Full Scale Engine Demonstration of Additively Manufactured High Gamma Prime Turbine Blades

DE-LC-000L059
ORNL/Solar Turbines
10/1/18-9/30/19

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Overview

Timeline:

Project Start Date: 10/01/2018

Budget Period End Date: 09/31/2019

Project End Date: 09/31/2019

Barriers and Challenges:

- High Temperature Ni Superalloys are extremely crack prone during processing (considered non-weldable material)
- Certified critical rotating components have not been implemented in the hot section of a gas turbine

Project Budget and Costs:

Budget	DOE Share	Cost Share	Total	Cost Share %
Overall Budget	$1,500,000	$3,800,000	$5,300,00	71.6%
Approved Budget (BP-1&2)	$1,500,000	$3,800,000	$5,300,000	71.6%
Costs as of 3/31/19	$786,198	$114,049	$900,247	14.5%

AMO MYPP Connection:

- Materials for harsh environments, combined heat and power, and additive manufacturing

Team

OAK RIDGE National Laboratory

Michael Kirka-Project Lead

Yousub Lee-Process Modeling

Vincent Paquit-Data Analytics Lead

Derek Rose-In-situ Defect Detection

Amir Ziabari-CT Reconstruction

Solar Turbines
A Caterpillar Company

David Adair-Project Lead

Daniel Ryan-Materials & Processes

Drew Dominique-Machining & Fixtures

Brian Drouin-3D Optical Scans

THE UNIVERSITY OF TENNESSEE KNOXVILLE

William Halsey-Data Sciences

ZEISS

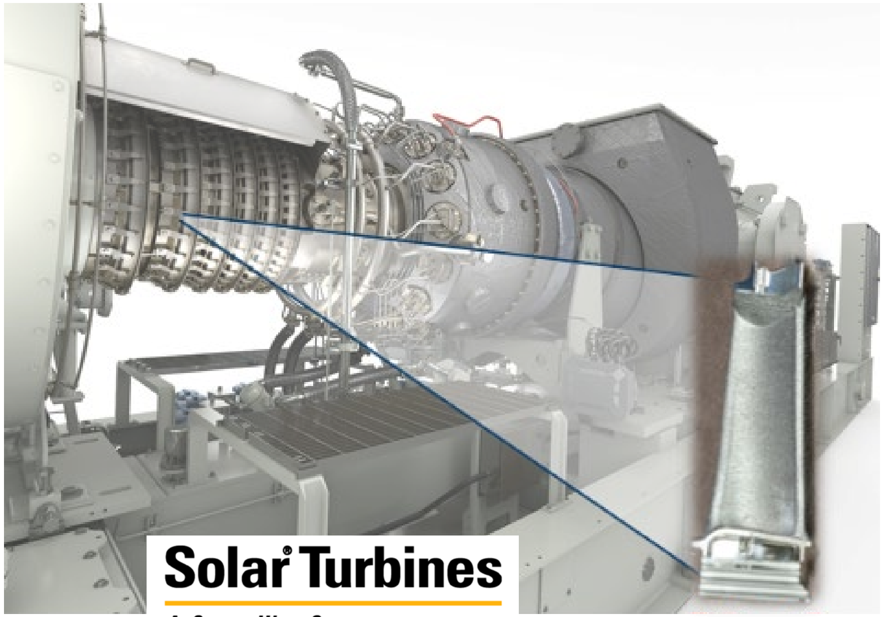
Paul Brackman-NDE Analysis

voxel

Daniel Herrington-Voxel innovations

Project Objectives

- Problem: Processing science and pathway for certification and qualification of defect prone materials critical rotating components fabricated through additive manufacturing do not exist
- Objective: Perform full-scale engine test using additive manufactured turbine blades to demonstrate similar or better performance to conventionally manufactured components
  - Approach: Utilize computational tools to certify a set of additively manufactured turbine blades to be hot-fired for an engine validation trial
  - Challenges:
    - Materials are traditionally non-weldable and defect prone
    - Certification and qualification tools do not exist for critical rotating AM components
    - Perceived notion AM material properties are inferior to cast material
- Project enables accelerated manufacturing of high performance components and systems for improving energy efficiency in gas turbine engines



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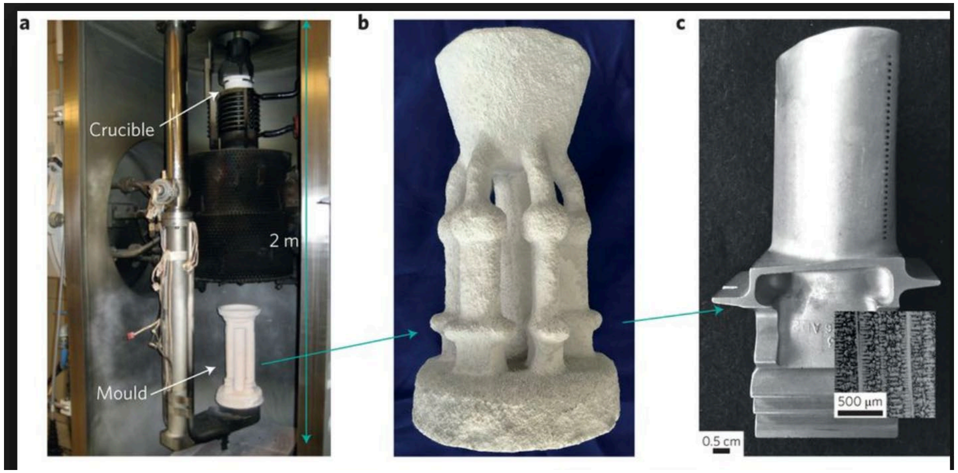
Technical Innovation

Present: Investment Casting

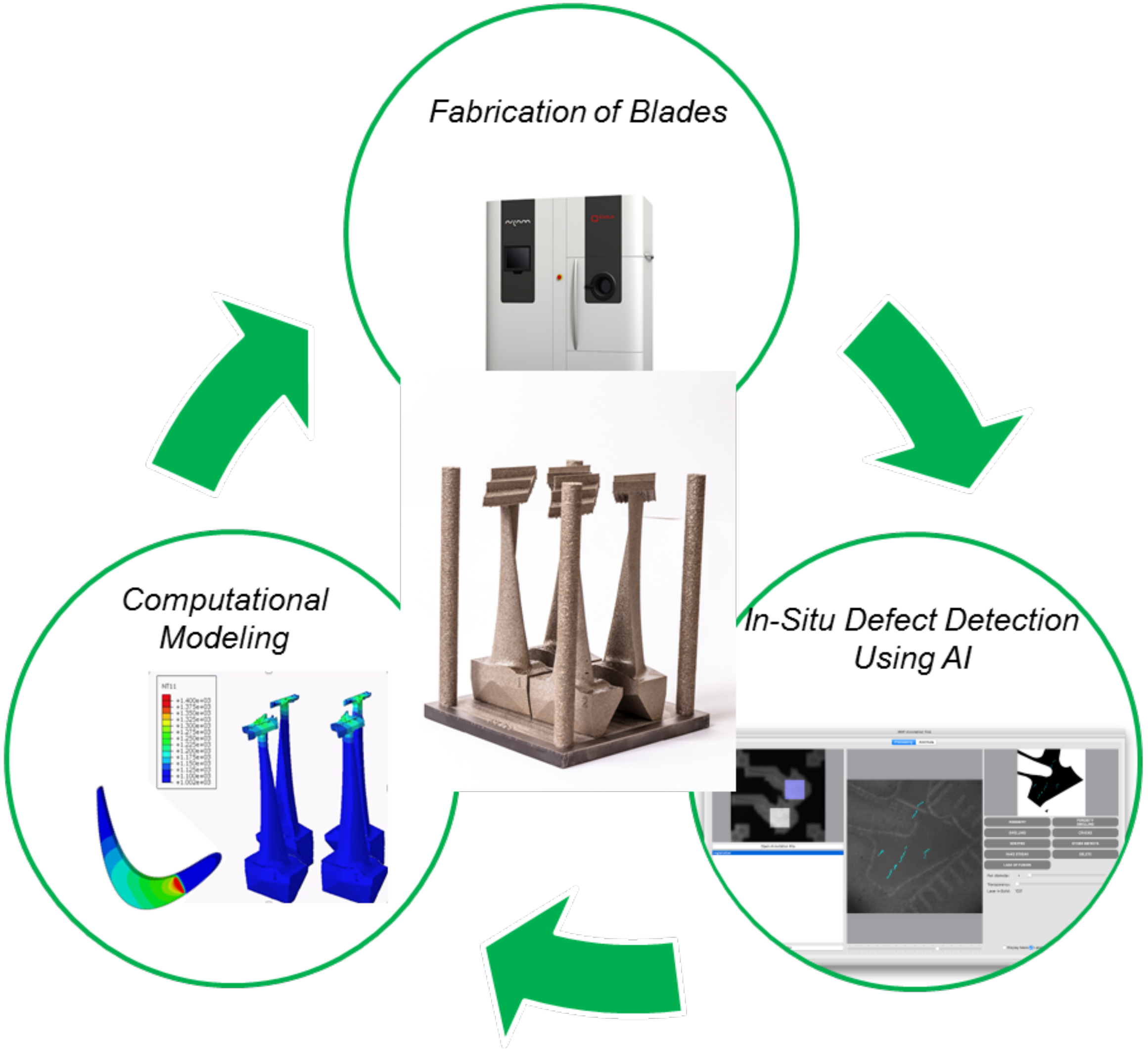


Proposed: Electron Beam Melting

- Enabling novel airfoil designs through AM enhances engine performance and reduces fuel consumption
  - Every 1% efficiency gain saves $2 million
- Impactful Outcomes:
  - Short Term: Enabled pathway for fabrication of novel prototype airfoil designs and decreased engine development cycles
  - Long Term: Digital framework for qualification and certification of critical AM components for commercial production with additional advancement of materials for extreme environements

Technical Approach:

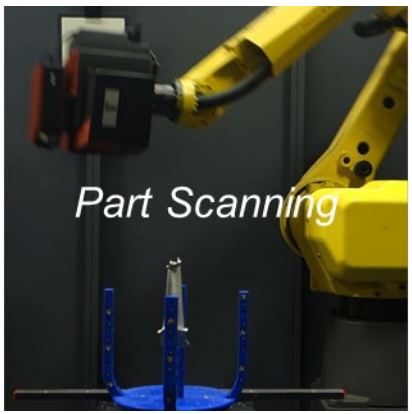
- Cracking in AM Ni-Superalloys is scan pattern dependent
- Process Optimization performed on Mercury 50 Blade Geometry
- Determined efficient procedure for eliminating cracking based on in-situ monitoring, data analytics and modeling
- Demonstration of multiple build to fabricate a full set of blades



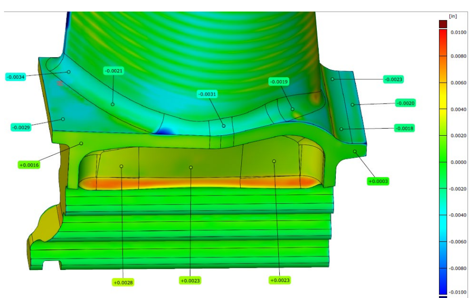
RESULT: Crack-free complex blade geometry

Technical Approach

- Determined methodology for final finishing, inspection, and qualification

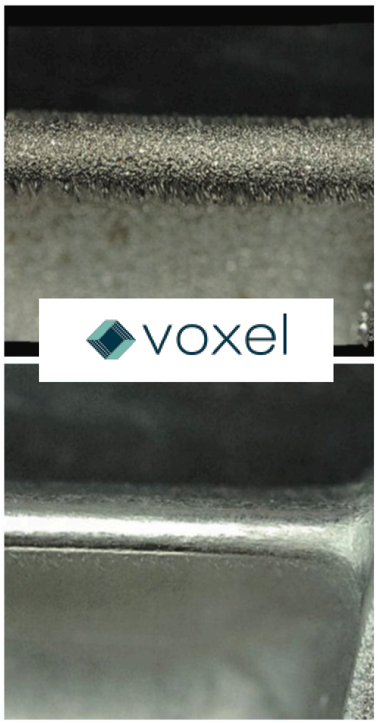


Part Scanning

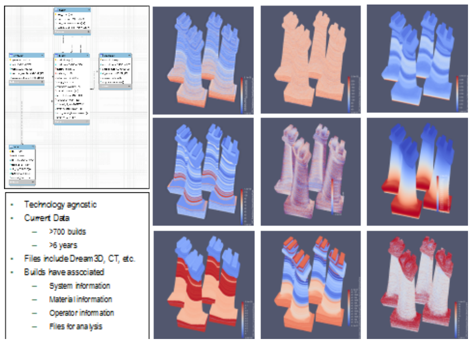


Geometric Accuracy

Surface Finishing



X-ray Computed Tomography



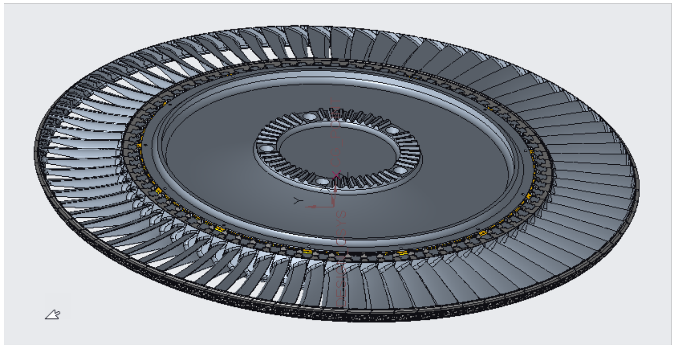
In-situ data registration for statistical analysis

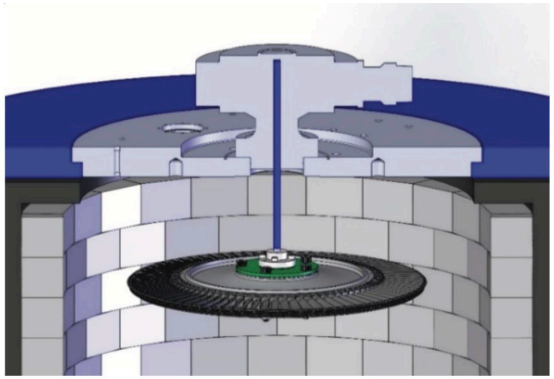
Results and Accomplishments

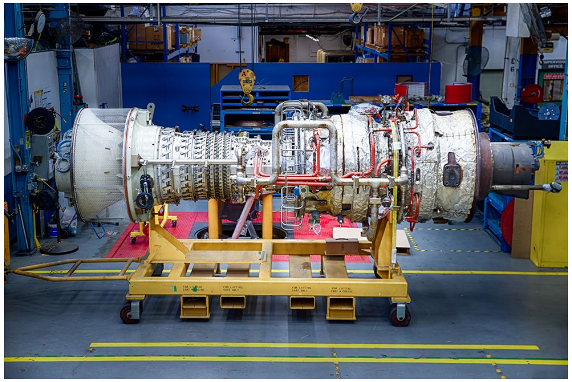
MS 1	Demonstrate ability to complete 10 builds and perform identical in-situ process monitoring to show no crack formations in the airfoil geometries using previously developed machine learning algorithms to analyze the in-situ data. ✓
MS 2	Confirmation of repeatable mechanical performance of the AM Inconel 738 as determined through destructive mechanical testing ✓
MS 3	Confirmation that a complete set of AM Inconel 738 airfoils through data analytics techniques are defect (crack) free to proceed with spin-pit testing
MS 4	Successful spin-pit test of rotor comprised of AM Inconel 738 airfoils as confirmed by Solar Turbines that no blade failed during room temperature testing
MS 5	Hot-fire of a Stage II rotor comprised entirely of AM fabricated Inconel 738 airfoils in a Mercury 50 engine

- Process parameters optimized for fabrication of defect-free airfoils
- Mechanical properties meet or exceed cast Inconel 738
  - Exhibit reliable repeatability
- Data analytics framework developed for identifying defective blades and creating a digital twin
- Manufacturing science for finishing blades successful with accuracy meeting or exceeding cast counterparts

<u>Next steps:</u>

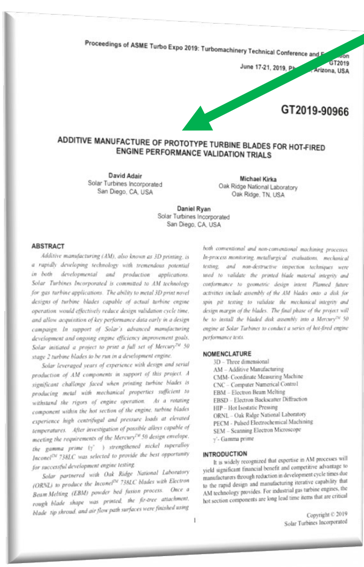






Transition (beyond DOE assistance)

- Moonshot program accelerated development cycle of new materials for AM through digital and computational means
  - Program enabled a strategy of engagement with turbine companies on additive and end applications
  - Technology readiness level (TRL) of 6 will be demonstrated
- Successful demonstration of rapid prototyping new blade designs to enhance engine performance/efficiency
- Program enabled dissemination of Inconel 738 materials processing coupled with data analytics tools
  - To be presented at ASME Turbo Expo 2019: Paper GT2019-90966
- Significant knowledge gained related to control processes, finishing processes, qualification and certification, high fidelity CT
  - Reassurance Ni–base superalloys fabricated via AM can be commercialized for critical applications
- GE, Siemens interested in Inconel 738 and other higher temperature Ni-base superalloys fabricated through EBM



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GT2019-90966

ADDITIVE MANUFACTURE OF PROTOTYPE TURBINE BLADES FOR HOT-FIRED ENGINE PERFORMANCE VALIDATION TRIALS

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ABSTRACT

Additive manufacturing (AM), also known as 3D printing, is a rapidly developing technology with tremendous potential in both developmental and production applications. Solar Turbines Incorporated is committed to AM technology for gas turbine applications. The ability to metal 3D print novel designs of turbine blades capable of actual turbine engine operation would effectively reduce design validation cycle time, and allow acquisition of key performance data early in a design campaign. In support of Solar's advanced manufacturing development and ongoing engine efficiency improvement goals, Solar initiated a project to print a full set of Mercury™ 50 stage 2 turbine blades to be run in a development engine.

Solar leveraged years of experience with design and serial production of AM components in support of this project. A significant challenge faced when printing turbine blades is producing metal with mechanical properties sufficient to withstand the rigors of engine operation. As a rotating component within the hot section of the engine, turbine blades experience high centrifugal and pressure loads at elevated temperatures. After investigation of possible alloys capable of meeting the requirements of the Mercury™ 50 design envelope, the gamma prime (γ') strengthened nickel superalloy Inconel™ 738LC was selected to provide the best opportunity for successful development engine testing.

Solar partnered with Oak Ridge National Laboratory (ORNL) to produce the Inconel™ 738LC blades with Electron Beam Melting (EBM) powder bed fusion process. Once a rough blade shape was printed, the fir-tree attachment, blade tip shroud, and air flow path surfaces were finished using both conventional and non-conventional machining processes. In-process monitoring, metallurgical evaluations, mechanical testing, and non-destructive inspection techniques were used to validate the printed blade material integrity and conformance to geometric design intent. Planned future activities include assembly of the AM blades onto a disk for spin pit testing to validate the mechanical integrity and design margin of the blades. The final phase of the project will be to install the bladed disk assembly into a Mercury™ 50 engine at Solar Turbines to conduct a series of hot-fired engine performance tests.

NOMENCLATURE

3D – Three dimensional
AM – Additive Manufacturing
CMM- Coordinate Measuring Machine
CNC – Computer Numerical Control
EBM – Electron Beam Melting
EBSD – Electron Backscatter Diffraction
HIP – Hot Isostatic Pressing
ORNL – Oak Ridge National Laboratory
PECM - Pulsed Electrochemical Machining
SEM – Scanning Electron Microscope
γ'- Gamma prime

INTRODUCTION

It is widely recognized that expertise in AM processes will yield significant financial benefit and competitive advantage to manufacturers through reduction in development cycle times due to the rapid design and manufacturing iterative capability that AM technology provides. For industrial gas turbine engines, the hot section components are long lead time items that are critical