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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Derek O'Neal

256-544-2543
derek.oneal@nasa.gov

MARSHALL SPACE FLIGHT CENTER

ENGINEERING DIRECTORATE
PROPULSION SYSTEMS DEPARTMENT
PROPULSION COMPONENT DESIGN & DEVELOPMENT DIVISION
TURBOMACHINERY DESIGN & DEVELOPMENT BRANCH

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

$$\frac{Power}{Weight}$$ ↑ Maximize

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

Typical Design Goal

Reliability

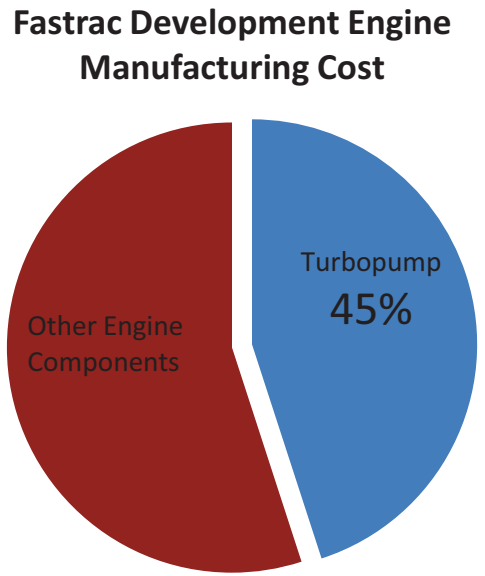
↑ Maximize

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



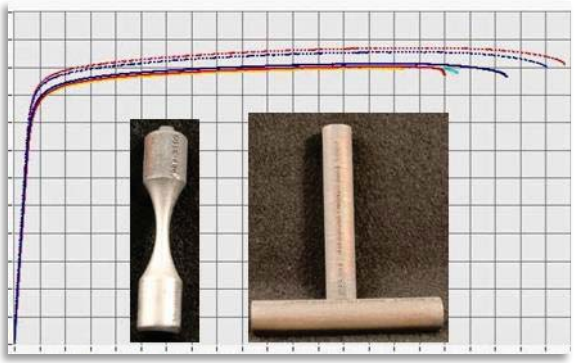
Can we use **Additive Manufacturing** techniques to:

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

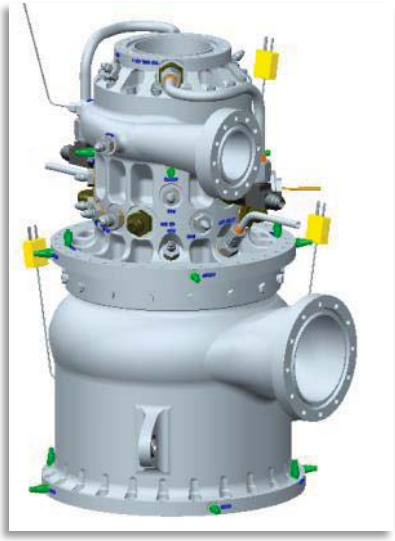
Turbomachinery Branch AM Goals

- 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.

SLM Impeller



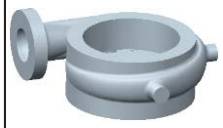
Material Testing



Integrate AM into turbopump

SLM Hardware Demonstrations

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

Part	Model Image	Vendor	Surface Finishing	WLS	Surface Evaluation	Z Tensile	XY Tensile	Fatigue Surface Finish	Z Fatigue	XY Fatigue
Impeller		A	MMP	✓	✓	4	2	MMP	6	0
		B	Ext: Bead Blast Int: Extrude Hone		✓	4	2	Bead Blast	6	0
Pump Volute		A	Ext: Bead Blast Int: Extrude Hone	✓	✓	4	2	Hand Polish	6	0
		B	Ext: Bead Blast Int: Extrude Hone	✓	✓	4	2	Bead Blast	6	0
Turbine Blisk		A	MMP	✓	✓	4	2	MMP	6	0
		B	Bead Blast	✓	✓	4	2	Bead Blast	6	0
Turbine Nozzle		A	MMP	✓	✓	4	2	MMP	6	0
		B	Bead Blast	✓	✓	6	0	Bead Blast	4	2
Turbine Stator		A	MMP	✓		4	2	MMP	6	0
		B	Bead Blast	✓		6	0	Bead Blast	4	2
Turbine Exit Guide Vanes		A	MMP	✓		4	2	MMP	6	0
		B	Bead Blast	✓		6	0	Bead Blast	4	2

MMP: Proprietary Micro Machining Process

WLS: White Light Scan

SLM Hardware Demonstrations

Impeller

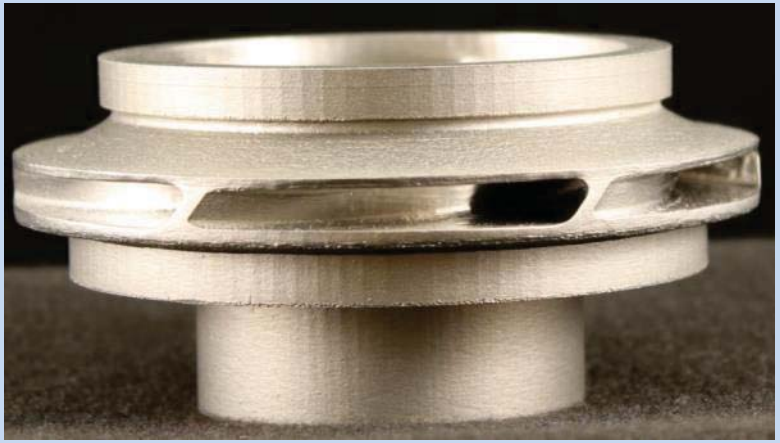
Vendor A

Surface Finish:
MMP

Build Direction

Vendor B

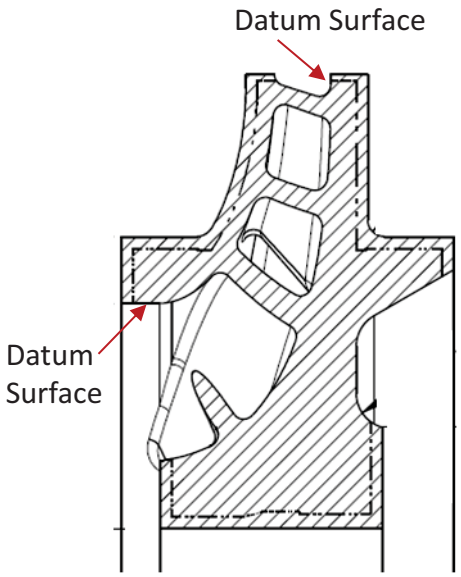
Surface Finish:
Ext: Bead Blast
Int: Extrude Hone

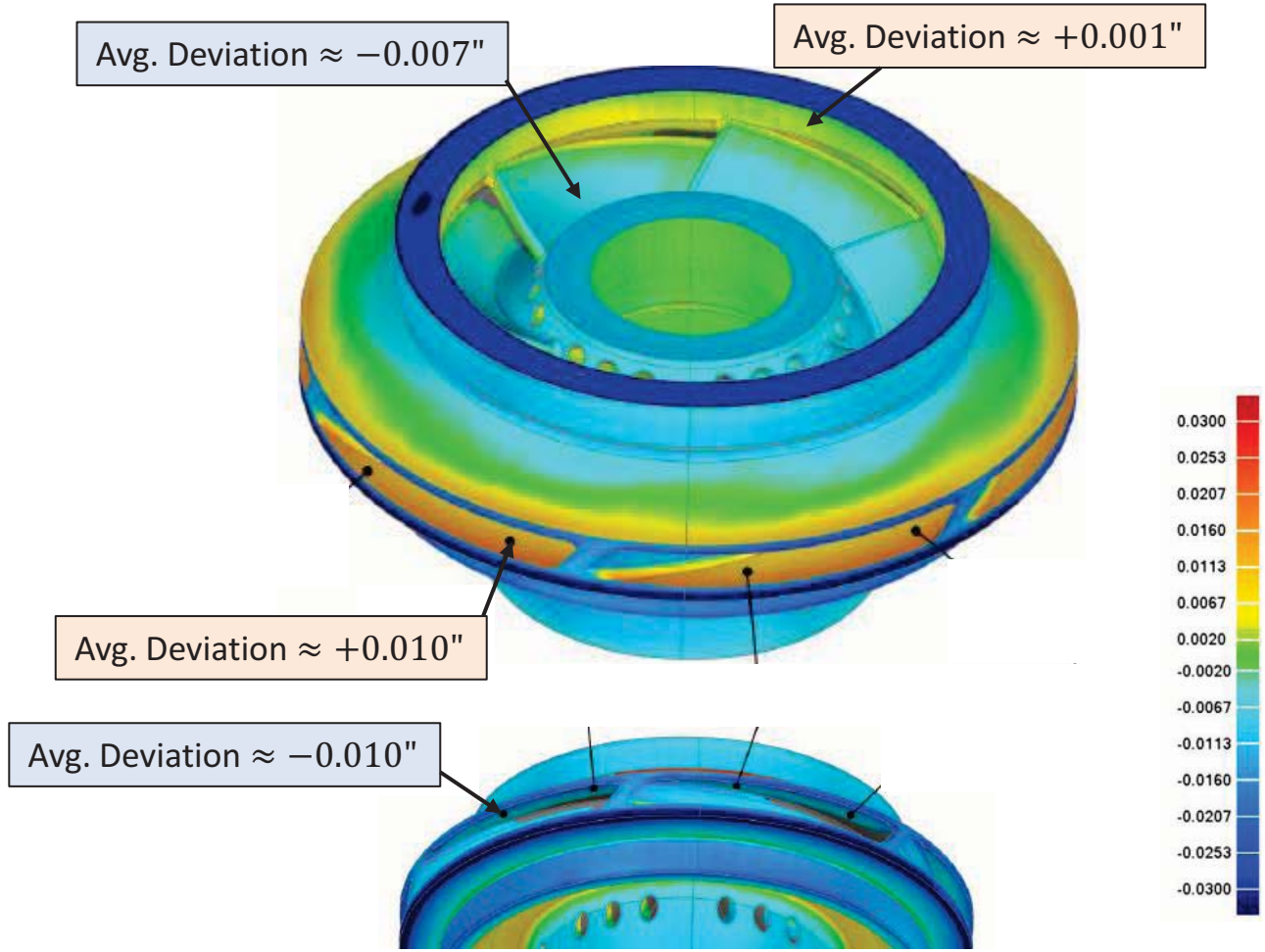


Build Direction

SLM Hardware Demonstrations

Impeller – White Light Scan (Vendor A)

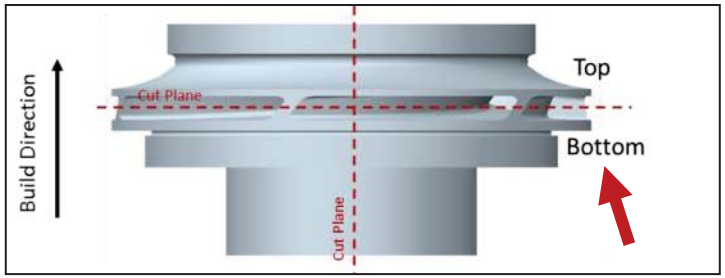




Extra material is provided on external surfaces. Internal flow path surfaces are net shape.

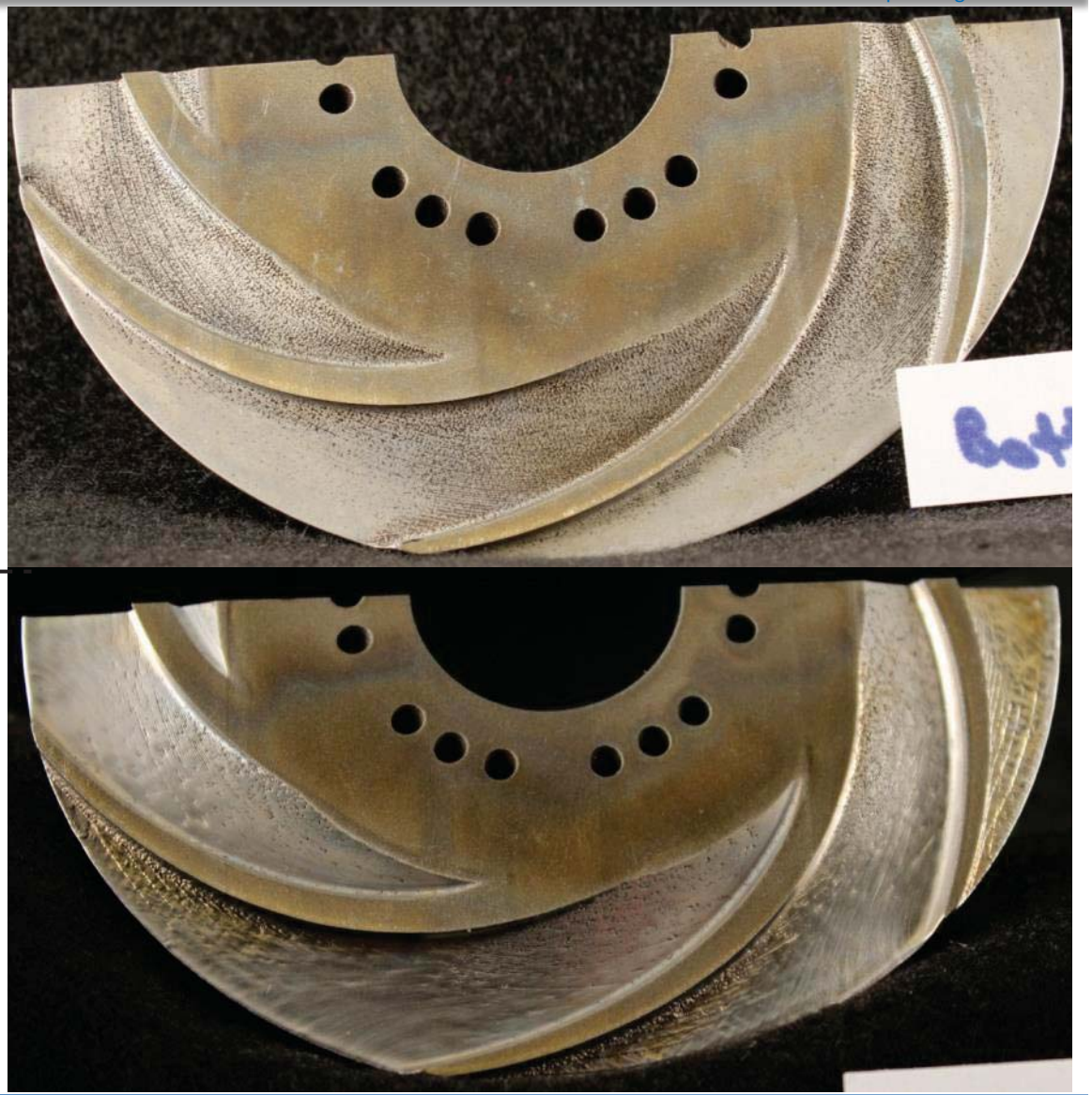
SLM Hardware Demonstrations

Impeller - Surface Evaluation



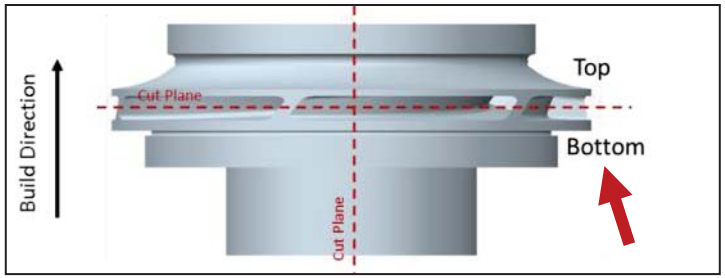
Vendor A – MMP
(Bottom Surface)

Vendor B – Extrude Hone
(Bottom Surface)

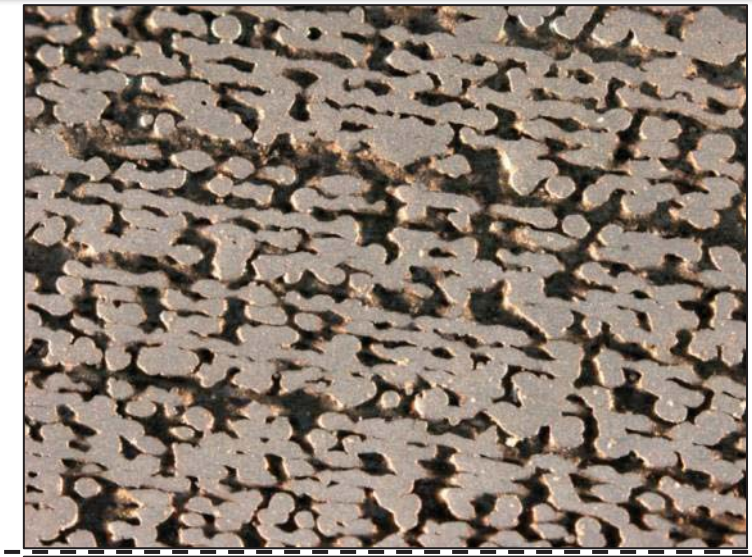


SLM Hardware Demonstrations

Impeller - Surface Evaluation



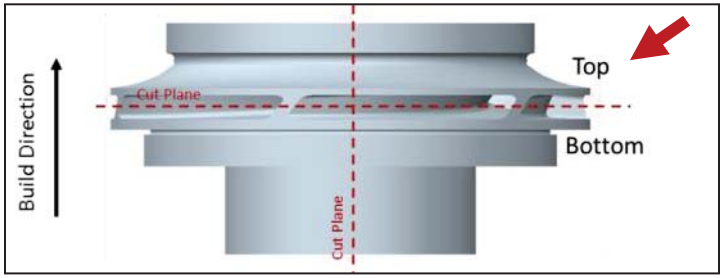
Vendor A – MMP
(Bottom Surface)



Vendor B – Extrude Hone
(Bottom Surface)

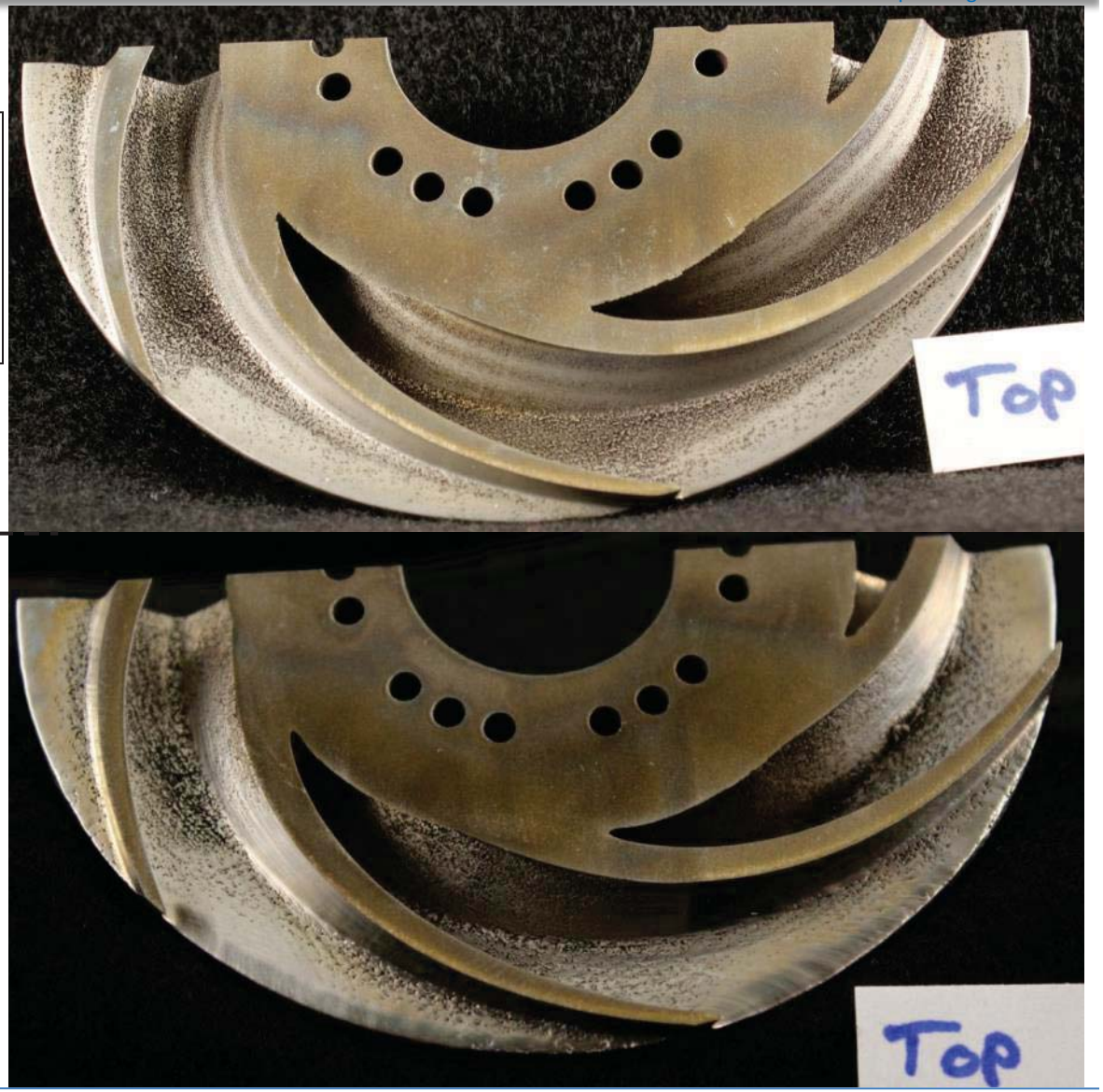
SLM Hardware Demonstrations

Impeller - Surface Evaluation



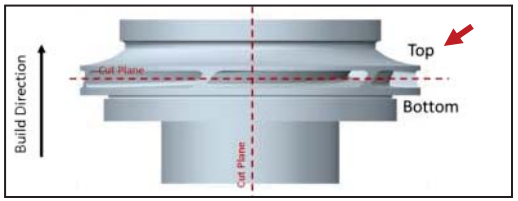
Vendor A – MMP
(Top Surface)

Vendor B – Extrude Hone
(Top Surface)



SLM Hardware Demonstrations

Impeller - Surface Evaluation



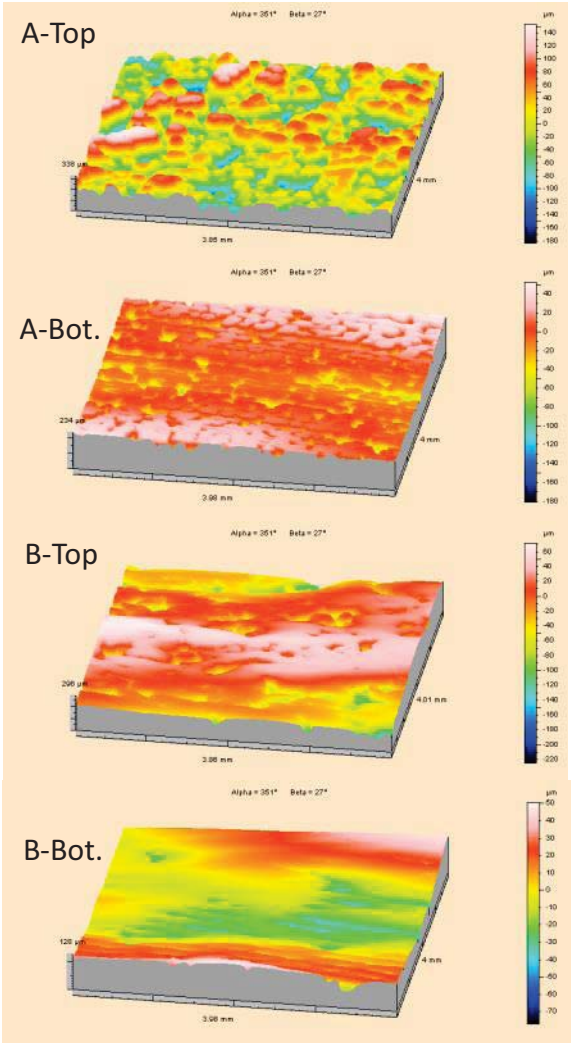
Vendor A – MMP
(Top Surface)

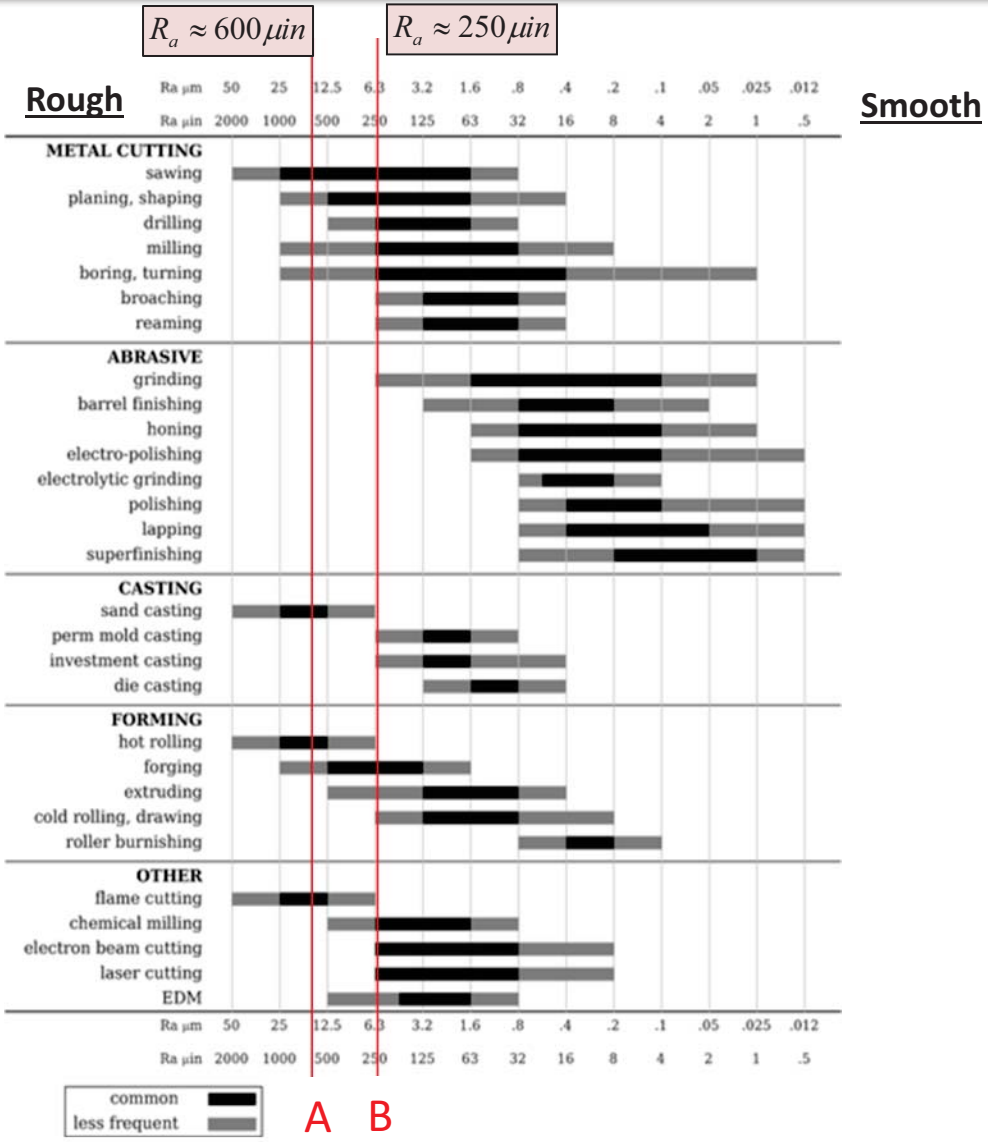
Vendor B – Extrude Hone
(Top Surface)

SLM Hardware Evaluation

Impeller - Surface Evaluation

A – MMP
B – Extrude



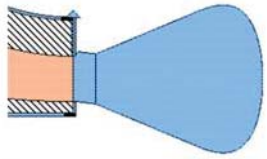


SLM Hardware Demonstrations

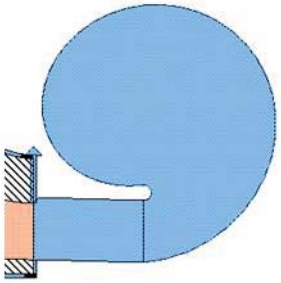
Pump Volute – Design Considerations

- SLM Constraint – Unsupported ceiling radii should be minimized

Typical volute cross sections are designed for hydrodynamic performance.



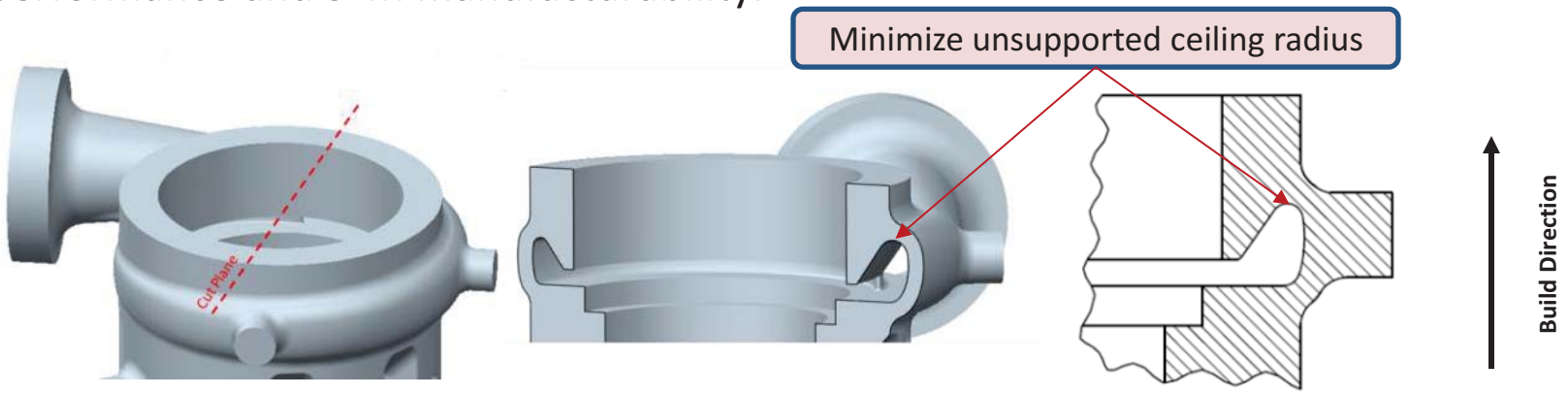
Symmetric



Overhung

Circular

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

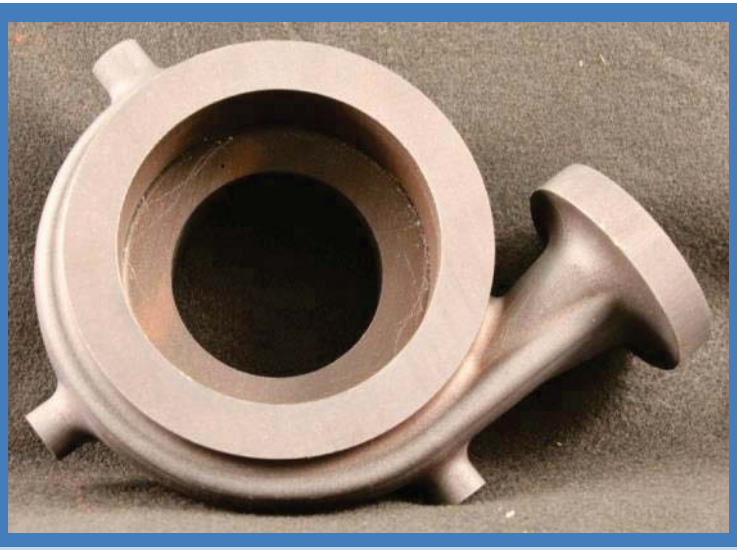


SLM Hardware Demonstrations

Pump Volute

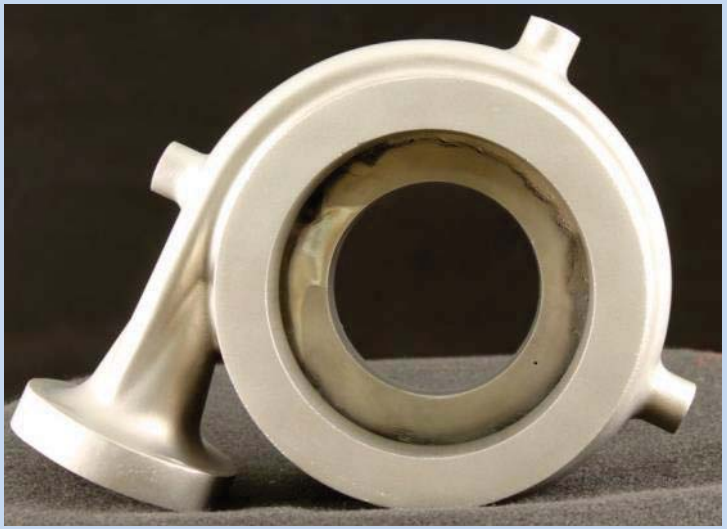
Vendor A

Surface Finish:
Ext: Bead Blast
Int: Extrude Hone



Vendor B

Surface Finish:
Ext: Bead Blast
Int: Extrude Hone

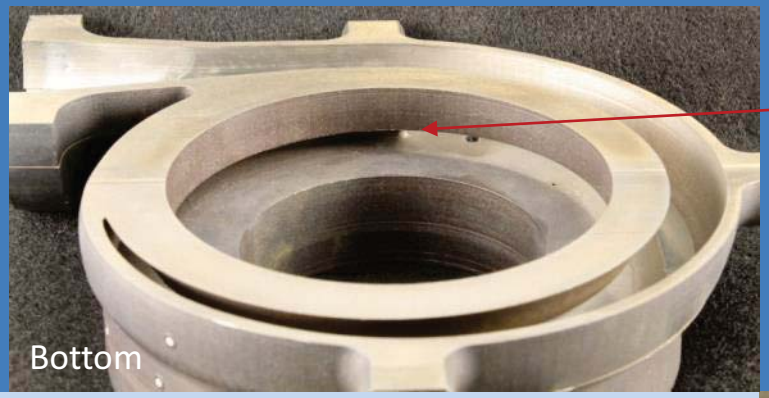


SLM Hardware Demonstrations

Pump Volute

Vendor A

Surface Finish:
Ext: Bead Blast
Int: Extrude Hone

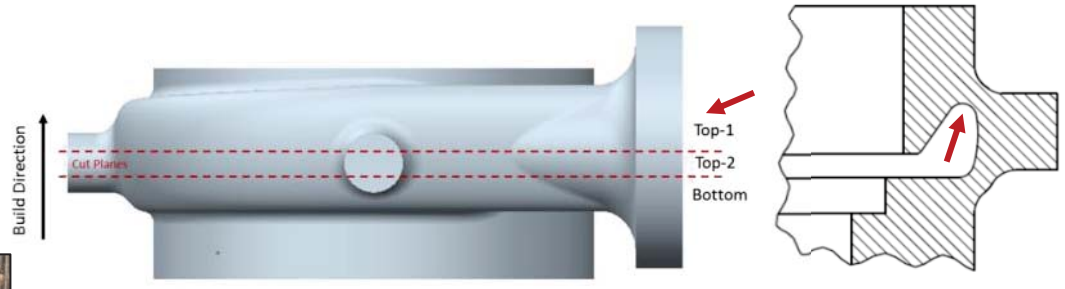


Vendor B

Surface Finish:
Ext: Bead Blast
Int: Extrude Hone

SLM Hardware Demonstrations

Pump Volute – Surface Evaluation



Vendor A – Extrude Hone
(Top Surface)

Vendor B – Extrude Hone
(Top Surface)

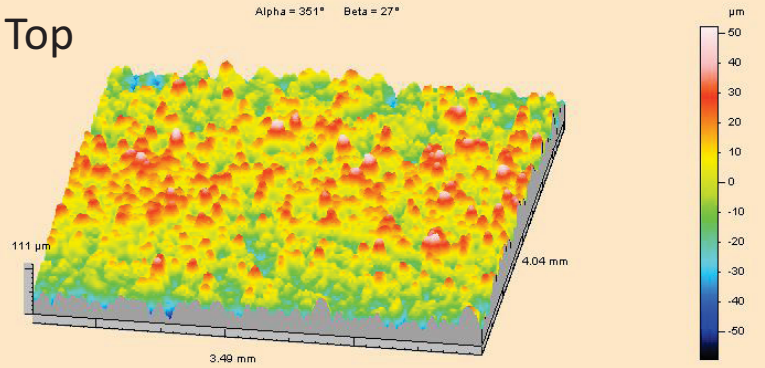
SLM Hardware Demonstrations

Marshall Space Flight Center

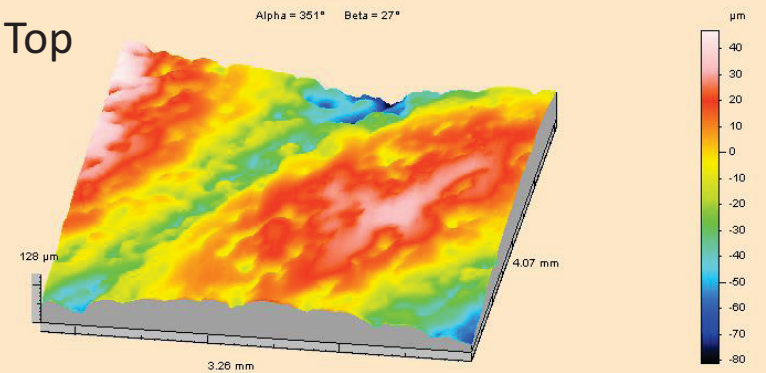
Pump Volute – Surface Evaluation

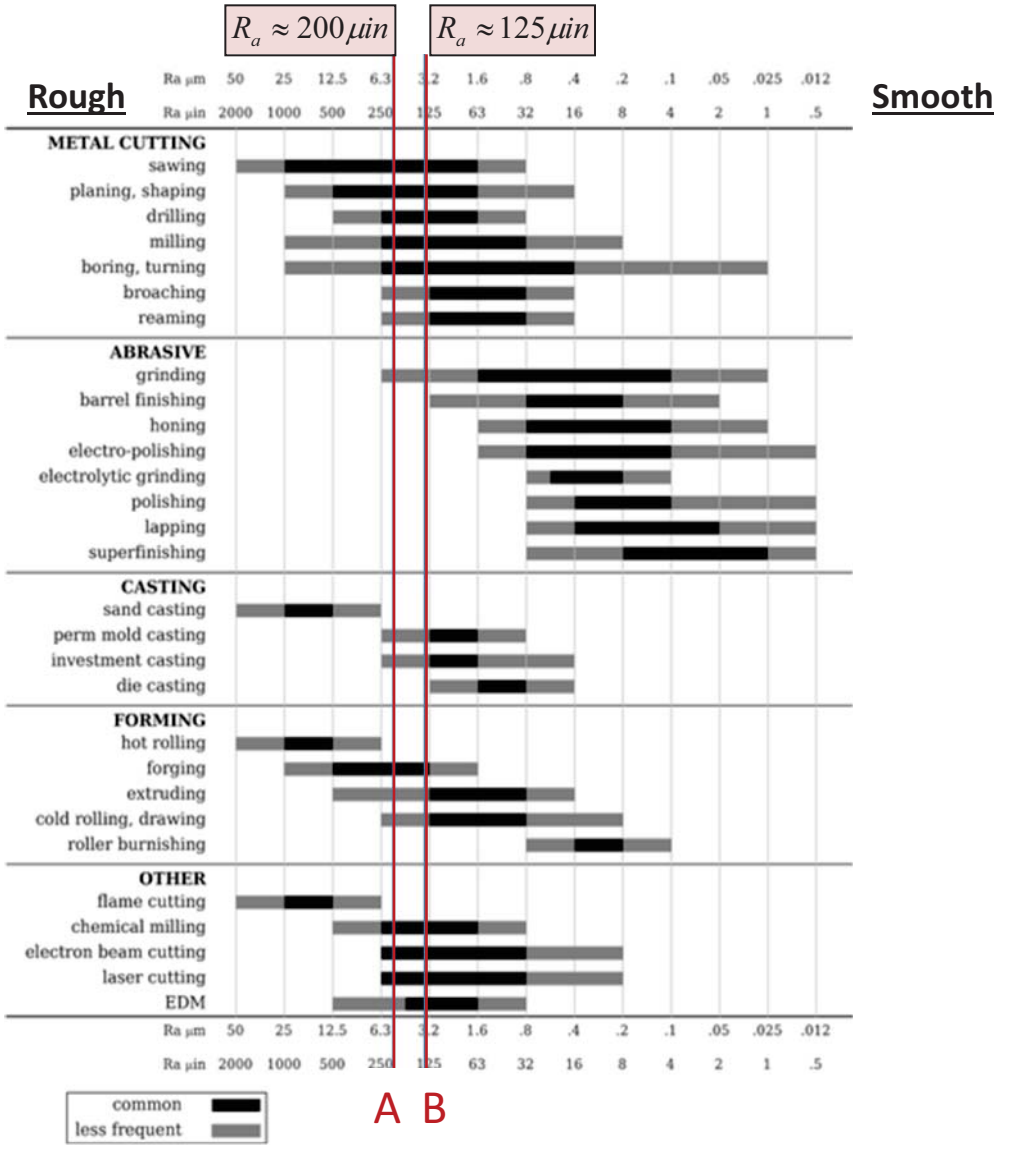
Vendor A – Extrude Hone
Vendor B – Extrude Hone

A – Top



B – Top





SLM Hardware Demonstrations

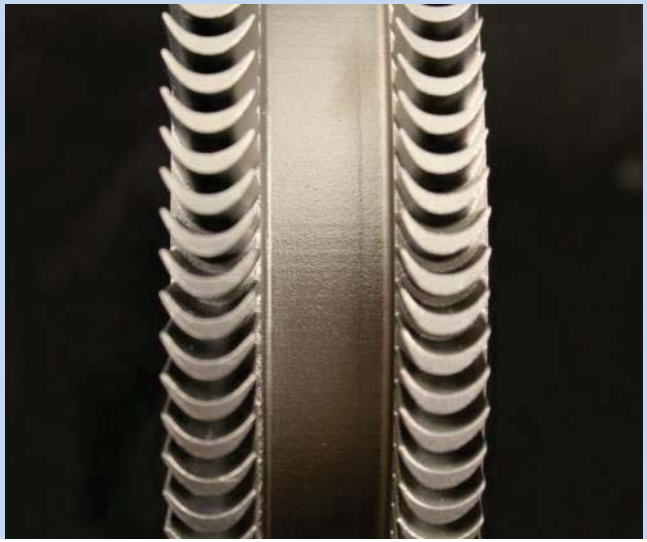
Turbine Blisk

Vendor A

Surface Finish:
MMP

Vendor B

Surface Finish:
Bead Blast

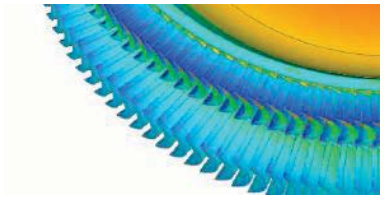


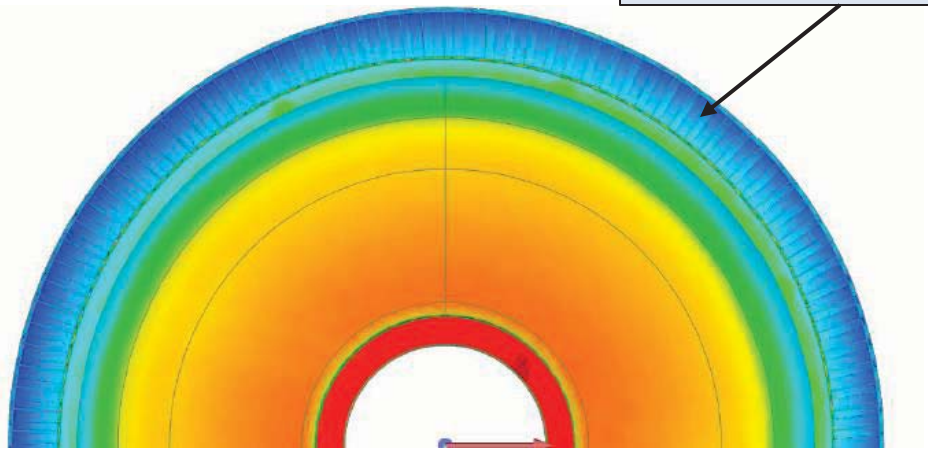
SLM Hardware Demonstrations

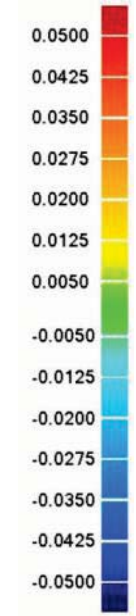
Turbine Blisk – White Light Scan

Avg. Deviation ≈ −0.025"

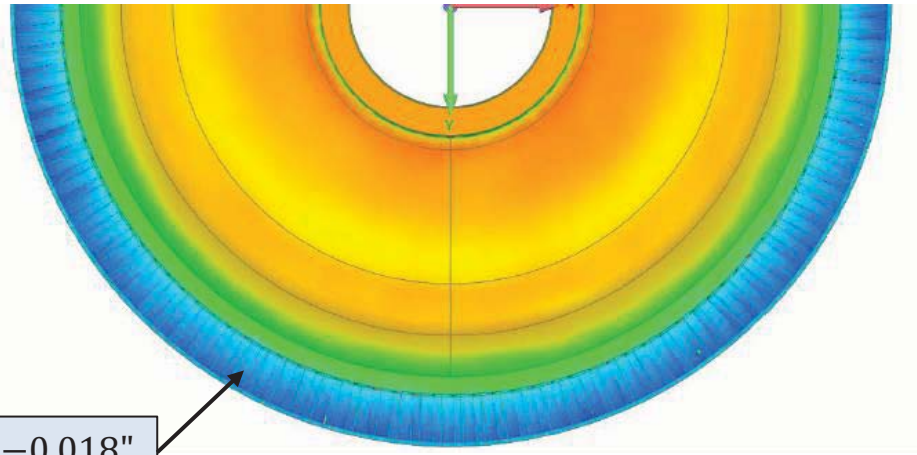
Vendor A
(Bottom Surface)

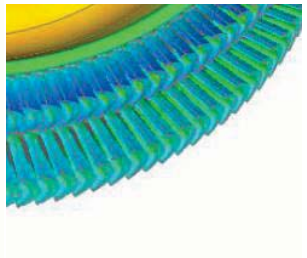






Vendor B
(Bottom Surface)

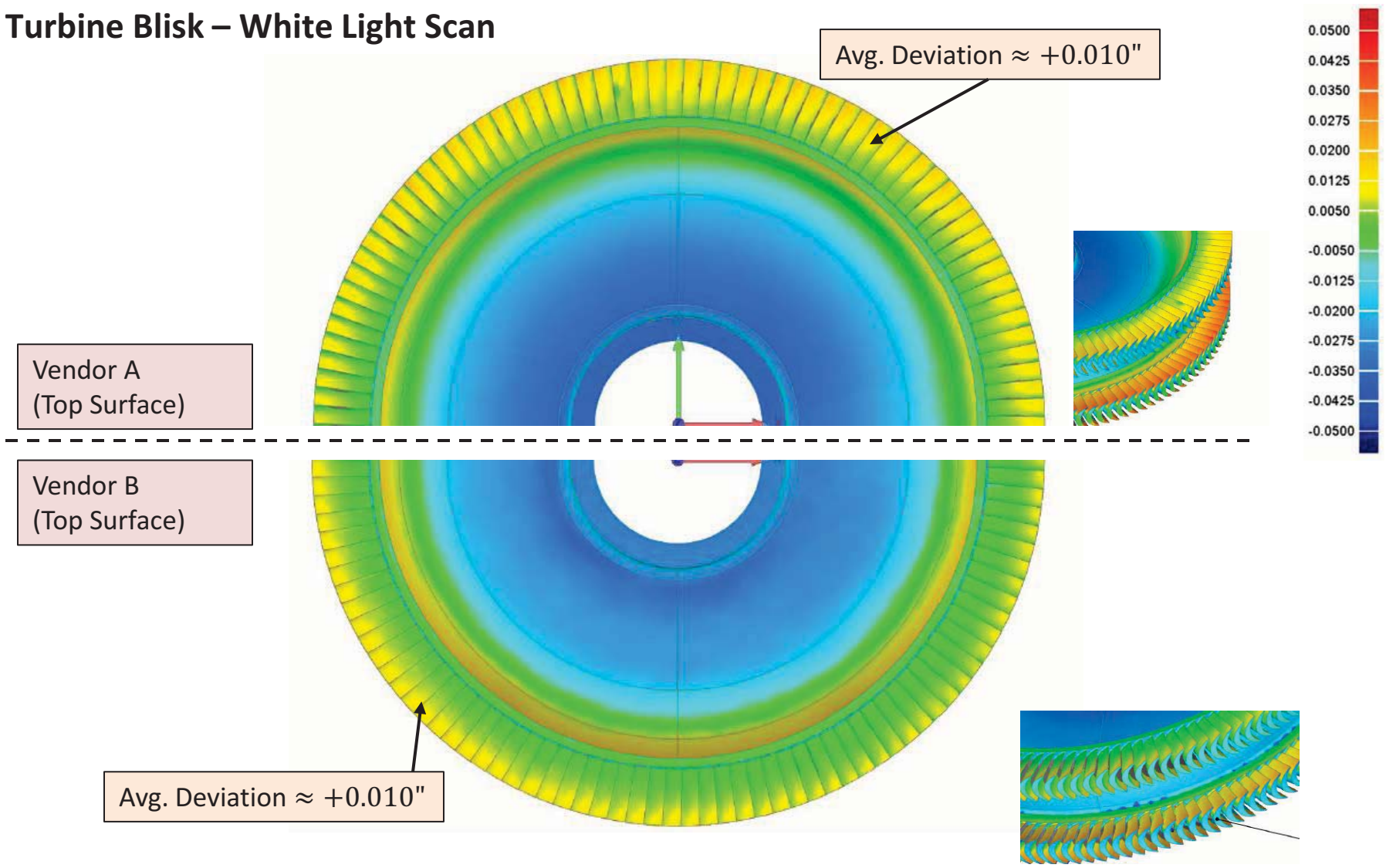




Avg. Deviation ≈ −0.018"

SLM Hardware Demonstrations

Turbine Blisk – White Light Scan



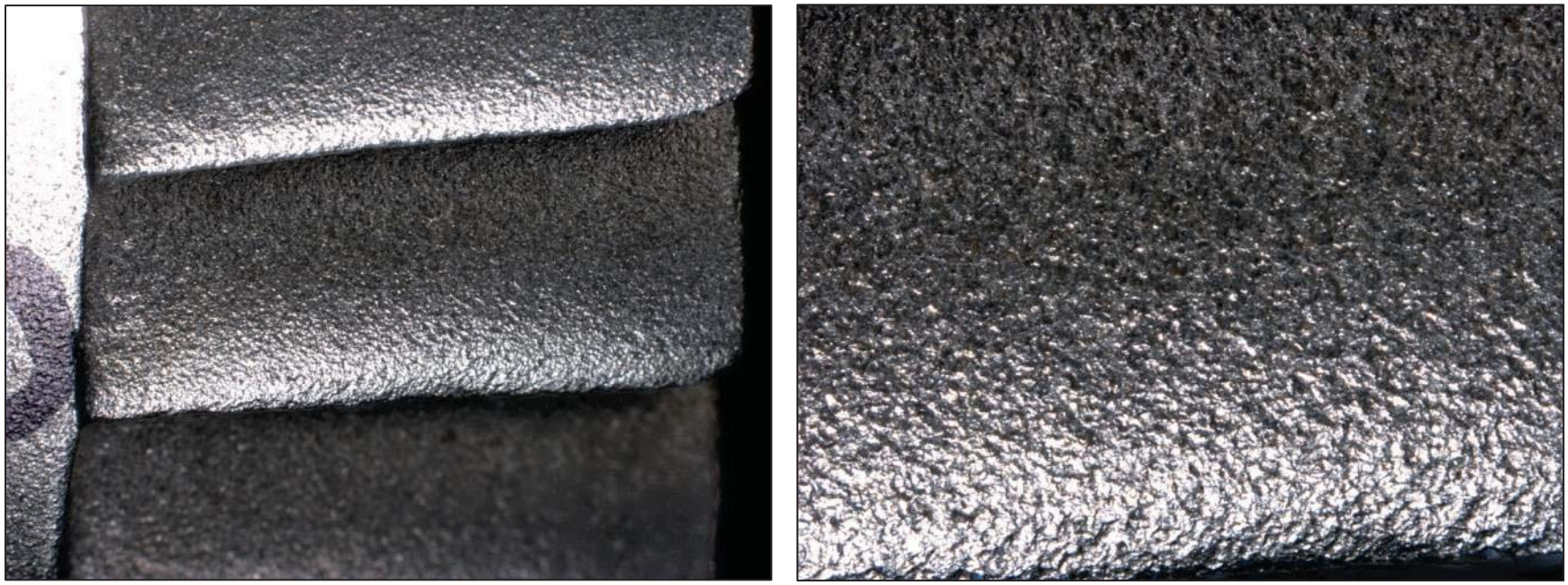
SLM Hardware Demonstrations

Turbine Blisk – Surface Evaluation

Vendor A – MMP

SLM Hardware Demonstrations

Turbine Blisk – Surface Evaluation



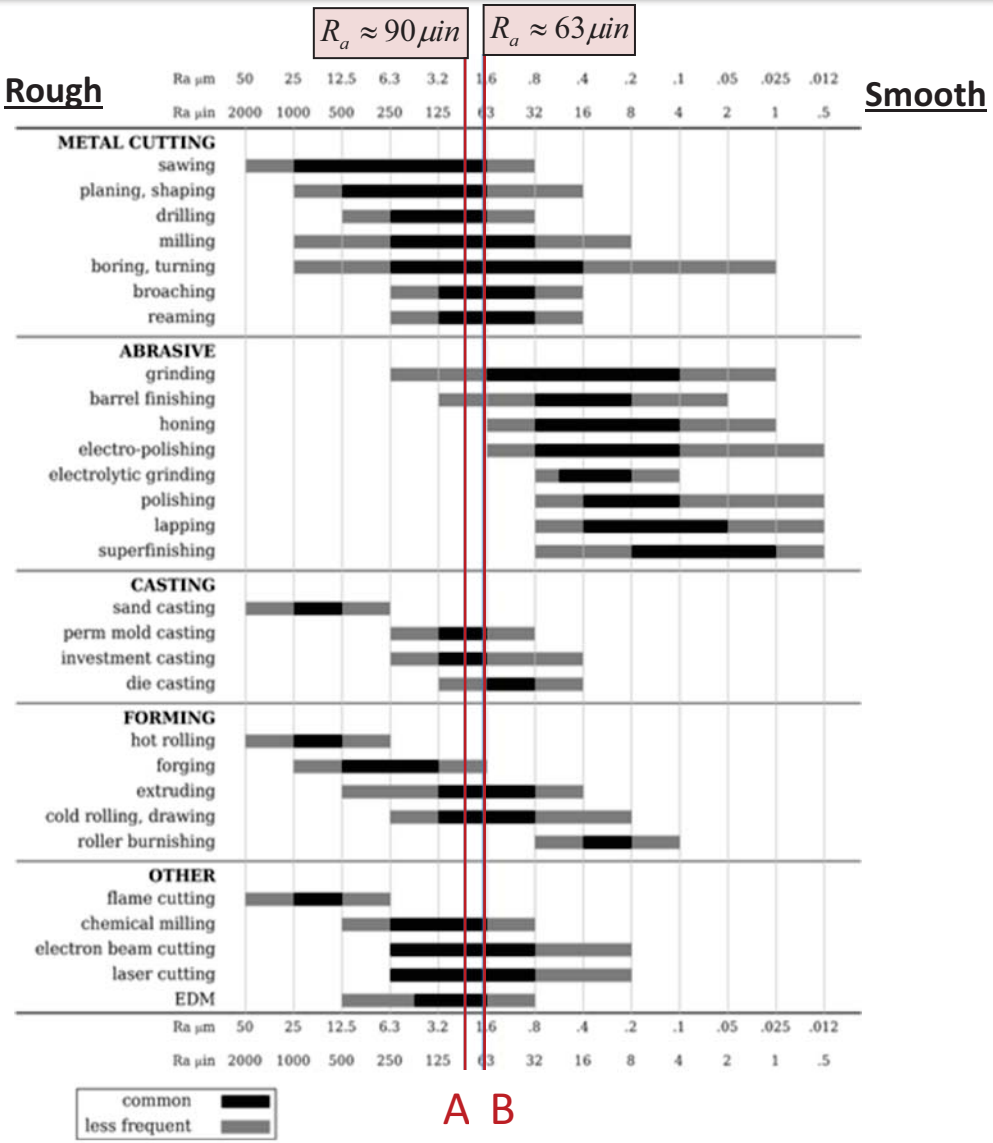
Vendor B – Bead Blast

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

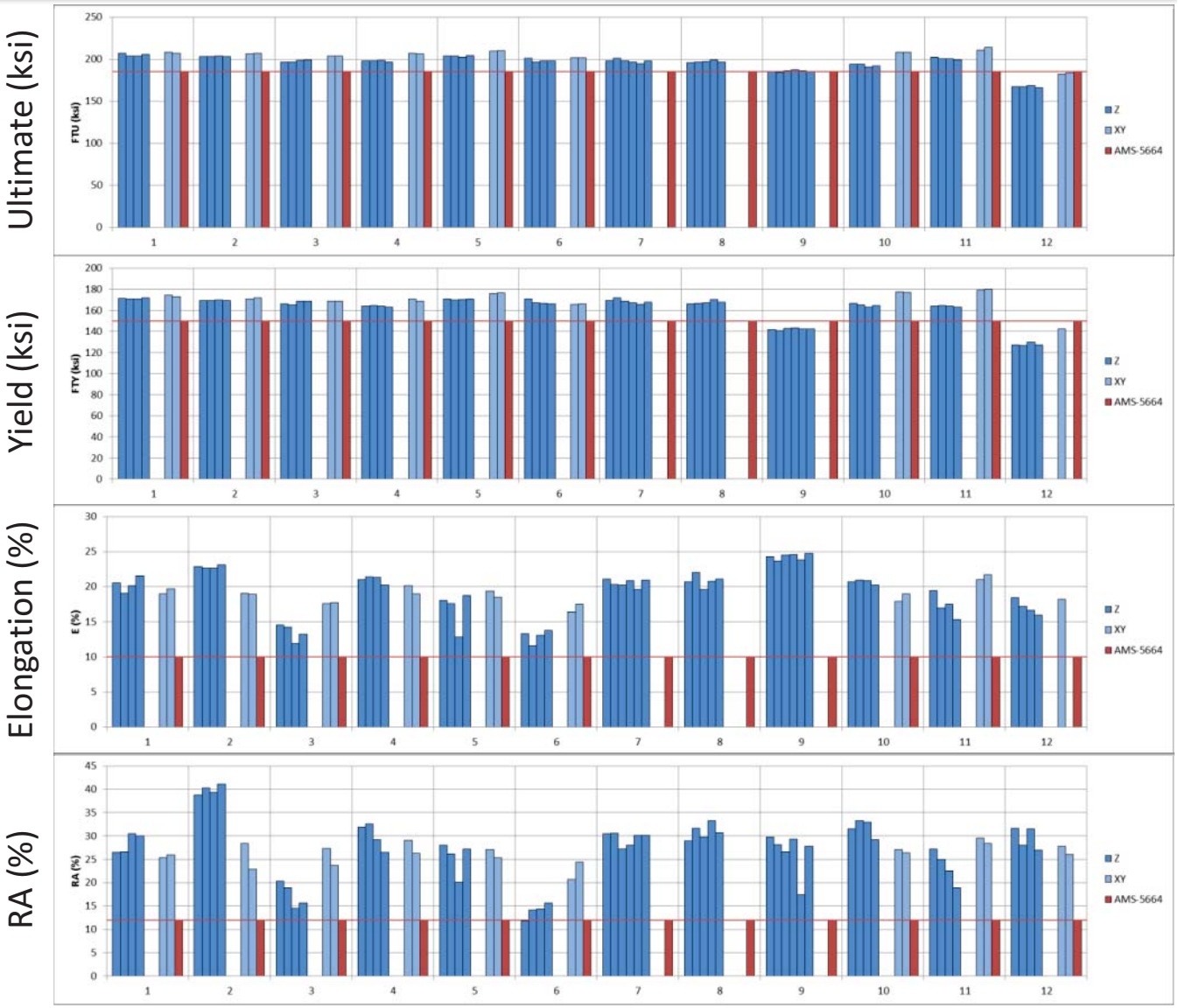
X-Axis

Vendor A Builds

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

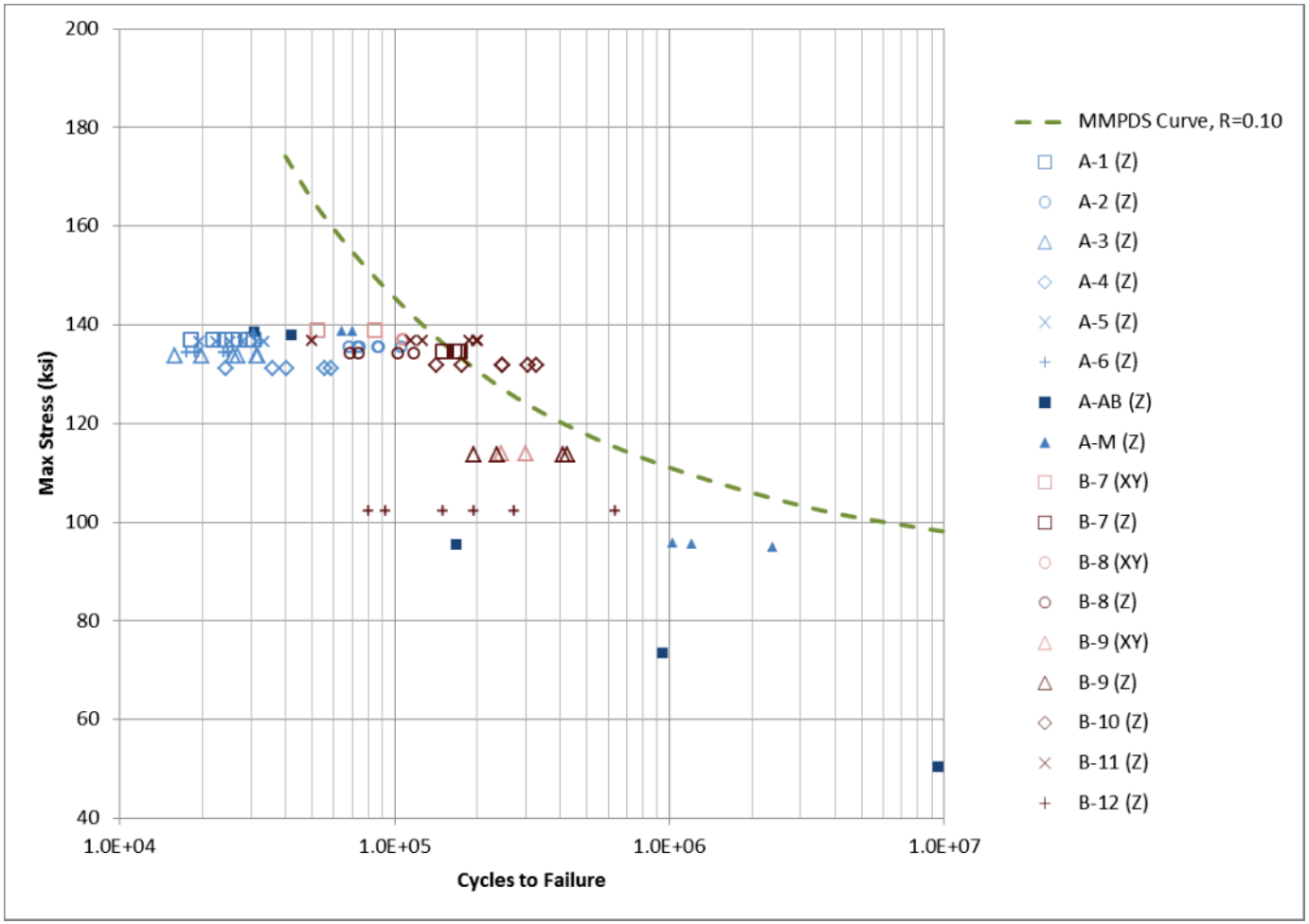
Vendor B Builds

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



SLM Material Test Specimens

Fatigue Test Results



Legend

<u>Vendor A</u>
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

<u>Vendor B</u>
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

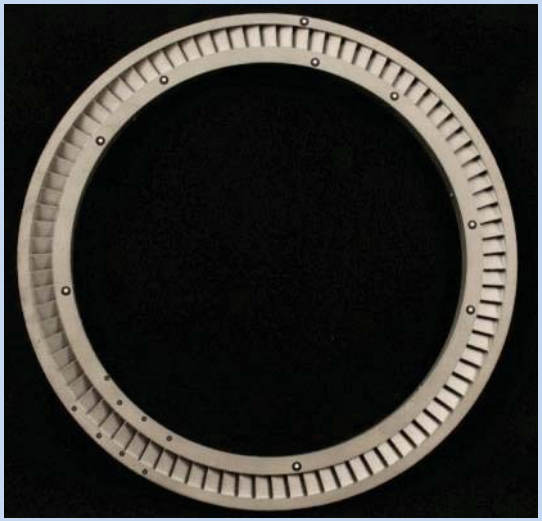
Turbine Nozzle

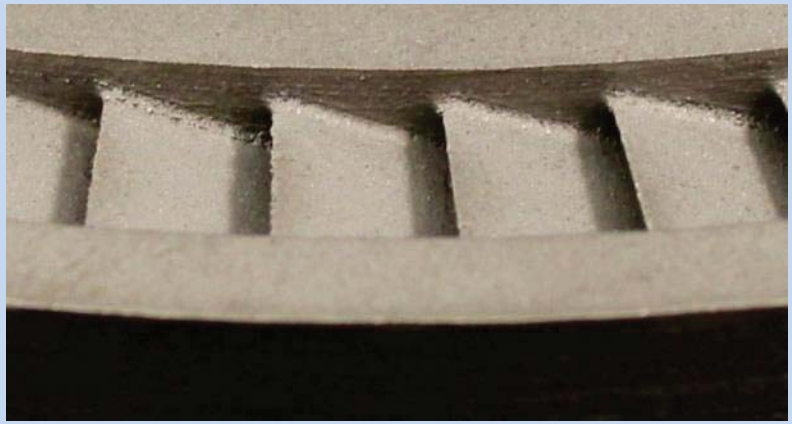
Vendor A

Surface Finish:
MMP

Vendor B

Surface Finish:
Bead Blast



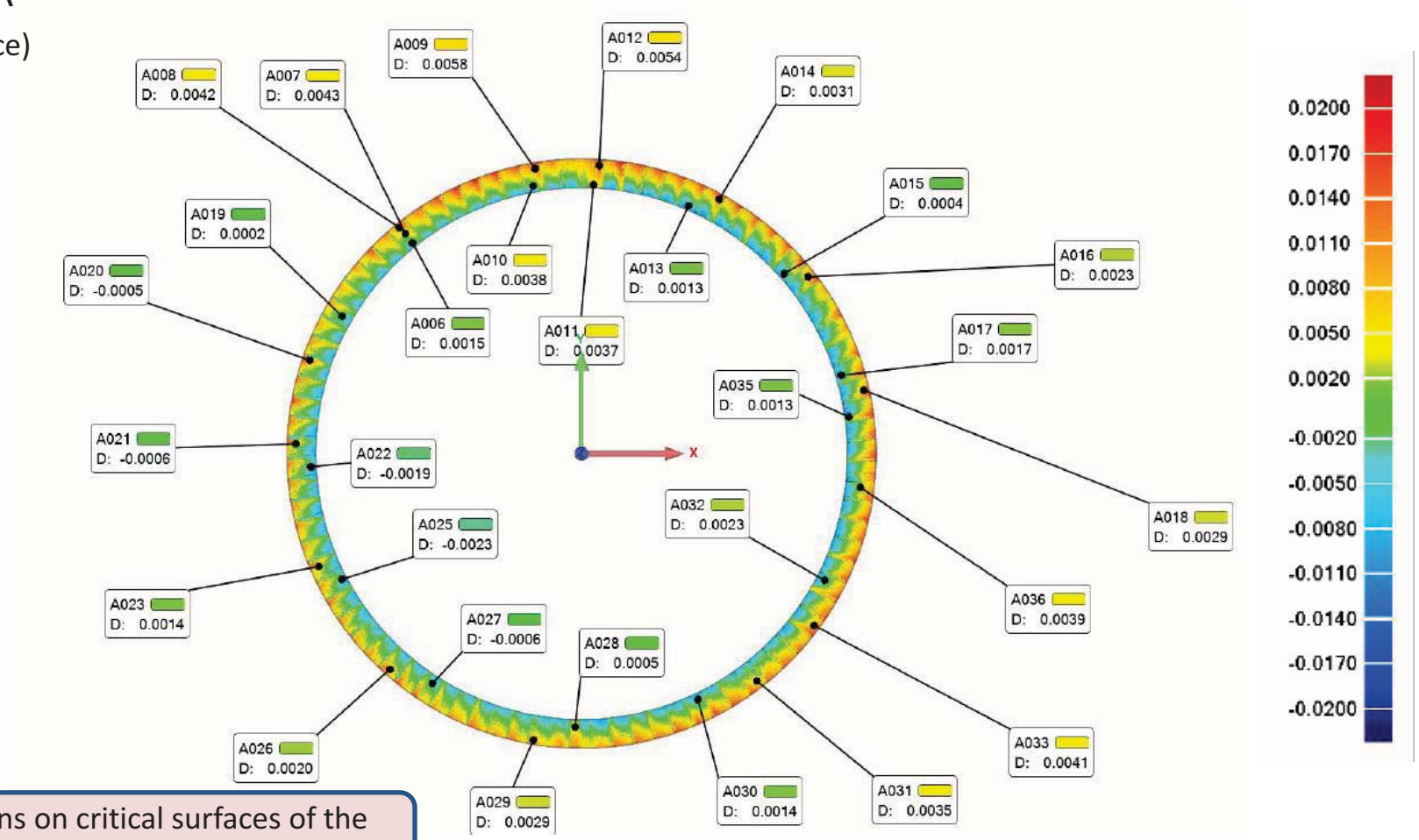


SLM Hardware Demonstrations

Turbine Nozzle – White Light Scan

Vendor A

(Top Surface)



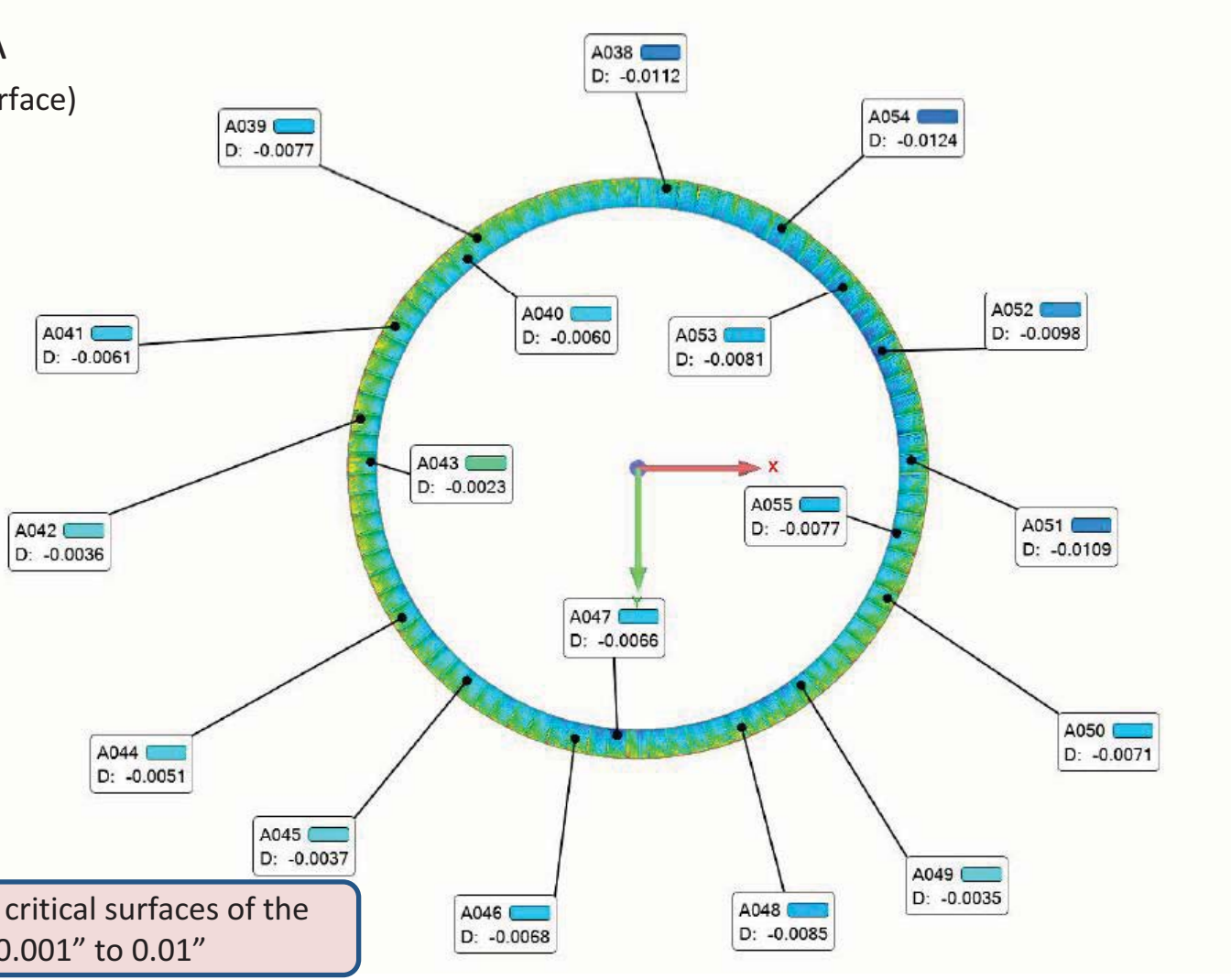
Deviations on critical surfaces of the order 0.001”

SLM Hardware Demonstrations

Turbine Nozzle – White Light Scan

Vendor A

(Bottom Surface)



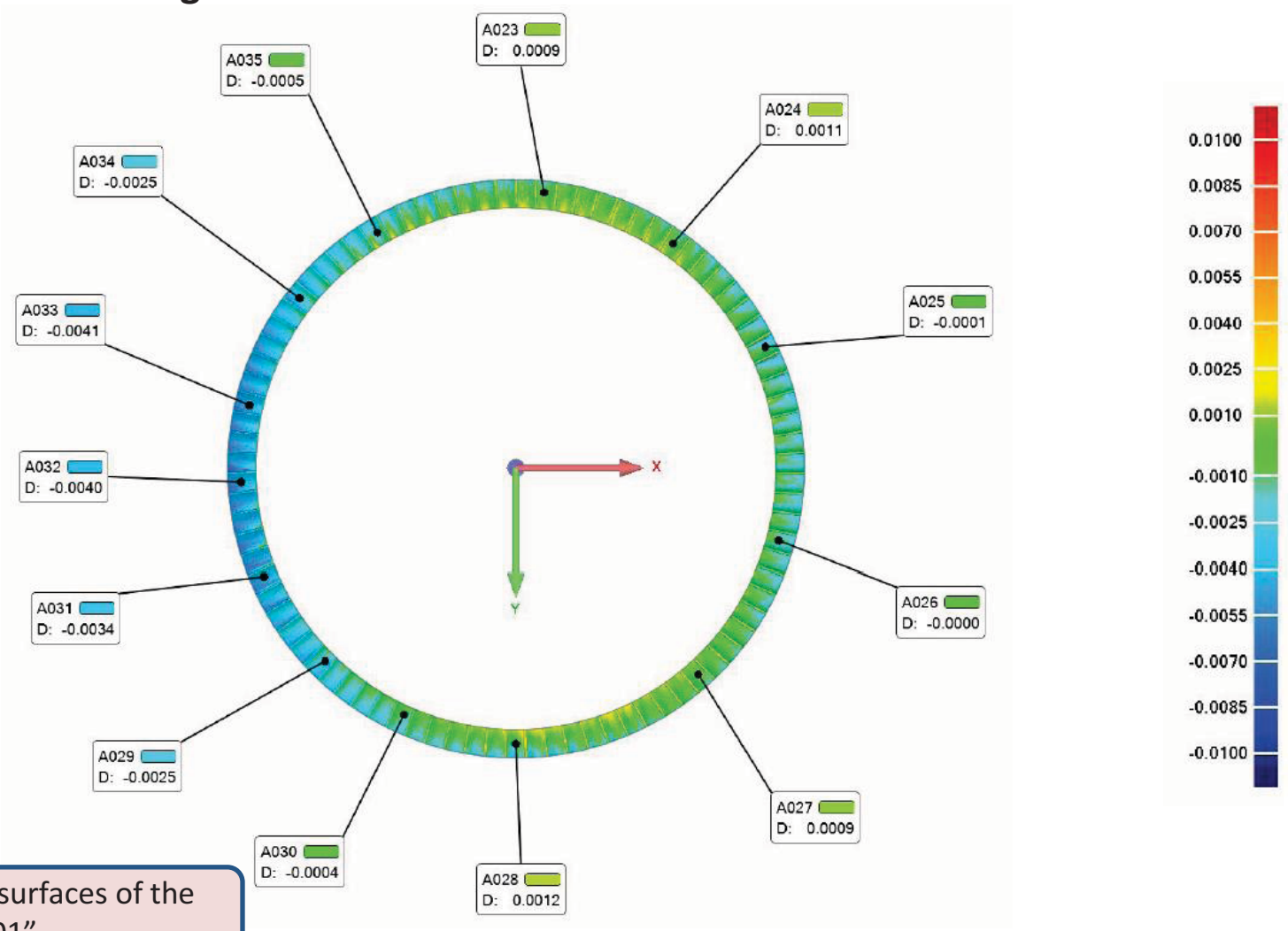
Deviations on critical surfaces of the order 0.001” to 0.01”

SLM Hardware Demonstrations

Turbine Nozzle – White Light Scan

Vendor B

(Top Surface)



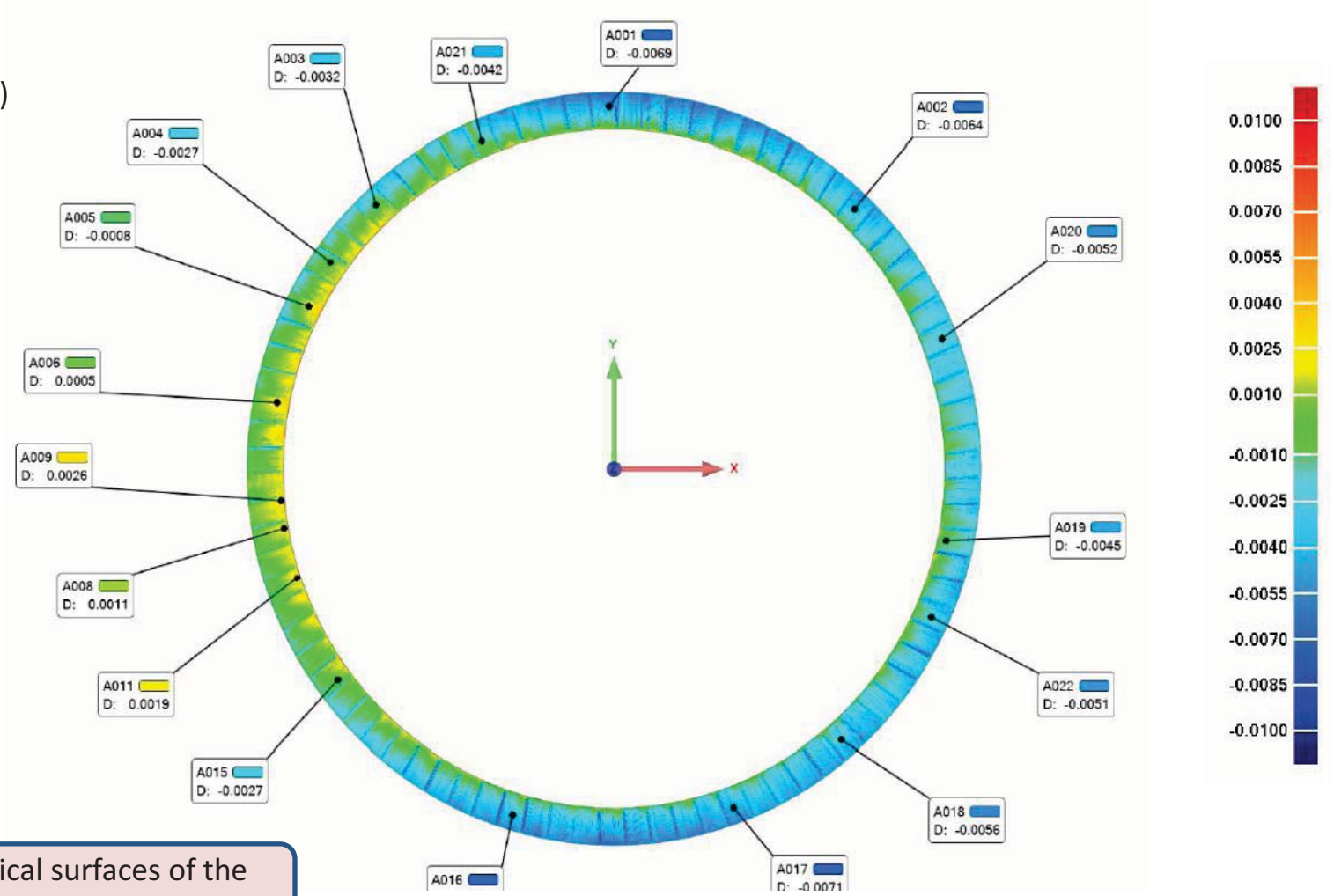
Deviations on critical surfaces of the order 0.001”

SLM Hardware Demonstrations

Turbine Nozzle – White Light Scan

Vendor B

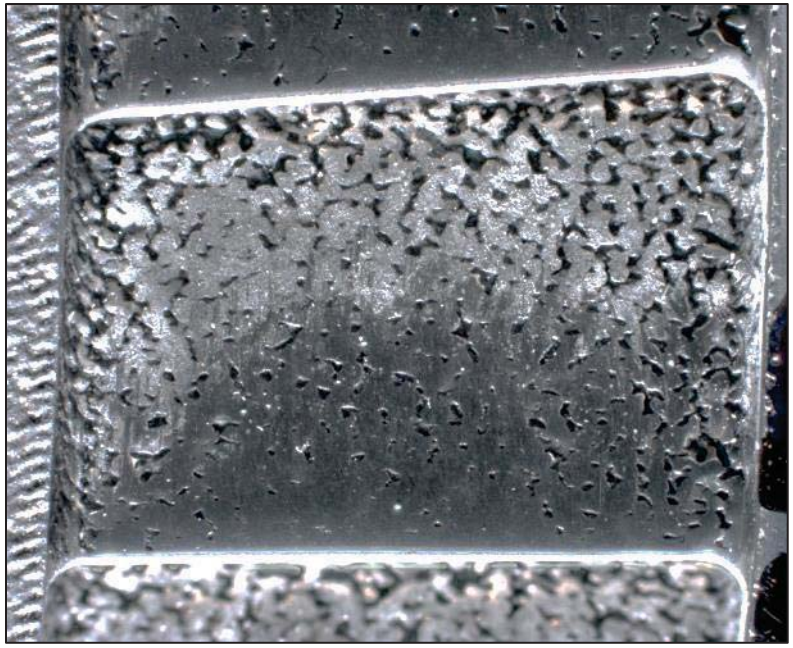
(Bottom Surface)



Deviations on critical surfaces of the order 0.001”

SLM Hardware Demonstrations

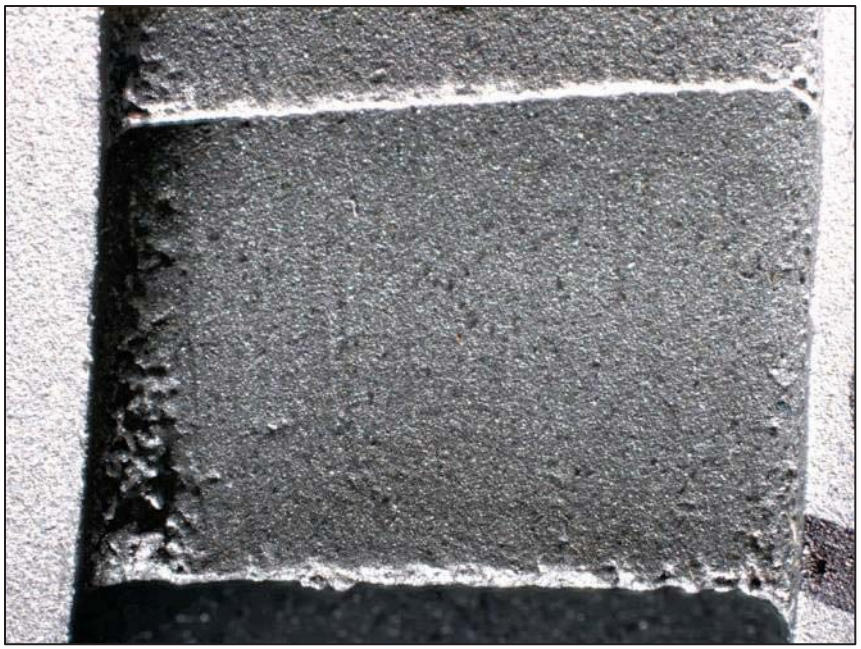
Turbine Nozzle – Surface Evaluation



Vendor A – MMP

SLM Hardware Demonstrations

Turbine Nozzle – Surface Evaluation

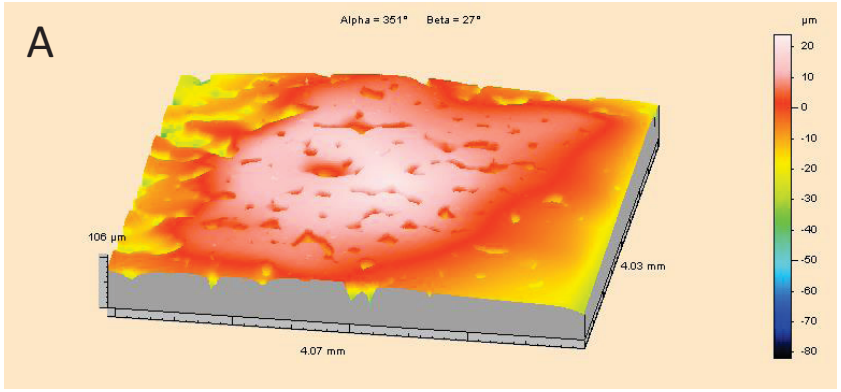


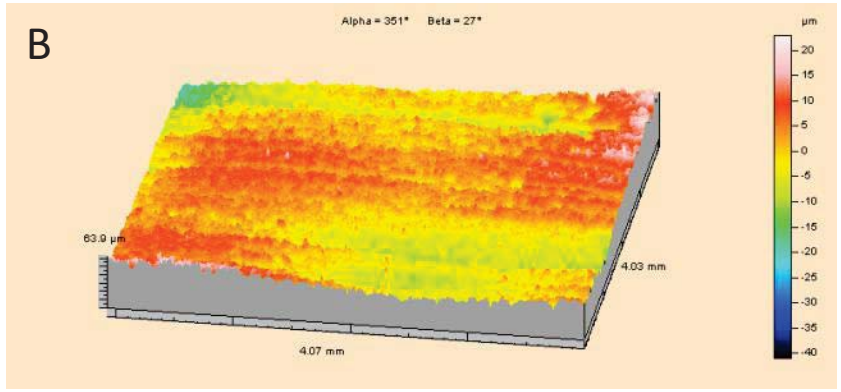
Vendor B – Bead Blast

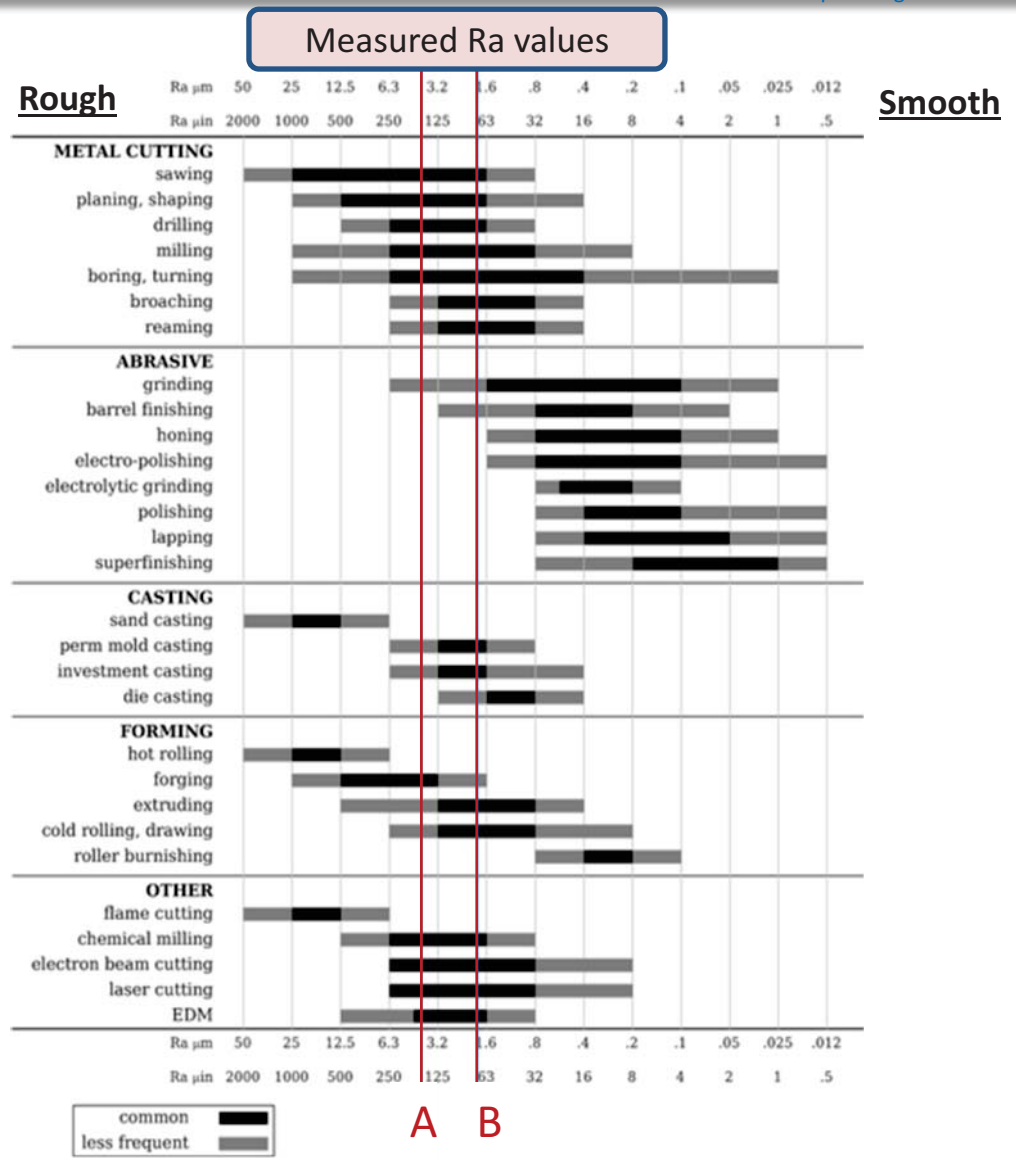
SLM Hardware Demonstrations

Turbine Nozzle – Surface Evaluation

Vendor A – MMP
Vendor B – Bead Blast





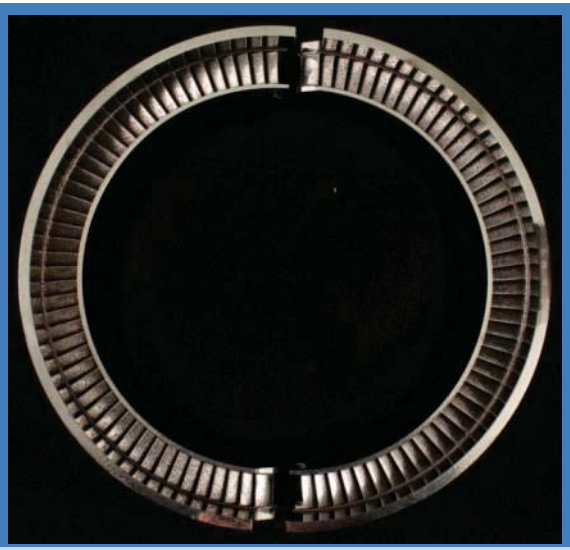


SLM Hardware Demonstrations

Turbine Stator

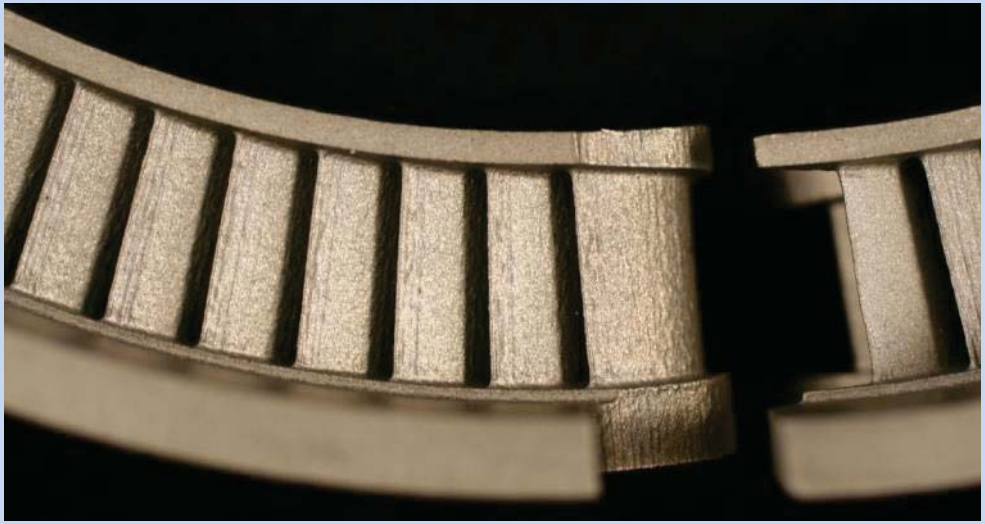
Vendor A

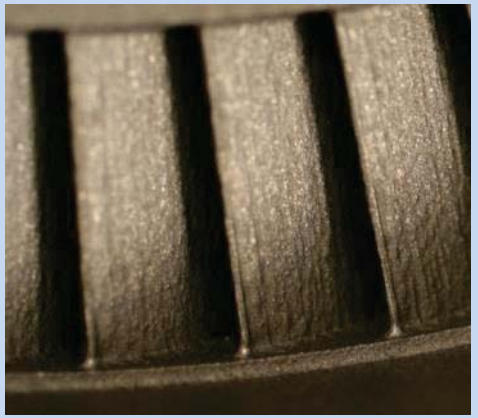
Surface Finish:
MMP



Vendor B

Surface Finish:
Bead Blast

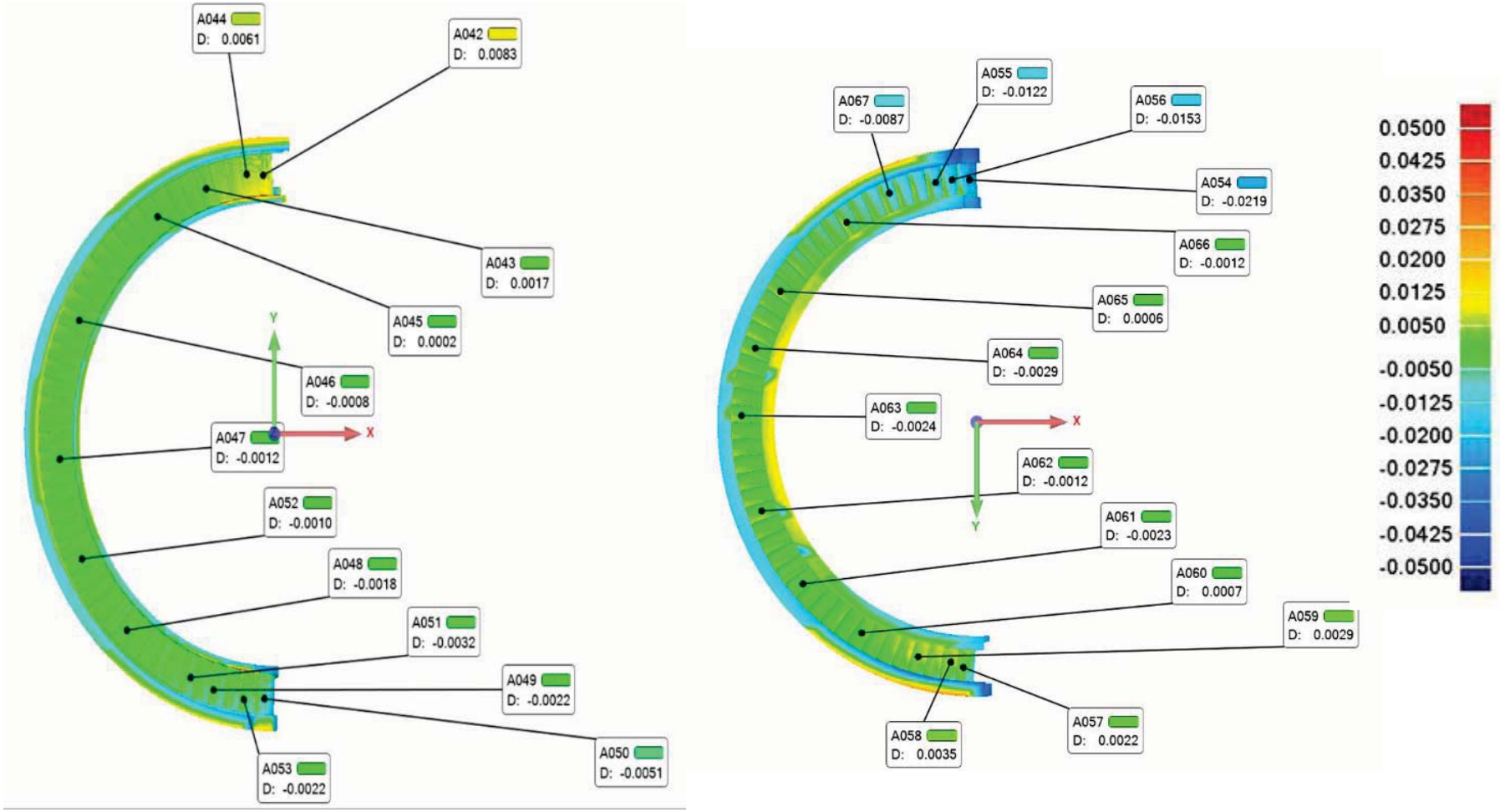




SLM Hardware Demonstrations

Turbine Stator – White Light Scan

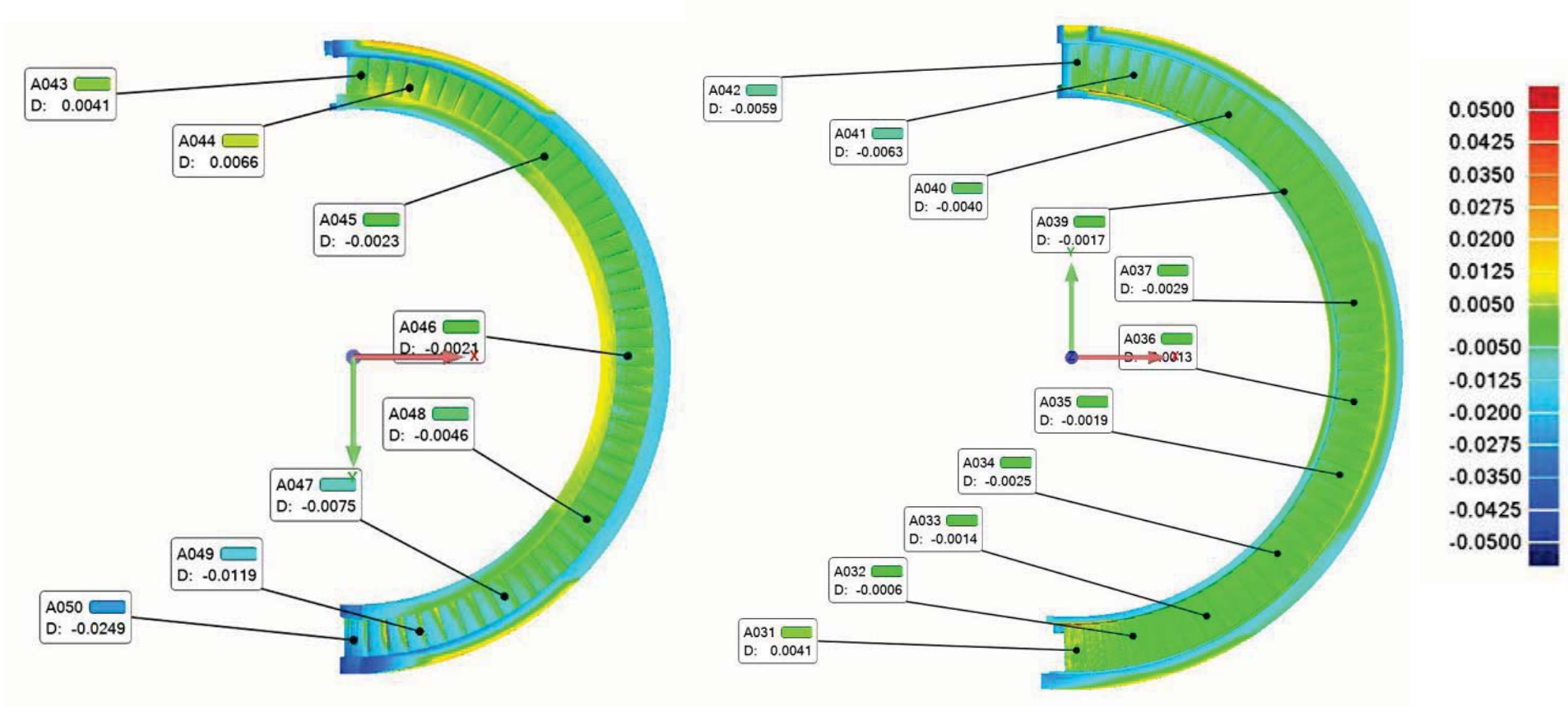
Vendor A – LPS01240



SLM Hardware Demonstrations

Turbine Stator – White Light Scan

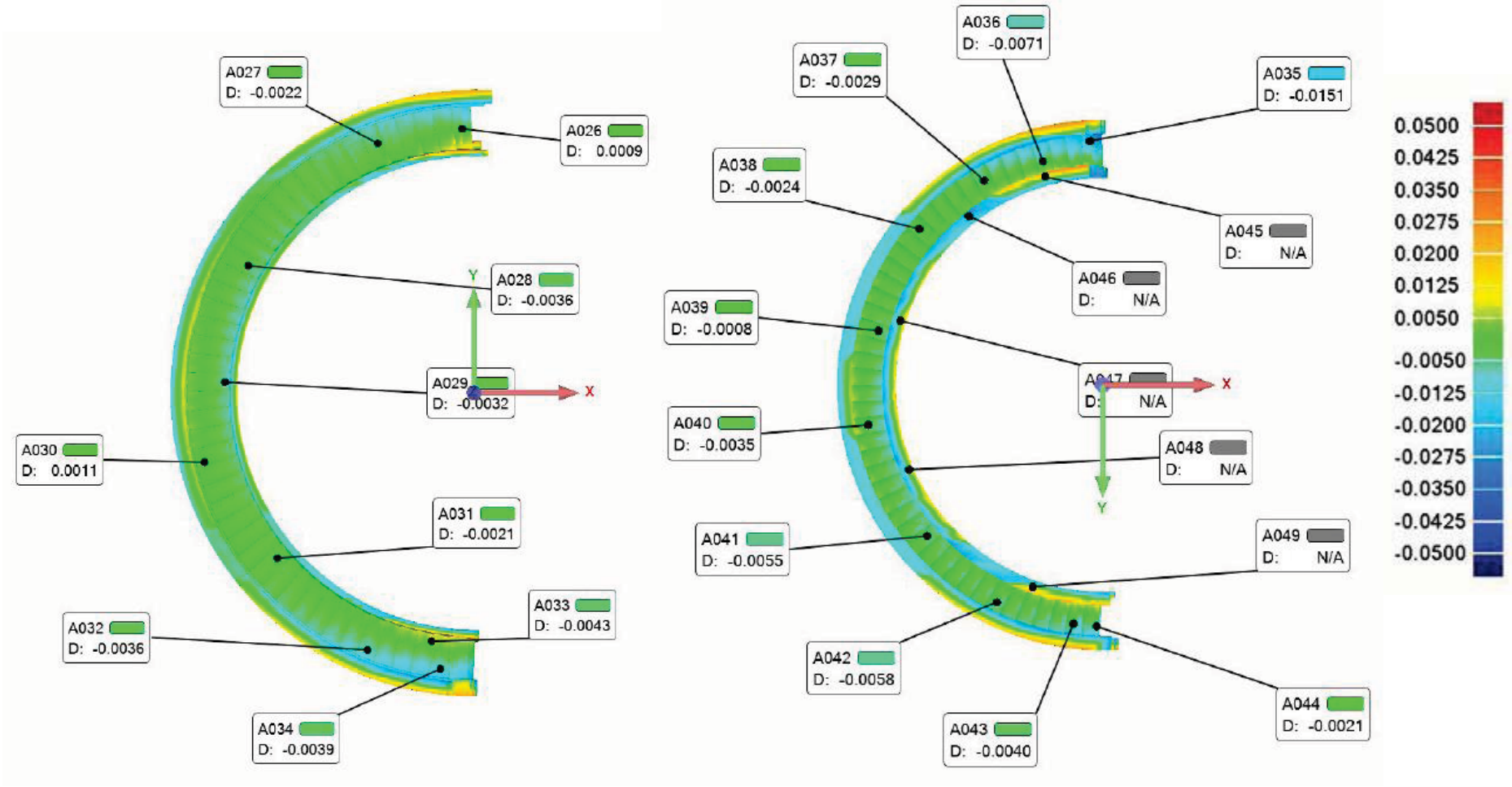
Vendor A – LPS01241



SLM Hardware Demonstrations

Turbine Stator – White Light Scan

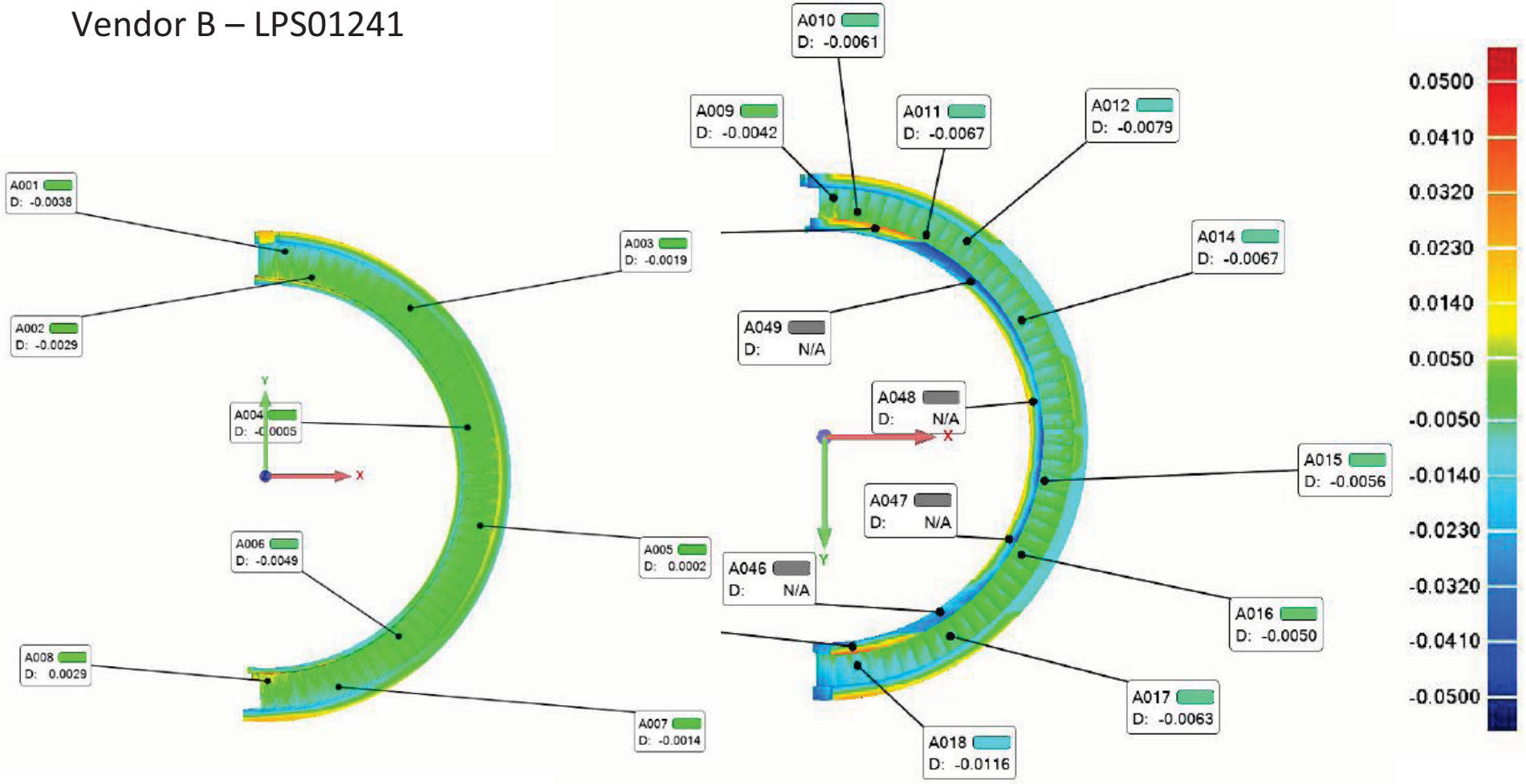
Vendor B – LPS01240



SLM Hardware Demonstrations

Turbine Stator – White Light Scan

Vendor B – LPS01241

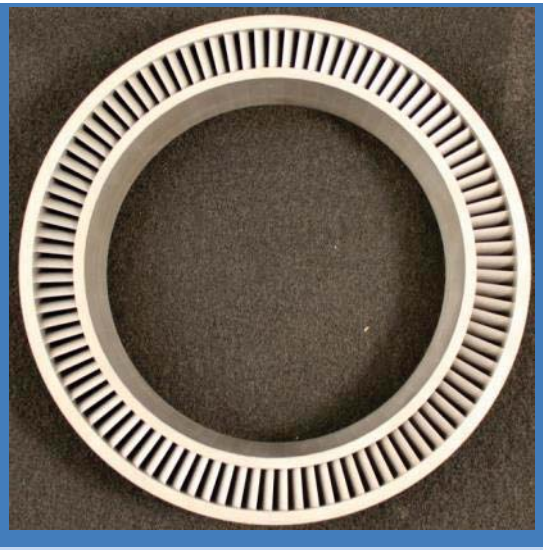


SLM Hardware Demonstrations

Turbine Exit Guide Vanes

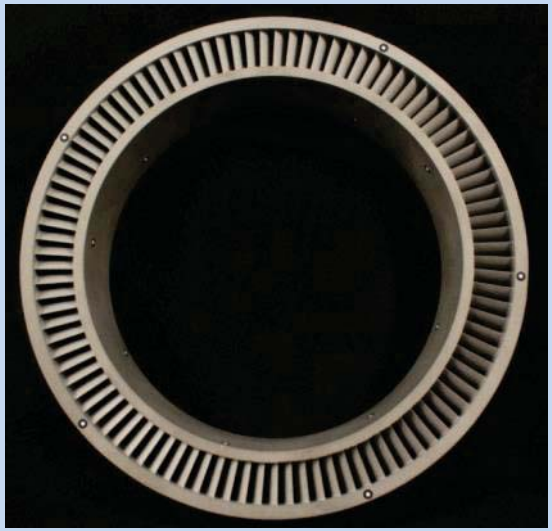
Vendor A

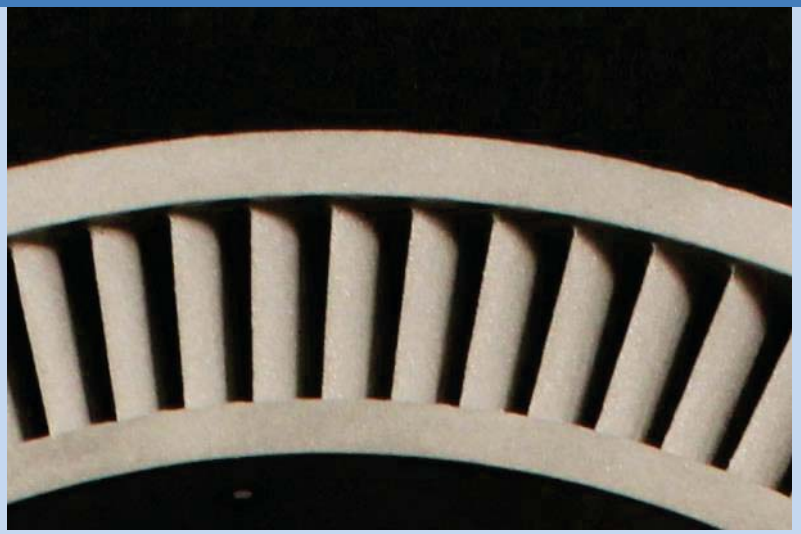
Surface Finish:
MMP



Vendor B

Surface Finish:
Bead Blast

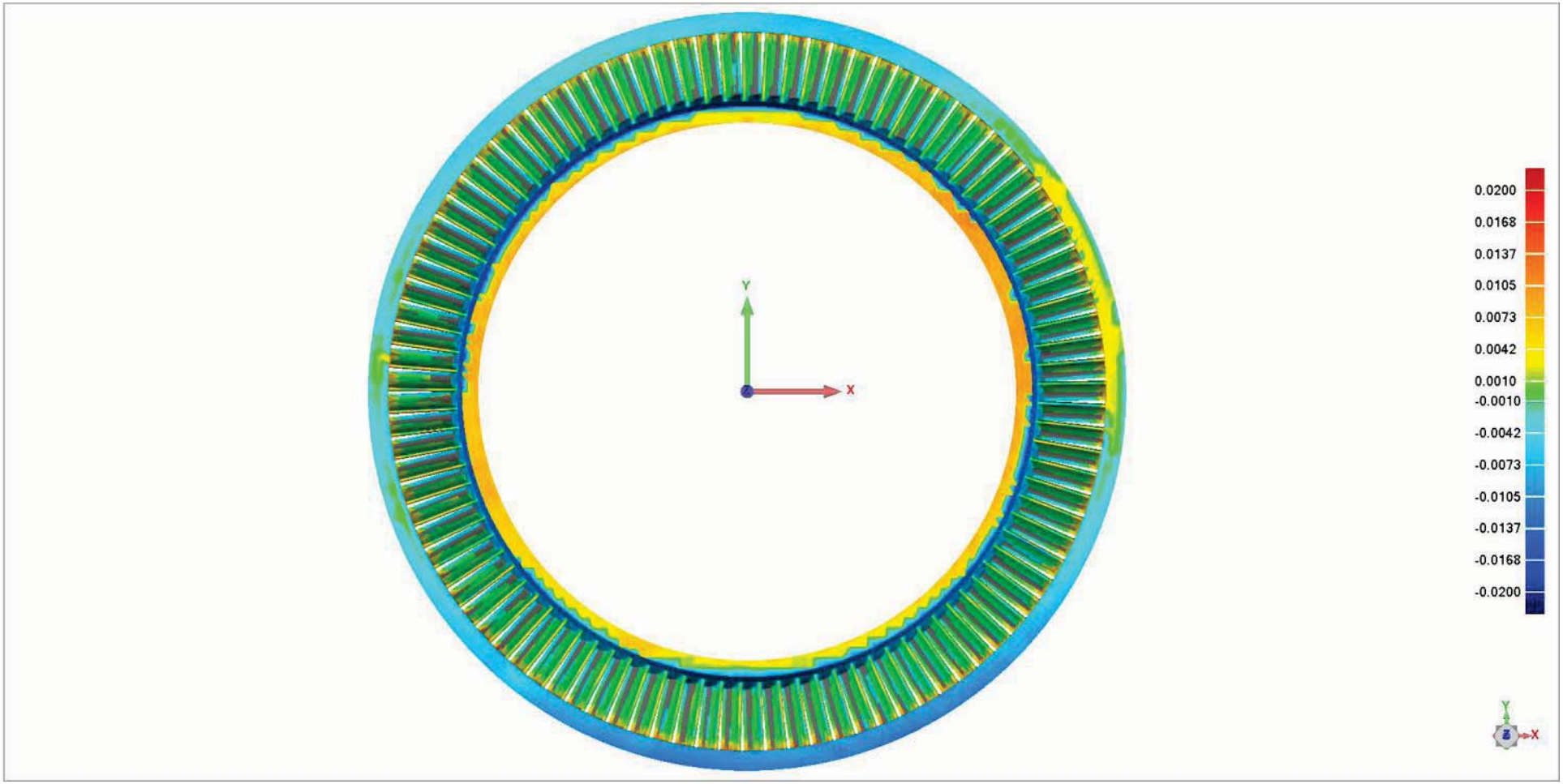




SLM Hardware Demonstrations

Turbine Exit Guide Vanes – White Light Scan

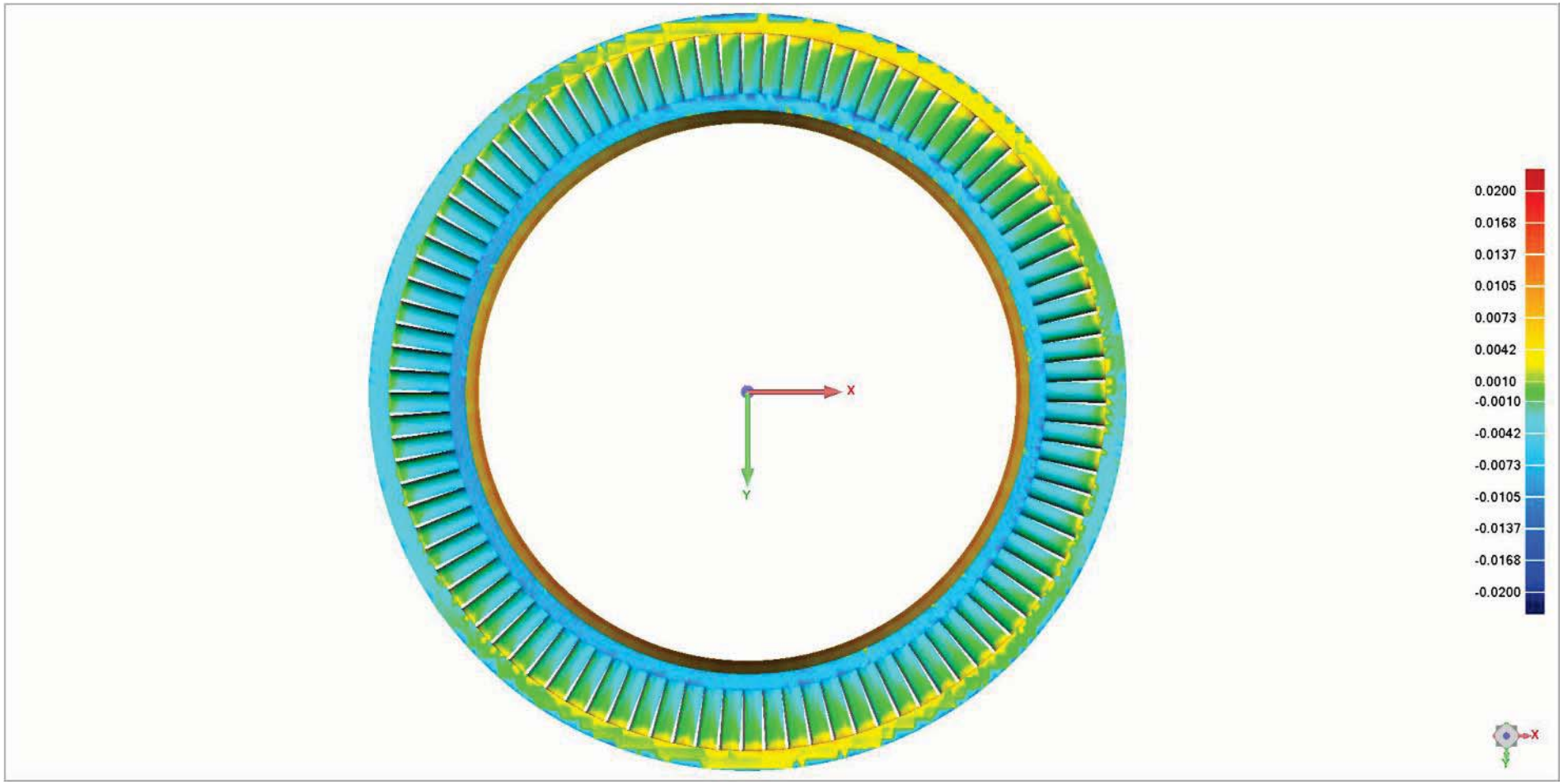
Vendor A - Top



SLM Hardware Demonstrations

Turbine Exit Guide Vanes – White Light Scan

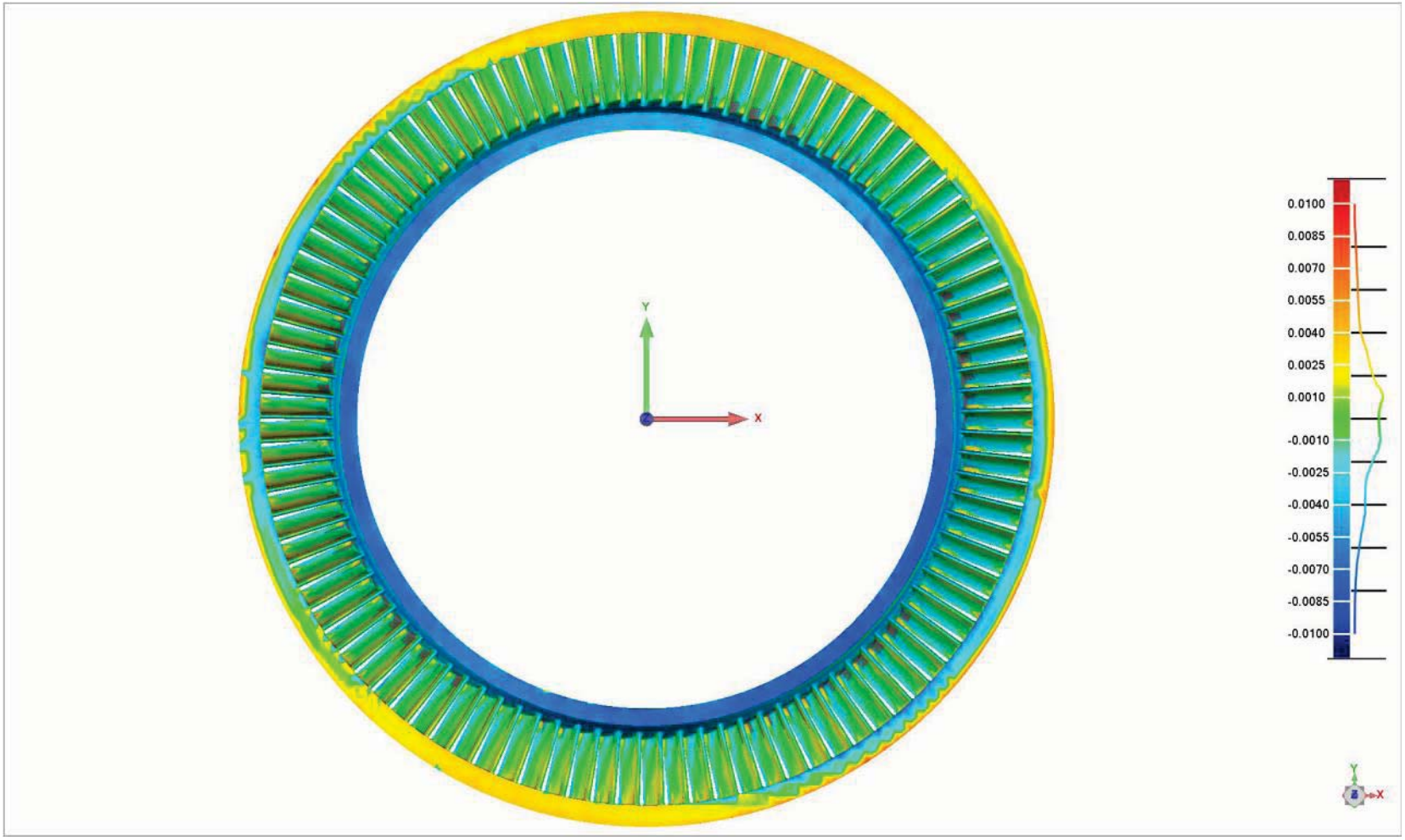
Vendor A - Bottom



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