GE Additive
Additive Manufacturing for Space
Large Format Additive Challenges
A full ecosystem of additive offerings

Machines
- Direct metal laser melting (Concept Laser)
- Electron beam melting (Arcam EBM)
- Binder Jet

Powders
- CpTi grade 1
- CpTi grade 2
- Ti-6Al-4V grade 5
- Ti-6Al-4V grade 23
- Ti-6Al-2Sn-4Zr-6Mo
- Ni Alloy 718
- Ni Alloy 625
- Al-Si7-Mg (F357)
- Al-Si10-Mg
- CoCrMo
- 316L Stainless Steel
- M300 Stainless Steel
- 17-4 PH Stainless Steel
- remanium star® CL
- rematitan® CL

AddWorks™ consultancy
Workshops
Learn foundational knowledge and additive strategies in a classroom environment. Workshops typically run three to five days.

Sprints
Combine workshops, hands-on consulting and print services to fast-track the path to full production. Sprints vary in length from one to 10 months.

Software
- Design
- Build Preparation
- Machine Printing
- Monitoring

Customer Experience Centers
Designed to host customers; to educate, train, collaborate and demonstrate the processes, products and technology involved with AM and how GE Additive can help them achieve their full potential.

- Munich, Germany (Europe)
- Mitsubishi Customer Experience Centre (Japan)*

GE Additive Partners
- Manufacturing Partner Network:
  - Carpenter
  - Protolabs
- Binder Jet Development partners:
  - Cummins
  - Wabtec

*Sales Partner in Japan
Additive Manufacturing for Space – Why?

<table>
<thead>
<tr>
<th>Advantages</th>
<th>Challenges</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Cost/Lead time</td>
<td>• Available data</td>
</tr>
<tr>
<td>• Part complexity</td>
<td>• Capability v. productivity</td>
</tr>
<tr>
<td>• System integration</td>
<td>• Part transferability (plug’n play)</td>
</tr>
<tr>
<td>• Multiple alloys available</td>
<td>• Most desired alloy may not exist</td>
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<tr>
<td></td>
<td>• PBF Limitations in space (ISS)</td>
</tr>
<tr>
<td></td>
<td>• Gravity based systems</td>
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<tr>
<td></td>
<td>• EHS</td>
</tr>
<tr>
<td></td>
<td>• Size</td>
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<tr>
<td></td>
<td>• Post-processing/quality</td>
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</tbody>
</table>
AM Cost Metrics

3 PRIMARY COST DRIVERS

1. Part Geometry (Part Complexity)
2. Material Parameter and Behavior
3. Machine Architecture

Contributing Cost by Category (Example)
Typical requirements and trade-offs

- Stability
- Density
- Productivity
- Surface Quality
- Requirements
- Fatigue
- Mech. Properties

- Vertical walls
- Up/Downsides
- Non machined
- Machined
- Soot/ Weld spatter formation
- Recoating behavior
- Bulk porosity
- (Sub)contour porosity
- Exposure time
- Recoating time
- As built
- Post processed
Typical requirements and trade-offs

- Soot formation
- Recoating behavior
- Vertical walls
- Up/Downsides

Requirements:
- Stability
- Density
- Surface Quality
- Fatigue
- Mech. Properties

Productivity:
- Exposure time
- Recoating time
- As built
- Post processed

Density
- Requirements

Mech. Properties
- As built
- Post processed

Surface Quality
- Requirements

Fatigue
- Requirements

Stability
- Requirements

Competing requirements need careful optimisation of parameter set.
GE Additive large format additive for space

Rocket Nozzle Demo – ATLAS

- Printed in 718
- Time to Print: ~30 days

Advantages and Challenges

- **Advantages**
  - Leverage known alloy/processing
  - DfAM/Part complexity
  - Time

- **Challenges**
  - Stitching/material capability
  - Post-processing/distortion
  - Risk of failure for longer prints
Comparison of alloy 718 tensile properties

Additive tensile properties: greater than cast, comparable to wrought
Process development – impact of heat treatment

**STRESS RELIEF**
- Reduce internal residual stress
- Allows for removal from platform with minimum distortion
- N/A for EBM

**HIP**
- Reduce internal porosity
- Initiates recrystallization
- Transforms microstructure

**SOLUTION**
- Homogenizes structure
- Sets grain size after quench
  - ↓ strength
  - ↑ ductility

**AGE**
- Precipitation of strengthening phases
- Stabilizes structure
- Best balance of properties

All micrographs are XY plane
Surface finish

<table>
<thead>
<tr>
<th>ATLAS</th>
<th>Laser Powder Bed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum Beam Diameter</td>
<td>~65 µm</td>
</tr>
<tr>
<td>Powder Layer Thickness</td>
<td>50-60 µm</td>
</tr>
<tr>
<td>Powder Size</td>
<td>~15-53 µm</td>
</tr>
<tr>
<td>Surface Finish (Ra)</td>
<td>~6.5 – 25 µm</td>
</tr>
</tbody>
</table>

Factors affecting AM surface finish:
- Layer thickness
- Particle size range and distribution
- Local surface slope
- Material
- Gas flow (laser)
- Beam parameters
- Coater blade orientation
Large format parameter development - stitching

Porosity

<table>
<thead>
<tr>
<th>XY Plane</th>
<th>XZ Plane</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pin 10 – No Stitch</td>
<td>Pin 08 – Stitch</td>
</tr>
</tbody>
</table>

Minimal evidence of stitch line metallurgical

Surface finish

Stitch line

Round bar

Representative component geometry

Potential impact in fatigue for as-printed surface fatigue
Process Development – Parameter Optimization

**Typical Requirements**

Balance properties like:

- Density
- Productivity
- Mechanical Properties
- Surface Quality
- Build Stability

**Surface Finish Example**

![Fractured Surface: Initiation site](image)

![Side Wall](image)

![As printed bar](image)

![Fractured surface: Initiation site](image)

![Side Wall](image)

![Machined bar](image)

Or “improved surface”

**718 Fatigue Behavior**

Bulk fatigue life approaches wrought capability

Strong influence of surface quality on fatigue life

[Graph showing fatigue behavior]
A framework for additive qualification

ACROSS THE ECOSYSTEM

Design Qualification
Material Property DB and Design Standards

Machine & Material Qualification
Machine Acceptance Spec and Material Spec

Process Qualification
Powder Process and Additive Process Control

Part Qualification
Quality Specs and Inspection Specs

Certification
Regulations, Policy and Guidance Documents
Summary

• GE Additive actively working large format additive for multiple space applications
• Material parameter/capability large driver in decisions around AM business case
• Understanding requirements, both regulatory and design, first step towards qualification

Broad Know-how necessary, not only about the:

• DMLM Process
• Powders
• Microstructure & mechanical properties
• Post processing
• Design & Application

but also on:

• GE Global Research
• GE Aviation
• AP&C

AddWorks™
# Aviation qualification documents

<table>
<thead>
<tr>
<th>Qualification</th>
<th>Policy, Specs, Standards, Database, Documents</th>
<th>Example</th>
<th>Industry</th>
<th>Proprietary</th>
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<tbody>
<tr>
<td>Design</td>
<td>Design standards</td>
<td>OEM</td>
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<td>🔴</td>
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<tr>
<td>Design</td>
<td>Material property database</td>
<td>MMPDS</td>
<td>🔴</td>
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<tr>
<td>Machine &amp; material</td>
<td>Machine acceptance standard</td>
<td>ISO</td>
<td>🟦*</td>
<td>🔴</td>
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<tr>
<td>Machine &amp; material</td>
<td>AM material &amp; process specs</td>
<td>SAE</td>
<td>🟦*</td>
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<td>Part</td>
<td>Inspection standards</td>
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<tr>
<td>Certification</td>
<td>Regulations &amp; rules</td>
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<tr>
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<td>Policy &amp; guidance</td>
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<td>🔴</td>
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</tbody>
</table>

- 🟦 Not available
- 🟦* Content exists, but incomplete for regulated qualification
- 🟦 Content available

* Limited machine and material combinations currently available