Transformative Aeronautics Concepts Program

Development of an Additive Manufacturing Ecosystem for Qualification of Additive Manufacturing Processes and Materials in Aviation

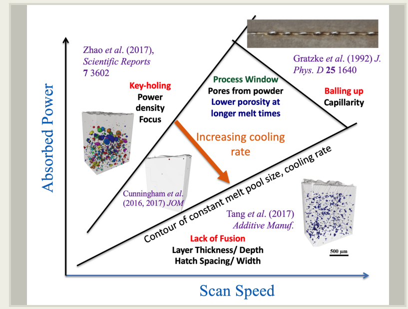
Active Technology Project (2019 - 2022)

Project Introduction

The major challenges associated with additive manufacturing (AM) are an ability to qualify parts and the costs associated with the technology. Our team will study and mature technologies as detailed below to develop an ecosystem for the qualification of AM machines, which in turn supports the certification of part production.

Additive manufacturing offers unique opportunities for the aviation industry in the fabrication of original components and replacement parts. Aggressive use of metals AM has, for example, allowed the rapid development and production of new launch vehicle designs, at substantially reduced costs. Aviation has unique challenges, such as higher production volumes, but the potential value of integrating AM into aviation manufacturing is clear.

To implement the ecosystem for AM qualification, the team will run a set of six multi-disciplinary projects. Each of these projects will address a current barrier to AM process qualification, and efficient production.



The figure shows an example of how the defect structure in laser powder bed fusion machines varies in a systematic but highly non-linear manner across power-speed space. In one corner, lack of overlap of melt pools induces lack-of-fusion...

Table of Contents

1. *AM Flaw Management:* Flaw (dominated by pore structure) management is currently the most important need in the fabrication of aviation components subjected to fatigue. This project will define the processing window to achieve flaw/porosity control within defined limits and further demonstrate how process optimization can control porosity levels within that processing window. Mechanical properties such as fatigue will be used to quantify the effects of porosity and build the necessary data portfolio for process qualification.
2. *Qualification Aware Process Maps:* There is a concern in the aero industry that any changes in process variables require a full re-qualification of an AM process and this is leading to qualification efforts focusing on a single process variable set (usually defined by a machine manufacturer). This project will address this concern by defining multiple process variable points within the process window (Project #1) and developing data for each of them for qualification.
3. *Qualification Aware Post Processing:* Post processing of an aviation part can easily cost as much as the additive fabrication itself, yet little science has been applied to post processing of AM parts. In particular, there is an important coupled relationship between AM processing and post processing to achieve optimal cost and performance. This project will investigate and implement more efficient post-processing methods that support qualification.
4. *Database Analytics:* This project will compile data from all members on process-structure- property relationships, with a focus on porosity and fatigue. This project will apply data science to develop a model for qualification that will be used in training and education (next project).
5. *Training and Education:* We will disseminate project results across University, Small Business and Partner Company and Government Laboratory team members and will train small businesses looking to become Tier 1 AM suppliers. Dissemination will occur through student and industry employee exchanges executed at the academic team member sites. We will also train potential AM component suppliers (subcontractors) to achieve various defined levels (tiers) of AM expertise and thus qualify their processes using the results of these projects.
6. *Scaling to Production:* A critical barrier to widespread use of AM in aviation manufacturing is the scaling from research-based component fabrication to small-scale production at the rate of hundreds or thousands of parts per year. This project will investigate optimal configurations of combined pre-processing, processing and post-processing cells that exploit robotic automation and its integration with human workers.

Organizational Responsibility

Responsible Mission Directorate:

Aeronautics Research Mission Directorate (ARMD)

Lead Organization:

Carnegie Mellon University

Responsible Program:

Transformative Aeronautics Concepts Program

Project Management

Program Director:

John A Cavolowsky

Project Manager:

Koushik Datta

Principal Investigator:

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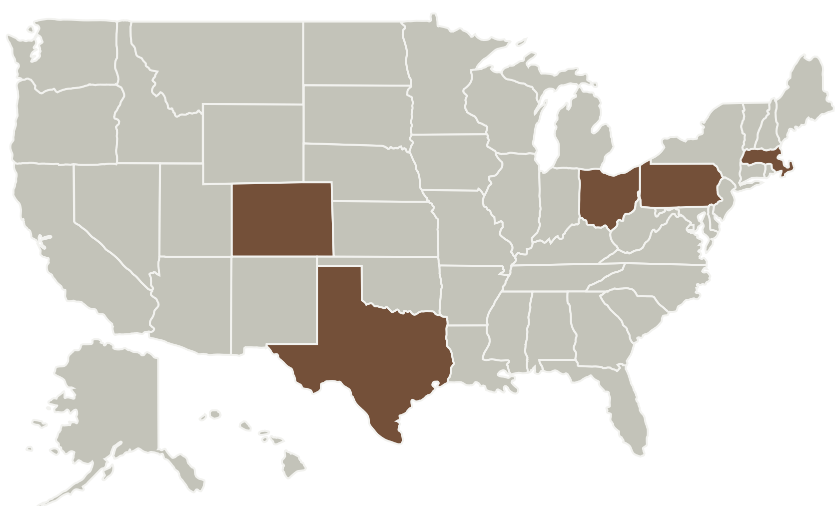
Anticipated Benefits

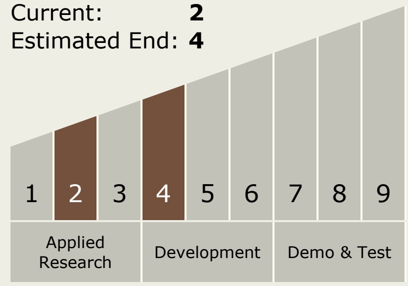
Over the last eight years, metals Additive Manufacturing (AM) has impacted aviation manufacturing for jet engine components, airframe structural elements, and other applications. Looking ahead, AM is likely to substantially impact the desired outcomes for aviation manufacturing identified by NASA for this project. Accordingly, the over-arching project goal is the demonstrated establishment of an ecosystem for qualification of powder bed additive manufacturing processes that is based on flaw management. Solving the technical challenges and disseminating the qualification protocol to companies, especially Tier 1 suppliers and below will move aviation manufacturing towards achieving NASA Aeronautics Research Mission Directorate's objectives for innovative solutions that reduce time-to-production, improved process control, and product tailoring. The successful implementation of the proposed qualification framework for AM powder bed should substantially advance U.S. manufacturing capabilities in terms of flexibility of design, time-to-market etc. It will also bring down the cost of manufacture particularly for short production run parts and replacement parts. Economic growth will be boosted, particularly through enabling small contractors who lack access to Research and Development depth to qualify their AM processes and equipment and keep them qualified over time. Interaction with large original equipment manufacturers has indicated that most of them plan to eventually subcontract much of their AM fabrication work to small AM contractors. As small suppliers gain confidence in their ability to produce qualified parts, they will add machines and people to increase production.

Primary U.S. Work Locations and Key Partners



Technology Maturity (TRL)

Start: **2**
Current: **2**
Estimated End: **4**



Technology Areas

Primary:

- TX12 Materials, Structures, Mechanical Systems, and Manufacturing
  - └ TX12.4 Manufacturing
    - └ TX12.4.2 Intelligent Integrated Manufacturing

Target Destination

Foundational Knowledge

Supported Mission Type

Push

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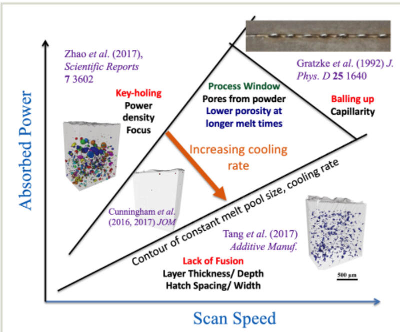
Organizations Performing Work	Role	Type	Location
Carnegie Mellon University	Lead Organization	Academic	Pittsburgh, PA
Barnes Global Advisors	Supporting Organization	Industry	Pittsburgh, PA
Case Western Reserve University	Supporting Organization	Academic	Cleveland, OH
Colorado School of Mines	Supporting Organization	Academic	Golden, CO
Materials Resources LLC	Supporting Organization	Industry	Dayton, OH
University of Pittsburgh	Supporting Organization	Academic	Pittsburgh, PA
University of Texas at El Paso	Supporting Organization	Academic	El Paso, TX
Worcester Polytechnic Institute	Supporting Organization	Academic	Worcester, MA

Primary U.S. Work Locations	
Colorado	Massachusetts
Ohio	Pennsylvania
Texas	

Images



Process window defined by defect type

The figure shows an example of how the defect structure in laser powder bed fusion machines varies in a systematic but highly non-linear manner across power-speed space. In one corner, lack of overlap of melt pools induces lack-of-fusion porosity. In the opposite corner, excessive keyhole depth results in instability and keyhole porosity. In between these two limits there is a region of high density that nevertheless can be disrupted if the combination of high speed & power results in too-long melt pools and the bead-up problem. Inside these limits there is a process window within which one expect within which one expect near full density.
(https://techport.nasa.gov/image/40776)

Links

A Comprehensive Comparison of the Analytical and Numerical Prediction of the Thermal History and Solidification Microstructure o
(https://doi.org/10.1016/J.ENG.2017.05.023)

A Process Map for Consistent Build Conditions in the Solid Freeform Fabrication of Thin-Walled Structures
(https://doi.org/10.1115/1.1370497)

An Investigation of Process Parameter Modifications on Additively Manufactured Inconel 718 Parts
(https://doi.org/10.1007/s11665-018-3612-3)

Analyzing the effects of powder and post-processing on porosity and properties of electron beam melted Ti-6Al-4V
(https://doi.org/10.1080/21663831.2017.1340911)

Anomaly detection and classification in a laser powder bed additive manufacturing process using a trained computer vision algori
(https://doi.org/10.1016/j.addma.2017.11.009)

Characterization of metal additive manufacturing surfaces using synchrotron X-ray CT and micromechanical modeling
(https://doi.org/10.1007/s00466-017-1531-z)

Computer Vision and Machine Learning for Autonomous Characterization of AM Powder Feedstocks
(https://doi.org/10.1007/s11837-016-2226-1)

Critical instability at moving keyhole tip generates porosity in laser melting
(https://science.sciencemag.org/content/370/6520/1080)

Defect Structure Process Maps for Laser Powder Bed Fusion Additive Manufacturing
(https://www.sciencedirect.com/science/article/pii/S2214860420309246?via%3Dihub)

Defects-dictated tensile properties of selective laser melted Ti-6Al-4V
(https://doi.org/10.1016/j.matdes.2018.08.004)

Effect of Laser-Matter Interaction on Molten Pool Flow and Keyhole Dynamics
(https://doi.org/10.1103/PhysRevApplied.11.064054)

Evaluating the Effect of Processing Parameters on Porosity in Electron Beam Melted Ti-6Al-4V via Synchrotron X-ray Microtomograp
(https://doi.org/10.1007/s11837-015-1802-0)

Evaluation of Orientation Dependence of Fracture Toughness and Fatigue Crack Propagation Behavior of As-Deposited ARCAM EBM
(https://doi.org/10.1007/s11837-015-1298-7)

High-speed Synchrotron X-ray Imaging of Laser Powder Bed Fusion Process
(https://doi.org/10.1080/08940886.2019.1582280)

Keyhole threshold and morphology in laser melting revealed by ultrahigh-speed x-ray imaging
(https://doi.org/10.1126/science.aav4687)

Keyhole Threshold and Morphology in Laser Scanning Melting Revealed by Ultrahigh-Speed X-ray Imaging
(https://doi.org/10.1126/science.aav4687)

Location specific solidification microstructure control in electron beam melting of Ti-6Al-4V
(https://doi.org/10.1016/j.addma.2017.10.003)

Measurement and Analysis of Porosity in Al-10Si-1Mg Components Additively Manufactured by Selective Laser Melting
(https://doi.org/10.1520/MPC20160037)

Numerical modeling and experimental validation of thermal history and microstructure for additive manufacturing of an Inconel 71
(https://doi.org/10.1007/s40964-018-0039-1)

Overview of Materials Qualification Needs for Metal Additive Manufacturing
(https://doi.org/10.1007/s11837-015-1810-0)

Prediction of lack-of-fusion porosity for powder bed fusion
(http://dx.doi.org/10.1016/j.addma.2016.12.001)

Progress Towards Metal Additive Manufacturing Standardization to Support Qualification and Certification
(https://doi.org/10.1007/s11837-017-2265-2)

Real-time monitoring of laser powder bed fusion process using high-speed X-ray imaging and diffraction
(https://doi.org/10.1038/s41598-017-03761-2)

Synchrotron-Based X-ray Microtomography Characterization of the Effect of Processing Variables on Porosity Formation in Laser Po
(https://doi.org/10.1007/s11837-016-2234-1)

Ultrafast X-ray imaging of laser–metal additive manufacturing processes
(https://doi.org/10.1107/S1600577518009554)