Additive Manufacturing Overview

National Academies of Aeronautics and Space Engineering Board

October,13 2016

Aerojet Rocketdyne

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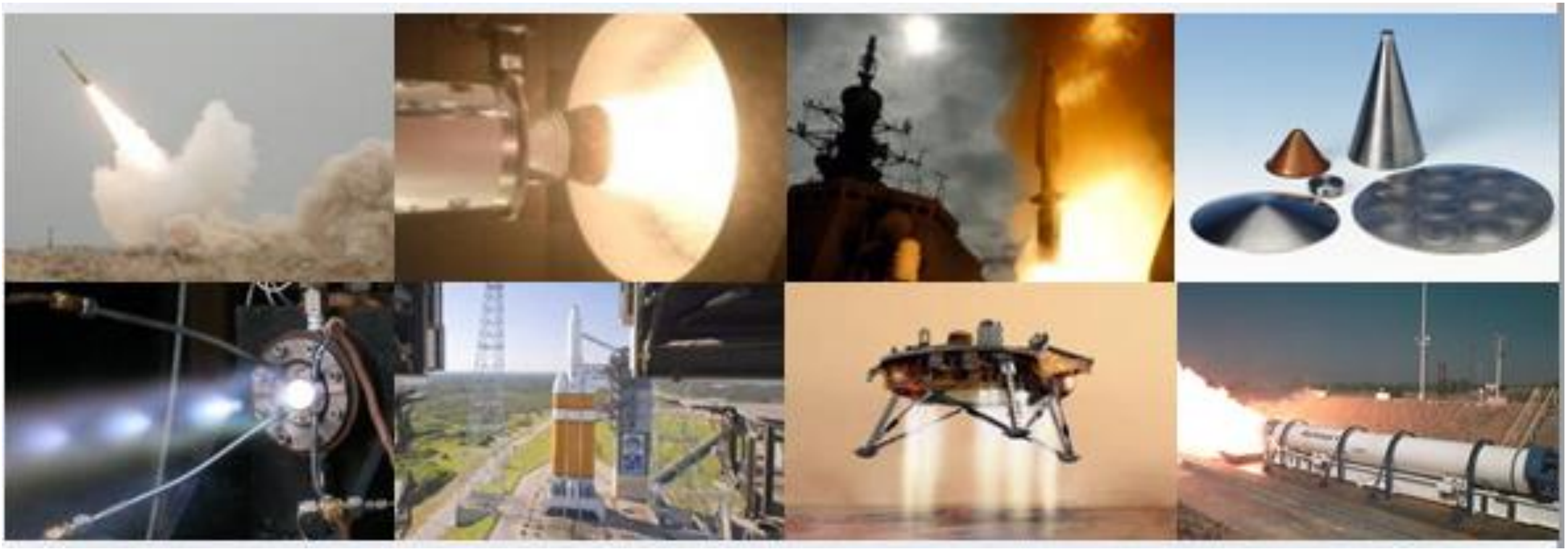
ABOUT AEROJET ROCKETDYNE

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.**



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Heritage of Powering Virtually All US Space Exploration

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

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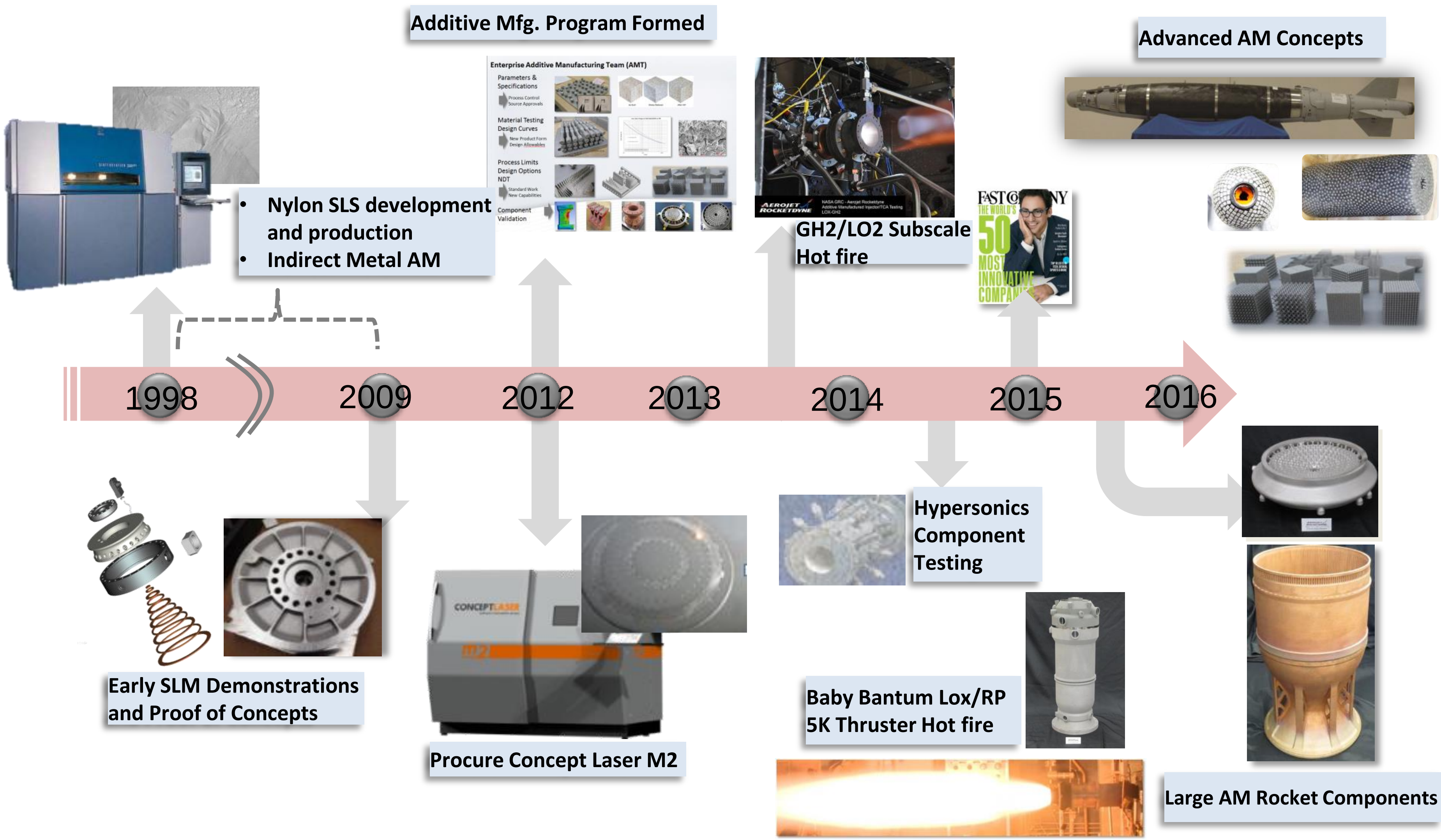
Additive Manufacturing History

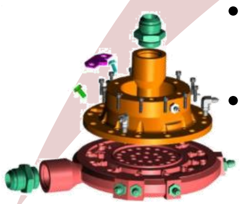


Additive Manufacturing Value Proposition

Value to Enterprise

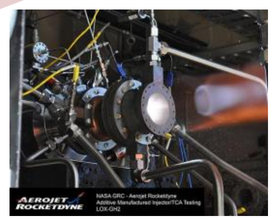
Conventional Manufacturing Production Path

Prototypes, Tooling, Support Equipment



- Accelerated Development
- Cost/Risk Reduction Opportunities

Functional Prototyping



- Concurrent Functional Testing for Rapid Concept Down Selection

For Service Applications

- AM Enabled Performance
- Manufacturing approach supports business case

Concept → **Development** → **Production**

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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

RL10 Main Injector
SLM Printed

RL10 Sheet Metal + Welded Inlets *now SLM*

- **Early example of F1A Preburner Injector (2009)**

AM

  - Cost savings: 70%, Lead time: 60%, Weight: 9-lbs (4-kg), Parts 14:2

Early Demonstration of Potential Benefits

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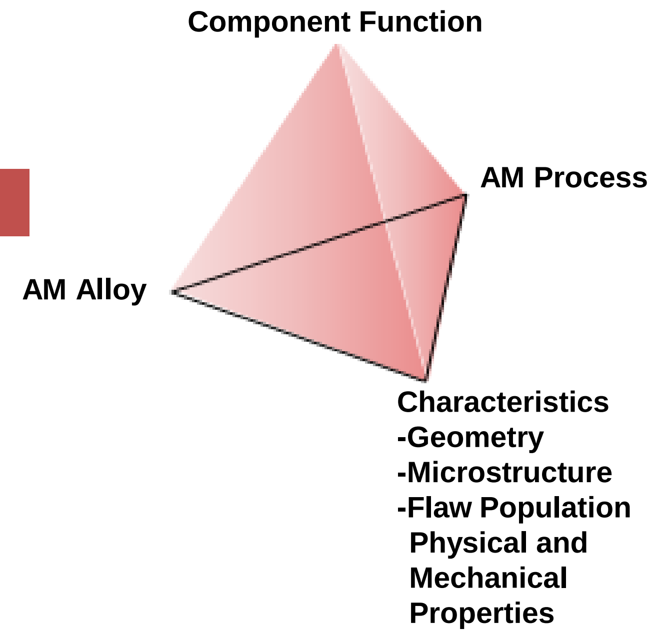
Aerospace Additive Manufacturing Requires Integrated Development

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

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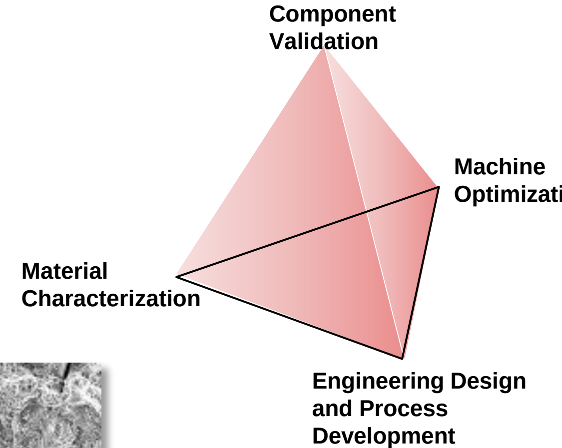
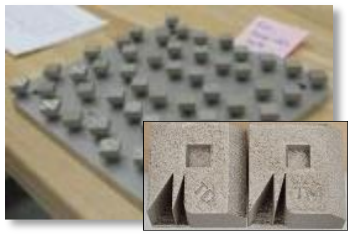
Development Approach for AM

Enterprise Additive Manufacturing Team (AMT)



Parameters & Specifications

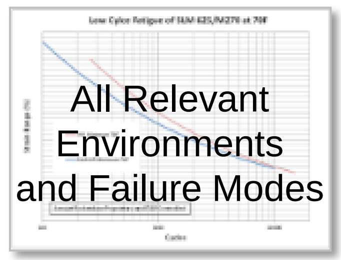
Process Control
Source Approvals



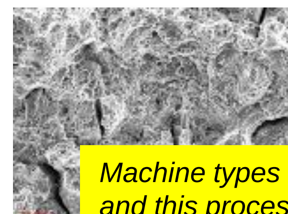
Refine OEM Machine Parameters

Material Testing Design Curves

New Product Form
Design Allowables



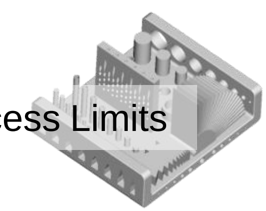
All Relevant Environments and Failure Modes



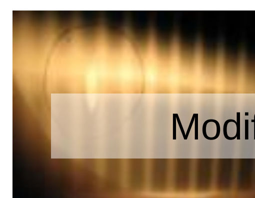
Machine types are all independent and this process is followed for a ***specific model***

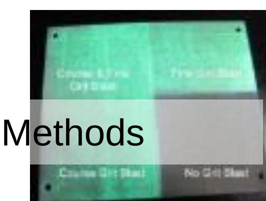
Process Limits Design Options NDT

Standard Work
New Capabilities



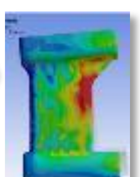
Process Limits





Modified NDE Methods

Component Validation



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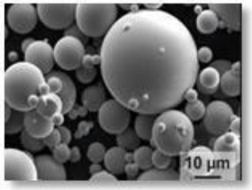
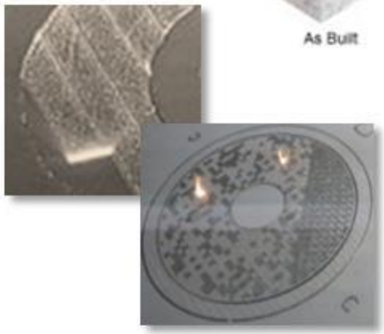
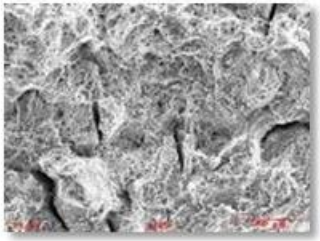
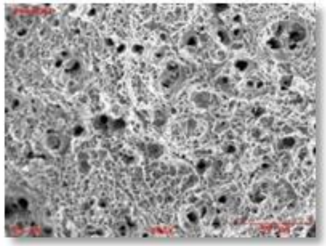
Key Challenges in AM Component Development

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

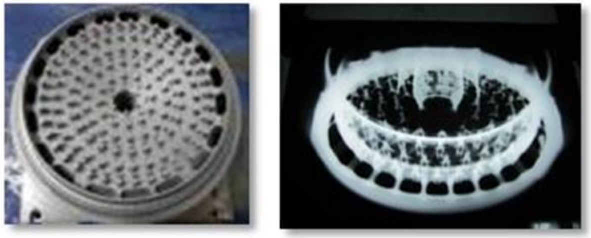








- **Complex part designs pose inspection challenges**
  - Now … powder-to-part approach



RL10 Main Injector CT image

Process Optimization, Design / Features, and Inspections Can Pose Challenges for AM

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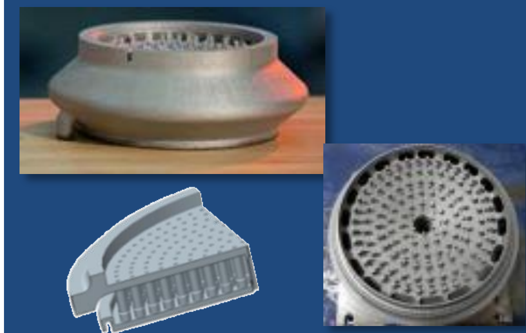
Additive Manufacturing Qualification
Air Force SMC Booster Propulsion Tech Mat Program

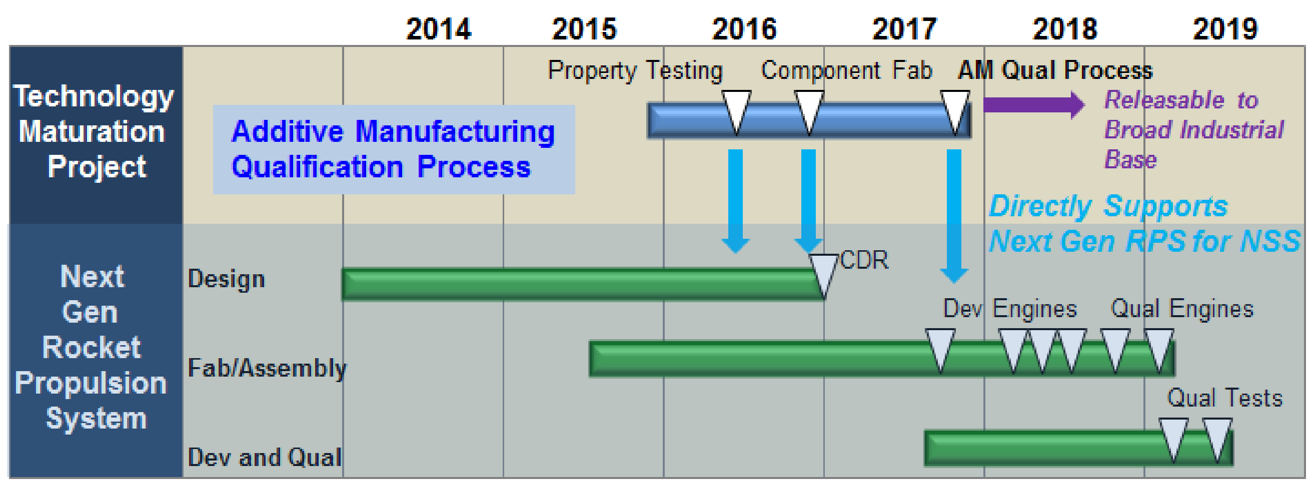
Can make these today…



Complex internal geometry

This process will improve confidence in part quality

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

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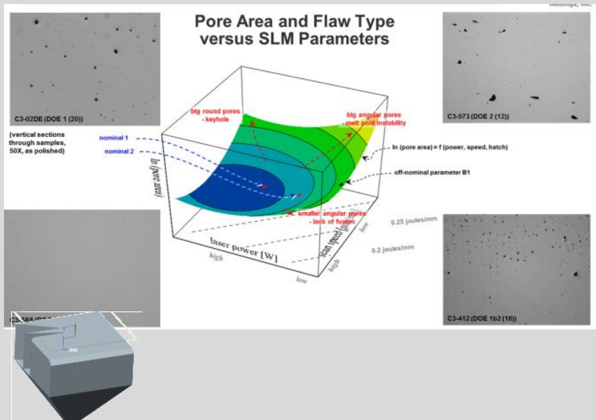
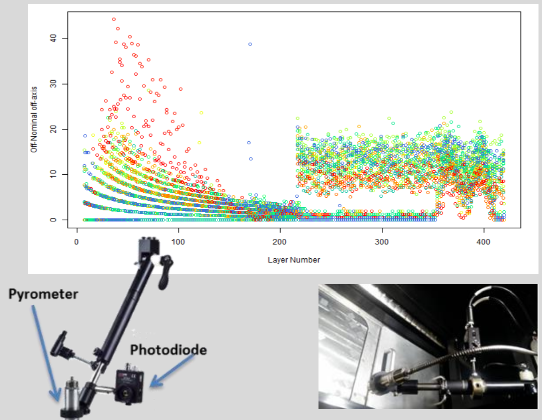
Process Sensitivity | Process Data Collection | NDE Inspections | Statistical Defect Survey

Methodology Documentation and Component Demonstration

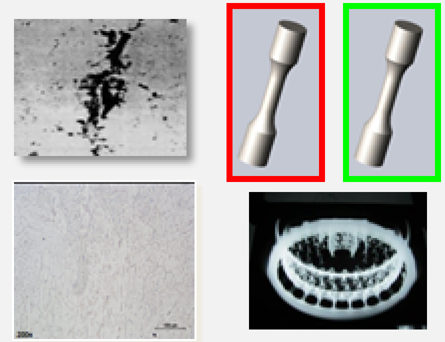
AM Qualification Methodology



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*

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

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AM Breakthrough Projections

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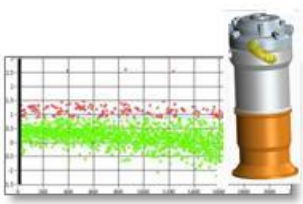
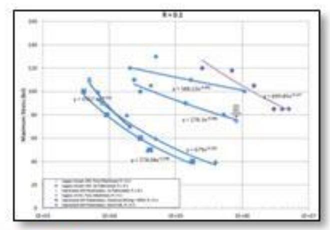
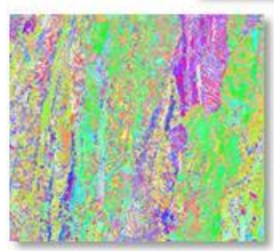
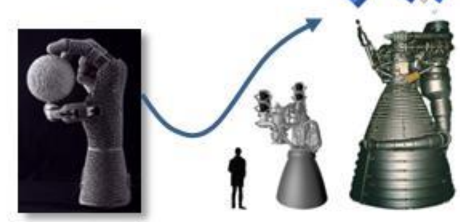
1-3 Years	3-8 Years	8+ Years
Advanced Process Monitoring	**Higher Production Rates**	**Hybrid AM Processes**
Industry Standards	**Material Property Database**	**Consolidated OEM base**
Design for AM/Topology Optimization	**Customized Microstructure**	**All AM System (Printed)**





Projected Breakthroughs Based on Recent Trends and Experience

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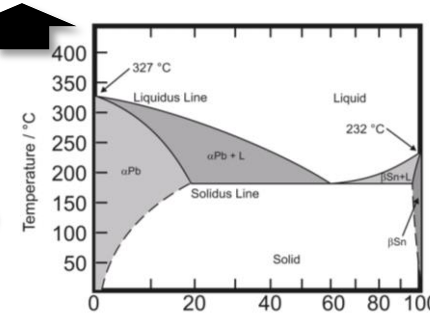
Agency / Industry Cooperation Opportunities

- **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

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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

Additive Manufacturing Offers Tremendous Potential, But Must be Applied Properly

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BACKUP

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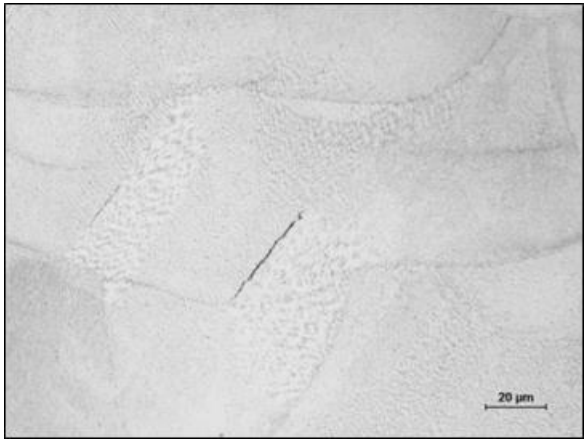
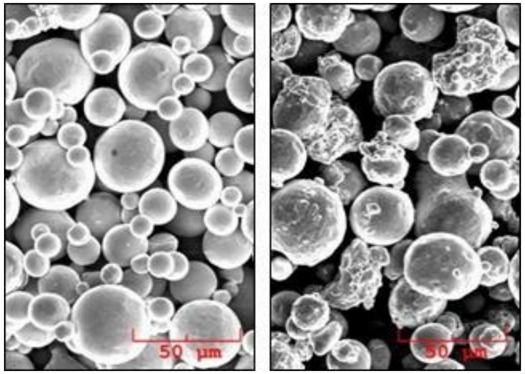
Alloy and Powder Requirements

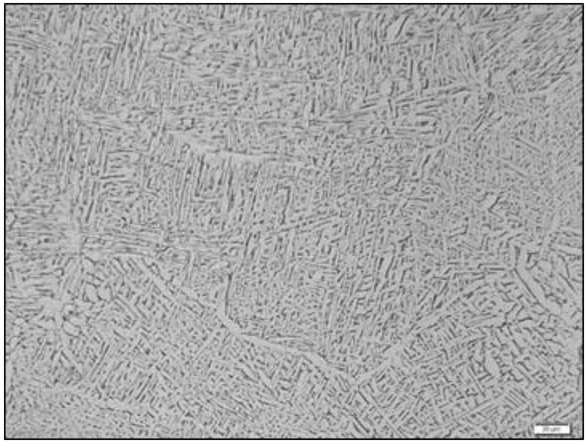
- **"SLM-weldable" Alloy**
  - severe weld cracking in certain alloys
  - sensitive to composition variations
- **Powder Shape, Size, and Distribution**
  - consistent spreading
  - uniform, sufficient packing
- **Viable Post-processing Heat Treatment**
  - example: Ti-6Al-4V; α-β phase field enables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



SLM Superalloy Weld Crack; (≤ 1 layer)



Uniform, Spherical Powder Improves Flow



AM Ti-6Al-4V wrought-like structure after HIP

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

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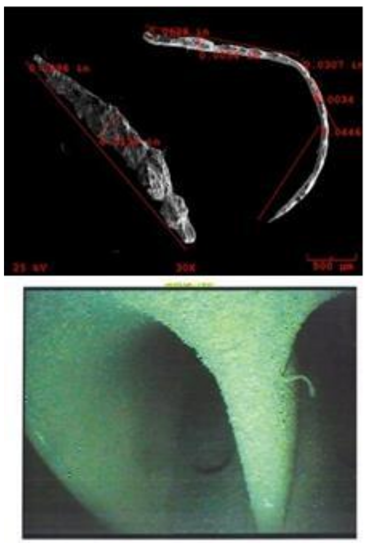
SLM Parameter Requirements

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

SLM Parameters Optimized for Geometry Precision



Part Layer Damaged by Recoater

Vertical Crack Propagated by Thermal Strain

Optimum

Non-optimum

SLM Parameters Optimized for High Density

Subtle part geometry changes can have significant impact

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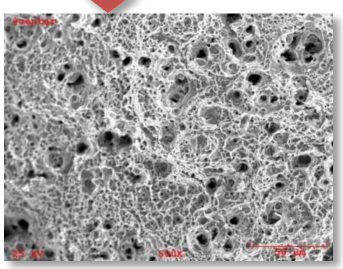
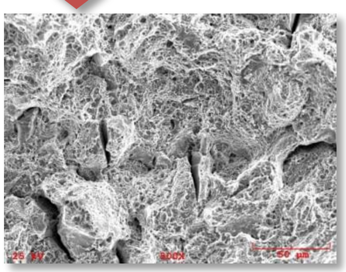
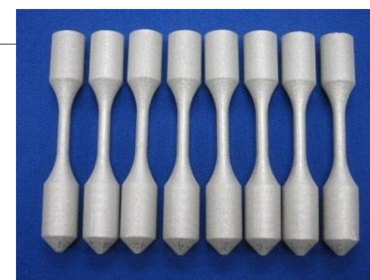
AM High-Performance Component Design Requires AM Properties Data

- Alloy and Environment Design Database Testing:
  - tensile
  - fatigue
  - creep
  - fracture toughness
  - Air / LN_2 / GH_2







As Built Fatigue Samples (Surface Finish Effect)

New product form being fully characterized for design capability

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Influences on Part Characteristics

AM System

Component Design

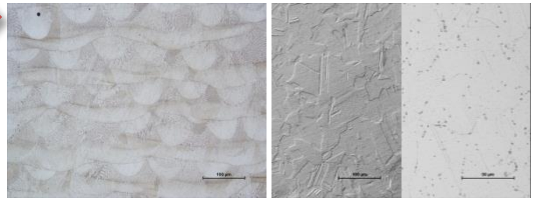
AM Features (supports, etc.)

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

AM Process
- Procedures
- Parameters

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

<u>Characteristics</u>
- Geometry
  - dimensions
  - surface finish
- Microstructure
- Flaw Population
- Material Properties



Wide Range of Considerations Impact AM Component Capability

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