Evaluation of Additively Manufactured Demonstration Hardware for a Turbopump Application

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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

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

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

Typical Design Goal

Reliability

Maximize

Complex hardware, designed near the limits of the state-of-the-art, with predicted or demonstrated high reliability 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.
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>
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MMP: Proprietary Micro Machining Process  
WLS: White Light Scan

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SLM Hardware Demonstrations

Impeller

Vendor A

Surface Finish:
MMP

Vendor B

Surface Finish:
Ext: Bead Blast
Int: Extrude Hone

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Impeller – White Light Scan (Vendor A)

Datum Surface

Avg. Deviation ≈ −0.007"

Avg. Deviation ≈ +0.001"

Avg. Deviation ≈ +0.010"

Avg. Deviation ≈ −0.010"

Extra material is provided on external surfaces. Internal flow path surfaces are net shape.
Impeller - Surface Evaluation

Vendor A – MMP
(Bottom Surface)

Vendor B – Extrude Hone
(Bottom Surface)
Impeller - Surface Evaluation

Vendor A – MMP
(Bottom Surface)

Vendor B – Extrude Hone
(Bottom Surface)
Impeller - Surface Evaluation

Vendor A – MMP
(Top Surface)

Vendor B – Extrude Hone
(Top Surface)
Impeller - Surface Evaluation

Vendor A – MMP
(Top Surface)

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

Impeller - Surface Evaluation

A – MMP
B – Extrude

\[ R_a \approx 600 \mu m \]
\[ R_a \approx 250 \mu m \]

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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.
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
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)

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Pump Volute – Surface Evaluation

Vendor A – Extrude Hone
Vendor B – Extrude Hone

\[ R_a \approx 200 \mu \text{in} \]
\[ R_a \approx 125 \mu \text{in} \]

A – Top

B – Top

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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

Avg. Deviation $\approx -0.025"$

Vendor A
(Bottom Surface)

Vendor B
(Bottom Surface)

Avg. Deviation $\approx -0.018"$
SLM Hardware Demonstrations

Turbine Blisk – White Light Scan

Vendor A (Top Surface)

Vendor B (Top Surface)

Avg. Deviation $\approx +0.010''$

Avg. Deviation $\approx +0.010''$
SLM Hardware Demonstrations

Turbine Blisk – Surface Evaluation

Vendor A – MMP
SLM Hardware Demonstrations

Turbine Blisk – Surface Evaluation

Vendor B – Bead Blast
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

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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)

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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”
SLM Hardware Demonstrations

Turbine Nozzle – White Light Scan

Vendor A
(Bottom Surface)

Deviations on critical surfaces of the order 0.001" to 0.01"

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SLM Hardware Demonstrations

Turbine Nozzle – White Light Scan

Vendor B
(Top Surface)

Deviations on critical surfaces of the order 0.001”

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SLM Hardware Demonstrations

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
Turbine Nozzle – Surface Evaluation

Vendor A – MMP
Vendor B – Bead Blast

Measured Ra values

A

B

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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

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SLM Hardware Demonstrations

Turbine Stator – White Light Scan

Vendor A – LPS01241

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

Turbine Stator – White Light Scan

Vendor B – LPS01240

Approved for public release; distribution is unlimited.
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

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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