Ensemble Manufacturing Techniques for Steam Turbine Components Across Length Scales

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Acknowledgements

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Outline

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Introduction

Project Objective and Team

Project Approach to Meet Technical Targets

Task 2.0 - Digital Manufacturing Efforts for Optimization of Parts for Additive Manufacturing (AM)

Task 3.0 – Steam turbine materials development using AMs for Process-Structure-Property (PSP) relationships

Task 4.0 – Design and component build efforts using AM

Task 5.0 - Non-destructive evaluation (NDE) inspection of printed components

Task 6.0 – Conduct Rig/Engine testing of AM Steam turbine Components

Task 7.0 - Data-driven AM Qualification & Production scale-up

Conclusions

Development Approach For Technology Maturation Plan

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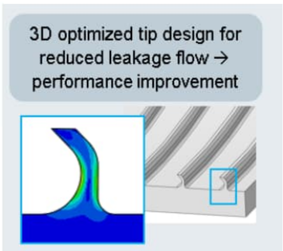
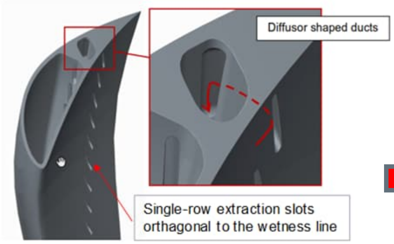
Design for AM – Improved designs

Repair of models

Advanced seal designs



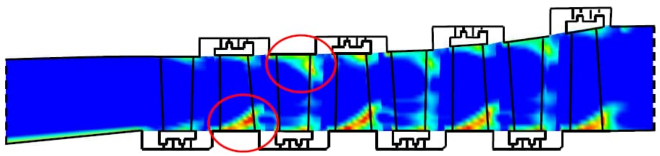


Advanced blade designs

Process-Structure-Property Relationships

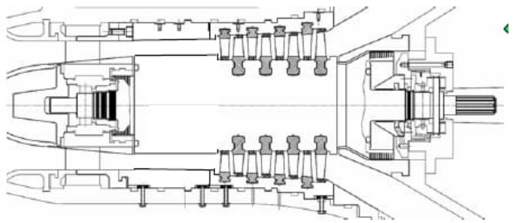
AM Process developments

Component Performance Validation

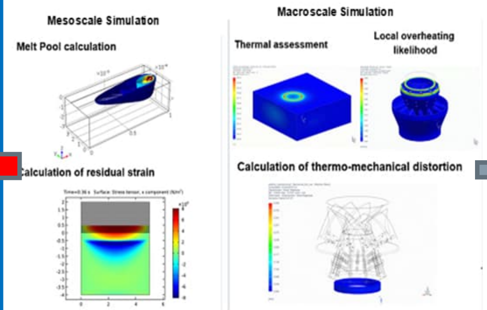


CFD Simulations

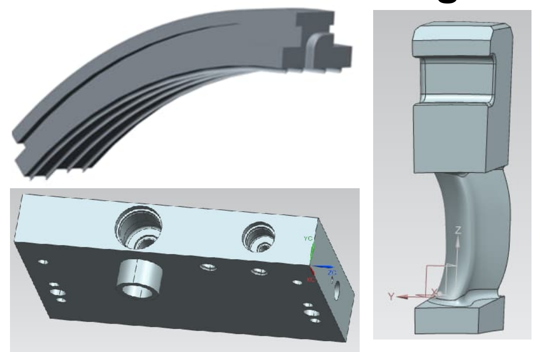
Component rig Validation for performance improvements



Component (Advanced) Manufacturing



AM Process simulations



Component buildup/inspections

Project Team and Activities

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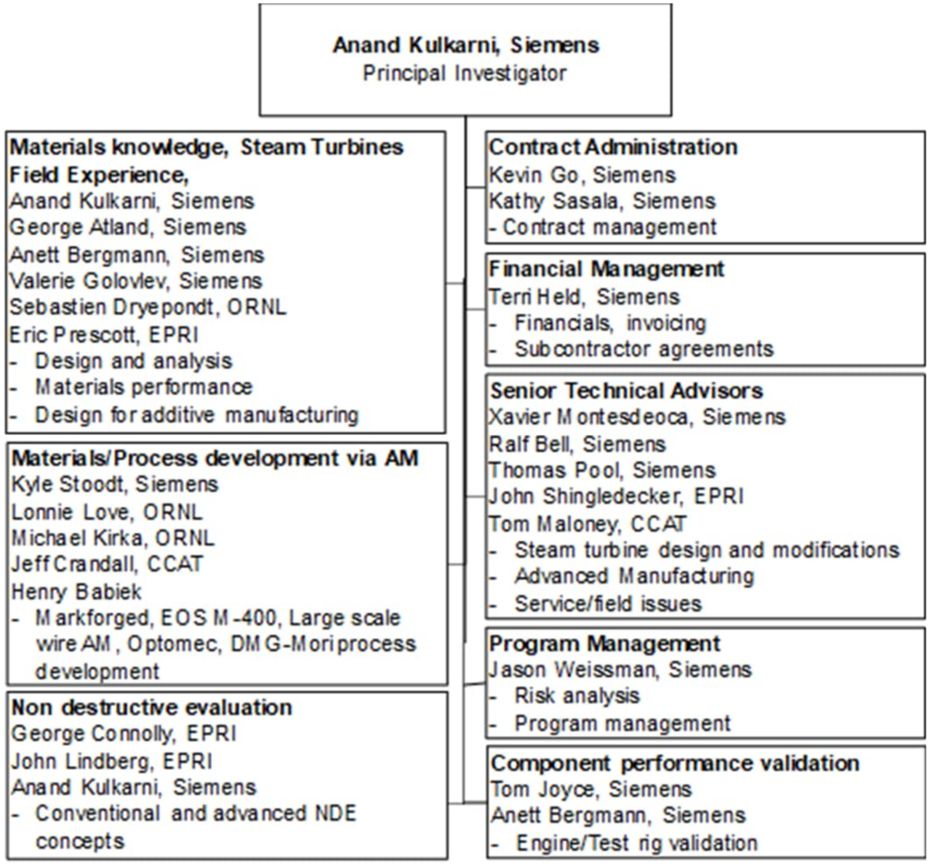
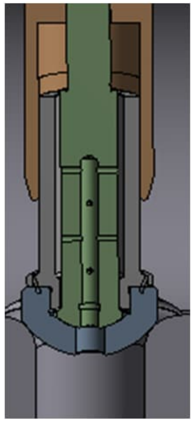
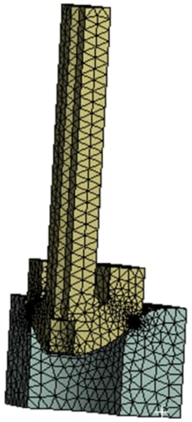


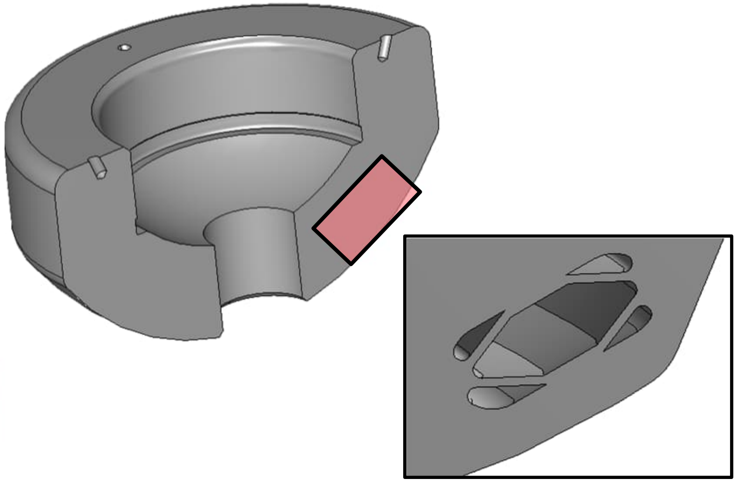
Siemens	Overall Project Lead. Activities involve repair component scanning and CAD model repair, Design for AM, CFD modeling, Markforged/Selective Laser Melting (EOS-M400) materials development, NX based toolpath design for repaired and redesigned components, Component buildup, Steam turbine rig testing, Technology maturation into supply chain.
ORNL	Large scale metal AM fabrication Lead. This includes materials feasibility selection, process optimization, controls, and toolpath design for repaired and redesigned components. Component build up.
EPRI	NDE task Lead. Conduct Field and shop deployable NDE for secondary check of finished component quality and critical to the life management cycle of new and repaired components. Will utilize its in-house state-of-the-art volumetric and surface NDE technologies (including standard and advanced techniques) to determine the best methods and limitations for NDE for the different AM methods and component geometries built within this project.
CCAT	Direct energy deposition AM Lead. CCAT will utilize their advanced manufacturing assets (Optomec and DMG-Mori systems) to develop processes and fabricate components of interest identified for this program. This includes materials development, build components using additive and/or hybrid machine tools, and measure quality metrics for the builds.

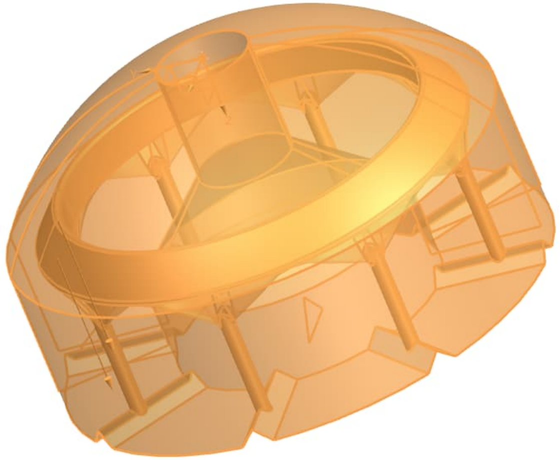
Task 2 - Digital Manufacturing Efforts - Design for AM for Valve Component

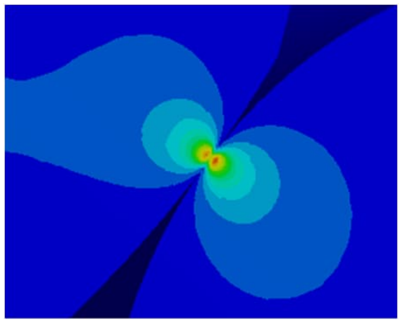
Redesign to facilitate AM processing

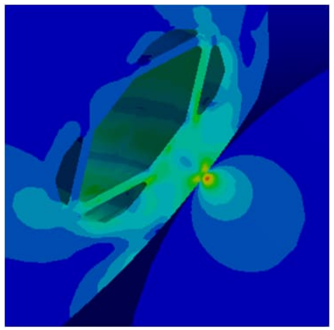








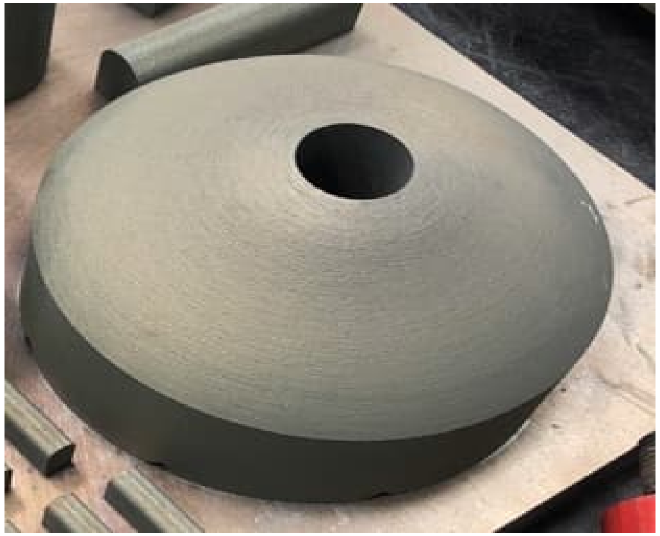




Reduced Contact stress
Reduced Contact width
Reduced Deflection

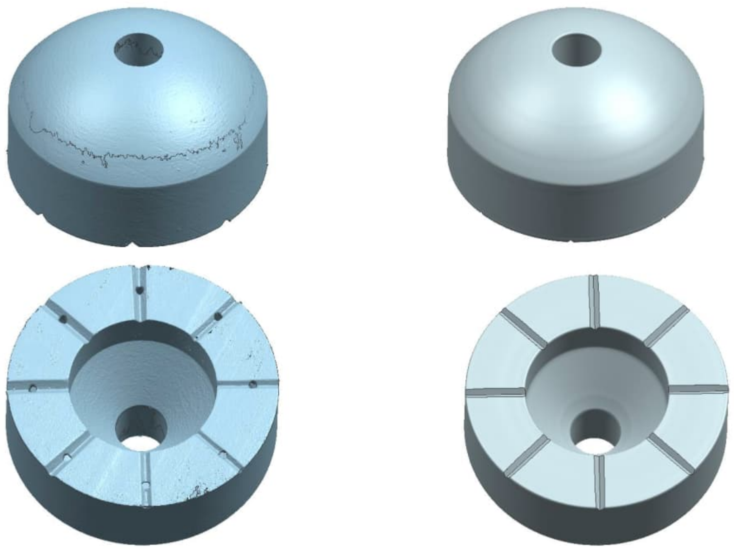
Design for AM to improve contact wear of valve components

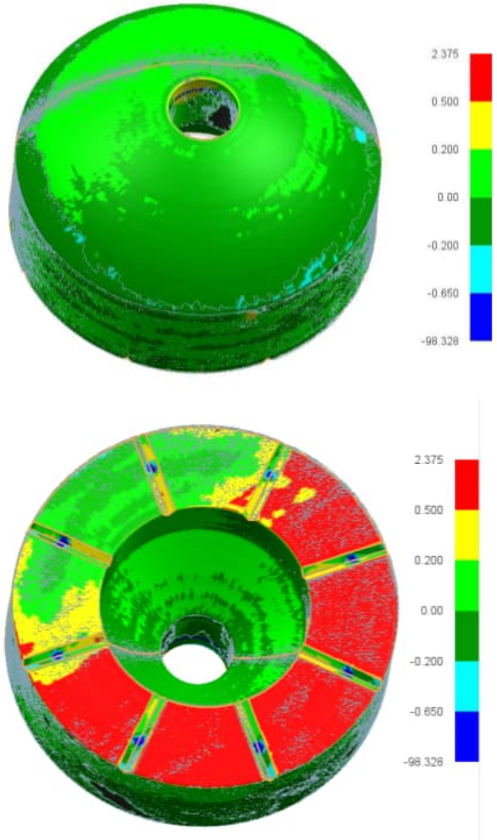
Task 2 - CAD Guided Machining/Repair of Components



Majority of the machining is external

First efforts, data correlates well on the dome side with original CAD with little deviations





Parts are oversized in AM to facilitate machining.

Scan approach to rebuild CAD model and define machining path virtually and physically

Task 2 – Digital Manufacturing of AM Components

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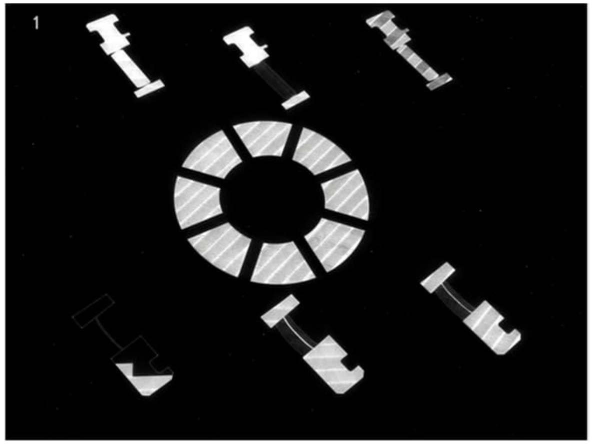
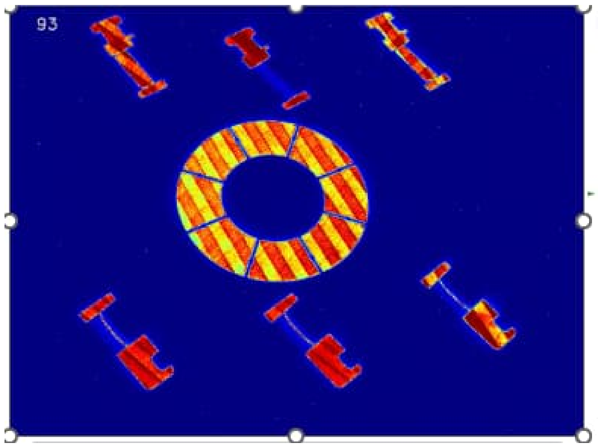
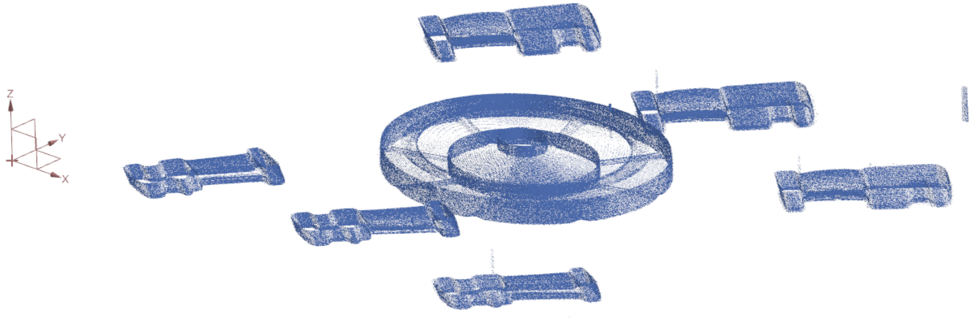
Camera view

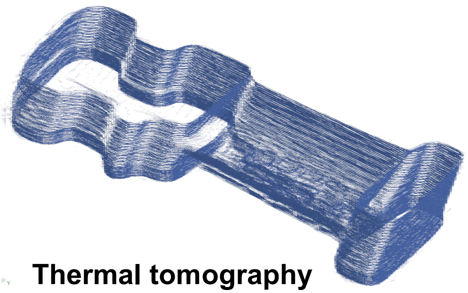


Thermal Tomography Heat map

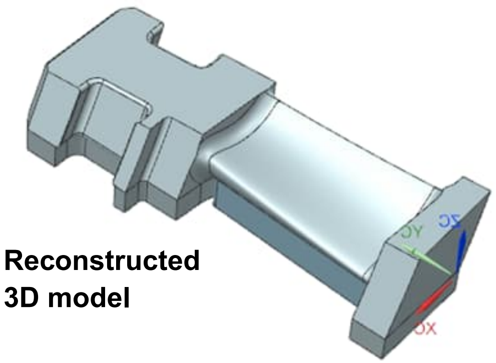


Layered monitoring to trace defects/dimensions





Thermal tomography data



Reconstructed 3D model

Digital twin of printed components utilizing in-situ monitoring data

Deviation Gauge Analysis from Digital Models

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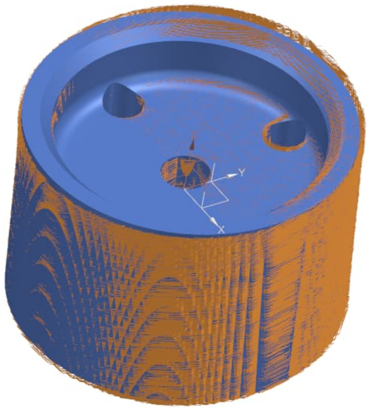
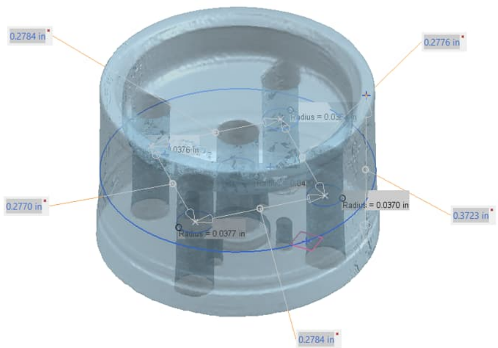
Overlap of CAD and 3D models

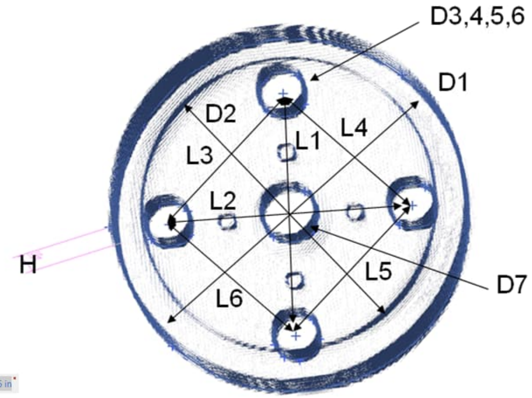


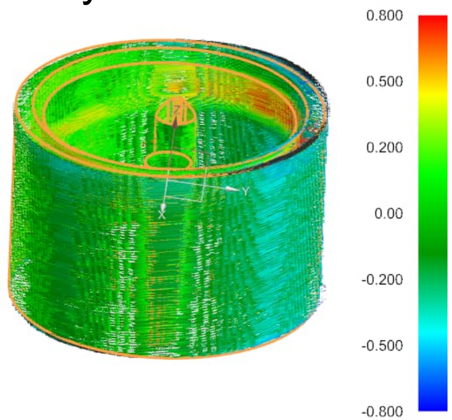
AMsense

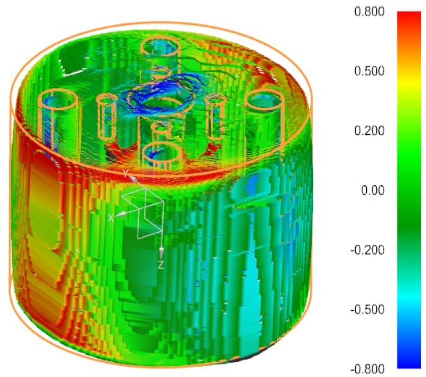


CT Scan

Deviation gauge analysis of and CAD models







Deviation report

Feature	Amsense mm	CAD mm	Error mm
D1	37.32	37.34	0.02
D2	30.40	30.28	0.12
D3	5.0	4.66	0.34
D4	4.88	4.66	0.22
D5	4.86	4.66	0.2
D6	4.84	4.66	0.18
D7	5.88	5.50	0.38
L1	25.73	25.40	0.33
L2	25.65	25.40	0.25
L3	18.28	17.96	0.32
L4	18.15	17.96	0.19
L5	18.29	17.96	0.33
L6	17.98	17.96	0.02
H	24.16	24.18	0.02

Feature	CT mm	CAD mm	Error mm
D1	36.88	37.34	0.46
D2	31.12	30.28	0.84
D3	4.48	4.66	0.14
D4	4.30	4.66	0.36
D5	4.28	4.66	0.38
D6	4.32	4.66	0.34
D7	5.32	5.50	0.18
L1	24.92	25.40	0.48
L2	24.59	25.40	0.81
L3	17.11	17.96	0.85
L4	17.87	17.96	0.09
L5	17.06	17.96	0.9
L6	17.95	17.96	0.01
H	23.32	24.18	0.86

CT data showed larger deviation due to edge effects

Task 3 – Materials Development and Process-Structure Property Relationships

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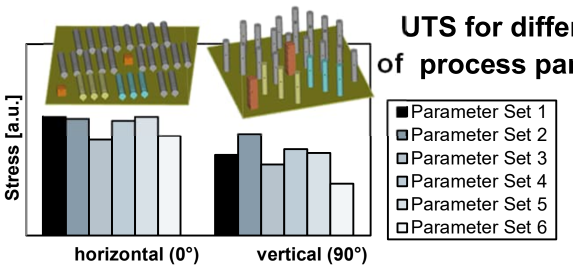
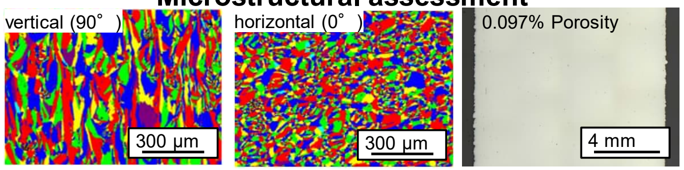
Process Development

UTS for different sets of process parameters

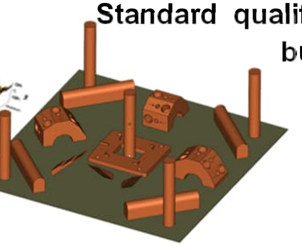


Microstructural assessment



Surface quality

Standard qualification build job



Materials Data Generation

Huge range of data for several temperatures needed:
tensile, HCF, LCF, creep/stress rupture, TMF, corrosion, physical props….

Test Matrix defined for IN718, 17-4PH and X12CrMoWVNbN10-1-1

#Sealing segments - weight: ~3 kg
length ~ 48 to 70 mm

#Stationary drum blades - weight: ~0.1 - 0.6 kg
length: ~70 to 350 mm

#Rotating drum blades - weight: ~0.1 - 0.6 kg
Length: ~70 to 350 mm

#Last stage blades
Second last end stage - weight: ~12 kg
Length: ~520 mm

Stationary blade end stage - weight: ~28 kg
Length: ~1200 mm

Materials Testing

SLM IN718 (40/80 um build)

Testing duration (days)	Material	Test Type	# Tests	Test Details	Target Cycles
45	SLM 718	**Tensile**	8	X and Z, RT and 650C	
28	SLM 718	**LCFTesting**	12	X and Z, no hold	Tests with 1000, 10k and 30k cycles to fracture
417	SLM 718	**Creep**	6	X and Z, 650 C	Up to 10k hours
60	SLM 718	**Wear**	4	X and Z	

SLM X12 (40 um)

Test	Test temperature °C	Comments
Creep Rupture 10kh 0°	550	250MPa, 1% strain after 3kh
Creep Rupture 10kh 0°	**600**	**160MPa, 1% strain after 3kh**
Creep Rupture 10kh 0°	**600**	**200MPa, 1kh**
Creep Rupture 10kh 0°	650	70MPa, 1% strain after 3kh
Creep Rupture 10kh 90°	**600**	**160MPa, 1% strain after 3kh**
HCF smooth 0°	**20**	**3 A ratios (sm=0, sm=sa, sm=0,3*sa)**
HCF smooth 0°	**450**	**1 A ratio (sm=sa)**
HCF smooth 0°	**600**	**3 A ratios (sm=0, sm=sa, sm=0,3*sa)**
LCF 0°	**20**	**Tests with 1000, 10k and 30k cycles to fracture**
LCF 0°	600	Tests with 1000, 10k and 30k cycles to fracture
LCF 0°	600	Tests with 1000, 10k and 30k cycles to fracture
LCF 0°	**625**	**Tests with 1000, 10k and 30k cycles to fracture**
LCF 0°	**625**	**Hold-time 1000LW**

Materials Testing Underway

Task 4 - Design and component build efforts using AM

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Directed Energy Deposition

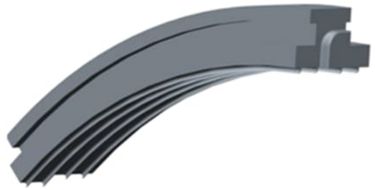
Selective Laser Melting

Markforged

Large scale Wire deposition

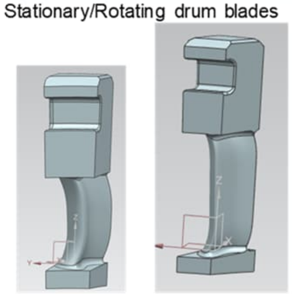
Binder Jetting

Sealing segments



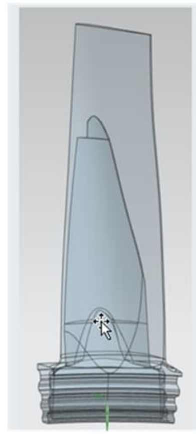
48-70 mm

Stationary/Rotating drum blades



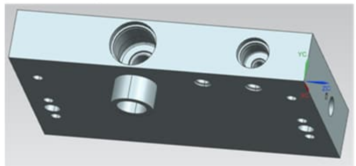
75-350 mm

Last stage blades



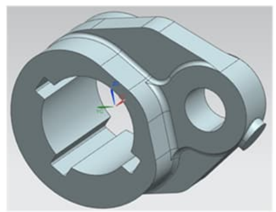
520-1200 mm

Hydraulics Control Block



60 mm

Valve lever



70 mm

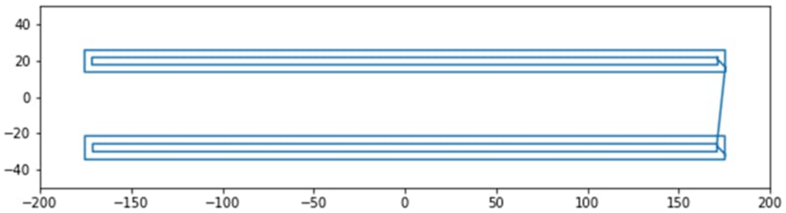
AM Component Redesign	Typical heat rate improvement
Steam valves	Upto 1% (life time extension)
High pressure (HP) turbine	1.5-2.5% (Reduced losses)
Intermediate pressure (IP) turbine	Upto 1% (Reduced losses)
Low pressure (LP) turbine	0.5-2.0% (Reduced losses)
Advanced seal design	Upto 3% (Degradation recovery)

Six AM Process Developments happening in parallel

Wire Arc AM: Effect of Process on Melt Pool Geometry and Grain Morphology - Correlation to Property

- Lincoln/Wolf Wire Arc system
  - ABB 6DOF manipulator
  - ABB 2DOF positioner
  - Lincoln Powerwave R500 welder

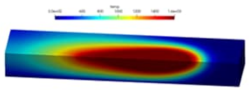
Tool Path sequence:
1. infill and 2. outfill



355 mm (L) x 17.2 mm (W) x 100 mm (H)

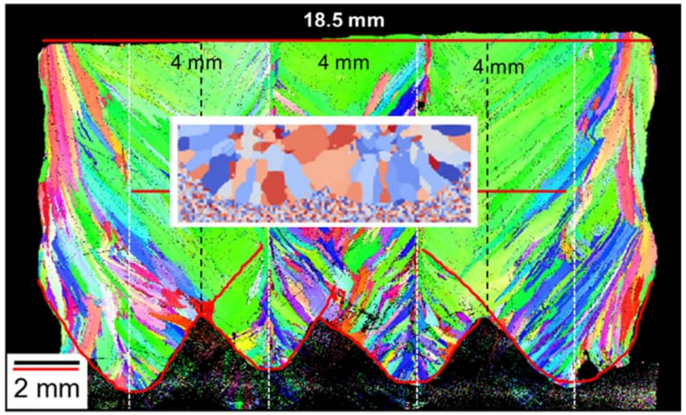
✓ **Linking of Process to Microstructure**

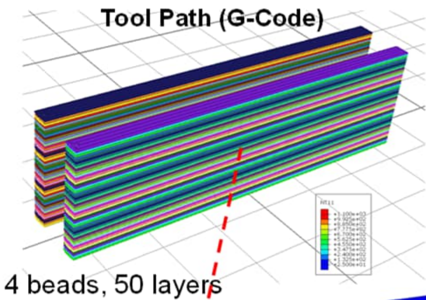
Process

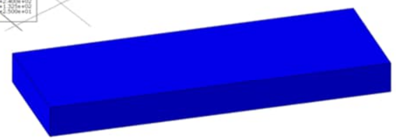


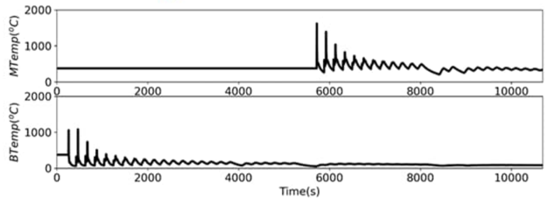
Tool path & Melt Pool

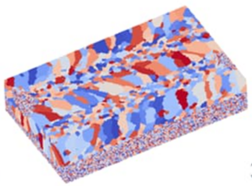
Microstructure











Overlap (mm)	Material	Weld 1		Weld 2		Weld 3		Weld 4	
		Width (mm)	Height (mm)	Width (mm)	Height (mm)	Width (mm)	Height (mm)	Width (mm)	Height (mm)
4	316 SS	4.13	2.21	4.24	1.89	5.07	2.17	4.71	2.34

Rotational Blade L-1R Wire Arc Build

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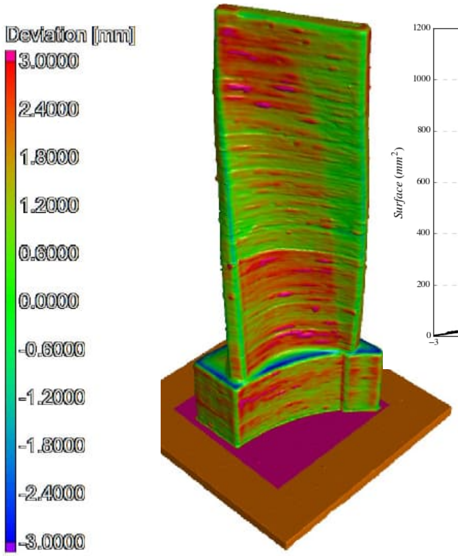
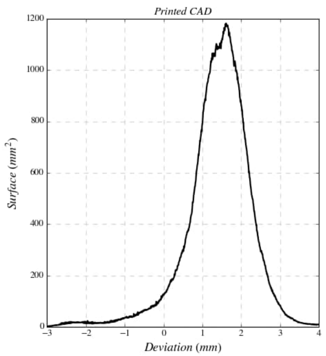
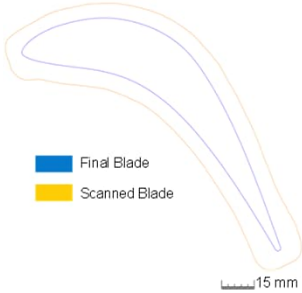
Printed blade scanned using FARO arm and compared against printed CAD and final machined CAD model

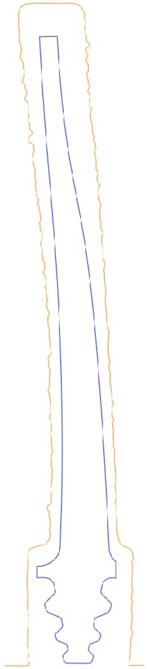
- Max deviation of as-printed blade ~3 mm oversized
- Final blade geometry fits in as-printed part
  - Minimum excess material ~5 mm

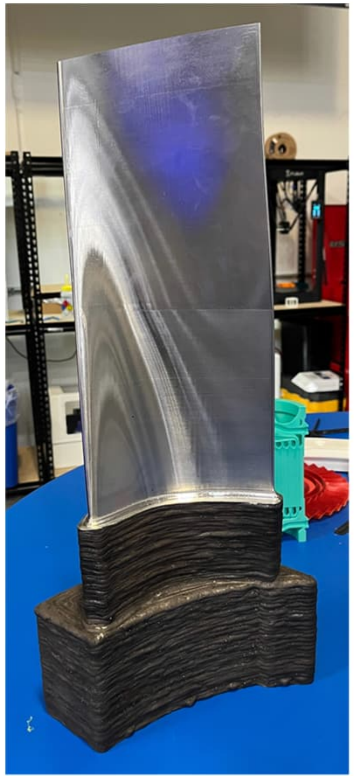
Printed CAD Deviation to As-Printed Part











12 hours build time

Task 5 - Non-Destructive Evaluation (NDE) Inspection of Printed Components

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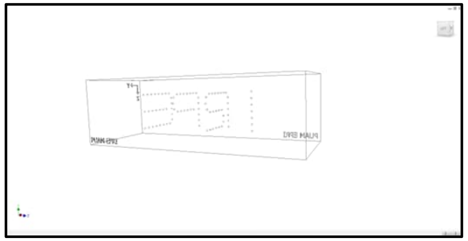
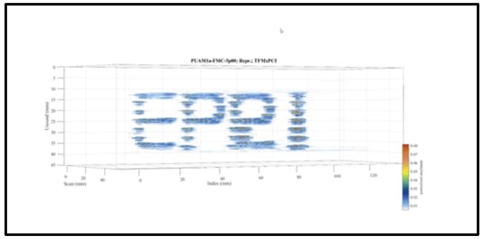
This task will advance NDE plans for the selected component geometries for quality inspection for process repeatability. Both surface and volumetric techniques will be evaluated via multiple techniques including conventional NDE (eddy current testing and ultrasonic testing (UT)) and advanced NDE (phased-array ultrasonics (PAUT), state-of-the-art UT using full matrix capture (FMC) and total focusing method (TFM)).

Potential NDE Processes for Additively Manufactured Steam Turbine Components				
Type	Process	Example Uses	Rational	Question for Additive
Eddy Current	Surface-Conv.	Airfoil surfaces, blade root (exposed), shrouds (verification of visual) and seals	Conventional surface inspections beyond visual methods	New geometries may make inspection more difficult, different AM processes give different surface textures
Flexible Eddy Current	Surface-Adv		Enhanced inspections for curved geometries, hard to access locations	
Phased Array UT	Vol.-Conv.	Disc attachments, blade roots (attached), repair quality of blades, new blade geometry and quality	Today's state-of-art for crack detection	New geometries may hinder conventional UT process inspections, new grain structures will attenuate UT signals differently, new potential defect/damage locations
TFM/FMC	Vol.-Adv.		Full volumetric Data with less part knowledge, Multiple Data Evaluation Schemes (data science enabled), Non-linear examinations	
Process Compensated Resonant Technique (PCRT)	Vol.-Adv.	Entire Blade Volume	Quality' Measure for Part-to-part variations, post-test exposure shape and material changes	Can process variations in additive be identified using resonance techniques

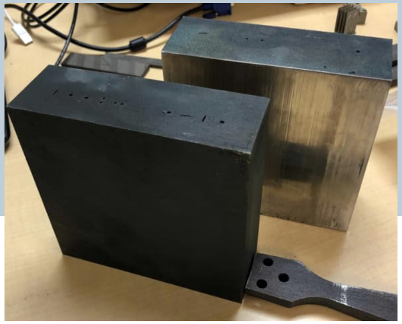




EPRI has NDE technologies/techniques used currently on steam turbines and being considered for AM produced components

AM Test Artifact for UT

Selected Conventional UT Scan Results



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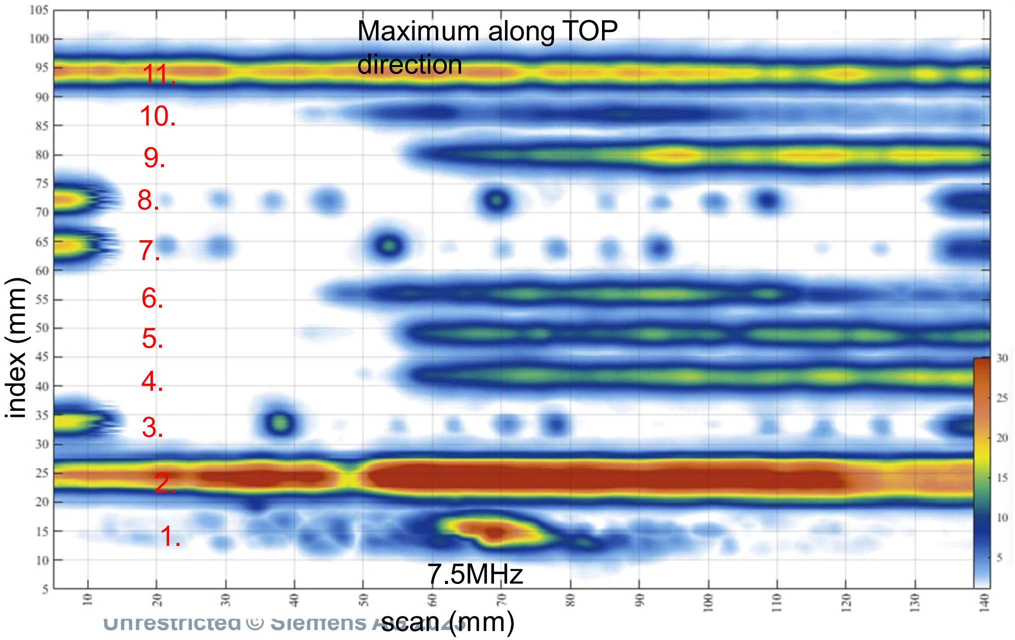
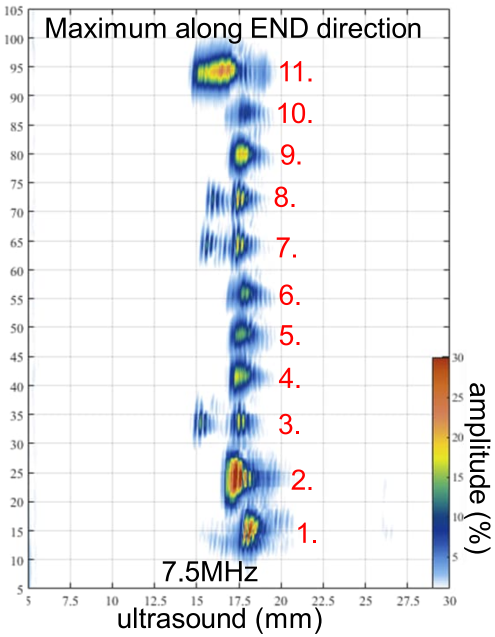
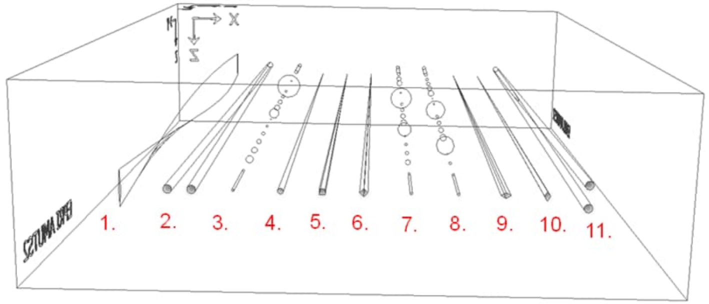
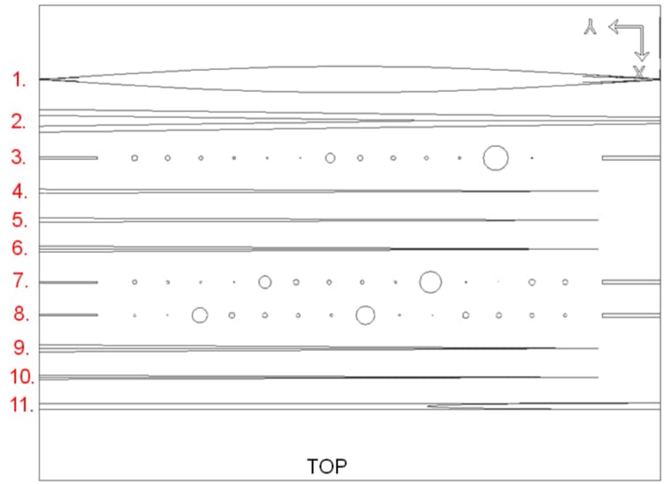
- Scanned in immersion from top and bottom using Ø0.375in. conventional UT probes
  - Instrument: Zetec DYNARAY Lite
  - Four frequencies: [2.25, 3.50, 5.00, 7.50]MHz
- Observations:
  - Variation in surface coupling evident
  - SDH pairs difficult to distinguish
- Limit in detection computed as a function of feature dimension or orientation







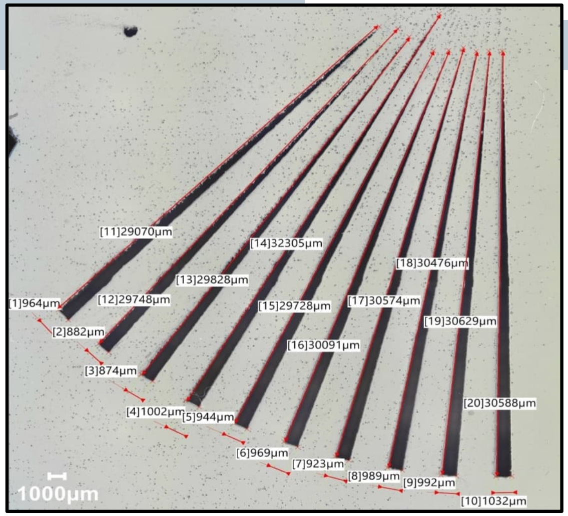


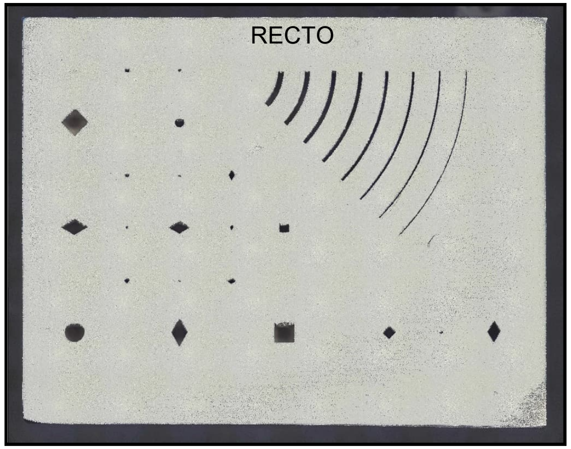
UT and VT comparison
Test Block

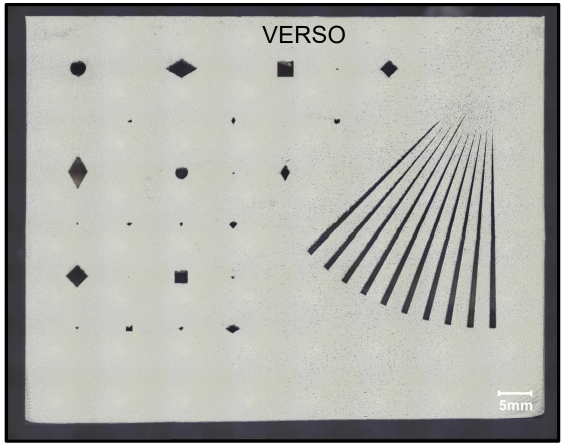
A smaller accompanying block built alongside the AM test artifact by the same instrument and same build parameters

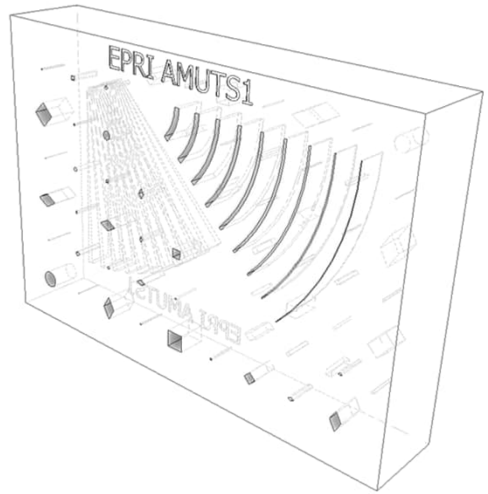
- Overall dimensions (80×56×15)mm
- All features are surface-connected
  - Spokes and “wedges” of varying angle and thickness
  - Pits of varying dimension match the shapes and size range of the five tapering features of the AM test artifact
- Intended for VT for quantitative comparison against the volumetric UT results extracted from the AM test artifact

Image processing measures as-built feature dimension and area for quantitative analysis; compared against nominal or expected values [3]









[3] *Ultrasonic Testing (UT) Reference Standard for Additive Manufacturing (AM) Quality Control*. EPRI, Palo Alto, CA: **2022**. 3002025339

UT and VT comparison

Feature Visibility and Feature Distortion

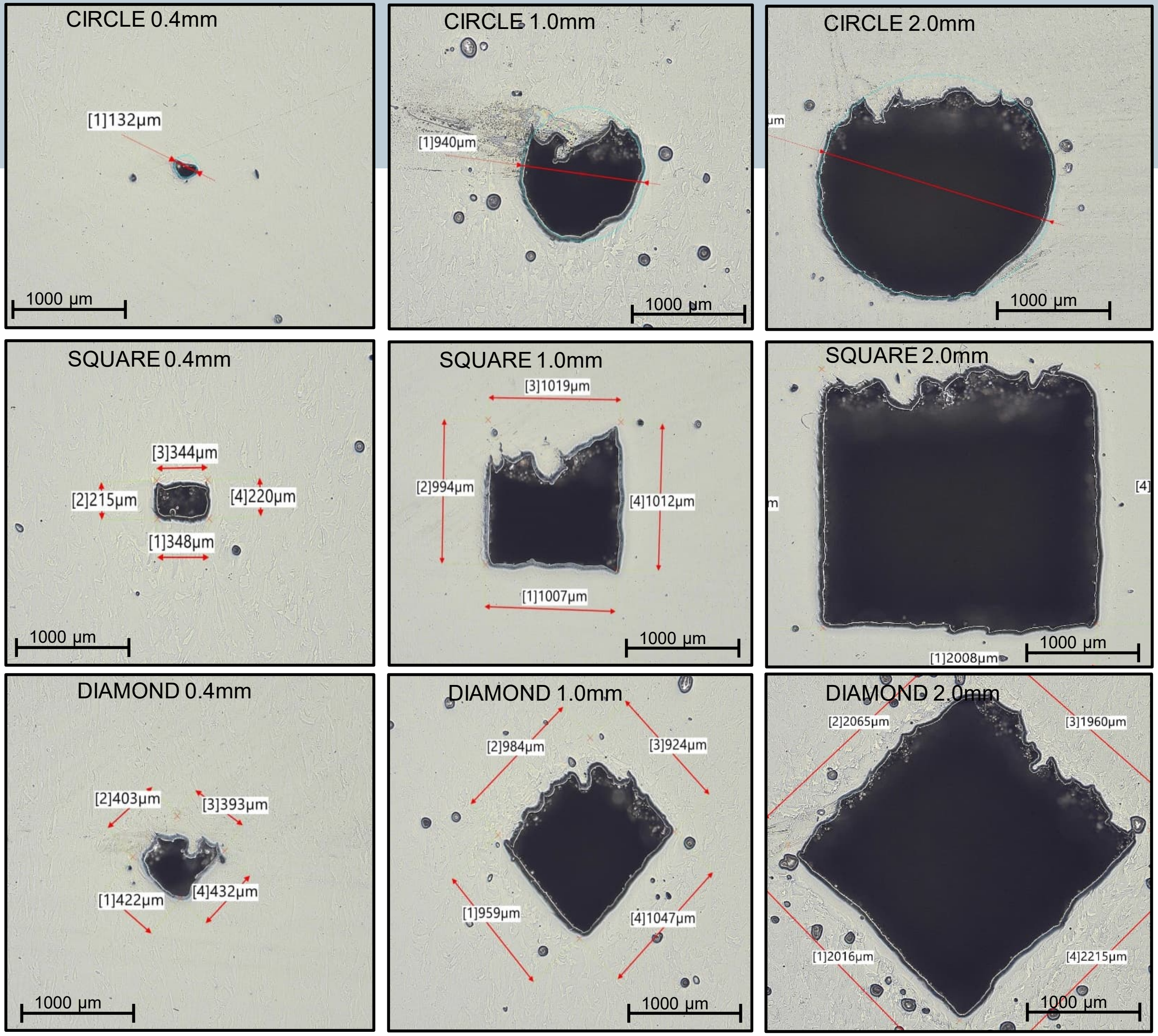
VT observations:

- Evident feature distortion, though improve as dimension increases
- Limits of detection depend on shape
- Detection limit in the range 0.30mm to 0.40mm

Comparative limits of detection in table for certain shapes (UT and VT) shown in table

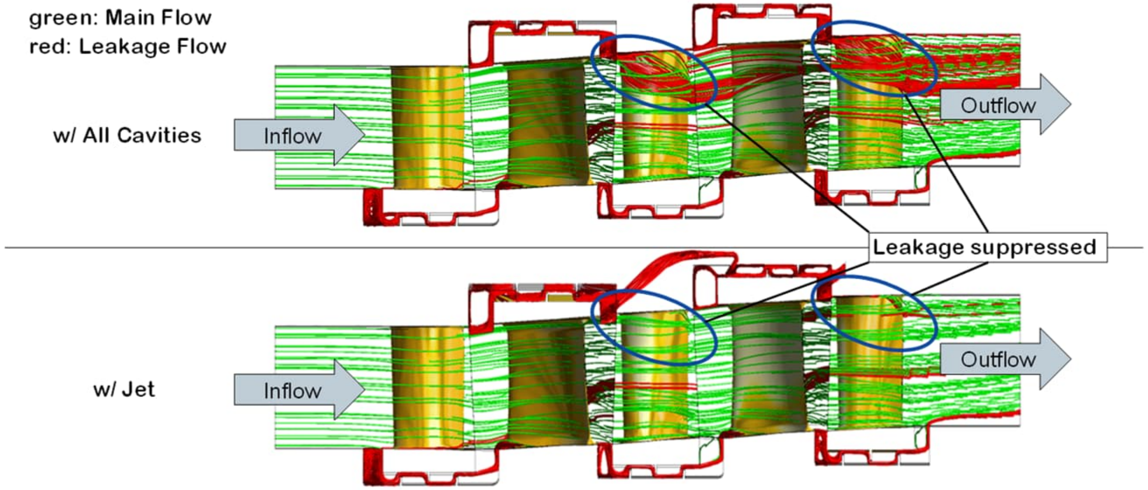
Feature	VT	Conventional UT 5MHz	Conventional UT 7.5MHz	FMC/TFM 5MHz	FMC/TFM 10MHz
Circle	0.40	0.29	0.27	0.20	0.25
Square	0.40	0.26	0.20	0.18	0.20
Diamond	0.40	0.25	0.23	0.16	0.26

build direction

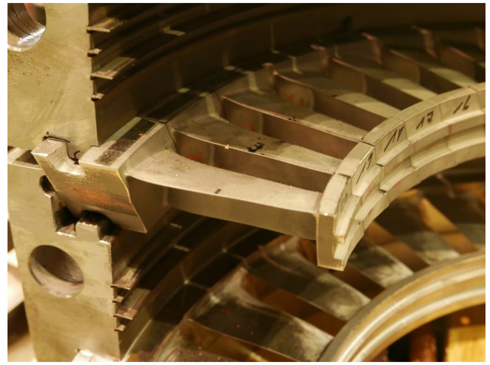


[X] *Ultrasonic Testing (UT) Reference Standard for Additive Manufacturing (AM) Quality Control*. EPRI, Palo Alto, CA: **2022**. 3002025339

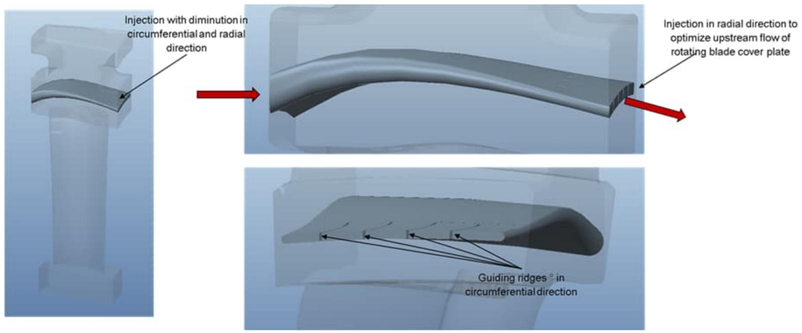
Task 6 - Conduct Rig/Engine Testing of AM Steam turbine Components



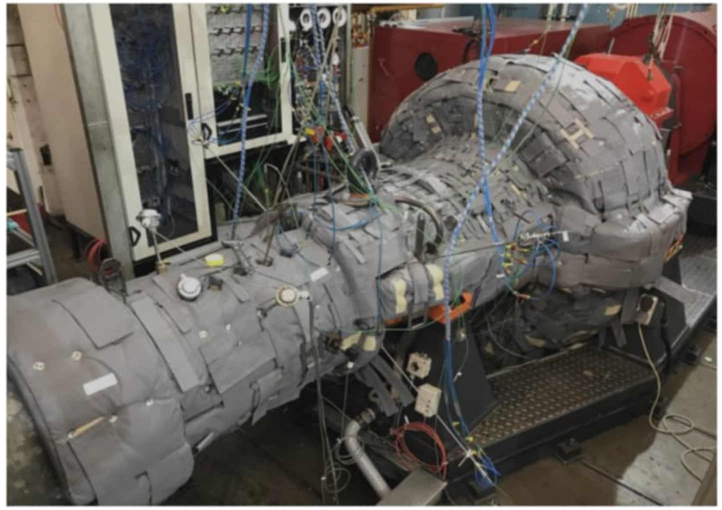
SLM printed blades for rig testing



Stationary drum blade design

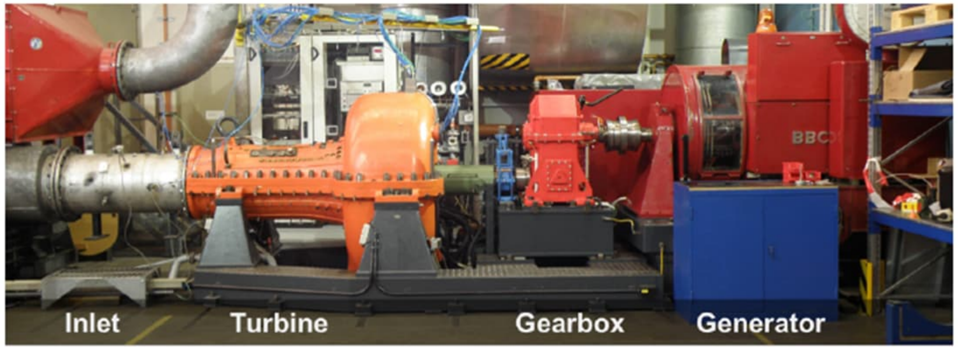


Assembled test rig

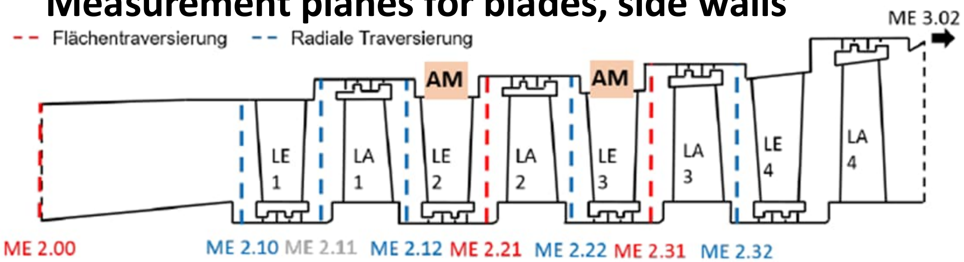


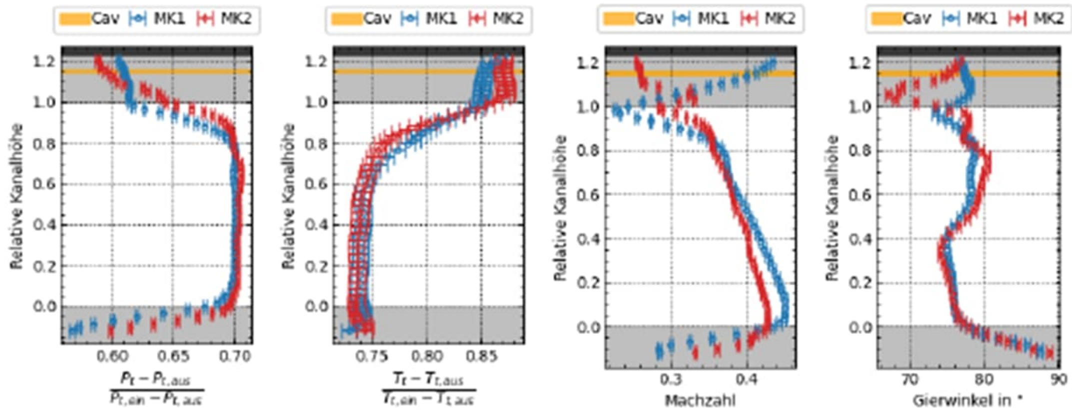
At the university in Hannover, a multistage turbine designed by Siemens is used to analyze turbine flows

Task 6 – 1st Rig Test Results

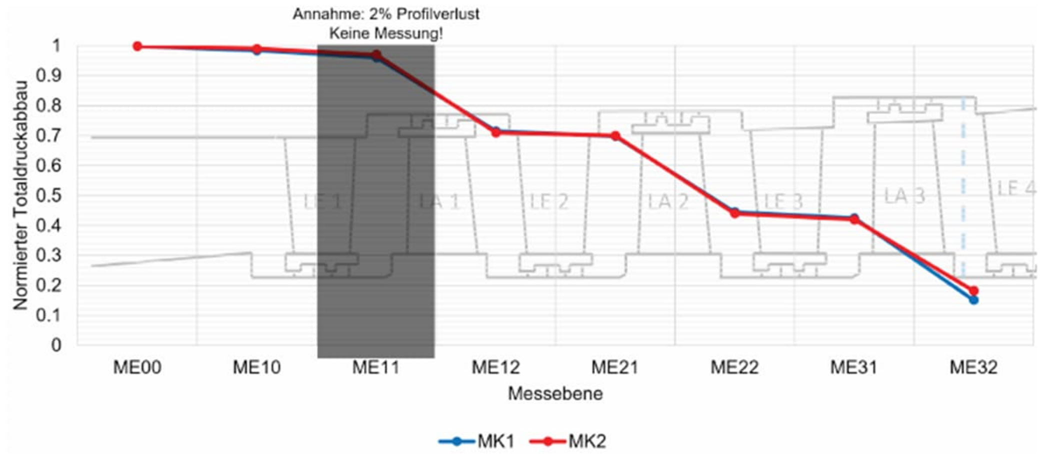


Measurement planes for blades, side walls





The pressure losses are shifted to the outer side wall which clearly indicates the impact of the bypass blades.

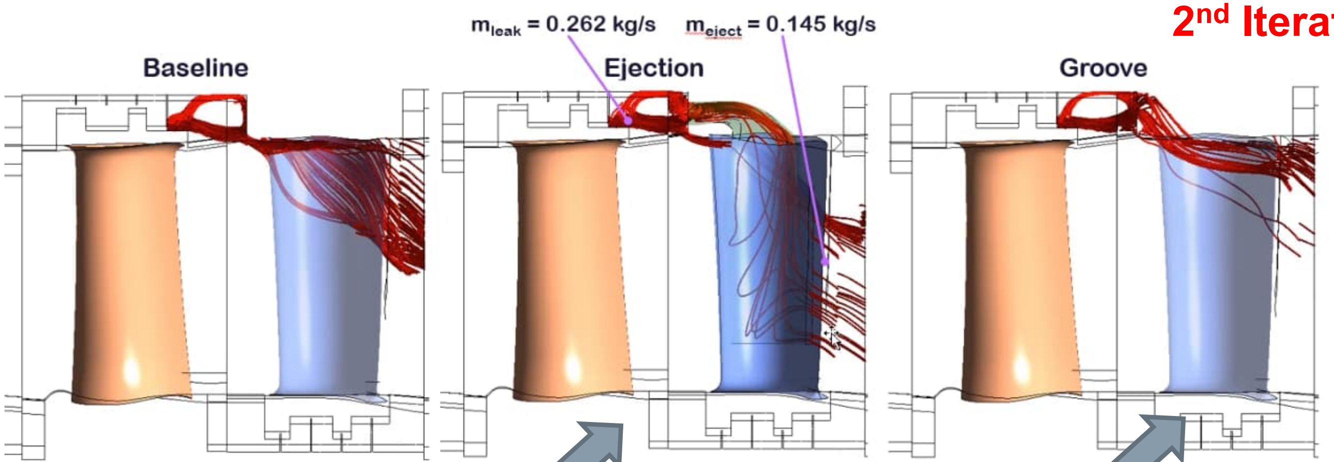


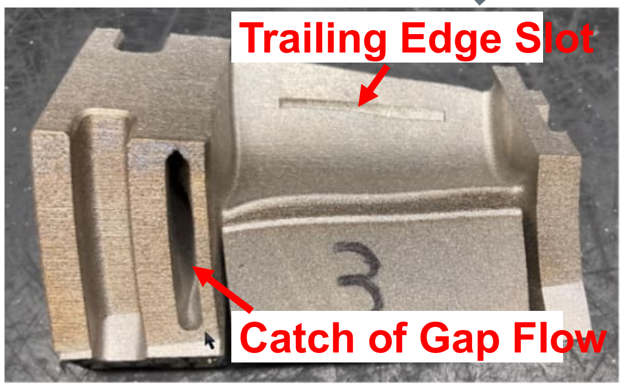
A lower normalized total pressure loss or profile loss of 0.7% is observed with 1st iteration

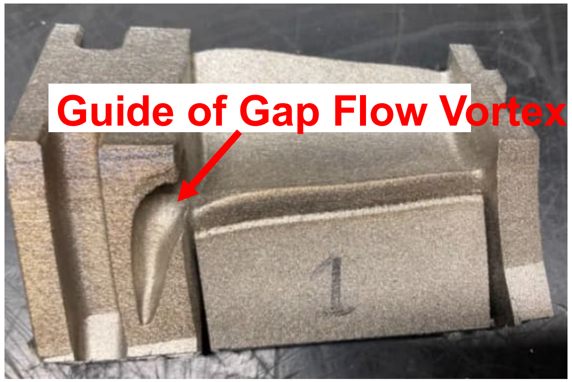
Stationary Drum Stages Blades

1st Iteration

2nd Iteration







- First trial platform printed in January
  - ➢Heat treatment test(on air and on vacuum)
  - ➢Sand blasting test
  - ➢Dimensional check →optimization of print model needed

2nd Test Campaign for AM Printed Blades

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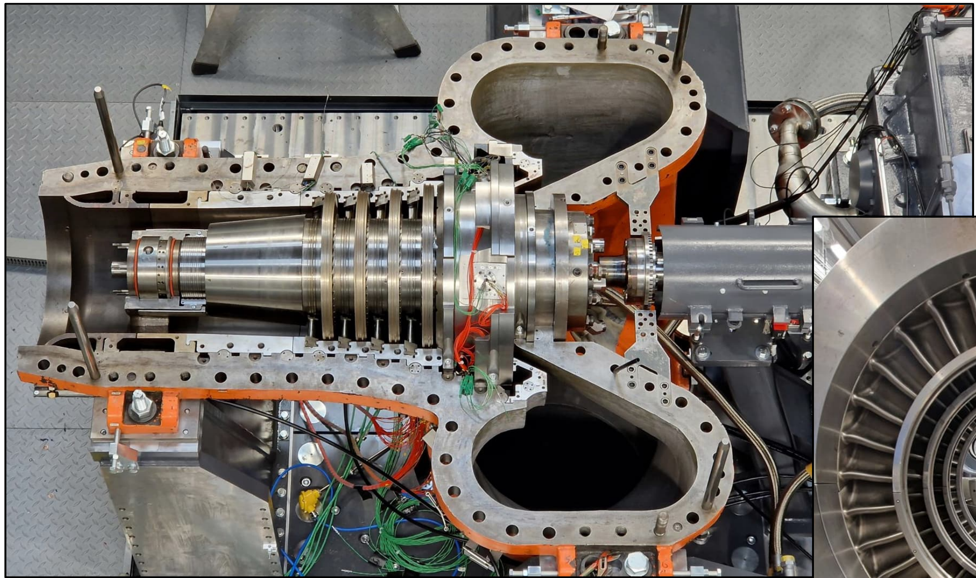
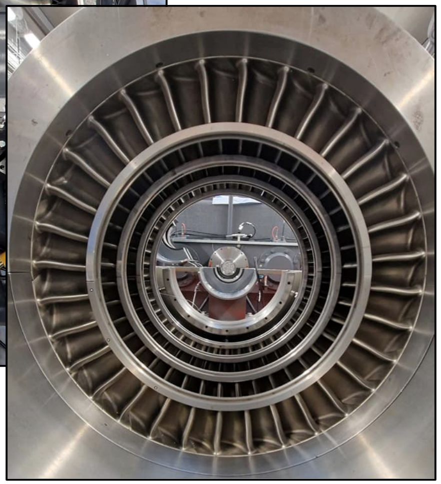
Instrumented Engine





Final rig test delayed due to facility maintenance and upgrades. Testing planned for early November ‘23. Upgraded control systems will enable more consistent engine operation such that all measurements will possess near identical environments.

Task 7 - Data-driven AM Qualification & Production scale-up

Pilot setup established in Siemens/ Siemens Energy Charlotte AM facility

Conclusions

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- Siemens and its partners are accelerating deployment of AM components into Steam turbines
- Digital tools aid with design optimization for AM, support CAD guided machining/repair of components, reverse engineering along with rapid qualification efforts for AM components.
- Materials have been downselected (X12CrMo materials for blades, 17-4 PH for last stage blade and IN718 for valve components) Design analysis showed that IN718 has better properties than IN625. Material property curve comparison with conventional manufacturing underway
- Component manufacturing efforts demonstrated for LPBF, DED, WAAM and Binder jetting process. Anisotropy in samples eliminated Markforged process from further component evaluation.
- NDE of all AM samples underway at EPRI and an NDE report will be issued comparing multiple NDE techniques and their potential for inspection of AM components.
- 1st iteration of AM blade design yielded 0.7% reduced losses in steam path. Multiple iterations are underway to demonstrate further improvement and being design reviewed for field deployment.
- A digital process flow is being implemented to demonstrate end to end AM process for faster data qualification