Appendix A
Workshop Agenda

Joint FAA – EASA Workshop on Qualification / Certification of Additively Manufactured Parts

October 17-20, 2022

Venue: ***virtual*** *(Zoom)*

- **Workshop Co-organizers**: Michael Gorelik (*FAA*) and Simon Waite (*EASA*)
- **Workshop Facilitator**: Rollie Dutton (*ARCTOS*)

Note: all times listed below are in ***EDT***

Day 1 – October 17

9:00 – 9:30 Arrival and Zoom Orientation (optional, but recommended to verify system compatibility)

9:30 – 9:55 Welcome / Agenda Review / Workshop Format – *M. Gorelik, S. Waite, R. Dutton*
9:55 – 10:05 FAA Leadership Opening Remarks – *Bruce DeCleene, Deputy Director, Policy and Innovation Division*
10:05 – 10:40 Keynote Presentation – *Mark Shaw, Director of Additive Programs, GE Edison Works*
10:40 – 11:00 FAA Update – *M. Gorelik (FAA)*
11:00 – 11:20 EASA Update – *S. Waite (EASA)*

11:20 – 11:40 Break

11:40 – 12:00 "Wire DED Processes, Control and Quality Assurance" – *C. Johnson (Norsk Titanium)*
12:00 – 12:20 "Overview of NASA ULI program" – *A. Rollett (CMU)*
12:20 – 12:40 "Dynamic NDE with Online Process Monitoring - A Safer and More Economical Approach?" – *S. Rott (MTU)*

12:40 – 13:30 Introduction of Breakout Sessions for Days 2 and 3 (and summary of 2021 results)

- Working Group 1: Qualification of AM Parts of No, or Low, Criticality (for use in Certified products) -- *Co-chairs: S. Waite (EASA) and O. Kastanis (EASA)*
- Working Group 2: F&DT and NDI Considerations for Metal AM -- *Co-chairs: M. Gorelik (FAA), A. Fischerworring-Bunk (MTU)*
- Working Group 3: Improved Communication and Data Sharing between AM Machine Makers and End Users -- *Co-chairs: D. Godfrey (SLM), F. Lartategui Atela (ITP Aero), R. Mellor (Rolls Royce)*

13:30 Adjourn of Day 1

Day 2 – October 18

9:00 – 9:30 Arrival / Log-in / System Checks (optional)

9:30 – 11:30 Parallel Breakout Sessions *(including breaks)* – ***Part 1***

Breakout Session #1 – "Qualification of AM Parts of No, or Low, Criticality (for use in Certified products)"

Co-chairs: S. Waite (EASA) and O. Kastanis (EASA)

Breakout Session #2 – "F&DT and NDI Considerations for Metal AM"
Co-chairs: M. Gorelik (FAA) and A. Fischersworring-Bunk (MTU)

Breakout Session #3 – "Improved Communication and Data Sharing between AM Machine Makers and End Users", *Co-chairs: D. Godfrey (SLM), F. Lartategui Atela (ITP Aero), and R. Mellor (Rolls Royce)*

11:30 – 11:50 "JMADD - Public Ti-6Al-4V LPBF Qualification" – *J. White (NIAR)*

11:50 – 12:10 "MMPDS and Additive Metals" – *D. Hall (Battelle)*

12:10 – 12:30 "The Concept of Material "Engineering Equivalence" in Achieving and Sustaining Efficient Qualification and Certification of AM Materials and Parts" – *D. Wells (NASA)*

12:30 – 13:30 Mini-Symposium on Computational Materials

- "Model-Assisted Validation and Certification of AM Components" – D. Furrer (Pratt & Whitney)
- "Computational Framework for Rapid Qualification" – *M. Maher (Maher & Associates LLC)*

13:30 Adjourn of Day 2

Day 3 – October 19

9:00 – 9:30 Arrival / Log-in / System Checks (optional)

9:30 – 9:50 "Extreme Value Statistics of Metal AM and Fatigue" – *L. Bruder (MTU)*

9:50 – 10:10 "AM Part Family Qualification & Certification for Aviation" – *M. White (ASTM)*

10:10 – 10:30 "Methods for Zoning AM Components Using Machine Learning" – *M. Groeber (OSU)*

10:30 – 10:50 "Powder Reuse in Additive Manufacturing" – *E. Bono (6K Inc.)*

10:50 – 11:10 Break

11:10 – 13:30 Parallel Breakout Sessions *(including breaks)* – ***Part 2***

Breakout Session #1 – "Qualification of AM Parts of No, or Low, Criticality (for use in Certified products)"
Co-chairs: S. Waite (EASA) and O. Kastanis (EASA)

Breakout Session #2 – "F&DT and NDI Considerations for Metal AM"
Co-chairs: M. Gorelik (FAA) and A. Fischersworring-Bunk (MTU)

Breakout Session #3 – "Improved Communication and Data Sharing between AM Machine Makers and End Users", *Co-chairs: D. Godfrey (SLM), F. Lartategui Atela (ITP Aero), and R. Mellor (Rolls Royce)*

13:30 Adjourn of Day 3

Day 4 – October 20

9:00 – 9:30 Arrival / Log-in / System Checks (optional)

9:30 – 10:45 ***Authorities Panel***

10:45 – 11:05 "The Use of AM for Repairs – An SAE AMS-AM Perspective" – *D. Abbott (GE Aerospace)*

11:05 – 11:25 "Progress in Development of NDE Tools for Classification, Process Monitoring and Acceptance of AM products" – *L. Schaefer (General Atomics)*

11:25 – 11:40 Break

11:40 – 13:10 ***Breakout Sessions Debriefs***

- Breakout Session #1 – *Co-chairs: S. Waite (EASA) and O. Kastanis (EASA)*
- Breakout Session #2 – *Co-chairs: M. Gorelik (FAA) and A. Fischersworring-Bunk (MTU)*
- Breakout Session #3 – *Co-chairs: D. Godfrey (SLM), F. Lartategui Atela (ITP Aero), and R. Mellor (Rolls Royce)*

13:10 – 13:30 Wrap-up and Closing Comments – *M. Gorelik (FAA) and S. Waite (EASA)*

13:30 Adjourn of the 2022 Workshop

Appendix B
Table of Presentations

Appendix T) "Progress in Development of NDE Tools for Classification, Process Monitoring and Acceptance of AM products" – L. Schaefer (General Atomics)

Appendix U) Wrap-up and Closing Comments
– Michael Gorelik (FAA) and Simon Waite (EASA)

Breakout Sessions:

Appendix V) Breakout Session #1 – "Qualification of Low-Criticality AM Parts"
Co-chairs: S. Waite (EASA) and
J. Mallory (Delta TechOps)

Appendix W) Breakout Session #2 – "F&DT and NDI Considerations for Metal AM"
Co-chairs: M. Gorelik (FAA) and
A. Fischersworring-Bunk (MTU)

Appendix X) Breakout Session #3 – "Improved Communication and Data Sharing between AM Machine Makers and End Users"
Co-chairs D. Godfrey (SLM), F. Lartategui Atela
(ITP Aero), and R. Mellor (Rolls Royce)

Authorities Panel:

Appendix Y) Authorities Panel Questions & Answers

Appendix C

Welcome / Agenda Review / Workshop Format – M. Gorelik, S. Waite, R. Dutton

Welcome to the 5th Joint FAA – EASA AM Workshop

Workshop Overview

October 17-20, 2022

Presented by:

Michael Gorelik

https://www.faa.gov/aircraft/air_cert/step/events/additive_mfg_workshop

- **Dr. Simon Waite (EASA) – workshop co-organizer**
- **Dr. Rollie Dutton (ARCTOS) – workshop facilitator**
- **Breakout Sessions Co-Chairs (listed in the Agenda) and supporting core WG members**
- **All the Presenters**
- ***Repeat* Workshop Participants - for many years of support, encouragement and contributions**
- ***New* workshop participants – *Welcome !***
- **Erin Crowder and Nancy Heino (FAA STEP) – for media, registration and Zoom support**

Disclaimer

- **While this workshop is an FAA and EASA co-sponsored event, the specific content of the presentation materials has not been vetted or approved by the FAA or EASA**
- **Technical presentations in this workshop are being offered to the participants in the spirit of government – industry – academia *technical interchange* and, as such, the specific messages in individual presentations are not endorsed by the FAA or EASA**

Virtual Workshop – “Rules of Engagement”

- **Stay on mute when not speaking**
- **Minimize the use of video (when not presenting)**
- **Use Chat Box to submit a question**
  - Due to a tight schedule and a large number of participants, there may not be an opportunity to address all the questions in real time.
    - *For these reasons, the “Raise Hand” feature will not be utilized during the General Sessions, but could be potentially used during the Breakout Sessions (at the discretion of the breakout session co-chairs) and Regulatory Panel*
  - However, the *Chat Box content will be recorded* and presenters will be requested to provide responses either during or after the sessions
- **Workshop’s sessions will <u>not</u> be recorded** *(except for Chat)*
- **Breakout sessions will be conducted using *Breakout Rooms* feature in Zoom** → *you won’t need a separate Zoom link*

➢ *Please contact Erin Crowder with questions regarding the Zoom session or registration* (Erin.N-CTR.Crowder@faa.gov)

2022 Workshop – *General Observations*

- **5th joint FAA – EASA workshop**
- ***Third virtual workshop***
  - Leveraging off the experience of the 2020 and 2021 virtual events
    - However, using Zoom platform for the first time
  - More than 2x increase in the number of participants vs. F2F events
  - However…
    - Less time than during F2F meetings (20 min presentation time slots)
    - **No networking or side meetings**
- **Continuing with Breakout Sessions**
  - More interactive than seminar-style presentations
- **Focus on new technical developments, not "organizational updates"**
- **Highly diverse industry "demographics"**
  - OEMs, Tier 1/2/… suppliers, machine makers, tools / methods developers, …
- **Regulatory Panel included based on feedback from 2021 event**

Agenda at a Glance

- **Opening remarks:**
  - *Mr. Bruce DeCleene, Deputy Director of Policy and Innovation Division, FAA*
- **Keynote – *GE Edison Works***
  - *Mr. Mark Shaw, Director of Additive Programs*
- **15 presentations from the industry, government, academia and SDOs / Consortia / WGs**
- **3 Breakout Sessions**

1. *Low Criticality AM Parts*
2. *F&DT and NDI Considerations*
3. *Knowledge transfer between machine makers and end users*

- **Session on Computational Materials / ICME**
- **Regulatory Panel**


EASA
Joint FAA – EASA Workshop on Qualification / Certification
of Additively Manufactured Parts
October 17-20, 2022
Venue: virtual (Zoom)
Day 1 – October 17

Workshop "Demographics"

435 registered participants

22 Countries

Over 110 organizations

B/O Session #1	**247**
B/O Session #2	**138**
B/O Session #3	**50**

as of 10/13/22

- Austria
- Belgium
- Brazil
- Canada
- China
- France
- Germany
- Iceland
- Ireland
- Italy
- Japan
- Kenya
- Netherlands
- Norway
- Singapore
- South Africa
- Spain
- Sweden
- Switzerland
- Turkey
- United Kingdom
- United States

The largest FAA-EASA AM workshop to date

Organizing Committee

Co-organizer and Host

Dr. Michael Gorelik

FAA Chief Scientist - *Fatigue and Damage Tolerance*

Previously:

Engineering Fellow, Honeywell Aerospace

Co-organizer

Dr. Simon Waite

EASA Senior Expert - *Materials*

Previously:

UK CAA, Aircraft Design Surveyor

Workshop Facilitator

Dr. Rollie Dutton

Director - *Materials and Manufacturing,* ARCTOS

Previously:

ManTech Division Chief, AFRL / USAF

Turning it over to Simon and Rollie for additional comments…

Appendix D

Keynote Presentation – Mark Shaw, Director of Additive Programs, GE Edison Works


We are the music makers…
and we are the dreamer of dreams
- Willy Wonka

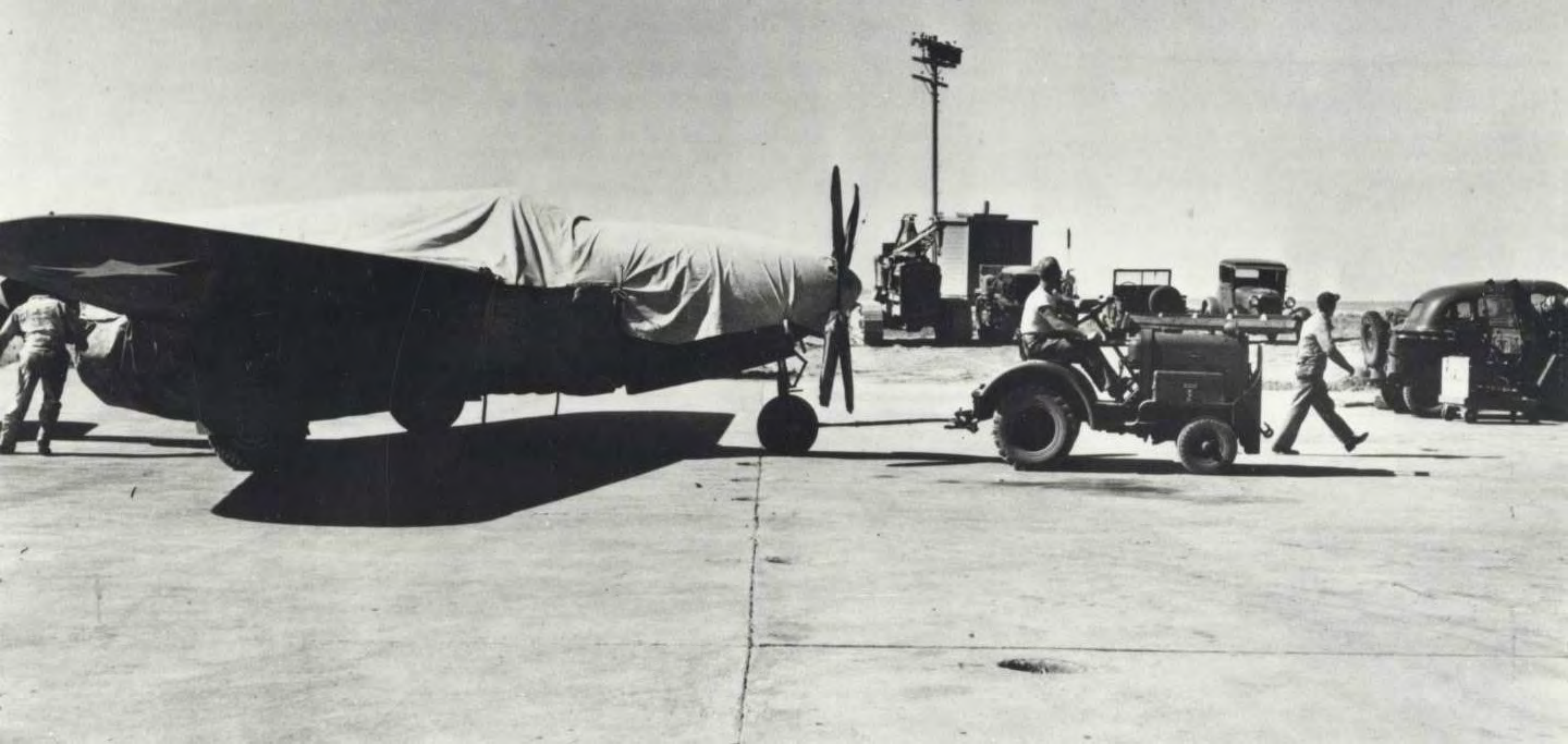
You are the influencers


2018

2019

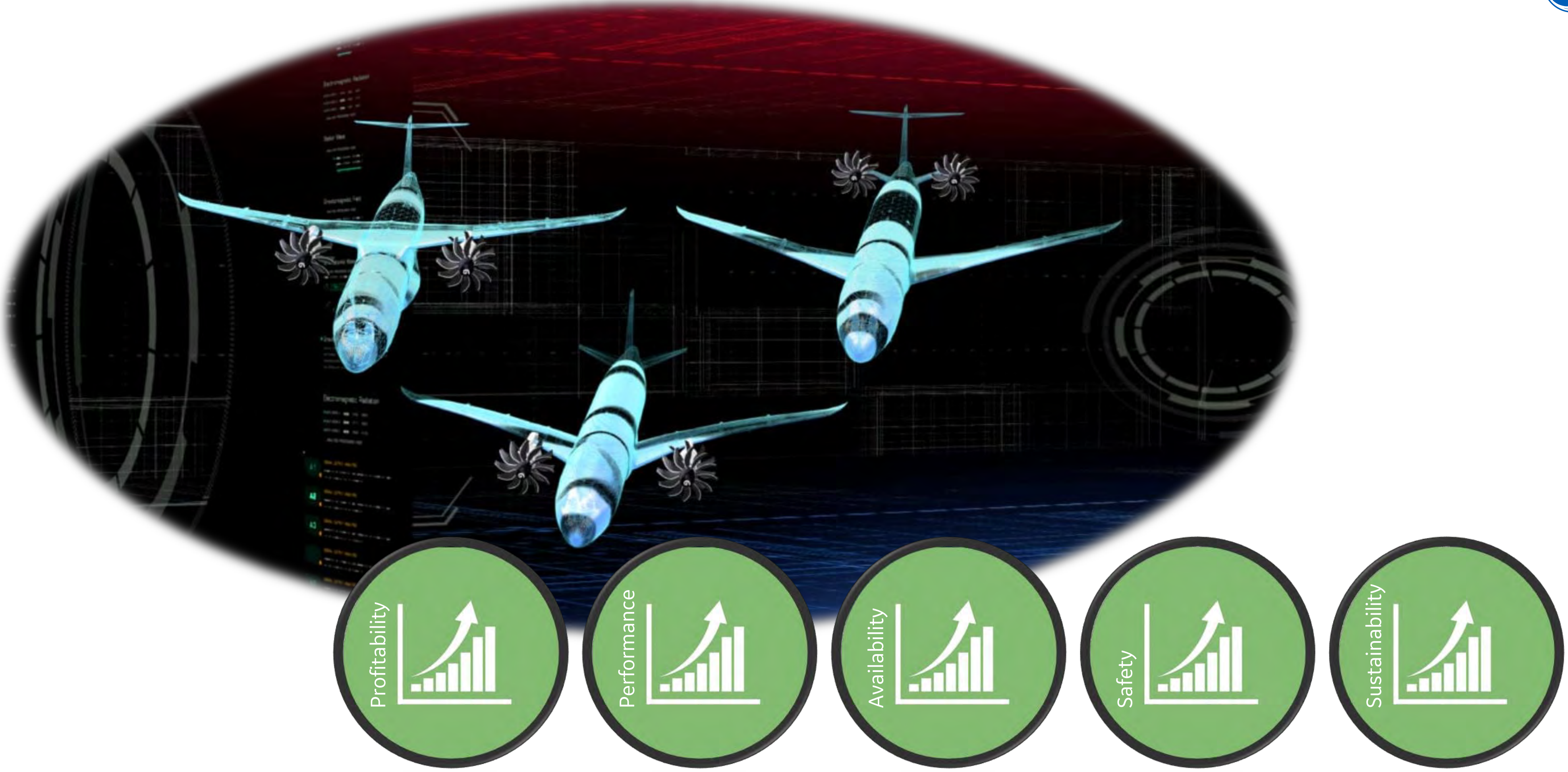
2022

Jet powered XP-59A, from drawing to flight in exactly one year



Why are you here?

Why do we believe in the future of AM in Aviation?



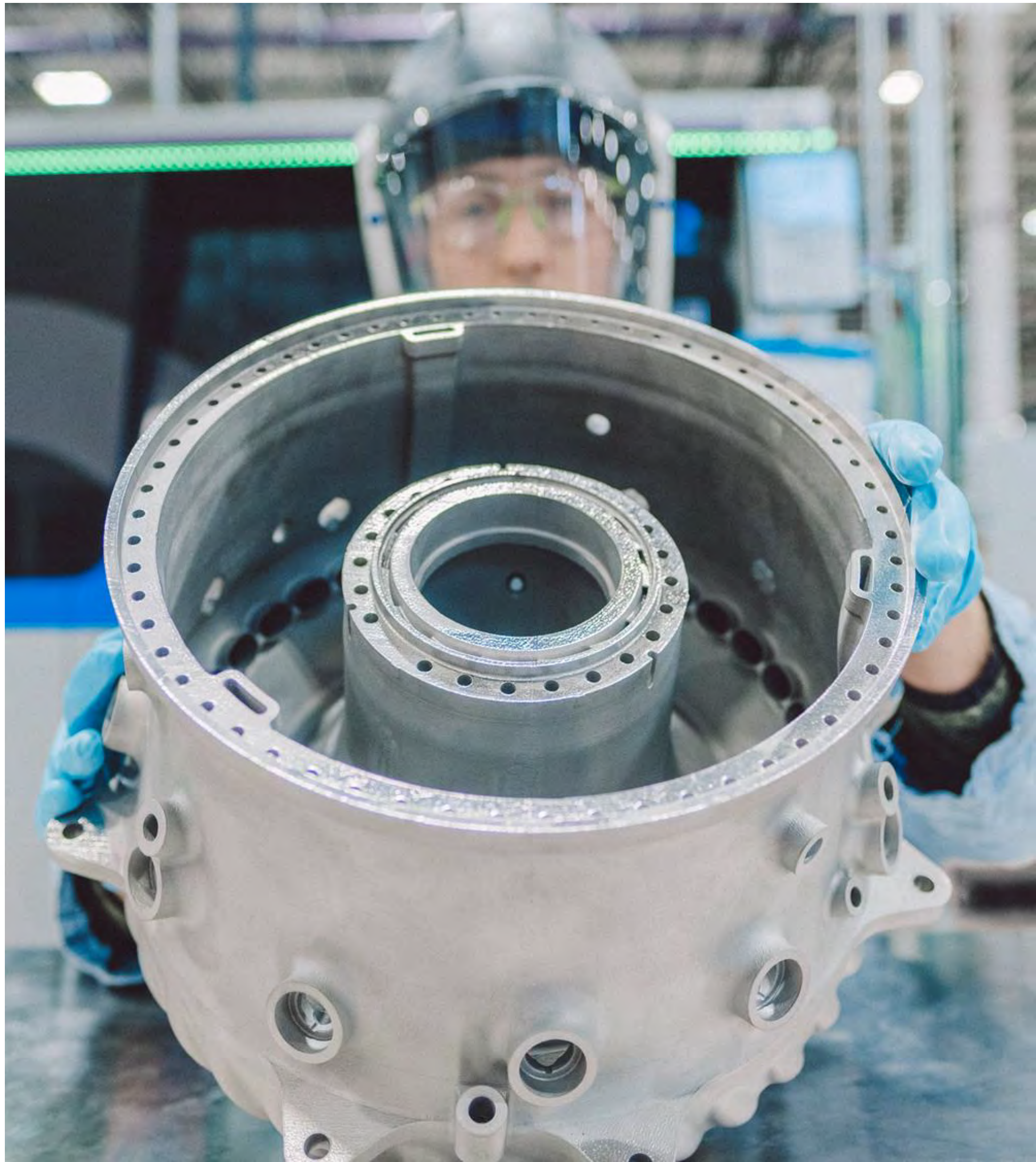
Profitability – **Consolidated Supply Chain**

CT7 Frame – Ground Test Demonstrators

7-to-1 assembly reduction

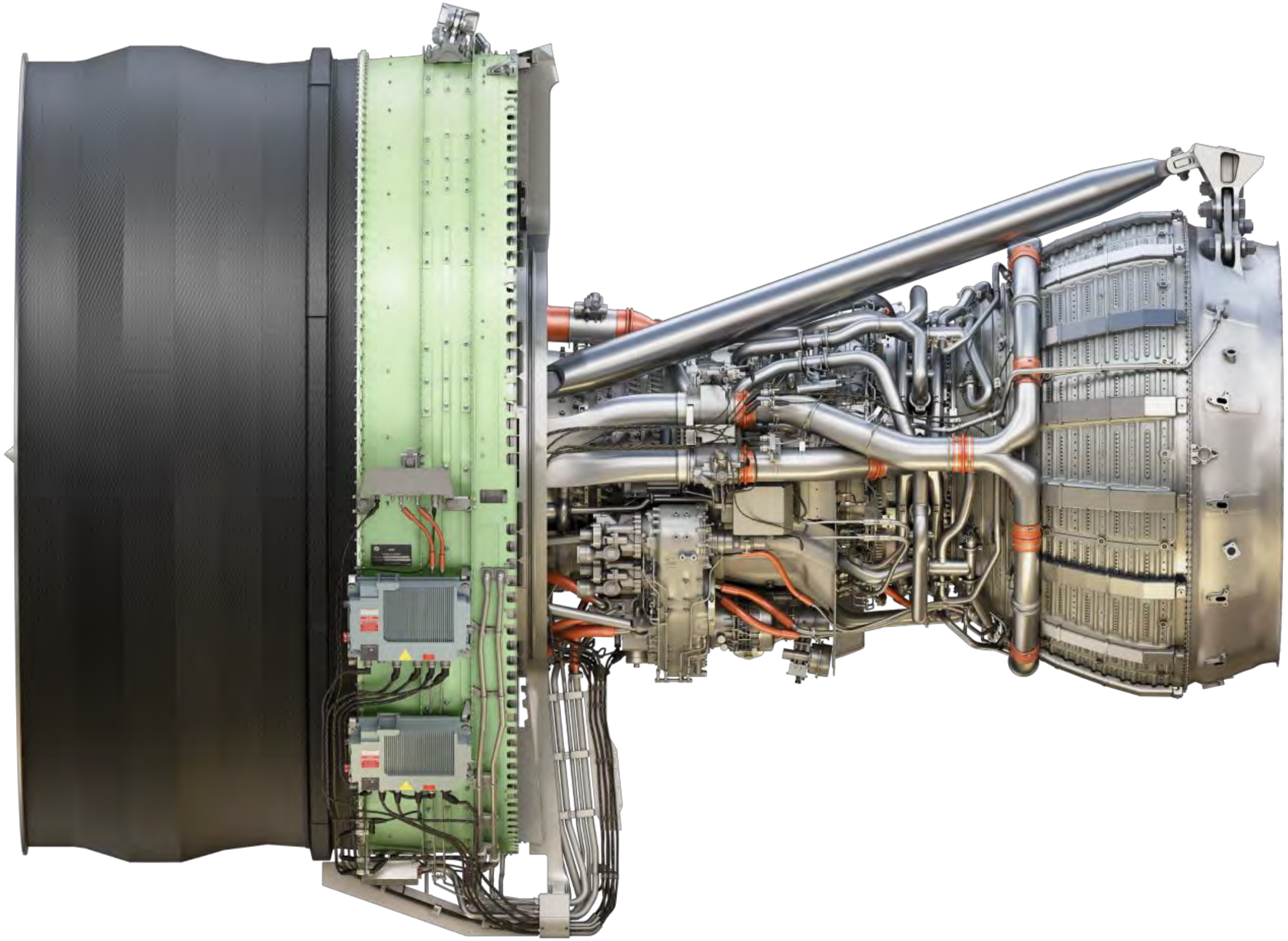
300-to-1 part reduction

>10 lb weight reduction



Profitability – **Consolidated Supply Chain**

Oct. 2020: GE9X engine receives FAA certification with ~300 AM parts



Additive Parts

1 - T2.5 Sensor

28 - Fuel Nozzles

28 - Combustor Mixers

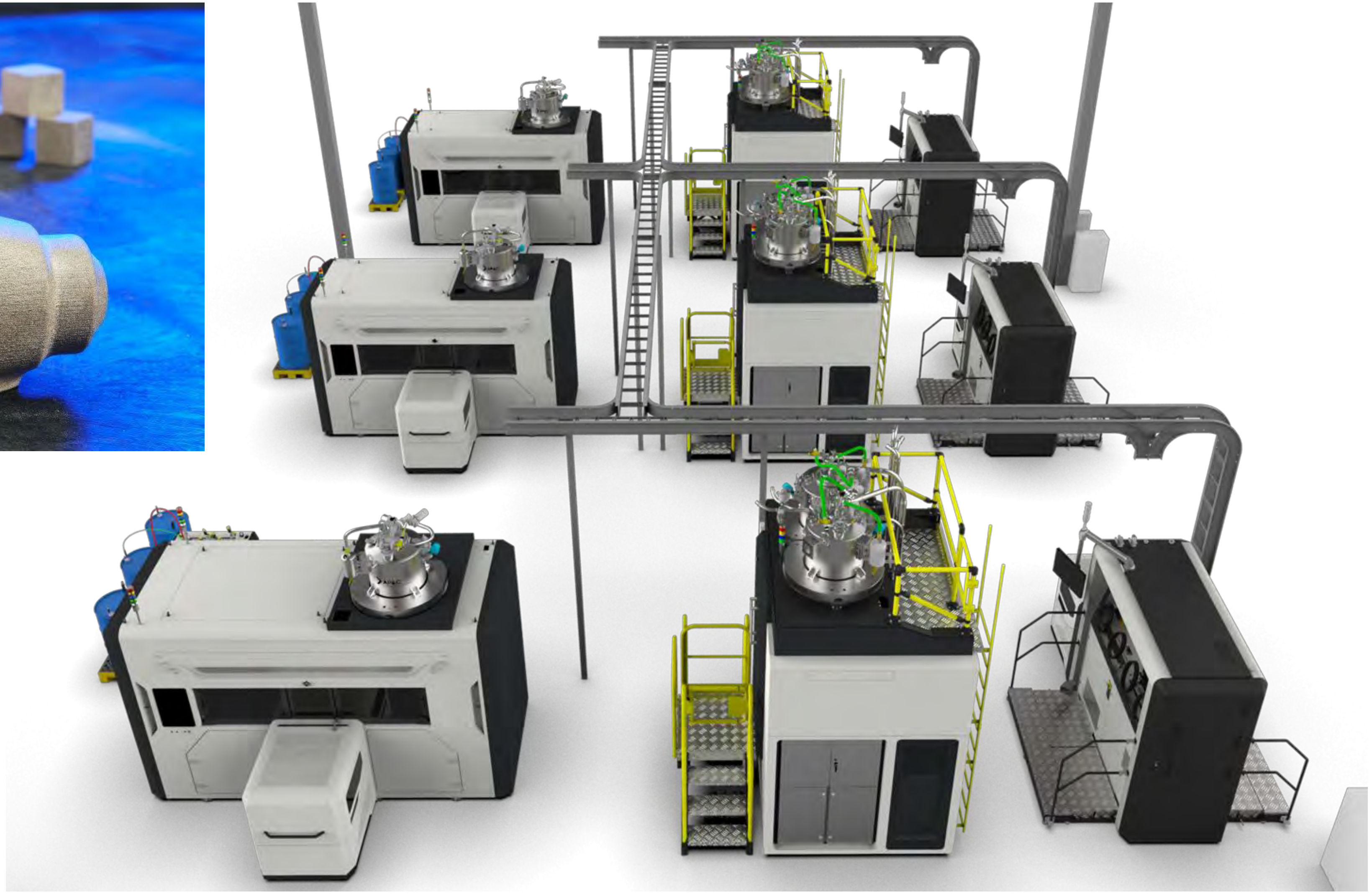
1 – Heat Exchanger

8 – Cyclonic Inducers

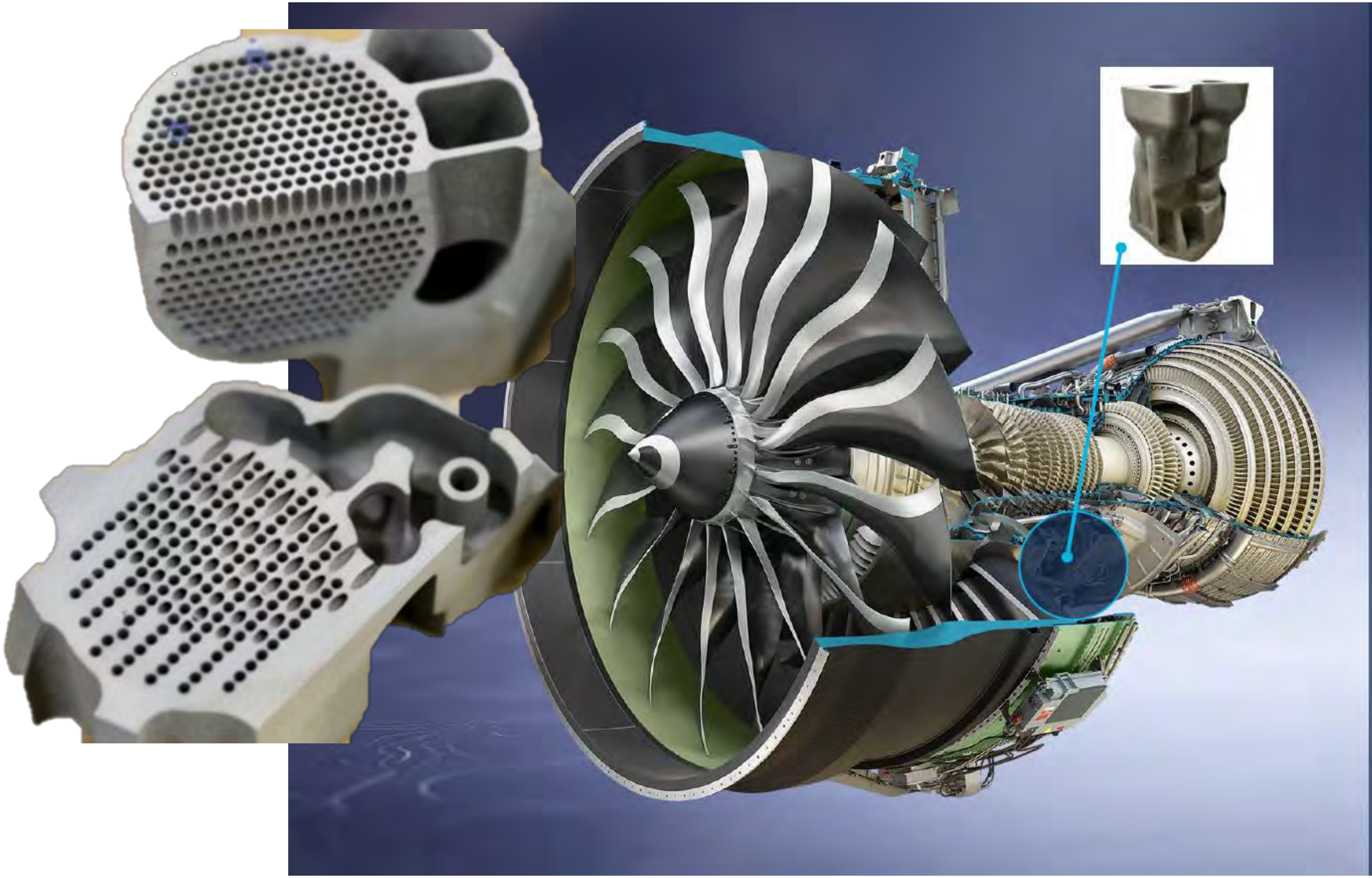
228 – Stage 5 & 6 LPT Blades

Profitability – **Automated factories** (Binder Jet H3)

Automating additive to achieve cost, quality, and scale



Performance – **Physics based designs**
(GE9X Oil Cooler)



Heat Exchanger

WHY ADDITIVE?:

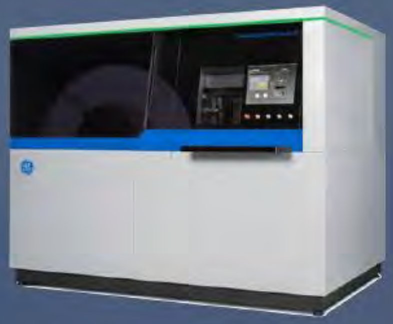
- Smaller, lighter, cheaper, improved durability

ADDITIVE BENEFITS*:

- 40% lighter
- 163 traditionally manufactured parts, now additively printed as one part
- 25% less cost to produce

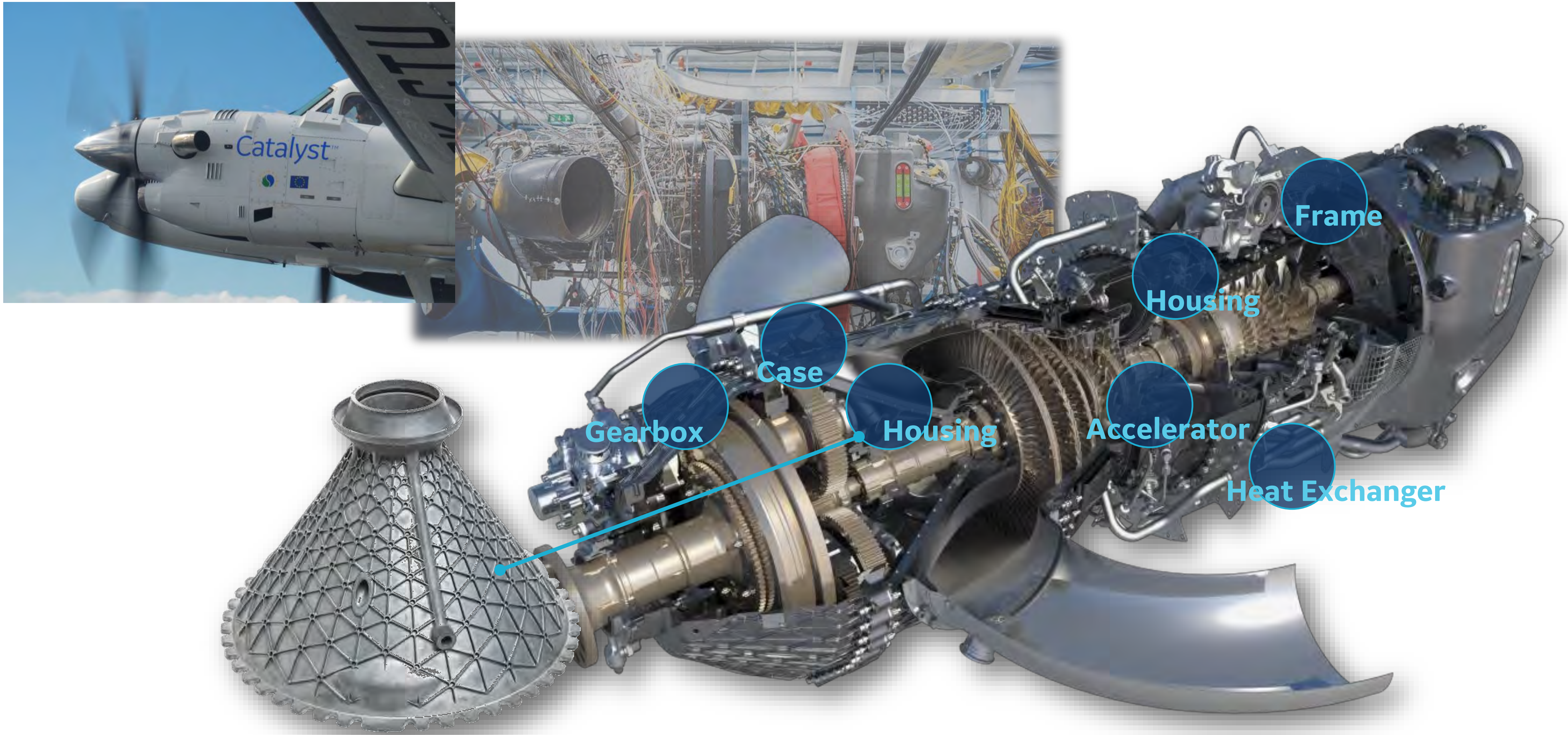
MACHINE:
Concept Laser M2

POWDER:
Aluminum (F357)



*Compared to traditional manufacturing

Performance – **Integrated systems**
(855 parts to 12)



Availability – **Resilient Logistics**
(F110 Spare Part)

“The F110 sump cover was a terrific pathfinder, allowing us to exercise the USAF’s airworthiness process. There are numerous [spare] parts in queue that are ideal candidates for metal 3D printing. Next, we are focused on refining the airworthiness process, so it is as responsive as the technology,”
- Melanie Jonason, chief engineer, USAF’s Propulsion Sustainment Division.

B52 first flight - 15 April 1952

Availability – **Additive Repair** (Airfoil Repair)

"In this part of the supply chain our customers truly value faster turn-around time, and that's what we are achieving. Using our GE Additive Concept Laser M2 machines typically halves the amount of time it takes us to repair these aircraft parts."
- Iain Rodger, managing director at GE AESS

An Approach to Metal AM Qualification

Industry Working Group Guidance for Metal AM Qual/Cert

Contributing Organizations:
Airbus
Boeing
Bombardier
Collins Aerospace
Delta Air Lines
FAA
GAMA
GE Aviation
HEICO
Honeywell
Lockheed Martin Sikorsky
Parker Aerospace
Rolls-Royce
SAFRAN
Spirit Aero Systems
Textron

Machine Installation Qualification (IQ)
"IQ starts with machine set-up, initial calibration, and a site acceptance test (SAT)."

Machine Operational Qualification (OQ)
"OQ is to be performed under sufficient process control to maintain stable material performance… to ensure the machine meets their material specification."

Process Performance Qualification (PQ)
"PQ has occurred when it has been demonstrated all product requirements are met."

- Process Control Documents (PCD)
  - Infrastructure Control Plans
  - Machine Qualification Plans
  - Feedstock Control Plans
  - Part Production Plans
  - Post-Process Plans

Part Design Qualification

- Design Value & Allowable Qualification
- System Qualification

Quality Controls

- Build Quality Plan
- Inspection

Additive Manufacturing Qualification

3 Step Qualification: IQ, OQ, PQ

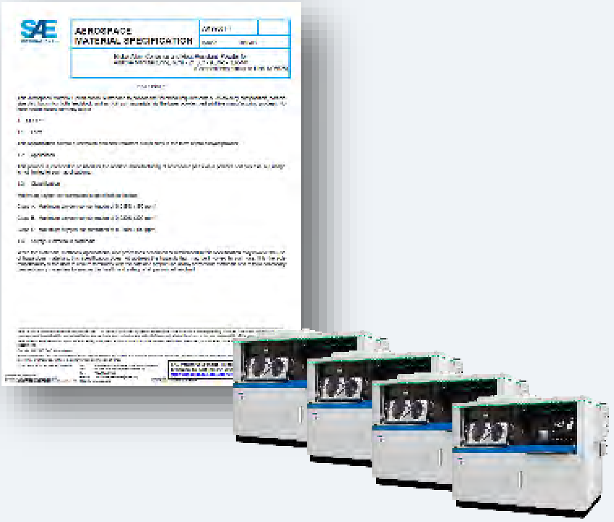
AIA Additive Manufacturing Working Group: ***"Recommended Guidance for Certification of AM Component"***

Machine Installation Qualification (IQ)

IQ verifies that machine has been installed and configured according to the **machine manufacturer's specifications**

Machine Operational Qualification (OQ)

*OQ verifies that equipment performance is consistent with the **user material specification***



Process Performance Qualification (PQ)

PQ verifies that the process is working with reproducible results to meet **specific part requirements**

AS9100D

- Design Authority Engineering Requirements
- Part Producer Quality System
- Blueprint Specifications
- Fixed Process Requirements
- Part Producer Fixed Process Procedure
- Work Instructions
- Fixed Process Control Documents (PCD)

PCD Categories:

- Infrastructure Control Plans
- Machine Qualification Plans
- Feedstock Control Plans
- Part Production Plans
- Post-Process Plans

What → **How** *(Manufacturing Know-How)*

Additive Specifications Required for Qualification

… *Provides the <u>what</u>, but does not the define <u>how</u>*

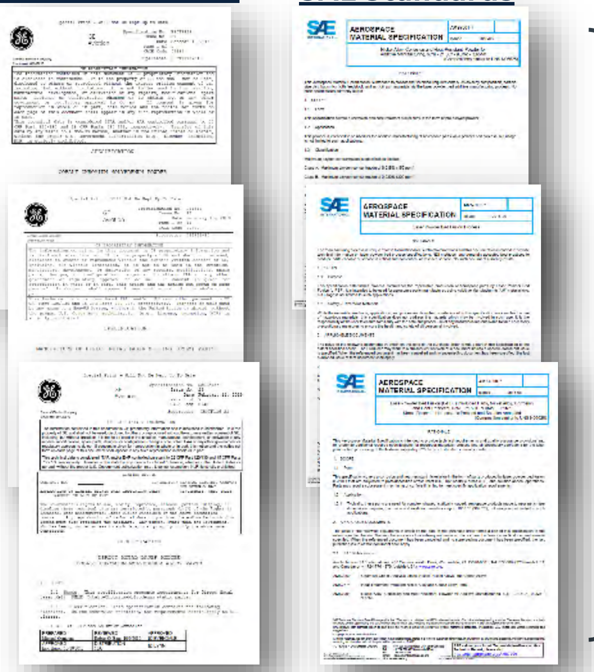
<u>OEM Secification</u>

<u>SAE Standards</u>

Powder

Process

Material



<u>ASTM Standard</u> (3-in-1)

<u>OEM, SAE, & ASTM All include:</u>

Composition Chemistry Tolerance

Full Heat Treatment Tolerances

Minimum Tensile Strength Requirements

<u>OEM</u>

*"**Microstructure** Requirements… shall consist of **XXXXXX**"*

*"The average **grain** size shall be **XXXXXX**"*

*"**Porosity**. A representative test coupon or actual part… shall be used to verify… Porosity… that is greater than **XXXXXX** shall be rejected"*

<u>SAE</u>

*"**Metallography**… shall exhibit **XXXXXX**"*

*Average **grain** size shall be **XXXXXX**"*

*"Parts and test specimens shall be uniform in quality and condition; shall meet the **destructive and non-destructive criteria** defined in the technical data package authorized by the Cognizant Engineering Organization."*

<u>ASTM</u>

*"The **microstructural** requirements and frequency of examinations shall be mutually agreed upon by the supplier and purchaser."*

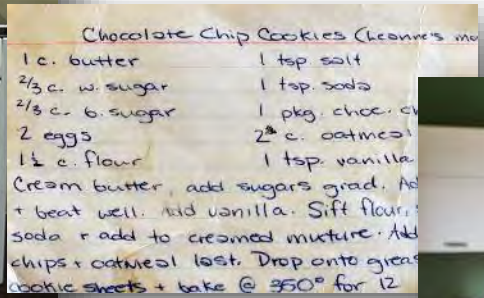
*"Allowable **porosity**… Inspection requirements as agreed between the purchaser and component supplier"*

A Qualified Process Analogy

Raw Materials

Equipment

Specifications



Manufacturing Know-how

Quality

Post Processing and Finishing

I use grandma's recipe. Why don't my cookies taste the same?

Photo credits: Romain Behar, Usman Dar, Airbnb, Pillsbury

A Qualified Process Analogy

Raw Materials

Equip

uality

Post Processing and Finishing

I use grandma's recipe. Why don't my cookies taste the same?

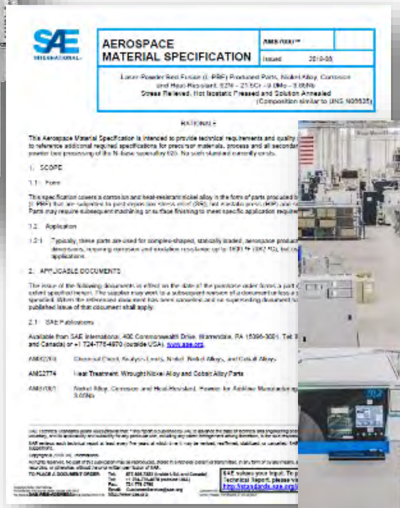
Photo credits: Romain Behar, Usman Dar, Airbnb, Pillsbury

A Qualified AM Process

Raw Materials

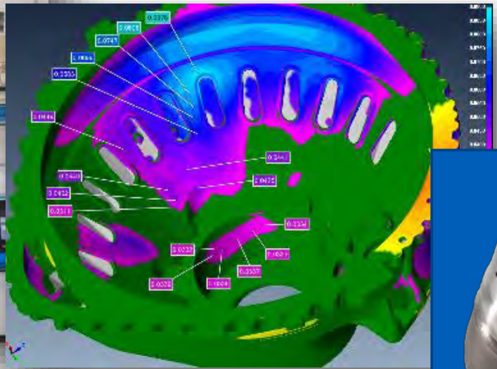
Equipment

Specifications

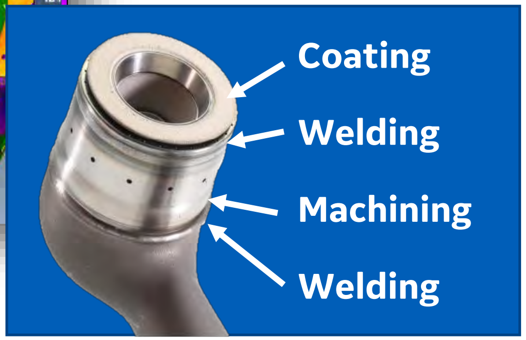

AEROSPACE MATERIAL SPECIFICATION

Manufacturing Know-how

Quality



Post Processing and Finishing

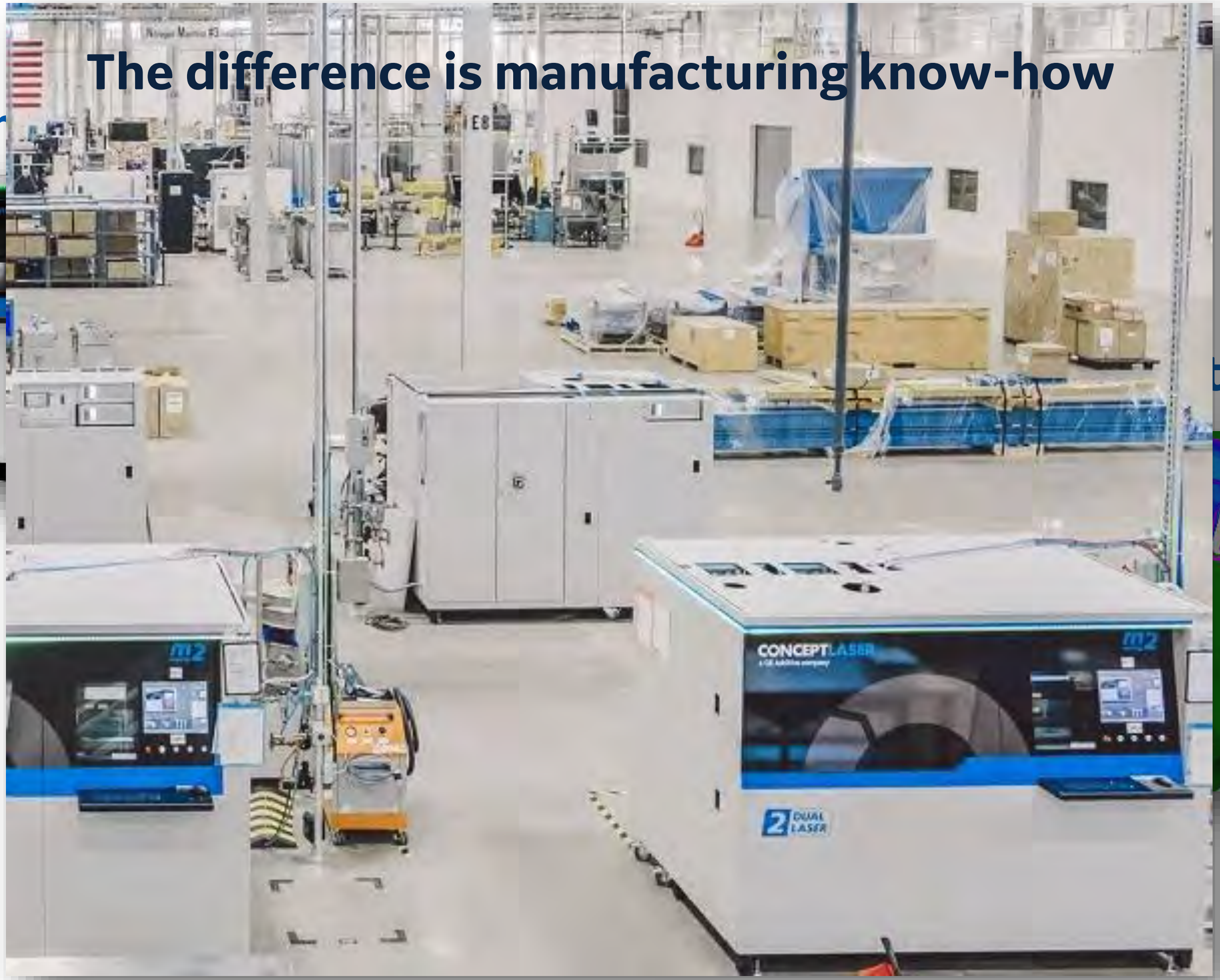


I used the industry specification. Why is there so much variation?

A Qualified AM Process

Raw Materials

Equipr



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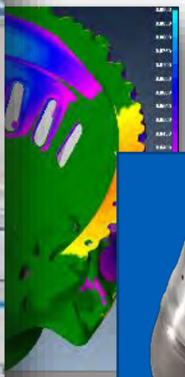
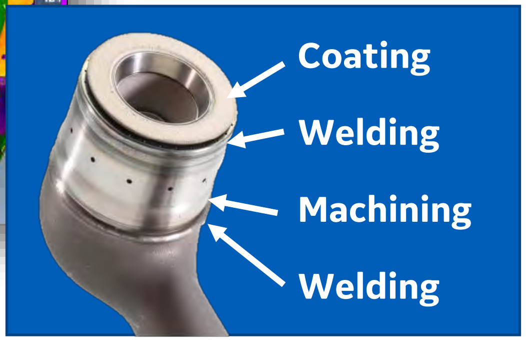


Post Processing and Finishing



I used the industry specification. Why is there so much variation?

Part Design Qualification Example

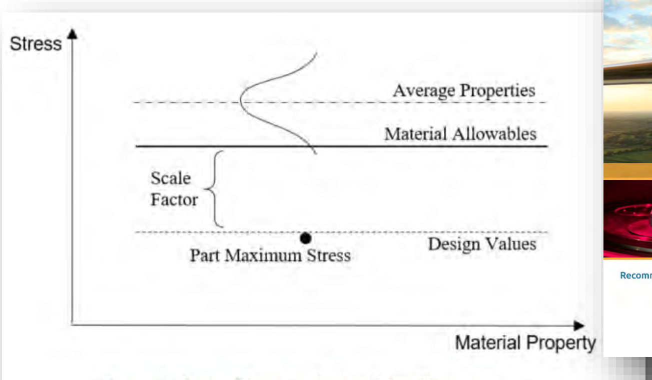
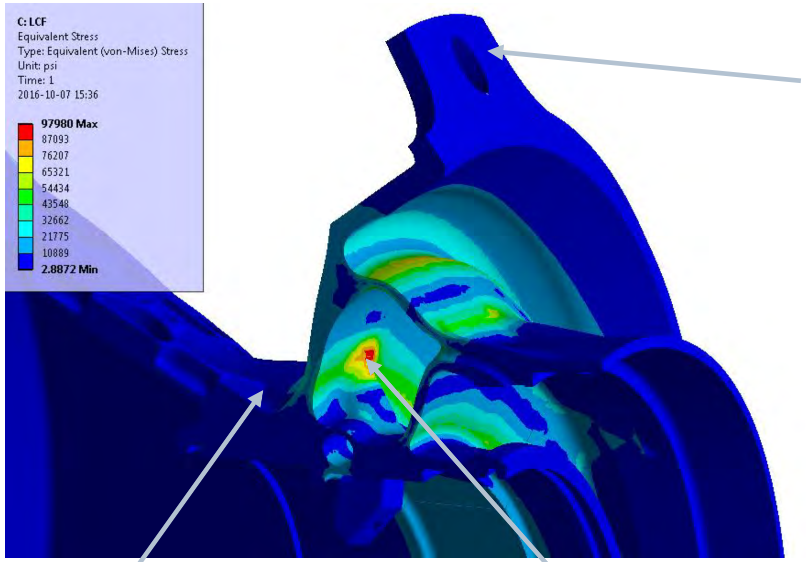


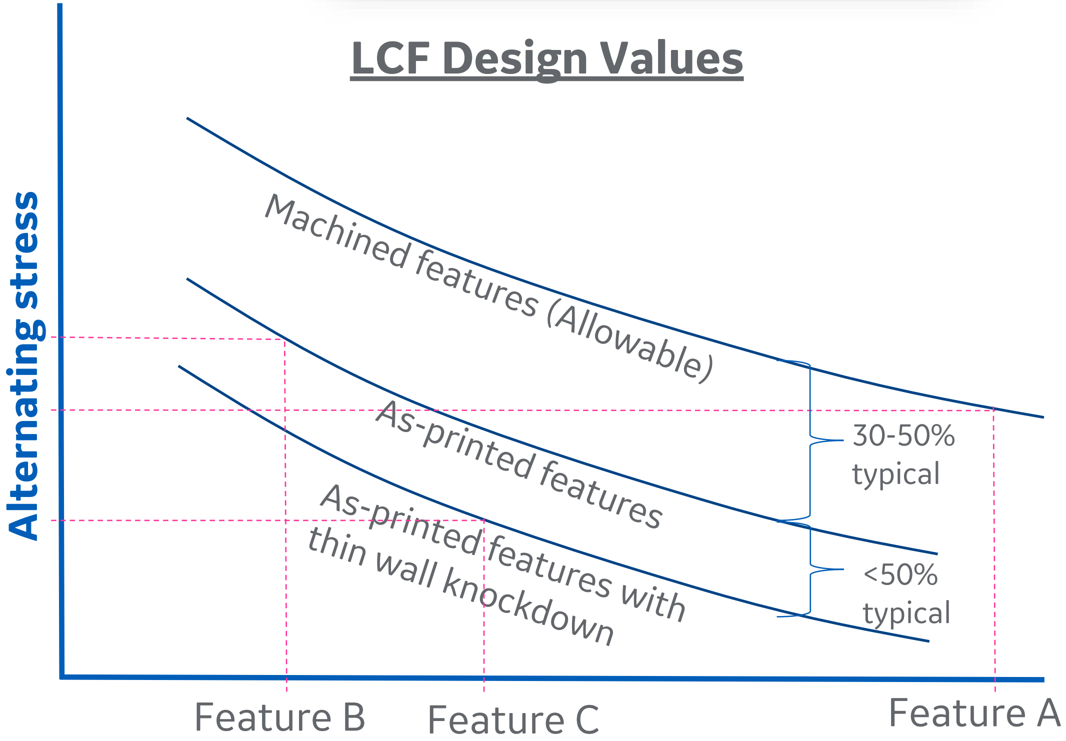
Figure 9: Design Margin to Design Value Illustration



Feature A
Machined bolt hole

Feature B
As-printed surface

Feature C
As-printed, thin wall

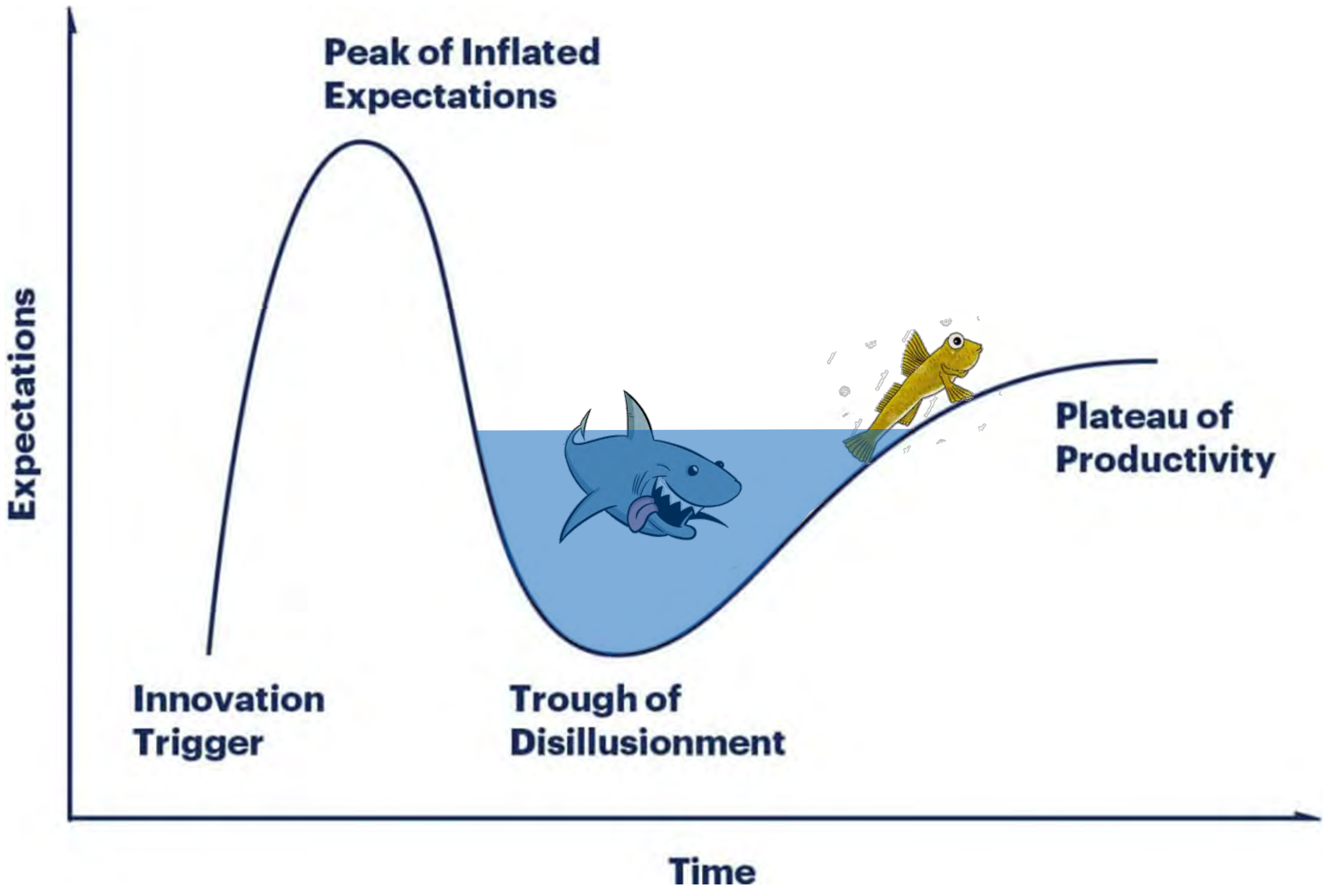


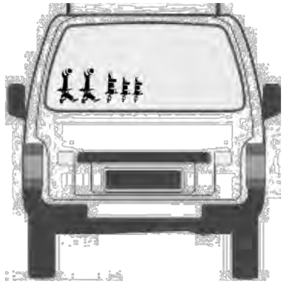
This is what I have learned…

Finding our way out of the "Trough of Disillusionment"

Barriers are NOT technical

- ❑ Incumbent Culture
- ❑ Material Allowables
- ❑ Manufacturing Know-how (trade secrets)
- ❑ Supply Chain Modernization Costs
- ❑ Workforce Training
- ❑ Regulatory Policy





Part Family: One Name with so Many Meanings…

Certification Part Family – A group of parts, assemblies, or applications which can be shown to meet certification requirements under a single test program (e.g. seat families, minor part changes)

Feature Part Family – A group of part features which by common test method can be shown to meet qualification requirements (e.g. AM surface texture, AM thin wall, AM radii)

Qualification Part Family – A group of parts designed using the same material spec and allowables. (e.g. GE Fuel nozzle, GE90 T2.5 Sensor, GE B-Sump Module, GE Heat Exchanger)

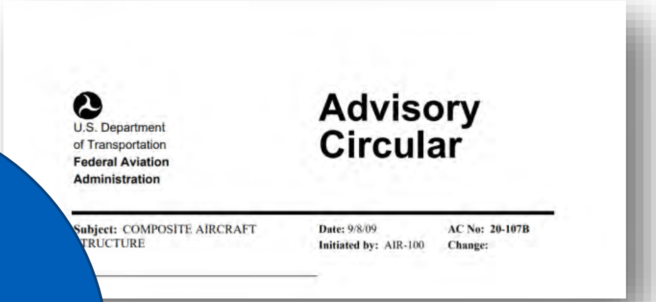
Sustainment Part Family – A group of spare parts with similar application, shape, and manufacturing method. (e.g. pylon fairings, knobs)

ASTM Part Family – A group of AM parts which share a common qualification and certification framework such that part qualification time and resources can be reduced. (ASTM F42.05)

… and I am sure there are more definitions….

AM certification: How does it all fit together?

Application & criticality



Guidance Material

Type Certificate

Production Certificate

Metals Approach

Qualification of supply chain…

to a **part family material** standard

Part Family

Material Specs & Allowables

Composite & Polymer Approach

Qualification of supply chain…

to a single **part number material** requirements

Part Number

Material Specs & Allowables

Point Design Approach

Qualification of supply chain…

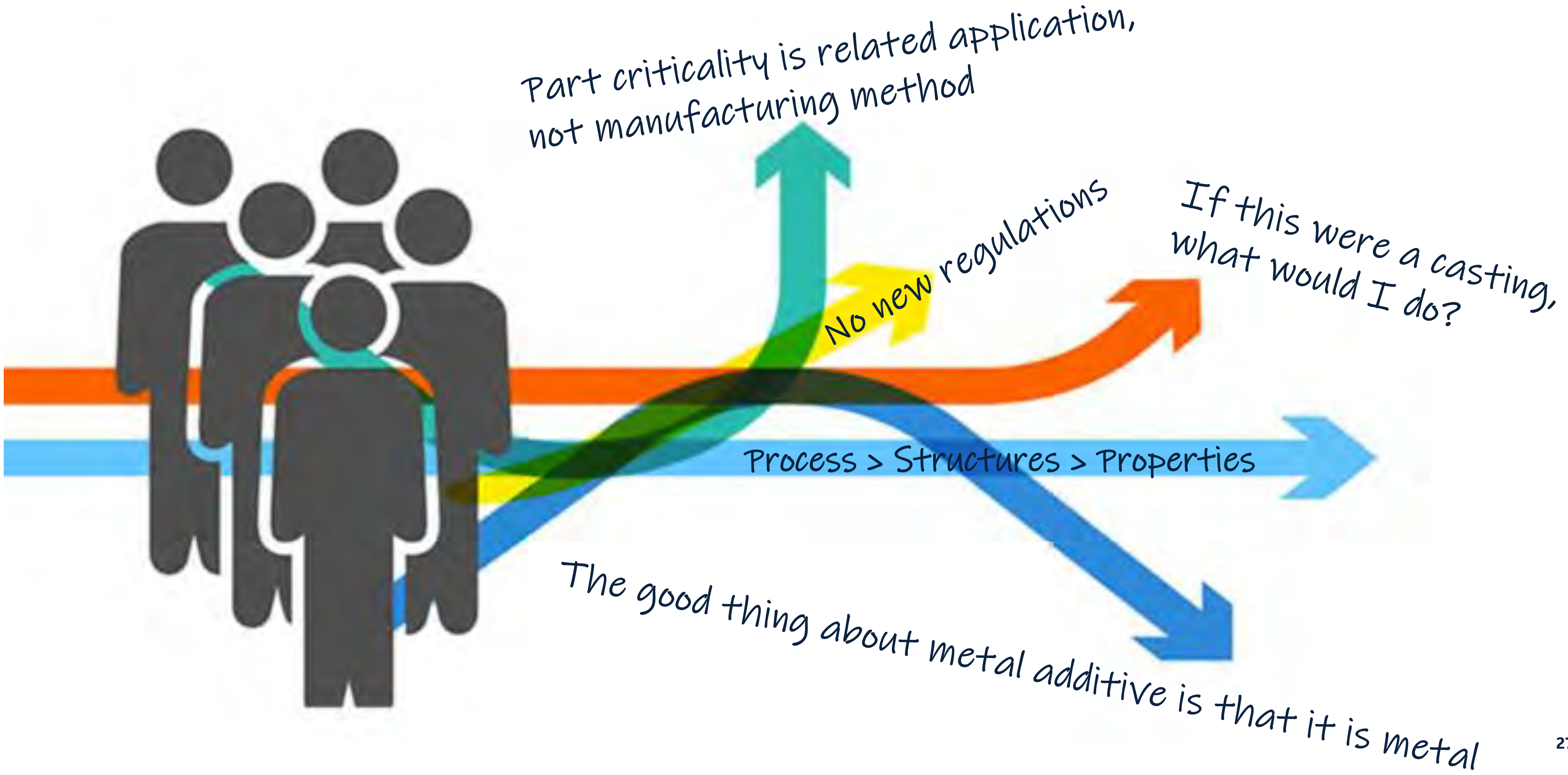
to a single **part number performance** requirements

Part Number

Part Performance

Stay on the familiar path

Relating to what we know to be true, how it is similar to something which is proven, and using existing regulations is the lowest risk approach to change.



NO is the first step towards YES

"No" often means, "I am not ready". It is our responsibility to help others become ready

I am uncomfortable!

Where is the data?

This is unfamiliar to me.

What will happen if I don't say yes?

I need to know more.

I don't understand.

Frankly, it is easier to not change.

Never Give In!

Credit: War Office official photographer, Major W. G. Horton

Never give in...
never, never, never, never,
in nothing great or small,
large or petty, never give
in except to convictions of
honor and good sense.
Never yield to force;
never yield to the
apparently overwhelming
might of the enemy.

- Winston Churchill -

Appendix E

FAA Update
– M. Gorelik (FAA)

2022 AM Workshop Overview and FAA AM Update

Presented at:

Joint FAA-EASA AM Workshop (*virtual*)

October 17, 2022

Presented by:

Dr. Michael Gorelik,

Chief Scientist for Fatigue & Damage Tolerance

Federal Aviation Administration

Outline

- Workshop Objectives
- Observed Trends in AM
- Examples of Internal FAA Activities
- R&D
- Engagement with External Organizations
- Summary

Workshop Objectives

A rising tide lifts all boats

John F. Kennedy

<u>Context</u>:

- **The importance of sharing knowledge to lift safety all across the world**
- **Introduction of new technologies (such as AM)**

see next slide for details

Workshop Objectives *(cont.)*

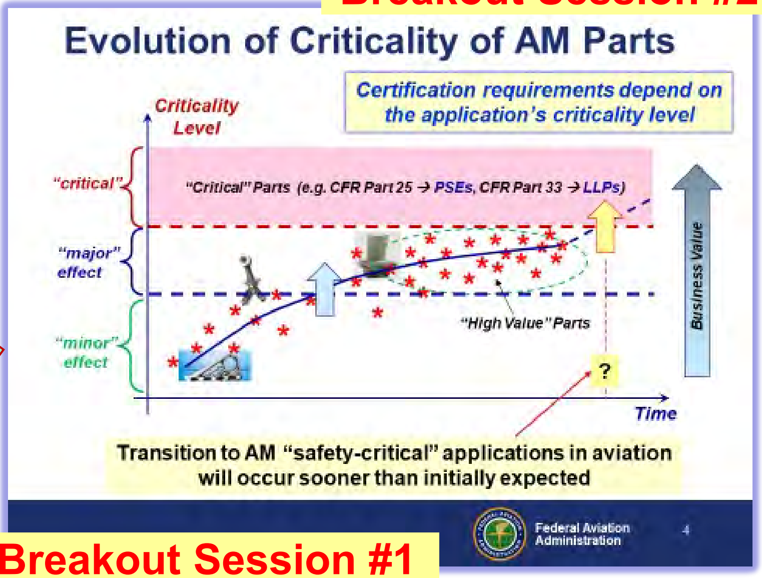
- **Sharing of information in a pre-competitive format**
  - Best practices / new technology developments / lessons learned /etc.
  - All proceeding are released in public domain
- **Learning opportunities**
  - Workshop participants' experience level ranges between experts, end users / practitioners, regulators / QA professional, standards developers, and new entrants
- **Development of new content**
  - Through *breakout sessions* and supporting working groups

Continuing Evolution of AM Landscape…

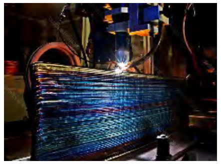
- **By product type**
  - **From "conventional" products…**
    - Engines
    - Transport Airplanes
    - Rotorcrafts
    - GA Airplanes
  - **…to UAVs / UAMs / eVTOL**
- **By criticality level**
- **By AM process type**
  - **From PBF and DED to →**
    - ***"Solid-state" AM processes***
    - ***Hybrid AM (3D printing + CNC machining)***
- **By application type**
  - **From OEM products to →**
    - ***MROs (including owner-produced parts)*** **Ref. 12**
    - ***PMAs***

Ref. 8, 10

Breakout Session #2



Breakout Session #1

Other Trends in AM *(incomplete list)*

- **Evolution of NDE methods, including in-situ process monitoring** Ref. 3, 13
- **Better understanding of process parameters space** Ref. 2
- **Improvement in modeling capabilities** Ref. 7, 10
- **Increasing interest in powder reuse (*and its limits*)**
- **Understanding of machine re-qualification requirements** Breakout Session #3
- **Development of AM materials allowables**
  - both data and framework Ref. 4, 5, 6
- **Significant increase in R&D focused on Q&C of AM**

*Reference in **red** correspond to Agenda items on pp. 12-14*

FAA R&D Areas *(partial list)*

- **Development of material databases (JMADD – PI: NIAR)** Ref. 4
- **Effect of volumetric defects (PI: Auburn U.)**
- **Surface integrity assessment (PI: Auburn U.)**
- **Understanding of process parameters drift / KPVs (PI: Auburn U.)**
- **Characterization of variability in properties and round-robin studies (PI: U. of Washington)**
- **Probabilistic DT framework for AM (PI: SwRI)**
  - collaboration with NASA, USAF and NAVAIR
- ***Benchmarking* of NASA ULI Program (PI: CMU)** Ref. 2
- ***Benchmarking of Modeling and Simulation R&D***
  - collaboration with NASA, NIST, DoD, industry

*Reference in **red** correspond to Agenda items on pp. 12-14*

Federal Aviation Administration

Engagement with SDOs, Consortia and Working Groups *(partial list)*

- **ASTM F42** (multiple standards and specs)
- **SAE AMS-AM** (multiple standards and specs)
- **MMPDS Vol. 2** (development of allowables for metallic AM) Ref. 5
- **CMH-17** (development of allowables for non-metallic AM)
- **America Makes** (various R&D programs)
- **AMSC** (update of the AM Standardization Roadmap – Rev. 3)

*Reference in **red** correspond to Agenda items on pp. 12-14*

Summary *(largely unchanged from 2021)*

- **All existing FAA *rules* apply to AM**
- ***However*… need to consider unique / *AM-specific attributes*, especially for higher criticality components**
- **Leverage experience with other relevant material systems and historical "lessons learned"**
- **Increasing role of public standards, specifications and data – *part of the performance-based regulatory landscape***
  - ***Support development of Means of Compliance (MOCs)***
- **Significant interest in developing public material allowables and corresponding eco system**
- **Increasing industry's interest in maturing Computational Materials / ICME capabilities**

Discussion

Dr. Michael Gorelik

Chief Scientist, *Fatigue and Damage Tolerance*

Aviation Safety

Federal Aviation Administration

michael.gorelik@faa.gov

2022 Workshop Agenda

Agenda – Days 1/2

Workshop Agenda (rev. 10/14/22)

Joint FAA – EASA Workshop on Qualification / Certification of Additively Manufactured Parts

October 17-20, 2022

Venue: *virtual (Zoom)*

- **Workshop Co-organizers:** Michael Gorelik (*FAA*) and Simon Waite (*EASA*)
- **Workshop Facilitator:** Rollie Dutton (*ARCTOS*)

Note: all times listed below are in EDT

Day 1 – October 17

9:00 – 9:30 Arrival and Zoom Orientation (optional, but recommended to verify system compatibility)

9:30 – 9:55 Welcome / Agenda Review / Workshop Format – *M. Gorelik, S. Waite, R. Dutton*
9:55 – 10:05 FAA Leadership Opening Remarks – *Bruce DeCleene, Deputy Director, Policy and Innovation Division*
10:05 – 10:40 Keynote Presentation – *Mark Shaw, Director of Additive Programs, GE Edison Works*
10:40 – 11:00 FAA Update – *M. Gorelik (FAA)*
11:00 – 11:20 EASA Update – *S. Waite (EASA)*
11:20 – 11:40 Break
11:40 – 12:00 "Wire DED Processes, Control and Quality Assurance" – *C. Johnson (Norsk Titanium)* **Ref. 1**
12:00 – 12:20 "Overview of NASA ULI program" – *A. Rollett (CMU)* **Ref. 2**
12:20 – 12:40 "Dynamic NDE with Online Process Monitoring - A Safer and More Economical Approach?" – *S. Rott (MTU)* **Ref. 3**

12:40 – 13:30 Introduction of Breakout Sessions for Days 2 and 3 (and summary of 2021 results)

- Working Group 1: Qualification of AM Parts of No, or Low, Criticality (for use in Certified products) -- *Co-chairs: S. Waite (EASA) and O. Kastanis (EASA)*
- Working Group 2: F&DT and NDI Considerations for Metal AM -- *Co-chairs: M. Gorelik (FAA), A. Fischerworring-Bunk (MTU)*
- Working Group 3: Improved Communication and Data Sharing between AM Machine Makers and End Users -- *Co-chairs: D. Godfrey (SLM), F. Lartategui Atela (ITP Aero), R. Mellor (Rolls Royce)*

13:30 Adjourn of Day 1

Day 2 – October 18

9:00 – 9:30 Arrival / Log-in / System Checks (optional)

9:30 – 11:30 Parallel Breakout Sessions *(including breaks)* **– Part 1**

Breakout Session #1 – "Qualification of AM Parts of No, or Low, Criticality (for use in Certified products)"

Agenda – Days 2/3

Workshop Agenda (rev. 10/14/22)
Co-chairs: S. Waite (EASA) and O. Kastanis (EASA)

Breakout Session #2 – "F&DT and NDI Considerations for Metal AM"
Co-chairs: M. Gorelik (FAA) and A. Fischersworring-Bunk (MTU)

Breakout Session #3 – "Improved Communication and Data Sharing between AM Machine Makers and End Users", *Co-chairs: D. Godfrey (SLM), F. Lartategui Atela (ITP Aero), and R. Mellor (Rolls Royce)*

11:30 – 11:50 "JMADD - Public Ti-6Al-4V LPBF Qualification" – *J. White (NIAR)* **Ref. 4**

11:50 – 12:10 "MMPDS and Additive Metals" – *D. Hall (Battelle)* **Ref. 5**

12:10 – 12:30 "The Concept of Material "Engineering Equivalence" in Achieving and Sustaining Efficient Qualification and Certification of AM Materials and Parts" – *D. Wells (NASA)* **Ref. 6**

12:30 – 13:30 Mini-Symposium on Computational Materials **Ref. 7**

- "Model-Assisted Validation and Certification of AM Components" – D. Furrer (Pratt & Whitney)
- "Computational Framework for Rapid Qualification" – *M. Maher (Maher & Associates LLC)*
- "Demonstrating Computation Materials Engineering Solutions" – *D. Lamm (LMCO)*

13:30 Adjourn of Day 2

Day 3 – October 19

9:00 – 9:30 Arrival / Log-in / System Checks (optional)

9:30 – 9:50 "Extreme Value Statistics of Metal AM and Fatigue" – *L. Bruder (MTU)* **Ref. 8**

9:50 – 10:10 "AM Part Family Qualification & Certification for Aviation" – *M. White (ASTM)* **Ref. 9**

10:10 – 10:30 "Methods for Zoning AM Components Using Machine Learning" – *M. Groeber (OSU)* **Ref. 10**

10:30 – 10:50 "Powder Reuse in Additive Manufacturing" – *E. Bono (6K Inc.)* **Ref. 11**

10:50 – 11:10 Break

11:10 – 13:30 Parallel Breakout Sessions *(including breaks)* **– Part 2**

Breakout Session #1 – "Qualification of AM Parts of No, or Low, Criticality (for use in Certified products)"
Co-chairs: S. Waite (EASA) and O. Kastanis (EASA)

Breakout Session #2 – "F&DT and NDI Considerations for Metal AM"
Co-chairs: M. Gorelik (FAA) and A. Fischersworring-Bunk (MTU)

Breakout Session #3 – "Improved Communication and Data Sharing between AM Machine Makers and End Users", *Co-chairs: D. Godfrey (SLM), F. Lartategui Atela (ITP Aero), and R. Mellor (Rolls Royce)*

13:30 Adjourn of Day 3

Agenda – Day 4

Workshop Agenda (rev. 10/14/22)

Day 4 – October 20

9:00 – 9:30 *Arrival / Log-in / System Checks (optional)*

9:30 – 10:45 ***Authorities Panel***

10:45 – 11:05 "The Use of AM for Repairs – An SAE AMS-AM Perspective" – *D. Abbott (GE Aerospace)* **Ref. 12**

11:05 – 11:25 "Progress in Development of NDE Tools for Classification, Process Monitoring and Acceptance of AM products" – *L. Schaefer (General Atomics)* **Ref. 13**

11:25 – 11:40 Break

11:40 – 13:10 ***Breakout Sessions Debriefs***

- Breakout Session #1 – *Co-chairs: S. Waite (EASA) and O. Kastanis (EASA)*
- Breakout Session #2 – *Co-chairs: M. Gorelik (FAA) and A. Fischersworring-Bunk (MTU)*
- Breakout Session #3 – *Co-chairs: D. Godfrey (SLM), F. Lartategui Atela (ITP Aero), and R. Mellor (Rolls Royce)*

13:10 – 13:30 Wrap-up and Closing Comments – *M. Gorelik (FAA) and S. Waite (EASA)*

13:30 Adjourn of the 2022 Workshop

Appendix F

EASA Update
– S. Waite (EASA)

EASA – Structures and Materials Safety

FAA - EASA AM

INDUSTRY – REGULATOR EVENT

EASA – WELCOME & UPDATE

(virtual meeting)

October 2022

S.Waite, Senior Expert Materials, Certification Directorate, EASA

M.Gorelik, Chief Scientific and Technical Advisor Fatigue and Damage Tolerance, FAA

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2022

FAA - EASA

Industry-Regulator AM Event (Virtual)

Further to the 2021 Event, EASA thanks FAA for hosting the 2022 Event

… Michael Gorelik, Roland Dutton, in particular, for their efforts and preparation

… and the Working Groups

1. Qualification of Additive Manufacturing (AM) Parts of No, or Low, Criticality (for use in Certified products)
2. Fatigue and Damage Tolerance (F&DT) and Non-Destructive Inspection (NDI) Considerations for Metal AM
3. AM Machine Makers and End Users – Key Process Parameters (KPPs), Qualification, Requalification, and the Ideal ‘End State’

2022

EASA - FAA

Industry-Regulator AM Event (Virtual)

Further to the 2021 Event…

Since 2021…

- growing number of new and potential applications
- majority of applications of 'no or low' criticality

EASA effort attempting to prioritise developing industry needs, e.g. WG1 'no and low' criticality activities with respect to
'step by step' approach to criticality

Since 2021…

- supported by:
  - EAAMIRG activities
  - EASA AM WG (internal)
  - Industry WG/SDO activities
  - developing EASA AM CM-S-008 revision

EASA - AM

Reminder: EASA AM First Points of Contact (across products and disciplines):

(EASA CM-S-008 issue 3 Draft Revision changes)

Materials	S. Waite	simon.waite@easa.europa.eu
Aircraft Structures	W. Hoffmann	wolfgang.hoffmann@easa.europa.eu
Propulsion (Engines, Propellers & APU)	O. Kastanis*	omiros.kastanis@easa.europa.eu
Cabin Safety	T. Ohnimus	thomas.ohnimus@easa.europa.eu
	F. Negri	fabrizio.negri@easa.europa.eu
Systems	M. Weiler	michael.weiler@easa.europa.eu
Design Organisation Approvals	C. Caruso*	claudio.caruso@easa.europa.eu
Production Organisation Approvals	D. Lamothe	dominique.lamothe@easa.europa.eu
Maintenance Organisation Approvals	R. Tajes	rosa.tajes@easa.europa.eu
+ ETSO	TBD	

*original members M. Mercy (propulsion), A. Enache (DOA)

EASA - AM

EASA Update:

1/ Regulation context reminder (existing and recent/new)

2/ Advanced Materials and Processes - Developing Rulemaking and Guidance

- EASA AM CM-S-008 ‘Additive Manufacturing’ revision
- NPA 2020-11 ‘Miscellaneous’

3/ European Aviation AM Industry Regulator Group (EAAMIRG)

4/ Working Groups… see later WG updates

Questions?

easa.europa.eu/connect

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European Union Aviation Safety Agency

Federal Aviation Administration

EASA – Structures and Materials Safety

FAA - EASA AM

INDUSTRY – REGULATOR EVENT

EASA - UPDATE

(virtual meeting)

October 2022

S.Waite, Senior Expert   Materials, Certification Directorate, EASA
M.Gorelik, Chief Scientific and Technical Advisor   Fatigue and Damage Tolerance, FAA

Your safety is our mission.

An Agency of the European Union

EASA - AM

EASA Update:

1/ Regulation context reminder (existing and recent/new)

2/ Advanced Materials and Processes - Developing Rulemaking and Guidance

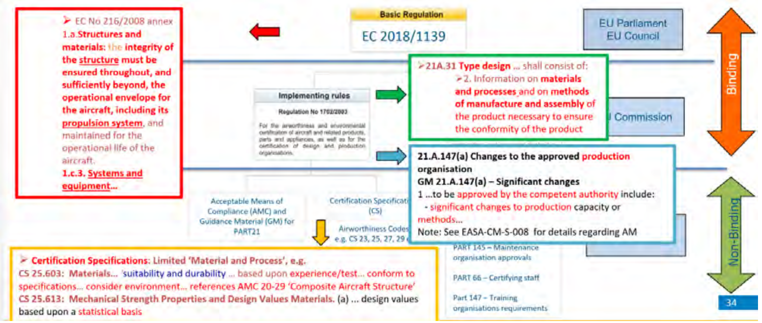
- EASA AM CM-S-008 ‘Additive Manufacturing’ revision
- NPA 2020-11 ‘Miscellaneous’

3/ European Aviation AM Industry Regulator Group (EAAMIRG)

EASA – AM (see back up slides)

1/ Reminder: Existing Regulatory Context/Framework (moving toward, **performance' based regulations**)

- Regulations relating to 'material, process, manufacturing methods' are built into the 'Binding Regulations'



Where are the 'engineering properties' developed in the pyramid?

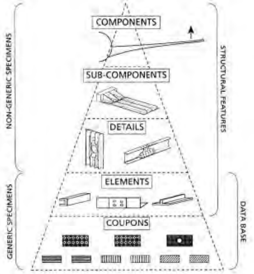
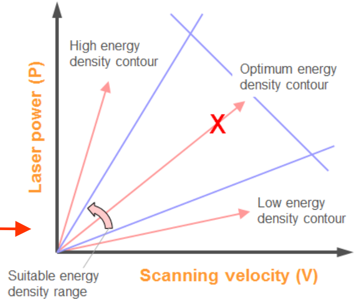


Figure 1 - Schematic diagram of building block tests for a fixed wing.

- 'Engineering Properties' are defined by 'material, process, manufacturing methods' & built directly into the (complex) part or repair

- sensitive processes and competing damage modes
- identify Key Process Variables & Parameters, including sensitivity of engineering properties to these...



- change not to reduce the existing 'acceptable' level of safety
  - complex reference point
  - use 'robust' design concepts
  - 'Step by Step' approach wrt criticality
  - test v analysis?
  - optimised design?

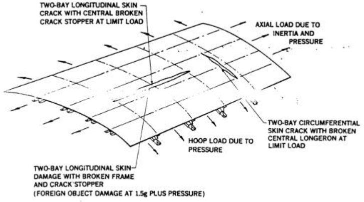


FIGURE 2. FUSELAGE DAMAGE TOLERANCE SIZES FOR STRUCTURAL DESIGN

EASA

EASA - AM

EASA – move towards ‘performance’ based regulations*:

Performance-Based Regulation (PBR): A regulatory approach that focuses on desired, measurable outcomes.

Prescriptive Regulation: A regulation that specifies requirements for mandatory methods of compliance.

- work with standardisation organisations and other industry groups, e.g. SAE, ASTM, NCAMP**, CMH-17*** , EAAMIRG, AIA etc

Note: ‘Certification Efficiency’ could benefit from co-ordinated complementary SDO activities…

Note: PBR has been, and is being, applied to other industries, so there may be some useful ‘lessons learned’ for aviation (see the Food and Drug Administration presentation EASA FAA AM Event 2021 WG)

*https://www.easa.europa.eu/sites/default/files/dfu/Report%20A%20Harmonised%20European%20Approach%20to%20a%20Performance%20Based%20Environment.pdf
** extending shared database activities beyond composites to include AM
***new non metallic AM Volume 7 in development

EASA – Regulatory Framework and Change

EASA priorities and resources…

Need for 'harmonised' position continues to be noted!

21.B.100 Level of Involvement (LoI) (Part21 amdt Autumn 2019)

…. (a) ***The Agency shall determine its involvement*** *in the verification of the compliance demonstration activities and data related to the application for a type-certificate etc… and* ***consider at least the following elements****:*

1. ***… the novel or unusual features of the certification project, including operational, organisational and knowledge management aspect…***

3. … the ***criticality of the design or technology*** *and the related safety and environmental risks, including those identified on similar designs*

- Certification effort to be proportionate to criticality

EASA - AM

Certification – Proportionate Certification – Proportionate to criticality?:

- **What is '*Criticality*'?** (PART 21 AMC 21.B.100(a) 'Level of Involvement' (LoI))… **as defined** **in context of LoI**:

  '… measure of ***the potential impact of a non-compliance with part of the certification basis on product safety*** *or on the environment'*

  The supporting guidance continues:

  '…The ***potential impact of a non-compliance*** *within a Compliance Demonstration Item (CDI) should be* ***classified as critical if****, for example: …a function, component or system is introduced or affected where the* ***failure of that function, component or system may contribute to a failure condition that is classified as hazardous or catastrophic at the aircraft level**** *…'*

  * also systemic failure at pax. Level, e.g. multiple seat failures

- **any application with potential criticality clearly would be expected to fully comply with all requirements** (noting the **novelty** (and **complexity**) aspects of AM, such applications are unlikely to initially be considered by EASA, other than under experienced TCH control supported by an appropriate **'step by step' approach**)

- **for other less critical applications 'certification proportionality' requires understanding of technical criticality…**

need for broader awareness and understanding of Safety Assessment…
- key to developing WG1 activities

EASA - AM

Categorisation of criticality for AM – ASTM F3572-22 ‘Standard Practices for Additive Manufacturing – General Principles – Part Classifications for Additive Manufactured Parts Used in Aviation’
(and EAAMIRG Action 1)

Classification	Consequence of Failure	General Description
A	High	Part the failure of which can directly affect continued safe flight and landing Part the failure of which can result in serious or fatal injury to passenger or cabin crew Part the failure of which can result in excessive load for the flight crew
B	Medium	Part the failure of which can indirectly affect continued safe flight and landing Part the failure of which can result in injury to passenger or cabin crews or maintenar Part the failure of which can result in a significant increase in workload for the flight
C	Low	Part the failure of which has no affect on continued safe flight and landing Part the failure of which has no affect on passengers and cabin crews Part the failure of which can result in a slight reduction in operational/functional cap Part the failure of which can result in a slight increase in workload for the flight crew
D	Negligible or No Effect	Part not covered above Part the failure of which would pose no risk of damage to other equipment or person Part not affecting operational/functional capabilities

Note: Various definitions of criticality/safety classification exist across products. However,

- these can be mapped to this table
- not intended to change existing ‘criticality’ processes
- link to proportionate MoCs?
- NOT NEW, but AM offers potentially more competing damage modes and safety outcomes

Simplify and standardise criticality/safety classification… potentially functions in the context of Performance Based Regulations (beyond AM) across products, particularly for integrated technologies… (**aircraft and pax safety level**)

EASA

EASA - AM

Changing technology… and supply chain knowledge management

Other relevant regulations and regulatory activities: Operational Suitability Data (OSD)

- **need for the user communities**

– ***mandating that aircraft manufacturers***, *including those building helicopters, to* ***submit data EASA considers important for safe operations****.* ***OSD covers*** *pilot training,* ***maintenance staff*** *and simulator qualification; the master minimum equipment list (MMEL); and possibly other areas, depending on the aircraft's systems.'*

increasingly important if relying upon 'performance' based regulation

Example: Composites…

CM-MCSD-001 Issue 1 'Development of **OSD** for **Maintenance Certifying Staff**'

- training/knowledge link to AC20-107B/AMC 20-29/SAE AIR 5719

Composite Training Guidance

- similar concept for AM?

(avoid re-inventing the wheel when appropriate!)

New Technology - some form of mitigation strategy necessary to link TCH technology evolution with the appropriate level of in-service **knowledge base and training**

EASA - AM

Changing technology… and supply chain knowledge management

‘Step by Step’ approach… ensure that no or low criticality applications remain so…

Other relevant regulations and regulatory activities: support/awareness PART145 activities,
e.g. Point145.A.42(b)(iii) , CAO.A.20(c) or M.A. 603(c)

FABRICATION OF PARTS FOR INSTALLATION

(c) All necessary **data to fabricate the part should be approved either by the Agency** or the **type certificate (TC) holder**, or **Part 21 design organisation approval holder**, or **supplemental type certificate (STC) holder**.

(g) Examples of fabrication within the scope of a Part-145 approval may include but are not limited to the following:

(1) fabrication of bushes, sleeves and shims;

(2) fabrication of secondary structural elements and skin panels;

(3) fabrication of control cables;

(4) fabrication of flexible and rigid pipes;

(5) fabrication of electrical cable looms and assemblies;

(6) formed or machined sheet metal panels for repairs.

- ‘step by step’ approach relative to criticality…
- AM of growing interest for ‘Repair by Replacement’
- see developing WG1 and WG3 activities

All the above-mentioned **fabricated parts** should be in accordance with the data provided in the overhaul or repair manuals, modification schemes and service bulletins, drawings, or should be otherwise **approved by the competent authority**.

Note: It is **not acceptable to fabricate any item to pattern unless** an engineering drawing of the item is produced which **includes any necessary fabrication process and which is acceptable to the competent authority.**

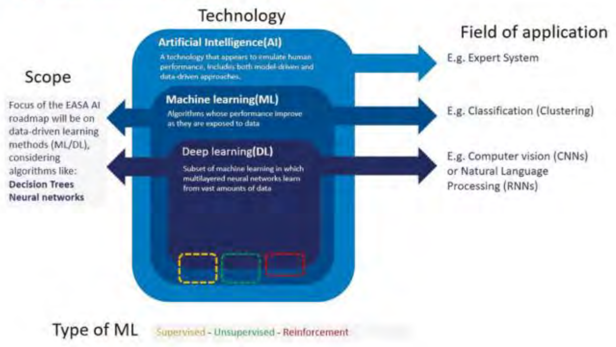
EASA - AM

Other developing and potentially relevant regulations and regulatory activities:

- **Artificial Intelligence (AI) and Machine Learning (ML)*** - initial focus upon ML**….

‘use of data to train algorithms to improve their performance’

Figure 1. AI taxonomy in this Roadmap



Potential ML impacts include:

- **design** and operation?
- **production** and **maintenance**?
- air traffic management?
- drones, urban air mobility?
- safety risk management?
- cybersecurity?
- environment?
- **regulations**… existing regs, e.g. CS2x.1309 + etc?

Note: ‘Modelling and Simulation’ also of growing interest/importance:

*EASA-AI-Roadmap-v1.0.pdf (europa.eu)
** https://www.easa.europa.eu/sites/default/files/dfu/easa_concept_paper_first_usable_guidance_for_level_1_machine_learning_applications_-_proposed_issue_01_1.pdf

EASA - AM

Other relevant regulations and regulatory activities: EASA – R&D:

- EASA Basic Regulation amendment… 2018/1139, Article 86.1… **assist the Member States** and the **Commission** in **identifying key research themes** in the field of civil aviation

- increasing number of EU integrated technology projects, e.g. combining Materials, Processes, Modelling and Simulation, Structural Health Monitoring etc…

- see EASA FAA AM Event 2021 for recent projects

https://www.clean-aviation.eu/clean-sky-2
https://research-and-innovation.ec.europa.eu/funding/funding-opportunities/funding-programmes-and-open-calls/horizon-2020_en

EASA - AM

EASA Update:

2/ Advanced Materials and Processes (AMP) - Developing Rulemaking and Guidance

- as communicated during the 2020 AM Event, no need identified to amend rules specifically for AM, but broader rapidly developing **Advanced Materials and Processes (AMPs),** and consideration of move towards '**performance**' based regs, will likely result in:
  - simplified CS across products, e.g. CS25, 27, 29, CS-E, CS-P (note: CS23 already simplified at amdt 5)
  - increased development of product and/or technology specific AMC, e.g. as CS25.603 does for composites:

'CS 25.603 Materials

(See AMC 25.603;For Composite Materials, see AMC 20-29…)'*

* Harmonised FAA AC 20-107B

To become AMC 20-xx for AMP, including Composites, AM, CMC etc?

EASA - AM

EASA Update:

2/ Advanced Materials and Processes - Developing Rulemaking and Guidance continued…

Example of likely evolution direction:

- recent **NPA 2020-11 'Miscellaneous'** (annual CS update cycle) used as opportunity to start process and provide:
    - minor update CS 25.605 to better reflect more recent AMP technology language and provide more continuity with language already used elsewhere, e.g. CS 25.603*…
    - update to AMC 25.603, 605, 613 to better reflect more recent integrated AMP technology considerations, e.g. emphasise use of the test/analysis pyramid etc

*' *The suitability and durability of materials used for parts, the failure of which could adversely affect safety, must –'*

Amended: CS25 amdt 27 (24/11/22)

EASA

EASA - AM

2/ Advanced Materials and Processes - Developing Rulemaking and Guidance, continued…

EASA CM-S-008 issue 3 Draft Revision changes in progress for 2023 (TBC)

(this revision largely driven by WG1 activities, to be discussed in break-out sessions):

To include changes relating to:

- criticality classification
- certification effort being proportionate to criticality (WG1 'no and low' criticality, particularly non-TCH applications)
- increased emphasis upon Safety Assessments, e.g. FHAs, FMECA, or RASs (WG1 'no and low' criticality, particularly non-TCH applications)
- addition of AM parts of 'no or low' criticality 'Examples'
- updates references

- aligned with 'step by step' approach relative to criticality, and EAAMIRG Action Items
- represents real current industry certification activities
- this amendment driven by WG1 activities

European Aviation AM Industry Regulator Group (EAAMIRG)

EAAMIRG – Summary

Scope/Mission:

- define European Aviation AM interests and priorities
  - safe and efficient AM design, production, in-service utilisation, and certification
- work constructively with other AM groups, e.g. AIA
  - recognising need for harmonisation in increasing complex global industry
  - avoid 'reinventing the wheel'

Organisations initially involved European TCHs, 1st Tier suppliers, EASA, European NAAs

- meetings (approx. 3 per year)

EAAMIRG – **Industry** and EU Regulator membership:

- **Airbus – Commercial**
- **Airbus – Defence and Space**
- **Airbus – Helicopters**
- **Boeing***
- **BAZL** (Switzerland)
- **CAA UK***
- **Dassault**
- **EASA**
- **FAA***
- **GE***
- **GKN**
- **ITP**
- **LBA** (Germany)
- **Liebherr**
- **MTU**
- **Rolls Royce**
- **Safran**
- **TCCA* (2022)**
- **Thales**
- **Traficom** (Finland)

* non-EU 'associate members' invited to **support harmonisation intent**

2022:
- new members
- recognise need to engage with MROs etc
- increasing EAAMIRG applications of increasing criticality

EASA

European Aviation AM Industry Regulator Group (EAAMIRG)

EAAMIRG Activities:

- support **revision to EASA CM-S-008 issue 3**

- identify **EAAMIRG priorities** (based upon priority matrix, and outputs from various workshops etc)

  - **Part Classification and Authority Engagement** (LoI etc)

    - improve **standardisation of the 'criticality' determination process**
    - improve industry and regulator understanding of the subject

    (note: potential to support the CM 'Parts of No Criticality' discussion in user communities)

in progress, continuing to support WG 1, and CM 'no/low criticality' theme

  - **Standardisation: understanding and use of 'standards'**

    - **better understand and identify common 'good practices' when using standards** relative to
      - Criticality of application
      - organisation experience
      - organisational structure in the end to end product chain, e.g. large integrated organisations (including machine suppliers etc) v small organisations in extensive subcontractor chains

started, yet to be developed, supporting WG1, WG 3, and CM

to be continued…

EASA

EASA - AM

AOB: Project Certification – AM Certification Review Items (CRIs)

Note: CRIs are regulatory tools used to address delivery of Special Conditions (potential changes to CSs etc) and/or support Means of Compliance evolution, typically beyond established CSs and interpretation of the CSs, e.g. new technology applications

Recent certification projects:

- intent to continue to make reference to CM-S-008 for no/low criticality applications without CRIs, when applicable. However:
  - criticality of applications is increasing
  - increasing cross discipline applications, e.g. structures/systems, propulsion/systems
  - increasing use of multiple subcontractors (some not from aviation background)

- need to standardise/improve knowledge transfer within supply chains

therefore, need for CRIs likely to increase, particularly MoC CRIs
to be continued…

EASA – AM

Conclusions:

- increasing use of AM across aviation product applications of increasing 'criticality'

- Rulemaking adapting to 'advanced materials', e.g. developing Ceramic Matrix Composites (CMCs), Polymer Matrix Composite (PMCs), etc… not only AM!, e.g. EASA CM-S-008 revision, CS25 amdt, AMC 20-XX 'Materials and Processes' TBD

- Rulemaking adapting to 'performance' based approach
    - certification effort proportional to 'criticality', 'novelty', 'complexity' (LoI) etc

- need to consider impact of other developing technologies upon AM evolution, e.g. AI, ML, modelling and simulation, SHM etc*?

- need to consider impact of other developing technologies upon regulation**?

* How can this be substantiated and certified?...lack of predictability, explainability, robustness, unintended function, lack of standardisation, bias, variance, complexity, extensive data management… many interacting 'black boxes'? …need for 'trustworthiness' etc

** 'knowledge management' with industry via Innovation Partnership Contracts (IPCs) and Memoranda of Cooperation (MoC) + other mitigating actions, e.g. fleet leader, sampling?

EASA – AM

Conclusions… continued:

- Regulators adapting to industry lead need, e.g. EASA AM CM rev. 'Parts of no/low criticality' - improve safety and business case via refined understanding/management of 'criticality'?, use of shared databases, improve knowledge management?, use of CRIs (only if necessary - across panel disciplines, increasing criticality etc)'

- Industry – Regulator WGs and standards bodies of increasing importance to these processes
e.g. European Aviation AM Industry Regulator Group (EAAMIRG), NIAR, AIA, SAE, ASTM, CMH-17

- Industry and Regulators expected to continue with a '**Step by Step**' approach to using AM, supported by EU R&D etc

Questions?

EASA
European Union Aviation Safety Agency

Support Slides

EASA - AM

Federal Aviation Administration

EAAMIRG – Industry activities increasing…

- need to develop membership is recognised
- e.g. MROs, Operators etc?

EASA

EASA - AM

2/ Advanced Materials and Processes - Developing Rulemaking and Guidance, continued…

EASA CM-S-008 issue 1 'Additive Manufacturing'

- inform EASA early in process if intending to use AM (Project Cert, DOA, POA etc)
- '**Step by Step**' approach etc (no criticality/minimal airframe or pax safety first, iaw LoI etc)

EASA AM CM issue 1 released April 2017 - **needed revision**:

- **increasing criticality of applications** in TCH certifications
- **developing in-service community lead interest**, e.g. STCs, MROs, interiors etc
- **growing diverse spread of industry supply chain experience/knowledge management**
- input from EASA/FAA Workshops, SDO meetings, conferences etc

CM revision (30/4/21) iaw intent shared during the 2020 AM Event

Note: CM is a temporary document, next rev. early 2023?, subject to content evolution

https://www.easa.europa.eu/document-library/product-certification-consultations/final-certification-memorandum-ref-cm-s-008

Part of EASA AM Strategy supported by **EASA AM Working Group**

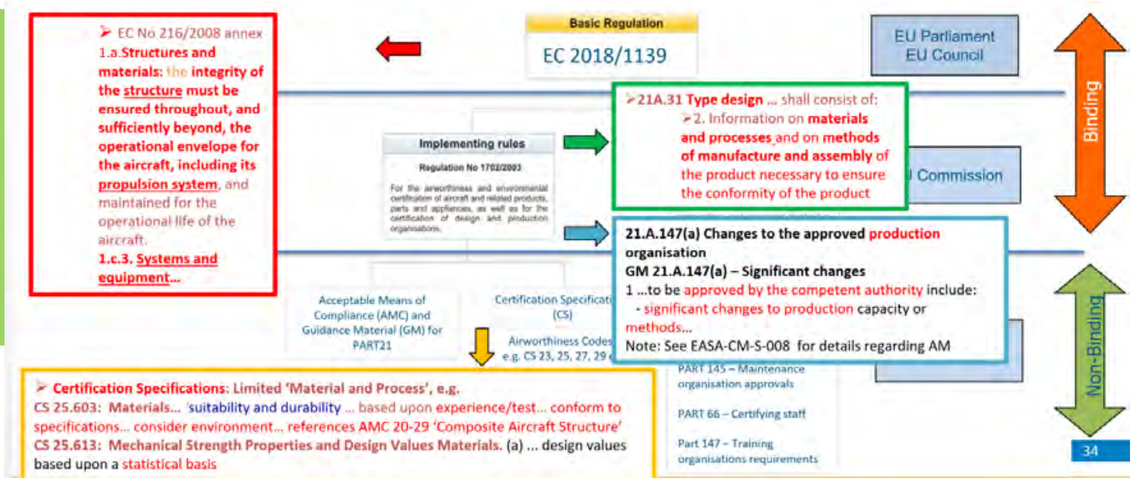
(internal, across products and domains, e.g. POA, DOA, PAT145 etc) and **EAAMIRG**

becoming broader EASA AMP WG (to be confirmed)

EASA - AM

Reminder: Existing Regulatory Framework (moving toward **performance based regulations**)

consideration of materials, processes, methods of manufacture and assembly' etc are 'binding' in the Basic Regulation (BR)



Regulations relating to 'material, process, methods of manufacture, and assembly' are generic from BR to CS/AMC guidance level

EASA - AM

AM ‘Engineering Properties’ are:

- defined by the ‘material and process’
- built directly into the part or repair

a challenge:

- ‘complex parts’ – base pyramid coupon data may not represent the complex part properties (although stable simple base pyramid data is essential…otherwise, how can the higher pyramid work be trusted?)

- ‘sensitive processes’ – a major challenge if completing production activities in a more challenging maintenance environment

Where are the ‘engineering properties’ developed in the pyramid?

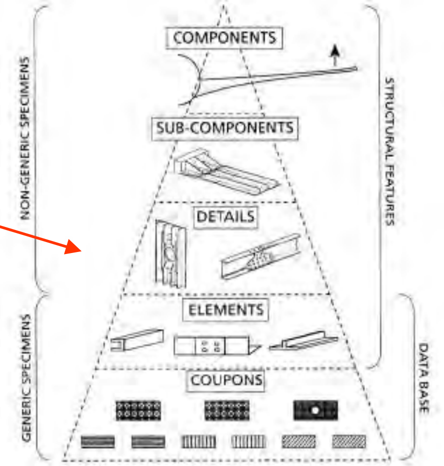
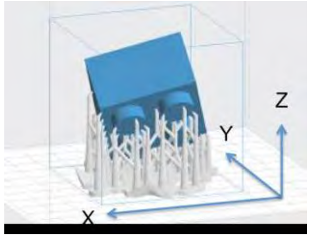


Figure 1 - Schematic diagram of building block tests for a fixed wing.

e.g. AM, composites, bonded joints, advanced alloys

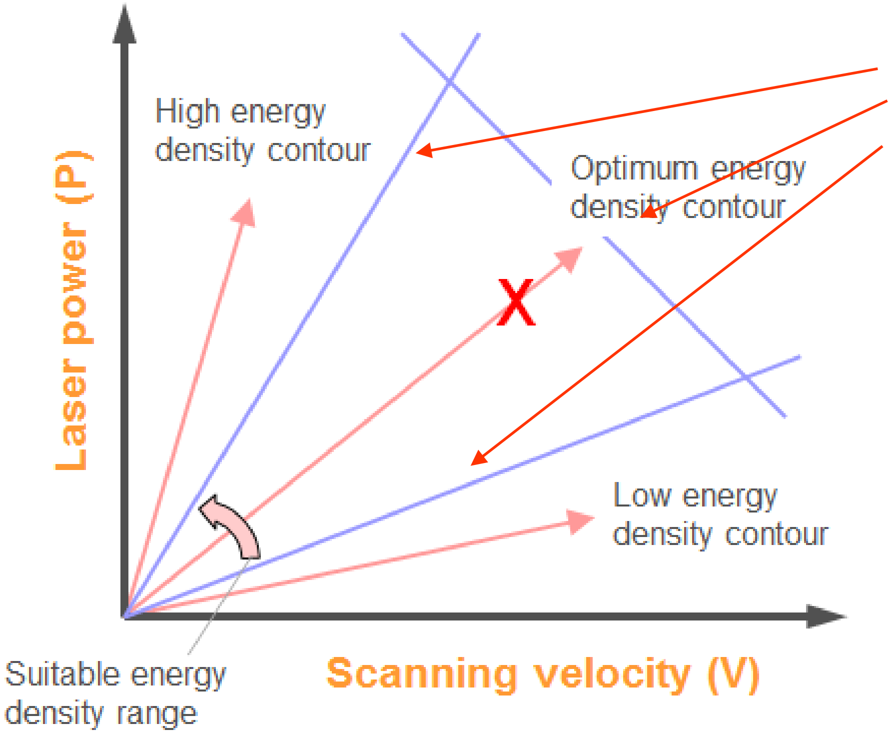
e.g. no access to free edges – fatigue issue?



e.g. support structure on the build platform

EASA - AM

Too many materials, processes, applications …what does EASA need to understand?



Metallic/non-metallic and many processes generalisation:

Boundary definitions:

- **Key Parameter (KP)** definition?
- **Competing defect/damage modes**?
- **Statistical credentials** (A, B-Basis etc)?
- **Sensitivity** (% change in '**engineering properties**' wrt boundaries and **KPs**?)

- 100+ control parameters 20, 30, 40….'KPs'?

EASA

EASA – Regulatory Framework and change

The Regulations – EASA priorities and resources:

applies to baseline structures, **changes, and repairs**

safety is the priority…

‘change should not reduce the existing acceptable level of safety’

Based upon:

- experience
- reaction to incidents and accidents
- R&D
- ‘engineering judgement’
- regulations existing at the time of certification
- Type Certificate Holder (TCH) in-house design pra[illegible]ces

Design with a ‘robust’ design concept

(beyond scope of detailed ‘threat assessment’)

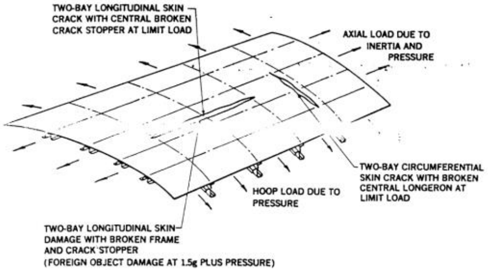


FIGURE 2. FUSELAGE DAMAGE TOLERANCE SIZES FOR STRUCTURAL DESIGN

e.g. Design for Redundant Structures …Tom Swift
For conventional metals, a cracked frame and 2 cracked frame bay skins

Note: part of broader ‘test v analysis’ issue relating to new technology, equivalence, and existing ‘acceptable’ level of safety – divergent situation… wish to replace test with analysis versus increased complexity and competing failure modes?

EASA

Reminder: applies to CS-22, CS-VLA, CS-23, CS-25, CS-VLR, CS-27, CS-29, CS-E, CS-P, CS-APU, + ETSOs

EASA - AM

CM–S-008 Issue 01: Additive Manufacturing* – Draft Revision Outline:

https://www.easa.europa.eu/document-library/product-certification-consultations/proposed-update-easa-cm-s-008-certification

add reference to developing 'certification' specific related documents: AIA Recommended Guidance for Certification of AM Component (Feb. 2020)

Table of Content

emphasise importance of identifying **key parameters** and demonstrate **sensitivity of the engineering properties to these key parameters in proportion to criticality (LoI).** Also added **caution regarding developing optimised designs** (potentially more low RFs and appropriate testing challenge)

added Policy sections (see following slides) addressing:
- **'Knowledge Management and Training'**
- **'Certification Plans and Means of Compliance (MoCs)'**
- '**Parts of No/Minimal Criticality'…. ensuring that they remain so!**

CM revision (30/4/21) iaw intent shared during the 2020 AM Event
- CM is a living/temporary document. Next revision planned in 2022, subject to content evolution and industry need

AM

Can we learn something useful from other 'similar' technologies and associated regulatory evolution...?

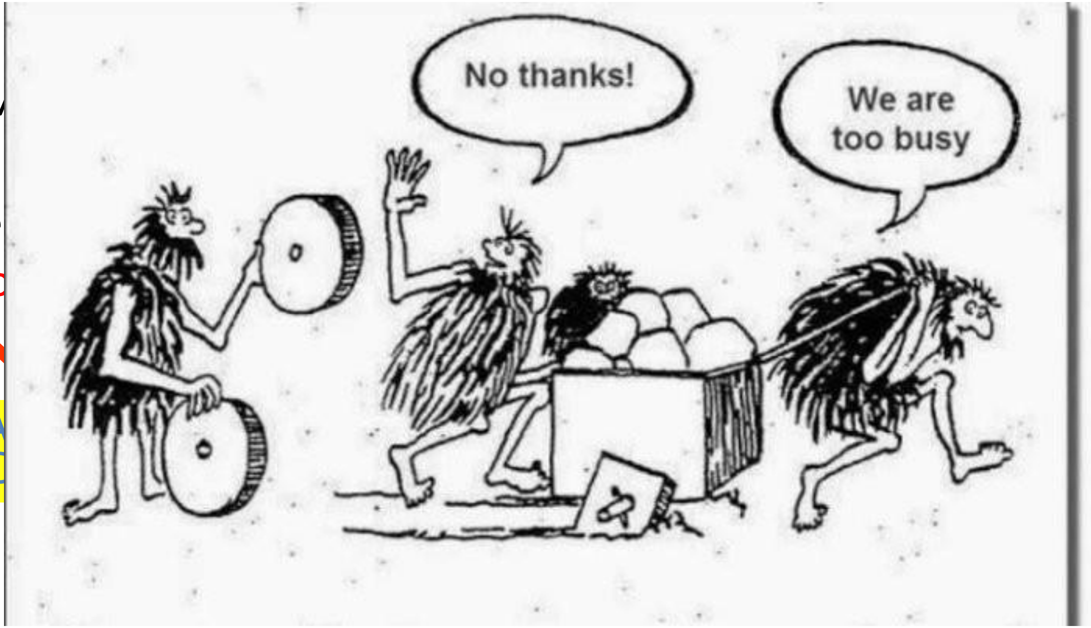
No need to re-invent the wheel
(when appropriate!)

Example: Composites:

EASA MDM.059 RM

- includes possible ng appendix linked to SAE AIR 5719 co

'A n
'C r'



Isaac Asimov – 3 Laws of Robotics

1. A robot must not injure a human being or, through inaction, allow a human being to come to harm.
2. A robot must obey the orders given it by human beings except where such orders would conflict with the First Law.
3. A robot must protect its own existence as long as such protection does not conflict with the First or Second Laws.

Note: These rules soon become problematic…. weak v strong AI etc

Appendix G

“Wire DED Processes, Control and Quality Assurance”
– C. Johnson (Norsk Titanium)

Norsk RPD® Technical Presentation + Development History

October 2022

NORSK TITANIUM

This document has been approved for public release

Wire DED Processes

- Like powder AM, Wire DED describes Multiple Processes based on energy source
  - Electron Beam
  - Laser
  - Plasma
- Wire DED is more suitable for larger, less intricate parts than powder processes; such as aircraft structures
  - Thicker walls
  - Higher deposition rates
- Resultant parts are pre-forms that require downstream processes
  - Machining (all surfaces)
  - Stress Relief or Heat treatment or HIP
  - Full volumetric Inspection

Norsk Titanium

- Manufacturer of structural Titanium parts certified for commercial aerospace since 2017
- Developed and qualified Wire & Arc AM *Rapid Plasma Deposition* (RPD™) a DED process
- Developed deposition machines for the RPD™ process
- **Technology center:** Hønefoss, Norway with focus on
  - 3D Printers - Machine Design, Software, Hardware, Process Control
  - Part development and qualification, Metallurgy & Process Development
- **Production center:** Plattsburgh, New York with focus on part production and industrialization
  - ITAR Compliant Facility

Eggemoen Technology Center in Hønefoss, Norway

Plattsburgh Production Center New York, USA

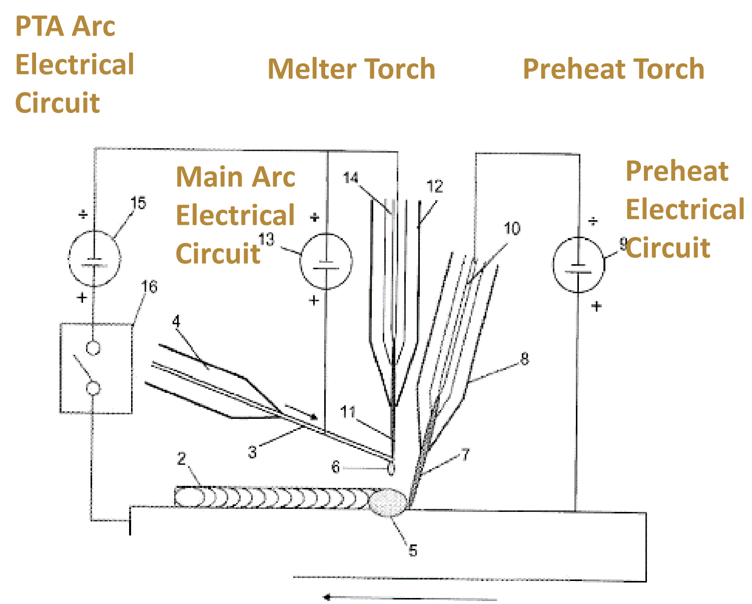
Norsk Titanium RPD® Process Overview

- NTi's Process uses two Plasma Arc Welding torches, a Preheat torch and a Melter torch in combination with a Wire Consumable Electrode and Substrate

- The Preheat Torch Preheats the Surface of Deposition to Ensure Good Wetting for Deposited Material. The Power of the Preheat Arc is Adjusted to Compensate for Thermal Variations in the Work Piece Due to Heat Accumulation/Loss and Geometry

- The Melter torch Electrode is Connected to Two Independent Electrical Circuits; the Main Arc (Transferred to the Wire) and the PTA Arc (Transferred to the Work Piece)

- Deposition Takes Place in a Chamber with Monitored Inert (Argon) Atmosphere Where Oxygen and Humidity are Controlled to Defined Limits



G4B

Capabilities include:

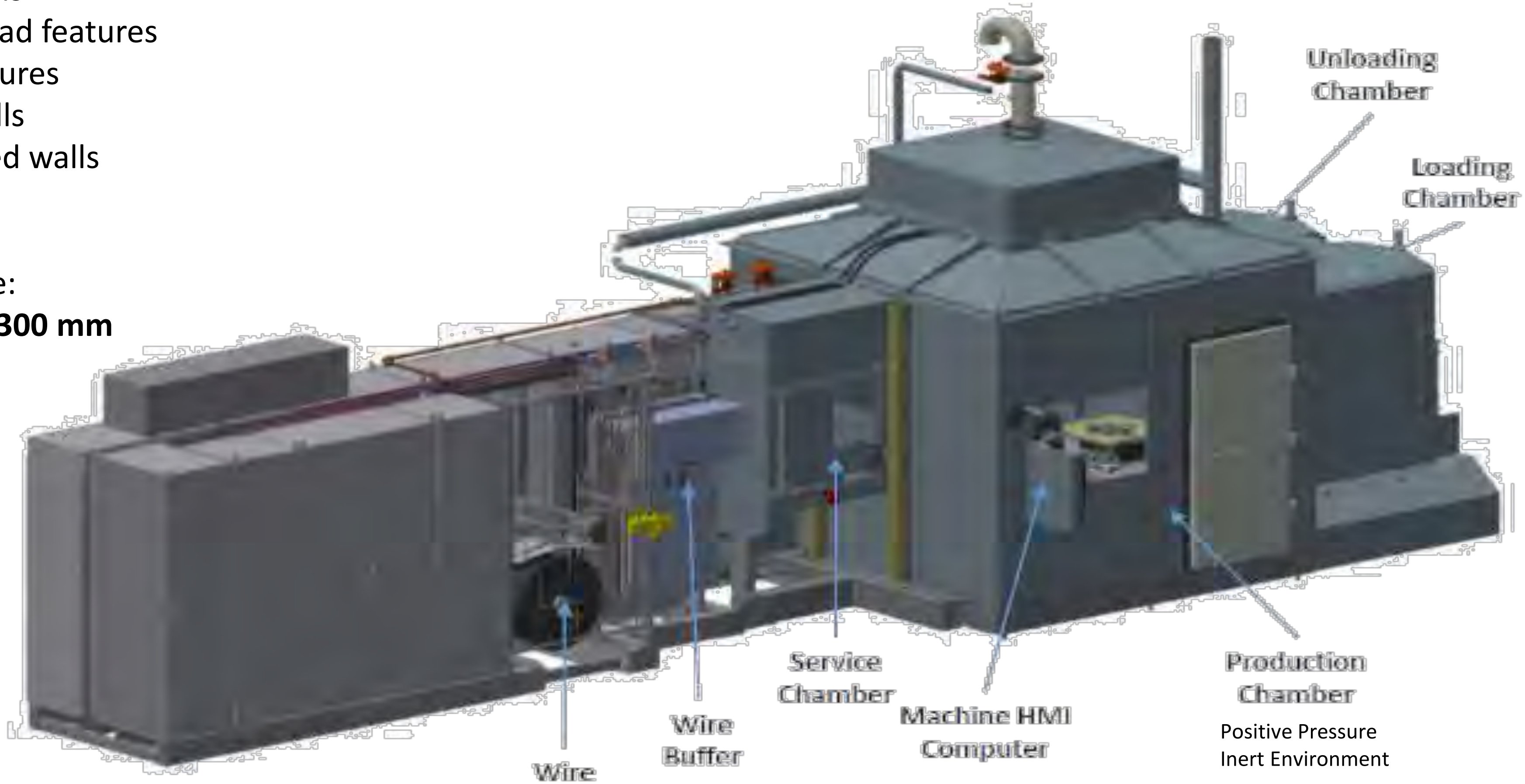
- Straight walls
- Multiple bead features
- Curved features
- Slanted Walls
- Double sided walls
- Overhangs

Print volume:

900 x 600 x 300 mm

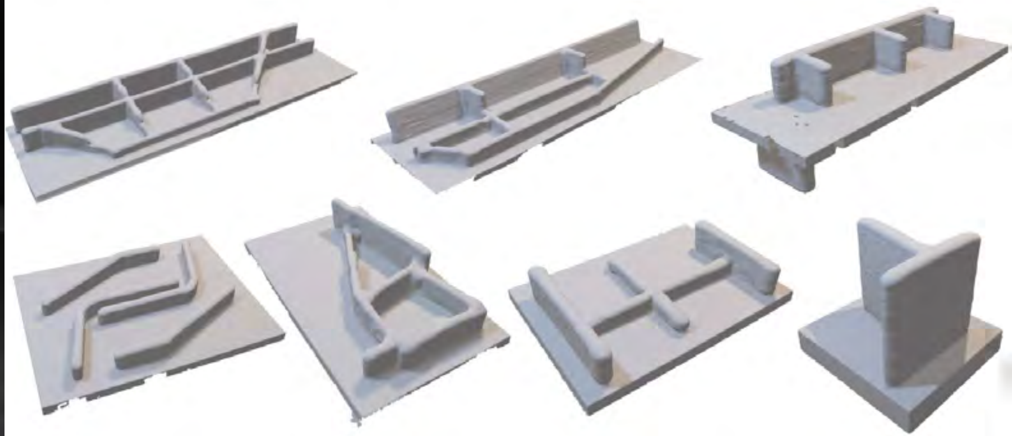
Part weight:

< 200 kg



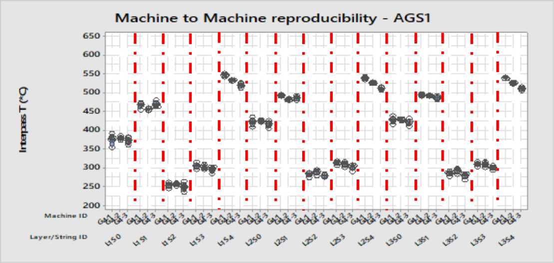
RDP® Process

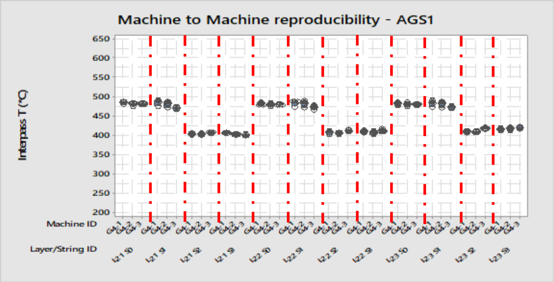

CamRight
Component: 2016-004-Cross-TP002-10-01 Layer: 1 String: 0
RECORDING
15.04.2016 09:49:24

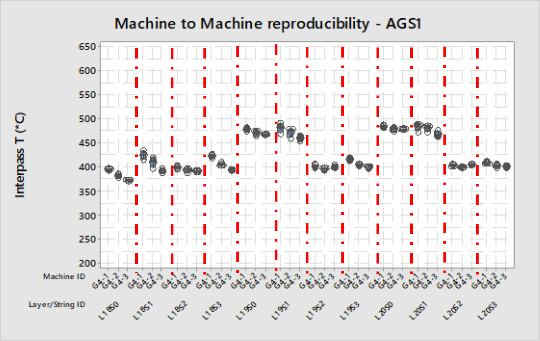


Machine to Machine Repeatability

- All subsystems that have a direct input to our process are calibrated
- Tight tolerances are maintained to minimize machine to machine variation
- 10 calibrated subsystems
- 90-day calibration cycle
- All subsystem must be calibrated for the machine to be released to production







Documented Calibration process Ensures consistent Quality over time and across machines

Design for Inspection

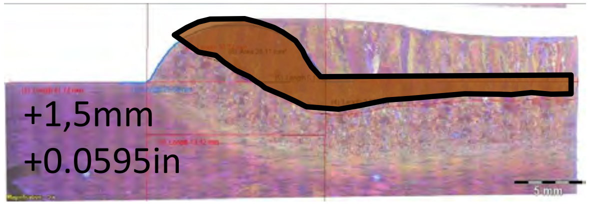
- Prior to development deposition, NTi NDT Engineers work extensively with the New Part Introduction teams to create preforms which are readily inspectable
  - Inspection Strategies are documented along with the Preform design
  - Depending on the required inspection method, preforms undergo pre-machining to prepare the material for surface and geometrical configurations necessary to provide 100% inspection coverage

The ability to ensure 100% inspection coverage of the material takes precedence over BTF optimization

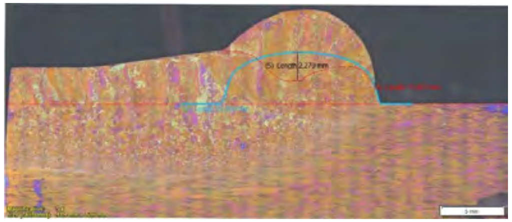
Multiple Process Studies Needed for Inspection Validation

- Key questions
  - What does the melt-in profile in a junction look like?
  - How much of the existing bead wall is re-melted?
  - Is there a difference between starting a bead on an existing bead and ending the bead on an existing bead?
  - How much of the bead cap/crown is re-melted?
- Several Studies completed to ensure inspection accuracy
  - Melt in studies
    - String on String
    - Start of string
    - End of string
    - Start of string on prior string
    - End of string on prior string
  - Ultrasonic Angulation studies to investigate the effect of skew angle and position of the Flat Bottom Holes (FBHs) with respect to the sides of the wall.
- Development of calibration blocks for each technique
  - X-ray
  - CT
  - Ultrasonic- immersion and TFM
- Single and multi-bead characterizations

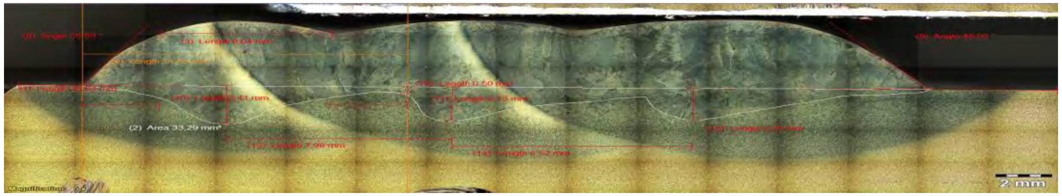
Studies



60°, TS = 9,5mm/s (0.374in/s)

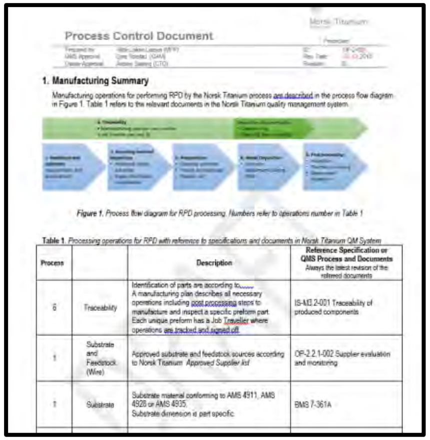


75°, L1 string deposited onto start-of-string junctions



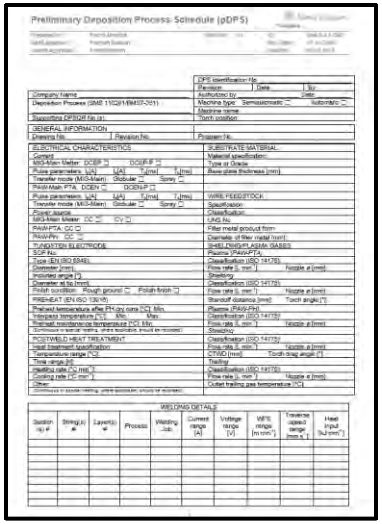
Process Control Documentation

Process Control Document
(PCD)



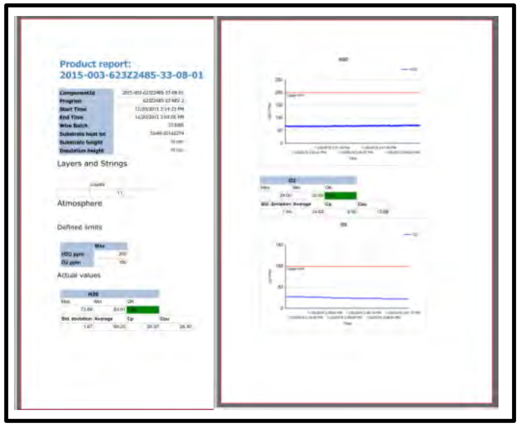
- Documents How We Will Meet Customer Specification
- Describes Manucturing Steps and Assocoated QMS Procedures
- Sets RPD™ Process Parameter Ranges and Tolerances Critical to Quality

Deposition Process
Specification for P/N
(DPS)



- Part Specific Deposition Specification

Production Report Per
Part



- Automatically Generated Report on Process Control Status and DPS Adherence

- NTi uses configuration-controlled recipes for part feature based on Design of Experiments and the Feature Library

Specifications

- Raw material specifications
- Calibration process and specifications
- Deposited Material and Process Specifications approved /published
  - **SAE AMS 7004** - Titanium Alloy Preforms from Plasma Arc Directed Energy Deposition Additive Manufacturing on Substrate Ti-6Al-4V Stress Relieved
  - **SAE AMS 7005** - Wire Fed Plasma Arc Directed Energy Deposition Additive Manufacturing Process
- Process unique Thermal/Stress Analysis Capability
- Industry Standard Non-Destructive Inspection Techniques qualified
  - Ultrasonic
  - X-Ray
  - Penetrant

Plattsburgh, NY Production Center

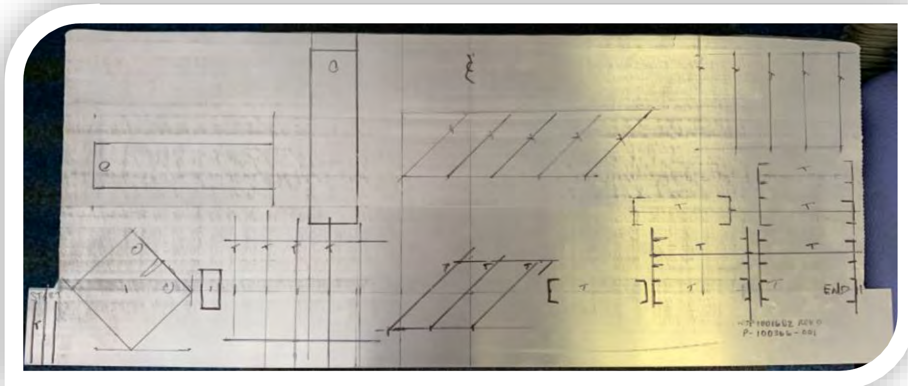
29 Available RPD® Machines

Qualification and Certification

- Qualification and certification of AM parts are generally dependent on the application of the part
- The organizations with design authority for commercial aerospace depend on *design allowables* values (statistically determined materials property values derived from test data) that are published in public sources such as the Metallic Materials Properties Development and Standardization (MMPDS) handbook **OR** the OEM's own internally developed design allowables values for certain materials
- The largest aerospace OEM's, Airbus and Boeing, have developed their own internal design allowables and their own internal specifications for suppliers like Norsk Titanium to follow
- MMPDS handbook currently does not have any AM material allowables design values published, but Volume II is currently being developed by the MMPDS committee along with industry and Norsk Titanium representatives

Qualification Efforts

- Industrial Specifications cover all aspects of supplier qualification, machine qualification, raw material requirements, manufacturing control and required material properties
- Boeing Specification
  - BMS-7-361
- Airbus Specification
  - AIMS03-29-000/1
- Development & Qualification Efforts with
  - Propulsion OEMs
  - Tier 1 Suppliers
  - DoD Primes




RPD™
MERKE IV
NORSK
TITANIUM
RPD™
MERKE IV
NORSK
RPD™
MERKE IV
NORSK

THANK YOU!

Appendix H

"Overview of NASA ULI program"
– A. Rollett (CMU)

Overview of the CMU-led NASA ULI program

FAA-EASA Workshop, Oct. 17th, 2022

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 (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 17 x 2022

Bottom Line Up Front (BLUF)

- 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 defect (pore) content and fatigue life.
- >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. 4-point bend fatigue successful as a high throughput method; shorter lifetimes expected for push-pull round bar because of larger volume.
- Gross porosity (> 20 μm) can be measured by imaging well machined surfaces; number densities are consistent with computed tomography (CT).
- As-printed surfaces equivalently poor performance as severe lack-of-fusion (LoF) porosity; no success to date with mitigation during printing. Middle of the process window conditions give good performance but a very large range of lifetimes.
- Based on a combination of experience and physics-based knowledge of process, establishing a Qualified Materials Process (for LPBF) requires experiments to determine 1) laser spot size, 2) melt pool dimensions, single track melt pool dimensions and 3) test cubes to check boundaries.

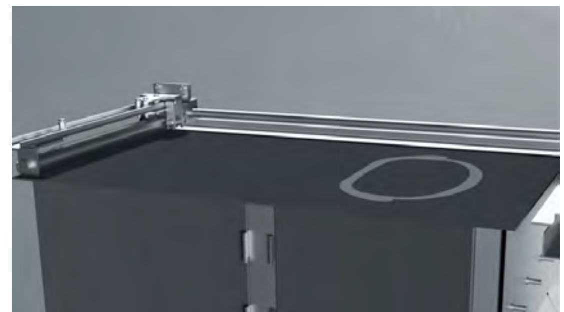
To Qualify a 3D-Printing Process

NASA-ULI Project
CMU/CWRU/UTEP
/CSM/MRL/UPitt/
TBGA

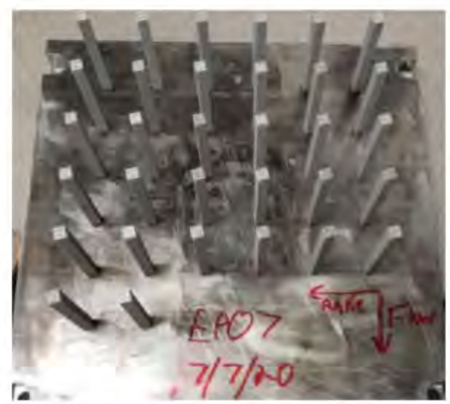
Enables Part Certification

Qualified Materials Process

Understand the physics of printing, minimize the defect content and maximize fatigue resistance

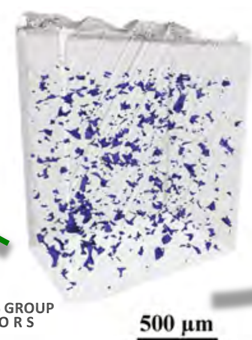


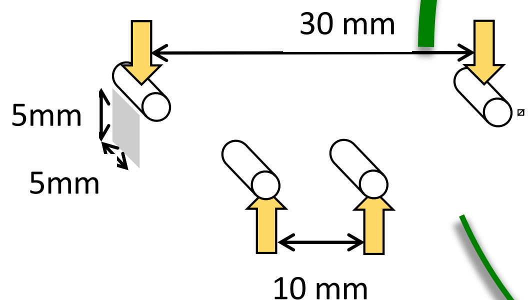
3D Printer



Test Parts

Quality via Defect Structure





4-point Bend Fatigue Test

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 does this project change the paradigm*? Our ULI team is demonstrating 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 is 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 + Operational Qualification + Performance Qualification**, which feeds into Part Qualification

NASA-STD-6030

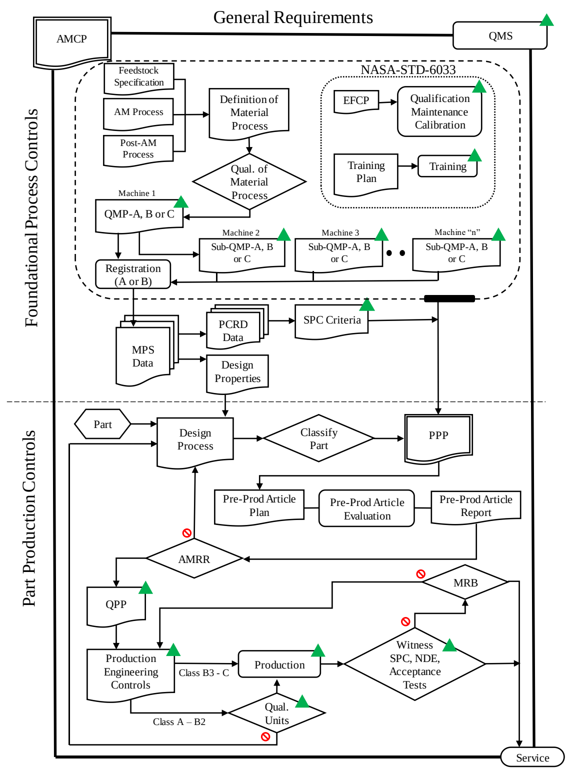
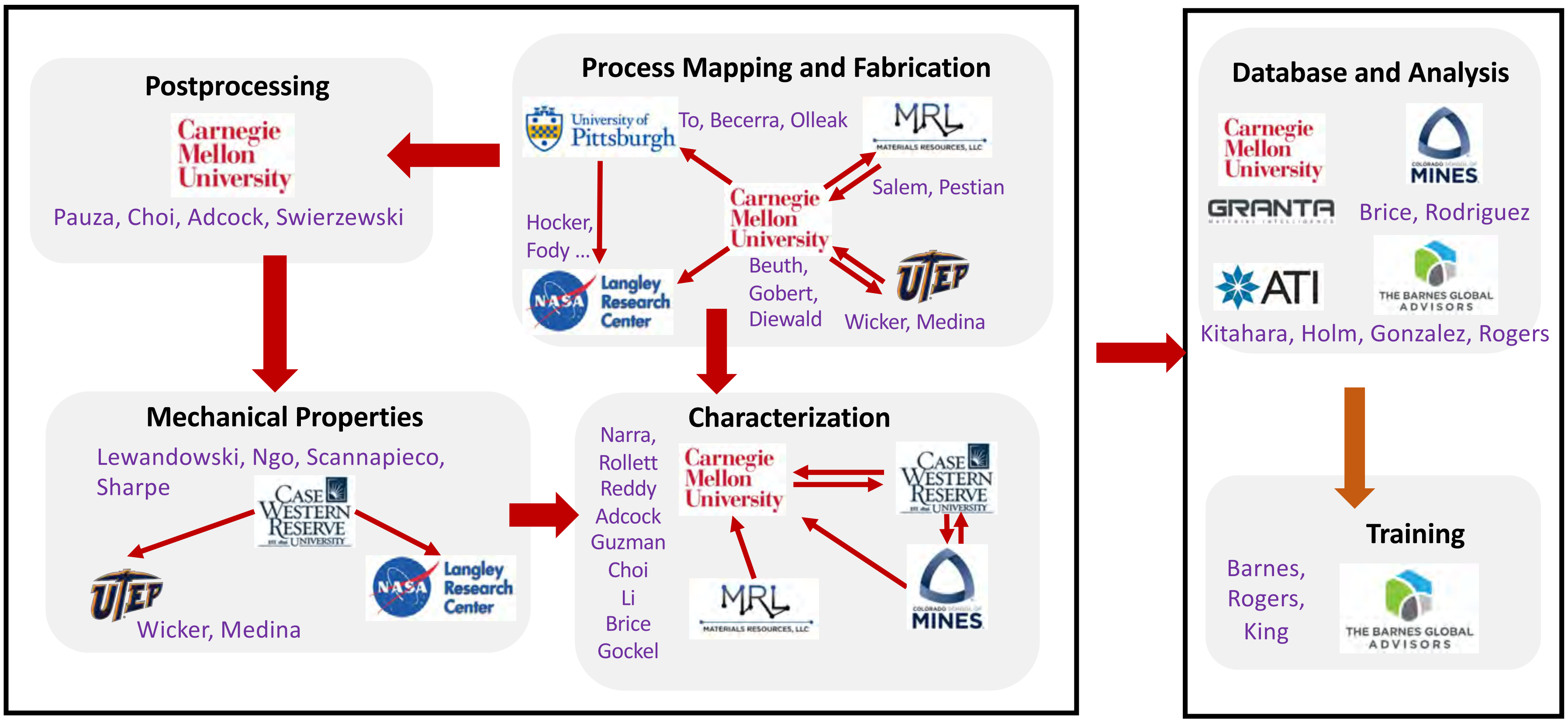


Figure 2—Key Products and Processes for NASA-STD-6030

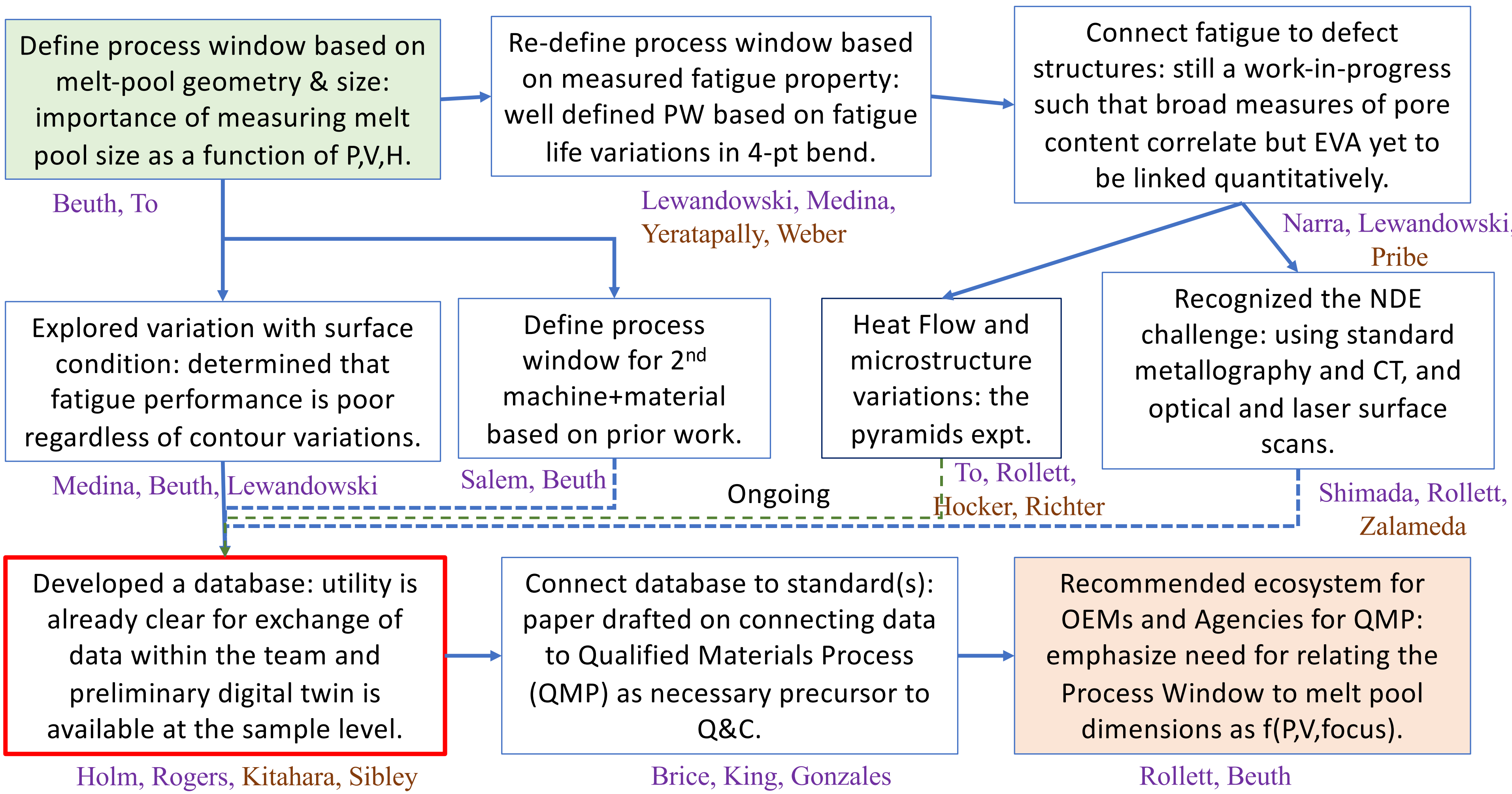
AM = Additive Manufacturing

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

Collaborations and Information Flow Diagram



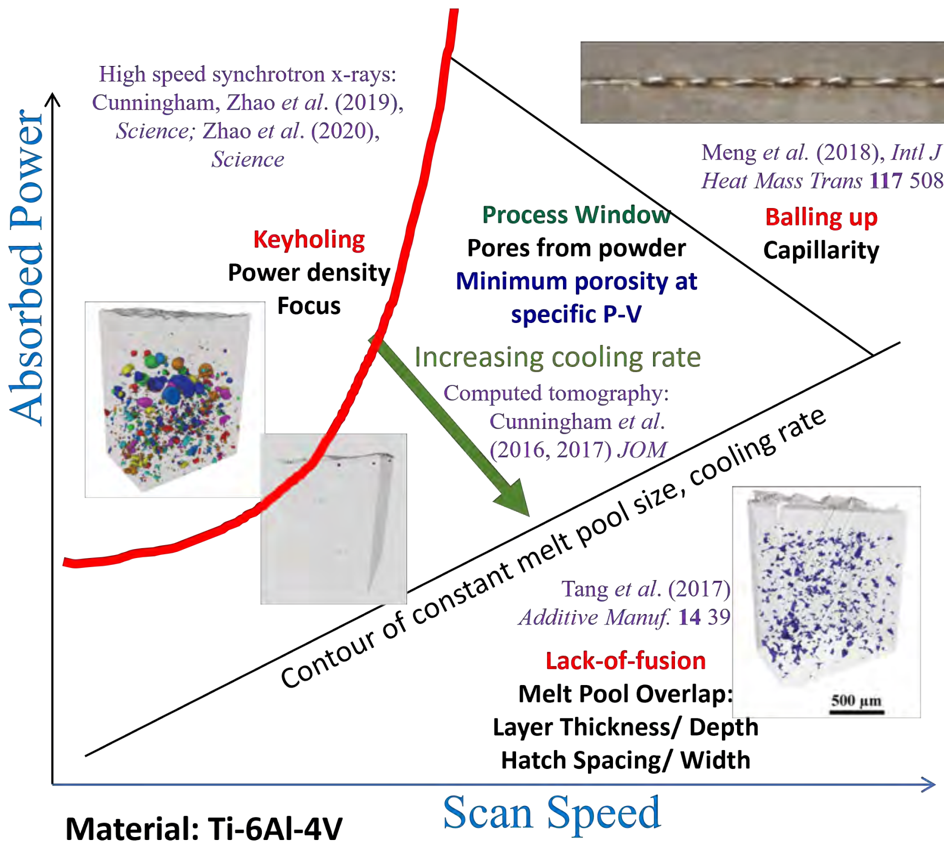
Major Milestones, Accomplishments and Connections



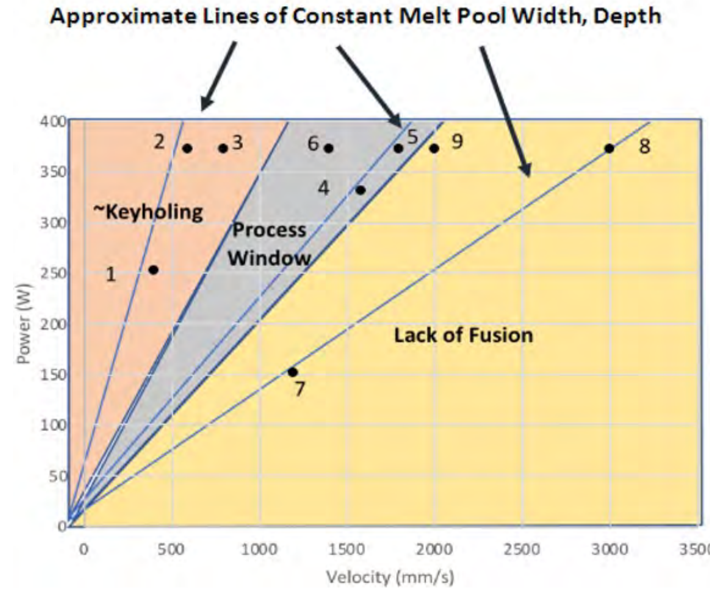
Multi-Dimensional Process Maps

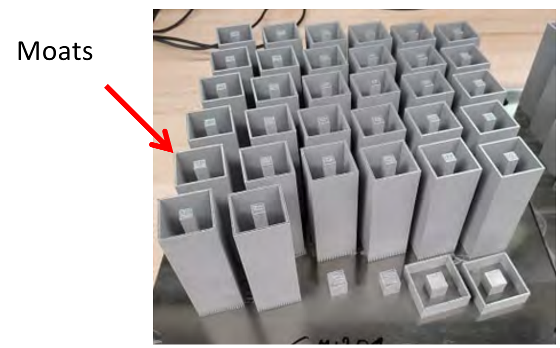
- Although a Power-Velocity map is a good place to start, there are many other variables that affect part quality.
- In descending order of importance (our opinion):
  – Hatch spacing: easy to adjust to in/decrease remelt ratio
  – Layer thickness: limited choices, thicker ⇒ less resolution
  – Pre-heat Temperature usually limited range (Pitt inverted pyramid shows how to predict it as a function of height)
  – Spot size: not always easy to adjust but a machine with continuous control would be useful
  – Scan strategy: e.g., stripes, contour options
  – Powder type: surprisingly irregular powder can be used, i.e., spherical powder is *not* essential
  – Gas type: say, Ar versus N_2
- Adding contours of print times help user to understand relative cost.
- UTEP's *Qualification Test Artifact* was influenced by the NASA Standards (MSFC 3717, 3716, NASA 6030, 6033).
- Bottom line: **Qualified Metallurgical Process**

Process map-based design of experiments

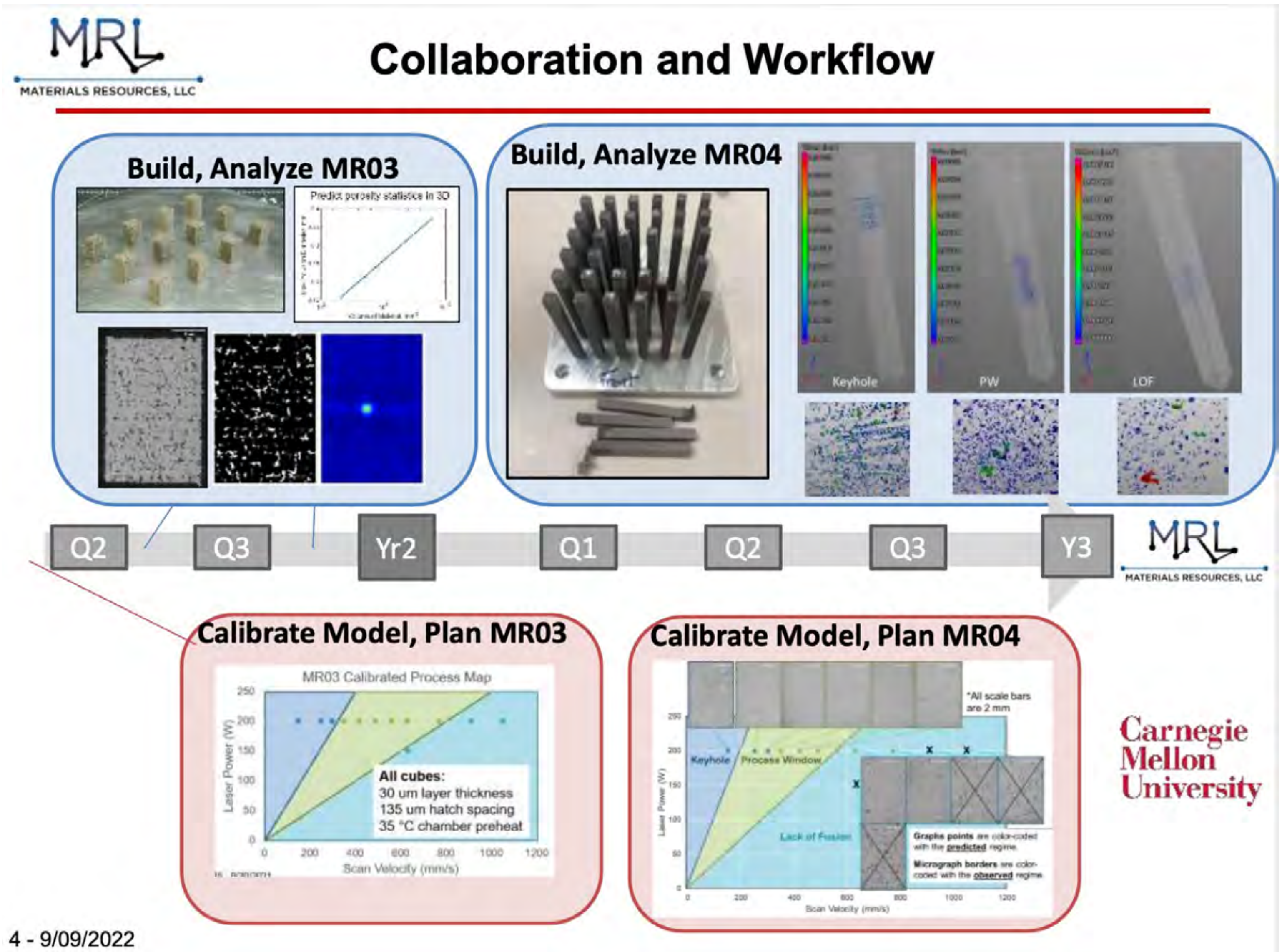


Gordon *et al*. (2020) *Additive Manuf.* **36** 101552;
Shahabi *et al*. (2022) *Materials Characterization* **190** 112027





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



Transfer of process window approach to MRL (Ayman Salem, Nellie Pestian)

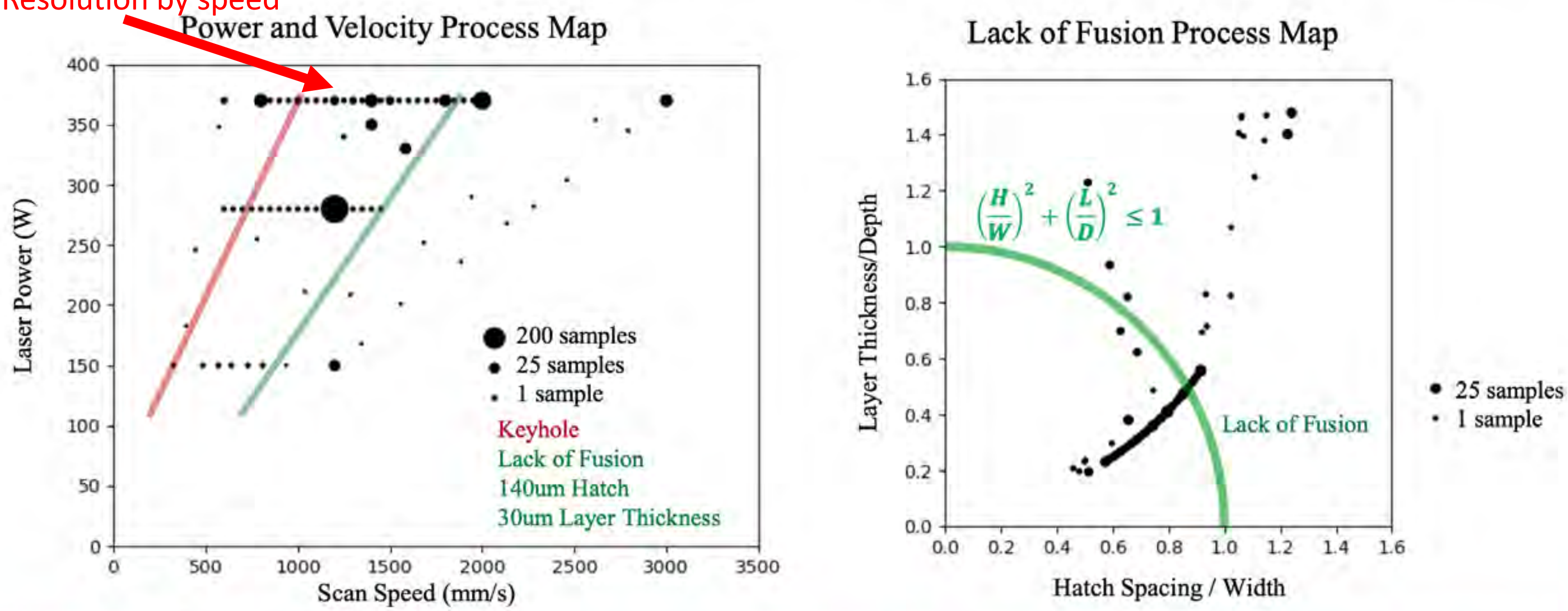
Collaboration with Beuth group at CMU

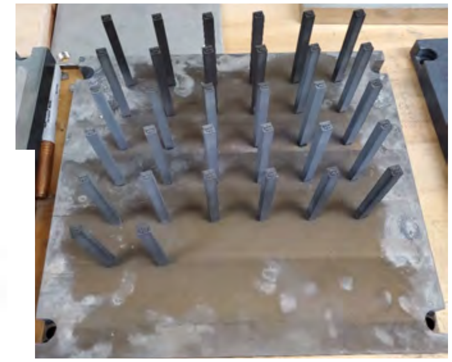
What We Have Printed

Parameter Exploration Builds – Graphical Summary

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

Resolution by speed





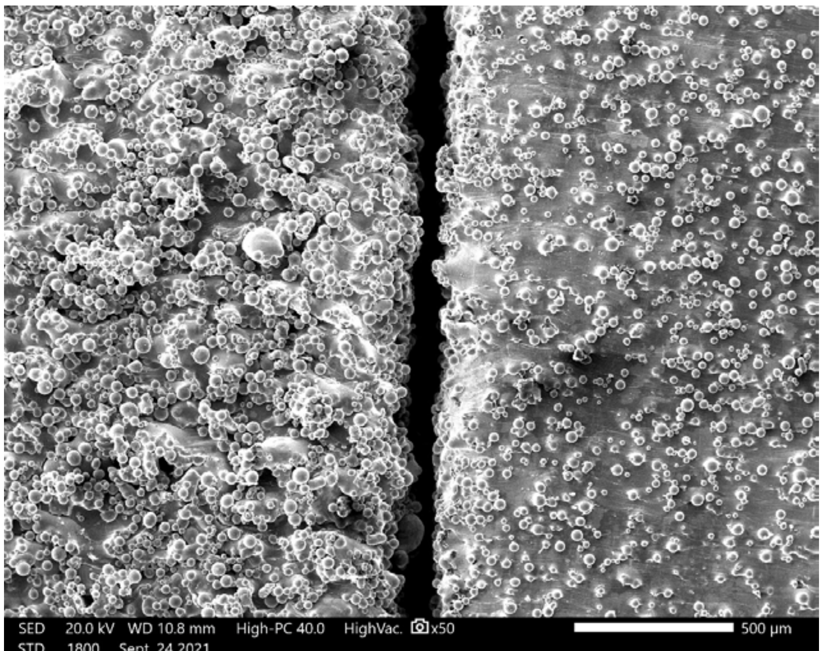
- UTEP: 4 builds + 1 Planned
- CMU: 15 builds
- U Pitt: 4 builds
- Materials Resources: 3 builds (advanced Al alloy)
- NASA-Langley: 3 builds

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

> 1,000 fatigue samples

Gobert & Beuth, Sept '22

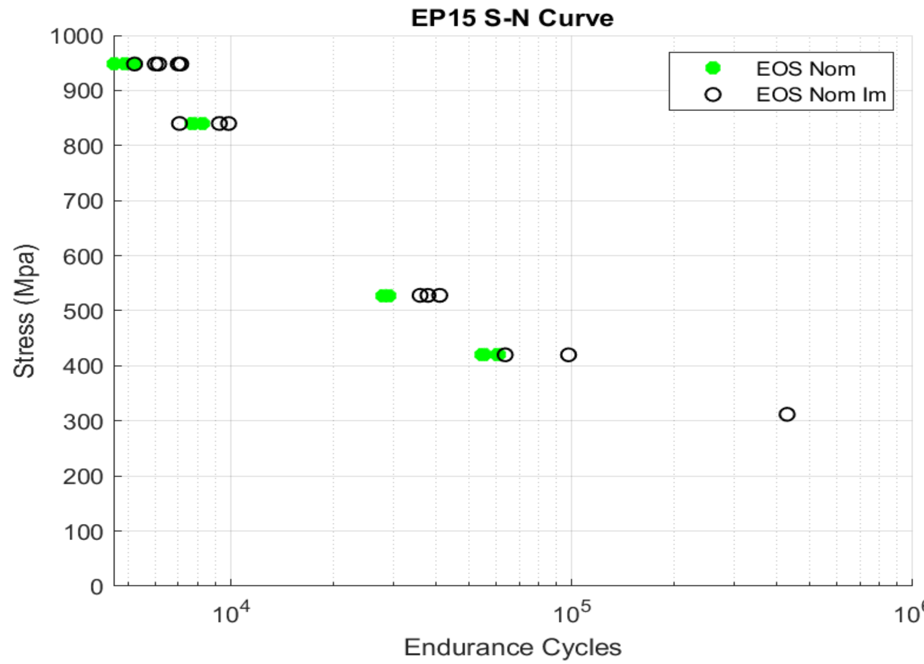
Results – as built "Nominal" Vs. "Improved" contours



EOS NOM

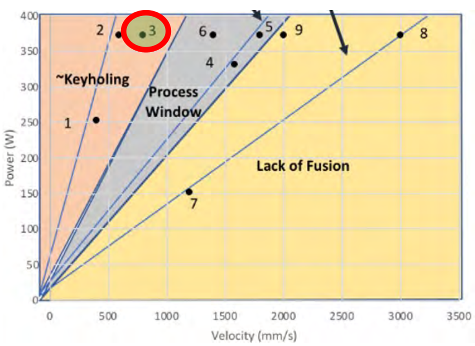
EOS Nom IM

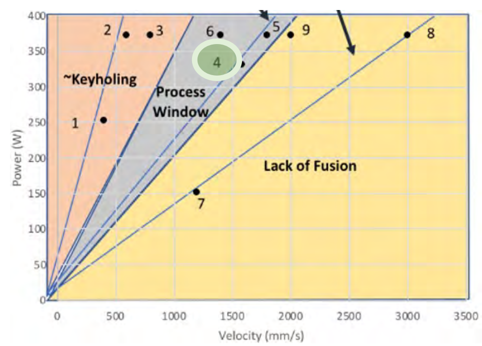
Build Direction

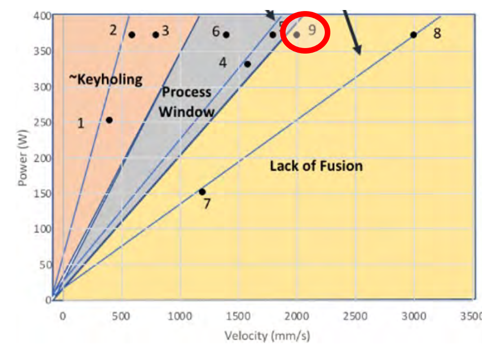


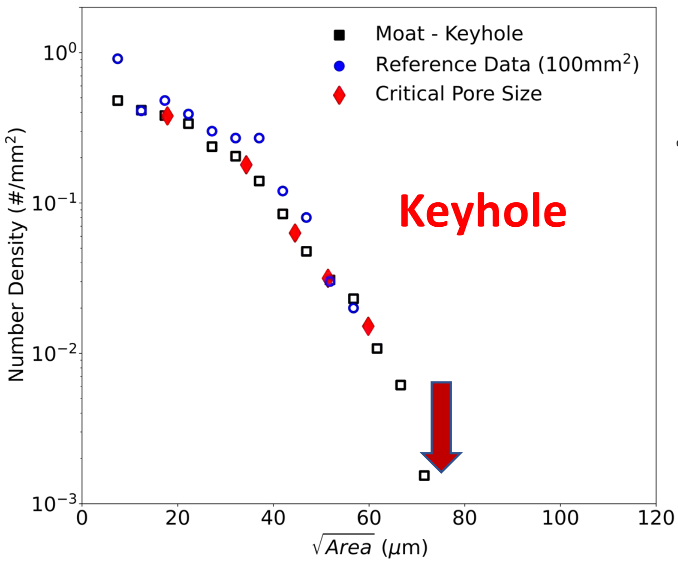
	Sa (µm)	Sv (µm)	Svk (µm)
EOS Nom	15.5	121.9	16.8
EOS Nom IM	7.1	91.8	8.6

Pore Size Distributions (Number density)

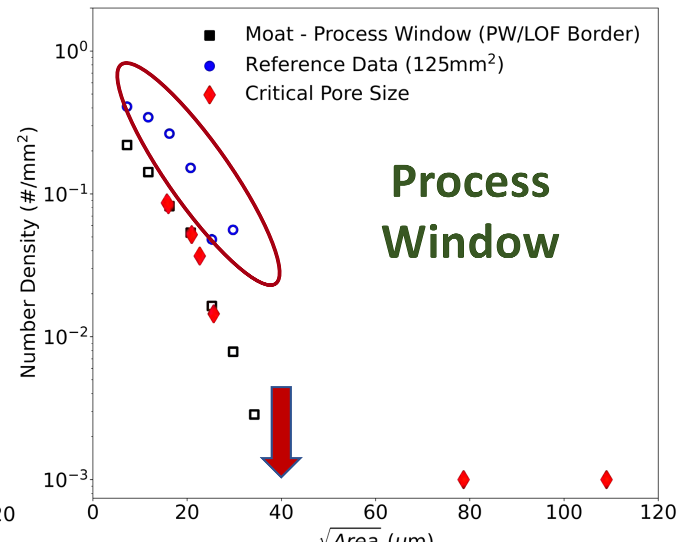




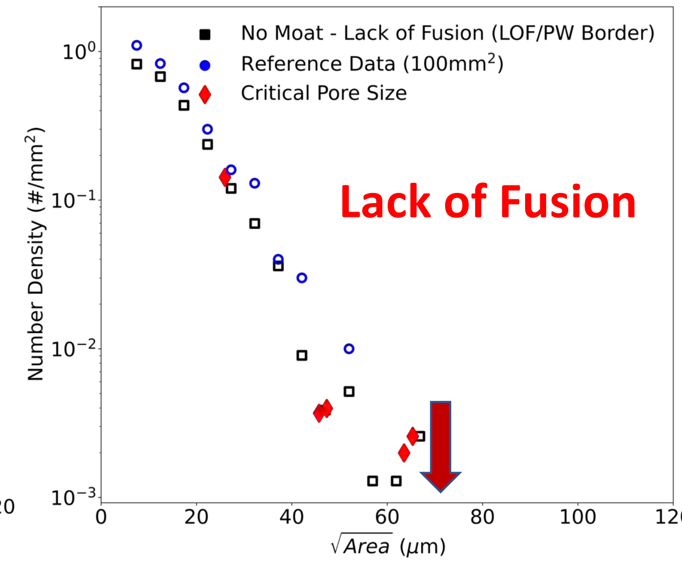




Area characterized = 650 mm^2



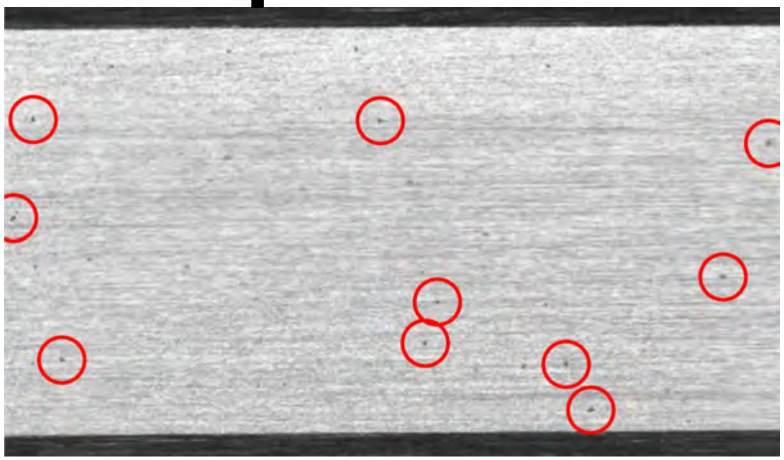
Area characterized = 1400 mm^2

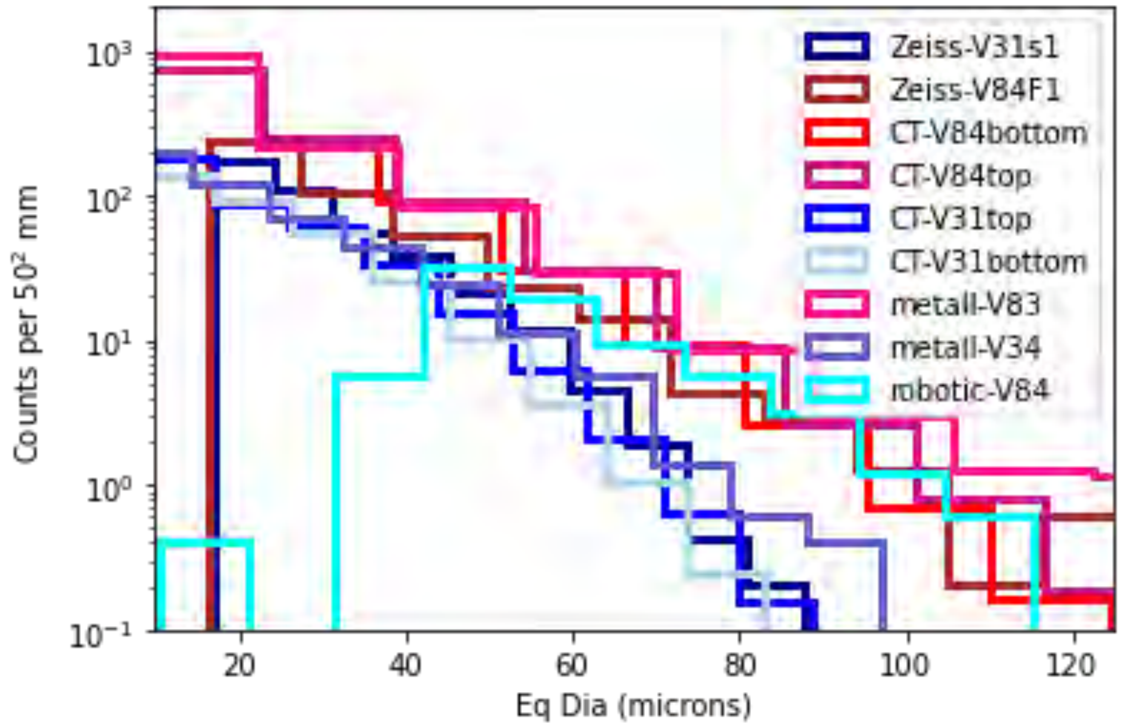


Area characterized = 775 mm^2

Comparison of Number Densities of Pores

Optical image of machined surface





- 4 methods: metallography, CT, optical of machined surfaces, robotic scanning (ditto)
- For two cases, one on the keyhole range (V31) and one in the lack of fusion range (V84), the number density distributions are in good agreement.
- Two separate CT scans (CSM) on halves of a sample.

Four (4) different methods result in the same number density distribution for V84

Metallography by Tharun Reddy, William Templeton, Sneha Narra; surface scans & segmentation by Kevin Zhou, Je Choi, Tomasz Swierzewski, Kenji Shimada (robotic), and Xingyang Li (CT)

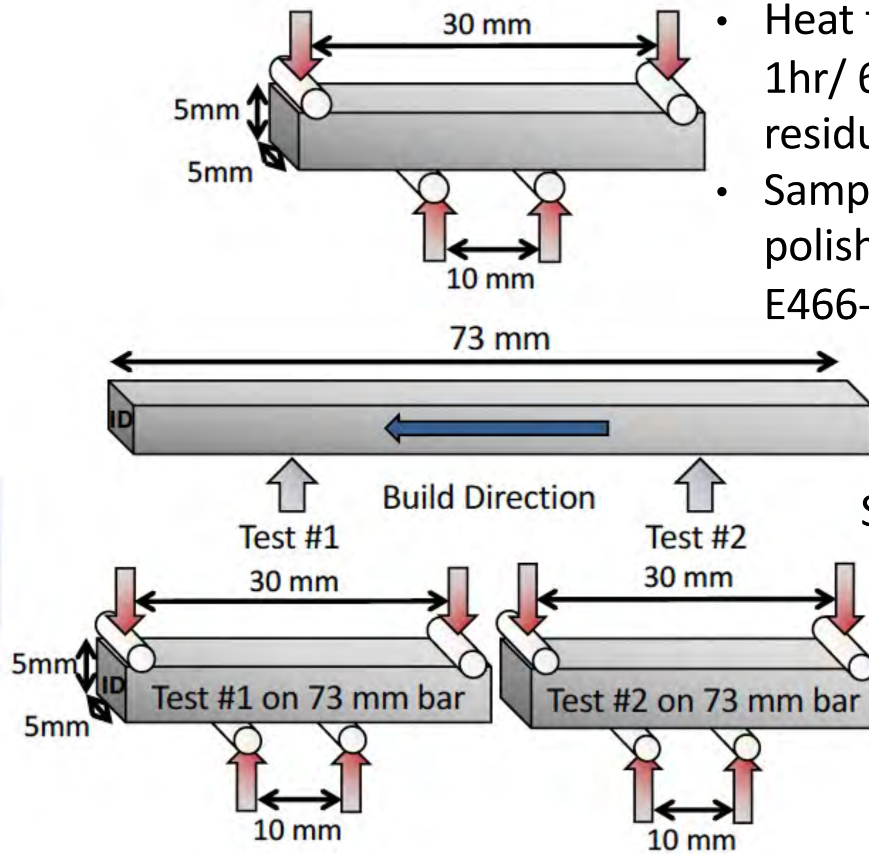
4-Point bend fatigue testing

Size Considerations:

- ≈ 35 mm/test
- > 73 mm, 2 Tests/Sample
- Multiple Tests/Sample:
  - ➢ Print homogeneity
  - ➢ Fatigue Anisotropy
  - ➢ Redundancy/fewer parts
  - ➢ Fatigue Initiation Focused on Surface

3, 10, 50 KIP MTS machines
AMMRC at CWRU

(https://ammrc.case.edu)



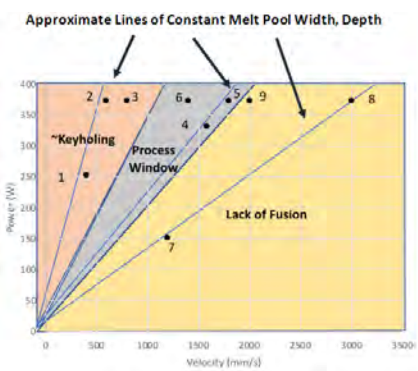
- Eight fatigue samples fabricated for each parameter combination
- Heat treated at 1hr/ 650 °C to lower residual stress
- Samples machined and polished as per ASTM E466-15 (2021) standard

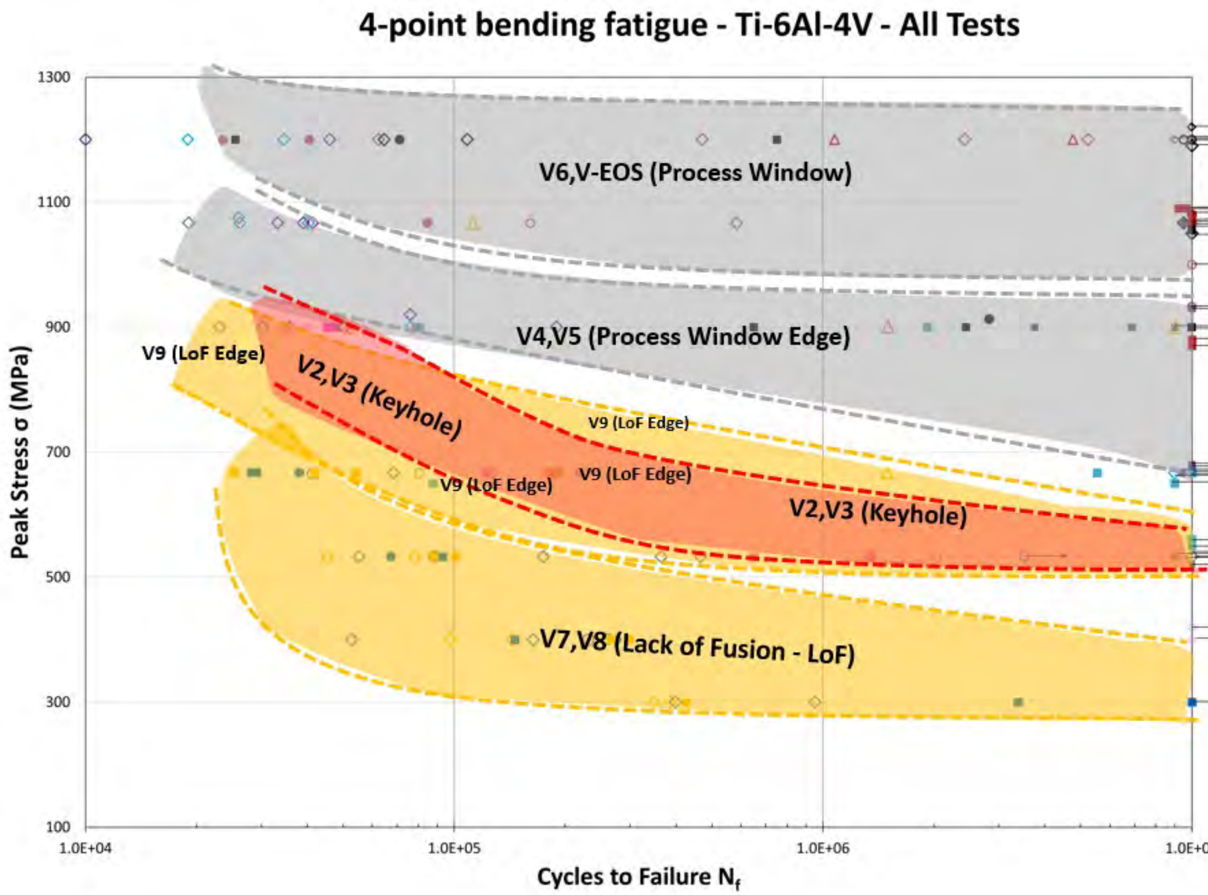
Stress ratio, R = 0.1

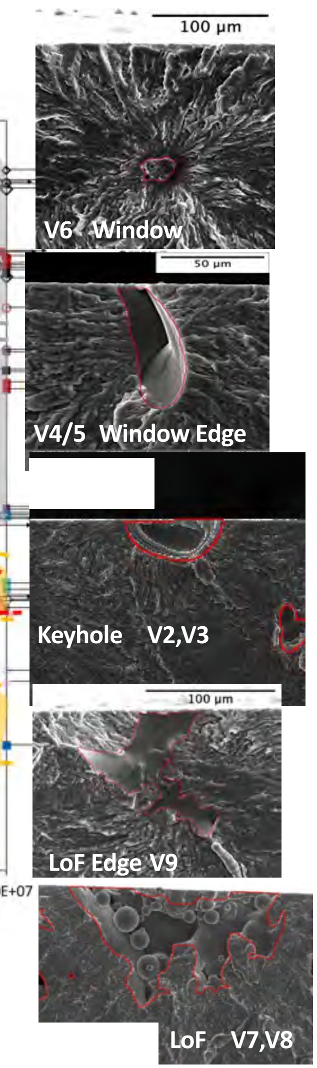
CASE WESTERN RESERVE UNIVERSITY EST. 1826

CWRU: John J. Lewandowski (Co-PI), Austin Ngo, David Scannapieco

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

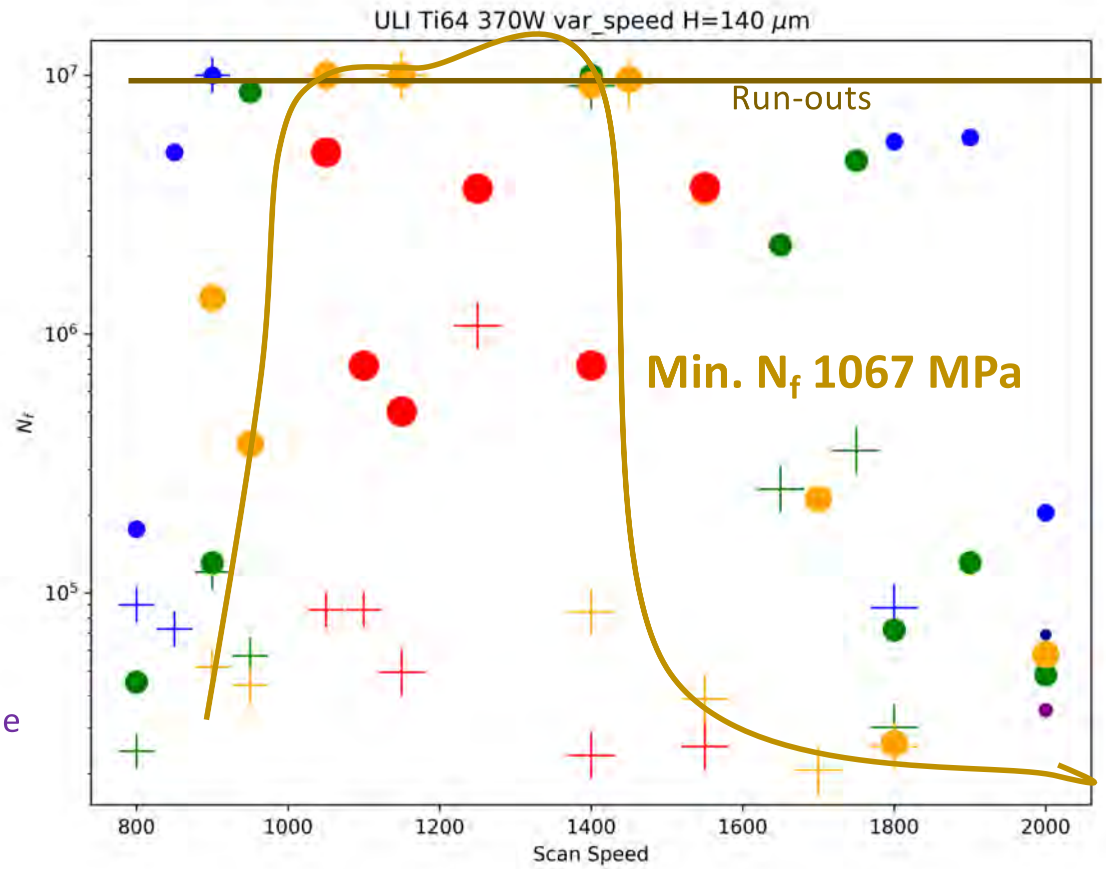
CWRU Graduate Students: A Ngo, D Scannapieco, C Sharpe

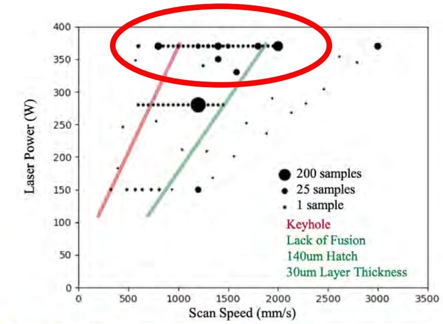
Median values of Nf *vs* scan speed

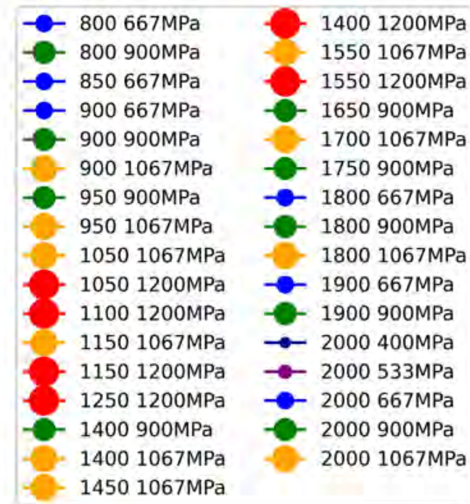
The general conclusion is that there is a steep roll-off in median lifetime on either side of the process window (PW).

Also, there is substantial variability inside the PW

4-pt bend fatigue at CWRU



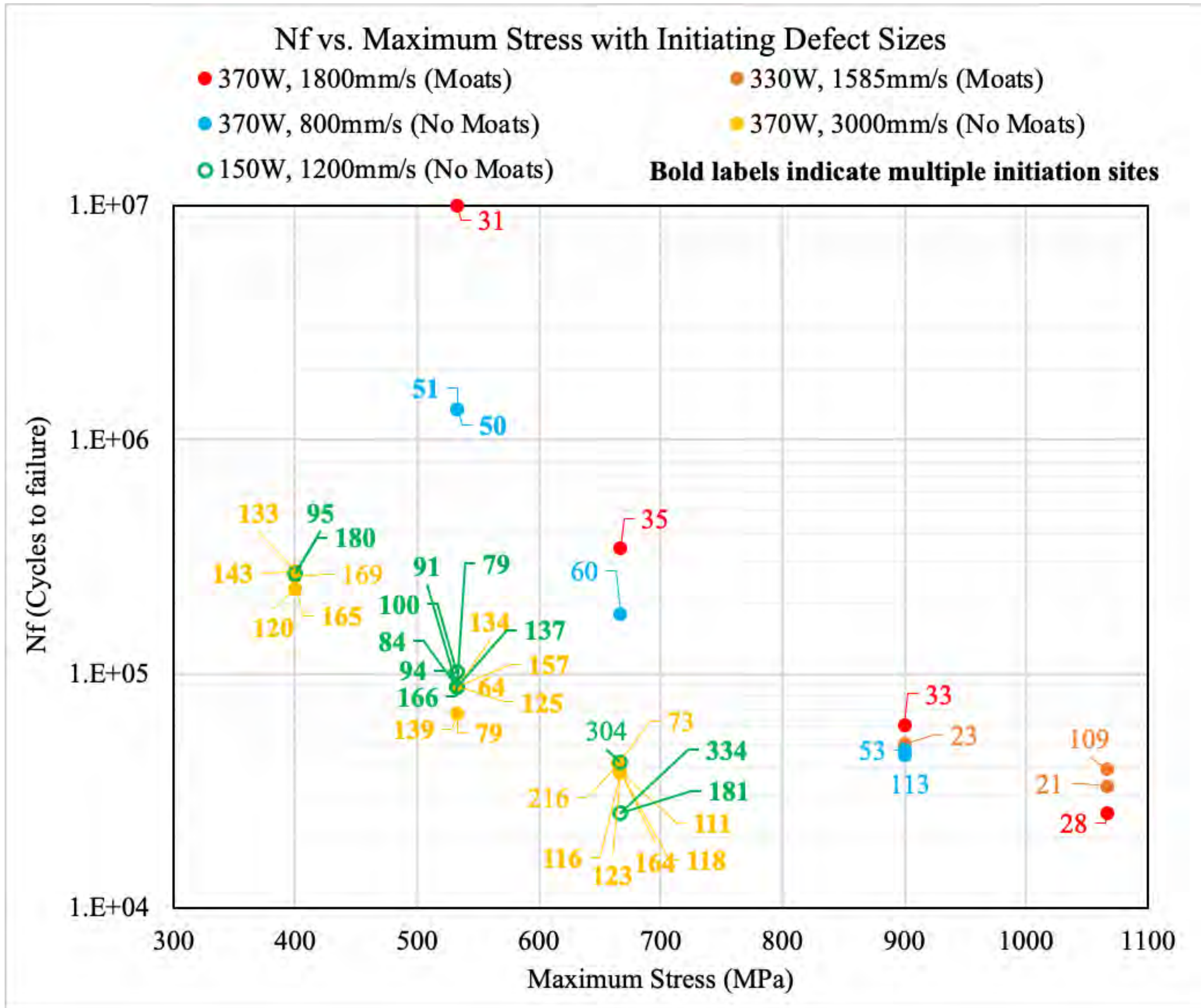




1200 MPa = red
1067 MPa = orange
900 MPa = green
667 MPa = blue
Etc.

N_f-S Annotated

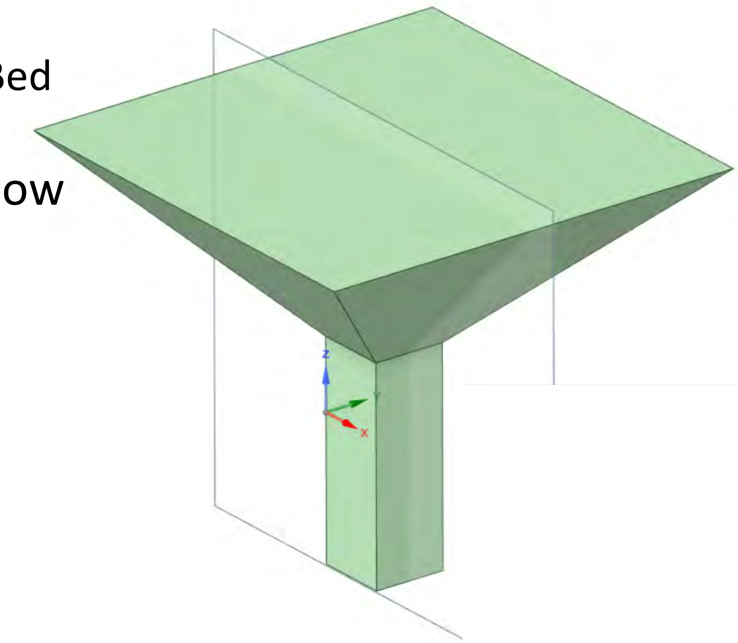
- Based on 600+ fatigue tests
- General reciprocal trend of Nf vs stress
- Larger pores associate with shorter lifetime
- No discernible effect of "moats"



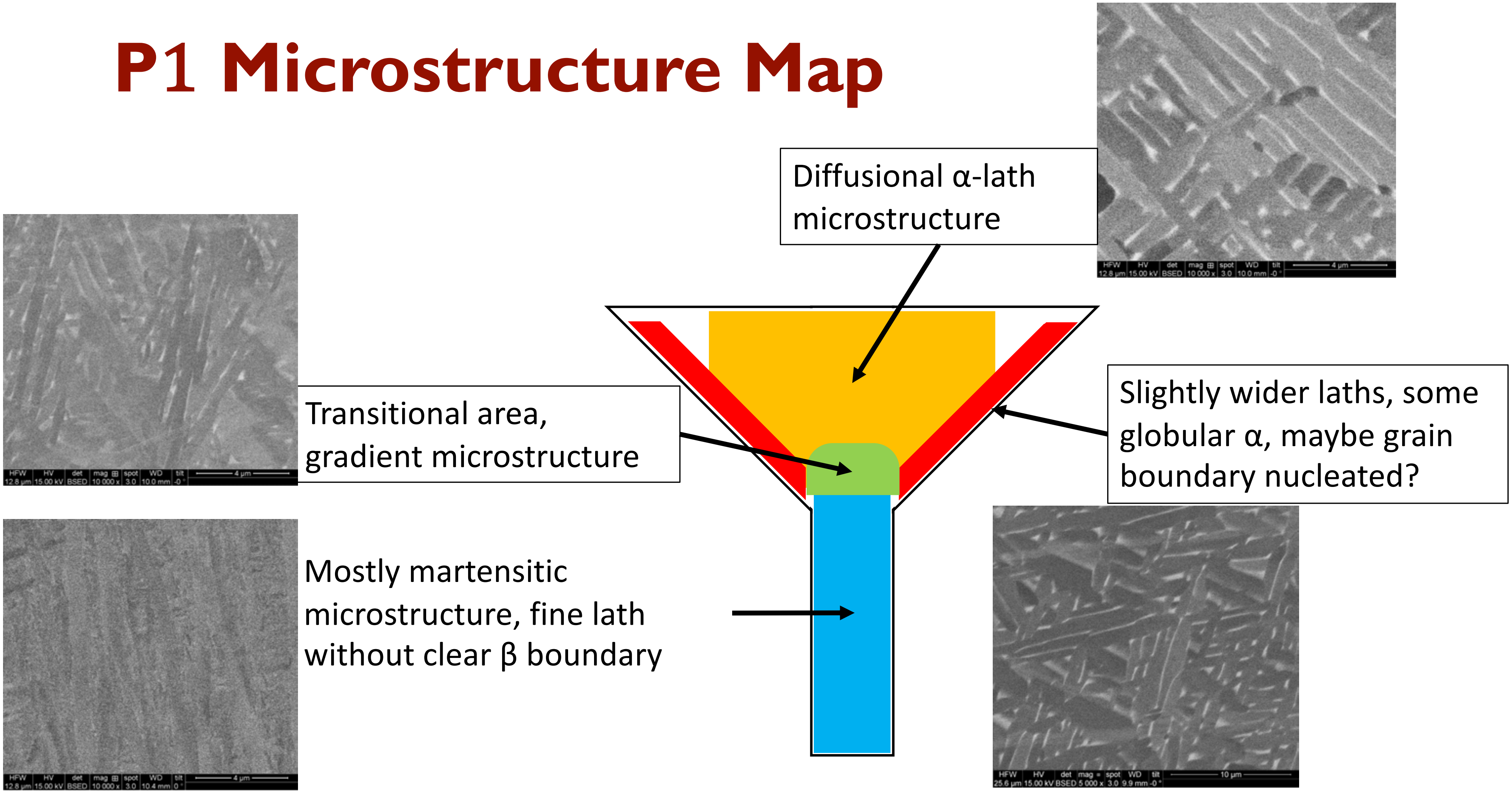
Courtesy of CWRU group, Sneha Narra and Tharun Reddy

Inverted Pyramid Builds for Heat Accumulation

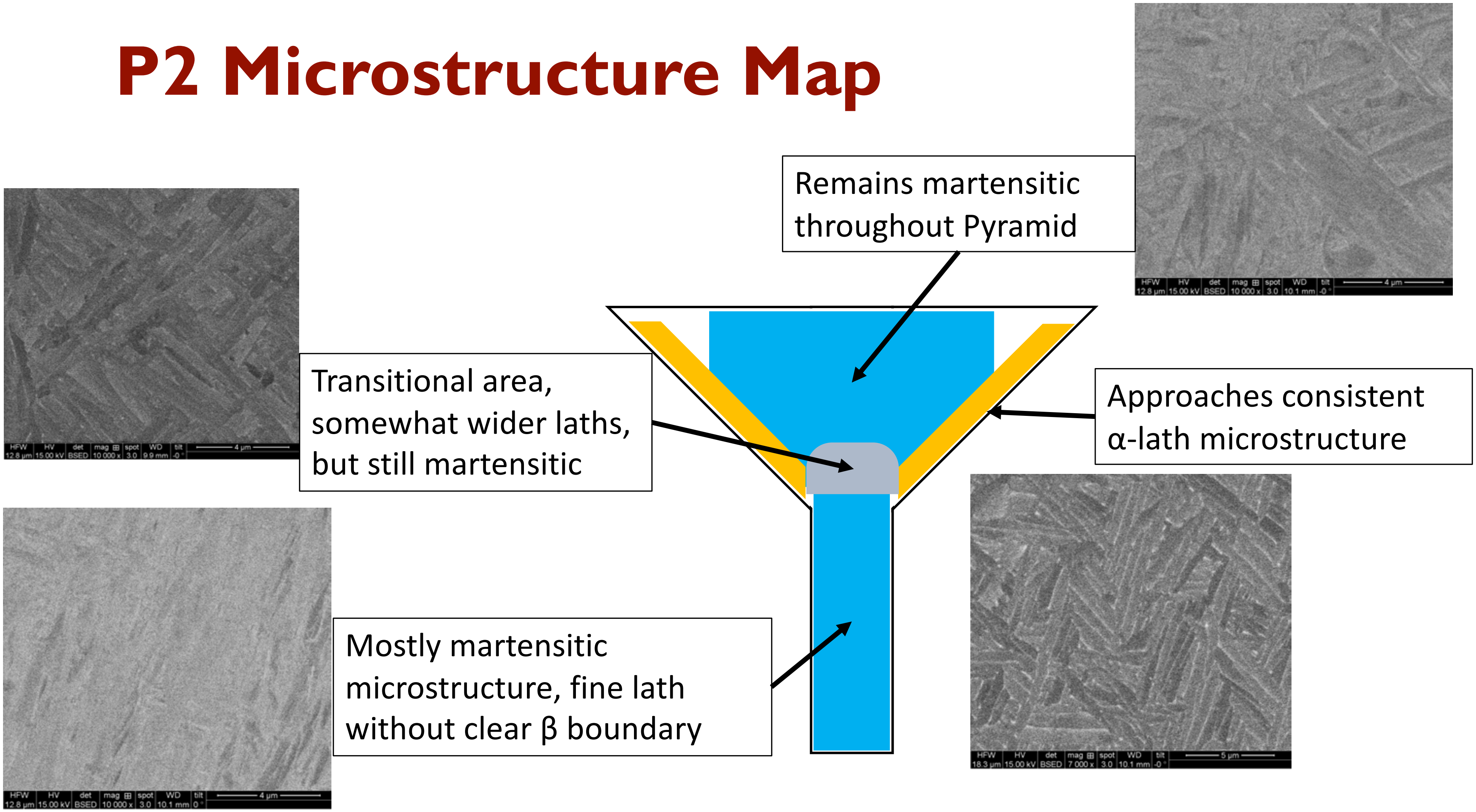
- Two “inverted pyramids” were built using Laser Powder-Bed Fusion called “P1” and “P2”
  - Build parameters match the “V6” Process Window set
  - 90° rotation scan strategy
- P1 was built as normal, a single build on the build plate
- P2 was built with “Ghost parts”
  - Two additional parts were “built” but at zero power
  - Effectively introduced a layer delay time
- *No appearance of keyhole porosity* despite pre-heat in P1
- P1 accumulated heat from fast consecutive layers ($\rightarrow\alpha/\beta$ lath) while P2 had ample cooling time between layers to avoid elevated temperatures ($\rightarrow$martensite)



P1 Microstructure Map



P2 Microstructure Map



Workflow for Qualification Methodology

This approach focuses on development of the Qualified Materials Process

Transferable to EB-PBF

Transferable, with modifications, to Wire Feed

Developed for Ti-6Al-4V; demonstrated on Addalloy 5T (@MRL).

Note emphasis on laser spot size.

Statistical analysis provides sensitivity (UQ)

Characterize powder feedstock, including flow

↓

Measure the laser power and focus

↓

Predict melt pool size (at least width) from known properties

↓

Inscribe single bead lines over the full range of P & V to be used

↓

Measure bead widths and make corrections to the model, e.g., absorptivity (as a function of power)

↓

Print test bars with a range of P-V[–H] combinations

↓

Machine test bars; validate surface scans w/ X-sections (subset) and CT (small subset); quantify initiating defect and fracture surface defects

↓

Use results to refine the model that predicts the process window

↓

Publish the model for the process window with supporting data

Bottom Line (Up Front)

- 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 defect (pore) content and fatigue life.
- >1,000 4-point bend fatigue bars printed at 5x5x75 mm, consistent powder feedstock, consistent machining & stress relief (no HIP, no heat treatment); round robin printing in EOS M290 (3 locations) and other systems. 4-point bend fatigue successful as a high throughput method; shorter lifetimes expected for push-pull round bar because of larger volume.
- Gross porosity (> 20 µm) can be measured by imaging well machined surfaces; number densities are consistent with computed tomography (CT).
- As-printed surfaces equivalently poor performance as severe lack-of-fusion (LoF) porosity; no success to date with mitigation during printing. Middle of the process window conditions give good performance but a very large range of lifetimes.
- Based on a combination of experience and physics-based knowledge of process, establishing a Qualified Materials Process (for LPBF) requires experiments to determine 1) laser spot size, 2) melt pool dimensions, single track melt pool dimensions and 3) test cubes to check boundaries.

Appendix I

“Dynamic NDE with Online Process Monitoring
- A Safer and More Economical Approach?”
– S. Rott (MTU)

Dynamic NDI with Online Process Monitoring

A Safer and More Economical Approach?

October 17, 2022 / Sebastian Rott

Permission to include presentation in the proceedings as marked was received 28 Nov 2022

Agenda

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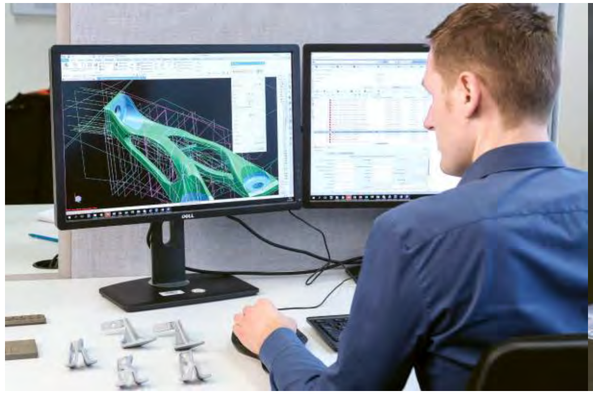
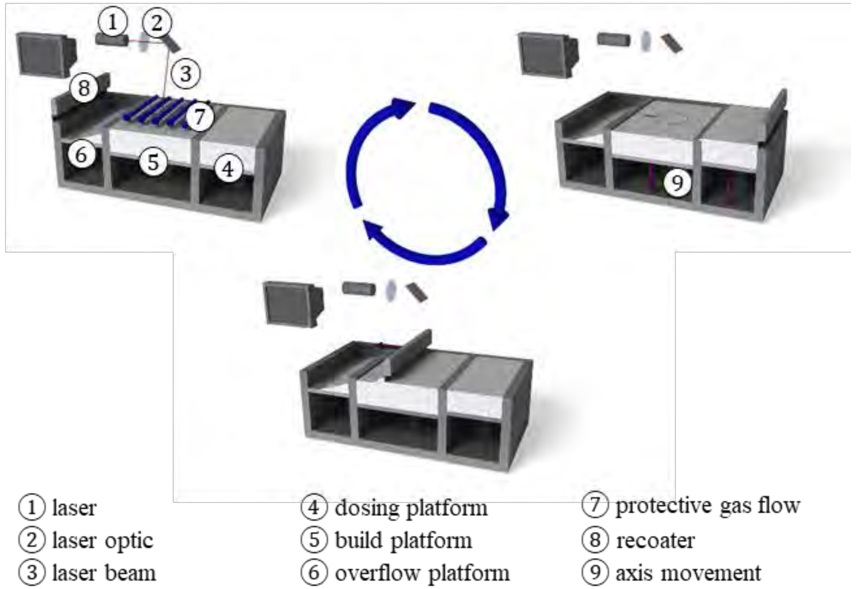
Online Process Monitoring in PBF-LB/M

Motivation:

- High potential of PBF-LB/M parts in aerospace
- Material quality exceeds casting and is almost on the level of forging
- **Nevertheless, PBF-LB/M parts are rarely economical compared to conventional manufacturing**
- One main cost driver is NDI for class 1 and 2 parts
- New possibilities in monitoring due to layer-wise build in PBF-LB/M
- New level of quality and quantity of data in PBF-LB/M (level of detail, resolution, process insight)





Focus of today's presentation:

- Potential of online process monitoring (OPM)
- Internal defects (Surface defects are not considered)
- **Can the use of OPM be an approach for dynamic NDI?**

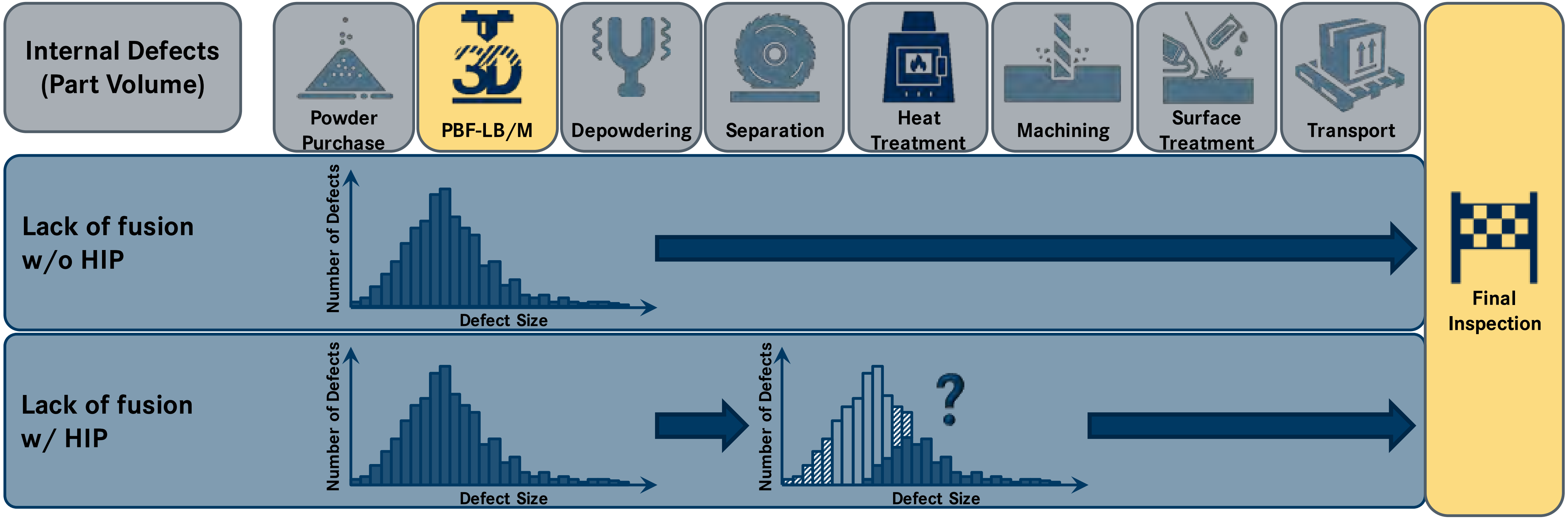
Dynamic NDI ≙ Gradual reduction of the NDI test ratio in the course of a series production based on proven OPM correlations and increased OPM analysis while maintaining the same level of part safety

Potential Defects Along the PBF-LB/M Process Chain

Internal Defects (Part Volume)	Powder Purchase	PBF-LB/M	Depowdering	Separation	Heat Treatment	Machining	Surface Treatment	Transport	Final Inspection
Cracks		X	X	X	X	X	X	X	
Pores	X	X			X				
Inclusions	X	X							
Lack of fusion		X							

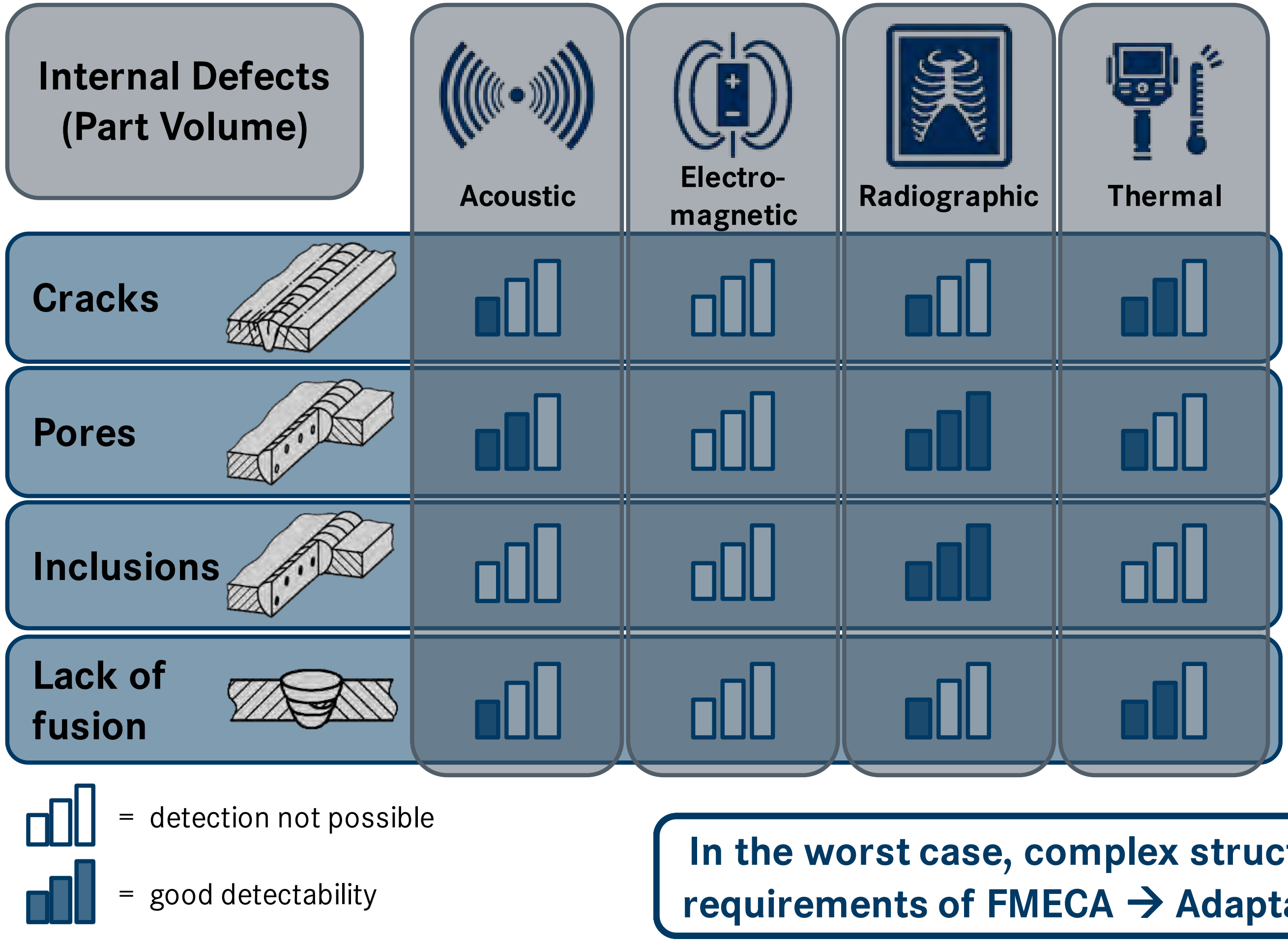
Potential defects along the PBF-LB/M process chain

Potential Defects Along the PBF-LB/M Process Chain



Healing of lack of fusion possible?
Defect removed or transformed to kissing bond?

Potential NDI Methods for Detection of PBF-LB/M Defects in Final Inspection



Detection of defects is dependent on:

- Part size and geometry
- Material
- Surface quality
- Defect size and orientation
- …

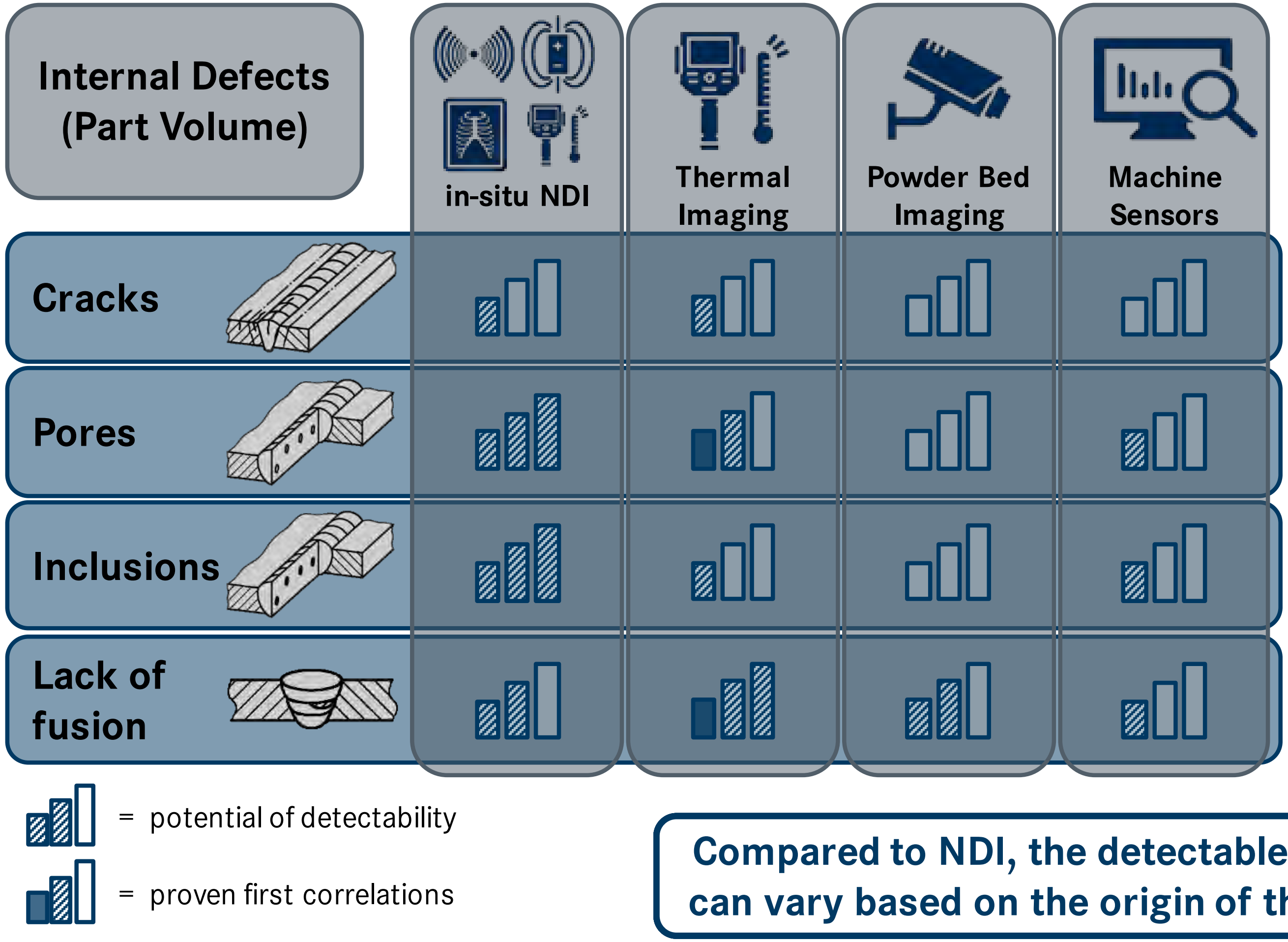
Those must align to:

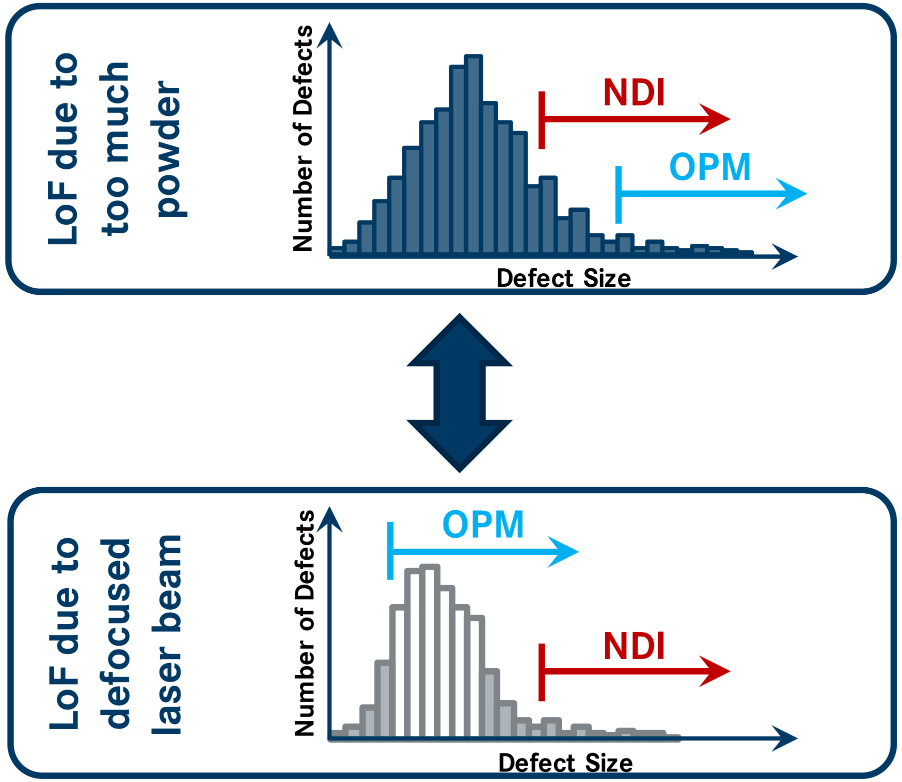
- Safety class of part
- Design philosophy
- PoD requirements

In the worst case, complex structures cannot meet the requirements of FMECA → Adaptation of part geometry

[1] - https://doi.org/10.1201/9780429436543

Potential OPM Methods for Identification of PBF-LB/M Defects





Compared to NDI, the detectable defect size with OPM can vary based on the origin of the defect in PBF-LB/M

Potential of OPM Methods Exemplified on the Optical Tomography

Systematic Global Lack of Fusion

Systematic Local Lack of Fusion

Singular Local Lack of Fusion

Systematic Local Pores

Initial situation:

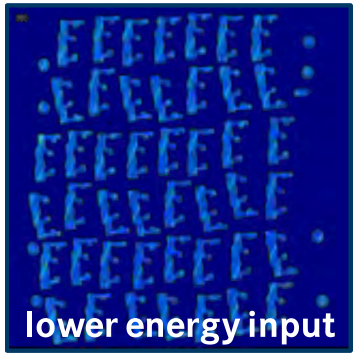
- Changes in machine calibration are only monitored with direct measurements
- Changes of machine calibration result in different thermal radiation of melt pool

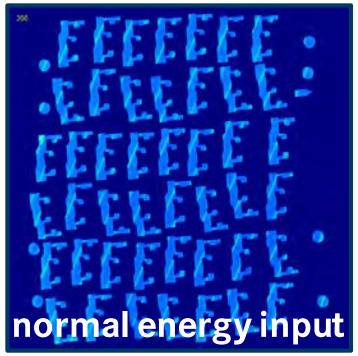
Approach:

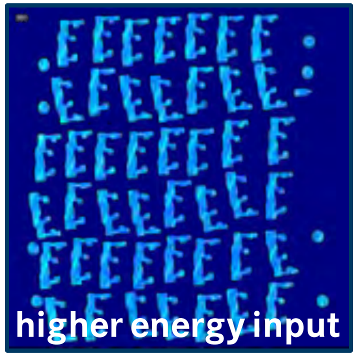
- Creating single value of radiation per layer
- Each build job has an unique thermal signature (due to geometry, exposure strategy, …)

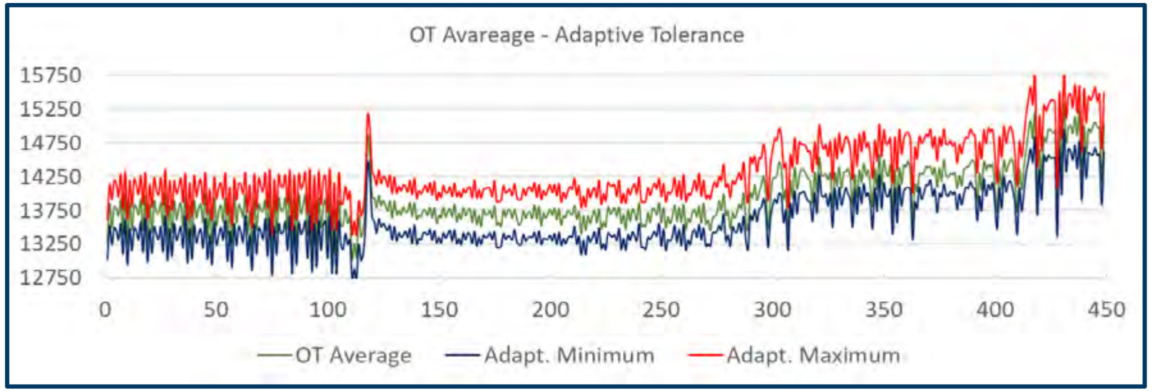
Result:

- Tolerance limits can be determined experimentally or simulatively
- Detection of systematic variations possible due to comparison to tolerance limits









Potential of OPM Methods Exemplified on the Optical Tomography

Systematic Global Lack of Fusion

Systematic Local Lack of Fusion

Singular Local Lack of Fusion

Systematic Local Pores

Initial situation:

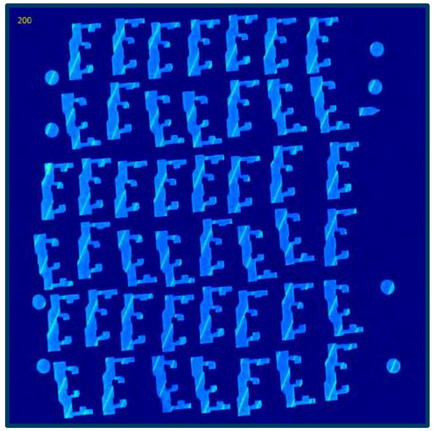
- Lens flaws can result in lack of fusion defects
- Lens flaws result in a systematic local reduction of power
- These are hard to detect in a single layer OT analysis

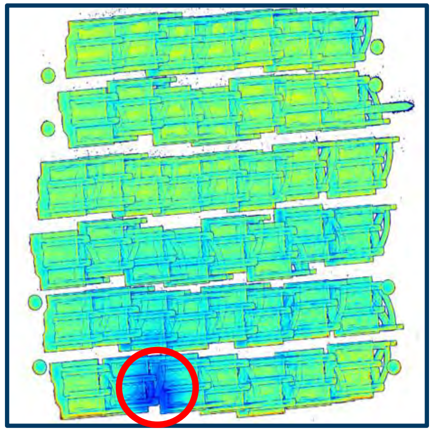
Approach:

- Creating mean image of every layer
- Each pixel per layer which is over a threshold will be considered

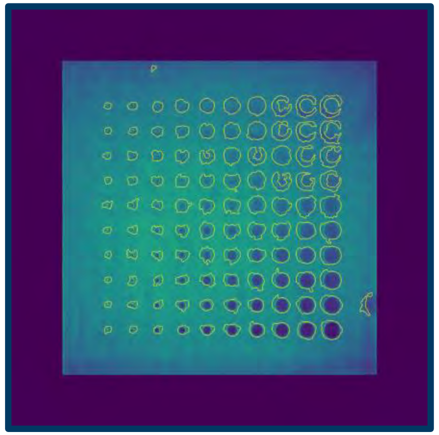
Result:

- Detection of lens flaws with simple gradient filters possible
- Artificial variation of power from 1 % to 10 % in a 1 to 10 mm spot can easily be detected





$$GV_{mean\ c-scan}(x,y) = \frac{\sum_{l=0}^{L} \begin{cases} GV(x,y), & if\ GV(x,y) > Tresh \\ 0, & else \end{cases}}{\sum_{l=0}^{L} \begin{cases} 1, & if\ GV(x,y) > Tresh \\ 0, & else \end{cases}}$$



Potential of OPM Methods Exemplified on the Optical Tomography

Systematic Global Lack of Fusion

Systematic Local Lack of Fusion

Singular Local Lack of Fusion

Systematic Local Pores

Initial situation:

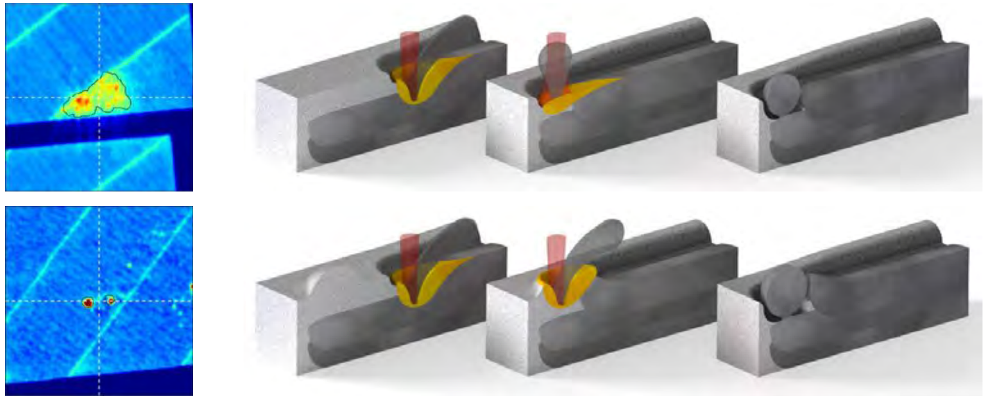
- Process deviations from different origins can result in balling effects [2]
- Balling effects can result in lack of fusion in the next layer due to insufficient energy input

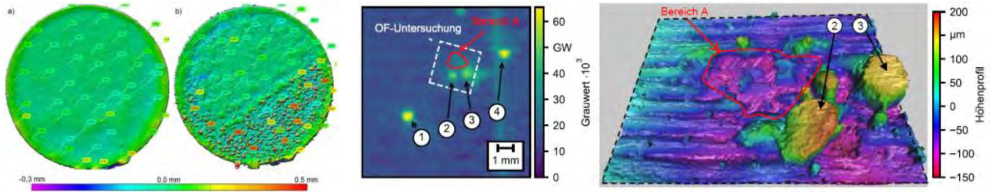
Approach:

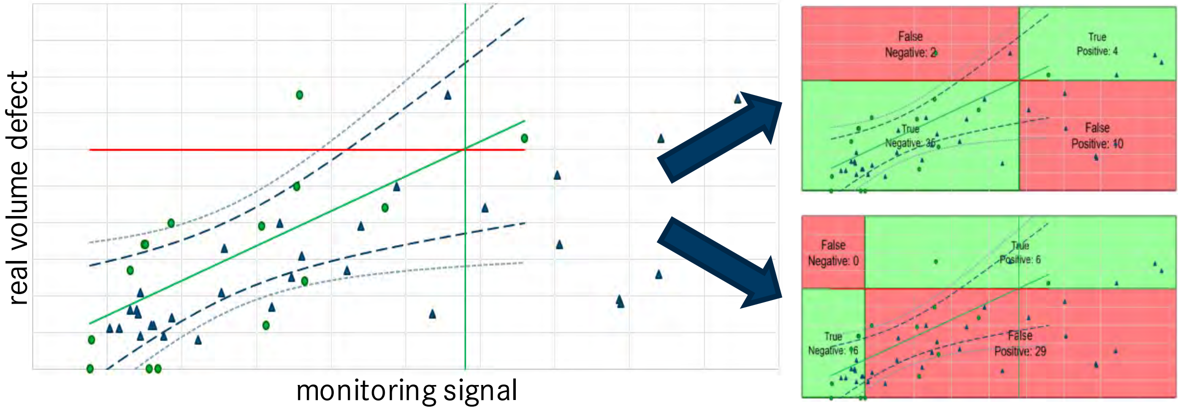
- Correlation of process indications in OPM based on their causes of origin with resulting lack of fusion defects in NDI

Result:

- Based on the correlation and a selected detectable defect size, a probability of detection (PoD) can be defined
- Classification in a confusion matrix based on the selected probability and confidence as well as the threshold







[2] - http://dx.doi.org/10.1016/j.addma.2016.01.004

Potential of OPM Methods Exemplified on the Optical Tomography

- Systematic Global Lack of Fusion
- Systematic Local Lack of Fusion
- Singular Local Lack of Fusion
- **Systematic Local Pores**

Initial situation:

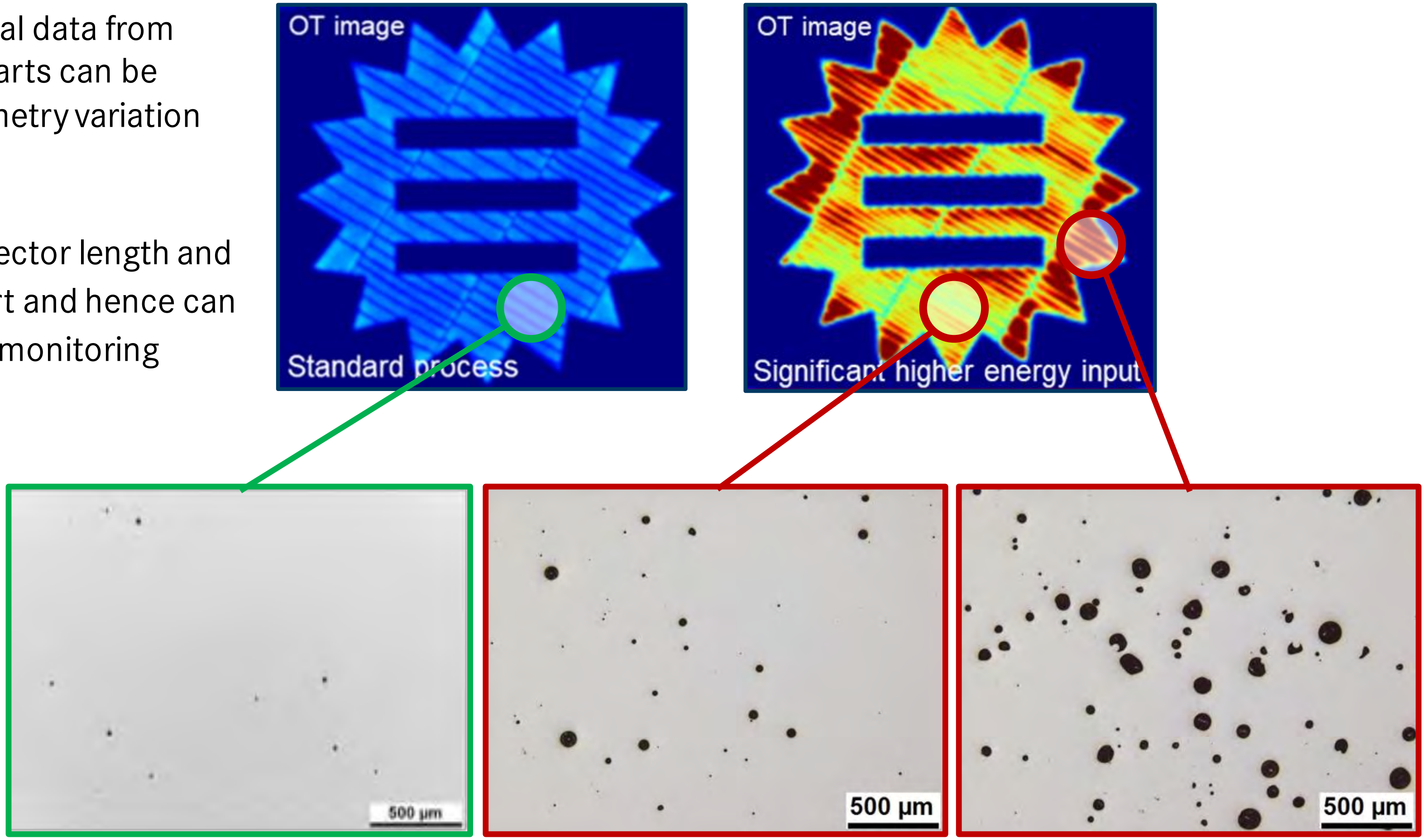
- Transferability of material data from bulk specimen to real parts can be challenging due to geometry variation

Approach:

- Part geometry affects vector length and thermal condition in part and hence can be observed in thermal monitoring

Result:

- Amount of pores can be correlated to gray values at specific region in part



Summary & Outlook

Summary:

- PBF-LB/M step predominantly defines the internal volume
- Limited detectability of internal PBF-LB/M defects with NDI
- OPM can partially identify smaller defects than NDI
- Origin of the defect needs to be considered in indirect OPM
- High potential of OPM Methods in PBF-LB/M

Outlook:

- Need for OPM standards, calibrations and proven correlations to defect types (e.g. LoF due to defocused laser beam)
- Impact of HIP on the defect distribution needs to be determined
- Usage of OPM must be able to guarantee equal part safety
- Comparison of OPM quality to NDI in series production possible through accompaniment

Implementation strategy f PM for internal defects

Scrap parts according OPM true/false positives	Part zoning with OPM support in evaluation	uided NDI (OPM defines NDI positions)	Dynamic NDI (OPM considered in part safety)
✓	⌛	⌛	⌛

Dynamic NDI with OPM can be safer more economical than complete NDI

Contact

Thank you for your attention
Please contact me if you have any further questions

Sebastian Rott

MTU Aero Engines AG

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Appendix J

“JMADD - Public Ti-6Al-4V LPBF Qualification” – J. White (NIAR)

America Makes

Driven by… NCDMM NATIONAL CENTER FOR DEFENSE MANUFACTURING AND MACHINING

Joint Metal Additive Database Definition (JMADD) Ti-6Al-4V Qualification

FAA-EASA AM Workshop

Tuesday, October 18th, 2022

Joel White

Senior Research Engineer

NIAR, Wichita State University

jwhite@niar.wichita.edu

Project Objective

- To produce a set of publicly available statistically substantiated material property data of bulk material properties for metallic AM material with a corresponding material and process specification as well as a framework for future database development projects.
- The selection of a single material and process is necessary to manage the scope of such project, and to begin the work of identifying a standard process to develop material allowables and design data for Metal AM. The initial process and material combination for the scope of this project is Laser Powder Bed Fusion (L-PBF) of Ti-6Al-4V grade 5 alloy.
- The overall objective is to achieve B and A-basis (T90 and T99) design allowable data and establish a best practice for developing AM allowables and specifications that is publicly available for L-PBF of Ti-6Al-4V.

Overview – JMADD Project Team

NIAR
John Tomblin
Rachael Andrulonis
Royal Lovingfoss
Joel White

Battelle
Doug Hall

Auburn University
Nima Shamsaei
Shuai Shao
Steve Taylor

EOS
Greg Hayes
Ankit Saharan

Boeing
Charles Park
Jim Dobbs
Corey Cunningham

CMU
PSU-CIMP3D

Government Stakeholders

U.S. Army, U.S. Air Force, NASA, Federal Aviation Administration, United States Marine Corps, United States Navy

Public Advisory Committee

Embraer, Textron Aviation, Tekna, AP&C A GE Additive Company, EWI, ASTM, Bombardier, Lockheed Martin, GE Additive, Northrop Grumman, Spirit, ATI, TBGA, SAE International

Program Tasks - Prequalification

- Task 1 – coordinate with current FAA CECAM activities from Auburn University on sources of variability; leveraging previous research on processing windows for Ti-6Al-4V from NIAR and others research
  - Form Public Advisory Committee
  - Prequalification Studies
    - Validate processing window or fabrication parameter set, thermal post processing, machining, and inspection for specimen production
    - Perform Parameter Set Comparison Study (added)
    - Perform Orientation Down-Selection Study
    - Perform Site Comparison Study with all three fabricators
  - Documentation
    - Develop Test Matrix and Test Plan
    - Create Feedstock, fabricated Additive Material, and Process specifications along with fabrication Process Control Document
  - Specimen geometry and build design to support fabrication matrix
  - Materials
    - Map out material requirements from build to lot and material supplier deliveries
    - Contract with and acquire feedstock from three material suppliers
  - Trial fabrication for all build designs
  - Define methods for powder retrieval and storage
  - Presentations to PAC, GSC, MMPDS ETTG, JAMWG, MMX, and FAA

Program Tasks

- Task 2 – Generate and inspect coupons, perform testing and completeT-90 for static properties utilizing virgin powder.
  - Final material and process specifications, including powder reuse instructions.
  - Intermediate Milestone: Definition of powder reuse strategy for future work and review by the Public Advisory Committee and Government Technical Team.
  - Review of Phase 1 results by the Government Technical Team. Refined test matrix and test plan before proceeding to next Phase, reviewed by the Government Technical Team.
  - Publish NCAMP B-Basis report.

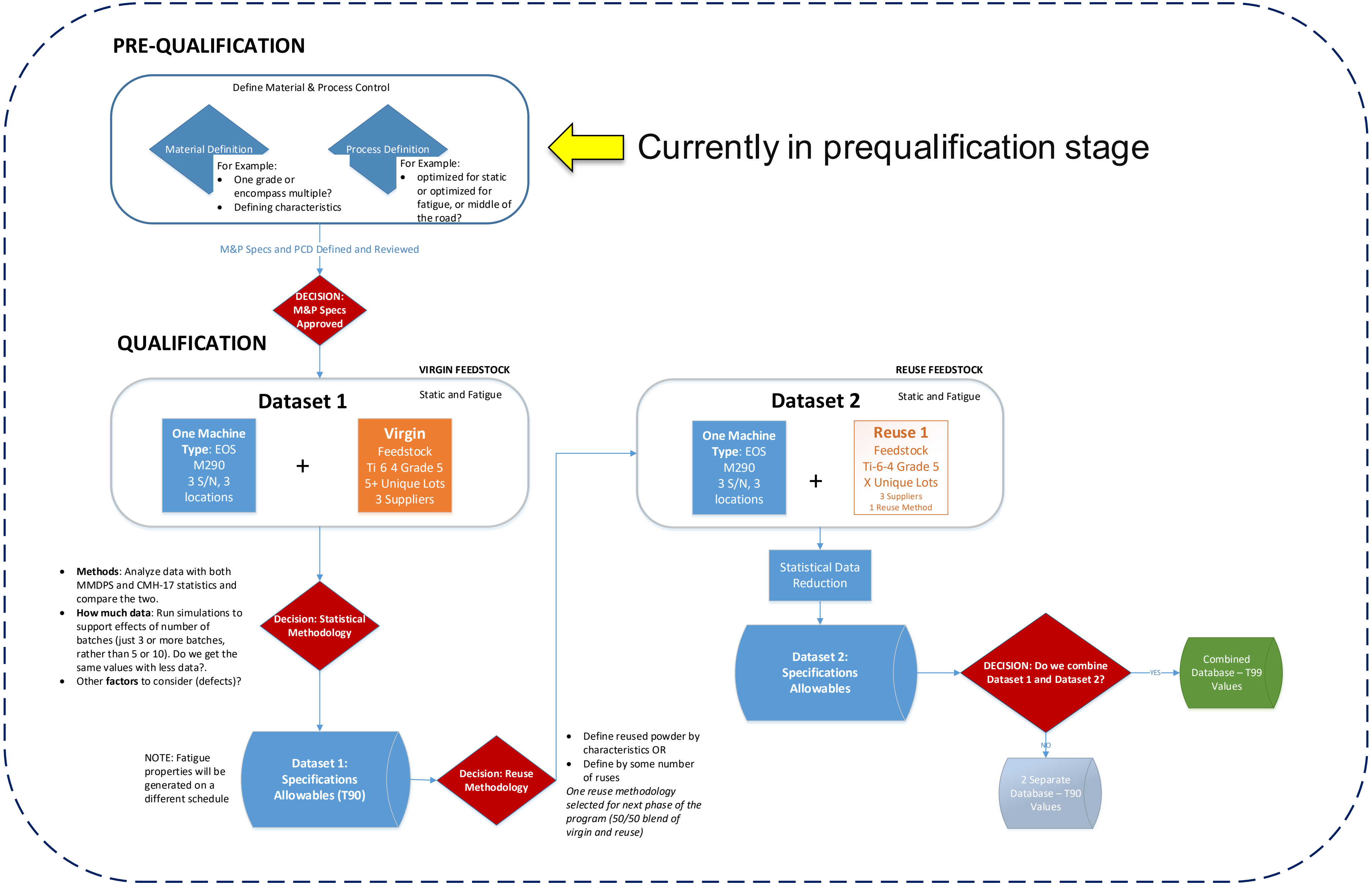
Program Tasks

- Task 3 – Generate and inspect coupons, and complete T-99 equivalent allowables for static properties using and comparing multiple statistical methods.
  - Begin investigation of powder reuse dataset.
  - Review of Phase 2 results, acceptance by the Government Technical Team.
  - Determine statistical grouping of powder reuse dataset.
  - Publish NCAMP A-Basis report followed by CMH-17 and MMPDS statistical analysis and review.

Scope of Current JMADD Program

America Makes

Driven by… NCDMM



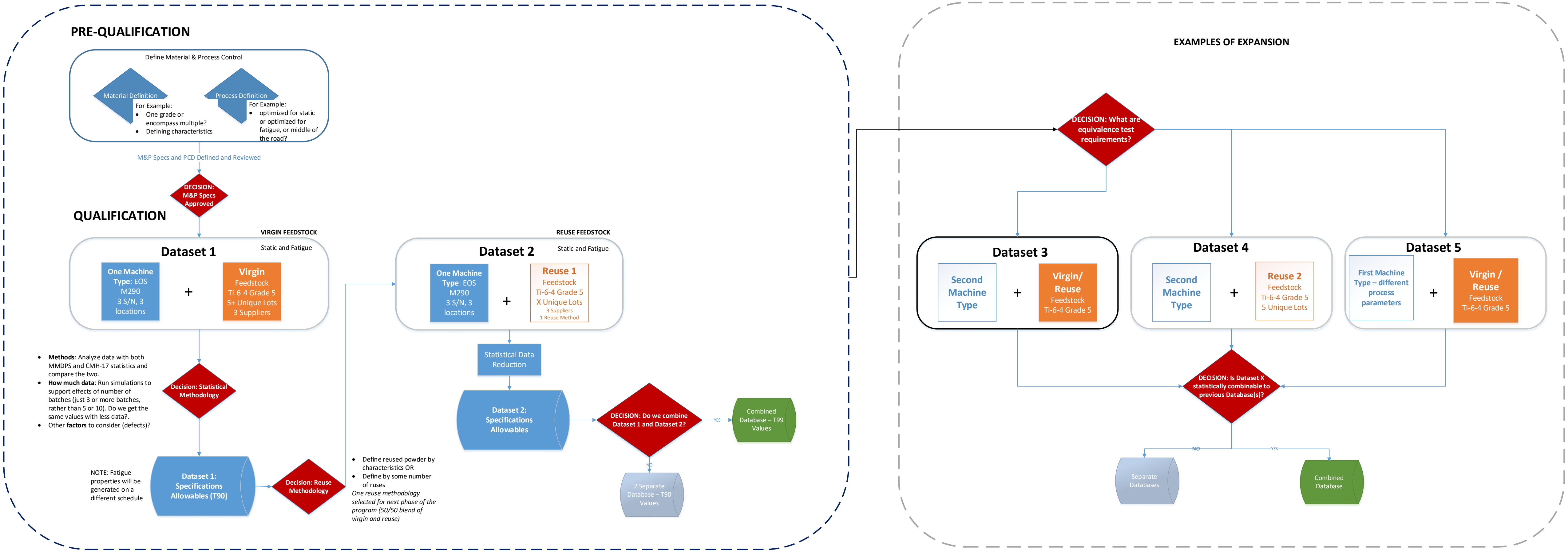
America Makes

Draft Project Roadmap - Overview

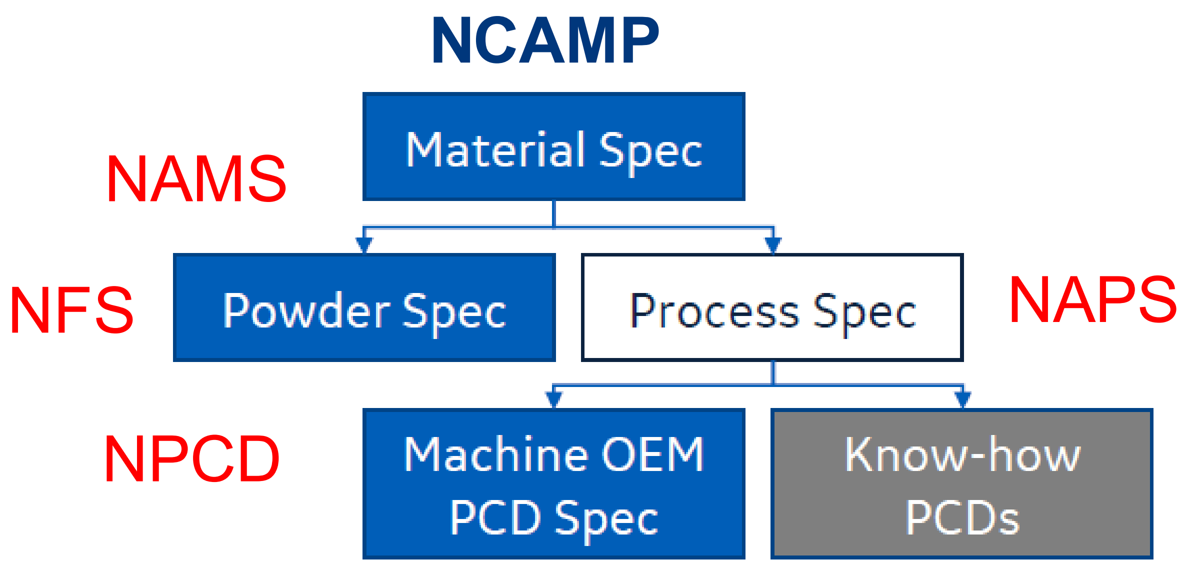
Driven by... NCDMM NATIONAL CENTER FOR DEFENSE MANUFACTURING AND MACHINING

SCOPE OF CURRENT JMADD PROGRAM

EXPANDING THE DATABASE – FUTURE WORK



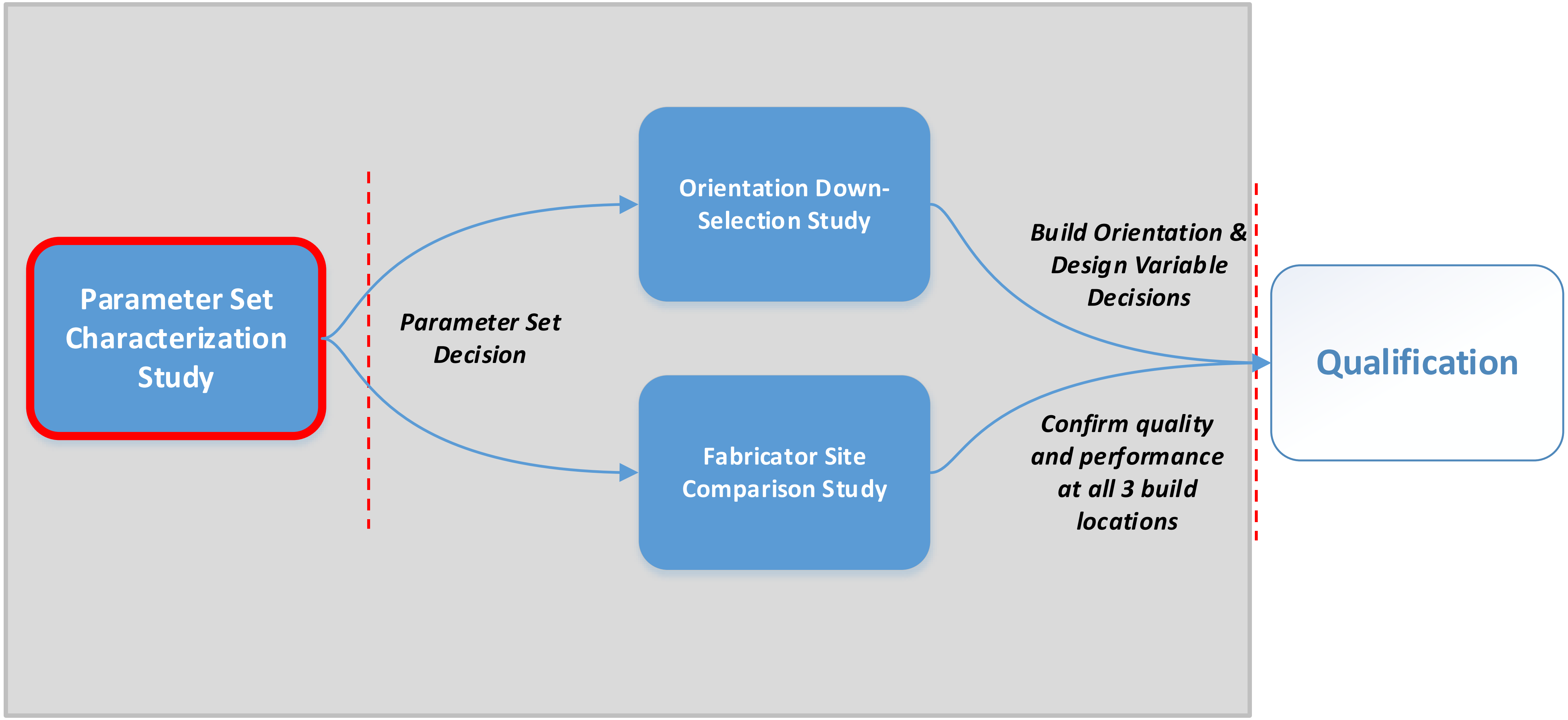
NCAMP Additive Documentation Framework



Adjustments

1) ***Added a material and machine agnostic L-PBF process spec (NPS)***
2) ***Including fully defined key characteristics in the NAMS (material spec) including chemistry, density, min tensile strength, grain size, porosity limit and surface finish.***

Prequalification Studies



Prequalification Studies

- Three separate prequalification studies will be performed prior to moving into the qualification program
  - Parameter Set Comparison Study

    Used to characterize and compare microstructure quality of specimens fabricated using the two EOS stock parameters of interest.

    One parameter set will be chosen for use in the program.
  - Orientation Down-Selection Study

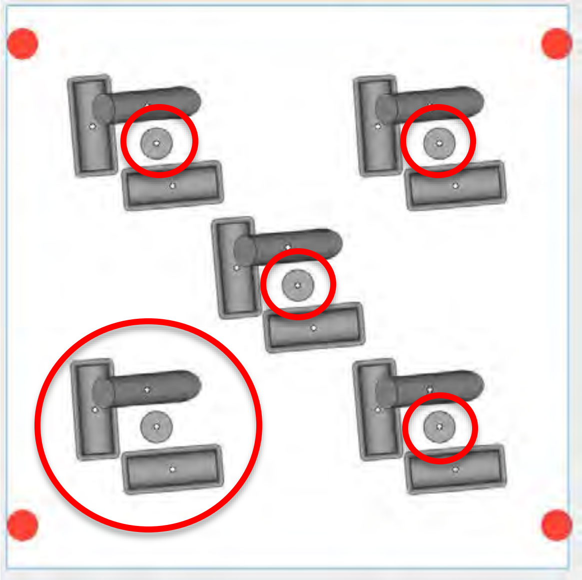
    Primary focus on down selection of XY/YX, ZX45/ZY45

    Also includes fab and test to confirm build design variables (min time intervals, specimen scaling, specimen spacing, build locations)
  - Fabricator Site Comparison Study

    Test matrix (static, fatigue, room temp, elevated temps) to confirm quality and performance across all three fabrication sites.

Parameter Set Comparison Study

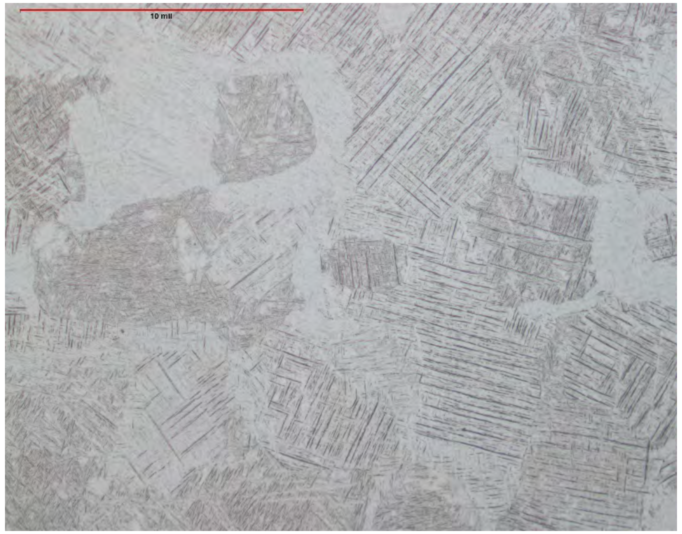
- Objective: To compare porosity and microstructure of specimens fabricated with each of the chosen two parameter sets in the as-fabricated and finished (post-processed and machined) configurations.
  - Build design created to be able to analyze multiple specimen orientations (4) and build locations (5) across the build plate
- Fabricate one build with each of two EOS parameter sets
- Specimens removed from build plate and machined
- Subset of specimens undergo CT pre and post thermal post processing (stress relief and HIP)
- All specimens undergo etching and imaging for microstructure characterization
- Specimens down-selected and analyzed by Electron Backscatter Diffraction (EBSD)
- Micro-hardness testing performed



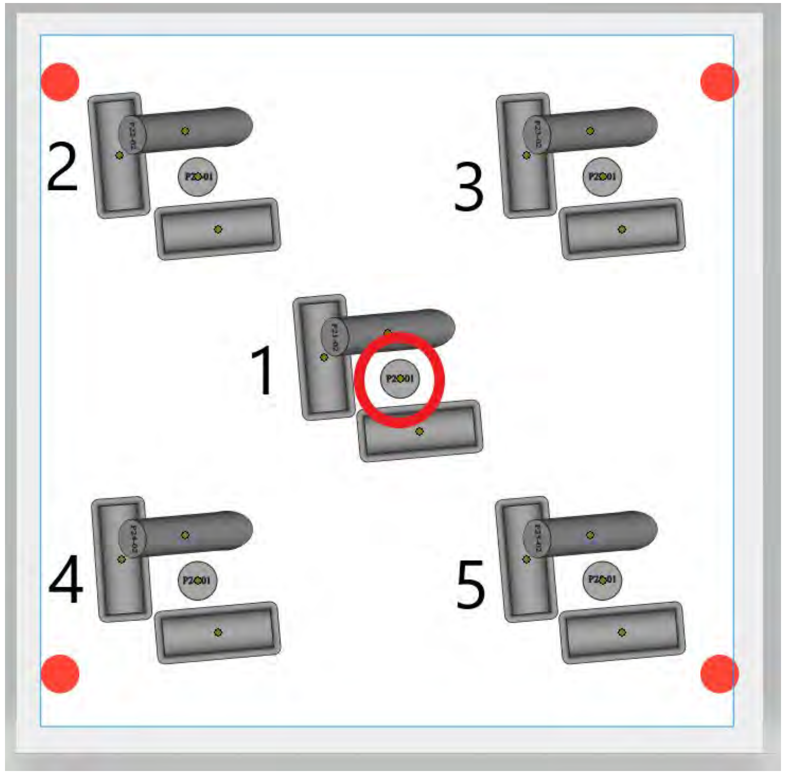
Prequalification Parameter Set Comparison Study

Ti Speed

P11-1 50X



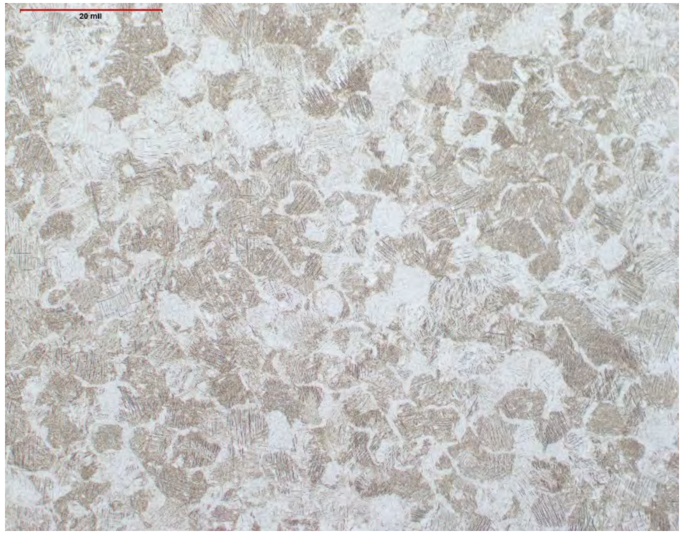
P11-1 200X



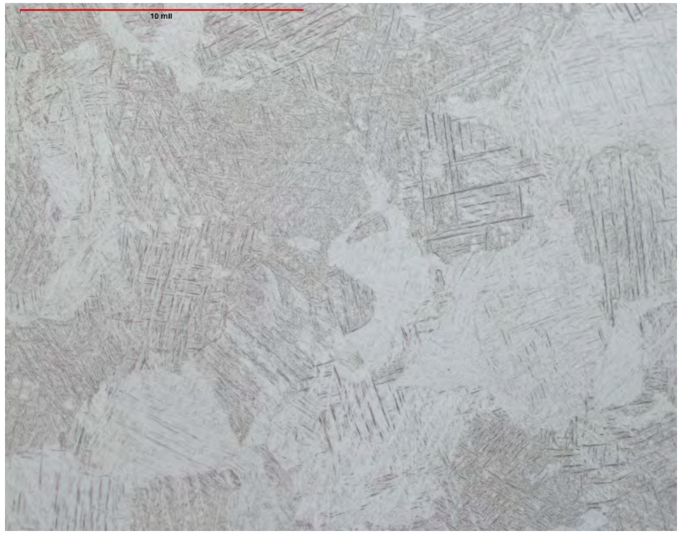
All ZX specimens imaged top-down, corresponding to build view

Example of microstructure analysis (1 of 32)

Hi-Performance



P21-1 50X



P21-1 200X

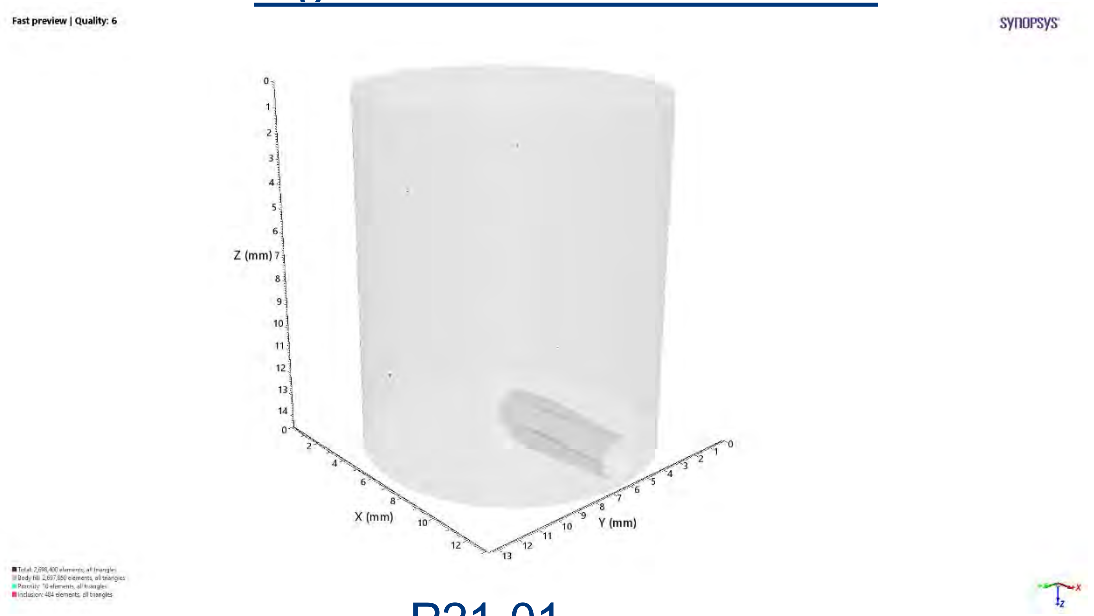
CT Analysis: Build Location 1 (ZX – Orientation)

Speed Parameter

P11-01

Percentage Porosity	0.000%
Percentage Inclusions	0.0001%
Minimum Porosity Length	0.02413mm
Maximum Porosity Length	0.1257mm
Minimum Inclusion Length	0.02413mm
Maximum Inclusion Length	0.1378mm

High-Performance Parameter



P21-01

Percentage Porosity	0.000%
Percentage Inclusions	0.0001%
Minimum Porosity Length	0.03413mm
Maximum Porosity Length	0.1142mm
Minimum Inclusion Length	0.02413mm
Maximum Inclusion Length	0.2724mm

The region around drill hole excluded from void analysis due to artifact affecting porosity analysis

Prequalification Orientation Study

			RTA	ETA 700°F
Orientation Study	**Specimen**	**Property**	**No. of Coupons**	
Tension	E8 / E21 / E111 (XY)	Strength and Modulus	5	5
	E8 / E21 / E111 (YX)	Strength and Modulus	5	5
	E8 / E21 / E111 (ZX)	Strength and Modulus	5	5
	E8 / E21 / E111 (ZY-45)	Strength and Modulus	5	5
	E8 / E21 / E111 (ZX-45)	Strength and Modulus	5	5
Compression	E9 / E209 / E111 (XY)	Compressive Strength, Yield, and Modulus	5	5
	E9 / E209 / E111 (YX)	Compressive Strength, Yield, and Modulus	5	5
	E9 / E209 / E111 (ZX)	Compressive Strength, Yield, and Modulus	5	5
	E9 / E209 / E111 (ZY-45)	Compressive Strength, Yield, and Modulus	5	5
	E9 / E209 / E111 (ZX-45)	Compressive Strength, Yield, and Modulus	5	5
Shear	B769 (XY)	Ultimate Shear Strength	5	5
	B769 (YX)	Ultimate Shear Strength	5	5
	B769 (ZX)	Ultimate Shear Strength	5	5
	B769 (ZY-45)	Ultimate Shear Strength	5	5
	B769 (ZX-45)	Ultimate Shear Strength	5	5
Tension	E8 / E21 XY/ZX/ZX45	Time Interval (20s)	3	3
	E8 / E21 XY/ZX/ZX45	Time Interval (100s)	3	3
	E8 / E21 XY/ZX/ZX45	Time Interval (180s)	3	3
Tension	E8 / E21 XY, ZX, Z45	Close Spacing (0.039)	3	3
	E8 / E21 XY, ZX, Z45	Nominal Spacing (0.6")	3	3
	E8 / E21 XY, ZX, Z45	Wide Spacing (2.0")	3	3
Tension	E8 / E21 ZX	Specimen Max Thickness	3	3
	E8 / E21 ZX	Specimen Min Thickness	3	3
	E8 / E21 ZX	Specimen X Thickness	3	3
LCF	E466 (XY)	T/C-1	2	N/A
	E466 (YX)	T/C-1	2	N/A
	E466 (ZX)	T/C-1	2	N/A
	E466 (ZY-45)	T/C-1	2	N/A
	E466 (ZX-45)	T/C-1	2	N/A

RTA – Room Temperature Atmosphere
ETA – Elevated Temperature Atmosphere

All specimens will undergo SR, HIP, and machining

Prequalification
Fabrication Site Comparison Study

Non-Gating Requirements				
			RTA	ETA (700°F)
Test Type	Specimen	Property	No. of Specimens	
Tension	E8 / E21 / E111 (XY)	Strength and Modulus	3	3
	E8 / E21 / E111 (ZX)	Strength and Modulus	3	3
	E8 / E21 / E111 (ZX-45)	Strength and Modulus	3	3
Compression	E9 / E209 / E111 (XY)	Compressive Strength, Yield, and Modulus	3	3
	E9 / E209 / E111 (ZX)	Compressive Strength, Yield, and Modulus	3	3
	E9 / E209 / E111 (ZX-45)	Compressive Strength, Yield, and Modulus	3	3
Shear	E238 (XY)	Ultimate Shear Strength	3	3
	E238 (ZX)	Ultimate Shear Strength	3	3
	E238 (ZX-45)	Ultimate Shear Strength	3	3
LCF, Stress Level 1	E466 (ZX)	T/C -1	5	N/A
LCF, Stress Level 2	E466 (ZX)	T/C -1	5	N/A
HCF	E466 (ZX)	T/C -1	5	N/A

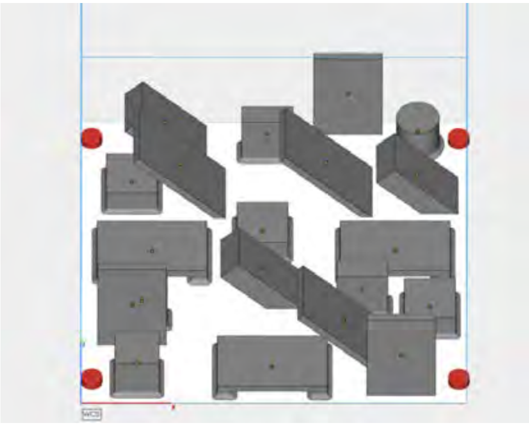
RTA – Room Temperature Atmosphere
ETA – Elevated Temperature Atmosphere

All specimens will undergo SR, HIP, and machining

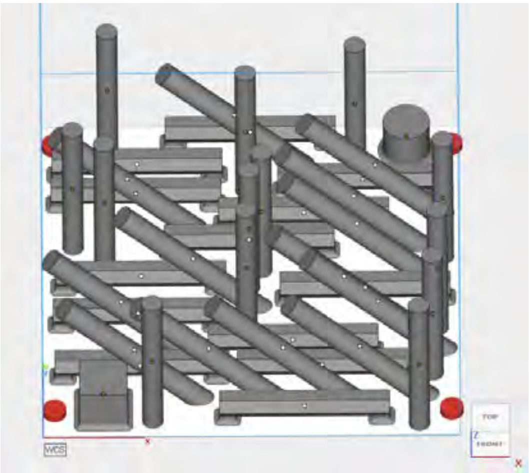
Approach for Material and Fabrication

- Three Ti-6Al-4V grade 5 powder suppliers
  - AP&C
  - ATI
  - Tekna
- 18 feedstock lots total (10+ req’d)
- Three fabrication sites
  - Auburn University
  - Boeing Commercial Airplanes
  - NIAR – Wichita State University
- Mixed build designs
- Fully pedigreed data

Qualification BD 11



Qualification BD 12



Qualification BD 13

Qualification Static Mechanical Tests

				Number of Heats x Number of Machines x Builds per Machine x Number of Specimens per build		
				Test Temperature / Moisture Condition		
Build Orientation	Test Type	ASTM Standard	Property	RTA (70°F)	ETA (Distributed)	Coupons Tested
XY	Tension	ASTM E8	Strength and Modulus	5x3x2x4	3x3x2x3	120 + 54
ZX	Tension	ASTM E8	Strength and Modulus	5x3x2x4	3x3x2x3	120 + 54
Z45	Tension	ASTM E8	Strength and Modulus	5x3x2x4	-	120
XY	Compression	ASTM E9	Compressive Strength, Yield, and Modulus	3x3x2x3	3x3x2x3	54 + 54
ZX	Compression	ASTM E9	Compressive Strength, Yield, and Modulus	3x3x2x3	3x3x2x3	54 + 54
Z45	Compression	ASTM E9	Compressive Strength, Yield, and Modulus	3x3x2x3	-	54
XY	Shear	ASTM B769	Strength and Modulus	3x3x2x3	3x3x2x3	54 + 54
ZX	Shear	ASTM B769	Strength and Modulus	3x3x2x3	3x3x2x3	54 + 54
Z45	Shear	ASTM B769	Strength and Modulus	3x3x2x3	-	54
XY	Bearing	ASTM E238	Strength and Deformation	3x3x2x3	-	54
ZX	Bearing	ASTM E238	Strength and Deformation	3x3x2x3	-	54
Z45	Bearing	ASTM E238	Strength and Deformation	3x3x2x3	-	54
XY	Fracture Toughness	ASTM E399	Linear-Elastic Toughness	3x3x2x3	-	54
ZX	Fracture Toughness	ASTM E399	Linear-Elastic Toughness	3x3x2x3	-	54
Z45	Fracture Toughness	ASTM E399	Linear-Elastic Toughness	3x3x2x3	-	54

Qualification test matrix to be performed twice. Once for Task 2 and an additional time for Task 3 utilizing some reuse powder.

Qualification Cyclic Mechanical Tests

					Number of Heats x Number of Machines x Builds per Machine x Number of Specimens per build		
					Test Temperature / Moisture Condition		
Build Orientation	**Test Type**	**ASTM Standard**	**R-Value**	**Property**	**RTA (70°F)**	**ETA (700°F)**	**Coupons Tested**
XY	Fatigue LCF (Note 4)	ASTM E466	T/C (-1, 0.5)	Fatigue Strength/Residual	1x1x2x6 (Note 1)	-	24
ZX	Fatigue LCF (Note 4)	ASTM E466	T/C (-1, 0.5)	Fatigue Strength/Residual	1x1x2x6 (Note 1)	-	24
Z45	Fatigue LCF (Note 4)	ASTM E466	T/C (-1, 0.5)	Fatigue Strength/Residual	1x1x2x6 (Note 1)	-	24
XY	Fatigue HCF (Note 4)	ASTM E466	T/C (-1, 0.5)	Fatigue Strength/Residual	1x1x2x6 (Note 2)	1x1x2x6 (Note 2)	48
ZX	Fatigue HCF (Note 4)	ASTM E466	T/C (-1, 0.5)	Fatigue Strength/Residual	1x1x2x6 (Note 2)	1x1x2x6 (Note 2)	48
Z45	Fatigue HCF (Note 4)	ASTM E466	T/C (-1, 0.5)	Fatigue Strength/Residual	1x1x2x6 (Note 2)	1x1x2x6 (Note 2)	48

Qualification test matrix to be performed twice. Once for Task 2 and an additional time for Task 3 utilizing some reuse powder.

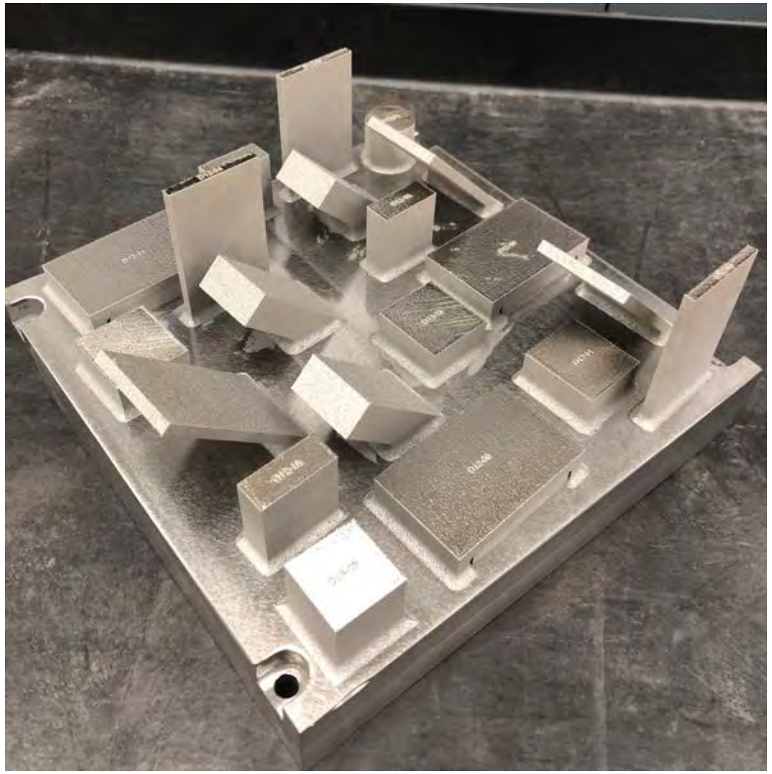
NOTES:
1) Machine A
2) Machine B
3) 4 stress levels with 3 specimens per level
4) All specimens run with frequency of 20-30 Hz

Task 1 - Results

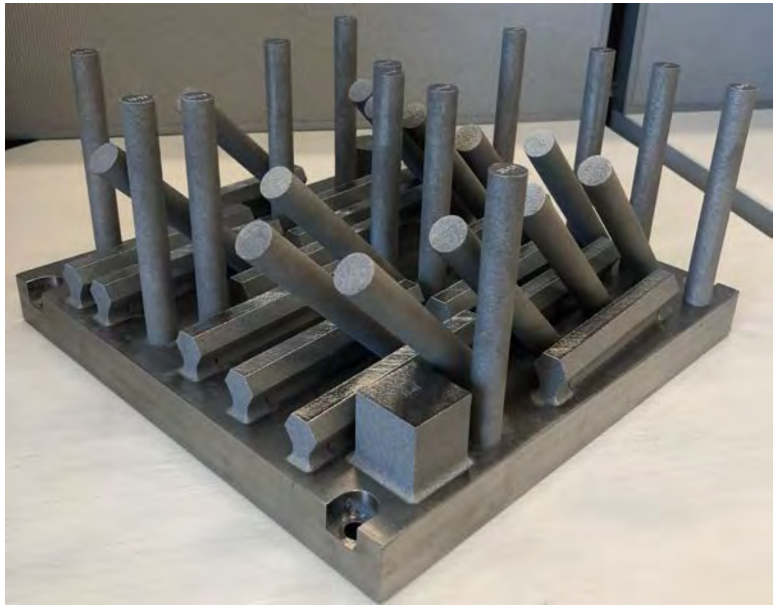
- Public Advisory Committee and Government Steering Committees formed and engaged.
- Prequalification Parameter Set Comparison Study completed.
- Feedstock acquired from all three material suppliers. Delivery schedule agreed upon.
- Mapping of powder suppliers & lots to each build and specimen type
- All NCAMP specifications created and have undergone two review cycles.
  - Feedstock Specification
  - Additive Material Specification
  - Additive Process Specification
  - Process Control Document
  - Test Plan
- All build designs finalized.
- Trial fabrication and machining performed for all prequal and qualification build designs.
- Methodology for powder retrieval and storage defined and hardware purchased to support effort.

Qualification Build Designs

Qualification BD11



Qualification BD12



Qualification BD13

Build designs 11-13 of 13 total

Results - Major Decisions

- Decisions made in coordination with PAC, GSC, and other technical experts:
  - Material: Ti-6Al-4V grade 5 to be used
  - Machine architecture: EOS m290
  - All specimens to undergo HIP and be machined
  - Three fabrication sites chosen
  - Three feedstock suppliers chosen
  - Parameter set study added in prequalification
  - Parameter set decision
  - Stress Relief and Hot Isostatic Pressing (HIP) parameter decision
  - Elevated Temperature Atmosphere (ETA) testing to be performed on distributed temperatures for curve creation (room temp to 900°F)
  - Documentation hierarchy

Next Steps

- Prequalification Orientation Study and decision
- Prequalification Site Comparison Study
- Qualification kick-off
- Task 2 qualification builds, machining, HIP, and conformity
- Task 2 qualification testing
- Task 2 qualification data analysis
- Final reuse methodology definition
- Statistical Analysis via CMH-17 and MMPDS

Questions?

When America Makes America Works

America Makes

AmericaMakes.us @AmericaMakes /AmericaMakes

Appendix K

"MMPDS and Additive Metals"
– D. Hall (Battelle)

MMPDS Volume II Update: Material Allowables for Additive Metals

EASA-FAA AM Workshop
October 18, 2022

Doug Hall
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Program Manager - MMPDS
Battelle Memorial Institute
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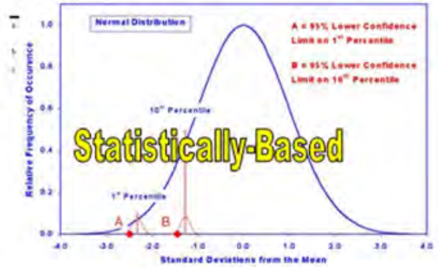
MMPDS

Battelle
The Business of Innovation

Metallic Materials Properties Development and Standardization



History

- ANC5 (1937-1954), MIL-HDBK-5 (USAF: 1954 – 2003), MMPDS (FAA: 2003-today)
- Battelle Memorial Institute - program Secretariat since 1956.
- MMPDS Handbook is the primary source of statistically-based material allowable properties for metallic materials and fasteners used in many different commercial and military weapon systems around the world.
- The MMPDS General Coordinating Committee (GCC) is a collaboration between government agencies, aerospace companies, testing and data service companies, and metallic material producers.
- Biannual meetings to review and approve statistical analyses and guidelines.

Scope

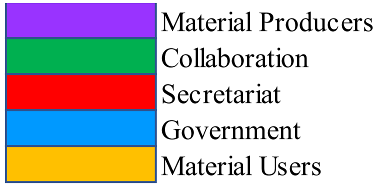
- The Handbook currently contains 600+ A/B-Basis and 1000+ S-Basis entries, 400+ unique metal specifications.
- Two to five new alloys are added each year.†
- For more information visit www.mmpds.org

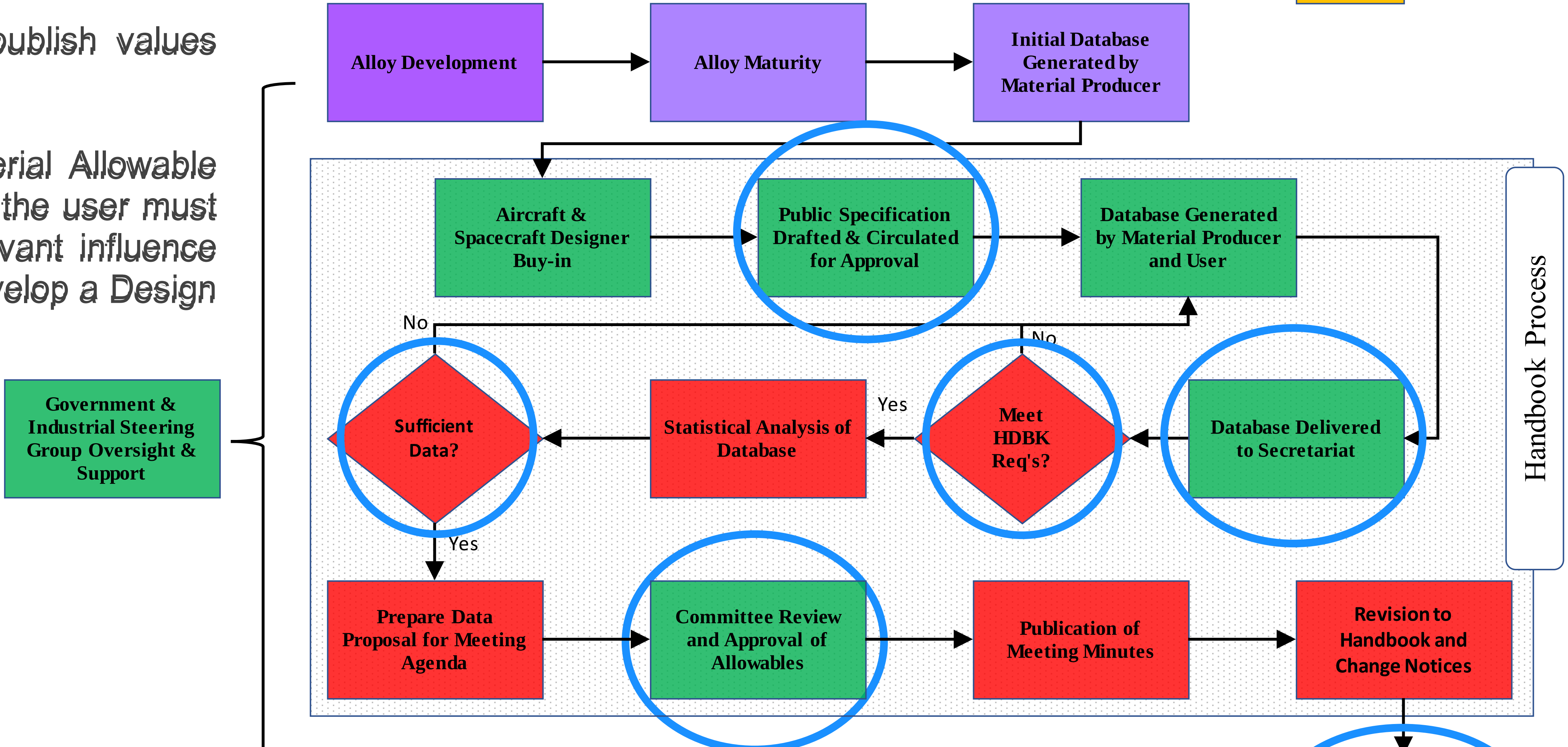
† Pandemic rate has been slower.

MMPDS Review & Approval DRAFT

Process to publish values in Volume II.

Once a Material Allowable is published, the user must consider relevant influence factors to develop a Design Value.





End-users may need to provide additional information to meet certification or qualification requirements of relevant regulators. Chapter 10 will outline a path to develop Design Values from the published Material Allowables.

Vol 2 TOC and Three Phases

Phase	No.	Chapter
Phase 1	1	General Information
Phase 2	2	Steel Alloys
Phase 2	3	Aluminum Alloys
Phase 2	4	Magnesium Alloys
Phase 2	5	Titanium Alloys
Phase 2	6	Heat Resistant Alloys
Phase 2	7	Miscellaneous Alloys
Phase 3	8	Metallurgical Joining Technologies – Welding, Friction-Stir Welding
Phase 1	9	Guidelines for the Presentation of Data
Phase 1	10	Guidelines for Use of Published Design Allowables

MMPDS relies on data submitted by sponsors to generate and submit data. Use data to guide future improvements to of Chapter 9 and 10.

One company has submitted a data set which was submitted and reviewed in 2021. Feedback to the sponsor is driving modifications to their specifications, new data, and Agenda Items for 2023.

Ongoing activity to develop data generation, analysis, and presentation guidelines for microstructure.

MMPDS will outline a path to approval, but regulators control that process.

MMPDS BATTELLE

Phase I Framework – Status

i. Handbook Organization
   i. 21-01: Foreword to Volume II – GSG declaration of applicability of MMDPS V2 – 40
   ii. 21-46: MMPDS Vol 2, Certification & Qualification “Further Showing” – Continued at 40th
   iii. 22-08: Chapter 1 for Volume II – 39H, 40A – Sections 1.1, 1.2, 1.4-1.6 – 40A
   iv. 22-09: Preface for MMPDS Volume I and II – 39A
   v. 22-21: Sections 10.1 and 10.2: Introduction & One-Sample Acceptance Test – 40A
   vi. 23-NIN: MMPDS-2023, Volume II, 41A

ii. Definitions
   i. 19-26: Definitions for Process Intensive Materials & Technologies – 34A
   ii. 20-20: Definitions for Volume II – 37A
   iii. 20-31: Definitions of “Design Allowable”, “Design Value”, and “Material Allowable” – 37A

Green text is approved items. Black text is active items. 39/40 are meeting numbers. A/H = Agenda/Handout

Phase I Framework - Status

iii. Material Specification Requirements
   i. 19-17: Minimum Specification Content Requirements for Public Specifications – 36A
   ii. 21-37: Update to Section 9.2.2 for Volume II – 38A
   iii. 21-20: Microstructural Submittal Requirements – 40H
   iv. 22-14: Modifications to Section 9.2.2, V2 – 39A

iv. Data Generation Requirements
   i. 19-20: Data Requirements for Volume II – 36A
   ii. 21-04: Sections 9.1, 9.2, 9.3 for Volume II – 40A
   iii. 21-41: Section 9.8.3 Tabular Data Presentation – 39A

Phase I Framework - Status

v. Data Analysis Requirements
   i. 21-11: Interim Data Analysis Methods: Volume II – 37A
   ii. 22-06: Combinability in Volume II – 39A
   iii. 22-10: Uniformity Test for More Than Three Bins – 39A

vi. Acceptance Test Methods
   i. 19-08: One-Sample Acceptance Testing Method – 34A

Data Requirements for Volume II - Mandatory

Mechanical or Physical Property	Customary Statistical Basis	Relative Importance in MMPDS Volume II	Extenuating Circumstances for Special Material Usage Requirements	Minimum Data Requirements				
				Sample Size	No. of Heats[g]	No. of Mfg. Lots	Machines[f]	Build Cycles
Bearing Yield and Ultimate Strength	S-Basis	Mandatory	Except for elevated temperature applications	30	3	3	3	3
Compression Yield Strength[a] (Derived)	Same as Tensile Properties	Mandatory		20	3	10	3	3
Density	Typical	Mandatory		3	3	3	3	3
Elastic Modulus - Tension Elastic Modulus - Compression Elastic Modulus - Dynamic Elastic Modulus - Shear	Typical	Mandatory Mandatory Recommended Recommended	Dynamic modulus is strongly recommended for some engine applications	9	3	3	3	3
Elastic Modulus (T, C, D) - Elevated Temperatures	Typical	Mandatory	For anticipated usage temperature range	9	3	3	3	3
Elongation	S-Basis	Mandatory	Two-inch gage length preferred	30	3	3	3	3
Shear Ultimate Strength[a]	S-Basis	Mandatory	Except for elevated temperature applications	30	3	3	3	3
Stress/Strain Curves (To Yield) Tension and Compression	Typical	Mandatory	Desirable to have accurate plastic strain offsets from 10^{-6} to 3×10^{-2}	6	3	6	3	3
Stress/Strain Curves (Full Range) Tension	Typical	Mandatory	The strain rate should be constant through failure.	6	3	6	3	3
Tension Yield and Ultimate Strength	S-Basis	Mandatory		30	3	3	3	3

A new indirect method is awaiting 60-day approval, reducing the amount of data needed for A/B/C/D-Basis for Fbru, Fbry, Fcy, Fsu

A new indirect method is awaiting 60-day approval, reducing the amount of data needed for A/B/C/D-Basis for Fbru, Fbry, Fcy, Fsu

Other requirements apply.

A new indirect method is awaiting 60-day approval, reducing the amount of data needed for A/B/C/D-Basis for Fbru, Fbry, Fcy, Fsu

Data Requirements for Volume II – Strongly Recommended

Mechanical or Physical Property	Customary Statistical Basis	Relative Importance in MMPDS Volume II	Extenuating Circumstances for Special Material Usage Requirements	Minimum Data Requirements				
				Sample Size	No. of Heats[g]	No. of Mfg. Lots	Machines[f]	Build Cycles
Coefficient of Thermal Expansion	Typical	Strongly recommended	For anticipated usage temperature range	6	3	3	3	3
Poisson's Ratio	Typical	Strongly recommended		6	3	3	3	3
Specific Heat	Typical	Strongly recommended	For anticipated usage temperature range	6	3	3	3	3
Tension Yield and Ultimate Strength	D-Basis	Strongly recommended	Especially for strength critical applications; a parametric representation of data is possible	100	10	10	5	10
Tension Yield and Ultimate Strength	C-Basis	Strongly recommended	Especially for strength critical applications; a parametric representation of data is possible	100	10	20	5	20
Tension Yield and Ultimate Strength	C-Basis & D-Basis	Strongly recommended	Especially for strength critical applications; a parametric representation of data is not possible	299	10	20	5	20
Thermal Conductivity	Typical	Strongly recommended	For anticipated usage temperature range	6	3	3	3	3

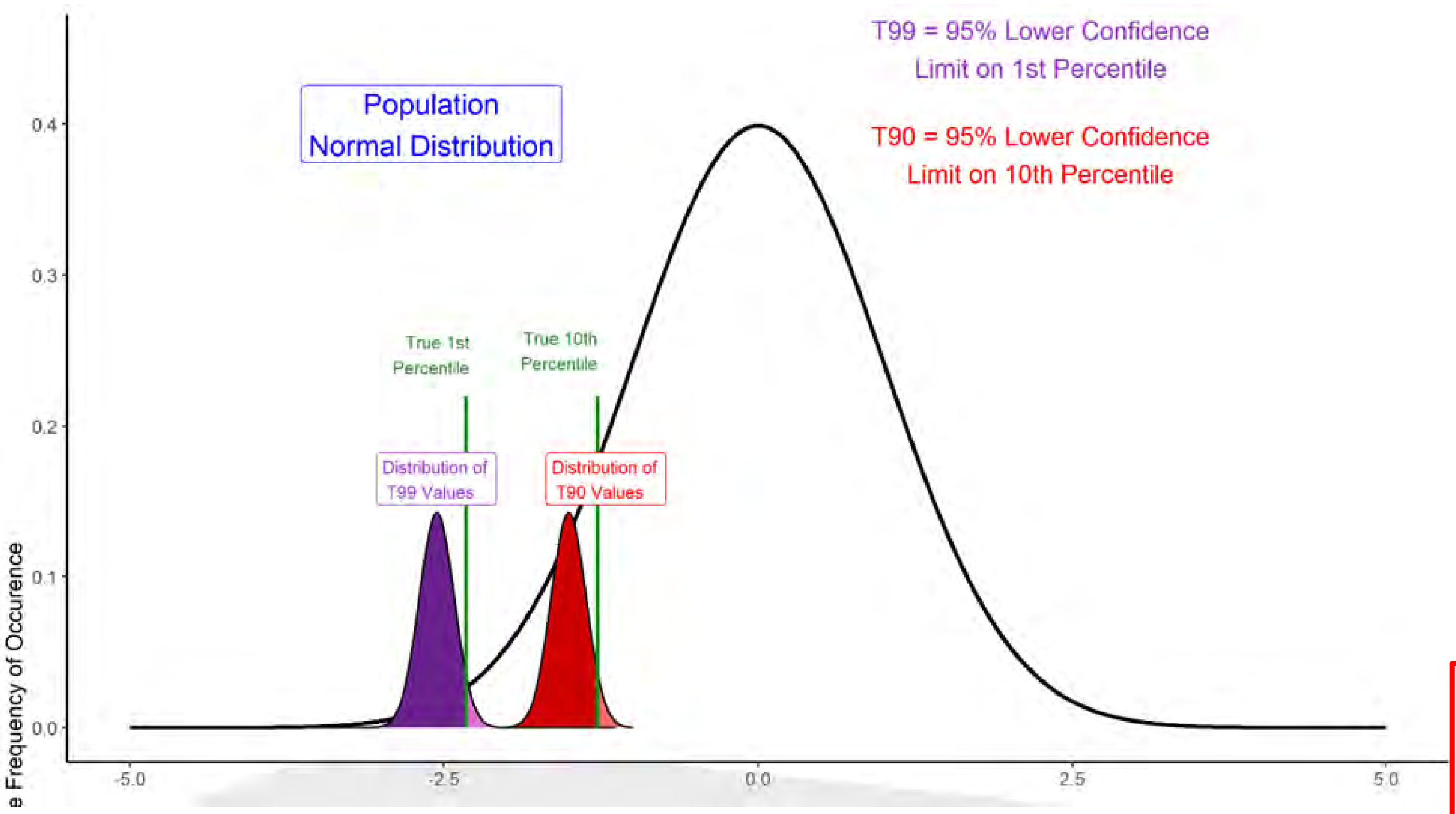
Other requirements apply.

Data Requirements for Volume II - Recommended

Mechanical or Physical Property	Customary Statistical Basis	Relative Importance in MMPDS Volume II	Extenuating Circumstances for Special Material Usage Requirements	Minimum Data Requirements				
				Sample Size	No. of Heats[g]	No. of Mfg. Lots	Machines[f]	Build Cycles
Creep and Rupture	Raw Data w/ Best-Fit Curves	Recommended	Especially for elevated temperature applications	6 tests per creep strain level and temp, at least 4 temps over usage range				
Effect of Temperature Curves	Same as Room Temperature Properties	Recommended	Especially for elevated temperature applications	5[b]	2[c]	5	5	5
Effect of Thermal Exposure	Same as Baseline Properties	Recommended	Especially for elevated temperature applications	5[b]	2[c]	5	5	5
Fatigue-Load Control	Raw Data w/ Best-Fit Curves	Recommended	Especially for high-cycle fatigue critical applications	6 test per stress ratio (R), 3 stress ratios, no minimum heat or lot requirements				
Fatigue-Strain Control	Raw Data w/ Best-Fit Curves	Recommended	Especially for low-cycle fatigue critical applications	10 tests for R_ε = -1.0, 6 tests other strain ratios				
Fatigue Crack Growth	Raw Data w/ Best-Fit Curves	Recommended	Especially for damage tolerance critical applications	Duplicate da/dN results for relevant stress ratios and stress intensity range				
Fracture Toughness - Plane Strain	Max., Avg., Min., Coef. of Variance, S- Basis	Recommended	Mandatory for materials with spec minimum requirements for plane strain fracture toughness	30	3	10	3	10
Fracture Toughness - Plane Stress	Raw Data w/ Best-Fit Curves	Recommended	Mandatory for materials with spec minimum requirements for plane stress fracture toughness	d	2	5	3	5
Reduction In Area	Typical	Recommended		When tested, use same criteria as for elongation				
Stress Corrosion Cracking	Letter Rating	Recommended		Conform to replication requirements in ASTM G 47				
Tension Yield and Ultimate Strength - Elevated Temps	Typical	Recommended	Mandatory for elevated temperature applications	e	2	5	5	5

Other requirements apply.

Volume II C-Basis, D-Basis, S-Basis: Material Allowables



T_{99} and T_{90} are one-sided lower tolerance bounds. Both are calculated from data.

C-Basis = the lower of the specification minimum or T_{99} value.

D-Basis = is the T_{90}. It is not related to the spec minimum.

S-Basis = is a T_{99} that does not meet C-Basis requirements for sample size or distribution fit.

Metallic C-/D-/S-Basis published in MMPDS Volume II require “further showing.” A large sample is required.

MMPDS is the primary publicly available, gov’t approved source for A/B/C/D/S-Basis material allowables for metals. Proprietary values require extra effort by the CEO.

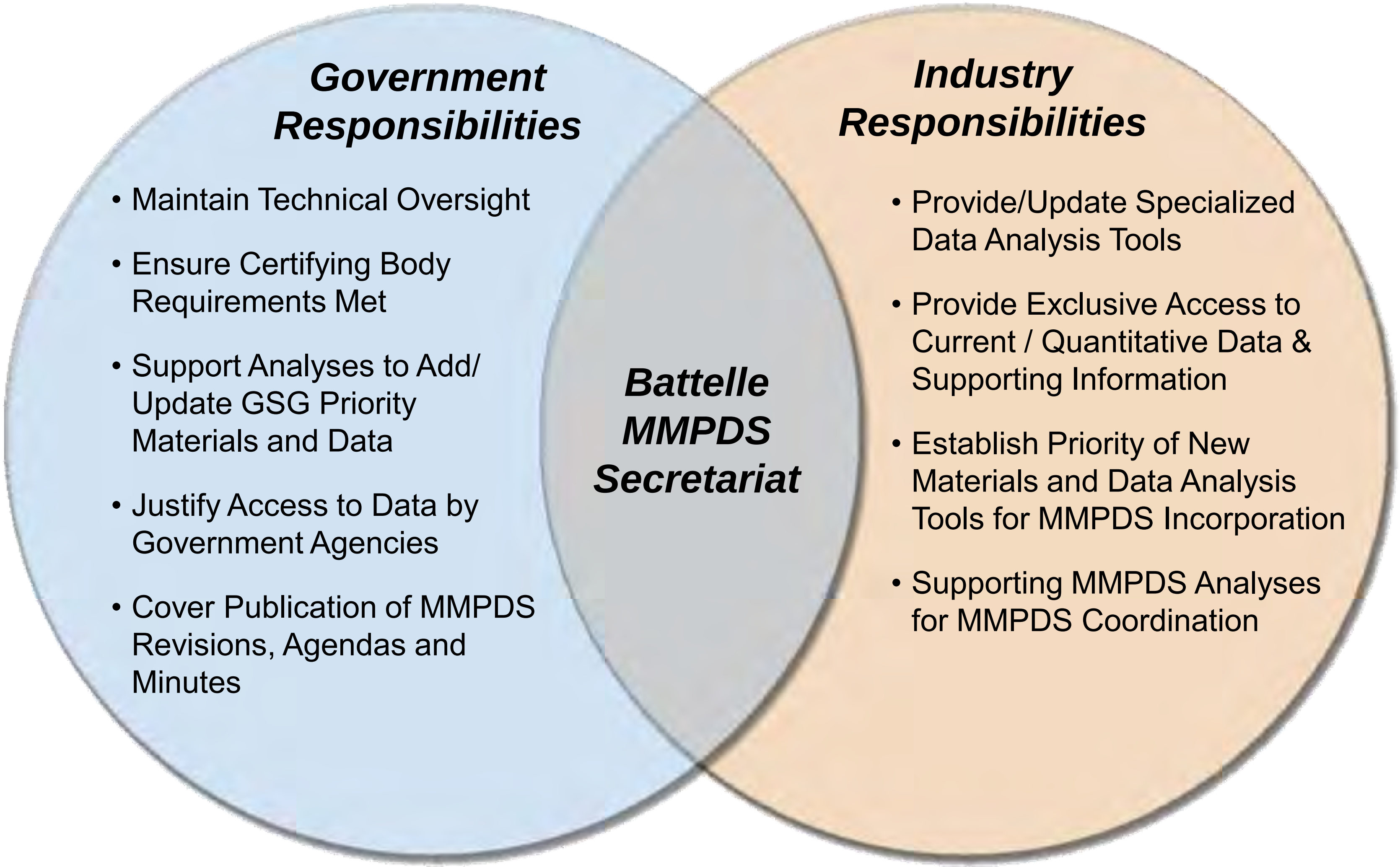
BATTELLE

It can be done

Coordination with SDOs & Other Organizations

- ASTM International
  - F42 membership
- FAA-EASA AM Workshops
  - WG1 - Discussing S-Basis as an acceptable material allowable for low criticality parts.
- NIAR
  - JMADD - Air Force/FAA funded project to develop a spec and allowables for PBF Ti 6-4
- NIST
  - Member of a NIST team defining data management standards. FAIR standards are guiding database development
- SAE AMS
  - Advisory Group & Metals Committee – K. Sabo - a GA for periodic testing of secondary props
  - Additive Manufacturing Data Consortium – Battelle is a Liaison member
  - SAE AMS AM Metals Committee
    - Update to the AM Data Submission Guideline – Andrew Steevens (Boeing) sponsor
    - Multiple specs being developed. Data will come to Battelle for analysis to set lot-release values.
    - AMS 7032 (Machine Qualification) – reporting requirement to send data to Battelle.

MMPDS General Coordination Committee



GCC makes final MMPDS program decisions based on Task Group recommendations.

Task Groups:
GTG – approve **all** guidelines
MTG – approve materials (Ch. 2-7)
FTG – approve fasteners (Ch. 8)
ETTG – approve V2 content

Steering Groups:
Industry sector input
ASG, MATSSG, PSG

Working Groups:
Technical input from industry
FatWG, SWG, WWG
V2WG – develop V2 tech details

39th-40th MMPDS GCC Meeting Results

- Volume II is under development. Information subject to further change.
- Agenda Items associated with Volume II
  - ➢21-04: Sections 9.1, 9.2, 9.3 for Volume II – 60-day approval at 40th
  - ❑21-20: Microstructural Submittal Requirements – Continued at 40th
  - ✓21-41: Section 9.8.3 Tabular Data Presentation – Approved at 39th
  - ❑21-46: MMPDS Vol 2, Certification & Qualification “Further Showing” – Continued at 40th
  - ✓22-21: Sections 10.1 & 10.2: Introduction & OSAT – Approved w/Changes at 40th
  - ✓22-06: Combinability in Volume II – Approved at 39th
  - ➢22-08: Chapter 1 for Volume II – 60-day approval at 40th
- Full Minutes of MMPDS meetings are shared with ISG, GSG, and registered non-member attendees.

These approve items are a small part of the Chapter 9 Guidelines. Other requirements apply.

Phase I Framework - Activity

i. Handbook Organization
ii. Definitions
iii. Material Specification Requirements
iv. Data Generation Requirements
v. Data Analysis Requirements
vi. Acceptance Test Methods

Appendix L

“The Concept of Material “Engineering Equivalence” in Achieving and Sustaining Efficient Qualification and Certification of AM Materials and Parts”

– D. Wells (NASA)

CENTER of EXCELLENCE
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ICAM2021

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Considerations on the evaluation of material "engineering equivalence" in achieving and sustaining efficient qualification and certification of AM materials and parts

Douglas N. Wells
Deputy Technical Fellow for Materials
NASA Marshall Space Flight Center

Samuel Cordner
Structural Materials
NASA Marshall Space Flight Center

www.amcoe.org

ICAM 2021

Douglas N. Wells

Mr. Douglas Wells is a structural materials engineer in the Materials and Processes Laboratory at the NASA Marshall Space Flight Center and serves as a deputy Technical Fellow for Materials for the NASA Engineering and Safety Center. Doug has thirty years of experience in fatigue, damage tolerance, and fracture control of flight structures. For the past nine years, he has focused on developing methodologies for the qualification and certification of additively manufactured spaceflight hardware, including the development of the NASA standards that establish requirements for incorporating additively manufactured hardware into flight vehicles for NASA and its commercial partners. In addition to standards development for NASA, Doug is actively engaged with the broader international standards community working in additive manufacturing, including ASTM and SAE. Currently, much of his time is spent on the interpretation of certification requirements for additively manufactured hardware on a variety of NASA missions. Doug came to NASA following his Bachelor of Science degree in Aerospace Engineering at Virginia Tech and also holds a Master of Science in Mechanical Engineering from Stanford University.

Presentation Outline

ICAM2021

Topics:

1. What is Engineering Equivalence?
2. Equivalence Baselines
3. Prerequisites for Engineering Equivalence
4. The Engineering Equivalence Toolbox
5. Applications of Engineering Equivalence
6. Summary and Conclusions

Engineering Equivalence

- Engineering equivalence is a methodology for evaluating the quality of AM materials that acknowledges the broad range of characteristics that must be assured for an alloy to meet all its expectations.
- Engineering equivalence as a concept differs from the determination of statistical equivalence for a material characteristic (such as ultimate strength) in that we determine equivalence holistically through engineering judgement by considering many interrelated and causal material characteristics as they contribute to the overall performance of the material
  - Often equivalence determinations must be made in the absence of statistically significant pools of data
- Engineering equivalence is the enabler that allows the AM material ecosystem to remain healthy and self-consistent in the face of sensitive processes with a multitude of known and unknown failure modes.
- Engineering equivalence is not an easy task - it requires reliable and diverse datasets, depth of knowledge in materials, good engineering judgement, and collaboration between engineering and quality assurance organizations.

What is Engineering Equivalence?

ICAM 2021

The purpose of an “engineering equivalence” approach

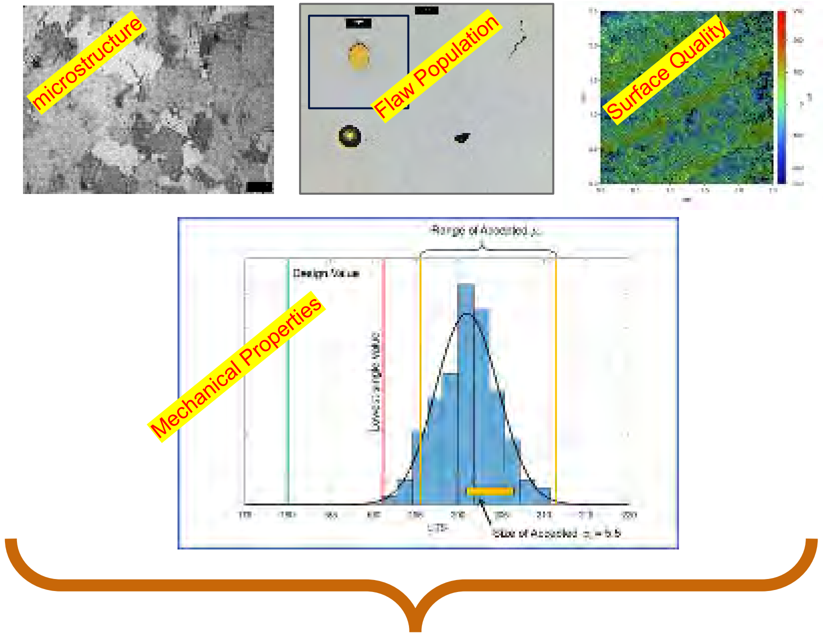
- **<u>To enable the material allowable and design value concepts in AM</u>**
- To enable a well-informed decision regarding the consistency of AM materials by leveraging all available information across a variety of metrics of engineering significance
  - Avoid fixating on strength alone as a determination of material equivalence
  - This is not a new concept, but as applied to AM, additional structure and standardization is needed
- To leverage the concept that material performance is derived from the Process → Structure → Property → Performance relationship
  - Equivalence does ***not*** generally mean “better than or equal to,” e.g., exceeds the specification minimum.
  - Equivalence implies fundamental characteristics and performance are “in-family” with a baseline set of data
  - Making determinations of what is, or is not, “in-family” generally requires engineering judgement
    - In many applications of engineering equivalence there are inadequate data for any one performance characteristic to establish true statistical confidence for equivalence of that particular characteristic
  - Engineering judgement is needed to keep the “false-call” rate and associated engineering review in balance.

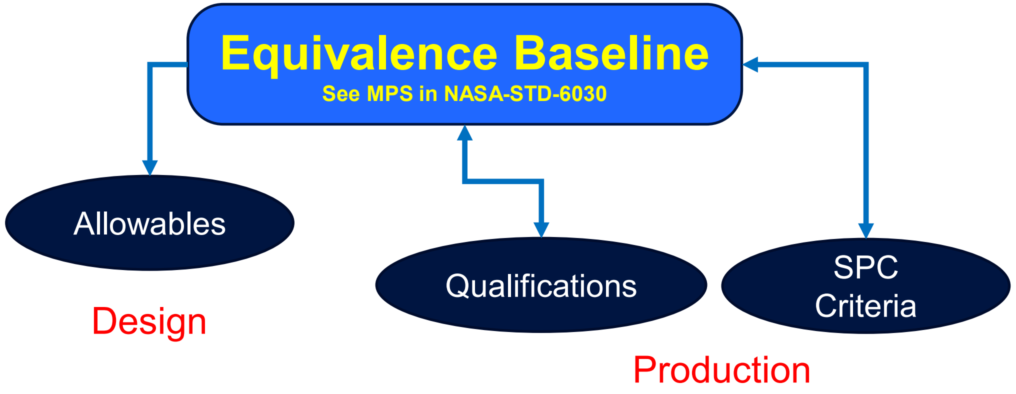
Baselines for Engineering Equivalence

Equivalent to what?

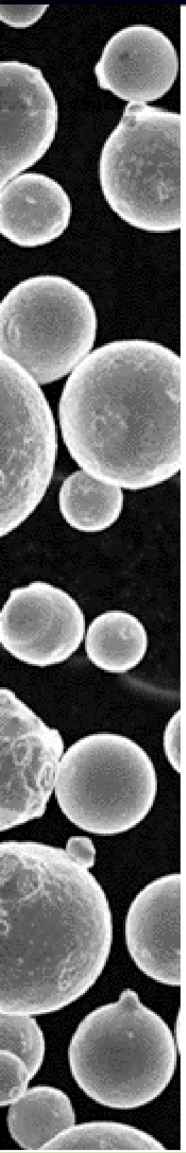
Equivalence Baselines

- Possession of a mature baseline for material equivalence is valuable and enabling for qualification and certification in AM
- Baselines mature with increasing quantities of data and should asymptotically converge on a consistent descriptor of the material
  - Definition of what range of material characteristics are “equivalent”
- Mature baselines:
  - Provide a basis for all the core tools of engineering equivalence evaluations
    - Microstructure, flaw population, surface quality, mechanical properties
  - Provide full descriptions and interpretive information for evaluation
  - Provide recommended evaluation metrics and acceptance criteria for a variety of end uses of equivalence: qualification, SPC, etc.



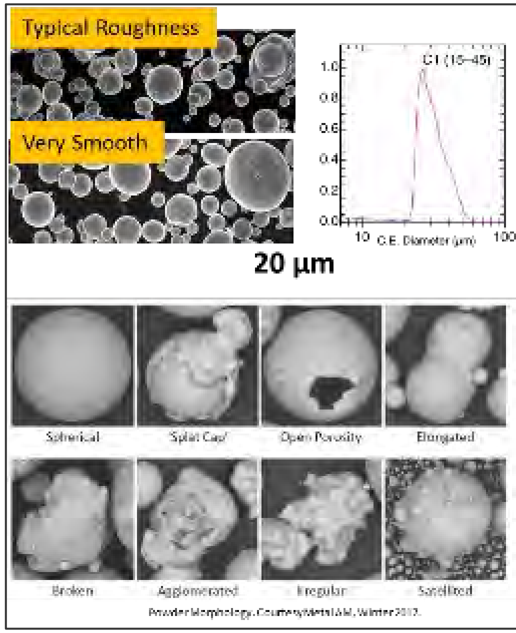


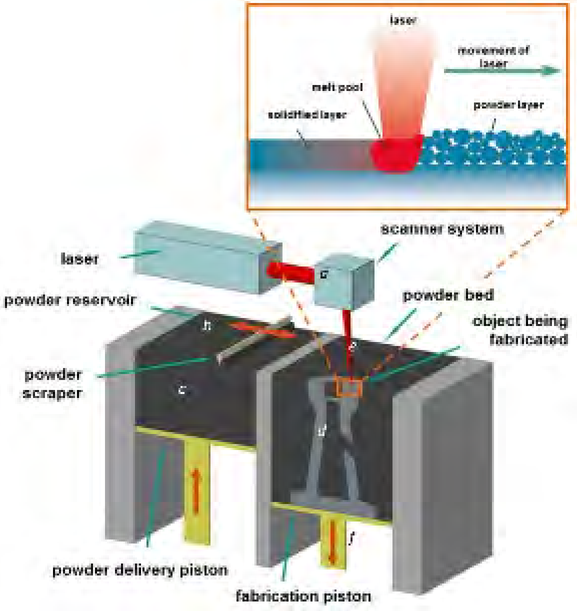
Prerequisites to Engineering Equivalence



Similitude in feedstock and process

- The starting point for equivalence generally must be a reasonable match to the starting point that created the equivalence baseline
- Avoid expecting equivalence between apples and oranges
- Look for similitude in the following
  - Feedstock specification
    - Alloy chemistry
    - Feedstock production controls
    - Physical characteristics
    - Identical specification is best for similitude
  - Basic process definition and ***qualified processes***
    - LB-PBF under compatible conditions
    - DED under similar build conditions and scope
- Engineering equivalence may be possible across broader differences in starting points, but expect the depth of equivalence evaluation to be more exhaustive.



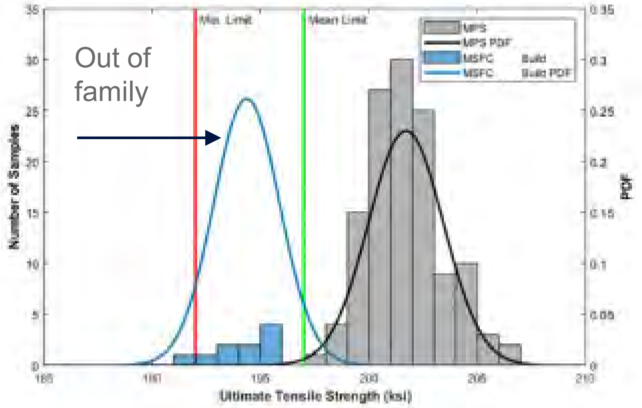


Engineering Equivalence Toolbox

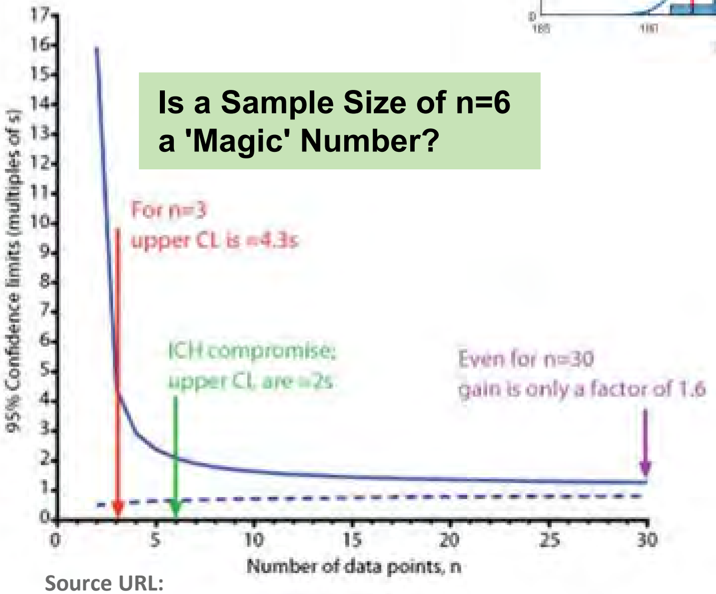
Statistics

- Core part of the equivalence toolbox
- Most situations in AM needing equivalence evaluation do not have the luxury of sufficient data quantities for statistical determinations, *at a desired level of confidence*
  - Despite this, statistics as a tool is indispensable in equivalence
- Leverage stats for definitive determinations whenever feasible
- Use for insight and decision making in engineering equivalence
- Design of acceptance tests, control charts, “in-family” evaluations

In-family / out of family “engineering assessments”



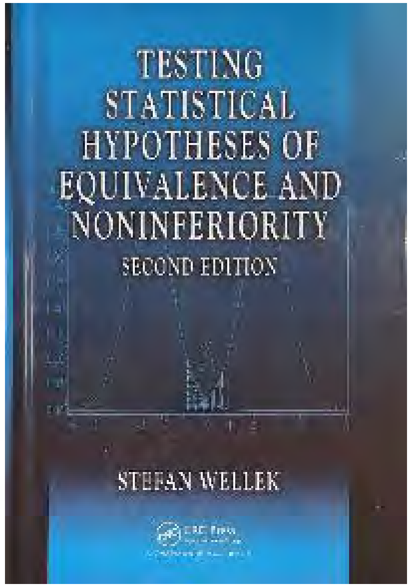
Is a Sample Size of n=6 a 'Magic' Number?



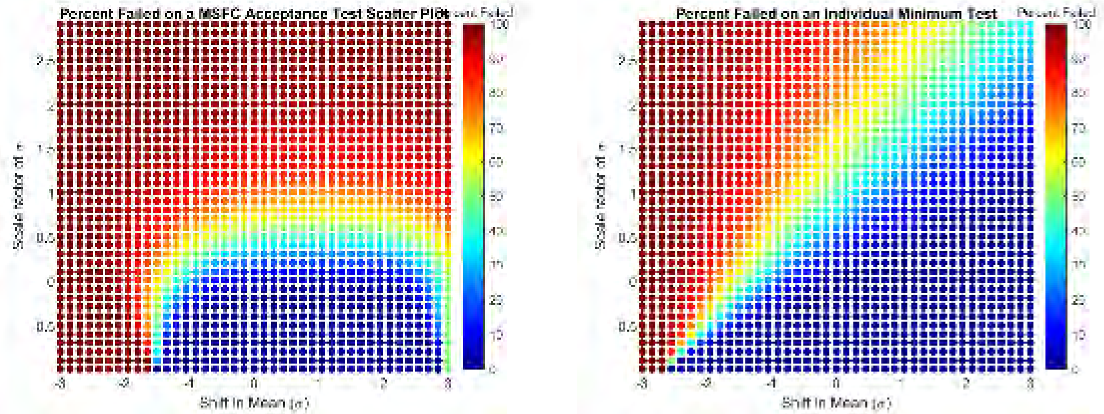
Source URL:

http://www.pharmtech.com/sample-size-n6-magic-number

By Chris Burgess, PhD

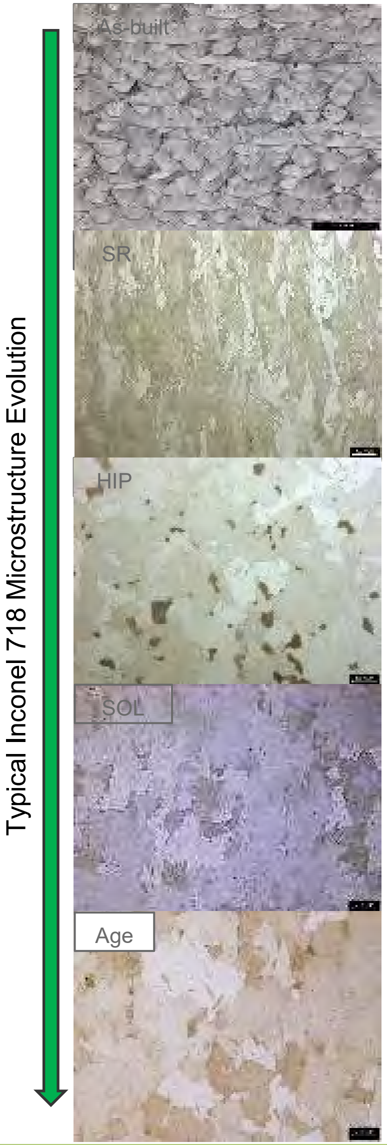


The Deep End…



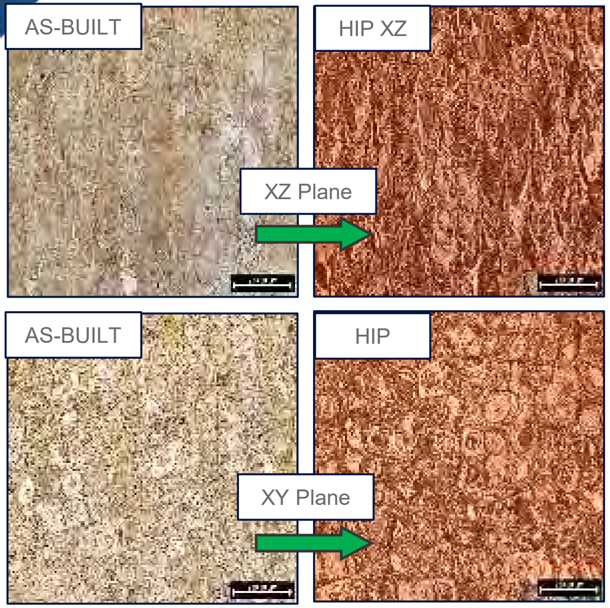
Monte Carlo simulations of acceptance test methodologies

Engineering Equivalence Toolbox

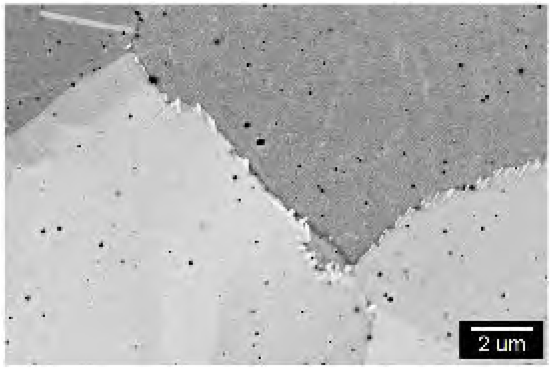


Microstructure

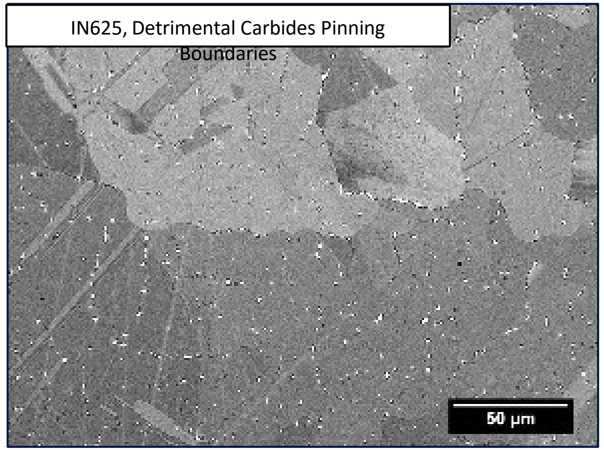
- Long term success in AM means understanding microstructure
- Material performance derives from microstructure, *particularly the details of performance*
  - E.g., corrosion or fatigue crack initiation are performance details not always well correlated to other properties
- Equivalence in microstructure can be difficult to quantify
  - Requires engineering judgement
- Understand the desired, or expected, microstructure
  - Define its core characteristics in the as-built and final forms
  - Phases, precipitates, recrystallization, grain size, grain shape, twinning, etc.
- Understand potential undesirable microstructures
  - Describe what the microstructure should NOT be



GR-COP42, Typical limited recrystallization



IN718 δ-phase at boundaries

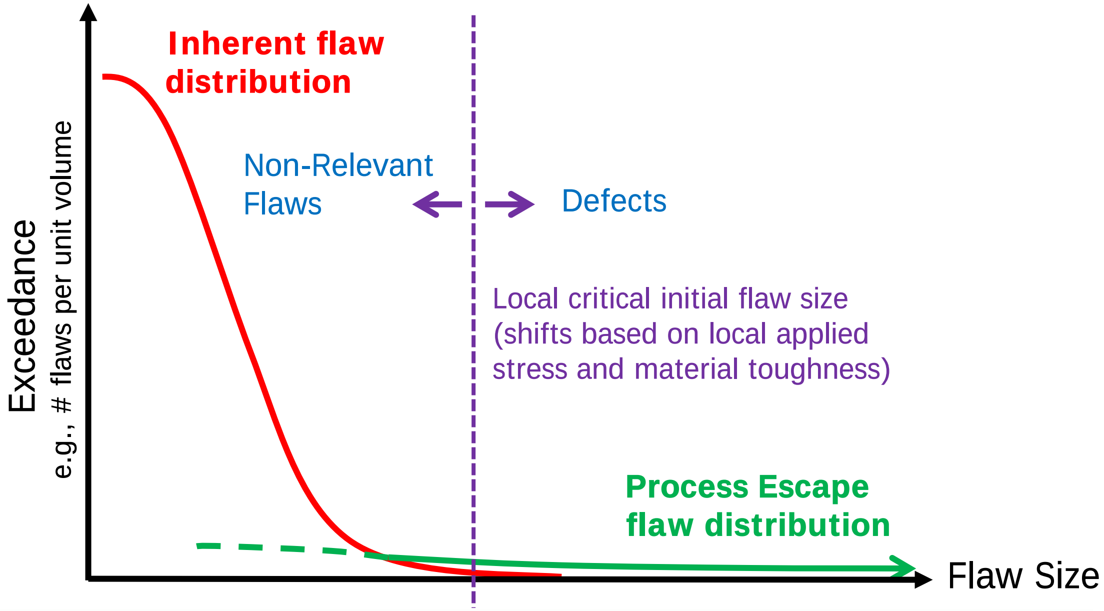


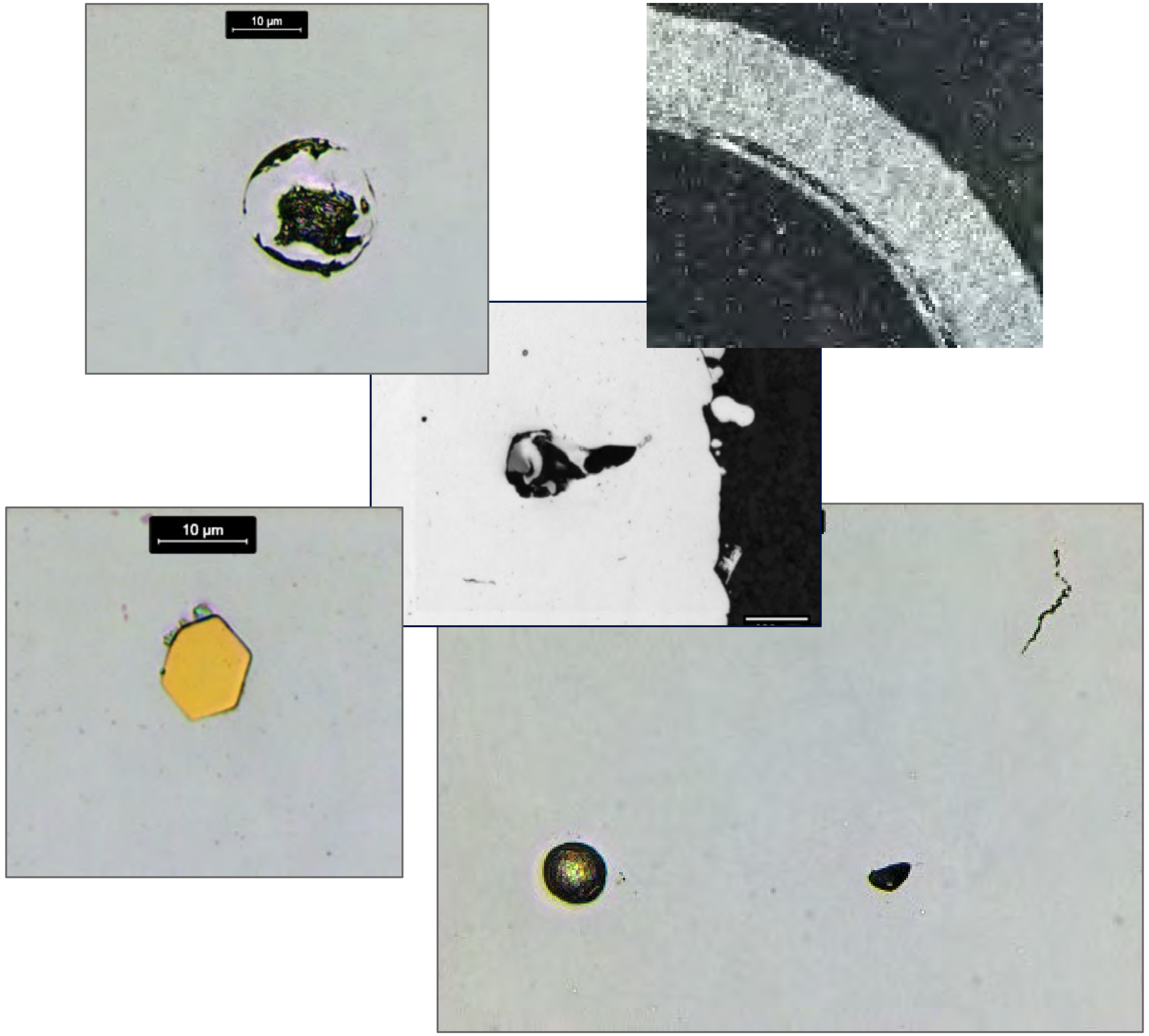
Undesired precipitates (carbides) on boundaries

Undesired lack of recrystallization in IN718

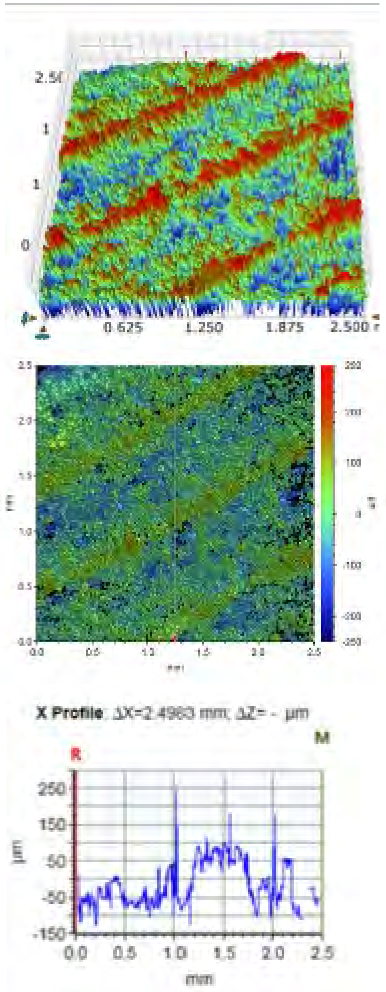
Flaw population

- In AM, the flaw population is a primary governor of material performance
- Quantifiable metrics are feasible to aid equivalency judgements for common inherent flaws — those flaws which are expected
  - Types, sizes, and frequencies of occurrence
- Equivalence in flaw population focuses on consistent material of intended quality — process escape flaws are not the focus here.



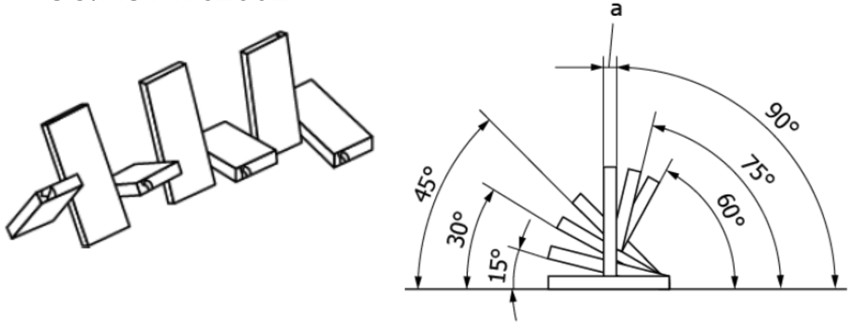


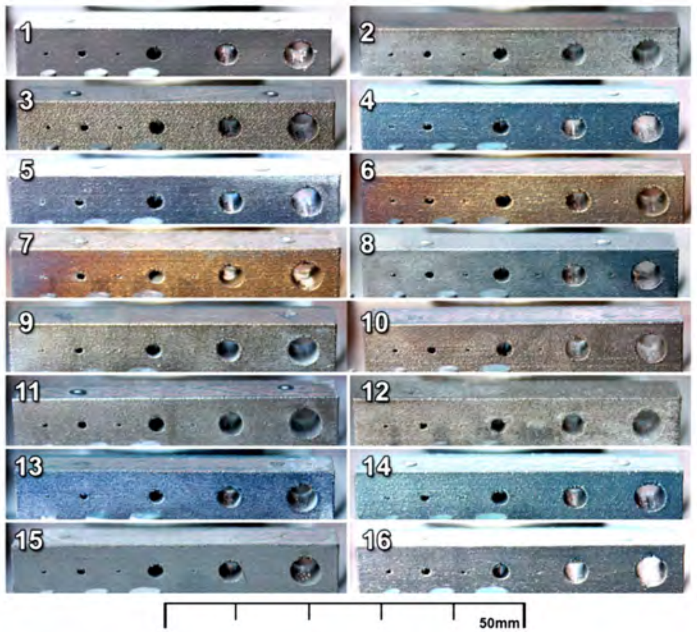
Surface Quality, Dimensional & Detail Resolution



- Evaluation of the surface quality, resolution of detail, and accuracy in dimensions can be important metrics when evaluating equivalency
- Surface quality may have direct influence on mechanical performance of AM materials when as-built surfaces remain
  - Fatigue life
  - Ductility
- Surface quality has numerous existing metrics defined, though their applicability to AM surfaces remains a topic of research
- Evaluations of equivalency regarding detail resolution can be difficult and subjective, not unlike microstructure comparisons
  - Brings "engineering judgement" to bear in engineering equivalency assessments

ISO/ASTM 52902

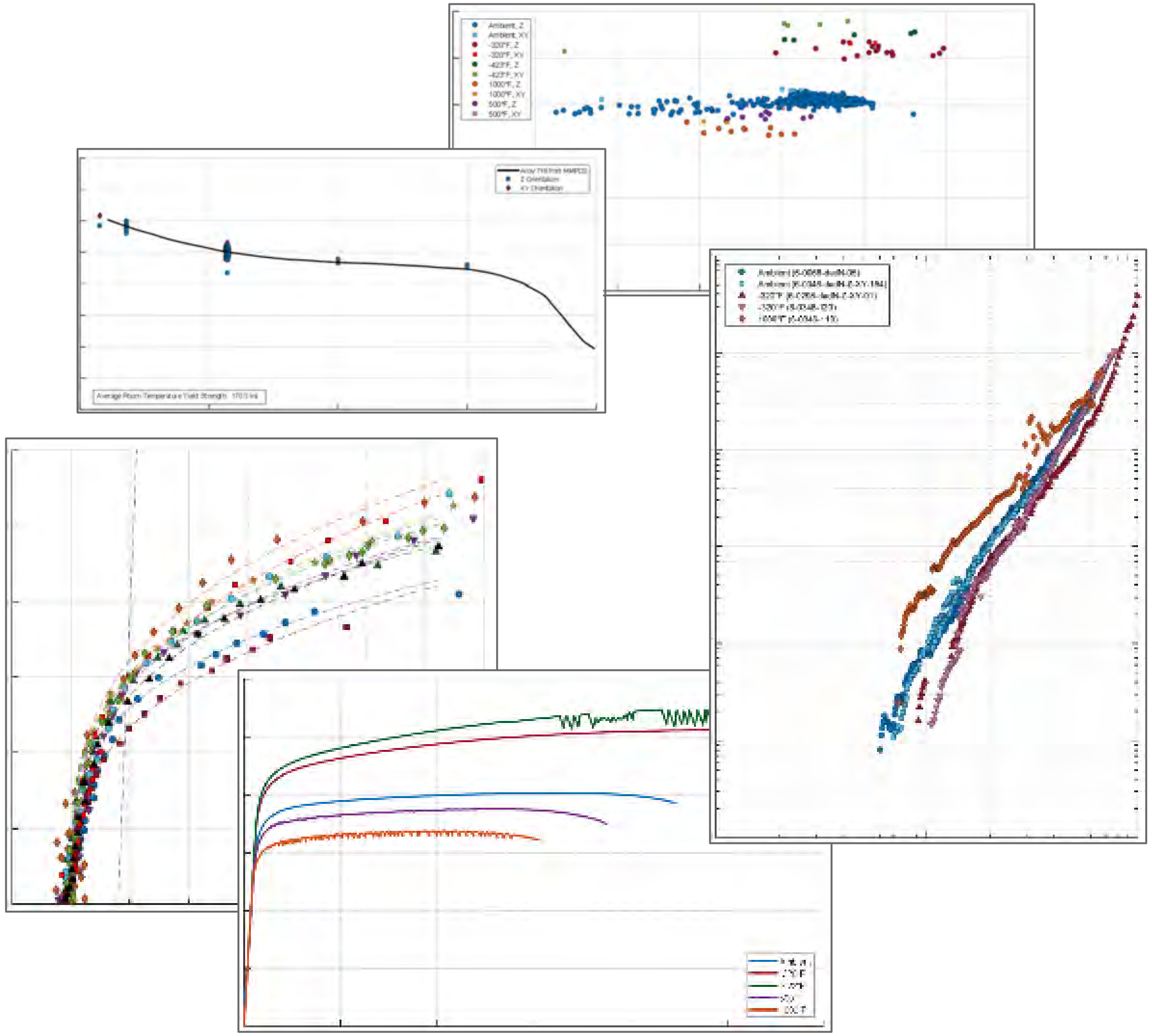




Gradl et al.,
Additive Manufacturing 47 (2021) 102305

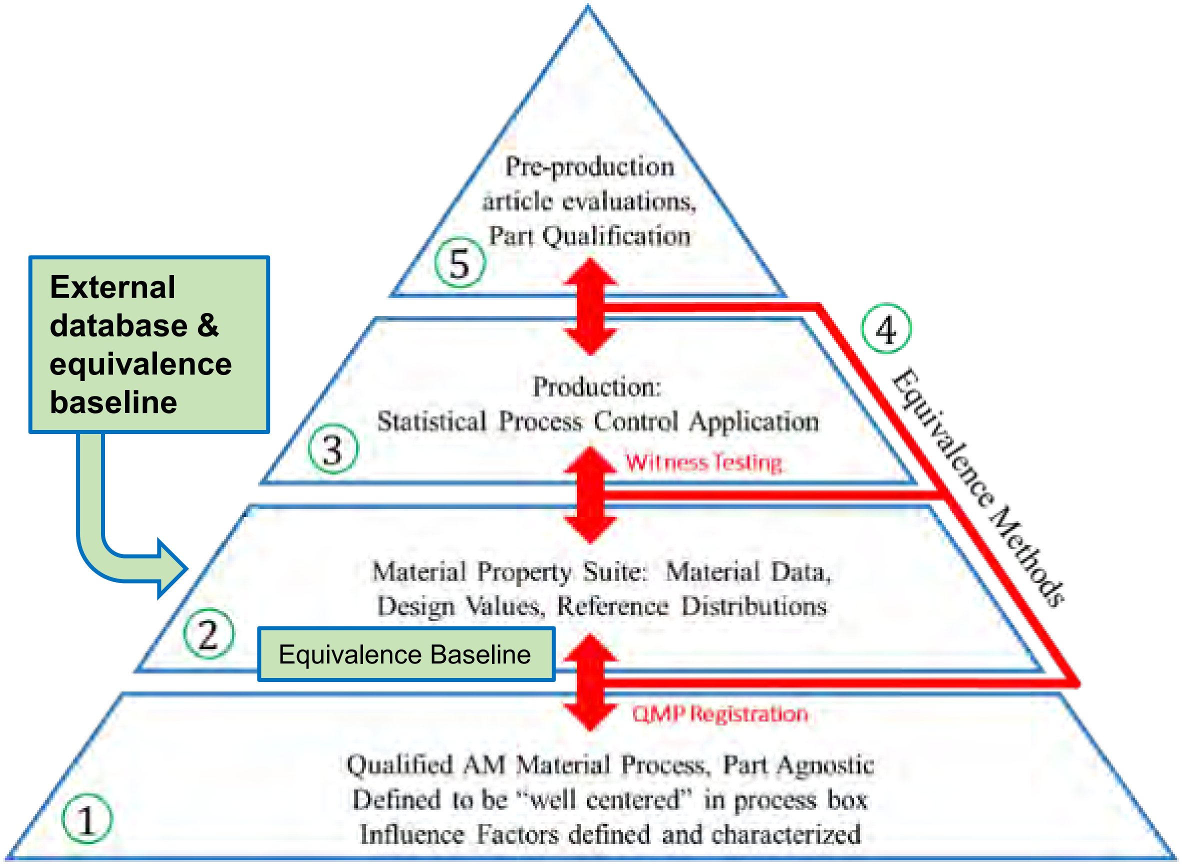
Mechanical Performance

- Tensile strength is the predominant indicator of performance
  - Ultimate and yield strength
  - *Ductility* (elongation and reduction in area)
- Consider other failure mechanisms in the material system
  - Various failure mechanisms may show some correlation to each other, but actual material capability in each will be independent
    - Fatigue crack initiation
    - Toughness and tearing resistance
    - Fatigue crack growth rate
    - Special interest properties
      - Stress rupture
      - Temperature dependence
      - Environmental (HEE, SCC, SLC…)



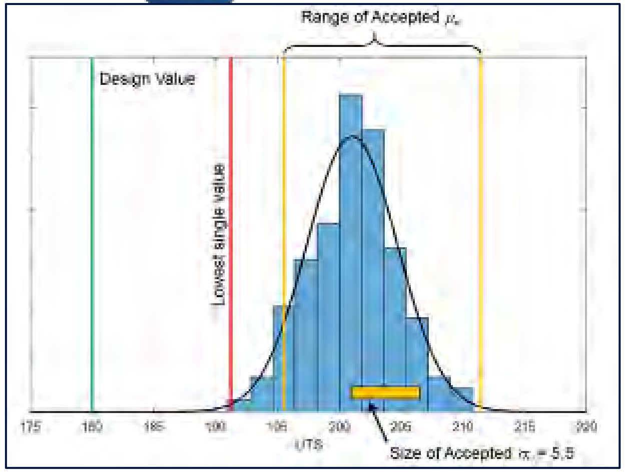
Scenarios for use of Engineering Equivalence

- Engineering equivalence evaluations enable the building block of AM material integrity
- The foundation of AM material control always starts with a qualified material process (see QMP, NASA-STD-6030)
- Data from qualified processes lead to the establishment of the equivalence baseline (property database)
- The equivalence baseline defines the targets for material engineering equivalence and provides:
  - A foundation for continued *process qualification and requalification*
  - A foundation for *build process witness test evaluation*
    - Ongoing *statistical process control*
  - A foundational role in *Part qualification* regarding material equivalence



AM Build Acceptance (Witness)

See PCRD in NASA-STD-6030



Objective:

Monitor consistency of material for production builds.

Why use Engineering Equivalence?

– Witness testing is the primary quantifiable metric used to monitor AM process quality.

– Witness testing acceptance through equivalence maintains the rationale for the applicability of material allowables and design values throughout production

Tools: (somewhat limited, depth will be dependent on part classification)

– Evaluate across various metrics with enough data to do equivalence: microstructure, flaw population, tensile (4-6 specimens), fatigue, surface quality, special interest, etc.

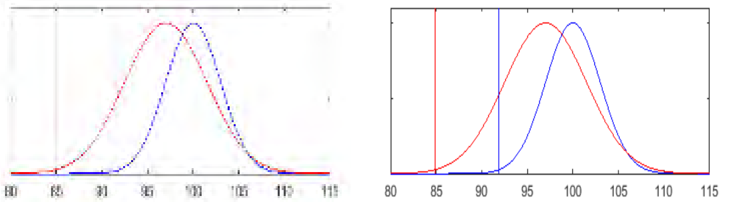
– Leverage small sample statistics to the degree possible, see simulation on the right.

– Use statistics to monitor mean and variance :: control charts in continuous production

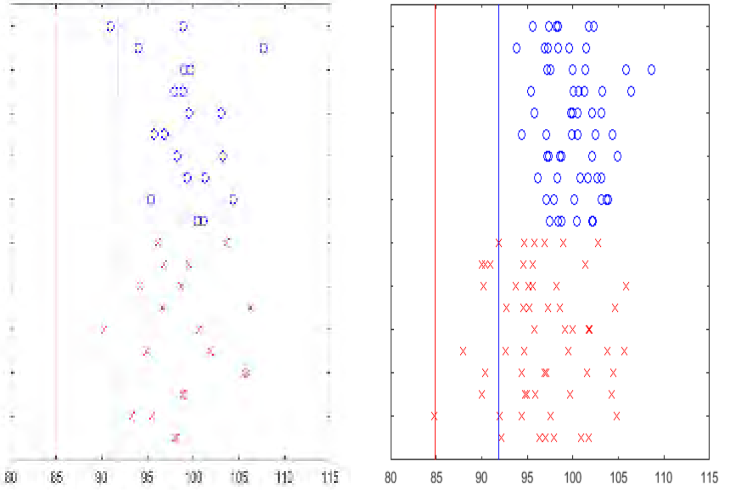
Equivalence Confidence:

Moderate, based on limited evaluations available across most tools, but robust for build acceptance.

Nominal process is blue, off-nominal in red



Two (2) witness tests per build | **Six (6) witness tests per build**



Process shift is hard to discern

Process shift discernable with analysis of mean and variation

Random draw from nominal and off-nominal process 10 times

Machine/Process Qualification (IQ/OQ)

See Qualified Material Process, QMP, and QMP Registration in NASA-STD-6030

Objective:

Demonstrate material quality from a specific machine under defined conditions is equivalent to past material used to set design properties.

Why use Engineering Equivalence?

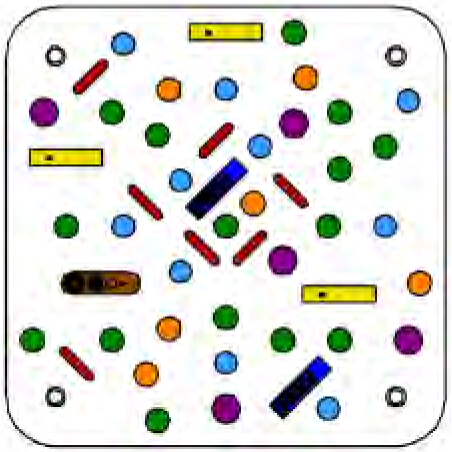
Re-occurring operation required of every AM machine. Testing quantities for high statistical confidence is generally impractical, or limited to a single attribute (e.g., tensile).

Tools: (use them all)

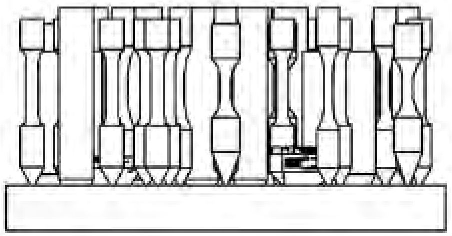
Feedstock similitude, microstructure, flaw population, surface quality, mechanical properties, statistical assessment

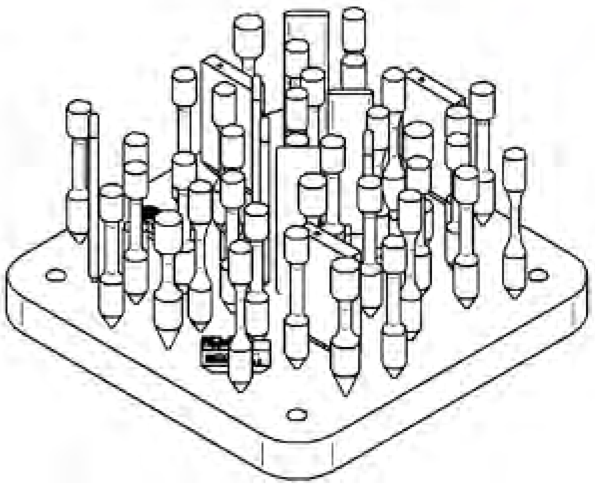
Equivalence Confidence:

Moderate to high, based on limited evaluations available across all tools.



Specimen Type	Qty	Name	Key
High Cycle Fatigue	10	HCF-1 thru HCF-10	
Low Cycle Fatigue	5	LCF-1 thru LCF-5	
Tensile (RT)	15	TN-1 thru TN-15	
Tensile (Cryo, ET)	6	TN-16 thru TN-21	
Fracture Toughness	3	FT-1 thru FT-3	
Metallographic Samples	7	MET-1 thru MET-7	
Dimensional Samples	2	D-1 thru D-2	
Contour Analysis Samples	1	C-1	





Part Qualification (PQ)

See Pre-production article evaluation and the QPP in NASA-STD-6030

Objective:

Substantiate within pragmatic limitations that the material quality throughout a new AM part is equivalent in the engineering sense to past material used to set design properties, i.e., substantiate specimen-to-part equivalence for applicability of allowables.

Why use Engineering Equivalence?

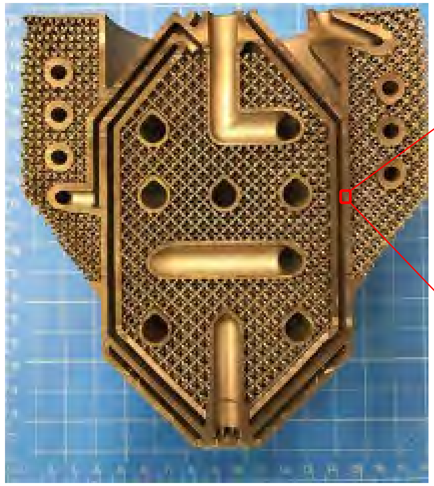
AM material quality within parts is likely to vary with geometry and build conditions. Evaluation of all properties directly is rarely feasible. Require internal quality and mechanical properties to be in family with the equivalence baseline. Engineering judgement is likely required.

Tools: (use all available, may be limited)

Feedstock similitude, *microstructure & flaw population (always)*, surface quality, mechanical properties (as available, even if sub-scale), statistical assessment (usually limited)

Equivalence Confidence:

Moderate, based on limited evaluations available across tools, but an indispensable aspect of part qualification.



Material Allowable and Design Value Databases

Objective:

Leverage pre-existing AM material databases for material allowables and design values to reduce cost.

Why use Engineering Equivalence?

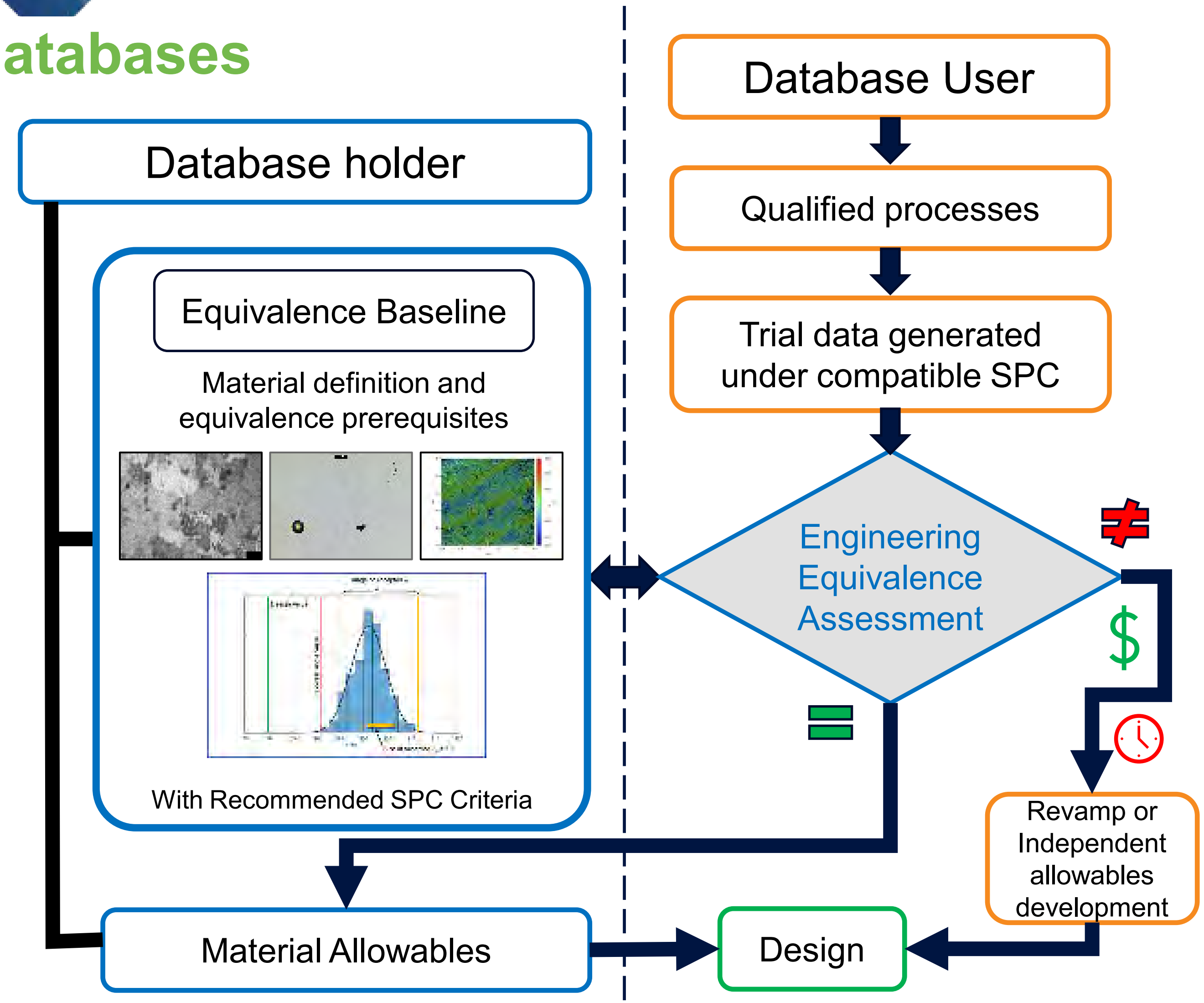
Equivalence evaluations will be less expensive than full characterization. Similitude across numerous metrics between baseline and trial data reduces the risk of unforeseen failure modes in the trial material and provides confidence trial material will meet expectations of the alloy.

Tools: (use all available)

Feedstock/process similitude, microstructure, flaw population, surface quality, mechanical properties, statistical assessment (usually moderately robust)

Equivalence Confidence:

High, based on evaluations available across all tools. Evaluations generally will have tangible statistical significance in sample quantity and lot variability.



Engineering Equivalence as an enabler in AM

- There is more to AM alloys than bulk chemistry and tensile strength.
- Most AM alloys are exceedingly complex and require precise metallurgical control to meet engineering expectations against a variety of failure mechanisms that are often assumed to follow a specific alloy or alloy class based on precedent from traditional product forms:
  - Strength, ductility, fatigue, heat resistance, cryogenic ductility, toughness, tearing resistance, fatigue crack growth, stress rupture, hydrogen embrittlement, intergranular cracking, general corrosion, stress corrosion cracking, etc.
- Engineering equivalence is a methodology for evaluating the quality of AM materials that acknowledges the broad range of characteristics that must be assured for an alloy to meet its expectations.
- Like all alloys, AM material capability is derived from the "Process → Structure → Property → Performance" relationship
- Engineering equivalence is the enabler that allows the AM material ecosystem to remain healthy and self-consistent in the face of sensitive processes with a multitude of known and unknown failure modes.
- Maintaining engineering equivalence in AM materials when qualifying processes, qualifying parts, applying SPC, and accepting builds is the cornerstone of enabling the reliable use of material allowables and design values.
- Equivalence means "in-family." ***Not*** "better than or equal to."
- Balance is needed in the application of engineering equivalence to maintain the objectives and advantages of material engineering equivalence without an undue burden on operations.
- The devil is in the details: engineering equivalence is not an easy task - it requires reliable and diverse datasets, depth of knowledge in materials, good engineering judgement, and collaboration between engineering and quality assurance organizations.

CENTER of EXCELLENCE
Research to Standards
ADDITIVE MANUFACTURING

ICAM 2021

ASTM INTERNATIONAL
Helping our world work better

Thank you.

Douglas N. Wells
Douglas.N.Wells@nasa.gov

www.amcoe.org

Appendix M

"Model-Assisted Validation and Certification of AM Components" – D. Furrer (Pratt & Whitney)

Model-Assisted Validation and Certification of AM Components

David Furrer
Pratt & Whitney

Sergei Burlatsky
Raytheon Technologies Research Center

Outline

- Materials definitions in the Information Age (Industry 4.0)
- Product and process design approaches
- Approaches for component material requirements
- Testing and qualification planning

Traditional Engineering Materials Development and Definitions

- Design Curves – Empirical; Data Driven
- Specifications
- Prints Notes
- Fixed Process Requirements

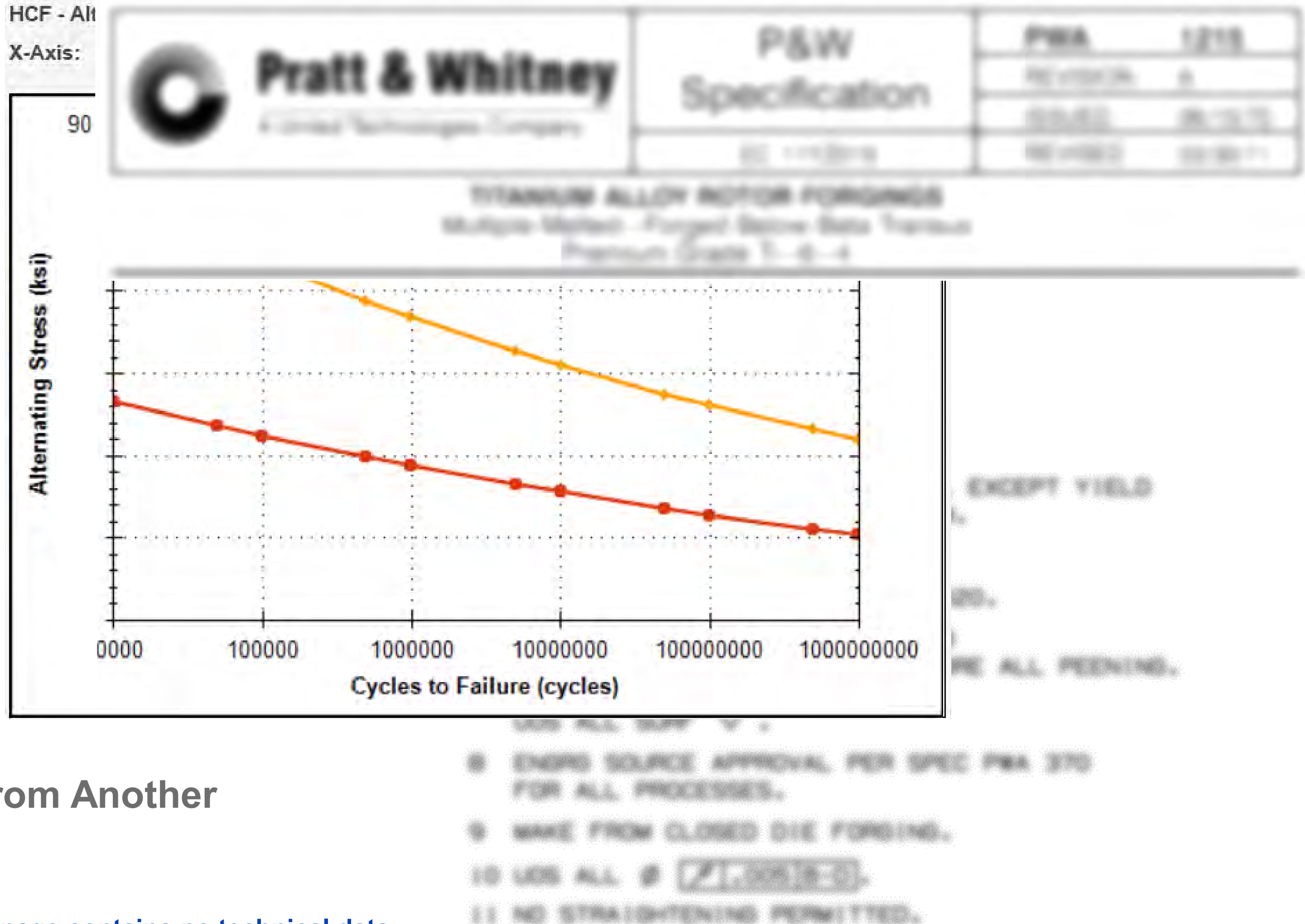
Material Equivalency - Material Pedigree - Application Space

Materials Definitions

Compilation of tools to define materials and establish equivalency

Traditionally:

- Specification Documents
- Design Curves
- Drawing Notes
- Quality Standards
- Component Testing and Qualification Approaches



Defining of Material Equivalency and Methods to Differentiate Material of One Controlled Pedigree from Another

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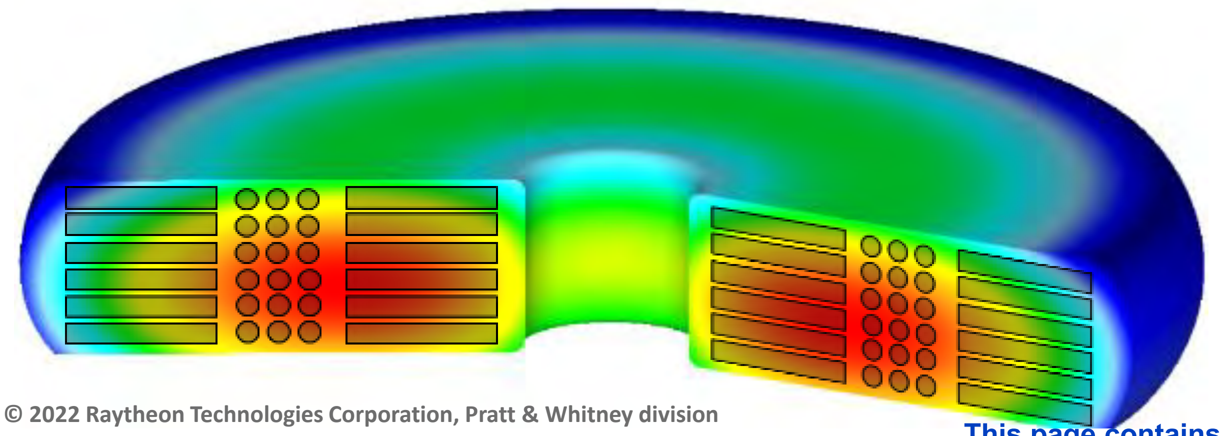
Specifications Defined Based on Statistical Minima*

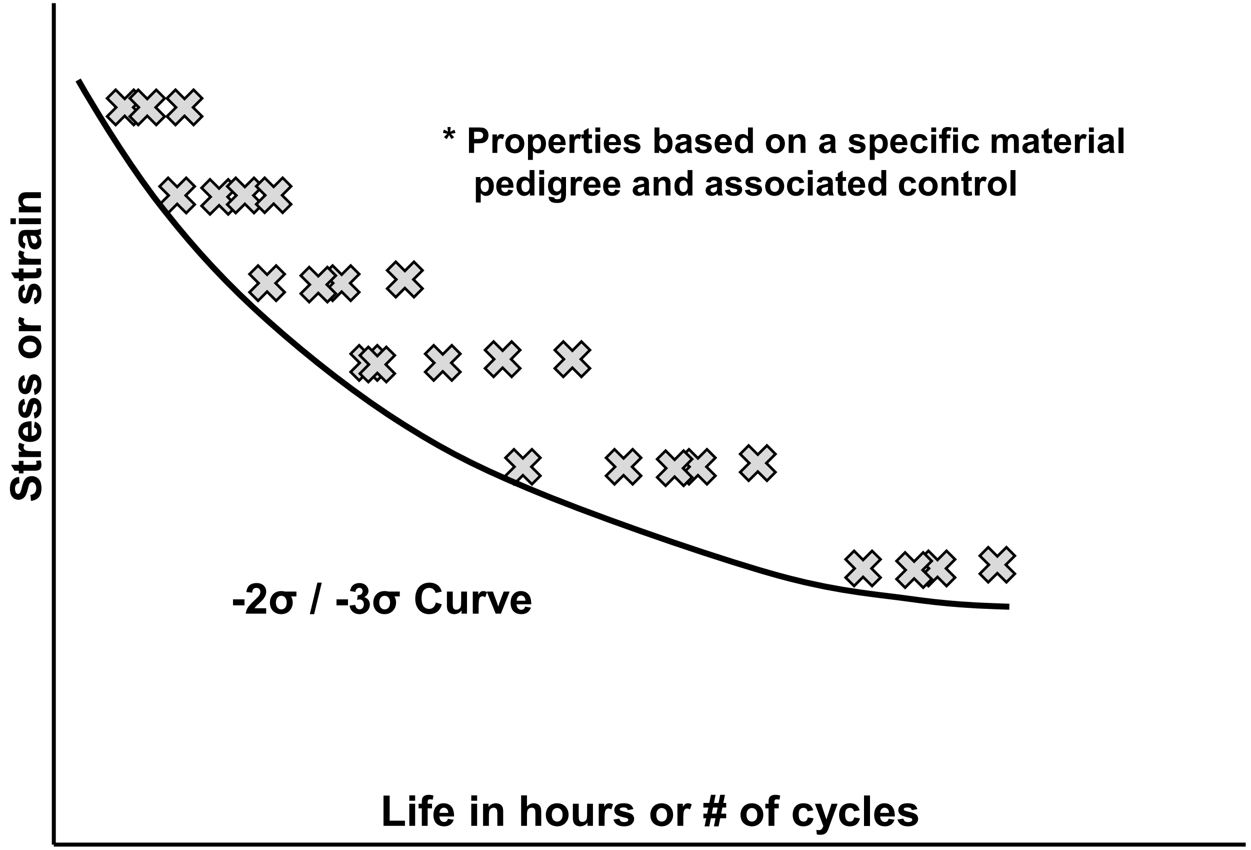
Material properties depend on processing path (manufacture and application)

Multiple components produced on manufacturing equipment

Test samples extracted from components using randomized locations, orientation, test conditions, etc.

Manufacturing path for components (pancakes, etc.) define range of pedigree space



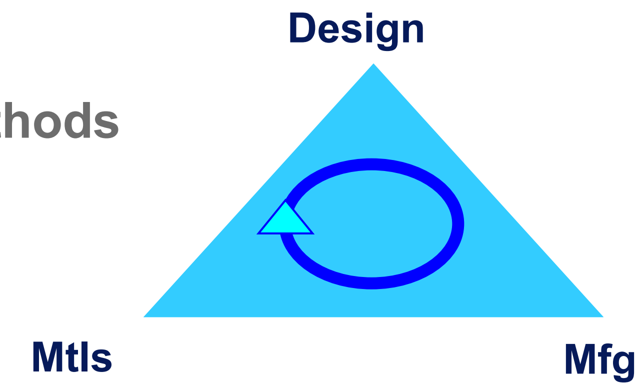


GO BEYOND

Materials & Product Engineering

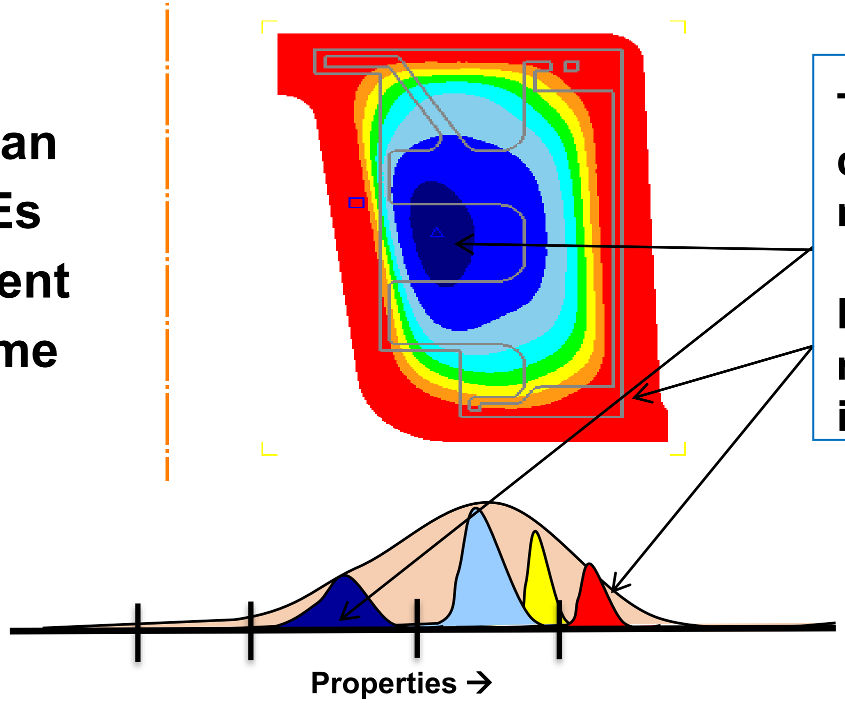
- Mechanical Properties → fn (chemistry and structure)
- Structure → fn (chemistry and processing)
- Processing → fn (component geometry)

Materials, Manufacturing Methods and Component Design are Strongly Coupled



Materials Definitions

Volumetric regions can be defined by SERVEs (Statistically Equivalent Representative Volume Elements)



True material capability and property distributions are controllable and reproducible; not "random variability".

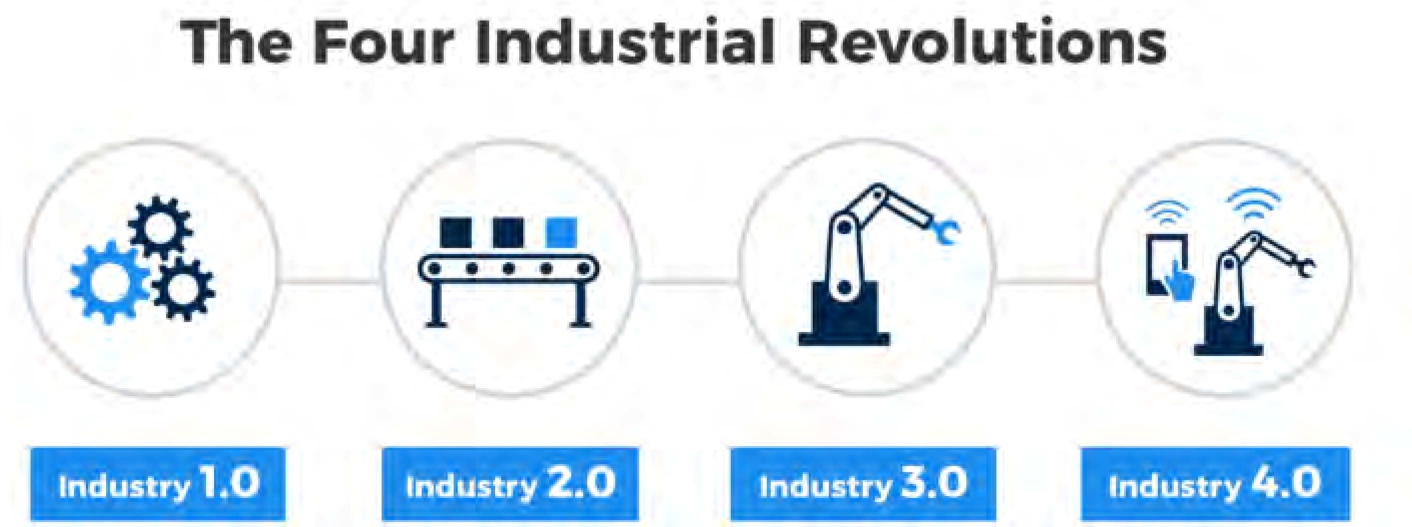
Properties are a fn (chemistry, microstructure, stain, cooling rate, etc.); i.e. pedigree.

Materials properties are path dependent and are often "location-specific". Engineering specifications often treat entire material volume as single, homogeneous property capabilities.

Modeling and simulation can help enhance material, process and component definitions

Industry 4.0

Industry 4.0 is a true technology revolution and not a buzz-word term



Framework for digital engineering, manufacturing, simulation, communication and optimization …. Including validation and certification

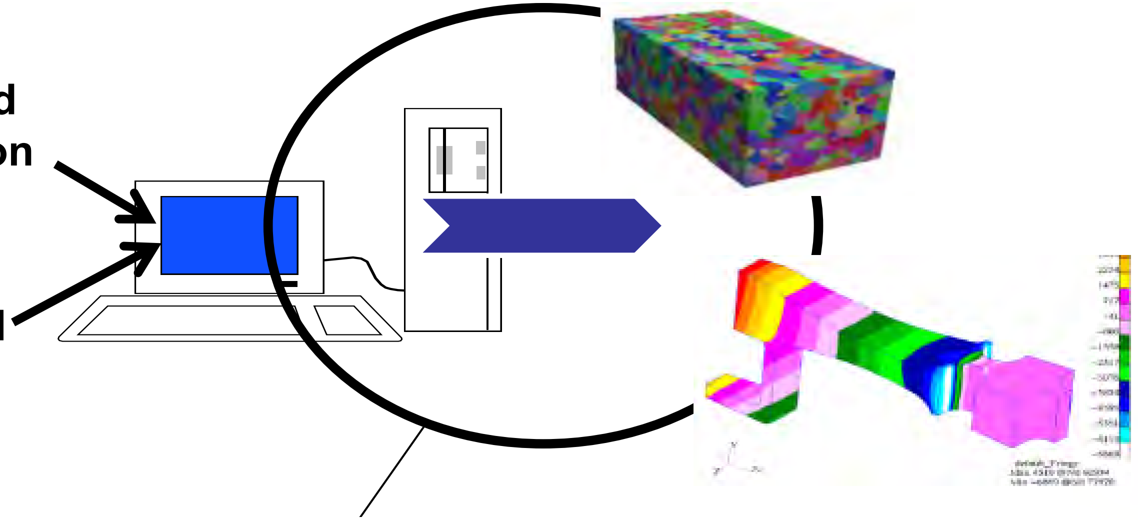
Integrated Materials & Process Modeling

Use of models to link design, producibility & component performance

Component Design

Model-based Mt'l definition

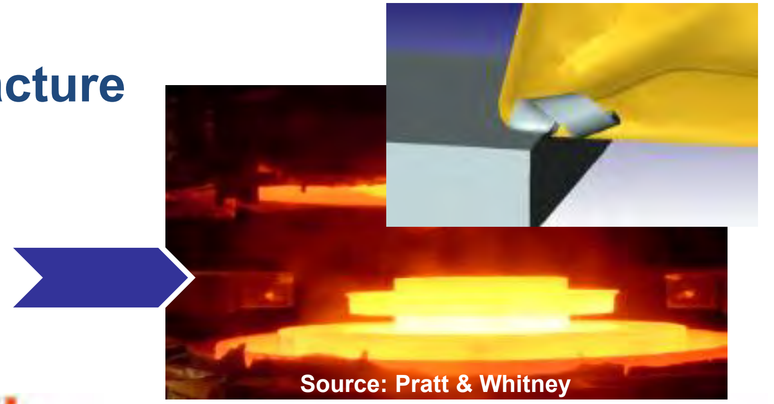
Model-based Mfg process definition

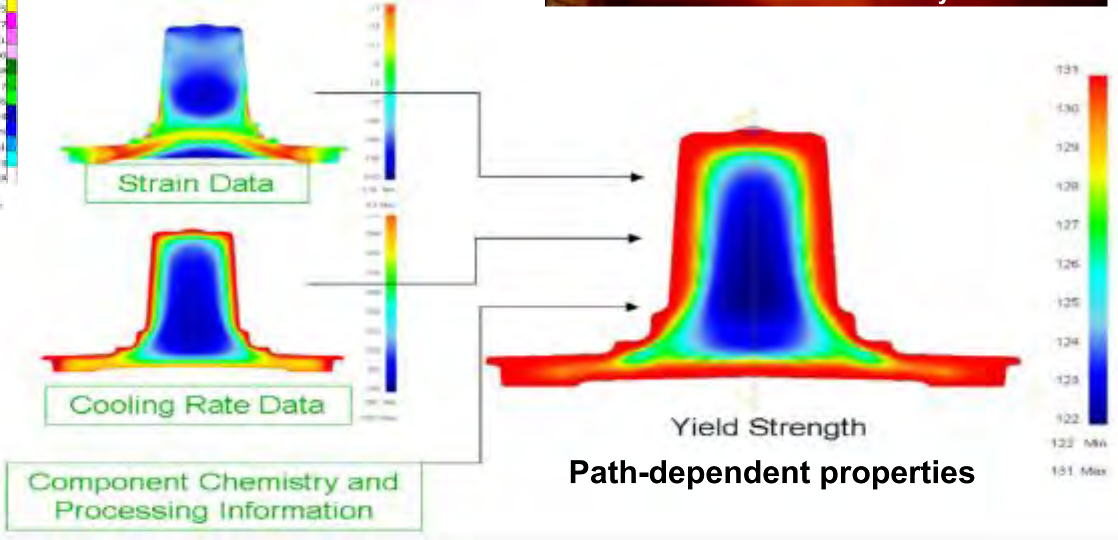


Parametric model includes local structure and properties

Component Manufacture

Model-based component definition





Path-dependent properties

Utilization of Modeling to Predict Component Capabilities and Proactively Mitigate Producibility Risks

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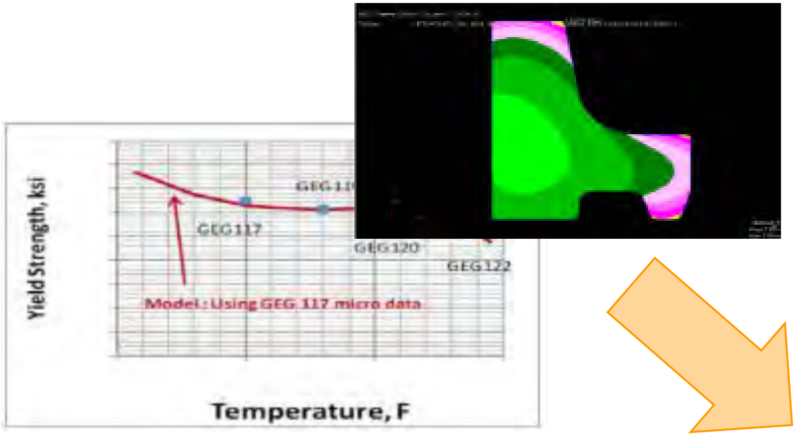
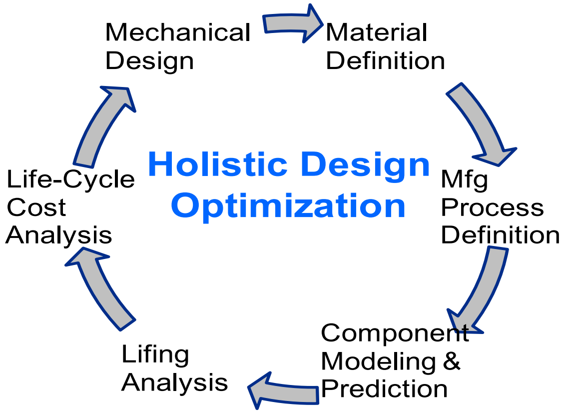
Probabilistic Property & Performance Predictions

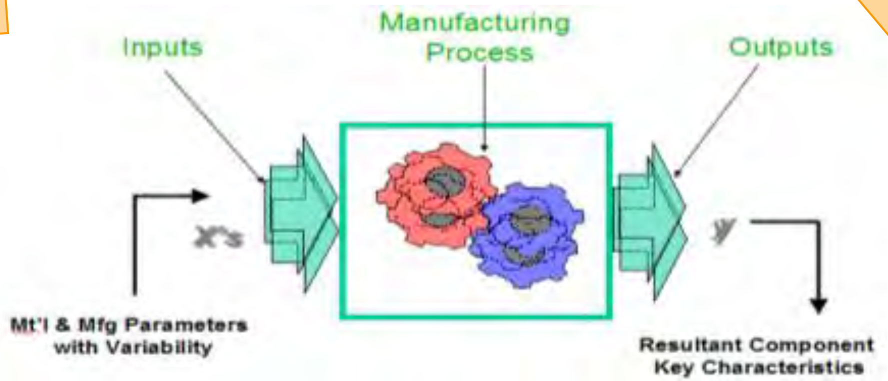
Material and manufacturing process modeling enables design for variation

Materials Modeling



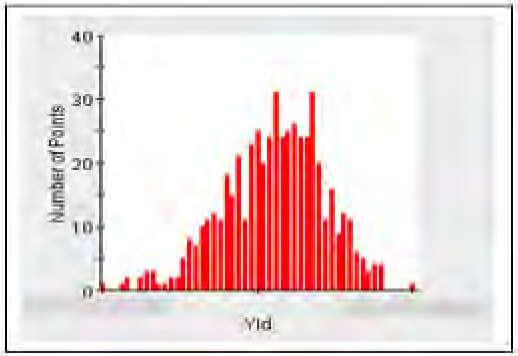
Development and Application of Physics-Based Models





Identification and Assessment of Material and Process Variability

Design for Variation



Predicted Material and Component Properties

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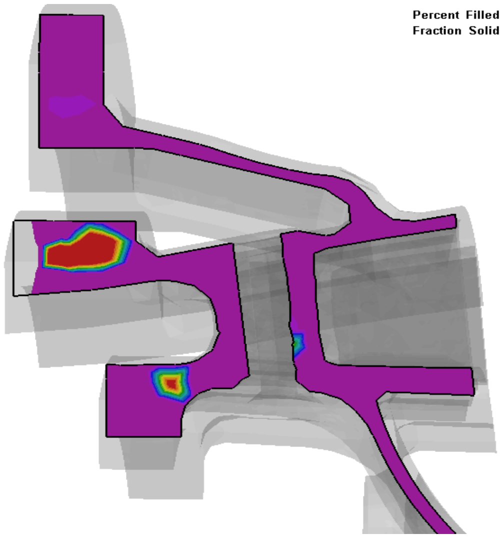
GO BEYOND

Model-Informed Process Controls and Product Testing

Engineered process controls and test location selection provides for efficient processes

- **Modeling methods are guiding process control requirements**
- **Prediction of component location-specific attributes provide insight relative to test locations that are most sensitive to processing**
  - **Smart testing to minimize tests and maximize value**



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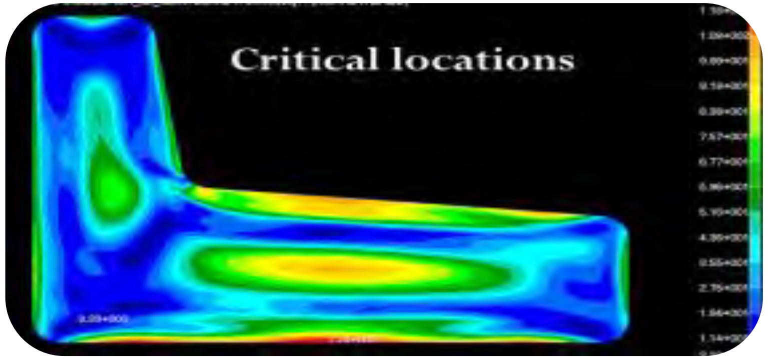
GO BEYOND

Smart Testing

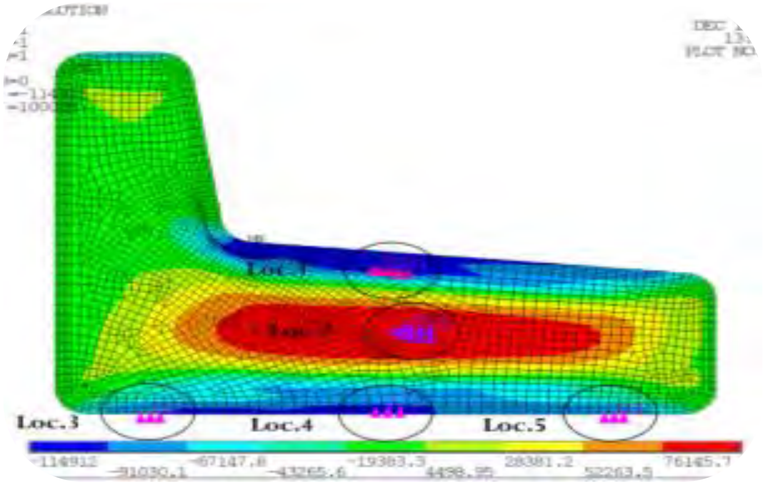
Engineered process controls and test location selection provides for efficient processes

Critical measurement locations from UQ perspective



Measurement requirements :

Locations (XYZ)
Components (xx, yy, zz)
Applied method and specifications
Report data format



Test to confirm component capabilities versus model prediction

Continuous learning about material and process with Bayesian updating approach

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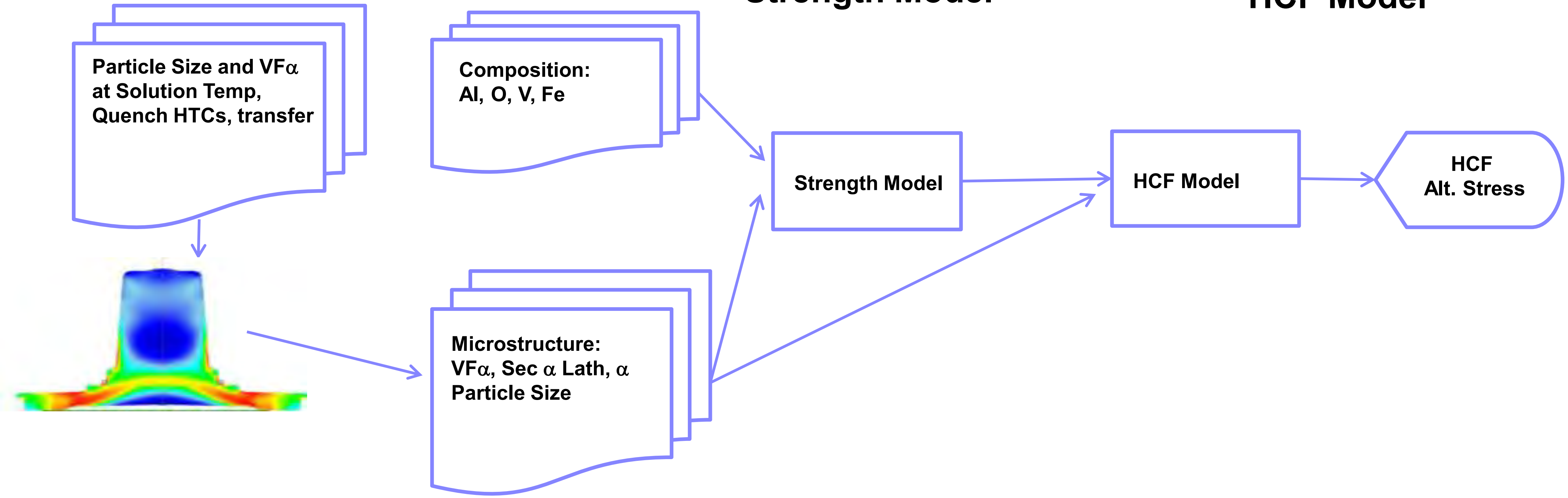
Model-Based Material Definition

MATERIAL – MICROSTRUCTURE – PROPERTY MODELS

Microstructure Model Implemented in DEFORM Code

Strength Model

HCF Model



Model-Based Material Definition Enabled Design and Lifing Optimization

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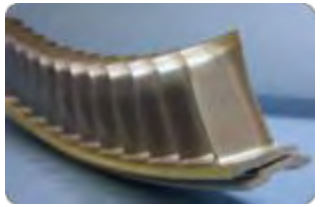
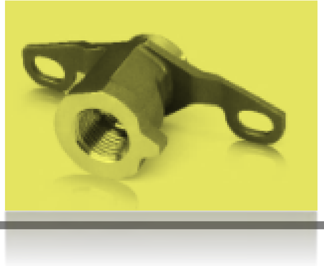
Application of Additive Manufacturing

- Polymer tooling
- Demonstration hardware
- Visual Aids




- Demonstration hardware
- Rig & test hardware
- Production hardware
- Tooling
- Certification



- Design system
- Material and process modeling data
- Process control capabilities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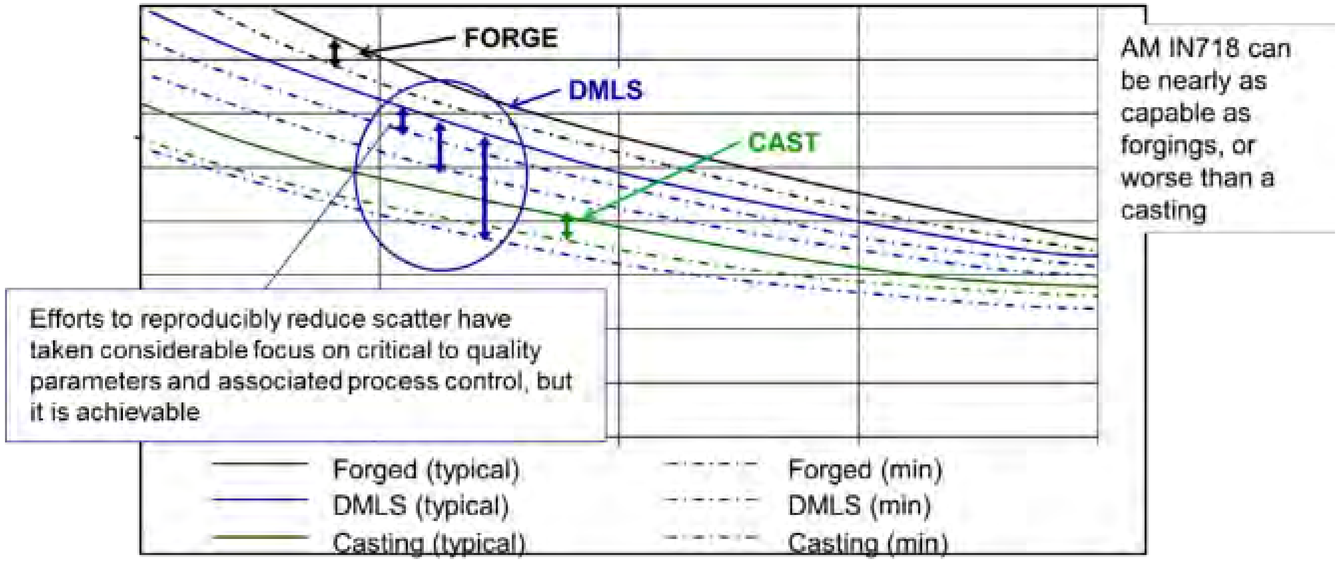
AM Certification and Qualification

- **Process defects**
- **Microstructure control**
- **Chemistry control**
- **Resultant property scatter**
- **Part-to-part/Batch-to-batch/ Machine-to-machine variability**
- **Powder handling and re-use**
- **Geometry control**
- **Surface finish**

Lack of fusion

Partially sintered powder



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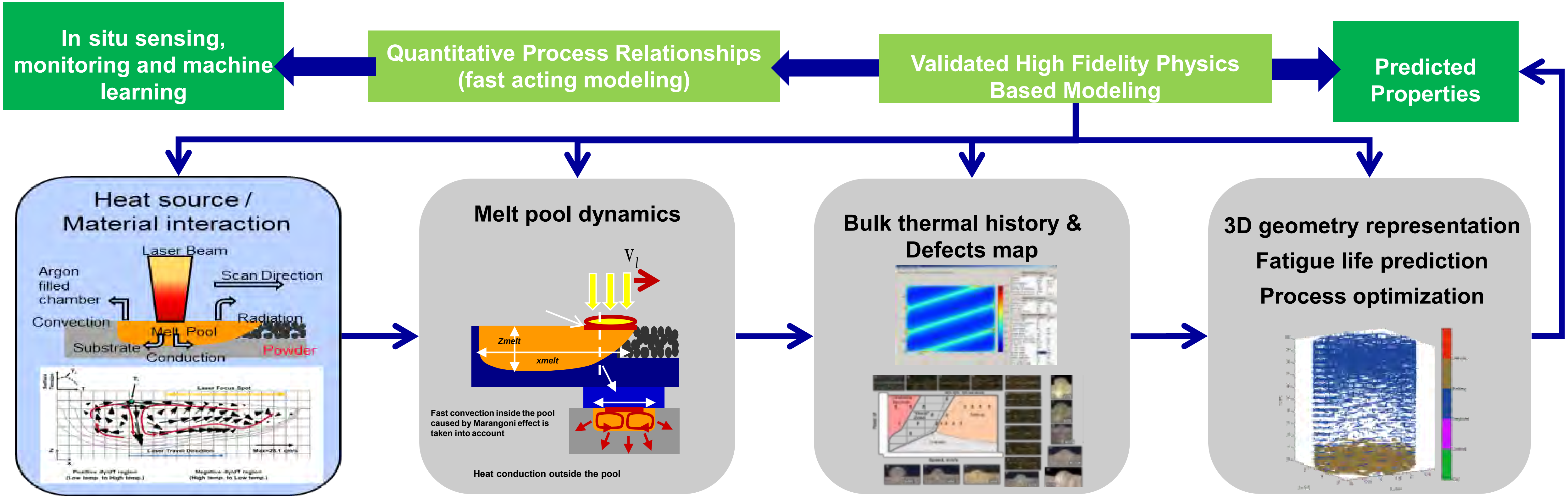
Laser Powder Bed Fusion Modeling Framework

Integrated physics-based simulation of AM processes to predict part level distortion defects, microstructure and establish correlation to performance (fatigue)



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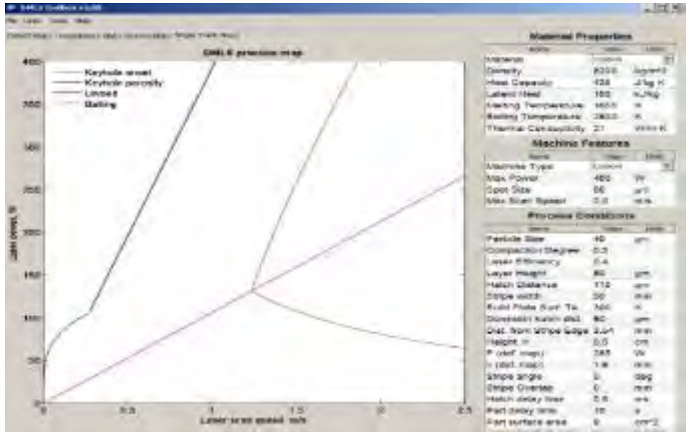
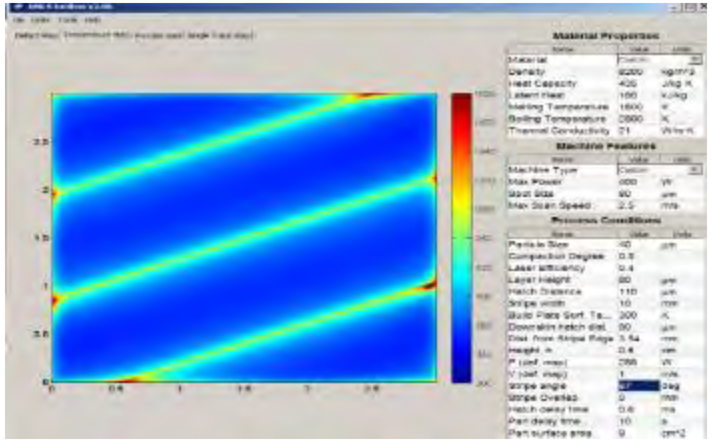
Model Input / Output

Model includes part geometry and location-specific processing path

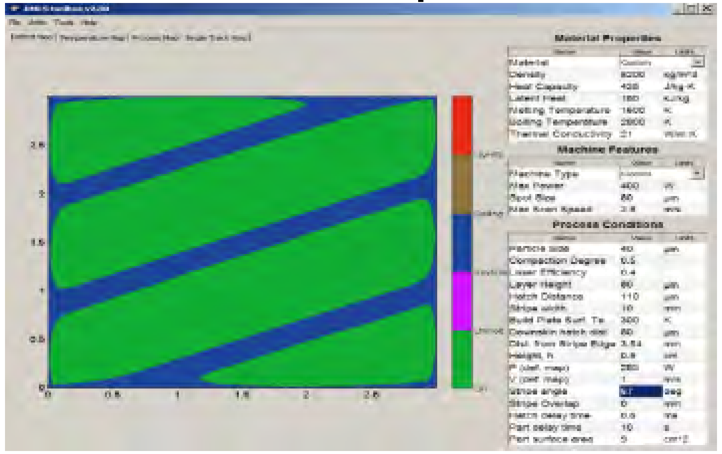
Single track map



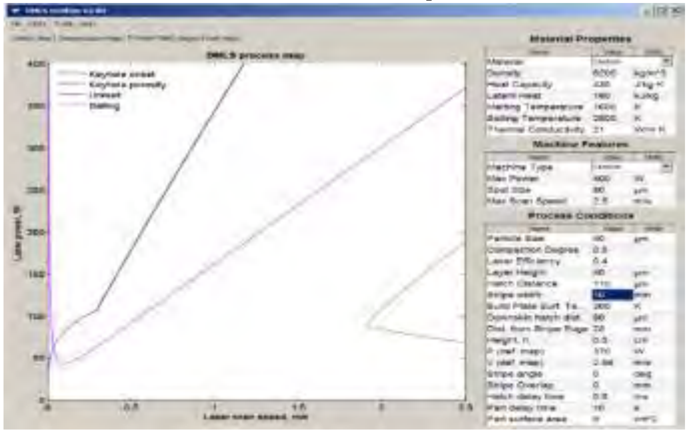
Temperature map



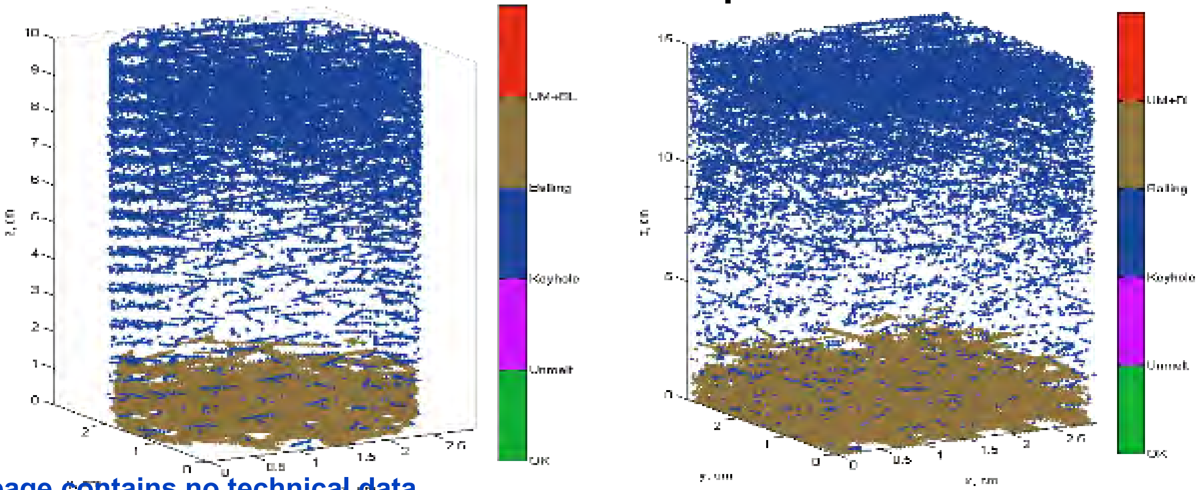
2D defect map



Process map



3D defect map



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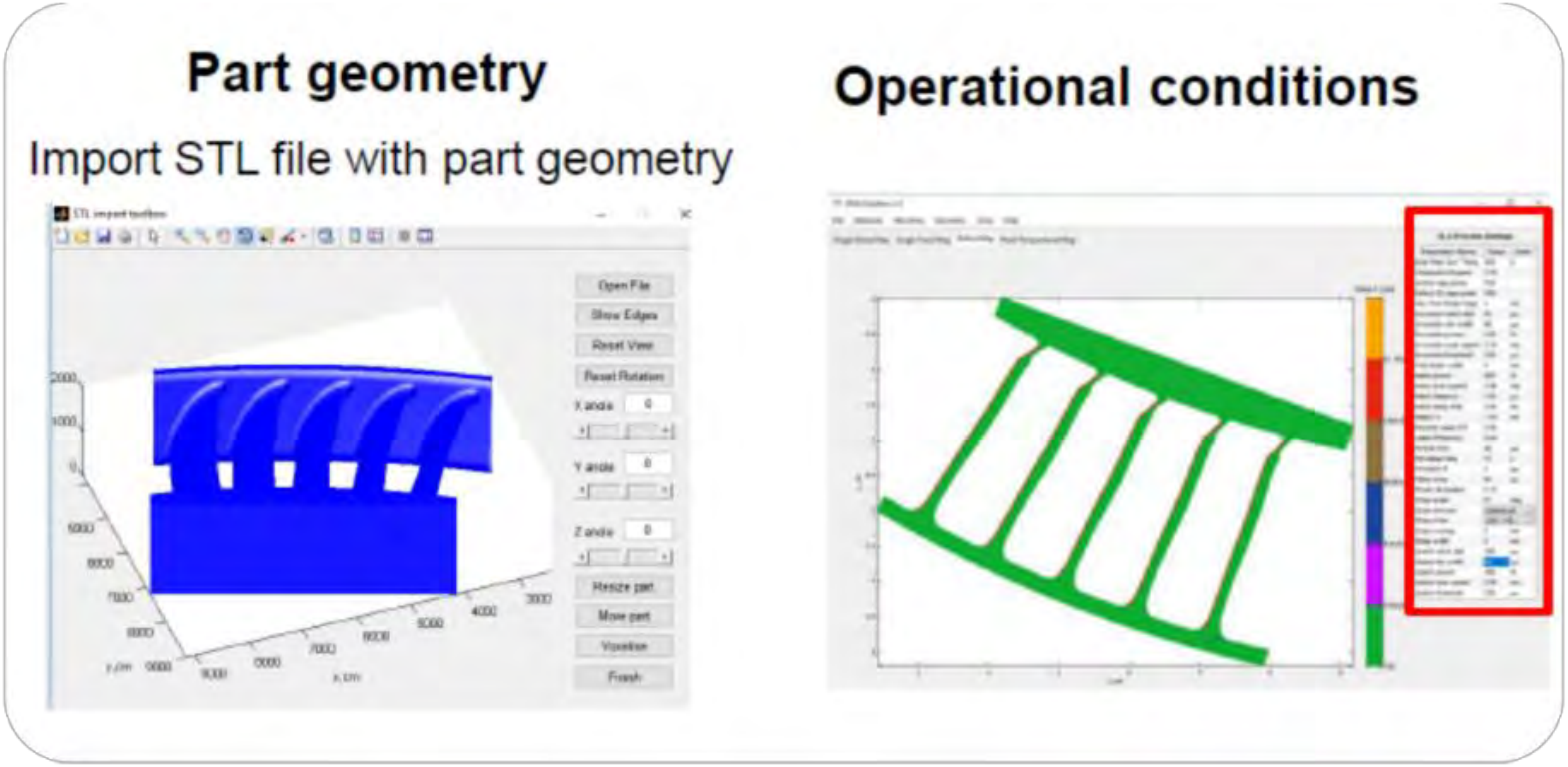
Modeling Applied to Component Configurations

Models provide optimal build paths (process operation conditions) for arbitrary geometries, build direction and bed loading density



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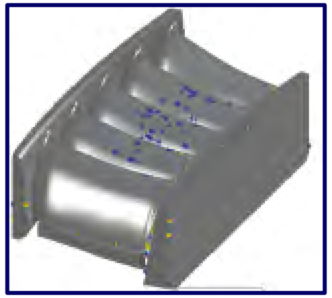
GO BEYOND

Additive Manufacturing Model Application

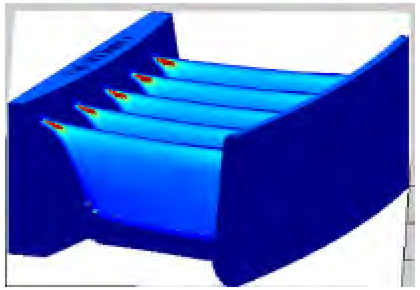
Component Model and Build Validation

STL part geometry

3D defect map



Surface roughness map



Final optimized built component

AM defect prediction model successfully applied to complex component build and final process design and control requirements

Physics-based fast acting tool for defects prediction

Analytical model-based approach does not require time-consuming simulations and extensive experimental calibration

Model capabilities and features

Calculation of process map. Visualization of defect free/rich areas in P(laser power) – V (scanning rate) cross-section of multi-parameter space

Calculation of 2D and 3D defect maps from first-principles with minimal and universal (is not part, material and shape) calibration

Calculation of 3D defect map for simple geometry takes ~ 7 s, for complicated geometry takes ~ 100 seconds on 4-core desktop

6 s

75 s

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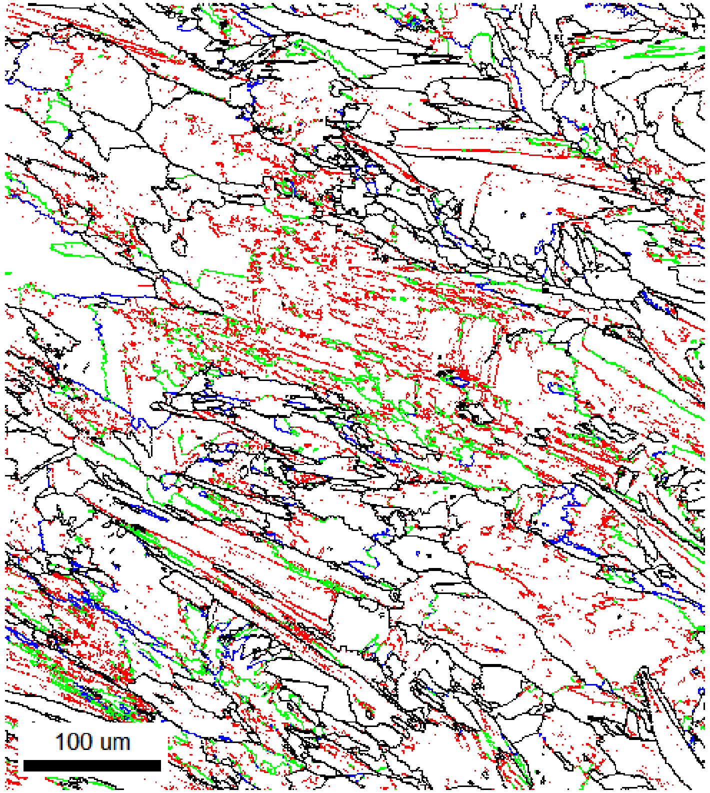
GO BEYOND

AM Material Microstructure Analysis and Control



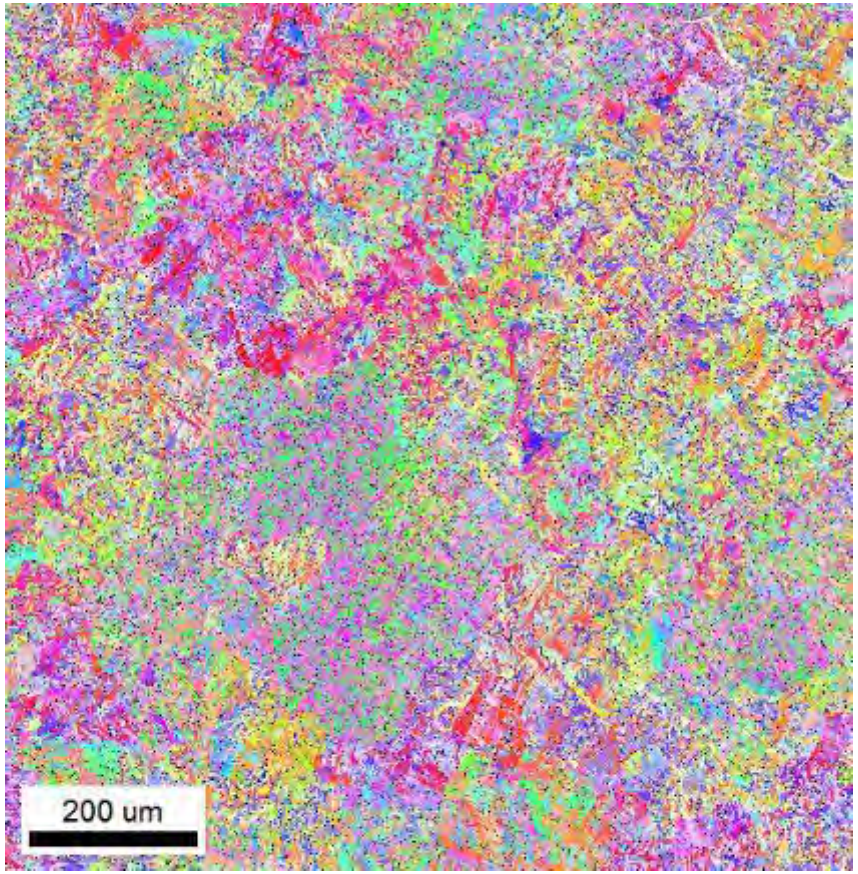
AM IN718 component microstructure

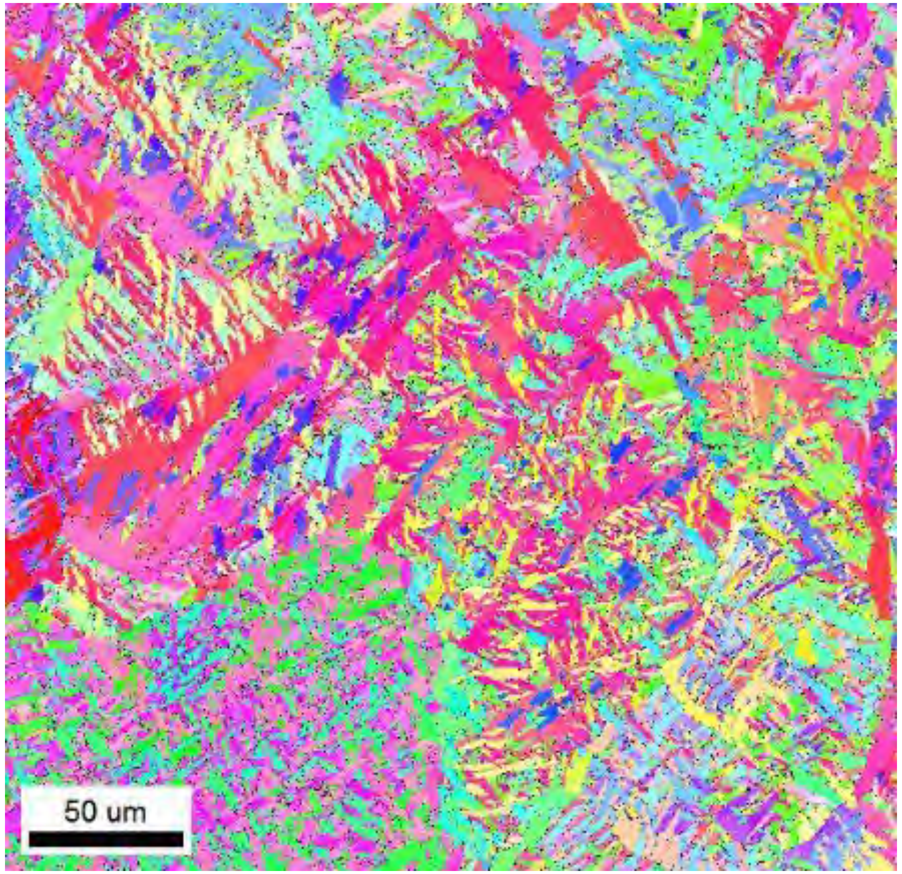
Boundaries: Rotation Angle

	Min	Max	Fraction	Number	Length
(red)	2°	5°	0.338	41325	2.39 cm
(green)	5°	10°	0.141	17204	9.93 mm
(blue)	10°	15°	0.060	7300	4.21 mm
(black)	15°	65°	0.462	56475	3.26 cm

GO BEYOND

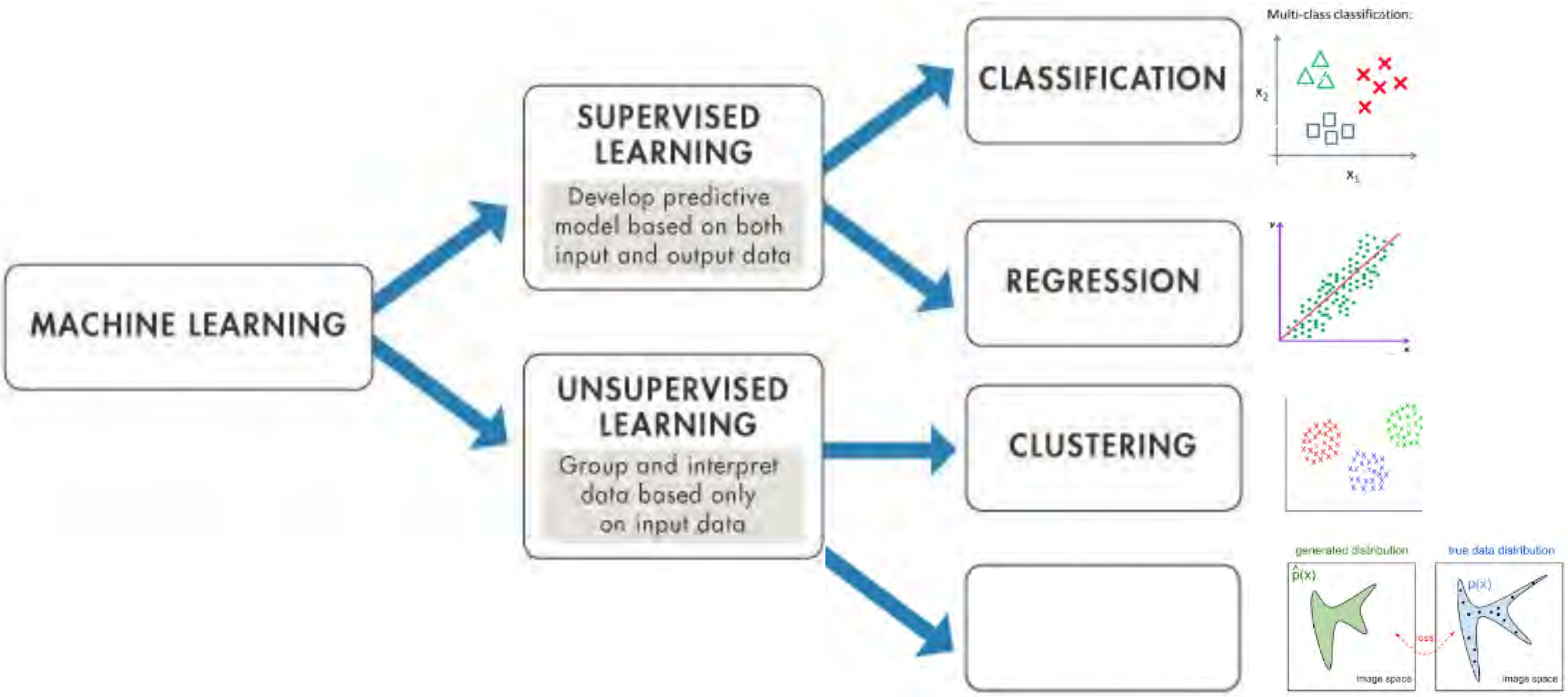
AM Material Microstructure Analysis and Control





EBM Ti 6-4 IPF Maps

Machine Learning Methods: Enhanced Material Definitions



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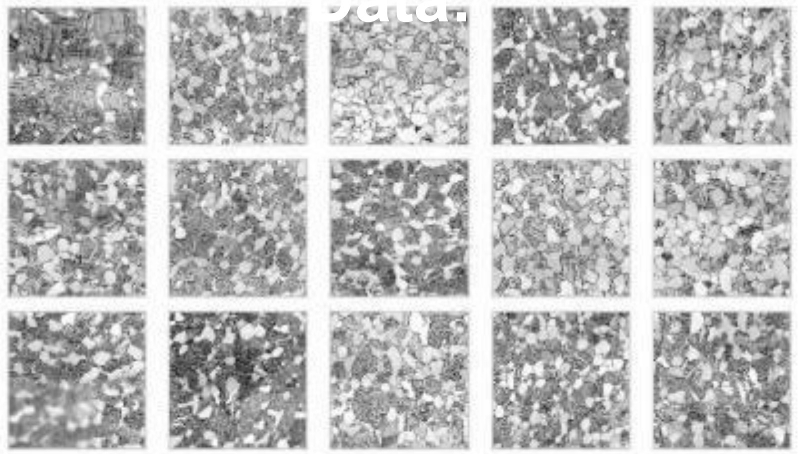
GO BEYOND

Machine Learning Providing New Understanding

Microstructure data can be used to predict properties and classify materials

CLASSIFICATION

REGRESSION



Microstructure dataset can be collected with variation in manufacturing pedigree

Machine Learning models can be used to provide principal component analysis (PCA)

Predictive models can also be developed to guide testing and process control understanding

Immediate applications for:

- Visual similarity assessment / lookup
- Outlier detection
- Quality control
- Process development

Models are fast -- analyze 100's of images / second

ML Tools and Methods can be applied directly to manufacturing data as well as component properties.

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Automated Data Capture and Analytics

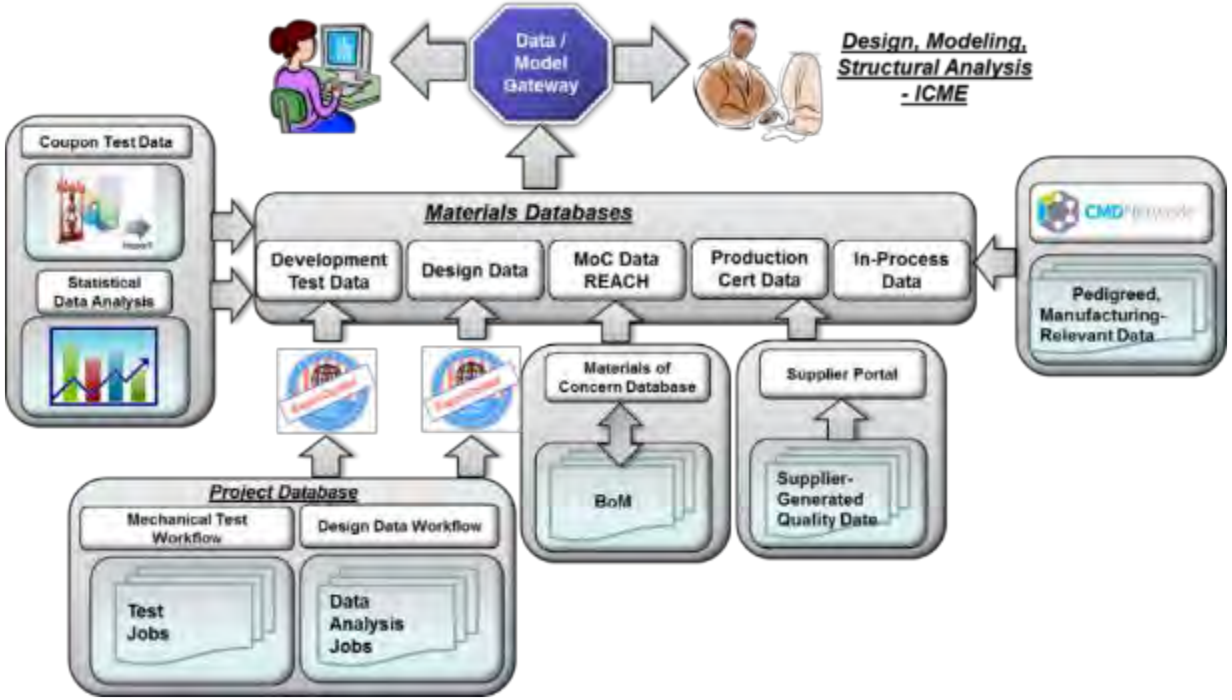
Industrial processes generate large amounts to data that produce digital thread elements

- Industry 3.0 provided manufacturing automation and computerization
- Industry 4.0 provides simulation, automated capture of sensor data which enables real-time automated process monitoring and controls
  - Linkage of process data capture, data analysis and modeling

Digital Data Management

Industry 4.0 requires a robust digital data infrastructure

- Material and process pedigree capture
- Performance correlation to processing
- Model-based data capture and visualization activities



Zero Cost for Data Capture • Zero Data Loss • Data Availability for Analytics

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Conclusions and Take-Away

- **Integration of modeling, sensors and data analytics are providing significant benefits**
- **Model-based material and process definitions are the new standard in holistic design, manufacturing and part/process validation and certification**

Appendix N

“Computational Framework for Rapid Qualification” – M. Maher (Maher & Associates LLC)

Computational Frameworks for Rapid Qualification

An Overview of DARPA's Open Manufacturing Program and Lessons Learned

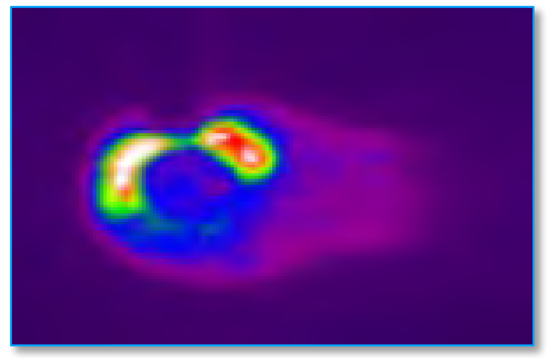
2022 FAA-EASA Additive Manufacturing

Mick Maher

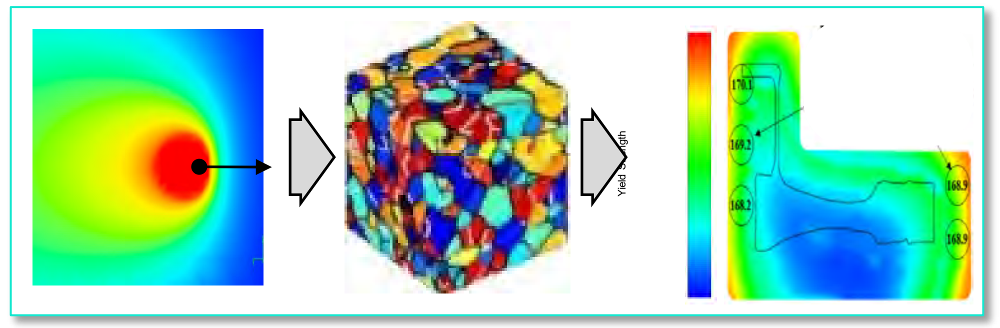
October 18, 2022

OM Approach and Goals

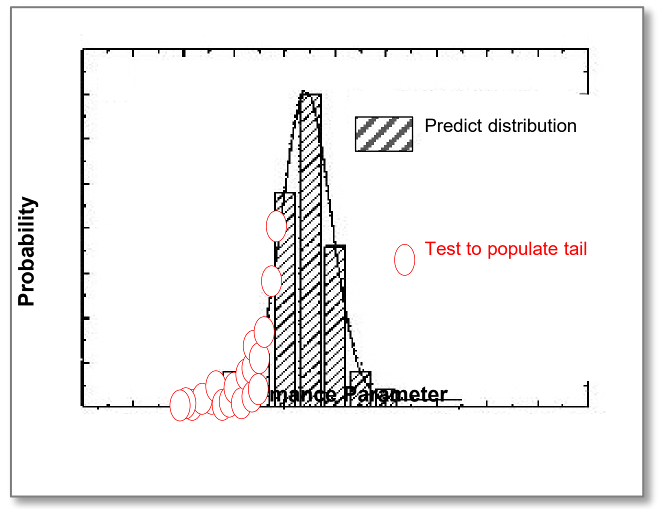
Probabilistic sensing and routine data-capture capabilities can be transferred to manufacturing environment



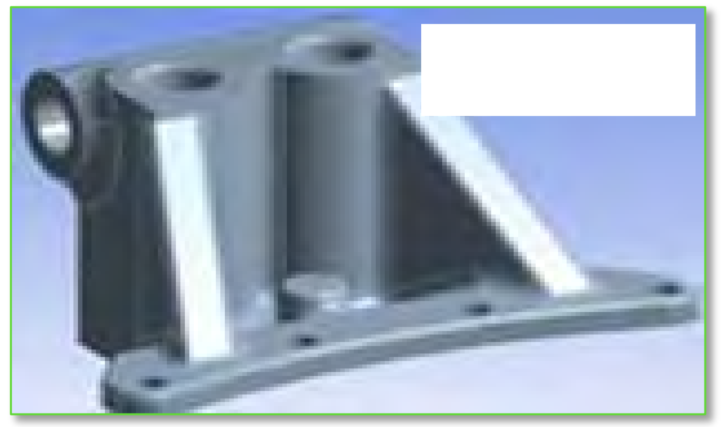
Maturing multi-physics and data-based models allow for understanding of process/microstructure/property relationships



New probabilistic frameworks and verification and validation techniques can link data sources and simulation modules to output product performance with quantified uncertainty

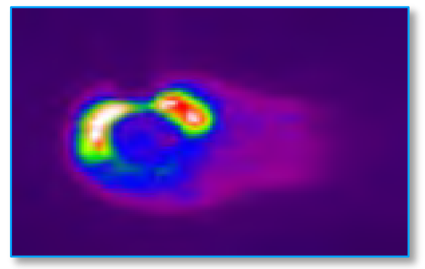


Location specific probabilistic description of product performance for rapid qualification



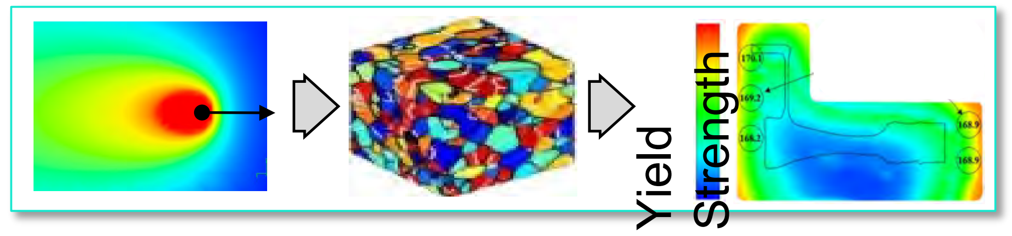
OM Efforts in Additive Manufacturing

Parameterization



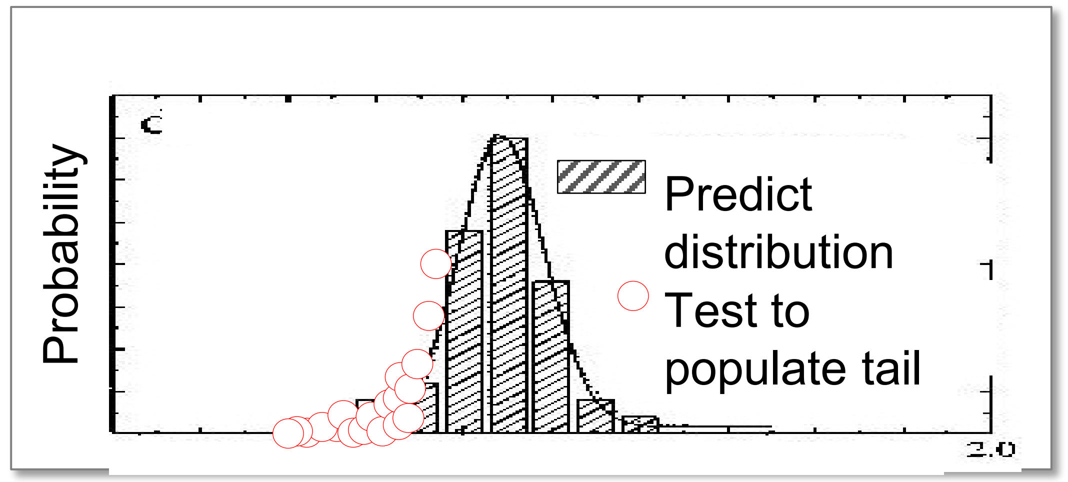
Early process quantification & capture

Predict



Process-material-performance

Targeted testing



Build confidence

Accelerate process maturity

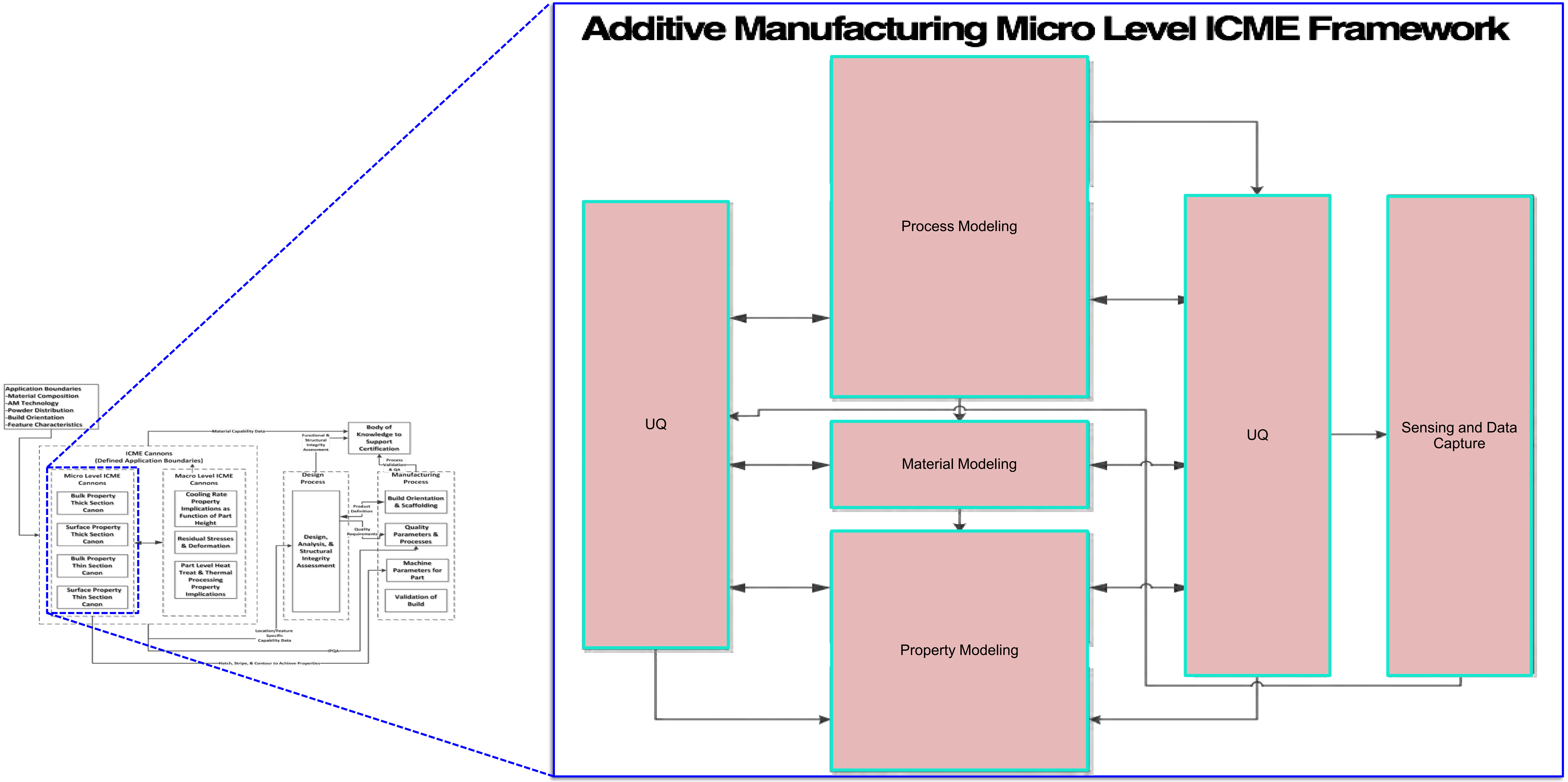
Qualification and systematic updating

Focus	Brief Description
RLCAM Rapid Low Cost Additive Mfg	First-principles materials models connected in a probabilistic software framework for physics-based predictions of the DMLS process
tiFAB Titanium Fabrication	Fully explore process window with scientific process models and minimal testing to determine key parameters that impact quality of manufactured product
MDF Manufacturing Demonstration Facility	Development, qualification, and implementation of enabling technologies for adoption of manufacturing processes

OM: Build and demonstrate rapid qualification technologies with comprehensive capture, analysis, and control of manufacturing variability

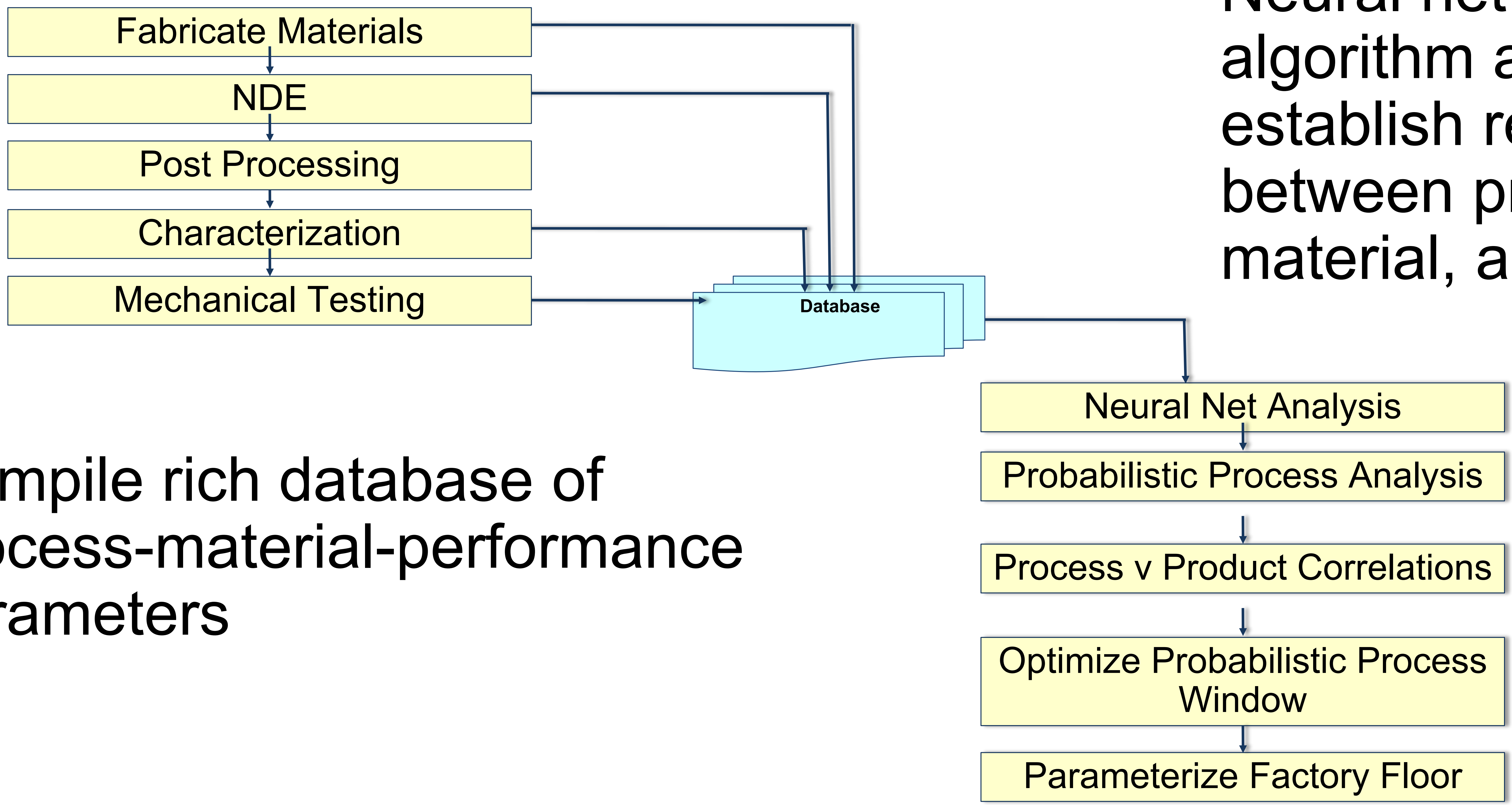
ICME Rapid Qualification Framework

Probabilistic software framework for physics-based predictions of DMLS process



Maher & Associates LLC

Rich Process-Material Database Enabling Manufacturing Predictions



Neural net and genetic algorithm analyses establish relationships between processing, material, and properties

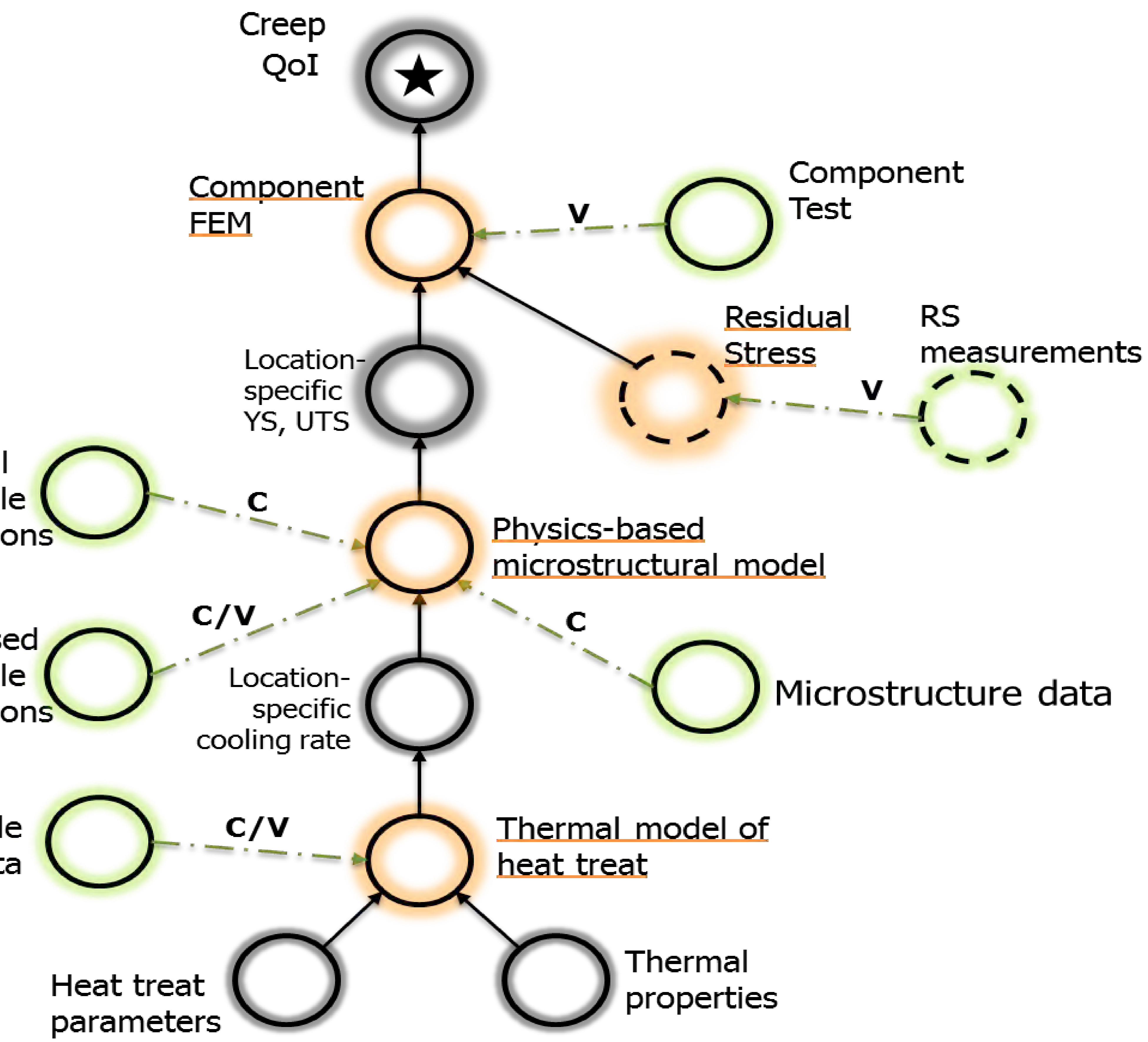
Compile rich database of process-material-performance parameters

Transition Reliable Unitized Structures (TRUST) Approach

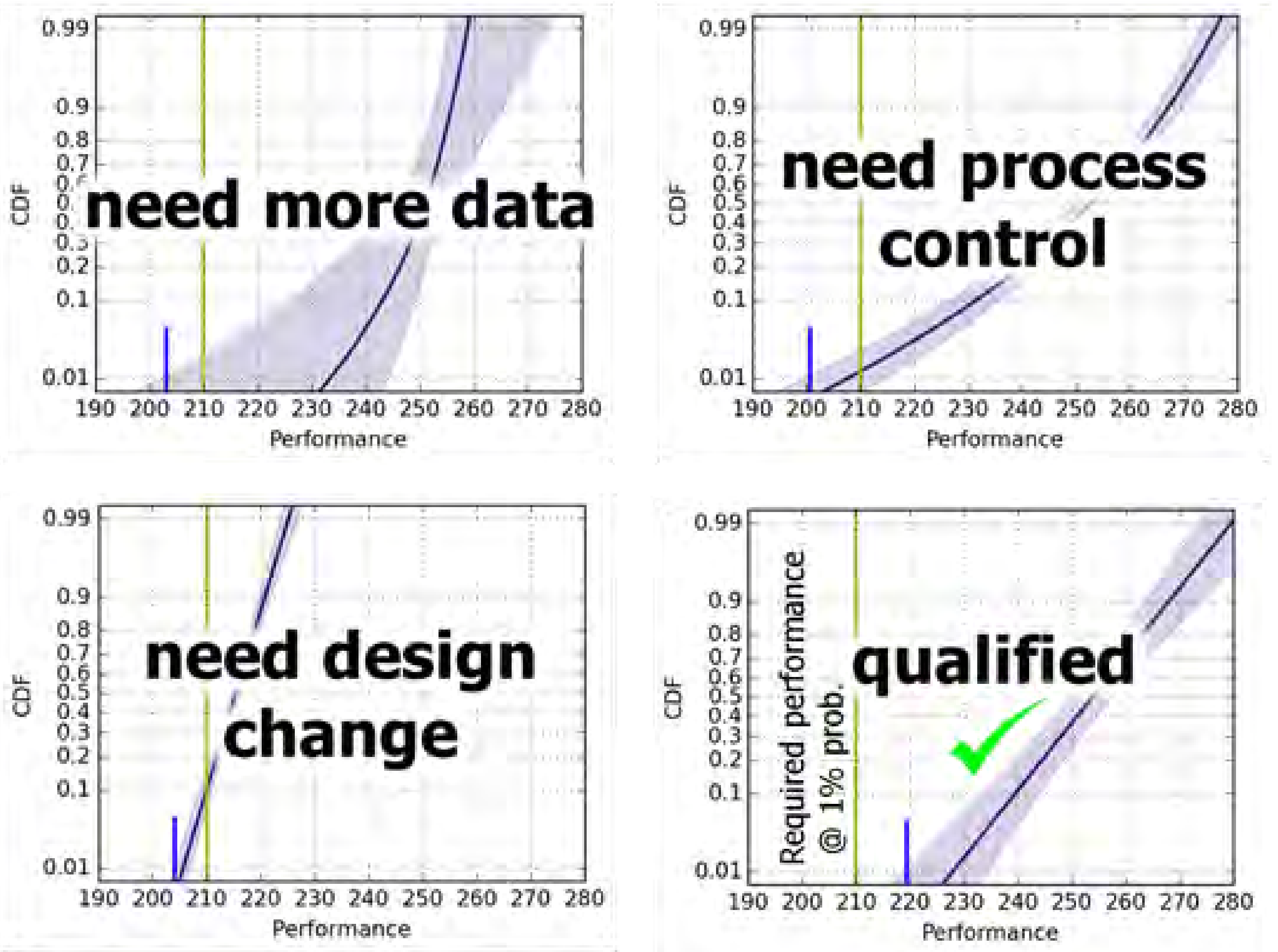
- Capture shop floor variability into informatics database that informs probabilistic Bayesian Process Control (BPC) model
- BPC model determines critical process parameters, predicts bond quality, and computes confidence to ultimately quantify bonding process

Case study: Honeywell powder metal turbine disk

Spin overspeed creep QoI



Characterize the QOI



Conduct uncertainty decomposition

Identify more modeling and experiments to reduce uncertainty

Probabilistically explore edges and corners of process window

Probabilistic qualification assessment and uncertainty reduction will help make decisions

Multi-Level OM Transitions

Open Manufacturing Transitions

- Government
  - FEDERAL AVIATION ADMINISTRATION: Data and process models
  - DEPARTMENT OF DEFENSE, UNITED STATES OF AMERICA
    - DEPARTMENT OF THE NAVY ONR Science & Technology: Future Naval Capability POMS; DMLS & EBAM frameworks; plasma surface prep for nut plates
    - NAVAIR: Direct technology transition
    - AFRL THE AIR FORCE RESEARCH LABORATORY LEAD | DISCOVER | DEVELOP | DELIVER: Out year POMS; composites bonding and AM frameworks
    - U.S.ARMY ARL: EBAM framework adopted for repair process qualification and vehicles; µIS for ARDEC & ARL
    - µFactory seedlings in MTO & BTO; A2P performer
  - MATERIALS GENOME INITIATIVE: Data and process models; AM data schema
- Industry
  - America Makes: Data and process models; AM data schema; DMLS and EBAM frameworks
  - Companies
    - Raytheon: Micro induction sintering
    - LOCKHEED MARTIN: Composites bonding framework for classified program; plasma for F-35 nut plates
    - THE CENTER FOR THE INTREPID, The National Armed Forces Physical Rehabilitation Center: Quick turn custom orthoses manufacturing
    - NORTHROP GRUMMAN: Composites bonding framework and plasma surface prep
    - DMLS framework for engine parts

Looking Back…………

Things I Liked

- Interaction with the services
- Lots of transitions; impact on the community
- Technologies eventually proved themselves out
- Excellent feedback on what needed to happen

Things I didn't Like

- Lack of true collaboration/coordination across agencies
- Internal struggle within DARPA to fund material and manufacturing technologies
- Lack of understanding of the qual and cert process within S&T community
- Robustness of the models remained an issue

Things I Wish I had Done

- Created a technology roadmap to drive collaboration across the agencies
- Initiated the capstone earlier
- Worked multiple materials in each approach
- Put more focus on building confidence in the models

Questions?

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mick@maher-associates.com

Appendix O

"Extreme Value Statistics of Metal AM and Fatigue" – L. Bruder (MTU)

Extreme Value Statistics & Fatigue

10/19/2022 / L.Bruder, A.Fischersworring-Bunk, J.Spachtholz

Permission to include presentation in the proceedings as marked was received 21 Nov 2022

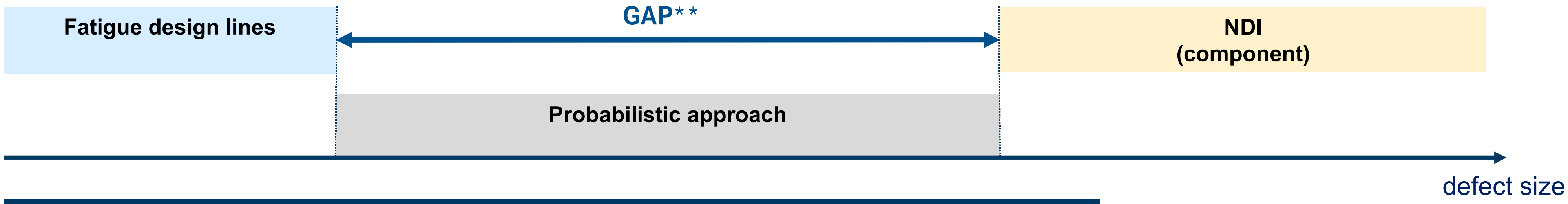
* Need to standardize e.g. by SDO / FAA / EASA
** Risk reduced by higher: confidence intervals / test volume / coupon number / field experience (stochastic)

Introduction

Challenge to use standard LCF/HCF design line lifing assessment

- **Fatigue design lines (transferability of defect statistics coupons to the component due to difference in local thermal temperature history):**
  - statistical requirements for material testing: confidence intervals / test volume / coupon number *
  - defect statistic component vs. coupon: cut up area / test volume NDI *
  - characterization of material data with representative microstructure and defect statistic: mini specimen vs. standard coupon *
  - characterization of rogue flaws in design lines: is this viable and meaningful? not economically possible by testing *

- **NDI (detectability component):**



→ GAP will still be remaining after material characterization
→ Probabilistic approach depending on part-specific criticality – the way forward?

Introduction

Probabilistic approach depending on part-specific criticality – the way forward?

Focus of today's talk

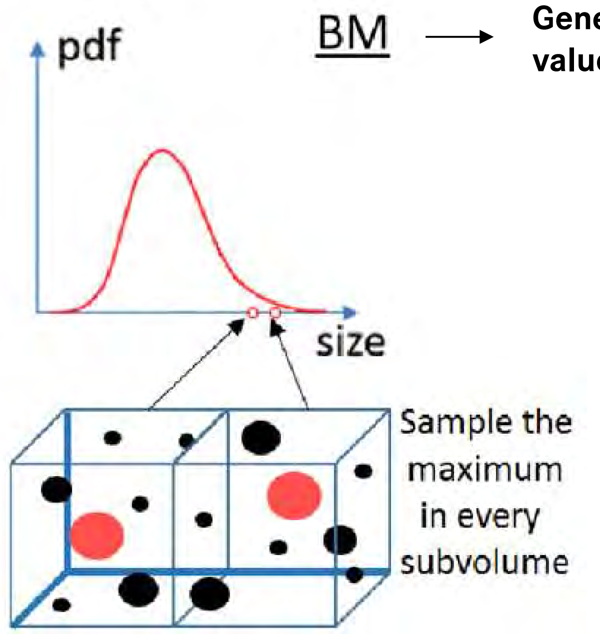
- **Probabilistic approach:**
  - FMECA for determination of acceptable component failure rates per EFH
  - Determination of defect statistics (area of cut-ups per criticality class of component)
  - Extreme value distributions for rogue flaws (generalized Pareto vs. generalized extreme value distribution)
  - Probabilistic assessment

Defect statistics

S. Beretta, “More than 25 years of extreme value statistics for defects: Fundamentals, historical developments, recent applications”, International Journal of Fatigue, Volume 151, 2021.

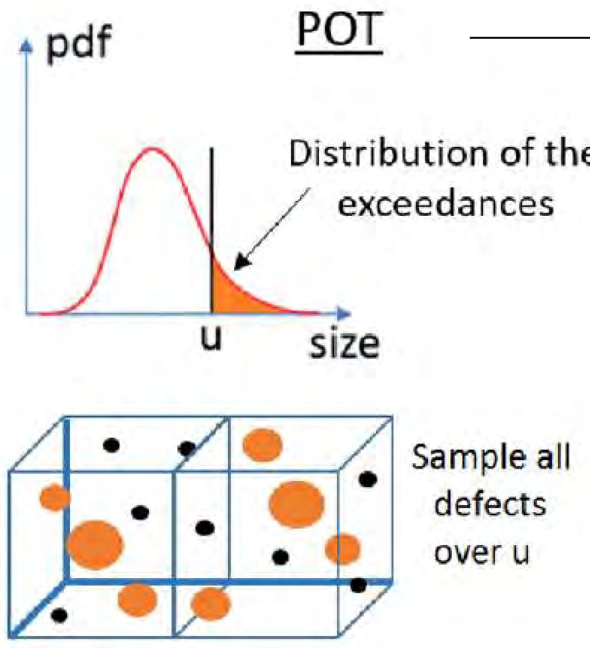
Different strategies to describe very large defect sizes

Block maxima (BM) sampling



Generalized extreme value distribution

Peak over threshold (POT) approach



Generalized Pareto distribution

u: defect size threshold

Defect statistics - Theory

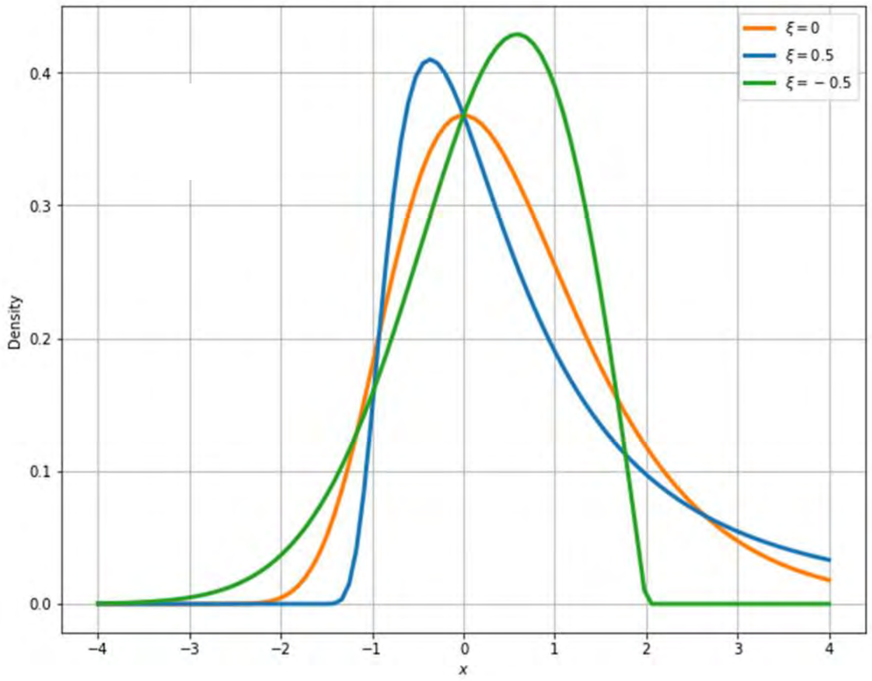
BM sampling – generalized extreme value (GEV) distribution

- PDF:

$$f(x) = \begin{cases} \exp(-z)\exp(-\exp(-z)) & \xi = 0 \\ (1+\xi z)^{-(1+\frac{1}{\xi})}\exp(-(1+\xi z)^{-\frac{1}{\xi}}) & \xi \neq 0, \quad \xi z > -1 \\ 0 & \text{otherwise} \end{cases}$$

- μ: location parameter
- σ: scale parameter
- ξ: shape parameter

$\xi = 0$ (exponential tail) → Gumbel (type I)
$\xi > 0$ (fat tail) → Fréchet (type II)
$\xi < 0$ (finite tail) → Reversed Weibull (type III)



$$z = \frac{x-\mu}{\sigma}$$

→ Models the distribution of the maximum defect sizes
→ Gumbel (ξ 0) used in ASTM E2283

Defect statistics - Theory

POT approach – generalized Pareto distribution

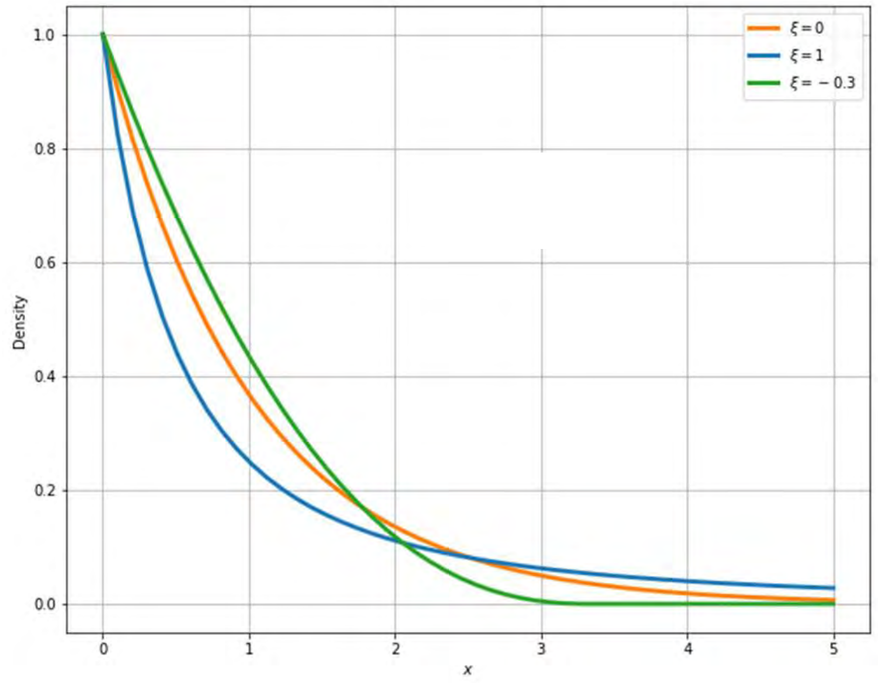
- PDF:

$$f(x) = \begin{cases} (1+\xi z)^{-\frac{\xi+1}{\xi}} & \xi \neq 0 \\ \exp(-z) & \xi = 0 \end{cases}$$

- μ: location parameter
- σ: scale parameter
- ξ: shape parameter

$\xi = 0$ (exponential tail)
$\xi > 0$ (fat tail)
$\xi < 0$ (finite tail)

→ Models the distribution of all defects above a threshold

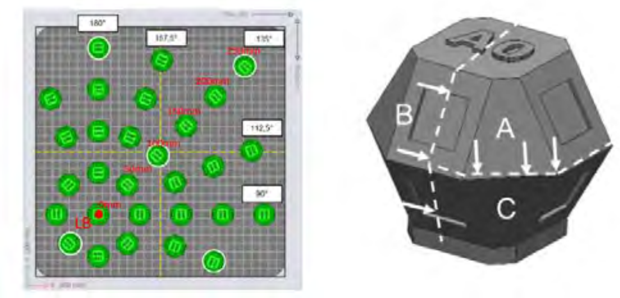


$$z = \frac{x-\mu}{\sigma}$$

Defect statistics - Data

Reference data IN718 L-PBF

2 orientations, 2 powder batches



Metallographic examination

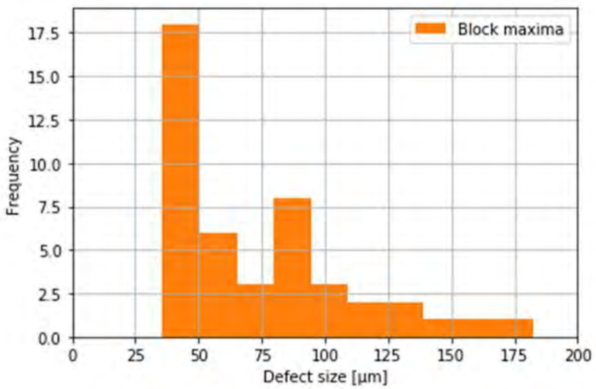
automatic defect detection per cut-up > 20µm

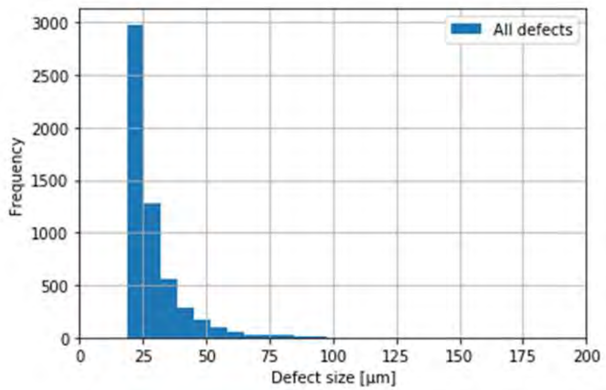
Calculation of defect density

$$\text{defect density} = \frac{\text{defects}}{\text{area} * \text{layer thickness}}$$

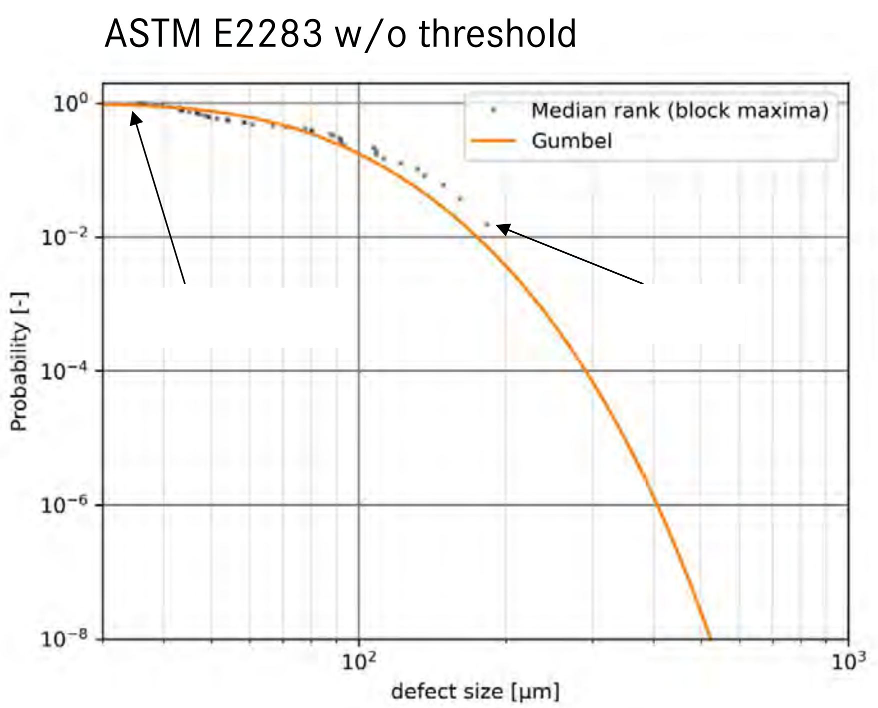
No. cut-ups	No. defects	Total cut-up area
45	5524	153 cm^2

max. defect
per cut-up





Defect statistics – ASTM E2283



Exceedance curve

- Log-log visualization of the probability of exceeding a given defect size
- Note: probability is not absolute (defects per volume) → the focus here is on the shape of the exceedance curve

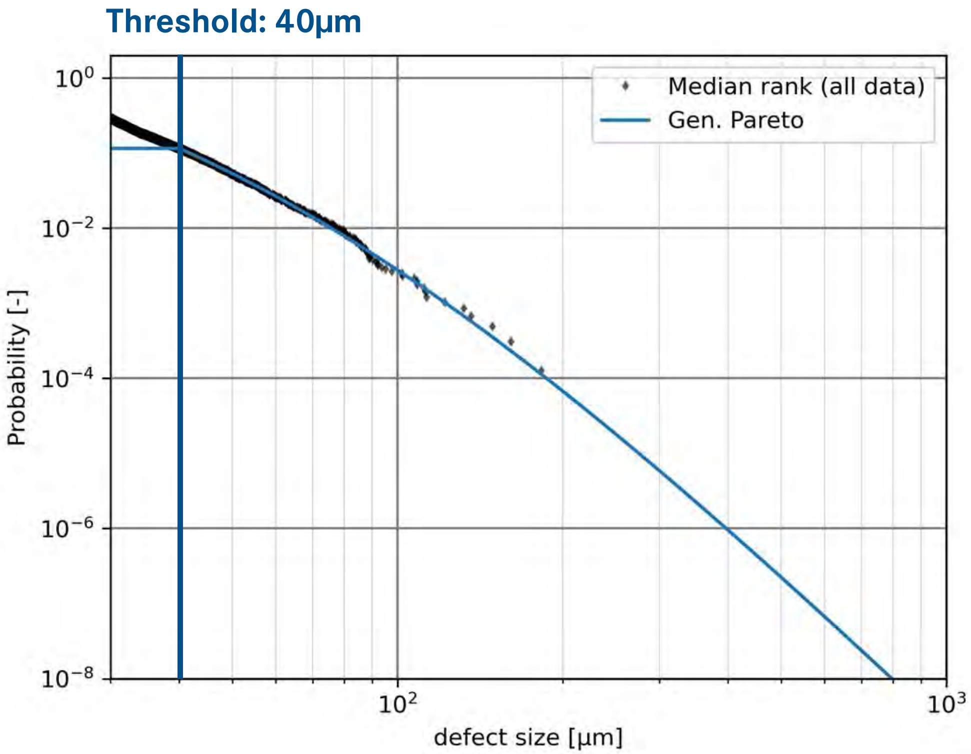
ASTM E2283

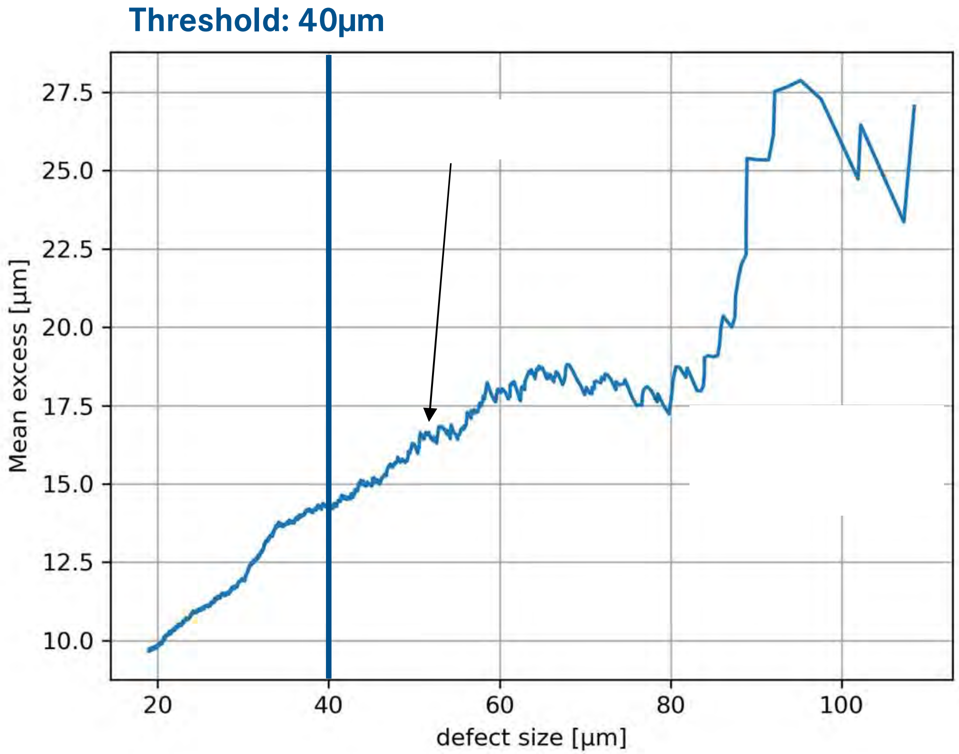
- Block maxima sampling on areas of 150mm² → **3.1cm² (per cut-up)**
- At least 24 maxima → **45**
- Analysis using the Gumbel distribution (Maximum-Likelihood method for parameter estimation)

→ **How to set an adequate threshold? How to define cut-up area (Metallography) or volume CT (NDI)?**

Defect statistics – POT approach with threshold

$\text{defects} > 40\mu m: 638$



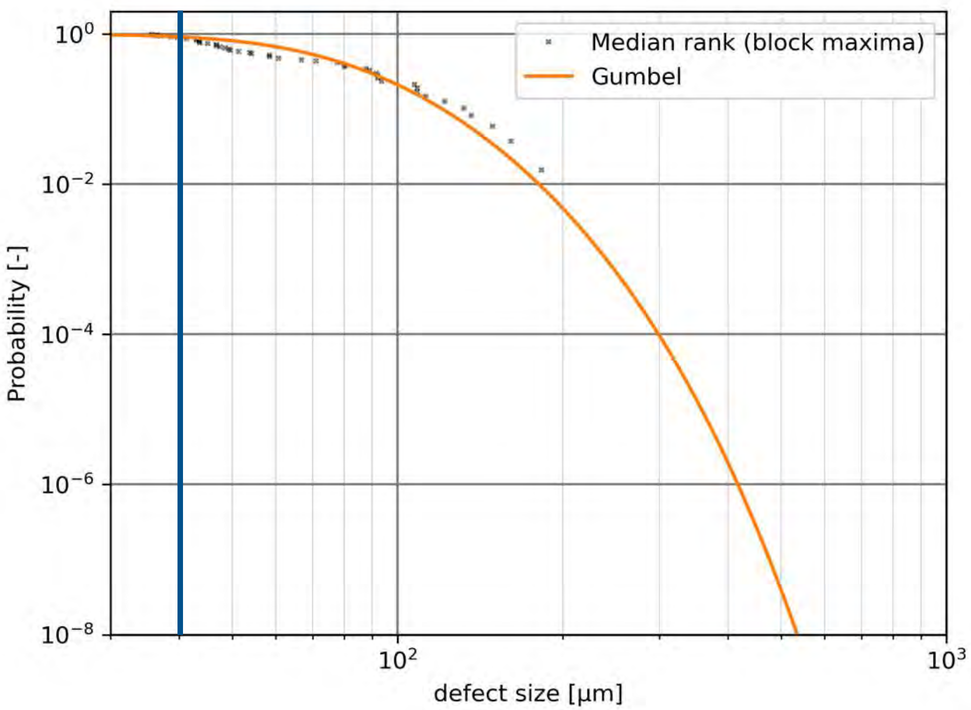


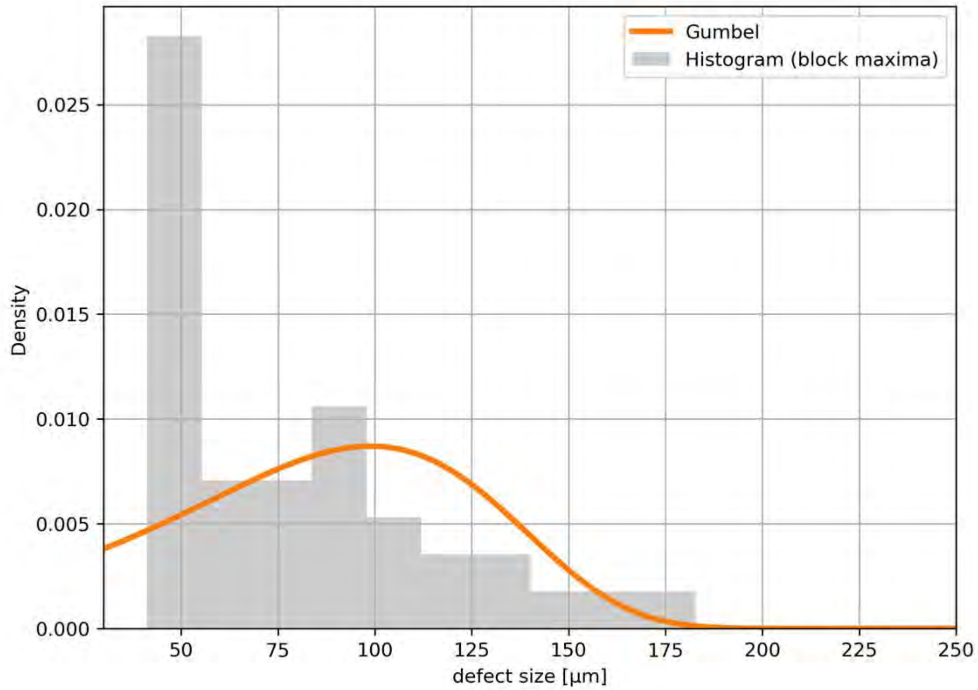
→ Gen. Pareto: models the distribution of all defects above a threshold

Defect statistics – BM approach with threshold

maxima > $40\mu m$: 40

Threshold: 40µm



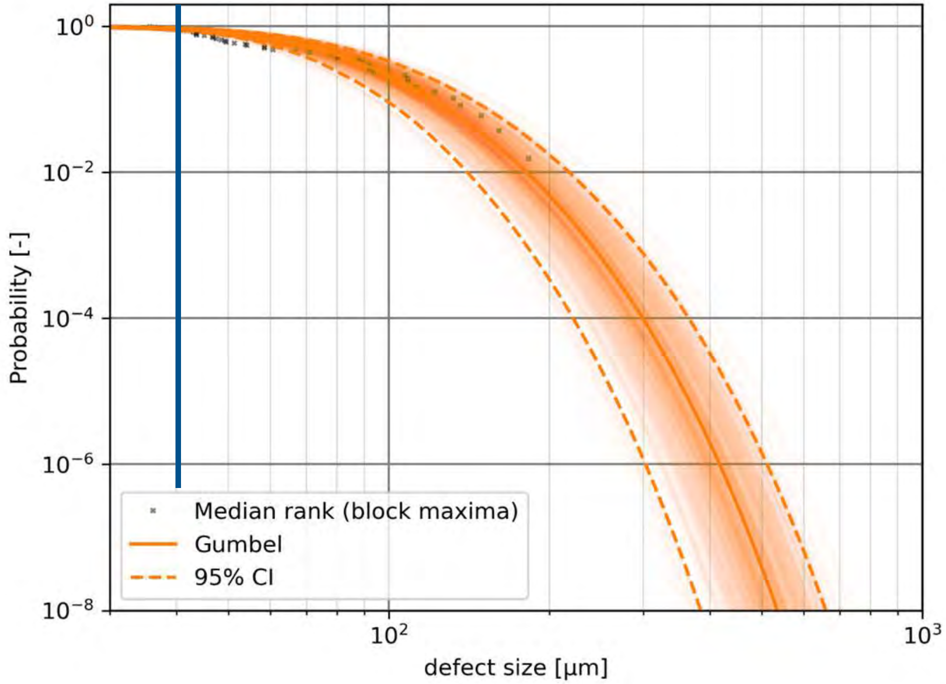


→ Gumbel: models the distribution of the maximum defect sizes

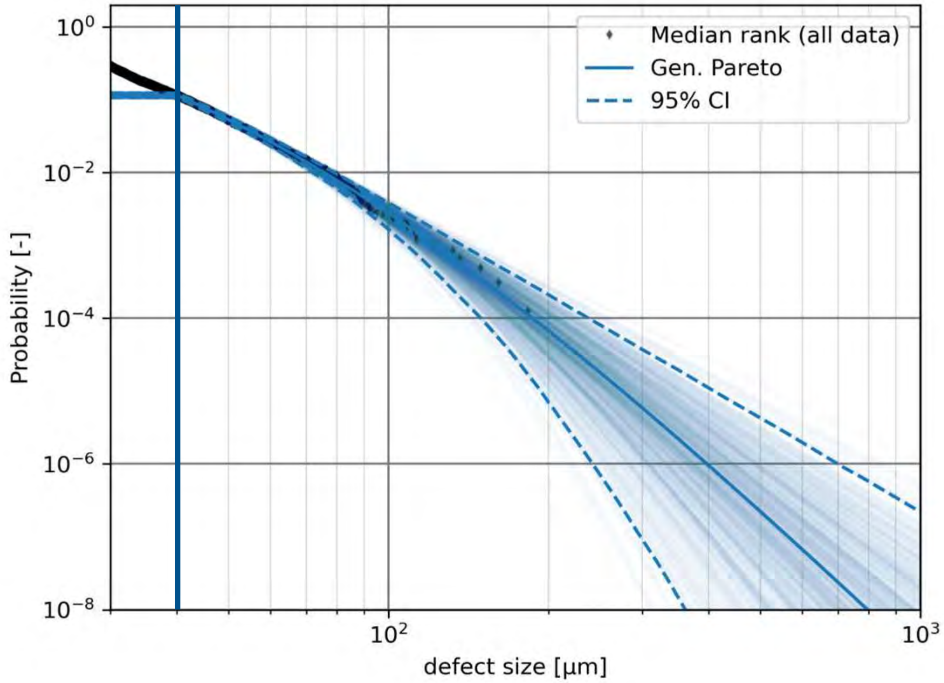
Defect statistics – POT and BM with threshold

Sensitivity analysis using bootstrapping

Threshold: 40µm



Threshold: 40µm



→ Gumbel more stable and suggested in ASTM E2283 (less degrees of freedom)

Defect statistics – another approach

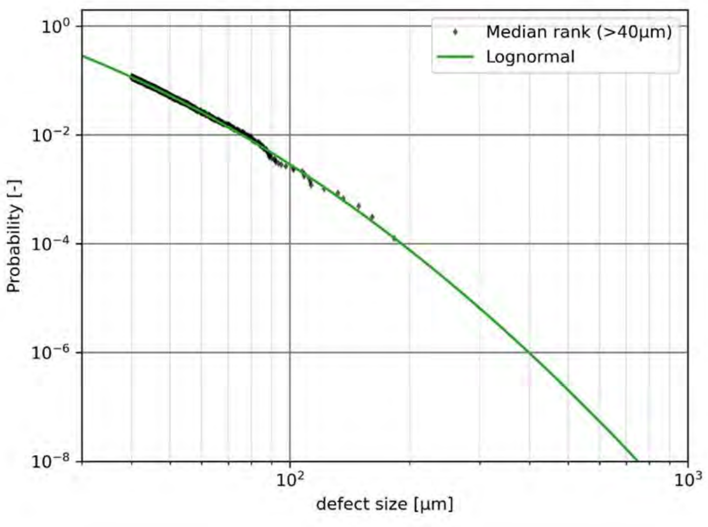
Issues with BM & POT:

- Superposition of pores and lack of fusion defects makes a direct application of standard approaches questionable
- Even with a threshold of 40µm, the right tails of the fits (the regions relevant for the probabilistic analysis) are sensitive towards the data

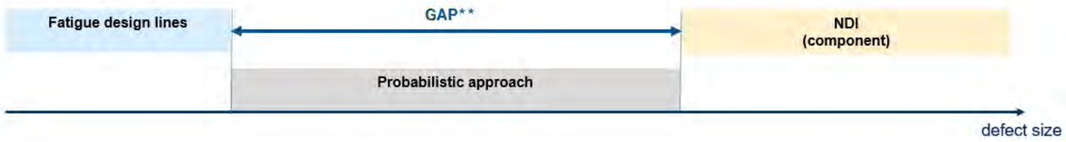
Another approach:

- Fit a distribution that describes the large defects well and is stable in the low-probability regions
- Example: Median rank fit of a Lognormal distribution on all defect data > 40µm

→ **For large data sets also classical distributions (non-extreme value) can provide a good description**



Summary & Discussion



Probabilistic approach

- Potential to reduce time and cost at characterization of standard coupon LCF/HCF design line for fatigue lifing assessment
- Not feasible to include max. defect size (rogue flaws) in standard LCF/HCF coupon to reduce GAP
- Not economically and technically possible to find defect size (a90/95) included in coupon specimens in component to reduce GAP
- Probabilistic approach to close/answer GAP which will be still remaining after material characterization

→ Probabilistic approach depending on parts criticality – the way forward? → Yes

Points for discussion

- Choice of evaluation method (POT vs. BM) significantly impacts the probabilistic analysis
- There are cases where a threshold value to cut off pores is required (automatic defect detection: lack of fusion & pores)
- Gumbel distribution to model the maximum defect size → more stable than gen. Pareto & suggested in ASTM E2283
- Component defect distribution vs. coupon defect distribution (e.g. cut-up area suggested in ASTM E2283)
- Different approaches to describe large defects: gen. Pareto vs. gen. extreme value vs. Lognormal (maximum likelihood vs. rank regression)

→ Review of ASTM E2283 for AM or a new ASTM standard for defect statistics needed? → Flexibility desired

Appendix P

"AM Part Family Qualification & Certification for Aviation" – M. White (ASTM)

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Additive Manufacturing Center of Excellence

AM Part Family Qualification & Certification for Aviation

Dr. Martin White
Head of Additive Manufacturing Programs – Europe Region

Dr. Alberto Bordin
Additive Manufacturing Technical Lead – Europe Region

ASTM Work Item: **WK81194** Specification for Additive Manufacturing -- Qualification Principles -- Part Families-based Qualification in AM

Oct. 19th 2022

www.amcoe.org

Overview

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KEY HIGHLIGHTS

- F42.07.01
  - Part Classification
- Relevant Activities

PART FAMILY

- America Makes Project
- Work so far…

WHAT NEXT?

- ASTM draft Standard process in progress for Part Family

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F42.07.01 Aviation Subsection Efforts

Slide courtesy of Charles Park from ASTM 8th Snapshot Workshop

CENTER of EXCELLENCE Research to Standards
ADDITIVE MANUFACTURING

- F42.07.01 kicked off in March 2019
  - Leadership: Charles Park, Michael Gorelik and Lloyd Schaefer
- Phased approach to review and develop standards
  - Phase 1: review and identify gaps in ASTM standards
  - Phase 2: improve high priority ASTM standards
  - Phase 3: connect with outside ASTM standards
  - Review results categorized from Cat1 to Cat4 address the level of risk associated with a part
- Three key items pursued based on priority
  - WK70164 Part Classifications for Aviation – Now issued (next slide)
  - WK75655 Reporting Data for Test Specimens (Revision of F2971-13)
  - WK75329 NDT for Laser Based Powder Bed Fusion for Aerospace Components

1. Standard is relevant, but guidance / level of details is not sufficient for Aviation
   - Develop an Appendix, to be included in the existing Standards
   - Only ballot aerospace specific Appendix without the ballot of the entire standard
   - Close coordination with the subcommittee who owns the document.
2. No standard exists covering an Aviation-essential topic
   - Develop new Standard
3. Standard Already Exists and is adequate for Aviation applications
   - No action needed
   - If the document is ASTM only standard, we may be able to put in ISO fast-tack
4. Standard not relevant to Aviation sector.
   - No action needed

Technical Category	***ASTM Standards Reviewed***	***Review Results***
Material & Process	WK66682 Evaluating Post-processing and Characterization Techniques for AM Part Surfaces F2924-14 Standard Specification for Additive Manufacturing Titanium-6 Aluminum-4 Vanadium with Powder Bed Fusion F3001-14 Standard Specification for Additive Manufacturing Titanium-6 Aluminum-4 Vanadium ELI (Extra Low Interstitial) with Powder Bed Fusion F3055-14a Standard Specification for Additive Manufacturing Nickel Alloy (UNS N07718) with Powder Bed Fusion F3056-14e1 Standard Specification for Additive Manufacturing Nickel Alloy (UNS N06625) with Powder Bed Fusion F3091/F3091M-14 Standard Specification for Powder Bed Fusion of Plastic Materials F3184-16 Standard Specification for Additive Manufacturing Stainless Steel Alloy (UNS S31603) with Powder Bed Fusion F3187-16 Standard Guide for Directed Energy Deposition of Metals F3301-18a Standard for Additive Manufacturing – Post Processing Methods – Standard Specification for Thermal Post-Processing Metal Parts Made Via Powder Bed Fusion F3303-18 Standard for Additive Manufacturing – Process Characteristics and Performance: Practice for Metal Powder Bed Fusion Process to Meet Critical Applications WK58219 Additive Manufacturing - Feedstock Materials-Creating Feedstock Specifications for Metal Powder Bed Fusion WK58220 Additive Manufacturing - Process Characteristics and Performance -Standard Guidance for Specifying Gases and Nitrogen Generators Used with Metal Powder Bed Fusion Machines WK65937 Additive Manufacturing Process Characteristics and Performance - Control and Qualification of Laser Beam Powder Bed Fusion Processes WK62190 Additive manufacturing Feedstock materials Technical specifications on metal powder WK65420 Additive Manufacturing Qualification Principles for Equipment - Standard Guidelines Laser Powder Bed Fusion (L-PBF) for Metal	Category 1: 11 Category 3: 3
NDI	WK47031 New Guide for Nondestructive Testing of Metal Additively Manufactured Metal Aerospace Parts After Build **-E3166** WK62181 New Guide for Standard Guide for In-Situ Monitoring (IPM) of Metal Additively Manufactured Aerospace Parts	Category 1: 2
Testing	F2971-13 Standard Practice for Reporting Data for Test Specimens Prepared by Additive Manufacturing F3122-14 Standard Guide for Evaluating Mechanical Properties of Metal Materials Made via Additive Manufacturing Processes ISO/ASTM52921-13 Standard Terminology for Additive Manufacturing-Coordinate Systems and Test Methodologies WK49229 Orientation and Location Dependence Mechanical Properties for Metal Additive Manufacturing WK55610 the Characterization of Powder Flow Properties for Additive Manufacturing Applications WK67454 Additive manufacturing -- Feedstock materials -- Methods to characterize metallic powders F3049-14 Standard Guide for Characterizing Properties of Metal Powders Used for Additive Manufacturing Processes WK67583 Additive Manufacturing -- Feedstock Materials -- Powder Reuse Schema in Powder Bed Fusion Processes for Medical Applications	Category 1: 5 Category 3: 3

AM Classification for Aerospace/Defense – ASTM F3572

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*"Without carefully defined part classes, the ability to accurately **gauge the consequence of failure** associated with additively manufactured aviation parts within and across programs, projects, and suppliers becomes exceedingly difficult…"*

Now RELEASED

- Alignment vs **Civilian** & **Military** documents
  - i.e. NAVAIR, AC25.571: Damage Tolerance & Fatigue Evolution of Structure

Classification	Consequence of Failure	Non-exhaustive Examples
A	High	Part whose failure can directly affect continued safe flight and landing Part whose failure can result in serious or fatal injury to passengers or cabin crews Part whose failure requires exceptional piloting skill of flight crew to compensate
B	Medium	Part whose failure can indirectly affect continued safe flight and landing Part whose failure can result in minor injury to flight crew, passengers, or cabin crews Part whose failure can result in significant increase in workload of flight crew
C	Low	Part whose failure has no effect on continued safe flight and landing Part whose failure has no effect on flight crew, passengers, or cabin crew Part whose failure can result in slight reduction in operational/functional capabilities Part whose failure can result in slight increase in workload of flight crew
D	Negligible or No Effect	Part whose failure would pose no risk of damage to other equipment or injury to the ground personnel Parts not affecting operational/functional capabilities

Published on 5th August 2022
Appreciate all the helps to publish this document (regulator, industry stakeholders, F42 commenters, other SDOs)
Special thanks to F42.07.01 "core" team

Key Highlights – Materials Data

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Consortium for Materials Data and Standardization (CMDS)

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ASTM INTERNATIONAL
Additive Manufacturing Center of Excellence

Consortium for Materials Data and Standardization (CMDS)

Companies from across a broad range of industries need to develop extensive material datasets in order to confidently implement Additive Manufacturing into the design and production of future products. Complete datasets required for part design and production control can cost upwards of $1M for one material dataset depending on the properties of interest. The CMDS brings together key organizations to standardize the requirements and best practices for materials data generation and creates shared high-pedigree "reference" datasets to greatly reduce the cost to each member organization.

To join, please contact Richard Huff
rhuff@astm.org | tel +1.202.948.4919 | www.amcoe.org/consortium

Industry Member Value

The ASTM CMDS works with the standards community to address the need for new and improved data-driven standards.

ASTM INTERNATIONAL
Helping our world work better

ASTM International Additive Manufacturing Center of Excellence Announces Consortium for Materials Data and Standardization

W. CONSHOHOCKEN, Pa., May 13, 2022 – ASTM International Additive Manufacturing Center of Excellence (AM CoE) and the founding industry members, are formally announcing the launch of the AM CoE Consortium for Materials Data and Standardization (CMDS) initiative. The mission of ASTM's CMDS is to bring key organizations together from across a broad range of industries representing the entire AM value stream. The consortium members will collaborate on standardization of the requirements for AM materials data generation and will create and manage shared high-pedigree "reference" datasets needed to accelerate qualification and greater adoption of AM technologies. The consortium is being launched with 21 founding members including:

1. Accurate Brazing
2. AddUp Inc.
3. ASTM International
4. Auburn University
5. BeamIT/3T-AM Ltd.
6. Boeing
7. Desktop Metal
8. Element Materials Technology
9. EOS
10. Edison Welding Institute (EWI)
11. Fraunhofer IAPT
12. Gasbarre Thermal Processing Systems
13. GE Additive
14. GKN Additive
15. Hexagon Manufacturing Intelligence, Inc.
16. HP Inc.
17. Morf3D
18. The Manufacturing Technology Center (MTC)
19. National Aeronautics and Space Administration (NASA)
20. Raytheon Technologies Corporation
21. Sigma Labs, Inc.

"GE Additive is pleased to continue its engagement with the AM CoE Industry

Official Announcement, May 2022

Process – Structure – Properties - Performance

25

2nd F2F meeting, Jun 2022

Key Highlights – In Situ Technologies

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Specialty Workshop: In-Situ Technology (sponsored by NASA MSFC)

Task 1: Process Qualification

Design, test, and standardize a qualification schema for laser beam powder bed fusion (LB-PBF).

Task 2: Defects & Inspection

Define **types and sources of rogue flaws (including PMFEA)** in AM, in-situ monitoring and NDI for **defects detection**, **Probabilistic analysis** methods for likelihood of defects occurrence and detection

Task 3: In Situ Monitoring

Assess current status of *in situ* monitoring technologies and develop a roadmap for prioritization moving forward.

- Readiness of in-situ technologies for applications in AM Qualification and Certification
- Outcome: Strategic guide/roadmap will be developed

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Problem Statement

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"Why is the Route to Certification so difficult for Additive Manufacturing?"

Challenge (Biggest?)

Current ***Qualification & Certification methods are costly****, and heavy on* ***time and resource***

How to reduce the burden?

<u>What's needed?</u>

A Pathway Towards More Efficient Q&C Approaches

Qualification

Certification

Single part

Material & machine S/N specific

Fixed ("Frozen") process parameters

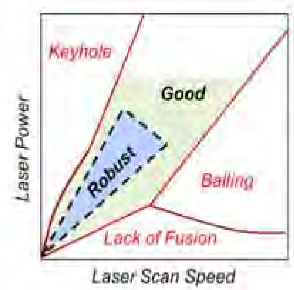
Today

Similar part complexity

Functional requirements and post-processing alike

Identified key process parameters

Near Future



In-depth process understanding

Machine agnostic physics-based models

Long Term

Aligned with Cert requirements [Part 25, Part 33, NASA MSFC, etc.]

Risk-based approach

Additive Policy

M&P specifications, Design Allowables

Statistical process control

Process understanding

- Physics-based models
- Machine qualification (PFMEA)

(From: Accelerating Adoption of Additive Manufacturing in Aerospace & Defense – RTX – ICAM2021 Conference)

ASTM Contribution on Part Family Adoption for Q&C

CENTER of EXCELLENCE Research to Standards
ADDITIVE MANUFACTURING

Project Name: Best Practices for Additive Manufacturing Part Families relating to Product Qualification & Certification

Funded Project by AFRL and Managed by America Makes
Project ID 5001.002.002.003
Period of Performance: 7 months* (Nov. 2021 – May 2022)

An advisory board has been established with experts from the following organizations

Objectives:
Define route to using Family of Parts methodology, such that Q&C can be shared across ***a number of 'similar' parts.***

Project Benefits:
Provide America Makes' members with a best practice on AM Part Family Qual. & Cert.

Opportunities – Part Family Concept

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ADDITIVE MANUFACTURING

The concept of a part family approach for AM Qualification and Certification has been discussed <u>many times</u> in recent years

How can we qualify similar parts with maximum efficiency?

Referenced in the 2020 AIA AM Working Group's report:

– "A part family may be established by defining the key characteristics (e.g., geometric features, feedstock, and processing window), and developing design values representative of the part family features and criticality. The resulting design values would then be applicable to any part defined to be within that family. This approach is more efficient than creating unique allowables and design values for every part."

https://www.aia-aerospace.org/wp-content/uploads/2020/02/AIA-Additive-Manufacturing-Best-Practices-Report-Final-Feb2020.pdf

Example: Moving Towards "Part Family" Qualification

Families for qualification

Successful qualification can be used to qualify a number of similar parts

Separate qualification of each AM part is not necessary.

To be considered as a 'family', the parts shall satisfy the following criteria:

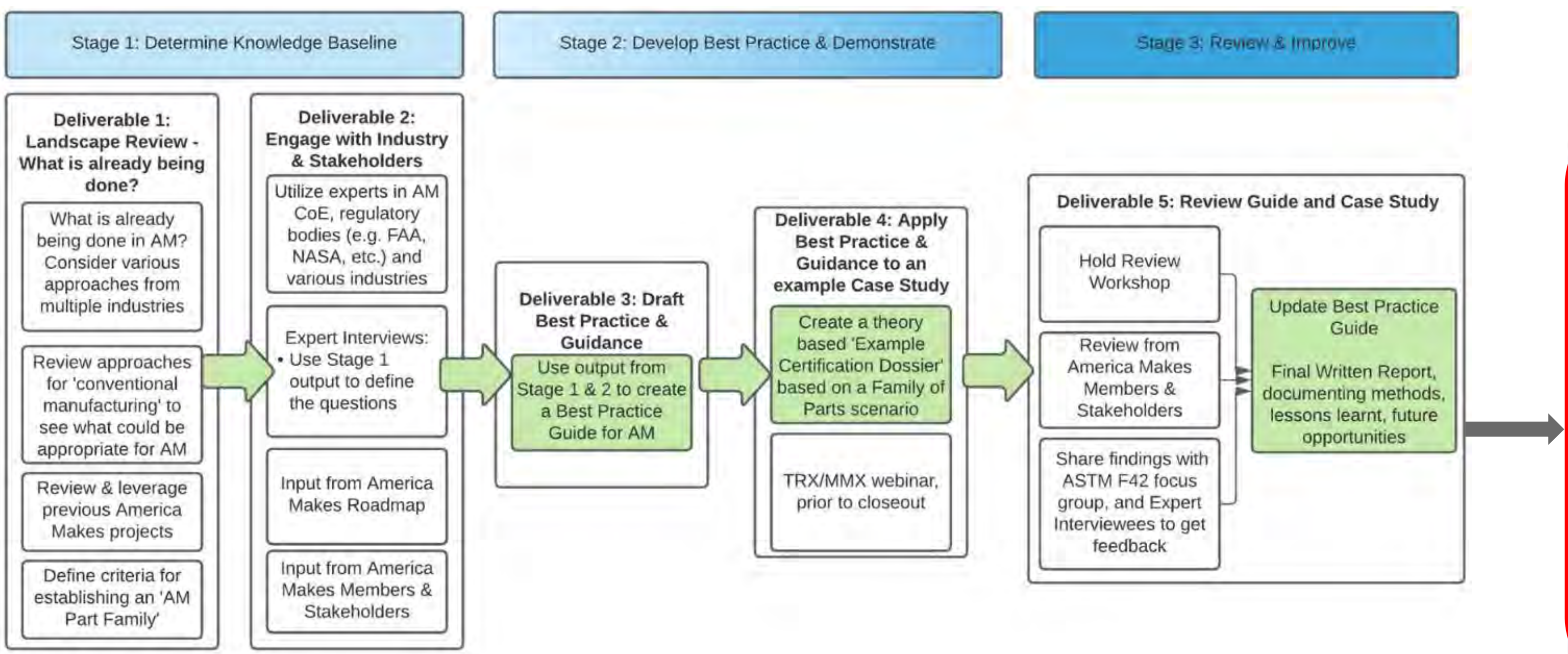
- Same material and post processing conditions
- Same classification of part and part function
- Same manufacturing and inspection programme
- Similar geometry and section thickness

Qualification of a number of similar parts = qualification by 'families'

15 29th August 2017 AIRBUS

Presented by J. van Doeselaar (Airbus) at the 2017 Joint FAA – AFRL AM Qual & Cert Workshop, Dayton, OH.

Approach and Methodology



Goals

- Gain consensus on the **part family definition**
- **Develop a guideline** to implement a part family approach for Qualification and Certification
- **Implement the guideline** on a real case study
- **Technology transition** to the companies supporting ASTM
- **Draft standard** to be created

State of the Art and Literature Findings

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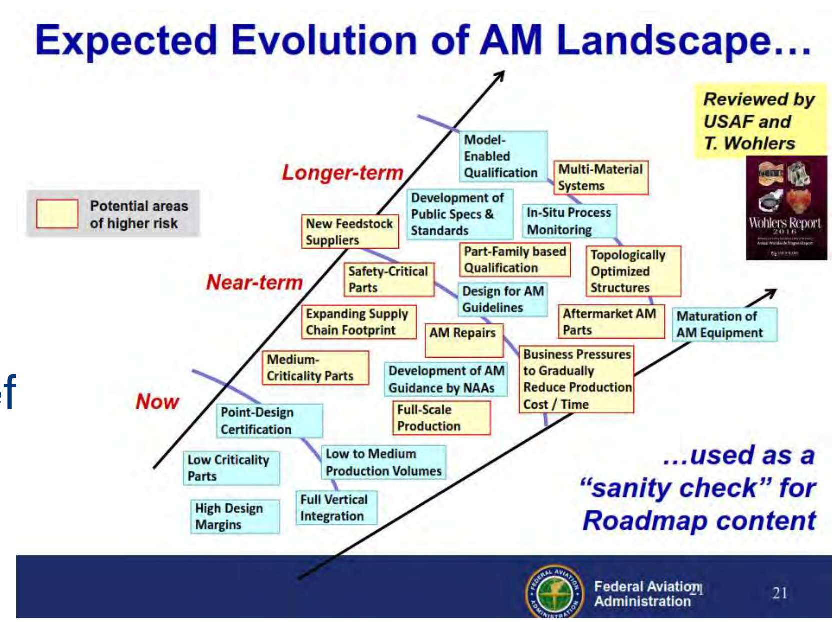
- *40 scientific published papers, conference proceedings, books, and technical reports were reviewed*
- *The concept of Part Family is investigated in terms of:*
  - *Production planning*
  - *Design optimization*
  - *Implementation of group technologies approaches*
- Some guidelines are available on the part family qualification and certification approach, but they are brief
- **Stakeholder input has therefore been key to this project**

Key take-away

*We have not identified **any scientific paper** on the Part Family approach for qualification and certification of Additive Manufactured products*



Literature Findings - Symposiums, Workshops and Conferences

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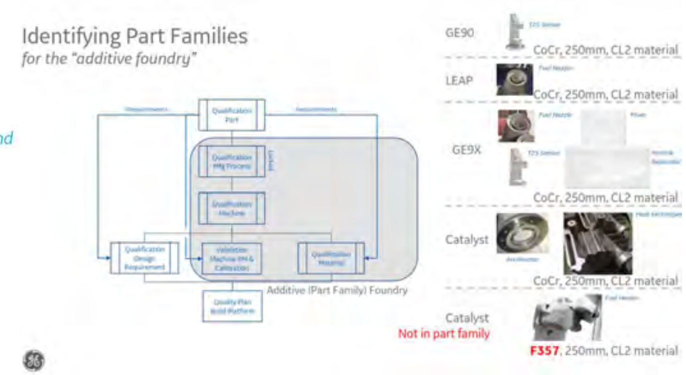
ADDITIVE MANUFACTURING

- Prior to standardized approaches, companies are moving away from a point design approach for some applications

What is in a Part Family?

Repair – AC No: 33-9 (e.g. HPT, LPC, HPT, Combustor, Externals...)
Quality – GE S1002, *"A group of parts with similar processes, materials, complex form, and tolerances, which have been produced by similar manufacturing methods"*
Material – GE Design Practice (Part type, Part criticality, Material property)
Design – GE Design Practice (Part criticality)
Supply Chain (Sustainment) – Part Qualification (Machine, Material, Process)
Certification – Part Certification (Type, Material, Criticality)
Industry – Standard (Part type, Part criticality, Material, Material Basis, Process, Part Feature, Tolerances, Anomalies Allowables...)



ASTM F3572

Part Family Considerations...

No Common Definition of Criticality Levels... *FAA, EASA, USAF, NAVAIR, TCHs*
- *Certification considerations... criticality, part type, material*
- *Process Agnostics... not unique to AM*

Many "Part Family" Definitions... *this is OK, but can be confusing*

Certification: Basis of evaluation has not changed
Supply Chain: based on process, is useful for economic manufacturing

GE - Joint FAA – EASA Workshop 2018

Aerospace OEM's are ***already*** *implementing their* ***approach*** *to part families*

State of the Art - Literature Findings

What can we leverage from composites ?

Material
All parts within a family must have the same material.

Infill
All parts within a family should have the same infill characteristics in the additive substructure.

Part complexity
Parts should be grouped into families by complexity.

Manufacturing process
A family must consist of all parts manufactured the same way.

Compaction cycles
Manufacturing driven compaction cycle frequency will differentiate part family candidates.

Cure cycles
If the composite face-sheets require different cure cycles, the parts will be in different part families.

Part size
Part size is also a differentiator for the part family. Parts of drastically different sizes should be grouped in separate part families.

Tooling concepts
Parts within a family should be tooled the same way with the same type of tooling.

Post processing
While post processing of parts will be similar, if any unique steps are necessary to produce a part that step is sufficient to drive a new part family.

Inspection method
Parts that are quality inspected using different methods are grouped in different families.

Stakeholders Engagement - Prioritization

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Focused Engagement through Advisory Board, workshops, 1-2-1 interviews, presentations

Priority
High
Medium
Low

Part family definition and design

Item	Priority
Definition of Part Family	High
Material Design Allowable	Medium
Part Classification and Criticality	High
Geometric Features and Wall Thickness	Medium
Applications	High

Manufacturing

Item	Priority
KPV	High
Quality System Documentation	High
Supply Chain	Medium
Machinery and Facility Layout	Low
AM Technologies	Medium

Qualification and Certification

Item	Priority
Master Part Q&C	High
Family Part Q&C	High
Suppliers Qualification	Medium
Machine to Machine Variation	High
Cost Reduction	Low

Post processing and NDE

Item	Priority
Defects Allowable	High
NDE and Inspections	High
In-Situ Monitoring	Low
Tooling and Jigs	Medium
Manual Operations	Medium

Main Results – Part Family Document

ASTM INTERNATIONAL

Best Practices for Additive Manufacturing Part Families relating to Product Qualification & Certification

Submitted By:
ASTM International
100 Barr Harbor Drive
West Conshohocken, PA 19428

America Makes Project Deliverable
Project ID:5001.002.002.003

ASTM Project PI
Martin White
E-mail: mwhite@astm.org

May 27, 2022

- **Inputs of more than 15 Industry Experts**
- **Based on focused consensus**
- **Not tied to any Industry Sector or Application**
- **Definition and implementation of a Part Family**
- **Set the basis for future standardization → Registered Work Item WK81194**
- **Methods implemented in a case study**

Main Results – Project Deliverables

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Part Family Definition:

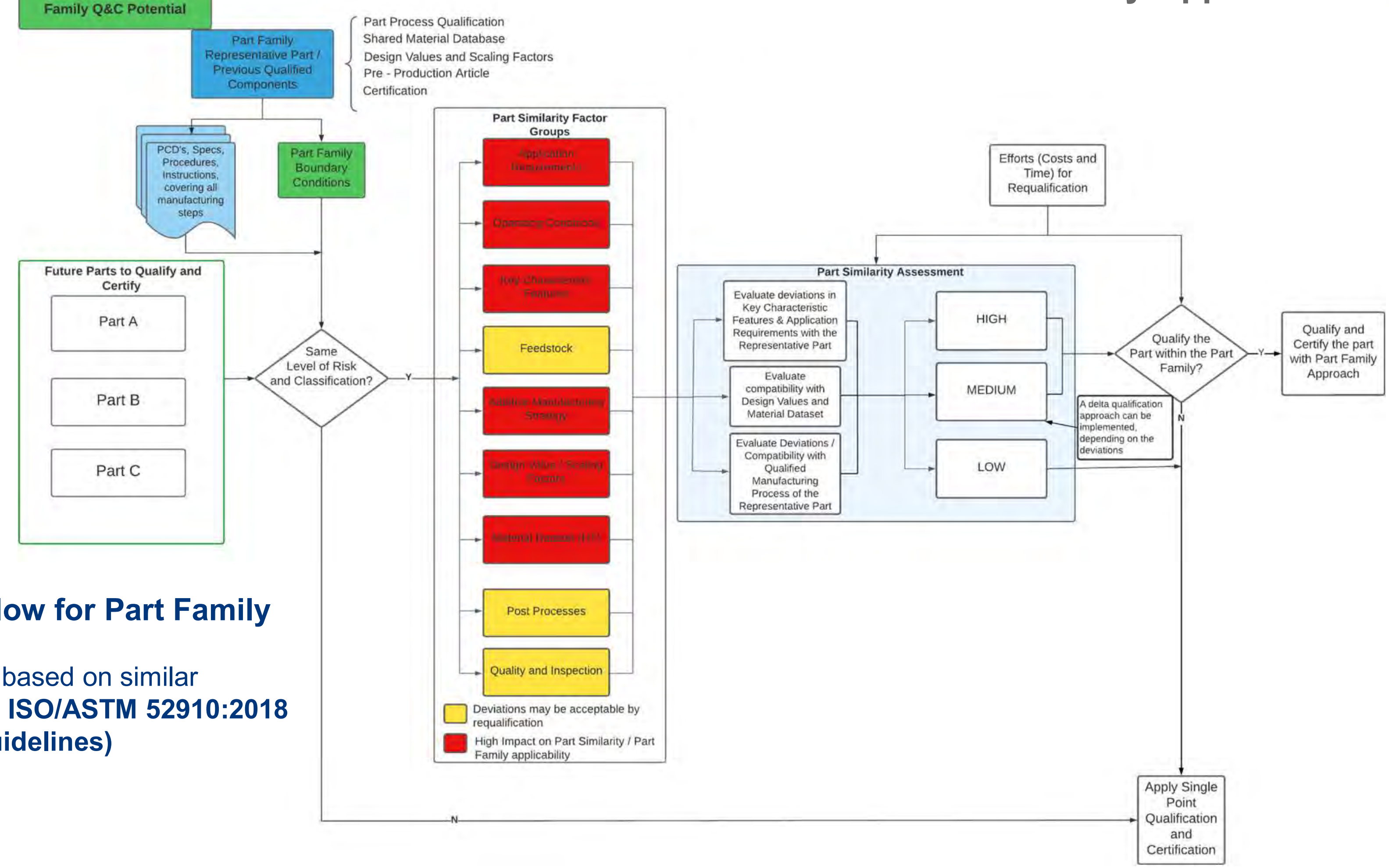
The Part Family consists of a defined group of AM products presenting the same level of risk and application, same ranges of physical features and manufacturing requirements such that they can be qualified and certified sharing a set of data and processes.

Terminology:

- **Similar:** Compatible ranges of quantifiable part features and manufacturing process attributes
- **Same:** Equivalent
- **Physical Features:** Product attributes that can be quantified including geometric features and material properties, or in general any quantifiable features that primarily influence its performance when in service.

Main Results – Project Deliverables

Framewor ntial Part Family Opportunities

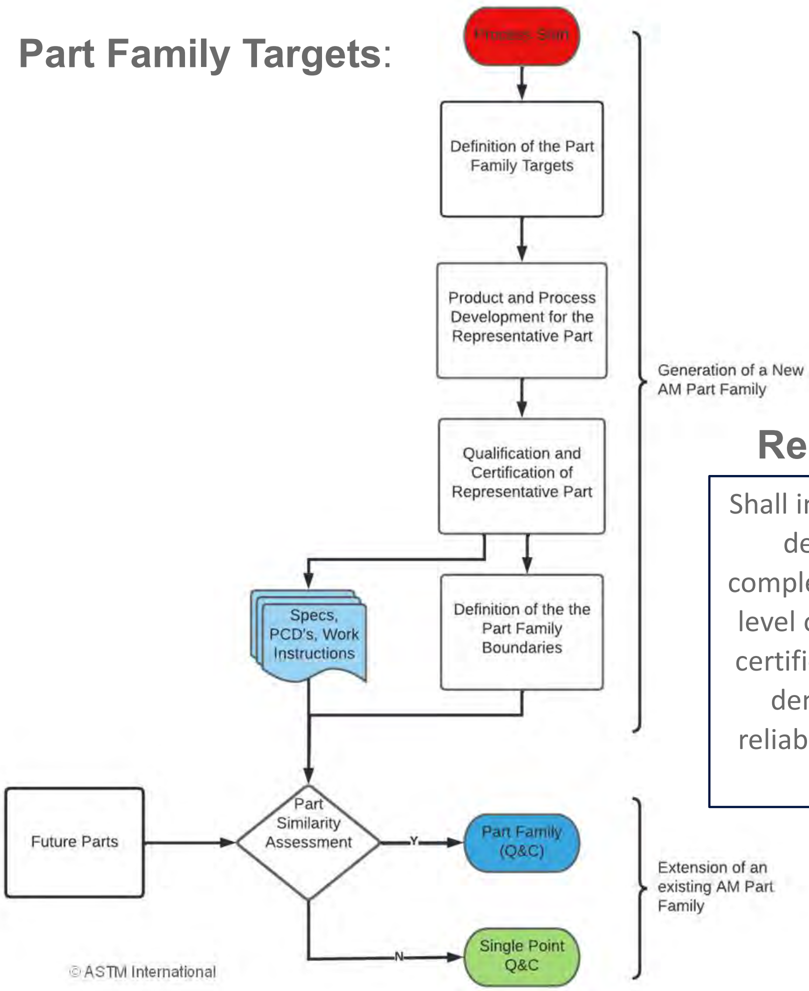


Logic Workflow for Part Family

- Framework based on similar approach in **ISO/ASTM 52910:2018 (Design Guidelines)**

Main Results – Project Deliverables

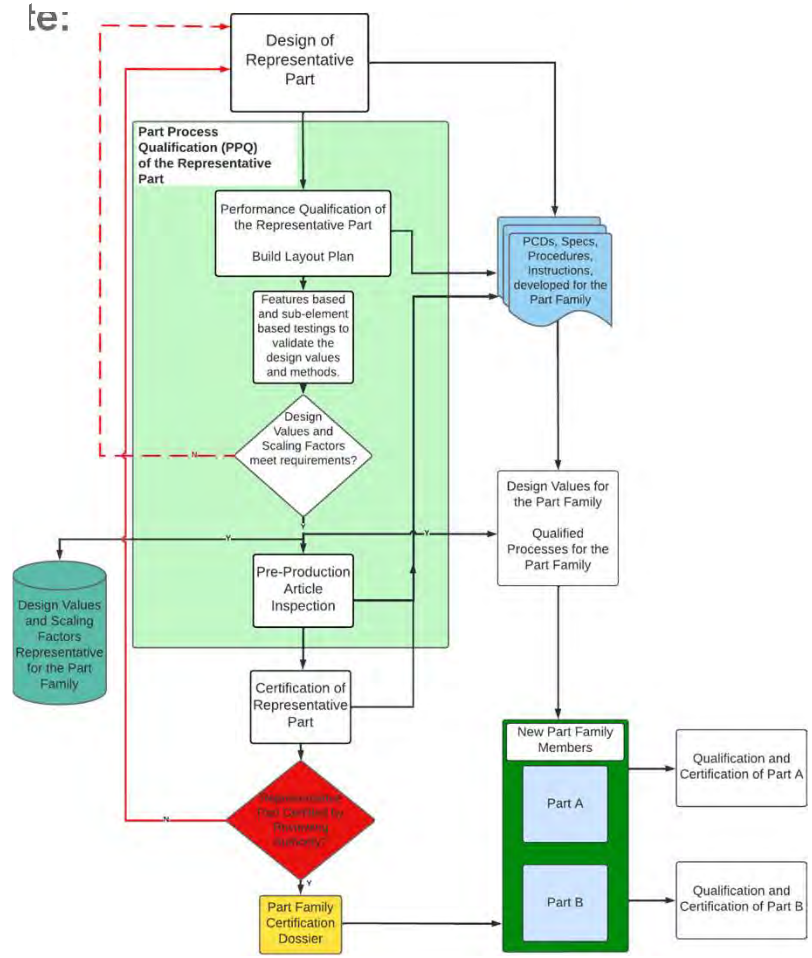
Part Family Targets:



Representative Part:

Shall introduce the highest level of design and manufacturing complexity and require the highest level of rigor for qualification and certification. It shall also allow for demonstrating the ability to reliably manufacture all the parts in the family.

te:



Key Technical Guidance

- **Part Family Definition**
  - Defined by consensus methods, and several iterations were required!
- **Qualification Route – Representative Part**
  - Qualify & Certify one (or more) part considered to be the *'reference part'*
  - Material Data & Qualified processes can then be shared with other AM parts that share 'similarities'
  - Part Family Members are then Qualified & Certified individually in a shorter time (and lower cost)
- **Part Classification – Level of Risk**
  - Part Family Approach is highly dependent on the AM Part classification
- **Assessing AM Parts Similarity**
  - Feature Based
  - Performance Based
  - Manufacturing Based

Table 4 Summary of the part design attributes variations to apply within an AM part family.

Attribute	Conditions to apply within an AM Part Family						
	Low-Risk Application			High-Risk Application			Applicable for different AM processes
	Remain Fixed	Variations Possible without Requalification	Variations Possible with Requalification	Remain Fixed	Variations Possible without Requalification	Variations Possible with Requalification	
Wall Thickness			●			●	YES
Aspect Ratios		●				●	YES
Un - Supported Overhangs		●				●	YES
Internal Part Cavities		●				●	YES
Part Size		●				●	YES

Example Table from the guide, focusing on part design attributes

Case Study

- An industrial case study was **not** found after engaging with multiple groups & stakeholders
- ASTM AM CoE technical team generated a pseudo case study application on a family of ‘typical’ AM Ti64 brackets
- Focused on the AM parts similarity assessment:
    - a simplified example of how an organization may implement a tool to assess the similarity of three brackets

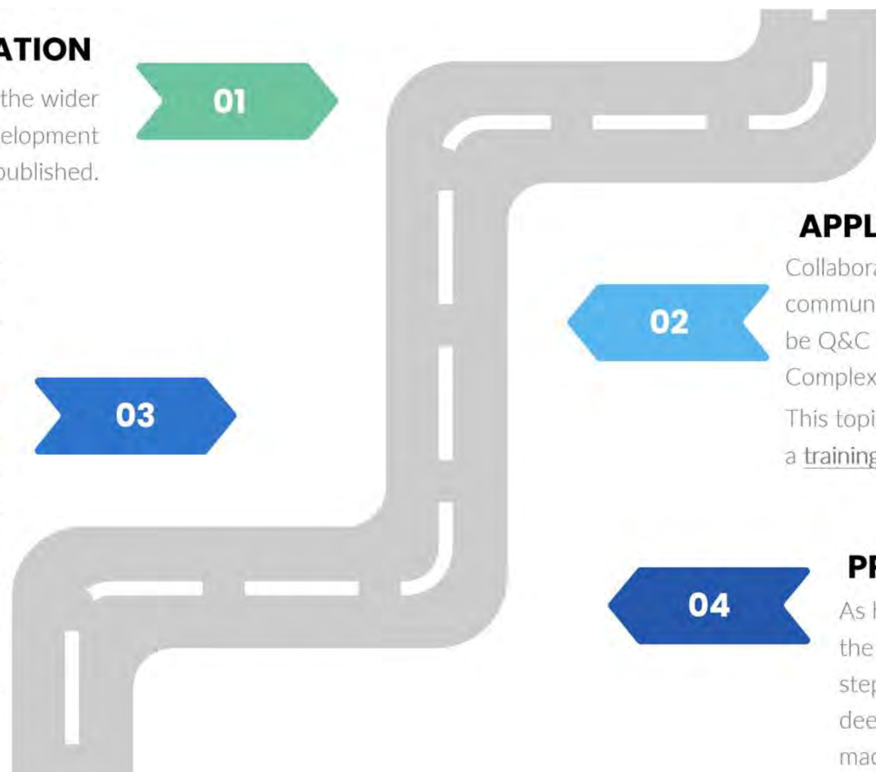
https://ati.mydigitalpublication.co.uk/publication/?i=685795&article_id=3832385&view=articleBrowser&ver=html5

https://www.materialsforengineering.co.uk/engineering-materials-features/the-long-road-to-qualification/86548/

- **Tool available on America Makes Storefront**

Conclusions

- **Best practices based on industry expert inputs n presented**
- **Further interaction with Industry stakeholders is needed to find consensus** – good initial engagement
- The best practices should be tested on real industrial case studies to be validated



01

CONSENSUS -> STANDARDIZATION

Best Practice Guide will be reviewed by the wider community as part of the Standard Development process, leading to a Standard being published.

02

APPLICATION & TRAINING

Collaborate on a *real* case study for further value to the community. Suggest considering components that may be Q&C through performance, such as Heat Exchangers. Complex lattice structures could be considered.

This topic, plus case study, would be a strong option for a training course.

03

EXPAND CONCEPT

The Best Practice Guide could be expanded to further advise on how to design for PF, or additional considerations to support procurement perspectives.

Specific guidance for other AM modalities could be included (i.e. are there specifics to DED?), as well as deeper consideration of industry specific requirements.

Can we collaborate as a community to create shared material databases to ease Q&C PF burden through equivalency?

04

PROCESS QUALIFICATION

As highlighted in this project, the industry sees the implementation of Part Family methods as a step towards the Process Qualification, based on deeper understanding of the process and machine agnostic physics-based models.

Thank you – Please Get Involved!

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Research to Standards
ADDITIVE MANUFACTURING

27 symposia

10+ live panel discussions

550+ presentations

6 Keynote addresses

Short Course Training

Standardization

- Work Item is registered – **WK81194**: New Standard Additive Manufacturing -- Qualification Principles -- Part Families-based Qualification in AM
- Key contact is **Amit Chatterjee**
- **ac@wohlersassociates.com**

Organized by:

U.S. COMMERCIAL SERVICE
United States of America Department of Commerce

ASTM INTERNATIONAL

ISO International Organization for Standardization

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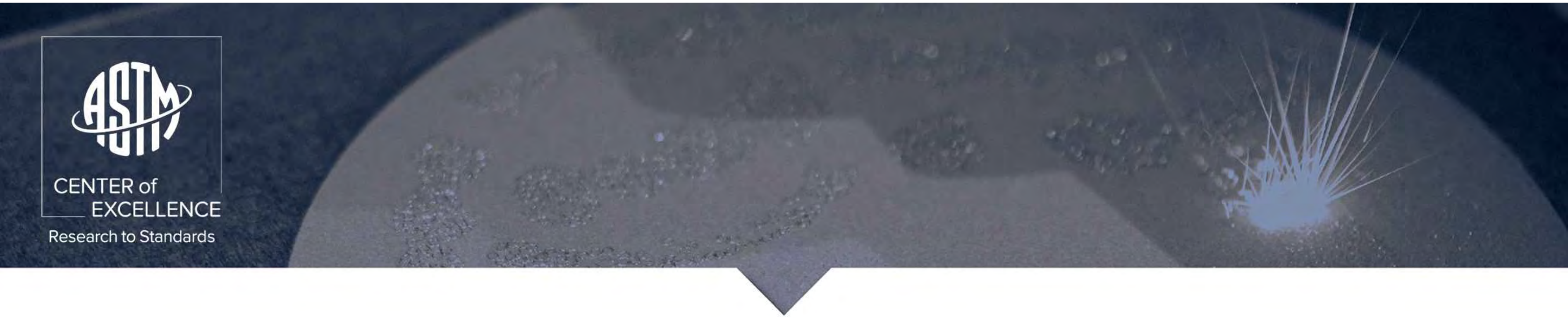
Dr. Alberto Bordin
abordin@astm.org



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Thank You

www.amcoe.org

Appendix Q

“Methods for Zoning AM Components Using Machine Learning” – M. Groeber (OSU)

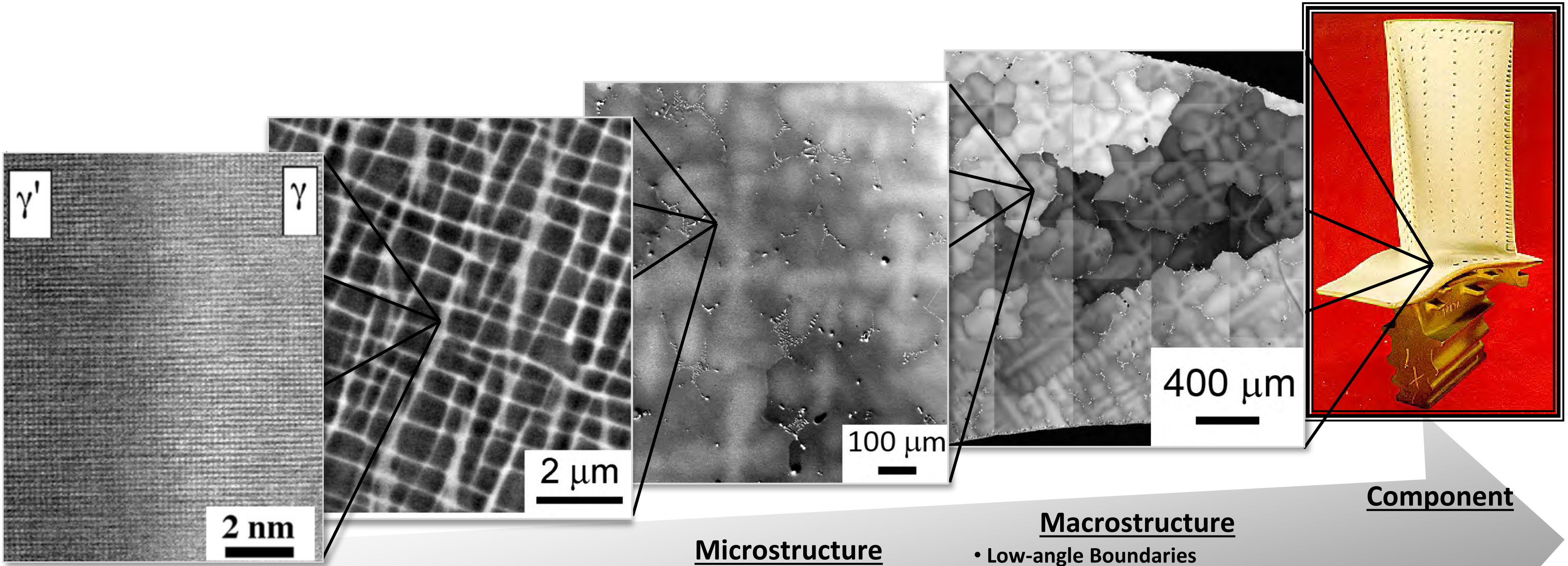
Zoning Processing Spaces for Additive Manufacturing: Applications for Inverse Design

Michael Groeber[a], Sean P. Donegan[b], Edwin Schwalbach[b], Matthew Krug[b]

FAA-EASA Workshop

[a] Ohio State University
[b] Air Force Research Laboratory

Bridging Length Scales



Atomic Structure
- Crystal Structure
- Interface Structure

Nanostructure
- g' Precipitates

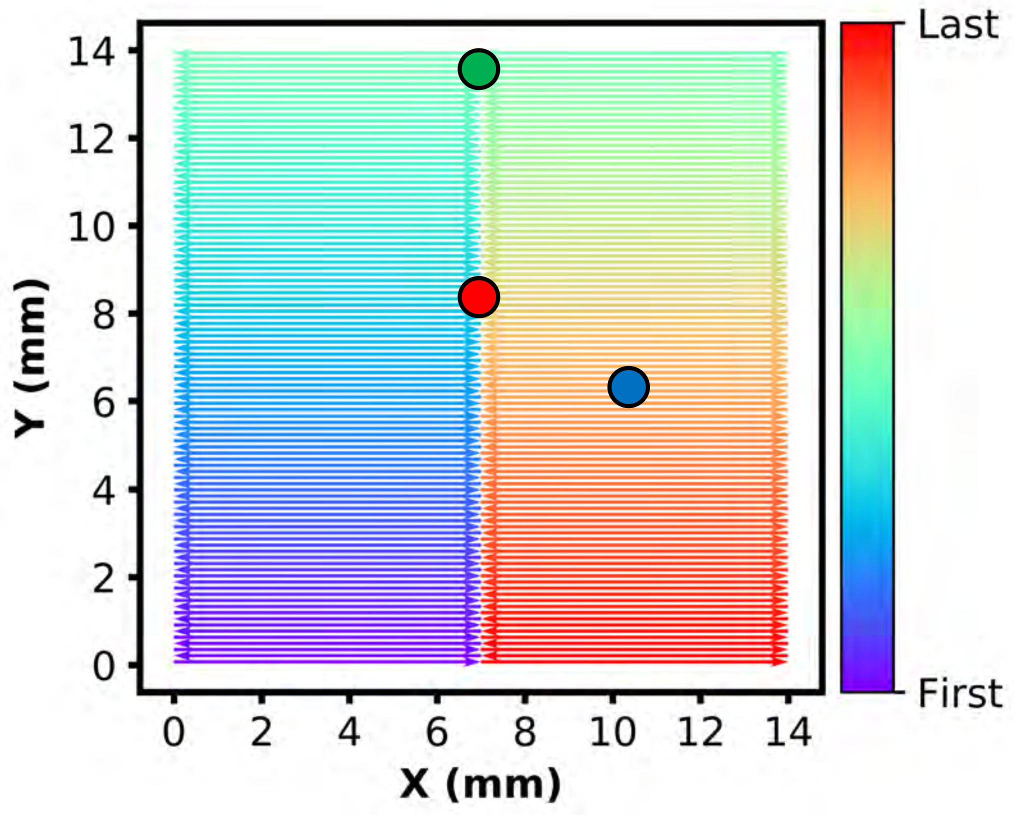
Microstructure
- Secondary Dendrites
- Eutectic Phases
- Micro-porosity
- Carbides
- Micro-segregation

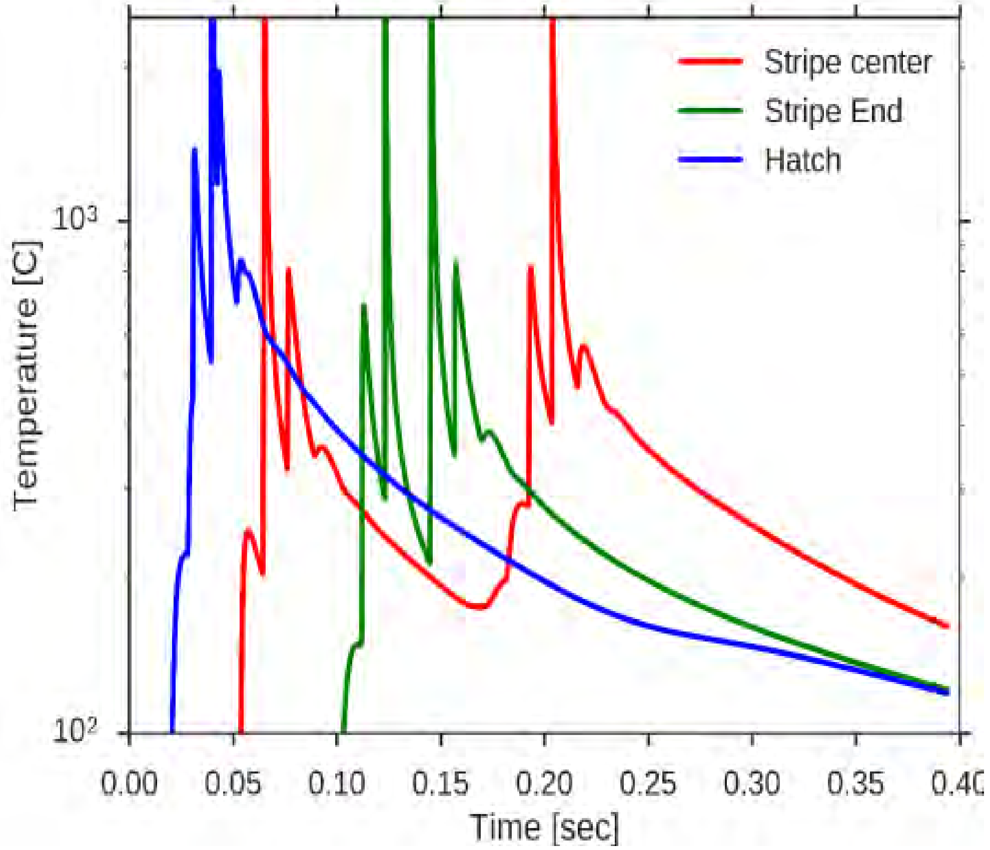
Macrostructure
- Low-angle Boundaries
- Primary Dendrites
- Freckles/Stray Grains
- Macro-segregation

Component

Process State as Thermal History

Donegan, Sean P., Edwin J. Schwalbach, and Michael A. Groeber. "Zoning additive manufacturing process histories using unsupervised machine learning." *Materials Characterization* 161 (2020): 110123.





- Want a representation of process state that best captures the ***latent variables*** that impact resulting microstructure
- Here we use ***thermal history***, which abstracts component geometry & scan strategy → allows for comparisons within a single component, between different components, and across different builds

Discrete Source Model

Assumptions: Conduction only, semi-infinite body with uniform diffusivity, constant thermal properties, uniform initial temperature

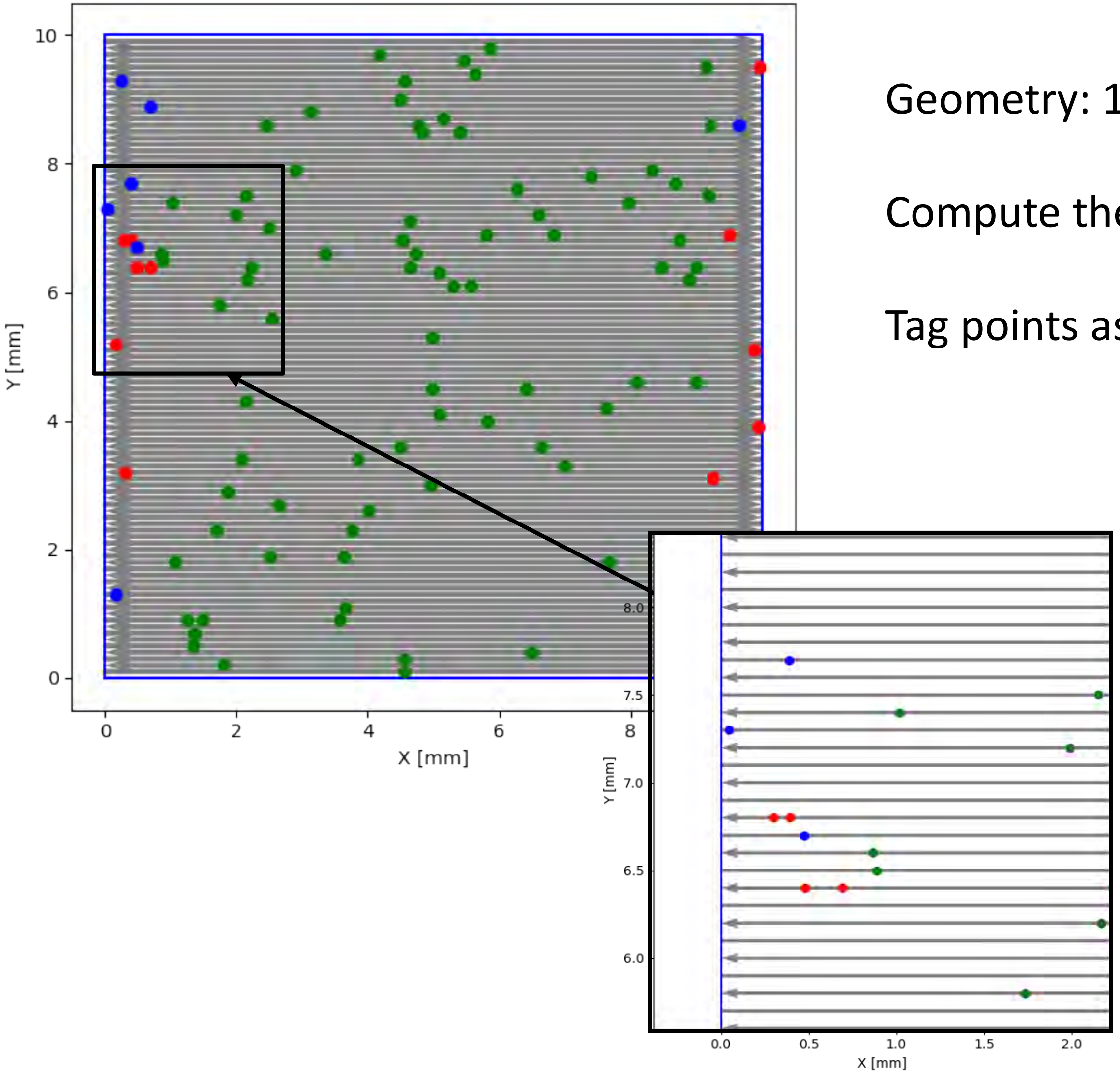
$$\frac{\partial T}{\partial t} - \alpha \nabla^2 T = f(\vec{r}, t) = \sum_i^N \frac{2 P_i \Delta t}{\rho c_p} \frac{1}{(2\pi\sigma^2)^{3/2}} \exp\left[-\frac{(\vec{r} - \vec{r}_i)^2}{2\sigma^2}\right] \delta(t - \tau_i)$$

T = Tempertaure (change)
P_i = effective laser power
$\vec{r}_i$ = source i position
$\vec{r}$ = solution location
σ = Gaussian spot size
τ_i = source i activiation time
ρ = density (const.)
c_p = heat capacity (const.)
α = diffusivity (const.)
Δt = time discretization

$$T(\vec{r}, t) = \sum_i^N \frac{P_i \Delta t\, \Theta(t - \tau_i)}{\rho c_p \sqrt{2} \left[\pi\left(\sigma^2 + \underbrace{\boxed{2\alpha(t - \tau_i)}}_{\text{time cutoff}}\right)\right]^{3/2}} \exp\left[\underbrace{\boxed{-\frac{(\vec{r} - \vec{r}_i)^2}{2\sigma^2 + 4\alpha(t - \tau_i)}}}_{\text{distance cutoff}}\right]$$

Edwin J. Schwalbach, Sean P. Donegan, Michael G. Chapman, Kevin J. Chaput, Michael A. Groeber. A discrete source model of powder bed fusion additive manufacturing thermal history. *Additive Manufacturing* **25** (2019) 485–498. https://doi.org/10.1016/j.addma.2018.12.004

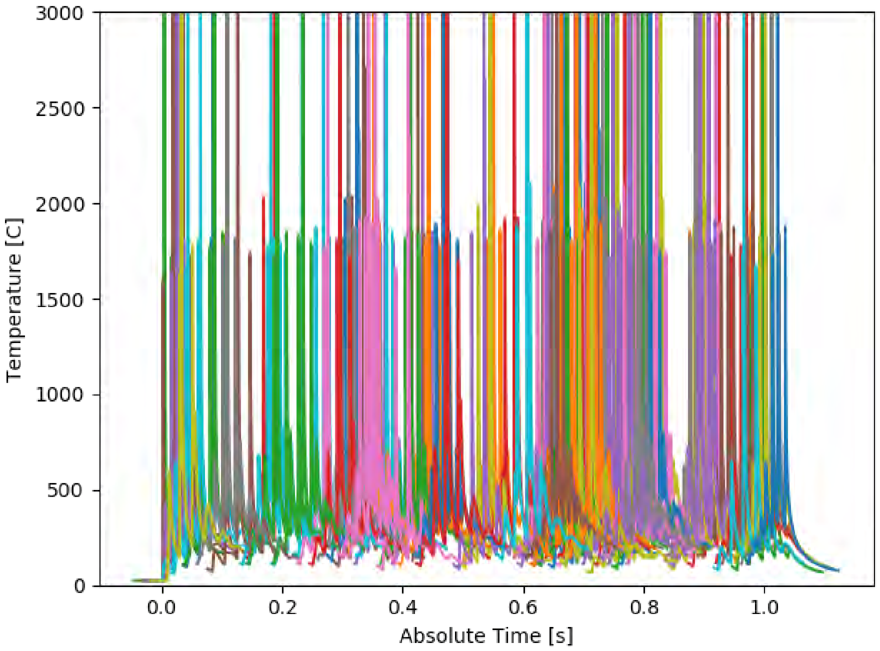
A “Simple” Example



Geometry: 10mm x 10mm square, standard “snake” scan strategy

Compute thermal histories at N points that lie directly on scan vectors

Tag points as being at the ***start***, ***middle***, or ***end*** of a vector



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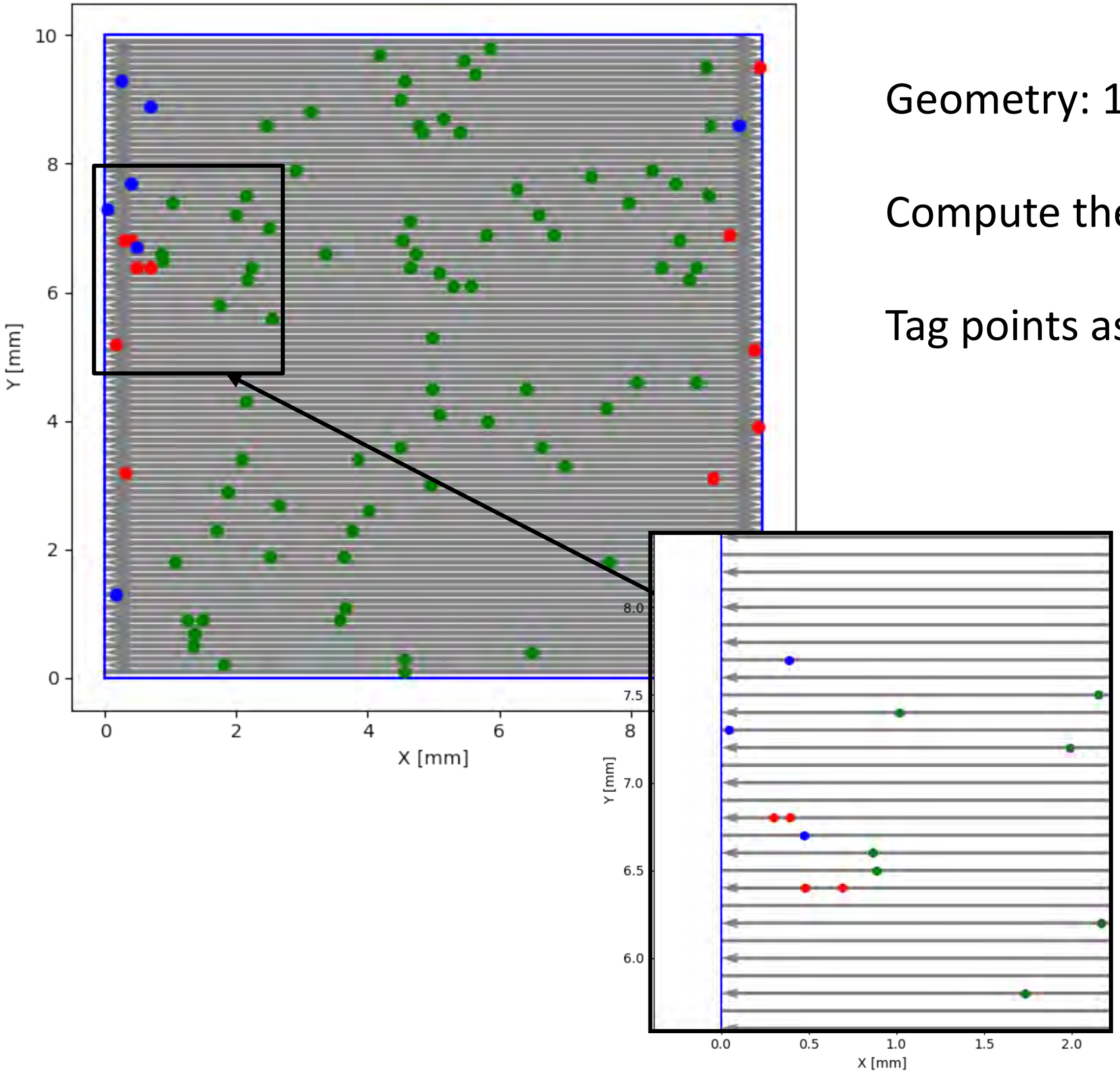
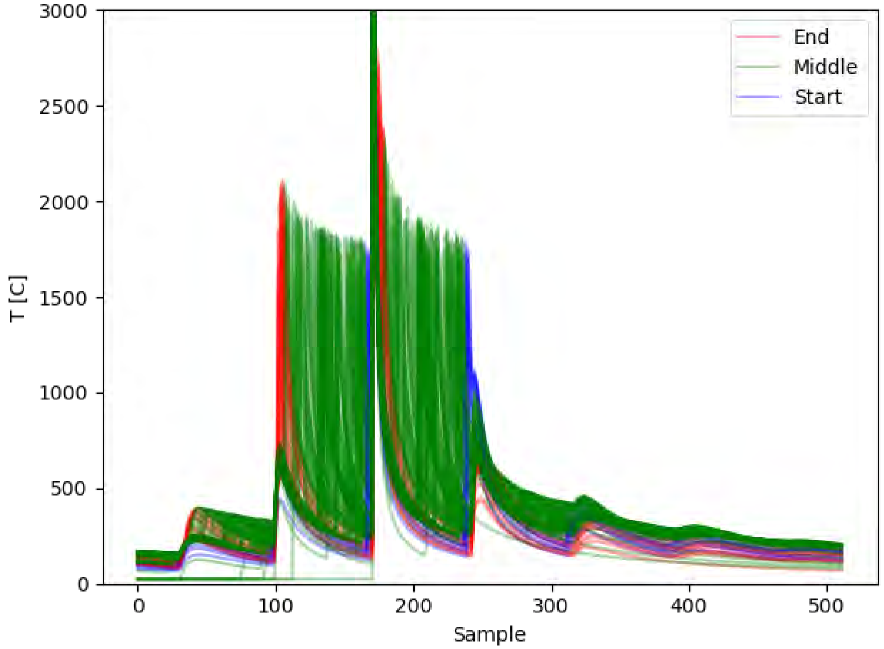
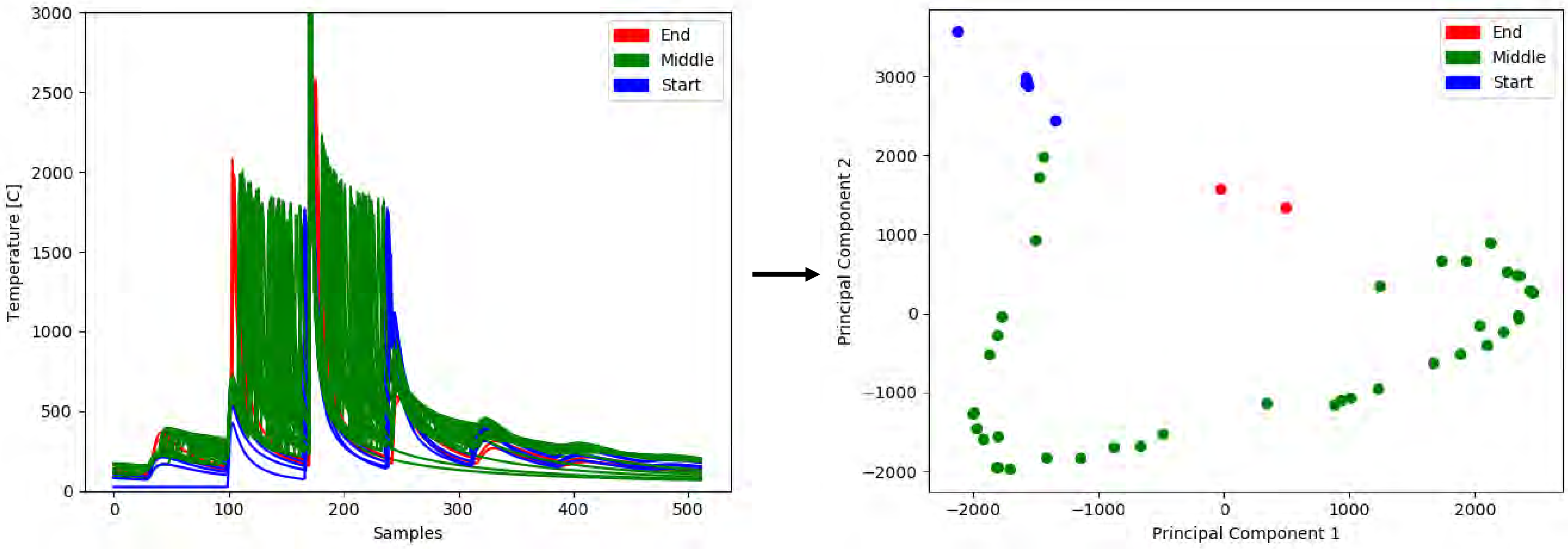




Dimensionality Reduction

*Dimensionality reduction transforms data **X** in **D** dimensions to data **Y** in **d** dimensions, where **D** >> **d**, such that the "shape" of the data is nearly preserved*



Principal Component Analysis

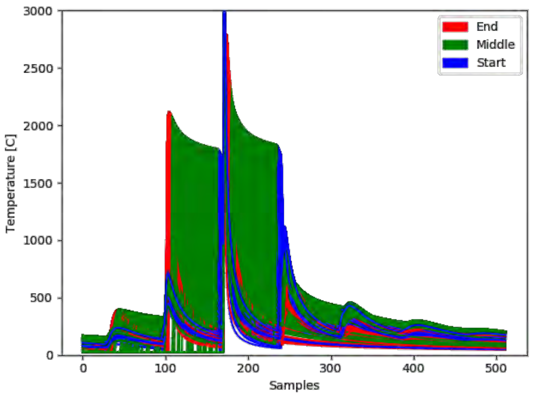
PCA seeks to find a linear basis that projects a data space into a lower dimensionality such that the variance is maximal

Find ***M*** such that:

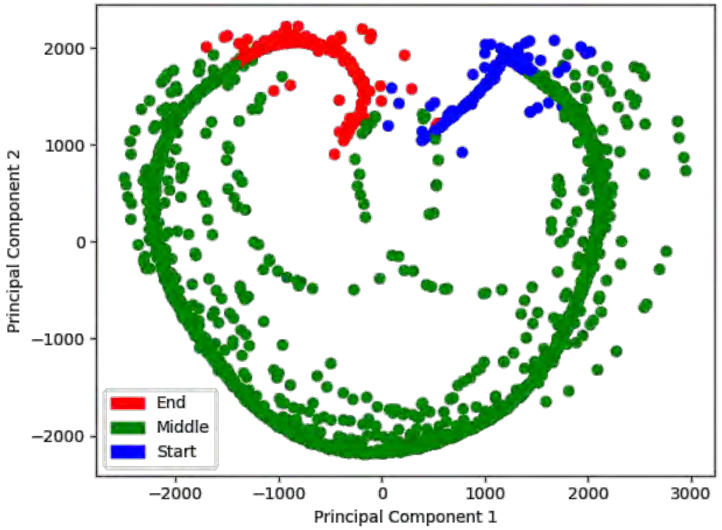
$$\max(\mathrm{trace}(\boldsymbol{M}^T \mathrm{cov}(\boldsymbol{X})\boldsymbol{M}))$$

where cov(***X***) is the sample covariance matrix of the data. The mapping is then formed from the eigenvectors of cov(***X***):

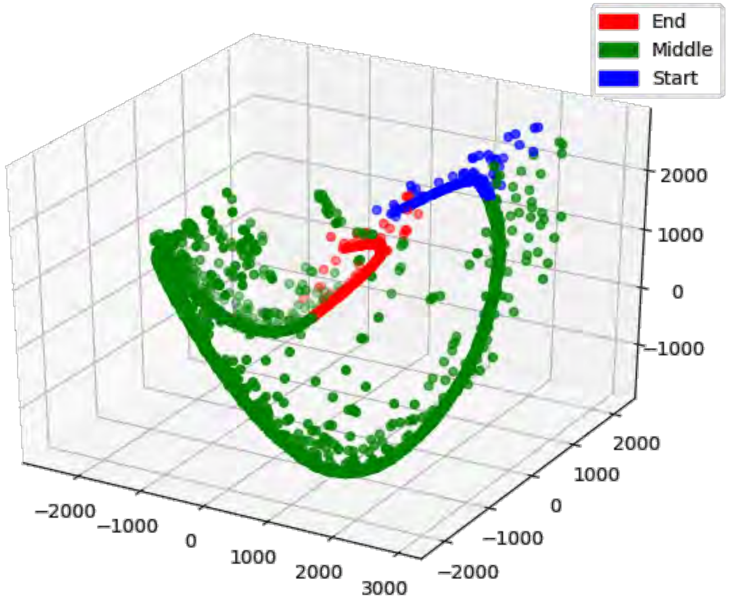
$$\mathrm{cov}(\boldsymbol{X})\boldsymbol{M} = \lambda \boldsymbol{M}$$



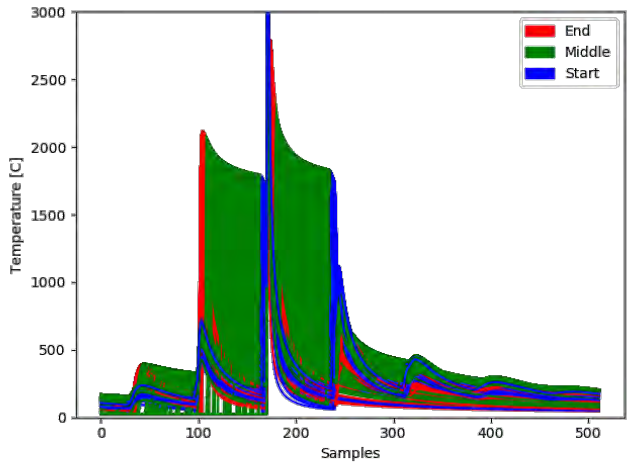
d = 2

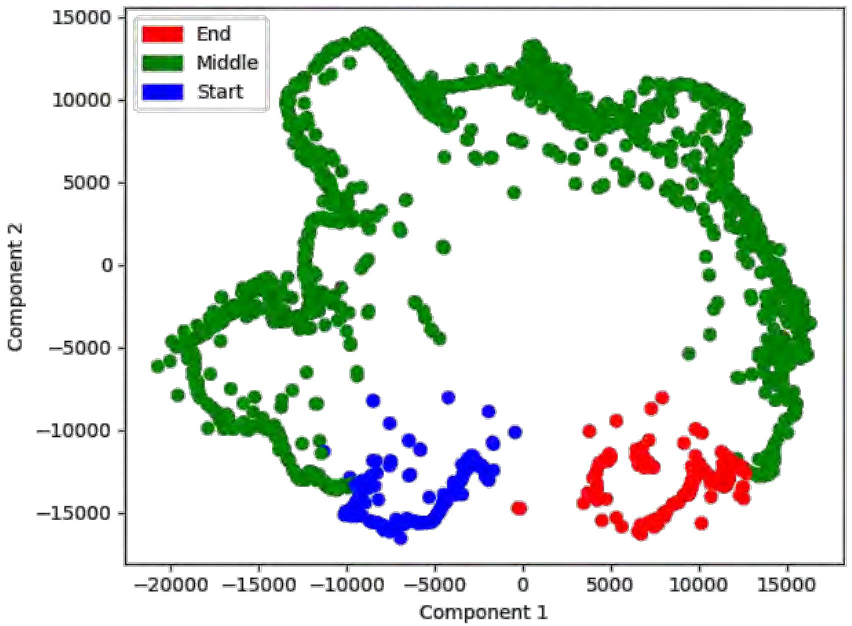


d = 3

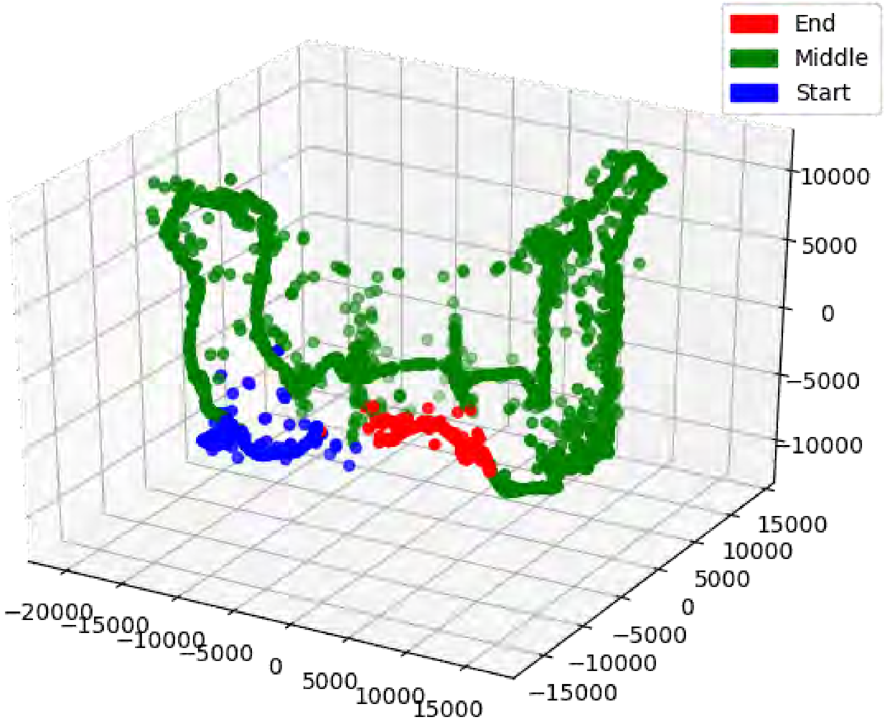


Isomap


3000
2500
2000
1500
1000
500
0
Temperature [C]
0
100
200
300
400
500
Samples
End
Middle
Start


15000
10000
5000
0
−5000
−10000
−15000
Component 2
−20000
−15000
−10000
−5000
0
5000
10000
15000
Component 1
End
Middle
Start

d = 2


End
Middle
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10000
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15000
10000
5000
0
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−10000
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−20000
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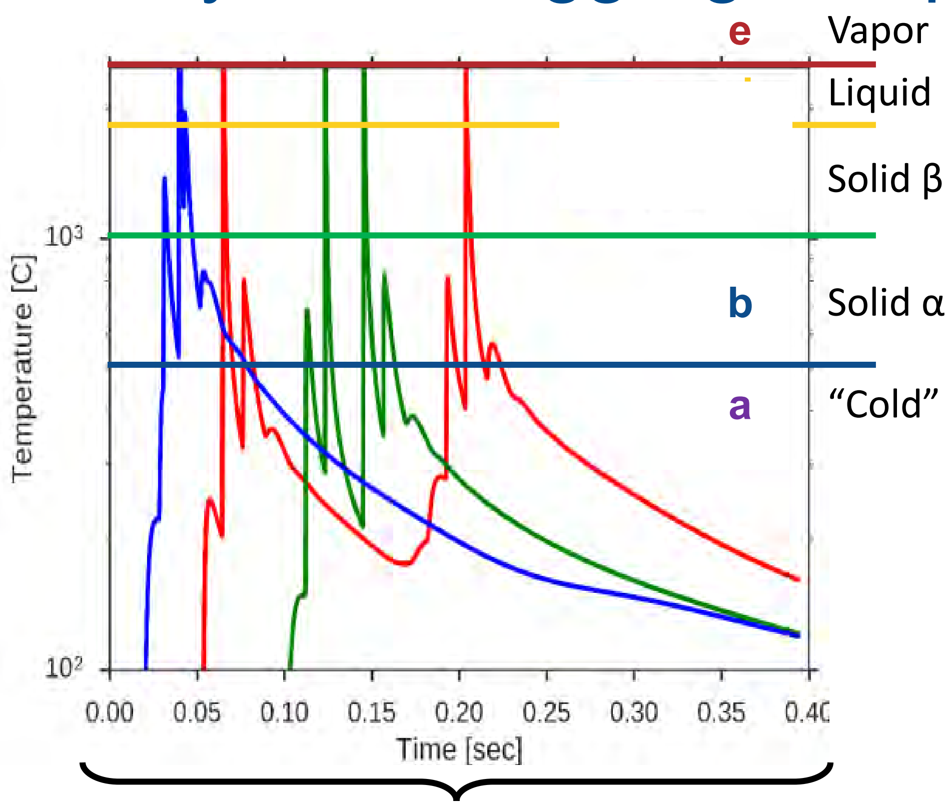
−10000
−5000
0
5000
10000
15000

d = 3

Symbolic Aggregate approXimation (SAX)

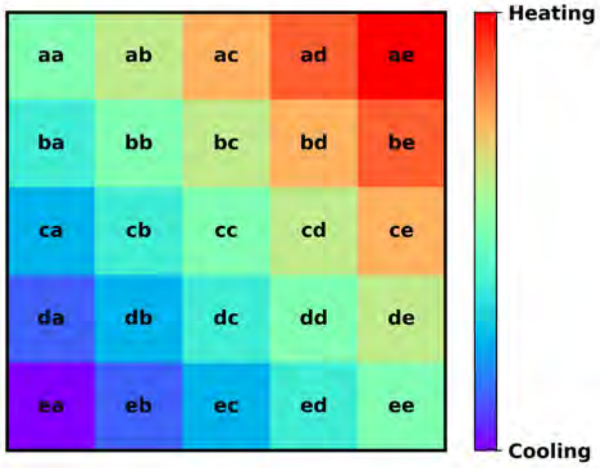


aabcdeddccccbbbbbbaaaaaaaaaaaaaabbbcc

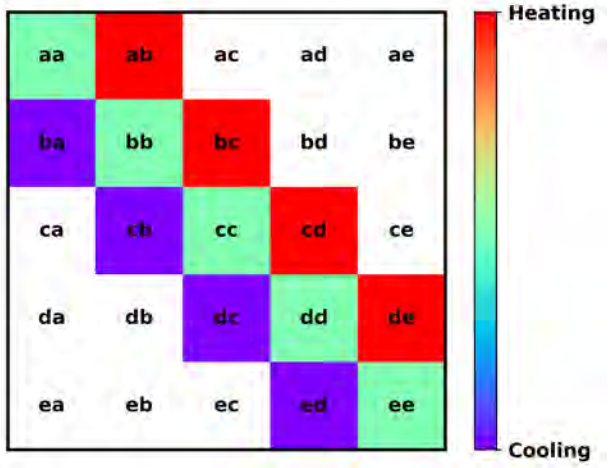
aaaaaaaabcdeddcccaaaaaabcdedddccccbdccc

aaaaaaabcdeddcccaaaaaabcdedddccccbaaaaa

Frequencies of "subwords"



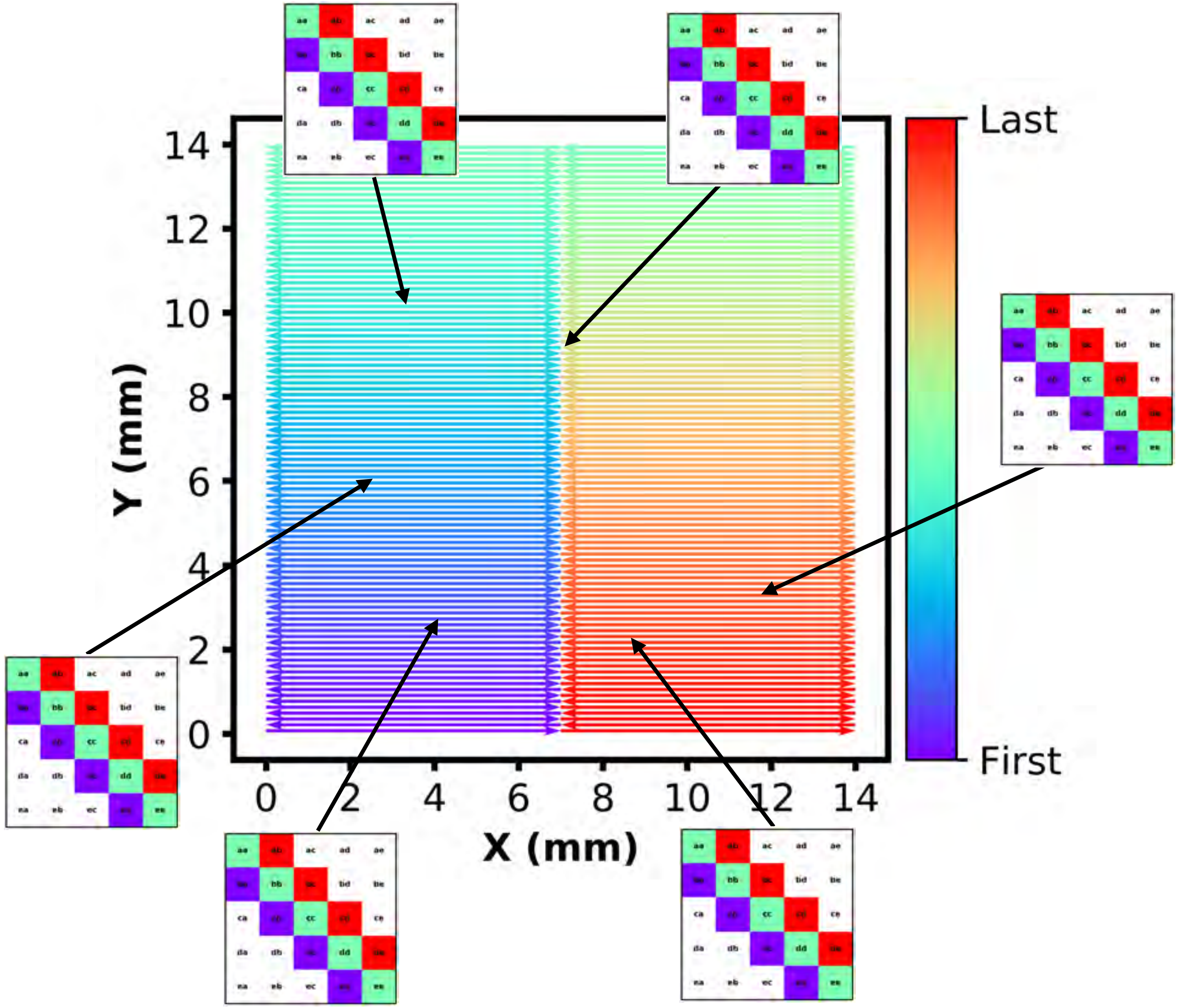
Final 13-dimensional feature vector



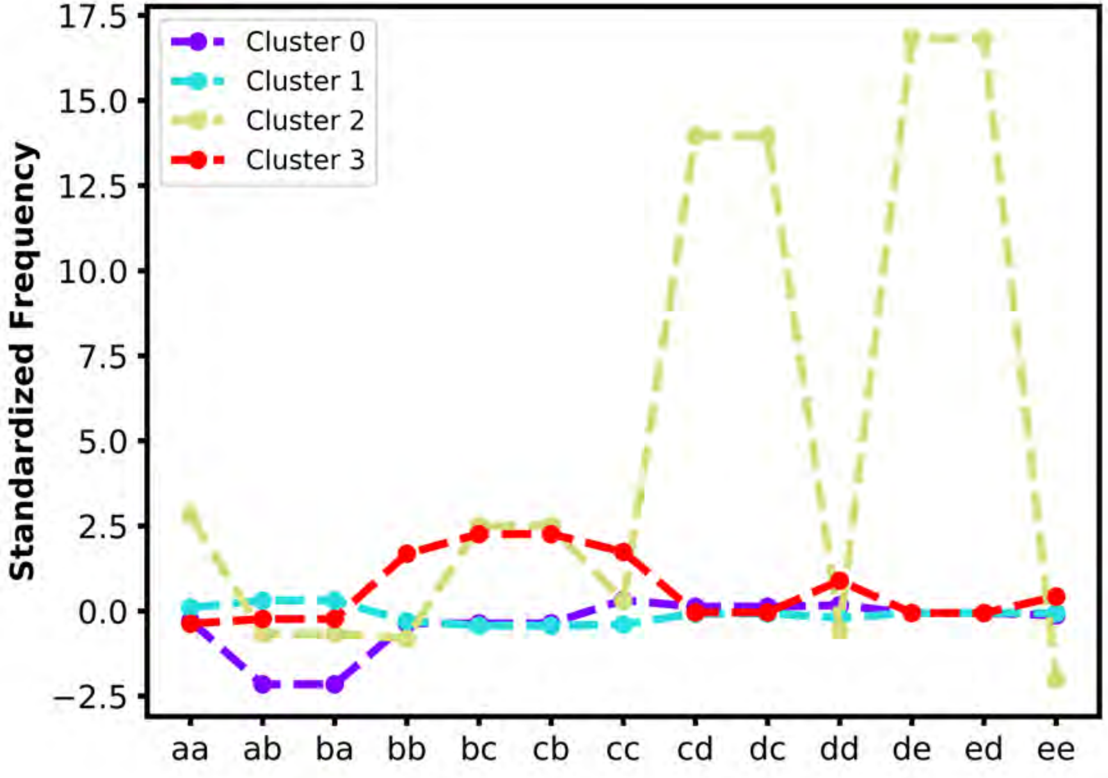
- Differences from original SAX:
  - X (time) is not binned further than simulation time step → simulation output is treated directly as piecewise aggregate
  - Y (temperature) is binned at specific (mostly phase transition) temperatures, not equiprobable
  - Artificial "increase" to time resolution (treating thermal history as continuous function) → certain heating transitions become empty

J. Lin et al., *Proc. 8th ACM SIGMOD Workshop*, 2-11, 2003

Zoning SAX Representations

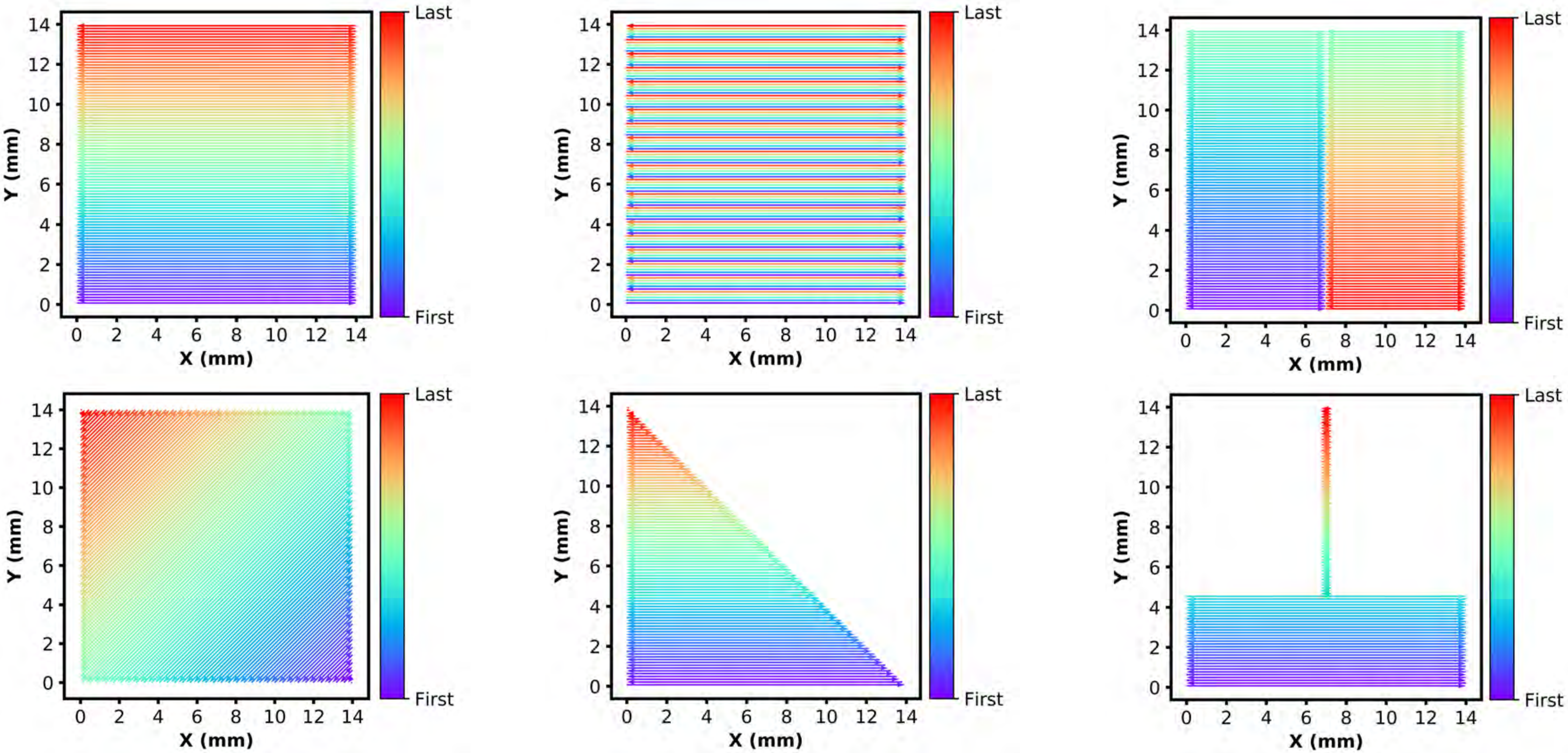


Cluster 13-dimensional feature vectors using *k*-means

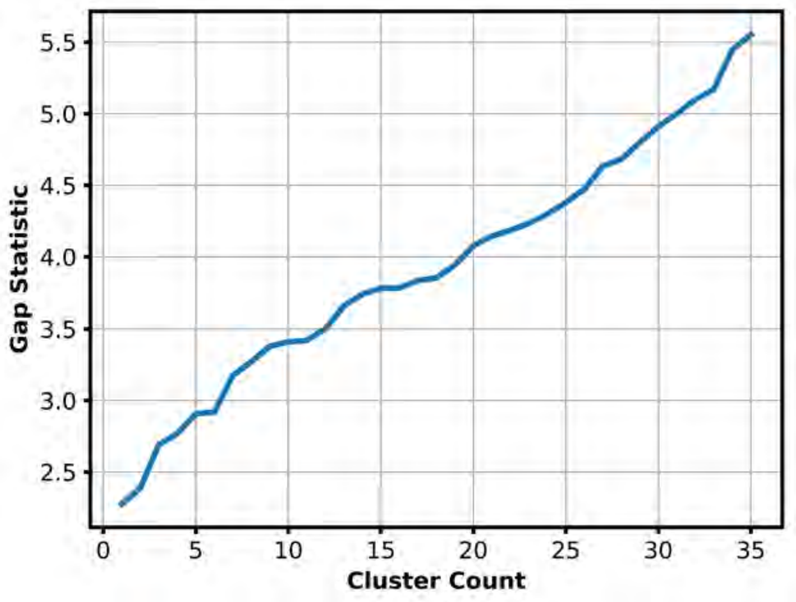


$$\min_{C} \sum_{i=1}^{k} \sum_{x_i \in c_k} \|x_i - \mu_k\|^2$$

Example Geometries



Determining Number of Clusters

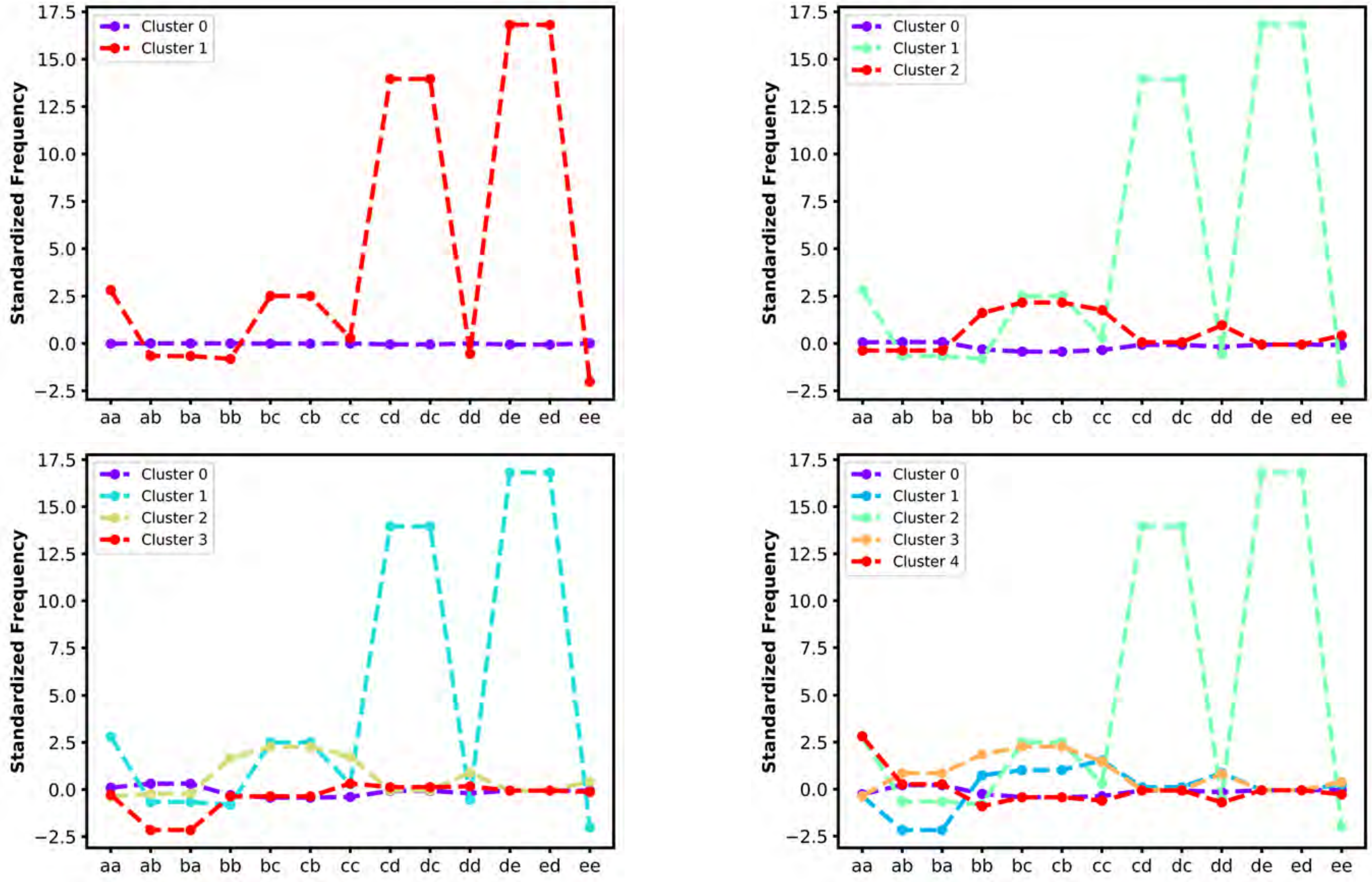


- Number of clusters is an important parameter for algorithms such as *k*-means
- Attempted to optimize number of clusters using gap statistic:

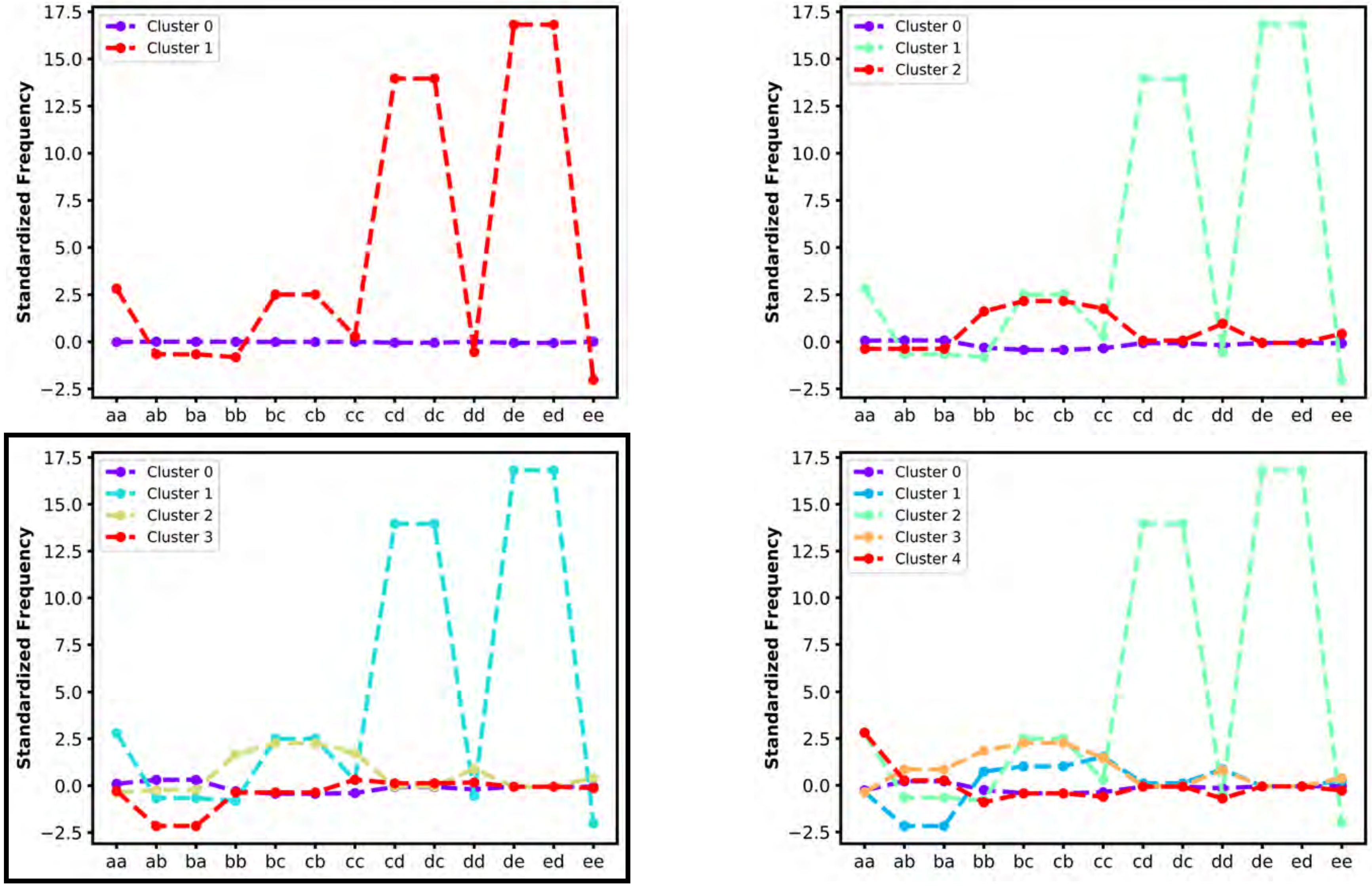
$$\text{Gap}(k) = \mathrm{E}[\log W_k] - \log W_k$$

- Choose *k* where $\max\big(\text{Gap}(k)\big)$ over some range of *k*
- Estimate $\mathrm{E}[\log W_k]$ by taking the mean of 5 reference distributions
- Over *k* = [1, 35], $\text{Gap}(k)$ monotonously increases → reflects continuity of thermal history space

Determining Number of Clusters



Determining Number of Clusters

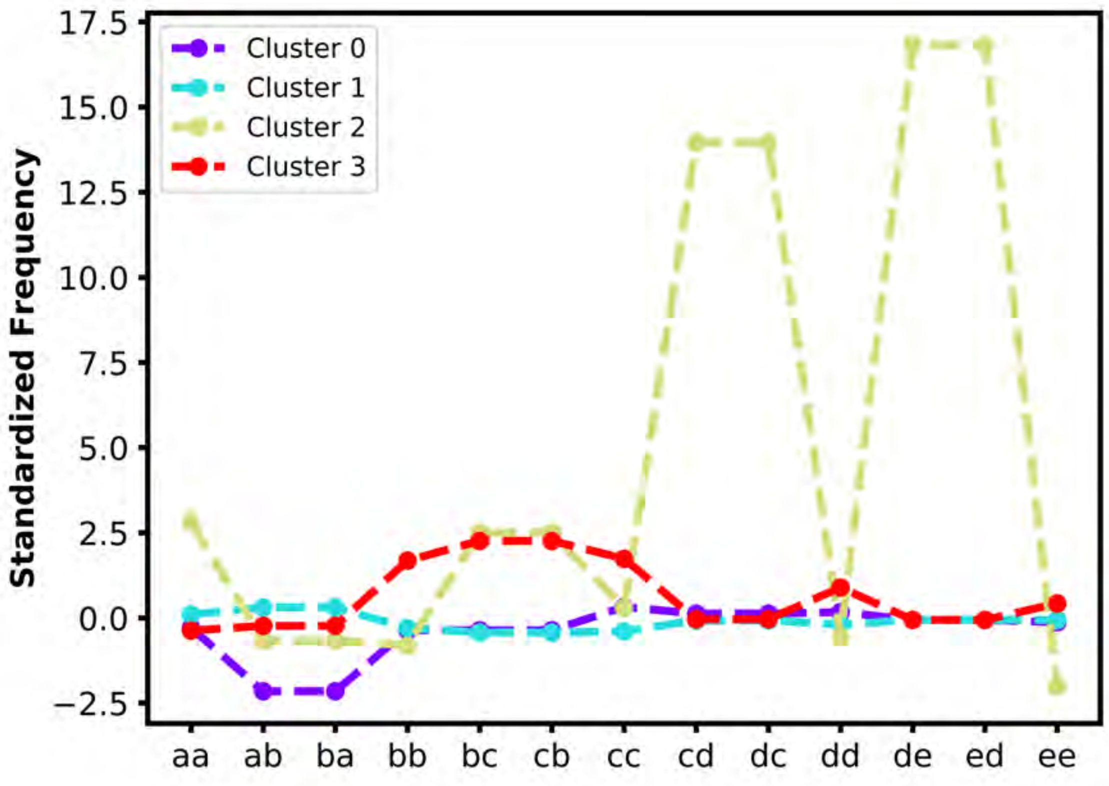


Cluster Centroid Behavior

Donegan, Sean P., Edwin J. Schwalbach, and Michael A. Groeber. "Zoning additive manufacturing process histories using unsupervised machine learning." *Materials Characterization* 161 (2020): 110123.

4 clusters showed 'best' separation of mean features

Key
e – Vapor
d – Liquid
c – β
b – α
a – Cold



Cluster 0: Low occurrence of low temp transitions

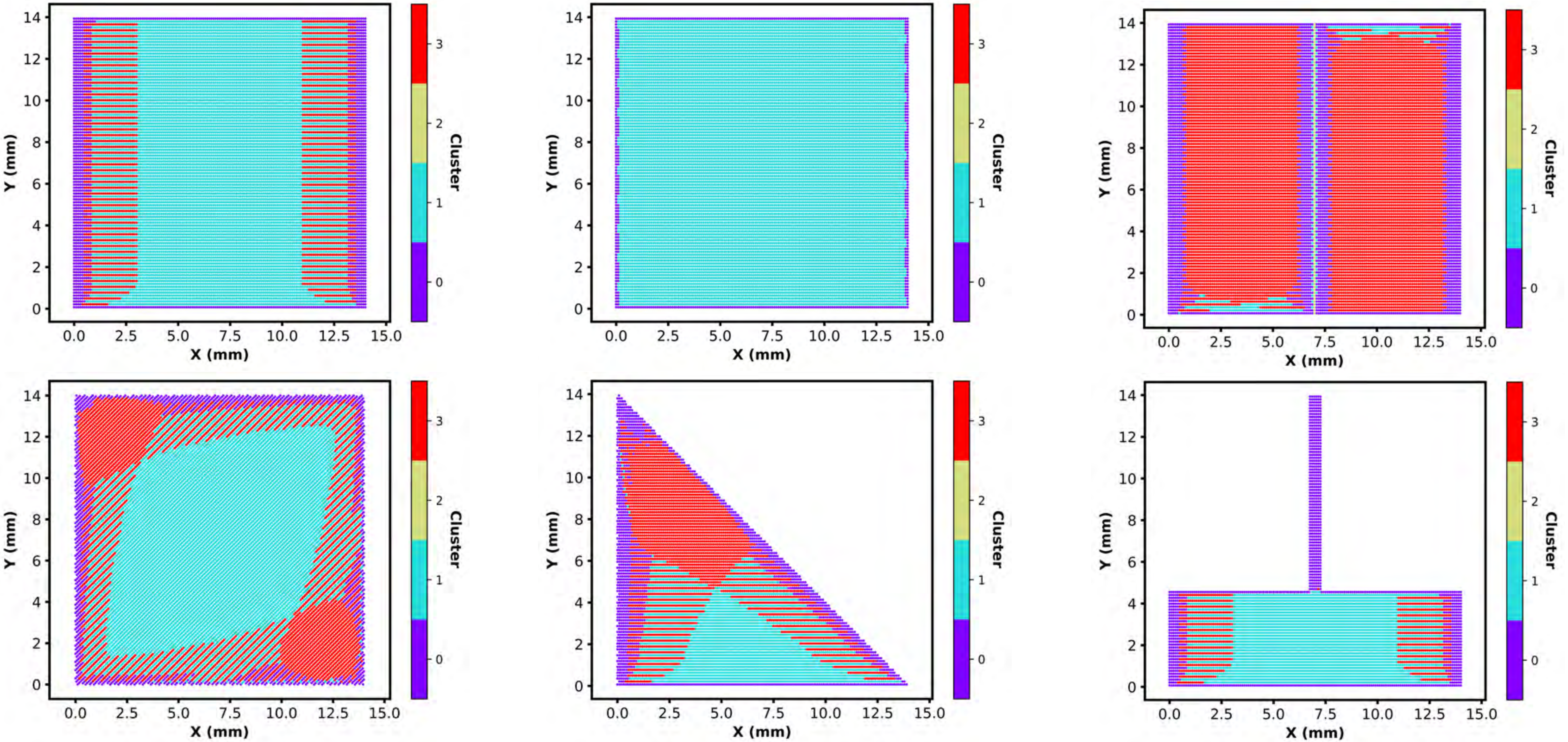
Cluster 1: Similar to the mean of the overall dataset (near zero for all subwords)

Cluster 2: Enhanced occurrence of melting and vaporization transitions

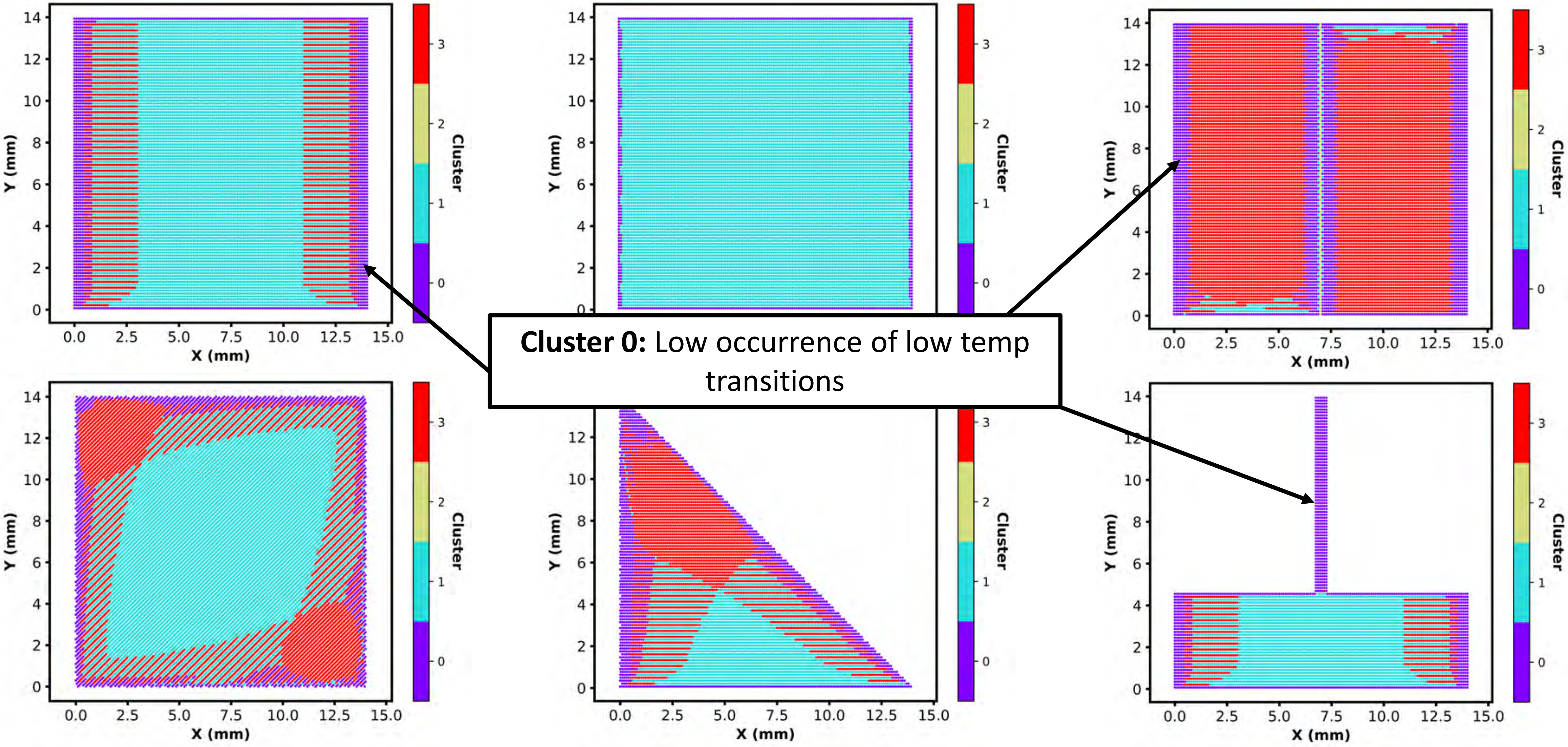
Cluster 3: Enhanced occurrence of intermediate temperature (α - β) transitions, with 'typical' amount of melting

All counts standardized to zero mean, unit variance

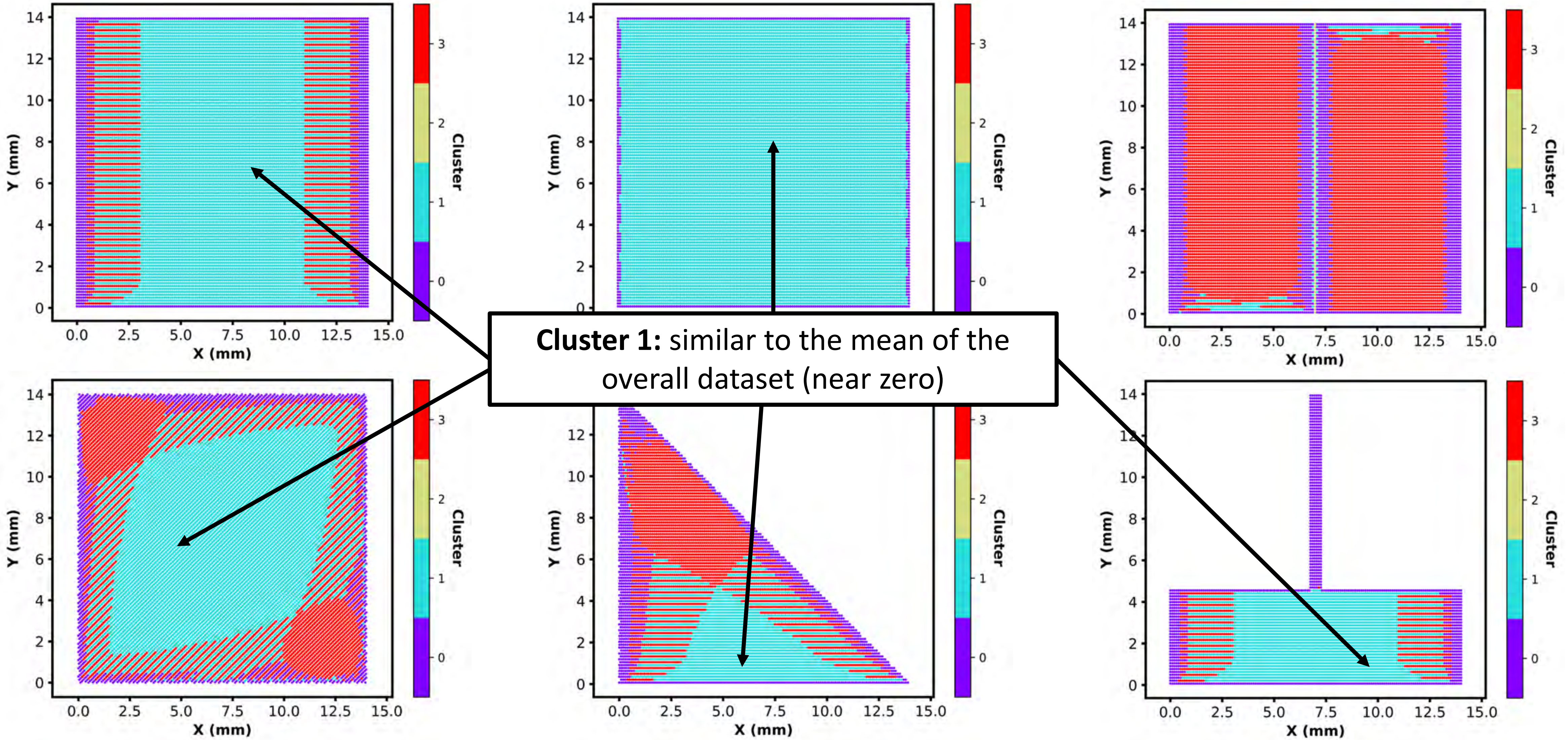
Zoned Maps



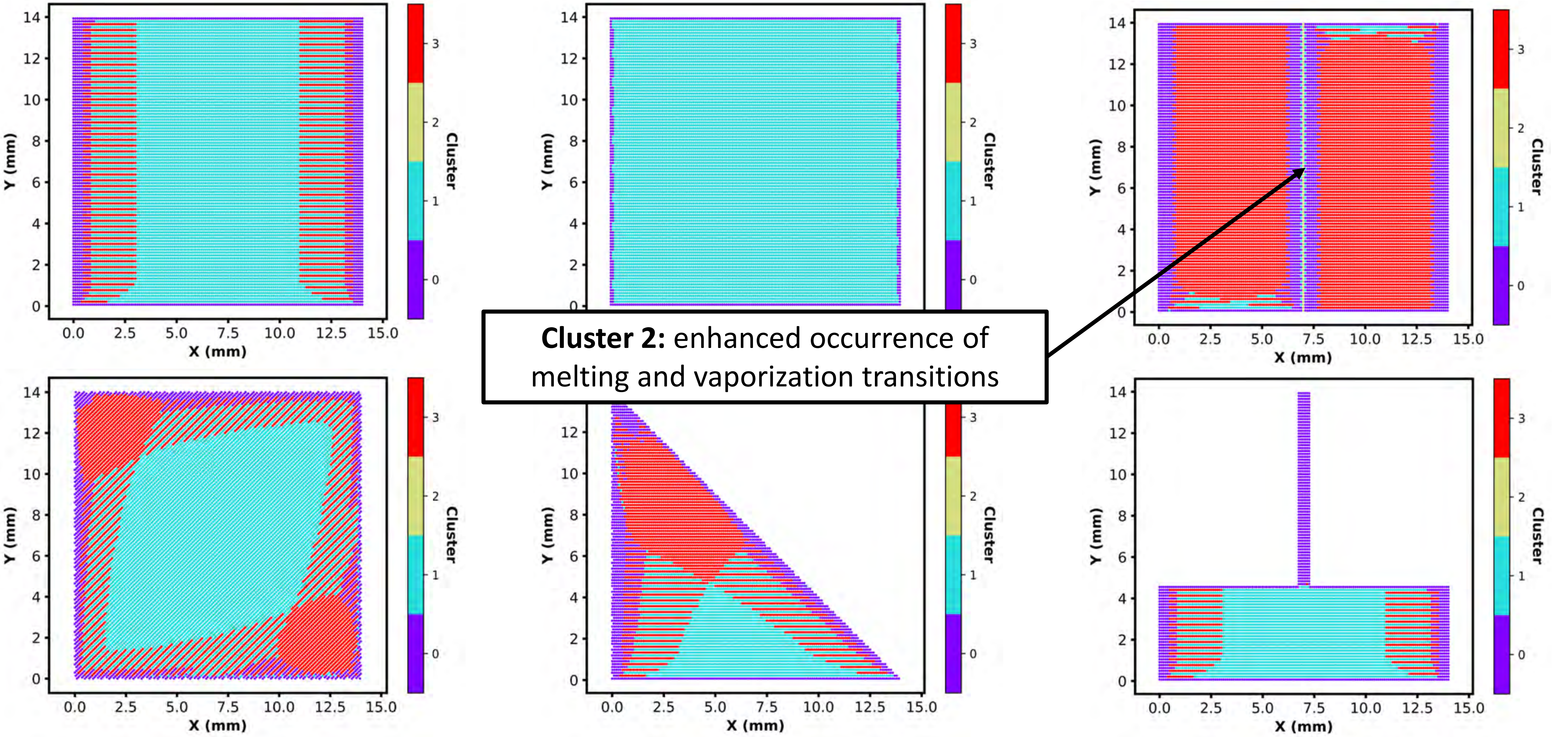
Zoned Maps


Cluster 0: Low occurrence of low temp transitions
Y (mm)
X (mm)
Cluster
0
1
2
3
0.0
2.5
5.0
7.5
10.0
12.5
15.0
14
12
10
8
6
4
2

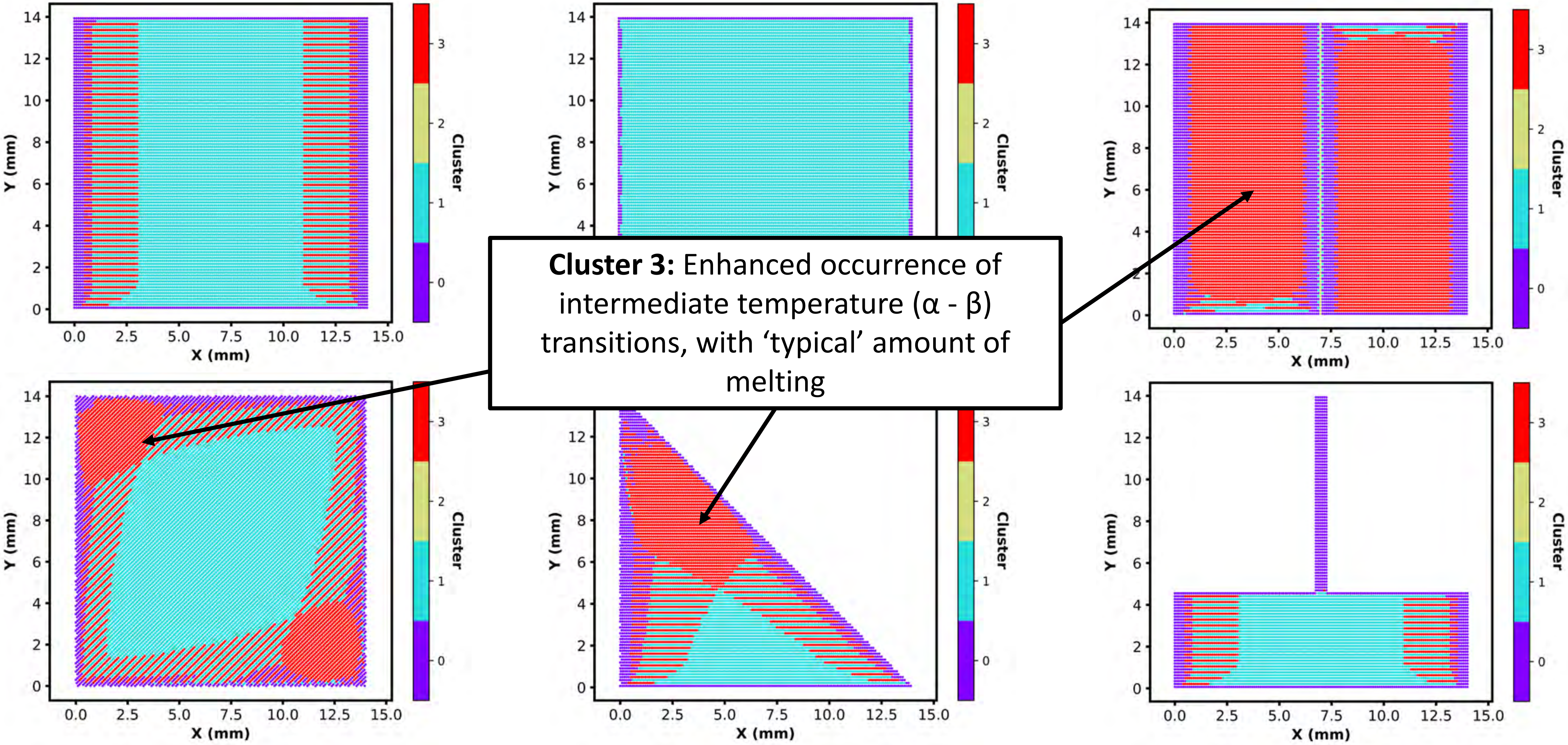
Zoned Maps


Cluster 1: similar to the mean of the overall dataset (near zero)
Y (mm)
X (mm)
Cluster
0.0
2.5
5.0
7.5
10.0
12.5
15.0
0
2
4
6
8
10
12
14
0
1
2
3

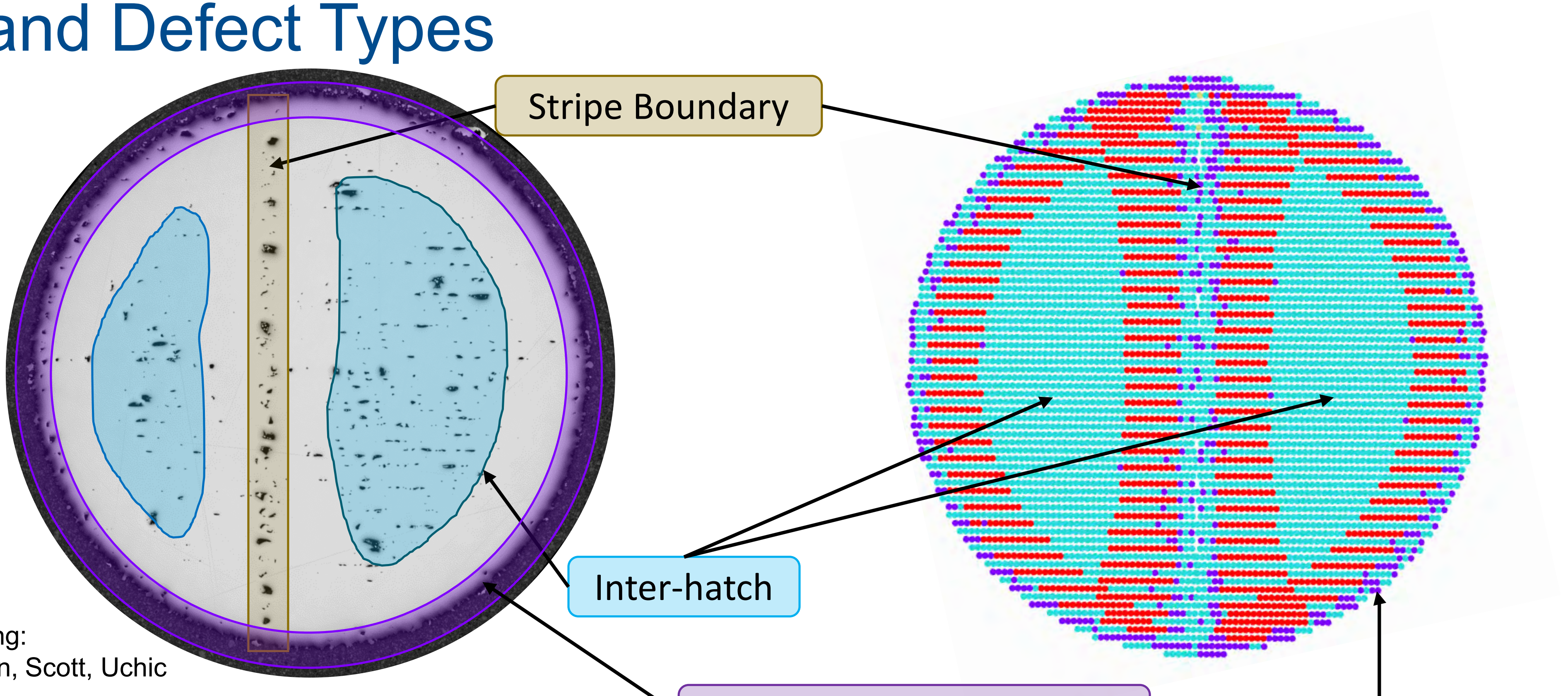
Zoned Maps


Y (mm)
X (mm)
Cluster
0
1
2
3
0.0
2.5
5.0
7.5
10.0
12.5
15.0
0
2
4
6
8
10
12
14
Cluster 2: enhanced occurrence of melting and vaporization transitions

Zoned Maps


Cluster 3: Enhanced occurrence of intermediate temperature (α - β) transitions, with 'typical' amount of melting
X (mm)
Y (mm)
Cluster
0.0 2.5 5.0 7.5 10.0 12.5 15.0
0 2 4 6 8 10 12 14
0 1 2 3

Zones and Defect Types

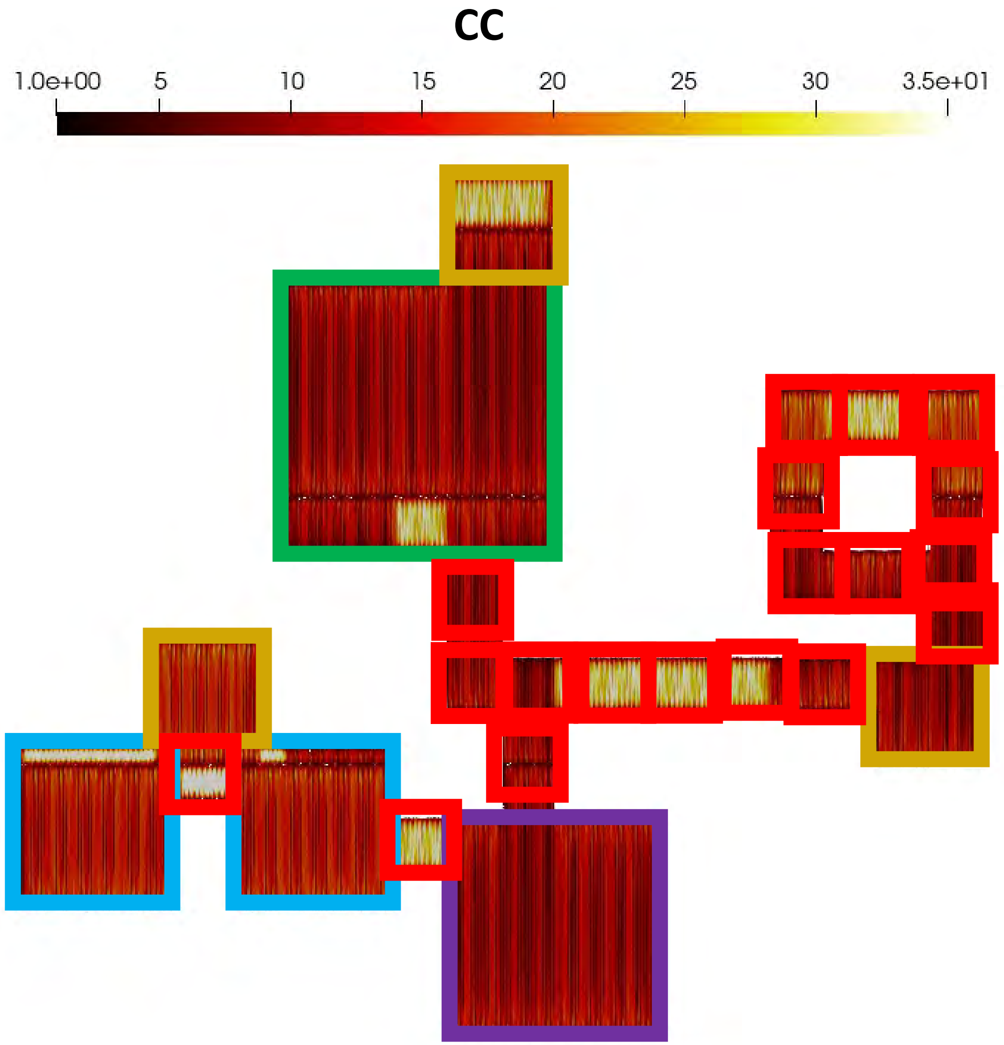


Sectioning:
Chapman, Scott, Uchic

Cylinder at 30um resolution, 58x10^6 voxels requires:

Representation	Values/vox	Data type	Size (GB)	Reduction	Bytes/vox
Full time series, 10s @1ms	10,000	float (32bit)	2167	1	40,000
PAA	10,000	char (8bit)	542	4	10,000
SAX Bitmaps	25	int (16 bit)	2.71	800	50
Cluster labels	1	char (8 bit)	0.054	40000	1

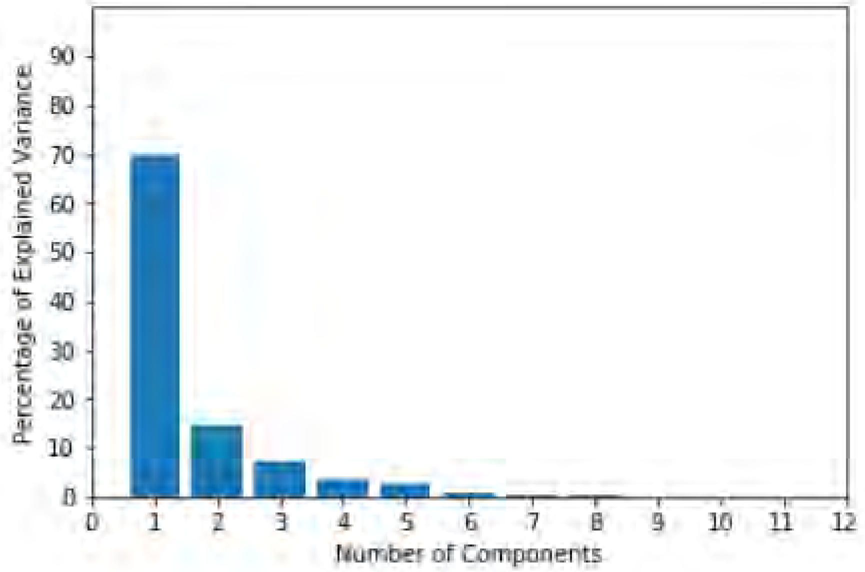
Local Processing Heterogeneity



Want to design scan path to yield desired thermal history spatially:

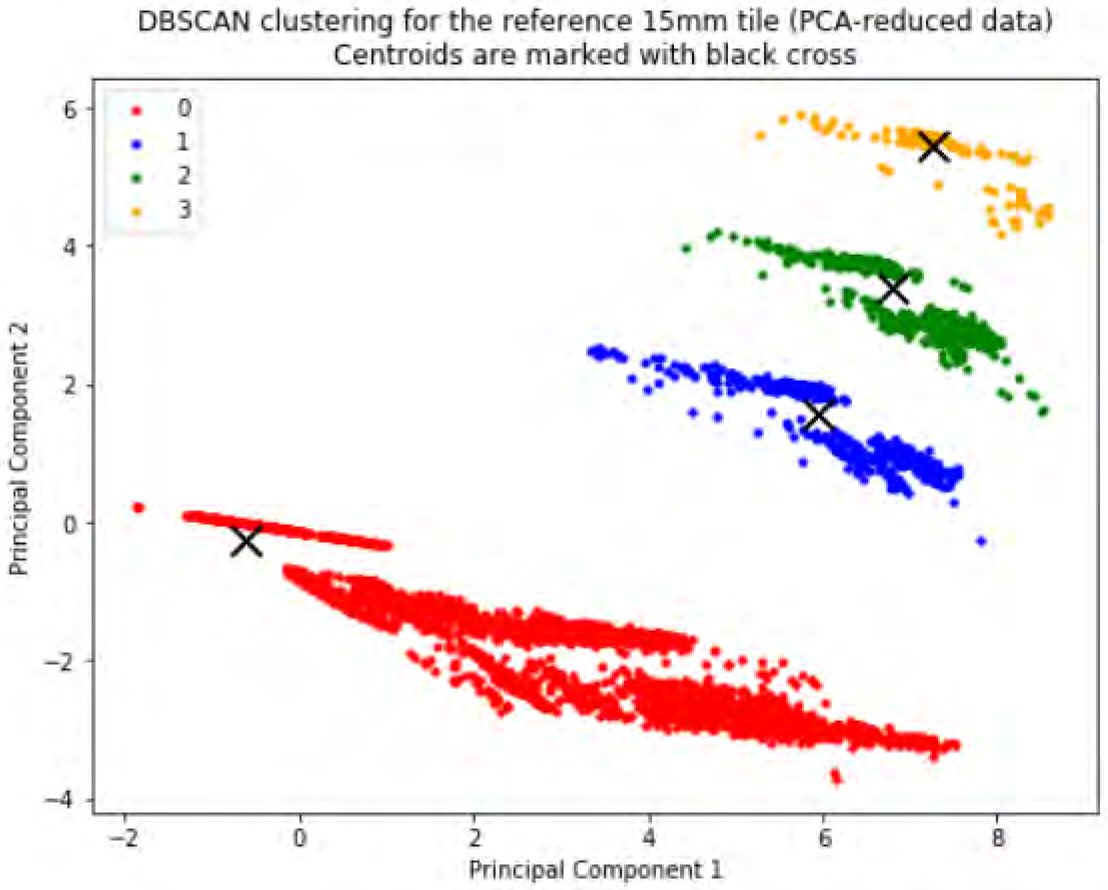
- Will need different parameters at different spatial locations
- Which direction to turn processing parameter "knobs" is not clear
- Need methods to compare local processing to desired state
- Need rapid methods to predict local processing 'quality' – to enable search

Dimensionality Reduction



Comparisons in high dimensional space is complicated

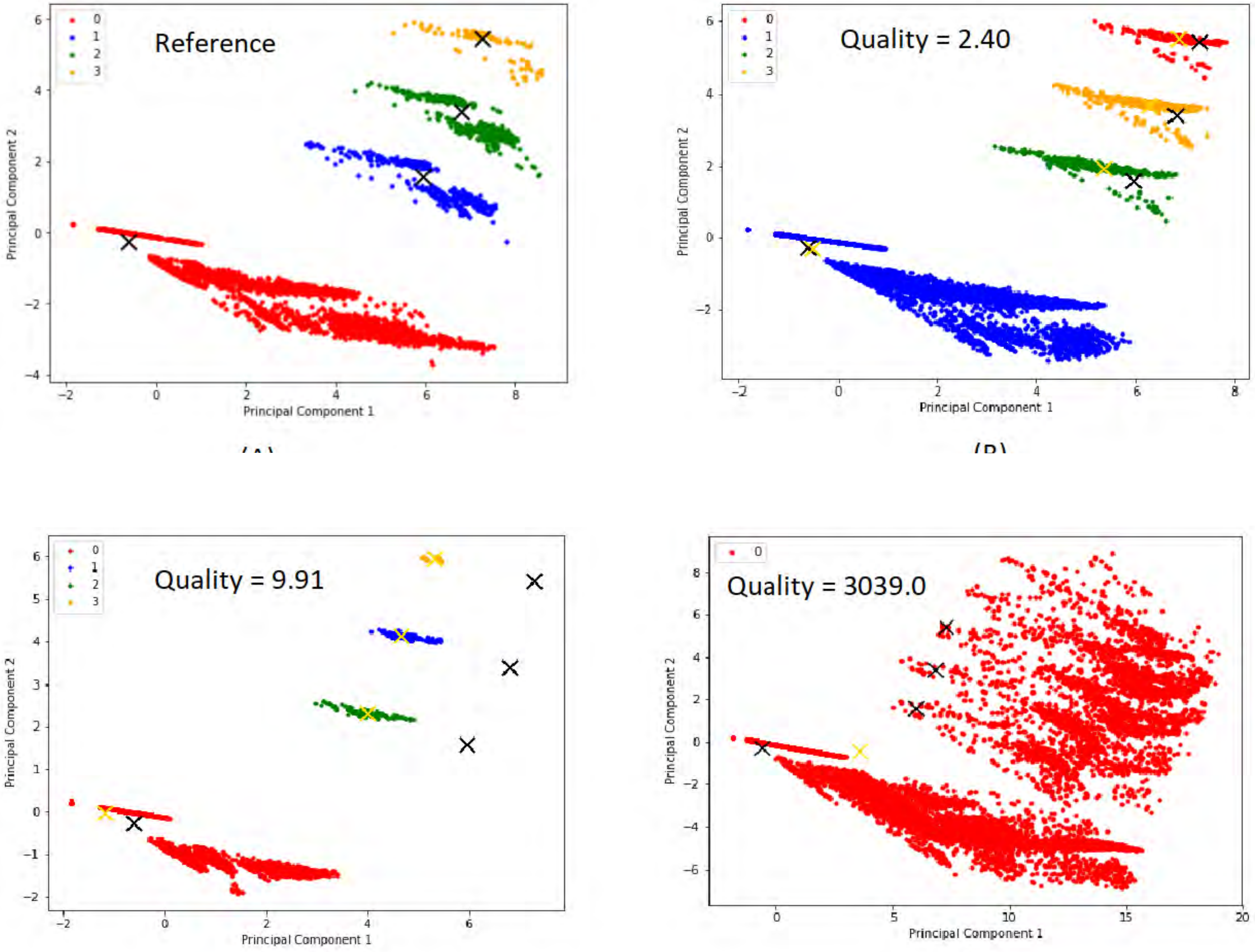
- Use principal component analysis to further reduce individual thermal histories (2 dimensions)
- Still 1,000s of dimensions to represent spatial patch
- Clustering (Kmeans, DBSCAN, etc) can further reduce dimensionality



Comparing Local Processing (9 mm square)

300 W, 1300 mm/s, 140 µm HS

375 W, 1400 mm/s, 200 µm HS



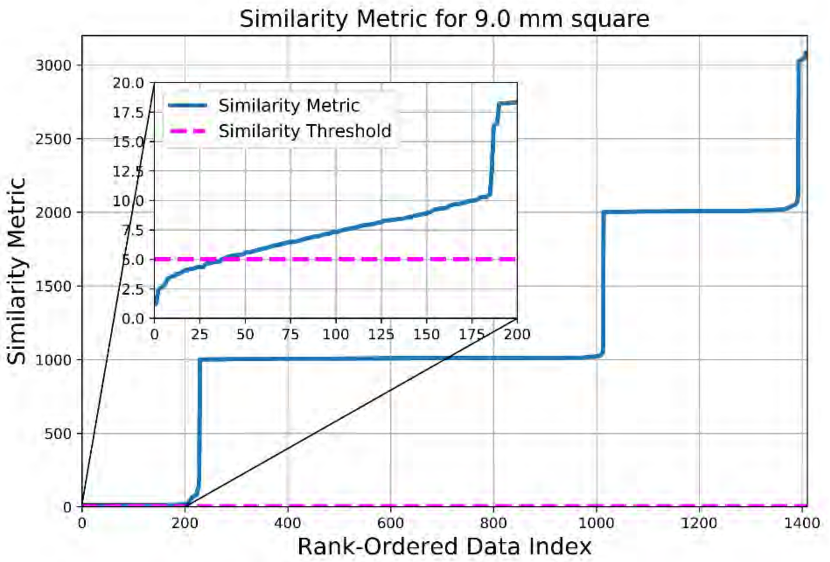
(C)

(D)

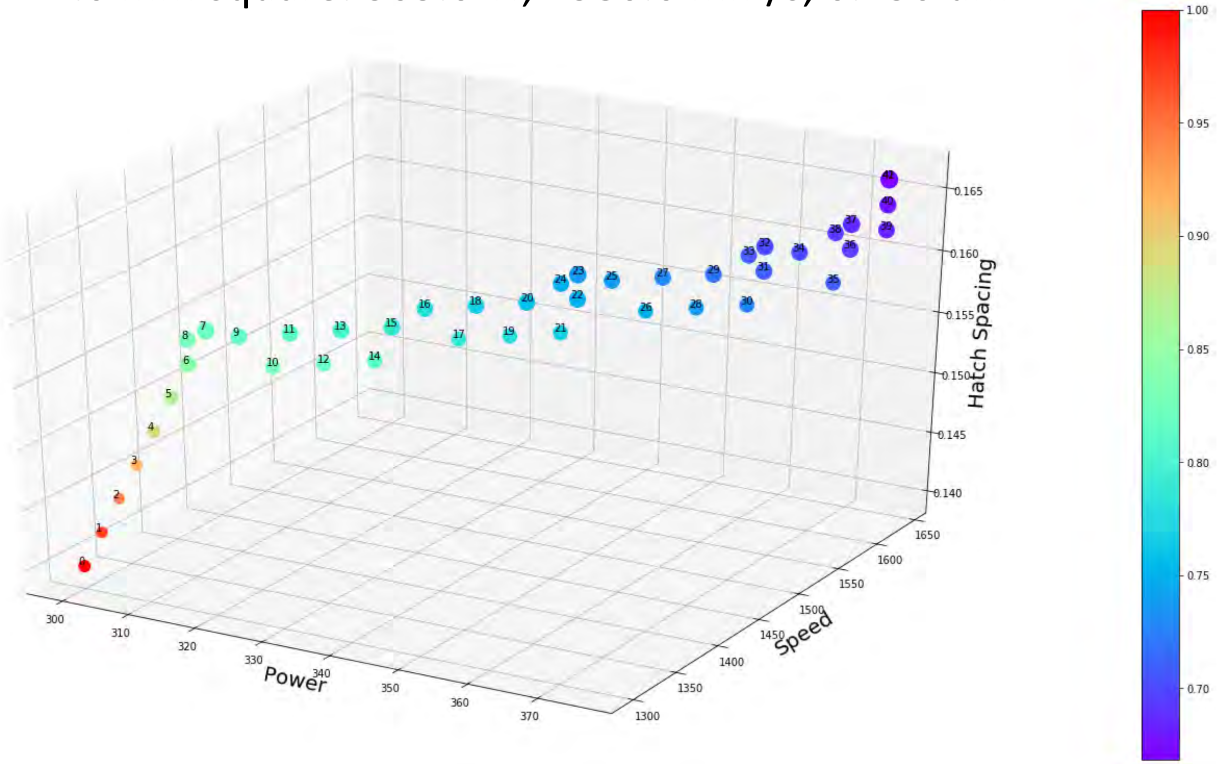
Need to define a similarity/quality metric and be able to predict it quickly

- Sparse sampling of potential processing states (power, velocity, hatch spacing)
- Assess metric at each state
- Statistical model fitting using support vector regression (SVR)

Local Processing Parameter Optimization



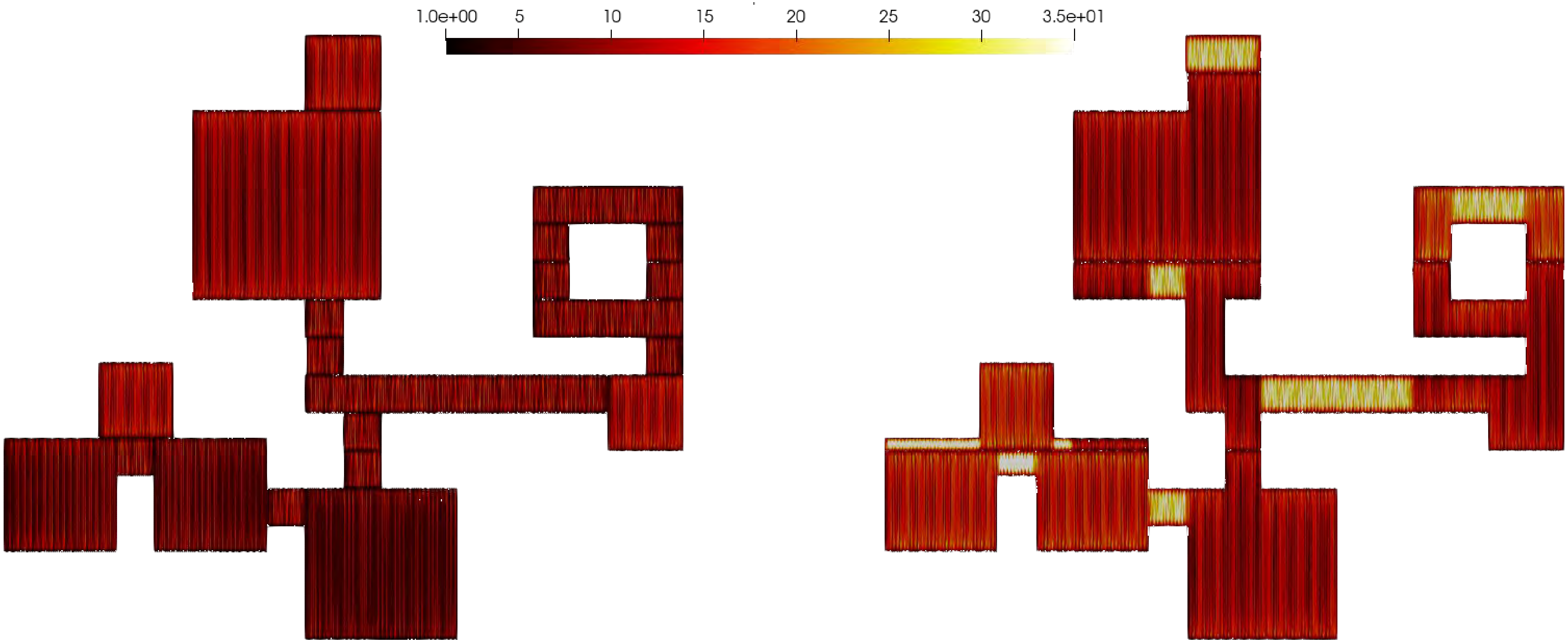
3.0 mm square: 280.0 W, 1420.0 mm/s, 0.150 um
6.0 mm square: 305.0 W, 1520.0 mm/s, 0.158 um
9.0 mm square: 375.0 W, 1560.0 mm/s, 0.160 um
12.0 mm square: 365.0 W, 1580.0 mm/s, 0.150 um



Need to search scan parameter space for sets that yield acceptable local processing histories

- Need to define acceptable – difficult
- Likely also have constraints on processing time
- Given fast statistical model – can use gradient-based approaches

Local Processing Parameter Results



Questions?

Appendix R

"Powder Reuse in Additive Manufacturing" – E. Bono (6K Inc.)

Examining the Practice of Powder Reuse in AM

Eric Bono
Ph: 1.412.260.8048
Em: ebono@6kadditive.com

6K ADDITIVE

Let’s Dissect the term “Powder Reuse”

Powder Reuse

Let’s focus on the first word “Powder”

Powder Reuse

Several types of powder and several ways to manufacture

Powder Reuse

Deliberately Made & By Products

Several types of powder and several ways to manufacture

Powder Reuse

Deliberately Made

Spherical

Atomization

- Gas
- Plasma
- PREP

Spheroidization

- Micro-Wave
- Inductively Coupled

Non-Spherical

Water Atomization

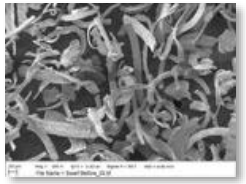
Chemical

By products are produced during conventional manufacturing

6K ADDITIVE

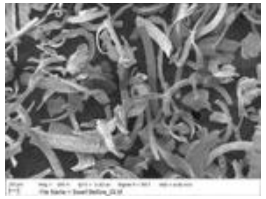
Powder Reuse

By Products



- Machining scrap
- Grinding swarf
- Saw swarf

Ti64 Grinding Swarf



Ti Alloying Compacts

Al Mill Forms

End Product

Different states of Spherical Powder

Powder Reuse

Focus on Spherical – But in what state?

- Virgin
- Blended (virgin + used)
- Oversized agglomerates
- Out-sized powder
- Splat
- Condensate

- Out of spec
  - Morphology – no flow
  - Interstitials – oxygen
  - PSD – shifted coarser
  - Used – how much
- Binder Jet
- Solids

- Failed builds
- Broken test specimens, etc.

Different states of Spherical Powder

6K ADDITIVE

Powder Reuse

Focus on Spherical – But in what state?

- Virgin
- Blended (virgin + used)
- Oversized agglomerates
- Out-size powder
- Splat
- Condensate

- Out of spec
  - Morphology – no flow
  - Interstitials – oxygen
  - PSD – shifted coarser
  - Used – how much
- Binder Jet
- Solids

- Failed builds
- Broken test specimens, etc.

Now let's focus on "Reuse" of Out of Spec Spherical Powder

6K ADDITIVE

Powder **Reuse**

- Put it back thru the printer after it's already been printed and **hope for the best**
- Blend with virgin to bring bulk PSD and chemistry back into spec **"on average"**
- Used powder that is remelted and reatomized to a virgin state
- Used powder that is rejuvenated via plasma spheroidization, such as 6K or Tekna, to a virgin state

Different ways to reuse “Out of Spec” Spherical Powder

6K ADDITIVE

Powder Reuse

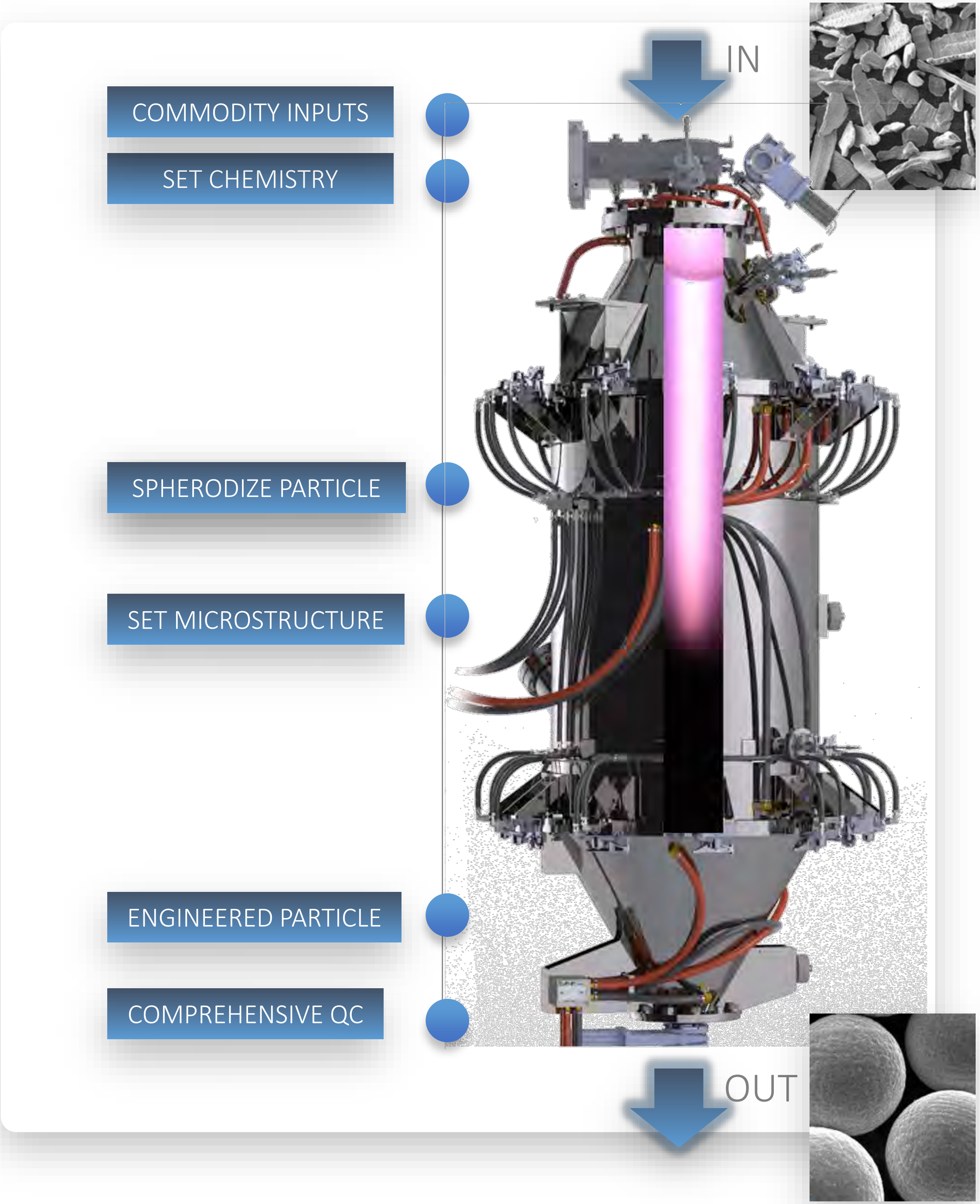
- Put it back thru the printer after it’s already been printed and **<u>hope for the best</u>**
- Blend with virgin to bring bulk PSD and chemistry back into spec **<u>“on average”</u>**
- Used powder that is remelted and reatomized to a virgin state
- Used powder that is rejuvenated via plasma spheroidization, such as 6K or Tekna, to a virgin state

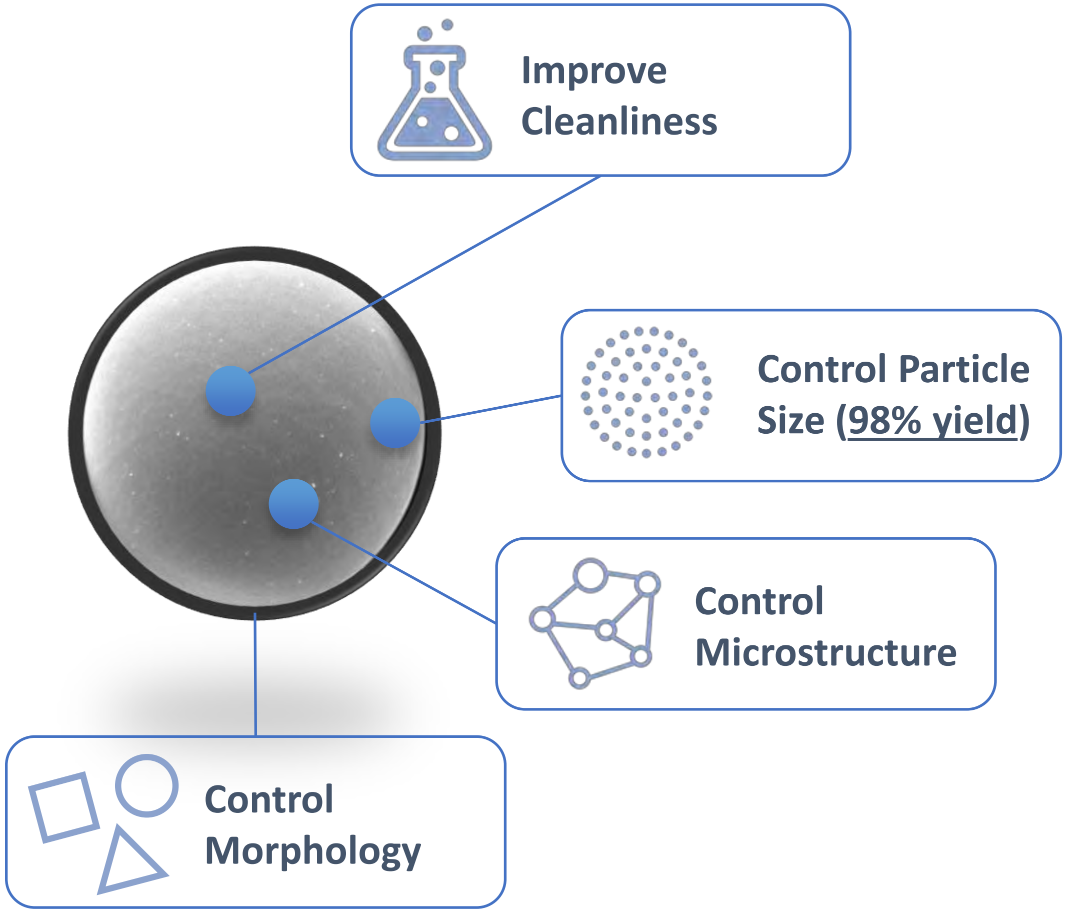
Reatomizing back to a virgin state:

- Difficult to remelt loose powder
- Careful control needed to monitor/control oxygen
- Still only get 25%-30% yield

UniMelt® Plasma System

High Throughput - Precise Particle Control



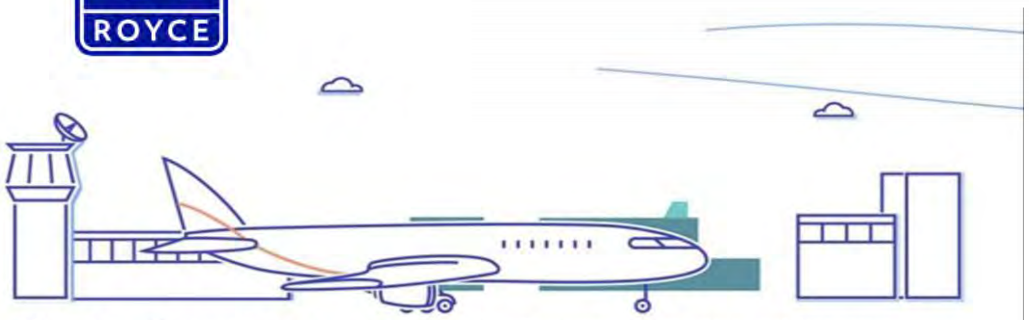


Recycling Metal – it's already a best practice!

6K ADDITIVE

ROLLS ROYCE

BOEING



Reducing demand

Our Revert programme of closed loop metals recycling reduces our demand for virgin exotic materials

Our world has finite resources

Our world has finite resources and demand for them is increasing. Recycling what we use is an essential part of a sustainable future. Our products rely on exotic materials that are critical to enabling them to perform in a safe and efficient manner, exotic metals that include rhenium, hafnium, nickel and titanium.

Our closed loop recycling programme

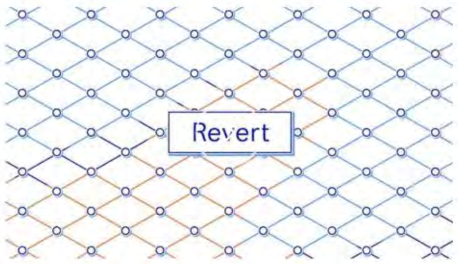
We use over 20,000 tonnes of high value metal alloys each year, equivalent to two and a half Eiffel Towers. That's why we work to reuse as much metal as we can through a closed-loop recycling programme we call Revert.

Pushing the boundaries

Over the past decade we have developed processes to maximise the recycling opportunity, now almost 95% of a used aero engine can be recovered and reused.

We have partnered with strategic service providers who specialise in waste metal handling and processing. Collaboratively we have developed new processes to remove coatings, separate alloys and clean up the waste metals.

Unserviceable engine parts and waste metal from machining and castings are recovered and returned to our material suppliers for re-melting and reuse, enabling them to be returned to aerospace grade alloys and safely reused to make new engines.



Almost half of a used aero engine can now be safely recycled to a standard where the quality of the recovered material is so high the materials can be reused to make new engine components as part of a fully closed loop recycling system. The remainder is reused as a lower grade alloy.

We continue to push the boundaries in metal recovery and recycling. As our product portfolio continues to develop and evolve we are exploring opportunities to recover alternative materials, such as composites and other alloys.

"Almost 95% of a used aero engine can now be recycled and around half of the recovered material is of such high quality it can be safely used again to make a new engine."

Issues printing "Out of Spec" Spherical Powder

Powder Reuse

What happens to powder during printing?

Printing Issue #1: Chemistry Drift – as powder is put thru the printing system, it picks up oxygen

Printing Issue #2: PSD Coarsening – PSD coarsens as fines get blown away or agglomerated

Printing Issue #3: Flow Deadening – as morphology worsens, flow is hampered

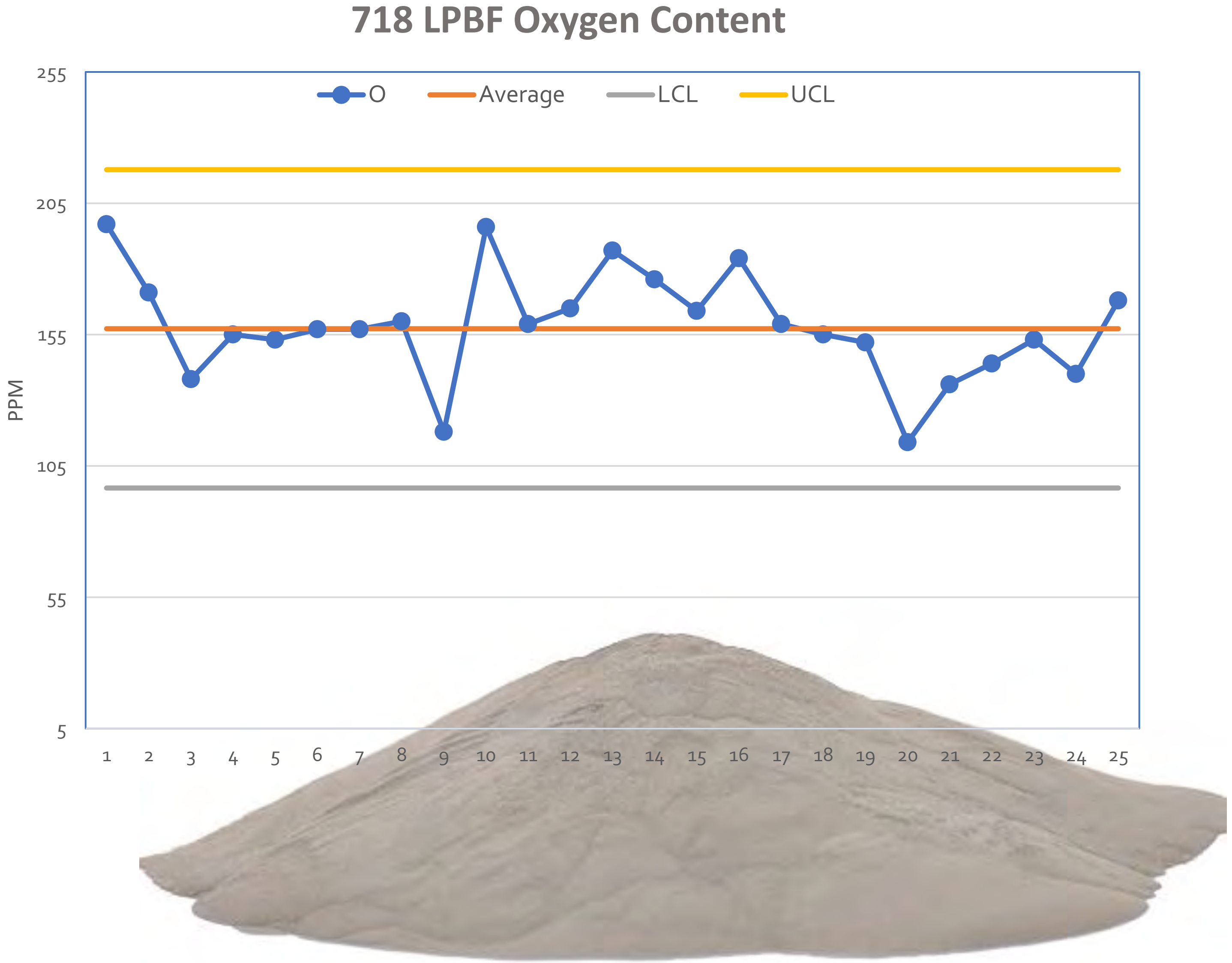
“Out of Spec” brought into Spec with UniMelt

Interstitial Chemistry (PPM)

	C	S	O	N	H
Average	338.1	16.3	157.9	87.3	2.8
Std. Dev.	75.3	5.5	21.0	26.1	0.5

Major Chemistry (wt %)

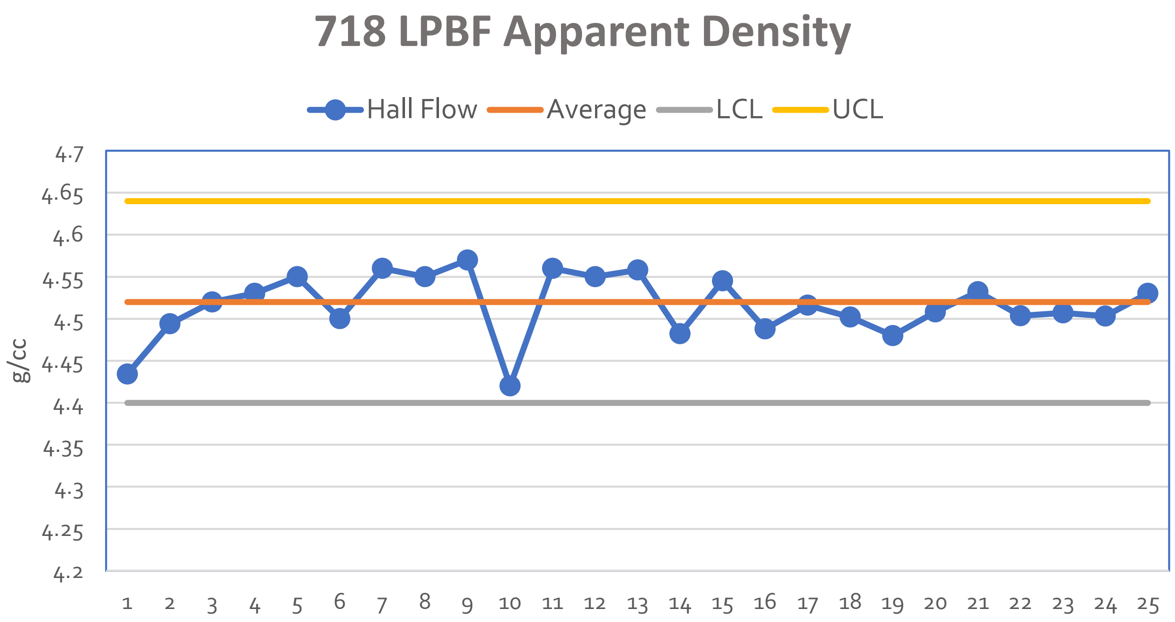
	Cr	Nb	Mo	Ti	Al	Fe
Average	18.45	5.07	3.07	0.96	0.54	17.56
Std. Dev.	0.30	0.05	0.06	0.04	0.05	0.26

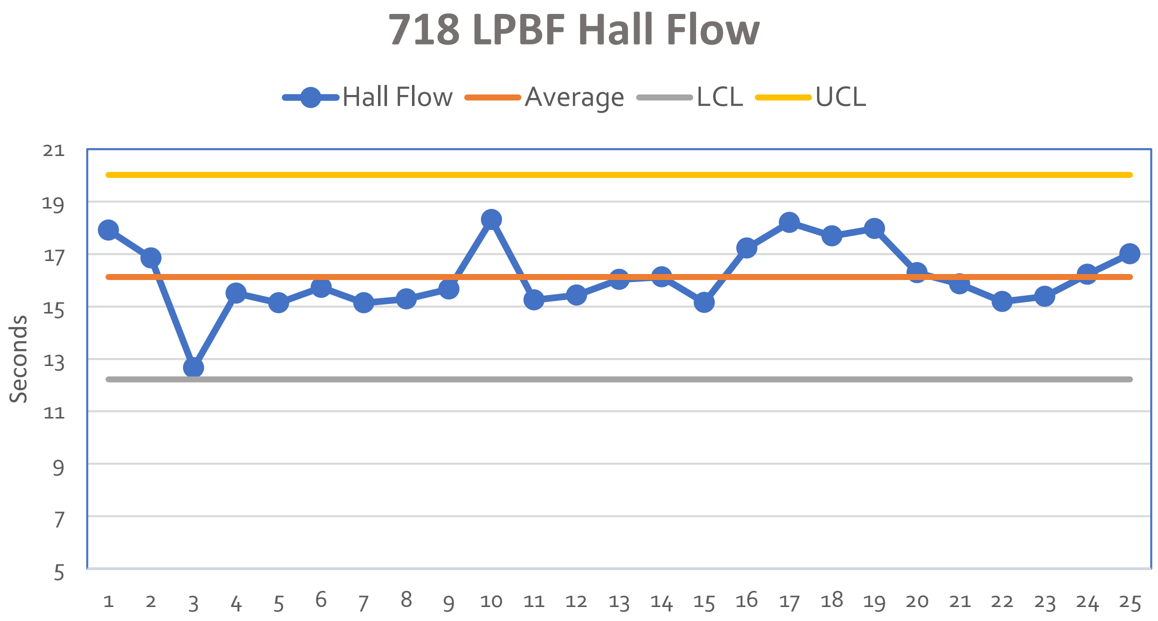


“Out of Spec” brought into Spec with UniMelt

6K ADDITIVE

	AD (g/cc)	Hall Flow (s)
Average	4.52	16.1
Std. Dev.	0.04	1.3





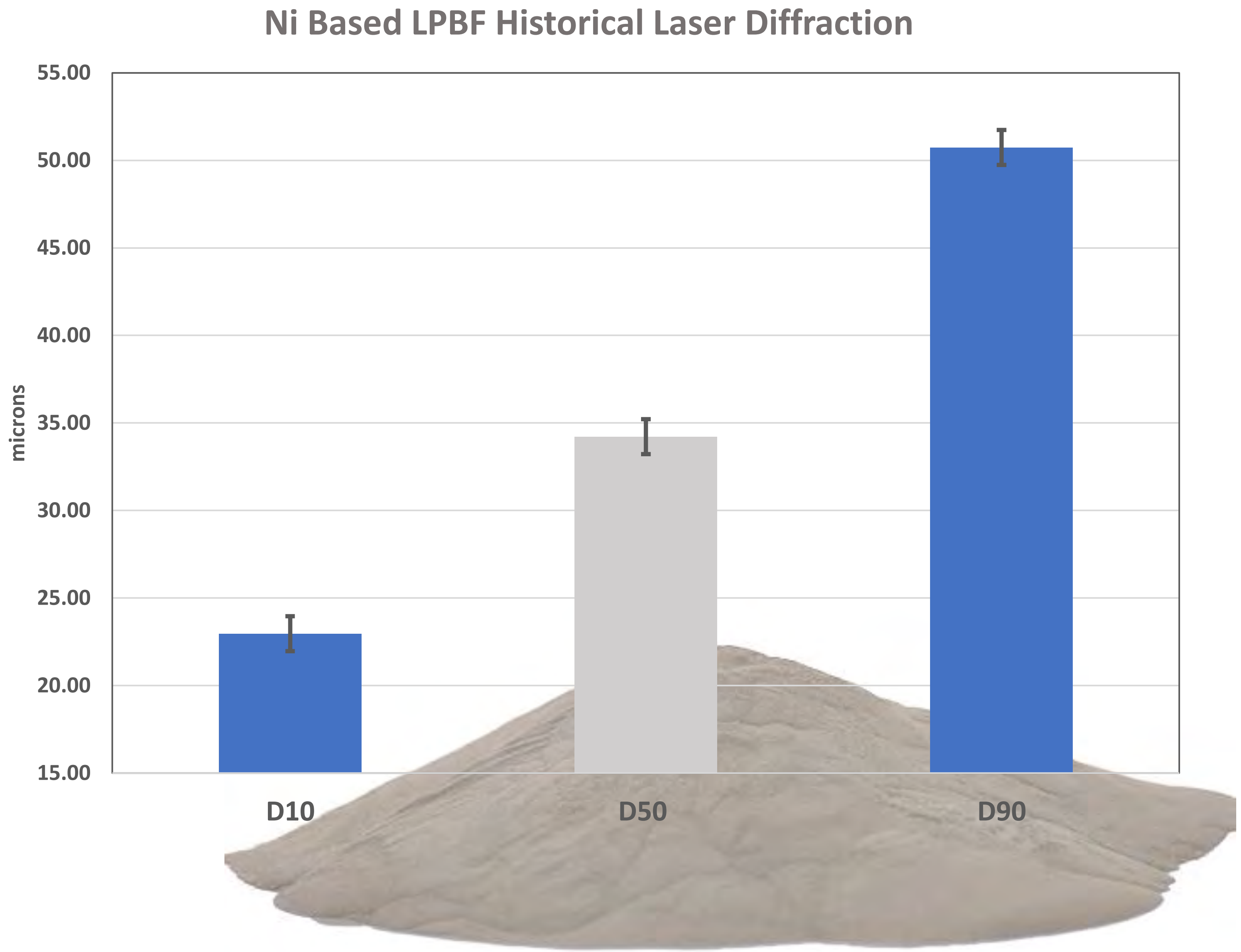
“Out of Spec” brought into Spec with UniMelt

Laser Diffraction (Microtrac)

	D10	D50	D90	-15 μ
Average	22.97	34.21	50.74	1.06
Std. Dev.	1.11	0.64	1.57	0.44

Sieve Analysis

	+325 (wt%)
Average	3.4
Std. Dev.	1.5



Solving the printing issues with UniMelt®

Powder Reuse

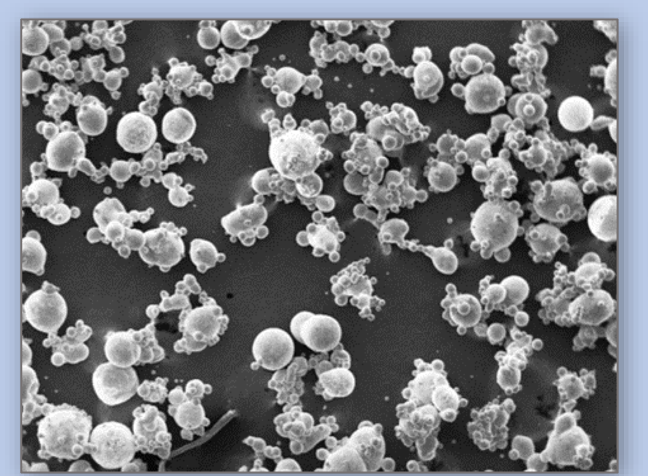
What happens to powder during printing?

Printing Issue #1: Chemistry Drift – as powder is put thru the printing system, it picks up oxygen

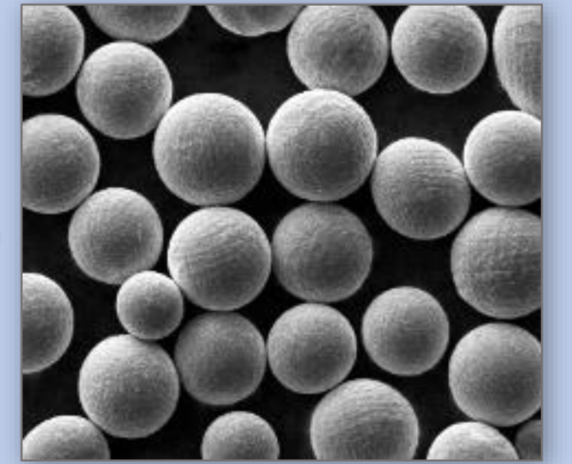
Printing Issue #2: PSD Coarsening – PSD coarsens as fines get blown away or agglomerated

Printing Issue #3: Flow Deadening – as morphology worsens, flow is hampered

Used Ni718 AM Powder



6K Rejuvenated Powder



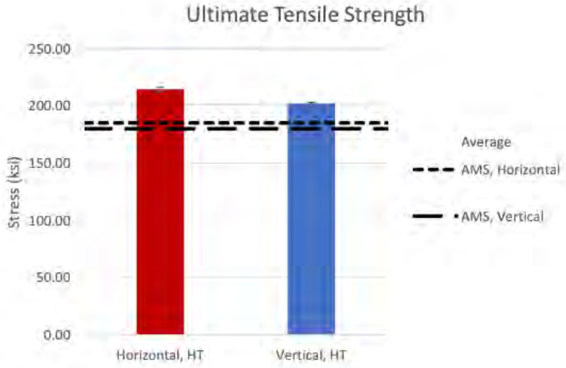
- 60% reduction in O_2 content
- 20% increase in tap density
- Improved Hall Flow Rate
- Tightened PSD

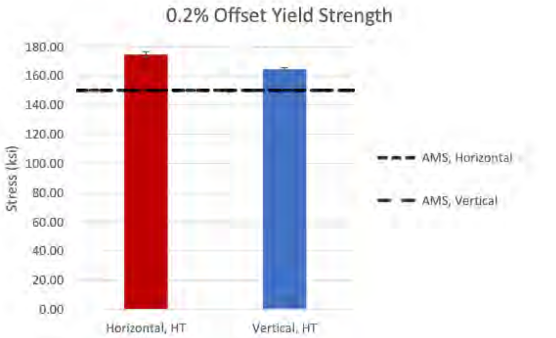
The Proof is in the Printing – Unsurpassed Quality!

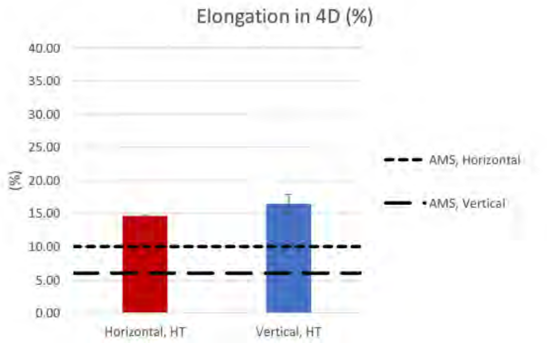
AMS 5663, Condition S1750 DP			
HT	Temperature	Time	Cooling Rate
Solution	1725 F	60 min	Air Cooled
Age	1325 F ; 1150 F	~480 min ; ~480 min	Cool at 100 F/hr ; Air Cooled

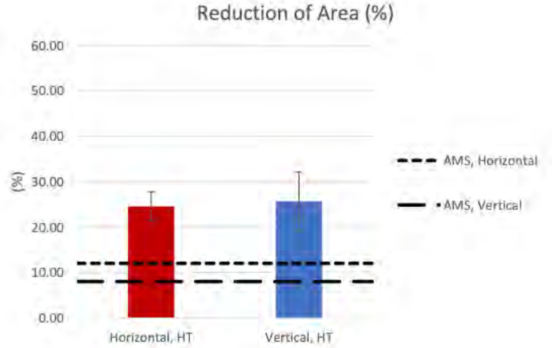
6K Nickel 718 – Machined
M400-4
40 micron layer

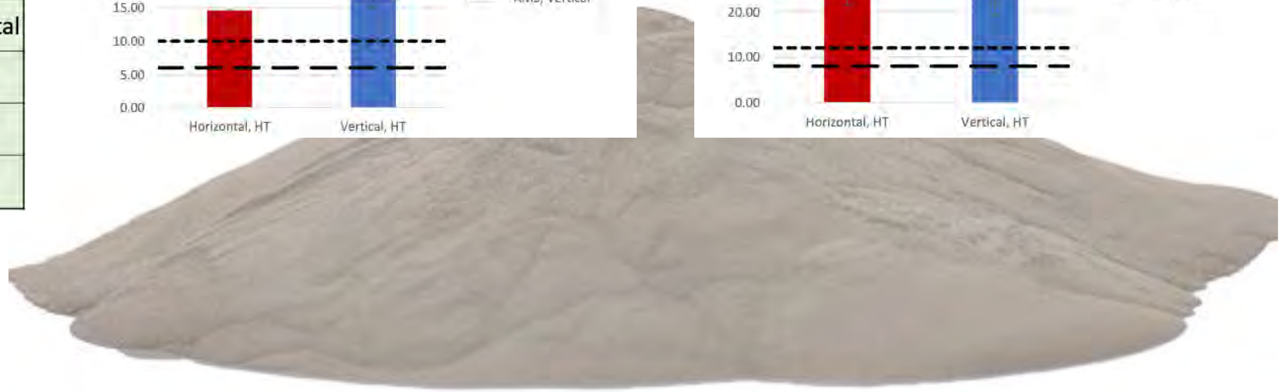
Property	Ultimate Tensile Strength (ksi)		0.2% Offset Yield Strength (ksi)		Elongation in 4D (%)		Reduction of Area (%)	
Build Orientation	Vertical	Horizontal	Vertical	Horizontal	Vertical	Horizontal	Vertical	Horizontal
Average	201.9	214.4	164.3	174.6	15.9	14.6	30.5	24.5
Std. Dev.	0.9	1.9	1.2	2.0	1.0	0.1	4.0	3.2
Specimen Count	20	4	20	4	20	4	20	4









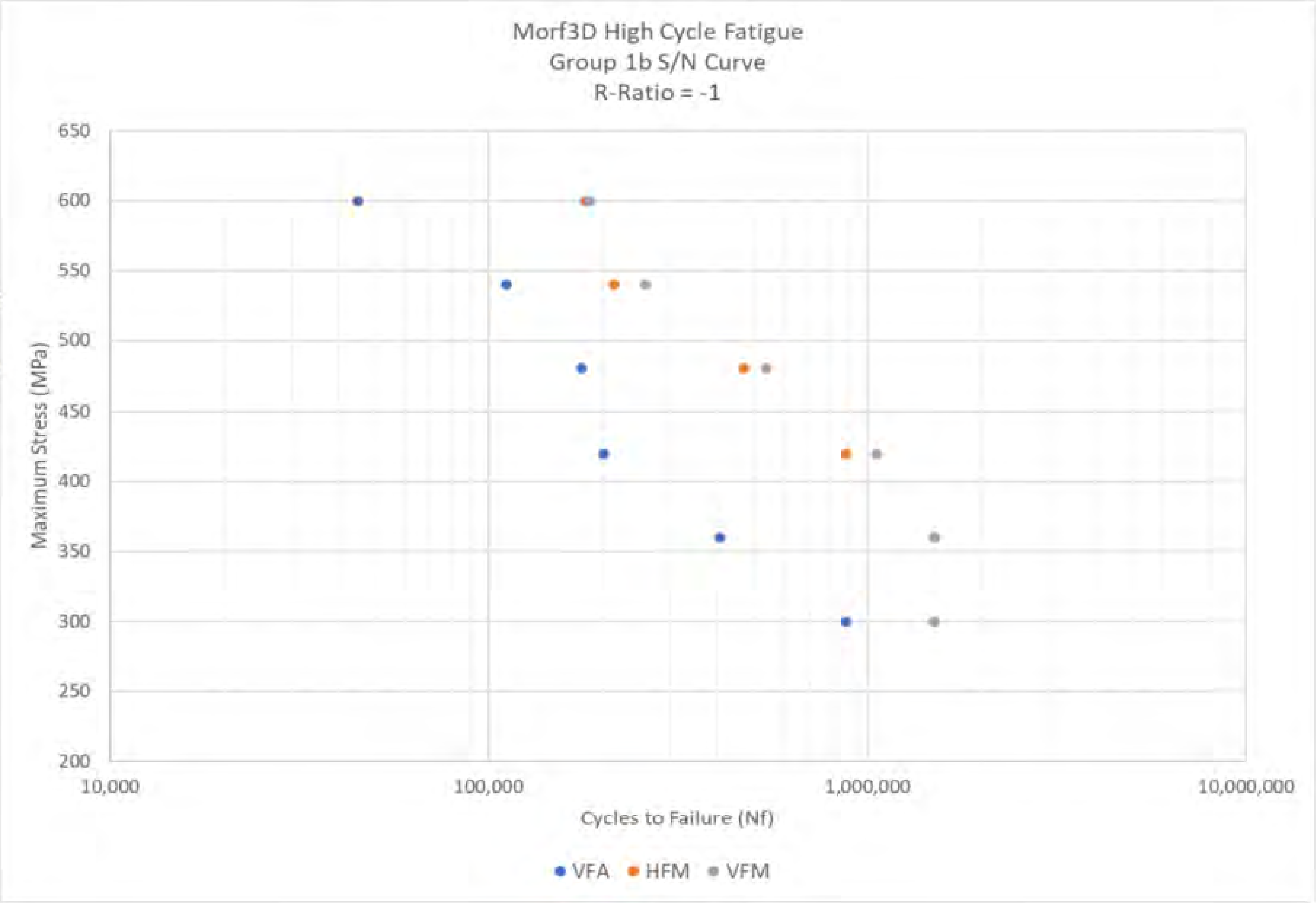


The Proof is in the Printing – Unsurpassed Quality!

Mechanical Data (Fatigue): Nickel 718

Heat Treated

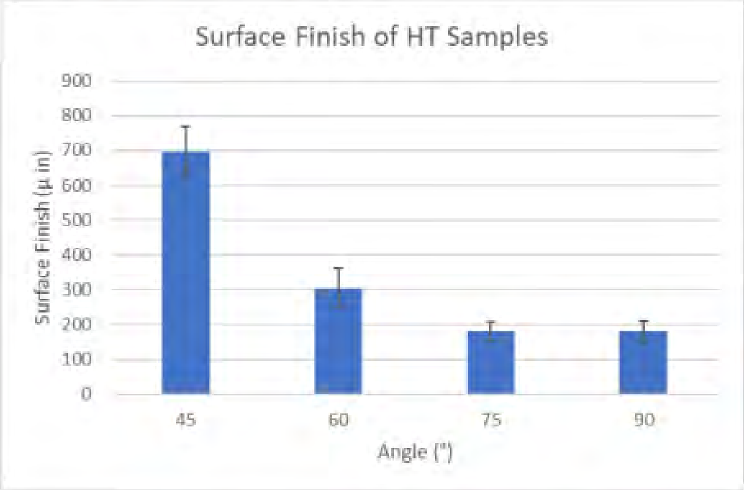
Vertical Fatigue As Printed
Horizontal Fatigue Machined
Vertical Fatigue Machined

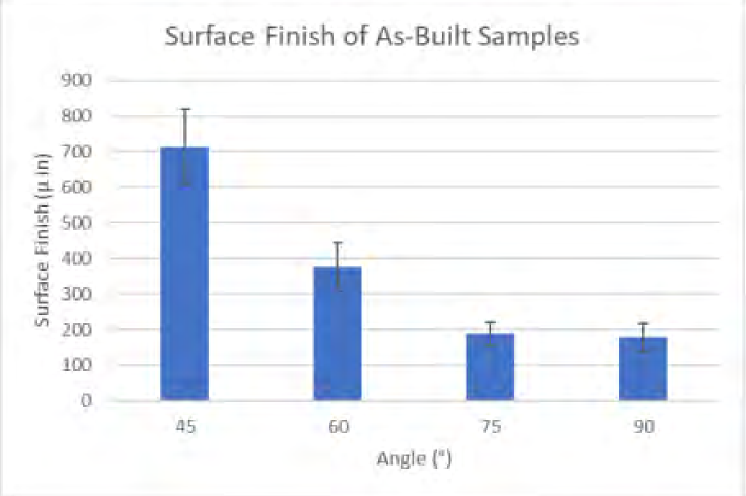


The Proof is in the Printing – Unsurpassed Quality!

6K ADDITIVE

Surface Finish





Surface Finish Measurements (µ-in)					
Heat Treated		Degrees			
		45	60	75	90
	Average	696	305	181	180
	St. Dev.	73	56	28	33
As-Built		Degrees			
		45	60	75	90
	Average	714	377	189	178
	St. Dev.	104	67	32	41

Powder Reuse and its effect on sustainability

LCA Report on powder manufacturing

Energy comparison we looked at include:

- Input Materials
- Gas Usage
- Power Usage
- Post Processing

6K Additive's targeted PSD ensures that all energy and power used is directly applied to your desired size range and results in NO wasted energy.

Life-Cycle Assessment Report

Life-Cycle Assessment Report
February 4th, 2022

Abstract

This study was conducted to quantify the environmental impacts associated with the production of Printable Metal Powders and specifically compare those impacts from traditional production methods to 6k Additives UniMelt® technology.

While many impact categories were modeled and are included in this report, the two most relevant categories showcasing how 6K Additive's UniMelt® process could significantly reduce environmental impacts associated with the production of Printable metal powders were Global Warming Potential & Energy usage.

It was found that for Ni, 6K's UniMelt® process used 13,508 MJ of energy and produced 623kg CO2-eq for every 100kg delivered to the customer. This is 58% energy reduction and 63% carbon emissions reduction from traditional processes in the Cradle-to-End User Scope.

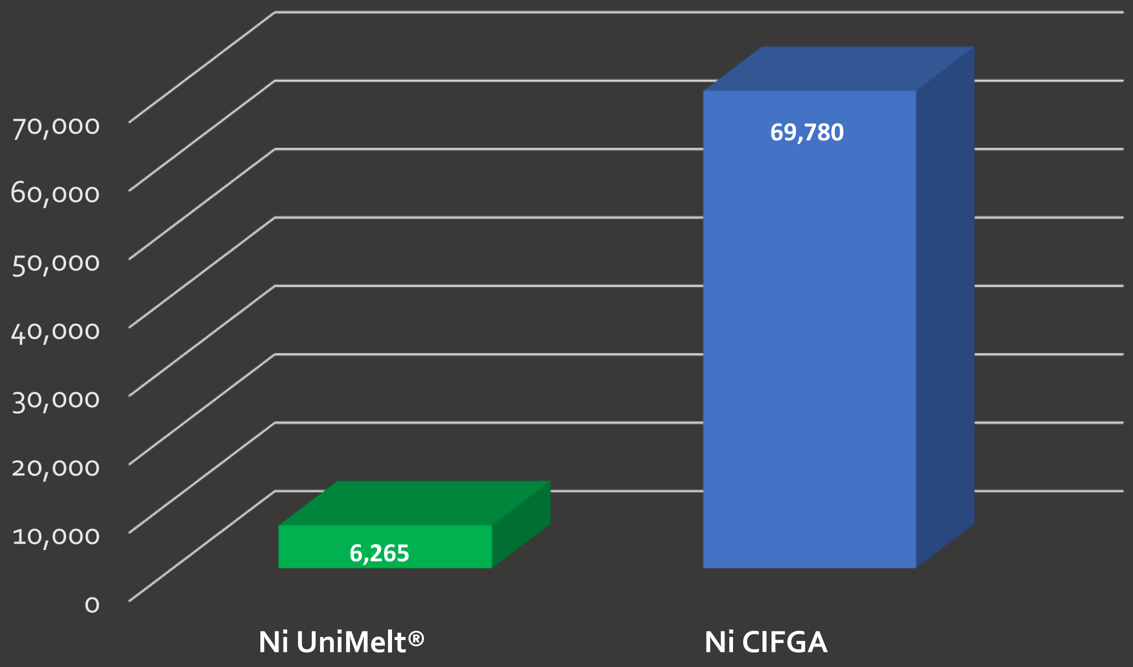
It was found that for Ti, 6K's UniMelt® process used 70,696 MJ of energy and produced 3,289kg CO2-eq for every 100kg delivered to the customer. This is, at minimum, a 53% energy reduction and 60% carbon emission reduction from traditional processes in the Cradle-to-End User Scope.

Process	Global Warming Potential (kg CO2-eq)	% Global Warming Potential Saving	Energy Use (MJ)	% Energy Use Savings
Ni Unimelt	623	51.5%	13,508	45.4%
Ni CIFGA	1,284		24,735	
Ti Unimelt	3,289	59.6% (CIFGA) 75.2% (EIGA)	70,696	52.8% (CIFGA) 71.2% (EIGA)
Ti CIFGA	8,132		149,817	
Ti EIGA	13,233		245,104	

UniMelt® Advantages over Traditional Processes for Nickel

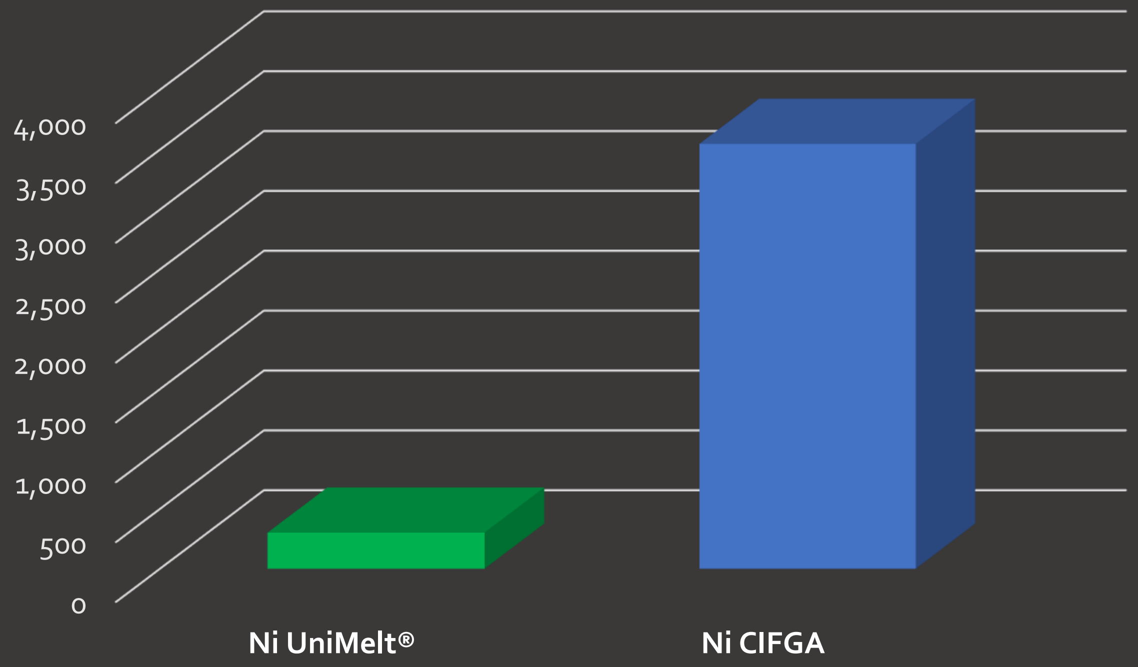
91%
Reduction

Energy Use (MJ)



91.5%
Reduction

Carbon Emissions (Global Warming Potential kg CO_2 eq)



Bringing Powder Reuse Home

IF you're talking about:

- Spherical, AM Powders
- THAT ARE out of spec in chemistry and/or morphology,

6K Additive's UniMelt allows you to:

- "Reuse" powders
- Bring them back into "spec"
- Save money and reduce your carbon footprint.

Thank you!

Eric Bono
Ph: 1.412.260.8048
Em: ebono@6kadditive.com

Appendix S

"The Use of AM for Repairs – An SAE AMS-AM Perspective" – D. Abbott (GE Aerospace)

SAE INTERNATIONAL

THE USE OF AM FOR REPAIR – AN SAE AMSAM PERSPECTIVE

FAA-EASA JOINT AM WORKSHOP

October 20, 2022

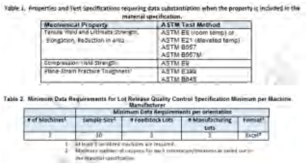
Dave Abbott, Chair
SAE AMS-AM-Repair

Outline

- Brief History and Overview of SAE AMS-AM Committee
- Overview of the Repair Subcommittee
- Overview of SAE AMS-AM Additive Standards Framework
- Adaptation of the framework to Additive Repair
- Discussion on Characterization and Qualification
- Closing Remarks

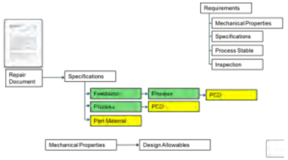
SAE AMS-AM Committee – Time Matters

1st AM spec
AMS 4999
Committee G



1st issued
guidance
document on
specification
minimums

Repair
subcommittee
formalized. 1st
non-metals
standards issued.
Response to
AMSC Roadmap.



Repair Framework

2002

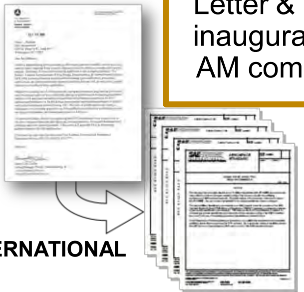
2015

2017

2018

2019

2020

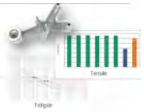


FAA Tasking
Letter & official
inauguration of
AM committee

1st issued
standards -
established
framework for
metals AM
standards

SAE-AMDC
formed under
SAE-ITC to
generate
mechanical
property data

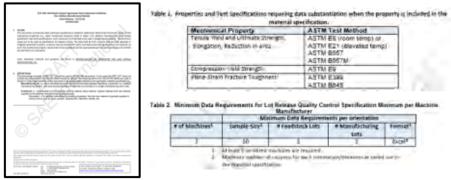
SAE AMS-AMDC
Additive Manufacturing Data Consortium
A Program of SAE ITC



SAE INTERNATIONAL

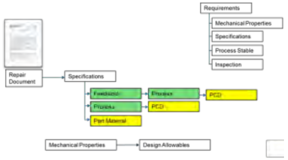
SAE AMS-AM Committee – Time Matters

1st AM spec
AMS 4999
Committee G



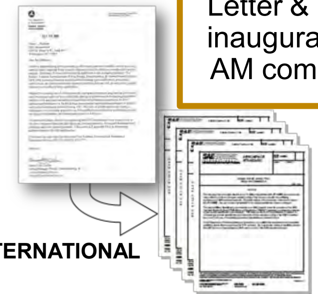
1st issued guidance document on specification minimums

Repair subcommittee formalized. 1st non-metals standards issued. Response to AMSC Roadmap.



Repair Framework

2002 | 2015 | 2017 | 2018 | 2019 | 2020



SAE INTERNATIONAL

FAA Tasking Letter & official inauguration of AM committee

1st issued standards - established framework for metals AM standards

SAE-AMDC formed under SAE-ITC to generate mechanical property data

SAE AMS-AMDC
Additive Manufacturing Data Consortium
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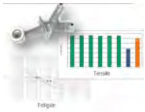

SAE AMS-AM Committee – Time Matters

1st AM spec
AMS 4999
Committee G

2002

2015

2017

2018

2019

2020

Me circa 2000

Repair Framework

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SAE-AMDC
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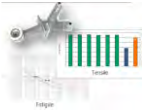
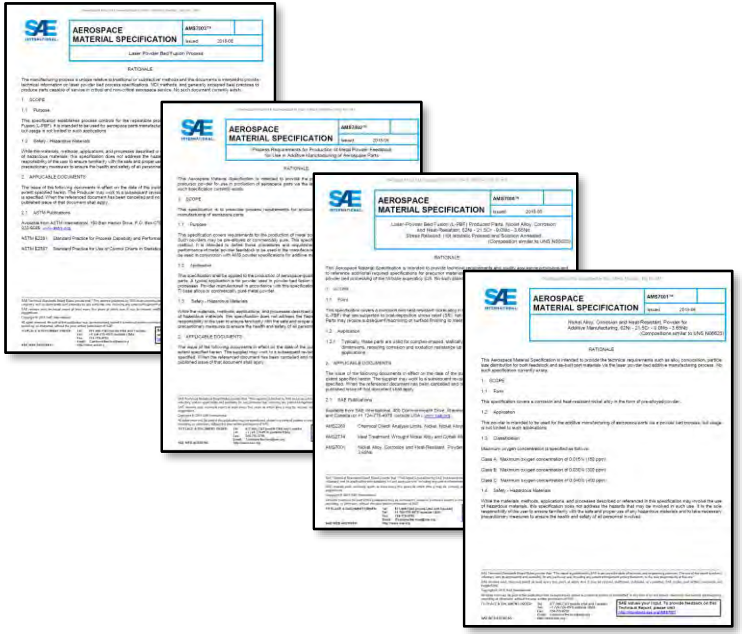
SAE-ITC to
generate
mechanical
roperty data

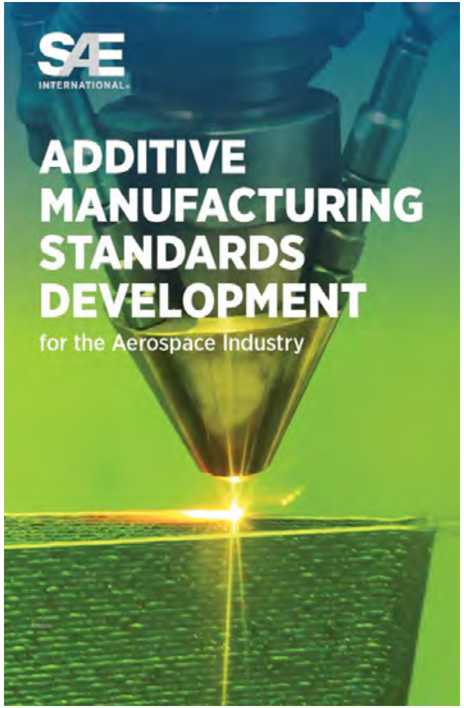


SAE INTERNATIONAL

SAE AMS-AM Committee Scope

To develop and maintain aerospace material and process specifications for additive manufacturing...





SAE AMS-AM By the Numbers – October 2022

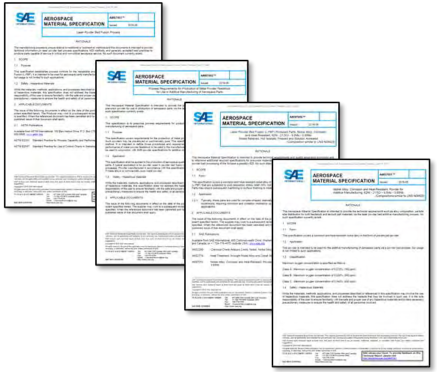
500+ Members

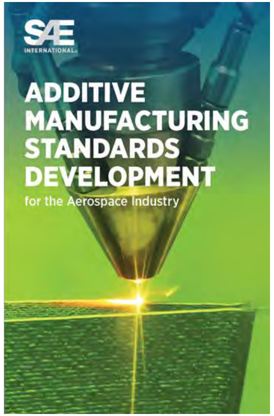
24 Countries

35 Standards
3 Guidance Documents
2 Data Submission Guidelines

31 Metals AMS Published
4 Non-metals AMS Published

28 Works in Progress
5 in revision





AMS-AM Committee – Top Level Organization

AMS-AM
Chair: Hector Sandoval

Coordinating Group

Guidance

AMS-AM-M
Chair: Liz Crisler

AMS-AM-P
Chair: Curt Davies/Paul Jonas

AMS-AM-R
Chair: Dave Abbott

Metals Subcommittee

Materials

Processes

Non-metals Subcommittee

Materials

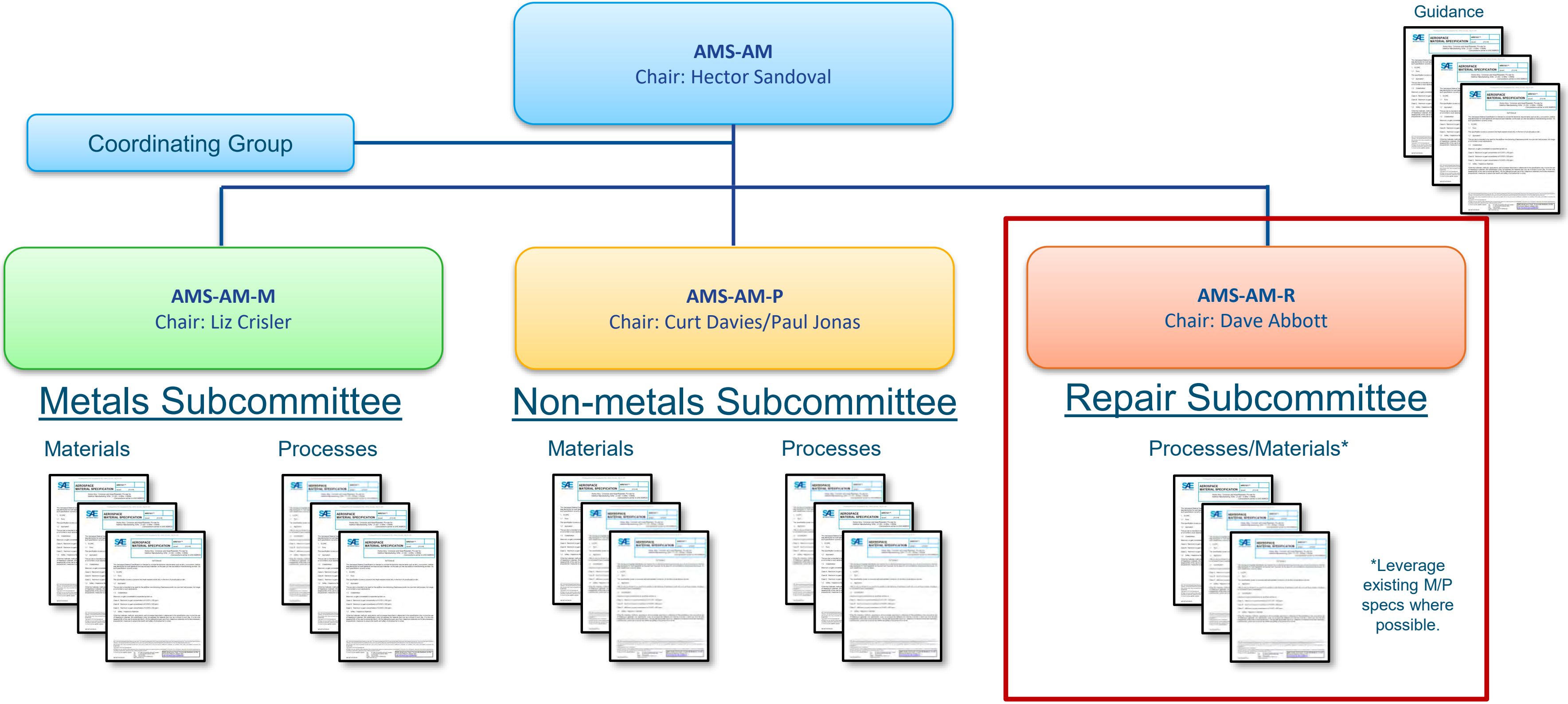
Processes

Repair Subcommittee

Processes/Materials*

*Leverage existing M/P specs where possible.

AMS-AM Committee – Top Level Organization



SAE AMS-AM Repair Subcommittee Overview

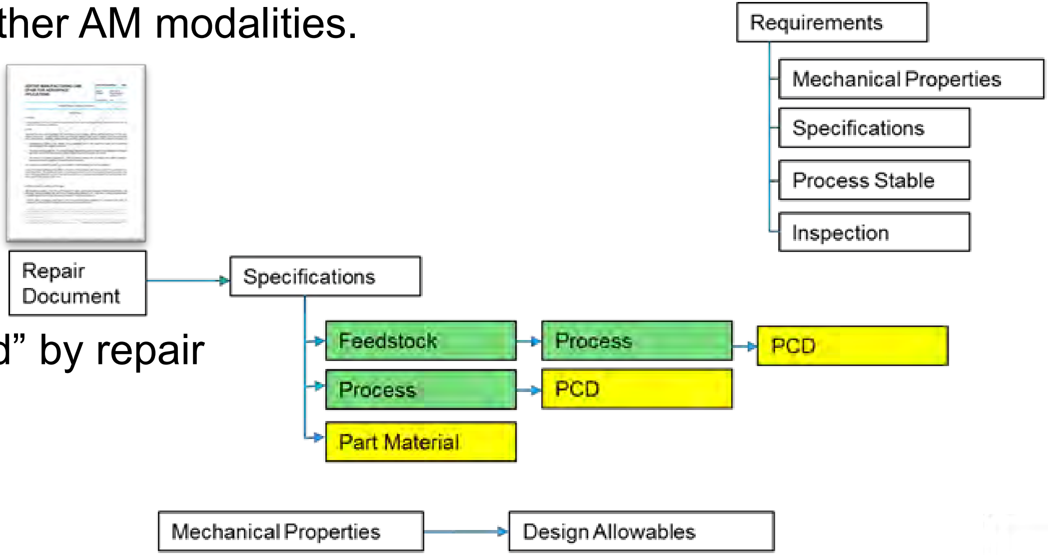
- Established Fall 2019
- Currently developing the specification framework for repair applications
- Creating repair scenario. Developing into guidance document.
- Ti-64, DED. Including PA and Laser DED, wire and powder. Easily extendable to other DED processes and other AM modalities.
- Including **four** types of repair scenarios:

  a) AM repair of conventional part

  b) AM repair of AM part

  c) AM repair where AM part is “consumed” by repair

  d) AM Repair by Replacement*



*Added 2022. Relevant to WG1.

Repair Guidance Document - Outline

Currently 8 sections:

1) Purpose
2) Scope
3) Applicable Documents
4) Repair Considerations
5) Repair Development and Qualification
6) Repair Process
7) Appendix 1 – Example Repair Scenarios
8) Appendix 2 – Useful References

ADDITIVE MANUFACTURING (AM) REPAIR FOR AEROSPACE APPLICATIONS	ARP/AIR EXAMPLE	REV. -
	Issued 2020-12-09 Revised Proposed Draft Updated 2021-04-07 Superseding N/A	

Additive Repair Guidance Document

RATIONALE

1. PURPOSE

To provide guidance for the use of additive manufacturing in the repair and replacement of components, both new make and in service, for aerospace applications.

2. SCOPE

This document provides general guidance for establishing a repair process utilizing additive technology for the repair of aerospace components. It covers the full repair cycle from part removal to part repair to delivery. It includes all modalities, materials, preprocessing, inspection, post processing operations and quality assurance as they pertain to the repair cycle.

- Consideration is given to the criticality of the application and to the impact their repair on the performance characteristics of the repaired component.
- This document is a guide only. The ultimate design responsibility/authority needs to be established and the proper approvals need to be obtained prior to introducing the repaired component into service.
- This version is for metallic applications. There is similarity/overlap with non-metallic since additive materials are processive intensive regardless of material (same framework).

3. APPLICABLE DOCUMENTS (ONLY LIST DOCUMENTS REFERENCED IN THE DOCUMENT)

The issue of the following documents in effect on the date of the purchase order forms a part of this specification to the extent specified herein. The supplier may work to a subsequent revision of a document unless a specific document issue is specified. When the referenced document has been cancelled and no superseding document has been specified, the last published issue of that document shall apply.

3.1 AIA Publications:

Available from Aerospace Industries Association, 1000 Wilson Boulevard, Suite 1700, Arlington, VA 22209-3928, Tel: 703-358-1000, www.aia-aerospace.org free online https://www.aia-aerospace.org/report/certification-of-am-component/

Report: Recommended Guidance for Certification of AM Components, AIA Additive Manufacturing Working Group, February 2020.

SAE values your input. To provide feedback on this Technical Report, please visit http://standards.sae.org/PRODCODE

Section	Topic
1	Purpose
2	Scope
3	Applicable Documents
3.1	AIA
3.2	ASTM
3.3	ISO
3.4	SAE
4	Repair Considerations
4.1	Repair versus Replacement
4.2	Part Criticality
4.3	Part Performance
4.4	Part Functionality
4.5	Qualification an
4.6	Types of Repair
	art Size and co
	aterial type
	Component
	Feedstock M
	esign Requiren
	epair supplier
	ost processing

5.0	REPAIR DEVELOPMENT AND QUALIFICATION
5.1	Design Evaluation
5.2	Modality Selection
5.3	Material Selection
5.4	Repair Process Design/Planning
5.4.1	Part Preparation
5.4.2	Initial NDI
5.4.2.1	Part/Repair Alignment to the Digital Model
5.4.2.2	
5.4.3	Toolpath Generation
5.4.4	AM-Process Development
5.4.5	Repair Process
5.4.5.1	Repair Trials - Basic
5.4.5.2	Evaluation
5.4.5.3	Heat Treat Trials
5.4.5.4	Evaluation
5.4.5.5	Repair Trials - Representative Geometry
5.4.5.6	Evaluation
5.4.5.7	Machining Trials
5.4.5.8	NDI
5.5	Qualification - Parameters/Schedule
5.5.1	Microstruc
5.5.2	Chemistry
5.5.3	Mechanic
5.6	Repair Docum
5.6.1	Creation
5.6.2	Approval

6	Repair Process
6.1	Part Removal
6.2	Part Cleaning/Prep for NDI
6.3	NDI
6.4	Machine Program/Deposition Program
6.5	Machine Prep
6.6	Verification
6.7	Deposit
6.8	Heat Treat
6.9	Machine
6.10	NDI
6.11	Surface enhancement/coating
6.12	Lot acceptance testing (chem, mech test)
6.13	Final inspection (visual, dimensional, functional)
6.14	Deliver
7	APPENDIX 1 - EXAMPLE REPAIR SCENARIOS
7.1	Example Repair 1 - L-DED Wire Ti-64 Structural Component - Wrought
7.2	Example Repair 2 - LPBF Blade Tip (proposed)
7.3	Example Repair 3 - Blisk repair
7.4	Example Repair 4 - Sliver repair
7.5	Example Repair 5 -
7.6	Example Repair 6 -
8	APPENDIX 2 - USEFUL REFERENCES

SAE AMS-AM Standards Framework -> “One to the Many to Make One”

Material Specification – AMS 7000 LPBF Alloy 625

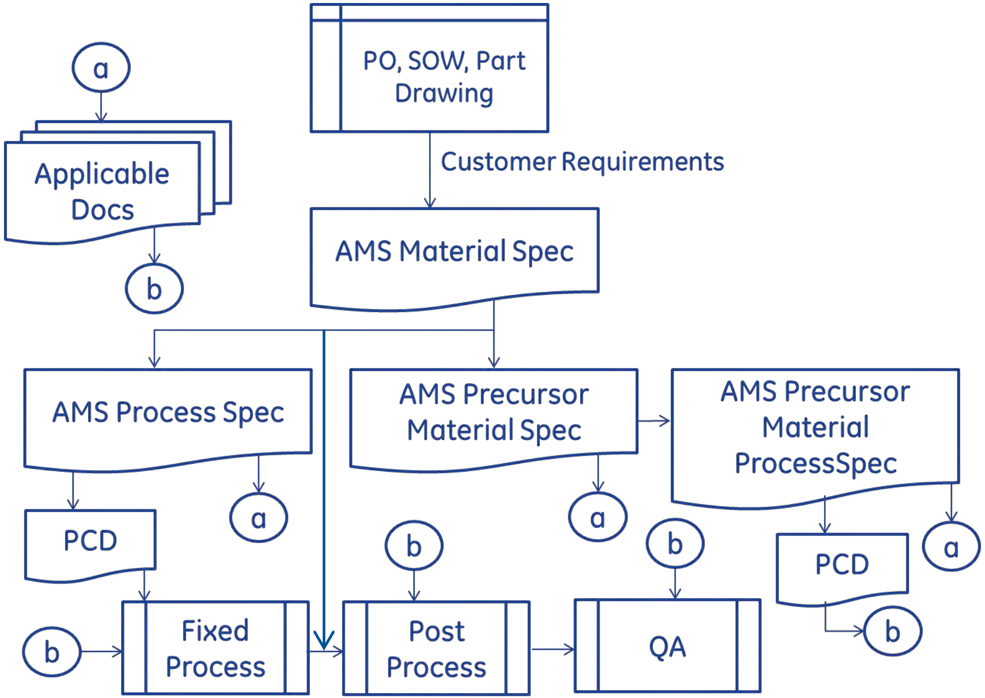
→ Process Specification – AMS 7003 LPBF Process

→ Feedstock Material Specification – AMS 7001 Alloy 625 Powder

→ Feedstock Process Specification – AMS 7002 Powder Process

- The SAE AMS-AM Specification Framework establishes the control of the AM component manufacturing process from the feedstock through the finish product.
- There are both prescriptive and performance-based aspects to the framework.

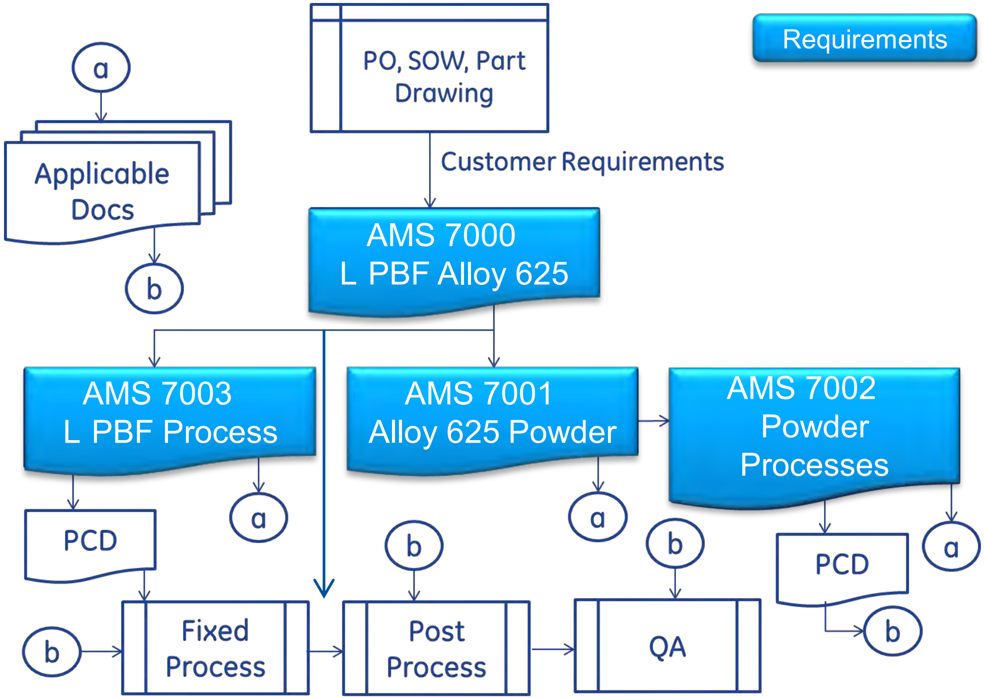
Typical Requirements Flowdown for an Additive Process



Representative Requirements Flowdown

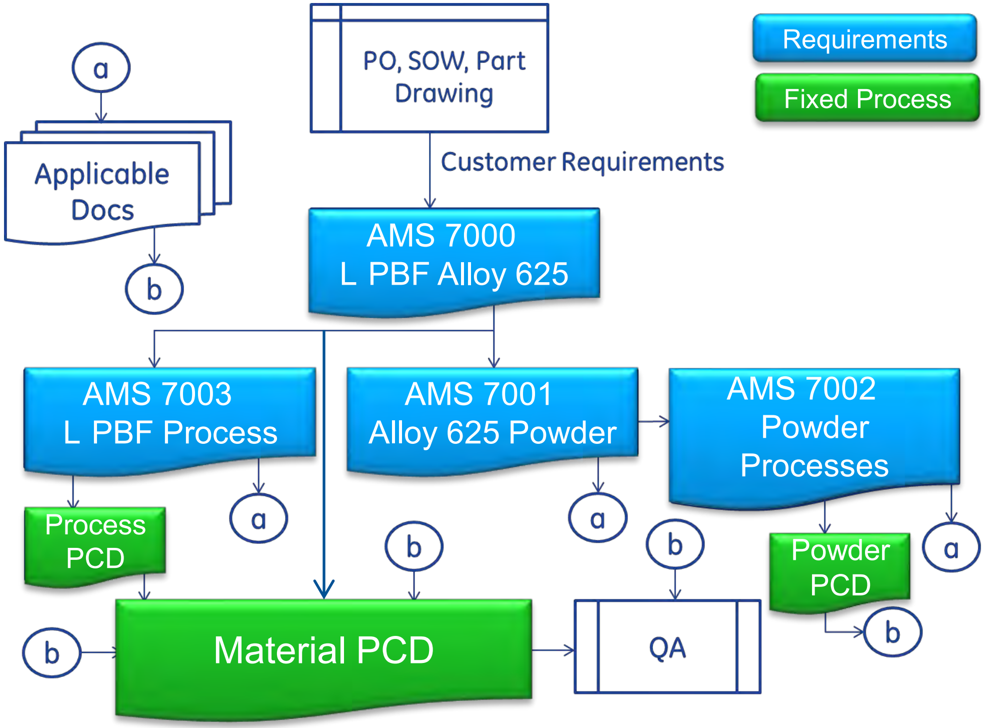
- Typical flowdown from the customer to the final product.
- PO → SOW → Drawing → Specification

Specification Framework Applied to First AMSAM Specifications



Framework valid for all AM processes and materials

Process Control Document (PCD) = Fixed Process for Consistency

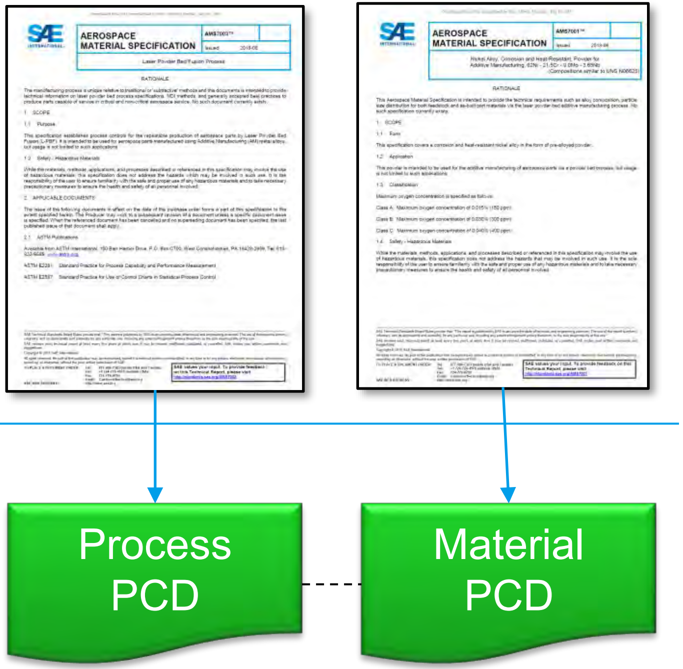


Framework valid for all AM processes and materials

Process Control: Two-level Control Model

Level 1: AMS Variable Process Standards

- AMS 7003, 7005, 7007, 7010, 7022, 7027, 7029, 7034
- Provide high level control.
- Require proper processes and procedures are in place to ensure quality and consistency in the final product.
- PCD is the vehicle to do that.



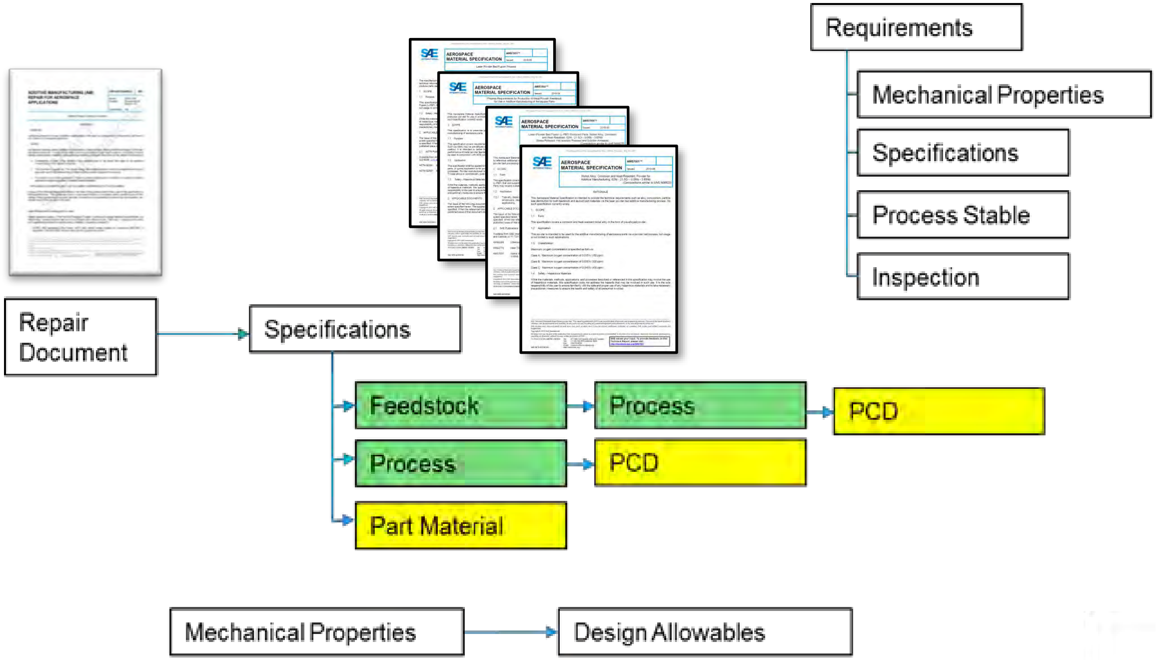
Level 2: Process Control Document (PCD)

- AKA “the process spec”, i.e., the “recipe”
- Affords IP protection
- Provides control
- Convertible to “Public PCD” for public data repositories

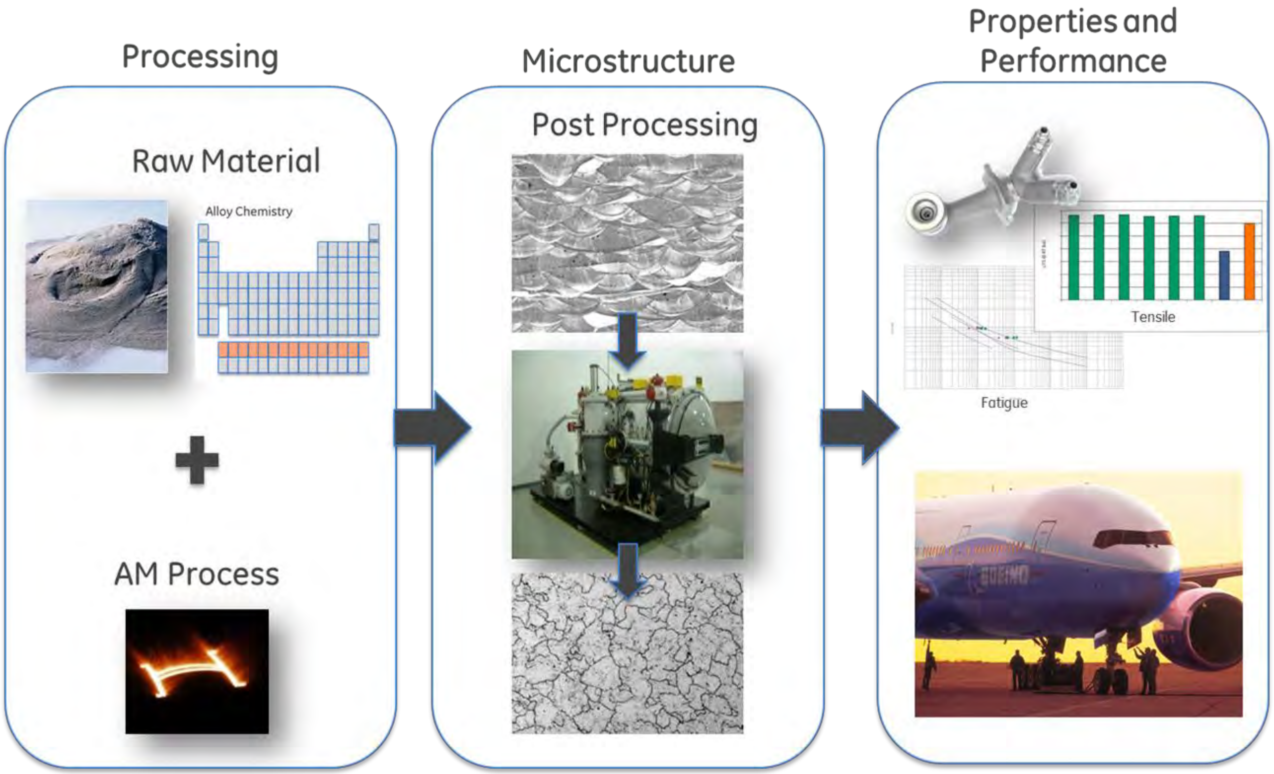
SAE AMS-AM Additive Repair Framework – Under Development

- Leveraging current framework for new parts.
- Leveraging existing specifications where possible (feedstock, processes).
- The challenge is a finish material specification that covers all of the part.
- Characterization and Qualification of both the material and the process are cost and time challenges.

Current AM Repair Framework

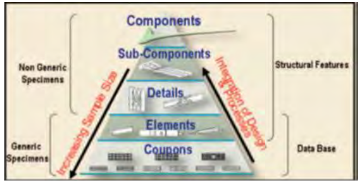


Additive Manufacturing Process Basics – Also Applies to Repair



Process – Structure – Property - Performance

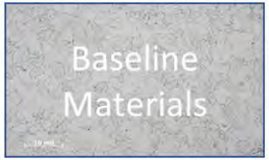
So does the Spectrum of Materials and Material Systems…



Advances in Composite Materials - Ecodesign and Analysis
Edited by Dr. Brahim Attaf

AM Materials

Commodity
- Recrystallization
- Equiaxed
- Homogeneous
- Isotropic



Tailored Microstructure
- Monolithic
- Continuous
- Some degree of anisotropy
- Some inhomogeneity

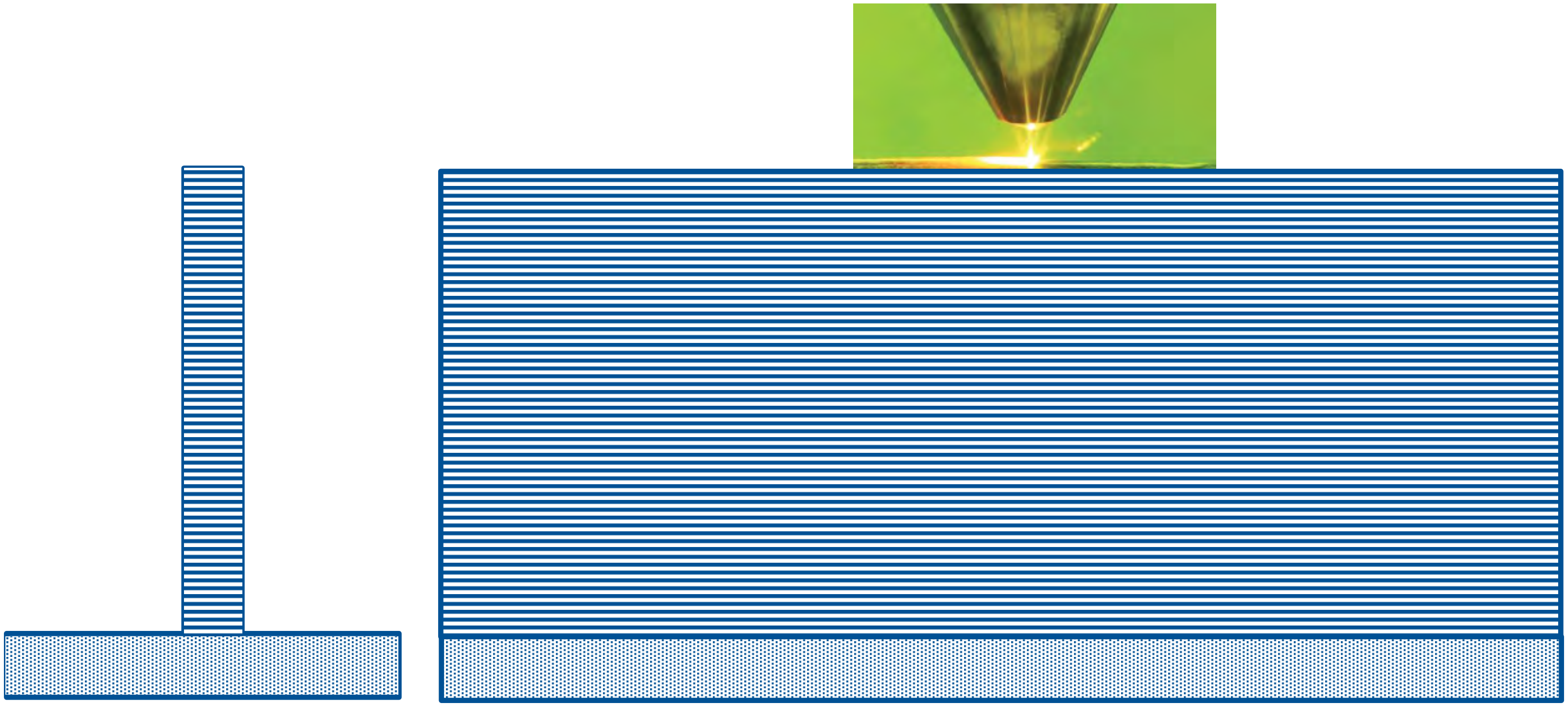
Composite
- Discrete phases
- Anisotropic
- inhomogeneous

AMS-AM Today → Future

Increasing Complexity

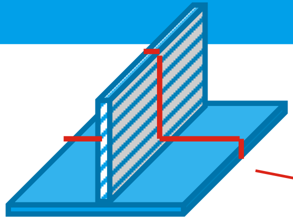
Process – Structure – Property - Performance

Laser-DED Repair Example – Thin Wall on Plate

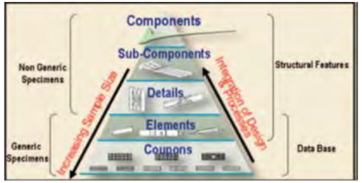


Process – Structure – Property - Performance

In Cross Section…



AM Materials



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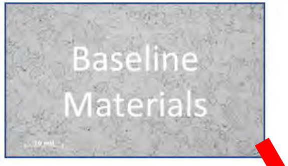


AMS-AM Today

Tailored Microstructure

Monolithic
Continuous
Some degree of anisotropy
Some inhomogeneity

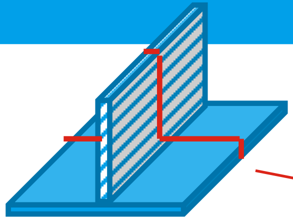
Composite

- Discrete phases
- Anisotropic
- inhomogeneous

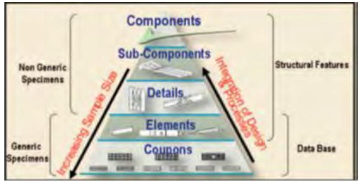
Increasing Complexity → Future

Hybrid Material.

Spectrum of Materials and Material Systems More Complex for Repair…



AM Materials



Advances in Composite Materials – Ecodesign and Analysis
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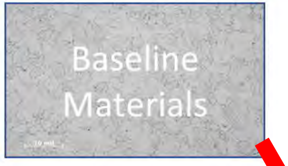


AMS-AM Today

Tailored Microstructure

Monolithic
Continuous
Some degree of anisotropy
Some inhomogeneity

Composite

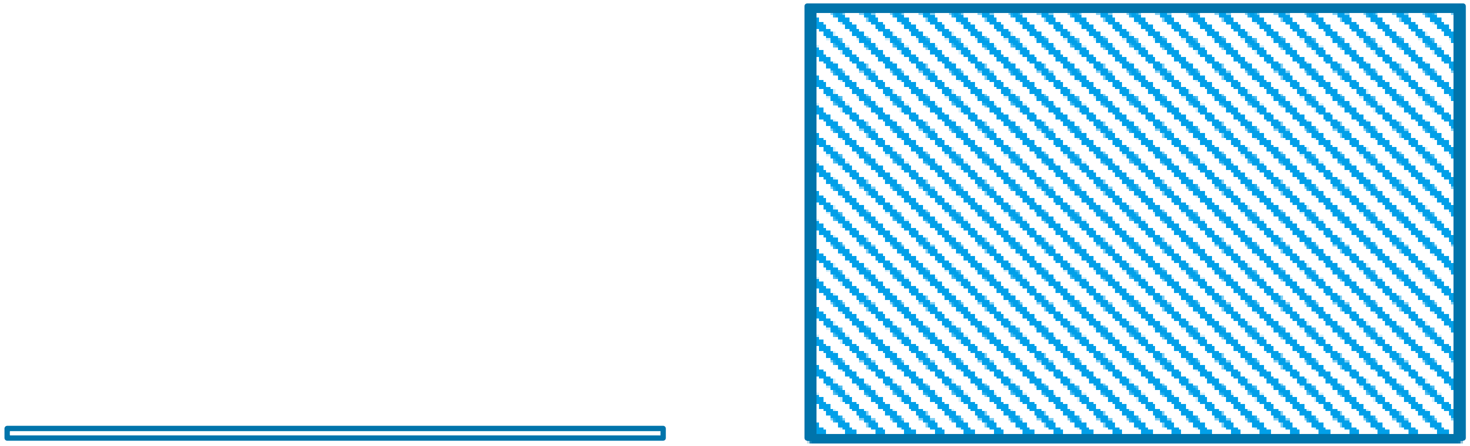
- Discrete phases
- Anisotropic
- inhomogeneous

Increasing Complexity → Future

Behaves more like a composite part.

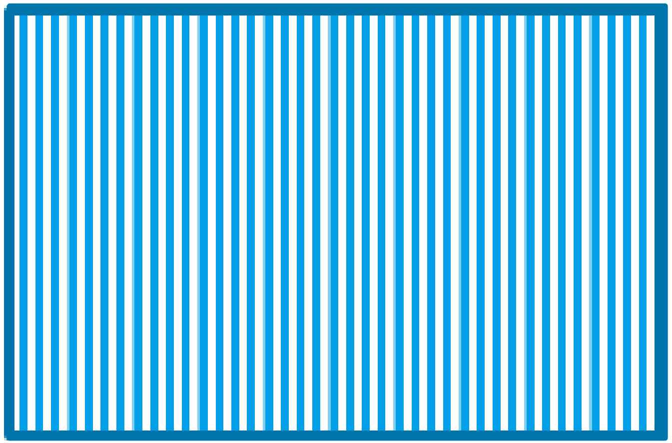
Repair Qualification -> Part Qualification -> Part Families

- Composites
  - Ply is consistent across the whole layer



Repair Qualification -> Part Qualification -> Part Families

- Composites
  - Ply is consistent layer to layer
  - Rotation affects directionality



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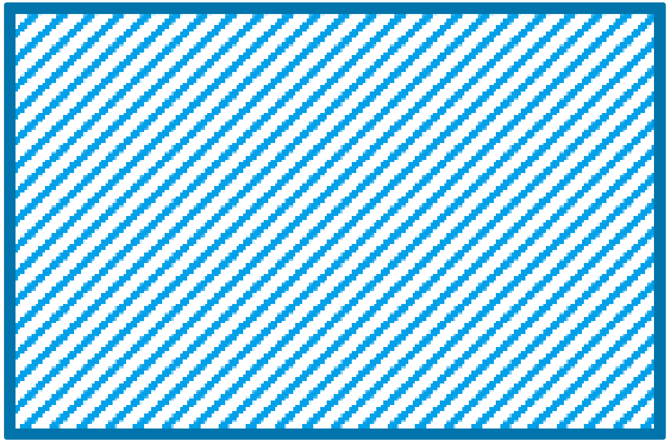
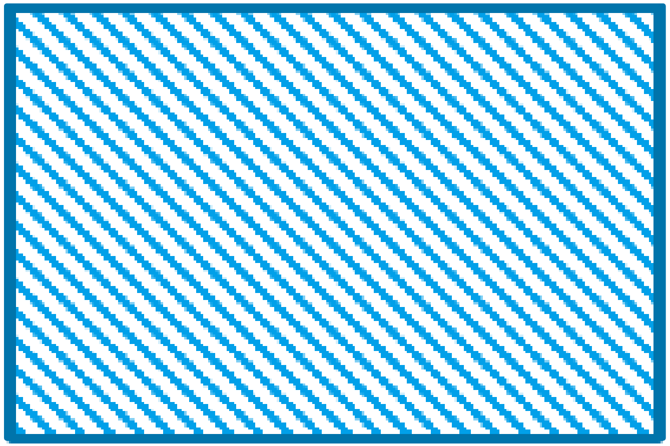


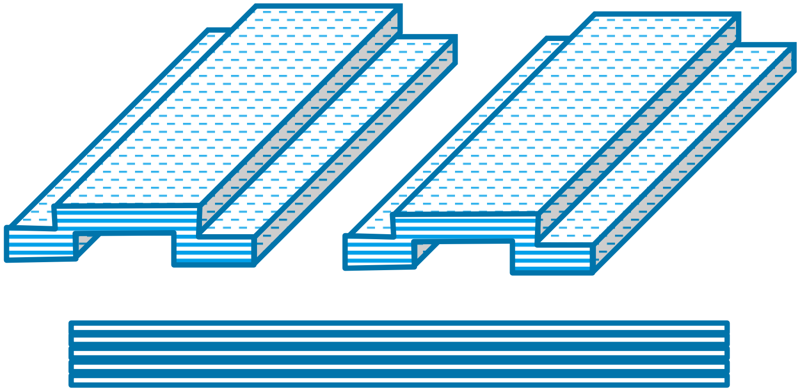
Repair Qualification -> Part Qualification -> Part Families

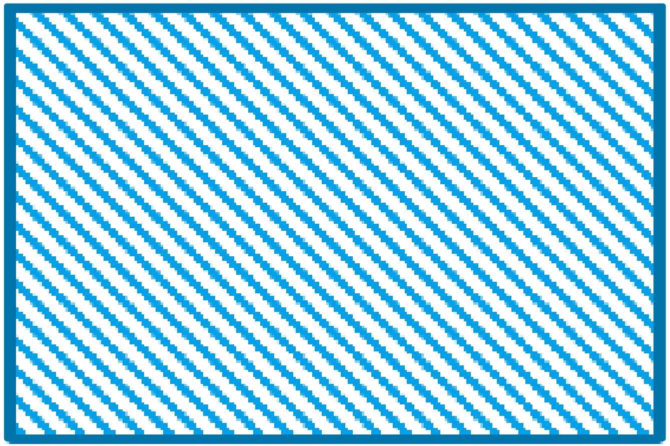
- Composites
  - Ply is consistent layer to layer
  - Rotation affects reduce directionality



Repair Qualification -> Part Qualification -> Part Families

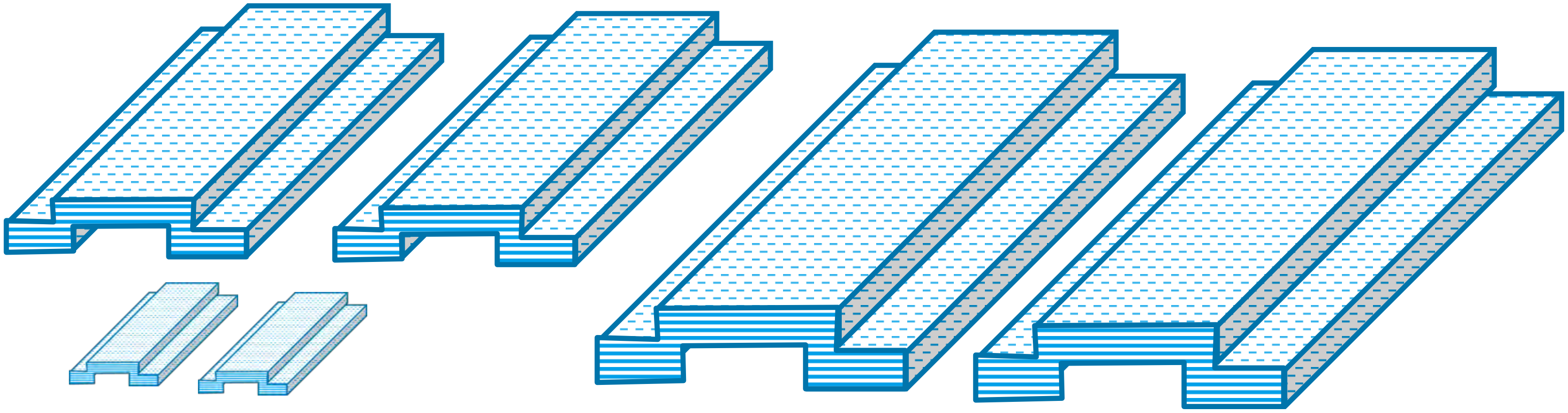
- Composites
  - Ply is consistent layer to layer
  - Rotation affects directionality
  - Consistent part to part





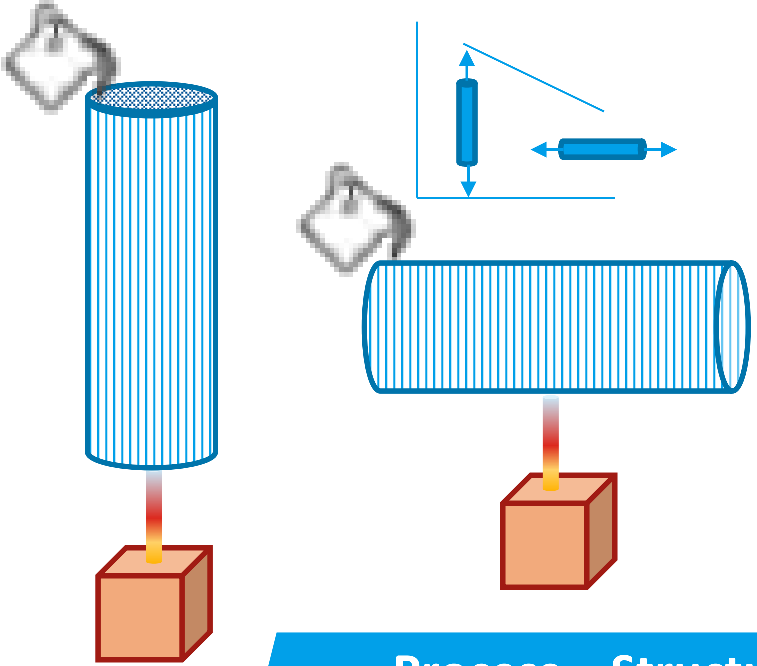
Repair Qualification -> Part Qualification -> Part Families

- Composites
  - Ply is consistent layer to layer
  - Rotation affects directionality
  - Consistent part to part and within part family



Repair Qualification -> Part Qualification -> Part Families

- Metals
  - Part families may work if microstructure and properties are consistent



Process – Structure – Property - Performance

Repair Qualification -> Part Qualification -> Part Families

- Metals
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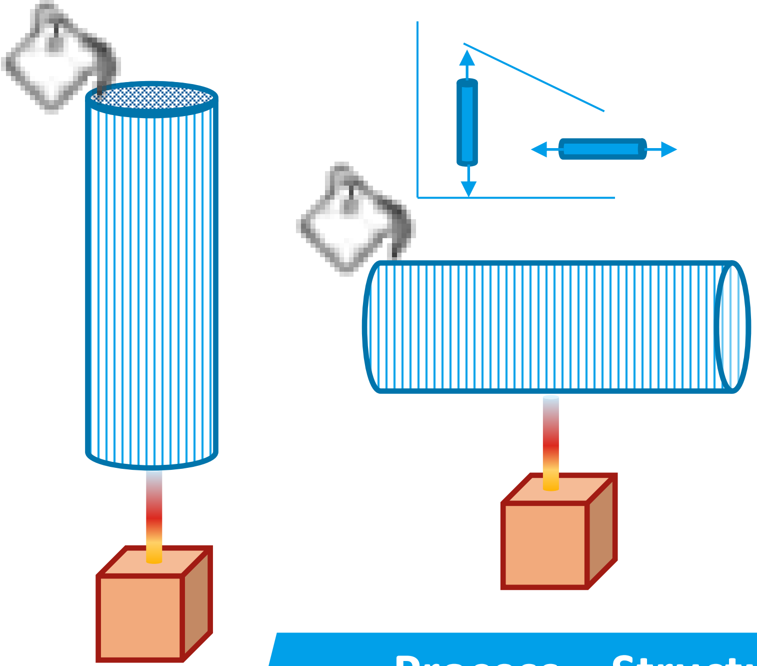
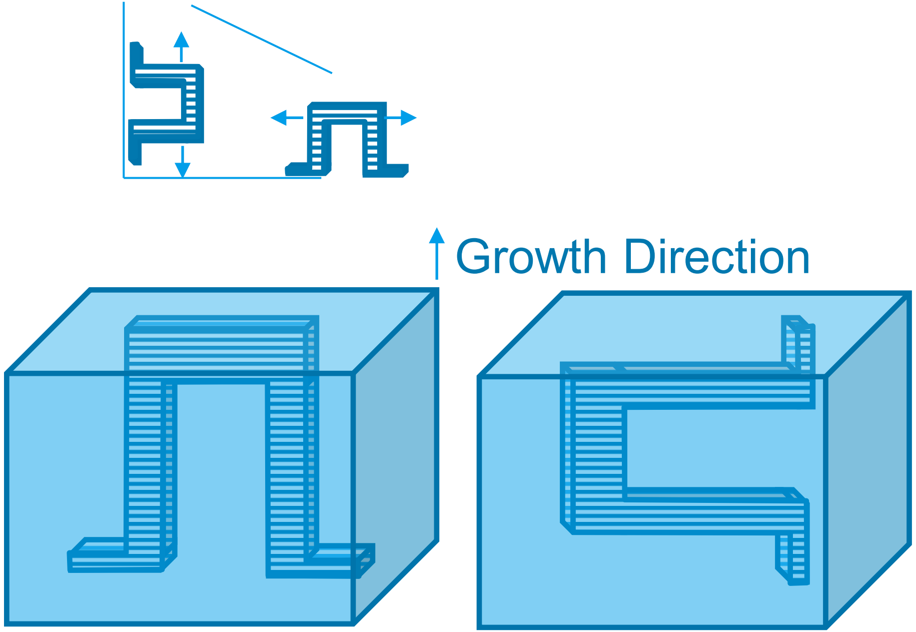
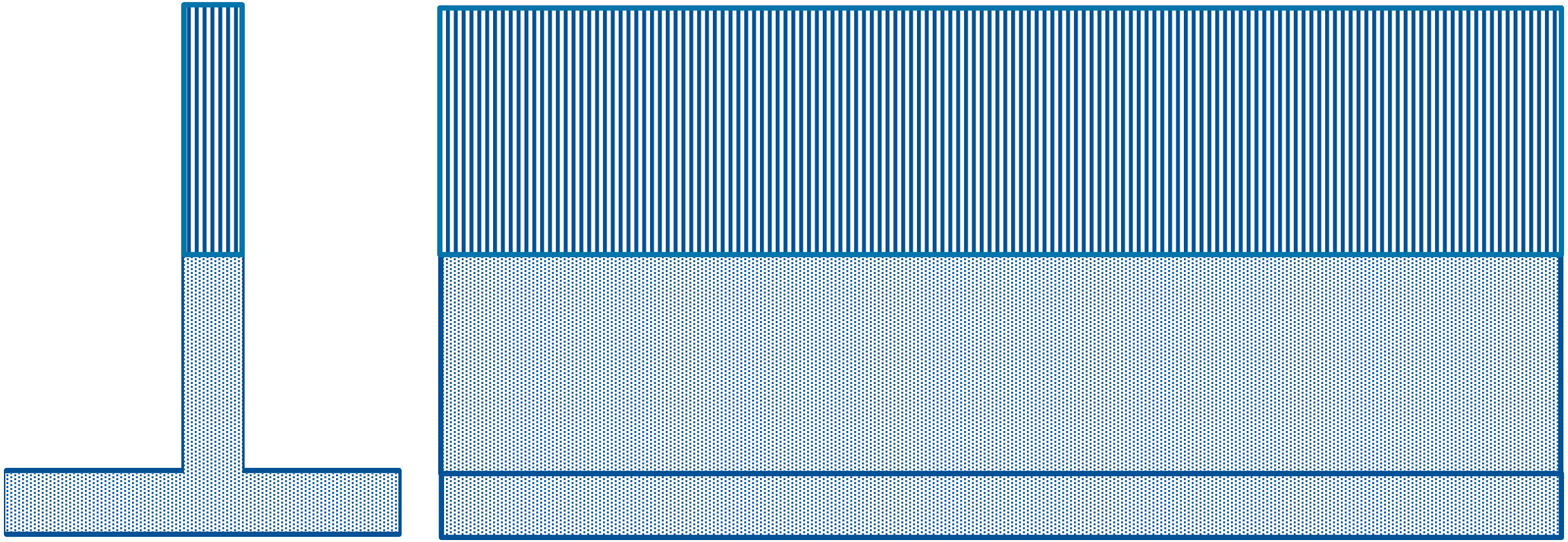




Process – Structure – Property - Performance

Repair Qualification -> Part Qualification

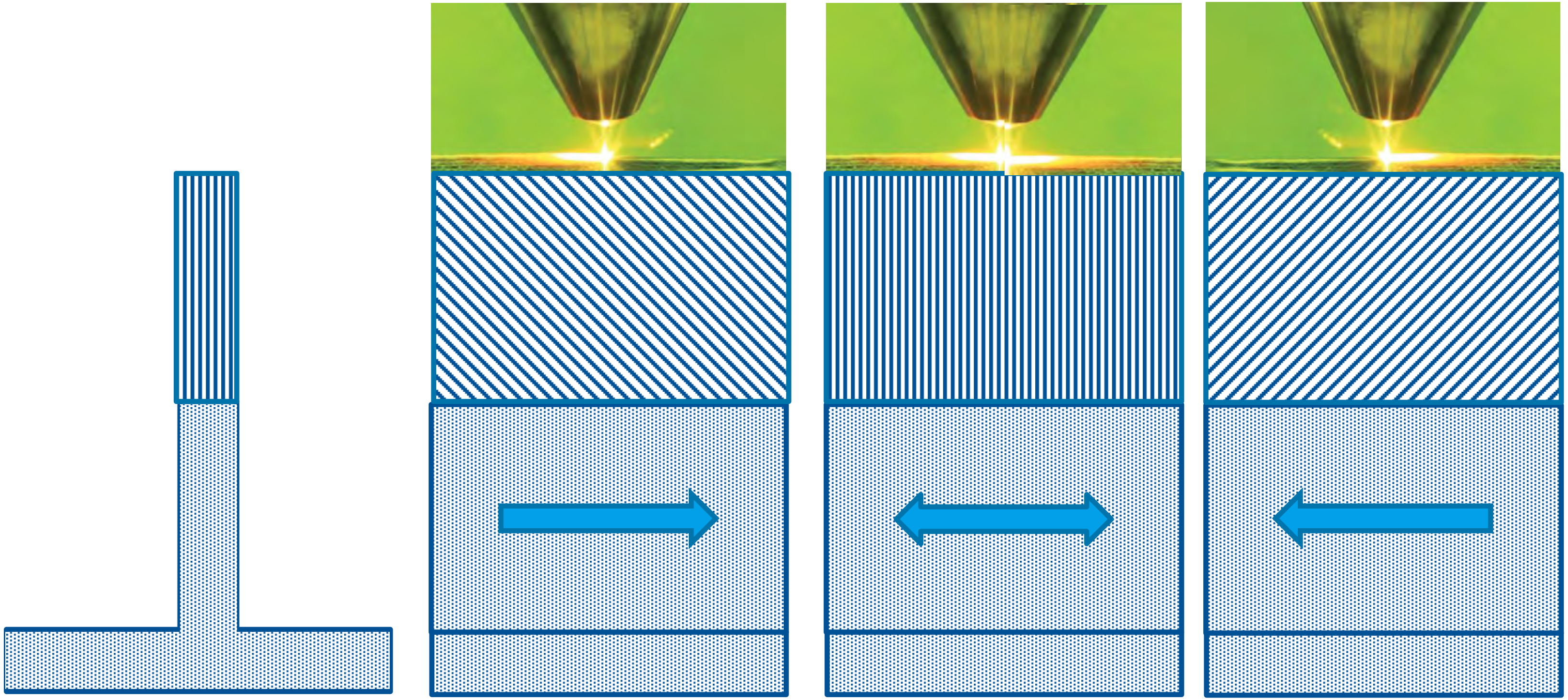
- Simplified repair example



Process – Structure – Property - Performance

Repair Qualification -> Part Qualification

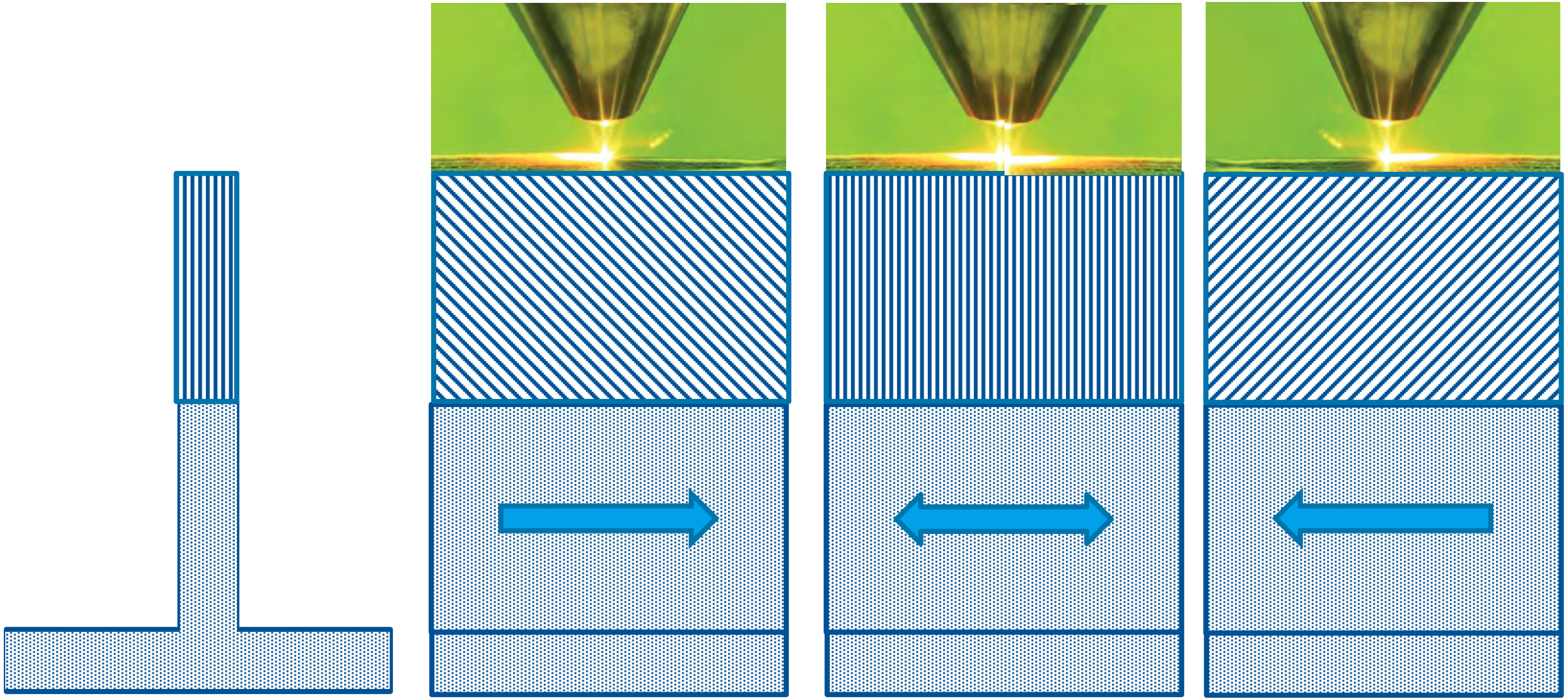
- Need process standardization.



Process – Structure – Property - Performance

Repair Qualification -> Part Qualification

- Process Standardization -> Additive Feature Qualification (AFQ)?



Process – Structure – Property - Performance

Repair Qualification -> Part Qualification -> Part Families

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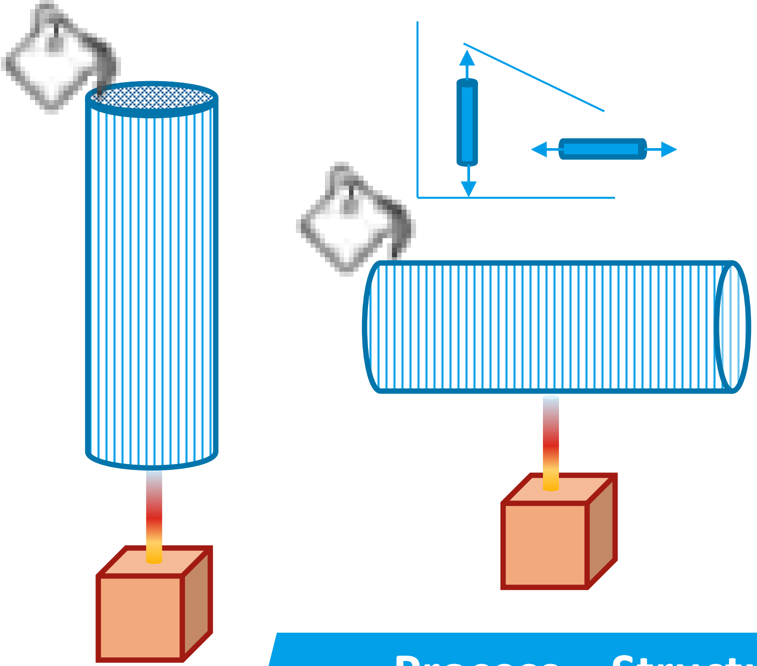
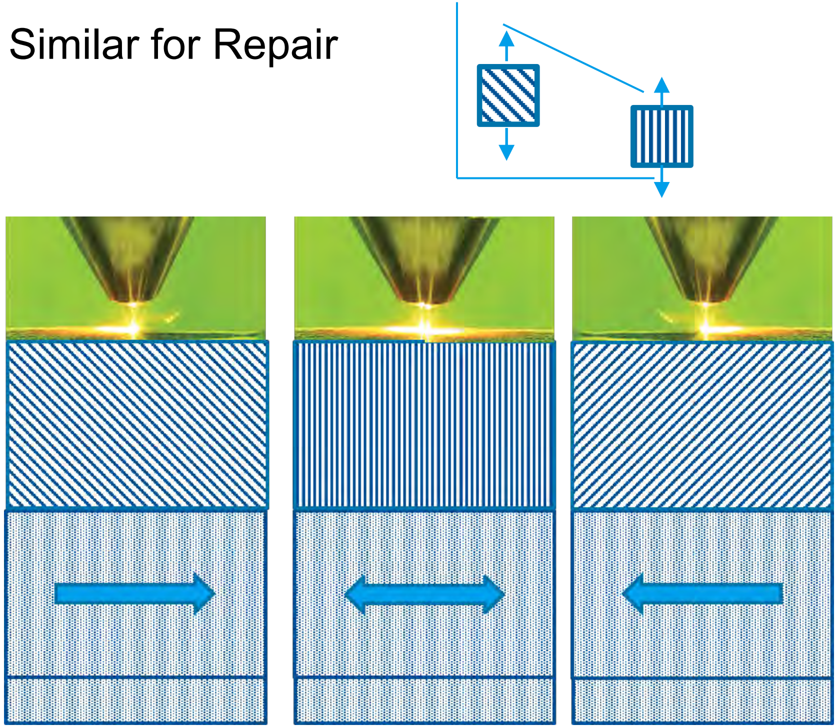


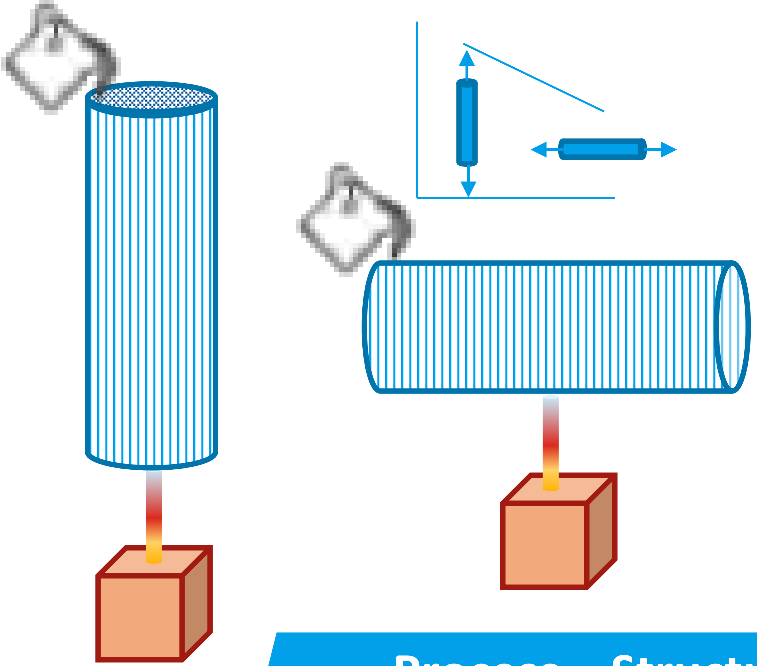
- Similar for Repair



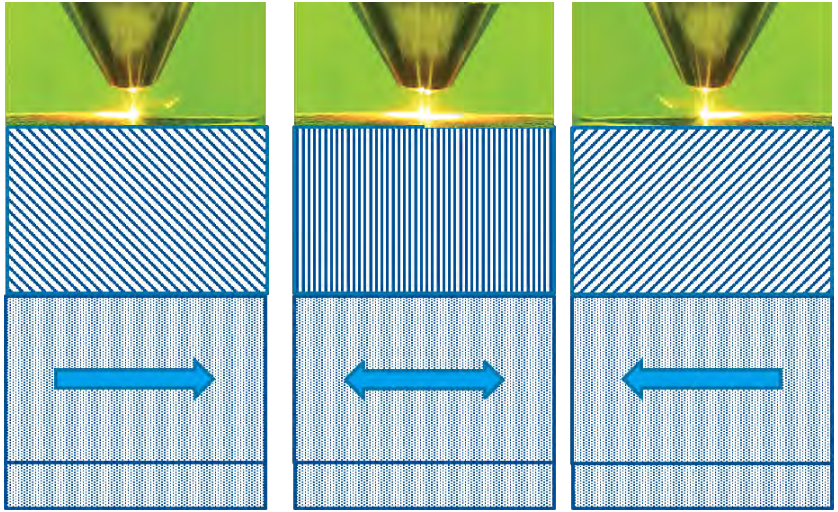
Process – Structure – Property - Performance

Repair Qualification -> Part Qualification -> Part Families

- Metals
  - Part families may work if microstructure and properties are consistent



- Similar for Repair
- Need to consider effect on both the material and the part performance characteristics



Process – Structure – Property - Performance

Additive Repair Opportunities and Challenges

Benefits of Additive Repair:

- Potential cost savings
- Potential time savings
- Enables repair of out-of-production parts

Where We Need Help:

- Standardized criticality classification
- Standardized qualification route
- Standards for Additive Repair
- Access to Data and Critical Information
  - Material Characterization
  - Design Requirements
    - Include performance and life considerations
  - Design Analyses

Questions?

If interested in participating, contact one of the following:

Dave Abbott
SAE AMS AM Repair Chair
GE Aerospace
m +1 513.284.9677
dave.abbott@ge.com

Appendix T

"Progress in Development of NDE Tools for Classification, Process Monitoring and Acceptance of AM products"
– L. Schaefer (General Atomics)

Progress in Development of NDE Tools for Classification, Process Monitoring & Acceptance of AM Products

FAA-EASA Workshop on Qualification/Certification of Additively Manufactured Parts
October 20, 2022

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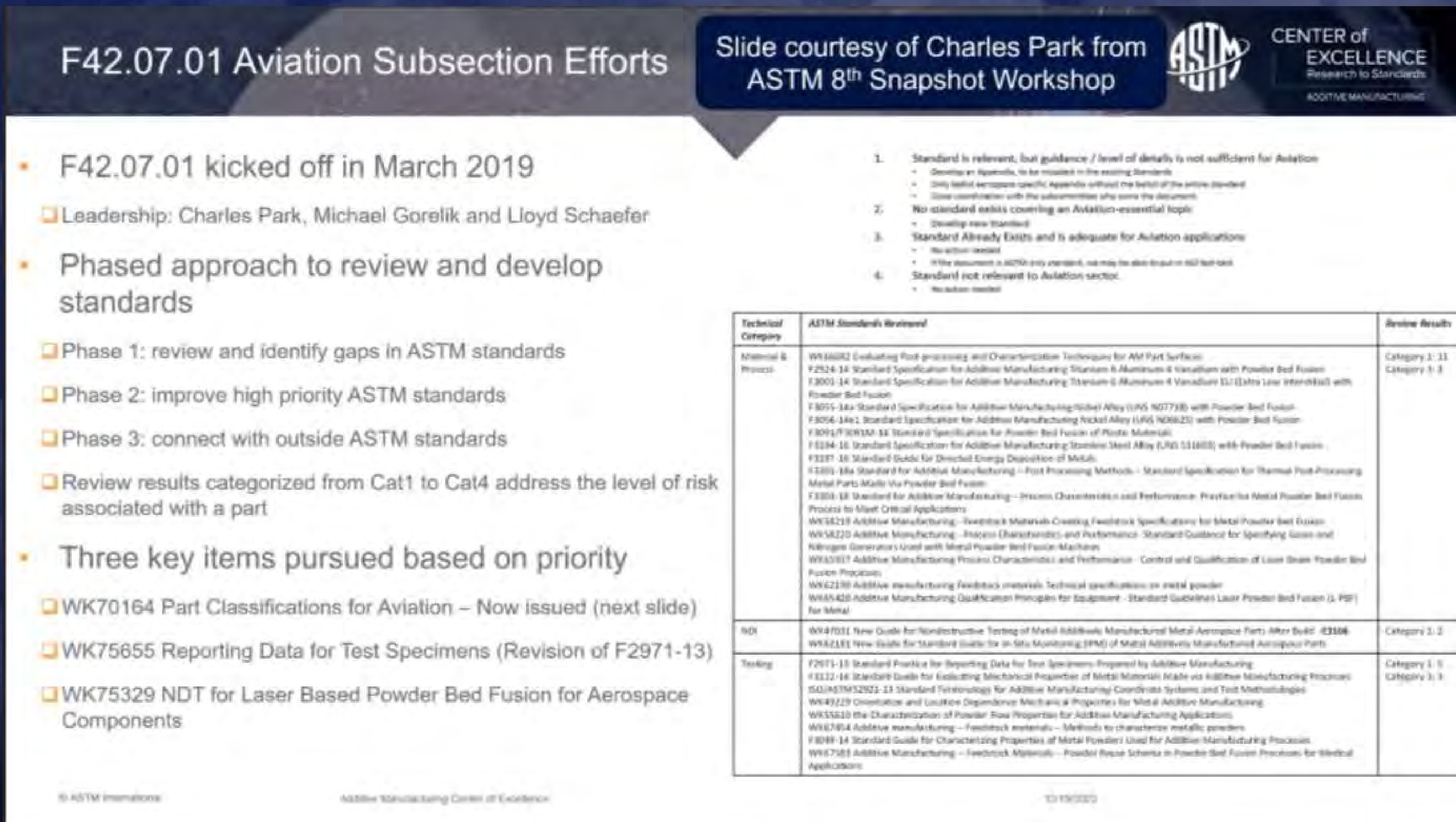
GENERAL ATOMICS AERONAUTICAL

Introduction

- We briefly review today the efforts of F42.07.01 with attention to the NDE subgroup efforts since 2019



GENERAL ATOMICS AERONAUTICAL

Introduction

- We proceed from the structure of ASTM E3166 plus upstream process monitoring to minimize sorting of finished product

Designation: E3166 – 20$^{\varepsilon 1}$

INTERNATIONAL

Standard Guide for Nondestructive Examination of Metal Additively Manufactured Aerospace Parts After Build[1]

This standard is issued under the fixed designation E3166; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

ε[1] NOTE—The caption for Fig. 10 was editorially corrected in August 2020.

1. Scope

1.1 This guide discusses the use of established and emerging nondestructive testing (NDT) procedures used to inspect metal parts made by additive manufacturing (AM).

1.2 The NDT procedures covered produce data related to and affected by microstructure, part geometry, part complexity, surface finish, and the different AM processes used.

1.3 The parts tested by the procedures covered in this guide are used in aerospace applications; therefore, the inspection requirements for discontinuities and inspection points in general are different and more stringent than for materials and components used in non-aerospace applications.

1.4 The metal materials under consideration include, but are not limited to, aluminum alloys, titanium alloys, nickel-based alloys, cobalt-chromium alloys, and stainless steels.

1.5 The manufacturing processes considered use powder and wire feedstock, and laser or electron energy sources. Specific powder bed fusion (PBF) and directed energy deposition (DED) processes are discussed.

1.6 This guide discusses NDT of parts after they have been fabricated. Parts will exist in one of three possible states: *(1)* raw, as-built parts before post-processing (heat treating, hot isostatic pressing, machining, etc.), *(2)* intermediately machined parts, or *(3)* finished parts after all post-processing is completed.

1.7 The NDT procedures discussed in this guide are used by cognizant engineering organizations to detect both surface and volumetric flaws in as-built (raw) and post-processed (finished) parts.

1.8 The NDT procedures discussed in this guide are computed tomography (CT, Section 7, including microfocus CT), eddy current testing (ET, Section 8), optical metrology (MET, Section 9), penetrant testing (PT, Section 10), process compensated resonance testing (PCRT, Section 11), radiographic testing (RT, Section 12), infrared thermography (IRT, Section 13), and ultrasonic testing (UT, Section 14). Other NDT procedures such as leak testing (LT) and magnetic particle testing (MT), which have known utility for inspection of AM parts, are not covered in this guide.

1.9 Practices and guidance for in-process monitoring during the build, including guidance on sensor selection and in-process quality assurance, are not covered in this guide.

1.10 This guide is based largely on established procedures under the jurisdiction of ASTM Committee E07 on Nondestructive Testing and is the direct responsibility of the appropriate subcommittee therein.

1.11 This guide does not recommend a specific course of action for application of NDT to AM parts. It is intended to increase the awareness of established NDT procedures from the NDT perspective.

1.12 Recommendations about the control of input materials, process equipment calibration, manufacturing processes, and post-processing are beyond the scope of this guide and are under the jurisdiction of ASTM Committee F42 on Additive Manufacturing Technologies. Standards under the jurisdiction of ASTM F42 or equivalent are followed whenever possible to ensure reproducible parts suitable for NDT are made.

1.13 Recommendations about the inspection requirements and management of fracture critical AM parts are beyond the scope of this guide. Recommendations on fatigue, fracture mechanics, and fracture control are found in appropriate end user requirements documents, and in standards under the jurisdiction of ASTM Committee E08 on Fatigue and Fracture.

NOTE 1—To determine the deformation and fatigue properties of metal parts made by additive manufacturing using destructive tests, consult Guide F3122.

NOTE 2—To quantify the risks associated with fracture critical AM parts, it is incumbent upon the structural assessment community, such as ASTM Committee E08 on Fatigue and Fracture, to define critical initial flaw sizes (CIFS) for the part to define the objectives of the NDT.

1.14 This guide does not specify accept-reject criteria used in procurement or as a means for approval of AM parts for

[1] This guide is under the jurisdiction of ASTM Committee E07 on Nondestructive Testing and is the direct responsibility of Subcommittee E07.10 on Specialized NDT Methods.

Current edition approved Feb. 1, 2020. Published July 2020. DOI: 10.1520/E3166-20E01.

GENERAL ATOMICS AERONAUTICAL

Agenda

- Activities in selecting/fitting legacy NDE methods to AM – CT, PAUT, EC, FPI…
- Round Robin studies of 316 and IN718 samples as printed and post HIP/HTx
- NDE signals for process health and mechanical properties (F357, AlSi10 et al)
- Guided by Effects of Defects, How well do our AM NDE tools work?
- Converting our learnings into standards to classify and accept AM products

Nomination of NDE Methods for AM

E3166 – 20ε1

TABLE 1 Nondestructive Test Detection of Typical Additive Manufacturing Flaws[A,B]

Flaw/Artifact[C]	Observed in PBF or DED?	Why?	Post-Process Detection	Comment
Porosity	both	Poor selection of parameters, moisture or contamination of feed material or process environment, inadequate handling, storage, vaporization of minor alloying constituents depending on material feedstock. Errors in precision of beam delivery.	Depending on sample geometry and size of porosity, may be detected using CT/ET[G] /IRT/PCRT/RT/UT	HIP recoverable (may not be fully recoverable)
Voids	both	Powder run out, changes in the energy density of the impinging beam creating keyhole melting or vaporization conditions that entrap voids or create spatter (spherical molten ejecta) leaving holes, and voids that may be covered by subsequent layers of fused materials. System drift or calibration issues may come into play to create conditions of LOF. Bridging of powder in the hopper/poor flow properties.	Depending on sample geometry and size of voids, may be detected using CT/ET[G] /IRT/PCRT/RT/UT	HIP recoverable depending on size (not fully recoverable regardless)
Layer flaws	Unique to AM[F]	Interruption to powder supply, optics systems errors (laser) or errors in data. Contamination of build environment purity (inert gas interruption) or other process interruption such as changing the filament emitter within an electron beam gun. Powder supply blending or mixing between one batch and another, a new lot of filler wire, etc.	Depending on sample geometry and size of flaw, may be detected using CT/ET[G] /PCRT/RT/UT	HIP recoverable depending on size (not fully recoverable regardless)
Cross-layer flaws	Unique to AM[F]	Poor selection of parameters, contamination or degradation of the processing environment. Discoloration (for example, DED-PA of Ti alloys) as detected visually can indicate a process out of control. Error in the precision of the beam delivery.	Depending on sample geometry and size of flaw, may be detected using CT/ET[G] /PCRT/RT/UT	HIP recoverable depending on size (not fully recoverable regardless)
Under melted material/ unconsolidated powder (LOF)	both	Poor selection of parameters, poorly developed and controlled process or a process out of control creating a poorly resolved flaw state. Errors in the precision of beam delivery.	Most probably CT, and PCRT, detectability depends on sample geometry and size	Only fixable during the process
Cracking[D]	Unique to AM[F]	AM PBF failure to clean one alloy powder completely from the build environment prior to processing another, DED large assemblies extensive solidification stresses present within large buildups. There is a host of metallurgical issues associated with crack susceptibility. Extremely large range of potential thermal and mechanical conditions present, across all AM processes, that may lead to cracking are poorly characterized.	Depending on sample geometry and size of crack, may be detected using CT/IRT/PCRT/ET[G] /RT/UT	–
Reduced mechanical properties	both	New powder out of spec or degraded through reuse, poorly developed/controlled process, interruption of feedstock supply. Residual stresses produced by rapid cooling, in a state of pre-stress, thus reducing the effective structural load that can be applied on the part, or causing structural weaknesses in a part in regions that have lower mechanical properties compared with the rest of the part.	Check powder (X-ray diffraction) at end of process and mechanical properties of finished part, stress related reduced properties can be detected using PCRT	–
Poor dimensional accuracy	both	Scaling/offset factors are effected by part geometry, beam intensity, and the density of the powder bed or build platform shift. SLM –scan head/optics problems. EBM – presence of EMF interference.	Usually easy (visually), as part has step on surface, but localized defects may require laser CMM and internal deviations with CT compared with CAD.	–
Inclusions	both	Debris from AM or post processing equipment.	Depends on the nature of the contamination and complexity of part, some inclusions are detectable using CT/ET[G] /IRT/PCRT/RT/UT	Remove all potential sources of contamination; sieve/ analyze powder before and after.
Residual stress	both	Poor selection of parameters.	Usually easy (visually), as part has step on surface, but localized defects may require laser CMM and internal deviations with CT compared with CAD. CT/ET[G] /PCRT	Poor selection of parameters.
Stop/start flaws[E]	both	Consequence of long builds or interruption of feedstock leading to reduced mechanical properties.	Check mechanical properties of finished part; PCRT individual frequencies may correlate also.	–
Surface flaws	Unique to AM[F]	Includes partially fused powder, linear or planar conditions or irregularities. Similar to spatter, undercut, irregular top bead, ropey bead, and slumping noted for welded parts.	ET/MET/PCRT/PT	–
Trapped powder	Unique to AM[F]	–	Most probably, CT or PCRT detectability depends on sample geometry and part size.	–

- From E3166, We have focused on CT, FPI, EC to characterize the surface and volumetric outcomes of the build process, with emphasis on imperfections unique to LPBF AM

GENERAL ATOMICS AERONAUTICAL

Round Robin Studies

225 uFocus CT/FPI

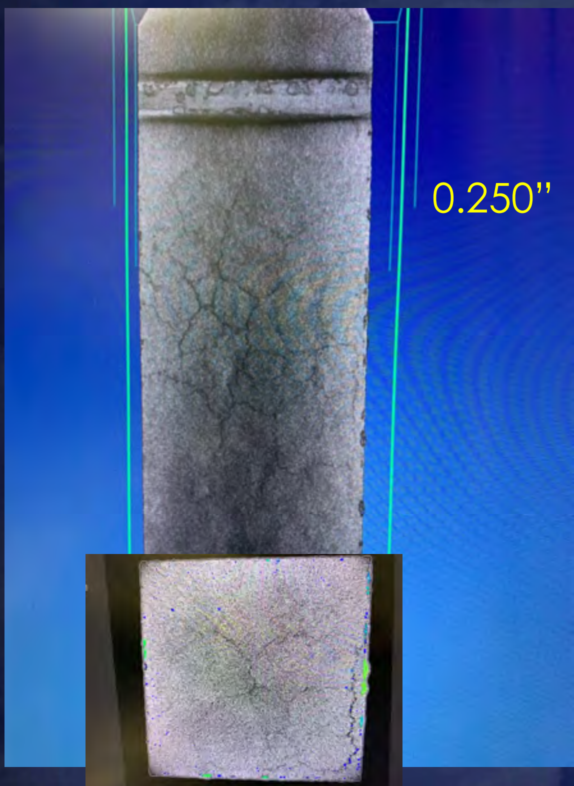
316 and 718 printed anomalies assessment

Other NDE Signals from AM builds

- Activities in selecting/fitting legacy NDE methods to AM – CT, PAUT, EC, FPI…
- Round Robin studies of 316 and IN718 samples as printed and post HIP/HTx
- **NDE signals for process health and mechanical properties (F357, AlSi10 et al)**
- Guided by Effects of Defects, How well do our AM NDE tools work?
- Converting our learnings into standards to classify and accept AM products

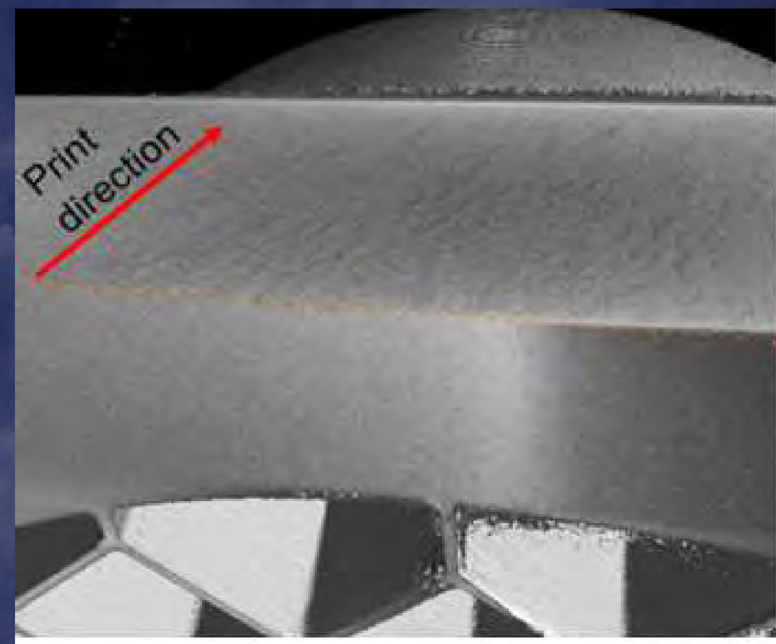
Grain Growth, Porosity Growth, Build Layer Imaging

- In addition to E 3166 anomalies, we see that fatigue & ductility property influencing variation can be detected with these same NDE



Grain growth &
Pores>>Blisters
Post HIP HTx

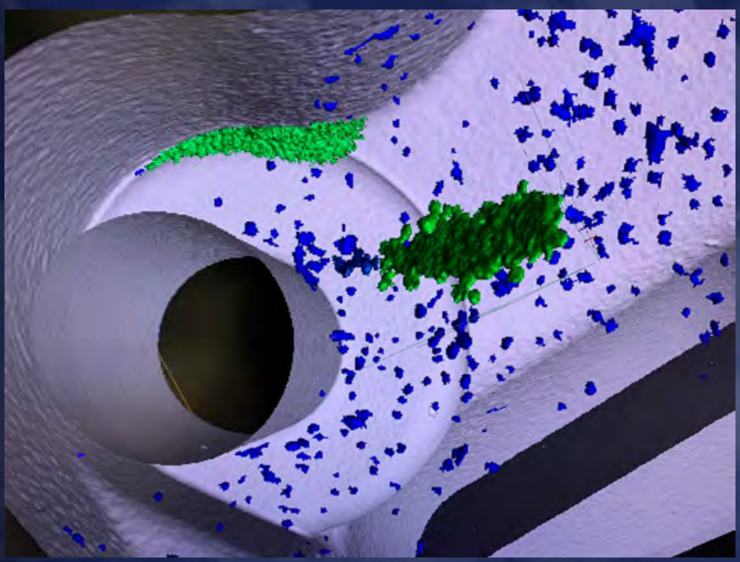
Large grain yields diffraction signals to exploit

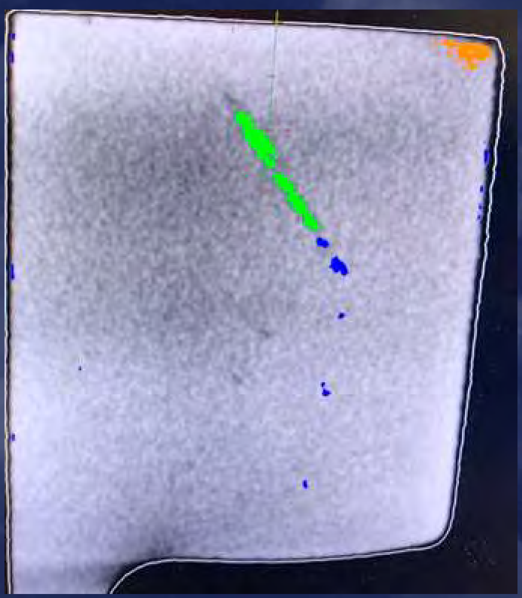


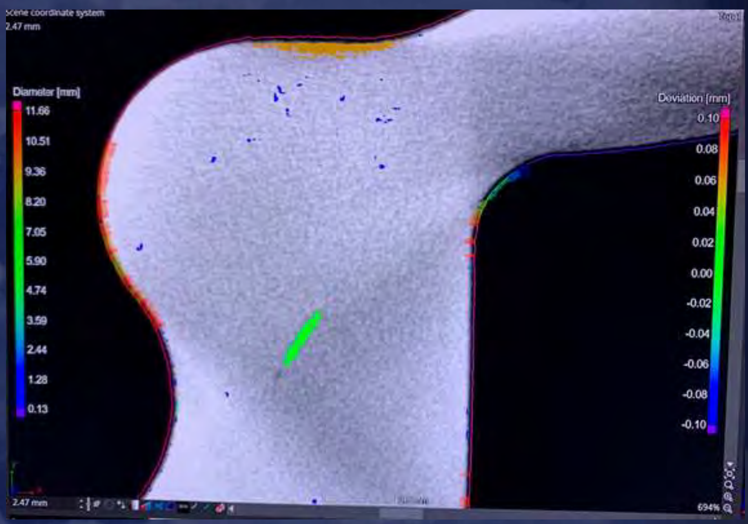
Layer anomalies sensed by CT

Grain Growth, Porosity Growth, Build Layer Imaging

- Traditional Casting Radiography IAW E1035 has weak capability for the detection of print layer defects
- Computed Tomography does better, but is $$$ compared to Build Layer Imaging being developed







How Well does our NDE work?

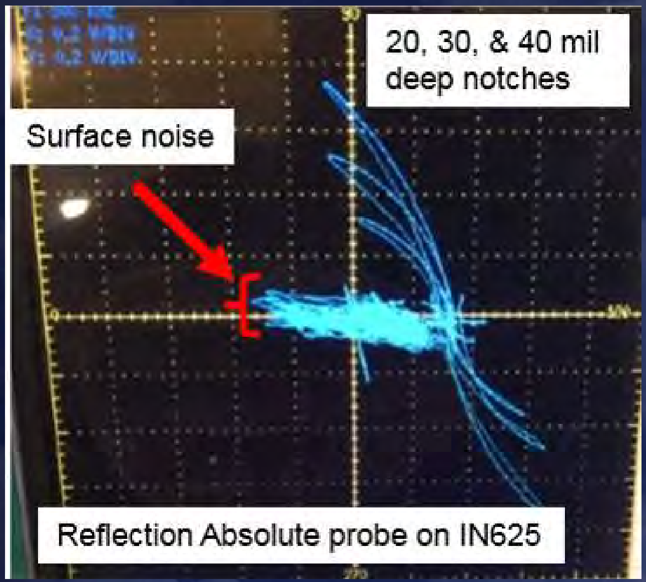
- Activities in selecting/fitting legacy NDE methods to AM – CT, PAUT, EC, FPI…
- Round Robin studies of 316 and IN718 samples as printed and post HIP/HTx
- NDE signals for process health and mechanical properties (F357, AlSi10 et al)
- **Guided by Effects of Defects, How well do our AM NDE tools work?**
- Converting our learnings into standards to classify and accept AM products

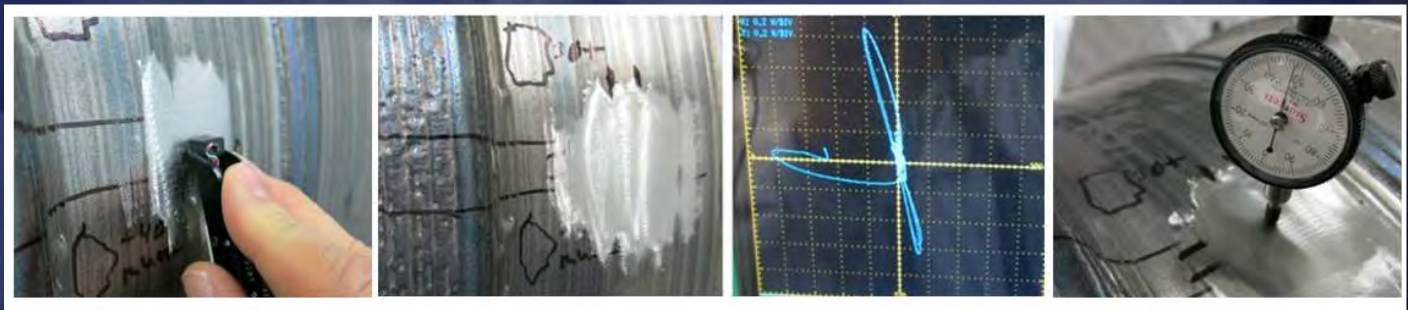
How Well does our NDE work?

- Building flaw sets to represent all imperfection signals and part signals (noise), is difficult and expensive
- Characterization of accidental, or intentional build parameter variation can result in larger yields of NDE signals per imperfection
- Model Assisted POD and Transfer functions:
- In General, the Reliability of an NDE is given by: $R = f(IC) - g(AP) - h(HF)$
  - There are substantial compendiums of POD information including detailed experimental parameters (CNDE, NTIAC….)
  - We can leverage such information, and adapt it to our AM environments
    - Simple cracks on flat panels can be transferred to more complex geometries using EDM notches
    - Direct viewing data for FPI can be transferred to indirect/hidden surface by rigging fixtures onto the flat panels
    - Variation in texture for EC (Eddy Current) can also be accounted for via EDM notches in the pristine and target surfaces
    - Creation of CT Phantoms
- **Workshops & Tools:** NDE-Reliabilty 2017 (nde-reliability.de)

How Well does our NDE work?

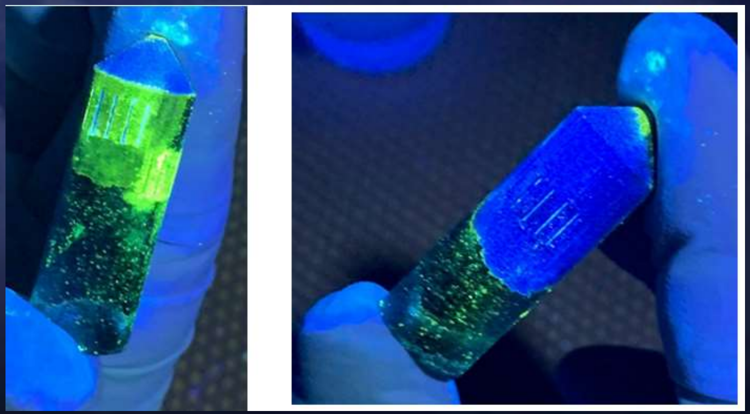
- EC example of part signal (noise) plus flaw signal using EDM notches





Note: DED

- FPI as printed part surface vs built imperfections



GENERAL ATOMICS AERONAUTICAL

Classification and Acceptance Deliverables

- Activities in selecting/fitting legacy NDE methods to AM – CT, PAUT, EC, FPI…
- Round Robin studies of 316 and IN718 samples as printed and post HIP/HTx
- NDE signals for process health and mechanical properties (F357, AlSi10 et al)
- Guided by Effects of Defects, How well do our AM NDE tools work?
- **Converting our learnings into standards to classify and accept AM products**

Classification Document Published F3572-22

- Classification and Equivalencies

F3572 – 22

TABLE 1 Part Classifications

Classification	Consequence of Failure	Non-exhaustive Examples
A	High	Part whose failure can directly affect continued safe flight and landing Part whose failure can result in serious or fatal injury to passengers or cabin crews Part whose failure requires exceptional piloting skill of flight crew to compensate
B	Medium	Part whose failure can indirectly affect continued safe flight and landing Part whose failure can result in minor injury to flight crew, passengers, or cabin crews Part whose failure can result in significant increase in workload of flight crew
C	Low	Part whose failure has no effect on continued safe flight and landing Part whose failure has no effect on flight crew, passengers, or cabin crew Part whose failure can result in slight reduction in operational/functional capabilities Part whose failure can result in slight increase in workload of flight crew
D	Negligible or No Effect	Part whose failure would pose no risk of damage to other equipment or injury to the ground personnel Parts not affecting operational/functional capabilities

F3572 – 22

TABLE A1.3 Alignment with Other Documents

F42 Classification	NASA-STD-6030	AWS D20.1	AMS2175
Class A	Class A	Class A Critical application. A component, whose failure would cause significant danger to personnel, loss of control, loss of a system, loss of a major component, or an operating penalty.	Class 1 A casting, the single failure of which would endanger the lives of operating personnel, or cause the loss of a missile, aircraft, or other vehicle.
Class B	Class B	Class B Semi-critical application. A component whose failure would reduce the overall strength of the equipment or system or preclude the intended functioning or use of equipment, but loss of the system or the endangerment of personnel would not occur	Class 2 A casting, the single failure of which would result in a significant operational penalty. In the case of missiles, aircraft, and other vehicles, this includes loss of major components, unintentional release or inability to release armament stores, or failure of weapon installation components.
Class C	Class C		Class 3 Castings not included in Class 1 or Class 2 and having a margin of safety of 200 percent or less.
Class D	Class D (Exempt)	Class C Noncritical application. A component whose failure would not affect the operation of the system or endanger personnel.	Class 4 Castings not included in Class 1 or Class 2 and having a margin of safety greater than 200 percent.

WK75329 – Acceptance Std Practice for LPBF

- In Balloting process

Title: Standard Practice for the Nondestructive Testing (NDT), Inspection Levels and Acceptance Criteria for Parts Manufactured with Laser Based Powder Fusion

- For both the classification and acceptance pieces, the design authority must own that which is applied, and tailor to the specific point design
  - Example, modifying the AMS STD 2175 casting acceptance levels (RT/FPI)

Table 1 Typical Inspection Usage

Inspection Method	Level 1	Level 2
Visual	X	X
Penetrant	X	X
PCRT	X[1]	X
Radiographic	X[1]	
Computed Tomography	X[1]	
Ultrasonic	X[1]	

WK75329 – Acceptance Std Practice for LPBF

- Table 2 & 3

Table 2: Maximum Flaw Sizes for Acceptance

Surface Discontinuities

Discontinuity	Level 1	Level 2
Surface		
Propagating Discontinuities[1]		
- Cracks [2] - Lack of Fusion or Incomplete Fusion - Build Layer Separations[3] - Through Wall Separations	0	0
Porosity		
Connected	0	0
Keyhole	0	0
Individual	0.060"	0.060"
Cluster	3 individual pores greater than 2.5% of the material thickness separated by 3 times the diameter of the largest pore.	7 individual pores greater than 2.5% of the material thickness separated by 3 times the diameter of the largest pore

Table 3: Maximum Flaw Sizes for Acceptance

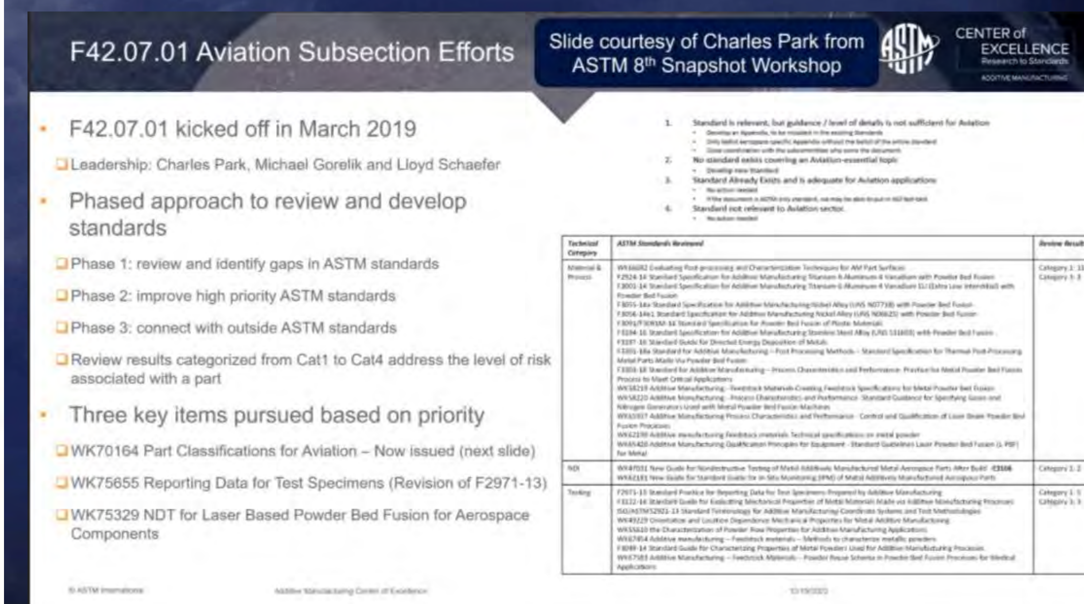
Subsurface Discontinuities

Discontinuity	Level 1	Level 2
Propagating Discontinuities[1]		
- Cracks [2] - Lack of Fusion or Incomplete Fusion - Build Layer Separations [3] - through wall separations	0	0
Voids	2.5% of the material thickness in its longest dimension.	0.060"
Inclusion	2.5% of the material thickness in its longest dimension	0.060"
Contamination	0	0
Trapped Powder	0	N/A
Porosity		
Connected	0	0
Keyhole	0	0
Gas Porosity[2]	2.5% of the material thickness in diameter.	N/A
Cluster[3]	3 or more individual pores greater than 2.5% of the material thickness in diameter separated by 3 times the diameter of the largest pore.	N/A

Summary & Conclusions

- The teams have accomplished significant deliverables against the Roadmap 2.0 and F42.07.01 section Goals
- Completion of Round Robin(s) and publication of LPBF Acc. lie in the year ahead as does OPM

NDE group members: ebiedermann@vibrantndt.com; engelbart301@sbcglobal.net; philip.riegler@norsktitanium.com; thomas.a.maeder@boeing.com; Chul.Y.Park@boeing.com; patrick.howard@ge.com; Mironets, Sergey Export License Required - US Collins <Sergey.Mironets2@collins.com>; Brandon Ribic <brandon.ribic@ncdmm.org>; Trey Gordon pilottrey@gmail.com; Steve James



GENERAL ATOMICS AERONAUTICAL

Appendix U

Wrap-up and Closing Comments
– Michael Gorelik (FAA) and Simon Waite (EASA)

5th Joint FAA – EASA AM Workshop

Closing Comments

October 17-20, 2022

Presented by:

Michael Gorelik

2022 Workshop – *General Observations*

"after-action report"

Upsides

- **Steady level of participation throughout 4 days**
- **Virtual environment worked well**
- **Active engagement in Breakout Sessions**
- **All agenda items completed as-planned**
  - *except for one recorded presentation (due to playback technical difficulties)*
- **Good mix of technical topics; novel material (vs. prior years)**
- ***Low travel cost!*** ☺

We welcome your feedback

Downsides (related to virtual format)

- **No opportunities for side-meetings and hallway conversations**
  - Although, some evidence of people / organizations making technical connections
- **Dynamics of breakout sessions very different in virtual format**
  - Not as good as in a F2F meeting
- **Trying to straddle multiple time zones**
- **Limited time (less Tech Talks, only 20 min each)**

Once again…

- **Dr. Simon Waite (EASA) – workshop co-organizer**
- **Dr. Rollie Dutton (ARCTOS) – workshop facilitator**
- **Breakout Sessions Co-Chairs (listed in the Agenda) and supporting core WG members**
- **All the Presenters**
- ***Repeat* Workshop Participants - for many years of support, encouragement and contributions**
- ***New* workshop participants – *Welcome !***
- **Erin Crowder and Nancy Heino (FAA STEP) – for media, registration and Zoom support**

Organizing Committee

Co-organizer and Host

Co-organizer

Workshop Facilitator

Dr. Michael Gorelik

FAA Chief Scientist - *Fatigue and Damage Tolerance*

Previously:

Engineering Fellow, Honeywell Aerospace

Dr. Simon Waite

EASA Senior Expert - *Materials*

Previously:

UK CAA, Aircraft Design Surveyor

Dr. Rollie Dutton

Director - *Materials and Manufacturing,* ARCTOS

Previously:

ManTech Division Chief, AFRL / USAF

Turning it over to Simon and Rollie for closing comments…

Appendix V

Working Group #1 Summary and Presentations
"Qualification of AM Parts of No, or Low, Criticality"
Co-chairs: S. Waite and O. Kastanis (EASA)

Appendix V

Working Group #1

“Qualification of AM Parts of No, or Low, Criticality”

Co-chairs: S. Waite and O. Kastanis (EASA)

Introductory Presentations

EASA – Structures and Materials Safety

FAA - EASA AM

INDUSTRY – REGULATOR EVENT

WG1 Qualification of Additive Manufacturing (AM) Parts of No, or Low, Criticality (for use in Certified products) - UPDATE

(virtual meeting)

October 2022

(133+ registered)

S.Waite, Senior Expert Materials, Certification Directorate, EASA

O. Kastanis, Expert Propulsion, Certification Directorate, EASA

Your safety is our mission.

An Agency of the European Union

EASA – AM WG1

Qualification of Additive Manufacturing (AM) Parts of No, or Low, Criticality (for use in Certified products) – Outline:

WG1 Scope: metallic and **non-metallic AM parts** (of no/low criticality), AM repairs (including repair by replacement), as applicable to a **range of products** (airframe, systems, cabin safety, propulsion etc)

Who is this for? - Decision makers, typically in the supply chain beyond Type Cert Holder:

Reminder: Decision makers/designers exist in a diverse range of organisations with a broad range of capabilities and experience supporting a broad range of approvals… impact upon safety may not be clear to some of these organisations

- Supplemental Type Cert Holders
- Design Organisation Approval (DOA) Holders supporting MROs etc, e.g. under minor change approval, provided all aspects of the change meet the requirements for minor classification.
- ETSO/TSOs
- PART 145 organisations interpreting PART 145 etc (for information - allows repair by replacement)
- Stakeholders new to aviation, e.g. AM Machine Manufacturers.
- Regulators (in order to help define a ‘level playing field’ for industry)

no/low criticality – broader generic concept, not only of interest to AM

EASA

EASA – AM WG1

Certification effort – ‘Proportionate to Criticality’?:

2022 AM Event - WG1 ‘Break-out session’:

- **to be managed as a ‘Working Meeting’… please feel free to contribute**

AGENDA:

- brief content outline EASA AM CM-S-008 revision
- ‘criticality’ definitions (see WG1 introduction slides)
- draft simplified ‘Safety Assessment’ (see WG1 introduction slides)
- draft ‘example’ content and format ‘Reference Example’
- draft ‘examples’
- Criticality and potential proportionate Means of Compliance (S. Waite, C. Ashforth)
- S-Basis Material Allowables (MMPDS - D. Hall)
- outline EASA AM CM-S-008 revision
- summarise progress for Thursday closing meeting

WG1 Meeting to be managed as a
‘Working Meeting’
Please feel free to contribute to the process…

EASA – AM WG1

WG1 development since 2021 AM Event:

- ‘Working Meetings’ (virtual) held:
  - 9/6/22, 7/7/22, 8/9/22, 26/9/22
- typically 30-40 participants at each meeting(of 80+ WG1 members)
- continue to identify and develop priority themes for WG1 communities
- develop guidance content for WG1 communities (via revision to EASA AM CM-S-008)
- define objectives and potential outcomes for the WGs and this FAA EASA AM Event 2022

EASA – AM WG1

WG1 development at 2021 AM Event: Spreadsheet shared (30+ pages) in order to establish priorities during break-out sessions.

WG1 No/Low Criticality AM DOCUMENT DEVELOPMENT - OUTLINE AND CONTENT THEMES

	VERY SIMPLIFIED CONTENT INTENDED			Please: respond to questions add bullet point themes considered worthy of document content
Please co-ordinate with attached slides				
Slide	**Questions**	y	n	**Other comments/suggestions**
1	AM no/low criticality document content to follow AMC 20-29/AC 20-107B format?	?	?	
	If not, propose alternative (other SDO document format etc)			?
	Do you agree that no/low criticality can be managed under a common document for airframe, systems, propulsion, interiors (including seats?)	?	?	
	If not, propose alternative			?
	Do you agree that no/low criticality items would benefit from a separate industry document supporting regulatory intent?	?	?	
	If not, propose alternative			?

PLEASE RETURN COMPLETED WG1 SPREADSHEET TO S. Waite

by Friday 19th November 2021

EASA

EASA – AM WG1

WG1 development since 2021 AM Event: Spreadsheet Response Summary (key points)

(18 organisations responded)

Criticality – need for industry/regulatory guidance (Slide 1: 17 yes/1 no):
The EAAMIRG/ASTM F42 draft document intent to define 4 generic criticality groups across parts and products seemed to be generally accepted. However, there was need for further input from the interiors (including regulator) and propulsion communities. Also need for some caveats/clarifications, e.g. significance of engine shutdown v engine debris release events etc.

Safety Analysis (Slide 5: 15 yes/2 no/1 no response).
The need for an appropriate 'simplified' Safety Assessment, e.g. FHA/FMECA/RAS etc in the AM part/product/repair certification process should be emphasised, particularly for non-TCH DOAs supporting MROs, STCHs, ETSOs, etc.

EASA – AM WG1

WG1 development since 2021 AM Event: Spreadsheet Response Summary (key points)

Means of Compliance – Cert effort proportionate to criticality (Composite Mod table):

(Slide 12: 17 yes/0 no/1 partial response): Do you agree that 'medium-low' and 'low' criticality approach to MoC would work for no/low crit AM parts?
note: possibly too difficult to define guidance beyond 'simplified' due to range of processes, applications etc

(Slide 12: 15 yes/2 no/1 no response): Is support for 'S = simplified compliance' content required in any supporting guidance
note: would benefit from examples being added

Note: Not New. Formalises well how 'engineering judgement' has been exercised for other conventional technologies, not only composites and AM…. but these technologies offer the potential for more competing failure modes and safety outcomes, e.g. due to M&P challenges. May be an issue in conjunction with 'simplified' MoCs

SAE Draft Standard for Composite Modifications

Criticality	Material Control	Process Control	Design Values	Static Strength	F&DT	Flammability
1. High – parts whose failure directly affects continued safe flight and landing	X	X	X	X	X	As Required
2. Medium-High – parts whose failure indirectly affects continued safe flight and landing	X	X	X	S	S	As Required
3. Medium-Low – (1) structure whose failure does not affect continued safe flight and landing and (2) parts whose failure can affect passengers and crew	S	S	S	S	N	As Required
4. Low – all other parts	S	S	S, As Required	S, As Required	N	N

Notes:
- May need other columns/categories for engine regulations
- X = "full" compliance, S = simplified compliance, N = compliance not applicable
- Simplified methods of compliance are not the same between the levels

November 9, 2021 AM Parts with Low or No Criticality Federal Aviation Administration 5

EASA – AM WG1

WG1 development since 2021 AM Event: Spreadsheet Response Summary (key points)

Examples: The examples discussions seemed to generate interest and potentially adds value. The intent is to update, summarise, add to, and document these examples. Document location to be determined. However, this will require time, commitment, and support from WG1.

(Slide 13: 13 yes/3 no/2 no response): Are the AM examples appropriate for medium-low crit parts?

(Slide 28: 15 yes/1 no/2 partial response): Add documented no and low crit examples (as an appendix)?

Note: Evident from comments provided relating to other slide questions, there is a consistent request for examples to support various aspects of any no/low criticality guidance

Examples to:

- use common format
- be concise, but include adequate detail to be useful
- not compromise IP

EASA - AM

Certification – 'Criticality'?:

- **What is 'Criticality'?** (PART 21 AMC 21.B.100(a) 'Level of Involvement' (LoI))… **as defined <u>in context of LoI</u>**:
  '… measure of ***the potential impact of a non-compliance with part of the certification basis on product safety*** *or on the environment'*

  The supporting guidance continues:

  '…The ***potential impact of a non-compliance*** *within a Compliance Demonstration Item (CDI) should be* ***classified as critical if****, for example: …a function, component or system is introduced or affected where the* ***failure of that function, component or system may contribute to a failure condition that is classified as hazardous or catastrophic at the aircraft level**** *…'*

  * also systemic failure at pax. Level, e.g. multiple seat failures

- **any application with potential criticality clearly would be expected to fully comply with all requirements**
  (noting the **novelty** (and **complexity**) aspects of AM, such applications are unlikely to initially be considered by EASA, other than under experienced TCH control supported by an appropriate **'step by step' approach**)

- **for other less critical applications 'certification proportionality' requires understanding of technical/safety criticality…**

need for broader awareness and understanding of Safety Assessment…
- key to developing WG1 activities

EASA - AM

Certification – 'Criticality'?:

Categorisation of criticality for AM – ASTM F3572-22 'Standard Practices for Additive Manufacturing – General Principles – Part Classifications for Additive Manufactured Parts Used in Aviation' (and EAAMIRG Action 1)

Classification	Consequence of Failure	General Description
A	High	Part the failure of which can directly affect continued safe flight and landing Part the failure of which can result in serious or fatal injury to passenger or cabin crews c Part the failure of which can result in excessive load for the flight crew
B	Medium	Part the failure of which can indirectly affect continued safe flight and landing Part the failure of which can result in injury to passenger or cabin crews or maintenance Part the failure of which can result in a significant increase in workload for the flight crev
C	Low	Part the failure of which has no affect on continued safe flight and landing Part the failure of which has no affect on passengers and cabin crews Part the failure of which can result in a slight reduction in operational/functional capabil Part the failure of which can result in a slight increase in workload for the flight crew
D	Negligible or No Effect	Part not covered above Part the failure of which would pose no risk of damage to other equipment or personnel Part not affecting operational/functional capabilities

Note: Various definitions of criticality/safety classification exist across products. However,

- these can be mapped to this table
- not intended to change existing 'criticality' processes
- link to proportionate MoCs?
- NOT NEW, but AM potential offers more competing damage modes and safety outcomes

Simplify and standardise criticality/safety classification? … potentially functions in the context of Performance Based Regulations (<u>beyond AM</u>) across products, particularly for integrated technologies… (aircraft and pax safety level)

EASA – AM WG1

FYI: Further recent 'no and low' criticality related regulation definitions:
EASA PART 21: GM1 21.A.307(b)(3) and (b)(4) Meaning of 'negligible safety effect'
(Comment: associated with parts permitted for release without EASA Form 1)

(a) ***for ELA*1 and ELA2 aircraft, at worst:***
(1) slightly reduces the operational or functional certified capabilities of the aircraft or its safety margins;
(2) causes some physical discomfort to its occupants; and
(3) slightly increases the workload of the flight crew; and

(b) ***for any other aircraft:***
(1) has no effect on the operational or functional certified capabilities of the aircraft, or on its safety margins;
(2) causes no physical discomfort to the occupants; and
(3) has no effect on the flight crew.'

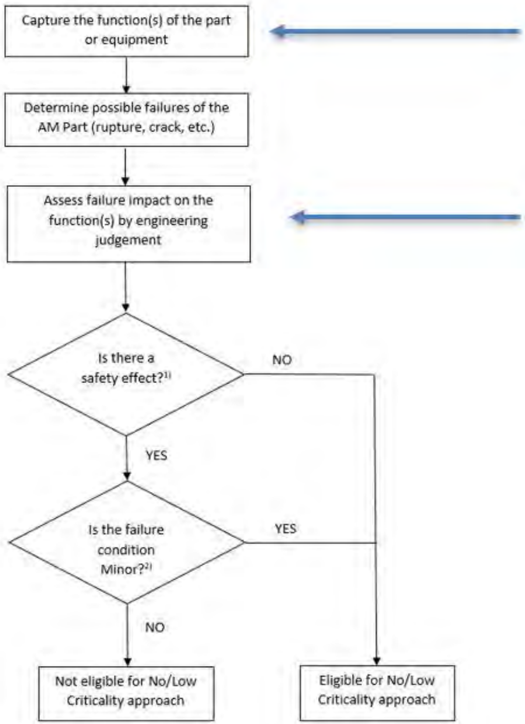
similar to Classification D

*ELA – European Light Aircraft
https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32021R0699&from=EN
https://www.easa.europa.eu/en/document-library/easy-access-rules/easy-access-rules-airworthiness-and-environmental-certification

EASA – AM WG1

Certification effort – ‘Proportionate to Criticality’?:

WG1 development since 2021 AM Event: Develop Safety Assessment intended to emphasis need for consideration beyond function… necessary to ensure a no or low criticilaty assessment is correct relative to a proportionate ‘simplified’ Means of Compliance



Consider any potential for interaction between functions
- Airframe, Systems, Propulsion, Interiors (including seats) etc

Also consider potential for any new failure modes (relative to conventional technologies and applications) to change the safety outcome beyond direct functionality of the part to include other potential threats, e.g. debris, PDA impact, system ingestion, flammability, introduction of sharp interior edges etc

1) <u>**No Safety Effect (Cat.D)**</u> Part the failure of which would pose no risk of damage to other equipment, personnel, or reduce operational/functional capabilities

2) <u>**Minor (Cat.C):**</u> Part the failure of which has no affect on continued safe flight and landing, no affect on pax or cabin crews, but can result in a slight reduction in operational/functional capabilities or a slight increase in workload for the flight crew

intended to support no and low classification icw ‘simplified’ MoCs

EASA

EASA - AM

Certification effort – ‘Proportionate to Criticality’?:

Needs further work!
- Does this work for airframe applications only?
- Does this need development for other products and requirements, e.g. dynamic, impact etc?

- **WG1 – spreadsheet outcome – Proportionate ‘Means of Compliance’ spreadsheet developed e.g.**

Criticality Classification	Consequence of Failure	Material Control	Process Control	Design Values	Static Strength	F&DT	Flammability
A	High	x	x	x	x	x	As required
B	Medium	x	x	x	SMoC	SMoC	As required
C	Low	SMoC	SMoC	SMoC	SMoC	N	As required
D	Negligible or No Effect	SMoC/VSMoC	SMoC/VSMoC	N	N	N	N

X = ‘full compliance’, SMoC = Simplified Means of Compliance,
VSMoC = Very Simplified Means of Compliance, N = compliance not applicable
Note: SMoC, VSMoC is different at each level and from product to product

(ref. SAE CACRC Composite Modifications developing guidelines)

To be discussed in break-out sessions

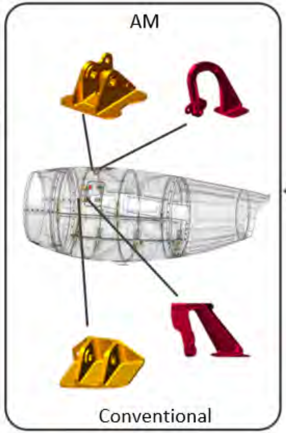
EASA – AM WG1

Certification effort – ‘Proportionate to Criticality’?:

WG1 development since 2021 AM Event: Standard ‘example’ format and content developed

EASA – AM WG1

PROPOSED SHARED EXAMPLE - NO or LOW CRITICALITY
(email 18th Aug 2022)
(PILATUS, GKN)



Example 1 : ***Airframe CS23 – Criticality D*?***
Nacelle Access Panel Assemblies (2 off), AM hinges and goosenecks, on fuselage mounted engines, T-tail configuration
(part introduced to already certified product (change of type design)).
Note: small access cover not attached to critical structure or systems

Note: includes some responses following communications with Andrea Palumbo (Avio)

*reminders for this WG1 ‘Working Meeting’:
- we continue to iterate regarding interpretation of example criticalities against criticality table text
- as discussed, the MoCs for many of these initial examples are likely to exceed later MoC expectations for the identified criticalities

EASA – AM WG1

Certification effort – ‘Proportionate to Criticality’?:

2022 AM Event - WG1 ‘Break-out session’:

- **to be managed as a ‘Working Meeting’… please feel free to contribute**

AGENDA:

- brief content outline EASA AM CM-S-008 revision
- ‘criticality’ definitions (see WG1 introduction slides)
- draft simplified ‘Safety Assessment’ (see WG1 introduction slides)
- draft ‘example’ content and format ‘Reference Example’
- draft ‘examples’
- potential proportionate Means of Compliance table
- S-Basis Material Allowables (MMPDS - D. Hall)
- outline EASA AM CM-S-008 revision
- summarise progress for Thursday closing meeting

WG1 Meeting to be managed as a
‘Working Meeting’
Please feel free to contribute to the process…

EASA

European Union Aviation Safety Agency

Questions?

easa.europa.eu/connect

Your safety is our mission.

An Agency of the European Union

WG1 Breakout Session

a ‘Working Meeting’

EASA – AM WG1

Qualification of Additive Manufacturing (AM) Parts of No, or Low, Criticality (for use in Certified products) – Outline:

WG1 Scope: metallic and **non-metallic AM parts** (of no/low criticality), AM repairs (including repair by replacement), as applicable to a **range of products** (airframe, systems, cabin safety, propulsion etc)

Who is this for? - Decision makers, typically in the supply chain beyond Type Cert Holder:

Reminder: Decision makers/designers exist in a diverse range of organisations with a broad range of capabilities and experience supporting a broad range of approvals… impact upon safety may not be clear to some of these organisations

- Supplemental Type Cert Holders
- Design Organisation Approval (DOA) Holders supporting MROs etc, e.g. under minor change approval, provided all aspects of the change meet the requirements for minor classification.
- ETSO/TSOs
- PART 145 organisations interpreting PART 145 etc (for information - allows repair by replacement)
- Stakeholders new to aviation, e.g. AM Machine Manufacturers.
- Regulators (in order to help define a ‘level playing field’ for industry)

no/low criticality – broader generic issue, not only of interest to AM

EASA – AM WG1

Certification effort – 'Proportionate to Criticality'?:

2022 AM Event - WG1 'Break-out session':

- **to be managed as a '<u>Working Meeting</u>'… please feel free to contribute**

AGENDA:

- brief content outline EASA AM CM-S-008 revision
- 'criticality' definitions (see WG1 introduction slides)
- draft simplified 'Safety Assessment' (see WG1 introduction slides)
- draft 'example' content and format 'Reference Example'
- draft 'examples'
- Criticality and potential proportionate Means of Compliance (S. Waite, C. Ashforth)
- S-Basis Material Allowables (MMPDS - D. Hall)
- outline EASA AM CM-S-008 revision
- summarise progress for Thursday closing meeting

This meeting objective: Enable the next revision to the EASA AM CM-S-008 for early 2023, based mostly upon WG1 input

WG1 Meeting to be managed as a 'Working Meeting'
Please feel free to contribute to the process…

EASA – AM WG1

What is a Certification Memo? - Reminder

EASA Certification Memoranda clarify the European Union Aviation Safety Agency's general course of action on specific certification items. They are intended to provide guidance on a particular subject and, as non-binding material, may provide complementary information and guidance for compliance demonstration with current standards. Certification Memoranda are provided for information purposes only and must not be misconstrued as formally adopted Acceptable Means of Compliance (AMC) or as Guidance Material (GM). Certification Memoranda are not intended to introduce new certification requirements or to modify existing certification requirements and do not constitute any legal obligation.

EASA Certification Memoranda are living documents into which either additional criteria or additional issues can be incorporated as soon as a need is identified by EASA.

EASA - AM

2/ Advanced Materials and Processes - Developing Rulemaking and Guidance, continued…

EASA CM-S-008 issue 3 Draft Revision changes in progress for 2023 (TBC)

(this revision largely driven by WG1 activities, to be discussed in break-out sessions):

To include changes relating to:

- criticality classification
- certification effort being proportionate to criticality (WG1 ‘no and low’ criticality, particularly non-TCH applications)
- increased emphasis upon Safety Assessments, e.g. FHAs, FMECA, or RASs (WG1 ‘no and low’ criticality, particularly non-TCH applications)
- addition of AM parts of ‘no or low’ criticality ‘Examples’
- updates references

No and low criticality content moved to Appendices:
Appendix 2: Design certification of AM parts of no or low criticality
Appendix 3: Simplified Safety Assessment for no or low criticality
Appendix 4: Examples for AM parts of no or low criticality

- aligned with ‘step by step’ approach relative to criticality, and EAAMIRG Action Items
- represents real current industry certification activities

EASA – AM WG1

Reference Example format and content level:

Develop Examples* relative to Table 'SMoC' content?:

- **for the purposes of consistency, develop existing (and new) examples* to include**
  - **Title information**
    - **Part title/description**
    - **Function** (airframe, system, propulsion, interior etc… including cross application/discipline considerations, e.g. system-structure etc)
    - **Replacing old 'similar' conventional part/new configuration?**
    - **Design driver** (safety, commercial etc)
      - Key safety requirements referenced?
    - **Criticality** (extent of FHA, FMEA, RAS considered relative to direct function criticality <u>and</u> potential to influence other function criticality, e.g. debris impacting/jamming other structures or systems, or impacting flammability performance)
    - **Material and Process** (for original part, if a 'replacement', and/or new part)

***examples already on certified product and/or in discussion with regulators?**
(including those discussed in previous WG1 meetings)

EASA – AM WG1

Reference Example format and content level:

Needs further work!

Develop Examples relative to Table ‘SMoC’ content?:

Note: Thanks to those who supported previous efforts to start this process

- **for the purposes of consistency, develop existing (and new) examples* to include**
  - **Content supporting ‘SMoC’ values in table (Category 3 and 4?):**
    - **material control**
      - WG1 to identify potential common content elements for this text?
    - **process control**
      - WG1 to identify potential common content elements for this text?
    - **design values**
      - WG1 to identify potential common content elements for this text?
        e.g. use of test v analysis
    - **static strength**
      - WG1 to identify potential common content elements for this text?
        e.g. test coupons, point design tests, test numbers, load cases etc
    - **flammability**
      - WG1 to identify potential common content elements for this text?

EASA – AM WG1

Reference Example format and content level:

Examples to be considered:

- **for the purposes of consistency, develop existing (and new) examples to include**
    - **add non-metallic example(s) title/contributor?**
    - **add metallic example(s) title/contributor?**

  Note: for cross function applications, e.g. system-structure parts, categorise by lead function

Add further draft examples:

- **Airframe?**
- **System?**
- **Propulsion?**
- **Interiors?**

EASA – AM WG1

Certification effort – ‘Proportionate to Criticality’?:

2022 AM Event - WG1 ‘Break-out session’:

REFERENCE EXAMPLE:

EASA – AM WG1

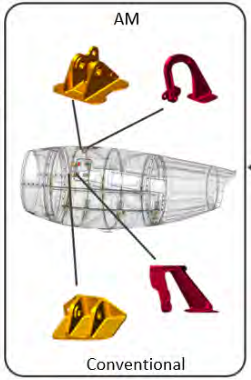
PROPOSED SHARED EXAMPLE - NO or LOW CRITICALITY
(email 18th Aug 2022)
(PILATUS, GKN)

Example 1 : *Airframe CS23 – Criticality D*?*
Nacelle Access Panel Assemblies (2 off), AM hinges and goosenecks, on fuselage mounted engines, T-tail configuration
(part introduced to already certified product (change of type design)).
Note: small access cover not attached to critical structure or systems

Note: includes some responses following communications with Andrea Palumbo (Avio)

*reminders for this WG1 ‘Working Meeting’:

- we continue to iterate regarding interpretation of example criticalities against criticality table text
- as discussed, the MoCs for many of these initial examples are likely to exceed later MoC expectations for the identified criticalities



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EASA – AM WG1

2022 AM Event - WG1 'Break-out session':

Further 'EXAMPLES':

Title, organisation, presenter(s)

Reference Example: '***Nacelle Access Panel Assemblies (2 off), AM hinges and goosenecks, on fuselage mounted engines, T-tail configuration*' (Pilatus, GKN),** Jean-Luc Belon, Martin Hagel, Juerg Kradolfer, Andrea Palumbo

Airframe: add examples

'*Camera Housing*' (SOGECLAIR), Gwennole Quenet (for next WG1 meeting)

***'Door Latch Backup Fitting'* (Spirit Aero),** Paul Toivonen

Systems: add examples

EASA – AM WG1

2022 AM Event - WG1 ‘Break-out session’:

Further ‘EXAMPLES’:

Title, organisation, presenter(s)

Propulsion: add example

Interiors (including Seats): add examples

***‘????’* (Materialise, Stirling Dynamics)**, Erik de Zeeuw, Konrad Lehmann (Thursday)

‘***Bumper Mounted on Seat Surrounding Furniture assembly’ (SAFRAN),*** *Mehdi Bolaky*

EASA – AM WG1

Further potential 'EXAMPLES':

Product/Discipline	Title	Criticality To Be Confirmed	status (beyond feasability)	Organisation(s)		
AIRFRAME						
Metallic						
(structure - propulsion)	Nacelle Access Panel Hinge	D	certified	GKN/PILATUS	Jean Luc	Belon
					Mark	Bosman
					Chris	Dordlofva
	Nose Radome Attachments?	C	certified	DASSAULT	Justine	Chaput
	Camera Housing (TBC)	C/D?	flight test	SOGECLAIR/AIRBUS?	Gwennole	Quenet
	Access Door Latch Fitting	C		SPIRIT	Paul	Toivonen
Non-Metallic	??					
SYSTEMS						
Metallic						
(system -structure - propulsion)	Metallic Duct Fitting	C	certified	LHT	Rob	Van den Bosch
					Jan	Nelle
(system - structure)	NLG Lock Stay Bracket	D		LIEBHERR	Andre	Danzig
Non-Metallic	??			LHT		
PROPULSION						
Metallic	??			SAFRAN? (Roger to dicuss possibilities)		
	??			Doug to explore possibilities		
Non-Metallic	??					
INTERIORS						
Metallic	Interior Housing Assembly	D	certified	ST AEROSPACE ENGINEERING	Guoying	Zheng
Non-Metallic	AFI ALM Parts of no criticality	D		AIRFRANCE	Frederic	Becel
	Dado Panel and Cover Fitting	D		MATERIALISE/EXPLEO	Erik	de Zeeuw
					Gert	Brabants
	Bumper Pad	D		SAFRAN INTERIORS	Muhammad	Khan
	Decorative Panel	D			Mehdi	Bolaky
	Interiors Vibration Damper	C/D		MECAER	Vincenzo	Massarelli
	Interiors Duct	?		(Chris to explore possibilities)		
SEATS						
Metallic	??					
Non-Metallic	Seat Back Video Surround	D		SAFRAN SEATS	Muhammad	Khan
					Mehdi	Bolaky

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EASA - AM

Certification – ‘Criticality’?:

Categorisation of criticality for AM – ASTM F3572-22 ‘Standard Practices for Additive Manufacturing – General Principles – Part Classifications for Additive Manufactured Parts Used in Aviation’ (and EAAMIRG Action 1)

Need to develop separate MoC tables for each product?
What level of detail? Unmanageable?

Classification	Consequence of Failure	General Description
A	High	Part the failure of which can directly affect continued safe flight and landing Part the failure of which can result in serious or fatal injury to passenger or cabin crews or ma Part the failure of which can result in excessive load for the flight crew
B	Medium	Part the failure of which can indirectly affect continued safe flight and landing Part the failure of which can result in injury to passenger or cabin crews or maintenance pers Part the failure of which can result in a significant increase in workload for the flight crew
C	Low	Part the failure of which has no affect on continued safe flight and landing Part the failure of which has no affect on passengers and cabin crews Part the failure of which can result in a slight reduction in operational/functional capabilities Part the failure of which can result in a slight increase in workload for the flight crew
D	Negligible or No Effect	Part not covered above Part the failure of which would pose no risk of damage to other equipment or personnel Part not affecting operational/functional capabilities

Note: Various definitions of criticality/safety classification exist across products. However,

- these can be mapped to this table
- not intended to change existing ‘criticality’ processes
- link to proportionate MoCs?
- NOT NEW, but AM offers potentially more competing damage modes and safety outcomes

Simplify and standardise criticality/safety classification? … potentially functions in the context of Performance Based Regulations (beyond AM) across products, particularly for integrated technologies… (aircraft and pax safety level)

EASA

EASA - AM

Certification effort – ‘Proportionate to Criticality’?:

Example: for discussion purposes only, … does this work for all/most of the industry? (Airbus/Safran presentation developed from WG1 26/9/22 presentation)

For AM parts classification it is proposed to complete the table with two last columns:

Classification	Consequence of Failure	General Description	Application for engine products (CS-E 510) and propellers (CS-P 150)	Application for aircraft products (CS-25.1309, CS-23, CS-27, CS-29, CS-22, CS-VLA)
A	High	Part whose failure can directly affect continued safe flight and landing Part whose failure can result in serious or fatal injury to passengers or cabin crews or maintenance personnel Part whose failure can result in excessive workload of flight crew	**HAZ** engine/propeller Effects	**CAT/HAZ** aircraft effects
B	Medium	Part whose failure can indirectly affect continued safe flight and landing Part whose failure can result in injury to passengers or cabin crews Part whose failure can result in significant increase in workload of flight crew	**MAJ** engine/propeller Effects	**MAJ** aircraft effects
C	Low	Part whose failure has no effect on continued safe flight and landing Part whose failure has no effect on passengers Part whose failure can result in slight reduction in operational/functional capabilities Part whose failure can result in slight increase in workload of flight crew	**MIN** engine/propeller Effects	**MIN** aircraft effects
D	Negligible or No Effect	Part not covered above Part whose failure would pose no risk of damage to other equipment or personnel Parts not affecting operational/functional capabilities	No effect	No effect

Reminder: This is WG1 ‘no and low’ (C and D) criticality.
However, this needs to be part of a coherent ‘end to end’ process

EASA - AM

Certification effort – ‘Proportionate to Criticality’?:

Example: for discussion purposes only, … does this work for all/most of the industry? (Airbus/Safran presentation developed from WG1 26/9/22 presentation)

Proposed MoC table for engines:

		Design Values / Material soundness	Material control	Process Control	Static Strength	Fatigue / vibration	Damage Tolerance	Flammability
Requirements for	Engines	CS-E 70 (a) Material and Manufacturing Methods	CS-E 70 (b) Material and Manufacturing Methods	CS-E 70 (b) Material and Manufacturing Methods	CS-E 100 (a) (c) Strength	CS-E 100 (a) (c) Strength	CS-E 515 Engine Critical Parts (a)	CS-E 130 (b)(c)(d)(e)(g) Fire Protection
Part Classification	A	X	X	X	X	X	X*	As required
	B	X	X	X	S	S	N	As required
	C	S	S	S	S	S	N	As required
	D	SV if required	S/SV	S/SV	SV if required	SV if required	N	N

* only applicable for Engine Critical Parts

Content of the table to be discussed/ agreed

X = ‘full compliance’, S = Simplified Means of Compliance, VS = Very Simplified Means of Compliance, N = compliance not applicable

Note: S, VS is different at each level and from product to product (Note: do not confuse S with S-Basis in this table!)

EASA - AM

Need to add other regs, e.g. dynamic threats… bird strike, seat crashworthiness etc? Does this become unmanageable?

Certification effort – ‘Proportionate to Criticality’?:

Example: **for discussion purposes only,** … does this work for all/most of the industry? (Airbus/Safran presentation developed from WG1 26/9/22 presentation)

Proposed MoC table for Airbus group (Large Aircraft, Light Rotorcraft, Large Rotorcraft: (red – developed from previously shared Cindy Ashforth presentation)

		Design Values / Material soundness	Material control	Process Control	Static Strength	Fatigue / ~~vibration~~	Damage Tolerance	Flammability Fireproofness
Requirements for	Airbus Commercial Airbus Defense & Space	CS 25.613 Material strength properties and Material Design Values	CS 25.603 Materials	CS 25.605 Fabrication methods	CS 25.305 Strength and deformation CS 25.307a Proof of structure	CS 25.571 Damage tolerance and fatigue evaluation of structure	CS 25.571 Damage tolerance and fatigue evaluation of structure	CS 25.853 Compartment interiors CS 25.867 Fire protection: other components CS 25.869 Fire protection: systems CS 25.1191 Firewalls (b) ....
Airbus Group Structures	Airbus Helicopters	CS 27/29.613 Material strength properties and design values	CS 27/29.603 Materials	CS 27/29.605 Fabrication methods	CS 27/29.305 Strength and deformation CS 27/29.307a Proof of structure	CS 27.571 Fatigue evaluation of flight structure CS 29.571 Fatigue tolerance evaluation of metallic structure CS 27/29.573: Damage tolerance and fatigue evaluation of composite rotorcraft structures	CS 29.571 Fatigue tolerance evaluation of metallic structure CS 27/29.573: Damage tolerance and fatigue evaluation of composite rotorcraft structures	CS 27/29.853 Compartment interiors CS 27/29.861 Fire protection of structure, controls, and other parts CS27/ 29.863 Flammable fluid fire protection CS 27/29.1191 Firewalls ......
Part Classification	**A** (CAT)	X	X	X	X	X	X	As required
	A (HAZ)	X	X	X	X	N	N	As required
	B (MAJ)	X	X	X	S	N	N	As required
	C (MIN)	S	S	S	S	N	N	As required
	D (NSE)	N	S/VS	S/VS	N	N	N	N

X = ‘full compliance’, S = Simplified Means of Compliance, VS = Very Simplified Means of Compliance, N = compliance not applicable

Note: S, VS is different at each level and from product to product (Note: do not confuse S with S-Basis in this table!)

EASA

European Union Aviation Safety Agency

Questions?

EASA
European Union Aviation Safety Agency

Support Slides

EASA – AM WG1

Working Groups building upon previous meeting WG activities:

WG1: Qualification of Additive Manufacturing (AM) Parts of No, or Low, Criticality (for use in Certified products)

https://www.easa.europa.eu/newsroom-and-events/events/easa-faa-industry-regulator-am-event-0)

…The intent of this breakout session is to build upon initial 2020 Event discussions, including developing European Aviation AM Industry Regulator Group (EAAMIRG) Actions*, and further amendments to the recently released EASA AM CM-S-008 revision.
*EAAMIRG Actions, i.e. 'Part Classification and Authority Engagement' (LoI etc), 'Standardisation: understanding and use of 'standards'

The recent CM revision added content which may benefit from further discussion and development by interested parties, e.g. MROs, interiors organisations etc, relating to themes including:

- development of common industry standards regarding expectations for potential compliance data, e.g. statistics, testing etc., for parts of 'no criticality'
- simple common data presentation protocols for the purposes of certification of parts of 'no criticality'
- develop better understanding and definition of thresholds distinguishing parts of 'no criticality' from those of 'low criticality', including associated additional expectations for the latter, e.g. minimal supporting fatigue data, point design strategies etc

- **sharing of examples of certification or planned certification of parts of no or low criticality**
- **improved standardization and awareness of criticality** **(including need for better awareness/understanding of Failure Hazard Analysis/ development of simplified approach? etc)**
- **improved use of standards**
- **potential associated regulatory guidance development, e.g. CM revision, content for EASA CS-STAN etc**

most likely tangible WG1 outputs associated with:

EASA

EASA - AM

Ce

- WG1 – spreadsheet outcom –

Needs further work!

- Do we separate material and process issues from product issues?
- Do we have separate tables for each product?
- Will this becoming unmanageable?

Criticality Classification	Consequence of Failure	Material Control	Process Control	Design Values	Static Strength	F&DT	Flammability
A	High	x	x	x	x	x	As required
B	Medium	x	x	x	SMoC	SMoC	As required
C	Low	SMoC	SMoC	SMoC	SMoC	N	As required
D	Negligible or No Effect	SMoC/VSMoC	SMoC/VSMoC	N	N	N	N

X = 'full compliance', SMoC = Simplified Means of Compliance,
VSMoC = Very Simplified Means of Compliance, N = compliance not applicable
Note: SMoC, VSMoC is different at each level and from product to product

(ref. SAE CACRC Composite Modifications developing guidelines)

Appendix V

Working Group #1
"Qualification of AM Parts of No, or Low, Criticality"
Co-chairs: S. Waite and O. Kastanis (EASA)
Summary Presentation

EASA
European Union Aviation Safety Agency

Federal Aviation Administration

EASA – Structures and Materials Safety

FAA - EASA AM

INDUSTRY – REGULATOR EVENT

WG1 Qualification of Additive Manufacturing (AM) Parts of No, or Low, Criticality (for use in Certified products) - Summary

(virtual meeting)

October 2022

(133+ registered)

S.Waite, Senior Expert   Materials, Certification Directorate, EASA
O. Kastanis, Expert   Propulsion, Certification Directorate, EASA

Your safety is our mission.

An Agency of the European Union

EASA – AM WG1

Qualification of Additive Manufacturing (AM) Parts of No, or Low, Criticality (for use in Certified products) – Outline:

WG1 Scope: metallic and **non-metallic AM parts** (of no/low criticality), AM repairs (including repair by replacement), as applicable to a **range of products** (airframe, systems, cabin safety, propulsion etc)

Who is this for? - Decision makers, typically in the supply chain beyond Type Cert Holder:

Reminder: Decision makers/designers exist in a diverse range of organisations with a broad range of capabilities and experience supporting a broad range of approvals… impact upon safety may not be clear to some of these organisations

- Supplemental Type Cert Holders
- Design Organisation Approval (DOA) Holders supporting MROs etc, e.g. under minor change approval, provided all aspects of the change meet the requirements for minor classification.
- ETSO/TSOs
- PART 145 organisations interpreting PART 145 etc (for information - allows repair by replacement)
- Stakeholders new to aviation, e.g. AM Machine Manufacturers.
- Regulators (in order to help define a 'level playing field' for industry)

no/low criticality – broader generic concept, not only of interest to AM

EASA – AM WG1

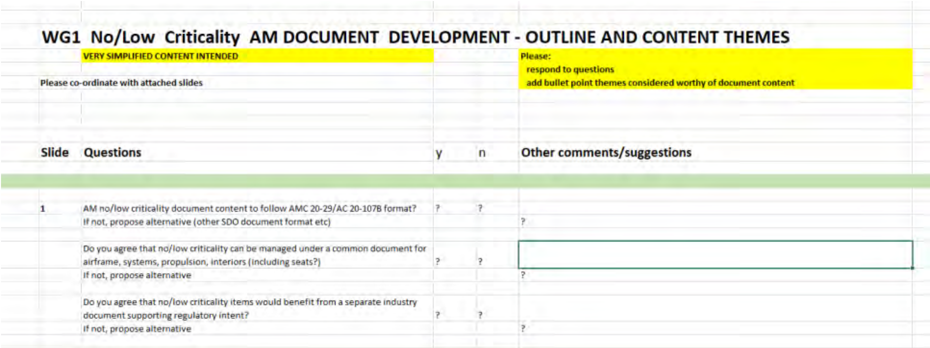
WG1 – 2022 Break-Out session (‘Working Meeting’) **objective:**
(133 registered)

Explore potential for use of AM in no and low criticality applications, supported by further revision to EASA AM CM-S-008, based upon 2021 Spreadsheet feedback

Identified themes for next revision:

- definition of Criticality
- develop meaningful ‘Certification effort proportionate to criticality’ guidelines
- need for broader and increased use of Safety Assessment to support ‘Engineering Judgement’
- add ‘examples’ – support ‘normalisation’ of AM technology application certification expectations

Reminder: All parts, products, and appliances need to satisfy the appropriate regulations



WG1 No/Low Criticality AM DOCUMENT DEVELOPMENT - OUTLINE AND CONTENT THEMES

VERY SIMPLIFIED CONTENT INTENDED

Please:
respond to questions
add bullet point themes considered worthy of document content

Please co-ordinate with attached slides

Slide	Questions	y	n	Other comments/suggestions
1	AM no/low criticality document content to follow AMC 20-29/AC 20-107B format?	?	?	
	If not, propose alternative (other SDO document format etc)			?
	Do you agree that no/low criticality can be managed under a common document for airframe, systems, propulsion, interiors (including seats?)	?	?	
	If not, propose alternative			?
	Do you agree that no/low criticality items would benefit from a separate industry document supporting regulatory intent?	?	?	
	If not, propose alternative			?

EASA – AM WG1

WG1 AGENDA 'Working Meeting':

- brief content outline EASA AM CM-S-008 revision
- 'criticality' definitions (see WG1 introduction slides)
- Certification effort proportionate to criticality
- draft simplified 'Safety Assessment' (see WG1 introduction slides)
- draft 'example' content and format 'Reference Example'
- draft 'examples'
- S-Basis Material Allowables (MMPDS - D. Hall)
- outline EASA AM CM-S-008 revision
- summarise progress for Thursday closing meeting

EASA – AM WG1

Definition of Criticality/Classification:

- not ‘re-inventing the wheel’, but providing link between existing product criticality classification and potential for certification effort being proportionate criticality

- WG1 generally accepted ASTM F3572-22 ‘Standard Practices for Additive Manufacturing – General Principles – Part Classifications for Additive Manufactured Parts Used in Aviation’ table:

Classification	Consequence of Failure	General Description
A	High	Part the failure of which can directly affect continued safe flight and landing Part the failure of which can result in serious or fatal injury to passenger or cabin crews or maintenance personnel Part the failure of which can result in excessive load for the flight crew
B	Medium	Part the failure of which can indirectly affect continued safe flight and landing Part the failure of which can result in injury to passenger or cabin crews or maintenance personnel Part the failure of which can result in a significant increase in workload for the flight crew
C	Low	Part the failure of which has no affect on continued safe flight and landing Part the failure of which has no affect on passengers and cabin crews Part the failure of which can result in a slight reduction in operational/functional capabilities Part the failure of which can result in a slight increase in workload for the flight crew
D	Negligible or No Effect	Part not covered above Part the failure of which would pose no risk of damage to other equipment or personnel

Reminder: PBR – addresses outcomes, **aircraft level and pax level safety…**

EASA – AM WG1

Definition of Criticality/Classification:

- discussion point: WG1 generally agreed with concept, existing criticality classification processes map to F3572-22 table, but potential complication challenge regarding terminology/process differences across disciplines, e.g. structures, propulsion, and systems approach ('engineering judgement' wrt numbers applied to systems approach etc… however, the 'performance/outcome' is the same from PBR perspective (aircraft and pax level safety issues identified and prioritised)…probabilities* etc, only support the 'engineering judgement'/classification, e.g. discussed below (Airbus/Safran proposal)

*Note: historic numbers may only have limited value relative new material, process, and applications

to be concluded…

For AM parts classification it is proposed to complete the table with two last columns:

Classification	Consequence of Failure	General Description	Application for engine products (CS-E 510) and propellers (CS-P 150)	Application for aircraft products (CS-25.1309, CS-23, CS-27, CS-29, CS-22, CS-VLA)
A	High	Part whose failure can directly affect continued safe flight and landing Part whose failure can result in serious or fatal injury to passengers or cabin crews or maintenance personnel Part whose failure can result in excessive workload of flight crew	**HAZ** engine/propeller Effects	**CAT/HAZ** aircraft effects
B	Medium	Part whose failure can indirectly affect continued safe flight and landing Part whose failure can result in injury to passengers or cabin crews Part whose failure can result in significant increase in workload of flight crew	**MAJ** engine/propeller Effects	**MAJ** aircraft effects
C	Low	Part whose failure has no effect on continued safe flight and landing Part whose failure has no effect on passengers Part whose failure can result in slight reduction in operational/functional capabilities Part whose failure can result in slight increase in workload of flight crew	**MIN** engine/propeller Effects	**MIN** aircraft effects
D	Negligible or No Effect	Part not covered above Part whose failure would pose no risk of damage to other equipment or personnel Parts not affecting operational/functional capabilities	No effect	No effect

Reminder: This is WG1 addressing 'no and low' (C and D) criticality.
However, this needs to be part of a coherent 'end to end' process throughout

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EASA – AM WG1

Certification effort proportionate to criticality :

- discussion points/Clarification of WG1 objectives:

Note: **Concept Not New**. **What is new is that the table starts to formalise well how 'engineering judgement' has been exercised for other conventional technologies, not only composites and AM…. but these technologies offer the potential for more competing failure modes and safety outcomes, e.g. due to M&P challenges. Could be an issue in conjunction with 'simplified' MoCs… e.g.**
- **need for other mitigations to work safely?**, e.g. increased awareness/broader use of Safety Assessments to ensure no and low criticality applications remain in that design space?

Important!
- 'S' = Simplified MoCs are different from level to level and from product to product… 'S' only indicates a potential to use a simplified approach
- details need to be defined on product and/or discipline 'case by case' or group basis
- this level of detail unlikely to be given in PBR regulatory guidance, potential for SDO development?

- need to separate out table M&P issues from other product level issues?, e.g. interiors flammability, HIC, vibration, dynamic behaviour, a challenge when 'engineering properties' are defined in final consolidation of a complex part configuration?

SAE Draft Standard for Composite Modifications

Criticality	Material Control	Process Control	Design Values	Static Strength	F&DT	Flammability
1. High – parts whose failure directly affects continued safe flight and landing	X	X	X	X	X	As Required
2. Medium-High – parts whose failure indirectly affects continued safe flight and landing	X	X	X	S	S	As Required
3. Medium-Low – (1) structure whose failure does not affect continued safe flight and landing and (2) parts whose failure can affect passengers and crew	S	S	S	S	N	As Required
4. Low – all other parts	S	S	S, As Required	S, As Required	N	N

Notes:
- May need other columns/categories for engine regulations
- X = "full" compliance, S = simplified compliance, N = compliance not applicable
- Simplified methods of compliance are not the same between the levels

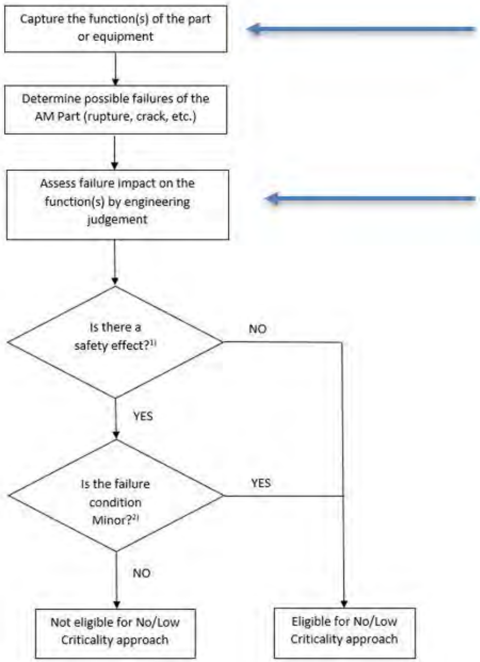
Note: Potential for 'S-Basis data' (not to be confused with 'S' used in the table above) to be used to support the process in some cases.

EASA – AM WG1

Draft simplified 'Safety Assessment' – to support classification process for C or D classification:

- discussion point: WG1 generally agreed, Safety Assessment would benefit from being both 'simplified' Top Down and Bottom Up approach… retain adapted FHA draft below + add text to indicate both approaches should be considered?

to be concluded…



Consider any potential for interaction between functions
- Airframe, Systems, Propulsion, Interiors (including seats) etc

Also consider potential for any new failure modes (relative to conventional technologies and applications) to change the safety outcome beyond direct functionality of the part to include other potential threats, e.g. debris, PDA impact, system ingestion, flammability, introduction of sharp interior edges etc

1) **No Safety Effect (Cat.D)** Part the failure of which would pose no risk of damage to other equipment, personnel, or reduce operational/functional capabilities

2) **Minor (Cat.C):** Part the failure of which has no affect on continued safe flight and landing, no affect on pax or cabin crews, but can result in a slight reduction in operational/functional capabilities or a slight increase in workload for the flight crew

EASA – AM WG1

Certification effort proportionate to criticality :

- discussion points (Airbus/Safran proposal for discussion): WG1 in general agreement with idea, but need for some caveats/development regarding some points, e.g. for Class A/B what approach is required for 'non-critical' Engine Parts DT (similar thought process necessary for C & D?)

Proposed MoC table for engines:

		Design Values / Material soundness	Material control	Process Control	Static Strength	Fatigue / vibration	Damage Tolerance	Flammability
Requirements for	Engines	CS-E 70 (a) Material and Manufacturing Methods	CS-E 70 (b) Material and Manufacturing Methods	CS-E 70 (b) Material and Manufacturing Methods	CS-E 100 (a) (c) Strength	CS-E 100 (a) (c) Strength	CS-E 515 Engine Critical Parts (a)	CS-E 130 (b)(c)(d)(e)(g) Fire Protection
Part Classification	**A**	X	X	X	X	X	X*	As required
	B	X	X	X	S	S	N	As required
	C	S	S	S	S	S	N	As required
	D	SV if required	S/SV	S/SV	SV if required	SV if required	N	N

* only applicable for Engine Critical Parts

Content of the table to be discussed/ agreed

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EASA – AM WG1

to be concluded…

Certification effort proportionate to criticality :

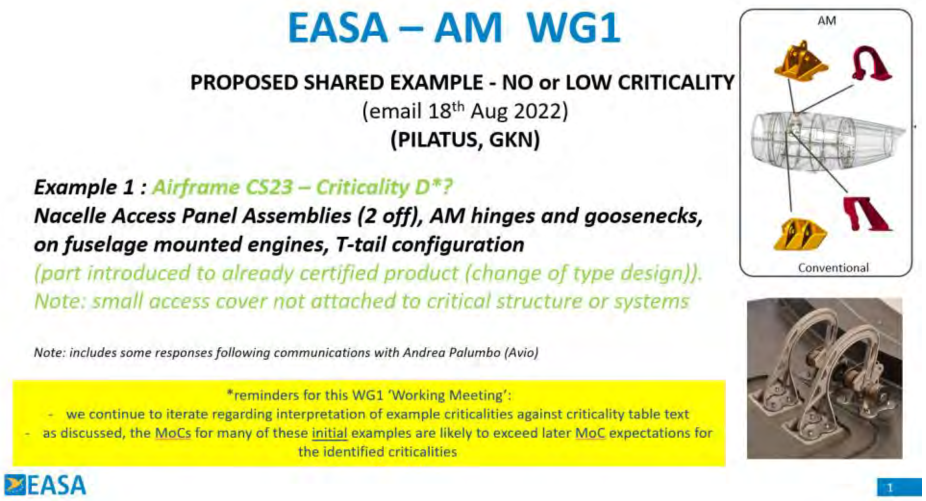
- discussion points (Airbus/Safran proposal for discussion): WG1 in general agreement with idea, but need for some caveats/development regarding some points, e.g. for Class A, B, and C, what approach to Fatigue work is required to justify ‘N’… some level of credible material selection work, should this be ‘S’?

			Design Values / Material soundness	Material control	Process Control	Static Strength	Fatigue / ~~vibration~~	Damage Tolerance	Flammability Fireproofness
Requirements for	Airbus Commercial Airbus Defense & Space		CS 25.613 Material strength properties and Material Design Values	CS 25.603 Materials	CS 25.605 Fabrication methods	CS 25.305 Strength and deformation CS 25.307a Proof of structure	CS 25.571 Damage tolerance and fatigue evaluation of structure	CS 25.571 Damage tolerance and fatigue evaluation of structure	CS 25.853 Compartment interiors CS 25.867 Fire protection: other components CS 25.869 Fire protection: systems CS 25.1191 Firewalls (b) ….
Airbus Group Structures	Airbus Helicopters		CS 27/29.613 Material strength properties and design values	CS 27/29.603 Materials	CS 27/29.605 Fabrication methods	CS 27/29.305 Strength and deformation CS 27/29.307a Proof of structure	CS 27.571 Fatigue evaluation of flight structure CS 29.571 Fatigue tolerance evaluation of metallic structure CS 27/29.573: Damage tolerance and fatigue evaluation of composite rotorcraft structures	CS 29.571 Fatigue tolerance evaluation of metallic structure CS 27/29.573: Damage tolerance and fatigue evaluation of composite rotorcraft structures	CS 27/29.853 Compartment interiors CS 27/29.861 Fire protection of structure, controls, and other parts CS27/ 29.863 Flammable fluid fire protection CS 27/29.1191 Firewalls ……
Part Classification	A	(CAT)	X	X	X	X	X	X	As required
		(HAZ)	X	X	X	X	N	N	As required
	B	(MAJ)	X	X	X	S	N	N	As required
	C	(MIN)	S	S	S	S	N	N	As required
	D	(NSE)	N	S/VS	S/VS	N	N	N	N

EASA – AM WG1

Examples :

- discussion point: Agreed that the ‘examples’ discussed add value and justify addition to the CM revision?



Also discussed:

Airframe: add examples

- ‘*Camera Housing*’ (SOGECLAIR), Gwennole Quenet (for next WG1 meeting)

- ‘*Door Latch Backup Fitting*’ (Spirit Aero), Paul Toivonen

Interiors (including Seats): add examples

- ‘*Title*’ (Materialise, Stirling Dynamics), Erik de Zeeuw, Konrad Lehmann (Thursday)

‘Bumper Mounted on Seat Surrounding Furniture assembly’ (SAFRAN), *Mehdi Bolaky*

‘Monitor shroud/bezel Seat Surrounding Furniture assembly’ (SAFRAN), *Mehdi Bolaky*

EASA – AM WG1

Examples:

- discussion point: Examples discussion supported development of ‘Criticality’ classification process supporting ‘Engineering Judgement’ and appropriate MoC:

- Initial criticality assessment – ‘worst case’ (most critical) potenti

- Final criticality assessment (and basis for accepting simplified approach) – based upon assessments and mitigations on case by case basis

***‘Interior Panel Repair Kit Clips’* (Materialise, Stirling Dynamics)**, Erik de Zeeuw, Konrad Lehmann

- ‘clip’ is part of decompression component (initial/potential Class A or B?), but assessment indicates ‘clip’ failure of no consequence to potential critical function, either from system function or flammability (negligible size) perspective… Class D… justifying ‘simplified’ approach

‘Monitor shroud/bezel Seat Surrounding Furniture assembly’ (SAFRAN SEATS), *Mehdi Bolaky*

- ‘surround’ is part of assembly with potential HIC and flammability issues (initial/potential Class A or B?), but assessment indicates not in HIC strike area, and worst case coupon orientation fire test reference (not specific component fire test (size limitation for this?))… Class C or D… however, this is a complete approach, suggesting that flammability could be addressed differently relative to the proposed potential table, some alleviation and flexibility existing within existing AC materials, e.g. size?

EASA – AM WG1

Examples – Other potential example content:

- discussion point: Agreed that the examples discussed add value and justify addition to the CM revision.

Product/Discipline	Title	Criticality To Be Confirmed	status (beyond feasability)	Organisation(s)		
AIRFRAME						
Metallic						
(structure - propulsion)	Nacelle Access Panel Hinge	D	certified	GKN/PILATUS	Jean Luc	Belon
					Mark	Bosman
					Chris	Dordlofva
	Nose Radome Attachments?	C	certified	DASSAULT	Justine	Chaput
	Camera Housing (TBC)	C/D?	flight test	SOGECLAIR/AIRBUS?	Gwennole	Quenet
	Access Door Latch Fitting	C		SPIRIT	Paul	Toivonen
Non-Metallic	??					
SYSTEMS						
Metallic						
(system -structure - propulsion)	Metallic Duct Fitting	C	certified	LHT	Rob	Van den Bosch
					Jan	Nelle
(system - structure)	NLG Lock Stay Bracket	D		LIEBHERR	Andre	Danzig
Non-Metallic	??			LHT		
PROPULSION						
Metallic	??			SAFRAN? (Roger to dicuss possibilities)		
	??			Doug to explore possibilities		
Non-Metallic	??					
INTERIORS						
Metallic	Interior Housing Assembly	D	certified	ST AEROSPACE ENGINEERING	Guoying	Zheng
Non-Metallic	AFI ALM Parts of no criticality	D		AIRFRANCE	Frederic	Becel
	Dado Panel and Cover Fitting	D		MATERIALISE/EXPLEO	Erik	de Zeeuw
					Gert	Brabants
	Bumper Pad	D		SAFRAN INTERIORS	Muhammad	Khan
	Decorative Panel	D			Mehdi	Bolaky
	Interiors Vibration Damper	C/D		MECAER	Vincenzo	Massarelli
	Interiors Duct	?		(Chris to explore possibilities)		
SEATS						
Metallic	??					
Non-Metallic	Seat Back Video Surround	D		SAFRAN SEATS	Muhammad	Khan
					Mehdi	Bolaky

EASA

Many thanks to those who have presented, and are offering, 'examples'

EASA – AM WG1

Summary:

- Progress made regarding next revision to CM-S-008 revision … to continue based upon refining points discussed in previous slides (next revision draft planned for early 2023)

- Reminder: next revision will be made available for public comment

- further WG1 ‘Working Meetings’ planned (dates TBD)

- need to pick up at future meetings (dates TBD):
    - the flammability proportionate MoC discussion
    - Airbus/Safran Criticality/Proportionate MoC tables
    - further thoughts on S-Basis use?

European Union Aviation Safety Agency

Questions?

FAA – EASA AM Event 2022 - WG Summary:
WG1: Qualification of AM Parts of No, or Low, Criticality
(*for use in Certified products)*

Cochairs: S. Waite (EASA), O. Kastanis (EASA)

The intent of the WG1 breakout sessions was to build upon initial 2021 Event WG1 discussions and outputs, also considering the developing European Aviation AM Industry Regulator Group (EAAMIRG) Actions* and further planned amendments to the 2021 revision to EASA AM CM-S-008:

https://www.easa.europa.eu/document-library/product-certification-consultations/final-certification-memorandum-ref-cm-s-008

*EAAMIRG Actions, i.e. 'Part Classification and Authority Engagement', 'Standardisation: understanding and use of standards'.

The final scope for preparation for the WG1 sessions, and output from these sessions, can be found on the FAA website posting for the FAA EASA AM Event. Furthermore, the WG1 Summary presentation addressing the points in this Summary text will be added to the proceedings package once processed.

https://www.faa.gov/aircraft/air_cert/step/events/additive_mfg_workshop

Preparation for the WG1 activities at the 2022 FAA EASA AM Event started in early 2022, involving the development the WG1 team and organization of preparation meetings (4 off) throughout the year, intended to identify and develop common themes requiring attention across a range of products (airframe, systems, propulsion, interiors (including seats)). For the purposes of the 2022 FAA EASA AM Event, the 2022, feedback from the 'Spreadsheet' (18 organisations responding) was used to support this process, the following themes being identified:

- definition of Criticality (now supported by ASTM F3572-22 'Standard Practices for Additive Manufacturing – General Principles – Part Classifications for Additive Manufactured Parts Used in Aviation'', published in 2022)
- Certification effort proportionality to Criticality
- Safety Assessment
- use of 'examples' to help develop the points above, and support industry and regulator awareness and 'normalisation' of AM applications at this level

Building upon these points, the WG1 process for the Event was primed by sharing with the broader Event audience some introduction slides from the WG1 preparation meetings in order to establish a base upon which the WG1 break-out session could be run as a 'Working Meeting' (also allowing for input from the broader audience).

The WG1 sessions agenda comprised of:

- brief content outline EASA AM CM-S-008 revision
- ‘Criticality’ definitions (see WG1 introduction slides)
- Certification effort proportionate to criticality
- draft simplified ‘Safety Assessment’ (see WG1 introduction slides)
- draft ‘example’ content and format ‘Reference Example’
- draft ‘examples’
- S-Basis Material Allowables
- outline EASA AM CM-S-008 revision

WG1 Session summary: (note: the following represents a summary of discussion as captured by the author and does not represent a concluding regulatory position)

- the majority of the agenda was addressed. However, due to the timeline development of the meeting discussion, and limited availabilities, not all examples were presented. Apologies to those unable to present on the day.
- WG1 established ‘verbally’ (subject to confirmation as the draft CM revision develops):
    - **Criticality:**
        - WG1 generally accepted that existing product criticality assessments could be mapped into the recently released ASTM F3572-22 table, although some further work may be necessary due to different discipline approaches to identifying and classifying criticality, e.g., some disciplines use historical probabilistic data support, e.g., systems, whilst others, e.g. structures, typical do not. However, Performance Based Regulation, which addresses outcomes, potentially allows the diverse range of existing processes to arrive at the common outcome e.g., identify, classify, and address aircraft and pax level safety using a more standardized approach.
          Note: some aspects of historic probabilistic data support could be of limited value to an assessment for new material, process, and/or application configurations.
          Note: the proposed classification process is intended to provide a link between existing classification processes and some potential level of standardized management of Certification effort being proportionate to Criticality. However, potential exists for future development of the Criticality table to be more integrated into product processes
    - **Certification effort proportionality to Criticality:**
        - Historically, ‘Engineering Judgement’ has supported Certification effort approaches being proportionate to criticality for ‘conventional’ technologies and applications. Therefore, this concept and discussion is not new.

- AM introduces a new technology to aviation applications which involves Material, Process, and Fabrication methods for which the final ‘engineering properties’ can be sensitive to process throughout raw material processing through to consolidation of the final complex part configuration. Furthermore, and relative to conventional technology experience, AM technology allows for configuration differences, e.g. optimization and/or reduced part counts, e.g. thin walls etc. These characteristics offer the potential for anisotropy and new, and competing, failure modes (local and aircraft level), some of which may be difficult to detect, potentially resulting in new safety outcomes, and criticalities, relative to convention technology assessments for similar applications (depending upon the extent and detail of the aircraft and/or pax level Safety Assessments).This information regarding the baseline product Safety Assessment may not be available to some supply chains, e.g. those associated with maintenance, modifications, ETSOs etc. Therefore, the potential to use a ‘simplified’ proportionate approach to certification for AM may require further mitigations relative to conventional technologies (until better understood), e.g. more thorough Safety Assessment (e.g. combining top down and bottom up assessments) in order to ensure that the application remains of no or low criticality (note: part of a ‘step by step’ approach to AM), allowing for the potential for failures to influence other disciplines, e.g. structural debris jamming a system, or being ingested by an engine etc.
- details associated with a ‘simplified’ and proportionate MoC may vary from one level of criticality to another and from one product to another. Due to the diversity of such considerations, the regulators will be unable to provide this level of guidance, particularly in a PBR regulatory context. However, the potential exists for other industry guidelines to be developed to support some applications. The proposed draft table discussed during the 2022 Event simply starts to identify the scope to explore a ‘simplified’ means of compliance for no and low criticality applications and requires further development.
- Material and Process issues may need to be identified in a table separately from product level issues. Furthermore, some engineering properties/characteristics may not be easily placed into the table, e.g. flammability, which requires further discussion.
- Although WG1 addresses no and low criticality applications (Class C and D), the management of these applications

should function coherently relative to the management of high criticality applications

- **Safety Assessment:**
  - WG1 generally agreed that there was benefit to considering both ‘top down’ and ‘bottom up’ processes in a Safety Assessment in order to help ensure that no and low criticality applications remain so. It is important to the regulator that the applicant has demonstrated consideration of the potential for the AM application to introduce new failure modes and/or impact more than its immediate function, e.g., part debris jamming systems, engine ingestion, inaccessible surfaces to adversely impact fuel flow etc. etc.
- **Examples:**
  - the proposed draft reference no and low criticality certified ‘example’ was presented (thanks to Pilatus/GKN) and generally accepted as providing a reasonable, but concise, level of detail to be of value for the purposes of increasing awareness and ‘normalising’ the introduction of AM into aviation.
  - further examples were presented in order to support this process, and also the development of the considerations above
  - future examples to be presented in the reference format at future meetings
- **S-basis:**
  - MMPDS presented S-Basis as a potential tool for use in the context of no and low criticality applications.

Future WG1 activity:

- WG1 meetings to continue (dates TBD)
- themes above to be developed in revision to EASA AM CM-S-008 (draft early 2023). Further discussion required regarding:
  - flammability
  - the ‘certification effort proportionality to criticality’ table
  - use of S-basis (material allowable relative to design values etc.)

Appendix V

Working Group #1
"Qualification of AM Parts of No, or Low, Criticality"
Co-chairs: S. Waite and O. Kastanis (EASA)
EASA Presentations

EASA – AM WG1

SOGECLAIR - Example: Camera Housing

Located on fuselage nose cone upper area
Contains a looking forward camera system and its electronics
Certification date: *N/A*

Housing:
- ***250mm diameter***
- ***Less than 1kg***

Airframe:
- ***Large aeroplane (MTOW 300T)***
- ***Wing mounted engine***

EASA – AM WG1

Design Driver: *Static Strength*
Criticality: *Cat.3 Medium Low / C*

Extent of FHA, FMECA, RAS completed: *Equipment is not essential (in development flight test); the part is operated only a few months, it is not subjected to high vibrations frequencies*
Safety analysis lead to birdstrike analysis to ensure that the part could sustain damage without damaging further the A/C (no separation or big debris, load transfer to airframe lower than allowable)

Material and Process: *AlSi7Mg0,6, Laser Powder Bed Fusion*

Material Control: *Supplier spec. based on AMS 7003; based on statistical control process*
Process Control: *Supplier spec. based on AMS 7003 & AMS 7032; using traction coupon built at the same time as the part on each corner of the built plate*

EASA – AM WG1

Design Values: *based on supplier specification established on over 100 coupons.*

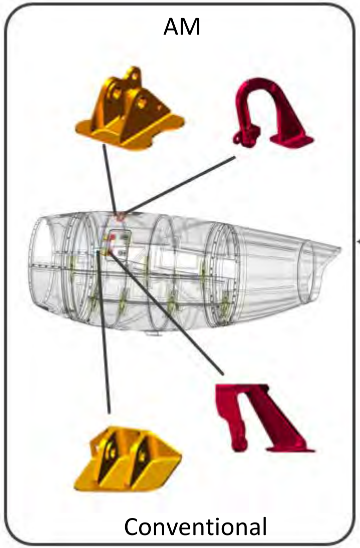
Static Strength*: FE analysis + 6 tensile specimen (MOC: 2)*

Flammability (and/or other considerations): *N/A*

Further Comments: *N/A.*

EASA – AM WG1

PROPOSED SHARED EXAMPLE - NO or LOW CRITICALITY
(email 18th Aug 2022)
(PILATUS, GKN)



Example 1 : *Airframe CS23 – Criticality D*?*
Nacelle Access Panel Assemblies (2 off), AM hinges and goosenecks, on fuselage mounted engines, T-tail configuration
(part introduced to already certified product (change of type design)).
Note: small access cover not attached to critical structure or systems

Note: includes some responses following communications with Andrea Palumbo (Avio)

*reminders for this WG1 'Working Meeting':

- we continue to iterate regarding interpretation of example criticalities against criticality table text
- as discussed, the MoCs for many of these initial examples are likely to exceed later MoC expectations for the identified criticalities

EASA – AM WG1

Example 1: Nacelle Access Panel Assemblies (2 off), AM hinges and goosenecks, on fuselage mounted engines, T-tail configuration… continued

Design Driver: *Static Strength against handling loads*

Extent of Safety Assessment, FHA, FMECA, RAS completed: *Safety Assessment, including consideration beyond functionality, e.g. potential for PDA impact, system jam etc*

Material and Process: *Ti-6Al-4V, Laser Powder Bed Fusion*

EASA – AM WG1

Example 1: Nacelle Access Panel Assemblies (2 off), AM hinges and goosenecks, on fuselage mounted engines, T-tail configuration… continued

Material and Process Control (per CM-S-008 issue 1 in accordance with 21A31):

- *the qualified supplier for the process provides the supplier specs which detail the basic requirements of the process specification from the type certificate holder.*

- *separate specs for powder and melted material. Process specification for virgin powder based upon AMS 4998 (min. requirements) and AMS 7002 (powder production). The manufacturing approval only valid for specific powder (type and manufacturer). Handling of recycled/blended powder is detailed in a supplier spec (ref. AMS 7002 and ASTM F2924).*

- *for manufactured parts, selective use of the majority of AMS7003 and partial use of AMS7028 (draft). AMS7028 para. 3.2., 3.3.1 - stress relief (not HIP).*

EASA – AM WG1

Example 1: Nacelle Access Panel Assemblies (2 off), AM hinges and goosenecks, on fuselage mounted engines, T-tail configuration… continued

- *for a new process, additional production process controls are specified in the process specification from the type certificate holder.*
- *details on sampling are specified in supplier spec.*
- *control supported by Statistical Process Control (SPC), PCD, and other broader supplier documented processes.*

Machines/Locations: *The manufacturing approval is only valid for one specific AM printer. Therefore the type and serial number (S/N) is specified*

Post Processing: *Machining of the part interfaces is performed according to the process specification from the type certificate holder.*

EASA – AM WG1

Examples – Airframe continued:

Example 1: Nacelle Access Panel Assemblies (2 off), AM hinges and goosenecks, on fuselage mounted engines, T-tail configuration

Design Values: ***(per CM-S-008 issue 1 in accordance with 21A20):***
Material Qualification tests to determine design values. 300 coupons from parallel builds (10 batches - 3 virgin powder, 7 recycled powder), at qualification. Specimen orientation selected with lowest mechanical properties.

Static Strength*: 10x part tests to failure (2 batches – supported by batch witness coupon data, i.e. tensile, chemical, and micro/macro inspect), assembly static tests of each assembly (UL and 1.5xUL, ground handling loads). No fatigue or vibration testing. Part and assembly tests supported by FE (using the established design values).*

EASA – AM WG1

Examples – Airframe continued:

Example 1: Nacelle Access Panel Assemblies (2 off), AM hinges and goosenecks, on fuselage mounted engines, T-tail configuration

Flammability (and/or other considerations): *EASA Interpretative Material documented from the CRI D-54 issued for this application: "Most commonly used (on engine and APU mounts) and previously accepted materials, such as steel (AISI 4100 series, 15-5PH CRES), nickel-chromium (Inconel 718) and titanium (Ti-6Al-4V, Ti-6Al-2Sn-4Zr-2Mo) alloys, can be considered fireproof without further substantiation."*

Further Comments: *The structure is redundant, i.e. more than one point must fail until the door detaches in flight. As shown in the attached pictures, the parts are easy accessible and inspectable. The quality controls are specified in the PIL process specification. More detailed information for supplier staff may be documented in supplier specs.*

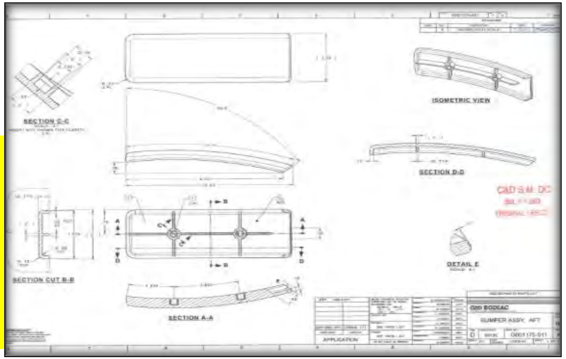
EASA – AM WG1

PROPOSED SHARED EXAMPLE - NO or LOW CRITICALITY
(Safran Seats)

AM Geometry

Example 1 : ***Airframe CS25 – Criticality C*?***
Bumper Mounted on Seat Surrounding Furniture assembly.
(part introduced to already certified product).
Note: The bumper is not installed in the passenger area, but in the aisle area.

Conventional
(Injection Moulded)



*reminders for this WG1 'Working Meeting':

- we continue to iterate regarding interpretation of example criticalities against criticality table text
- as discussed, the MoCs for many of these <u>initial</u> examples are likely to exceed later MoC expectations for the identified criticalities

EASA

EASA – AM WG1

Example: Bumper Mounted on Seat Surrounding Furniture assembly. Bumper mounted on the aisle side of the seat surrounding furniture and remains within the geometrical requirements of the original component.

Design Driver: *Retention and Impact loads.*

Extent of Safety Assessment, FHA, FMECA, RAS completed:
This is not located in the passenger interaction area, and therefore does not require occupant safety assessment (i.e. Cat B). However, it is located on the aisle egress pathway and needs to be evaluated from egress perspective.

Material and Process: *Ultem 9085 Fused Deposition Modeling (FDM)*

EASA – AM WG1

Example: Bumper Mounted on Seat Surrounding Furniture assembly… continued
Material and Process Control (per local approved process in accordance with 21A31):

- *The qualified material provider controls the applicable specification used to manufacture the raw materials.*
- *The qualified material provider manufactures and supplies the filament raw material in accordance with approved Safran specification requirements.*
- *Specifications for the filaments are defined based on test campaign that define the design allowable.*
- *The Machine, software and environment are also defined and controlled throughout the parts manufacturing phase.*

EASA – AM WG1

Example: Bumper Mounted on Seat Surrounding Furniture assembly… continued

- *The Specification defines the type and grade of the material used for the FDM process..*
- *Details on test sampling are specified in the Safran Specification.*
- *Control of the fabrication is via the PCD, and other documented processes applicable to the FDM process.*

Machines/Locations: *The manufacturing approval is only valid for one specific AM printer. Therefore the Machine Type and Serial number (S/N) is specified within the Process Specification.*

Post Processing: *Any defects post processing/printing of the part, are reviewed against an already agreed defect criteria established in the process.*

EASA – AM WG1

Example – Interiors continued:

Example: Bumper Mounted on Seat Surrounding Furniture assembly… continued

Design Values: ***(per local approved Specification accordance with 21A20):***

Material Qualification tests to determine design values.

(4 material batches), at qualification. 3 Machines, and 4 samples for each orientation and batch.

All Specimen orientations selected with and worst orientation taken further to identify lowest mechanical properties.

Static Strength*: 3x part tests to failure (see snapshot), assembly static tests of each assembly (retention and impact loads). No fatigue or vibration testing.*

EASA – AM WG1

Example – Interiors continued:
Example: Bumper Mounted on Seat Surrounding Furniture assembly… continued

Flammability (and/or other considerations):
Worst case printing orientation was established through component testing. Worst case with trim and finish was then tested to ensure compliance with the applicable flammability requirements.

Further Comments: *The bumper is intended to protect the shroud assembly from damage. From the impact loading perspective, failure of the component is allowed, so long as it does not affect occupant egress. Evaluation was carried out against the original injection moulded component failure mode.*

EASA – AM WG1

PROPOSED SHARED EXAMPLE - NO or LOW CRITICALITY
(Safran Seats)

Example 1 : ***Airframe CS25 – Criticality B*?***
Monitor shroud/bezel Seat Surrounding Furniture assembly.
(part introduced to already certified product as an alternative spare part).
Note: The monitor bezel is in the occupant interaction area.

*reminders for this WG1 'Working Meeting':
- we continue to iterate regarding interpretation of example criticalities against criticality table text
- as discussed, the MoCs for many of these <u>initial</u> examples are likely to exceed later MoC expectations for the identified criticalities

Part with 4 attachment to the back of Seat Furniture

- Establish the affected CS 25 specifications
- 25.561, 25.562 (Structural & Occupant safety), 25.601, 25.605, 25.613 25.785, 25.853
- Classified as Minor (based on part usage – non structural trim item)
- Static Substantiation
  - Strength & Stiffness
  - Retention under 9g Static,
  - Behaviour when break by an impact (produce sharp edges)
  - Cyclic/endurance testing to establish the fatigue/cracking
- Occupant Safety Substantiation (Head/Neck Injury) – full evaluation required
  - This could classify as 'Major Change' if **Head Contact is established**
    - *In this application part is outside of head strike zone*
- Flammability Properties
  - Establish the worst case - testing in different layers' orientation – no décor
  - Certification testing in combination with décor (paint, laminate or cladding)
  - Meet EASA's Heat Release Special Conditions (where applicable)
- Environmental Consideration
  - Establishing the worst case for temperature & humidity

Video monitor bezel mounted on the back of seat furniture

ALM Material

Evaluation of HIC compliance required

Currently an injection moulded part

Note: Installation of part as well as interaction with aircraft cabin occupants are considered when deciding about the criticality of parts

EASA – AM WG1

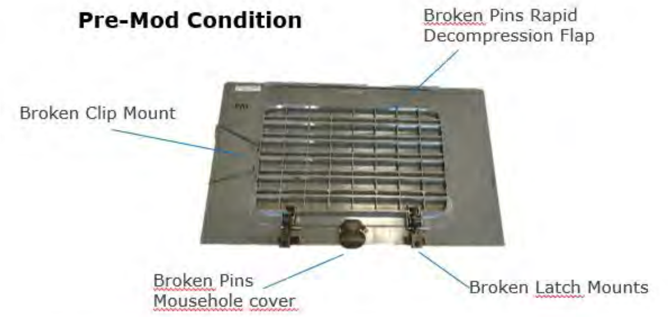
PROPOSED SHARED EXAMPLE - NO or LOW CRITICALITY

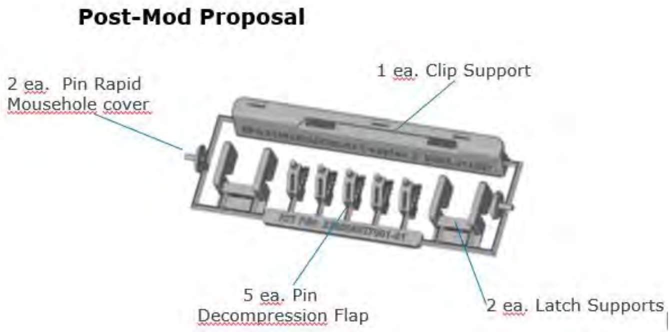
(Materialise , Stirling Dynamics GmbH (formerly Expleo Germany))

Example 1 : No criticality

Part 25 aircraft interior panel repair kit *(part introduced to already certified product (change of type design)).*

Notes: Failure of the repair would not impact the pressure equalisation functionality of the panel. Very low level structural requirements.





EASA – AM WG1

Example 1: Part 25 aircraft interior panel repair kit

Design Driver: *sustainable, cost-effective repair solution with low lead time rather than component replacement (scrapping), possibility to provide strengthening of the original design to prevent breakage*

Extent of Safety Assessment: Engineering assessment of functionality of the panel and the associated rapid decompression flap. Fire hazard assessment.

Material and Process: *PA2241-FR, Selective Laser Sintering*

EASA – AM WG1

Example 1: Part 25 aircraft interior panel repair kit

Material and Process Control:

- the qualified supplier for the process provides the supplier specs which detail the basic requirements of the process specification (internal process document) from the type certificate holder.

- *Material :*

Incoming Goods Inspection

Particle Size Analysis

Bulk Density

Pourability

Melting Point

Flammability

Melt Flow Rate

COA

EASA – AM WG1

Example 1: Part 25 aircraft interior panel repair kit

<u>Machines/Locations:</u> *The manufacturing approval is only valid for a specific process applied at Materialise.*

Process	PCD AERO_PA2241-FR
Material	PA2241-FR
Machine Type	EOS P760, P770
Test Method	ISO527-2/A1

<u>Production Process :</u> *control supported by Statistical Process Control (SPC), PCD, and other broader supplier documented processes. 30+ KC defined and controlled (from data prep over maintenance to breakout) eg : layer thickness, recoater speed , nesting density, ..*

<u>Post Processing:</u> *standard blasting*

EASA – AM WG1

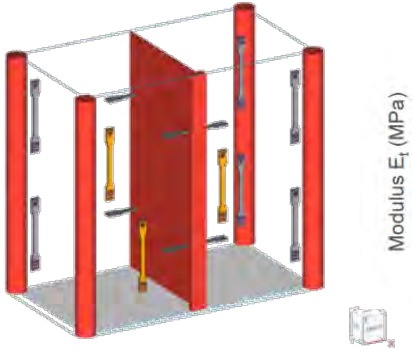
Examples – Airframe continued:

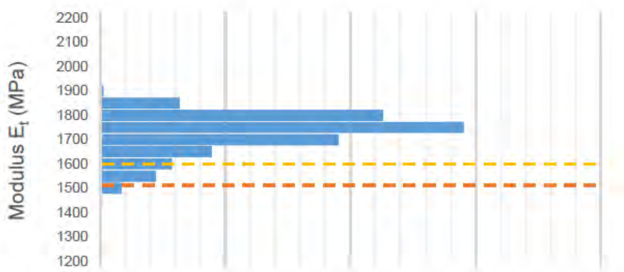
Example 1: Part 25 aircraft interior panel repair kit

<u>Design Values:</u> *Material Qualification tests to determine design values.*

MECHANICAL PROPERTIES

Production Period	11/2019	to	10/2021
# Measurements	1966 (ZX) &		635 (XY)
# Production Builds	232		
# Raw Material Batches	8		
# Mixed Material Batches	128		





<u>Static Strength</u>*: Case based on engineering judgements mostly. Verification and possible substantiation by materialise provided on : tensile, elongation, modulus and density*

EASA – AM WG1

Examples – Airframe continued:

Example 1: Part 25 aircraft interior panel repair kit

<u>Flammability</u> ***:*** *PA2241-FR is inherently flame resistant. The repair components are of very small volume and weight which allows flammability assessment based on coupons tested by EOS (powder manufacturer) during material development*

Verification by POA through subsititute KC : density

<u>Further Comments</u>: *The interior panel fulfils the following functions:*

a) Allowing for rapid decompression (airflow cabin to side-wall cavity) by opening of the pressure baffle
b) Keeping dust and FOD out of the side wall cavity
c) Allowing for low pressure airflow from the cabin to side-wall cavity (part of cabin air cycle) and vice versa
d) Closing the lower end of the sidewall aesthetically

None of the functionalities a), b) or c) are affected by failure of one of more of the repair kit components. Furthermore, even panels that aren't fully secured in place anymore, are prevented to moving out of location by the adjacent seats (very common finding in non-repaired pre-mod condition).

Appendix V

Working Group #1
"Qualification of AM Parts of No, or Low, Criticality"
Co-chairs: S. Waite and O. Kastanis (EASA)
FAA Presentation

Level of Criticality for Flammability

Classification	Consequence of Failure	General Description
A	High	Part the failure of which can directly affect continued safe flight and landing Part the failure of which can result in serious or fatal injury to passenger or cabin crews or maintenance personnel Part the failure of which can result in excessive load for the flight crew
B	Medium	Part the failure of which can indirectly affect continued safe flight and landing Part the failure of which can result in injury to passenger or cabin crews or maintenance personnel Part the failure of which can result to a significant increase in workload for thee flight crew
C	Low	Part the failure of which has no affect on continued safe flight and landing Part the failure of which has no affect on passengers and cabin crews Part the failure of which can result in a slight reduction in operational/functional capabilities Part the failure of which can result in a slight increase in workload for the flight crew
D	Negligible or No Effect	Part not covered above Part the failure of which would pose no risk of damage to other equipment or personnel Part not affecting operational/functional capabilities

- Some obvious examples of what we mean by high and medium criticality for occupant safety related to crashworthiness:
  - ➢ Class A = component in the seat primary load path
  - ➢ Class B= interior monuments, overhead bins
- Not as clear what we mean when it comes to flammability

Level of Criticality for Flammability

- **What about parts that have to meet flammability requirements?**
  - Would their failure to meet flammability standards "have no affect on passengers and cabin crews"? (as described for Class C / Low Criticality)
  - Or is it our intent that any component in the cabin that has a flammability standard fall into Class B / Medium Criticality "Part the failure of which can result in injury to passenger or cabin crews or maintenance personnel"?
  - Perhaps we mean the failure to meet flammability standards could "result in a slight reduction in operational/functional capabilities"? (Also part of Class C / Low Criticality definition)
- **In practice, we have two options to assure flammability performance during production:**
  1. Print and test flammability coupons with each build
  2. Control the M&P sufficiently to ensure consistent fabrication, thus ensuring consistent flammability performance
     - This may involve some in-process testing of non-flammability chemical, physical, and/or mechanical properties
- **My point is that we either move all flammability-critical parts into Class B, or we acknowledge that Class C may still require flammability demonstration, even though it says "no affect on passengers and cabin crews"** (and we develop appropriate standards / requirements / MOC to ensure compliance during production)

Appendix V

Working Group #1
"Qualification of AM Parts of No, or Low, Criticality"
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Battelle Presentation

S-Basis Material Allowables in MMPDS

EASA-FAA AM Workshop
WG1 – Qualification of AM parts of No or Low Criticality Parts
October 18, 2022

Doug Hall
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Program Manager - MMPDS
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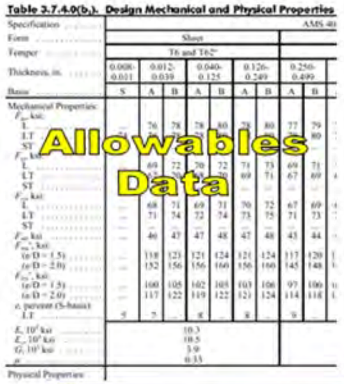
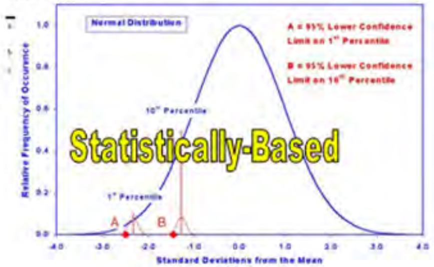
MMPDS

Battelle
The Business of Innovation

Metallic Materials Properties Development and Standardization





History

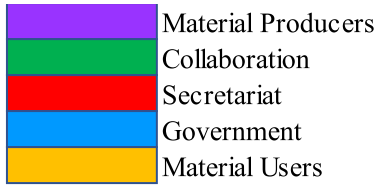
- ANC5 (1937-1954), MIL-HDBK-5 (USAF: 1954 – 2003), MMPDS (FAA: 2003-today)
- Battelle Memorial Institute - program Secretariat since 1956.
- MMPDS Handbook is the primary source of statistically-based material allowable properties for metallic materials and fasteners used in many different commercial and military weapon systems around the world.
- The MMPDS General Coordinating Committee (GCC) is a collaboration between government agencies, aerospace companies, testing and data service companies, and metallic material producers.
- Biannual meetings to review and approve statistical analyses and guidelines.

Scope

- The Handbook currently contains 600+ A/B-Basis and 1000+ S-Basis entries, 400+ unique metal specifications.
- Two to five new alloys are added each year.†
- For more information visit www.mmpds.org

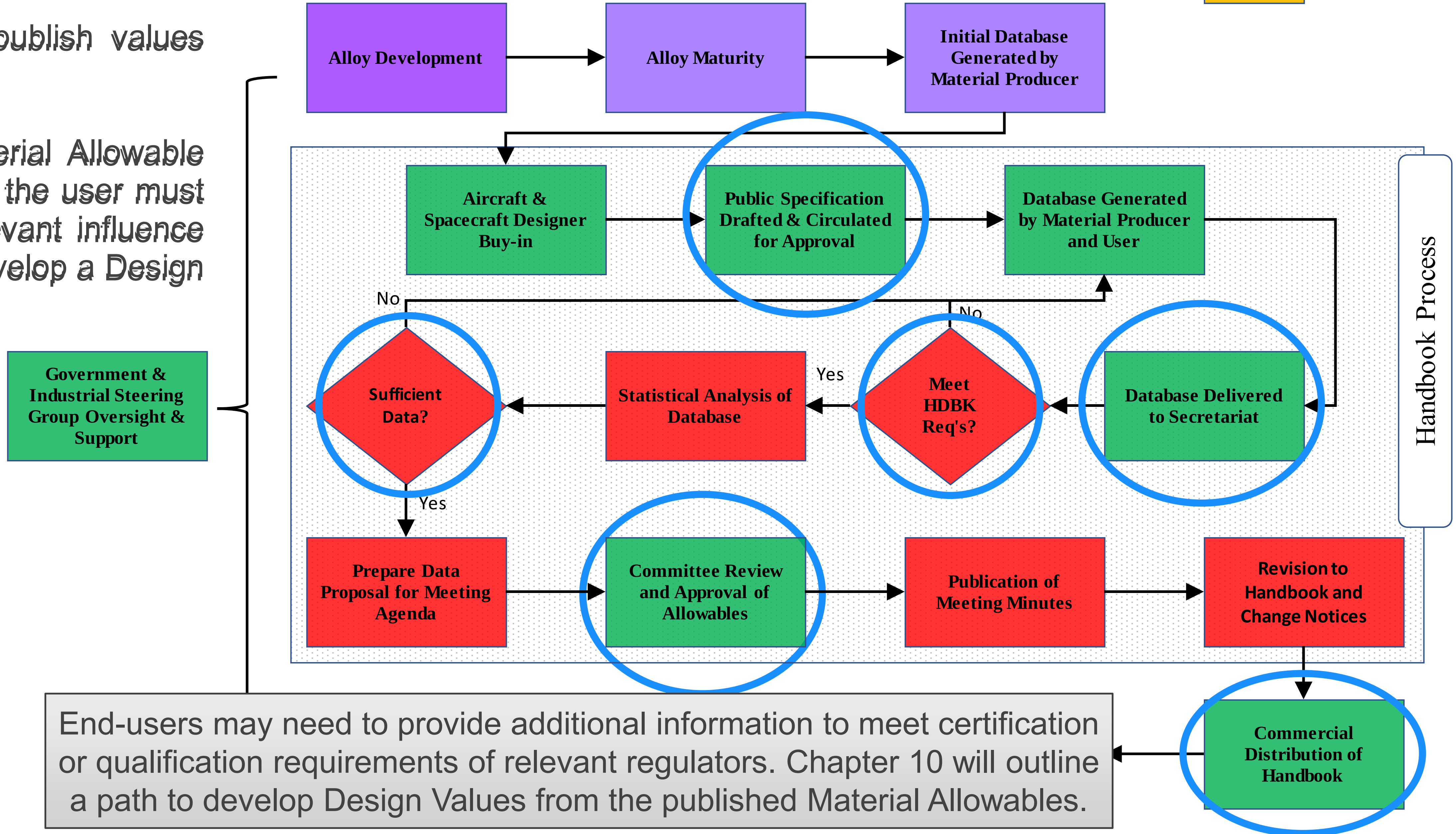
† Pandemic rate has been slower.

MMPDS Review & Approval DRAFT



Process to publish values in Volume II.

Once a Material Allowable is published, the user must consider relevant influence factors to develop a Design Value.



End-users may need to provide additional information to meet certification or qualification requirements of relevant regulators. Chapter 10 will outline a path to develop Design Values from the published Material Allowables.

39th-40th MMPDS GCC Meeting Results

- Volume II is under development. Information subject to further change.
- Agenda Items associated with Volume II
  - ➢21-04: Sections 9.1, 9.2, 9.3 for Volume II – 60-day approval at 40th
  - ❑21-20: Microstructural Submittal Requirements – Continued at 40th
  - ✓21-41: Section 9.8.3 Tabular Data Presentation – Approved at 39th
  - ❑21-46: MMPDS Vol 2, Certification & Qualification "Further Showing" – Continued at 40th
  - ✓22-21: Sections 10.1 & 10.2: Introduction & OSAT – Approved w/Changes at 40th
  - ✓22-06: Combinability in Volume II – Approved at 39th
  - ➢22-08: Chapter 1 for Volume II – 60-day approval at 40th
- Full Minutes of MMPDS meetings are shared with ISG, GSG, and registered non-member attendees.

These approve items are a small part of the Chapter 9 Guidelines. Other requirements apply.

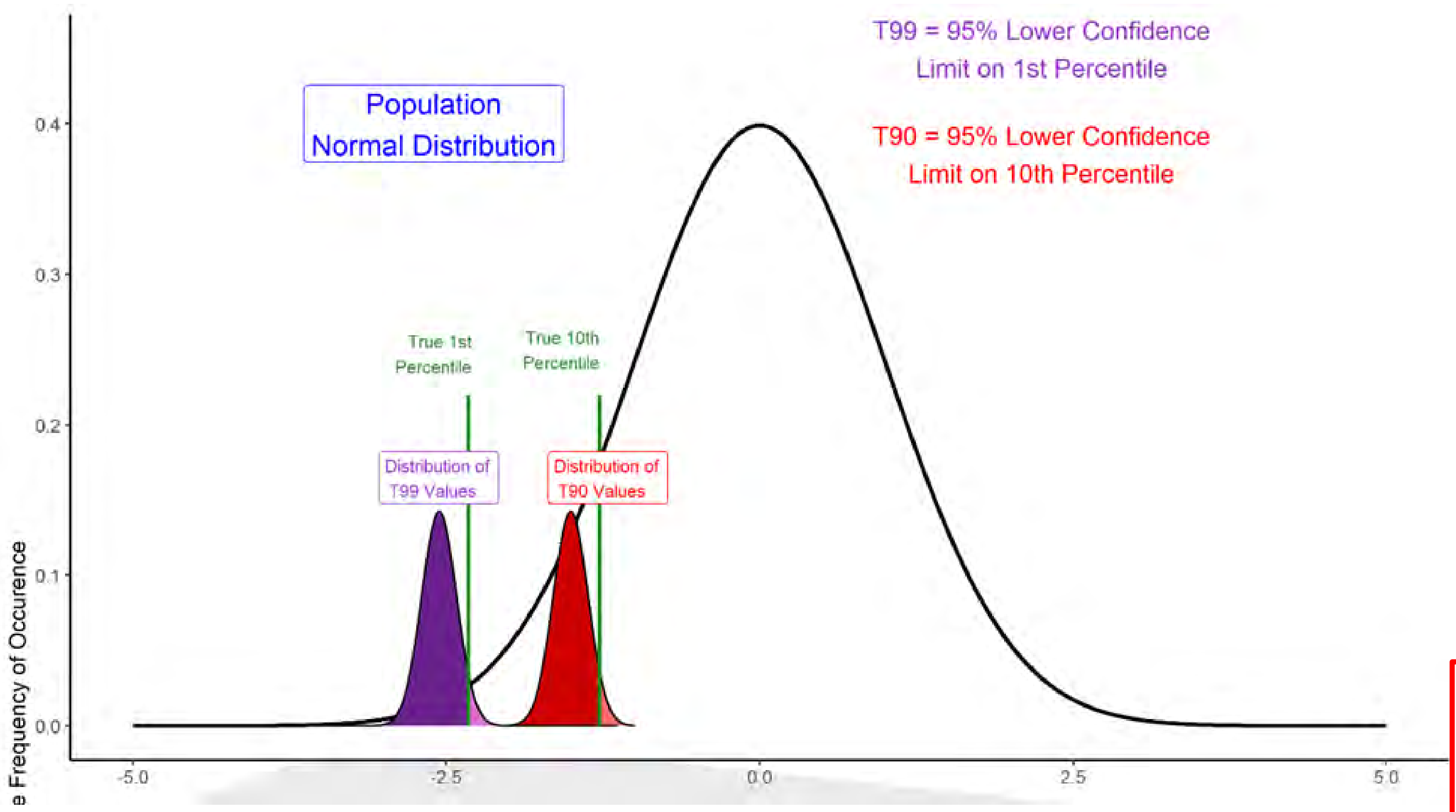
Data Requirements for Volume II - Mandatory

Mechanical or Physical Property	Customary Statistical Basis	Relative Importance in MMPDS Volume II	Extenuating Circumstances for Special Material Usage Requirements	Minimum Data Requirements				
				Sample Size	No. of Heats[g]	No. of Mfg. Lots	Machines[f]	Build Cycles
Bearing Yield and Ultimate Strength	S-Basis	Mandatory	Except for elevated temperature applications	30	3	3	3	3
Compression Yield Strength[a] (Derived)	Same as Tensile Properties	Mandatory		20	3	10	3	3
Density	Typical	Mandatory		3	3	3	3	3
Elastic Modulus - Tension Elastic Modulus - Compression Elastic Modulus - Dynamic Elastic Modulus - Shear	Typical	Mandatory Mandatory Recommended Recommended	Dynamic modulus is strongly recommended for some engine applications	9	3	3	3	3
Elastic Modulus (T, C, D) - Elevated Temperatures	Typical	Mandatory	For anticipated usage temperature range	9	3	3	3	3
Elongation	S-Basis	Mandatory	Two-inch gage length preferred	30	3	3	3	3
Shear Ultimate Strength[a]	S-Basis	Mandatory	Except for elevated temperature applications	30	3	3	3	3
Stress/Strain Curves (To Yield) Tension and Compression	Typical	Mandatory	Desirable to have accurate plastic strain offsets from 10^{-6} to 3×10^{-2}	6	3	6	3	3
Stress/Strain Curves (Full Range) Tension	Typical	Mandatory	The strain rate should be constant through failure.	6	3	6	3	3
Tension Yield and Ultimate Strength	S-Basis	Mandatory		30	3	3	3	3

Other requirements apply.

MMPDS BATTELLE

Volume II C-Basis, D-Basis, S-Basis: Material Allowables



T_{99} and T_{90} are one-sided lower tolerance bounds. Both are calculated from data.

C-Basis = the lower of the specification minimum or T_{99} value.

D-Basis = is the T_{90}. It is not related to the spec minimum.

S-Basis = is a T_{99} that does not meet C-Basis requirements for sample size or distribution fit.

Metallic C-/D-/S-Basis published in MMPDS Volume II require "further showing." A large sample is required.

MMPDS is the primary publicly available, gov't approved source for A/B/C/D/S-Basis material allowables for metals. Proprietary values require extra effort by the CEO.

Data Requirements for Volume II – Strongly Recommended

Mechanical or Physical Property	Customary Statistical Basis	Relative Importance in MMPDS Volume II	Extenuating Circumstances for Special Material Usage Requirements	Minimum Data Requirements				
				Sample Size	No. of Heats[g]	No. of Mfg. Lots	Machines[f]	Build Cycles
Coefficient of Thermal Expansion	Typical	Strongly recommended	For anticipated usage temperature range	6	3	3	3	3
Poisson's Ratio	Typical	Strongly recommended		6	3	3	3	3
Specific Heat	Typical	Strongly recommended	For anticipated usage temperature range	6	3	3	3	3
Tension Yield and Ultimate Strength	D-Basis	Strongly recommended	Especially for strength critical applications; a parametric representation of data is possible	100	10	10	5	10
Tension Yield and Ultimate Strength	C-Basis	Strongly recommended	Especially for strength critical applications; a parametric representation of data is possible	100	10	20	5	20
Tension Yield and Ultimate Strength	C-Basis & D-Basis	Strongly recommended	Especially for strength critical applications; a parametric representation of data is not possible	299	10	20	5	20
Thermal Conductivity	Typical	Strongly recommended	For anticipated usage temperature range	6	3	3	3	3

Other requirements apply.

MMPDS BATTELLE

Data Requirements for Volume II - Recommended

Mechanical or Physical Property	Customary Statistical Basis	Relative Importance in MMPDS Volume II	Extenuating Circumstances for Special Material Usage Requirements	Minimum Data Requirements: Sample Size	No. of Heats[g]	No. of Mfg. Lots	Machines[f]	Build Cycles
Creep and Rupture	Raw Data w/ Best-Fit Curves	Recommended	Especially for elevated temperature applications	6 tests per creep strain level and temp, at least 4 temps over usage range				
Effect of Temperature Curves	Same as Room Temperature Properties	Recommended	Especially for elevated temperature applications	5[b]	2[c]	5	5	5
Effect of Thermal Exposure	Same as Baseline Properties	Recommended	Especially for elevated temperature applications	5[b]	2[c]	5	5	5
Fatigue-Load Control	Raw Data w/ Best-Fit Curves	Recommended	Especially for high-cycle fatigue critical applications	6 test per stress ratio (R), 3 stress ratios, no minimum heat or lot requirements				
Fatigue-Strain Control	Raw Data w/ Best-Fit Curves	Recommended	Especially for low-cycle fatigue critical applications	10 tests for R_ε = -1.0, 6 tests other strain ratios				
Fatigue Crack Growth	Raw Data w/ Best-Fit Curves	Recommended	Especially for damage tolerance critical applications	Duplicate da/dN results for relevant stress ratios and stress intensity range				
Fracture Toughness - Plane Strain	Max., Avg., Min., Coef. of Variance, S- Basis	Recommended	Mandatory for materials with spec minimum requirements for plane strain fracture toughness	30	3	10	3	10
Fracture Toughness - Plane Stress	Raw Data w/ Best-Fit Curves	Recommended	Mandatory for materials with spec minimum requirements for plane stress fracture toughness	d	2	5	3	5
Reduction In Area	Typical	Recommended		When tested, use same criteria as for elongation				
Stress Corrosion Cracking	Letter Rating	Recommended		Conform to replication requirements in ASTM G 47				
Tension Yield and Ultimate Strength - Elevated Temps	Typical	Recommended	Mandatory for elevated temperature applications	e	2	5	5	5

Other requirements apply.

BATTELLE

It can be done

800.201.2011 | solutions@battelle.org | www.battelle.org

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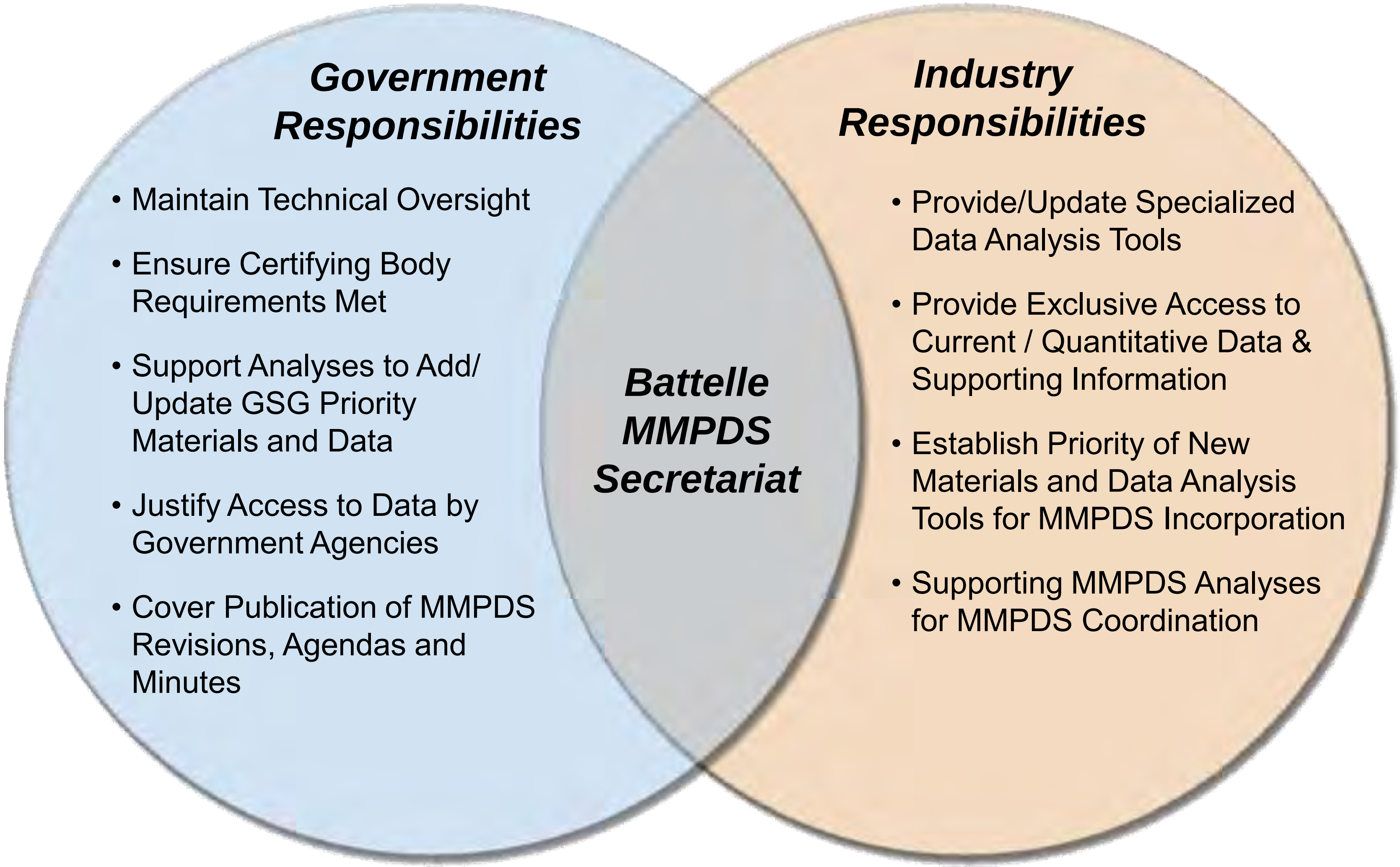
MMPDS General Coordination Committee



GCC makes final MMPDS program decisions based on Task Group recommendations.

Task Groups:
GTG – approve **all** guidelines
MTG – approve materials (Ch. 2-7)
FTG – approve fasteners (Ch. 8)
ETTG – approve V2 content

Steering Groups:
Industry sector input
ASG, MATSSG, PSG

Working Groups:
Technical input from industry
FatWG, SWG, WWG
V2WG – develop V2 tech details

Vol 2 TOC and Three Phases

Phase 1	1	General Information
Phase 2	2	Steel Alloys
Phase 2	3	Aluminum Alloys
Phase 2	4	Magnesium Alloys
Phase 2	5	Titanium Alloys
Phase 2	6	Heat Resistant Alloys
Phase 2	7	Miscellaneous Alloys
Phase 3	8	Metallurgical Joining Technologies – Welding, Friction-Stir Welding
Phase 1	9	Guidelines for the Presentation of Data
Phase 1	10	Guidelines for Use of Published Design Allowables

MMPDS relies on data submitted by sponsors to generate and submit data. Use data to guide future improvements to of Chapter 9 and 10.

One company has submitted a data set which was submitted and reviewed in 2021. Feedback to the sponsor is driving modifications to their specifications, new data, and Agenda Items for 2023.

Ongoing activity to develop data generation, analysis, and presentation guidelines for microstructure.

MMPDS will outline a path to approval, but regulators control that process.

Phase I Framework - Activity

i. Handbook Organization
ii. Definitions
iii. Material Specification Requirements
iv. Data Generation Requirements
v. Data Analysis Requirements
vi. Acceptance Test Methods

Phase I Framework – Status

i. Handbook Organization
   i. 21-01: Foreword to Volume II – GSG declaration of applicability of MMDPS V2 – 40
   ii. 22-08: Chapter 1 for Volume II – 39H, 40A – Sections 1.1, 1.2, 1.4-1.6 – 40A
   iii. 22-09: Preface for MMPDS Volume I and II – 39A
   iv. 22-21: Sections 10.1 and 10.2: Introduction & One-Sample Acceptance Test – 40A
   v. 23-NIN: MMPDS-2023, Volume II, 41A

ii. Definitions
   i. 19-26: Definitions for Process Intensive Materials & Technologies – 34A
   ii. 20-20: Definitions for Volume II – 37A
   iii. 20-31: Definitions of “Design Allowable”, “Design Value”, and “Material Allowable” – 37A

Green text is approved items. Black text is active items. 39/40 are meeting numbers. A/H = Agenda/Handout

Phase I Framework - Status

iii. Material Specification Requirements

  i. 19-17: Minimum Specification Content Requirements for Public Specifications – 36A
  ii. 21-37: Update to Section 9.2.2 for Volume II – 38A
  iii. 21-20: Microstructural Submittal Requirements – 40H
  iv. 22-14: Modifications to Section 9.2.2, V2 – 39A

iv. Data Generation Requirements

  i. 19-20: Data Requirements for Volume II – 36A
  ii. 21-04: Sections 9.1, 9.2, 9.3 for Volume II – 40A
  iii. 21-41: Section 9.8.3 Tabular Data Presentation – 39A

Phase I Framework - Status

v. Data Analysis Requirements
   i. 21-11: Interim Data Analysis Methods: Volume II – 37A
   ii. 22-06: Combinability in Volume II – 39A
   iii. 22-10: Uniformity Test for More Than Three Bins – 39A

vi. Acceptance Test Methods
   i. 19-08: One-Sample Acceptance Testing Method – 34A

Coordination with SDOs & Other Organizations

- ASTM International
  - F42 membership
- FAA-EASA AM Workshops
  - WG1 - Discussing S-Basis as an acceptable material allowable for low criticality parts.
- NIAR
  - JMADD - Air Force/FAA funded project to develop a spec and allowables for PBF Ti 6-4
- NIST
  - Member of a NIST team defining data management standards. FAIR standards are guiding database development
- SAE AMS
  - Advisory Group & Metals Committee – K. Sabo - a GA for periodic testing of secondary props
  - Additive Manufacturing Data Consortium – Battelle is a Liaison member
  - SAE AMS AM Metals Committee
    - Update to the AM Data Submission Guideline – Andrew Steevens (Boeing) sponsor
    - Multiple specs being developed. Data will come to Battelle for analysis to set lot-release values.
    - AMS 7032 (Machine Qualification) – reporting requirement to send data to Battelle.

Data Requirements for Volume II - Mandatory

A new indirect method is awaiting 60-day approval, reducing the amount of data needed for A/B/C/D-Basis for Fbru, Fbry, Fcy, Fsu

A new indirect method is awaiting 60-day approval, reducing the amount of data needed for A/B/C/D-Basis for Fbru, Fbry, Fcy, Fsu

A new indirect method is awaiting 60-day approval, reducing the amount of data needed for A/B/C/D-Basis for Fbru, Fbry, Fcy, Fsu

Mechanical or Physical Property	Customary Statistical Basis	Relative Importance in MMPDS Volume II	Extenuating Circumstances for Special Material Usage Requirements	Minimum Data Requirements				
				Sample Size	No. of Heats[g]	No. of Mfg. Lots	Machines[f]	Build Cycles
Bearing Yield and Ultimate Strength	S-Basis	Mandatory	Except for elevated temperature applications	30	3	3	3	3
Compression Yield Strength[a] (Derived)	Same as Tensile Properties	Mandatory		20	3	10	3	3
Density	Typical	Mandatory		3	3	3	3	3
Elastic Modulus - Tension Elastic Modulus - Compression Elastic Modulus - Dynamic Elastic Modulus - Shear	Typical	Mandatory Mandatory Recommended Recommended	Dynamic modulus is strongly recommended for some engine applications	9	3	3	3	3
Elastic Modulus (T, C, D) - Elevated Temperatures	Typical	Mandatory	For anticipated usage temperature range	9	3	3	3	3
Elongation	S-Basis	Mandatory	Two-inch gage length preferred	30	3	3	3	3
Shear Ultimate Strength[a]	S-Basis	Mandatory	Except for elevated temperature applications	30	3	3	3	3
Stress/Strain Curves (To Yield) Tension and Compression	Typical	Mandatory	Desirable to have accurate plastic strain offsets from 10^{-6} to 3×10^{-2}	6	3	6	3	3
Stress/Strain Curves (Full Range) Tension	Typical	Mandatory	The strain rate should be constant through failure.	6	3	6	3	3
Tension Yield and Ultimate Strength	S-Basis	Mandatory		30	3	3	3	3

Other requirements apply.

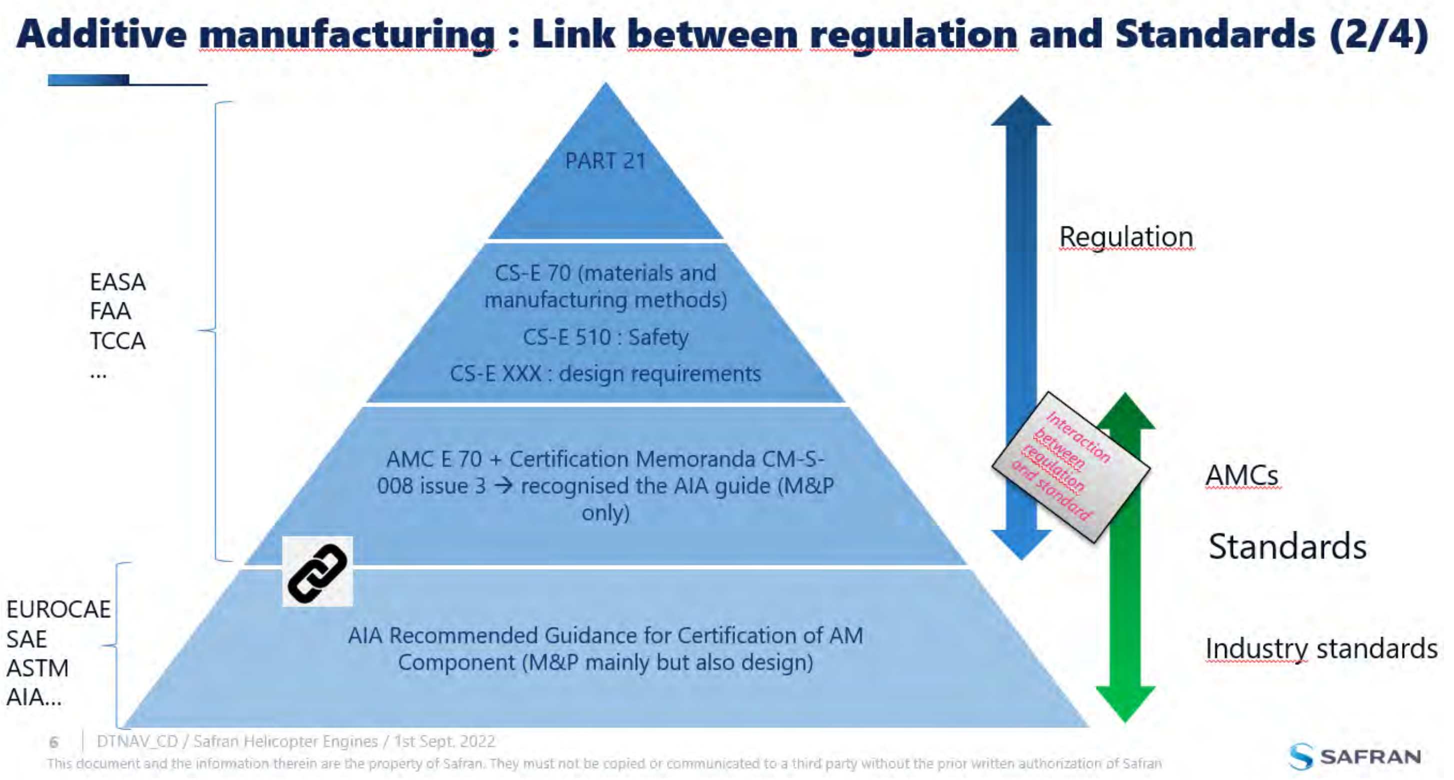
Appendix V

Working Group #1
“Qualification of AM Parts of No, or Low, Criticality”
Co-chairs: S. Waite and O. Kastanis (EASA)
Safran Presentation

Reasons explaining Safran proposal:

From Safran perspective it is essential to have a top-down approach between the technical requirements of the rule (CS-E, CS 25 etc…) to certify an aeronautical product (3 products as per basic Regulation: Aircraft, Engine, Propeller) and the guidance material / acceptable means of compliance to comply with the requirement (such as Certification Memorandum CM-S-008 issue 03 about Additive Manufacturing).
"*Certification Memoranda are not intended to introduce new certification requirements or to modify existing certification requirements and do not constitute any legal obligation*."
That's why, EASA CM should clearly cross reference CS requirements where guidance material are provided and should not create new requirements (such as part classification whereas classifications are already set in existing Certification Specifications).
Safran proposal would be then to rely as much as possible on existing content of existing Certification Specifications.

Example for Engine Product requirements:



For that reason, SafranHE proposes the following adaptations in order to clearly establish the link between the requirements and the guidance material / acceptable means of compliance:

For AM parts classification it is proposed to complete the table with two last columns:

Classification	Consequence of Failure	General Description	Application for engine products (CS-E 510) and propellers (CS-P 150)	Application for aircraft products (CS-25.1309, CS-23, CS-27, CS-29, CS-22, CS-VLA)
A	High	Part whose failure can directly affect continued safe flight and landing Part whose failure can result in serious or fatal injury to passengers or cabin crews or maintenance personnel Part whose failure can result in excessive workload of flight crew	**HAZ** engine/propeller Effects	**CAT/HAZ** aircraft effects
B	Medium	Part whose failure can indirectly affect continued safe flight and landing Part whose failure can result in injury to passengers or cabin crews Part whose failure can result in significant increase in workload of flight crew	**MAJ** engine/propeller Effects	**MAJ** aircraft effects
C	Low	Part whose failure has no effect on continued safe flight and landing Part whose failure has no effect on passengers Part whose failure can result in slight reduction in operational/functional capabilities Part whose failure can result in slight increase in workload of flight crew	**MIN** engine/propeller Effects	**MIN** aircraft effects
D	Negligible or No Effect	Part not covered above Part whose failure would pose no risk of damage to other equipment or personnel Parts not affecting operational/functional capabilities	No effect	No effect

Cross reference between Certification Specifications and Means of compliance covered by EASA CM-S-008 (could be added in appendix of the CM?):

Matrix making cross reference between certification specifications and means of compliance related to Additive Manufacturing developed in the EASA CM-S-008

(Matrix is only completed for engines product category – other categories to be reviewed and completed)

The matrix has been reviewed by Airbus group. In red what should be removed in Blue what was missing.

			Design Values / Material soundness	Material control	Process Control	Static Strength	Fatigue / vibration	Damage Tolerance	Flammability
Requirements for aeronautical products as per Basic Regulation	Aircrafts	CS-VLA ?							
		CS-22	CS 22.603 Materials CS 22.613 Material strength properties and design values	CS 22.605 Fabrication methods	CS 22.605 Fabrication methods	CS 22.305 Strength and deformation CS 22.307 Proof of structure	CS 22.627 Fatigue strength	NA	CS 22.1817 Fire prevention
		CS-25	CS 25.603 Materials CS 25.613 Material strength properties and Material Design Values	CS 25.605 Fabrication methods	CS 25.605 Fabrication methods	CS 25.305 Strength and deformation CS 25.307 Proof of structure ~~CS 25.651 Proof of strength~~	CS 25.571 Damage tolerance and fatigue evaluation of structure	CS 25.571 Damage tolerance and fatigue evaluation of structure	CS 25.853 Compartment interiors CS 25.867 Fire protection: other components CS 25.869 Fire protection: systems CS 25.1191 Firewalls (b)
		CS-23	CS 23.2260 Materials and processes CS 23.603 Materials and workmanship CS 23.613 Material strength properties and design values	CS 23.2260 Materials and processes CS 23.605 Fabrication methods	CS 23.2260 Materials and processes CS 23.603 Materials and workmanship CS 23.605 Fabrication methods	CS23.2240 Structural durability	CS 23.2240 Structural durability CS 23.571 Metallic pressurised cabin structures CS 23.572 Metallic wing, empennage and associated structures CS 23.627 Fatigue strength	CS 23.573 Damage tolerance and fatigue evaluation of structure CS 23.574 Metallic damage tolerance and fatigue evaluation of commuter category airplanes	CS23.2325 Fire protection
		CS-27	CS 27.613 Material strength properties and design values	CS 27.603 Materials	CS 27.605 Fabrication methods	CS 27.305 Strength and deformation CS 27.307 Proof of structure	CS 27.571 Fatigue evaluation of flight structure CS 27.573 Damage tolerence and fatigue evaluation of composite structures	CS 27.573 Damage tolerence and fatigue evaluation of composite structures	CS 27.853 Compartment interiors CS 27.861 Fire protection of structure, controls, and other parts CS 27.863 Flammable fluid fire protection CS 27.1191 Firewalls
		CS-29	CS 29.613 Material strength properties and design values	CS 29.603 Materials	CS 29.605 Fabrication methods	CS 29.305 Strength and deformation CS 29.307 Proof of structure	CS 29.571 Fatigue tolerance evaluation of metallic structure CS 29.573: Damage tolerance and fatigue evaluation of composite rotorcraft structures	CS 29.571 Fatigue tolerance evaluation of metallic structure CS 29.573: Damage tolerance and fatigue evaluation of composite rotorcraft structures	CS 29.853 Compartment interiors CS 29.861 Fire protection of structure, controls, and other parts CS 29.863 Flammable fluid fire protection CS 29.1191 Firewalls …

			Design Values / Material soundness	Material control	Process Control	Static Strength	Fatigue / vibration	Damage Tolerance	Flammability
		SC-VTOL	VTOL.2260 Materials and processes	VTOL.2260 Materials and processes	VTOL.2260 Materials and processes	VTOL.2235 Structural strength VTOL.2255 Protection of structure	VTOL.2235 Structural strength VTOL.2255 Protection of structure	?	VTOL.2325 Fire Protection
	Engines	CS-E	CS-E 70 (a) Material and Manufacturing Methods	CS-E 70 (b) Material and Manufacturing Methods	CS-E 70 (b) Material and Manufacturing Methods	CS-E 100 (a) (c) Strength	CS-E 100 (a) (c) Strength	CS-E 515 Engine Critical Parts (a)	CS-E 130 (b)(c)(d)(e)(g) Fire Protection
		SC-E 19 (EHPS)	EHPS.50 (a) Materials	EHPS.50 (b) Materials	EHPS.50 (b) Materials	EHPS.210 Strength	EHPS.210 Strength EHPS.230 Vibration Survey	EHPS.90 (a)EHPS Critical Parts	EHPS.100 Fire Protection
	Propellers	CS-P	CS-P.170 Materials and Manufacturing Methods	CS-P.170 Materials and Manufacturing Methods	CS-P.170 Materials and Manufacturing Methods	CS-P 240 Strength	CS-P 370 Fatigue Characteristics CS-P 550 Fatigue Evaluation	CS-P 370 Fatigue Characteristics CS-P 550 Fatigue Evaluation	CS-P 230 (f) Propeller Control System
ETSO	APU	CS-APU	CS-APU 60 Materials	CS-APU 60 Materials	CS-APU 60 Materials		CS-APU 300 Vibration	CS-APU 150 (a) Critical Parts	CS-APU 220 Fire Prevention

Proposed MoC table for engines:

		Design Values / Material soundness	Material control	Process Control	Static Strength	Fatigue / vibration	Damage Tolerance	Flammability
Requirements for	Engines	CS-E 70 (a) Material and Manufacturing Methods	CS-E 70 (b) Material and Manufacturing Methods	CS-E 70 (b) Material and Manufacturing Methods	CS-E 100 (a) (c) Strength	CS-E 100 (a) (c) Strength	CS-E 515 Engine Critical Parts (a)	CS-E 130 (b)(c)(d)(e)(g) Fire Protection
Part Classification	**A**	X	X	X	X	X	X*	As required
	B	X	X	X	S	S	N	As required
	C	S	S	S	S	S	N	As required
	D	SV if required	S/SV	S/SV	SV if required	SV if required	N	N

* only applicable for Engine Critical Parts

Content of the table to be discussed/ agreed

Proposed MoC table for Airbus group (Large Aircraft, Light Rotorcraft, Large Rotorcraft:

Important comment: care should be taken not to propose for AM requirements, which are beyond regulation. Fatigue is required for CAT parts only. Damage tolerance is required for PSEs* and PSEs are not existing in CS27.571. The matrix has been revised in accordance with CS25/27/29 regulation requirements. Red indications are the ones modified compared to Cindy proposal.

** **AMC 25.571** '**Principal structure element (PSE)**' is an element that contributes significantly to the carrying of flight, ground, or pressurisation loads, and whose integrity is essential in maintaining the overall structural integrity of the aeroplane.*

***AC29.2C.571** <u>**Principal Structural Elements (PSE)**</u> are structural elements that contribute significantly to the carrying of flight or ground loads and the **fatigue failure** of which could result in catastrophic failure of the rotorcraft.*

***AC27 & AC29.2C.573** <u>**Principal Structural Element (PSE)**</u>. A structural element that contributes significantly to the carrying of flight or ground loads and whose **failure** can lead to catastrophic failure of the rotorcraft.*

			Design Values / Material soundness	**Material control**	**Process Control**	**Static Strength**	**Fatigue / ~~vibration~~**	**Damage Tolerance**	**Flammability Fireproofness**
Requirements for	Airbus Commercial Airbus Defense & Space		CS 25.613 Material strength properties and Material Design Values	CS 25.603 Materials	CS 25.605 Fabrication methods	CS 25.305 Strength and deformation CS 25.307a Proof of structure	CS 25.571 Damage tolerance and fatigue evaluation of structure	CS 25.571 Damage tolerance and fatigue evaluation of structure	CS 25.853 Compartment interiors CS 25.867 Fire protection: other components CS 25.869 Fire protection: systems CS 25.1191 Firewalls (b) ….
Airbus Group Structures	Airbus Helicopters		CS 27/29.613 Material strength properties and design values	CS 27/29.603 Materials	CS 27/29.605 Fabrication methods	CS 27/29.305 Strength and deformation CS 27/29.307a Proof of structure	CS 27.571 Fatigue evaluation of flight structure CS 29.571 Fatigue tolerance evaluation of metallic structure CS 27/29.573: Damage tolerance and fatigue evaluation of composite rotorcraft structures	CS 29.571 Fatigue tolerance evaluation of metallic structure CS 27/29.573: Damage tolerance and fatigue evaluation of composite rotorcraft structures	CS 27/29.853 Compartment interiors CS 27/29.861 Fire protection of structure, controls, and other parts CS27/ 29.863 Flammable fluid fire protection CS 27/29.1191 Firewalls ……
Part Classification	**A**	(CAT)	X	X	X	X	X	X	As required
		(HAZ)	X	X	X	X	N	N	As required
	B	(MAJ)	X	X	X	S	N	N	As required
	C	(MIN)	S	S	S	S	N	N	As required
	D	(NSE)	N	S/VS	S/VS	N	N	N	N

Appendix V

Working Group #1
"Qualification of AM Parts of No, or Low, Criticality"
Co-chairs: S. Waite and O. Kastanis (EASA)
Spirit AeroSystems Presentation

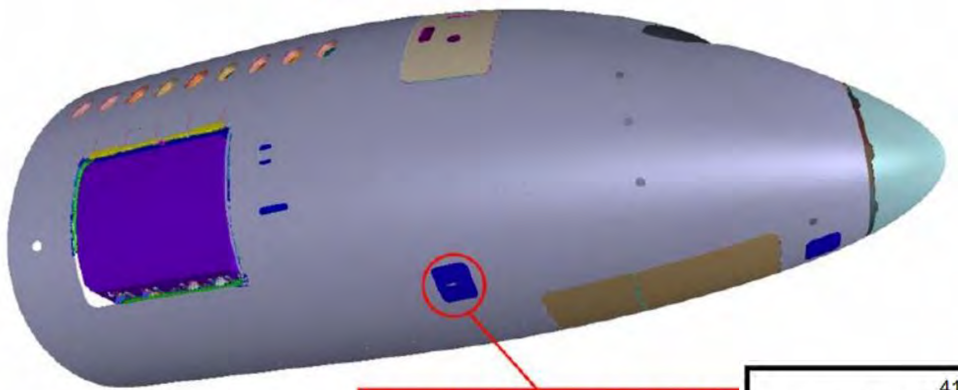
Spirit AeroSystems

Door Latch Backup Bracket – AM Pathfinder Part

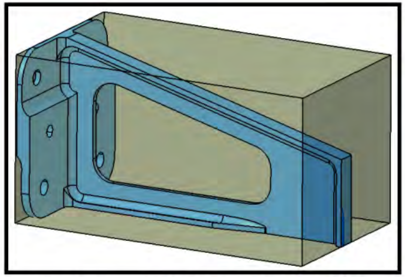
- NO or LOW CRITICALITY
- *Boeing 787 commercial transport category fuselage, Section 41 access door structure, Part # alternative – serial production*
- *Introduced to already certified product, equivalent to legacy design/material (machined plate = machined AM preform)*
- *Design Driver: Static Strength against handling + crash loads*
- *Design Values: OEM - full allowables (static, plus fatigue/DT)*
- *NTi Wire Fed Plasma Arc Directed Energy Deposition Additive Mfg Process AMS7005, substrate AMS7004*
- *OEM & Tier 1 AM/Rapid Plasma Dep. M&P specifications*
- *NTi: OEM qualified machine(s) and production facility (NY)*
- *Preform inspection: UT immersion (production, x-ray –dev.)*
- *Post-Processing: stress relief*
- *Part Qual: Dep Process Sched, DoE/perf & microstructure, FAI*
- *Cover Story in Additive Manufacturing Magazine, May 2019, (Vol 8 No 3)*

EASA

787 Section 41



Forward Electrical Access Door (FEEAD)



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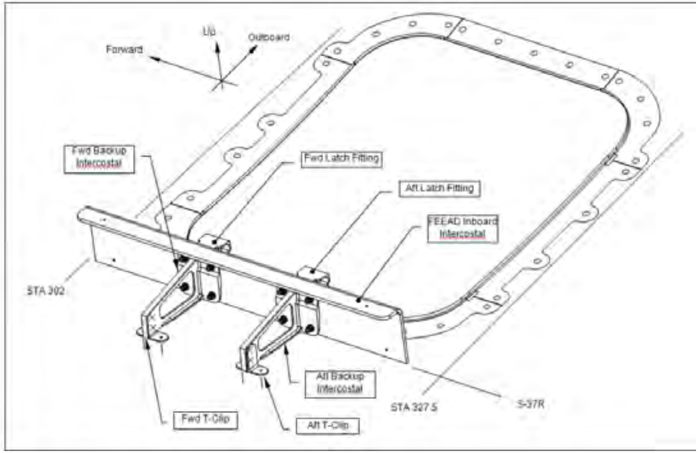


418Z8222-5
FEEAD_LATCH_FITTING_SPRT_FWD

- Current material: TI-6AL-4V - ANNEALED TITANIUM ALLOY PLATE PER AMS 4911
- Finished part weight: 0.45 lb
- Manufacture stock size weight: 12.03 lb

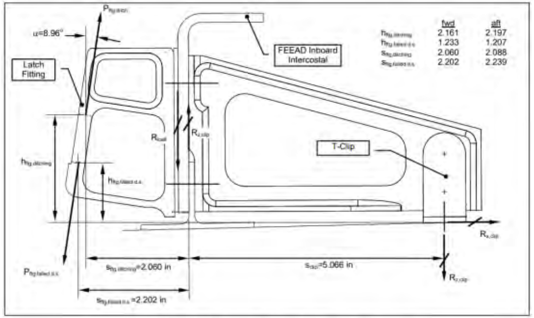


Figure 0-1: Latch Backup Structure Free Body Diagram

Min Static Margin +.02

Min Fatigue Margin >+3.0

Appendix W

Working Group #2 Summary Presentation
"F&DT and NDI Considerations for Metal AM"
Co-chairs: M. Gorelik (FAA) and A. Fischersworring-Bunk (MTU)

2022 FAA - EASA AM Workshop

(virtual meeting)

WORKING GROUP 2:

Fatigue and Damage Tolerance (F&DT) and Non-Destructive Inspection (NDI) Considerations for Metal AM

WG2 co-chairs:

M.Gorelik, Chief Scientist for Fatigue and Damage Tolerance, FAA

A.Fischersworring-Bunk, Senior Fellow Structures, MTU AeroEngines

Final Briefing

Oct. 20, 2022

Core Team:

Alain Santgerma (Airbus); Andre Danzig (Liebherr); Andrew Perry (GE Aerospace); Angel Martinez (ITP Aero); Armando Coro (ITP Aero); Arnaud Longuet (Safran Group); David Mills (Rolls-Royce); Doug Wells (NASA); Federica Vico (Lilium); Hilde Larsen (Norsk Titanium); Jonathan Leblanc (Safran Group); Kishore Tenneti (LMCO); *Laura Kistler (Boeing)*; Markus Heinimann (Howmet Aerospace); Stefan Hermann (Liebherr); Tom Bertenshaw (GKN Aerospace); Lloyd Schaefer (General Atomics);

Stephane Bianco (Airbus); Morgan Mader (Joby Aviation); Jesse Boyer (Pratt & Whitney); Leo Kok (De Havilland); Paul Toivonen (Spirit); Ray Martell (GE Aerospace); Shane Nicholson (Parker); Sue Margheim (Collins); Yann Danis (Safran); Eric Sager (Boeing)

members of AIA AM WG sub-team shown in *italics*

WG#2 Description

Fatigue and damage toleration (F&DT) related qualification considerations and related certification requirements have historically presented more significant challenges for structural components produced using process-intensive manufacturing technologies, and additive manufacturing (AM) is no exception. While all the key tenets of the certification requirements apply to AM, *there is a number of material system specific considerations that need to be understood and properly accounted for*, including inherent material anomalies and their effect on fatigue life, residual stresses, non-destructive inspection (NDI) challenges, effects of post-processing, etc.

The need for developing a good understanding of these factors is further elevated by the *expected near-term introduction of high-criticality AM parts* in Civil Aviation that will be subject to F&DT regulatory requirements.

The intent of this working group is to discuss the most recent developments in these technical areas, while *building on the outcomes of the F&DT and NDI breakout sessions from the 2020 and 2021 AM Workshops*, and to further develop considerations for aviation application of AM.

The *desired outcomes* of this working group and the corresponding breakout sessions during the 2022 AM Workshop are listed *on Slide 4*.

2022 FAA - EASA AM Workshop

WORKING GROUP 2

WGs - development since 2020 Event (*note – breakout sessions format was used since 2018 workshop*)

- **Co-chairs and Core WG Teams identified and formed in advance of the 2022 event (leveraging off 2021 membership)**
- **WG2 theme is recognized as a carry-over from the 2021 event**

WG2 - Core Team (primarily Aerospace industry + government agencies)

- **WG2 objectives and priorities defined → *see next slide for priorities***
- **Need for *tangible outputs* recognized:**
  - ➢ **Gap Analysis and Technical Progress**
  - ➢ **Standardization landscape, and input into SDOs and Consortia work (as feasible)**
  - ➢ **Input into R&D prioritization (as feasible)**

WG#2 Topic (for 2022 breakout sessions)

- **Topics and priorities established by the core WG2 members prior to the Workshop, and reaffirmed by Breakout Session's participants**
  1. What are key remaining challenges for certification of high-criticality AM parts (fatigue, DT, NDE (including in-process monitoring), anomalies characterization, effect of defects, tools and methods, design data, role of Computational Materials / ICME, etc.) → at least get an update
     - Also discuss a set of enablers – visions of an "ideal state"
  2. Use, role and limitation of simplifying assumptions in the context of F&DT assessment (e.g. knockdown / safety factors; ignoring crack nucleation time; simplified approach to material anisotropy / heterogeneity (→ zoning?); simplified anomalies distributions, …)
  3. Recent progress in SDO and non-SDO domain (e.g. industry, government agencies – experience and guidance)
     - A "map" – who is doing what in this space
  4. Define supporting R&D topics (update of 2021 results) – *time permitting*

2022 FAA - EASA AM Workshop

WORKING GROUP 2

Agenda: B/O Session - Day 1 (Tuesday, October 18) ***– 2 hrs***

- **Discussion of the b/o sessions format**
- **Summary of 2021 outcomes and confirmation of 2022 objectives**
- **Briefing by AIA AM Working Group's sub-team on high criticality parts** *(L. Kistler)*
- **Work on Topic 1**

Agenda: B/O Session - Day 2 (Wednesday, October 19) ***– ~ 2.5 hrs***

- **Work on Topics 2 and 3** (and Topic 4, *time permitting*)
- **Summarize recommendations (*draft* – to be finalized shortly after the Workshop)**

Working Notes (Day 1)

- **Topic #1:**

  What are key remaining challenges for certification of high-criticality AM parts (fatigue, DT, NDE (including in-process monitoring), anomalies characterization, effect of defects, tool and methods, design data, role of Computational Materials / ICME, etc.)

    - Progress over the past 1-2 years
    - Discuss a set of enablers – visions of a "future state"

- **Notes:**
  - Need a spectrum of NDI tools, not just expensive methods. Identify NDI tools closest to maturity, and advance them for practical applications. Need to consider in-situ monitoring tools further upstream.
  - Need to focus on what anomalies / defects have quantifiable impact on the quality of the parts.
  - NDI is not infallible, need to focus on process controls to prevent defects from forming during the manufacturing process
  - Need to address small crack growth (under Topic 1)
  - Need to discuss how all the elements tie together to ensure safety; how to move from idealized tests and specimens to real parts

Working Notes – *Topic #1 (cont.)*

- ***Notes:***
  - Effect of defects – significant difference between surface and bulk / volumetric (different morphology, different physics of defects formation, different effect on performance, etc.). Also, need to consider the role of near-surface defects (some may not be completely random, e.g. tied to scan strategies etc.).
    - A potential sub-topic – role of near-surface defects for rolling fatigue (*out of scope..?)*
    - Need specific documentation for part feature size and build orientation (e.g. for heat exchangers)
    - Need to consider part(s) location within the build chamber, build volume needs to be sampled appropriately (e.g. as a part of FAIR)
  - Interest in ICME approach – what is the role of ICME tools in the context of Certification, how do we know we are using the “right” tools?

Working Notes – *Topic #1 (cont.)*

Notes:

- **What is the maturity of defects characterization methods?**
  - How to translate the knowledge of defects population(s) into DTA assumptions?
  - Characterization of defects at specimen vs. part level – may have different levels of maturity (and sensitivity)
  - Need to understand maturity of the different methods for different materials
  - Need to expand on the concept of “defects” – may not be just localized discontinuity (e.g. anisotropy, …). Not all anomalies are defects. Some microstructural anomalies could be “defects”, but not all. Also, NDE community may have different definitions of defect vs. F&DT community.
    - NDE interpretation – detectability threshold vs. decision threshold (relative to design requirements)
    - Inherent defects (may be below the threshold of “common” NDE). What is the defect population for “special causes” – e.g. process drifting out of bounds, mfg escapes, unique geometric features, etc.
    - Need to define the surface finish and acceptable level of surface roughness, as they may have an impact on fatigue
  - Expanding on the concept of defects characterization:
    - NDE (conventional) – CT use for qualification and process development.
      - POD considerations – have published data for panels (NASA POD studies, NTIAC); traditionally used transfer functions (with support of purpose-designed specimens) to work across different attributes (e.g. size / geometry / material / surface / …)
      - Surface roughness – one of the influencing factors for detection capabilities
    - In-situ monitoring – melt pool monitoring, other forms of condition monitoring,
    - Destructive characterization methods – metallography / serial sectioning, properties testing, fractography

Working Notes – *Topic #1 (cont.)*

Notes:

- **Elements of "future state" for F&DT and NDE**
  - Clear definition of allowable defects (similar to structural castings)
    - One ref. – NDE acceptance criterial for LPBF (F42 / in balloting)
    - Need to strengthen process-specific definitions of anomalies
  - Well defined inspection methods for: a) development / Qual, b) in-situ monitoring, c) point of manufacture / QA, d) in-service
  - Fatigue –
    - Need to understand acceptable performance "thresholds", e.g. min necessary quality of as-printed surfaces (not to adversely affect fatigue performance)
    - What is the right pedigree of material to establish S-N curves (ref. to Dave F. presentation)
    - Ability to accurately assess fatigue performance associated with a given surface quality / finish etc.
      - Most of the conventional surface finish metrics are not adequate for correlating to fatigue performance

Working Notes – *Topic #1 (cont.)*

Notes:

- **Elements of "future state" for F&DT and NDE**
  - **Fatigue (cont.)** – Do S-N curves work for metal AM?
    - Some of the surface quality metrics (including NDI) are very path-dependent; need to factor this in when developing or combining data sets
    - Note - if fatigue sample is notched, the surface finish affect may be minimal
    - If fatigue behavior is significantly influenced by underlying population of anomalies, need to understand how to establish representative volume of fatigues specimens (assuming final process state is reflected in specimens)
    - When characterizing fully finished (post-processed) specimens, need to account for effect of post-processing (e.g. HIP) not just on population of anomalies, but also on substrate microstructure. These considerations may affect both average fatigue behavior and min properties (scatter).
    - Is there a limit to using S-N based approach for metal AM? → Is it possible to create a "flexible" (hybrid?) S-N approach, e.g. combined with zoning, that will recognize location-specific populations of anomalies? Need to be in the position to decide when S-N is applicable or not (based on the attributes of given material / part, degree of process controls, etc.)
    - Key question – how representative are test bars to actual part, in several aspects: a) representative volume, b) location-specific properties (including anomalies population). Thermal history could be used as one similitude criterion between specimens and parts.

Working Notes – *Topic #1 (cont.)*

Notes:

- **Elements of "future state" for F&DT and NDE *(cont.)***
  - DT framework –
    - Need more work on small crack growth
    - Improvements in FM analysis – effects of plasticity (not necessarily drive by AM-specific needs)
    - Need standardized factors that will influence key DT assumptions (e.g. interaction of adjacent anomalies, clustering, surface connected anomalies, surface / subsurface anomalies interaction)
    - Need a set of engineering (and business?) criteria – when to switch between deterministic vs. probabilistic DT
    - "No growth" considerations – need to have a good understanding of near-threshold FCG behavior; could be useful for non- fatigue critical parts. Not an overarching criterion (one of the options).
  - General note: all of the above elements of the "future state" should not be viewed as show stoppers for the use of current state of maturity of these methods and tools
- In the above discussion, concentrated primarily on fatigue. How about EAC / SCC mechanisms? Changes in the microstructure resulting from AM process or post-processing could make some alloys (e.g. Al based) more susceptible to EAC / SCC. → *Future discussion on this topic is recommended*
- In case bulk properties (e.g. ductility) are different in AM alloys, may need to reconsider susceptibility to accidental (surface) damage

Working Notes – Topic #2

Topic #2: Use, role and limitation of simplifying assumptions in the context of F&DT assessment (e.g. knockdown / safety factors; ignoring crack nucleation time; simplified approach to material anisotropy / heterogeneity (→ zoning?); simplified anomalies distributions, …)

Notes

- For DT assumptions – approximating defect geometry by a surface area (i.e. Murakami approx.)
- Q: At what point does it make sense to go away from the "baseline" assumptions and methodologies, specifically for AM?
  - E.g., ignoring crack nucleation may not provide the same level of conservatism for certain AM materials (and anomalies) as for "conventional" alloys
- Simplified anisotropy assumptions for DT (i.e. using the worst-case orientation for da/dN properties) – likely to stay long-term. However, may be different for fatigue (e.g. for local orientation of as-built surfaces)
  - Potential special consideration – could ignoring anisotropy affect predictive capabilities, e.g. our ability to accurately predict crack propagation direction?
  - Another consideration – bi-modal fatigue behavior

Working Notes – Topic #2 (cont.)

Notes

- Using conservative assumptions in analysis may not allow for proper capture of variation, and therefore would complicate comparison of analytical predictions vs. sub-scale / full scale test results
- Heterogeneity – could be addressed through zoning; zoning in this context can be interpreted as a "multi-dimensional" concept – e.g. with respect to local properties (including anomalies population), local NDE capabilities (including POD), "criticality" of local failure mode
- Potential use of knockdown / safety factors → *main challenge* – how do we ensure that such factors are conservative for AM (false sense of security..?)
  - Discussion – using castings as a benchmarking example – when applying a particular factor, how do we ensure that all the corresponding engineering assumptions are still applicable?
  - Additional considerations – volume vs. surface related attributes driving safety factors (or a combination)
- Re. simplified anomalies distribution – need to consider what type of distributions are used to fit the data, and whether simplifying assumptions are consistent with the existing levels of process control

Working Notes – Topic #3

Topic #3: Recent progress in SDO and non-SDO domain (e.g. industry, government agencies – experience and guidance)

- A "map" – who is doing what in this space?

NOTES:

- ASTM F42 and E08 for F&DT, and E07 for NDE → need examples of specific documents (WG2 volunteers? – Eric Biedermann (Vibrant)
  - For NDE, can reference Lloyd's presentation on Day 4
  - For F&DT – under E08, a new WG stood up to address guidelines for crack initiation data generation (accounting for surface features etc.); another E08 effort (E08.06 sub-committee) to standardize fatigue specimens geometry for AM
- A useful model (under ASTM) – liaison function between several committees / WGs (e.g. for NDE)
- SAE - ? (*action → follow up off line with some SAE focals*)
- Note: AMSC started the effort to update AM Standards Roadmap (ver. 3) → can submit a request to AMSC for F&DT and NDE content
- AWS D20 - ? (*action → follow up off line with AWS focals*)
- UK: British Standards Institute is well aligned with ASTM / ISO work (TC261). EU: ?
- Non-SDOs
  - AIA AM WG kicked off sub-team on high-criticality parts
  - Other..?

Summary

- **Discussed opportunities for collaboration with AIA AM WG *(sub-team on high-criticality parts)***

Topic #1:

- **Main themes discussed: NDE, Fatigue, Characterization of Anomalies, Effect of Defects, Use of ICME Tools**
- **Highlights / Examples -**
  - **Need to account for small crack growth**
  - **Lack of work / data on EAC / SCC for metal AM (e.g. for *Al* alloys)**
  - **NDE - need to focus on anomalies / defects that have quantifiable impact on parts performance**
  - **DT – some discussion re. the use of deterministic vs. probabilistic methods**
  - **Effect of defects – significant difference between bulk (volumetric) and surface defects (physics, characterization methods, impact on fatigue life, etc.)**
  - **Some discussion regarding terminology harmonization (defects vs. anomalies, inherent vs. rogue)**
  - **Significant discussion regarding defects characterization considerations and methods**
  - **Significant discussion regarding the elements of the “future state” for F&DT and NDE of AM**
    - ➢ ***However, acknowledged that not all elements of the “future state” are required to conduct appropriate assessment in the interim***

Summary (cont.)

- **Topic #2:**
  - **Several common simplifying (conservative) assumptions acknowledged - zero crack initiation time from anomalies; conservative treatment of heterogeneity, anisotropy, etc.**
  - **Typical trade-offs: more conservative assessment vs. reduced level of testing / characterization**
  - **Challenges: a) does not allow for proper capture of variation, makes comparison of predictions with test more challenging; b) potential use of knockdown / safety factors – how do we ensure that such factors are conservative for AM?**
- **Topic #3:**
  - **Relatively little work by SDOs in the area of fatigue and fracture of metal AM (some new efforts are starting, e.g. by ASTM E08 committee)**
  - **A number of activities and published documents relative to NDE of AM**
  - **Most of the EU and UK based standardization efforts in this area are linked through ISO**
  - ➢ **Actions: to follow up with several SDOs (SAE, AWS) to get status update on the above topics**
  - ➢ **Main recommendation: to connect with AMSC effort on the revision of AM Standardization Roadmap (Rev. 3) that has just been kicked off**

- ***Members of the core WG2***
- ***All participants of the Breakout Session #2*** *(138 registered)*

APPENDIX

Chat Notes (Day 2):

- To build on Ted's point about factors in DT other than fatigue, we have to consider whether Design for AM leads to part designs that have a different sensitivity to accidental damage than our existing subtractive manufactured designs
- Other things to consider are the discontinuity/defect aspect ratio, especially for the ones near surface. ...and AM-specific references for NDI techniques
- Two comments: 1) if S-N curve fatigue is a good method for characterization of cast/powder metallurgy/welded samples, then it is good for AM too; 2) Not sure if residual stress (RS) will be discussed or related to Topic 2. RS is not defect (& sometimes is good), but has a major effect on fatigue crack propagation rate.
- One additional aspect with the thermal history tracking is that we may have to extend it to post-processing too (HIP, heat treatment).
- Differences in techniques for measuring roughness aside (profilometry vs. X-Ray CT), R_a isn't necessarily the greatest fatigue life predictor. Considering R_sk, R_v, R_5p variables are potentially the more 'potent' variables.

Appendix X

Working Group #3 Presentations

“Improved Communication and Data Sharing between AM Machine Makers and End Users”

Co-chairs: Don Godfrey, SLM, F. Lartategui Atela, ITP Aero and Richard Mellor, Rolls Royce

Appendix X

Working Group #3 Introduction

"Improved Communication and Data Sharing between AM Machine Makers and End Users"

Co-chairs: Don Godfrey, SLM, F. Lartategui Atela, ITP Aero and Richard Mellor, Rolls Royce

EASA – Structures and Materials Safety

FAA - EASA AM

INDUSTRY – REGULATOR EVENT

WG3 Improved Communication and Data Sharing between AM Machine Makers and End Users

(virtual meeting)

October 2022

R. Mellor, Chief of Manufacturing Engineering, Rolls Royce plc

D. Godfrey, Global Business Development Director, SLM Solutions

F. Lartategui Atela, Senior ALM technologist, ITP Aero

FAA/EASA – AM WG3

WG3 Improved Communication and Data Sharing between AM Machine Makers and End Users – Outline:

Scope: Additively manufactured parts for use in aerospace applications to include e.g. airframe, system, propulsion, interiors.

This group has both AM equipment suppliers and end users. Need to consider other stakeholders at various positions within the supply chain and with differing levels of capability.

Aim: Process and material agnostic guidance.

Tailored to criticality (ref WG1): All AM structures and systems need to comply with the applicable regulations; however, the level of rigor in compliance findings may be scaled depending on the risk to continued safe flight and landing. The level of necessary rigor for a given structure/system is established considering the classification of structure/system.

FAA/EASA – AM WG3

2021 Summary

Topic 1 - Maintaining certainty after an intervention:

End users invest significant time, effort and cash to qualify part, process, equipment and facilities.
Typically these are ‘fixed processes’

The suppliers of AM equipment typically want to ‘improve’ their machines, but may lack understanding of effects, consequences or airworthiness requirements.

The machines are subject to varying levels of intervention:

- services
- replacement of consumables
- repair following failure
- ‘upgrades’

A range of examples from low impact minimal requalification through to high impact more extensive requalification.

EASA

FAA/EASA – AM WG3

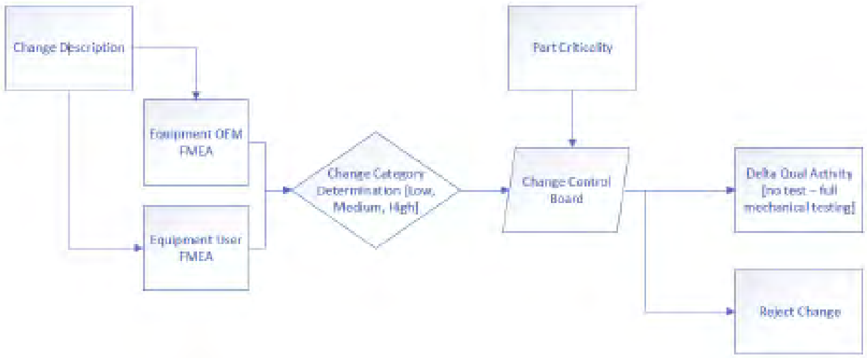
2021 Summary

Topic 1 - Maintaining certainty after an intervention:

<u>RISK CONTROLLED CHANGE:</u>

Why:

When service is performed on a machine qualified as part of a "fixed process", some changes can result in requalification of a machine / process causing downtime an
offer advantages.



1. Low criticality changes
2. Medium criticality changes
3. High criticality changes

Will require greater transparency from 3D printer suppliers

(2021) Output of WG3 Meeting:

Companies agreed this issue is indeed real and needs to be addressed. Instead of simply making a matrix of repairs/upgrades, it was decided that SAE member Liz Crisler (Textron), Marijan Jozic (Octonx), Dave Abbott (GE), and Hector Sandoval (LMCO) will champion the idea before the next SAE meeting to determine if the organization should generate a standard as part of an already existing specification.

FAA/EASA – AM WG3

2021 Summary

Topic 2 – Near term process monitoring opportunities

Ensure to the FAA / EASA organizations that the printed part is identical to the qualified part and that the final build / quality report quickly informs a reader the printer part is either 1) A quality part and can be pasted onto the next step; 2) The part exhibited some abnormalities and requires further inspection; 3) The part should be scrapped.

The output should also be a digital report that can connect to an ERP manufacturing router and the machine should have the ability to have data extracted in a usable way to compare previous builds by part number.

Process monitoring and risk analysis:

Goal:

Short term:

Build foundation to capture machine technology to begin validating process monitoring values to known inspection technologies so to minimize future post build inspection efforts.

Long term:

All proves have a degree of natural variation. We design to accommodate this natural variation. We build an understanding of how capable monitoring systems are and thus how confident we can be that any deviation outside of our design assumptions will be reported. When we achieve this state, we may reduce our conventional inspection and rely on process monitoring.

FAA/EASA – AM WG3

2021 Summary

Topic 2 – Near term process monitoring opportunities

<u>**Voice of the industry:**</u>

- Nearly every piece of melting equipment collects data
- This varies from basic data – temperature, pump speed… to more complex solutions such as melt pool monitoring

- This data is not always accessible to the user
- The same variable is recorded in different ways complicating the end user experience
- There is no common format for data export

- Final report (after build) misses mark on producing report to tell operator if the part is good / bad / suspect - It requires expert review

- Near term the technology should be focused on monitoring process parameters and reporting if they keep within process window tolerances

Aerospace manufacturers are frustrated by lack of accessible data

FAA/EASA – AM WG3

2021 Summary

Topic 2 – Near term process monitoring opportunities

Voice of the customer – Long term:

- All current data should be made available
- New forms of monitoring will evolve
  - Needs to consider use / cost / accuracy

- Focus on making operator interaction easier – Go/no go
  - Clear status – Go / No go / review
  - Identify 'points of interest' – Layer and location for further review

- Ambition: Use machine and process monitoring to reduce down stream costs
  - Significant effort to relate KPV to defect types

FAA/EASA – AM WG3

2022 WG3 topics:

1- Conclusion of ‘Maintaining certainty after an intervention’ (2021 topic)

Bring to a conclusion to last years topic by creating a SAE Aerospace Recommended Practice (ARP). As you may know, SAW has three tiers of regulations being:

Tier 1:	Aerospace Specification
Tier 2:	Aerospace Recommended Practice (ARP)
Tier 3:	Aerospace Information Report (AIR)

Liz Crisler (Textron) has been part of a team that co-wrote, reviewed and eventually released a SAE specification on a topic very similar to our topic, and has written most of an ARP for 2021 topic: ‘Requalification of AM machine’.

2- Pipeline of AM manufacturing thoughts from industry & governmental agencies

Topics that companies / government agencies can plan for future FAA/ EASA conferences and not have to respond to a condensed / compressed schedule.

EASA
European Union Aviation Safety Agency

Questions?

EASA
European Union Aviation Safety Agency

Support Slides

FAA/EASA – AM WG3

2021 Summary

Topic 1 - Maintaining certainty after an intervention:

Potential low criticality changes

- → Mechanical component in the 3D machine that does not impact the printing process
- → Electronic component (if it has the same function and specification
- → Software changes that do not influence printing processes (need information from OEM)

- → What about replacement of a seal?
  - → An identical seal could be verified from observation- gas pressure, oxygen level in build chamber etc

- → What if it is geometrically the same but of a different material?
  - → Wear rates may differ, potential for contamination, changes to service intervals?

FAA/EASA – AM WG3

2021 Summary

Topic 1 - Maintaining certainty after an intervention:

Potential medium criticality changes

- → Annual service etc where multiple parts of the system may be dismantled
- → Mechanical systems- eg gas pump
- → Laser (or other energy source) calibration file

FAA/EASA – AM WG3

2021 Summary

Topic 1 - Maintaining certainty after an intervention:

Potential high criticality changes

1. Anything in the optic system
2. Any changes in the gas flow process
3. Scanning algorithm
4. Slicing software
5. Re-coater blade- form or material
6. Powder sieving / handling
7. Powder/ wire delivery for blown powder or wire feed applications.

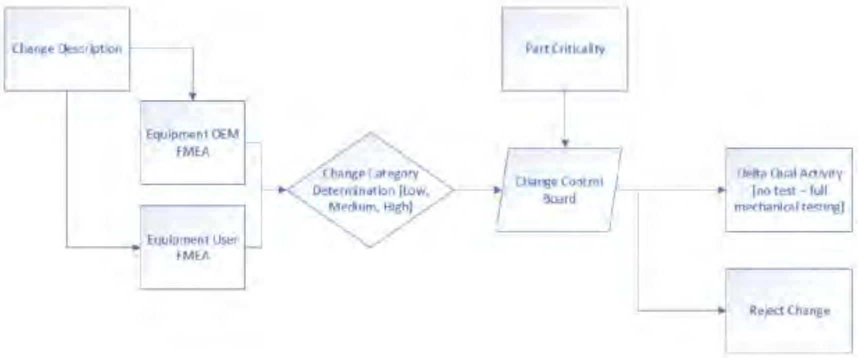
FAA/EASA – AM WG3

2021 Summary

Topic 1 - Maintaining certainty after an intervention:

A risk based approach

- Proposed changes are assessed and a scaled validation exercise is then carried out.
- AM equipment supplier may be wary of this approach
  - Exposes their IP?
  - May not have sufficient understanding of Airworthiness requirements
  - Maybe a higher level of effort than required for some markets
- Approach requires greater upfront understanding by user



EASA

FAA/EASA – AM WG3

2021 Summary

Topic 2 – Near term process monitoring opportunities

To what extent can process monitoring be used today to inform better decisions?

Lots of sources of data- machine producers and third parties
How accessible is this to the user?

Do we have data or information?
How do we consolidate the disparate data feeds?
Can it be more comprehensive?
Data records, retention and storage?

To what extent can sentencing be automated to reduce specialist or operator burden?

X	?	OK
So far from the process that it should be scrapped	Some element of deviation which requires review- MRB etc	The comprehensive build fingerprint is entirely within expectations and so the part is good to progress through its normal production route including inspection, nde etc

Topic 2 – Near term process monitoring opportunities

Process monitoring

→ examples

1. Machine Parameters
    1. Laser Powder
    2. Oxygen
    3. Moisture
    4. Build Plate Temperature
    5. Due Point Sensor
    6. Inert Gas Pressure in Chamber
    7. Filter Pressure
    8. Shielding Gas Flow (pressure or volume)
    9. Turbine Speed
2. Process Monitoring
    1. Melt Pool Monitoring
    2. Grid Value
    3. IR Images

FAA/EASA – AM WG3

2021 Summary

Topic 2 – Near term process monitoring opportunities

Prompts for discussion

Can we build consensus about what is important (by process)?

Can we be consistent in format? Is that important?

- units
- types of sensor
- pump speed as a proxy for gas flow?

Where/ how is it reported?

On the face of the machine control
Buried in a file
Exported for analysis

Requires expert analysis or Go/no Go indicator?
What goes with the traveller?

FAA/EASA – AM WG3

2021 Summary

Topic 2 – Near term process monitoring opportunities

3 output conditions?

- So far from the process that it should be scrapped, ideally killed early in process.
- Some element of deviation which requires review- MRB etc
- The build fingerprint is entirely within expectations and so the part is good to progress through its normal production route including inspection, nde etc
  An appropriate endorsement to the manufacturing job card/ traveller etc required

To what extent can sentencing be automated to reduce specialist or operator burden?

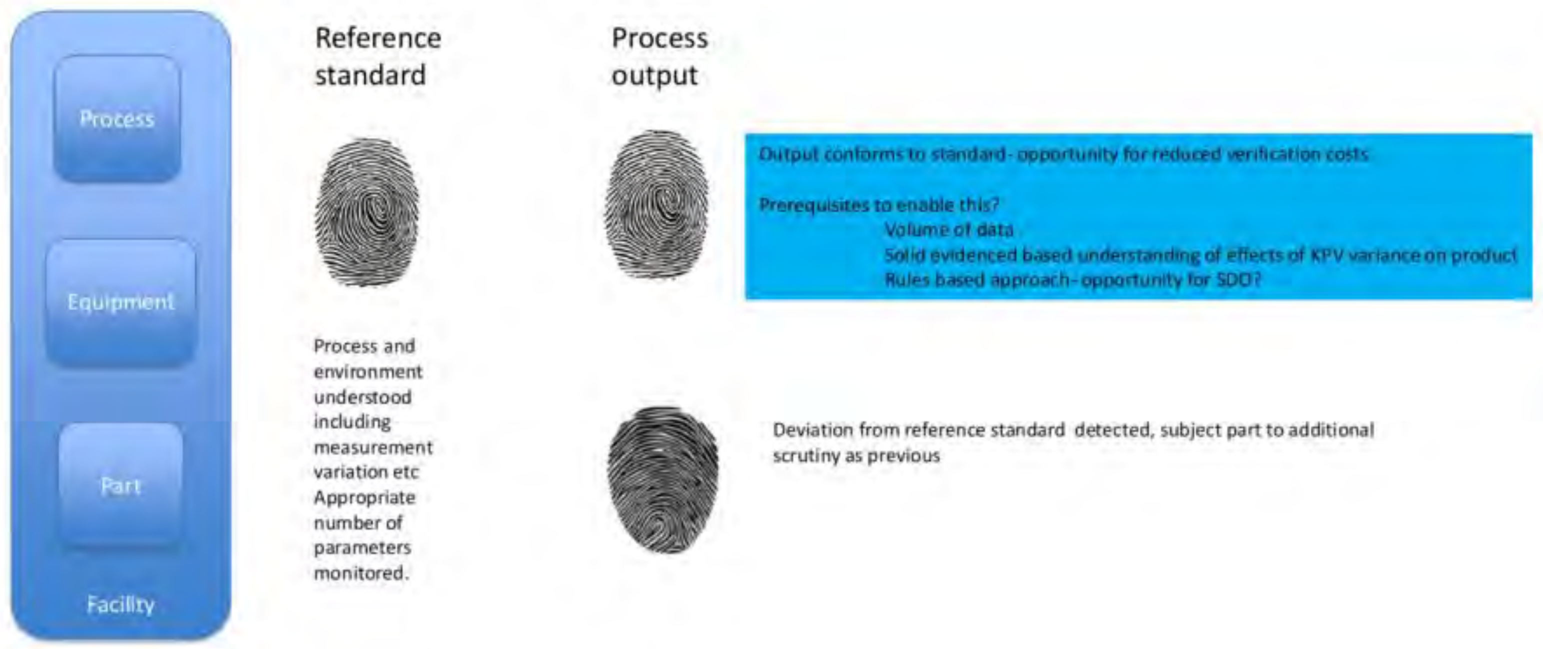
How much data?
Retained for how long?
Security of storage?

FAA/EASA – AM WG3

2021 Summary

Topic 2 – Near term process monitoring opportunities

Future state: Process monitoring as a quality and safety tool at lower overall cost?



Appendix X

Working Group #3 Summary

"Improved Communication and Data Sharing between AM Machine Makers and End Users"

Co-chairs: Don Godfrey, SLM, F. Lartategui Atela, ITP Aero and Richard Mellor, Rolls Royce

European Union Aviation Safety Agency

Federal Aviation Administration

EASA – Structures and Materials Safety

FAA - EASA AM

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Your safety is our mission.

An Agency of the European Union

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FAA/EASA – AM WG3

Breakout Session #3 topics:

1- SAE Aerospace Recommended Practice ARP7064 [Liz Crisler]

‘Machine Requalification Considerations for Fusion-Based Metal Additive Manufacturing’

Bring to a conclusion to last years topic by creating a SAE Aerospace Recommended Practice (ARP). As you may know, SAE has three tiers of regulations being:

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Tier 2: Aerospace Recommended Practice (ARP)
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FAA/EASA – AM WG3

1- SAE Aerospace Recommended Practice ARP7064 [Liz Crisler]

The team:

- 58 on the mailing list
- 13 meetings
- Average 14 per meeting

A year ago…

Activity Component change/repair (no modification, no parameter change)	Execution [or function]				x = Measurement after xx = Measurement before and after * = see remarks												Approval by [and function]					
	Manufacturer	Calibration Department	Operator	**Technical documentation needed**	Process monitoring measurement	Process monitoring analysis	Process monitoring calibration	Axes geometry	Scanner beam position	Laser focus	Scanner speed	Laser power	Skywriting	Oxy-file analysis	Others (see remarks)	**(Renewal) machine approval**	Quality department	Welding Supervisor	Certifying Agent	Machine Owner	Planner	approved Operator
New machine installation	x	x			x	x	x	x	x	x	x	x	x	x	x	**x**		x			x	
Yearly maintenance	x	x					x	x	x	x	x	x								x	x	
Machine displacement	x	x			x	x	x	x	xx	xx	x	x	x	x	x	**x**		x			x	
Machine modifications	x	x														**x**		x	x		x	
Optical System																						
aser linearisation (Laser power out of tolerance)	x	x										xx								x	x	
Laser linearisation (Laser power in tolerance)	x	x										xx										x
Laser change	x			**x**	x	xx			x	xx		xx	x						x			
Energy supply	x	x																				x
Scanner change	x			**x**	x	xx			x	xx		xx	x						x			
F-theta change	x			**x**	x	xx			x	xx		xx							x			
Protection glass laser change	x	x																				x
Collimator / other Beam shaping optics	x			**x**	x	xx			x	xx		xx	x						x			
fiber optics	x	x																				x
Build platform																						
Z-axis motor	x	x		**x**				x												x		
linear scale	x	x		**x**				x												x		
platfom topplate	x	x		**x**											x					x		
Dosing platform																						
motor	x	x		**x**				x												x		
platform topplate	x	x																		x		
Collector platform																						
motor	x	x																			x	
platform topplate	x	x																			x	
Recoater																						

First attempt

	Requal Level, per AMS7032 Table x					
	L-PBF AMS7003	**EB-PBF AMS7007**	**L-DED (pwd) AMS7010**	**L-DED (wire) AMS7010**	**EB-DED (wire) AMS7027**	**PA-DED (wire) AMS7005**
All Modalities						
Calibration of melt source		1			1	
Calibration of motion axes		1			1	
Calibration of beam focus		1			1	
Calibration of beam astigmatism		1			1	
Calibration of beam position		1			1	
Calibration of substrate alignment		1			1	
Calibration of substrate positional accuracy and motion speed		1			1	
Calibration of temperature sensors		1			2	
Calibration of gas inlet pressure		1			n/a	
Calibration of cooling circuit pressure		2			2	
Calibration of recoater or wire feed system alignment		1			1	
Calibration of recoater or wire feed positional accuracy and motion speed		1			1	
Calibration of compressed air pressure		2			n/a	
Calibration of feedstock regulation sensors		n/a			n/a	
Powder						
Wire						
Calibration of beam-to-wire ~~alignment~~ positioning		n/a			1	
Laser						
Calibration of galvo mirrors		n/a			n/a	
Electron Beam						
Calibration of vacuum sensors		1			2	
Calibration of power supply		1			1	
Plasma Arc						
Unscheduled Maintenance						
Software/Firmware						
Upgrade firmware						
Upgrade machine control software						

EASA

Impact analysis

FAA/EASA – AM WG3

1- SAE Aerospace Recommended Practice ARP7064 [Liz Crisler]

Re-adjust:

Provide modality-agnostic guidance on how the document user can generate their own impact list

Create the list:

- KPV list in associated process specification (e.g. AMS7003)
    - In particular, KPVs which employ Statistical Process Control (SPC), should be included in this list.
- AM machine OEM operation manual
    - This may include certain environmental operating conditions to be maintained, such as vibration limitations, electromagnetic field restrictions, etc. AM Machine OEM maintenance manual
    - This may include periodic maintenance or repair activities that should be included in the list.
- AM Machine OEM operation manual
    - This may include standard operating activities that should be included in the list.
- Machine Architecture List

EASA

FAA/EASA – AM WG3

1- SAE Aerospace Recommended Practice ARP7064 [Liz Crisler]

Determine impact level:

- FMEA
- KPV List
- Part Criticality
- Repair vs. Modification

Discussion:

- Machine Configuration

  Vs.

- Machine Architecture

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AEROSPACE RECOMMENDED PRACTICE

ARP7064

Issued

RATIONALE

2. APPLICABLE DOCUMENTS

Status:

- Drafted
- To Do: a few edits to wrap up from previous group discussions
- GOAL:
  - Send to ballot before the end of the year
  - 1st issue expected for Q1 2023

BIG

THANKS LIZ

FAA/EASA – AM WG3

2- Pipeline of of AM manufacturing thoughts from industry & governmental agencies

Six concerns were initially identified, but finally reduced to three:

1. Software updates
2. Develop a Methodology for OEM Field Service Engineers to Utilize Industry Specifications To Provide Additional Transparency Related to Work Instructions
3. Develop a Methodology to Reduce Frequency of Inspection After the Build

FAA/EASA – AM WG3

2- Pipeline of of AM manufacturing thoughts from industry & governmental agencies

TEAM MEMBERS:

- James Fonda – Boeing
- Mark Coffin – Tronos
- Dr Mathew Harding - Tronos

1. Software updates

Voice from industry:

- No service technician is able to update software without permission
- Testing of software updates
  - How should/could industry standardize and validate these updates?
  - Standard for software validation update by OEM?
    - More transparency required by OEM on software test qualification/validation.
- Standardization of software revision communication
- Standardizing the level of communication regarding what they modify on equipment

FAA/EASA – AM WG3

2- Pipeline of of AM manufacturing thoughts from industry & governmental agencies

2. <u>Methodology for OEM FSE to utilize industry specs</u>

Voice from industry:

- Lack of procedures on calibrations
- Machine maintenance shall be aligned to Industry specs:
  - NASA 6030
  - NASA 6033
  - AMS 7003
- Machine OEMs conferences are required
  - To allow owners and users to voice concerns
- How should governmental agencies address this issue with machine OEM?

TEAM MEMBERS:

- Scott Wiggin – Collins Aviation
- Kyle Agne – Honda Aero
- Richard Mellor– Rolls Royce UK
- Liz Crisler – Textron Aviation
- Tom Ocken – Collins Aviation

More machine OEMs are required on WG3

FAA/EASA – AM WG3

2- Pipeline of of AM manufacturing thoughts from industry & governmental agencies

3. Methodology to reduce frequency of inspection after build

Voice from industry:

- How can industry use build data to reduce inspections
  - Foundation required to use monitoring data as validation – Follow up with ASTM report
  - How to assess gradual reduction of the NDI test in the course of a series production based on proven OPM correlations and increased OPM analysis while keeping the same level of part safety
  - Linked to WG1 responsibility
- Monitoring and sensors data at end of build
  - Quality reports

TEAM MEMBERS:

- Donald Godfrey – SLM Solutions
- Sebastian Rott – MTU Aerospace
- Fernando Lartategui – ITP Aero

EASA
European Union Aviation Safety Agency

Questions?

Appendix Y

Authorities Panel
Questions & Answers

**Michael Gorelik (FAA), Simon Waite (EASA),
Thierry Ansart (DGA), Natasa Mudrinic (TCCA),
Cindy Ashforth (FAA), Doug Wells (NASA),
Dietmar Goldschmidt (LBA)**

Initial Panel Questions:

1) It is broadly acknowledged that to conduct a full qualification and characterization of AM process and parts is a lengthy and expensive effort. Do you see the feasibility of a "simplified" qualification framework where material performance margins could be traded off for reduced levels of qualification testing (e.g., via the use of "knockdown" or safety factors)?

    - The consensus of the Panel was that it is currently not possible to answer to this question.
    - Industry needs to create a database of pedigreed use cases as a foundation for numerical simulations.
    - It will be necessary to pay close attention to this approach as history has shown many times that numerical simulations have given results that were not confirmed experimentally.
    - A risk-based regulatory approach can be assessed by the regulator depending on the application of the component created by AM.
    - The AM field is very specialized and probably cannot be managed directly by the authorities with a compliance-based approach. What we are experiencing has already been seen with the advent of composite materials, we need to take as example from what has been done in the past. What is needed in the aerospace field is the reliability in terms of prediction of catastrophic failures or events.

2) In the context of the data-rich AM ecosystem, what elements of the data / digital information should be configuration-controlled and included as a part of the Qual/Cert package?

    - Defining a "certification package" of a component produced via AM and specifying what data it should contain is premature.

3) Regarding the expanding use of Modeling & Simulation / Computational Materials – any advice to Industry on how to best pursue the "smarter testing" approach (i.e., conventional but reduced test pyramid supported by modeling) from the regulatory perspective? What are the key enablers and challenges from the regulatory perspective?

    - Need to identify key points in test and analysis pyramid and seek to understand the potential defects, failure modes, and aircraft/pax level safety sensitivity to those modes.

Questions from Audience

4) Where do you see the biggest gap, in terms of standards?

    - Further development of ‘end to end’ guidance for data stakeholder interface management for fragmented supply chains, e.g., develop SAE 7042, 7043 etc.
    - industry wide process for determination of ‘Key Parameters’, including guides to understanding sensitivity and pass/fail criteria (partly defining the Key Parameters)

5) Do you envision a world where in situ monitoring and perhaps feed forward process control can play the primary role in the part qualification?

    - Yes, but extensive equivalence work is necessary supported by accessible use of statistics.

6) EASA intends to make a revision of CM-S-008 issue 03 about AM. Are equivalent guidance materials expected to be issued by FAA or TCCA?

    - The CM is linked to the FAA guidance, e.g., AIA.
    - The FAA has the ASGM guidance (which addresses initial assessment expectations intended to help understand likely FAA engagement levels with projects), see the 2021 EASA FAA Event presentation by Bob Grant

7) After having characterized a material on a specific Serial Number (SN) and after production of a low-critical part on this SN, what are the steps to follow to realize the same part on a different machine SN?

    - No formal AM guidance available. At this time, an adapted version of the composite approach will be taken on ‘case by case’ basis (similar in the sense that process is sensitive), e.g., an ‘engineering judgement’ would be made regarding number of tests necessary relative to understanding competing failure modes etc. and where the design drivers are in the test and analysis pyramid.
    - Associated machine configuration and installation, operation, and initial part qualification would be important (ref. AIA Feb 2020 guidance), supported by comparison similar details produced by each machine (representative of the likely product configuration)- needs a standardized approach/process.

8) Process check on where we are with AM. After this workshop, where do we go from here? What do see as the top priorities in addressing AM?

    - WG activities provide direction for guidance development and future EASA FAA AM Events

- Priority is to understand where industry believes it has late TRL and MRL activities and react accordingly. WG1 at the moment, but WG2 output will be important as more critical applications appear.

9) Is there a goal to be able to develop "in-family" property sets for AM material systems for which a machine can be qualified to so that low and mid criticality AM parts can be designed and qualified by analysis for fabrication on these qualified machines?

   - Industry to decide, but composite equivalence model could be used. Reminder: certification is by test or analysis supported by test

10) It is very hard to get a sense of the extent of AM use currently in aviation (certified and flying). With the current panel (representing the bulk of regulatory agencies), would you be able to give a general sense of current certified parts (10s of part numbers, 100s, 1000s)? What is the breakdown of polymer vs metals? Are the regulators seeing a large increase in AM applications?

   - EASA has approximately 12 major projects on my immediate list, involving mostly system-structures, and propulsion in particular (this does not include many mostly non-metallic Class D projects/parts)
   - 1000s of LEAP fuel nozzles have been flying successfully for years (probably the most critical application flying)

11) What is the greatest challenge to true AM industrialization: machine cost, qualified materials, machine reliability, part throughput, workforce, "qualified" suppliers, certification path, other?

   - All the above are challenges, the greatest challenge however is showing compliance to all applicable certification requirements.
   - It is difficult to identify a challenge bigger than other in the above list. Everything needs to progress in parallel. Experience gained and lessons learnt with current certified parts will certainly be a primary enabler for extension of AM application. Standardization shall also be added to the list.
   - Everything from a business perspective! I don't believe that the regulator is a blocker at this point for low criticality (but could be with higher criticality applications in the future)… we need to identify key parameters at the key points in the test and analysis pyramid and mine that data if this is to work from both safety and commercial perspectives

12) What role Integrated Computational Materials Engineering (ICME) can play in process and part qualification? combined with part performance modeling, can it offset some of the materials and part testing?

   - Understanding how processes produce material <u>structures</u>, how those structures give rise to <u>material properties</u>, and how to <u>select materials</u> for a given application. It could potentially offset some of materials and part testing if the above is achieved.

- ICME will help to reduce the number of tests especially at the bottom of the test pyramid. In particular it can be very useful to perform parametric/sensitivity study, at least for some parameters for which simulation has shown it can well predict their effect.
- However, a key point is the ability of models to predict scatter at pyramid bottom level whatever is the source of scatter and to propagate them up at part level. Predicting material variability through modelling is very challenging.
- A decrease of testing at part level also requires the ability of models to account for 3D effects and scale effects (coupon properties might be different from a component material).
- It is a building block/design tool, which needs to be substantiated at some point in the test and analysis pyramid… certification is by test, or analysis supported by test.

13) Do authorities plan to handle major/minor change classification the same way for AM? For say a casting that is converted to AM where form, fit and function remains the same and AM properties are higher - would that still fall under a minor change or will AM changes be handled differently?

- Transport Canada major/minor change classification is not completed by satisfying only the same form, fit and function. Part Design Approvals could be considered for casting converted to AM where form, fit and function remains the same.
- According to existing guidance material (e.g., EASA appendix A to 21.A.91), giving examples of major changes per discipline, changes to materials, processes or methods of manufacture of primary structural elements, such as spars, frames and critical parts are major. So, change of material/process on non-critical/primary parts including AM could be considered as minor changes. For sure changes for AM parts will be addressed in the same way as for other parts.
- Major/minor will be addressed within the scope of an organization's capability as usual (From a cert perspective, we will manage via Level of Involvement, (LoI) – driven by criticality, novelty, complexity). Furthermore, Part 21 can drive a minor to a major simply based upon the initial work necessary the introduce the technology/application, i.e., to show that something the project is understood and possibly of limited safety concern. Once established, 'similar' applications may simply be minor within the scope of the organization (which may be slightly amended), see EASA slides and CM-S-008 for further comments.
- Note, stability of process is the key confidence builder, and stronger is not necessarily better…it can indicate poor drifting process at a production level, or may fundamentally change load paths (and change safety assessments) at the design level (if replacing existing conventional parts in an existing typical configuration)

14) Is safe-life approach with extensive fatigue testing of the end product more suitable for Primary Structures until the DT methodology becomes more mature (unless you can design below the no-growth stress value)?

- Safe life approach might not be more mature than DT approach and showing impracticality before deciding on safe life approach would be needed. Damage tolerance approach below no-growth value might be more appropriate first choice to consider.
- Safe life approach is only accepted if DT is impractical. Having a DT methodology that is not mature enough cannot be considered in my opinion as "DT being impractical."
- Although this was the basis for older structure cert many years ago (conventional) it is not preferred (metals) and has been minimized to applications with other design limiting criteria, e.g., undercarriage. For rotorcraft we have flaw tolerant safe life, whereby some acceptance of defects is part of the 'safe life' cert approach. Similarly, composites have many 'flaws' or 'anomalies' and non-growth is to be demonstrated etc. Noting that AM allows for complex shapes, and the engineering properties are defined at the final state of consolidation, then fatigue should address this by test at this level until we can better understand crack growth for DT purposes. However, the practicality of doing this at a statistically credible level is challenging and financially impossible for many complete parts. Use of fatigue coupons cut from the part might help but generating believable/conservative load inputs (Boundary Condition issues) to coupons representative of the actual complex part may be a real challenge. At this time, I see AM as being like bonding in composites, what matters most is process, process, process. Furthermore, we are yet to fully understand equivalence and appropriate test and analysis pyramid definitions.