Development of an Ecosystem for Qualification of Additive Manufacturing Processes and Materials in Aviation: 2019-2023 (with extension)

ASEB Meeting, Oct. 17, 2023

A.D. (Tony) Rollett, PI (CMU)
John Lewandowski (CWRU), Jack Beuth, [Elizabeth Holm, Erica Fuchs], Sneha Narra (CMU), Ayman Salem, [Nellie Pestian] (MRL), Albert To (Pitt), Frank Medina, [Ryan Wicker] (UTEP), Craig Brice, Joy Gockel (Colo Schl Mines), Kirk Rogers, Wayne King (TBGA)

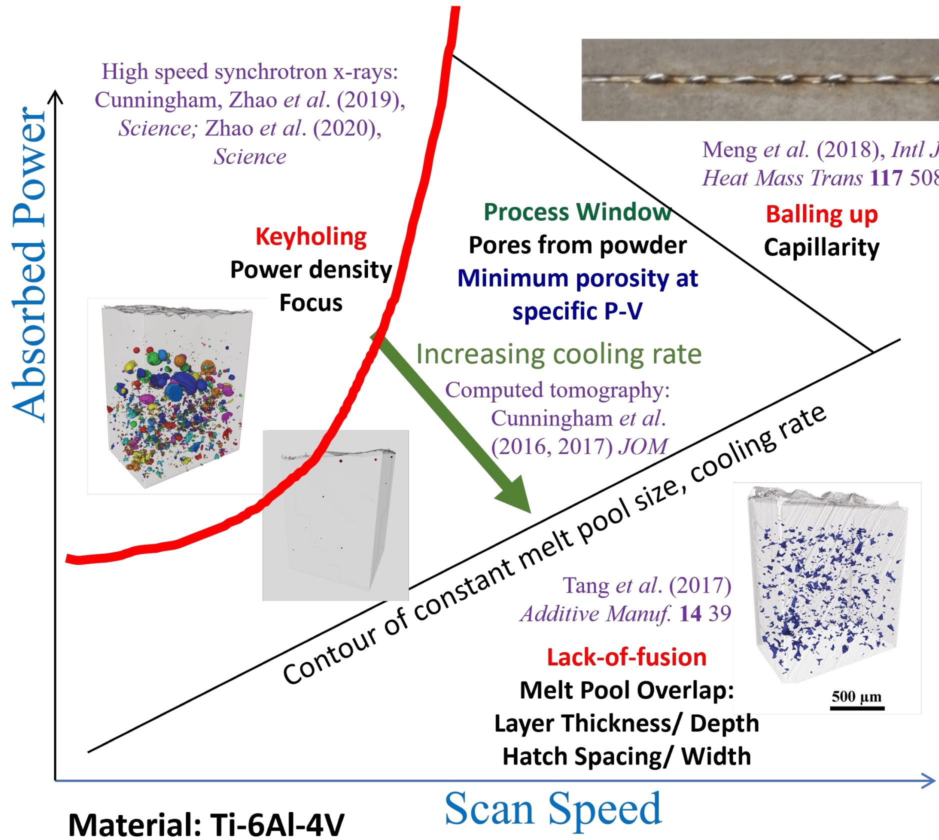
- CMU, CWRU, CSM, UPitt, UTEP, WPI, Materials Resources, Barnes Global Advisors,
- NASA via a SAA: Langley, Glenn, Ames and JPL
- Northrop Grumman, Lockheed Martin, Eaton, ANSYS/Granta, Trumpf, Air Force Materials Research Lab. (AFRL), Argonne Natl. Lab. (ANL) - Advanced Photon Source, Pratt & Whitney, GE-GRC, ATI, US Army.

Revised 15 x 2023

Bottom Line Up Front (BLUF)

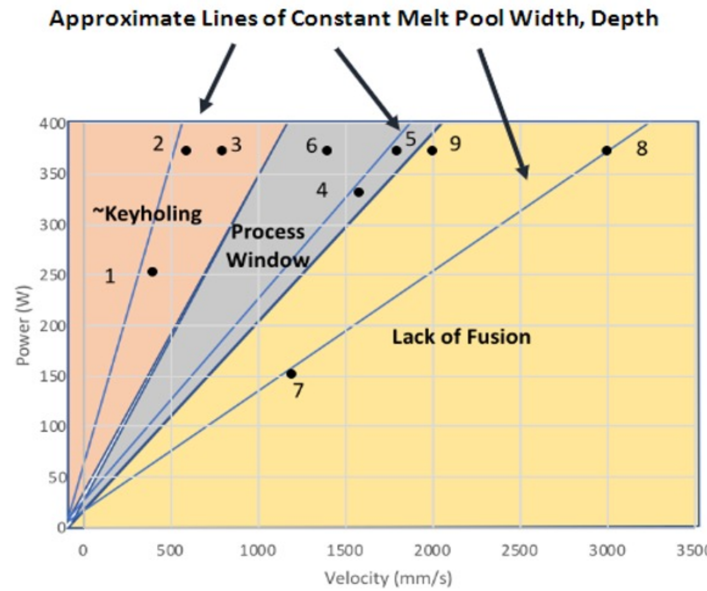
- *Main technical result*: the process window in Power-Velocity(-Hatch-Layer) space for laser powder bed fusion (LPBF) of Ti-6Al-4V is clearly evident in terms of both a minimum in P=V space for defect (pore) content and a maximum in fatigue life; demonstrated in multiple printers, multiple locations, multiple materials.
- *Data*: >1,000 4-point bend fatigue bars printed at 5x5x75 mm, consistent powder feedstock, machining & stress relief (no HIP, no heat treatment); round robin printing in EOS M290 (3 locations) and other systems.
- *Mechanical Behavior*: 4-point bend fatigue successful as a high throughput screening technique; shorter lifetimes found for conventional round bar.
- *Characterization*: Pores with size >≈ 20 µm can be measured by optical imaging of well machined surfaces; number densities are consistent with computed tomography (CT) and cross-sectional metallography.
- *Key Outcome*: Based on a combination of experience and physics-based knowledge of process, establishing a Qualified Materials Process (for LPBF).

Process map-based design of experiments

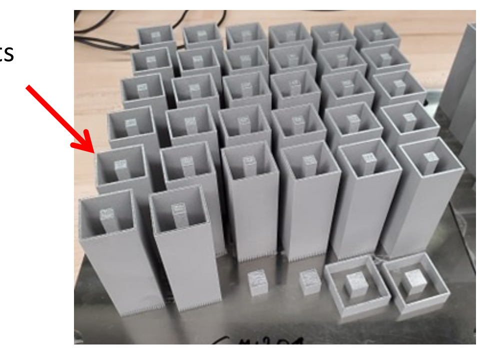


Material: Ti-6Al-4V

Gordon *et al*. (2020) *Additive Manuf*. **36** 101552;
Shahabi *et al*. (2022) *Materials Characterization* **190** 112027



Moats



Maximizing the process window and reducing uncertainty at the boundaries via moats

What Motivated This ULI Project?

- *Why does this matter for aviation*? Average age* of (civilian) aircraft is >13 years and maximum =44 (DC-10-10). AM is convenient for low volume legacy parts. AM often buys its way in by shortened time-to-delivery, no-other-way-to-do-it applications, and the ability to change the design with high frequency.
- *How are parts typically qualified*? Testing is required to demonstrate confidence that the part's properties (e.g., strength, fatigue resistance) meet, say, 99% of the design requirement with 95% confidence. Given the known variability between different 3D printers, the qualification is tied to a specific machine.
- *How did this project change the paradigm*? Our ULI team demonstrated that there is a physics-based *process window* for metals AM that any machine should possess. Within that window, high quality parts can be produced with low defect content. Moreover, that same low defect is quantitatively and causally linked to high fatigue resistance (as the exemplary material property).
- *What was the desired outcome of our ULI*? A methodology for AM of metal parts that equates a Qualified Materials Process† to consistent operation of the AM 3D printer within the process window. Accompanied by the database of print histories, characterization and mechanical property data.
- *Addressing in the AIA Value Chain*[+]*:* **Installation Qualification + <u>Operational Qualification</u> + <u>Performance Qualification</u>**, which feeds into Part Qualification

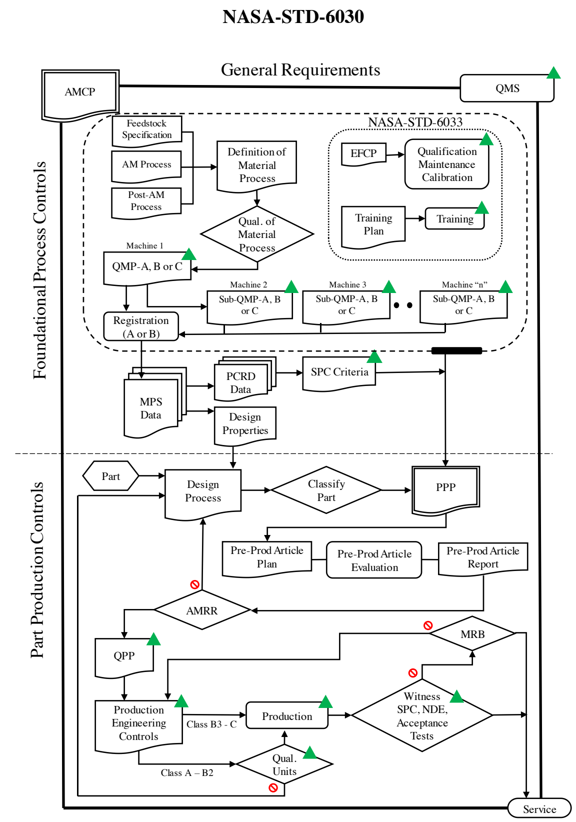
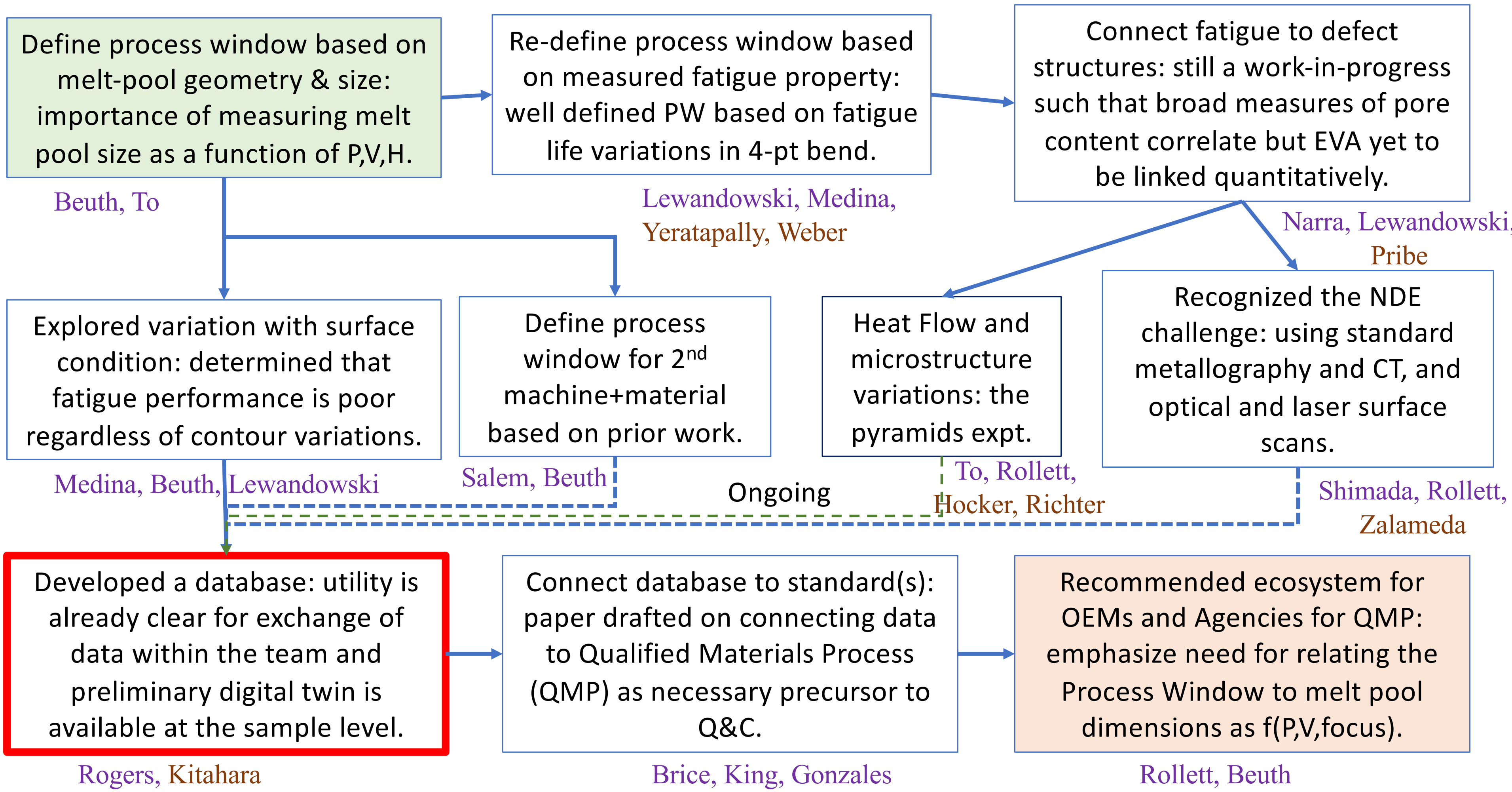


Figure 2—Key Products and Processes for NASA-STD-6030

AM = Additive Manufacturing   † NASA-STD-6030   *https://www.bts.gov/average-age-aircraft-2019
+AIA-Additive-Manufacturing-Best-Practices-Report-Final-Feb2020.pdf

Major Milestones, Accomplishments and Connections



Impact, Outcomes

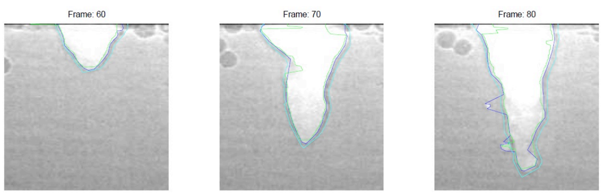
- Demonstrated that a Process Window exists based on both microstructure and mechanical behavior (fatigue) within which reliable 3D printing can be performed
- Presentations (e.g., APICAM) and publications
- Internships of students with NASA, e.g., Evan Adcock
- Employment of students at NASA, e.g., Andrew Kitahara
- Large body of data, *e.g.*, >1,000 fatigue tests, likely to attract strong interest over a long period
- CMU partnered with Hopkins to win a NASA STRI: will develop an end-to-end model, *aka* digital twin, for process-structure-properties in metals AM.
- Broader impacts:
  - NAS workshop
  - Multiple talks about the ULI to FAA-EASA workshops
  - Steering group on Computational Methods for Qual & Cert
  - Joint Metal Additive Database Definition (JMADD) run out of NIAR
  - Southwest Research Institute

Impact: Students

One student (**Joseph Pauza**, Rollett group) completed his PhD in MSE at CMU and is working for a major failure analysis company (Exponent). Another student (**Christian Gobert**, Beuth group) completed his PhD in MechE at CMU is now working for Sentient Science. A postdoc with Prof. Albert To at the University of Pittsburgh (Pitt) continues his work on modeling at Ansys. A former postdoc at Pitt, **Florian Dugast**, is now at Ecole Centrale de Nantes as a research associate. The other Pitt students (**Xavier Jimenez, Shawn Hinnebusch, Mehrdad Ashtari**) involved in the ULI are still here and have not graduated yet. Extensive collaborations with NASA, the funding agency, continue on for many of the researchers involved. For example, **Evan Adcock** (Rollett group) completed an internship in Glaessgen's group at LaRC in the summer of 2023 and is now doing a second internship there in the Fall of 2023. **Nellie Pestian** headed up the ULI project at Materials Resources LLC under Dr. Ayman Salem, discovered a passion for research and is now a CoorsTek Fellow at the Colorado School of Mines with Prof. Joy Gockel as a PhD student. This latter outcome was particularly gratifying to see, *i.e.*, a member of an under-represented group in STEM deciding to pursue further education. Prof. Sneha Narra advised **Mahya Shahabi** at Worcester Polytechnic who is now with Ambri; she also advised **Tharun Reddy** as a Masters student at CMU and he entered the PhD program at Stanford. The Federal Aviation Authority and many other bodies are absorbing the results and coordinating with other research projects, *e.g.*, the Joint Metal Additive Database Definition (JMADD). **Alex Gonzales** at the Colorado School of Mines (advised by Prof Craig Brice) is still working on this PhD. **Tomasz Swierzewski** was advised by Proj. Kenji Shimada as a Masters student and took a position as a staff researcher at CMU's Robotics Institute but is considering returning to the ECE department at CMU for a PhD. **Hunter Taylor**, former on the ULI project at the Univ. of Texas at El Paso (UTEP) is the Founder and CEO of "Tailored Alloys" company; from their website "Tailored Alloys develops novel process parameters and alloys for high-tolerance hypersonic vehicles applications." Other UTEP students active on the project include **Edel Arrieta, Brandon Ramirez, Alex De La Cruz, Cristian Banuelos, Diego Ariza and Saul Barraza**; **Brandon Ramirez** has a position with Invisalign and **Cristian Banuelos** has started a PhD program at UTEP. PhD students at Case Western University in Prof. John Lewandowski's group included **Austin Ngo** and **Brett Ley**, both of whom are still in the program; **David Scannapieco** graduated and took a position with NSL Analytical in Cleveland OH.

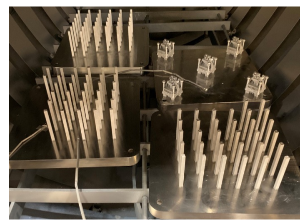
Collaborations with NASA's Transformational Tools and Technologies (TTT) Project

Data Science



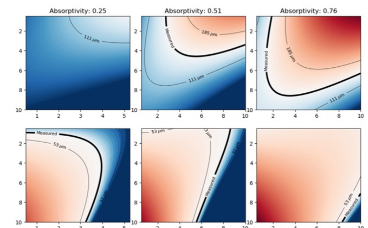
Automated vapor depression boundary identification using machine vision

PSP Round Robin



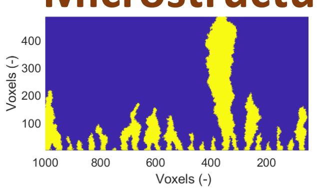
Process structure property (PSP) round robin for laser powder bed fusion machine variability

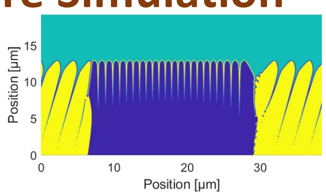
Thermal Simulation



Efficient and flexible probabilistic calibration of finite element (FEM) process models using measured data

Multi-Fidelity Microstructure Simulation





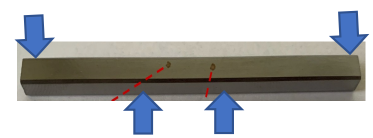
Crystallographic texture evolution modeling through joint Monte Carlo & Phase Field simulations

Microstructure Simulation and Validation

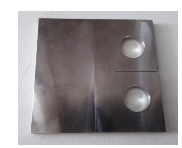
Experiment Simulation

Simulated grain shapes and textures compared with experiment

Mechanical Testing



4 Point Bend Specimen



Compact Tension Specimen

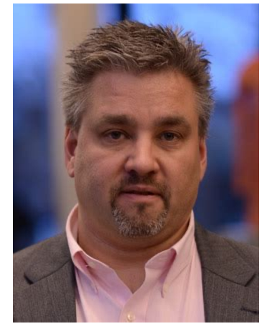
Understanding the effects of processing defects on fatigue crack initiation and propagation

External Advisory Board

Michael Gorelik
FAA

Wayne King
Barnes Global Advisors

Mark Benedict
AFRL



Ola Harrysson
(Chair) NCSU

Brandon McWilliams
ARL

Dan Thoma
U. Wisconsin

David Bourell
UT Austin

The ULI Team is profoundly grateful to the EAB for the advice and commentary!

Milestones

- **Definition of Process Windows #1** – this milestone has obviously been accomplished but we have continued to expand the parameter variations.
- **Definition of digital twin for printed parts #2** – this milestone was implemented via data capture and data analytics.
- **Map of mechanical properties … #3** – This has been accomplished
- **Validation of process windows against external data #4** – limited activity: see presentation by Wayne King
- **Robotic post-processing #5** – morphed into robotic scanning of machined surfaces of fatigue bars (micro-epsilon scans), complemented by optical
- **Integrated processing for part manufacture #6** – accomplished via transfer of … process window methodology to Materials Resources.
- **Assessment of part selection and cost by OEMs #7** – morphed into evaluation of impact of our methodology on AM standards (Mines+TBGA). Techno-economic analysis (TEA) is a sub-discipline. Our ULI focused on the technical issues.
- **Added Milestone**: Functional Prototype of the Ecosystem for Qualification: 1) qualification documents (Mines and TBGA); 2) functional form for the porosity variation as a function of the available parameters; 3) comparison (ML) with literature data; 4) linkage (via EVA) between porosity and fatigue, also between 4-point and round-bar fatigue.

Response to EAB Input

- More concise project goal statement: Our goal for the project is to show that the qualification eco-system can be implemented … measuring the process window … defects … property. This qualification protocol is being developed and … supported by data.
- … the rate of qualification "acceleration" over state of the art is important: developing tools for **acceleration of qualification …** local variation in conditions can be shown to be predictable
- Too much time on samples far from the process window: have printed several series in scan speed to demonstrate transition to/from the process window
- Rogue defects in the PW? – addressing this via extreme value analysis: note the wide scatter, however, within the PW and extremely small critical defect size at highest stress levels
- Should … add H, D, and pre-heat: addressing this via surface scanning for higher throughput defect quantification; microstructure (heat treat) emerges as a significant variable but insufficient time.
- … may be useful to have a better link of surface roughness to fatigue: addressed via testing as-printed surfaces, surface scanning …
- … role of microstructure within PW should be considered: evidence of microstructural origins for crack initiation (process window) causing us to pay attention to microstructure
- Database project seems … least connected … better integration: we appointed a **data czar** and have collaborated across the team to assemble a complete data set.
- Computational modeling … very promising … should be fully supported: calibrating & validating Pitt's thermal model and quantifying the variations in defects + microstructure -> detailed comparison with microstructures in the "inverted pyramid" experiment

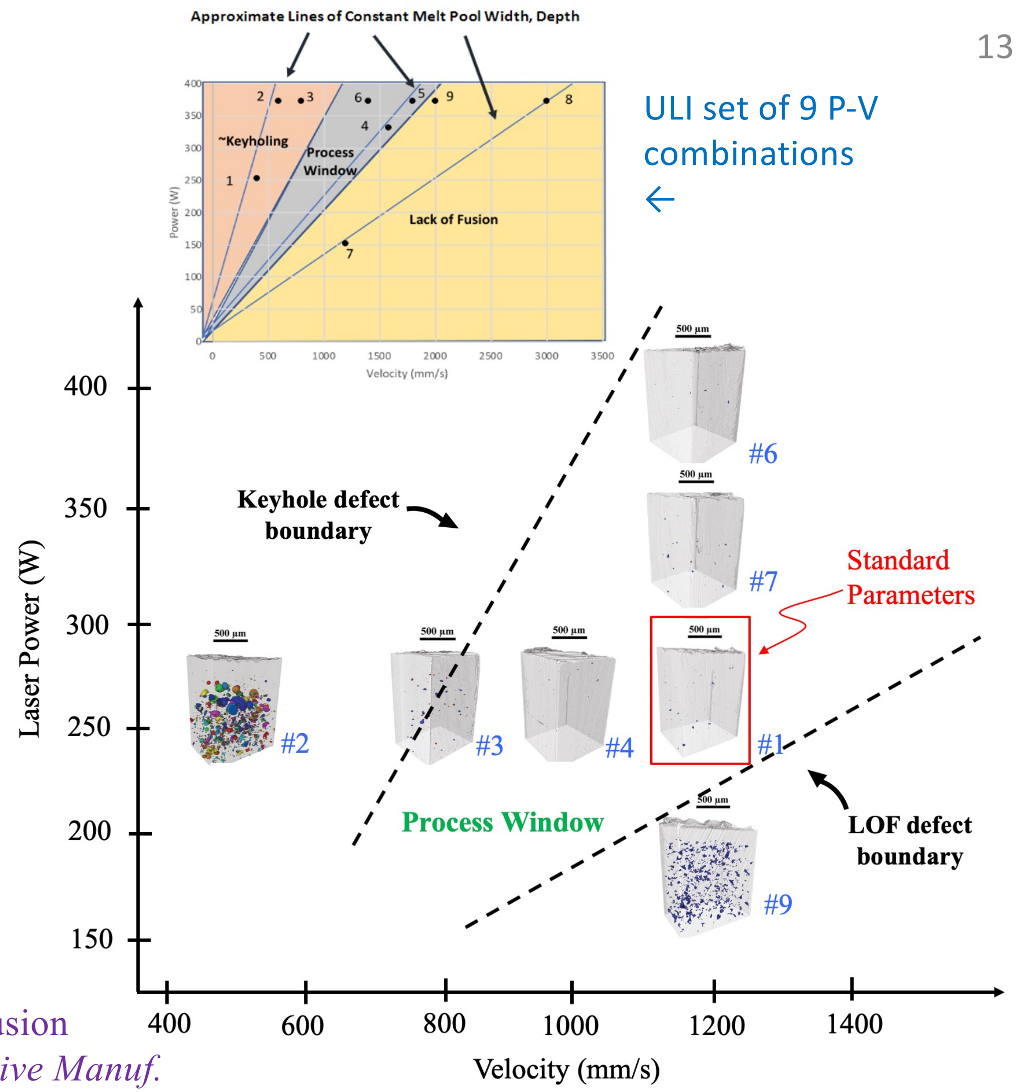
Talking Points from the ULI Project

- The accomplishments of this project could never have been achieved as individual projects. Those who participated in the weekly meetings know that the regular exchange of ideas and requests was critical to progress. In a huge dimensional space, we found ways to probe for what we needed. The whole was truly greater than the sum of the parts.
- We demonstrated that mechanical behavior clearly connects back to microstructure (defects, at least) and reaches further back to the printing conditions.
- We assert (but more remains to be investigated) that we have captured the main sources of variability, *i.e.*, power, speed, spot size, hatch, layer thickness. Gas flow, pre-heat, feedstock, and many others remain to be quantified (but other groups are tackling these).
- Exchange of data worked even better than anticipated. Nevertheless, we have to be careful when using data from other team members. At some point, we need to publish the data because it is obvious that it will attract world-wide interest. We propose a 1-year time limit to get papers submitted. Much longer than that and the data ages out and we forget crucial details.
- CMU commits to maintaining the database, including the collection of (physical) samples, for at least five years.

Previous Process Window for Ti64

- Prior to the ULI, CMU had printed (both EB-PBF & L-PBF) test cubes and performed (synchrotron, voxel size 0.65 µm) CT. No pre-heat was applied
- The coverage of P-V space (with some variations of H) was good for the time but nevertheless sparse.

ULI set of 9 P-V combinations ←

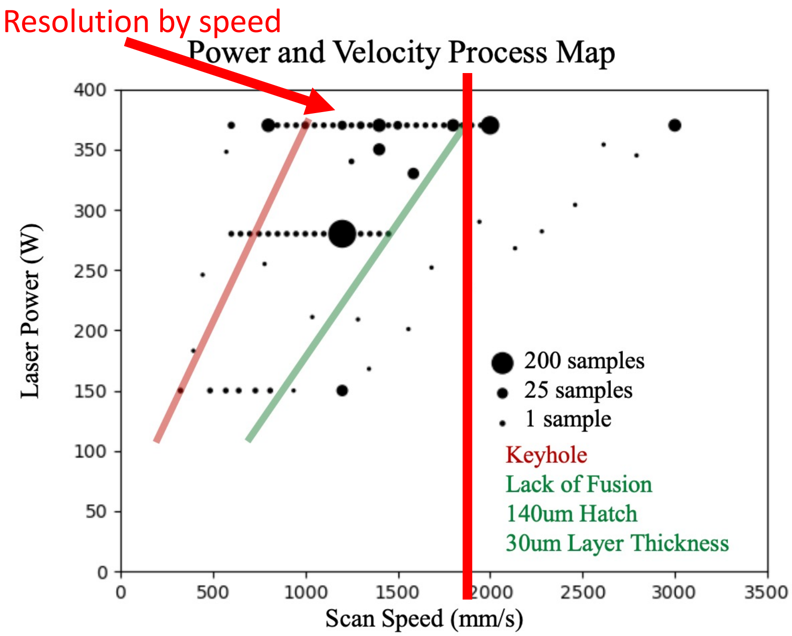


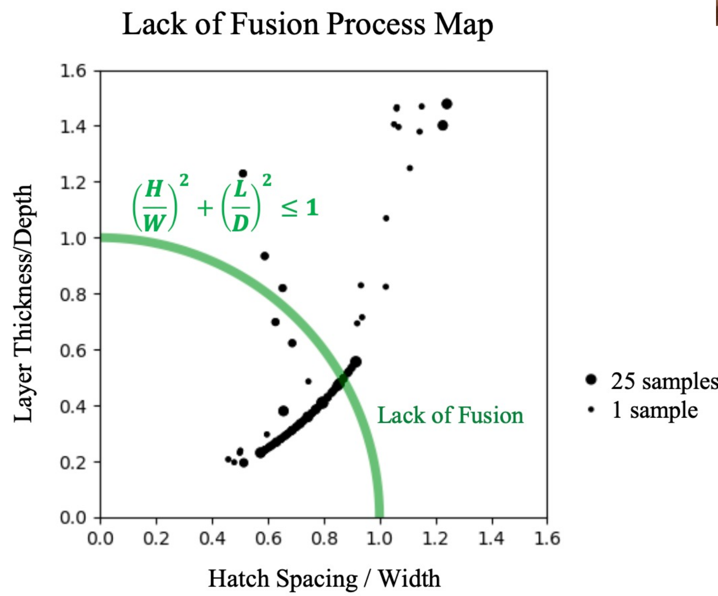
"Defect Structure Process Maps for Laser Powder Bed Fusion Additive Manufacturing", J.V. Gordon *et al*. (2020) *Additive Manuf.*

What We Have Printed

Parameter Exploration Builds – Graphical Summary

All P-V and LOF variables in ULI Program (CMU,UTEP,NASA,PITT) for TI64, >700 fatigue tests





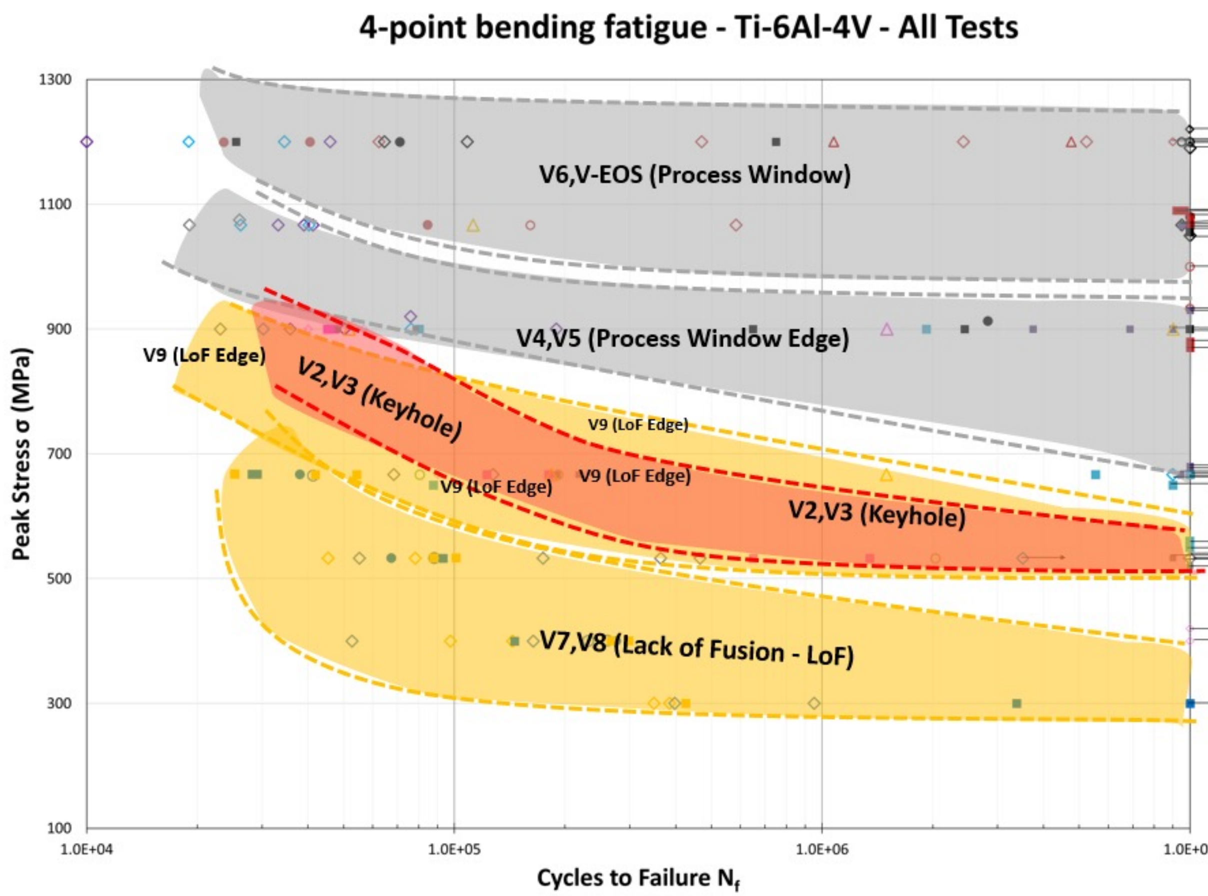
- UTEP: 4 builds + 1 Planned
- CMU: 15 builds
- U Pitt: 4 builds
- Materials Resources: 3 builds (advanced Al alloy)
- NASA-Langley: 3 builds

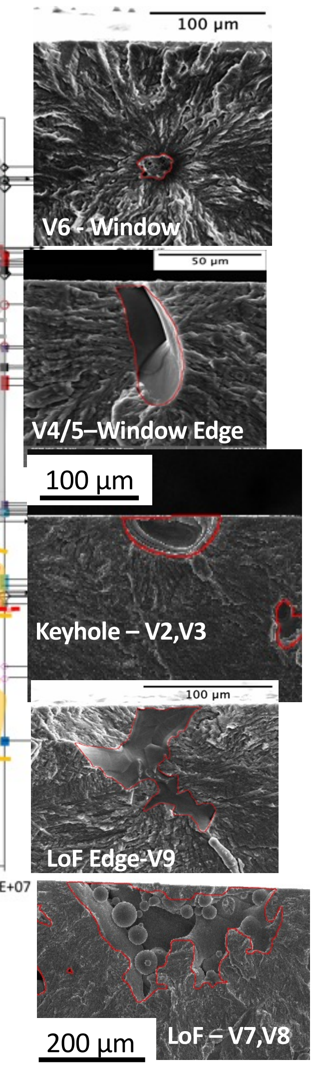
Each Build ≈ 35 samples on each plate. Most samples are 5x5 mm bars. Machined to remove ½ mm each side.

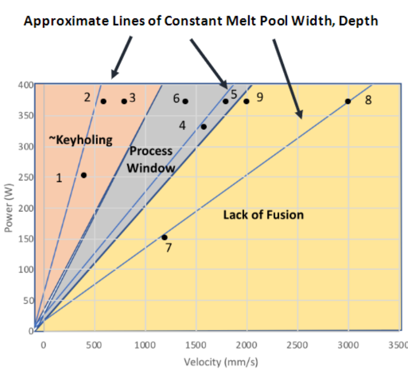
> 1,000 fatigue samples

S. P. Narra *et al*., Process qualification of laser powder bed fusion based on processing-defect structure-fatigue properties in Ti-6Al-4V, Journal of Materials Processing Technology, 311, 117775 (2023)

4-point Bend Fatigue S-N Plot for Different P-V (R = 0.1)







EP05 & EP07: 112 tests total

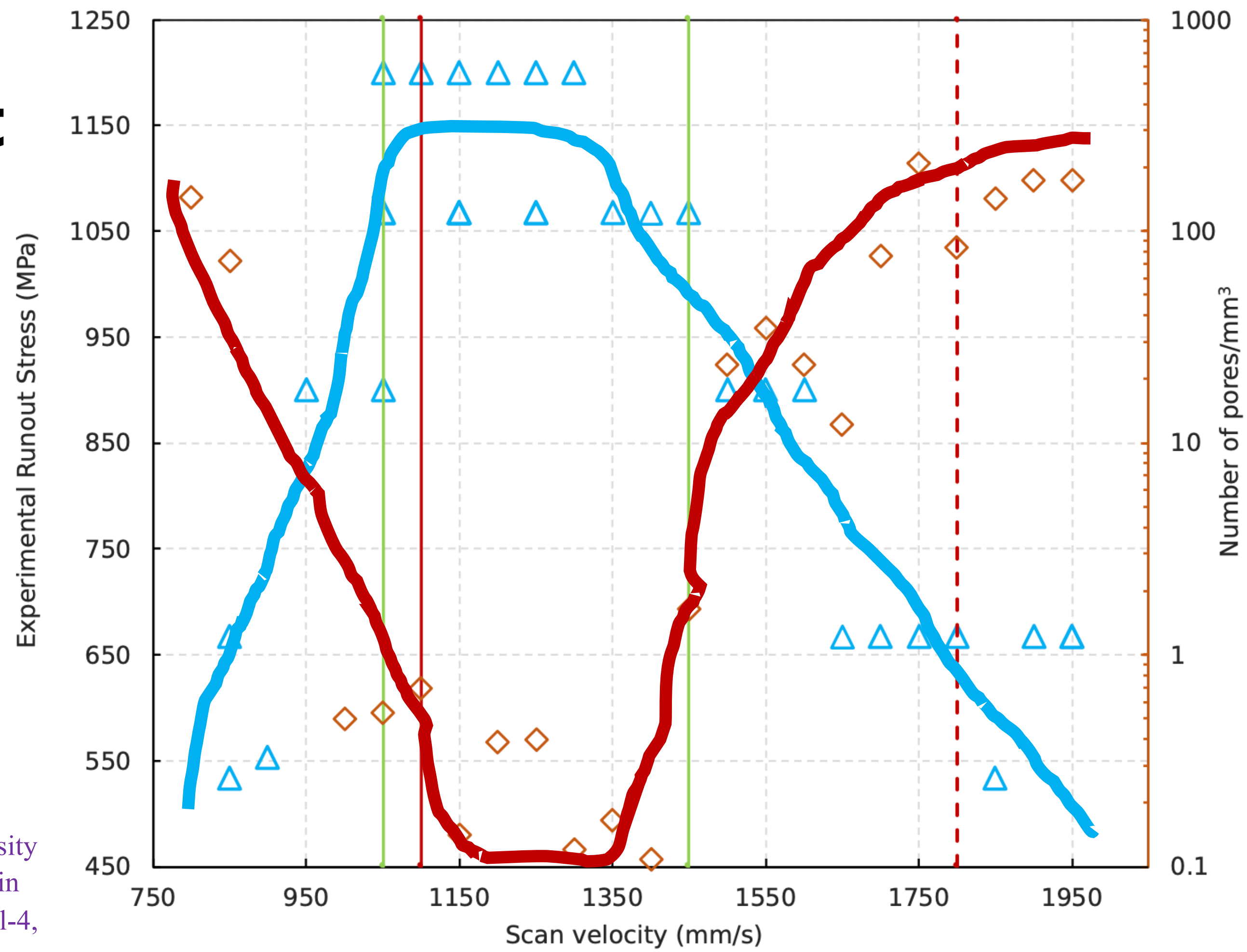
CASE SCHOOL OF ENGINEERING
CASE WESTERN RESERVE UNIVERSITY

CWRU Graduate Students: A Ngo, D Scannapieco, C Sharpe

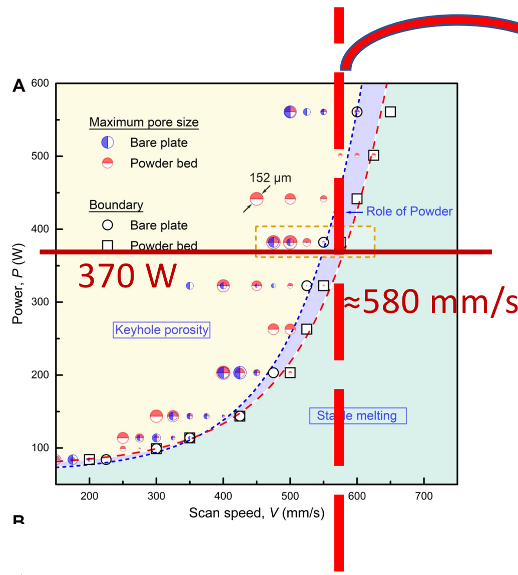
Process Window: Fatigue vs. Defect Number Density

- An obvious inverse relationship between defect number density and fatigue life (expressed in terms of runout stresses).

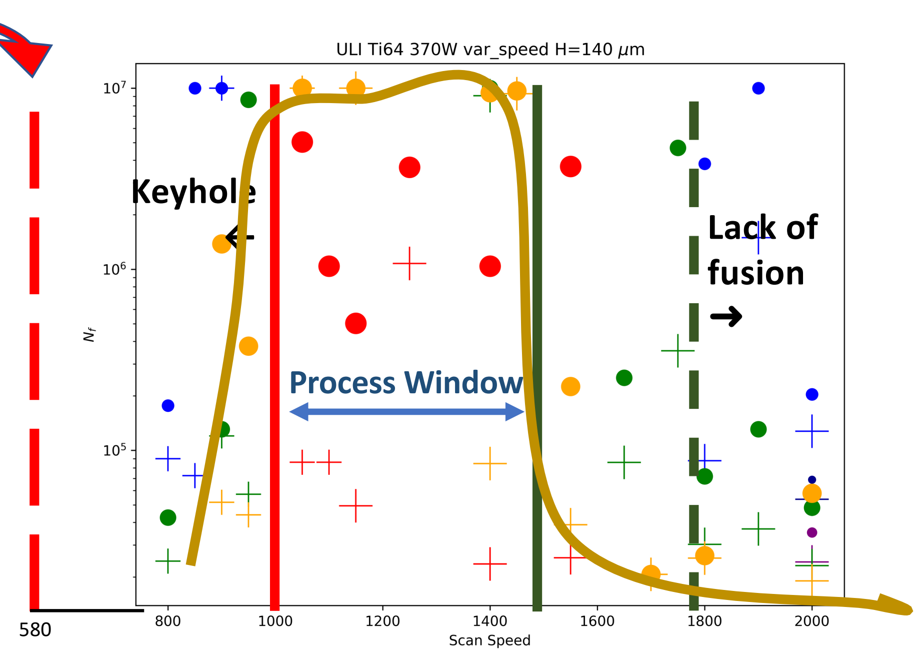
Quantifying the Impact of Sparse Lack-of-Fusion Porosity from Melt Track Geometry Variability on Fatigue Life in Powder Bed Fusion - Laser Beam Manufactured Ti-6Al-4, Justin P. Miner *et al.* (2023)



Compare keyhole boundaries



Zhao *et al.* (2020) *Science*



- Bottom line: the "keyhole" boundary defined by the (dashed bars) from synchrotron experiments *is far from conservative*; for fatigue, especially, it is close to original suggestion by the Beuth group
- The LoF geometrical criterion (Tang et al.) *is also far from conservative* and is at a significantly higher speed. Note the large scatter on the lack of fusion side of the plot (associated w/ variable porosity?), at least compared to the drop-off in fatigue life on the LHS.