Ensemble Manufacturing Techniques for Steam Turbine Components Across Length Scales

Anand Kulkarni, Siemens Corporation

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Acknowledgements

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Outline

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Synergistic Research for Technical Advancements to meet the Cost/Performance Targets Utilizing Additive Manufacturing

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Project information

PI: Anand Kulkarni

Funder: DOE Office of Fossil Energy (FE) – NETL

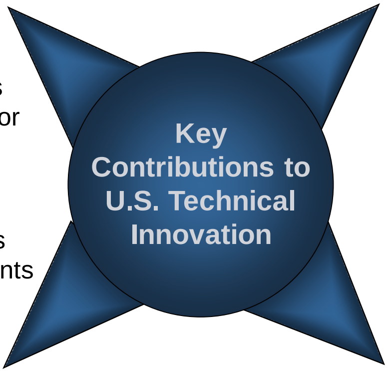
Strategic Partner: Siemens Gas and Power, EPRI, ORNL, CCAT

Total Project Funding: ~$7,600K (~$6M Federal, ~$1.6M cost share)

Key Research Areas

Advanced turbine design
- Novel blade designs for increased efficiency and reduced CO_2 emissions
- Advanced internal cooling circuit for reduced leakages
- Hollow structured blades for reduced loading

Advanced Materials/ NDE
- Improved alloy chemistries for performance improvements
- Process-structure-property linkages for multiple AM methods for design window
- Advanced NDE concepts for rapid qualification of AM components



Advanced Manufacturing
- High powered additive manufacturing process for steam turbine alloys
- Adaptive process for rapid buildup of steam turbine parts
- Ensemble processing across length scales for cost reduction

Component scale up & Validation
- Steam turbine rig for performance evaluation of AM components vs baseline
- Validated flow CFD simulations for improved performance (reduced losses/leakages)

Technical Highlights

Funding Opportunity Objective	Objective of Proposed Program
Applying current AM technologies to an existing part	The application of existing AM processes (Directed energy deposition (Optomec/DMG-Mori, Large area wire manufacturing), Selected laser melting (EOS-M400) and Atomistic diffusion AM (Markforged) for redesigned steam turbine components across length scales for new/repair opportunities.
Improve cost and performance of steam turbine components	Topology optimization for performance improvements for blades, seals and valve components planned. Potential activities include novel blade designs for increased efficiency and reduced CO_2 emissions, advanced internal cooling circuit for reduced leakages and hollow structured blades for reduced loading
Retire all risks associated with a follow-on field test	Advanced NDE development for rapid qualification/inspection of AM components. Functional/performance testing of Steam turbine test rig for turbine flow CFD validation to demonstrate reduced leakages, improved efficiency and reduced CO_2 emissions
Potential for repair/replacement of existing part	Potential to develop an on-site repair process via scan to print option for damage parts to create a 3D model to repair or re-print a new one

An ensemble of multidisciplinary technologies to accelerate the development of materials, high-throughput experiments for their qualification and design flexibility/topology optimization for repair/redesign of components for AM

Steam Turbines - Broad range for 50- and 60-Hz-grids and drive application

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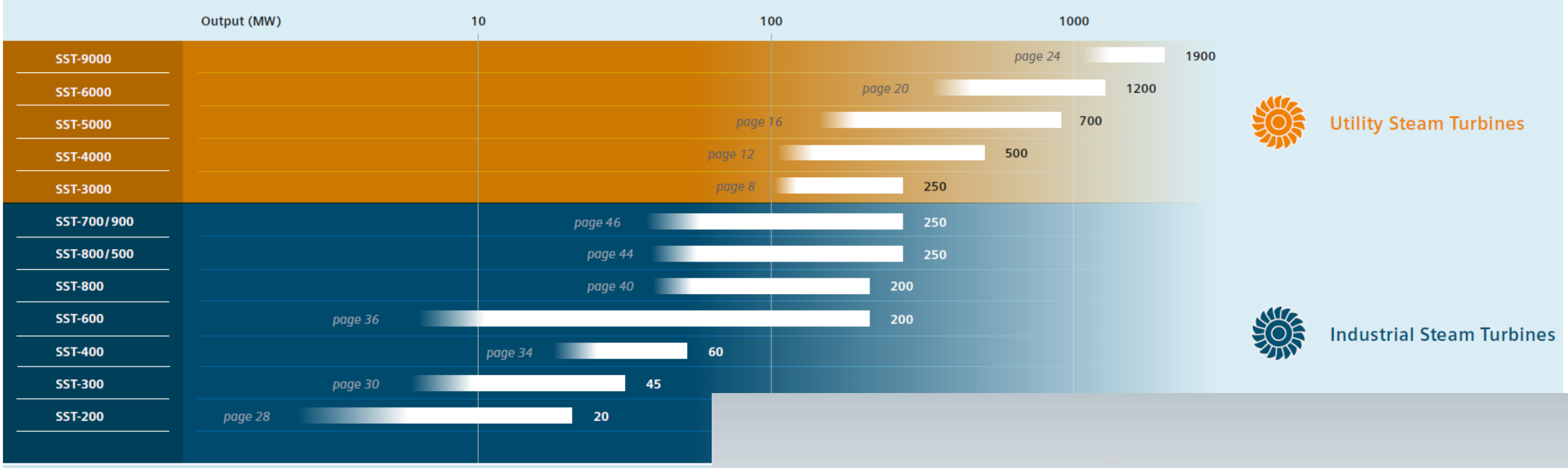

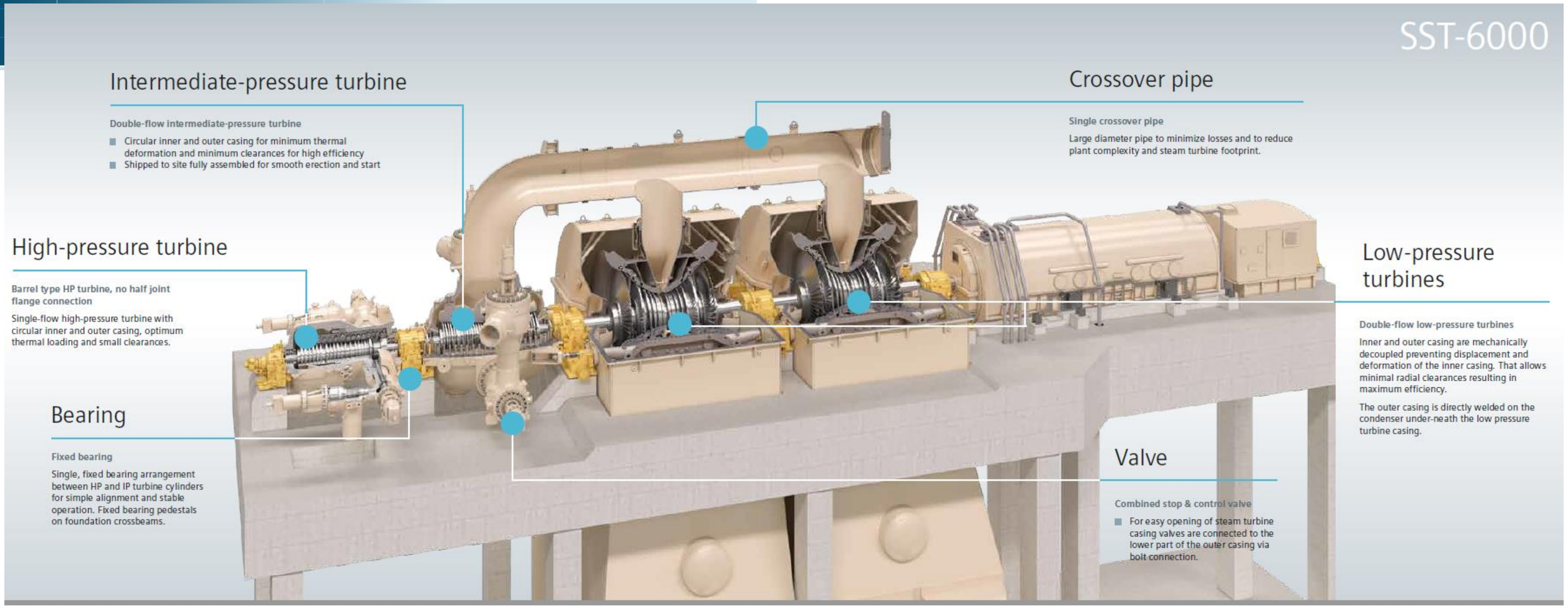

Project Team and Activities

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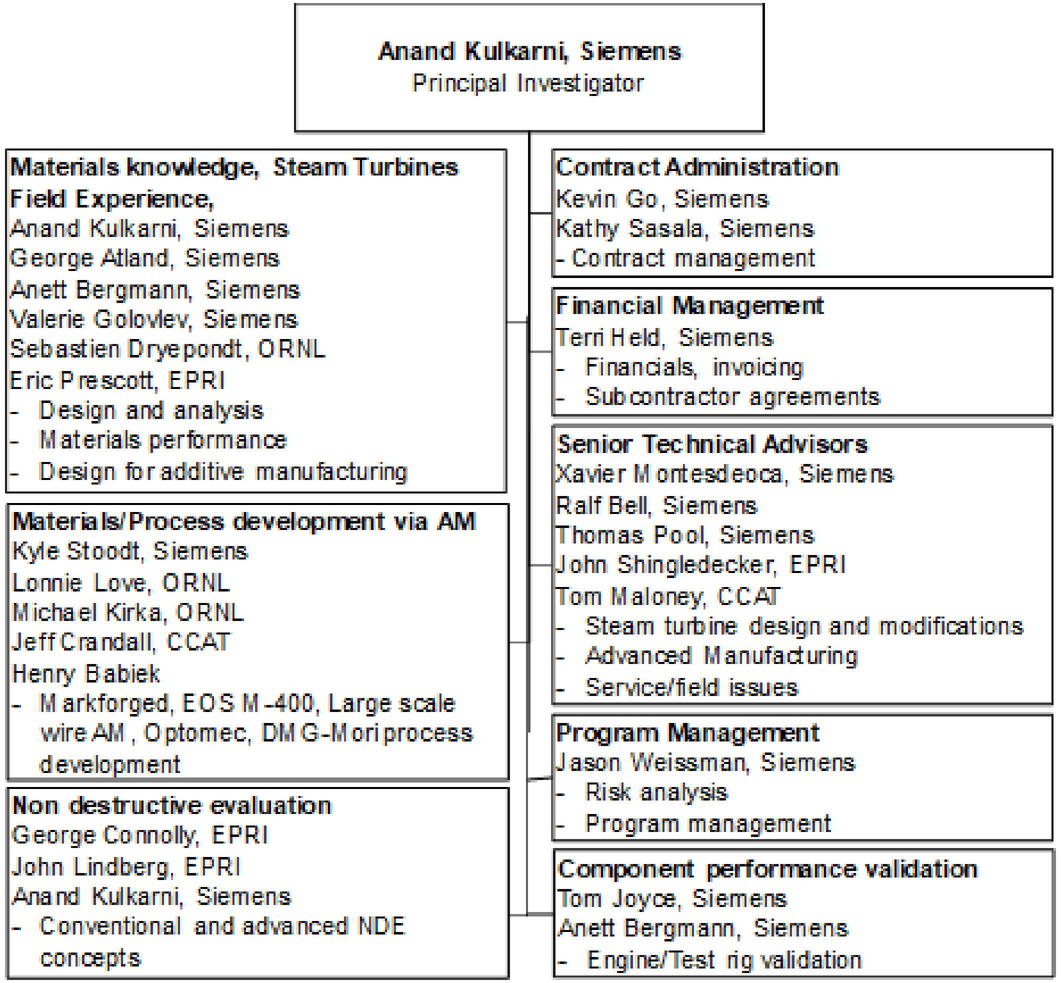

Siemens	Overall Project Lead. Activities involve repair component scanning and CAD model repair, Design for AM, CFD modeling, Markforged/Selective Laser Melting (EOS-M400) materials development, NX based toolpath design for repaired and redesigned components, Component buildup, Steam turbine rig testing, 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.

Development Approach For Technology Maturation Plan

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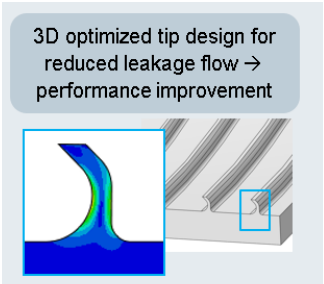
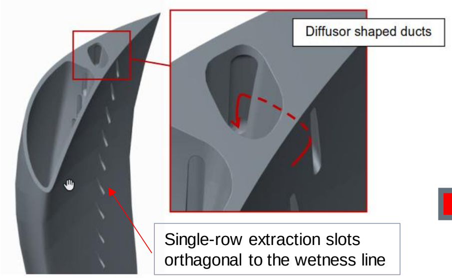
Design for AM – Improved designs

Repair of models

Advanced seal designs



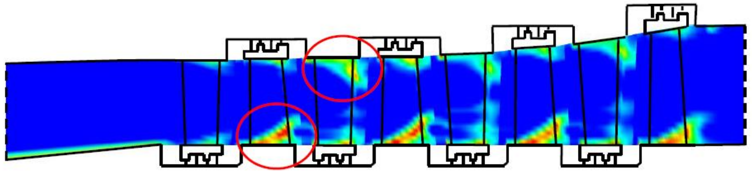


Advanced blade designs

Process-Structure-Property Relationships

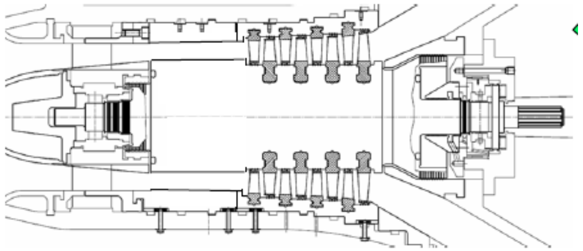
AM Process developments

Component Performance Validation

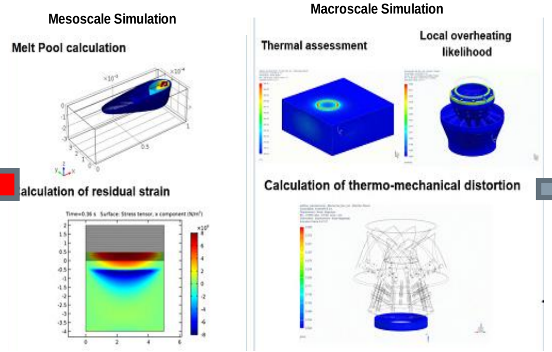


CFD Simulations

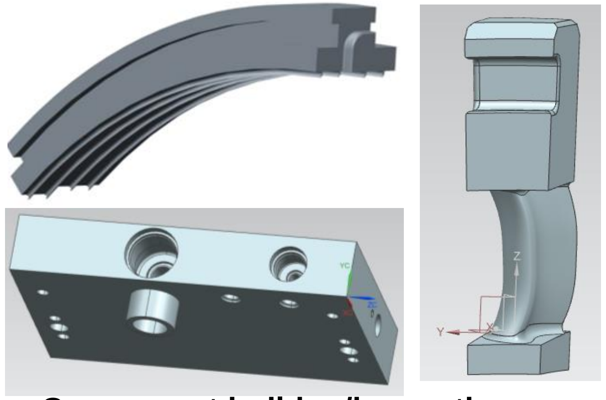
Component rig Validation for performance improvements



Component (Advanced) Manufacturing

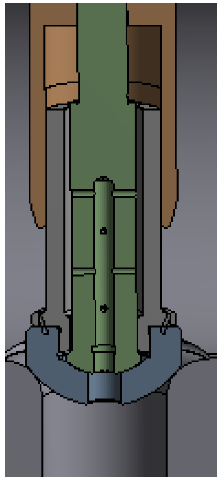
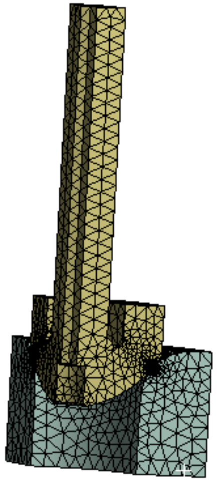
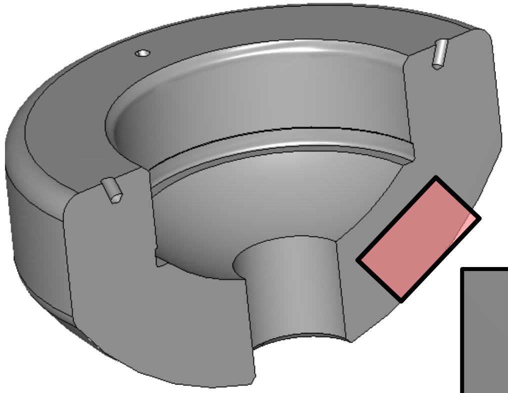
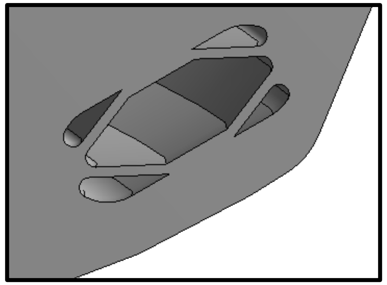
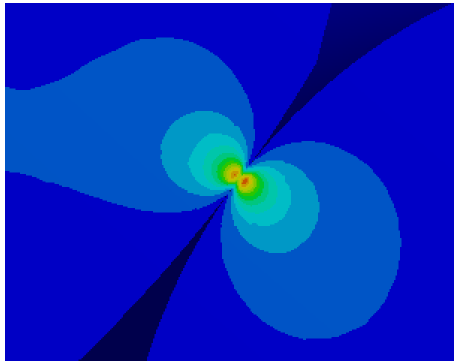
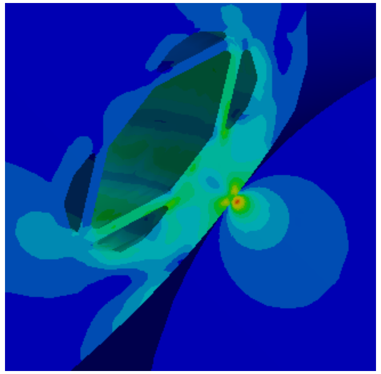


AM Process simulations



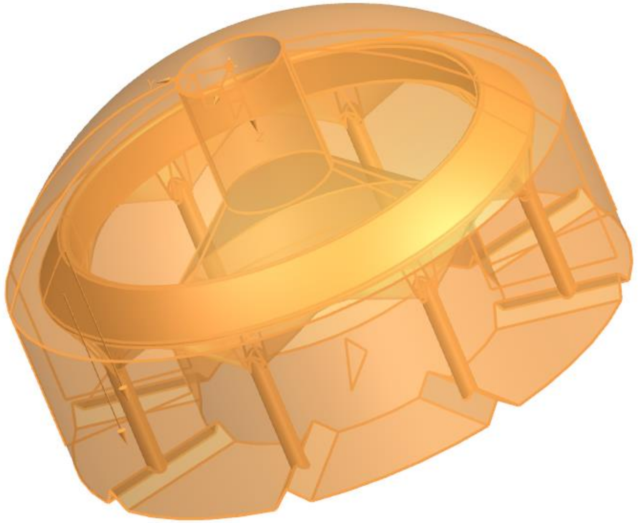
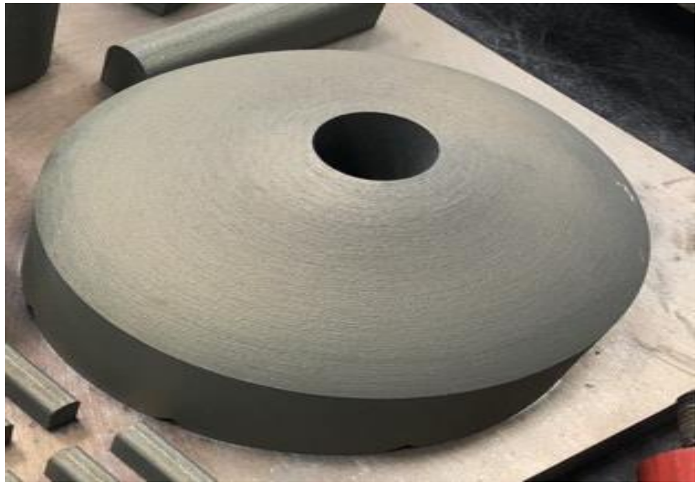
Component buildup/inspections

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

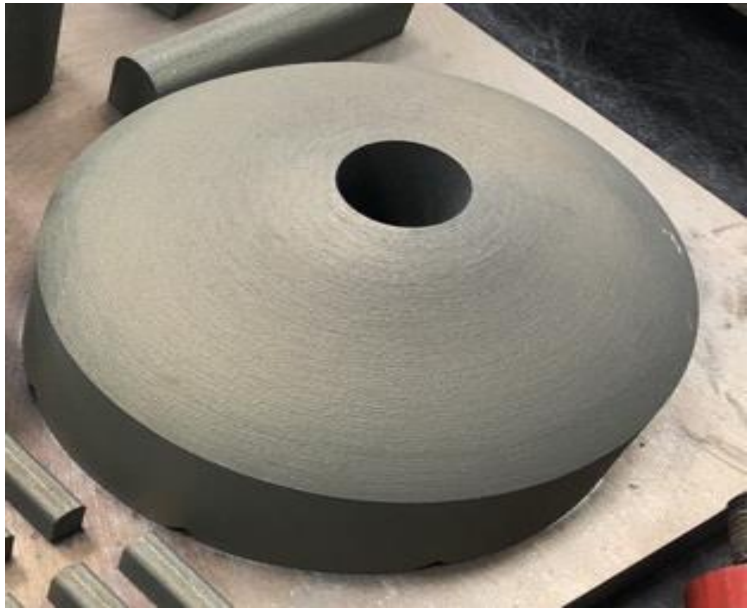
Reduced Contact stress
Reduced Contact width
Reduced Deflection

Redesign to facilitate AM processing

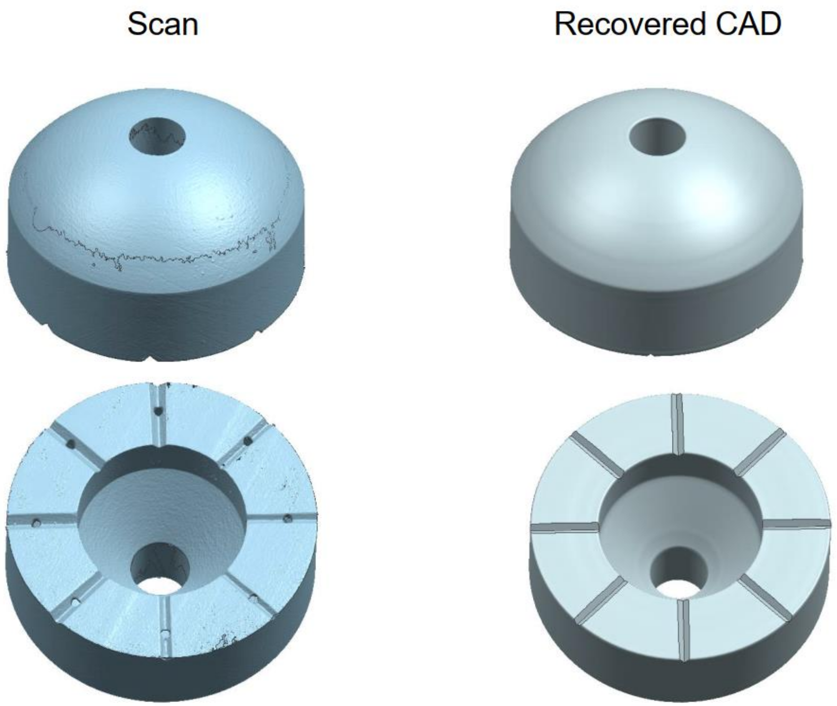
Design for AM to improve contact wear of valve components

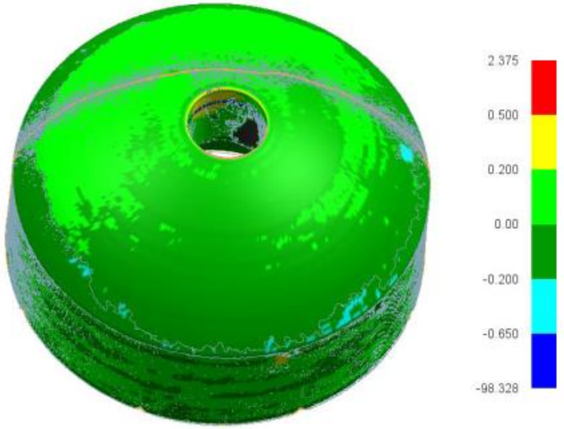
Task 2 - CAD Guided Machining/Repair of Components

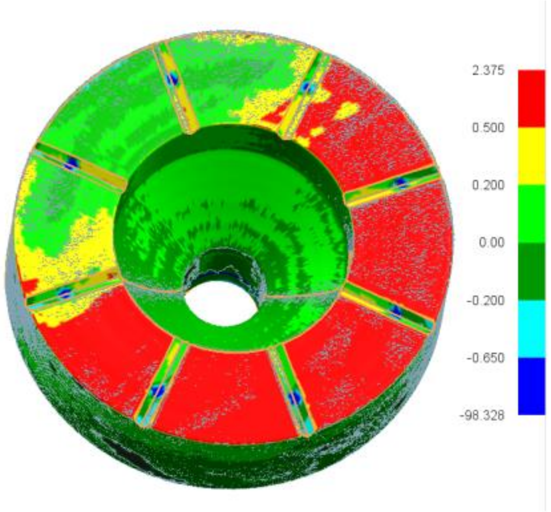


Majority of the machining is external

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







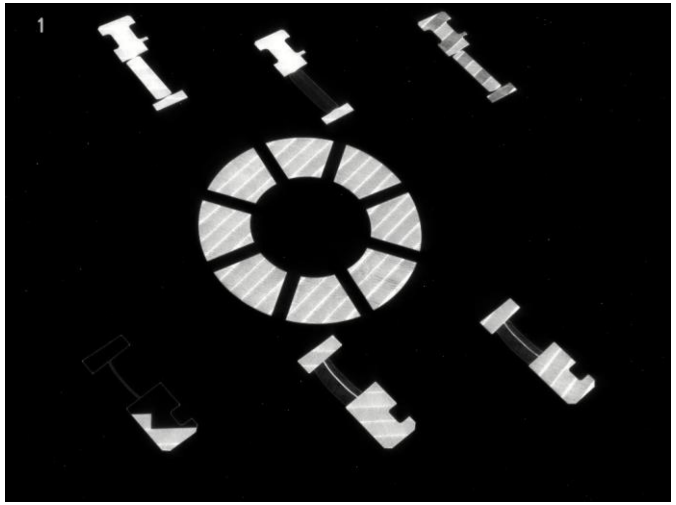
Parts are oversized in AM to facilitate machining.

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

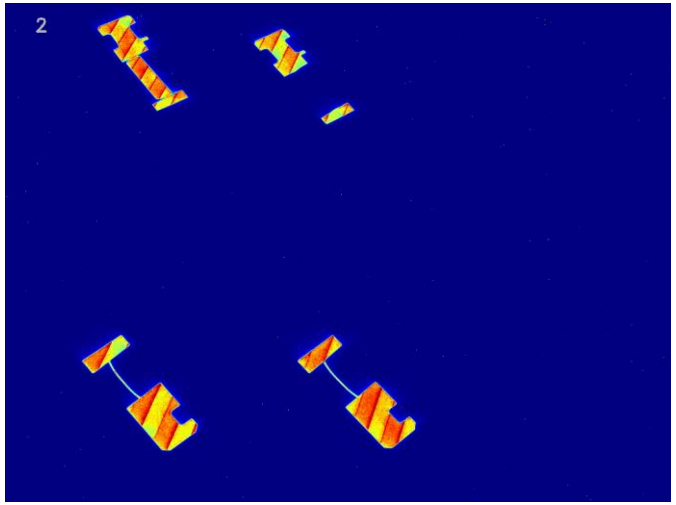
Bionic valve deviation is likely due to inaccuracy of measuring main axis direction

Task 2 – Digital Manufacturing of AM Components

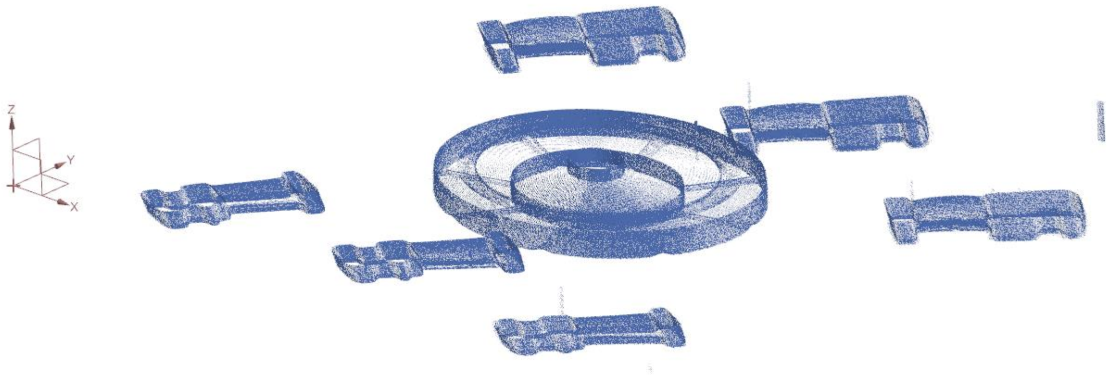
Camera view

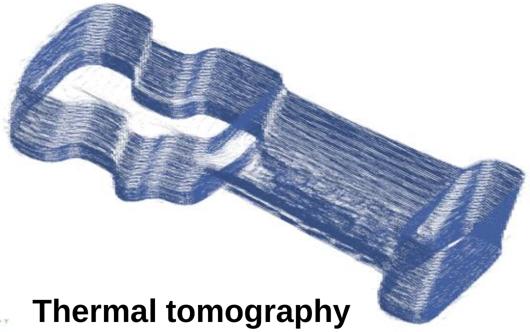


Thermal Tomography Heat map

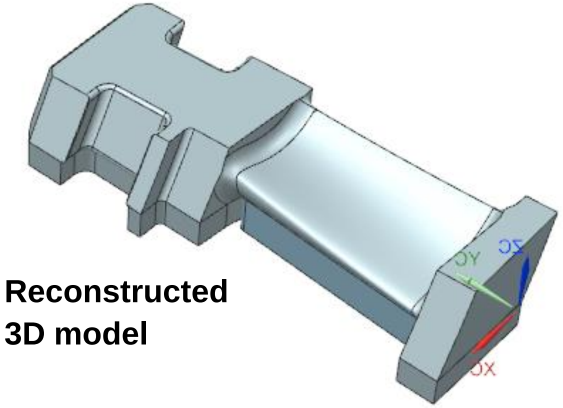


Layered monitoring to trace defects/dimensions



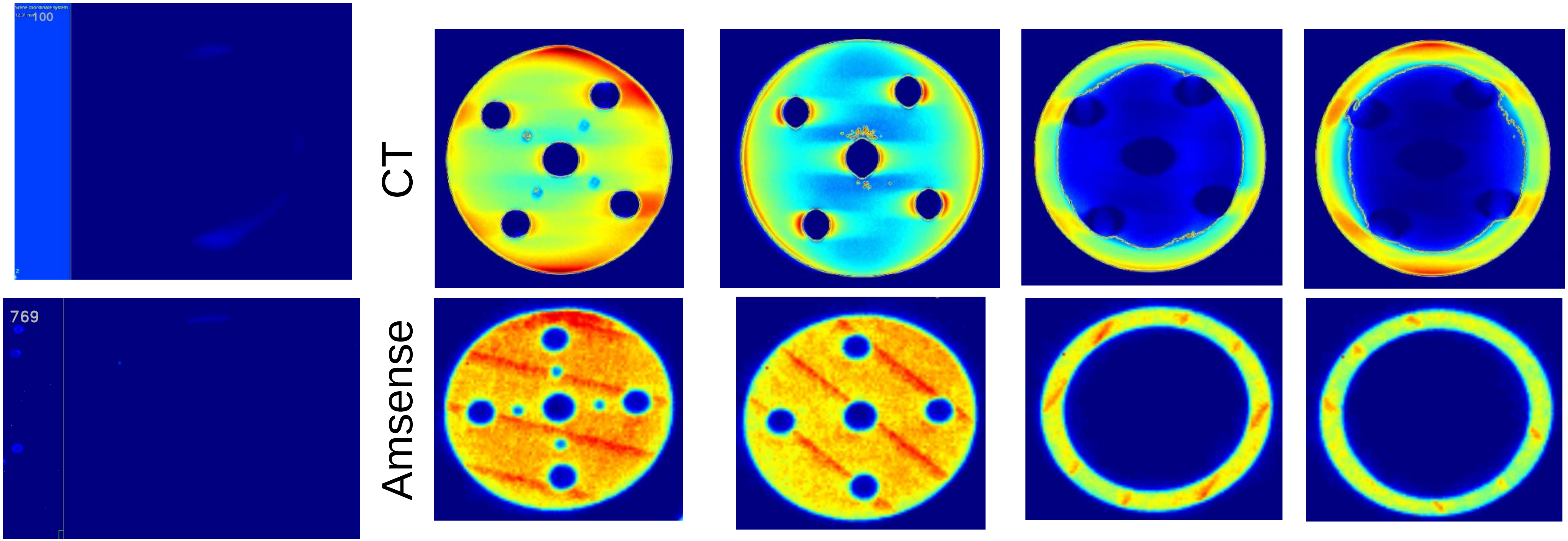


Thermal tomography data



Reconstructed 3D model

AMSense vs CT Scan – Potential for Rapid Qualification



Layer by layer analysis to capture materials and features

Deviation Gauge Analysis from Digital Models

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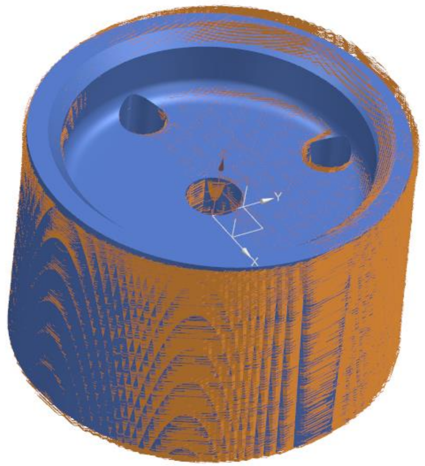
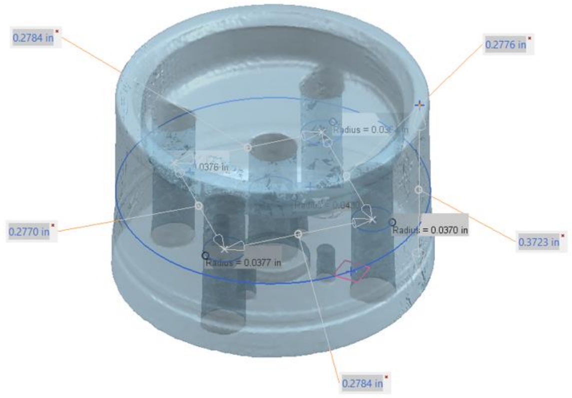
Overlap of CAD and 3D models

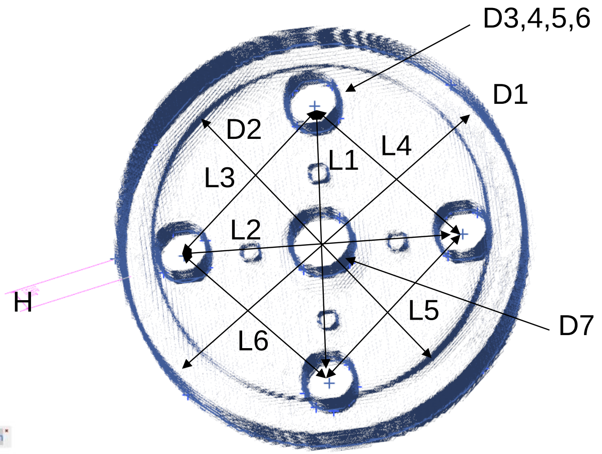


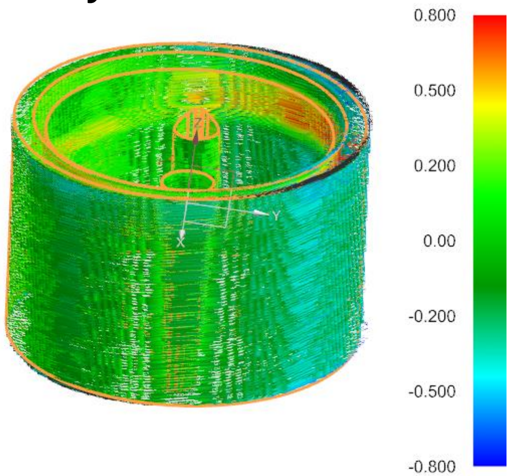
AMsense

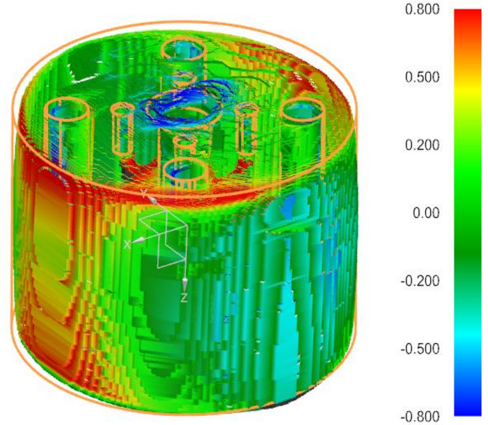


CT Scan

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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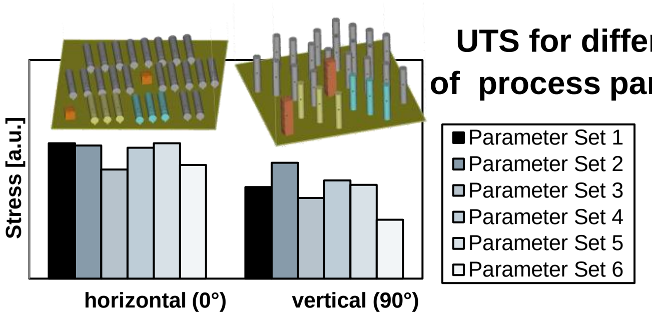
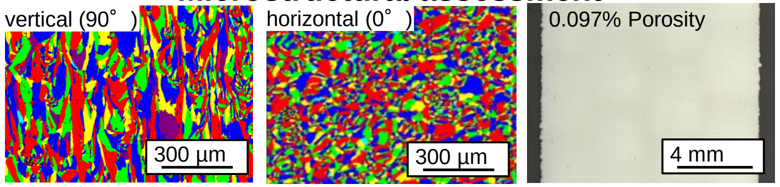
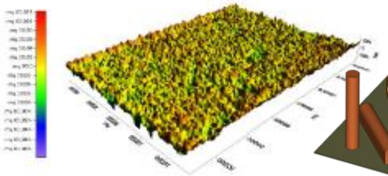
Process Development



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 3 - Materials property generation Ongoing

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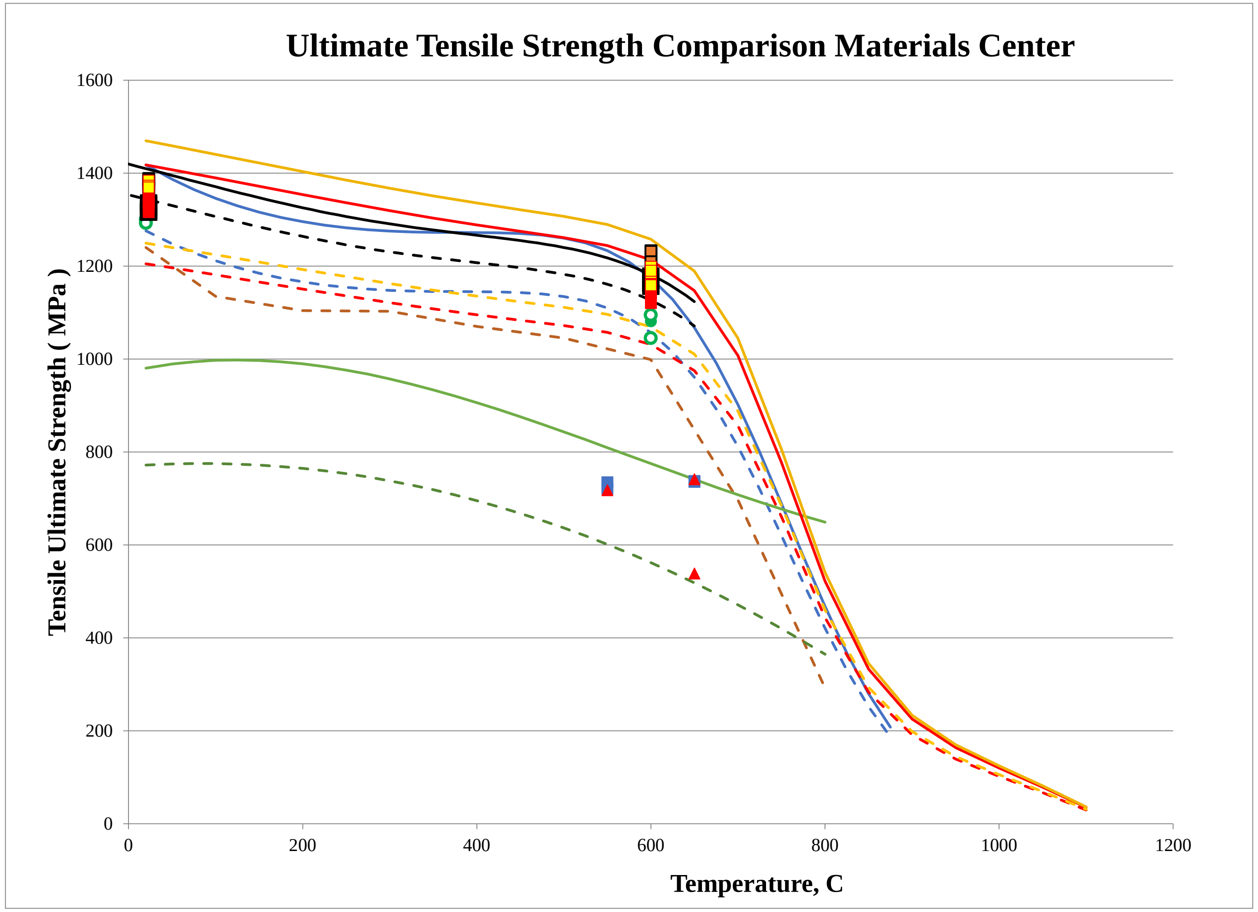
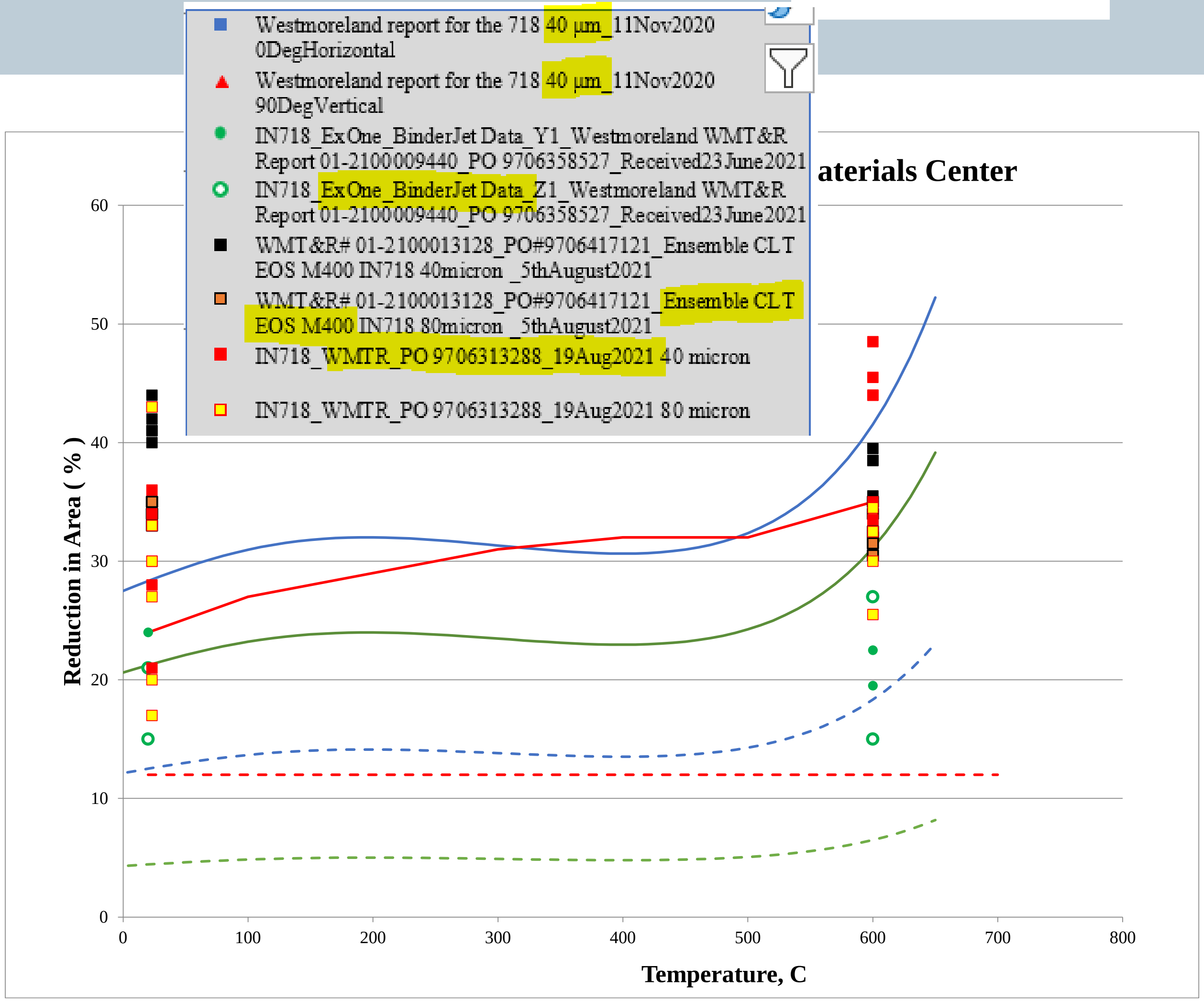




Materials data generation for multiple AM processes for performance comparison

Task 4 - Design and component build efforts using AM

Directed Energy Deposition

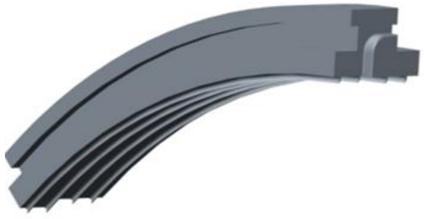
Markforged

Large scale Wire deposition

Selective Laser Melting

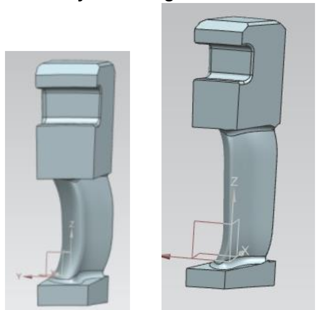
Binder Jetting

Sealing segments



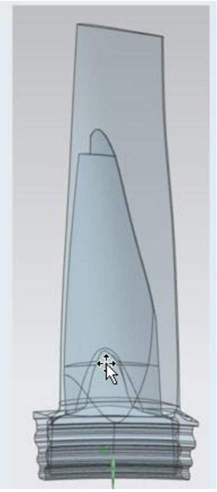
48-70 mm

Stationary/Rotating drum blades



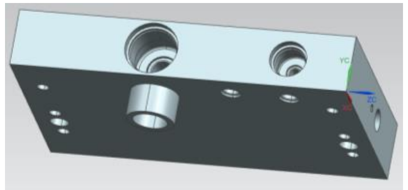
75-350 mm

Last stage blades



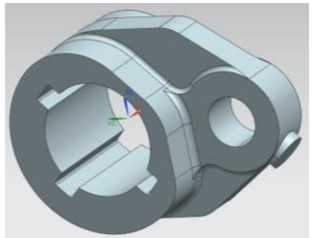
520-1200 mm

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

Task 4 – Laser Powder Based Fusion

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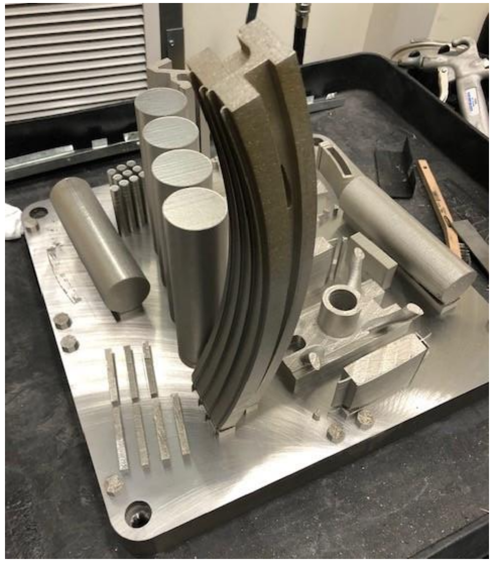
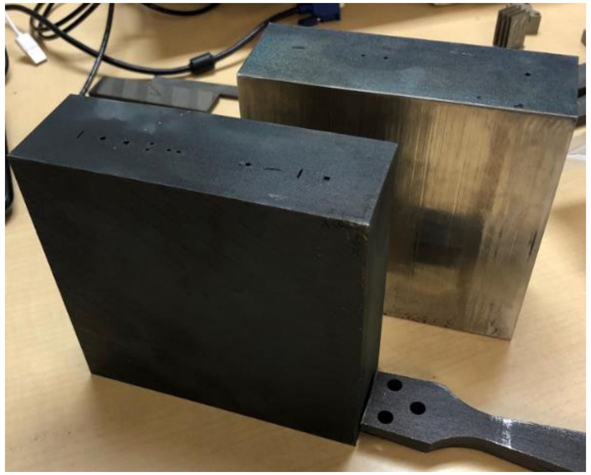
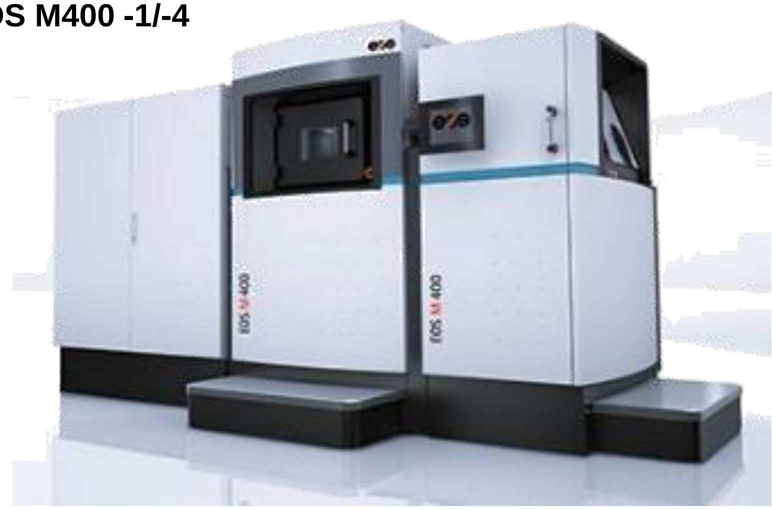
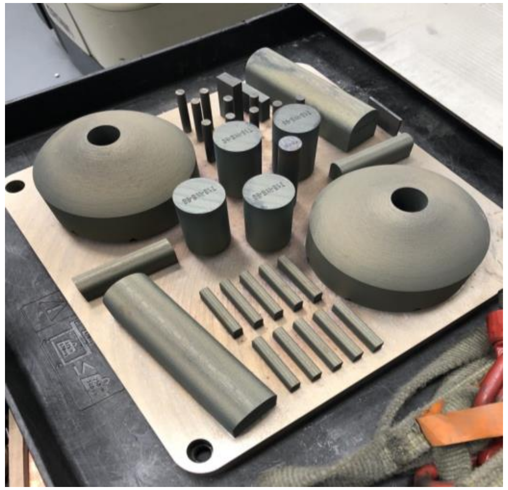




EOS M400 -1/-4



Build volume – 400 x 400 x 400 mm

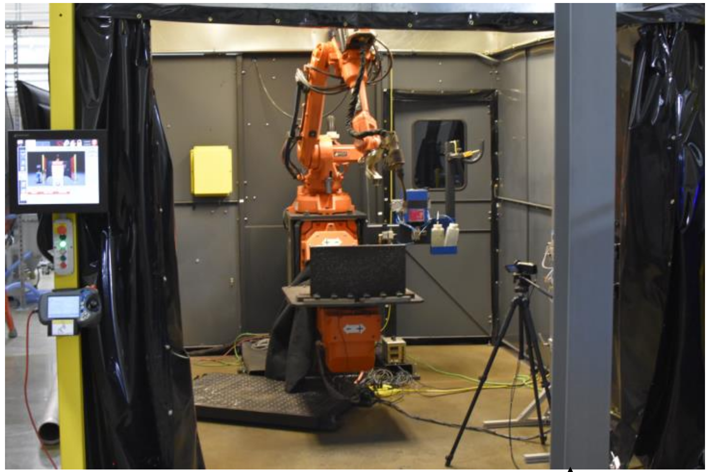


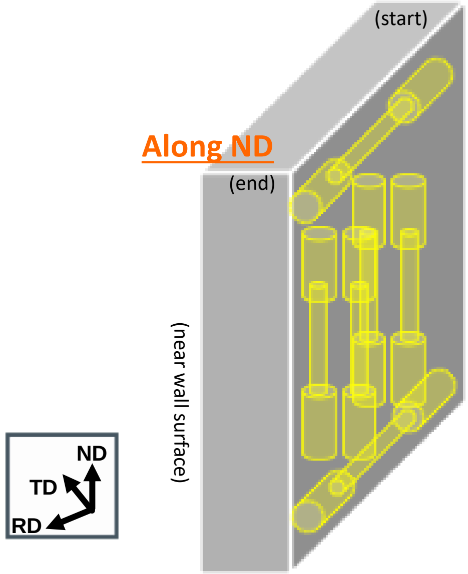
High performance components with complex design and high potential to improve customer value (efficiency, durability)

- Industrial implementation of SLM has successfully started **BUT** additional development needs are substantial:
  - **Design for Additive Manufacturing**
  - **Costs**
  - **Quality -** Robustness and repeatability → process control
  - **Production Line integration** → standardized interfaces are required

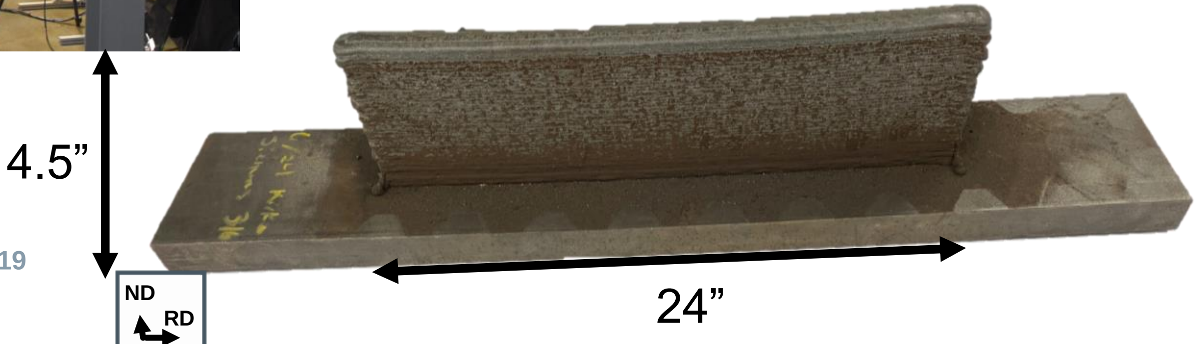
Task 4 - Large area Wire Arc AM

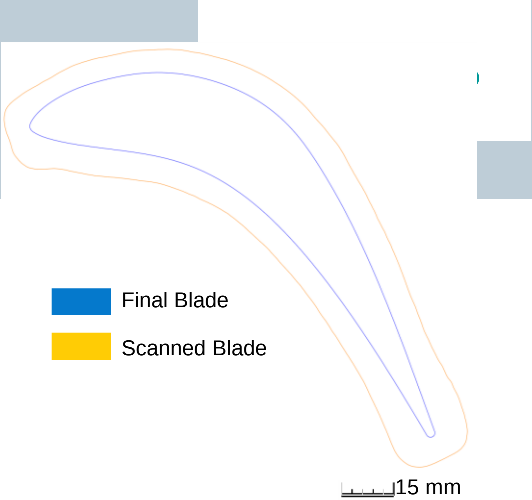
- Feasibility studies conducted with 316SS
- Sample Fabrication (Lincoln/Wolf Wire Arc)
  - ABB 6DOF manipulator
  - ABB 2DOF positioner
  - Lincoln Powerwave R500 welder with with dual wire feeders (multi-torch)

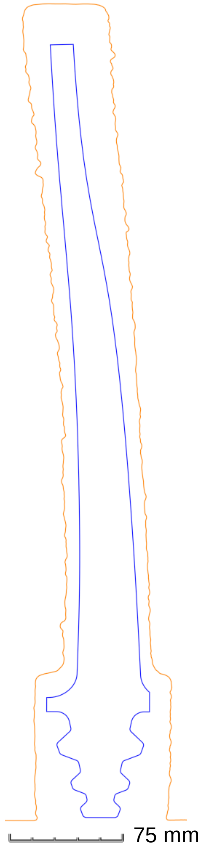




Mechanical Sample Extraction Plan







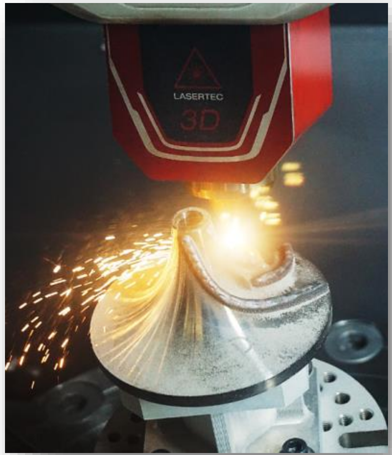
Task 4 – Directed Energy Deposition AM

DMG-Mori Lasertec 65 3D/ Optomec LENS 850R – Hybrid Precision Machining and Laser Powder Directed Energy Deposition

SIEMENS

Connecticut Center for Advanced Technology, Inc.

- 5-Axis Metal Powder Additive/Subtractive System
- Milling and Turning
- 2.5 kW Laserline Laser
- Build complex components reducing part count
- Wide range of geometries with 5-axis motion
- Reactive and Non-reactive Metals (alloys of: aluminum, steel, nickel, cobalt, titanium, refractory metals; limited studies with graphite, ceramics)



Kulkarni/ Siemens

Task 4 – Low-cost Binder Jet 316/IN718 for Feasibility/Resolution Studies

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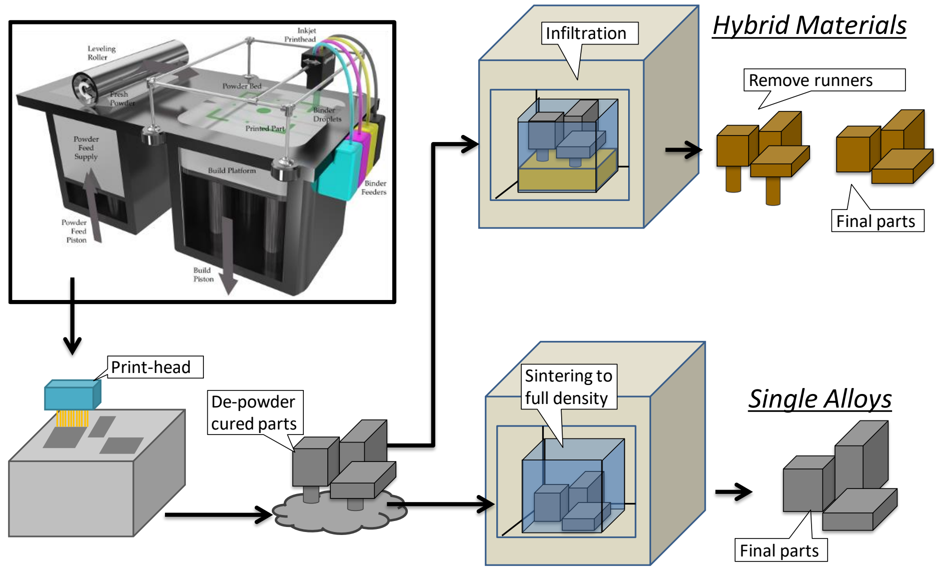

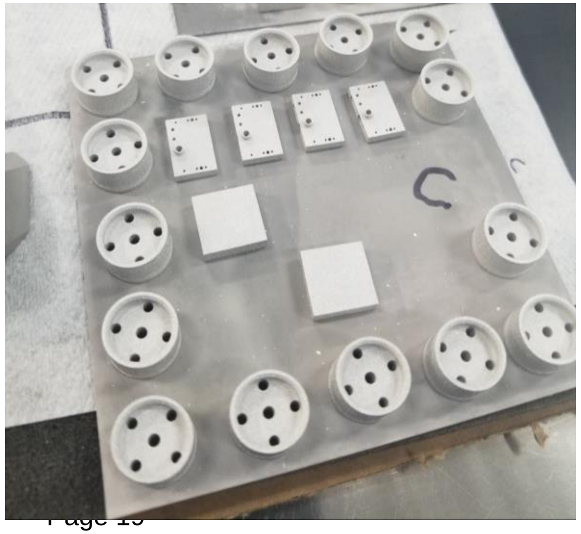

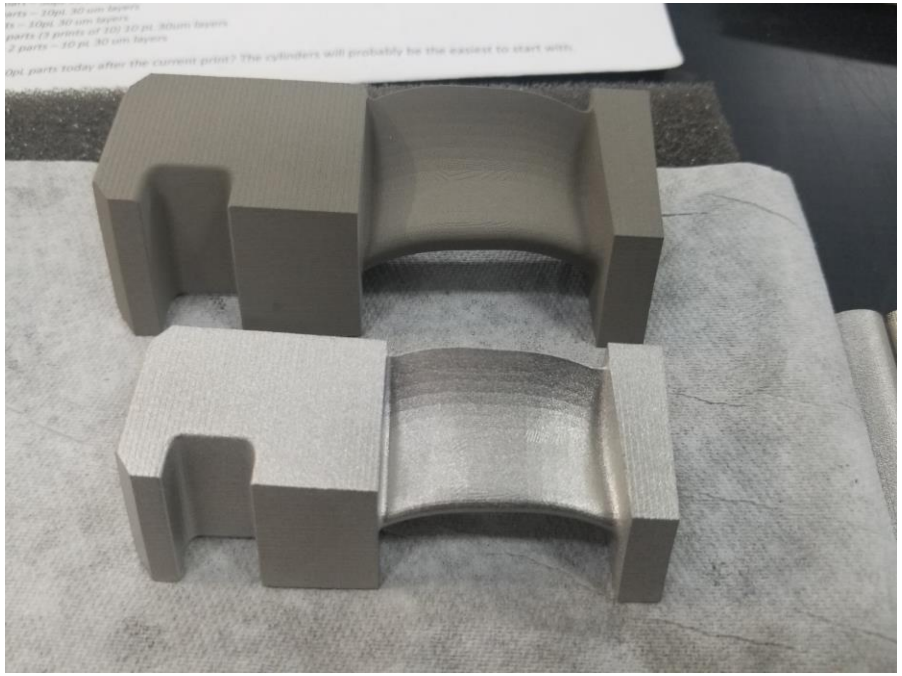

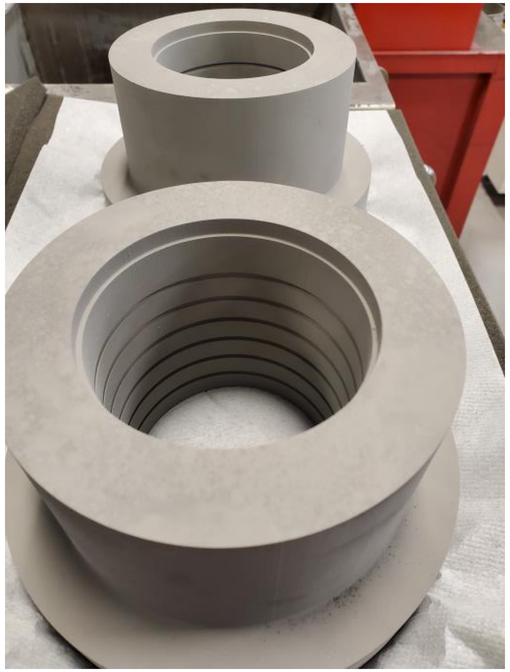

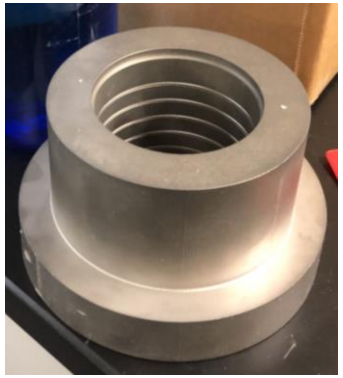

Valve components, drum blades and NDE standards printed on new Binderjet process to establish the cost/resolution evaluation. Preliminary trials done with 316 and IN718 (>99% density)

Cost-Performance Comparison

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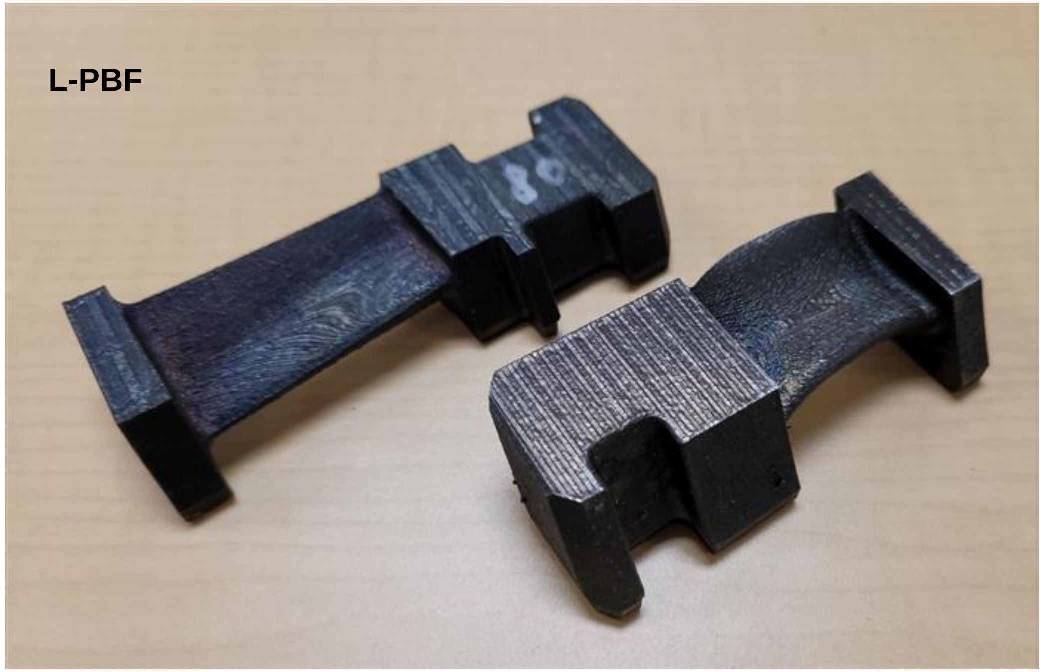
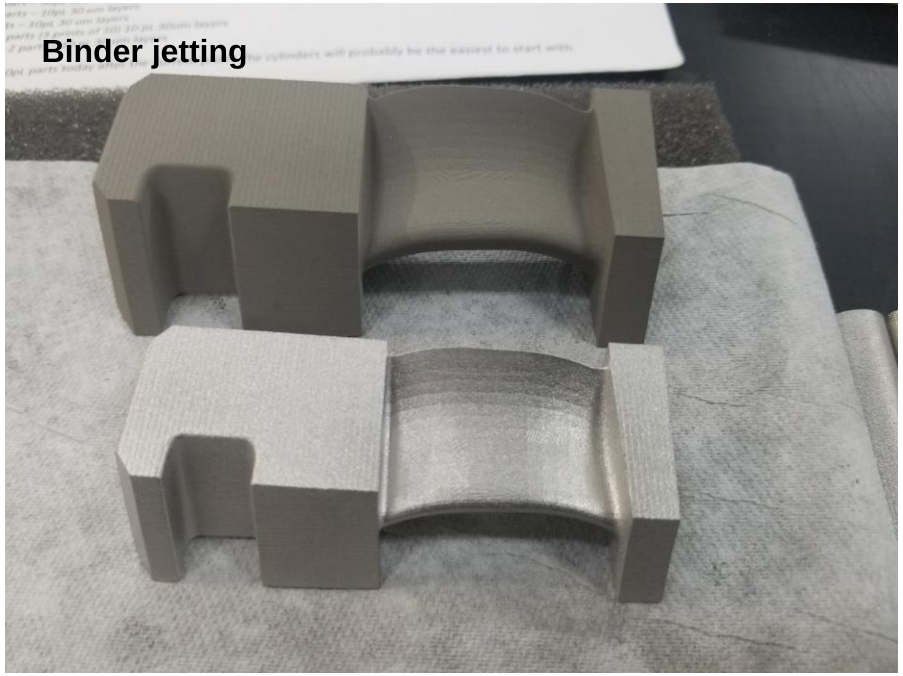
High precision, tinted during heat treatment and will be tumbled



High precision, near finish

High precision, Low cost



- **All blades currently being CT scanned for defects before sectioning for microstructural comparison**
- **All materials properties to be compared for input to design for cost/performance model**
- **Working with OEMs on cost model for large volume production costs**
- **Rainbow set of blades to be manufactured for next rig testing**

Stellite-6 Bushings

ExOne Binder Jet

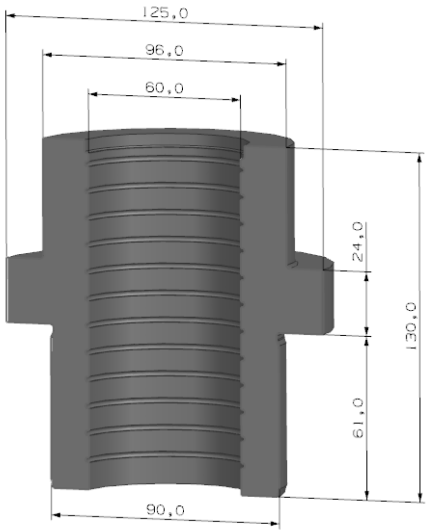
Geometry: Acceptable for AM, can be printed with grooves

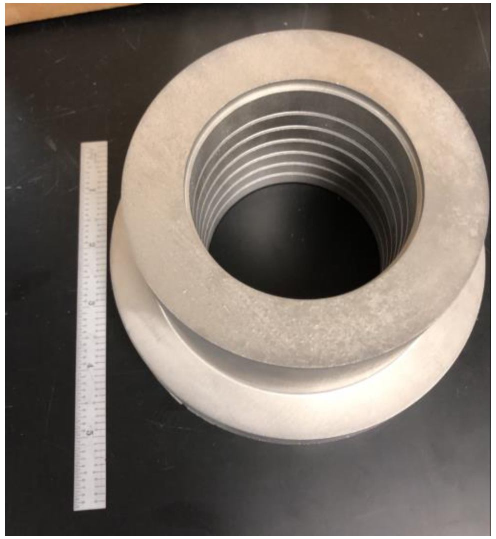
Material: Currently Stellit-6 per TLV997903

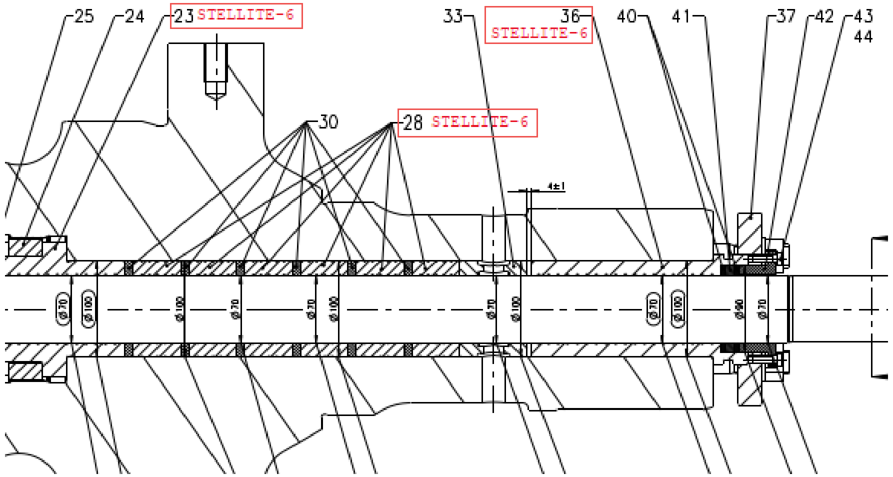
AM material: Evaluating IN718 wear properties to see if viable alternative and will evaluate other AM materials

Evaluating EBIT for component ranking within ORD

- Stellite 6 bushings – Complete cost for new app four valve arrangement $58,600 for 62 bushings total
- Lead time 120 to 270 days







HP Stop Valve cross-section

Creating a thin shell component further reduced the printing cost, but the L-PBF components are still much more costly

All printing costs are based on a full build plate of components to reduce the heat treat and post processing costs

Binder jet trials, which is a cheaper process to produce IN718 components from powder, were successful for 5-6” parts, scale up efforts planned after confirmation

Current L-ring Seal Business case – WAAM

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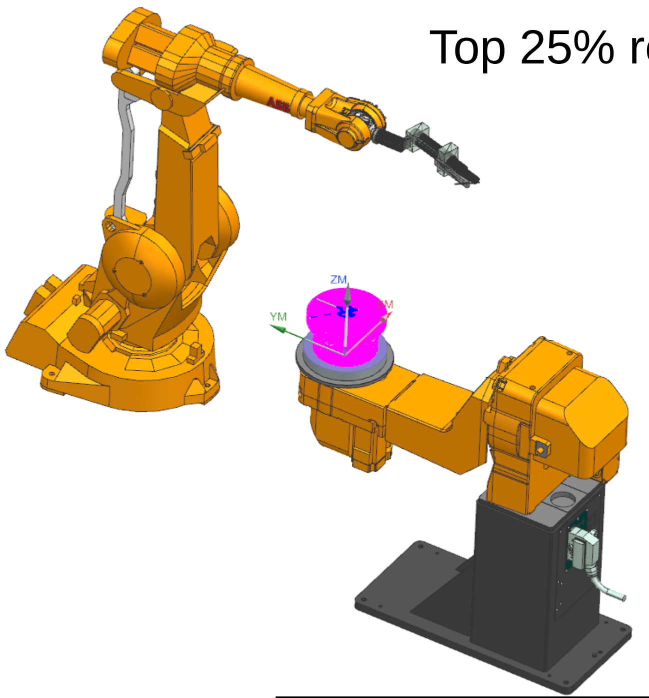


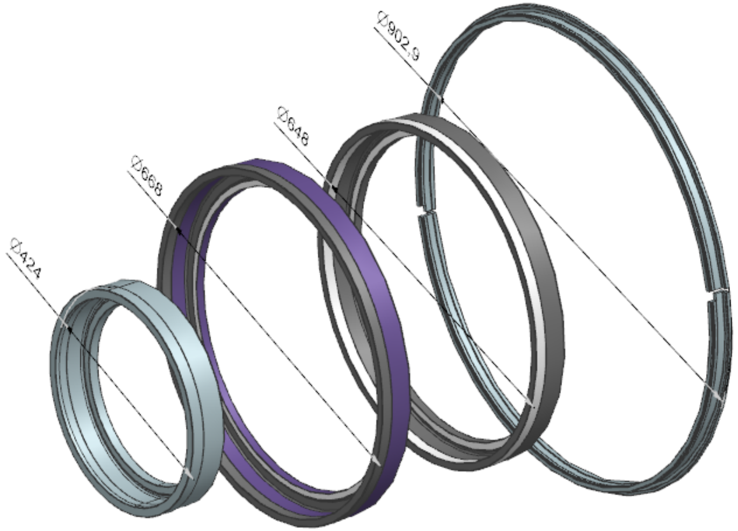
Top 25% repair

1.2m tall L0 blade

Full build

0.5m tall L1 blade

L-rings for HP/IP turbine



Prioritized due to supply chain issues (210 days lead time to 3 weeks)

Description	**Material Master**	**Conventional Cost Average**	**Cost estimate WAAM** **Wire + Consumables + Build time + Mach**	**Business Case** **(cost relative to conventional)**
HP Valve Connection	P0035920500	$7293	$5,486.00	Positive (25% lower)
IP Valve Connection	P0053092200	$7813	$6,164.87	Positive (21% lower)
HP Exhaust Connection	P0060824600	$4378	$3,764.25	Positive (14% lower)
IP Diagonal Stage	P0056255300	$9176	$5,641.68	Positive (39% lower)

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

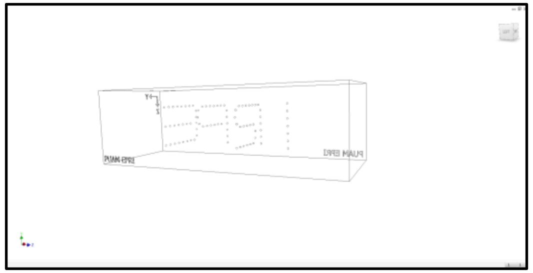
SIEMENS

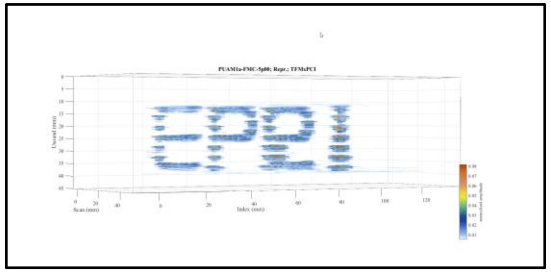
EPRI ELECTRIC POWER RESEARCH INSTITUTE

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

NDE Capabilities

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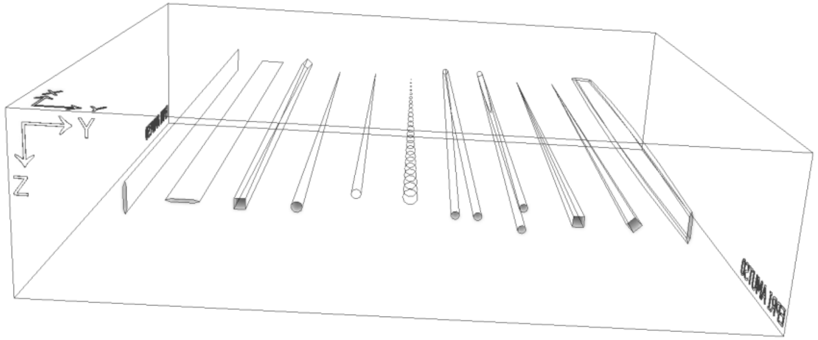
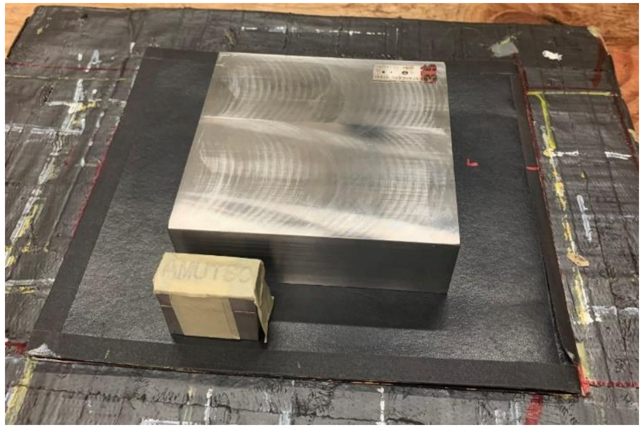
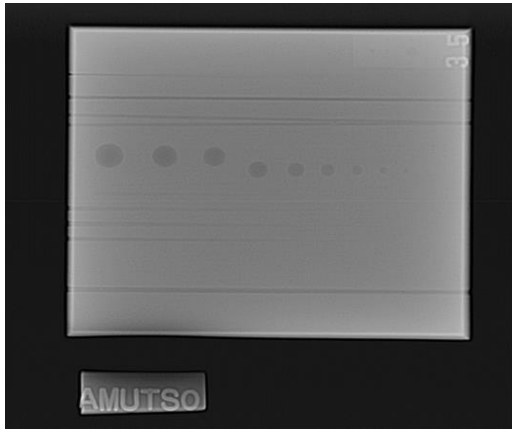


Radiography carried out by MISTRAS Group, Inc. (Monroe NC)
- Ir^{192} source; source distance=19in. (483mm); exposure time=23mins*
- Procedure: 100-RT-001 Rev. 18 based upon ASME Sec. V

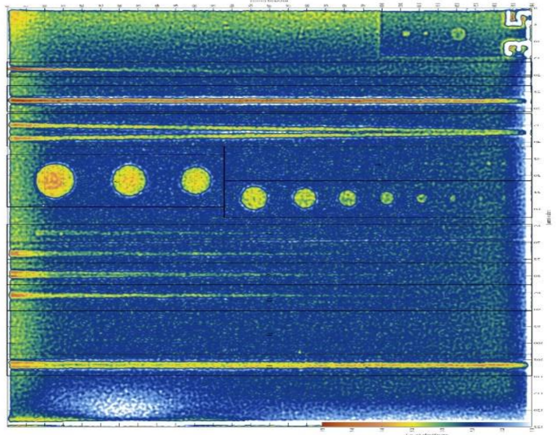
General observations:
- Success in qualitative identification of most internal features *except* horizontal bridge
- UT imaging superior in detection and SNR
- RT SNR generally lower than 6dB; corresponding metrics could not be extracted for quantitative comparison against UT



AMUTS0 block, ASTM IQI plaque and film arrangement



Digitized radiograph

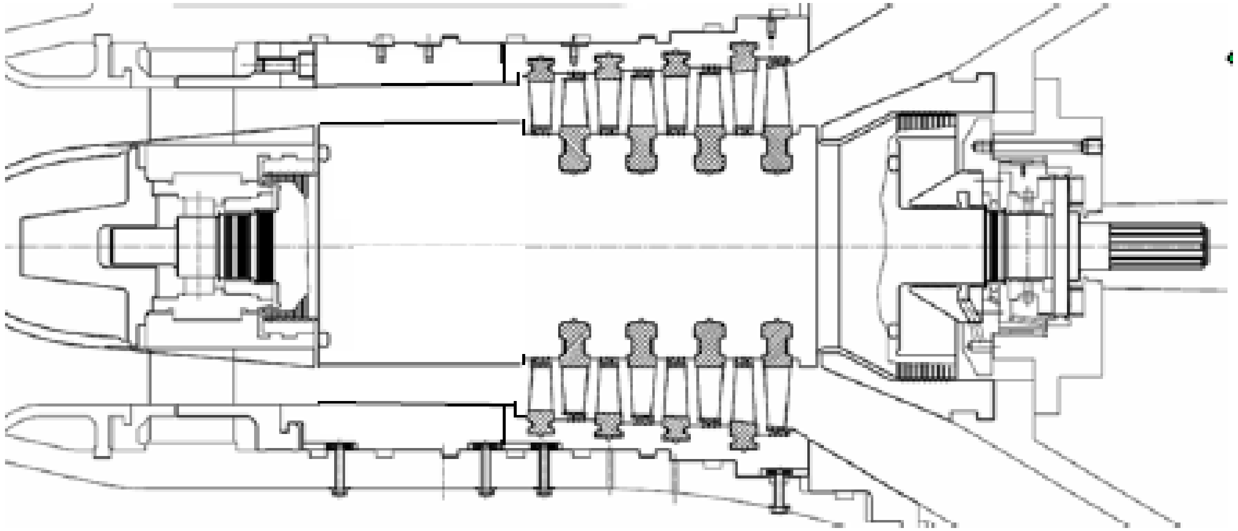


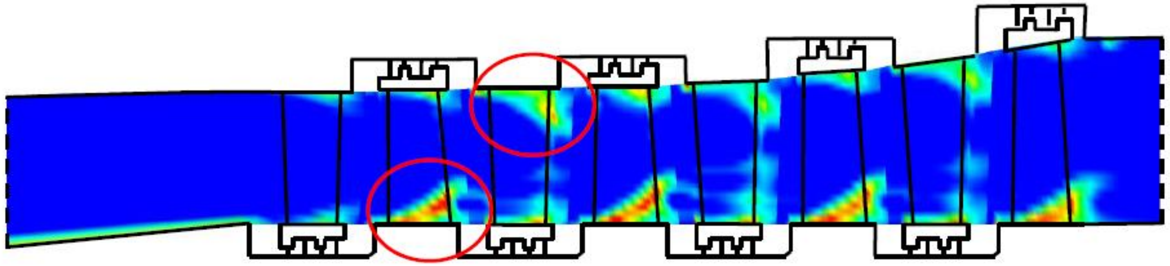
Processed image

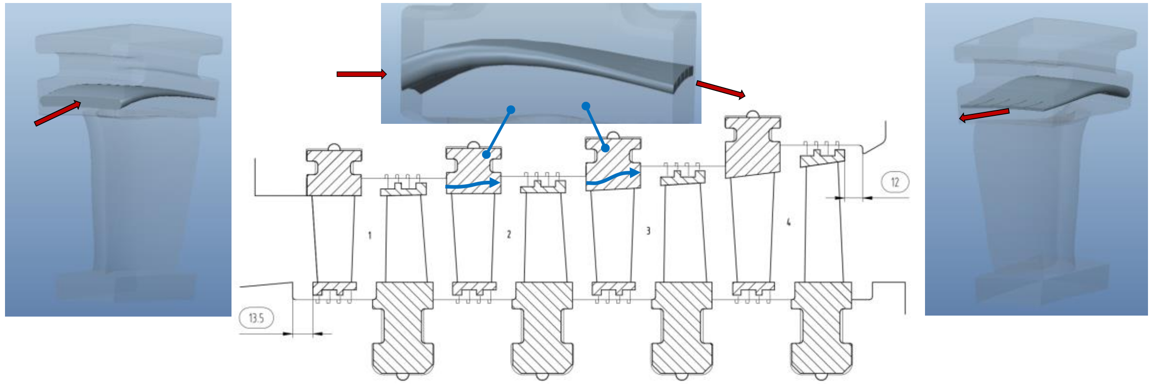
* Exposure time empirically determined from experience by MISTRAS staff; longer time would improve contrast but would worsen radiographic undercutting

Conventional UT and FMC/TFM outperform conventional RT

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

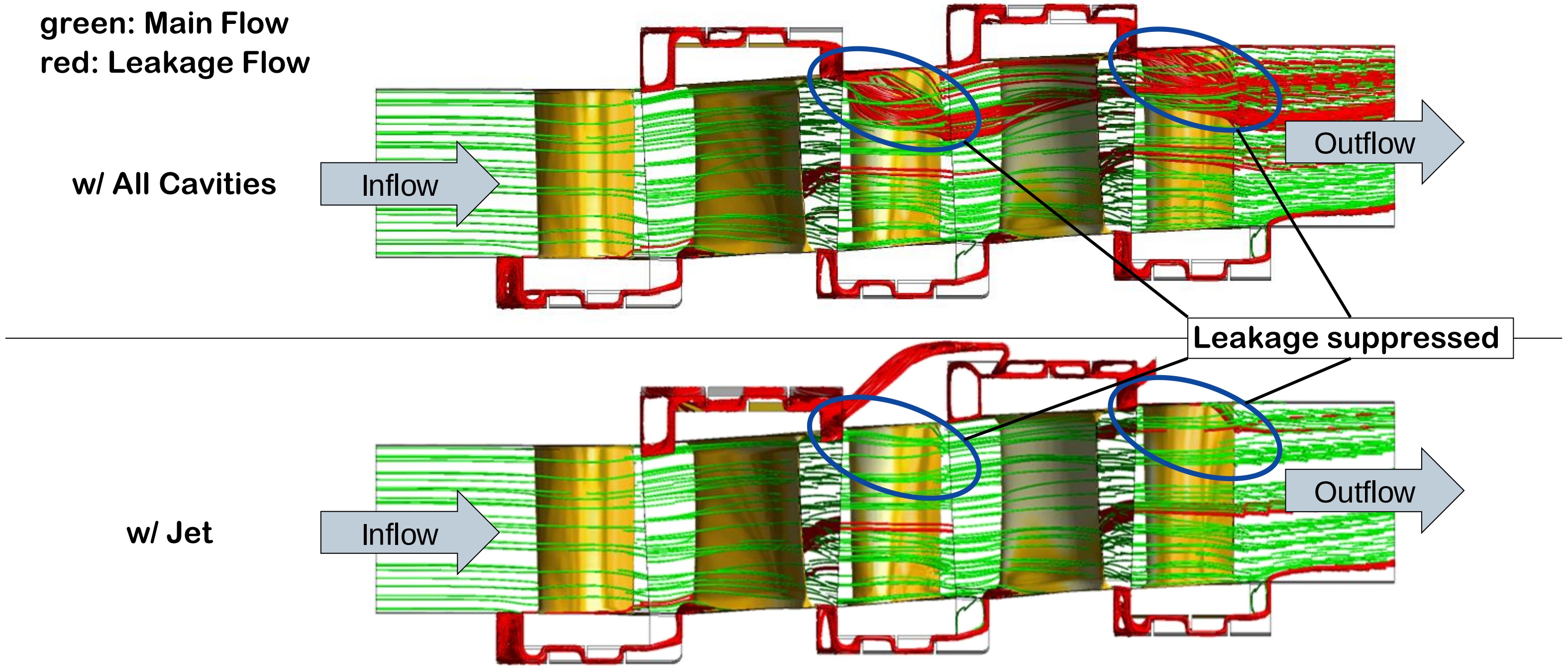




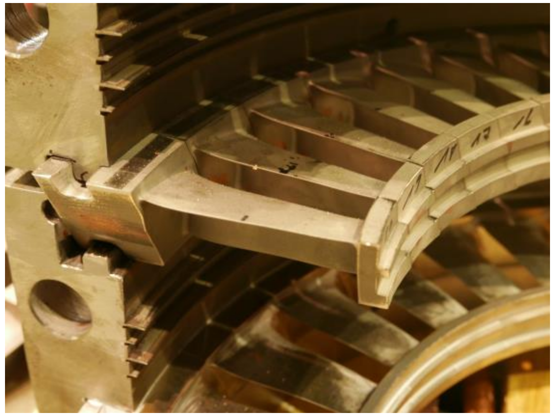


- At the university in Hannover, a multistage turbine designed by Siemens is used to analyze turbine flows.
- The current set-up was investigated thru exhaustive measurements and CFD simulations and is a good reference for the planned modifications of blades and new measurement program.
- In blade paths, losses are mainly caused by profile losses, secondary losses and leakages. The leakage flow re-enters the main flow behind the row and interacts with the main flow causing additional losses.
- If the re-entering of the leakage flow can be avoided, substantial reduction of losses are expected as seen by numerical investigations.

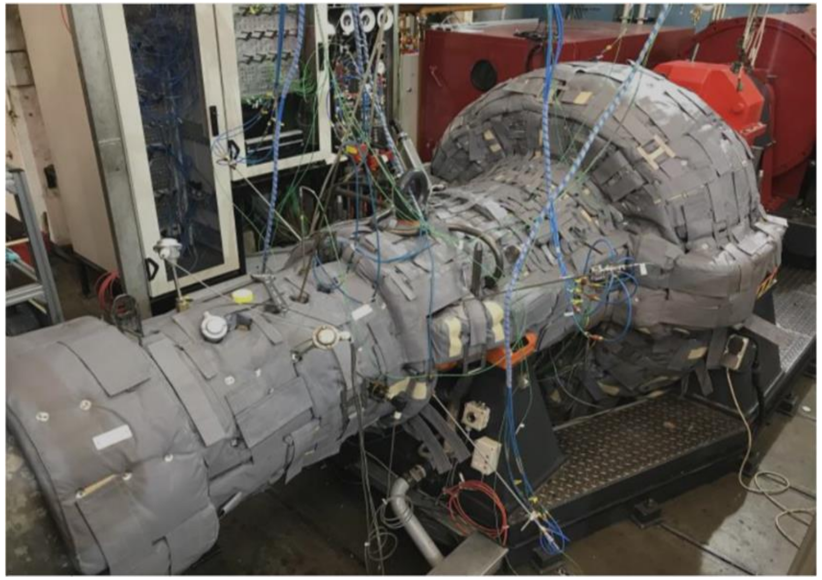
Task 6 - Conduct Rig/Engine Testing of AM Steam turbine Components



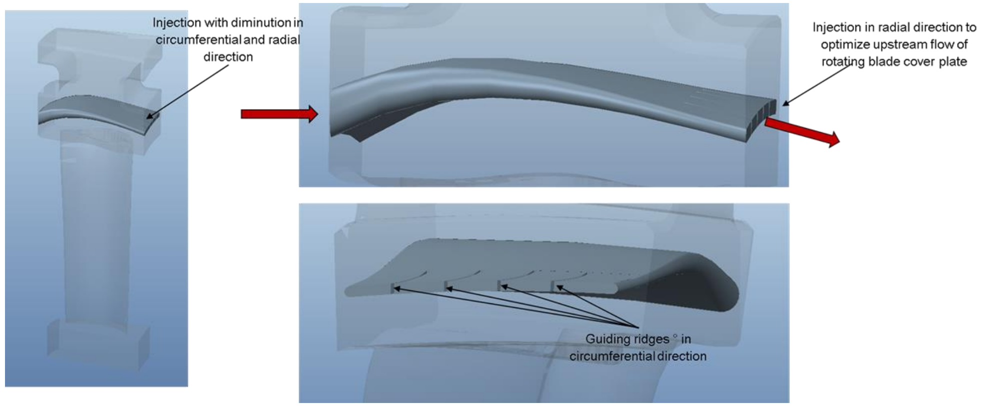
SLM printed blades for rig testing



Assembled test rig



Stationary drum blade design



Task 6 – Rig Test Results

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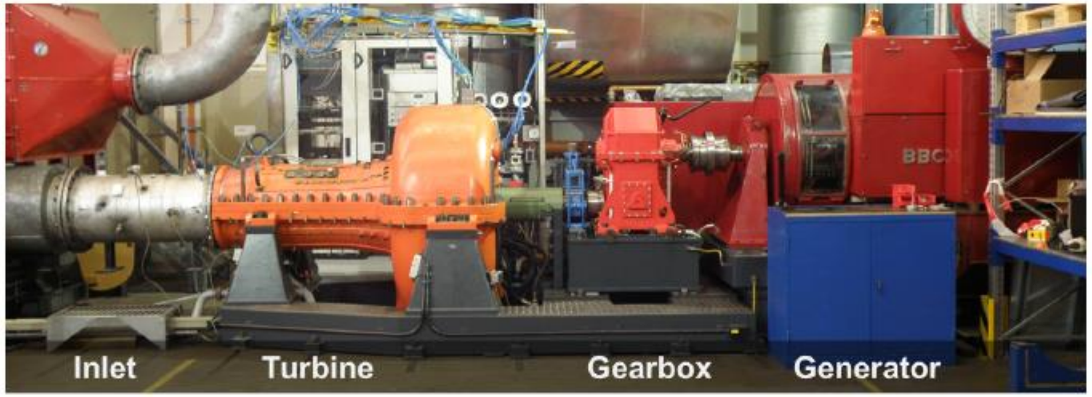
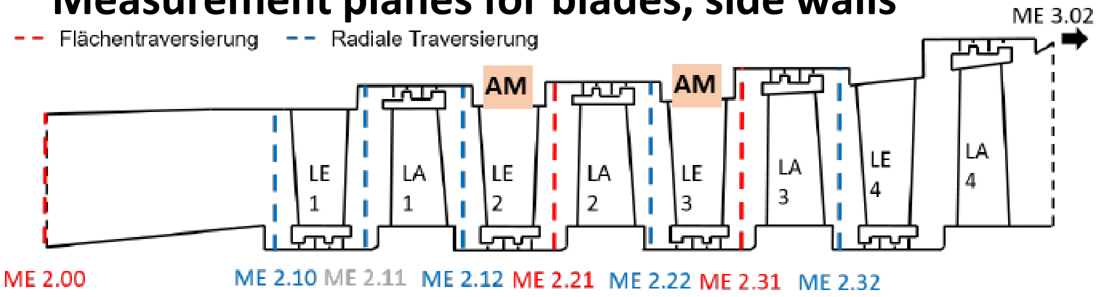
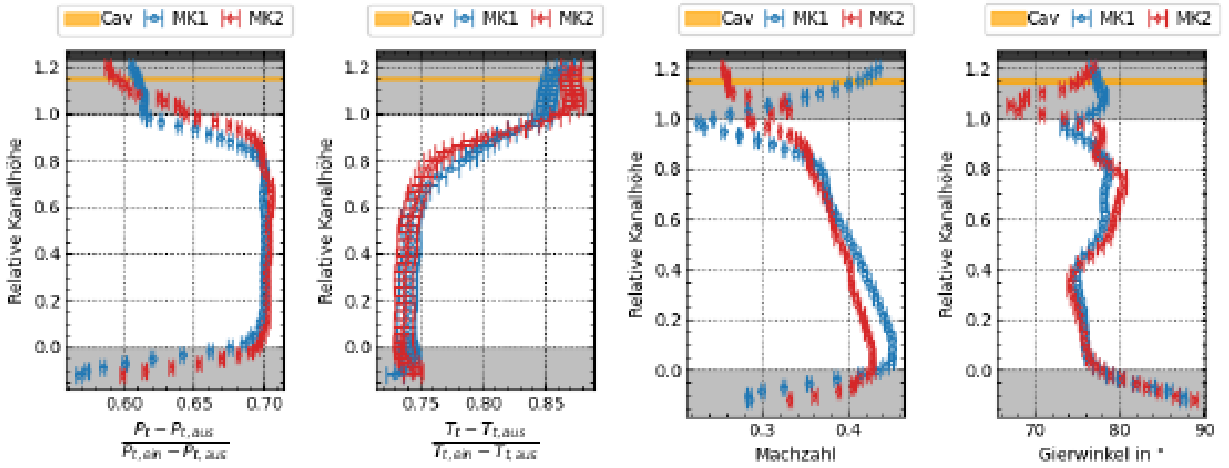
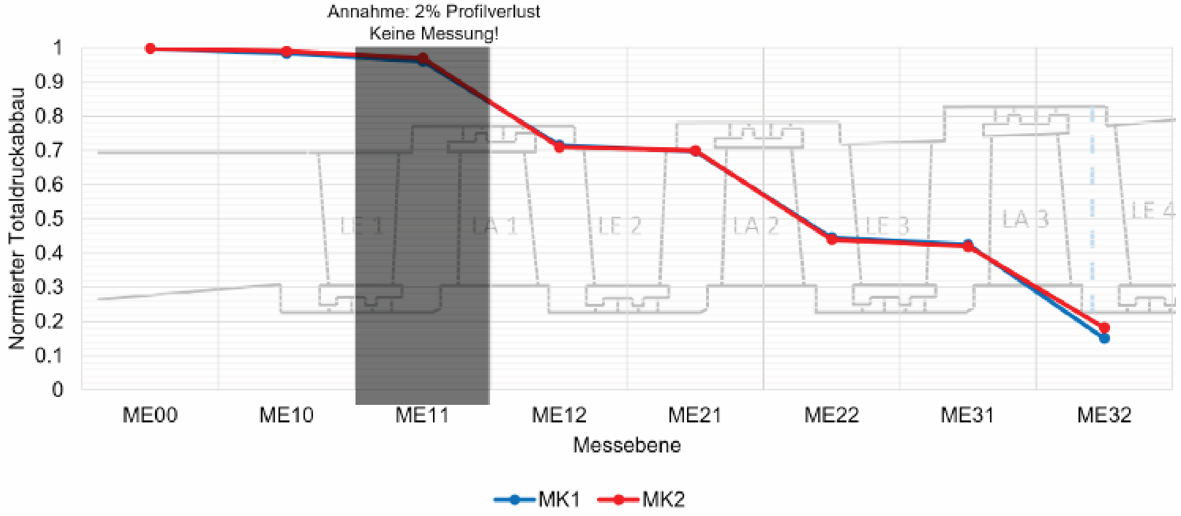






The pressure losses are shifted to the outer side wall which clearly indicates the impact of the bypass blades.



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

Kulkarni/ Siemens

Stationary Drum Stages Blades

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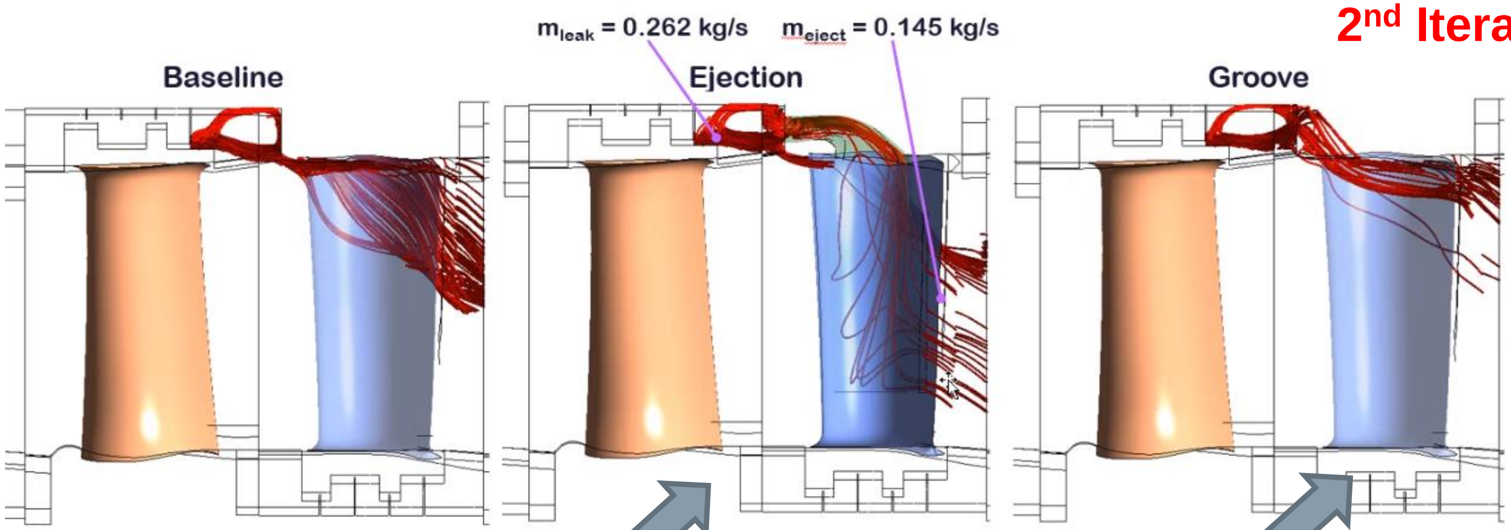
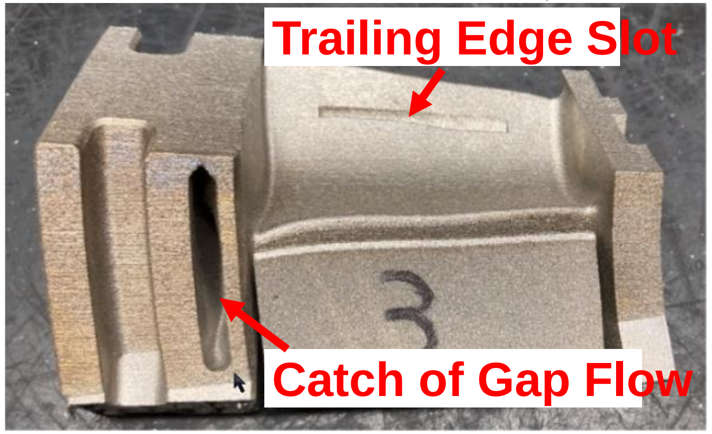
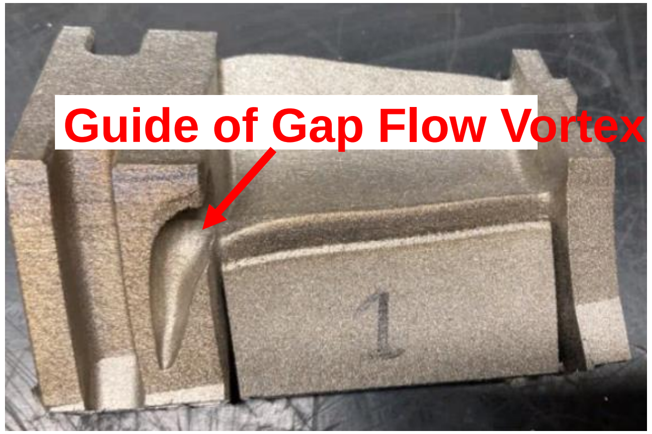
1st Iteration

2nd Iteration

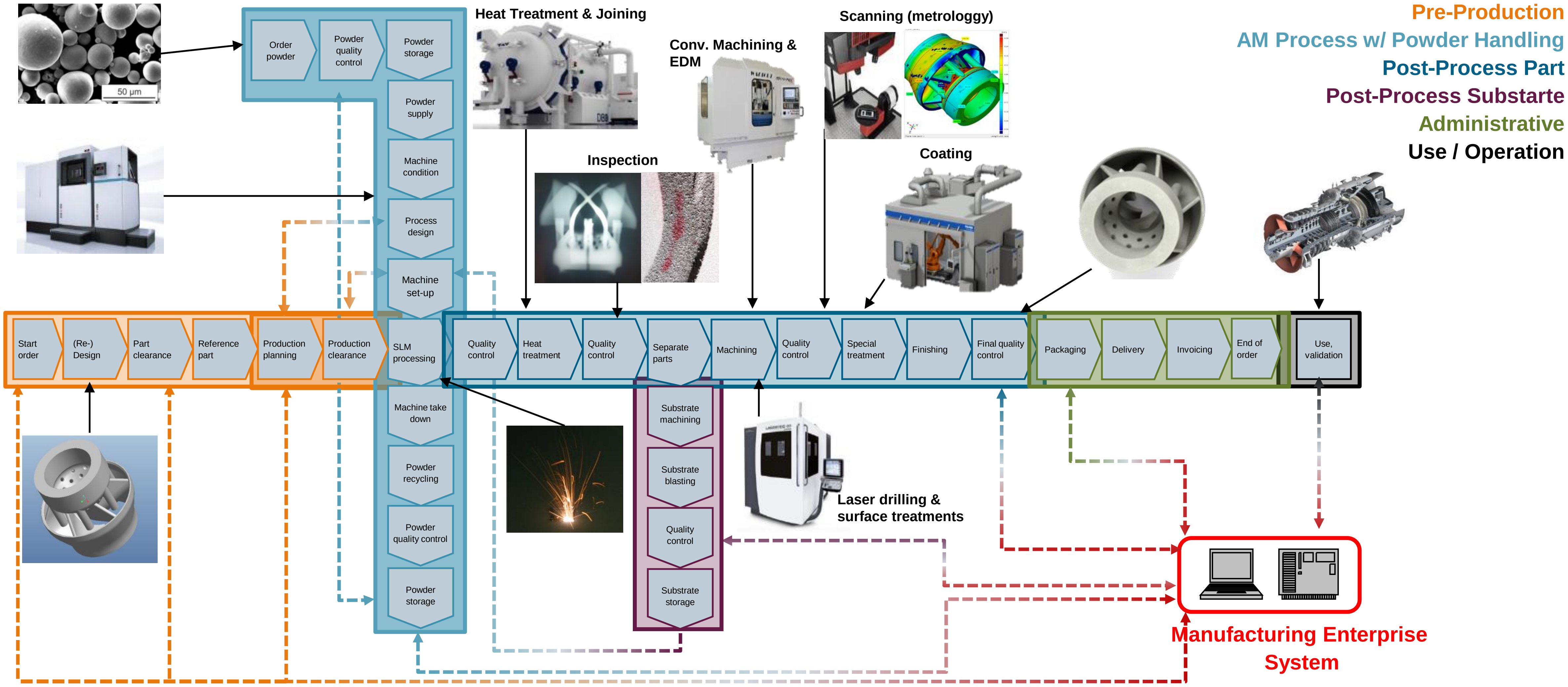


- First trial platform printed in January
  - ➢Heat treatment test(on air and on vacuum)
  - ➢Sand blasting test
  - ➢Dimensional check →optimization of print model needed





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



Task 7 – Data Storage (End-to-End solution for industrialized AM)

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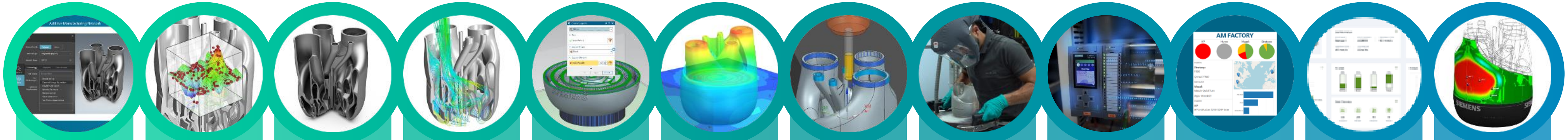
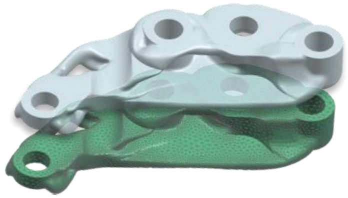


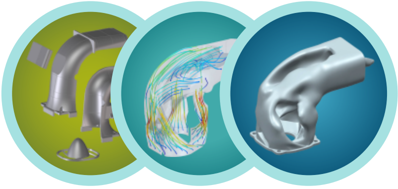
Order Management | Generative Engineering | Design for AM | AM Design Validation | Build Preparation | Build Simulation | Post Processing | Scheduling & Execution | Automation Technology | Machine Connectivity | Factory Monitoring | Quality & Analytics

Five Key Differentiators

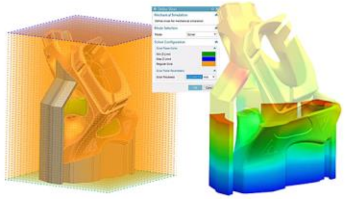
Unified solution for additive idea-to-part



Multi-disciplinary generative engineering

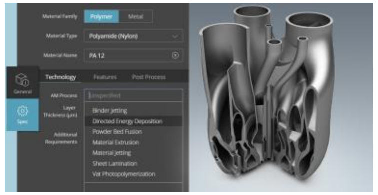


Simulation-driven first-time-right 3D printing



AM machine automation, control and connectivity

Managed environment from order-to-service



Project Approach for AM Process Technologies for Field Trial Ready Components for Steam Turbines

SIEMENS

Year 1	Year 2	Year 3
Process optimization and design for AM for improved component performance	PSP linkages and component buildup for production scale-up	Performance improvements for AM Components in Steam turbine test rig

Year 1

Technical Progress

- Topology optimization demonstrated for optimal
- functionality of components
- Process parameter for optimal materials microstructure optimization

Go / No-Go

- Down-selection of process parameter for optimal deposit density/surface finish across length scales
- Design for AM for performance /cost improvements

Year 2

Technical Progress

- Materials PSP linkages established for design
- Demonstration of robust production control for AM of advanced steam turbine alloys across length scales

Go / No-Go

- Components demonstrated via AM compared to conventional manufacturing (MRL 4)
- First Rig test to demonstrate performance improvements of AM components

Year 3

Technical Progress

- AM component performance improvements in test rig
- AM of multiple components for repeatability and scale-up
- Defined product specification for NDE inspection of AM parts

Program Success

Demonstration of field ready AM components in multi-stages to demonstrate reduced leakages and secondary losses in steam turbine (TRL6)/(MRL5)

Conclusions

- 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 evaluation 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