Additive Manufacturing Development Methodology for Liquid Rocket Engines

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Distribution Statement A: Approved for public release, distribution is unlimited
Presentation Outline

• The additive manufacturing “opportunity”

• Specific additive manufacturing process considerations

• Scale up challenges

• Aerojet Rocketdyne development and production approach

• Considerations and gaps to be closed for production
Demonstrated Benefits of Additive Manufacturing

**Liquid Rocket Engine Attributes**
- Low production volumes
- High complexity, compact designs
- High value = high quality levels

**Additive Manufacturing**
- Print parts when needed
- Complexity adds no cost
- Bulk material like wrought not cast

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**Heritage Saturn V F1 Gas Generator Injector**

**Printed F1 GG Injector (2009)**

**Early Demonstrated Realization of Potential**
Transforming heritage engines and ... enabling new ones

- **Complex injector assemblies**
  - Reduce part count
  - Eliminates long lead forgings
  - Eliminates high touch labor machining
  - Eliminates hundreds of braze joints

- **Sheet metal parts**
  - Eliminates skilled labor forming
  - Eliminate many welds
  - Reduces part dimensional variability
  - Reduces non-conformances

- **New Designs**
  - LOX/RP thrust chamber assembly
  - Cubesat propulsion module

**Demonstrated Benefits of Additive Manufacturing**

- **RL10 “Printed” Injector Inlets**
- **RS-25 Ball Shaft (left)**
- **RL10 Main Injector (right)**
- **14-inch diameter**
- **Bantam “Printed” Engine**
- **After Hot Fire (No Issues)**
Demonstrated Benefits of Additive Manufacturing

Fully additive manufactured injector and **Copper** combustion chamber

- Additive Copper alloy combustion chamber with **46% increased heat transfer**
  - Design features applied to inner wall to transfer additional heat to hydrogen
  - Net effect is to shrink engine size or enable higher performance in same envelope

New Alloys (Copper) Possible Through AR Development for Thermal Management
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Additive Manufacturing Development

Selective Laser Melting is...a micro-welding process

- **As built structures**
  - Columnar grain structure
  - Small defect sizes, mostly spherical
  - Fully isotropic ... once heat treated

- **Equipment differences in scan strategies**
  - Laser traverse/motion differences
  - Effects on localized thermal input
  - Effects on surface condition

- **Alloy 625 post processing**
  - Stress relief
  - Hot Isostatic Press (optional)
  - Solution Heat Treat

**SLM Output is Dependent on Equipment / Scan Strategy / Post Processing**
Additive Manufacturing Development

• **Operational Environment Testing**
  – Air tensile strength data shows fracture surface like wrought (ductile)
  – Testing in gaseous hydrogen performed
  – Material behaves like powder metallurgy product in response to environment testing

• **Surface Effects on Fatigue and Cleanliness**
  – Measurable HCF debit resulting from as-built surface finishes
  – Factor into design
  – Develop finishing methods
  – Build angle dependent
  – Particulate impact cleaning
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Additive Manufacturing Development

Scale Up Equipment Differences

- Last ~6 years 10-inch cubes to 400W

- Concept Laser X Line 1000R
  - 6X volume increase from M2
  - 1000W laser
  - AR owns 3 (two are Title III assets)

- EOS M400
  - 4X volume increase from M280
  - 1000W laser
  - AR owns 1 (Title III asset)

Scale Up to Larger Sizes is Just Beginning
Equipment Delivery and Installation

• **Title III Team:** Aerojet Rocketdyne – Prime Contractor
  – University of Tennessee / ORNL
    ➢ Concept Laser X Line #1
    ➢ Al-10SiMg
  – Aerojet Rocketdyne
    ➢ Concept Laser X Line #2
    ➢ IN718
  – Atlantic Precision, Inc.
    ➢ EOS M400
    ➢ Copper

• **Goal:** Demonstrate ability to produce an alloy on large scale SLM machines with robust material capability and component design tolerances and non-destructive inspection validation.

Long Lead Machine Procurement and Installation Complete
EOS M400

- Machine checkout with IN718 (EOS Parameters)
- Transition to Inco 625 study and material screening program
- Cleaned and transition to copper powder

EOS M400 Transition to Inco 625 Demonstration

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EOS M400

- Subscale Copper work on M280 successful
- Transition to M400 machine for full scale demonstrations
Aluminum X Line 1000R

- SLM Aluminum material property evaluation in process (Al-10Si-0.3Mg)
  - Structural margins to retain factor of safety require some added material
  - Full characterization of properties on X Line in process
• RS-25 (Space Shuttle Main Engine) need for large SLM IN718
  • Scaling from Concept Laser M1 machine capability
  • X Line requires significant process optimization for IN178 alloy

20+ Different part numbers in engine apply

Large IN718 Additive Flanges Contribute to Cost Savings
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Development Approach for AM at AR

Enterprise Additive Manufacturing Team (AMT)

Parameters & Specifications
- Process Control
- Source Approvals

Material Testing
- Design Curves
- New Product Form
- Design Allowables

Process Limits
- Design Options

NDT
- Standard Work
- New Capabilities

Component Validation

Refine OEM Machine Parameters

All Relevant Environments and Failure Modes

Modified NDE Methods

Machine types are all independent and this process is followed for a specific model

Aerojet Rocketdyne Approach to Additive Manufacturing for AEROSPACE Grade Material

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Defect Inspection Limitations

- Complex part designs now possible with AM introduce dilemma on how to inspect for volumetric flaws/defects
  - Surface finish (as-built) limits penetrant inspection and cleaning
  - No longer have forging shapes to UT or X-Ray
  - Complex shapes preclude most NDE methods from full access
  - Typical AM defects are spherical, not linear
  - First article inspection + CT likely
  - *Process control may be only path forward*

Thickness and Geometry Limit X-ray Effectiveness

*Image intentionally Distorted (AR IP)*
Defect Statistical Analysis

• Statistical Defect Study for Nominal Processing
  – Database will be used to validate process control
  – Correlation of statistical defect population on material properties
  – Fracture data generated to establish critical flaw size limitations
  – Focused NDE methods in areas where critical flaw locations would exist

Gaseous Hydrogen Burst Test SLM Inco 625 Part

Statistical Defect Analysis Helps Drive Inspection Requirements and Part Acceptance

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Defect Statistical Analysis

- **Statistical Analysis Results**
  - Surface and sub-contour anomalies are statistically significant and larger than bulk material defects
  - Part geometries and machines are not statistically significantly different
  - Same machine model used - does not show variation (AFRL program)

Surface Defects are Largest and Different Machines Produced Similar Defects
Summary

- Liquid Rocket Engines fit an ideal model for Additive Manufacturing insertion due to low production volumes, high complexity and a shrinking conventional manufacturing service sector.

- Additive Manufacturing development at Aerojet Rocketdyne has focused on alloy parameter optimization, material characterization in relevant environments and geometry optimization studies.

- Risk-based approach, leading to component and system level demonstrations, is critical to ensure full understanding of new production form (Additive Manufacturing).

- Process control in absence of full volumetric inspections will be critical acceptance criteria.