Regulatory Considerations for AM and “Lessons Learned” for Structural Alloys

Presented at:

NRC Workshop on Advanced Manufacturing Technologies – *Session 6*

December 10, 2020

Presented by:

Dr. Michael Gorelik

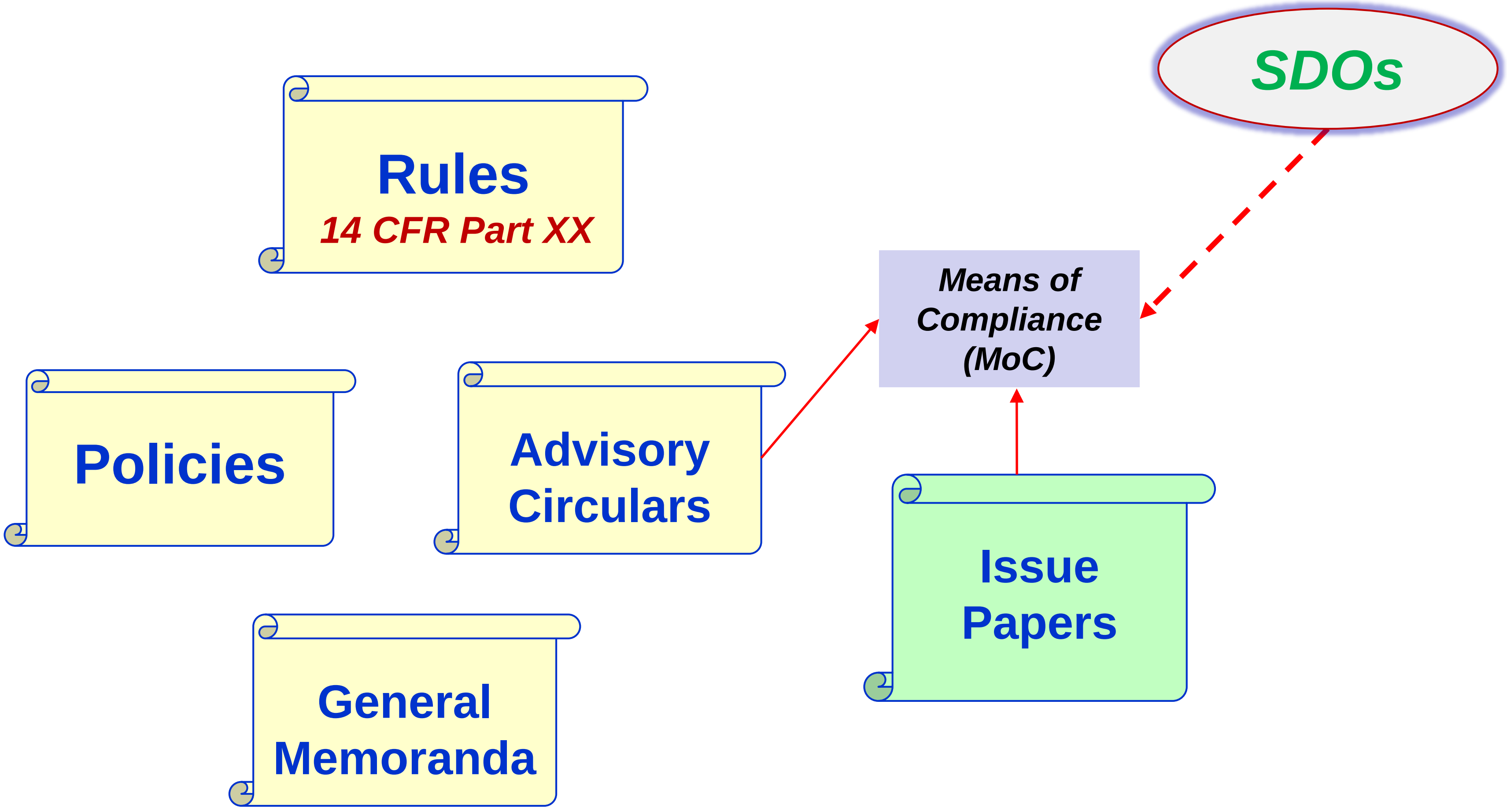
FAA Chief Scientist and Technical Advisor
for Fatigue and Damage Tolerance

BLUF *(bottom line upfront)*

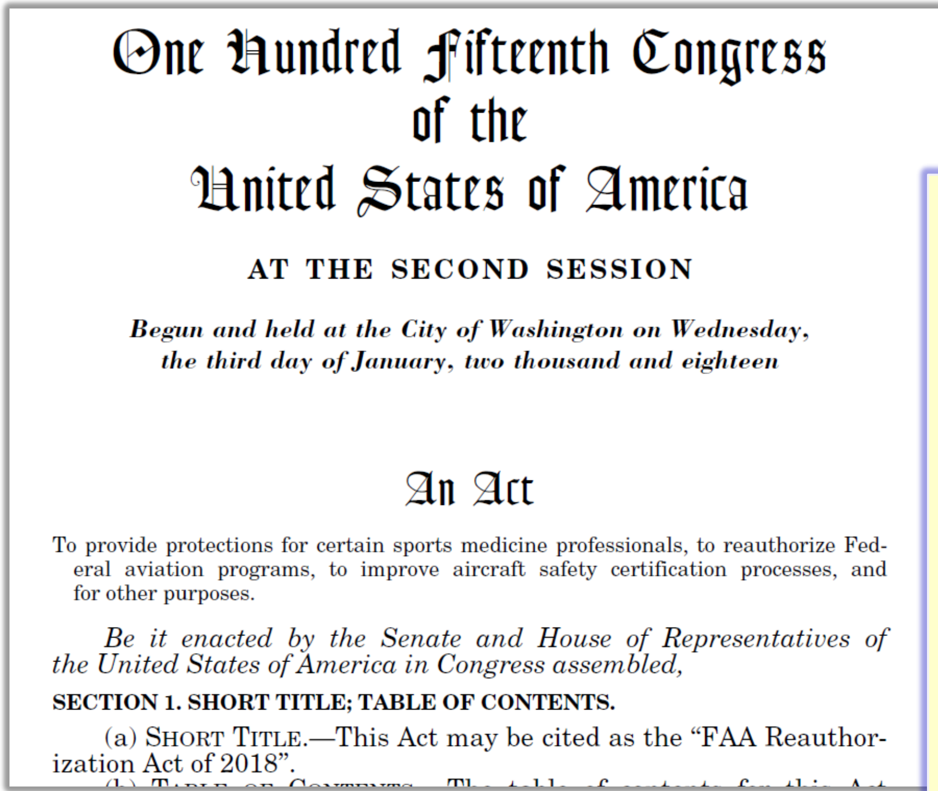
- **All existing FAA *rules* apply to AM**
- **Leverage experience with other relevant material systems and historical "lessons learned"**
- ***However*… need to consider unique / *AM-specific attributes*, especially for high-criticality components**
- **Increasing role of public standards**
- **Increasing role of Computational Materials / ICME**

The same message as in 12/09/20 presentation

FAA Regulatory Documents



H.R. 302 “FAA Reauthorization Act of 2018”



One Hundred Fifteenth Congress
of the
United States of America

AT THE SECOND SESSION

Begun and held at the City of Washington on Wednesday, the third day of January, two thousand and eighteen

An Act

To provide protections for certain sports medicine professionals, to reauthorize Federal aviation programs, to improve aircraft safety certification processes, and for other purposes.

Be it enacted by the Senate and House of Representatives of the United States of America in Congress assembled,

SECTION 1. SHORT TITLE; TABLE OF CONTENTS.

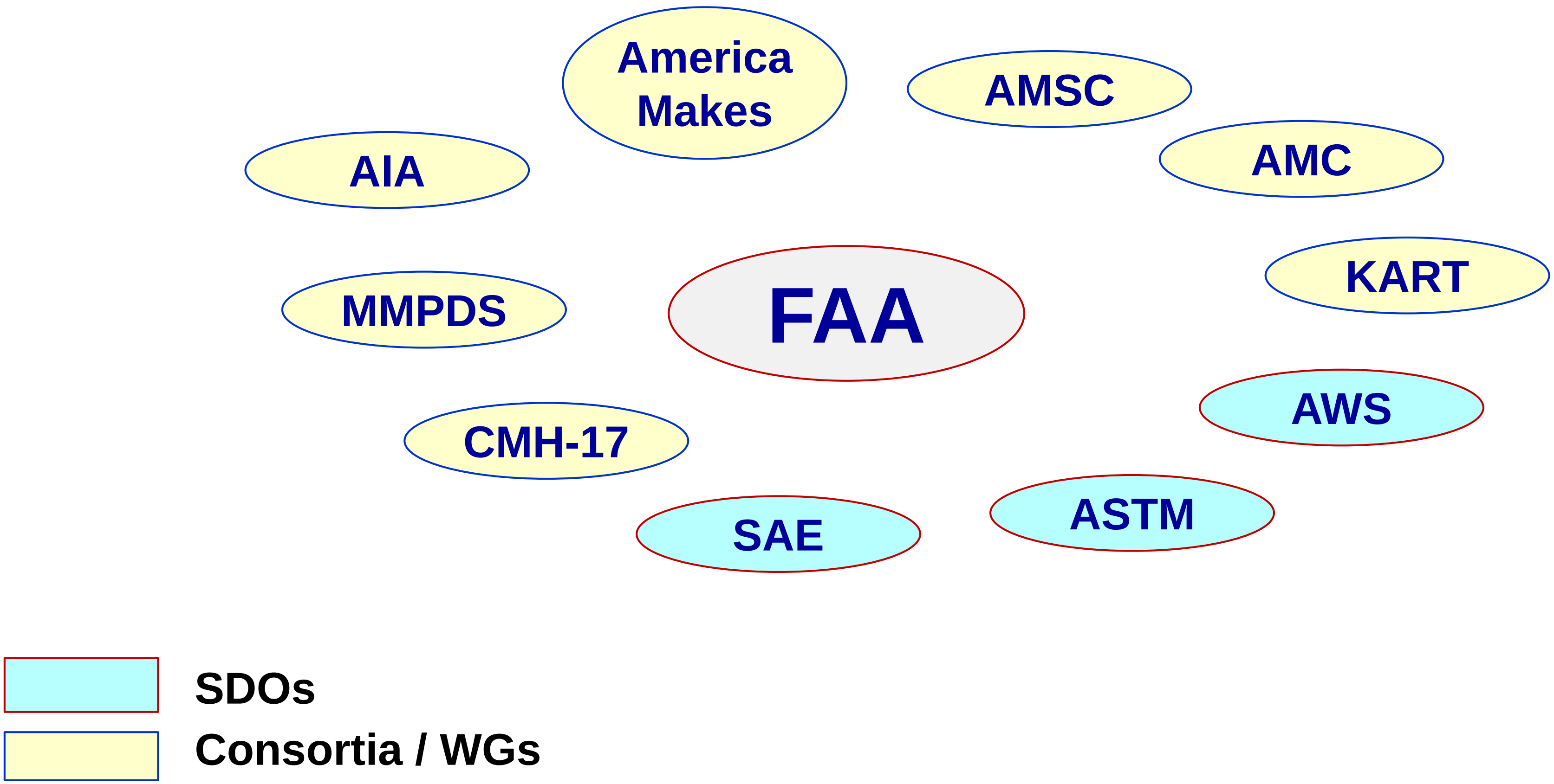
(a) SHORT TITLE.—This Act may be cited as the “FAA Reauthorization Act of 2018”.

SEC. 329. PERFORMANCE-BASED STANDARDS.

The Administrator shall, to the maximum extent possible and consistent with Federal law, and based on input by the public, ensure that regulations, guidance, and policies issued by the FAA on and after the date of enactment of this Act are issued *in the form of **performance-based** standards*, providing an equal or higher level of safety.

Engagement with SDOs and Consortia

A partial list…



Some AM-Specific Attributes

- Characterization and role of inherent (and rogue) material anomalies / defects
- Anisotropy
- Location-specific properties
- Residual stresses
- High process sensitivity / large number of controlling parameters
- Effects of post-processing (HIP, heat treatment, surface improvements, …)
- Material-specific NDI considerations
- Effect of surface conditions
- Susceptibility to environmental effects

> - Each individual category has been encountered in other material systems
> - Unique nature of AM – *all of these categories apply*

FAA Regulatory Environment

(driven by different product types)

Transport Airplanes

(14 CFR Part 25)

Small Airplanes

(14 CFR Part 23)

Engines and Propellers

(14 CFR Parts 33, 35)

Rotorcraft

(14 CFR Parts 27, 29)

14 CFR Part 25 Regulations - Materials

(Transport Category Aircraft)

§ 25.613 Material Strength Properties and Design Values

a) **Material strength properties *must be based on enough tests of material meeting approved specifications to establish design values on a statistical basis*.**

b) **Design values must be chosen to minimize the probability of structural failures *due to material variability*.**

d) **The *strength, detail design, and fabrication* of the structure must *minimize the probability of disastrous fatigue failure*, particularly at points of stress concentration.**

14 CFR Part 25 Regulations – Special Factors

(Transport Category Aircraft)

§ 25.619 Special Factors

The factor of safety prescribed in § 25.303 must be multiplied by the highest pertinent special factor of safety prescribed in §§ 25.621 *(Casting Factors)* **through 25.625 for each part of the structure whose strength is—**

a) Uncertain;

b) Likely to deteriorate in service before normal replacement; or

c) Subject to appreciable variability because of uncertainties in manufacturing processes or inspection methods

Excerpts from 14 CFR 25.571

(Transport Category Aircraft)

§ 25.571 Damage—tolerance and fatigue evaluation of structure

(a) General. **An evaluation of the strength, detail design, and fabrication must show that *catastrophic failure* due to fatigue, corrosion, manufacturing defects, or accidental damage, will be avoided throughout the operational life of the airplane.**

AC 29-2C on Flaw Tolerance

(Transport Category Rotorcraft)

- **To determine types, locations, and sizes of the probable damages, considering the time and circumstances of their occurrence, the following should be considered:**
  - **Intrinsic flaws and other damage that could exist in an as-manufactured structure based on the evaluation of the details and potential sensitivities involved in the specific manufacturing work processes used.**
- **The flaw sizes to be considered should be representative of those which are likely to be encountered during the structure's service life resulting from the manufacturing, maintenance, and service environment.**
- **An analysis may be used combining the distribution of likely flaw sizes, the criticality of location and orientation, and the likelihood of remaining in place for a significant period of time.**

AC 29-2C on Inspections

(Transport Category Rotorcraft)

- **The specific *inspection methods* that are used to accomplish fatigue substantiation *should be*:**
  - **Compatible with the threats identified in the threat assessment, paragraph f.(5), and provide a high probability of detection in the threat assessment and their development, under the operational loads and environment.**

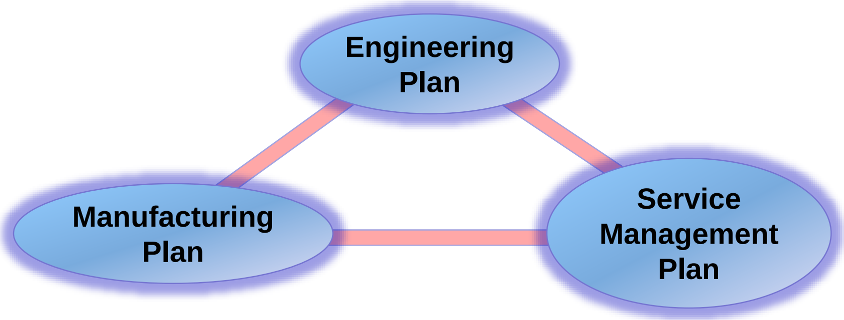
Excerpts from 14 CFR 33.70

(Aircraft Engines)

- **WHY: Industry data has shown that manufacturing-induced anomalies have caused about 40% of rotor cracking and failure events**
- **WHAT: 33.70 rule requires applicants to develop coordinated engineering, manufacturing, and service management plans for each life-limited part**
  - This will ensure the attributes of a part that determine its life are identified and controlled so that the part will be consistently manufactured and properly maintained during service operation

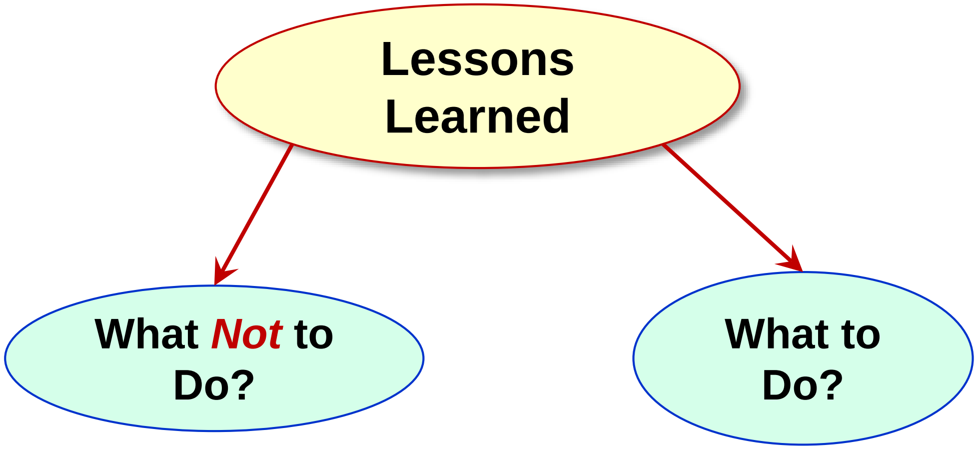
"The *probabilistic approach to damage tolerance* assessment is one of two elements necessary to appropriately assess damage tolerance".

AC 33.70-1, GUIDANCE MATERIAL FOR AIRCRAFT ENGINE LIFE-LIMITED PARTS REQUIREMENTS, 7/31/2009.



"History is a Vast Early Warning System"

Norman Cousins

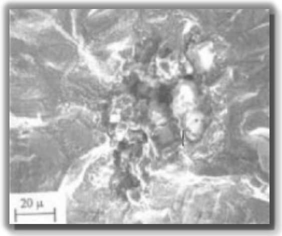


Relevant Material Technologies - *Examples*

- **Structural Castings**
  - Empirical life management system (design knock-downs, NDI acceptance criteria etc.)
  - Effect of material anomalies understood, but not well quantified
- **Powder Metallurgy (PM)**
  - Gave rise to PM-specific fatigue and DT methodologies, explicitly accounting for the presence of inherent material anomalies
- **Forgings**
  - Process controls (lessons learned), advanced NDI
  - Location-specific microstructure and residual stresses
- **Welding**
  - Highly process-sensitive
  - Susceptible to manufacturing anomalies
  - Defects detectability challenges

Plan to leverage regulatory experience with other process-sensitive material systems

Lessons Learned



[***Powder Metallurgy (PM)***]

- **Effect of defects may not be well understood for new technologies**
- **Transition from well-controlled development environment to full-scale production *may introduce new failure modes***
- **Solution: development of adequate process controls, NDI and *PM-specific life management system***
  - ***explicitly accounts for material anomalies (via probabilistic fracture mechanics)***

➢ ***Outcome: Several decades of successful field experience***

Lessons Learned

Structural Castings

- **Empirical – effects of material anomalies are not well understood or quantified → *no explicit feedback loop to process controls and QA***
- **No means to assess / quantify risk**
- **May be overly conservative in some cases**

Question →

Can we do better for AM..?

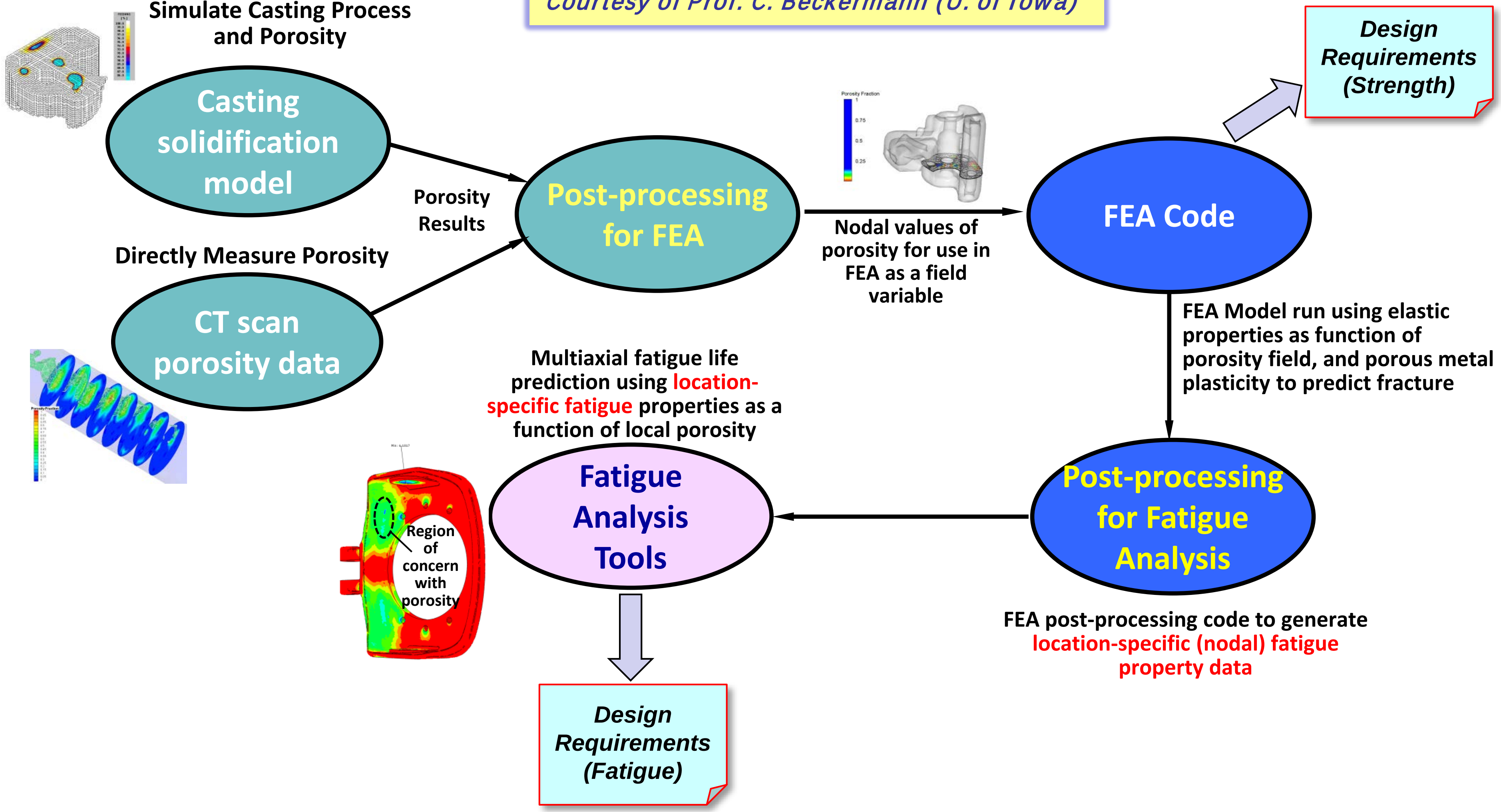
Computational Materials models / ICME can help

Performance = f (microstructure | *anomalies population*)

Example: Modeling Framework for Castings

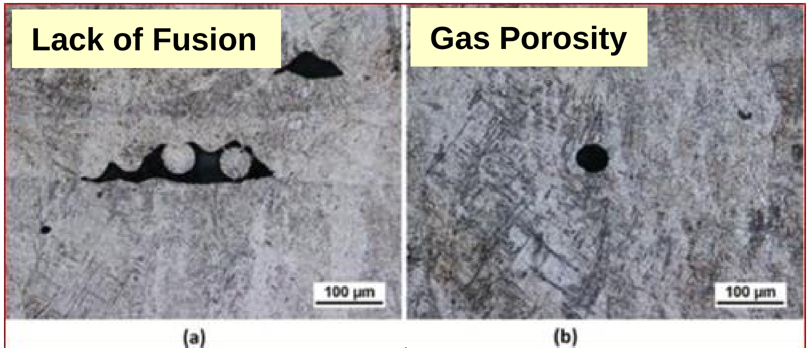
Linking Modeling Tools to Predict Stress/Strain, Fracture and Fatigue Life

Courtesy of Prof. C. Beckermann (U. of Iowa)



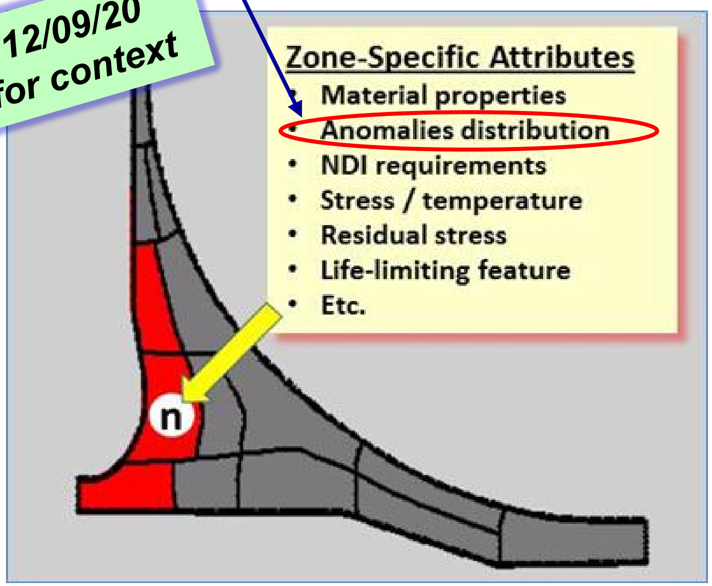
R. A. Hardin, C. Beckermann, "Integrated design of castings: effect of porosity on mechanical performance", IOP Conference Series: Materials Science and Engineering, Vol. 33, 2012.

AM Part Zoning and Probabilistic DT

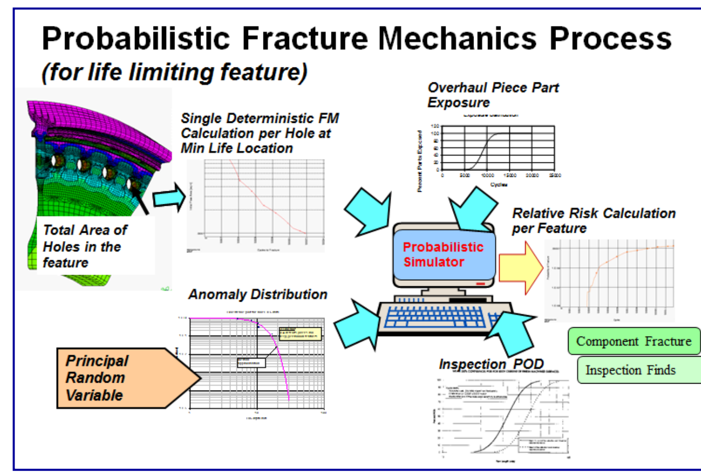


- AM parts are uniquely suited for ***zone-based evaluation***
- Concept is similar to zoning considerations for castings…
- … however, modeling represents a viable ***alternative to empirical*** "casting factors"

Included from 12/09/20 presentation for context



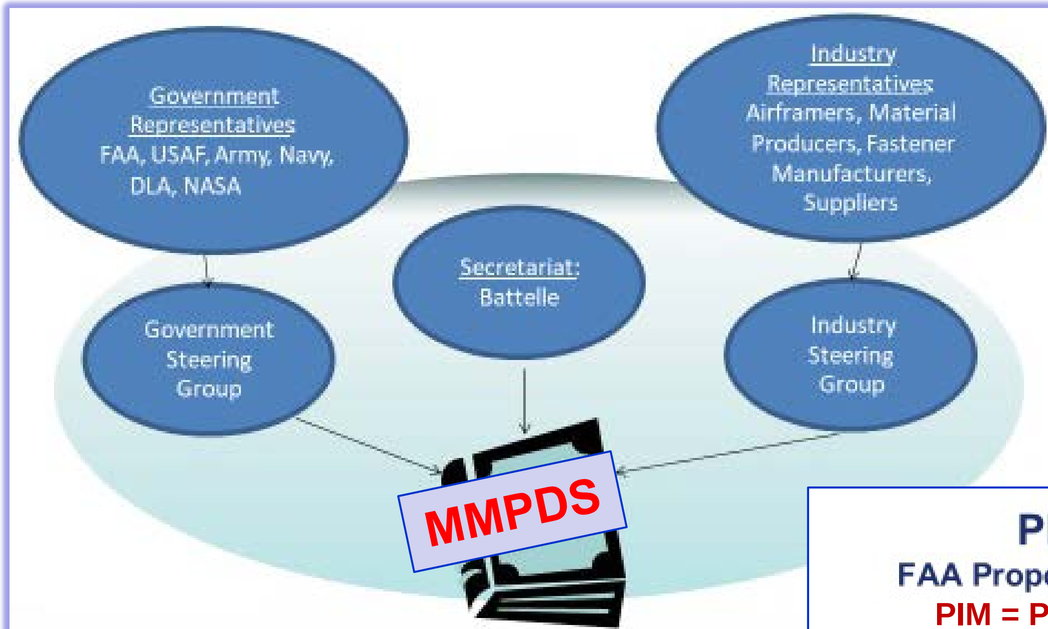
*One Assessment Option – PFM *)*



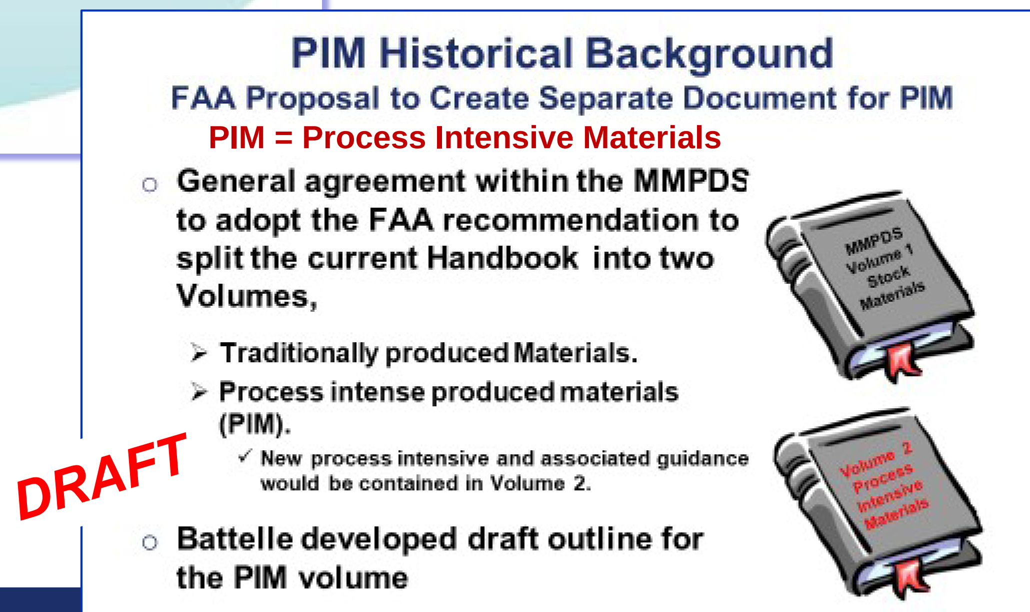
*) PFM - Probabilistic Fracture Mechanics

Reference: M. Gorelik, "Additive Manufacturing in the Context of Structural Integrity", International Journal of Fatigue 94 (2017), pp. 168–177.

Design Allowables Considerations



- Generation of design allowables is ***contingent upon mature material and process specifications***
- Cross SDOs and WGs collaboration is essential

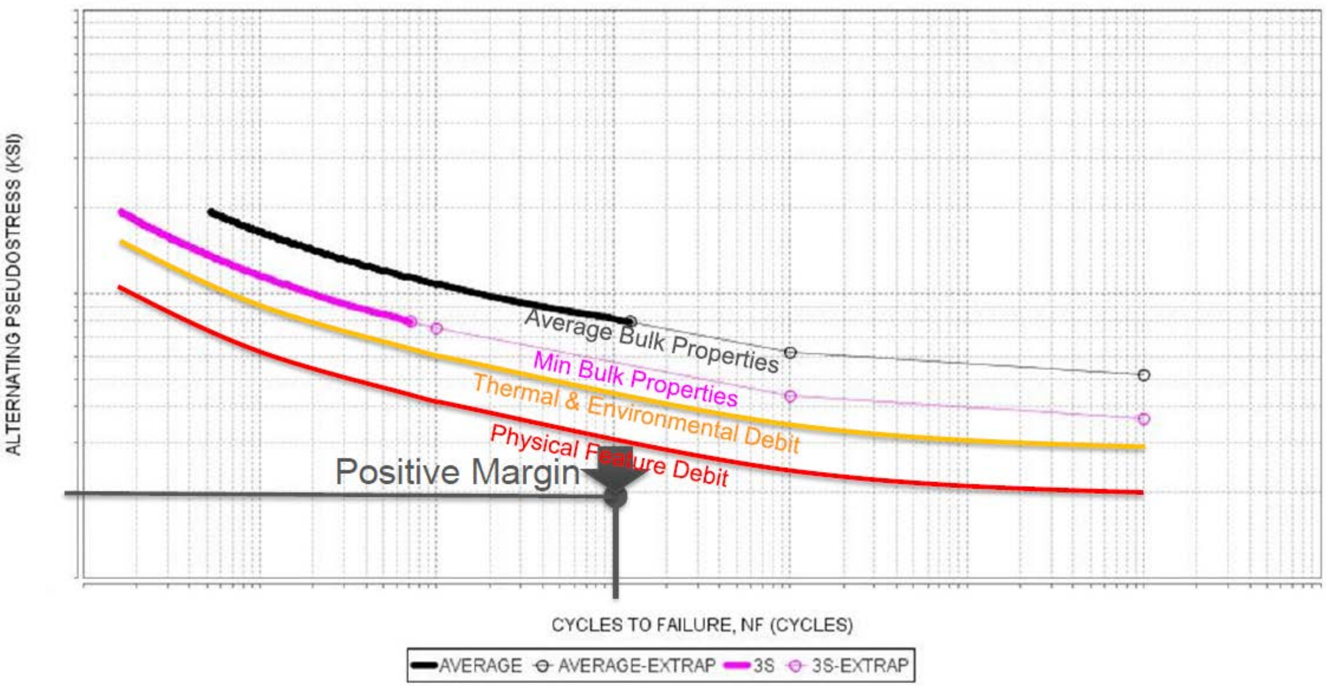


Material Allowables vs. Design Values

JOINT FAA – AIR FORCE WORKSHOP ON QUALIFICATION / CERTIFICATION OF ADDITIVELY MANUFACTURED PARTS

Part Qualification

Meets full service life when accounting for all appropriate debits…



Credit: M. Shaw (GE Additive), presented at the 2018 Joint FAA – EASA Workshop on Q&C of Metal AM Parts, Wichita, KS, Aug. 2016.

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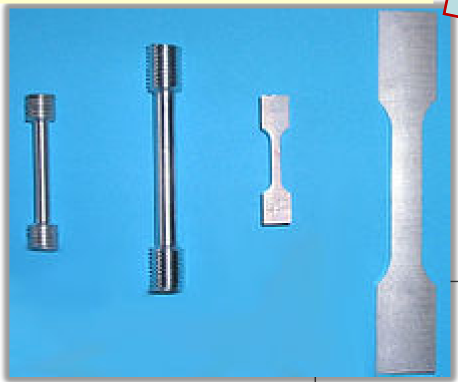
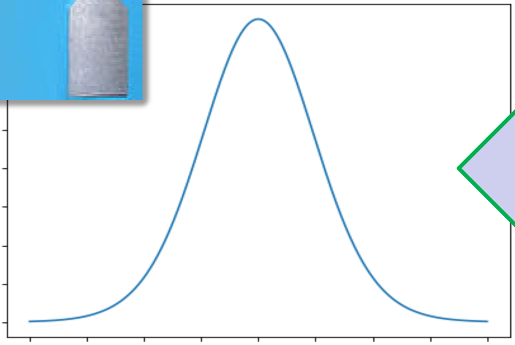
- **Top 2 curves – "bulk" *material allowables***
- **Bottom (red) curve – *design values***

Part vs. Coupon Properties

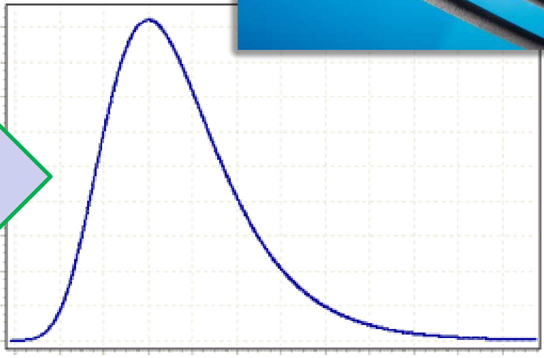
Purpose-built Coupon



Finished AM Part



Property of Interest



Property of Interest

This understanding can be enabled by physics-based ICME models

Example: Industry Lessons Learned

Developed by AIA RoMan Working Group

DOT/FAA/AR-06/3

Office of Aviation Research
and Development
Washington, D.C. 20591

Guidelines to Minimize Manufacturing Induced Anomalies in Critical Rotating Parts

for conventional (i.e. subtractive) manufacturing processes

EXECUTIVE SUMMARY

This report was developed by a partnership of the Aerospace Industries Association (AIA) Rotor Manufacturing Project Team (RoMan) and the Federal Aviation Administration (FAA) in response to accidents and incidents caused by manufacturing induced anomalies in critical rotating parts. According to a 1997 summary from the AIA Rotor Integrity Sub-Committee, about 25% of recent rotor cracks/events have been caused by post-forging manufacturing induced anomalies.

It is possible for even well developed and controlled manufacturing processes to have special cause events. Examples of special cause events are tool breakage, unexpected tool wear, loss of coolant, chip packing, machine failure, validated parameter limit exceedance, etc. The vast majority of these are immediately apparent, but on rare occasions they may give rise to undetected manufacturing induced anomalies.

This report summarizes guidelines useful to ensure the manufacturing process minimizes the likelihood of manufacturing induced anomalies reaching service usage. The following topics are presented:

- Process Validation
- Quality Assurance
- Process Monitoring
- Human Factors and Training
- Non-Destructive Evaluation (NDE)

- **Leveraged industry experience to reduce the likelihood of manufacturing-induced defects**
- ***Emphasizes the role of real-time process monitoring systems***

Recent Developments

- **Consortia / SDOs / Industry engagement**
- **R&D**
- **2020 FAA-EASA Workshop on Q&C of AM** *(appendix)*

Examples of External Engagements

(Consortia and WGs)

AIA AM WG

MMPDS

ETTG

Emerging Technologies Task Group

Volume 2

- **Guidance**
- **Data**

AIA AM Working Group Report: 2/28/20

“Recommended Guidance for Certification of AM Component”

https://www.aia-aerospace.org/report/certification-of-am-component/

Recommended Guidance for Certification of AM Component

AIA Additive Manufacturing Working Group

3 Executive Summary

Additive manufacturing is quickly growing in aerospace for production use because of weight savings, design freedom, flow time reduction, and cost savings. Today’s state-of-the-art equipment is increasingly utilized for fabricating components in prototyping while production clearance still presents a significant challenge in assuring part-to-part repeatability. The AIA Working Group for Additive Manufacturing was asked by the Federal Aviation Administration (FAA) to collaborate on a report addressing the unique aspects of certifying AM components for aerospace applications. This paper also provides guidance for compliance to 14 CFR 2x.603, 2x.605, 2x.613, 23.2260, 33.15, and 35.17 for metal powder bed fusion (PBF) and directed energy deposition (DED) additive processes. Additional guidance may be required for higher criticality parts subject to FAA rules 14 CFR 23.2240, 14 CFR 2X.571, 14 CFR 33.14, 14 CFR 33.70, and 14 CFR 35.37. This report delves into considerations and current industry best practices in the areas of material/process development, part/system qualification, and development of material allowables and design values. The authors are

AIA AM Working Group Report (cont.)

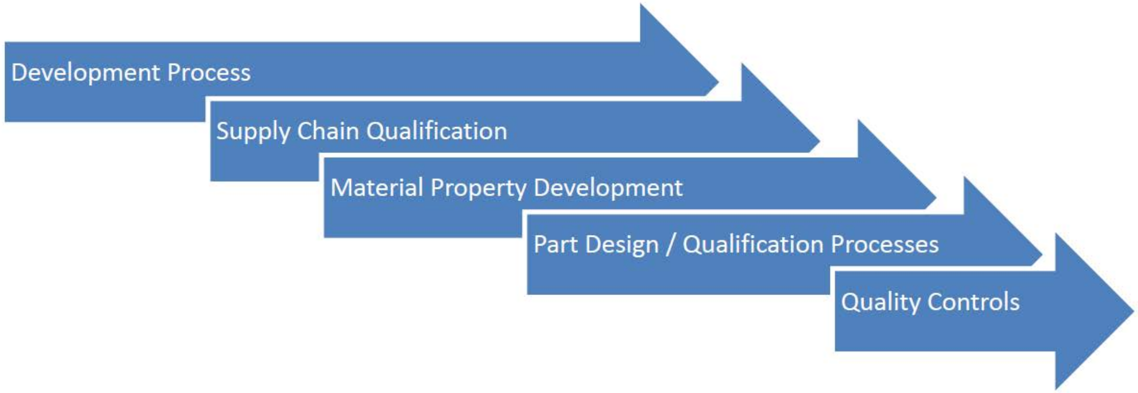


Figure 1: Additive Development and Qualification Areas

Federal Aviation Administration

MMPDS and Additive Manufacturing

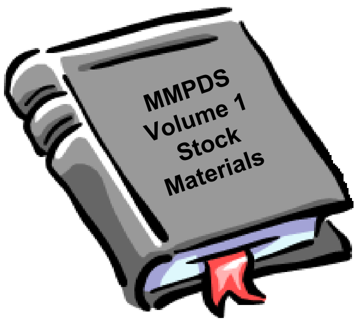
MMPDS Efforts to Address Emerging Metallic Process Intensive Materials (PIM)

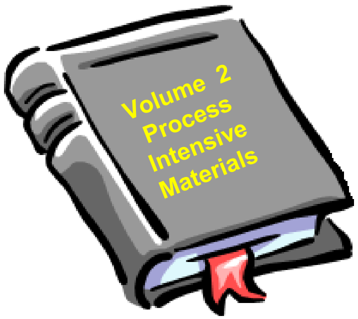
- **MMPDS recognizes the need to be proactive and keep pace with the rapid development of Emerging Metallic Structures Technologies by industry*, e.g., Additive Manufacturing (AM), Friction Stir Welding (FSW) that are considered PIM.***

- **Several efforts of PIM were presented to the MMPDS for allowables development but were found not to be compatible with current handbook procedures. Extensive amount of standardization efforts need to take place before design values for PIM can be considered for inclusion in the current handbook.**

- **General agreement within the MMPDS to create two Volumes:**
  - **Volume I – Current handbook for traditionally produced Materials.**
  - **Volume II - Properties for PIM ,e.g., Additive Manufacturing (AM), Friction Stir Welding (FSW).**

- **Emerging Technology Task Group (ETTG)** was established to develop processes and procedures best suited to derive and publish design information for PIM Volume II.





Emerging Technologies Task Group (ETTG) and its *Working Groups*

ETTG – Michael Gorelik (FAA) & Sam Cordner (NASA)

Data Generation & Applications

D. Hall (Battelle) & A. Steevens (Boeing)

- Data Submission Guidelines –9.2
- Data Analysis –9.5
- Design Philosophy –1 & 9
- Acceptance/Equivalence Testing –10.5
- Influence Factors -1
- SPC Methods –10.10

Materials & Machines

S. Cordner (NASA) & P. Sodouri (Nork Titanium)

- Specification Content Requirements –9
- Material Qualification –9 or 10
- Machine Qualification –9 or 10
- SPC Requirements -10

Certification & Qualification

R. Grant (FAA) & P. Guerrier (MOOG)

- Outline an approach to "Further Showing" -10
- OEM & Component Supplier perspectives
- Part Qualification -10

MMPDS Interaction with SDOs and Working Groups

SAE
- AM Material and Process Specs (AMS-AM)
- Use of MMPDS data analysis tools for spec min values

AWS
- Welding Specs
- AM Specs

ASTM
- Testing Specs
- AM Material Specs
- *Signed MOU with Battelle*

AIA AM WG
Developing best practices for Q&C of metal AM parts

CMH-17 AM WG
Cross-coordination to explore synergies and streamline communication between two groups

R&D – Internal / External

- **Development of material databases (joint with DoD and NASA) - *JMADD***
- **Seeded defects studies – effect of defects**
- **Understanding of process variability drivers**
- **Round-robin studies**
- **NASA ULI (University Leadership Initiative)**
- **Probabilistic DT framework for AM (collaboration with NASA, USAF and NAVAIR)**
- **CM*4*QC Steering Group –** ***see next slide***

Example: Development of Computational Materials (CM) Capabilities for Metal AM

NASA/TM–2020-
NIST/publication info
FAA/publication info

DRAFT

NASA / NIST / FAA Technical Interchange Meeting on Computational Materials Approaches for Qualification by Analysis

E.H. Glaessgen
NASA Langley Research Center, Hampton, Virginia

L. Levine, P. Witherell, A. Donmez
National Institute of Standards and Technology, Gaithersburg, Maryland

M. Gorelik
Federal Aviation Administration, Scottsdale, Arizona

N.A. Ashmore
Boeing Research and Technology, St. Louis, Missouri

R. Barto
Lockheed Martin Advanced Technology Laboratories, Cherry Hill, New Jersey

C.C. Battaile
Sandia National Laboratory, Albuquerque, New Mexico

H. Millwater
University of Texas at San Antonio, San Antonio, Texas

G.J. Nanni
Bell, Fort Worth, Texas

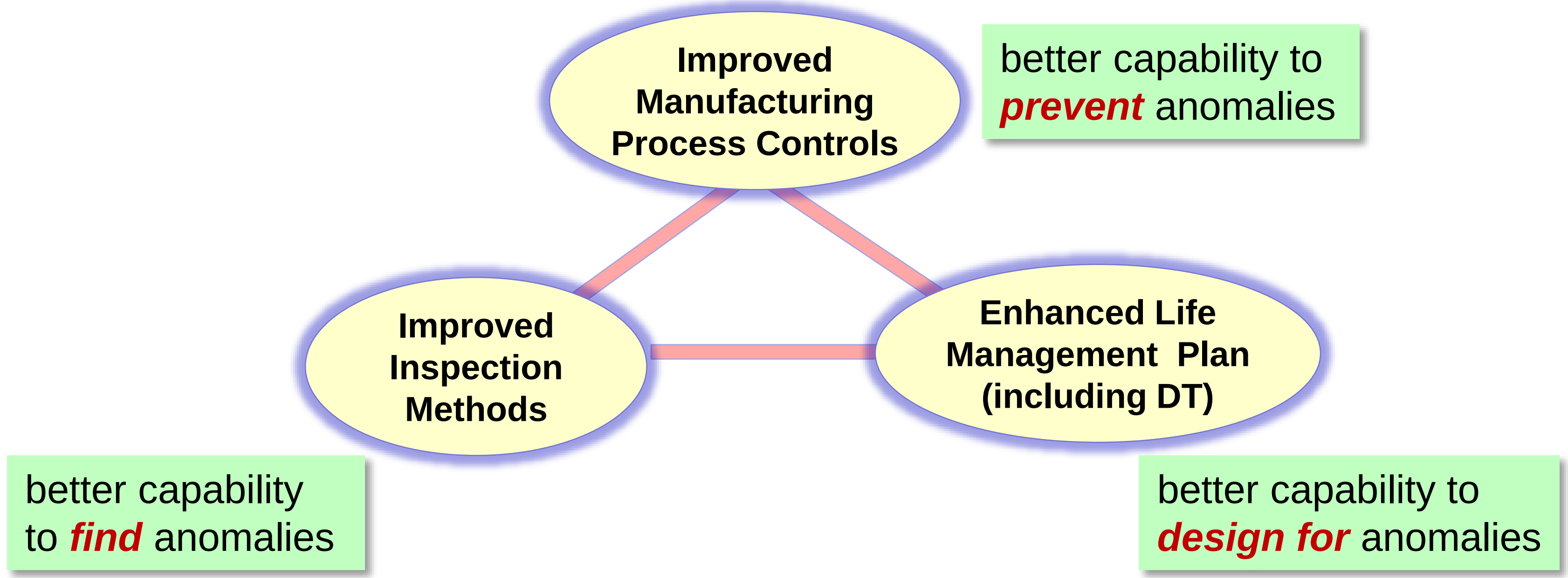
Co-organizers: NASA and FAA

Membership

Government	Industry	Academia
NIST	Boeing	Carnegie Mellon
AFRL	Lockheed-Martin / Sikorsky	UTSA
Sandia NL	Raytheon / P&W	Vanderbilt
NAVAIR	GE Aviation	Penn State
ORNL	Spirit Aerosystems	Northwestern
Army Aviation	Honeywell Aerospace	
	Howmet Aerospace	
	SwRI	
	Northrup-Grumman	
	Textron Aviation / Bell	

Summary

- **What worked well historically to reduce the rate of failures induced by material / manufacturing anomalies → *a three-prong approach:***



Discussion

Dr. Michael Gorelik

Chief Scientist, *Fatigue and Damage Tolerance*

Aviation Safety

Federal Aviation Administration

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(480) 284-7968

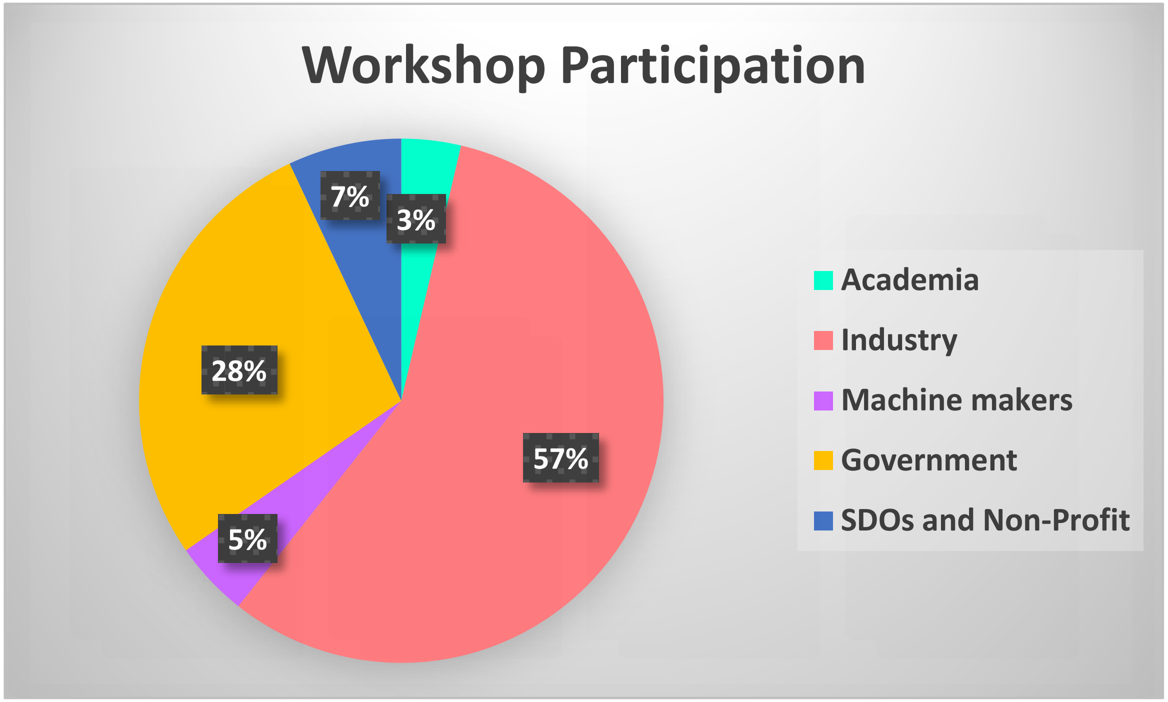
APPENDIX

3rd Joint FAA – EASA AM Workshop

November 2-6, 2020

Workshop "Demographics"

over 300 participants



https://www.faa.gov/aircraft/air_cert/step/events/2020_additive_mfg_workshop/

16 Countries

Austria
Belgium
Brazil
Canada
France
Germany
Italy
Netherlands
Norway
Poland
Portugal
Singapore
Spain
Sweden
UK
US

Workshop Evolution

2018 → 2020

(joint FAA-EASA workshops)

2018 Workshop

- ***First joint FAA – EASA workshop***
- ***First workshop with parallel breakout sessions***
- **Continued focus on Q&C**
- **Tracking of the key industry trends (in the Q&C context)**
- **Gradual increase in the industry "demographics" by segment**

2019 Workshop

- **Continued breakout sessions**
- **Significant participation from operators, Tier 2/3/… suppliers and machine makers**
- **Clear signs of Q&C framework maturation and common technical approaches**
- **Leveraged Machine Makers – End Users knowledge transfer workshop**

2020 Workshop

- ***First virtual workshop***
- **More balanced international participation**
- **More than 2x increase in participation**
- **Continued breakout sessions**
- ***Focus on new technical developments, not "organizational updates"***
- **Highly diverse industry "demographics"**
- **Big focus on standardization**

see next slide

Agenda at a Glance

- **Opening remarks:**
  - *Ms. Di Reimold, Deputy Director of Policy and Innovation Division, FAA*
- **Keynote -** ***SpaceX***
  - *Dr. Charlie Kuehmann, VP of Materials Engineering and NDE*
  - *Mr. Will Heltsley, Vice President of Propulsion Engineering*
- **22 presentations from the industry, government, academia and SDOs / Consortia / WGs**
- **3 Breakout Sessions** →
- **Standardization Day**
- **Regulatory Panel**

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

Preliminary Agenda (rev. 10/30/20)

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

November 2-6, 2020

Venue: *virtual (WebEX)*

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

Note: all times listed below are in EST

Day 1 – November 2

8:30 – 9:30 Arrival and WebEx 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 – 10:10 Opening Remarks by FAA Leadership – *Ms. Di Reimold, Deputy Director of the Policy and Innovation Division*
10:10 – 11:00 Keynote Presentation – *Dr. Charlie Kuehmann, VP of Materials Engineering and NDE, and Mr. Will Heltsley, VP of Propulsion Engineering* – SpaceX

11:00 – 11:20 Break

11:20 – 11:40 FAA Update – *M. Gorelik (FAA)*
11:40 – 12:00 EASA Update – *S. Waite (EASA)*
12:00 – 12:20 "Structural Assessments for Additive Manufacturing of a Bellcrank Family of Parts" – *J. 'Mike' Kasprzak (NAVAIR)*
12:20 – 12:40 "Thales' Application of MASAAG & EASA Guidance - Polymers & 'Systems' " - *S. Catt (Thales)*
12:40 – 13:00 "Evolution of Metal AM Qualification and Certification" - *K. Slattery (Barnes Global Advisors)*

13:00 Adjourn of Day 1

Day 2 – November 3

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

9:30 – 9:50 "Effect of Defects on AM Fatigue - Probabilistic Approaches", *J. Mardaras (Airbus)*
9:50 – 10:10 "Fatigue Life Prediction of Additively Manufactured Ti-6Al-4V", *M. Benedict (USAF/AFRL)*
10:10 – 10:30 "Qualification and Certification of a Wire-fed DED Additive Material Process", *H. Løken Larsen (Norsk Titanium)*

10:30 – 10:50 Break

10:50 – 13:00 Parallel Breakout Sessions *(including breaks)*

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

Co-chairs: V. Vijayan (EOS) and P. Guernier (MOOG)

13:00 Adjourn of Day 4