JANNAF
Liquid Propulsion Subcommittee and Advanced Materials Panel
Additive Manufacturing for Propulsion Applications
Technical Interchange Meeting

Evaluation of Additively Manufactured Demonstration Hardware for a Turbopump Application

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PROPULSION COMPONENT DESIGN & DEVELOPMENT DIVISION
TURBOMACHINERY DESIGN & DEVELOPMENT BRANCH

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Agenda

• Introduction – Turbomachinery and Additive Manufacturing (AM)
• NASA MSFC Turbomachinery Branch – AM Goals
• Selective Laser Melting (SLM) Hardware Demonstrations
  • Images of Hardware
  • White Light Scan Results
  • Surface Evaluation
• SLM Material Test Specimens
  • Tensile Test Results
  • Fatigue Test Results
• Conclusion
Introduction

Liquid Rocket Engine Turbopumps

Complex Geometries
- Blades/Vanes
- Complex Flow Passages & Ports

Typical Design Goal

**Power Density**

\[
\frac{\text{Power}}{\text{Weight}} \uparrow \text{Maximize}
\]

- High Shaft Speed
- Large Temperature Gradients
- High Pressure Loadings
- Dynamic Modes

Complex硬件，设计接近技术前沿的限制，具有预测或证明的高可靠性**leads to**...
Introduction

Liquid Rocket Engine Turbopumps

- Long design and development lead time
- Analyses for design and reliability
- Test data needed to verify models
- Long hardware fabrication lead times
- Process development (castings, welds, etc.)
- Complex parts with many features
- Increased cost

Can we use Additive Manufacturing techniques to:

- Reduce manufacturing cost and lead time?
- Get hardware into test early enough to anchor models and provide a more robust design?
Turbomachinery Branch AM Goals

• Develop design experience and techniques to take full advantage of AM process benefits while understanding constraints

• Advance technology readiness level (TRL) of AM turbomachinery components and materials, allowing for easier insertion into mainline programs.

• Demonstration of representative piece part designs

• Material property verification

• Develop and test a turbopump assembly that uses AM techniques to the greatest extent possible.

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Two SLM vendors were tasked with building selected turbopump components with lot test specimens from **IN718**.

<table>
<thead>
<tr>
<th>Part</th>
<th>Model Image</th>
<th>Vendor</th>
<th>Surface Finishing</th>
<th>WLS</th>
<th>Surface Evaluation</th>
<th>Z Tensile</th>
<th>XY Tensile</th>
<th>Fatigue Surface Finish</th>
<th>Z Fatigue</th>
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**MMP:** Proprietary Micro Machining Process  
**WLS:** White Light Scan

Approved for public release; distribution is unlimited.
Impeller

Vendor A
Surface Finish:
MMP

Vendor B
Surface Finish:
Ext: Bead Blast
Int: Extrude Hone

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Extra material is provided on external surfaces. Internal flow path surfaces are net shape.
SLM Hardware Demonstrations

Impeller - Surface Evaluation

Vendor A – MMP
(Bottom Surface)

Vendor B – Extrude Hone
(Bottom Surface)
SLM Hardware Demonstrations

Impeller - Surface Evaluation

Vendor A – MMP
(Bottom Surface)

Vendor B – Extrude Hone
(Bottom Surface)
SLM Hardware Demonstrations

Impeller - Surface Evaluation

Vendor A – MMP
(Top Surface)

Vendor B – Extrude Hone
(Top Surface)
SLM Hardware Demonstrations

Impeller - Surface Evaluation

Vendor A – MMP (Top Surface)
Vendor B – Extrude Hone (Top Surface)

Approved for public release; distribution is unlimited.
## SLM Hardware Evaluation

### Impeller - Surface Evaluation

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SLM Hardware Demonstrations

Pump Volute – Design Considerations

• SLM Constraint – Unsupported ceiling radii should be minimized

Typical volute cross sections are designed for hydrodynamic performance.

Demonstration volute is designed as a compromise between hydrodynamic performance and SLM manufacturability.

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SLM Hardware Demonstrations

Pump Volute

Vendor A
Surface Finish:
Ext: Bead Blast
Int: Extrude Hone

Vendor B
Surface Finish:
Ext: Bead Blast
Int: Extrude Hone

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SLM Hardware Demonstrations

Pump Volute

Vendor A
Surface Finish:
Ext: Bead Blast
Int: Extrude Hone

Vendor B
Surface Finish:
Ext: Bead Blast
Int: Extrude Hone

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SLM Hardware Demonstrations

Pump Volute – Surface Evaluation

Vendor A – Extrude Hone
(Top Surface)

Vendor B – Extrude Hone
(Top Surface)
SLM Hardware Demonstrations

Pump Volute – Surface Evaluation

Vendor A – Extrude Hone
Vendor B – Extrude Hone

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SLM Hardware Demonstrations

Turbine Blisk

Vendor A
Surface Finish:
MMP

Vendor B
Surface Finish:
Bead Blast

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SLM Hardware Demonstrations

Turbine Blisk – White Light Scan

Vendor A (Bottom Surface)

Vendor B (Bottom Surface)

Avg. Deviation $\approx -0.025''$

Avg. Deviation $\approx -0.018''$
Turbine Blisk – White Light Scan

Avg. Deviation ≈ +0.010”

Vendor A
(Top Surface)

Vendor B
(Top Surface)

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SLM Hardware Demonstrations

Turbine Blisk – Surface Evaluation

Vendor A – MMP
SLM Hardware Demonstrations

Turbine Blisk – Surface Evaluation

Vendor B – Bead Blast

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SLM Hardware Demonstrations

Turbine Blisk – Surface Evaluation

Vendor A – MMP
Vendor B – Bead Blast

Stylus profiling of Blisk Blade (EM10-Tribology)
SLM Material Test Specimens

Tensile Test Results

X-Axis

Vendor A Builds
1. Turbine Nozzle
2. Turbine Exit Guide Vanes
3. Turbine Stator
4. Turbine Blisk
5. Impeller
6. Pump Volute

Vendor B Builds
7. Turbine Nozzle
8. Turbine Exit Guide Vanes
9. Turbine Stator
10. Turbine Blisk
11. Impeller
12. Pump Volute

Approved for public release; distribution is unlimited.
SLM Material Test Specimens

Fatigue Test Results

Legend

Vendor A
A-1: w/Turbine Nozzle (MMP)
A-2: w/Turbine EGV (MMP)
A-3: w/Turbine Stator (MMP)
A-4: w/Turbine Blisk (MMP)
A-5: w/Impeller (MMP)
A-6: w/Pump Volute (Hand Polish)
A-AB: As-Built
A-M: Machined

Vendor B
B-7: w/Turbine Nozzle (Bead)
B-8: w/Turbine EGV (Bead)
B-9: w/Turbine Stator (Bead)
B-10: w/Turbine Blisk (Bead)
B-11: w/Impeller (Bead)
B-12: w/Pump Volute (Bead)
Conclusion

The SLM hardware demonstrations help fulfill Turbomachinery Branch, AM Goals:

• Develop AM design experience ✓
• Advance TRL of AM turbomachinery components and materials
  • Demonstration of representative piece part designs ✓
  • Continue to improve process (surface finishing, removing supports and powder, dimensional tolerance).
• Material property verification ✓
  • Continue to grow material property database. Build lot test specimens with all parts.
• Develop and test a turbopump assembly that uses AM techniques to the greatest extent possible. (The next step)

The SLM demonstration hardware met most of the design intentions. With a few process improvements, these geometries can be integrated into a turbopump assembly.
Acknowledgements

Mechanical Test Branch – EM10
Doug Wells (EM20) – Test Planning
Vann Bradford (EM10) – Material Test
Chip Moore (EM10) – Surface Evaluation
Brian West (EM42) – White Light Scanning
BACK UP
SLM Hardware Demonstrations

Turbine Nozzle

Vendor A
Surface Finish: MMP

Vendor B
Surface Finish: Bead Blast

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Deviations on critical surfaces of the order 0.001”
Marshall Space Flight Center

SLM Hardware Demonstrations

Turbine Nozzle – White Light Scan

Vendor A
(Bottom Surface)

Deviations on critical surfaces of the order 0.001” to 0.01”
Turbine Nozzle – White Light Scan

Vendor B
(Top Surface)

Deviations on critical surfaces of the order 0.001"
Turbine Nozzle – White Light Scan

Vendor B
(Bottom Surface)

Deviations on critical surfaces of the order 0.001”
SLM Hardware Demonstrations

Turbine Nozzle – Surface Evaluation

Vendor A – MMP
Turbine Nozzle – Surface Evaluation

Vendor B – Bead Blast
SLM Hardware Demonstrations

Turbine Nozzle – Surface Evaluation

Vendor A – MMP
Vendor B – Bead Blast

Measured Ra values

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Vendor A – MMP
Vendor B – Bead Blast

Approved for public release; distribution is unlimited.
SLM Hardware Demonstrations

Turbine Stator

Vendor A

Surface Finish:
MMP

Vendor B

Surface Finish:
Bead Blast

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SLM Hardware Demonstrations

Turbine Stator – White Light Scan

Vendor A – LPS01240
SLM Hardware Demonstrations

Turbine Stator – White Light Scan

Vendor A – LPS01241
SLM Hardware Demonstrations

Turbine Stator – White Light Scan

Vendor B – LPS01240
SLM Hardware Demonstrations

Turbine Stator – White Light Scan

Vendor B – LPS01241

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SLM Hardware Demonstrations

Turbine Exit Guide Vanes

Vendor A

Surface Finish:
MMP

Vendor B

Surface Finish:
Bead Blast

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SLM Hardware Demonstrations

Turbine Exit Guide Vanes – White Light Scan

Vendor A - Top
SLM Hardware Demonstrations

Turbine Exit Guide Vanes – White Light Scan

Vendor A - Bottom
SLM Hardware Demonstrations

Turbine Exit Guide Vanes – White Light Scan

Vendor B - Top
SLM Hardware Demonstrations

Turbine Exit Guide Vanes – White Light Scan

Vendor B - Bottom