Ensemble Manufacturing Techniques for Steam Turbine Components Across Length Scales

Anand Kulkarni, Siemens Corporation

DOE Award: DE-FE-0031808

siemens.com

Acknowledgements: DOE Fossil Energy
Patcharin Burke – DOE NETL Project Manager

Outline

SIEMENS

Introduction

Project Objective and Team

Project Approach to Meet Technical Targets

Digital Manufacturing Efforts for Optimization of Parts for AM

Ensemble Manufacturing Techniques and Process Envelope

Steam Turbine Materials Development using AMs for Process-Structure-Property (PSP) Relationships

Non-Destructive Evaluation (NDE) Inspection of Printed Components

Conduct Rig/Engine Testing of AM Steam turbine Components

Conclusions

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

SIEMENS

Project information

PI: Anand Kulkarni

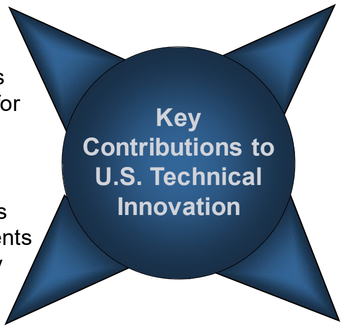
Funder: DOE Office of Fossil Energy (FE) – NETL

Strategic Partner: Siemens Energy, Electric Power Research Institute, Oak Ridge National Laboratory, Connecticut Center for Advanced Technology

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

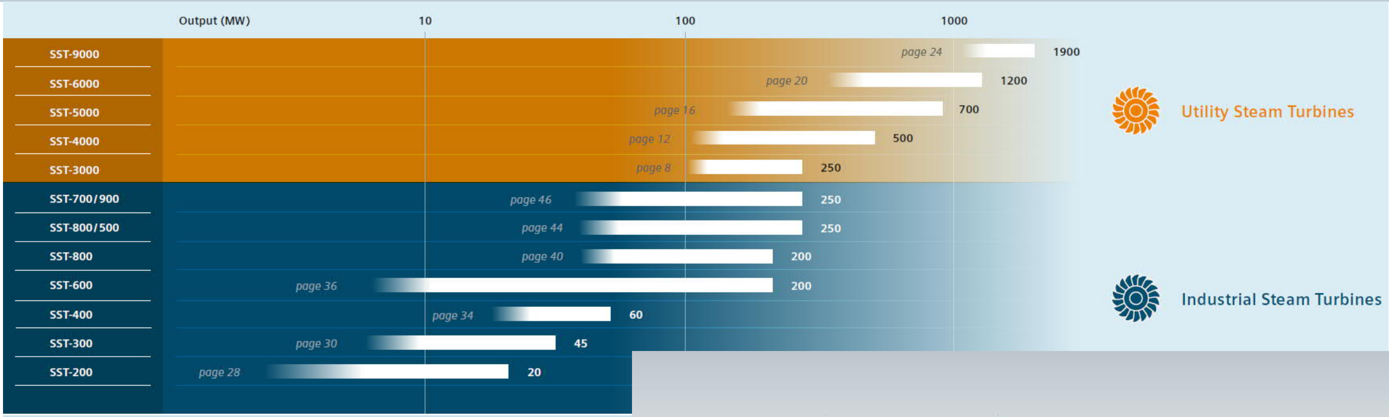
Component scale up & Validation
- Steam turbine rig for performance evaluation of AM components vs baseline
- Validated flow CFD simulations for improved performance (reduced losses/leakages)

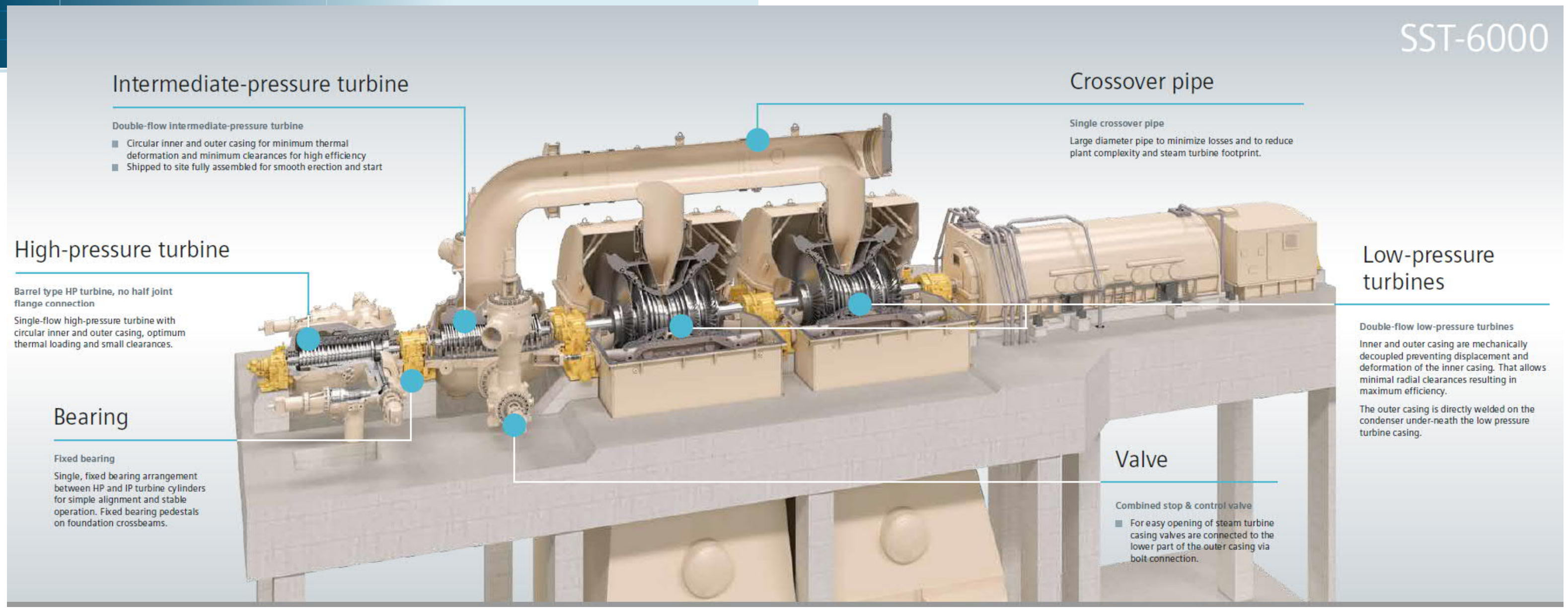
Technical Highlights

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

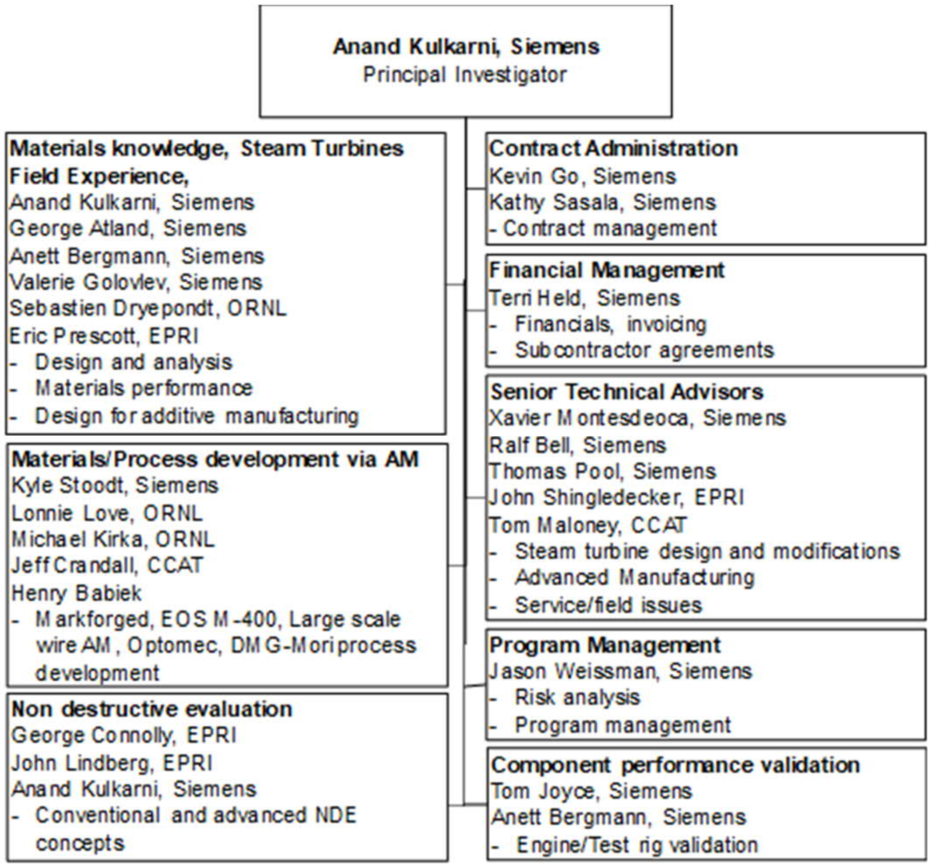
Steam Turbines - Broad range for 50- and 60-Hz-grids and drive application





Project Team and Activities

SIEMENS



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.

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

SIEMENS

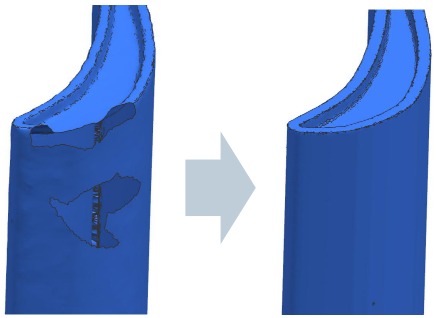
Year 1	Year 2	Year 3
Process optimization and design for AM for improved component performance	PSP linkages and component buildup for production scale-up	Performance improvements for AM Components in Steam turbine test rig
Technical Progress • Topology optimization demonstrated for optimal • functionality 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	**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	**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)

Digital Manufacturing Efforts for Optimization of Parts for AM

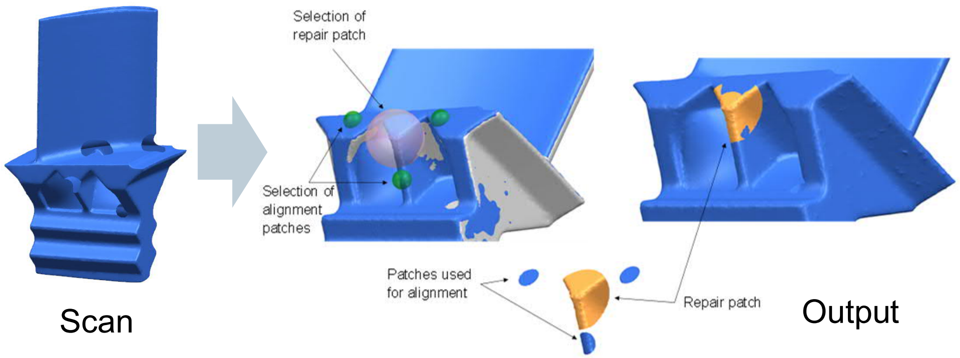
SIEMENS

CAD Guided Repair of Components

Corners and edges repair

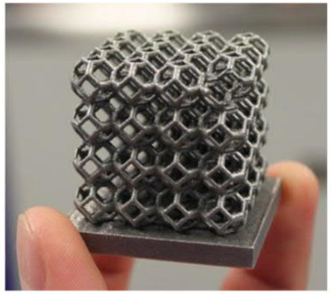


Scan Output

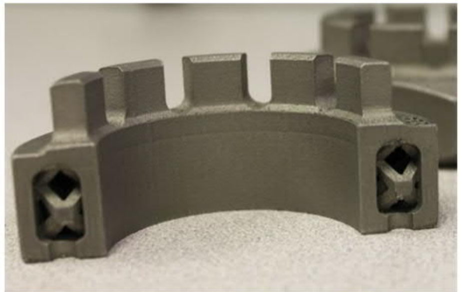


Scan Output

Design for Additive Manufacturing

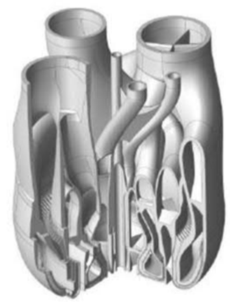


Design Freedom - Lattice

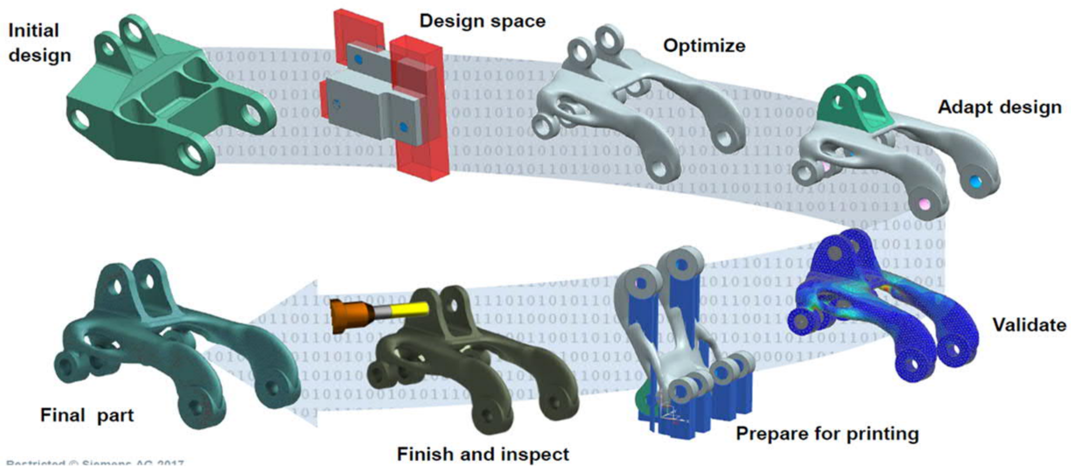


Light weighting/ Internal cooling

Topology optimization



Improved heat transfer



Design for AM needed for improved cost/performance of AM components

Ensemble Manufacturing Techniques and Process Envelope

SIEMENS

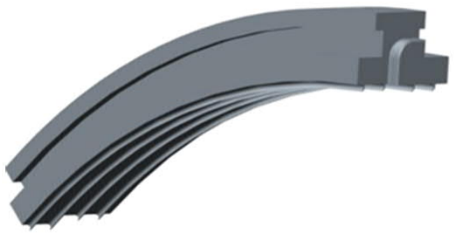
Directed Energy Deposition


Markforged

Large scale
Wire deposition

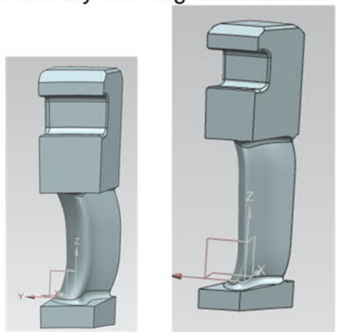
Selective Laser Melting

Sealing segments



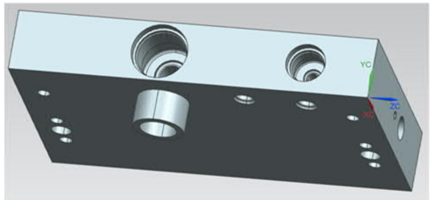
48-70 mm

Stationary/Rotating drum blades



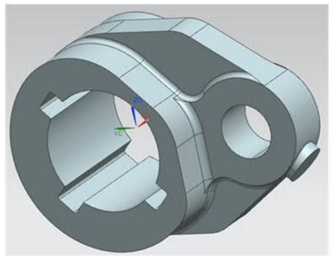
75-350 mm

Hydraulics Control Block



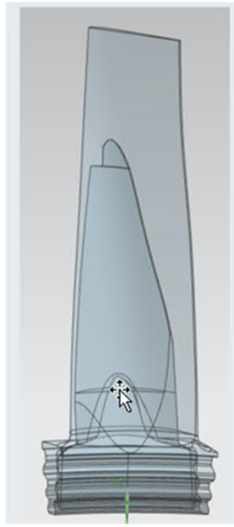
60 mm

Valve lever



70 mm

Last stage blades



520-1200 mm

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

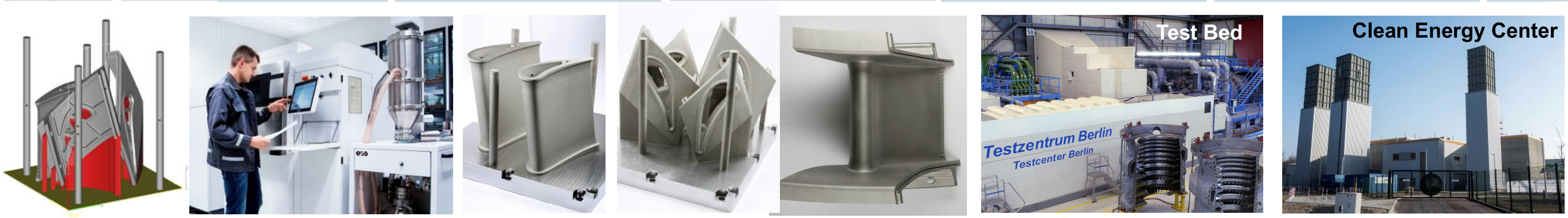
Fast Technology Validation

AM enables paradigm shift in design, testing & validation

SIEMENS

Integrated development: Accelerated iteration cycles in few months

3D (Re-)Design → SLM processing → Post processing → Instrumentation → Testing



Conventional process

"Testing is final validation at the end of development process"

- Sequential development processes
- Conservative development approach
- Moderate development goals
- Long development cycles

Novel paradigm

"Testing is integrated part of development process"

- Parallel and integrated development processes
- Radical development approaches
- Ambitious development goals
- Accelerated development goals, short iteration cycles

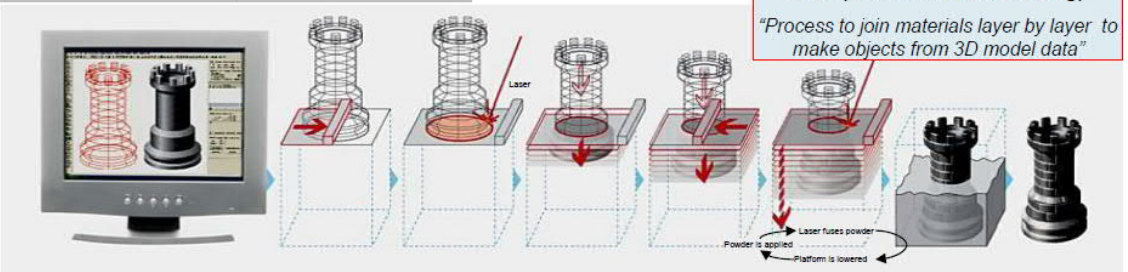
Selective Laser Melting

SIEMENS

Functional Principle

SLM (Selective Laser Melting)

"Process to join materials layer by layer to make objects from 3D model data"



Levers for cost reduction

for complex and unique parts

- **On-demand**, **instant**, **decentral** production (for e.g. service)
- **Saving** of material
- **Lead time** reduction
  ➔ faster technology validation & product development
- **Less** process steps
  ➔ simplified manufacturing & repair
- **Lower** tooling cost

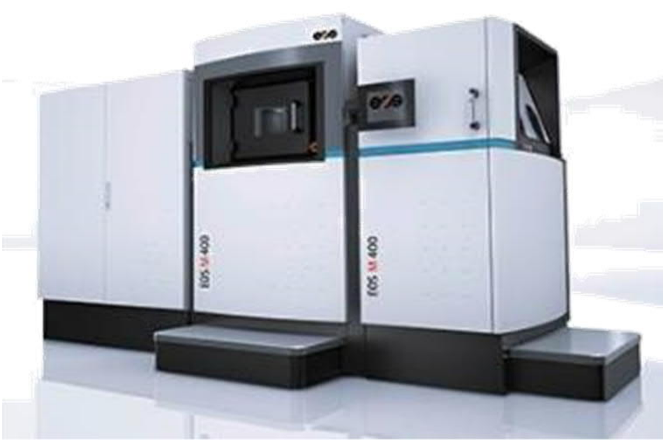
Levers for efficiency increase

through practically unlimited options for internal and external cooling duct design

- **Better** heat transfer
  ➔ thinner walls & higher surface areas
- **Improved** fluid mixing
  ➔ complex nozzle designs
- **Increased** coating adhesion
  ➔ micro-scale engineered surfaces
- **Novel** material characteristics
  ➔ combination of dissimilar materials

SLM
• limited and lower experience in comparison to LMD
limited by the process chamber (ø : 250 mm, height : 160 mm)
nearly unlimited
≥ 0.1 mm
2 - 10 cm³/h
• flat surface • flat preforms
30 - 50 µm
0,03 - 0,1 mm

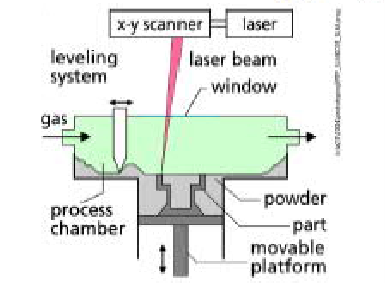
EOS M400 -1/-4



Build volume – 400 x 400 x 400 mm

- 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

Selective Laser Melting (SLM)



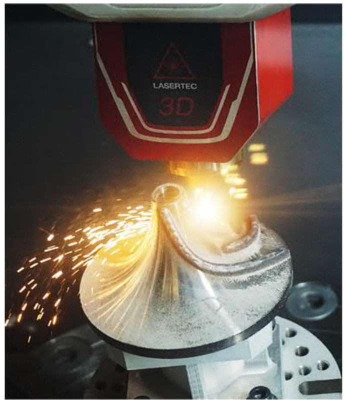
High performance components with complex design and high potential to improve customer value (efficiency, durability)

DMG-Mori Lasertec 65 3D– 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
- Additive Working Envelope: 19” x 19” x 13”
- Laser Powder Directed Energy Deposition
- 2.5 kW Laserline Laser
- Non-reactive metals (alloys of: steel, nickel, cobalt)
- Build complex components reducing part count
- Wide range of geometries with 5-axis motion



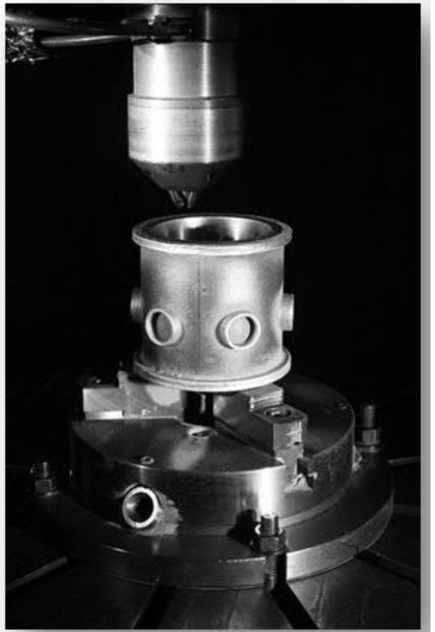
Kulkarni/ Siemens

Optomec LENS 850R – Laser Powder Directed Energy Deposition

SIEMENS

- 5 Axis Metal Powder Additive System
- 3 Powder Feeders for Mixed and Gradient Builds
- Working Envelope: 36” x 60” x18” (on top of the table)
- Argon Purged Enclosure (PPM Monitoring and O_2 Scrubber Control)
- 3 kW IPG Fiber Laser
- Reactive and Non-reactive Metals (alloys of: aluminum, steel, nickel, cobalt, titanium, refractory metals; limited studies with graphite, ceramics)

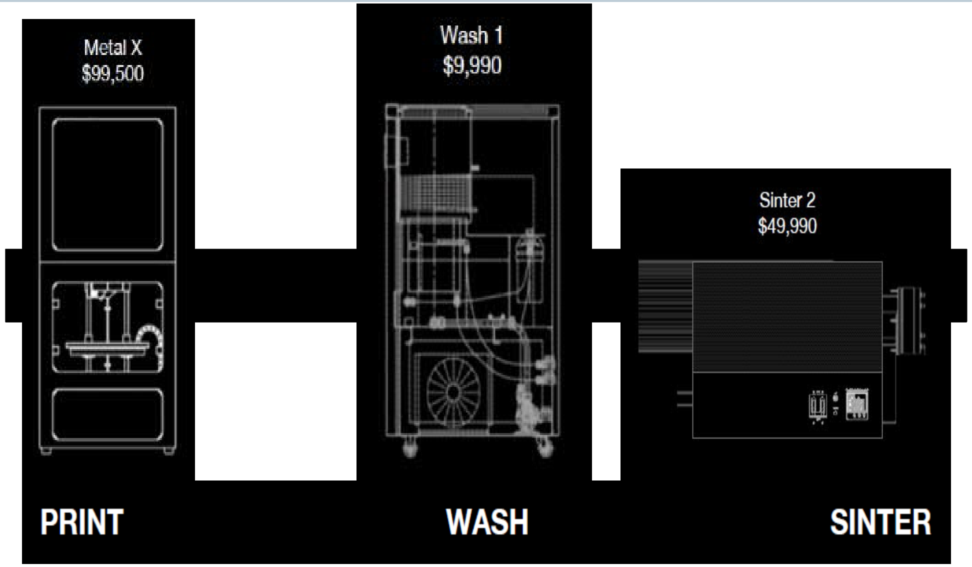
Connecticut Center for Advanced Technology, Inc.



Low Cost Markforged AM Printing

Industrial Printing Software:

Cloud software turns drawings into high strength printing - To anywhere from anywhere in the world



Industrial Printers:
Full range of printers for plastic, composite, & metal parts on a single platform

Industrial Materials:

Plastics, Composites, and Metals

Purpose-built for strong parts with a beautiful finish

Large Area Wire Deposition

SIEMENS

Tools, dies, construction, and more

Fewer Limitations

- Open-air environment
- MIG welding arm with 6 DOF and 2 rotational degrees
- Print size unrestricted
- Uses low-cost welding torches and wire
- CAD-to-path functionality

Developmental Activities to Systems

- **Design to Part**
  - Open source slicing software
- **Fast Deposition**
  - Multi-deposition technologies being developed
- **Geometry Control**
  - Residual stress modeling and distortion
- **Graded Structures**
  - Multi-material feed

Target Metrics

- High deposition rates: 100 lbs./hr.
- Low cost feedstocks: < $10/lb.
  - Iron, steel, aluminum
- Large components: > 6ft.

Project AME- Additively Manufactured Excavator

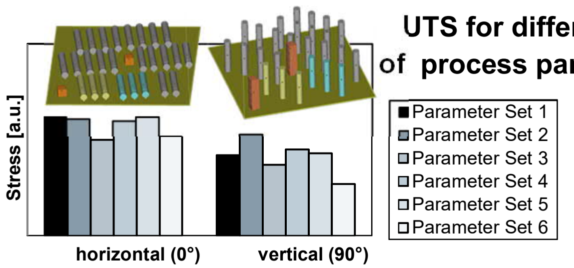
LINCOLN ELECTRIC WOLF ROBOTICS OAK RIDGE National Laboratory

Process-Structure Property Relationships

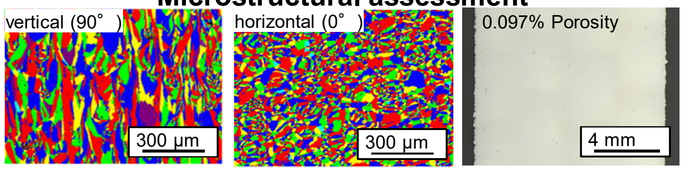
SIEMENS

Process Development

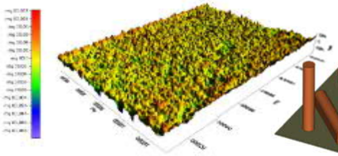
UTS for different sets of process parameters



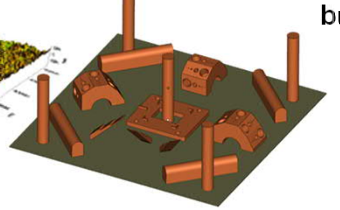
Microstructural assessment



Surface quality

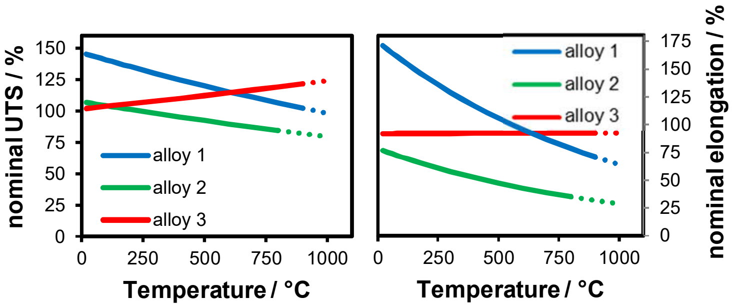


Standard qualification build job



Materials Data Generation

Properties compared to cast/forged material (≙100%)



Distinctive properties in AM materials:

T, t, dynamic, anisotropy, residual stress, distortion, defects, microstructure…

Huge range of data for several temperatures needed:

tensile, HCF, LCF, creep/stress rupture, TMF, corrosion, physical props….

Manufacturing Feasibility

X12CrMoWVNbN10-1-1
X21CrMoNiV4-7
17-4 PH Stainless Steel
IN625

#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

- Material design tools not available yet
- Limited range of materials for gas turbine applications available
- Time consuming and costly validation (full qualification: >> 500 k$; 1.5 to 2 years)
- Approach: provide i) estimated, ii) limited or iii) fully validated material data

Non-Destructive Evaluation (NDE) Inspection of Printed Components

SIEMENS

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

Milestones and Deliverables

SIEMENS

Task / Subtask Number	Deliverable Title	Due Date
1.0	Project Management Plan	Update due 30 days after award. Revisions to the PMP shall be submitted as requested by the NETL Project Manager.
1.0	Technology Maturation Plan	Update due 30 days after award.
2.0	Topology optimization demonstrated for optimal functionality of components	0.8 year after award.
4.0	Demonstration of Proof of concept (TRL3) for AM of advanced alloys for steam turbine components	1.25 years after award.
4.0	Components demonstrated via AM compared to conventional manufacturing (MRL 4)	1.75 years after award.
6.0	Demonstration of AM components in multi-stages to demonstrate reduced leakages and secondary losses in steam turbine (TRL6)	2.5 years after award.
7.0	Demonstration of AM manufactured process for advanced alloys (MRL 5)	2.75 years after award

	Success Criteria at Decision Points	
Milestone No.	**Year 1**	**Plan**
4	**Down-selection of process parameter for optimal deposit density/surface finish across length scales** - Process parameter optimization and materials characterization of builds to successfully meet defined material properties for the chosen component performance requirements and design constraints	07/15/20
Milestone No.	**Year 2**	**Plan**
7	**Components demonstrated via AM compared to conventional manufacturing (MRL 4)** - Demonstration of robust production control for AM of advanced steam turbine alloys for redesigned components with low cost/high performance. The success criterial would be repeatability and reproducibility analysis through quality assurance reports from multiple components that meet the product requirements	06/30/21
Milestone No.	**Year 3**	**Plan**
9	**Demonstration of AM components in multi-stages to demonstrate reduced leakages and secondary losses in steam turbine (TRL6)** Successfully conceive, develop, and demonstrate the performance of AM components vs baseline for reduced leakages and secondary losses in a steam turbine. Verify output with existing operational data.	04/06/22