Hatching Spacing
- CAD Model/ G-Code
- Plate Spacing
- Support Structures

Process

Collect materials, information, & Settings

↓

Print Part

↓

Post-Processing of Part

↓

Part Qualification

Output

- Ready to Use Part
- Predictable properties

Customer

- NW SPRINT Stakeholders
- NTESS
- NNSA

Test Artifact Requirements (from Meetings)

- Must test for specific requirements of parts
- Should occupy ~1” on build plate
- Should get 4-5 tests from single article
- Helpful to know where sample will break
- If possible, an article to test before removing from build plate is useful
- Should print more than one per plate (to avoid rare defect results)
- Must test hypothesis about material behavior and be able to have controlled variables in testing

Test Artifact Concept:

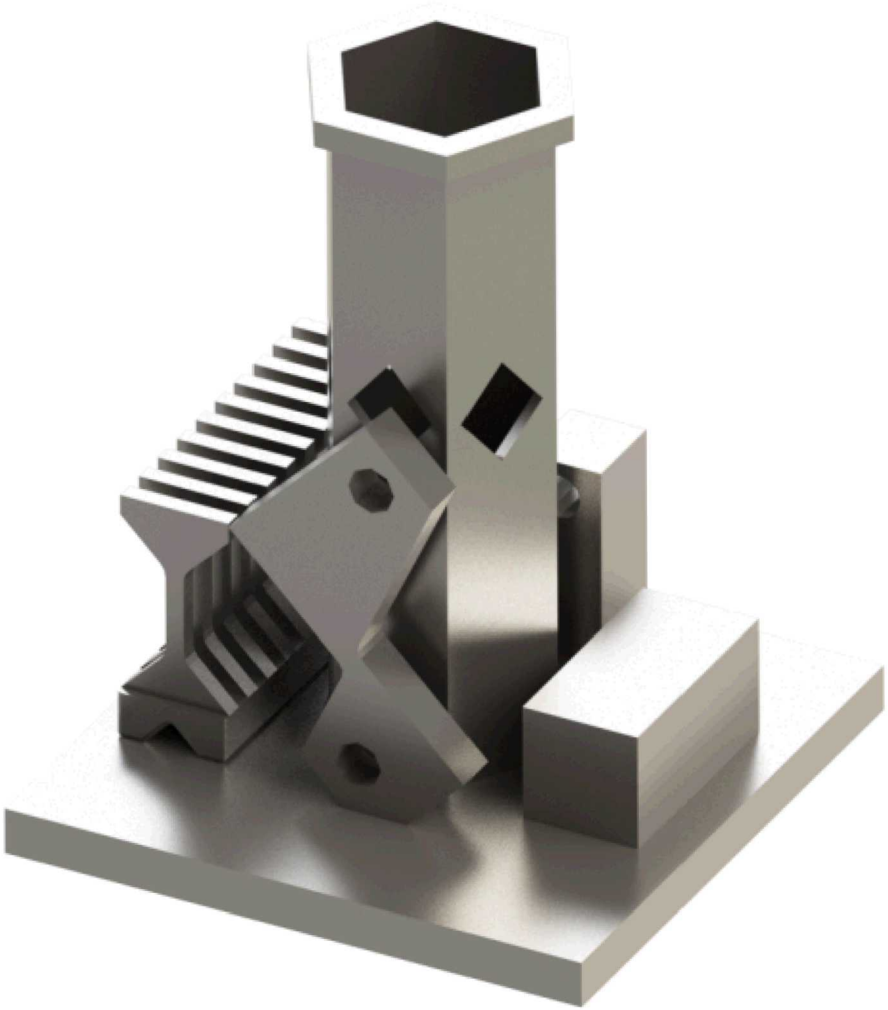


Figure 33: Full Test Artifact Rendering

Test Coupon Tear-offs: Go/No Go Tests

Torque Breakaway

- Stress concentration factor ensures break point location
- Fracture Analysis in ANSYS (K_{IC}) CI:
  - Acceptable: 8.52-8.95 Nm
  - Unacceptable: 6.5-7.6 Nm
- Requires adjustment with experimental data
- Design to be able to be broken by anyone in lab
- Standard Hex Size Compliant
  - 3/8" internal
  - ½" external
- Recommendation: High Accuracy Torque-Measuring Wrench (McMaster), 3/8" Square Drive, 2.8-28.2 Nm, with 1/2" Secure-Grip Tight-Clearance Offset Socket, 1% Accuracy

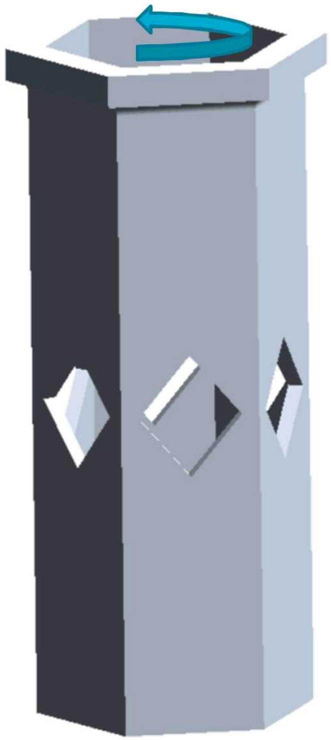


Figure 34: Torque Breakaway Rendering

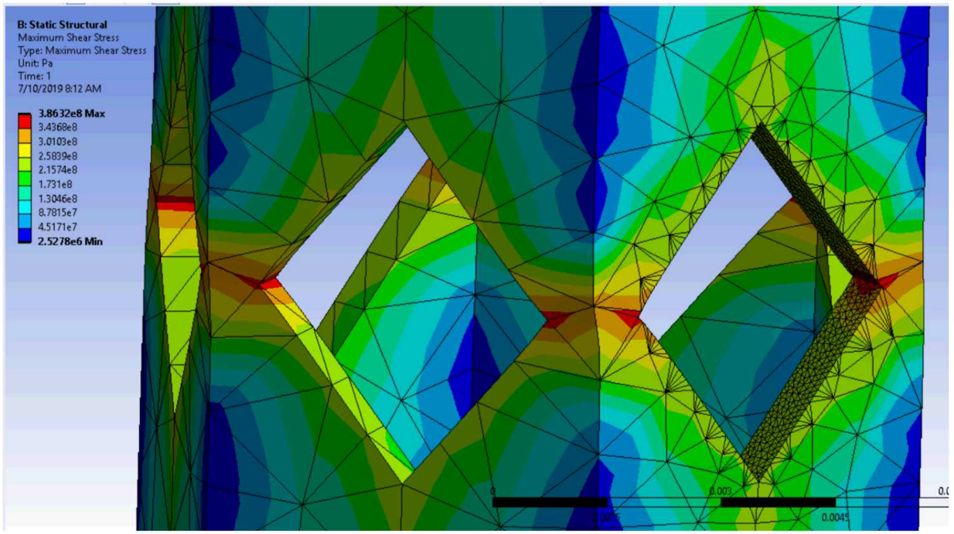


Figure 35: ANSYS Analysis of Torque Breakaway

Test Coupons: Fracture and Shear Articles

Fracture Coupon

- ASTM E1820 fracture toughness testing
  - Clevis tension test with displacement gauge to measure crack propagation
  - Starter notch and all dimensioning ASTM compliant
  - M2 Clevis pin connections
- No current fracture toughness data on metal AM
  - Porosity makes current parts subject to voids and internal fractures
  - Fracture toughness likely more important than impact toughness, especially for static load

Shear Coupon

- Influence by Sandia's Hat Shear Specimen
- No current data on shear modulus or strength
- M2 pin connection in tension test
- DIC analysis

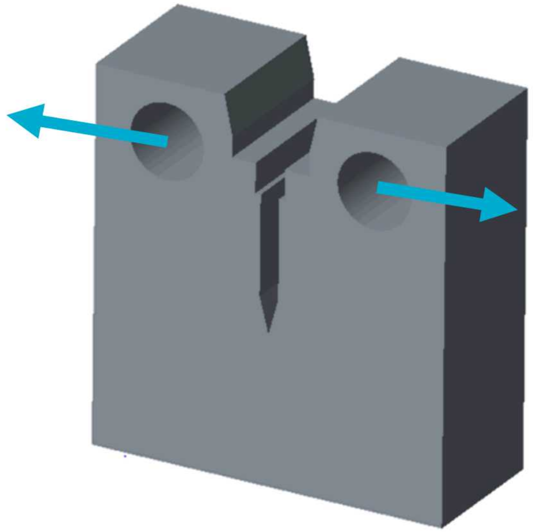


Figure 36: Fracture Toughness Coupon

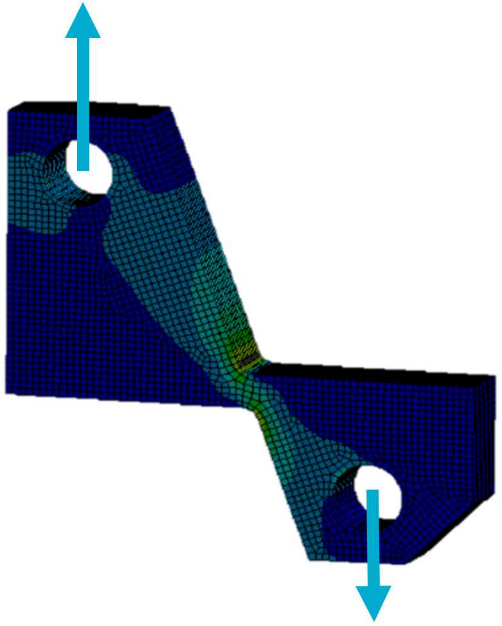


Figure 37: Shear Stress Coupon

Test Coupon: Ultrasound Coupon

- Ultrasonic Bar:
  - Can be extended to a standard Charpy bar if Charpy bar testing is needed
  - Ultrasonic tests can be performed to get a profile view or plan-type view of internal defects (porosity)

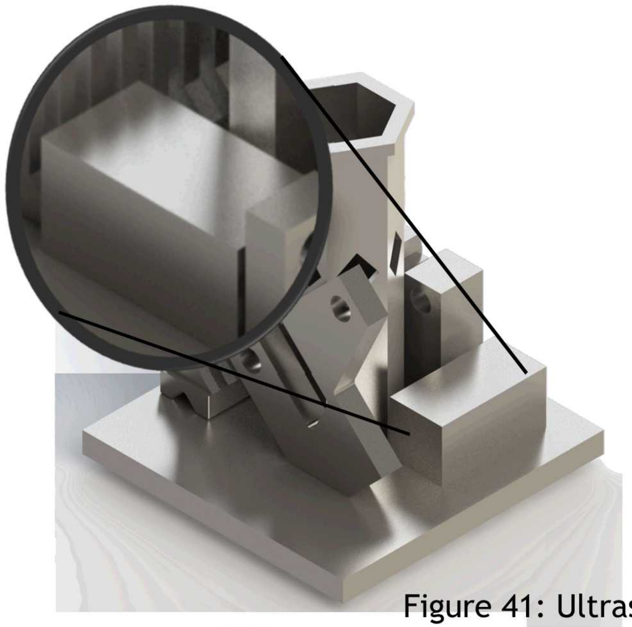


Figure 41: Ultrasonic Coupon

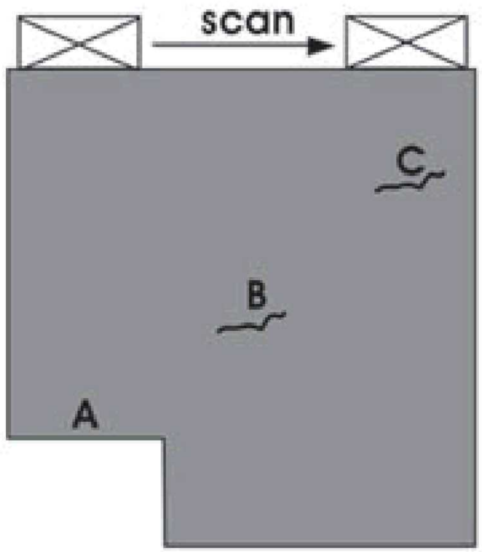


Figure 38: Example of a Test Sample (*NDT Resource Center)*

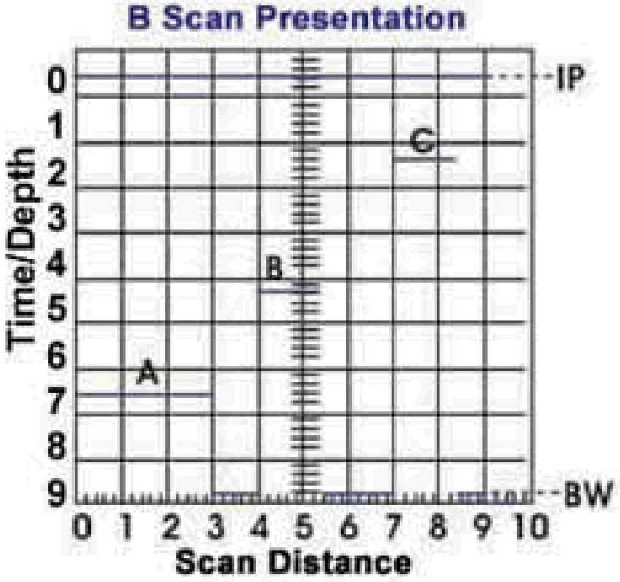


Figure 39: Potential Profile View Plot (*NDT Resource Center)*

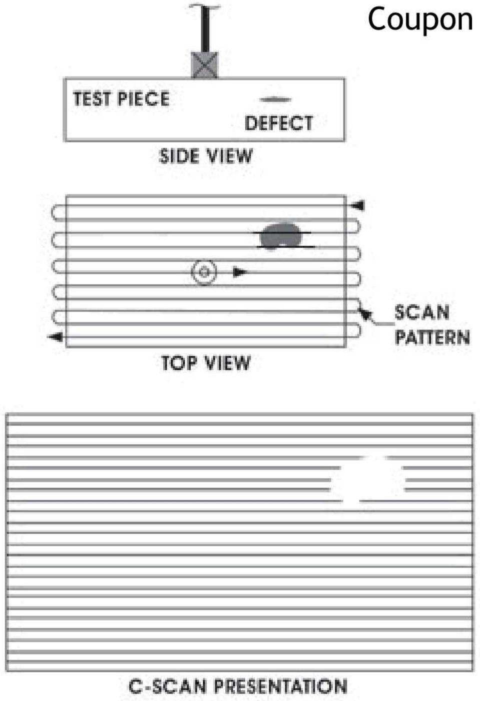


Figure 40: Potential Plane View Plot (*NDT Resource Center)*

Test Coupon Tear-offs: Go/No Go Tests

- **Tuning Fork**
  - Previous research has showed that examining frequency response can provide insight into print quality and material properties
  - Natural Frequency is determinant on ratio of Young's Modulus and Density
    - Research from Kansas City showed that lower quality prints generally had lower natural frequencies
    - $f = \frac{1.875^2}{2\pi l^2}\sqrt{\frac{EI}{\rho A}}$
  - Initial conception was to have a part that had would produce a audible sound when struck, whose frequency could be measured using audio recording devices
  - On-plate examination of printed forks matches previous research

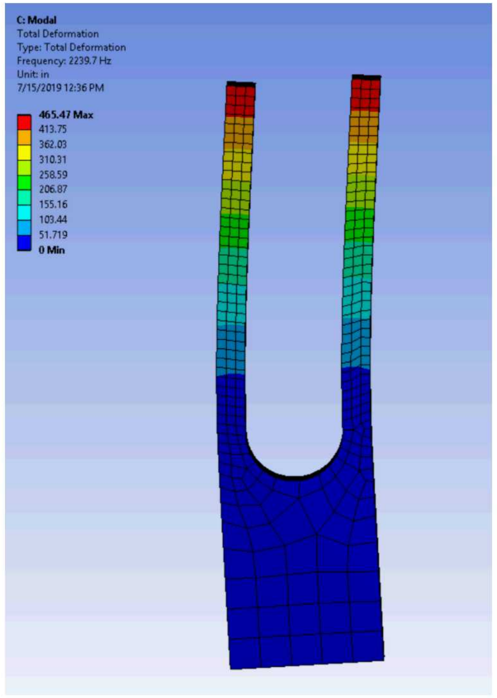


Figure 42: ANSYS Tuning Fork Analysis

Lot #	G (Good)	Y (Slightly Inferior)	R (Bad)
Density (g/ml)	7.888	7.827	7.490
Hardness (Rockwell C)	88.8	86.1	76.03
Frequency (hz)	**2636**	**2603**	**2338**

Table 6: Tuning Fork Material Results

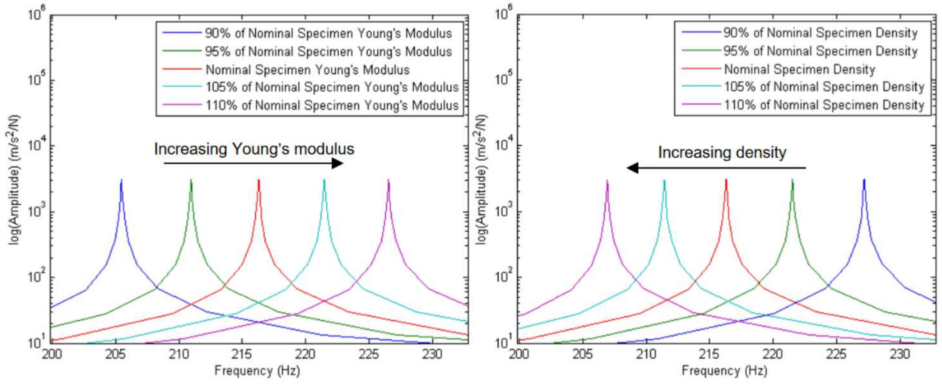


Figure 43: How Modulus and density affect Frequency

Test Artifact Concept:

Shear Article:
- Shear Modulus
- Shear Strength

Fracture Article:
- Fracture Toughness
- Ductile or Brittle Fracture

Tensile Bars:
- Youngs Modulus
- Yield Strength
- Yield Strain
- UTS

Ultrasound Coupon:
- Density
- Porosity
- Hardness

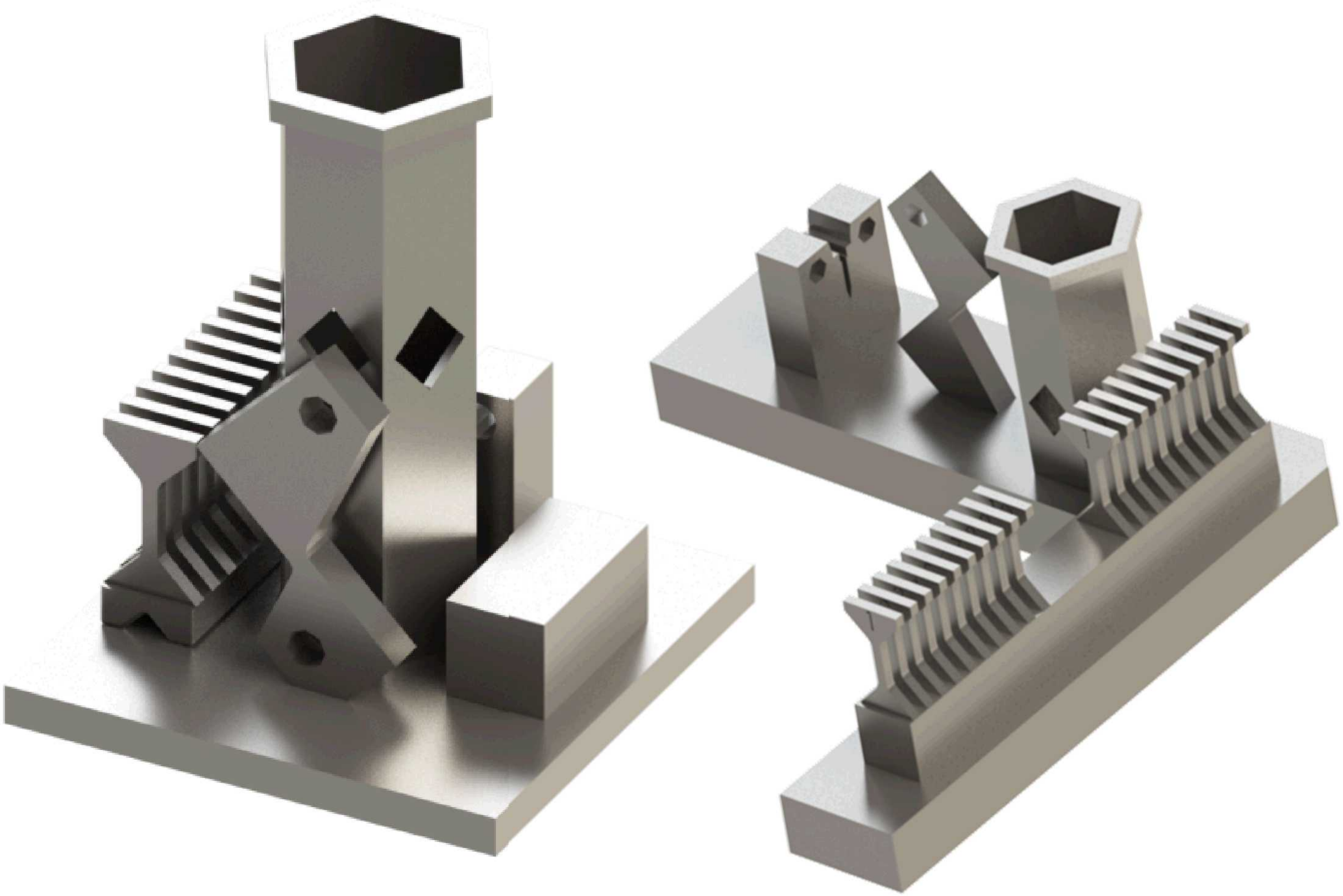


Figure 44-45: Full Test Artifact Renderings

Accepted Test Article Values to Qualify Part

Material Property Ranges	Cluster One (Acceptable Performance)		Cluster Two (Unacceptable Performance)	
Material Property	99.9% PI Upper	99.9% PI Lower	99.9% PI Upper	99.9% PI Lower
Yield Strength (Mpa)	472.5	442.7	432.7	326.9
Ultimate Tensile Strength (Mpa)	864.9	818.8	615.3	548.1
Elastic Modulus (Gpa)	130.5	127.0	124.0	120.1
Yield Strain (mm/mm)	0.0065	0.0058	0.0057	0.0050
Fracture Strain (mm/mm)	0.46	0.42	0.18	0.14
Density (kg/m^3)	7930.0	7820.0	7440.0	7300.0
Hardness (Rockwell B)	93	90	82	79

Table 4: Material Quality Ranges

Part Specific Qualification

- Ensure part meets general dimensional requirements
  - Measure with KEYENCE machine
  - Pass/Fail test with mock PCB and 2" cylindrical enclosure
- Proof test every part
  - 200% required load
  - Less than 50% failure strength of the housing
  - Preformed twice for 5 minutes each
  - Test at least one part from each lot to failure to verify the maximum strength

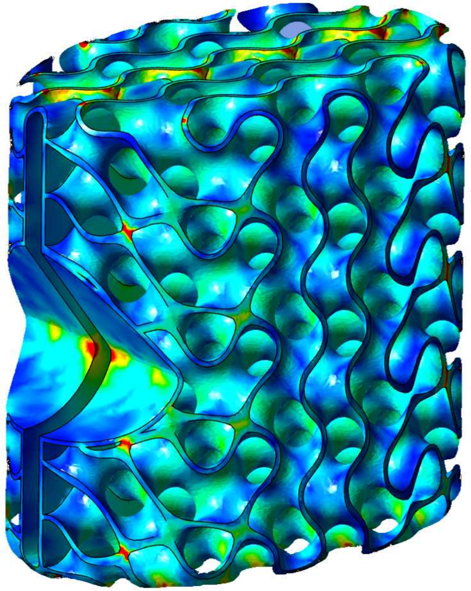


Figure 46: ANSYS simulation of the housing under a compressive load

Final Design Analysis

Figure 47: KEYENCE image of a printing error caused by a overhang

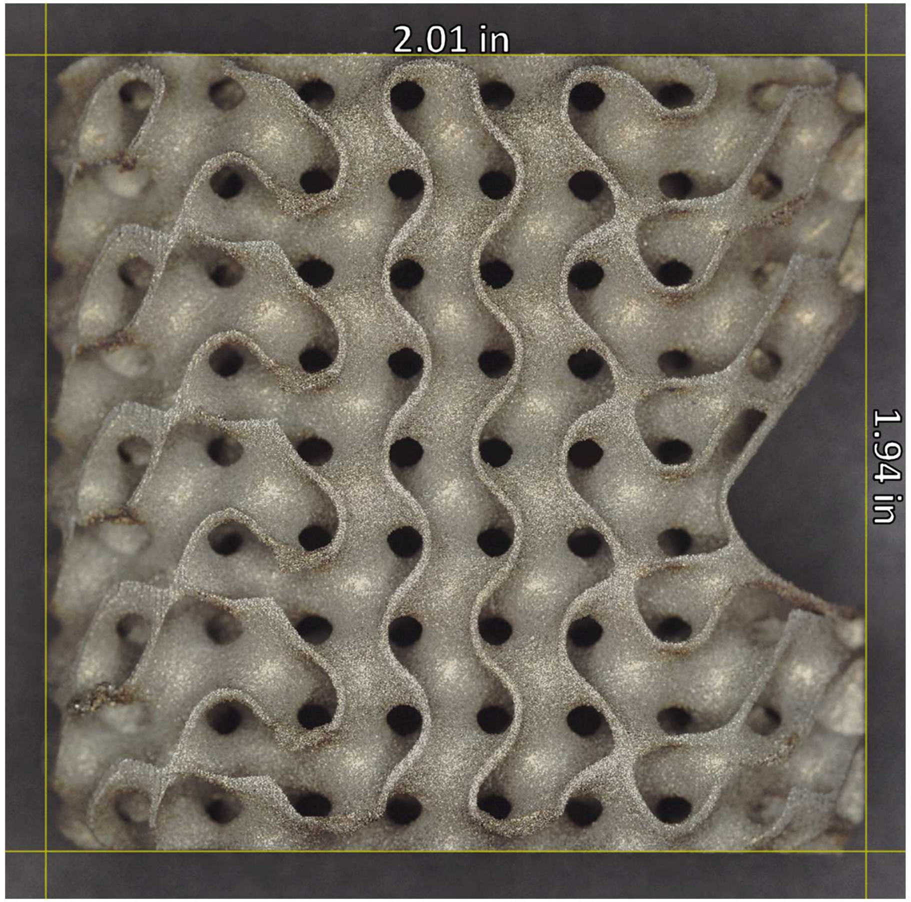


Figure 48: KEYENCE image of the length and height of the part

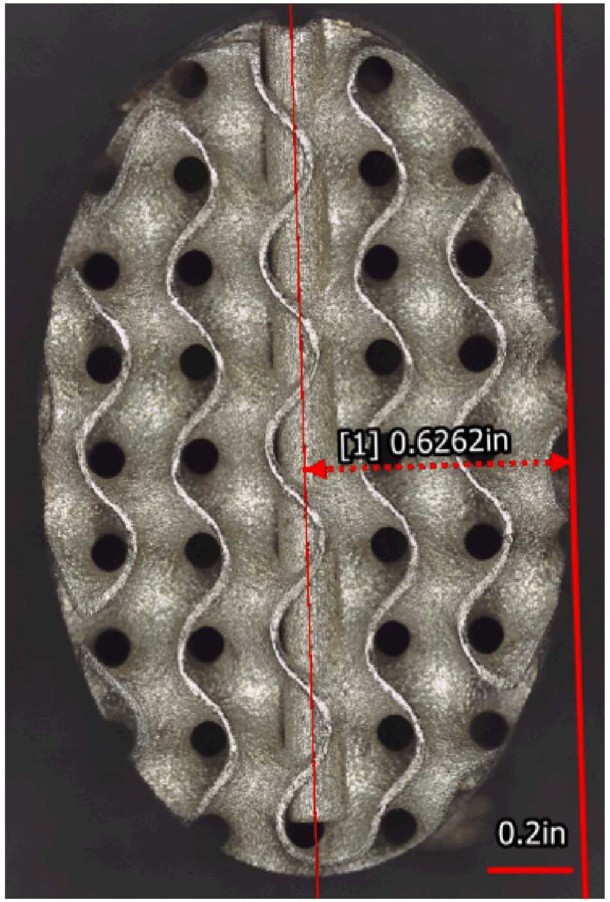


Figure 49: KEYENCE image of the width of the part

Final Design Testing

	Cluster One	Cluster Two
Force to Failure (lbf)	8,641	6,360
Maximum Force (lbf)	11,285	8,982

Table 7: Housing strength by material lot

	Lot 1	Lot 2	Lot 3
Weight (lbm)	0.194	0.169	0.154
Density (g/mL)	7.888	7.827	7.490

Table 8: Housing mass properties by material lot

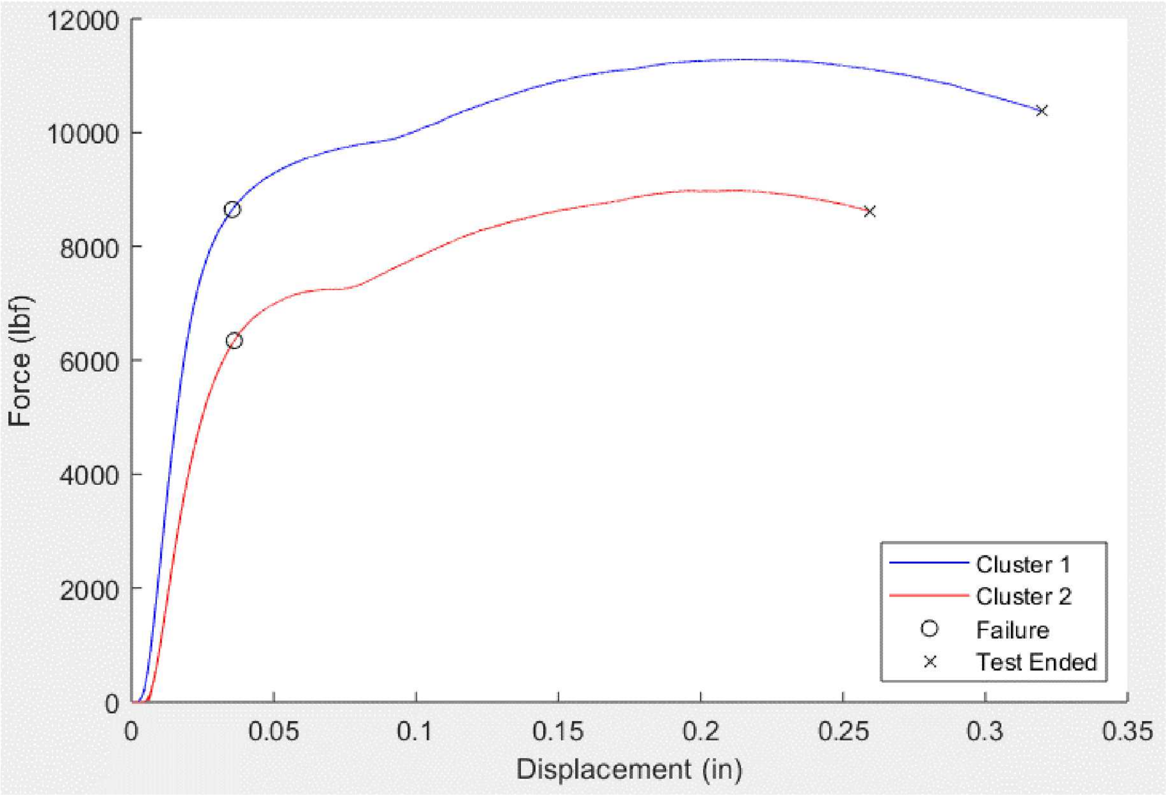


Figure 50: Graph of force vs displacement from the destructive testing of the part

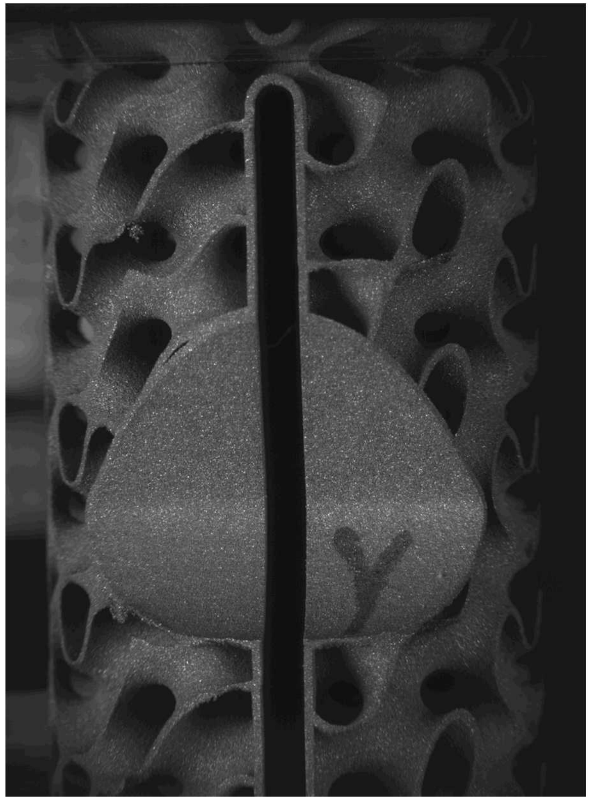


Figure 51: Video of the Cluster 1 test

Summary and Future of Project

- Housing Design
  - Gyroid: A novel use of Metal AM that more than meets all design requirements

- Qualification Plan
  - In brief:
    1. Torque or Tuning Fork Tear-off Test (Expected Acceptable Torque/Note: 7.6±1% Nm / ~2600 hz)
    2. Destructive and NDI inspection of Test Coupons (see slide 31 for acceptable performance ranges)
    3. Part Specific Inspection (for gyroid: proof loading of all parts, selective destructive testing)

- Future Suggestions
  - More study on possible use of a tuning fork or shear tear-off test as a quick qualification method
  - Collection of shear data for metal AM parts

Thank you to Everyone that Met with Us!

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"It's a marathon, not a SPRINT."