STRESS ENGINEERING SERVICES INC.® an employee-owned company

Additive Manufacturing Part Qualification Examples and Advanced Techniques

Design, Testing, and Full-Scale Qualification

Date: 18 January 2024

AADE AMERICAN ASSOCIATION of DRILLING ENGINEERS HOUSTON CHAPTER

Prepared by:

Matt Sanders, PE

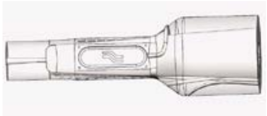
Prepared for:

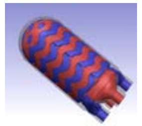
Innovative & Emerging Technology Group

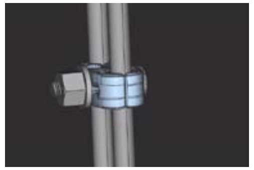
ENGINEERED SOLUTIONS

Outline

- Quick Intro on Stress Engineering
- The 7 Types of Additive Manufacturing (3D Printing)
  - Laser Powder Bed Fusion (LPBF)
  - Wire Arc Additive Manufacturing (WAAM)
- Additive Standards
- The Need for Qualification (Pressure Tube)
- Case Studies
  - Alloy 718 - Nozzle
  - Alloy 625 - Cross-Over Tool
  - AlSi10Mg - Heat Exchanger
  - 316 SS - Valve Body
  - F-16 Clamp
- Questions







Technology Highlight

Digital Image Correlation

Advanced Analysis

CT Inspection

Acoustic Emission

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Who is Stress Engineering

STRESS ENGINEERING SERVICES INC.®

Founded in 1972, Stress Engineering Services is an independent, employee-owned consulting engineering firm that provides professional engineering services to a variety of industries worldwide.

Engineering Disciplines

- MECHANICAL
- ELECTRICAL
- PIPELINES
- MARINE
- MATERIALS
- CIVIL
- TESTING
- SUBSEA

Help Solve Technical Challenges

Design Analysis Testing

- Pipeline Integrity Threat Assessments
- Geotechnical and Risk Assessment of Land Movement
- Laser Pipe Inspection
- Metallurgical Failure and Vintage Materials Analysis
- Defect Characterization and Assessment
- Facility Assessments and Fluid Mechanics
- Full-Scale Testing and Monitoring of Pipelines

50th ANNIVERSARY

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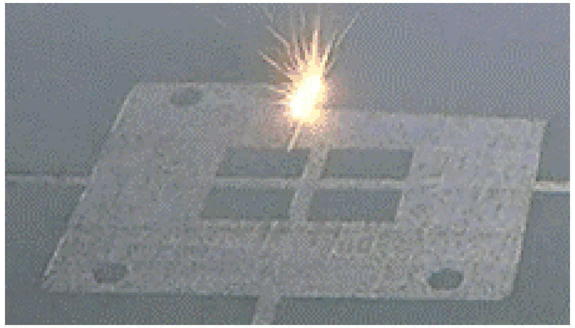
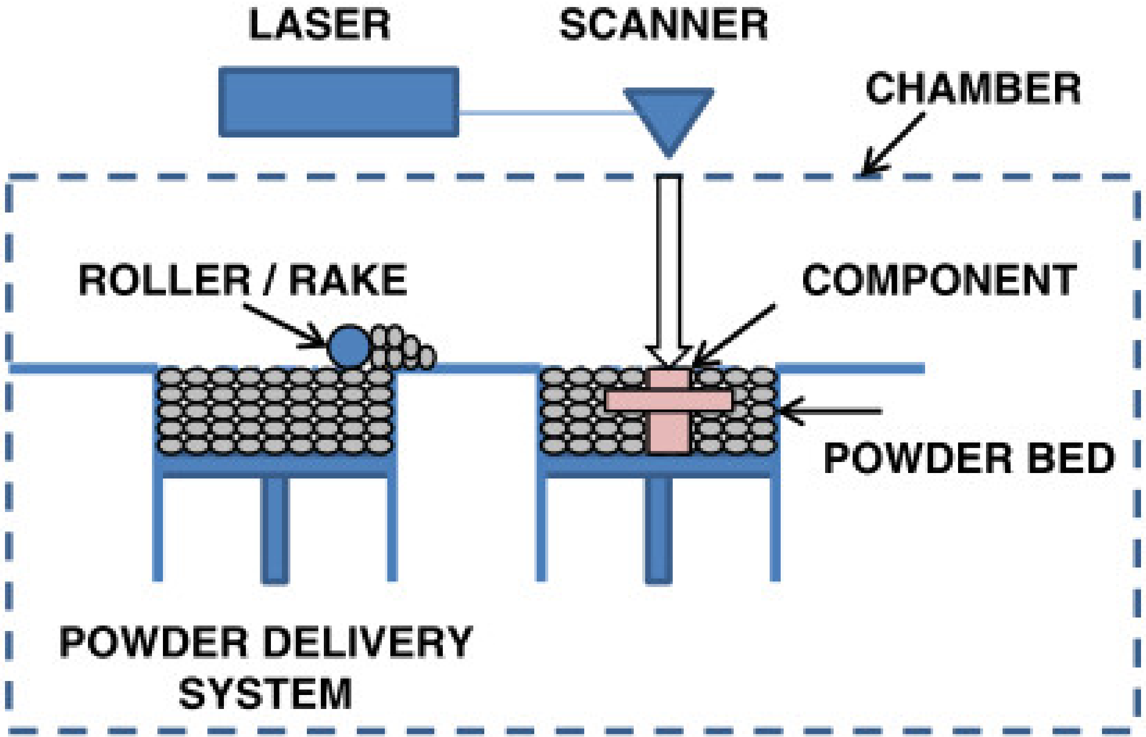
Laser Powder Bed Fusion (LPBF)

ISO/ASTM 52900:2015:
“powder bed fusion, —an additive manufacturing process in which thermal energy selectively fuses regions of a powder bed”



http://www.moog.com/news/blog-new/IntroducingVeripart_Issue2.html



https://www.linkedin.com/pulse/additive-manufacturing-101-5-what-powder-bed-fusion-silbernagel/

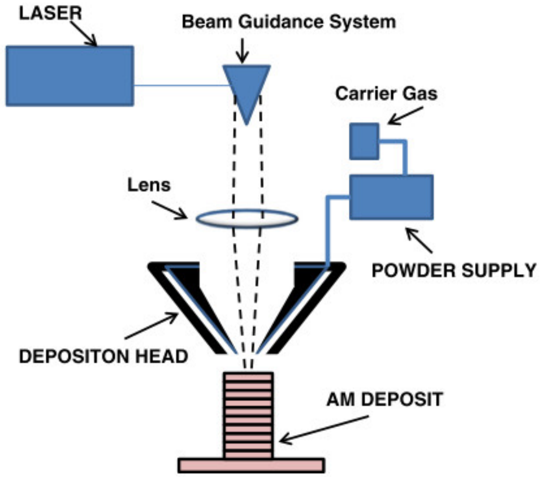
Rough Size: Microwave

choke cage valve used as flow control devices on water injection wellheads.

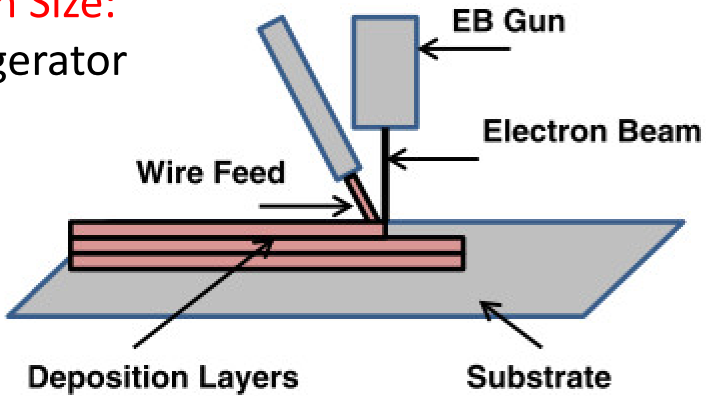
https://www.conocophillips.com/spiritnow/story/just-print-it-conocophillips-tests-additive-manufacturing/

Directed Energy Deposition (DED) / WAAM

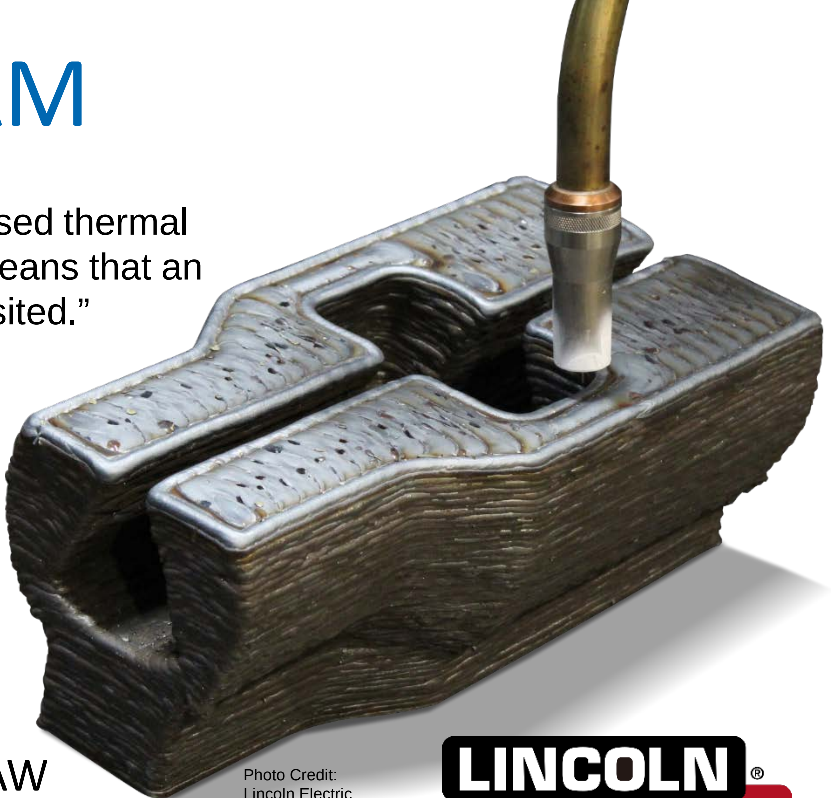
ISO/ASTM definition: “directed energy deposition, —an additive manufacturing process in which focused thermal energy is used to fuse materials by melting as they are being deposited. "Focused thermal energy" means that an energy source (e.g., laser, electron beam, or plasma arc) is focused to melt the materials being deposited.”



Rough Size:
Refrigerator



https://www.linkedin.com/pulse/additive-manufacturing-101-2-what-directed-energy-cassidy-silbernagel/



GMAW
Process

Photo Credit:
Lincoln Electric

LINCOLN ELECTRIC

d.

Why Additive Manufacturing?

- Parts on Demand
  - Big Parts Quickly
  - Supply Chain Issues
  - Maintain/Replace Legacy Parts
- Complex Shapes
  - New Design Freedom
- Less Wasted Material & Energy
  - ESG
- Reduced Inventory
  - Digital Warehouse
- Part Consolidation

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Chevron USA uses Lincoln Electric metal 3D printing tech to produce replacement parts just-in-time

BY SAM DAVIES 26 APRIL 2022 14:49

Lincoln Electric has harnessed its proprietary metal 3D printing technology to deliver just-in-time components to Chevron USA, helping to gets its refinery maintenance back on track.

Chevron USA recently underwent a routine maintenance shutdown, and with supply chain delays extending the lead times of traditionally manufactured parts, the company's planned restart schedule was disrupted.

https://www.tctmagazine.com/additive-manufacturing-3d-printing-news/metal-additive-manufacturing-news/chevron-usa-lincoln-electric-metal-3d-printing-tech-replacement-parts/

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Additive Standards (some)

- **API 20S(2021):** *Additively Manufactured Metallic Components for Use in the Petroleum and Natural Gas Industries*
- **ASME PTB-13 (2021):** *Criteria for Pressure Retaining Metallic Components Using Additive Manufacturing*
- **AWS D20.1 (2019):** *Specification for Fabrication of Metal Components using Additive Manufacturing*
- **DNV-ST-B203(2020):** *Additive Manufacturing of Metallic Parts*
- **ISO/ASTM 52901 (2017):** *Additive Manufacturing – General principles – Requirements for Purchased AM Parts*
- **ISO/ASTM 52910 (2018):** *Guidelines for Design for AM*
- .... → ∞

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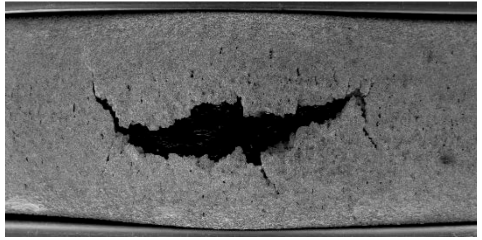
Why Conduct Testing?



Designation: A269/A269M – 15a

Standard Specification for Seamless and Welded Austenitic Stainless Steel Tubing for General Service[1]

PASSED

TABLE 2 Heat Treatment and Hardness Requirements

Grade	UNS Number	Austenitizing Temperature, min or range °F [°C]	Hardness, max
TP316L	S31603	1900 [1040] ✓	192 HBW/200 HV or 90 HRB ✓

Designation: F3184 – 16

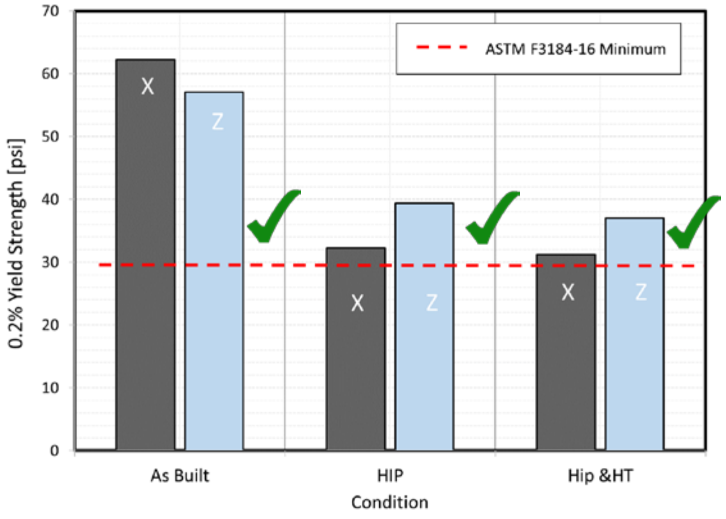
Standard Specification for Additive Manufacturing Stainless Steel Alloy (UNS S31603) with Powder Bed Fusion[1]

PASSED

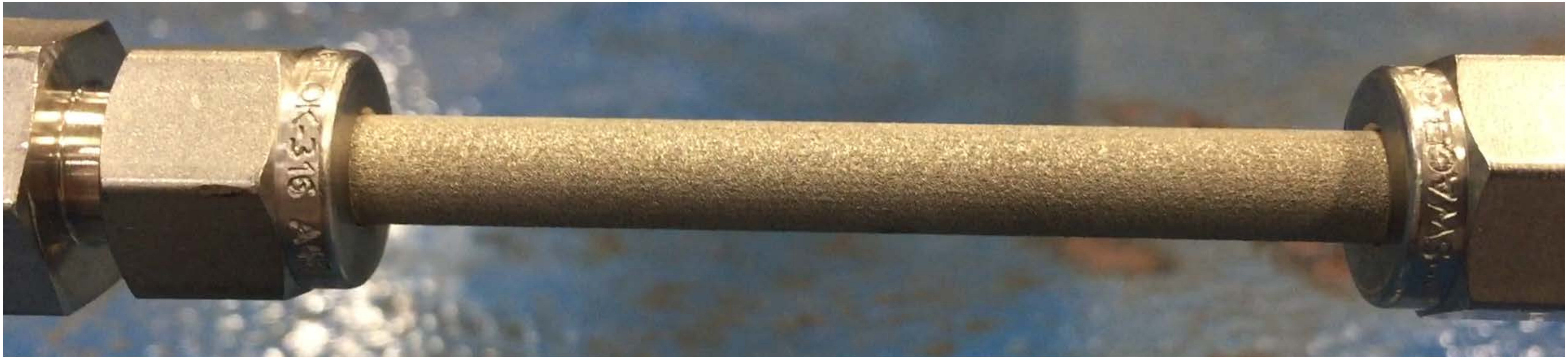
TABLE 3 Minimum Tensile Requirements[A]

Room Temperature Condition	Tensile Strength, MPa (ksi), X and Y Directions	Tensile Strength, MPa (ksi), Z Direction	Yield Strength at 0.2% Offset, MPa (ksi), X and Y Directions	Yield Strength at 0.2% Offset, MPa (ksi), Z Direction	Elongation in 50 mm (2 in.) or 4D, (%), X and Y Directions	Elongation in 50 mm (2 in.) or 4D, (%), Z Direction	Reduction of Area, %, X and Y Directions	Reduction of Area, %, Z Direction
A - Stress Relieved[B]	515 (75)	515 (75)	205 (30)	205 (30)	30	30	40	40
A - Solution Annealed	515 (75) ✓	515 (75) ✓	205 (30) ✓	205 (30) ✓	30	30	30	30
B	515 (75)	515 (75)	205 (30)	205 (30)	30	30	30	30
C	515 (75)	515 (75)	205 (30)	205 (30)	30	30	30	30
E	no requirement	no requirement	no requirement	no requirement	no requirement	no requirement	no requirement	no requirement

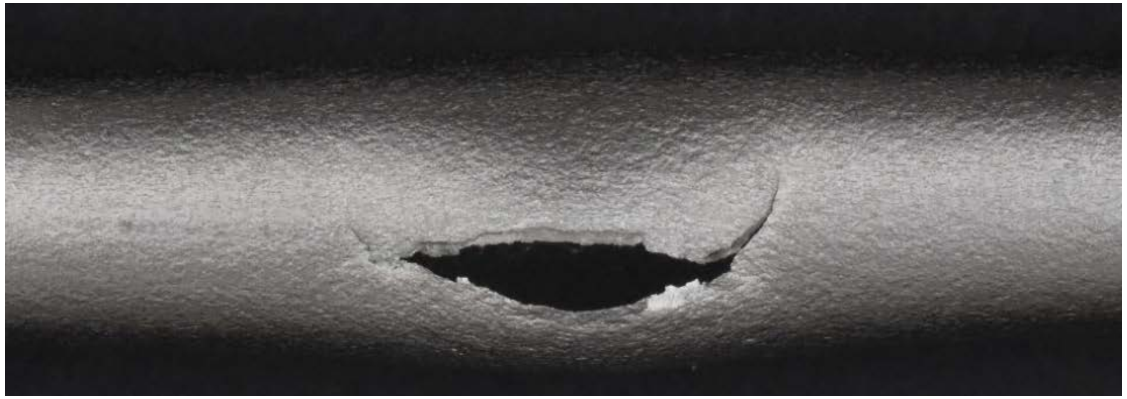
[A] A gauge length corresponding to ISO 6892 may be used when agreed upon by the component supplier and purchaser.
[B] Mechanical properties conform to Specification A479/A479M.



However:

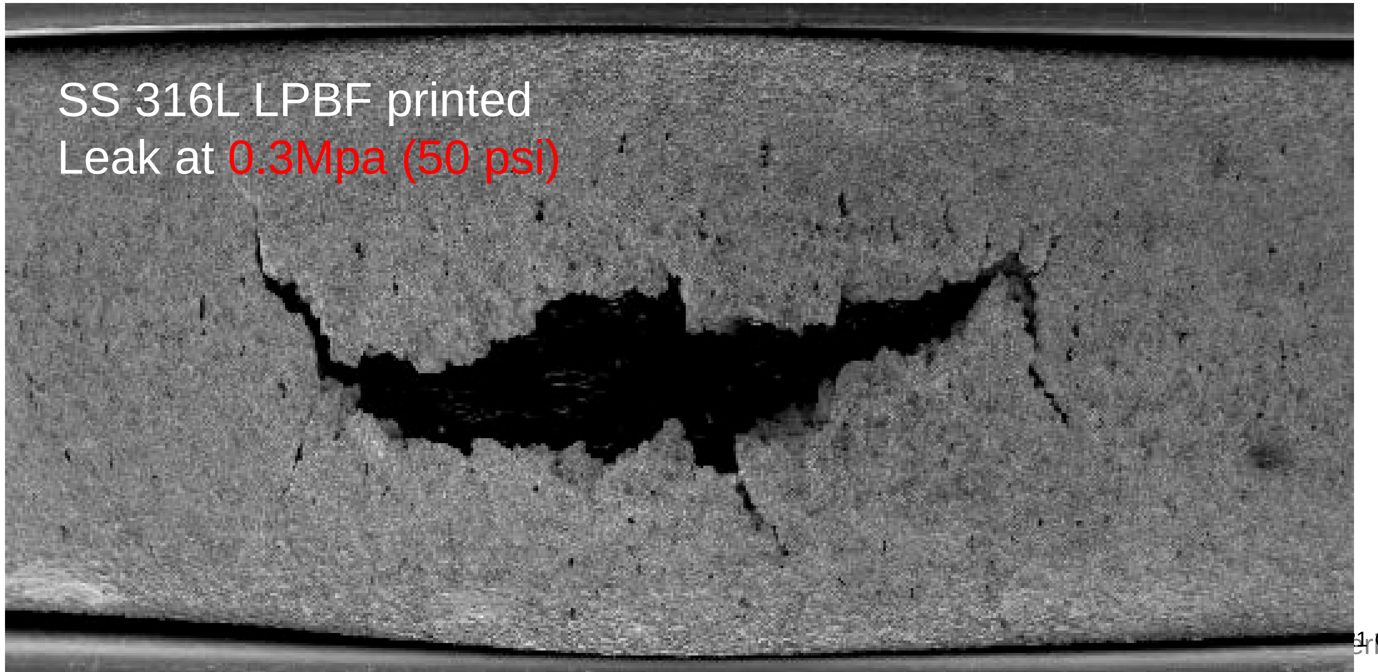


Pressure Testing – 316L Tube Burst Tests



Commercially Available ASTM A213 Annealed Tube
Burst Pressure: 174 Mpa (25,217 psi)

SS 316L LPBF
Burst Pressure: 218 Mpa (31,673 psi)



SS 316L LPBF printed
Leak at 0.3Mpa (50 psi)

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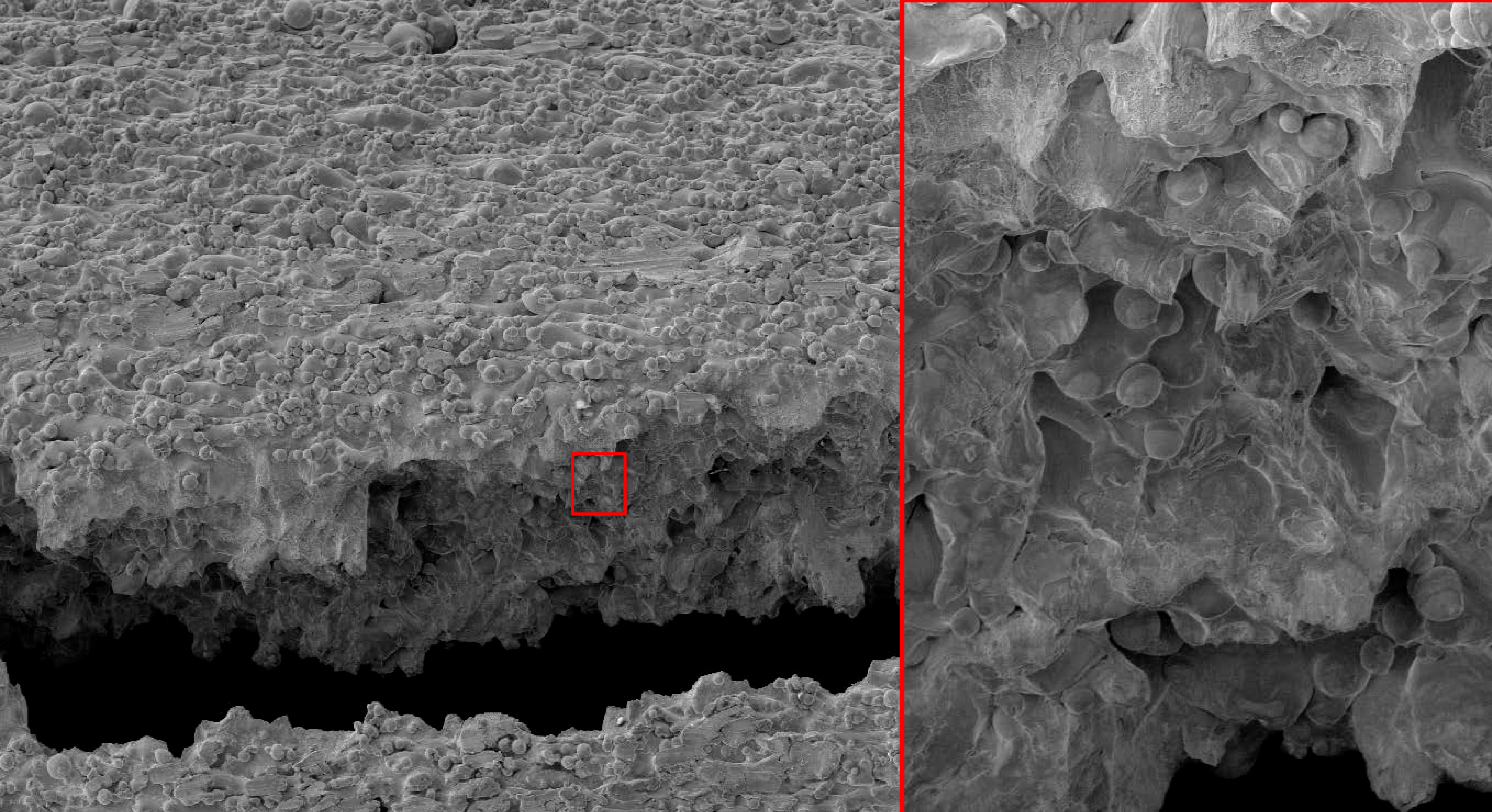
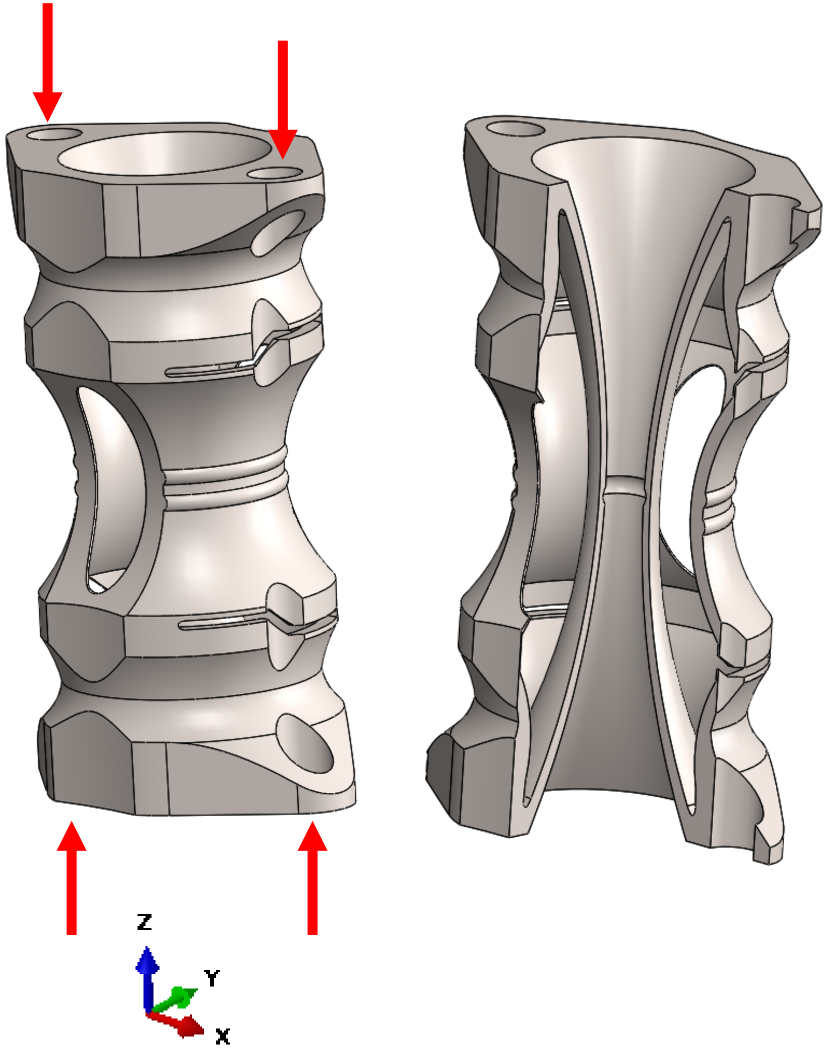
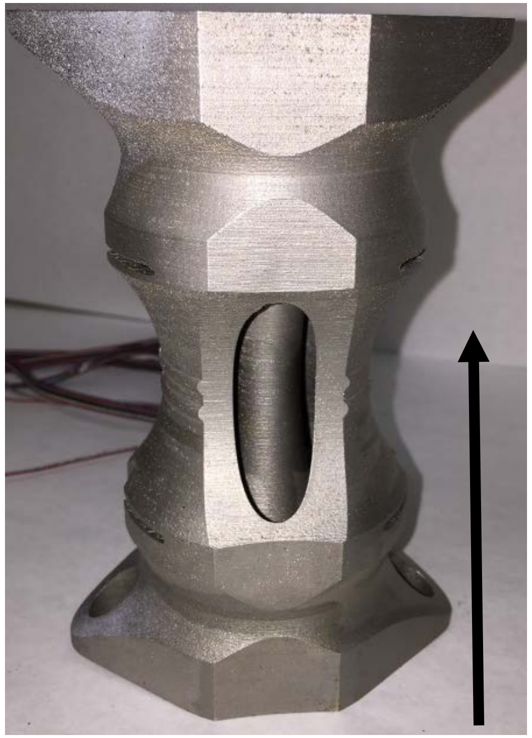


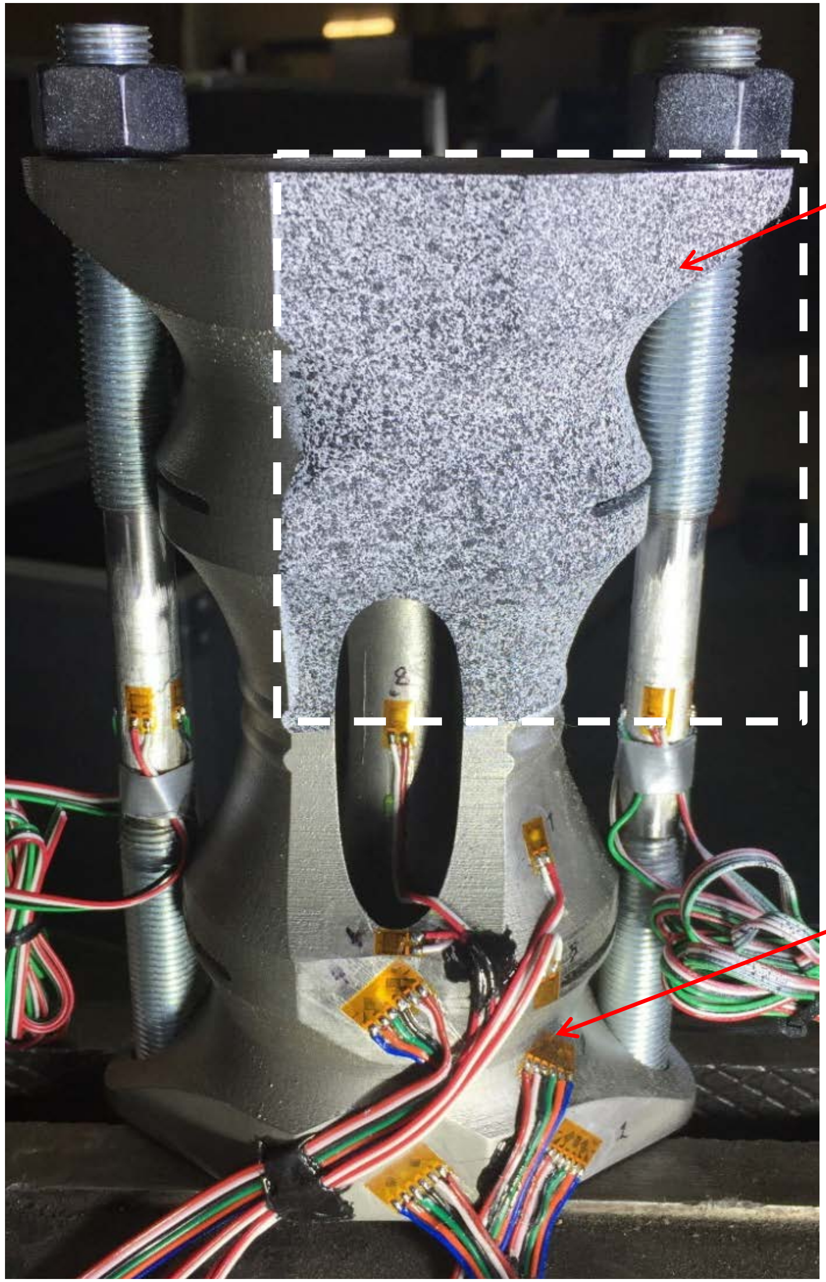
718 Nozzle





Build Direction

Roughly 6in Tall
4” x 4”



DIC Field

Strain Gages

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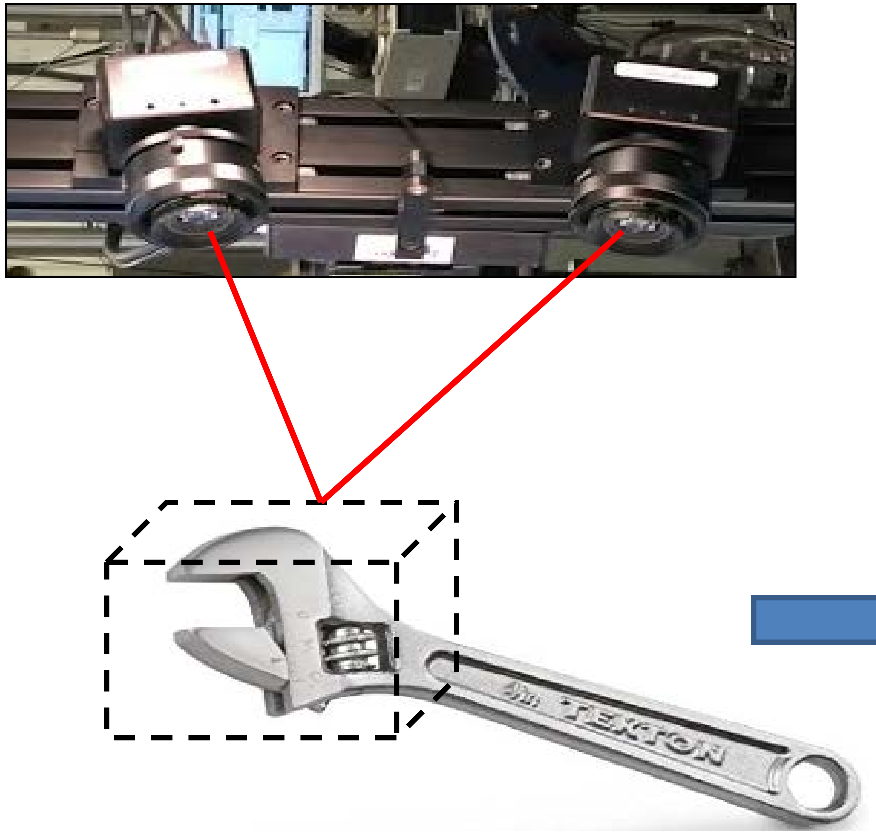
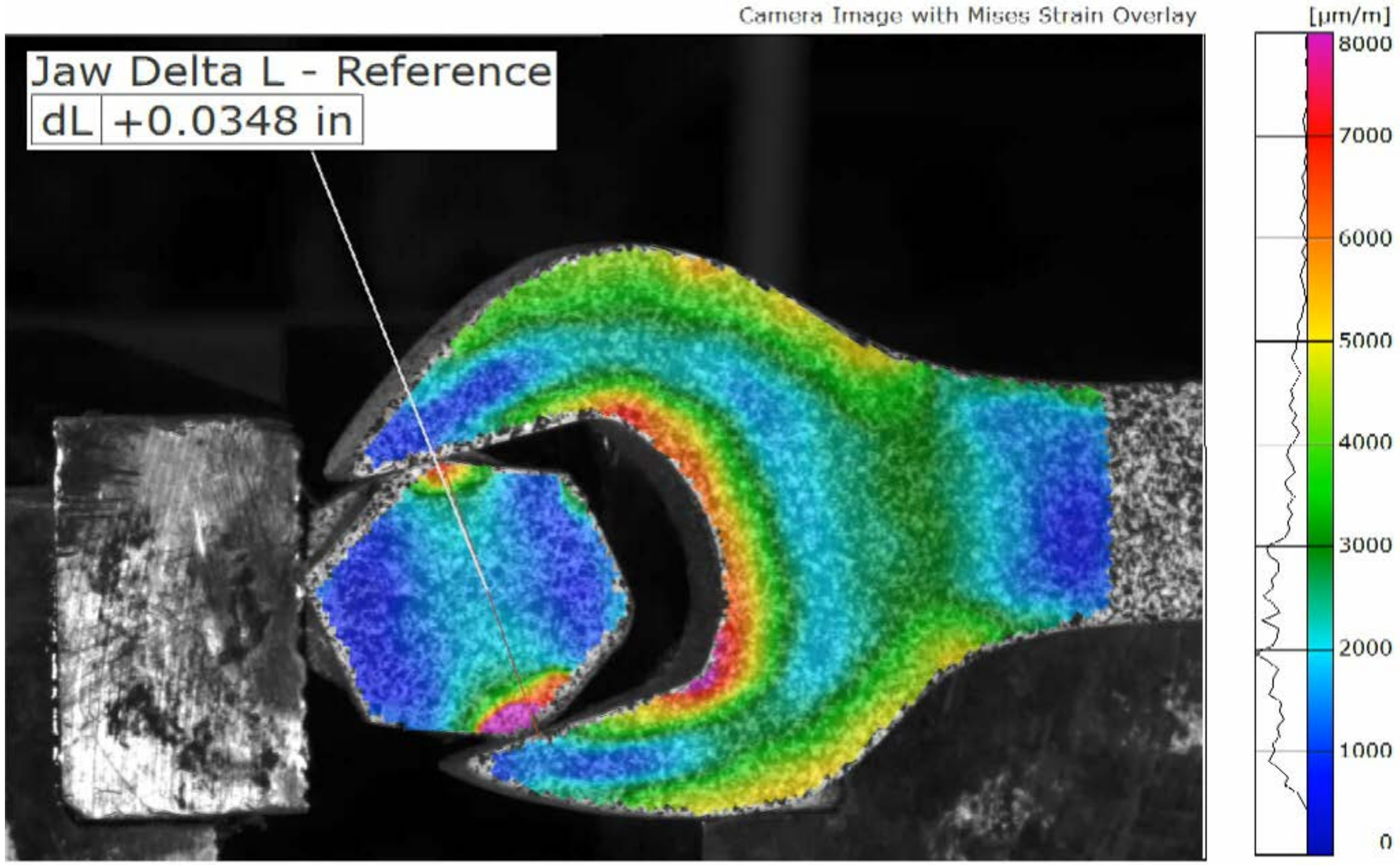
https://www.spacefoundation.org/tech_track_papers/enhancing-finite-element-analysis-with-digital-image-correlation-point-cloud-test-data/

Digital Image Correlation

Technology Highlight





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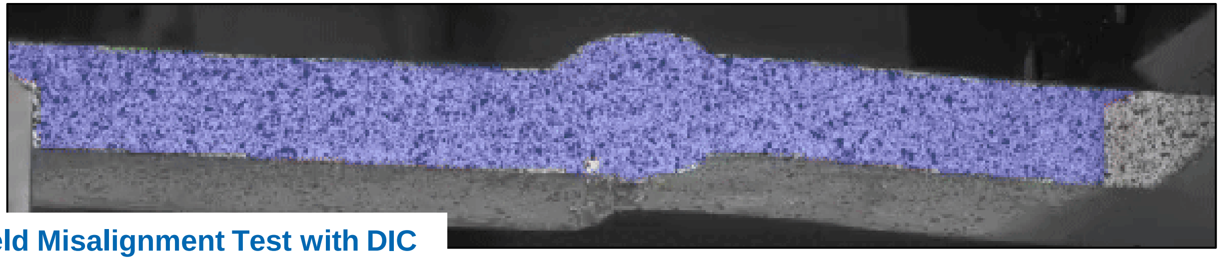
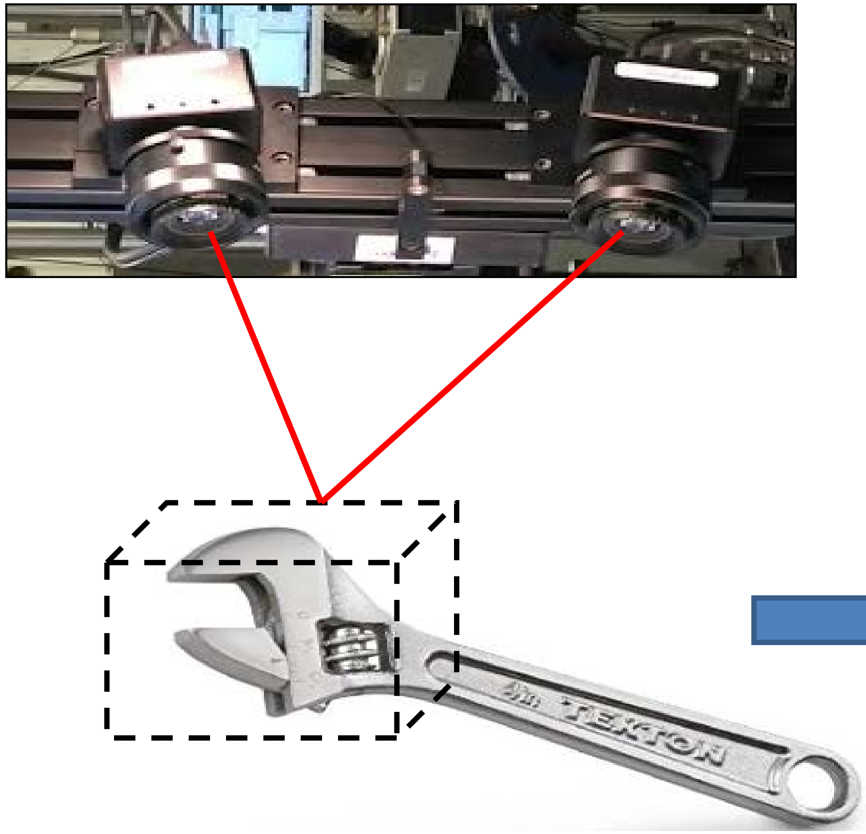
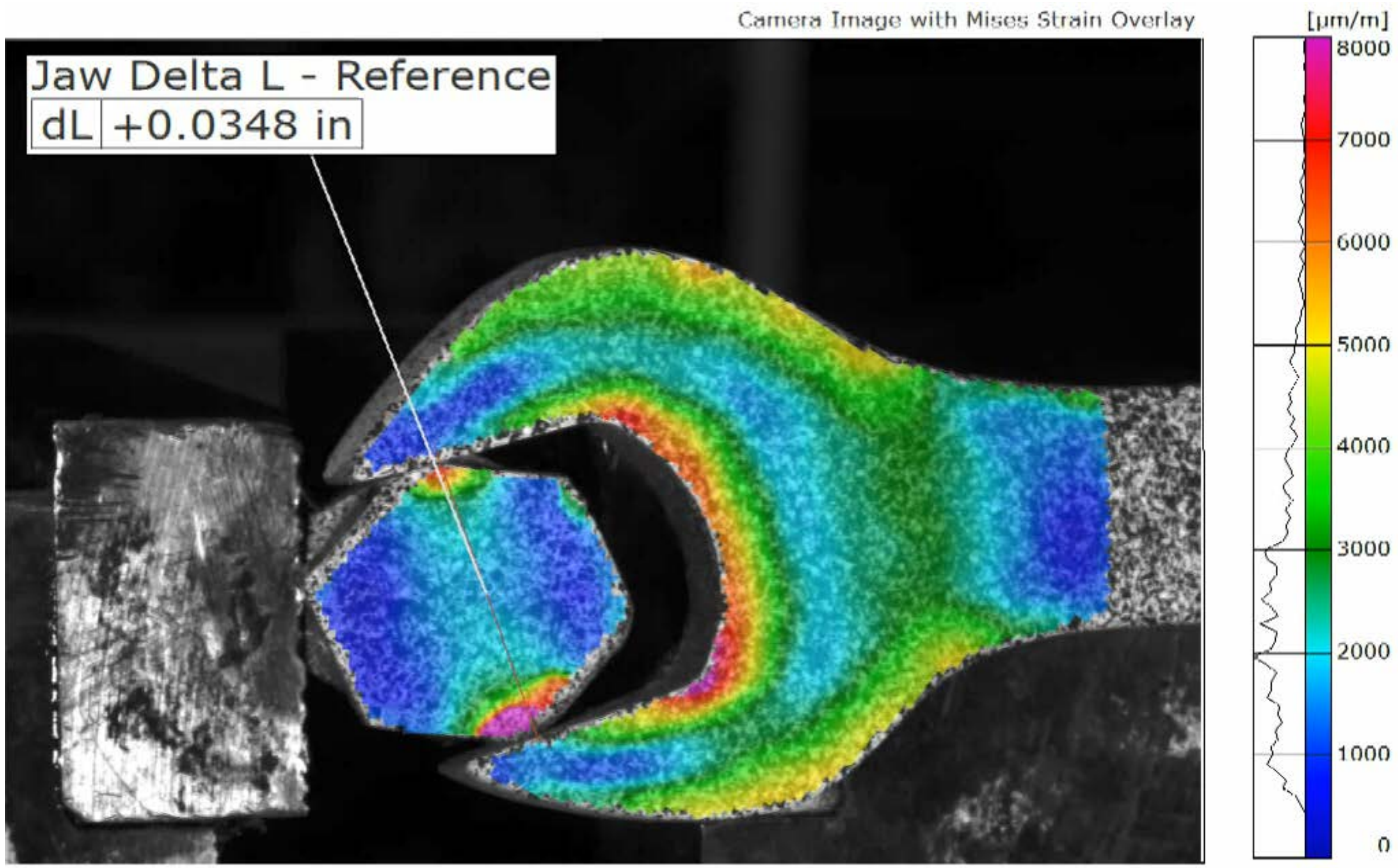
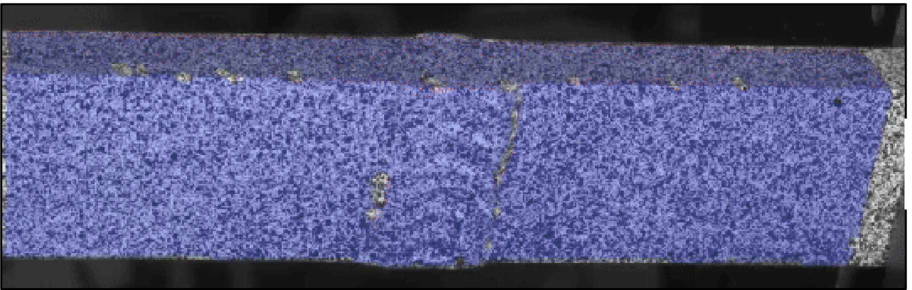
Digital Image Correlation



Weld Misalignment Test with DIC



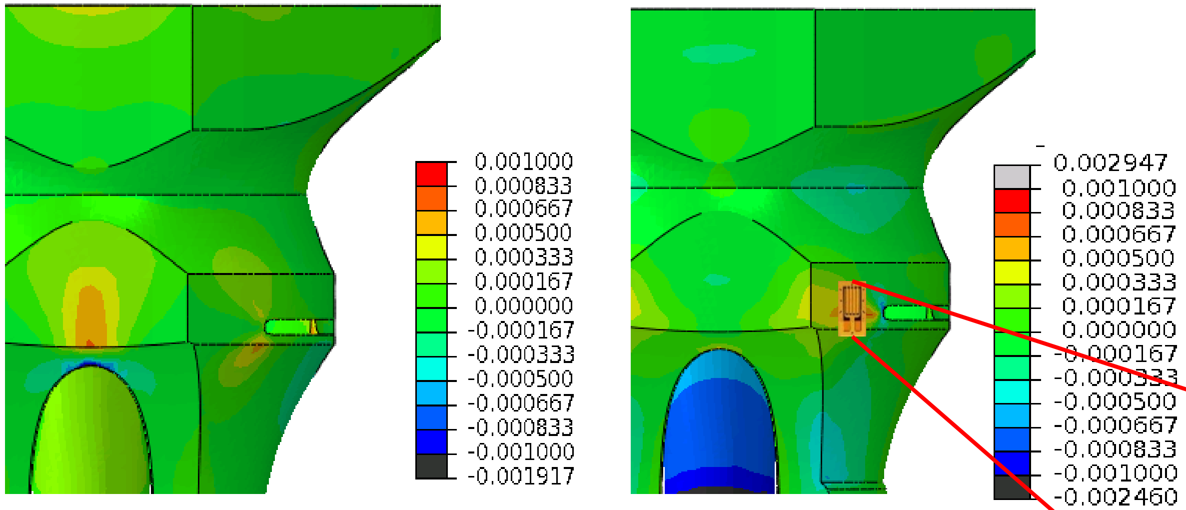




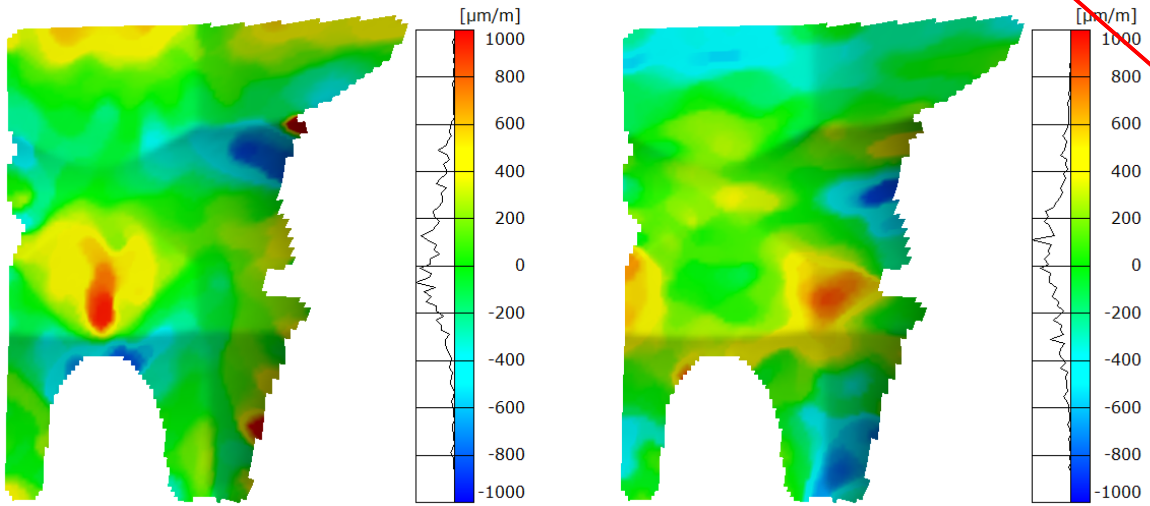
Welded Tensile Test with DIC

Alloy 718 AM Part Test Results

FEA

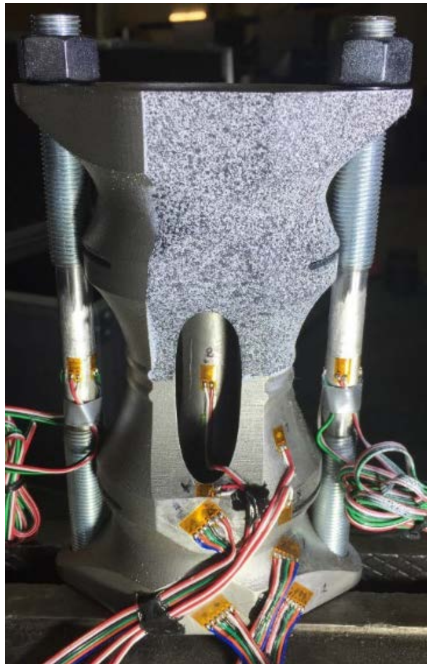


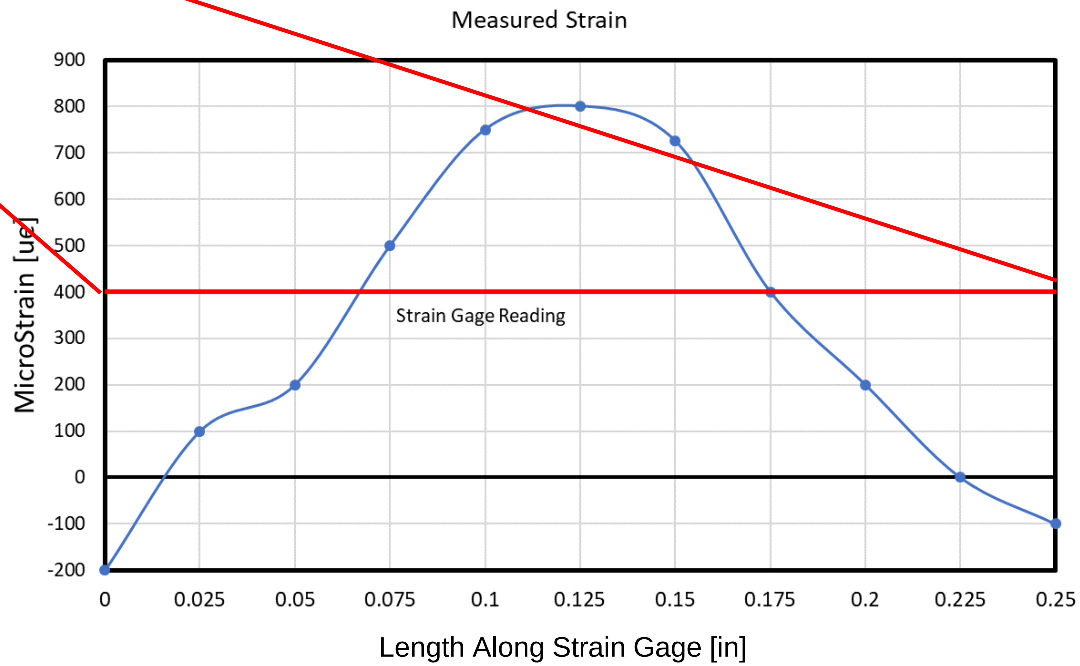
DIC



Strain Gages

Location	MicroStrain [ue]
1	150
2	-376
3	224
4	NA
5	714
6*	-866
7	-465
8	-1,273





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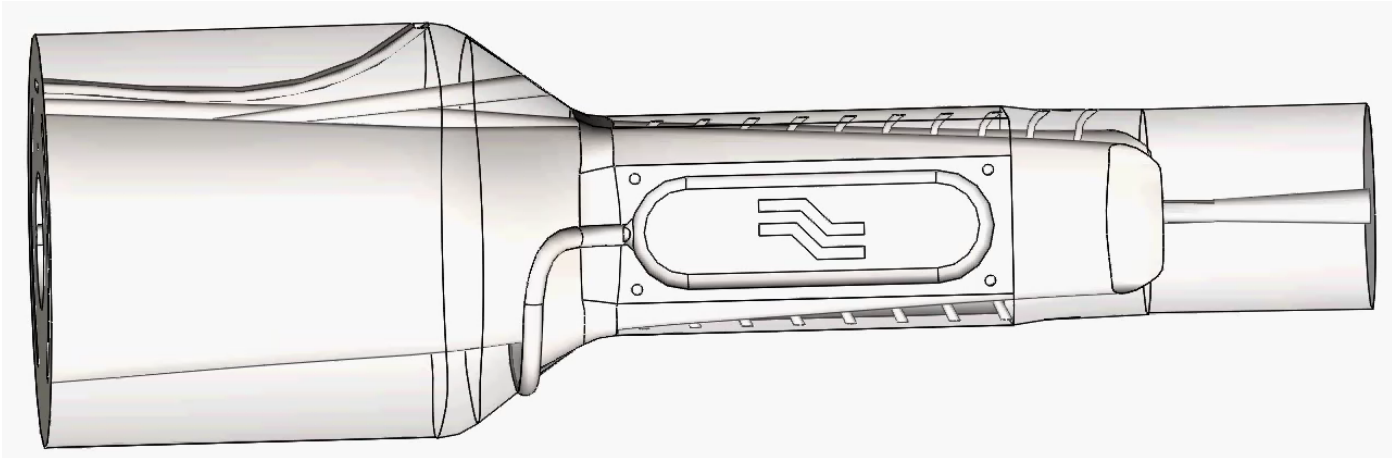
Cross-Over Sensor Body Case Study

A case study part was created to showcase the types of features that can be created with AM for Oil & Gas and evaluated for:

Hardness / Chemistry / Microstructure / Corrosion / Structural / Thermal Shock

- Alloy Powder Ni-625
  - Commonly used in O&G in valves, gaskets, tubing
- Printed on an EOS M290
  - (Laser Powder Bed Fusion)
- The parts were Stress Relieved per AMS 2774E
  - 1,040°C (1,900°F) for 1 hr
- Grit blasted with no machining

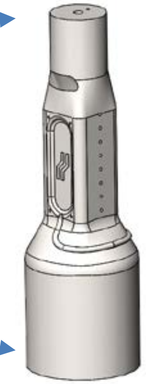
Build Direction

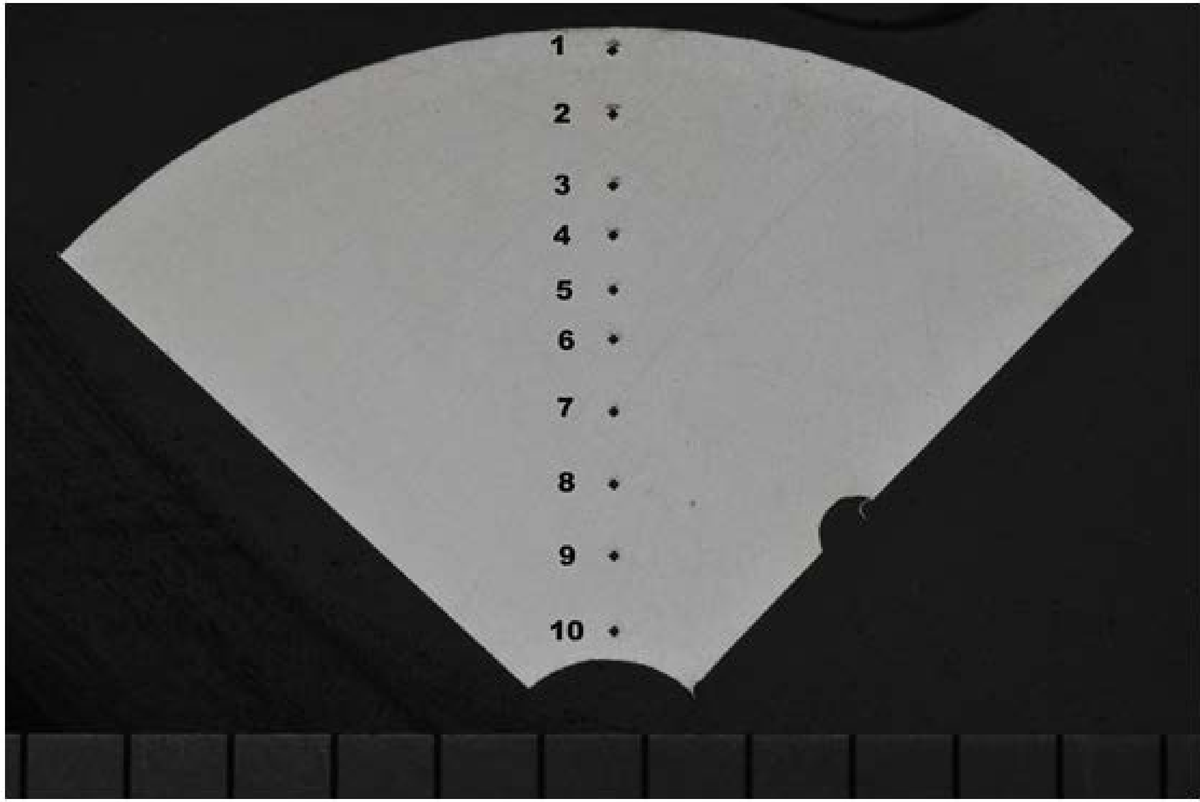


https://www.astm.org/catalog/product/view/id/1303871/

Hardness

- Good through-wall consistency
- Comparable to hardness values for annealed wrought alloy 625
- Brinell Hardness Measurements [HRB]
  - Top Layer:
    - 95.9, 94.7, 95.7, 94.2
    - (201 to 218 Vickers HV)
  - Build Plate Side:
    - 95.6, 96.4, 94.8
    - (201 to 222 Vickers HV)





HV 10		HV 10	
1.	220	6.	221
2.	218	7.	219
3.	223	8.	214
4.	222	9.	218
5.	221	10.	215

Below recommended maximum for Hydrogen Sulfide Service (H_2S) for wrought material

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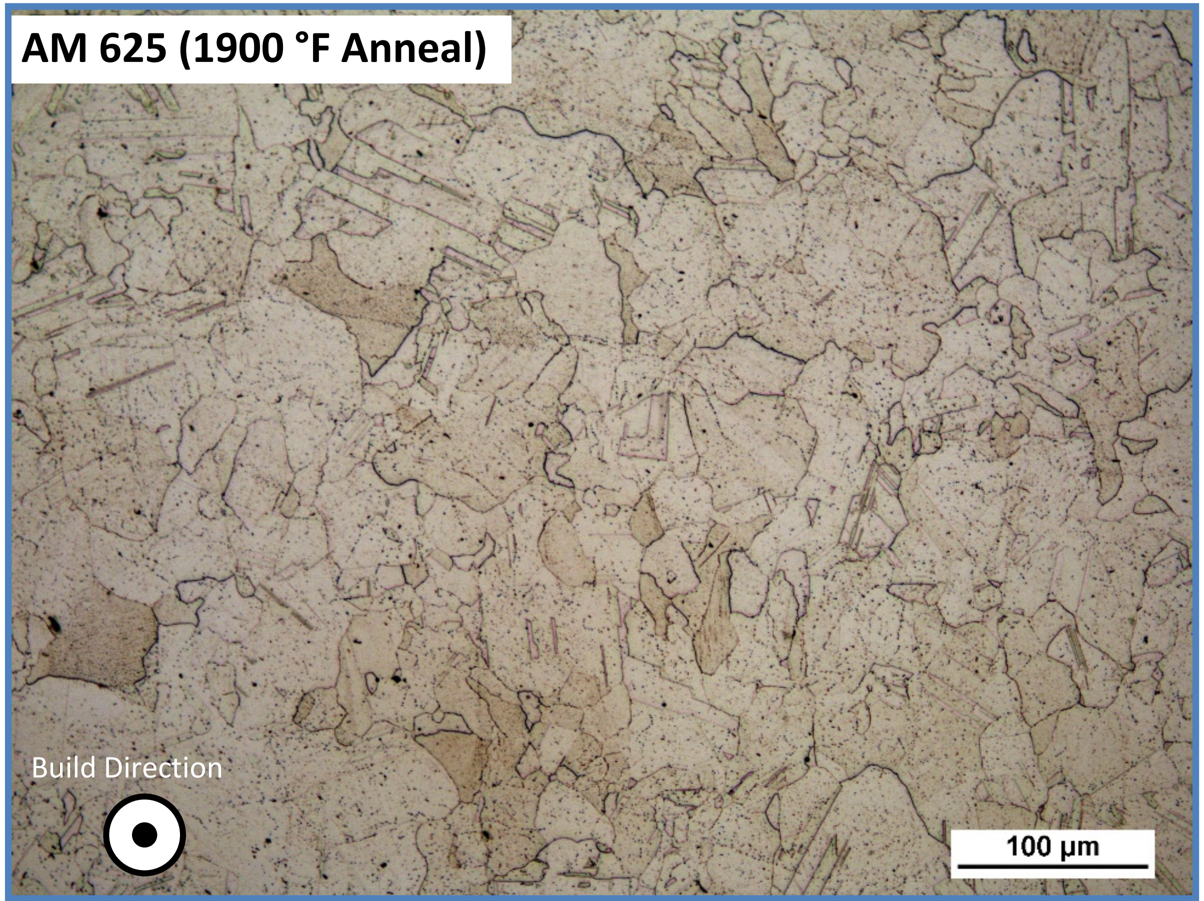
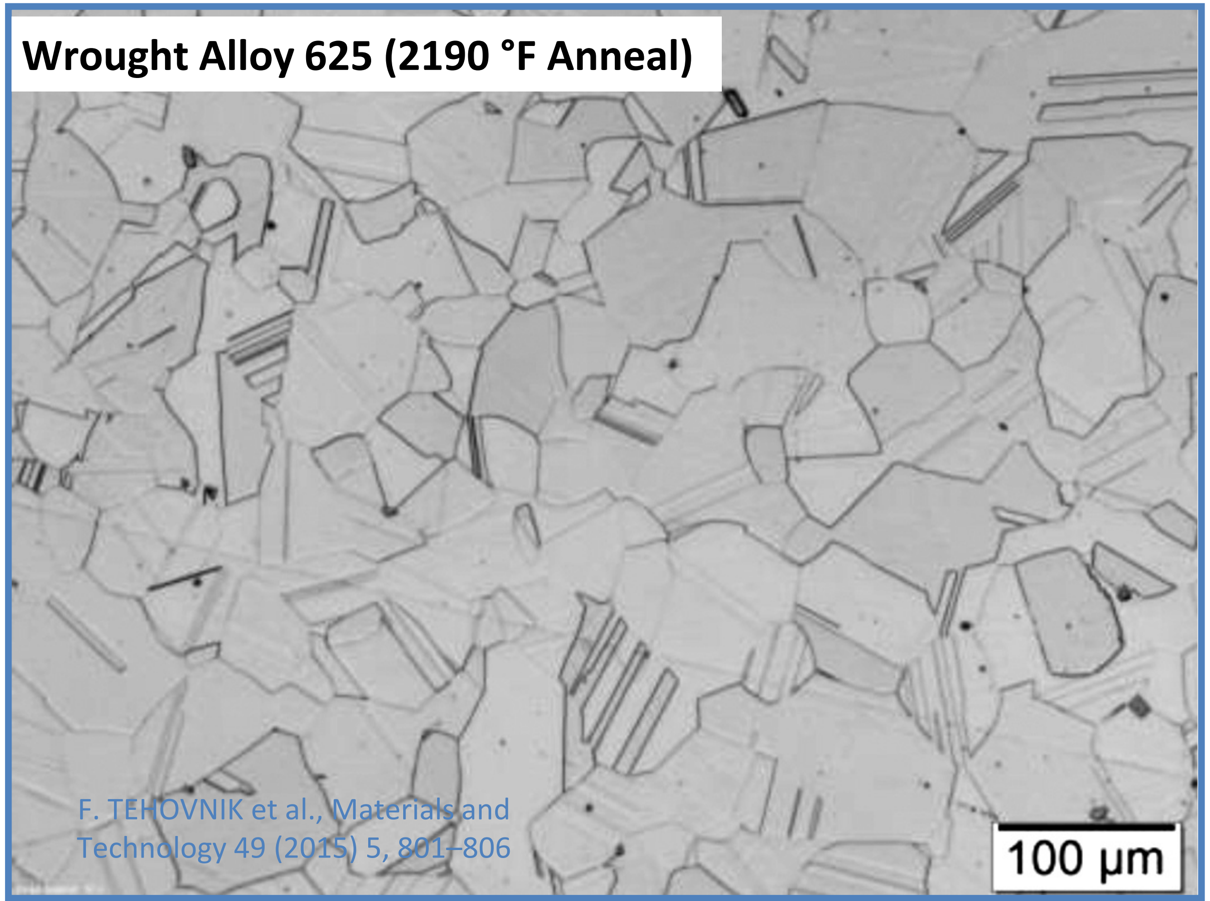
Chemistry & Microstructure Comparison

- Good build density with marginal porosity
- Annealed γ-phase (FCC) matrix with carbides
- Comparable with wrought structure after annealing
- Satisfied composition requirements for wrought alloy 625

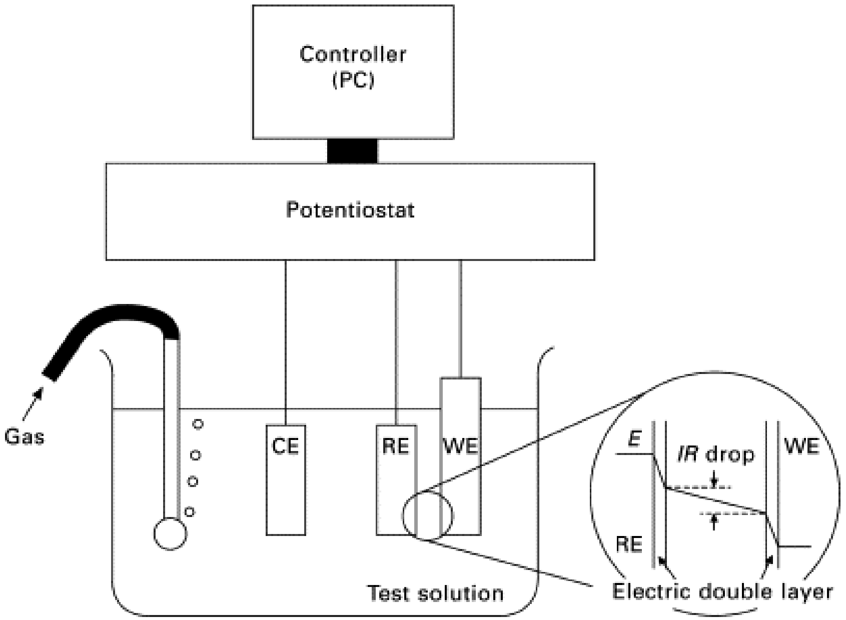
Element	AM 625	UNS N06625
Nickel	65.85	58 min
Chromium	20.73	20-23
Iron	0.12	5 max
Molybdenum	8.69	8-10
Niobium + Tantalum	3.85	3.15-4.15
Silicon	0.50	0.50 max



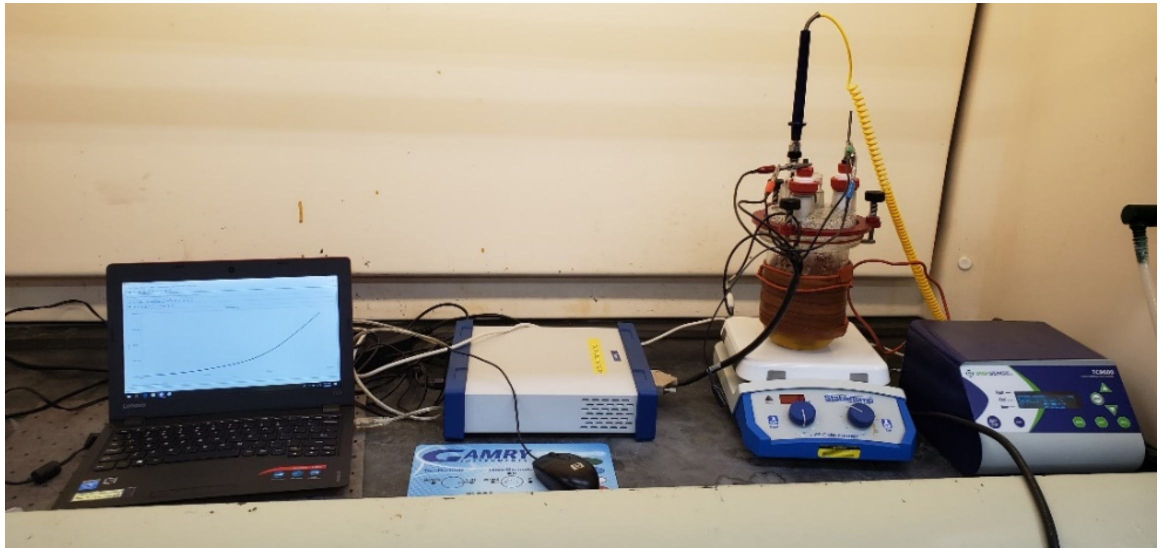


Corrosion Testing

- Electrochemical corrosion testing was performed on both AM alloy 625 and wrought alloy 625
- Potentiodynamic polarization scans of AM alloy 625 showed relatively higher current density at all potentials than wrought alloy 625 in ASTM G 48 solution C.
- ASTM G 150 testing was performed for both AM alloy 625 and wrought alloy 625 in ASTM G 48 solution C.
- Critical Pitting Temperature (CPT) of AM and wrought 625 is 64°C and 81°C, respectively.
- Electrochemical corrosion performance of AM alloy 625 was found to be less than wrought 625.

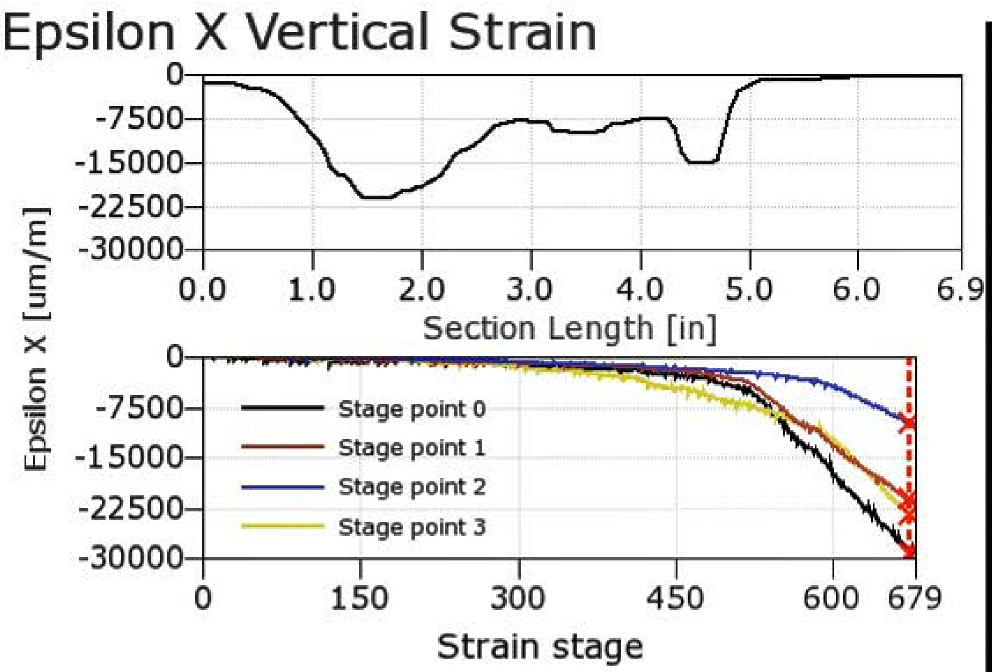


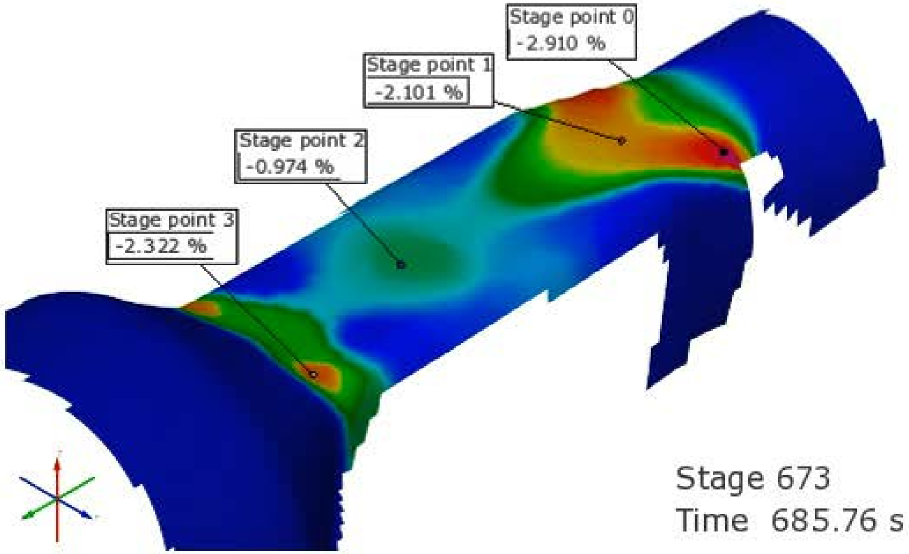
Schematic of Electrochemical Corrosion Test Setup

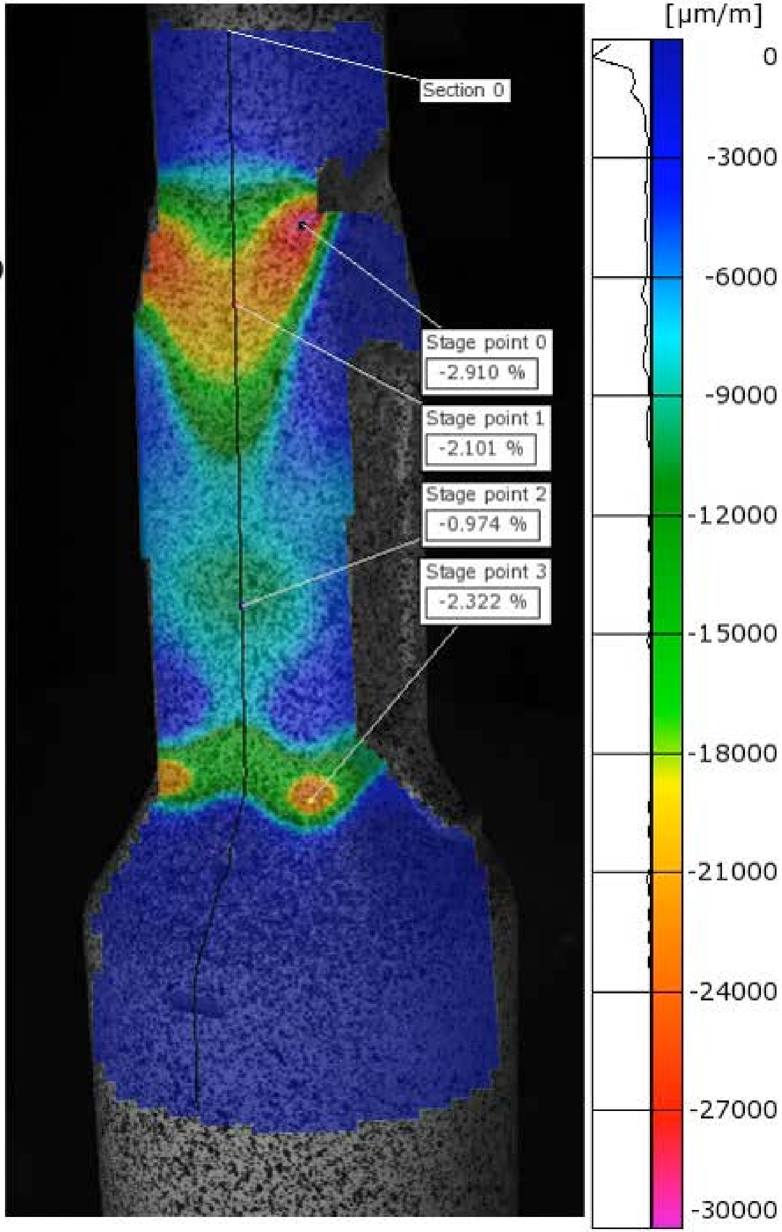


Full Scale Load Testing

356 kN (80,000 lbs)

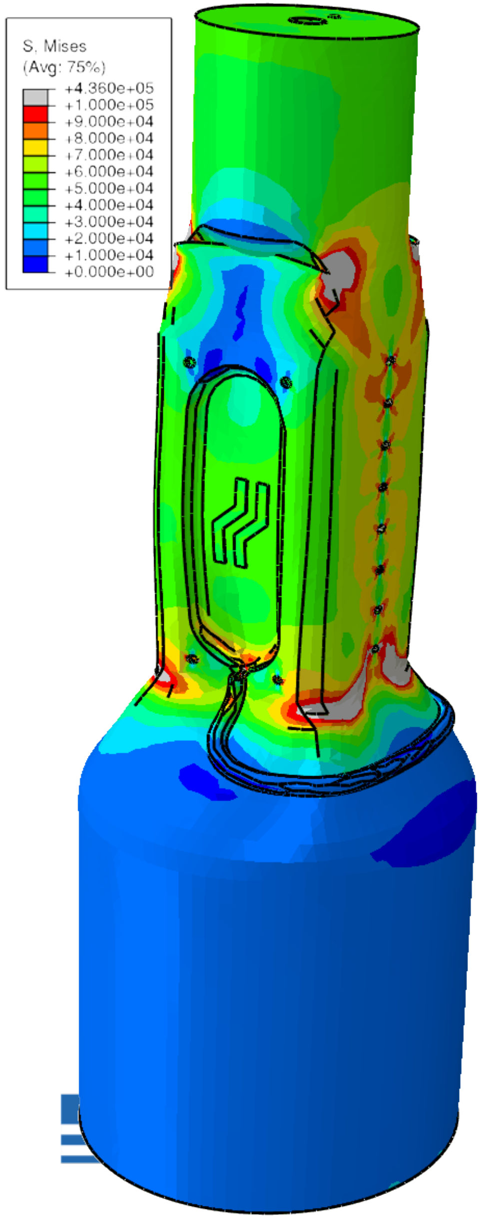


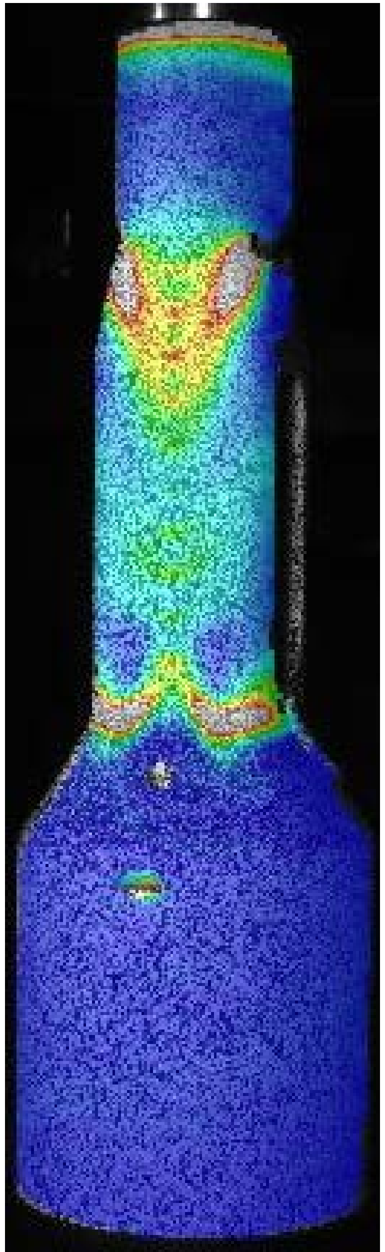




FEA Comparison to Digital Image Correlation Test Data

Technology Highlight

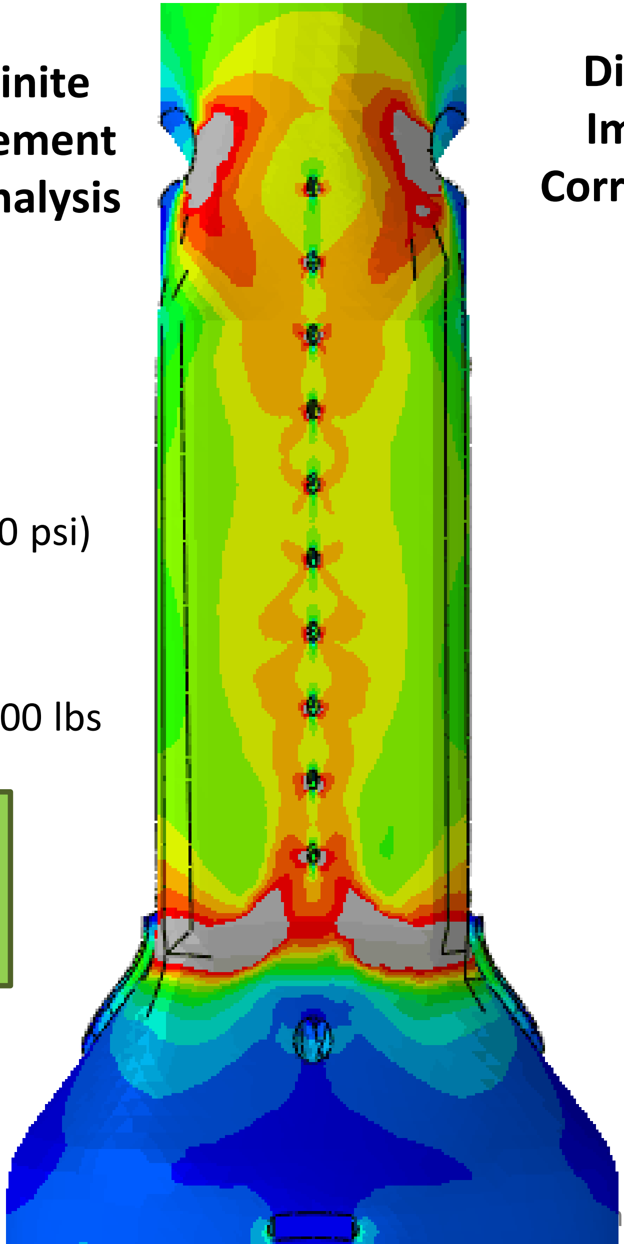




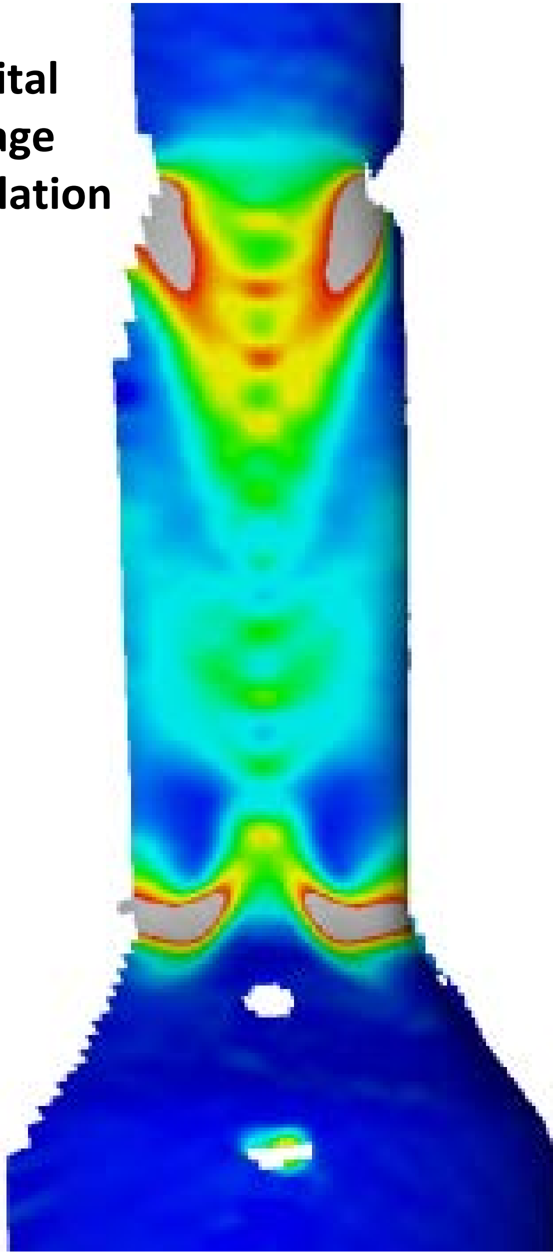
- Static Model
- Abaqus Software
- 206 GPa (30,000,000 psi) Modulus
- Poisson ratio = 0.3
- Load Tested to 80,000 lbs

Use DIC to tune the FEA Model for additive

Finite Element Analysis

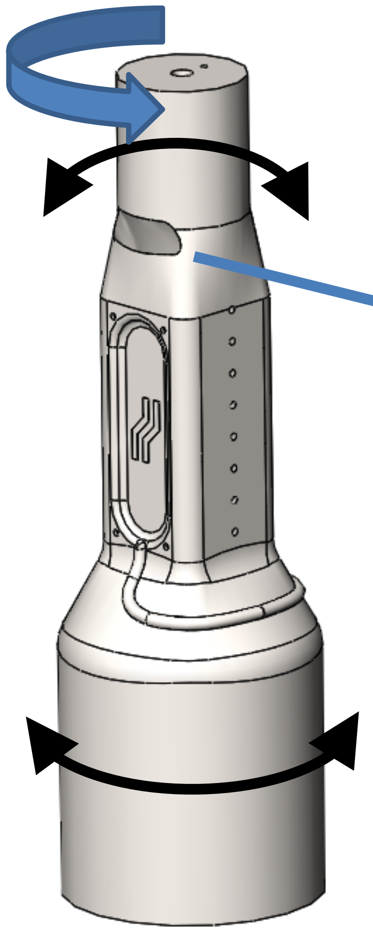


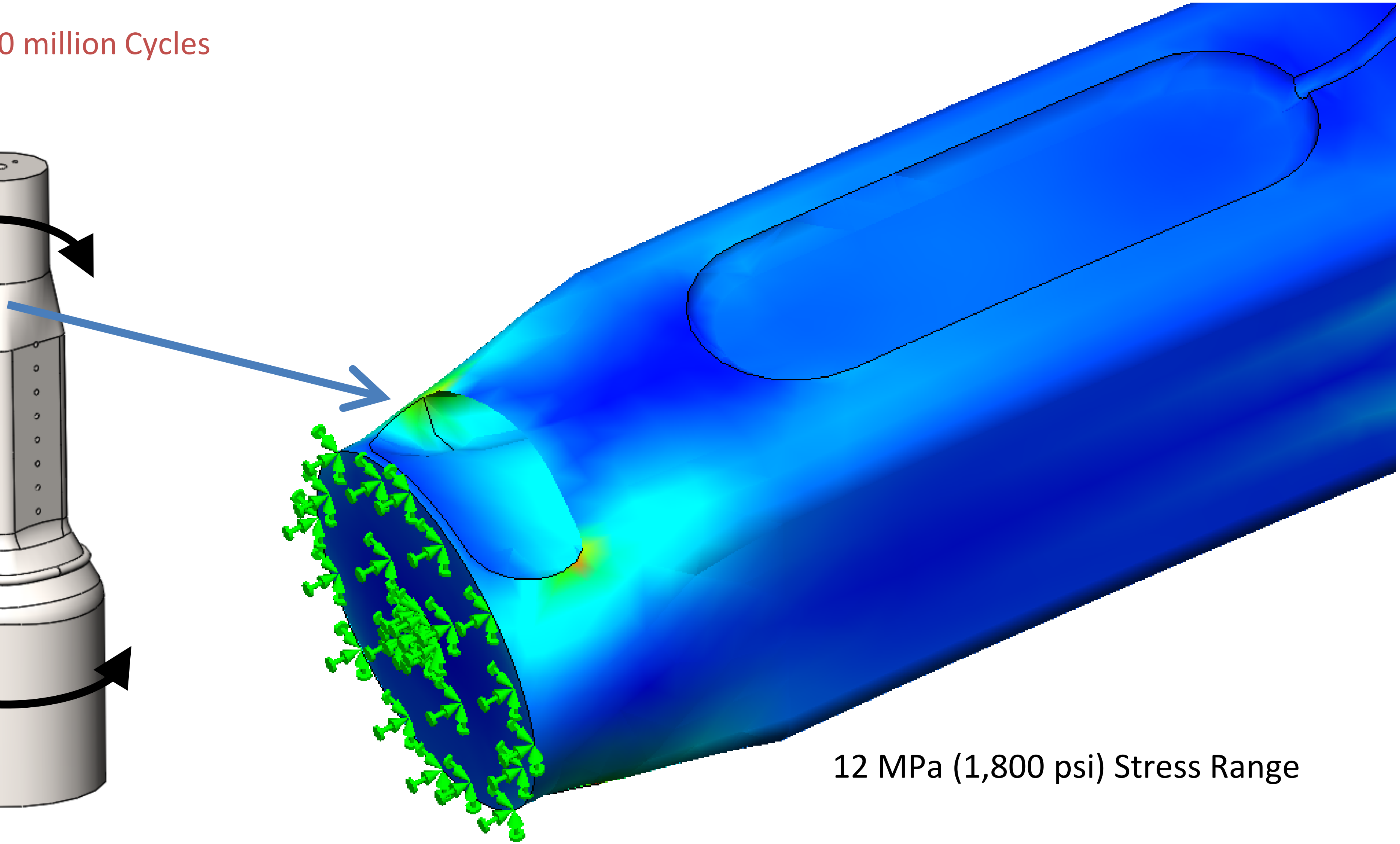
Digital Image Correlation



High Cycle Fatigue Testing

Rotational Bending Fatigue for 10 million Cycles





12 MPa (1,800 psi) Stress Range

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Thermal Shock Loading

SERVICES INC.

-195°C
(-320°F)

Up to 982°C
(1,800 °F)

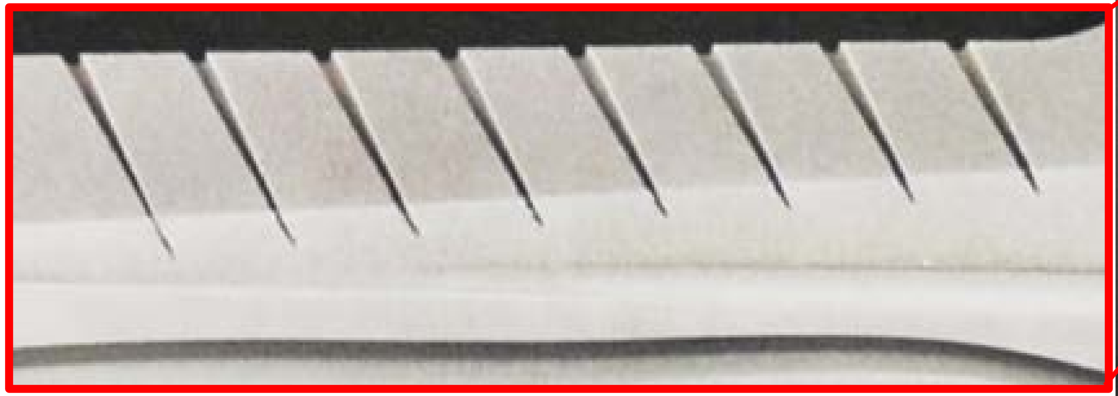
-195°C
(-320°F)

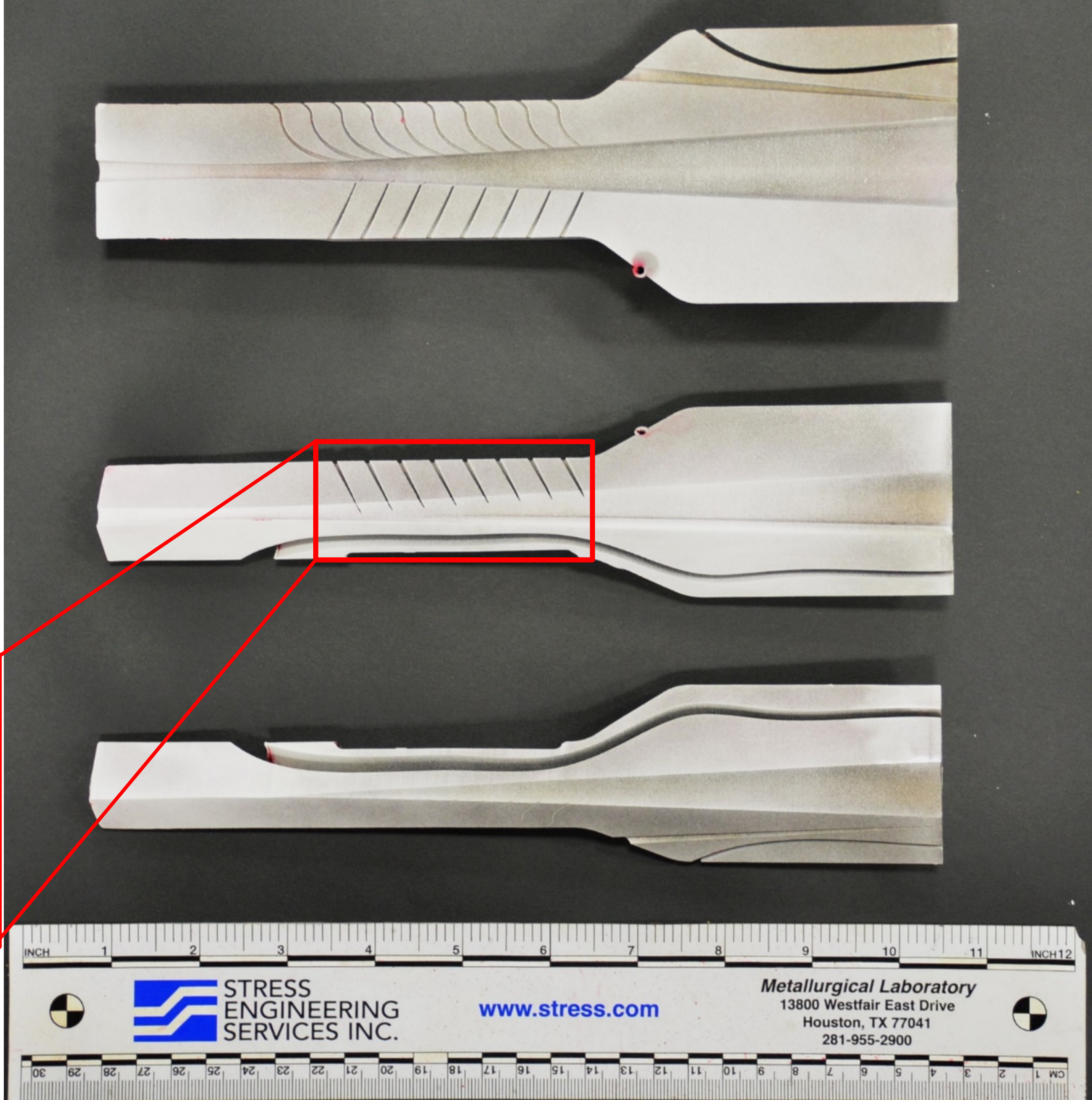
Up to 982°C
(1,800 °F)

-195°C
(-320°F)

Post Test Inspection

- No Post Test Surface Cracks Visible from Dye Penetrant Inspection





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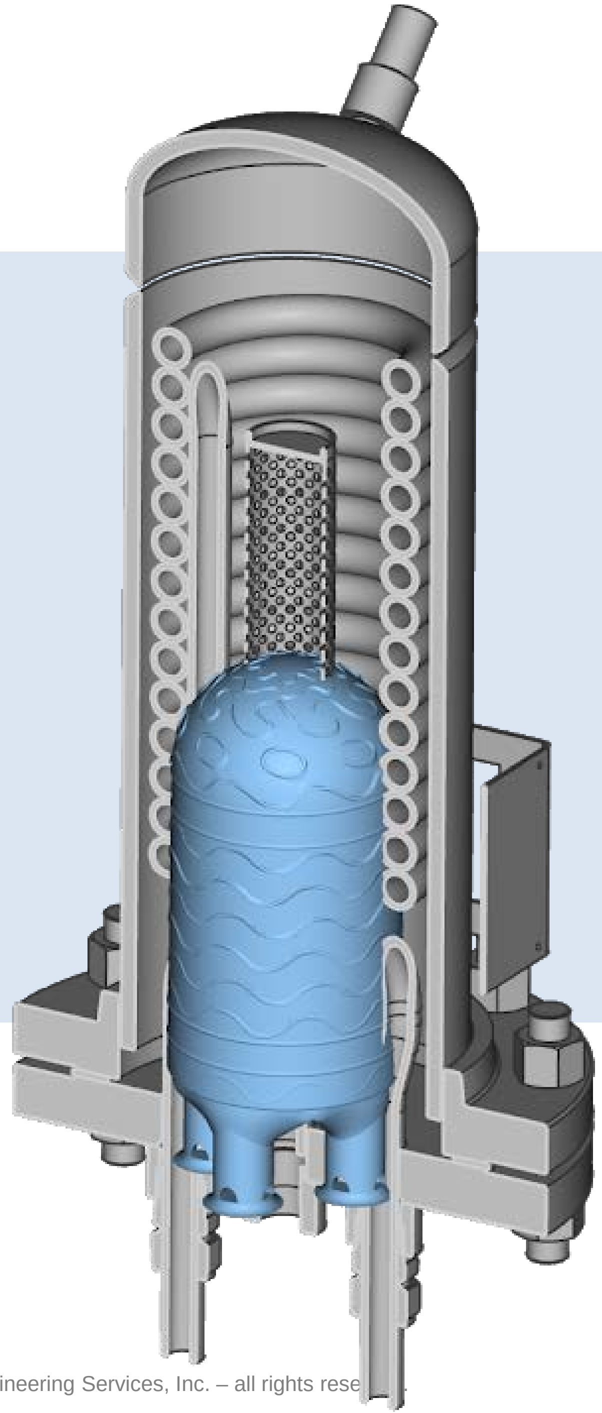
Additive Aluminum Heat Exchanger

Six industry leaders took on the challenge to develop a clean slate rapid design of an advanced heat exchanger leveraging each of the advanced capabilities that their companies offer.

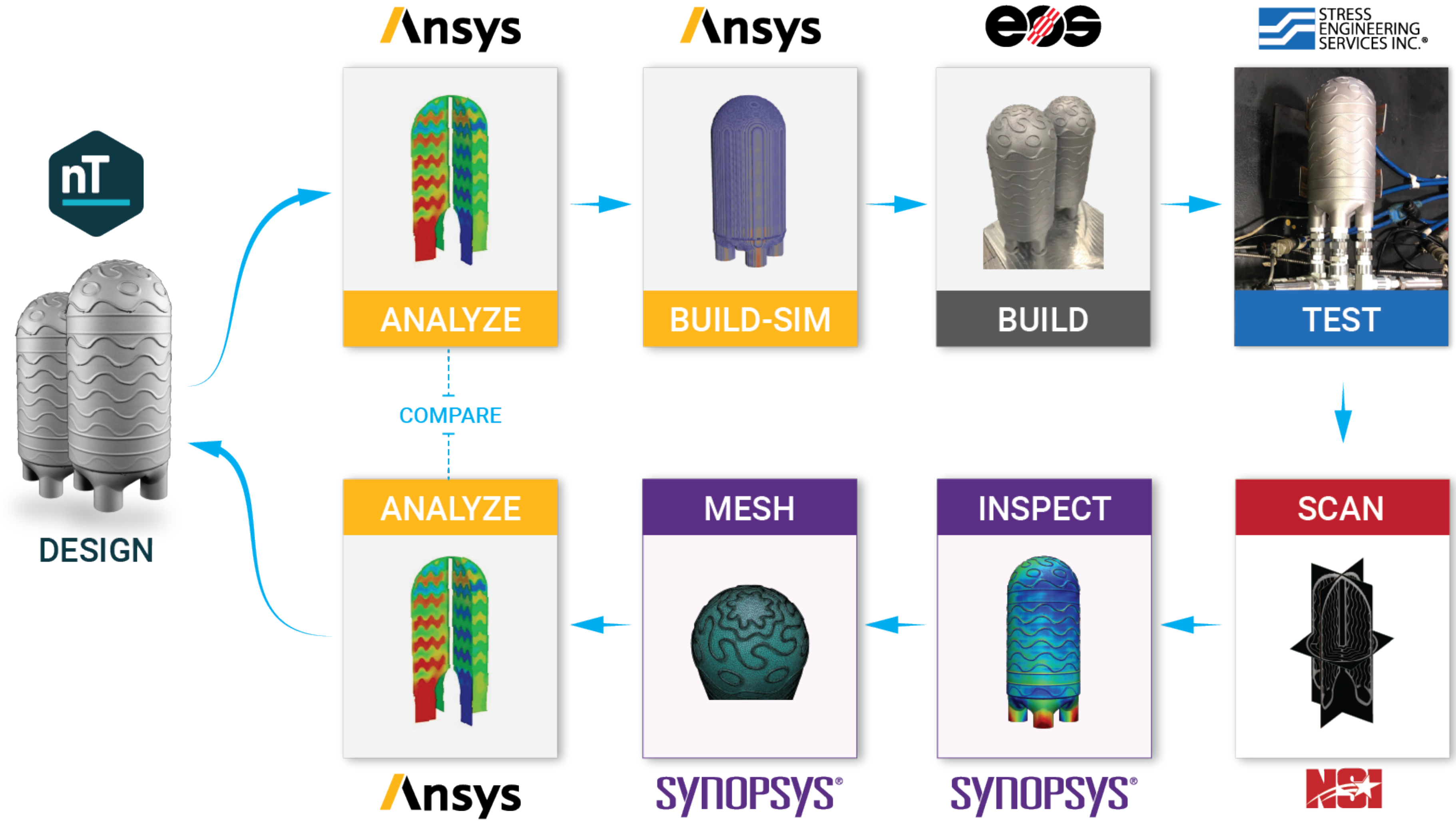
Part Reduction	- 40 parts → 1 part
Heat Transfer	- Doubled Heat Transfer in 20% of the volume
Pressure Drop	- 9.1x Reduction in Pressure Drop
Manufacture	- Successful Print on First Attempt
Inspection	- Full NDE Inspection with Zero Defects
Validation	- Full Heat Transfer Sim of As-Built Part



https://www.synopsys.com/simpleware/resources/case-studies/heat-exchanger.html

STRESS ENGINEERING SERVICES INC. nT Ansys eos NORTH STAR IMAGING NSI AN ITW COMPANY SYNOPSYS®

Key Technologies



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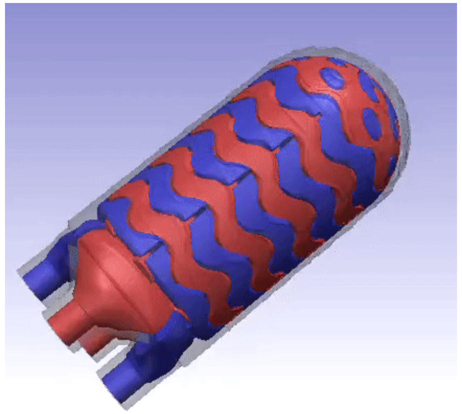
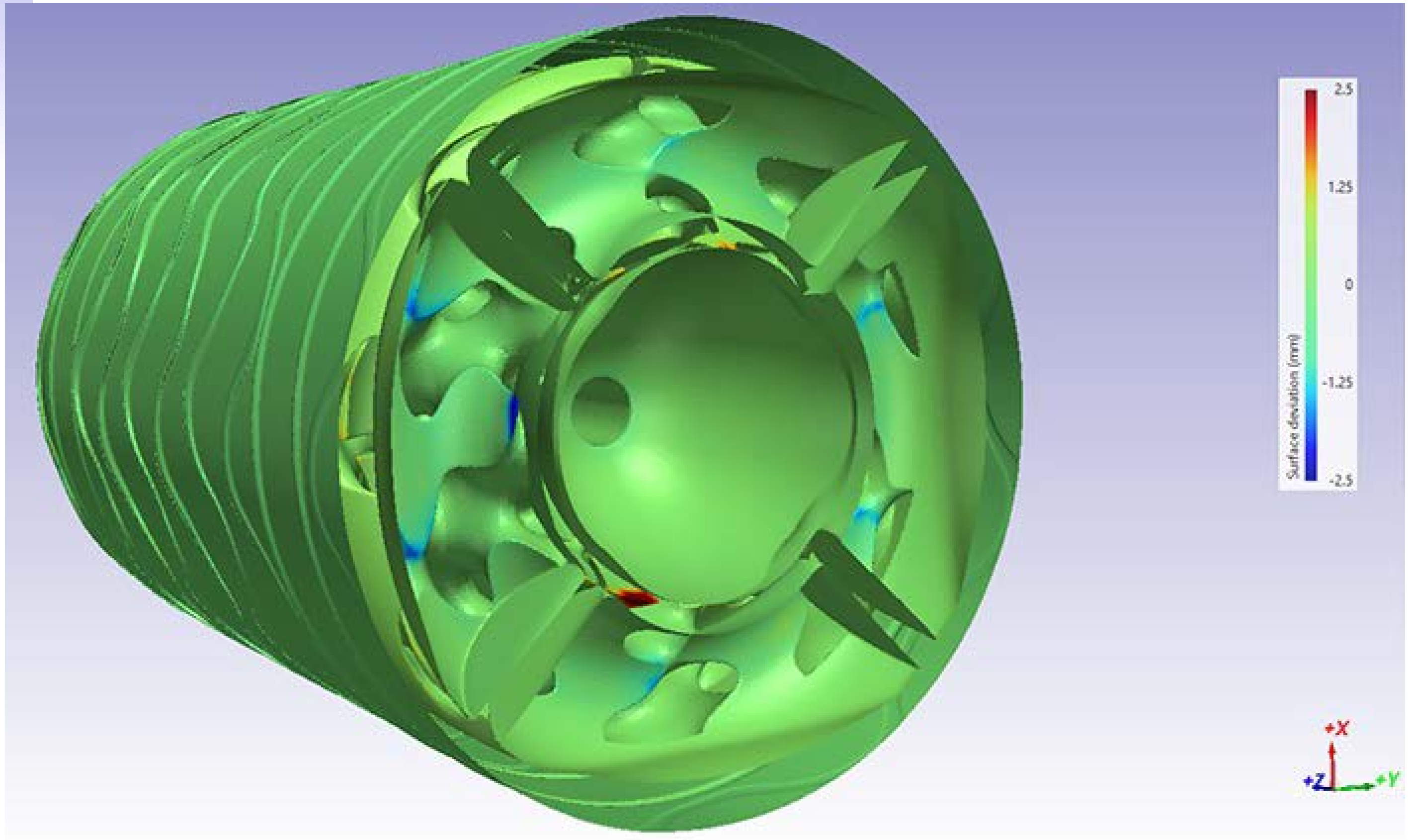
CT Scan Converted to 3D Model

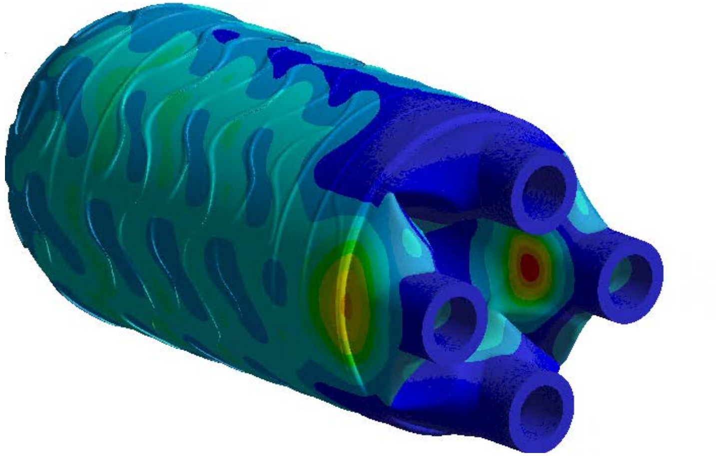
INSPECT
SCAN
SYNOPSYS

Technology Highlight

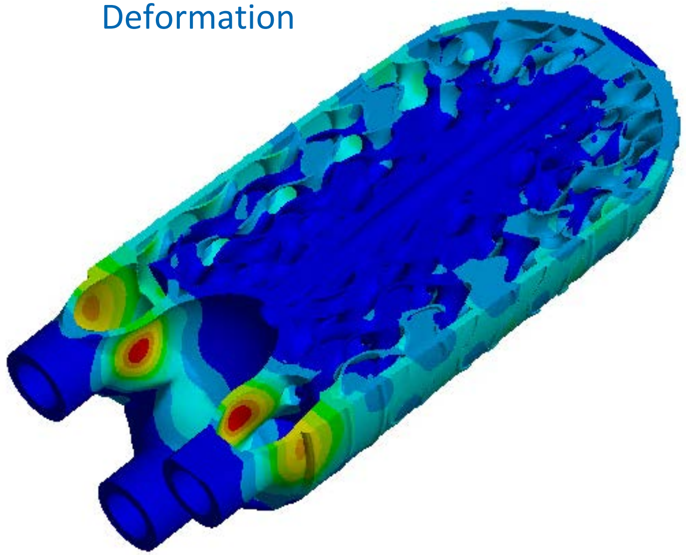




Burst Pressure Test Simulation Design vs As Built

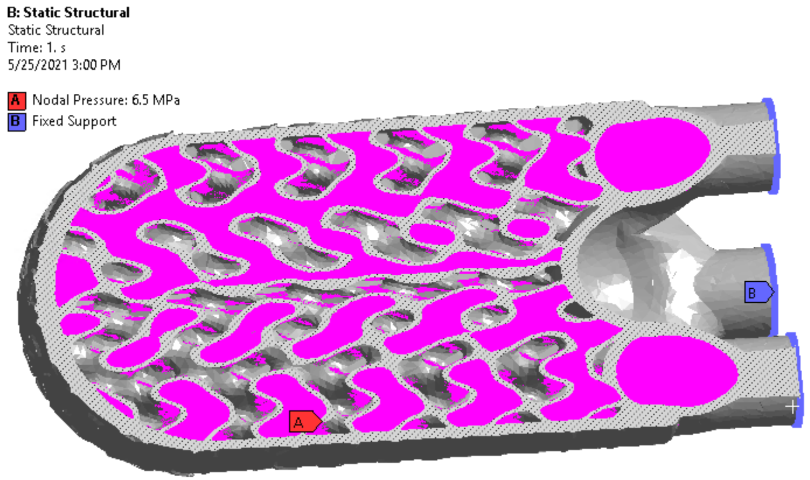


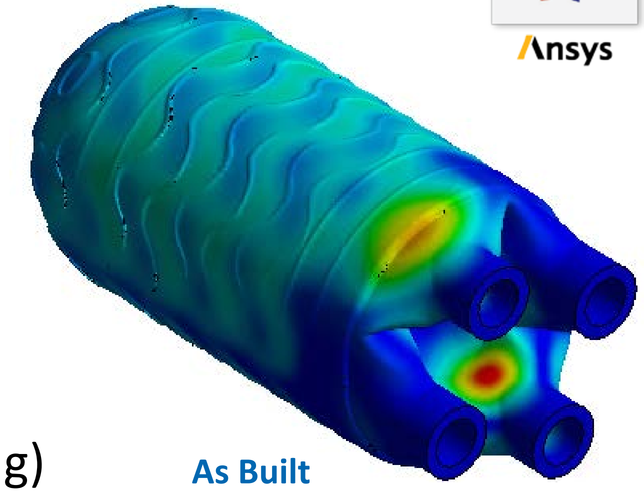
As Designed
Deformation



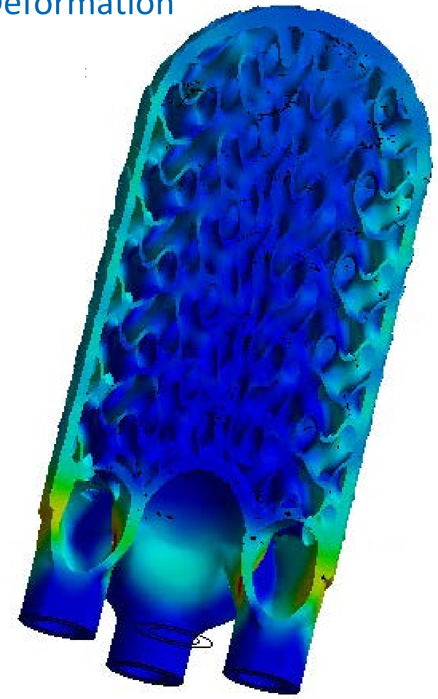
Able to Compare “As Designed” to “As Built”

- Large Deformation Plasticity Analysis
- Pressure = 6.5 MPa =943 psi) (6.25 x Pperating)
- Fixed at the base





As Built
Deformation



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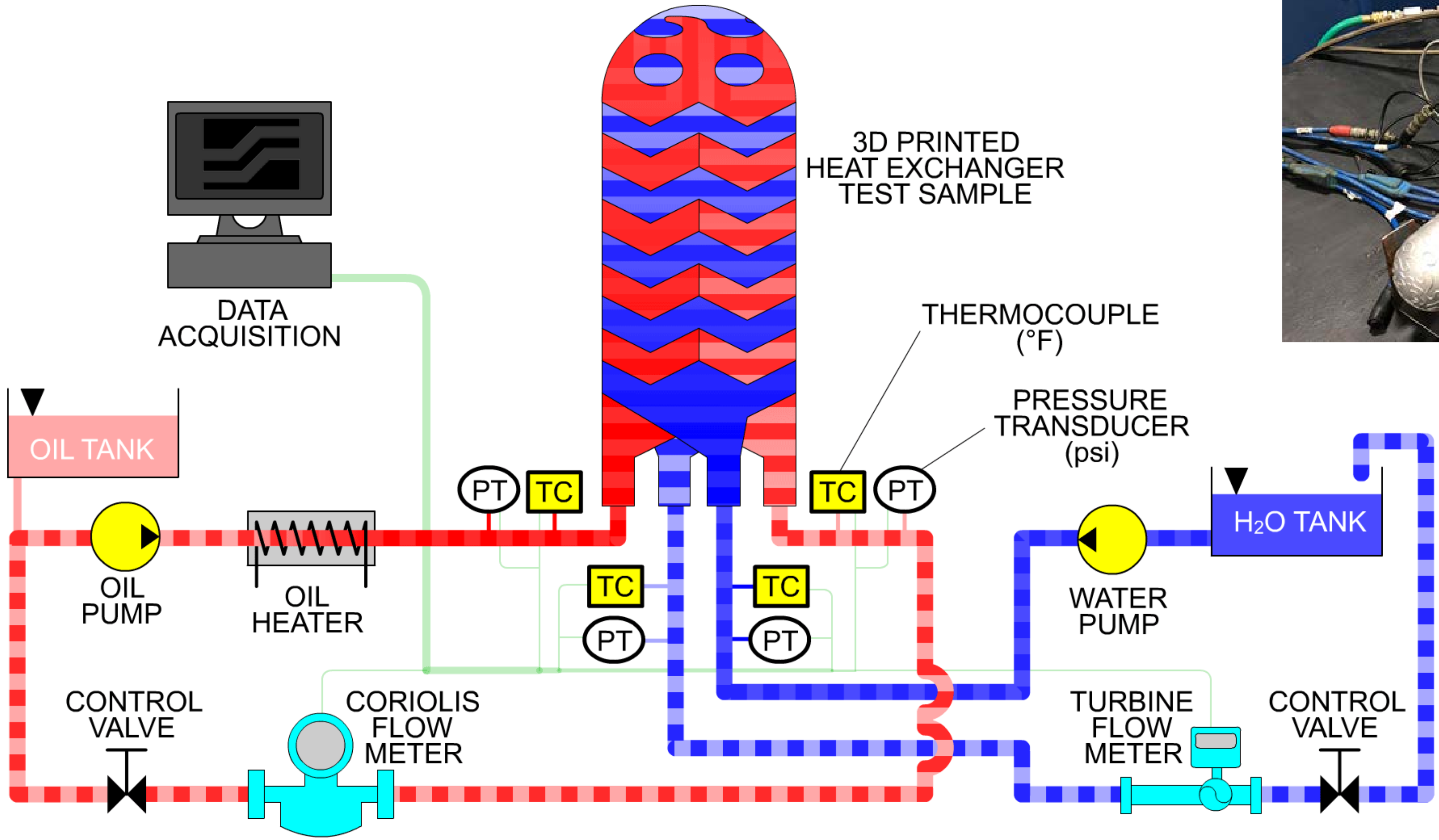
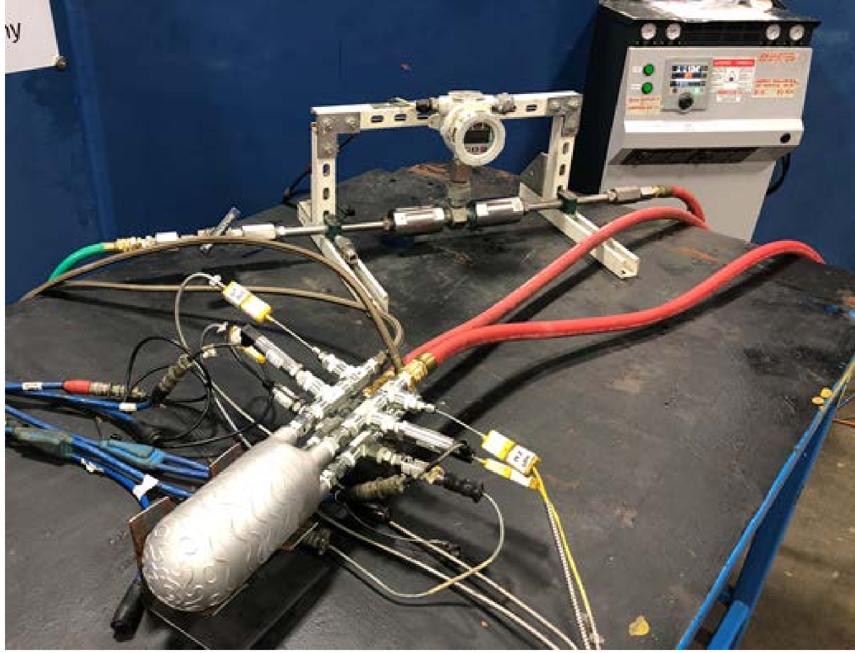
Heat Transfer Flow Testing





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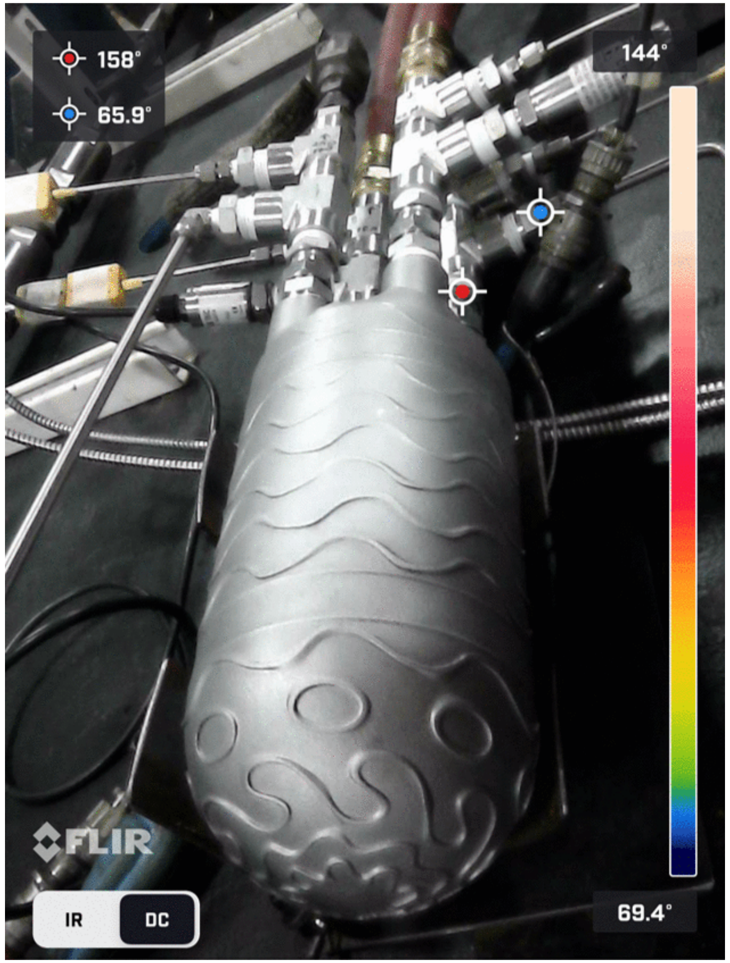
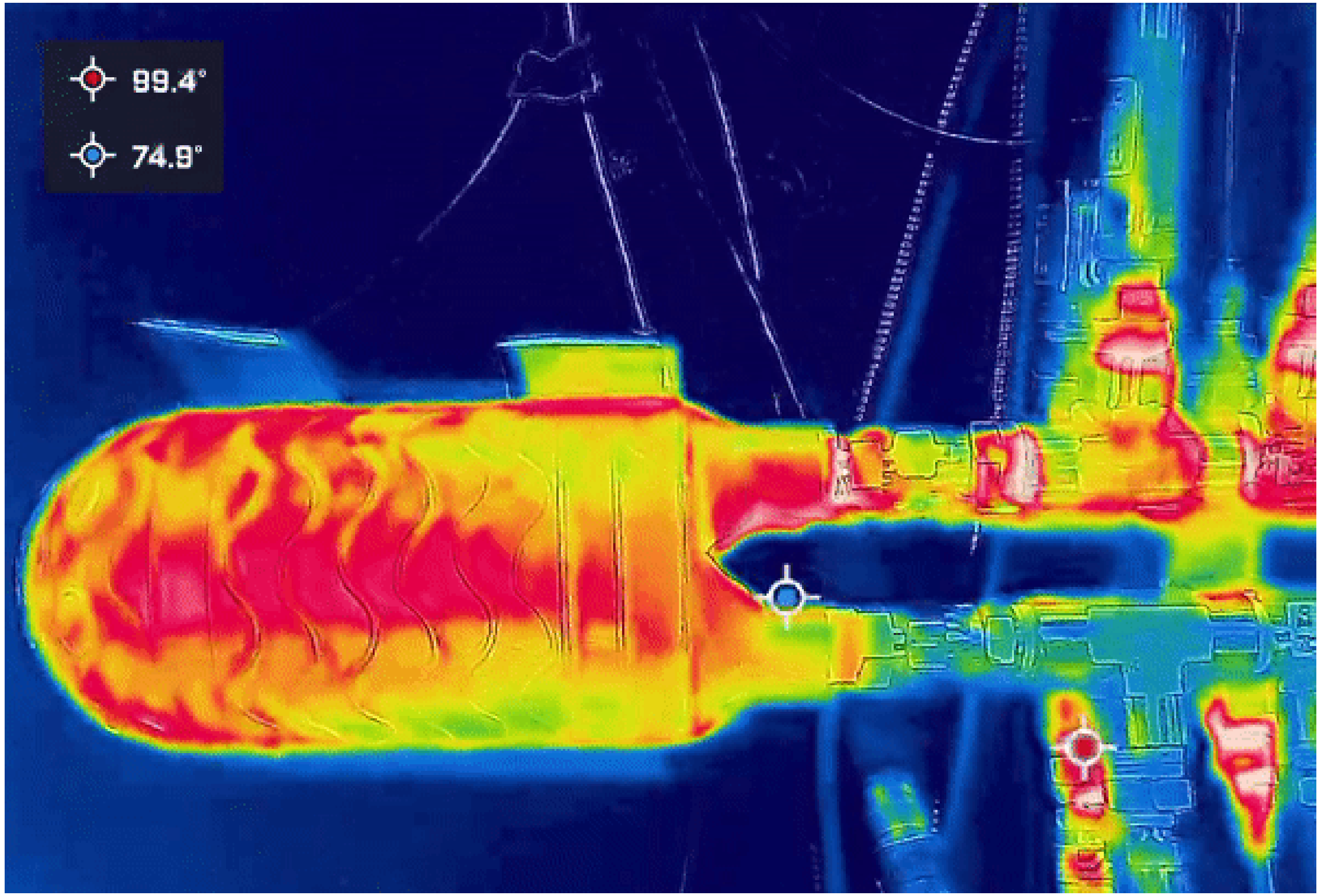
This experiment was configured and started in less than 4 days

Heat Transfer Flow Testing





Transient thermal and flow testing effectiveness visualized using thermal imaging

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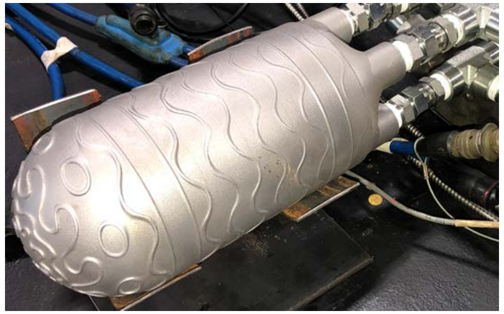
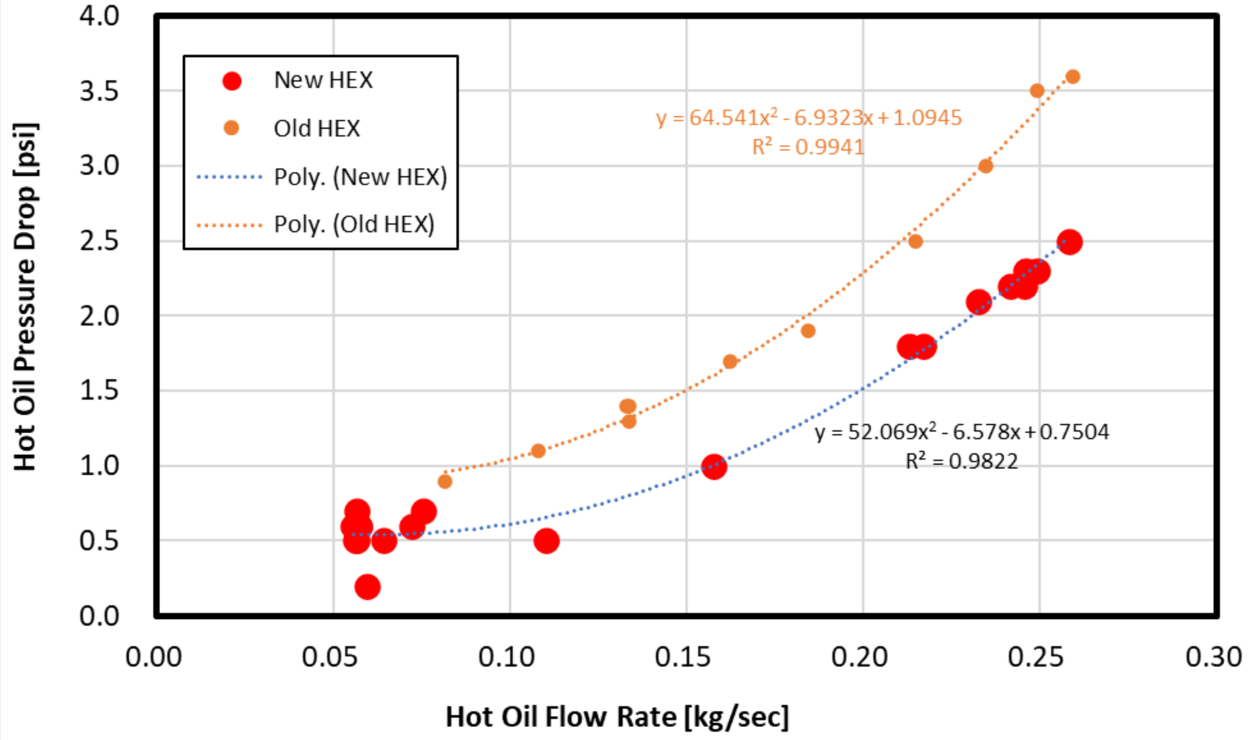
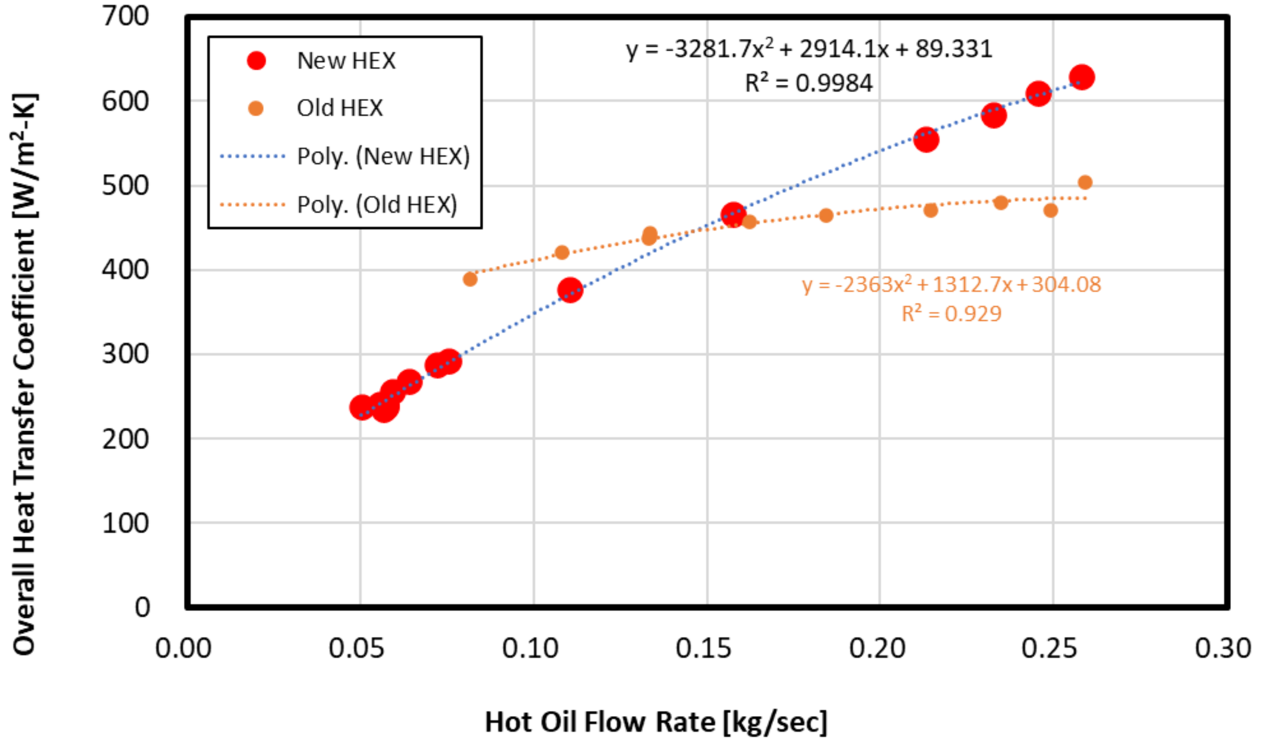
Heat Transfer Flow Testing



AlSi10Mg
9.3” x 4” x 4”
3.6 lbs

Brass Shell & Tube
17.125” x 4.5” x 4.8”
14 lbs





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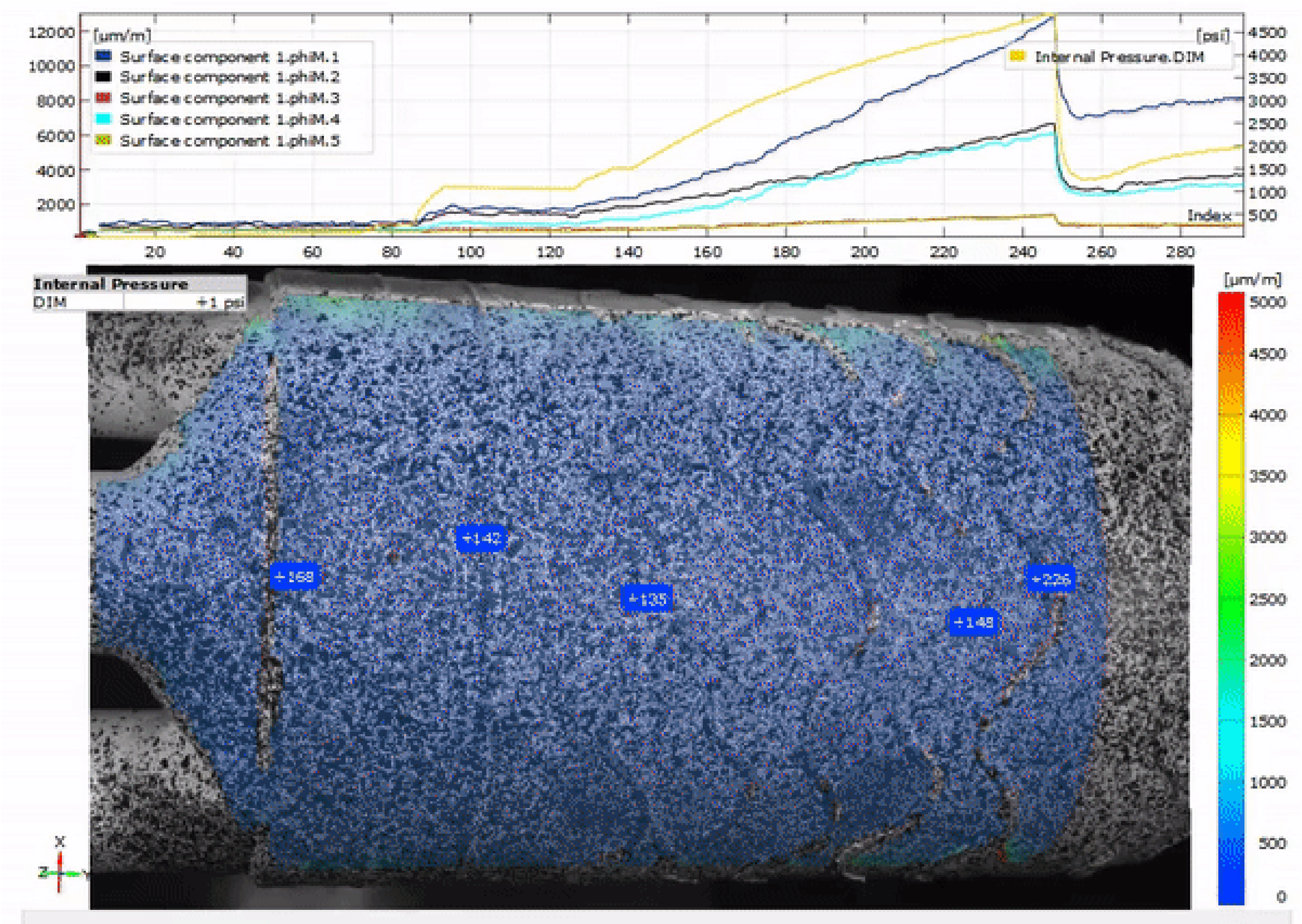
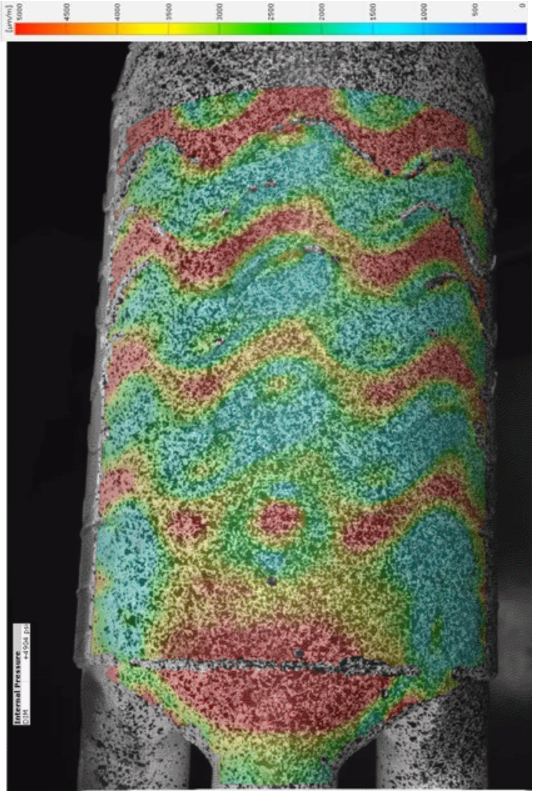
TPMS outperforms a COTS solution

Burst Test Strain using Digital Image Correlation (DIC)





DIC should aid in the location of failure for CT inspection NSI/Synopsys

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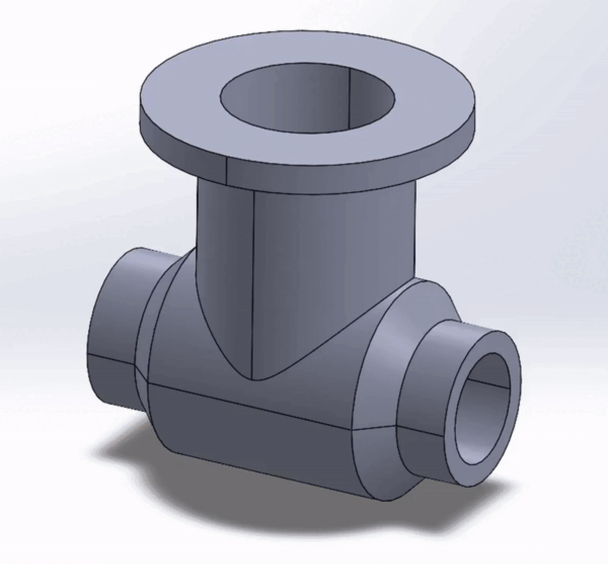
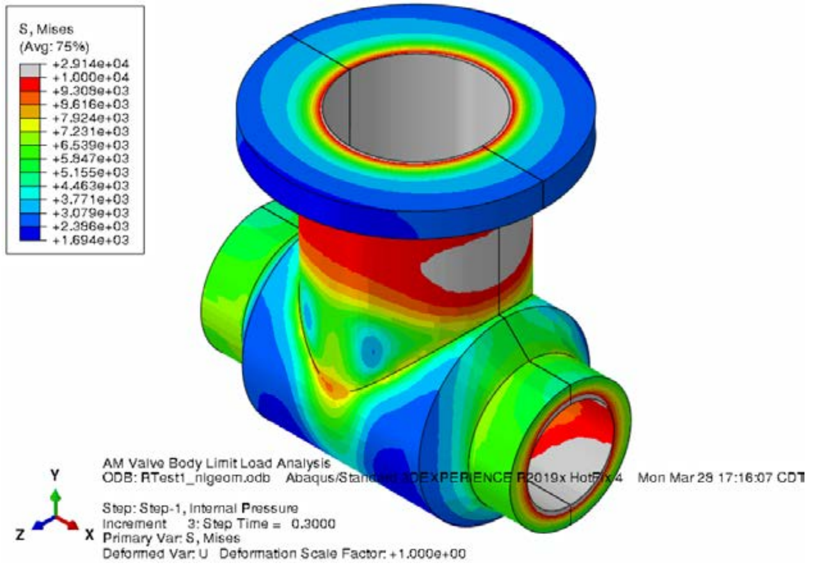
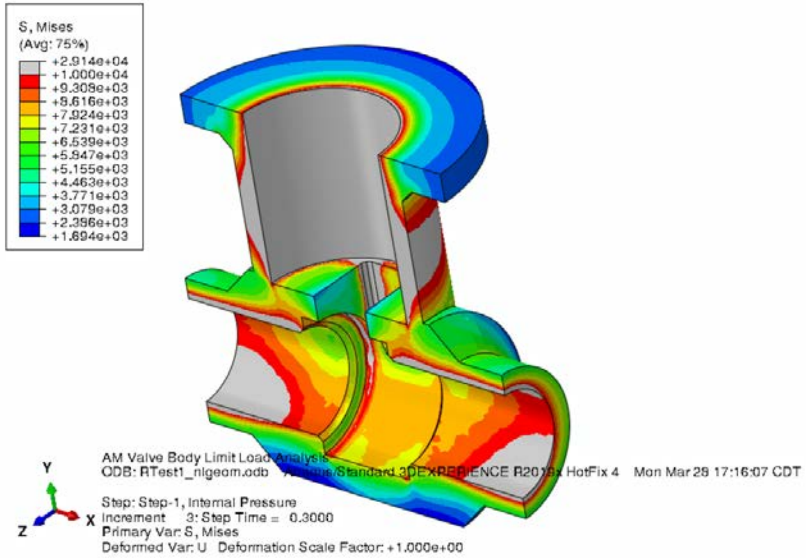
Large Scale Valve Body





316L stainless steel
1,700 lb valve body
11 days to produce

External Point Cloud Scan



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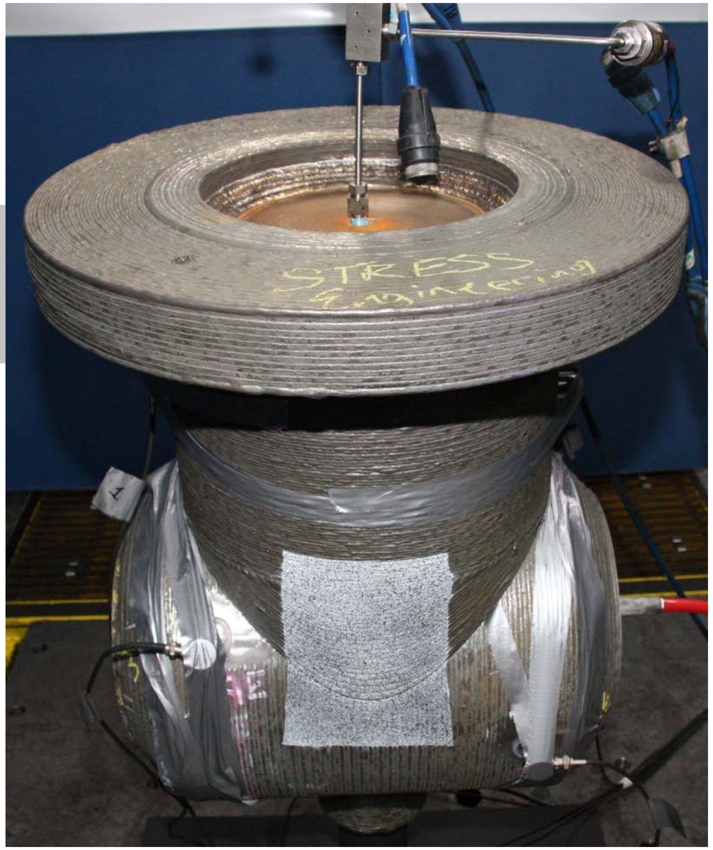
LINCOLN ELECTRIC | Additive Solutions

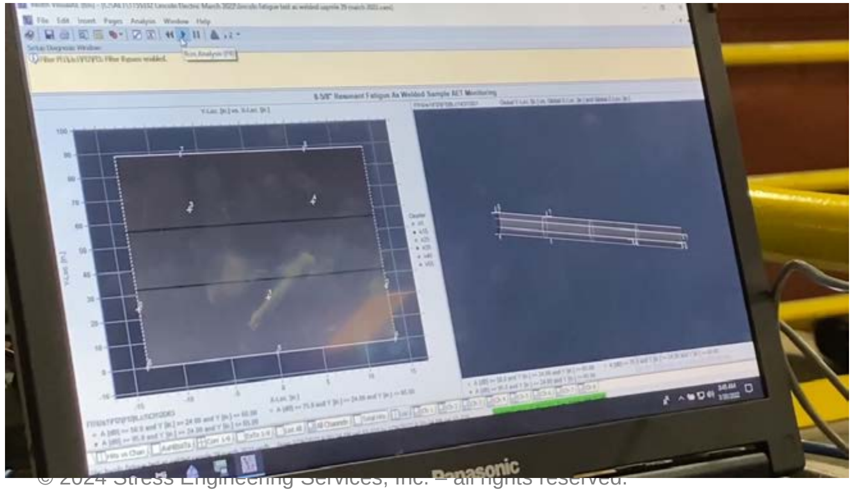
Full Scale Validation Testing

Test Fixture Design and Fabrication

Pressure Testing



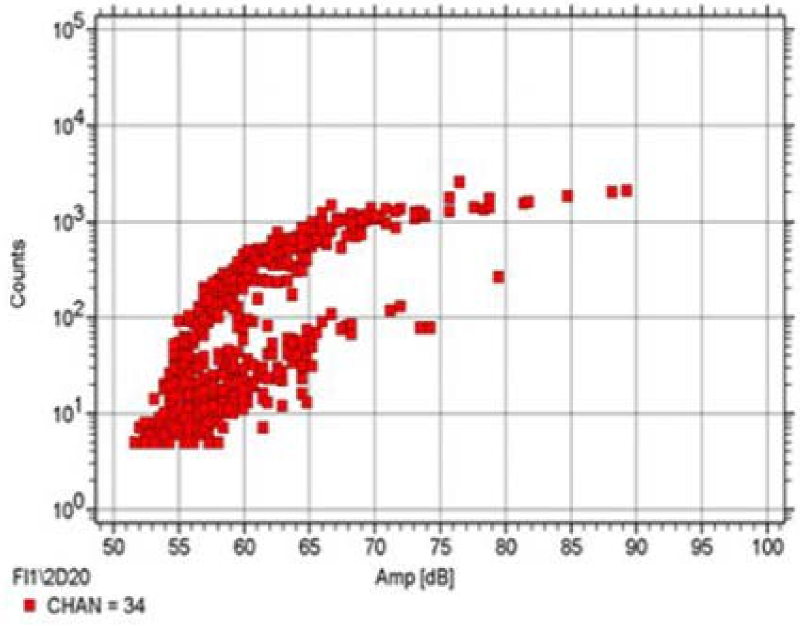
DIC on critical locations
Acoustic Emission

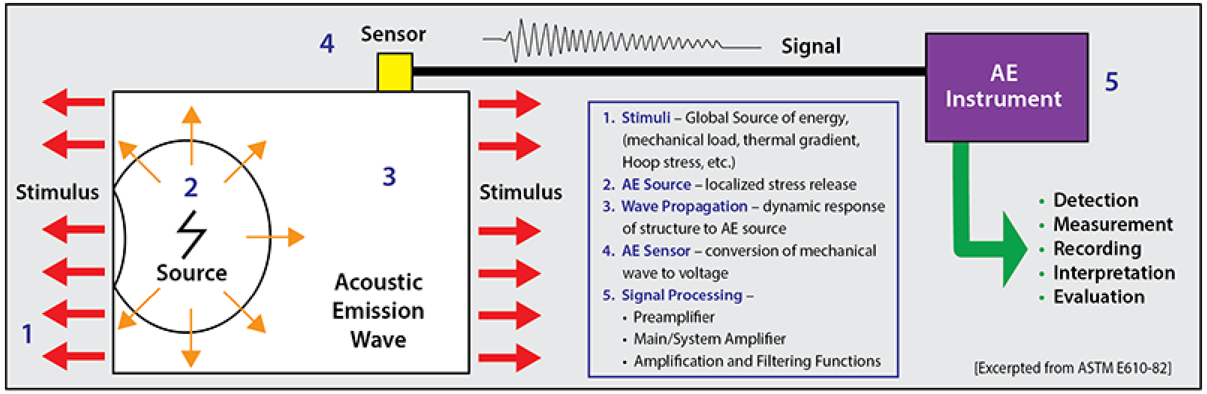


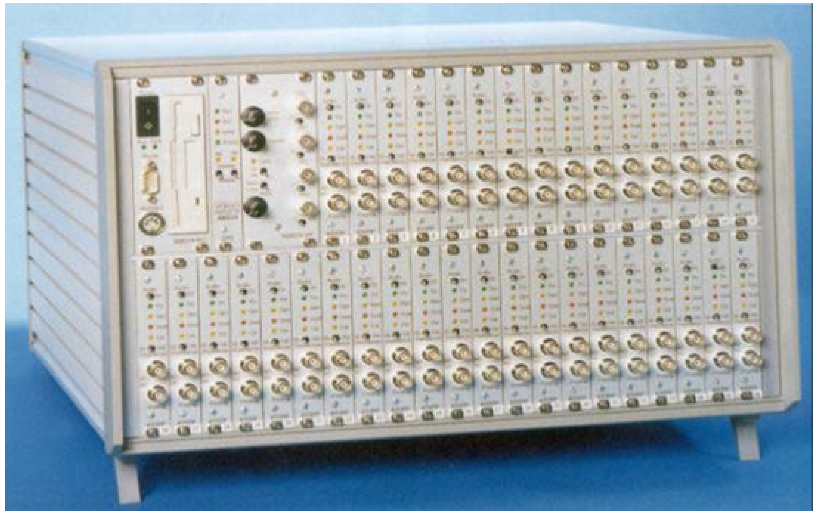
Acoustic Emission Testing (AET)

Technology Highlight

AET is a type of nondestructive test (NDT) that has various uses, including ensuring the structural integrity of vessels, monitoring weld quality and more. The process involves using sensors to detect AE and then converting the waves into electrical signals so that they can be recorded. You can then analyze the results to assess a material's condition and locate any defects. The recorded information can provide potentially valuable information about the origin and significance of a defect in a structure.







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https://www.stress.com/services/energy/downstream/primary-services/acoustic-emission-testing/

USAF Additive Challenge Winner

U.S. AIR FORCE

Stress Engineering organized and led an award-winning multi-company team utilizing virtual collaboration tools during the COVID pandemic to rapidly (< 4 weeks) design and qualify a replacement F-16 additively manufactured part for the USAF

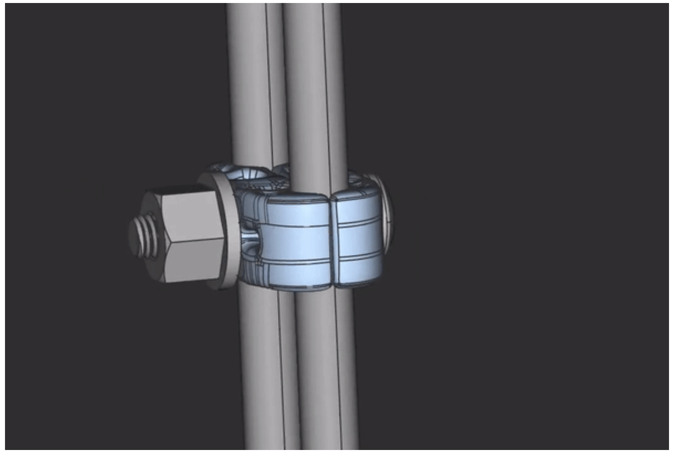
SES Developed a novel rapid qualification strategy to help support the sustainment of USAF aircraft with advanced manufacturing

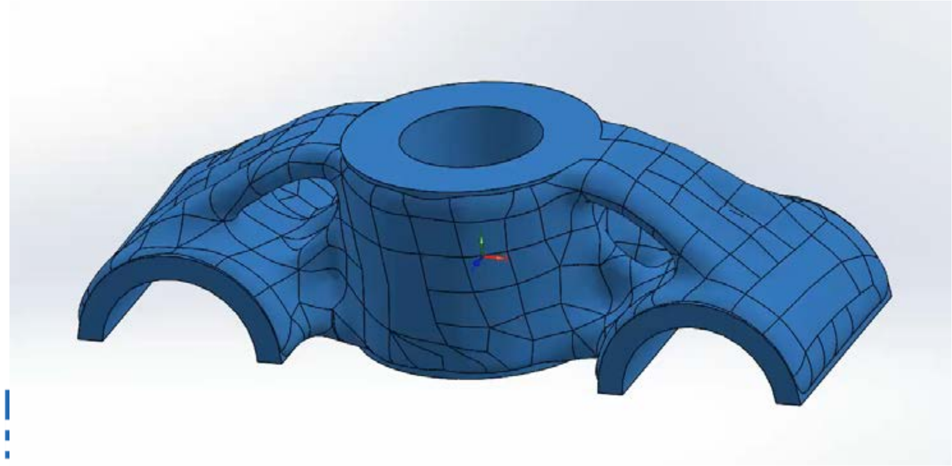
STRESS ENGINEERING SERVICES INC.

https://www.3dprintingmedia.network/us-air-force-advanced-manufacturing-olympics/

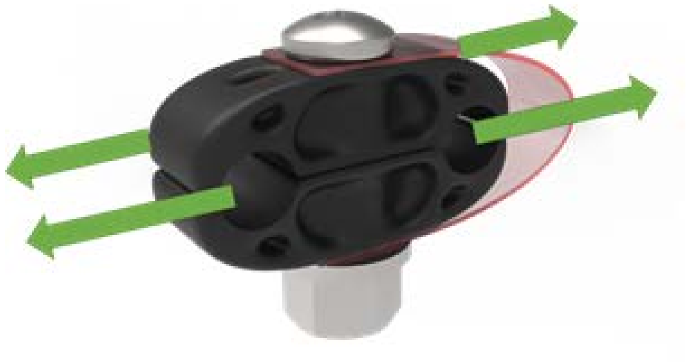
https://ntopology.com/webinars/webinar/rapid-design-of-a-polymer-component-for-flight-qualification/

Iterative Design/Analysis/Test Process

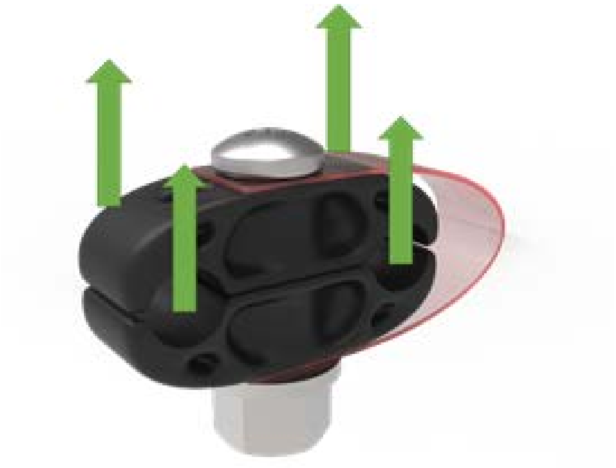




Full Scale Testing

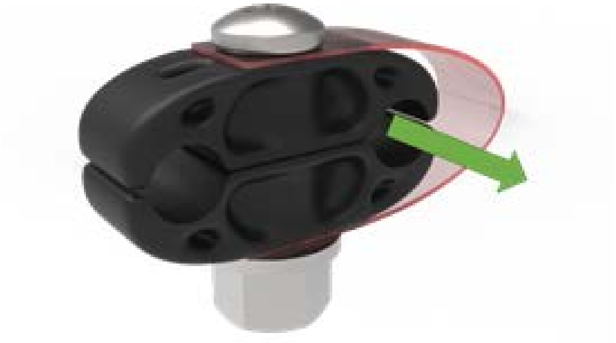


Horizontal Pull Testing Direction

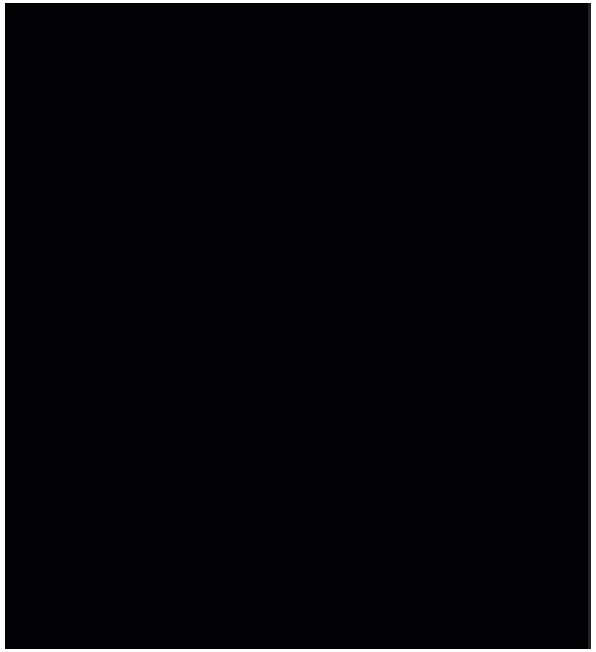


Vertical Pull Testing Direction

Double Pull-Out Testing Direction



Single Pull-Out Testing Direction



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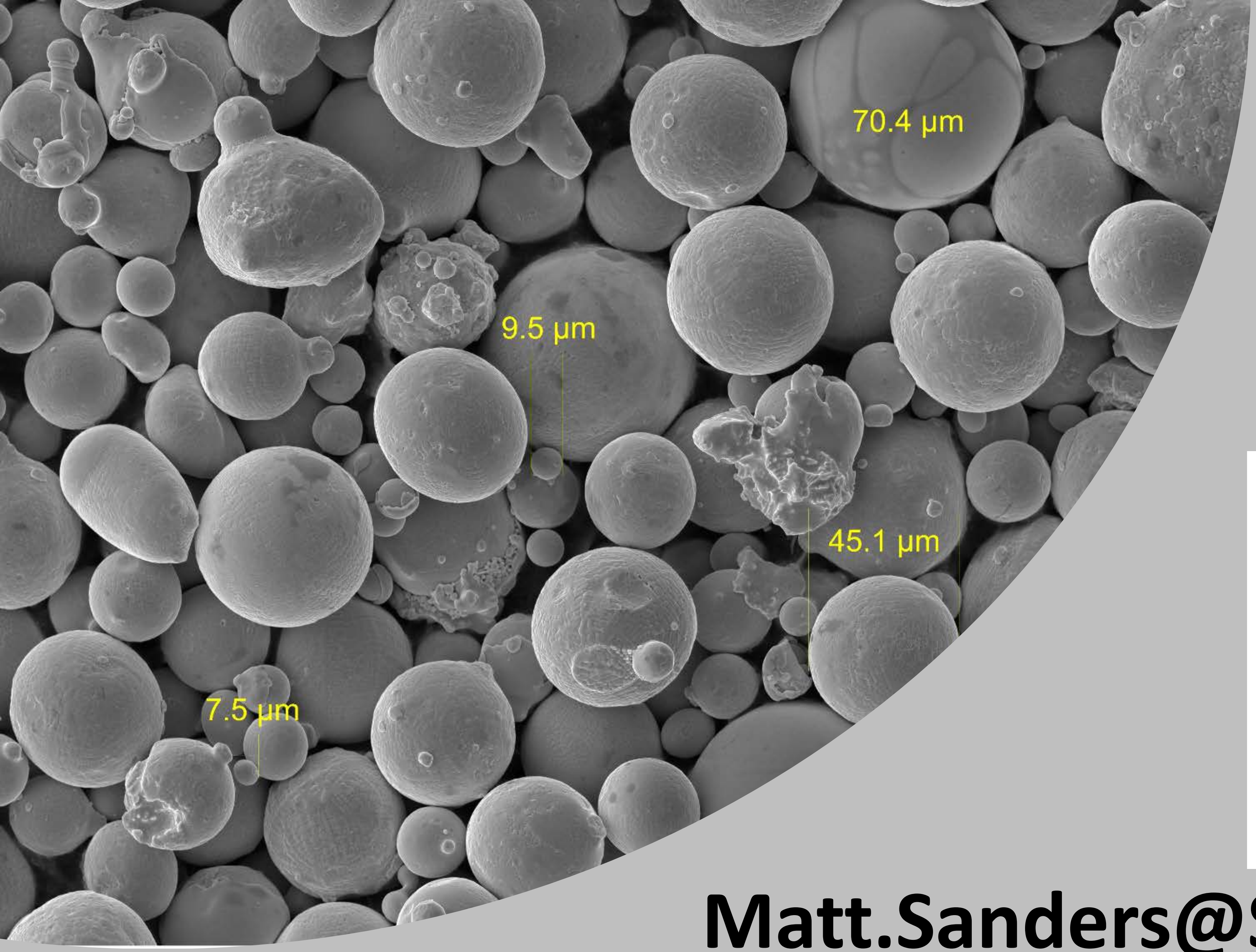

Thank you!

Matt.Sanders@Stress.com