Standardization, Qualification, & Inspection Challenges for Additive Manufacturing

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Missile Systems

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Raytheon: Who We Are

- Our Vision: **One global team creating trusted, innovative solutions to make the world a safer place.**

- Raytheon Company is a technology and innovation leader specializing in defense, space, security and civil markets throughout the world.
  - 2014 NET SALES: $23 BILLION
  - 61,000 EMPLOYEES WORLDWIDE

- Headquarters: Waltham, Massachusetts
Raytheon’s innovative technologies serve customers in more than 80 nations, with applications ranging from Command and Control to Missile Defense.
Raytheon Additive Manufacturing Centers

El Segundo, CA
- **Materials:** Plastics
- **Processes:** Polyjet, FDM

Fullerton, CA
- **Materials:** Plastics
- **Processes:** FDM

Indianapolis, IN
- **Materials:** Plastics
- **Processes:** SLA, FDM

Tewksbury, MA
- **Materials:** Plastics
- **Processes:** SLA, FDM

Lowell, MA
- **Materials:** Electronics
- **Processes:** Micro dispense, Aerosol Jet

Andover, MA
- **Materials:** Plastics
- **Processes:** FDM

Tucson, AZ
- **Materials:** Plastics
- **Processes:** FDM

Dallas, TX
- **Materials:** Metals
  - NonMetals
- **Processes:** L-PBF, SLA, SLS

McKinney, TX
- **Materials:** Plastics
- **Processes:** SLA, SLS

Richardson, TX
- **Materials:** Plastics
- **Processes:** Polyjet

Largo, FL
- **Materials:** Plastics
- **Processes:** FDM

Raytheon in-house AM capabilities models, tooling, prototypes, and production

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Design Verification, Assembly Check, & Human Factors Engineering

- Use of models to gather customer requirements and feedback
- Demonstrates interaction between multiple systems
- Confirm accuracy of a design – Form, Fit, Function
- Manufacturing Tooling
- Verify human factors

Product Scale Model for Fit Checks

Functional/Fit Check

Models for Human Factors

Display Model for Customers
StereoLithography AM Casting Pattern

Challenges Met:
- 16” x 18” x 24”, premium properties 45/35/3, cast net card guides & cooling fins
- State-of-the-art investment cast electronics box
- Machined, finished, and hardware assembled @ 25 hrs
- Single item versus 40 piece-part assembly
- Results: Simplified design & analysis
  Reduced assembly labor
  Lowest Total Cost of Ownership
Rapid Iteration Prototyping - Low Cost Development

- Early product design & development
- Multiple cycles vs traditional path to design + build + test
- Rapid design and validation
- Early design optimization
- Cost competitive with traditional processing for smaller quantities
- Transfer to traditional processing for cost efficiency at higher production rates

Example: Engineering Modeling Development
Electron Beam – Powder Bed Fusion

Cycles of Learning = Substantial ROI
Optimized Structures – Lightweighting

- Applied loads and constraints to legacy design
- Generated parametric model from optimized geometry
- Compared weight & performance: baseline design vs optimized structure

Baseline Design

Material – Cast Aluminum A357
Weight – 0.67 lbs

Optimized Design

Material – L-PBF Aluminum AlSi10Mg
Weight – 0.49 lbs

Simplified concept for producible design

~ 30% Weight Reduction
Missile – Additive Manufacturing Applications
Thermal Management
- Robust Hermetic Fluid Channels

- Fabricated and validated full scale liquid coldwalls.
- Geometric design rules for multi-planar internal channels in PBF structures.
- Developed powder removal techniques complimentary to channel geometry.
- Validated via manufacture, x-ray, CT scan inspection, 180psi pressure testing, vibration/shock testing to operational requirements.
- Demonstrated thermal and pressure drop performance in coldwall is equal or improved from traditional designs. Substantial design freedom.

Robust AM parts functionally validated (TRL), … but qualification & production QA developments still required. **Manufacturing Readiness Level** is key!
Process Variability: Equipment + Operation

Ultimate Tensile Strength

Materials Feedstock differences:
- Proprietary Formulations
- Powder Atomization Method
- Particle Size & Morphology

Machine platform differences:
- Laser Power Control
- Scanning Strategy
- Support Structure
- Build Speed

Post Processing differences:
- Stress Relief or Heat Treatment
- HIP or Not (Hot Isostatic Pressing)

Build orientation varies:
- Properties Anisotropic (X, Y ≠ Z)
Particle Size Distribution of Four AM Powder Suppliers

SEM Images from 4 Powder Suppliers to Produce L-PBF Test Coupons

Powder-thru-Part Process Control Critical to Developing Structural Components
Traditional Wrought Metal Process Flow

Starting Cast Ingot or HIP Powder Compact

Intermediate Product Traditionally Intended for Subsequent Forging or Conversion Mill Processing

Traditional Mill Processing to Produce Finished Wrought Product

- Hot Rolling
- AMS-T-9046 plate
- Hot Rolling
- AMS-T-9046 sheet and strip
- Hot Forging/Rolling
- AMS-T-9047 Bar
- High Deformation Processes
- Extrusions
- Die Forgings
- Rod
- Wire

Mature Technology: 100+ years
- 50-75 yrs of materials characterization data
- Variability & Defects well documented
- Process Controls yield cost-effective results
- NonDestructive Testing technology capable; Probability of Detection is proven for defect types

Traditional Wrought Processing
Handbook Material Properties

- **A-Basis = 99/95** applicable to primary structures
- **B-Basis = 90/95** applicable to secondary (redundant load path) structures
- MMPDS statistical analysis based on data submitted by all known producers
- Statistical analysis performed by Battelle
- More than tensile strength, also includes: bearing, shear, toughness, fatigue, et al.

### Table 3.7.4.0(b). Design Mechanical and Physical Properties of 7050 Aluminum Alloy Plate

<table>
<thead>
<tr>
<th>Specification</th>
<th>Form</th>
<th>Tempr</th>
<th>Thickness, in.</th>
<th>Basis</th>
<th>Mechanical Properties</th>
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<td>0.250-1.500</td>
<td>A</td>
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<td></td>
<td>1.501-2.000</td>
<td>B</td>
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<td>2.001-3.000</td>
<td>A</td>
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<td>3.001-4.000</td>
<td>B</td>
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<td>4.001-5.000</td>
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<td>5.001-6.000</td>
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<td>6.001-7.000</td>
<td>A</td>
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<td></td>
<td>7.001-8.000</td>
<td>B</td>
<td></td>
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<table>
<thead>
<tr>
<th></th>
<th>AMS 4050</th>
<th>Plate</th>
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<tbody>
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<td></td>
<td></td>
</tr>
<tr>
<td>L</td>
<td>74</td>
<td>76</td>
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<tr>
<td>LT</td>
<td>74</td>
<td>76</td>
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<tr>
<td>LT</td>
<td>42</td>
<td>43</td>
</tr>
<tr>
<td>ST</td>
<td></td>
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</tr>
</tbody>
</table>

**Notes:**
- A-Basis value is specification minimum. Rounding to values for $P_L$ are as follows: for 0.250-1.500 (L) = 75 ksi, for 1.501-2.000 (LT) = 75 ksi, for 2.001-3.000 (L) and (LT) = 74 ksi, for 3.001-4.000 (L) = 65 ksi, for 4.001-5.000 (L) and (LT) = 65 ksi, for 5.001-6.000 (L) = 65 ksi, for 6.001-7.000 (L) = 65 ksi, for 7.001-8.000 (L) = 50 ksi (ST) and (LT) = 50 ksi.
- B-Basis value is specification minimum. Rounding to values for $P_L$ are as follows: for 0.250-1.500 (L) = 65 ksi, for 1.501-2.000 (LT) = 65 ksi, for 2.001-3.000 (L) and (LT) = 65 ksi, for 3.001-4.000 (L) = 65 ksi, for 4.001-5.000 (L) and (LT) = 50 ksi, for 5.001-6.000 (L) = 50 ksi (ST) and (LT) = 50 ksi.
- See Table 3.13.1.1. Bearing values are 'dry-pin' values per Section 1.4.7.
Additive Manufacturing Attributes
Complexity + Customization

Part Application

Feedstock (Proprietary)
- Composition
- Sieve (Maximum Size)
- Particle Size Distribution
- Morphology (satellites & longfellows)
- Porosity/Microstructure
- Atomization Method & Gas
- Reclamation Process
- Reclaim Cycles (or % Revert)

AM Process (Proprietary)
- AM Process Type
- Equipment (Brand & Unit S/N)
- Preconditioning/Preparations
- Part-Specific Recipe (Orientation, Support Structure, Build Parameters + Environment, Process Variables + Tolerances, etc)
- Operator Actions
- InSitu Process Monitoring

Post-Process
- Surface Finishing
- Hot Isostatic Pressing
- Heat Treatment
- Other Part-Specific Operations

Part Qualification (FAI)
- Dimensional Precision
- Surface Finish
- Physical Properties
- Tensile Properties
- Dynamic Properties (dA/dN, FT, FCGR)
- Soundness (NDT PoD)
- Functional Test (Application Specific)

Production Inspection (LAT)
- Dimensional Precision
- Surface Finish
- Physical Properties
- Tensile Properties
- Dynamic Properties (dA/dN, FT, FCGR)
- Soundness (NDT)
- Functional/Proof Test (Application Specific)

Accepted Lot of Parts

Part Process Qualification

Statistically Combinable Data for the desired combination of essential variables (Battelle Analysis):
- Part 1
- Part 2
- Part 3
- Part N

MMPDS
A-Basis
B-Basis

End Item Material Specification

Design Rules

AM Part+Process Specification

MMPDS
A-Basis
B-Basis

Property Targets
Variability Analysis
Tensile Specimen Fracture Face

Porous fracture site
Unsintered powder in pores
Unsintered powder particles

~97.6% dense

<table>
<thead>
<tr>
<th>Property</th>
<th>A-Basis (est.)</th>
<th>B-Basis (est.)</th>
<th>Mean</th>
<th>Typ. Data Sheet</th>
<th>% of expected</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{UTS}_H$</td>
<td>26.3</td>
<td>30.4</td>
<td>36.4</td>
<td>50</td>
<td>-54%</td>
</tr>
<tr>
<td>Hardness (HRB)</td>
<td></td>
<td></td>
<td>30.9</td>
<td>69</td>
<td>-45%</td>
</tr>
<tr>
<td>Elongation</td>
<td></td>
<td></td>
<td>17.1 – 19.6%</td>
<td>9 – 14%</td>
<td>~159%</td>
</tr>
</tbody>
</table>

Designer Comment: I can design with low properties, as long as they are consistent and bounded……
### Mechanical Testing Schemes
#### A Challenge to be Resolved

Tests to qualify mechanical properties and/or to demonstrate process consistency:

<table>
<thead>
<tr>
<th>Specimen Source</th>
<th>Pros</th>
<th>Cons</th>
</tr>
</thead>
<tbody>
<tr>
<td>Separate Specimens</td>
<td>Convenient, Low Cost</td>
<td>Representative ?</td>
</tr>
<tr>
<td>Prolongations</td>
<td>Similar Parameters</td>
<td>Representative Enough ?</td>
</tr>
<tr>
<td>Building Blocks (*)</td>
<td>Representative of Part</td>
<td>Testability ?</td>
</tr>
<tr>
<td>Excise Specimens from Critical Areas</td>
<td>Most Representative</td>
<td>Testability ? What about Other Areas ? $ for Qual; $$ for Production</td>
</tr>
<tr>
<td>Proof Testing (*)</td>
<td>Simulates Functional Stress Pattern(s)</td>
<td>Untested Regions ? Simulate Worst Conditions ?</td>
</tr>
</tbody>
</table>

(*) Building Blocks:
Cross Section Shapes representing the actual part by duplicating each geometry and section thickness (therefore same build parameters) and built at the applicable z-plane (therefore same feedstock, atmosphere, and build layer variables).

(*) Proof Testing:
Part-specific loading pattern (fixture, stress, duration, et al) specified by designer; performed on manufactured items to demonstrate fitness for use.
Variability Analysis
Soundness

Designers perspective: \(I\ can\ design\ with\ lower\ properties,\ as\ long\ as\ they\ are\ consistent\ and\ bounded\ldots.\)

\textbf{Discontinuities}
- Unbonded Powder
- Incomplete Fusion
- Internal
- Linear
- One Build Layer Thick
NonDestructiveTesting screens out manufacturing flaws that would otherwise degrade the product performance below the fundamental material properties.

Damage Tolerant Structural Design Practice requires sizing the product cross section to tolerate the worst-case flaw that might be missed during NDT.

Flaw types created by traditional manufacturing processes are well-characterized and addressed by existing NDT technology.

Additive Manufacturing can introduce new flaw types that are:
   a) not yet characterized by NDT Test Methods and
   b) not yet quantified for Probability of Detection

Traditional NDT methods are not well suited to complex geometries and special flaw types that are common to Additive Manufacturing:
   a) Ultrasonic Testing is not well-suited to irregular features+surfaces
   b) Computed Tomography has proven useful, but expensive
   c) Emerging technologies (e.g., Acoustic Resonance, et al) are unproven
Role of In-Situ Monitoring for Process Control

- Automatic real-time coating control.
- Inspection of new powder material (composition & size + shape + distribution).
- Maintenance of powder material in-use by an external sieving system (inert).
- Online laser status and power control.
- Redundant analysis and control of oxygen concentration in the process gas.
- Analysis of filter status and flow rate.
- Real-time control and monitoring of meltpool behavior.
- Software modules to generate build protocols and parameters of entire build process.
Industry Standards Activities

American Society for Testing and Materials (Committee E42):
- Highest number and breadth of AM Specifications: Work Projects & Published Documents
- AM product+feedstock+testing documents provide a menu for tailoring key parameters, but do not standardize process requirements, nor acceptance tests. Very good starting point, but not accepted by the regulating authorities (USAF, FAA, NASA) for aerospace/defense applications.
- Key projects in work include: Feedstock Variability, NDT PoD, Design for AM, et al.

American Welding Society (Committee D20):
- Drafting an AM Metals Process Specification based on AWS D17.1; Class A-B-C, part+process qualification based on essential process variables.
- Working “standard part” and “building block” concepts for qualification.
- Initial ballot expected later in 2016.

Society of Automotive Engineers- Aerospace Material Specifications (Additive Mfg):
- AM Committee launched 3Q-2015.
- Starting with L-PBF of IN-625.
- Planning a specification system with 4 types of documents:
  + AM Product (unique to material & process; include statistically-based design allowable props)
  + AM Process Controls (common to the L-PBF process)
  + Feedstock/Powder (unique to alloy, perhaps common to several AM processes)
  + Feedstock/Powder Production Process (common to all feedstock supplied in same form)

Industry Consensus Standards Coordination (America Makes):
- Leading efforts to leverage contributions of each standards body and minimize redundancies.
Raytheon Academia and NNMI Partnering

- Raytheon is a Gold Member of National Network for Manufacturing Innovation’s America Makes.
  - Dr. Teresa Clement, Governance Board
  - Dave Brandt, Raytheon Technical POC

- Member of Additive Manufacturing Consortium (AMC)
  - John Moore (POC)

- Member of Digital Manufacturing and Design Innovation Inst. (DMDII)
  - John Moore (POC)

- Raytheon U Mass Lowell Research Research Institute (RURI)
  - Joint applied research facility for additive (printed) and flexible electronics
  - Dedicated floor in $80 million, 84,000-square-foot facility
  - Dr. Christopher P. McCarroll - Raytheon (RURI Co-Director)
  - Dr. Craig A Armiento – UML / Raytheon (RURI Co-Director)

- Multiple additional relationships with academia for applied AM research.
about the author

Bob Steffen is a Raytheon Principal Fellow, working as a Process Engineering Metallurgist from the Raytheon Precision Manufacturing site at Lemmon Avenue. He has over 35 years experience ranging from design development to manufacturing, with a focus on metals and process engineering. He chairs the Raytheon Mechanical, Materials, and Structures Technology Network Metals Interest Group, serves as Engineering Lead for the Casting Development & Supplier Strategy Team, holds NDT Level 3 qualification, CWI, and Professional Engineer credentials, working primarily with metal fabrication machining, welding, brazing, heat treating, and material design consulting.

Bob is chairman emeritus of the SAE Aerospace Materials Committee Metals Group - creating and maintaining industry consensus specifications used across the aerospace and defense industries.

Away from work, Bob is a Boy Scout leader who likes to spend summers canoeing and flyfishing in his native Missouri.