# Qualification and Certification for Additive Manufacturing Supported by Model-based Approach

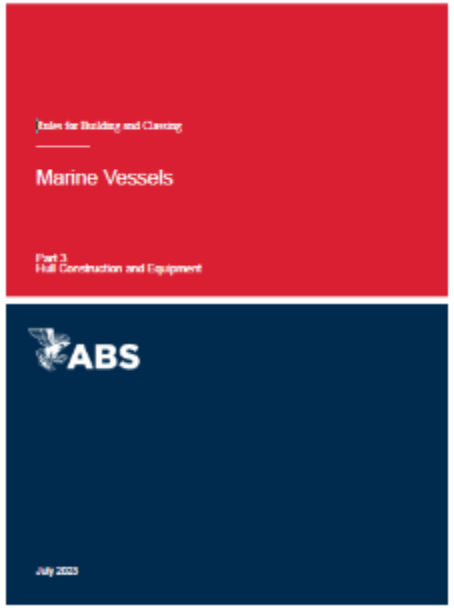
Dongchun (Mary) Qiao | October 25, 2023

# Acknowledgements

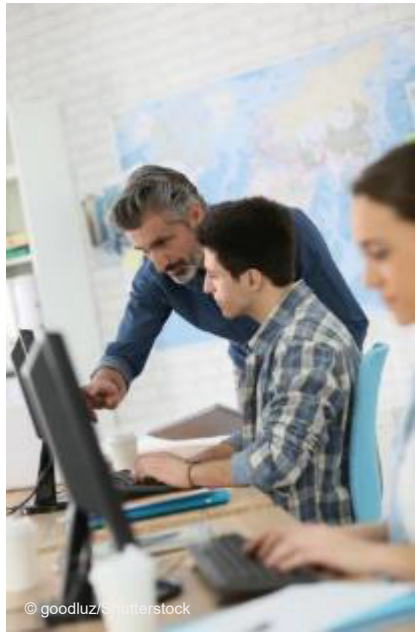

- This project is funded by Grant 70NANB21H038 from the U.S. Department of Commerce, National Institute of Standards and Technology (NIST).

# American Bureau of Shipping

**Establish Design Rules and Standards**

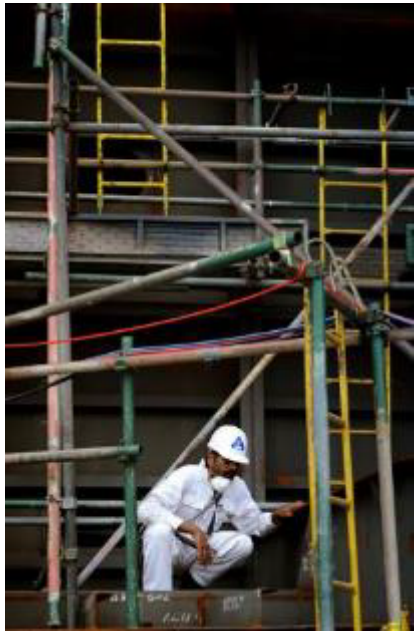



**Review Designs against Rules and Standards**




**Confirm Vessels/Equipment Built in accordance with Approved Plans**

**Verify Vessels/Equipment Maintained to Accepted Standards**

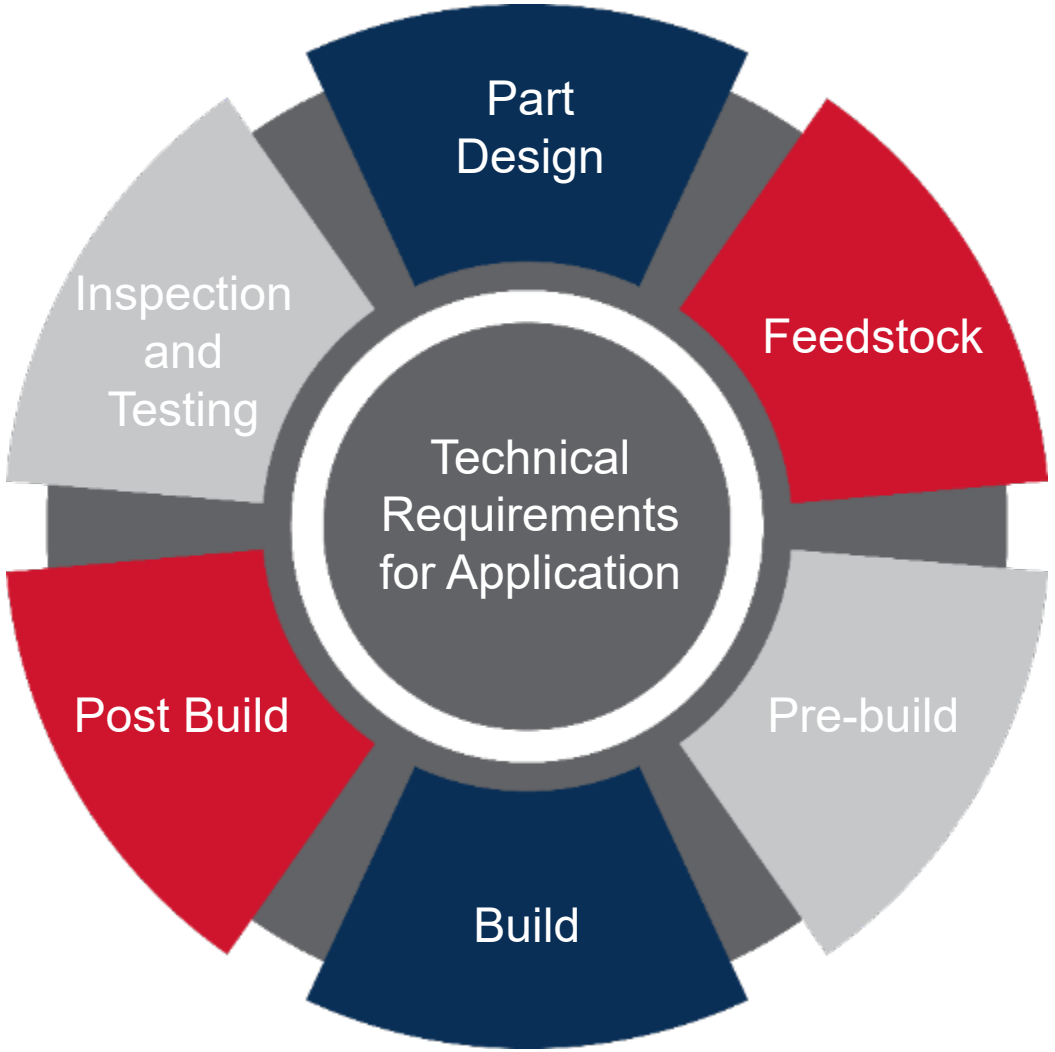


# Outline

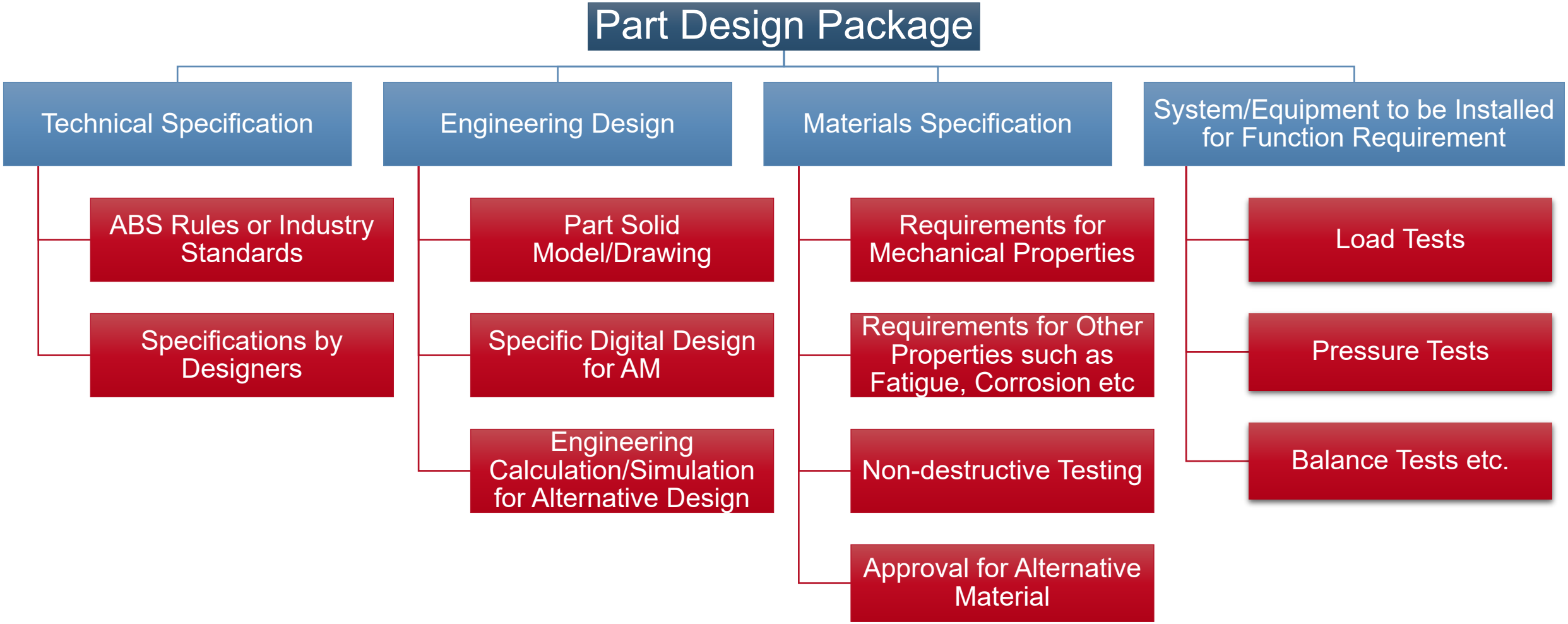
- Standard Qualification Approach
- Risk Assessment
- Rapid Qualification by Model-Based Approaches
- Summary

# Standard Qualification Approach

- Documentation
  - Part Design Package with Revision
  - Manufacturing Procedure/Process Plan
  - Inspection and Testing Plan
  - Applicable Rules, Industry Standards
- Qualification
  - Procedure Qualification
  - Material Qualification – AM Facility
  - Prototype Part Qualification – AM Part for Each Specific Part
- Production
  - Qualified AM Process
  - Agreed Inspection and Test Plan
  - Quality Control



# Part Design


Part Design Package
Technical Specification
ABS Rules or Industry Standards
Specifications by Designers
Engineering Design
Part Solid Model/Drawing
Specific Digital Design for AM
Engineering Calculation/Simulation for Alternative Design
Materials Specification
Requirements for Mechanical Properties
Requirements for Other Properties such as Fatigue, Corrosion etc
Non-destructive Testing
Approval for Alternative Material
System/Equipment to be Installed for Function Requirement
Load Tests
Pressure Tests
Balance Tests etc.

# Design Requirements

## Design Criteria

- Strength, ASME BPVC II D

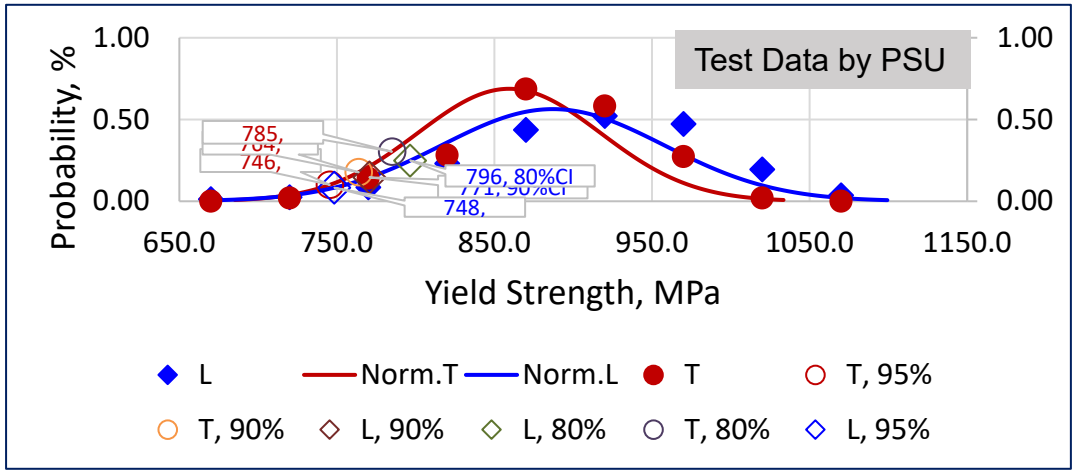
$$\sigma_{max} = \frac{\sigma}{f}$$

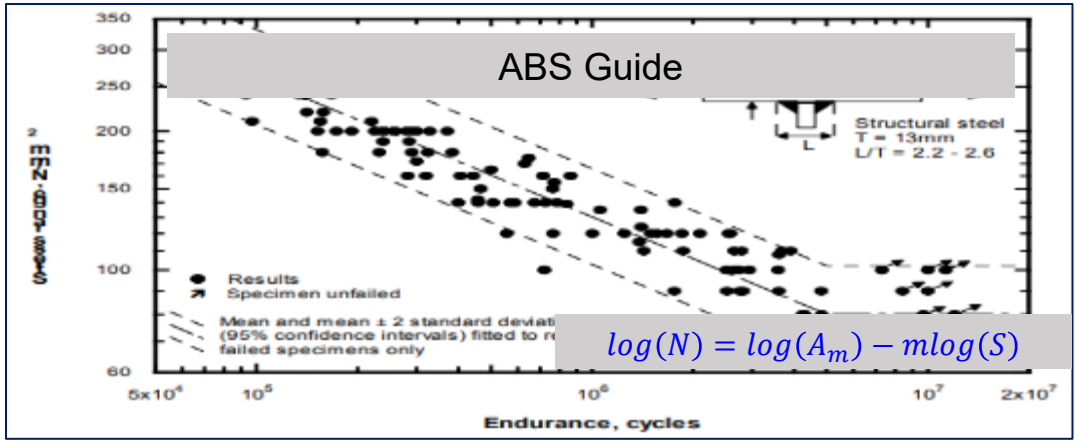
- Fatigue

$$Fatigue\ Design\ Factor\ (FDF) \geq 1$$

- Fracture

$$K = \sigma\sqrt{\pi a} \leq K_{Ic}$$



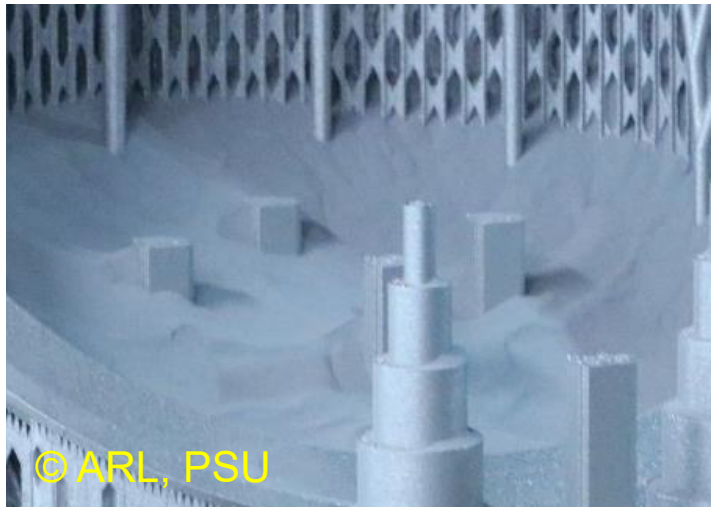
# Feedstock

## Powder Specification

- Material grade
- Chemical composition
- Powder manufacturing process
- Post-atomization classification
  Powder size & distribution
- Powder morphology and internal microstructure
- Flowability
- Applicable AM process
- Documentation

## Wire Specification

- Material grade
- Chemical composition
- Wire size
- The applicable additive manufacturing process
- Documentation




# Build Procedure Specification

## Industry Standards

- AWS D20.1 for Specification for Fabrication of Metal Components using AM
- ASME PTB-13 for Criteria for Pressure Retaining Metallic Components using AM
- ASTM F3303 for PBF Process
- ASTM F3187 for DED Process

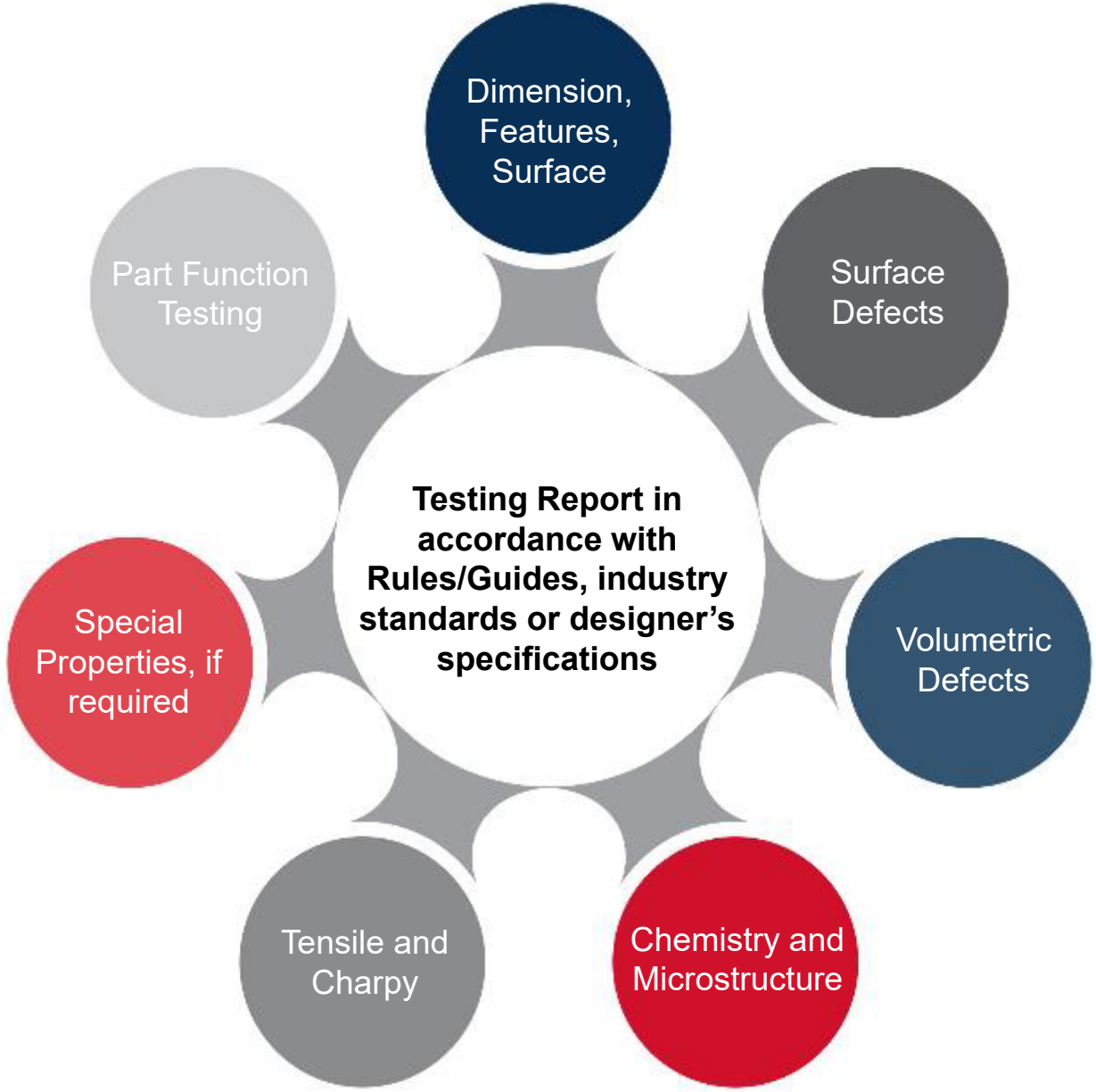
## PBF and DED Procedure Specification

- Heat Source
- Deposition
- Build Environment and Other Parameters
- Procedure Qualification Record (PQR) – Pre-build, Build and Post-Build



# Inspection and Testing

- ABS Rules for Materials and Welding and the applicable sections enclosed in other ABS Rules for application
- ASTM A751 for Chemical Analysis
- ASTM A370 for Mechanical Testing
- ASTM E8 for Tensile Testing
- ASTM E23 for Notched Bar Impact Testing
- ASTM E10 for Hardness
- ABS Guide for Non-Destructive Inspection or ISO 5817, ISO 10675-1
- Other recognized standards, such as ISO, ASTM, API, ASME

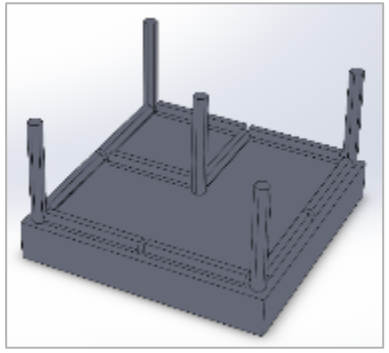


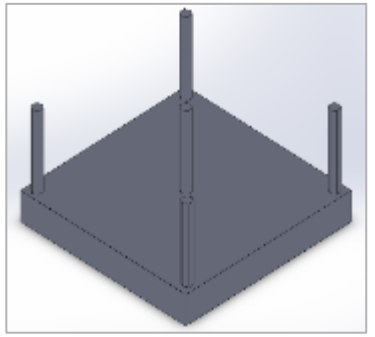
# Standard Qualification Approach

## Challenges

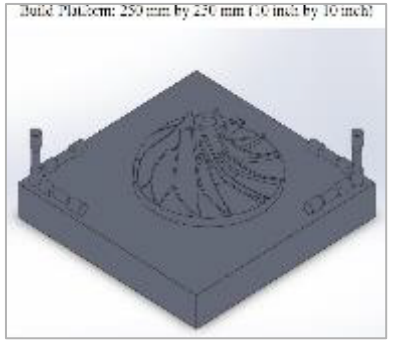
- Qualification is linked to each part design, material grade and AM machine.
- Qualification/approval cost is high.
- Standard qualification approach is not suitable for AM benefits in spare parts, obsolete parts, small batch production.
- High approval test scope is big hurdle for expanded adoption.

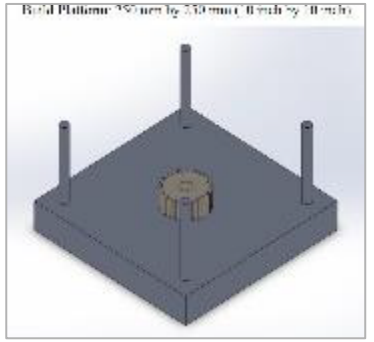
Standard Approval Tests - Materials





Standard Approval Tests - Parts





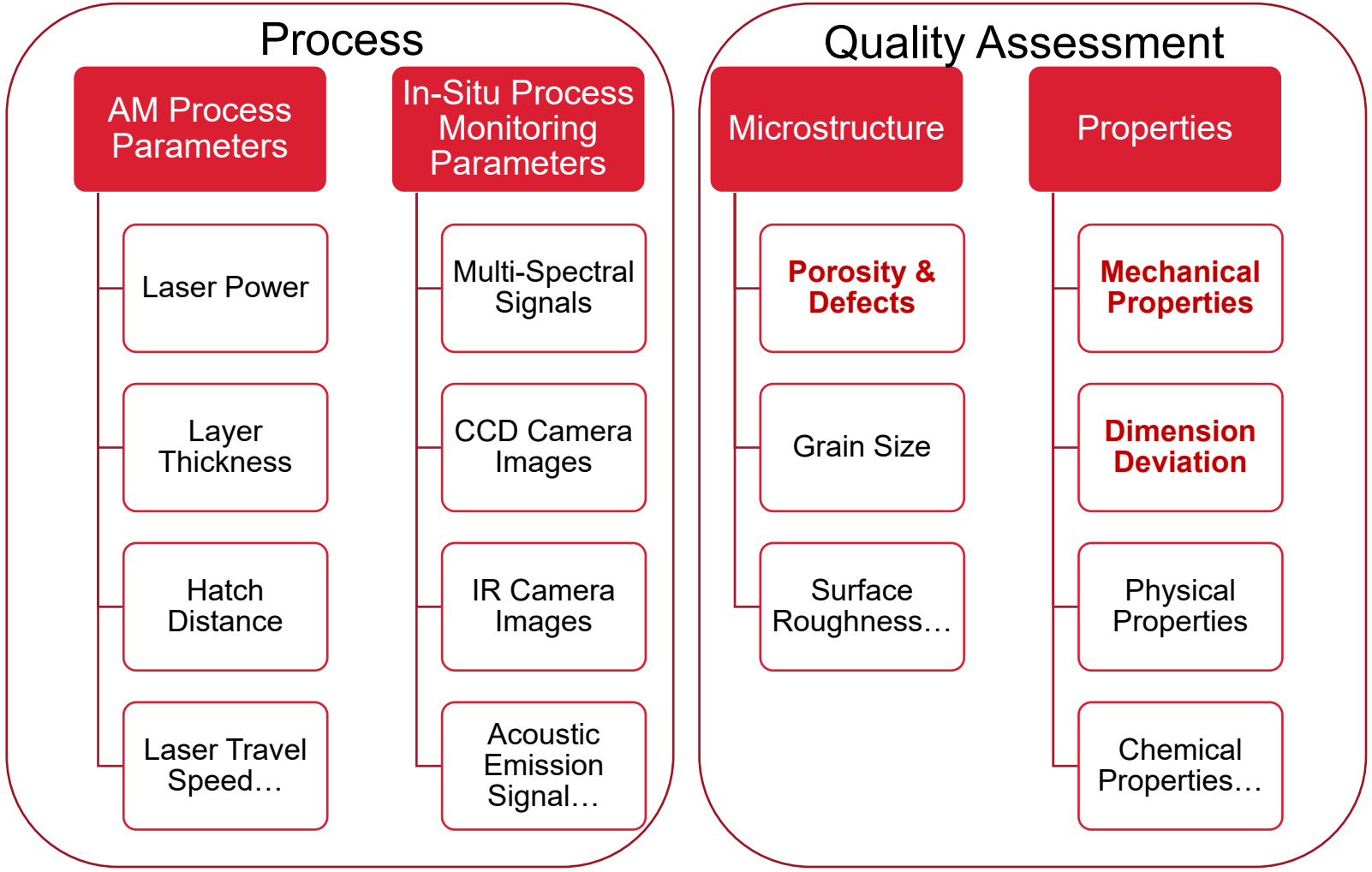
# Risk Assessment

- AM Test Level 1, 2, 3
  - Critical application (Test Level 3, High)
  - Semi-critical application (Test Level 3, Medium)
  - Non-critical application (Test Level 3, Low)

| | | | | | |
|---|---|---|---|---|---|
| Likelihood | (<20%, >10%) | 3 High | **3** | **6** | **9** |
| | (<10%, >5%) | 2 Medium | **2** | **4** | **6** |
| | (<5%) | 1 Low | **1** | **2** | **3** |
| Risk Assessment = Likelihood × Consequences<br>**AM Level 1, 2, 3** | | | 1 Low | 2 Medium | 3 High |
| | | | ISO 5817 Class D | ISO 5817 Class C | ISO 5817 Class B |
| | | | Consequences (Increasing Severity >>) | | |

# Rapid Qualification by Model-Based Approaches

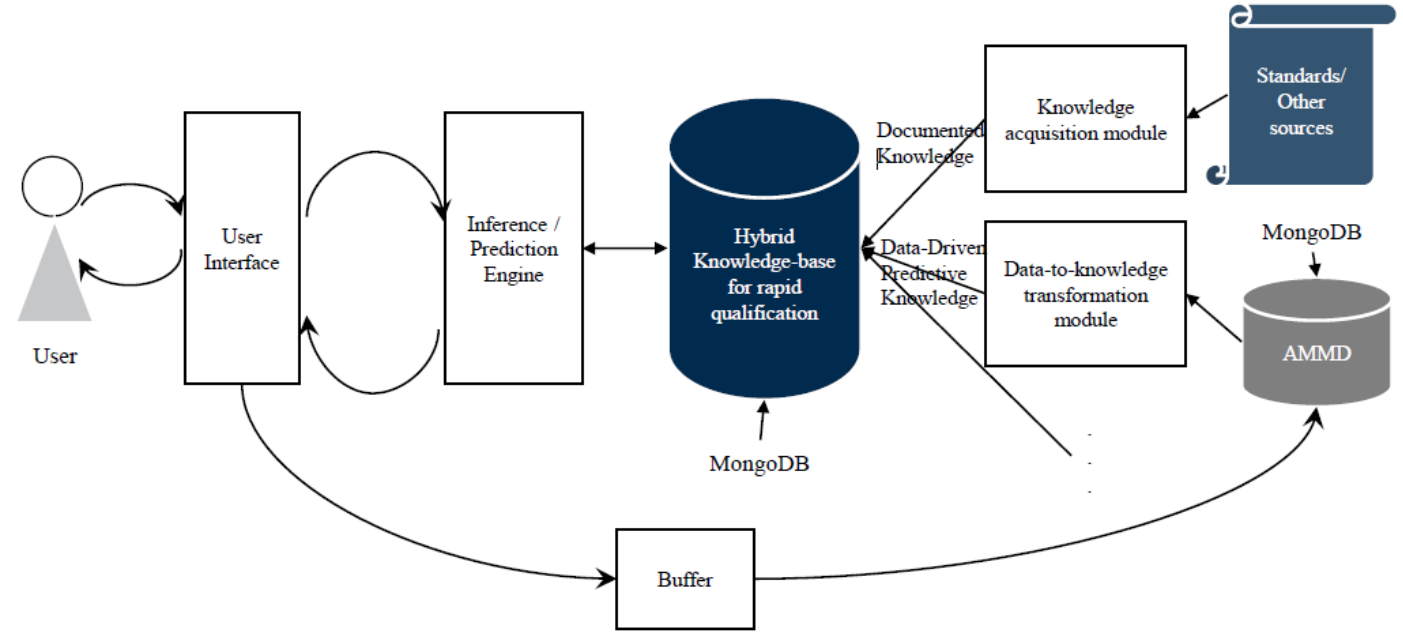
- Expert System/knowledge-Based Approach
- In-Situ Process Monitoring Approach
- Physics Model Approach
- Guidance for AM Industry – Rapid Qualification with Verified and Validated Model Based Approaches

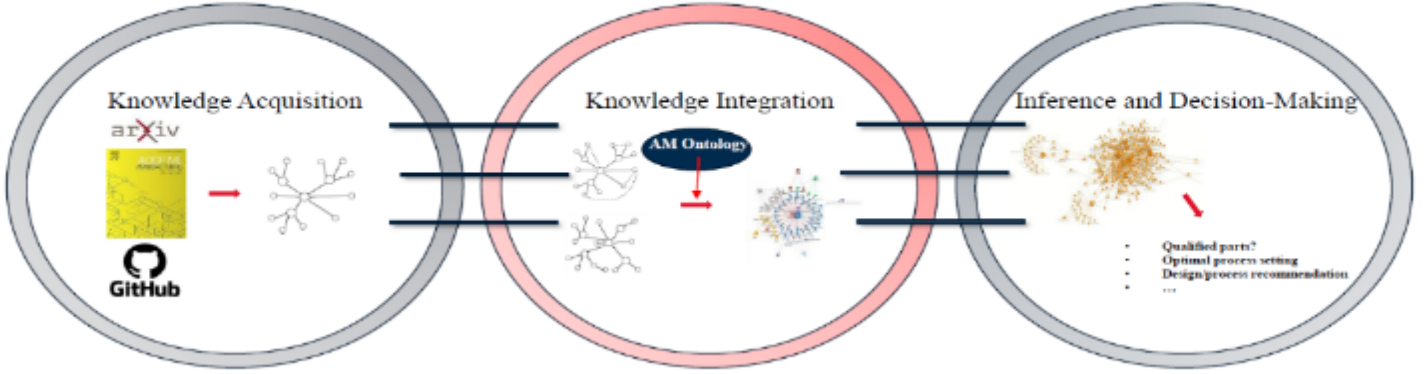



https://link.springer.com/article/10.1007/s11837-020-04155-y

# Expert/Knowledge-Based Model

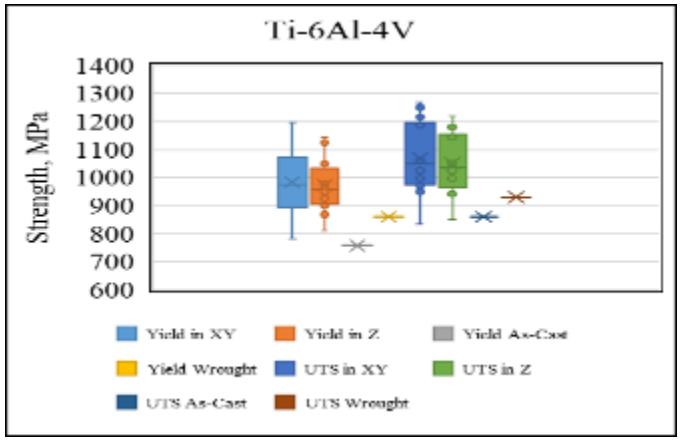
- User's Request
  - Knowledge Acquisition
  - Data to Knowledge Transformation
  - Hybrid Knowledge for Prediction
- Inference and Decision-Making

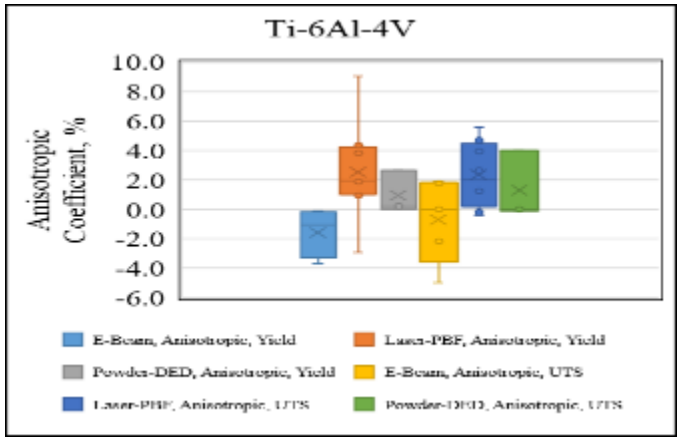


# Reduction of Test Scope Supported by Expert/Knowledge-Based Model

- Expert-System or Statistics Model
  - $f(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{X-\mu}{\sigma}\right)^2}$, for test data from literature or manufacturer
  - Design required yield and UTS
  - Anisotropic coefficient
- Reduce Test Scope for Approval Tests



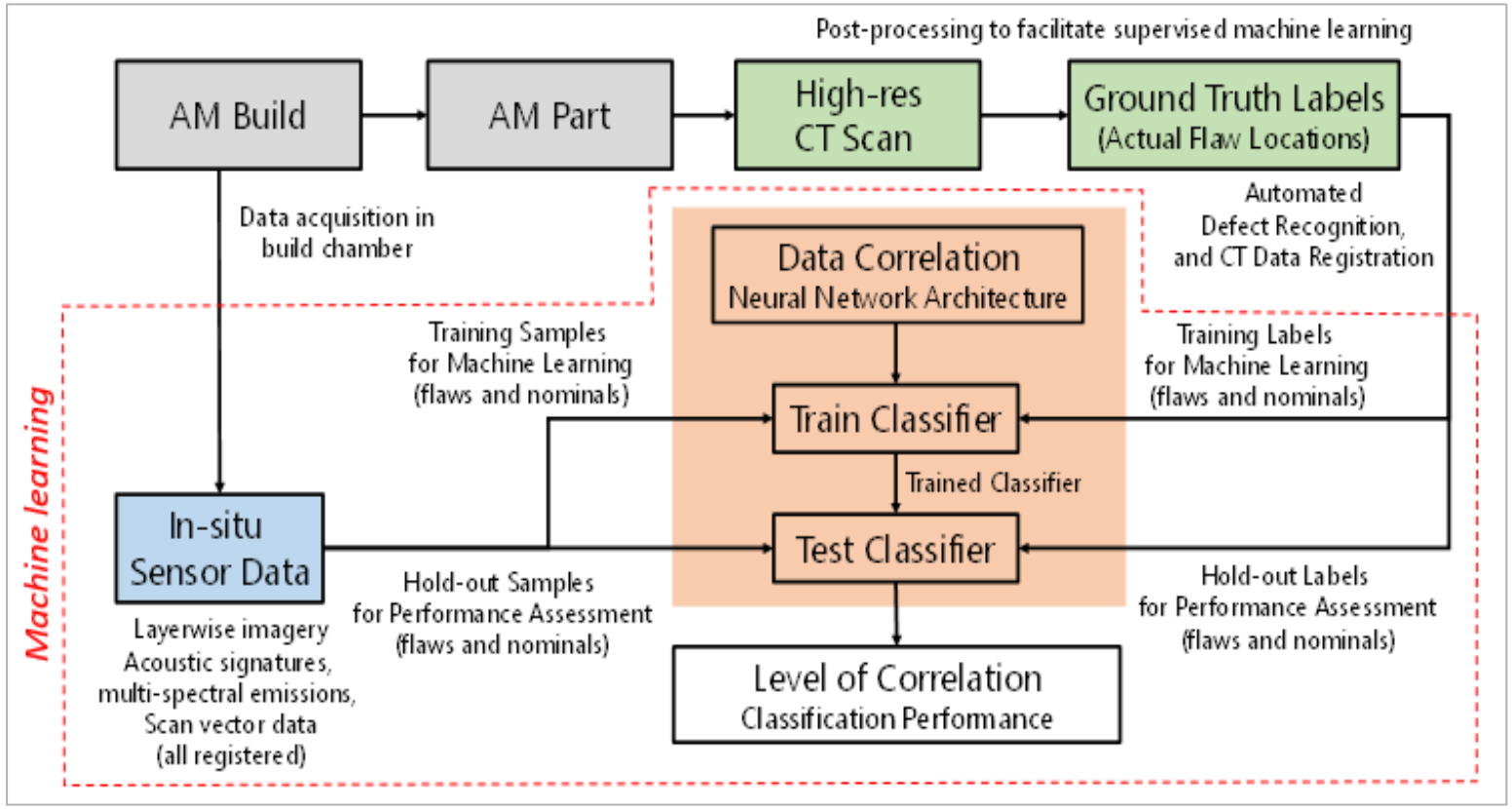

Yield, UTS and Anisotropic Coefficient in X/Y and Z direction for E-Beam-PBF, Laser-PBF and Laser-Powder-DED Ti-6Al-4V

Kok, Y. Anisotropy and Heterogeneity of Microstructure and Mechanical Properties in Metal Additive Manufacturing: A Critical Review, Materials and Design, 2018, 139: 565-586

| Direction | Yield, ksi | | Charpy, ft-lbs at 0 °C | |
|---|---|---|---|---|
| | Avg. | Std. Dev. | Avg. | Std. Dev. |
| X | 86.2 | 0.78 | 95.5 | 2.89 |
| Y | 86.0 | 1.38 | - | - |
| Z | 76.2 | 1.17 | 79.3 | 1.53 |
| ASTM F3184 for PBF 316L: Min. Yield 30.0 ksi | | | | |

# In-situ Monitoring and Machine Learning Model

- In-Situ Monitoring Flaw Detection
  - $P_2 = 1 - \sum_{x=s}^{N} \binom{N}{x} (P_1)^x (1 - P_1)^{N-x}$, for sufficient seeded defects and defined accuracy
  - Train and Test Classifier
  - Ground Truth Labels by CT Scan
  - Partial/full replacement of NDT



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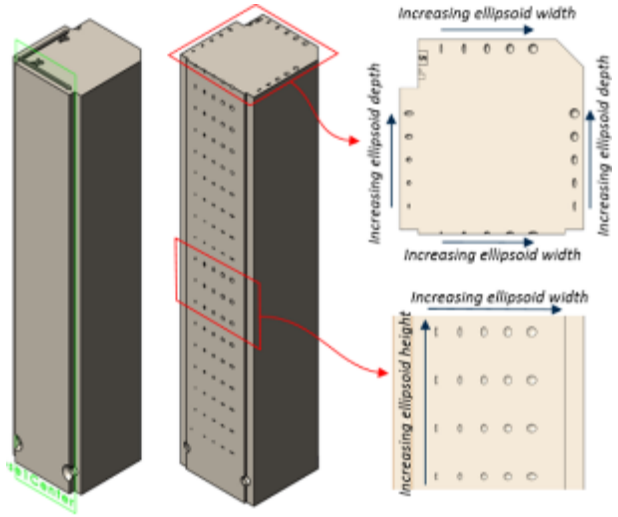
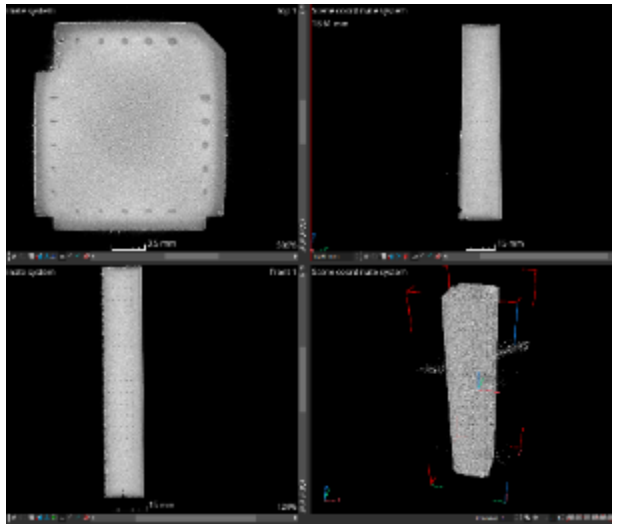
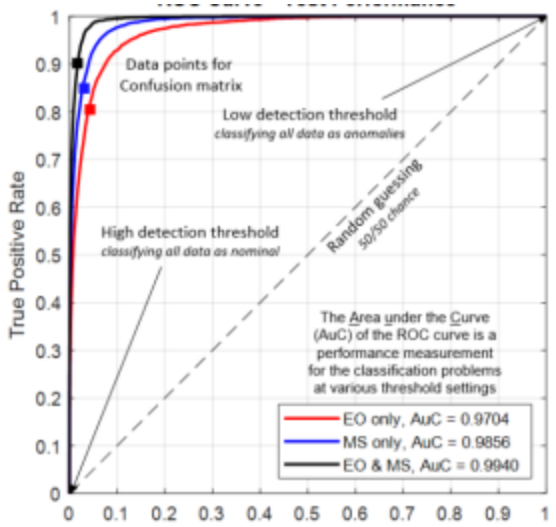
# Flaw Detection by In-situ Monitoring and Machine Learning Model




Surrogate Flaw © ARL, PSU

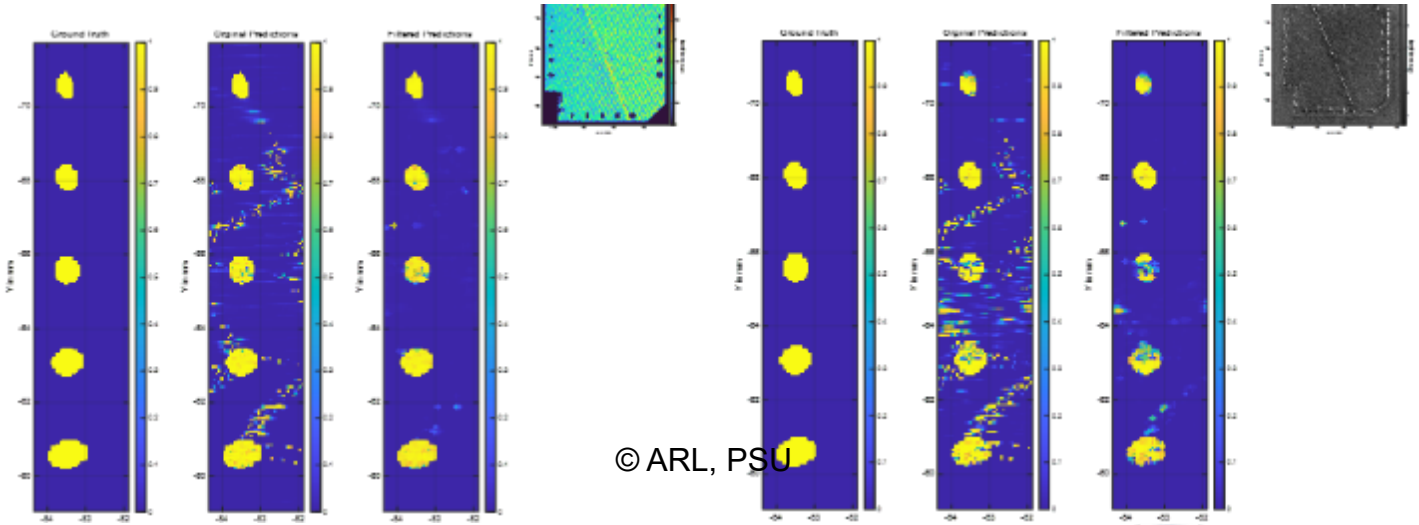


CT Scan © ARL, PSU




ROC Curve © ARL, PSU

- Ground Truth
- Original Predictions
- Filtered Prediction for Multi-Spectral (Left)



© ARL, PSU

- Ground Truth
- Original Predictions
- Filtered Prediction for Layerwise (Right)



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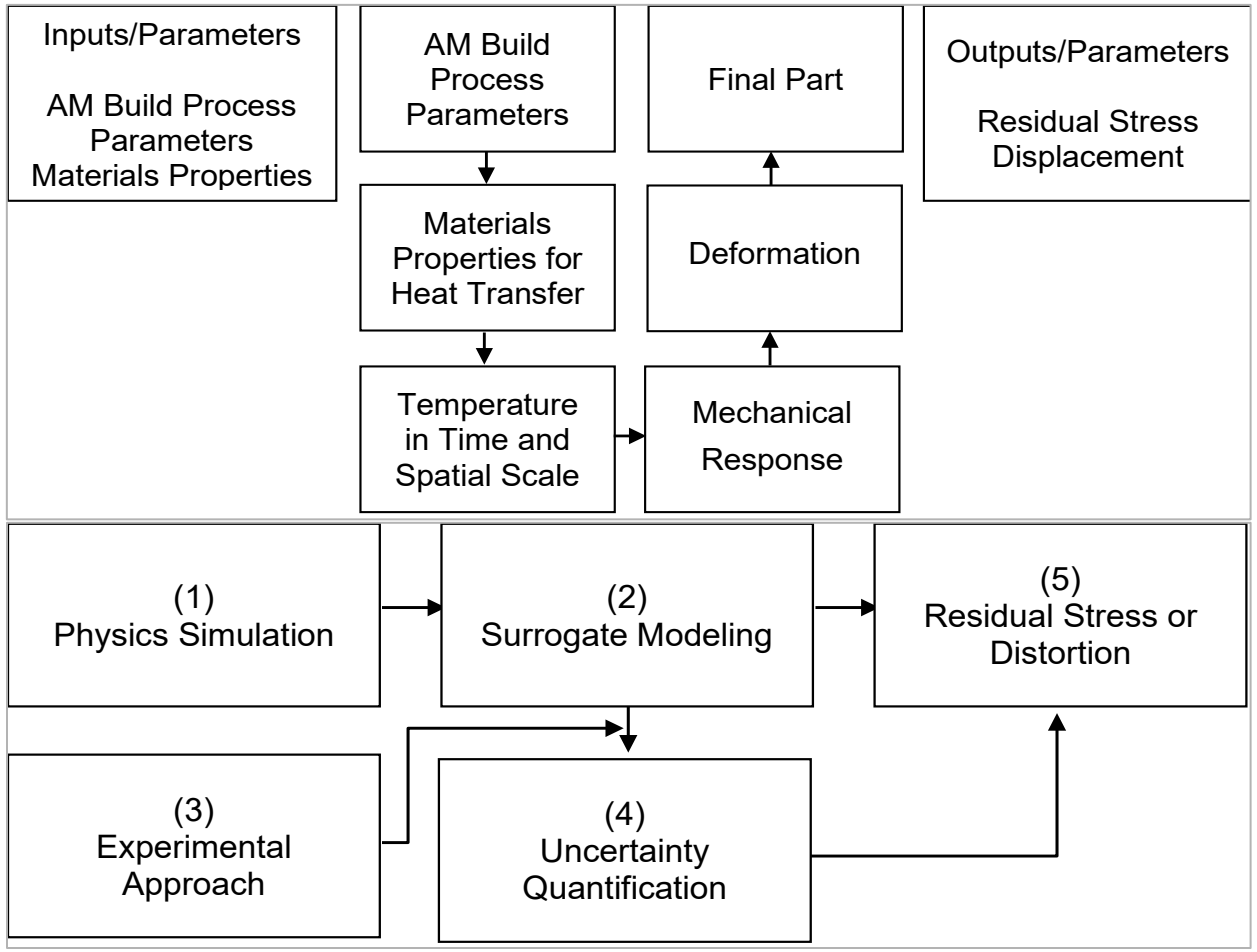
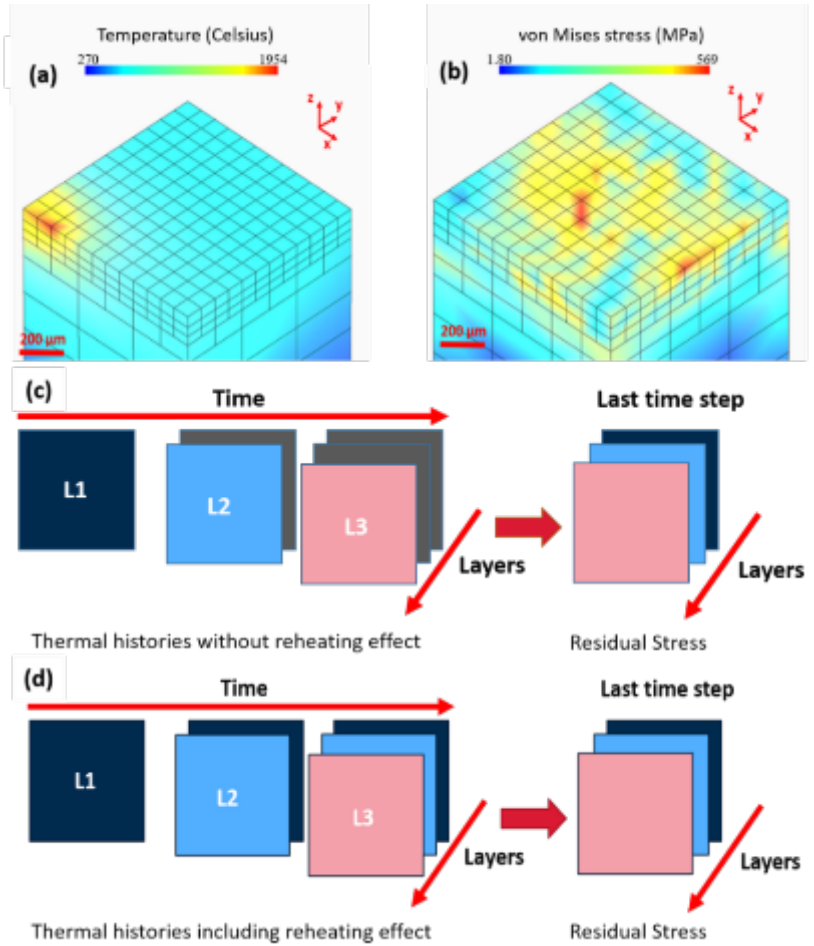
# Physics Simulation Model

- Physics Simulation

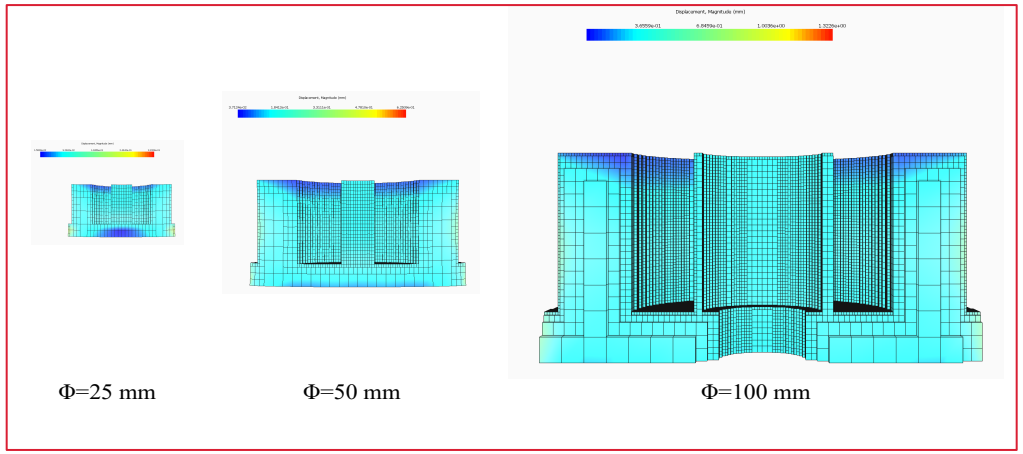


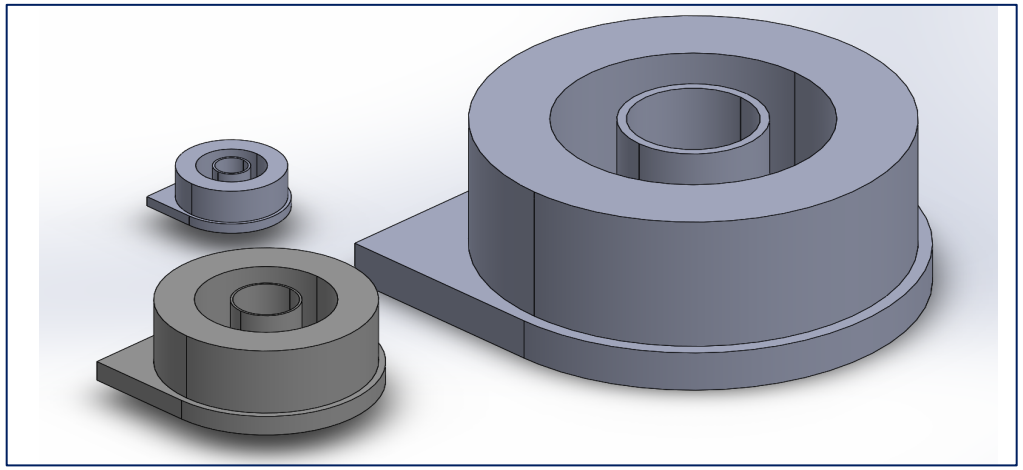

## Fine Scale Model

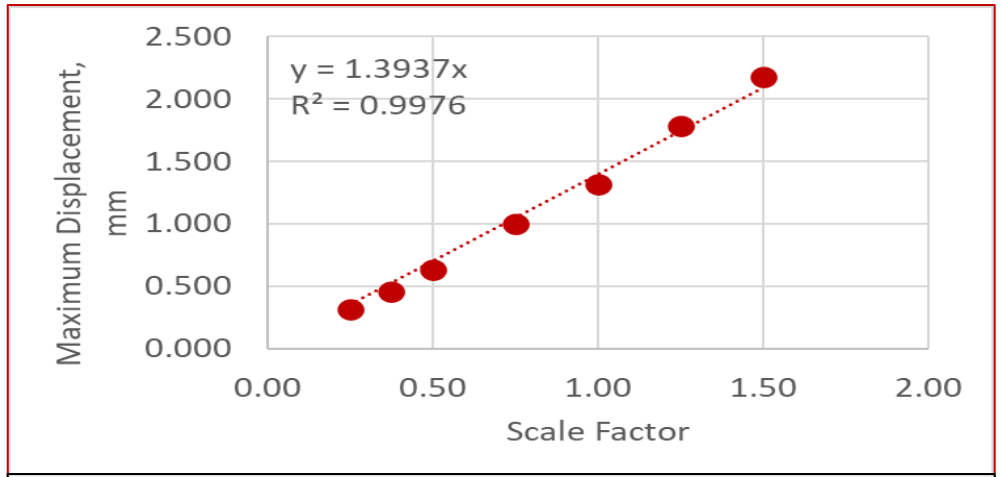


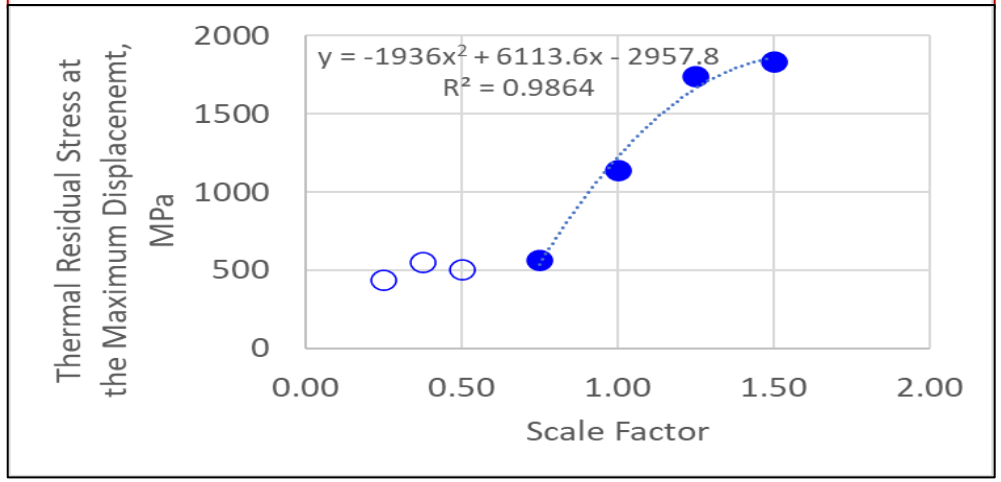
# Distortion and Residual Stress Prediction by Physics Simulation Model

- Cylinder Test Artifact Results – Part Scale Model



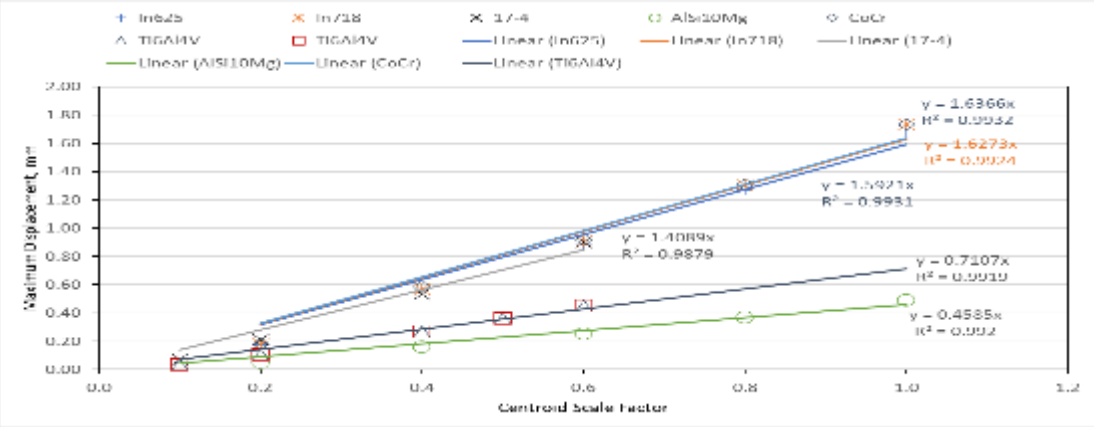





# Distortion and Residual Stress Prediction by Physics Simulation Model

- Nozzle Ring Results





| Scale Factor | Dimension, mm | Scale Factor | Dimension, mm |
|---|---|---|---|
| 0.1 | 22.277×22.277×4.76 | 0.7 | 155.94×155.94×33.32 |
| 0.2 | 44.554×44.554×9.52 | 0.8 | 178.22×178.22×38.08 |
| 0.4 | 89.108×89.108×19.4 | 1.0 | 222.77×222.77×47.6 |
| 0.6 | 133.66×133.66×28.56 | - | - |



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# Summary

## Purchase Specification

- Part Design Package – Solid Model and AM Final Material Specification
- Test Level – AM Level 1, 2, 3
- Any Additional Requirements for Intended Application

## Manufacturing Procedure

- Manufacturing Procedure and Specification
- Inspection and Testing Plan
- Procedure Qualification
- Material Qualification
- Part Qualification

## Rapid Qualification

- Reduced Essential Parameters for Range of Approval
- AM Level 3, 2, 1 – Qualification for Specific Part, by Part Family or by Design Feature Family
- Partial/Full Replacement NDT using In-situ Monitoring Tool
- Reduced Test Scope by Recognized Test Data from Literature or Manufacturer
- Potential Qualification by Material Group

# Thank You

www.eagle.org

# Recent ABS Projects on Additive Manufacturing

- ABS Requirements for Additive Manufacturing
- Robotic Arc Directed Energy Deposition (DED) – Marine Component or Repair
- Rapid Qualification of Metal-based AM Supported by Models
- Shore-Based Additive Manufacturing in Support of MSC (Military Sealift Command)
- Scaling Up 3D Printed Steel Castings
- Crane Hook with Design Load 80 Metric Tonnes using Wire Arc Additive Manufacturing
- Implementation of AM Spare Parts Onboard