Additive Manufacturing Overview

National Academies of Aeronautics and Space Engineering Board

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Aerojet Rocketdyne
Aerojet Rocketdyne is a world-recognized aerospace and defense leader providing propulsion and energetics to the space, missile defense and strategic systems, tactical systems and armaments areas, in support of domestic and international markets.
Heritage of Powering
Virtually All US Space Exploration

Redstone Navaho
Jupiter Thor
Atlas I/II/III
Saturn Gemini I/1B
Saturn V
Titan I/II/III/IV
Space Shuttle
Delta I/II/III
Atlas V
Delta IV

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Additive Manufacturing History

- **1998**
  - Early SLM Demonstrations and Proof of Concepts

- **2009**
  - Procure Concept Laser M2
  - Additive Mfg. Program Formed
  - Nylon SLS development and production
  - Indirect Metal AM

- **2012**
  - GH2/LO2 Subscale Hot fire

- **2013**
  - Baby Bantum Lox/RP 5K Thruster Hot fire

- **2014**
  - Hypersonics Component Testing

- **2015**
  - Advanced AM Concepts

- **2016**
  - Large AM Rocket Components
  - GH2/LO2 Subscale Hot fire

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Additive Manufacturing Value Proposition

Value to Enterprise

Concept

- Accelerated Development
- Cost/Risk Reduction Opportunities

Development

- Concurrent Functional Testing for Rapid Concept Down Selection

Production

- AM Enabled Performance
- Manufacturing approach supports business case

Conventional Manufacturing Production Path

Functional Prototyping

For Service Applications

Prototypes, Tooling, Support Equipment
Additive Manufacturing (AM) Application Opportunities

- AM is simply a new manufacturing “tool”
- Selective use must be applied:
  - Consolidation of complex assemblies
  - Elimination of long lead forgings
  - Reduction of touch labor
  - Reduction of weld and braze joints
  - Opens up new design space

- Early example of F1A Preburner Injector (2009)
  - Cost savings: 70%, Lead time: 60%, Weight: 9-lbs (4-kg), Parts 14:2
Aerospace Additive Manufacturing Requires Integrated Development

**AM is Complex and Interconnected**

- Machine operation, alloy, properties and component function are interconnected
- AM development for high-performance applications must address all in parallel

**Aerospace Requires Precision**

- Materials fully characterized
- Functional performance and variation understood
- Stringent quality control and part acceptance requirements

**AM is not “turn key” - Rigorous development is required for successful adoption**
Development Approach for AM

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

Process Limits

Modified NDE Methods

Machine types are all independent and this process is followed for a specific model
Key Challenges in AM Component Development

• Printing aerospace quality parts requires refinement of these:
  – Powder
    ▪ Chemistry, particle size, etc.
  – Parameters
    ▪ Optimized from OEM parameters
  – Properties
    ▪ For AM product

• Complex part designs pose inspection challenges
  – Now ... powder-to-part approach

RL10 Main Injector CT image
Additive Manufacturing Qualification
Air Force SMC Booster Propulsion Tech Mat Program

Can make these today...
Complex internal geometry

This process will improve confidence in part quality

Process Sensitivity  Process Data Collection  NDE Inspections  Statistical Defect Survey
Methodology Documentation and Component Demonstration
AM Qualification Methodology

Technology Maturation Project
Next Gen Rocket Propulsion System
Additive Manufacturing Qualification Process
Design  Property Testing  Component Fab  AM Qual Process
Releasable to Broad Industrial Base
Directly Supports Next Gen RPS for NSS
Dev Engines  Qual Engines  Qual Tests

To enable this (with lower risk)

Developing new methodology to qualify AM parts with improved confidence in quality

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Additive Manufacturing Qualification
Air Force SMC Booster Propulsion Tech Mat Program

Complex interaction of in-process data to correlate with “defective” or “good” volumetric quality

Classify the types of SLM M200 defects and the processing conditions when they occur

Demonstrate the ability to detect these processing conditions using process data

Validation Data
- Simple Geometry
- Complex Geometry
  - Metallography
  - NDE Data (CT/X-ray)
  - Material Properties
  - Functional Testing

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AM Breakthrough Projections

1-3 Years
- Advanced Process Monitoring
- Industry Standards
- Design for AM/Topology Optimization

3-8 Years
- Higher Production Rates
- Material Property Database
- Customized Microstructure

8+ Years
- Hybrid AM Processes
- Consolidated OEM base
- All AM System (Printed)

Projected Breakthroughs Based on Recent Trends and Experience

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Agency / Industry Cooperation Opportunities

- **Establish standards**
  - Powder for types of AM
  - Processing requirements
  - Develop material properties database

- **Enable rapid qualification of AM designs**
  - Test Bed needed to validate AM part designs
  - Develop *and accept* process monitoring

- **Advanced alloys**
  - Develop new materials enabled through AM
  - Agency computing resources combined with industry metallurgy knowledge

Joint AM Efforts Will Accelerate Acceptance of Technology and Open New Opportunities
Summary

- AM is a new tool to develop and apply properly
- Challenges to ensure aerospace quality material
- Complex part designs also open up inspection challenges
- Agency / Industry collaboration could enable accelerated AM insertion and adoption
- Aerojet Rocketdyne lessons learned being applied to AM applications
Alloy and Powder Requirements

- **“SLM-weldable” Alloy**
  - severe weld cracking in certain alloys
  - sensitive to composition variations
- **Powder Shape, Size, and Distribution**
  - consistent spreading
  - uniform, sufficient packing
- **Viable Post-processing Heat Treatment**
  - example: Ti-6Al-4V; $\alpha$-$\beta$ phase field enables heat treat for wrought-like structures and properties

Process considerations follow from welding, but with extreme cooling rate and size
SLM Parameter Requirements

- **Optimum SLM Parameters Provide**
  - Shape definition
  - Dense structure
  - Avoidance of “build faults”

![Part Layer Damaged by Recoater](image1)

![Vertical Crack Propagated by Thermal Strain](image2)

![Optimum SLM Parameters Optimized for Geometry Precision](image3)

![Non-optimum SLM Parameters Optimized for High Density](image4)

Subtle part geometry changes can have significant impact
AM High-Performance Component Design Requires AM Properties Data

- Alloy and Environment Design Database Testing:
  - tensile
  - fatigue
  - creep
  - fracture toughness
  - Air / LN$_2$ / GH$_2$

New product form being fully characterized for design capability
Influences on Part Characteristics

**AM System**  
- Component Design  
  - AM Features (supports, etc.)

**Powder**  
- Alloy type  
- Alloy details  
- Fab. method  
- Shape  
- Size

**AM Process**  
- Procedures  
- Parameters

**Post-processing**  
- Powder removal  
- Support removal  
- Heat treatment  
- Surface finishing

**Characteristics**  
- Geometry  
  - dimensions  
- surface finish  
- Microstructure  
- Flaw Population  
- Material Properties

Wide Range of Considerations Impact AM Component Capability