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Summary Report: Joint Federal Aviation Administration–Air Force Workshop on Qualification/Certification of Additively Manufactured Parts

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16. Abstract

The FAA and Air Force Research Laboratory jointly organized a workshop on Qualification and Certification of Additively Manufactured Parts, which was held September 1–3, 2015 in Dayton, Ohio. The workshop was conducted and sponsored within the framework of the FAA's annual Chief Scientific and Technical Advisors Workshop (workshop organizer – Dr. Michael Gorelik). It was attended by 61 people representing the FAA, Air Force, NASA, Navy, Defense Advanced Research Projects Agency, National Institute of Standards and Technology, industry, and selected other invitees. The objectives were to provide training and reference material on additive manufacturing (AM) processes to FAA employees and to review and discuss qualification and certification processes and needs relative to additively manufactured parts. The recently formed FAA Additive Manufacturing National Team (AMNT) was introduced and their charter presented.

The workshop consisted of nearly two dozen presentations addressing background; past and present programs; and qualification/certification challenges regarding additively manufactured metal parts. An industry panel provided the perspective and plans from propulsion and airframe original equipment manufacturers and a Tier-1 supplier to the industry. Results and conclusions from these sessions were collected and summarized.

FAA personnel completed the workshop with an extensive roundtable session on the final day. Comments from this session were collected, classified into general categories, and summarized for future action. The AMNT will have the proceedings of the workshop to facilitate development of future plans and roadmaps regarding AM. In addition, many of the presentations will be archived for future education and reference.

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- Rich Jennings (FAA)
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The presenters:

- Michael Gorelik, Jim Kabbara, and Mark Freisthler (FAA)
- Rollie Dutton, Mary Kinsella, Jon Miller, John Brausch, Jeff Calcaterra, and Mike Hirsch (AFRL)
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- Steve Daniewicz (Mississippi State University)
- Dave Abbott (GE Aviation)

The industry panel:

- Tom Chiang (Bell Helicopter)
- Matt Crill (The Boeing Company)
- Mark Shaw (GE Aviation)
- Brian Thompson (GKN Aerospace)
- Brian Hann (Honeywell Aerospace)
- Craig Brice (Lockheed Martin)
- Bill Brindley (P&W)

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Workshops such as this one with aggressive agendas and high expectations require a significant commitment of time, intellect, and expense on the part of participants and their organizations, especially presenters and sponsors. Thank you for your efforts.

TABLE OF CONTENTS

LIST OF ACRONYMS

ACO	Aircraft Certification Office
AFRL	Air Force Research Laboratory
AM	Additive manufacturing
AMNT	Additive Manufacturing National Team
AWS	American Welding Society
CFR	Code of Federal Regulations
CMH-17	Composite Materials Handbook-17
DARPA	Defense Advanced Research Projects Agency
DARWIN	Design Assessment of Reliability With Inspection
MIDO	Manufacturing Inspection District Office
MMPDS	Metallic Materials Properties Development and Standardization
MSFC	Marshall Space Flight Center
NAVAIR	Naval Air Systems Command
NDE	Nondestructive evaluation
NIST	National Institute of Standards and Technology
OEM	Original equipment manufacturer
OM	Open Manufacturing
PMA	Parts manufacturer approval
RISC	Rotor Integrity Sub-Committee

EXECUTIVE SUMMARY

Additive manufacturing (AM) is a rapidly emerging technology with potential for broad application and impact in the aerospace industry. The approach, which builds a part by adding material layer by layer using structural metal alloys, represents a significantly different approach than conventional wrought or cast processes. Parts or shapes may be produced with near-net or final geometry, including complex features and as-produced surfaces. Resulting microstructures, defect species, residual stresses, inspectability, post-processing requirements, and, ultimately, structural performance and durability may differ significantly from conventional processes. The requirements for design, structural assessment, quality assurance, and ongoing manufacturing quality control need review and careful consideration to ensure that qualification processes for AM parts are safe and robust.

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The workshop consisted of nearly two dozen presentations addressing background, past and present programs, and qualification/certification challenges regarding additively manufactured metal parts. An industry panel provided the perspective and plans from propulsion and airframe original equipment manufacturers and a Tier-1 supplier to the industry. Results and conclusions from these sessions were collected and summarized.

FAA personnel completed the workshop with an extensive roundtable session on the final day. Comments from this session were collected, classified into general categories, and summarized for future action. The AMNT will have the proceedings of the workshop to facilitate development of future plans and roadmaps regarding AM. In addition, many of the presentations will be archived for future education and reference.

1. INTRODUCTION AND BACKGROUND

Additive manufacturing (AM) is a rapidly emerging technology with the potential for broad application and impact in the aerospace industry. The approach to build a part by adding material layer by layer can be accomplished by many process types and is applicable to a wide range of materials, including metals, polymers, ceramics, and composites. Key process types for structural metals include directed energy deposition (such as electron beam melting and deposit of metal wire) and powder bed fusion processes (such as direct laser sintering of pre-alloyed metal powder). These processes have significantly matured in the past few years and now offer broad potential to manufacture aerospace parts with structural metal alloys. It is expected that many part applications will be brought forward for regulatory review and approval in the near future. Because the capital investment required for AM equipment is relatively modest, the potential sources for AM aerospace parts may be expanded beyond large aerospace manufacturers and their Tier-1 suppliers to include smaller and less-experienced companies.

AM using structural metal alloys represents a significantly different approach than conventional wrought or cast processes. Parts or shapes may be produced with near-net or final geometry, including complex features and as-produced surfaces. Resulting microstructures, defect species, residual stresses, inspectability, post-processing requirements, and, ultimately, structural performance and durability may differ significantly from conventional processes. The requirements for design, structural assessment, quality assurance, and ongoing manufacturing quality control need review and careful consideration to ensure that qualification processes for AM parts are safe and robust.

The FAA and Air Force Research Laboratory (AFRL) jointly organized a workshop on Qualification and Certification of Additively Manufactured Parts, which was held September 1–3, 2015, in Dayton, Ohio. It was attended by 61 people, representing the FAA, Air Force, NASA, Navy, Defense Advanced Research Projects Agency (DARPA), National Institute of Standards and Technology (NIST), industry, and selected other invitees. The objectives were to provide training and reference material on AM processes to FAA employees and to review and discuss qualification and certification processes, and needs relative to additively manufactured parts. This document is intended to provide a brief reference to summarize the background, objectives, and outcome of the workshop.

2. WORKSHOP OVERVIEW

2.1 OBJECTIVES

The workshop was planned as a 2 1/2 day event with three primary objectives:

1. Educating the FAA workforce in AM technology.
2. Benchmarking qualification/certification efforts of other agencies, and promoting inter-agency collaboration.
3. Establishing a stronger linkage between the recently formed FAA Additive Manufacturing National Team (AMNT) and FAA regional offices (Aircraft Certification Offices [ACOs] and Manufacturing Inspection District Offices [MIDOs]).

Though AM encompasses many processes and materials, this workshop focused on AM of structural metal alloys for aerospace parts manufactured by either powder bed fusion or directed energy deposition processes.

2.2 WORKSHOP FORMAT

The workshop was planned as a 2 1/2 day event and was held at the TecEdge facility in Dayton, Ohio. The following is a summary of the workshop format:

- Day 1 started with the FAA senior management perspective and was focused on training and education of the FAA attendees in AM technology, with seminar-type presentations on technology and applications from AFRL, followed by a perspective from NIST on AM development, measurement technology, and standards. This was followed by presentations from academia on current capabilities and process mapping for AM; prediction and characterization of microstructures resulting from the processes; and mechanical behavior of AM-produced materials and parts.

- Day 2 focused on perspectives on AM from other agencies; qualification and certification of AM parts; and an industry panel. Day 2 included an Air Force Senior Leader perspective; a review of relevant DARPA Open Manufacturing (OM) AM programs; and Air Force, NASA, and FAA perspectives on AM qualification and certification. The newly formed FAA AMNT members were introduced, and an overview was given. The afternoon of Day 2 included an industry panel with seven companies (six original equipment manufacturers [OEMs] and one Tier-1 supplier) participating, followed by a comprehensive overview of AM standards development (note that a planned Naval Air Systems Command [NAVAIR] perspective by teleconference was postponed because of NAVAIR scheduling conflicts).

- Day 3 consisted of a half-day session of government-only participants to solicit feedback regarding the workshop, discuss key findings, and identify recommendations for future activities. This was achieved through a roundtable discussion facilitated by M. Gorelik, in which all FAA participants from the regional offices were requested to share key workshop observations and expectations from AMNT. This format further promoted communication within the FAA team, especially between the personnel from field offices for manufacturing (MIDOs), certification (ACOs), and the newly formed AMNT. Feedback and comments from the day 3 session were captured during the meeting and used in preparation of this summary.

The agenda is presented in appendix A. It was executed as planned, except for the NAVAIR phone presentation that was postponed. The format was generally informal; it was a working meeting with questions and discussion during and after the presentations.

2.3 WORKSHOP ATTENDEES

There were 61 attendees registered for the workshop, including 36 FAA participants from 16 sites; 6 from the Air Force; 9 from industry (including The Boeing Company, Lockheed-Martin, P&W, GE, Honeywell, Bell Helicopter, and GKN), 3 from academia; 4 from NASA, 1 from

NIST, 1 from NAVAIR, and 1 contractor engaged as the workshop facilitator. Attendance was by invitation of the organizers. All participants attended in person.

A list of attendees and their affiliations is presented in appendix B. The FAA attendees represented many sites and directorates from around the United States, as shown in figure C-1 and table C-1 in appendix C.

3. SUMMARY OF WORKSHOP SESSIONS AND PRESENTATIONS

This section is intended to give a brief overview of the workshop sessions, including the presentations, speeches, and industry panel on Days 1 and 2, and the government-only summary session on Day 3. Except for the industry panel briefings, copies of the presentations were made available. The Department of Defense presentations had "Distribution C" markings, which limited the distribution to U.S. government agencies and contractors. Note that in the summaries that follow, the titles of the presentations were taken from the presentation title page; these generally differ slightly from the titles listed on the agenda. They are described in the order indicated by the agenda.

3.1 DAY 1 PRESENTATIONS

Day 1 focused on training and educational briefings on AM processes, materials, parts, and the development of standards.

1. M. Gorelik, FAA, and R. Dutton, AFRL, "Opening Remarks." This presentation stated workshop objectives and format, framed the challenges of AM aerospace parts, and reviewed the agenda. Brief introductions were then made by the participants. This presentation is provided in appendix G

2. R. Jennings, FAA headquarters, "FAA Management Perspective." Presented FAA senior leadership perspective on AM parts qualification, the high level of interest within the FAA, the need to educate the FAA workforce regarding AM, and expectations for the workshop. This presentation was given as a speech with no visual charts.

3. M. Kinsella, AFRL, "Additive Manufacturing Overview–FAA Workshop." An informative presentation summarizing the various AM processes and materials with details about seven AM processes. The presentation included graphics and video of processes in action, which was helpful for attendees not familiar with AM. An edited version of this presentation suitable for public release can be seen in appendix H.

4. J. Brausch, AFRL, "Nondestructive Inspection Challenges for Additive Manufacturing." This presentation focused on nondestructive evaluation (NDE) and the challenges presented by AM-processed parts. It illustrated issues with microstructure; surface condition; near-net or finished geometry inspections; and complex geometries typical of AM parts. The NDE requirements were derived initially from the American Welding Society (AWS) specification D17.1, "Fusion Welding for Aerospace Applications," and AMS2680, "Electron-Beam Welding for Fatigue Critical Applications." This presentation was not cleared for public release and is not included in this report.

5. J. Miller, AFRL, "Structural Materials Challenges to AF Implementation of AM." This presentation provided a detailed explanation of key considerations and challenges posed by AM parts for structural applications, beginning with Dr. Jack Lincoln's five keys to successful transition of technology: "Stability, Producibility, Characterized Properties, Predictability of Performance, and Supportability." These translate to AM via demonstrated process controls; NDE and quality assurance; post-deposit processing and residual stress management; and a statistically based property database. A roadmap or flowchart navigating these requirements was presented, and challenges specific to AM were described. In addition, the lack of clear business case or performance benefits of AM were cited as impediments to implementation. AM is a large opportunity, but poses significant challenges. This presentation was not cleared for public release but one covering the essential information is provided in appendix I.

6. J. Miller, AFRL, "Structural Materials: AM Research and Strategy." This presentation focused on the potential benefits of AM, current research efforts, and future applications. Use of a risk "decision tree" was presented, and development of an internal Air Force questionnaire regarding AM was discussed. It was agreed the questionnaire would be beneficial to the FAA community and would be provided in the Distribution A (approved for public release, distribution unlimited) form. This presentation was not cleared for public release but one covering the essential information is provided in appendix I.

7. K. Jurrens, NIST, "NIST Measurement Science for Additive Manufacturing." This presentation gave the NIST perspective on AM, especially on the integration of many AM efforts within the government and standards organizations. In addition, it provided status on the efforts for developing standards and high-level specifications addressing AM processes and materials. This presentation can be seen in appendix J.

   NIST is assuming a central integration role in measurement science and the development and integration of AM standards and procedures. Focus areas include AM materials characterization and specifications; AM processes and equipment; AM qualification and certification; and AM modeling and simulation. Many activities were of direct relevance to the joint FAA-AFRL workshop. NIST sponsored a workshop in June 2015 at Carnegie Mellon University that addressed certification of metals AM. The final report is available (presumably through NIST).

8. J. Beuth, Carnegie Mellon University, "AM Current Capabilities and Process Mapping Methods Tied to Qualification." This presentation highlighted the potential for analytical process mapping to understand AM process outputs and offer process control approaches in the future. This presentation can be seen in appendix K.

9. A. Rollett, Carnegie Mellon University, "Microstructure in AM." This presentation discussed the importance of understanding microstructure in AM materials; use of computer vision and image classification; measurement of input powder materials and defects (pore) produced by AM; and ultimately developing the ability to predict

mechanical responses using realist 3-D multiphase microstructure representations. This presentation can be seen in appendix L.

10. S. Daniewicz, Mississippi State University, “Mechanical Behavior of Components Fabricated Using AM.” This presentation examined yield strength, ultimate strength, ductility, and fatigue behavior (low-cycle fatigue and into the high-cycle fatigue cycle regimes) for selected AM materials, principally Ti6-4 and Al-Si alloys. The importance of defect species, especially voids or pores, was highlighted, and the effect of hot isostatic pressing processing to close such defects was presented. This presentation can be seen in appendix M.

3.2 DAY 2 PRESENTATIONS

Day 2 contained presentations focused on considerations and challenges for qualification/certification of additively managed parts and an overview of standards activity. The industry panel, which was held on Day 2, is described in section 3.3. Brief summaries of the presentations follow:

1. D. Carlson, U.S. Air Force Aeronautical Systems Center/EN, “Workshop on Qualification/Certification of Additively Manufactured Parts: AFLCMC Propulsion Perspective.” The challenges, opportunities, and risks of AM were discussed, with emphasis on the need for robust processes to ensure that any AM parts that are accepted for use by the U.S. Air Force are safe and fully meet requirements for intended applications. The significant messages from this presentation include: “AM is not ready to deliver organic manufacturing capability for aviation parts at our sustainment centers,” “replication is not duplication of design intent,” and “no shortcuts with AM: it is a journey.” This presentation was not cleared for public release and is not included in this report.

2. M. Maher, DARPA, “Additive Manufacturing in the Open Manufacturing Program.” This presentation highlighted objectives of the DARPA OM initiative to accelerate maturation of new manufacturing technologies. Mr. Maher summarized two OM programs using AM processes: the Honeywell program using INCO718+ in a powder bed process, and the Boeing Titanium Fabrication (tiFAB) program using Ti6-4 in a Sciaky electron beam-wire deposition process. Importance of material, microstructure, and process modeling in-process quality monitoring, post-fabrication NDE, and data for key process parameters were emphasized. These programs illustrate two potential approaches to AM qualification: one being enabled by physics-based integrated computational materials engineering (ICME) modeling framework and the other relying on more conventional, empirically based models. This presentation was not cleared for public release and is not included in this report.

3. E. McMichael, NAVAIR, “NAVAIR Additive Manufacturing.” This presentation was to be delivered via teleconference but was postponed until a later meeting because of workshop schedule overrun and NAVAIR scheduling conflicts. This presentation can be seen in appendix N.

4. J. Calcaterra, AFRL, “Air Force AM Certification Perspective.” This presentation outlined the planned Air Force AM certification procedure—the process flow map. Notably, if the AFRL/AFRL Materials & Manufacturing Directorate (RX) Chief Engineer determines that a new material or process may affect airworthiness, this approach is invoked and technical specialists are added to the “Change Evaluation Team.” It is expected that any AM process will require unique controls dependent on the application. There is no blanket approval process envisioned for AM. The closing comment of the presentation was: “Most organizations don’t seem to grasp the level of control needed for these (AM) processes.” This presentation can be seen in appendix O.

5. K. Morgan, NASA-Marshall Space Flight Center (MSFC), “NASA AM Certification Perspective.” This presentation provided the NASA-MSFC perspective, a comprehensive flow chart of the AM approval process and introduced an MSFC requirements document (EM20, “Engineering and Quality Standard for Additively Manufactured Spaceflight Hardware,” draft 1, dated July 7, 2015). The areas emphasized included standards, design, part classification (for criticality) fracture control, qualification testing, material properties, and process controls. Of note, process controls addressed metallurgical controls, part processes, equipment, and supplier controls. This presentation can be seen in appendix P.

6. K. Taminger, NASA-Langley Reseach Center, “NASA’s Additive Manufacturing Technology Development Activities.” Efforts described in this presentation included electron beam processes, tailored design efforts to take advantage of AM processes, in situ thermal monitoring, residual stress modeling, and applications with ceramics and composites to fabricate non-metallic gas turbine engine components. Functionally graded materials and non-structural applications are also research topics for NASA. This presentation can be seen in appendix Q.

7. M. Gorelik, FAA, “Additive Manufacturing and Risk Mitigation—A Regulatory Perspective.” This presentation gave the FAA perspective on risks and characteristics of the successful transition of structural technologies, and cited the diversity of AM processes and potential application domains as challenges. Application domains included new type and production certificates, maintenance, repair, and overhaul (MRO); and aftermarket parts (parts manufacturer approval [PMA]). The FAA regulatory environment is distributed over four major directorates and multiple regional certification offices, resulting in additional challenges in generating a consistent regulatory response to AM parts across the multiple product types. The FAA expectation is that business cases will drive AM applications, and target applications will be gradually increasing in level of criticality corresponding to higher business value, resulting in accumulation of AM applications just below the “critical parts” definition threshold. Comparisons were made to composite materials in the timeline and key attributes relative to regulatory considerations. An FAA roadmap for AM is under development, with the main focus on evaluation of the current regulatory framework relative to AM, definition of research and development thrust areas, and development of an inter-agency collaboration framework. This presentation can be seen in appendix R.

8. J. Kabbara, FAA, "FAA AM Certification Perspective and Go-forward Plans." This presentation extended the FAA perspective with a summary of the terms and categories for FAA certifications, distinguishing between "applicants" who produce aircraft, propellers, or engines and individual suppliers who produce parts. A distinction was also made between "type design" approval (engineering, design, and performance) and the "production" approval (manufacture). It is apparent that, with AM, the potential is there for individual suppliers to approach the FAA more often to seek approval for either PMA or Technical Standard Order Authorization (TSOA) parts. The FAA intent is to deal with "applicants." Members of the FAA AMNT and planned activities for the AMNT regarding FAA policy review, guidance documents, and participation in industry associations, including for AM standards development, were listed. This presentation can be seen in appendix S.

The industry panel was next in the workshop sequence of events, followed by presentations related to an overview of AM standards development. To maintain continuity of this summary document, the presentations regarding standards are described next, and the industry panel is described in section 3.3.

9. K. Jurrens, NIST, "AM Process Related Tolerance Specification Issues." This presentation covered AM standards development. Emphasis was on ASTM F42 activities, and the collaboration of ASTM F42 with ISO TC 261, in which there is agreement to develop joint and common standards for AM. A hierarchal framework was developed and presented for AM standards and specifications that illustrated the challenge of those standards and specifications, including many areas, processes, materials, and common technical considerations that must be addressed. Standards that have been developed or are in-progress were listed. Challenges for measurement and specification of tolerances for complex AM parts were illustrated. This presentation can be seen in appendix T

10. D. Abbott, GE, "SAE AM Committee." This presentation gave the history of SAE, a description of the SAE aerospace standards activity, and planned (recently initiated) SAE activities regarding AM. There is a newly formed SAE AMS-AM committee with 150+ members that will focus on AM and related specifications; the committee's inaugural meeting was in July 2015. The intention of the committee is to collaborate with other standards organizations and with Metallic Materials Properties Development and Standardization (MMPDS) Emerging Technology Working Group and Composite Materials Handbook-17 (CMH-17) (composites). This presentation can be seen in appendix U.

11. M. Freisthler, FAA, "FAA Perspective on Additive Manufacturing Values in MMPDS." This presentation described the MMPDS handbook and the FAA involvement with it; the considerations related to AM materials; analogy of AM materials to composite materials; and the intent of the FAA to use an "equivalency" test approach for AM materials. The presentation also described the intent to address AM materials as "Highly Process Intensive (or Dependent) Materials," similar to composite materials, and the use of National Center for Advanced Materials Performance (NCAMP) procedures and CMH-17 guidance for composite materials. This presentation can be seen in appendix V.

12. M. Hirsch, AFRL, “Overview of AM Standards Development: AWS.” The AWS is drafting AWS D20.1, “Specification for Fabrication of Metal Components Using Additive Manufacturing,” which will be based on AWS D17.1, “Specification for Fusion Welding for Aerospace Applications.” The committee has approximately 30 members. Qualification requirements in AWS D20.1 will be determined by class (A–C, for now), which will lead to requirements for mechanical testing, metallurgical evaluations, environmental testing, and NDE. One challenge is the broad range of industries, processes, and applications that will be covered (everything from jewelry to toys to flight hardware). In the end, much will depend on what is specified as the “Cognizant Engineering Authority.” This presentation was not cleared for public release and is not included in this report.

3.3 DAY 2–INDUSTRY PANEL

The industry panel consisted of a two-part structured panel discussion with seven participants. Participants included propulsion and airframe OEMs and a Tier 1 supplier to the industry. Time management was a factor in presentations and subsequent discussion because 2 1/2 hours were allocated for the panel session. The participating companies and presenters were:

- Bell Helicopter: T. Chiang
- Boeing: M. Crill
- GE Aviation: M. Shaw
- GKN Aerospace: B. Thompson
- Honeywell Aerospace: B. Hann
- Lockheed-Martin: C. Brice
- P&W: W. Brindley

Because of the limited time and specific objectives for the workshop, two sets of questions were generated and sent to the participants in advance. This was followed by a group teleconference prior to the workshop, in which the objectives, questions, and format for the panel session were discussed. The advance preparation was intended to facilitate a more effective and productive panel session within the limited time frame.

Part 1 of the industry panel consisted of brief presentations by each participant. Participants were asked in advance to briefly respond to the following three topics:

1. Key challenges for AM parts and qualification
2. Lessons learned to date
3. Expectations or needs from regulatory agencies

Participants brought presentation charts that described their company’s activities in AM and addressed, directly or indirectly, the three questions. The intent of these questions was to frame the general status of AM within the industry that will ultimately manufacture and implement AM parts.

Part 2 of the industry panel consisted of more targeted questions seeking information regarding how industry views AM processes and parts from a design, structural assessment, quality, manufacturing, and criticality perspective. The specific questions and their intent were quite detailed and are not presented here. Abbreviated versions of the questions are:

- What are the special considerations for design and assessment?
- What are the special considerations for quality and manufacturing?
- What are the categories of parts and criticality considerations?

Time constraints limited the discussion regarding these more focused questions, though some insight was derived from the individual company briefings given during Part 1 of the panel session.

The panel session was successful in that a number of common themes were indicated, including challenges, lessons learned, and special considerations required for AM processes and parts. The current status of AM within the companies, specifically for AM of structural metal alloys, ranged from investigative to imminent mass production. More specifics on results of the panel session are presented in section 3.4.

3.4 DAY 3–WORKSHOP SUMMARY AND FAA ROUNDTABLE

The Day 3 session was limited to government-only participants. There were approximately 43 attendees.

The session opened with an extended set of introductions by each participant. This included their background, responsibilities, and some commentary regarding the workshop. The extended introductions were intended to facilitate future participant networking and collaboration, especially regarding AM parts.

Introductions were followed by a roundtable discussion, in which each attendee had the opportunity to state their opinion on issues, concerns, or comments regarding AM and qualification/certification of AM parts. The main focus of this session was on capturing input from the non-AMNT FAA personnel (mostly ACO and MIDO representatives) because this was the first in-depth exposure to the subject of AM technology for many of them. Approximately 45 comments or concerns were recorded by the workshop facilitator and 10 "key expectations or needs from the regional FAA offices." The lists were edited and consolidated following the workshop. At the end of the Day 3 session, the workshop leader from the FAA (M. Gorelik) generated a list of seven discussion topics. These ranged from general items of information to near-term action items.

4. RESULTS AND CONCLUSIONS

This workshop was extensive, both in participation and content. Workshop participants represented a very diverse group in terms of familiarity and expertise with AM, which was essentially bi-modal in terms of AM experience for aerospace applications with structural metal alloys. Workshop content included nearly 2 dozen significant presentations[1] and an industry panel session involving seven companies, presented over a two-day period. This was followed by a half-day session on the third day soliciting government-only feedback and FAA "roundtable" comments.

Sections 4.1–4.4 capture the results, conclusions, and common themes that emerged from the workshop. In addition, these sections summarize results of the FAA roundtable event on Day 3 and make some general, high-level conclusions regarding the workshop and its objectives.

4.1 RESULTS DERIVED FROM THE PRESENTATIONS

The following general conclusions and observations were summarized from the presentations given during the workshop. Note that these observations and conclusions are made in the context of AM of metal alloy structural materials for aerospace part applications:

- There is an extremely high, broad, and sustained level of interest and investment in AM throughout industry, government, and academia. This is especially true for metals AM.

- AM for structural materials represents a broad suite of processes with many general categories and an equally broad range of potential applications in aerospace parts.

- AM for structural metals is on the verge of implementation into selected aerospace part applications in a mass-production environment, beyond tooling, prototyping, or development applications. (Although there have been a few notable examples of AM metal parts being qualified and flown in military aircraft, the first AM part for commercial use is, to the best of the author's knowledge, a flow-path sensor housing for a GE-90 commercial engine that was certified by the FAA in 2015[2]. The first known AM part with high-rate production was certified for a new commercial engine in November 2015. This is also a GE part, a CFM LEAP™ engine combustor fuel nozzle[3], which has a complex geometry, is made of a CoCr structural metal alloy, and could achieve production rates of up to 40,000 units per year.)

- The input or feedstock material, the specific AM process, and the resultant part are highly integrated and interdependent. This characteristic of AM poses significant challenges and affects requirements for qualification and certification.

- Traditional quality assurance, NDE methods, and detection/treatment of defects may be affected or limited by complex geometry, surface finishes, and the near-net-shape nature of parts produced by AM.

- The potential exists for a high degree of manufacturing variation because of the process, machines, suppliers, and input stock. This also needs to be considered and addressed with

[1] The intention is to make the presentations available for future reference, subject to distribution notices and restrictions.
[2] FAA Safety Briefing, May/June 2015. Available at: http://www.faa.gov/news/safety_briefing/2015/media/MayJun2015.pdf. Accessed 9/10/2015.
[3] Jet Engines with 3D-Printed Parts Power Next-Gen Airbus Passenger Jet GE Reports, May 19, 2015. Available at: http://www.gereports.com/post/119370423770/jet-engines-with-3d-printed-parts-power-next-gen. Accessed 9/10/2015.

the use of “frozen process” approaches and general quality assurance and process-control methods.

- There is considerable and sustained supporting effort to mature AM processes in several government agencies, including AFRL, NASA, the Navy, and DARPA. These efforts span method development (early Technology Readiness Level/Manufacturing Readiness Level [TRL/MRL]) through specific part qualification and include critical support activities like process monitoring; material and process modeling (ICME); and NDE development.

- Significant, sustained university efforts are also in progress. These include development of processes and process models; microstructure and property predictions; experimental assessments; and sensors and process-monitoring approaches. Note that few current process models are mature; they are useful today for trending but not necessarily “process control.”

- University efforts are extensive enough to help ensure a trained professional work force for future AM development and implementation.

- NIST and standards organizations, including ASTM, SAE, ISO, and AWS, are addressing general standards and specifications for AM. In addition, NIST is providing critical measurement science effort and standards integration for AM. Development of such standards is progressing and encouraging, but it is far from mature. In addition, such specifications and standards are generally too high-level for specific material/process/part certification requirements.

- Each specific AM application (at least in aerospace) will require detailed specifications addressing, at a minimum, input materials; process specification; resultant material and product characterization; and part conformance requirements. These will likely come from the industry advocate for a specific application.

4.2 RESULTS DERIVED FROM THE INDUSTRY PANEL

The following general conclusions and observations were summarized from the industry panel session during Day 2 of the workshop:

- Current general processes for design, development, and qualification are believed adequate for AM. These processes must be rigorously applied and address the specific nature and considerations required for AM processes.

- Extreme diligence on all aspects of AM processes will be required for:

    - Input material, especially powder for powder bed processes.
    - Machine and process parameters: qualification, control, monitoring, changes at the machine level, etc.

  - Final part quality assurance: characteristics and properties; NDE challenges; 1st article and cutup approaches; test data; etc.

- Part classification for criticality will be important.

- Industrial infrastructure for AM is regarded as immature: it appears most OEMs will continue to invest internally/work with high-level suppliers in the near term.

- Better input powder material was cited as a challenge: seeking powder manufactured with AM processes in mind for flowability and spreadability; size fractions; cleanliness; and, possibly later, for tailored alloys.

- Manufacturing variation was cited as a significant challenge, requiring large efforts to qualify input material (including re-use procedures), specific equipment, process specifications, and process controls necessary to ensure a consistent product (two OEMs cited ~6 months required to "qualify" a new or changed machine).

- Quality assurance and NDE procedures were also cited as a significant challenge. Near-net or finished shapes, complex geometries, and as-built, or even post-processed, surface finishes were all cited as challenges for inspection. Many parts may require sophisticated volume inspections, such as computed tomography, augmented by actual cutups.

- Feedback on regulatory support requests varied from need for additional guidance to "current processes are adequate if diligently followed…" (Note that the apparent ambiguity here by industry appears to result from two considerations: a desire to fully know the regulatory requirements in advance of extensive investment, and the belief by some OEMs that they have already addressed qualification requirements and extrapolated them to certification requirements, and, therefore, do not see a need for additional/different FAA certification requirements).

- GE fuel nozzles will be the first high-rate production part from a structural material. This appears to be a strategic decision for initial application because of the high investment required to fully develop and qualify the powder bed AM process for this part and the significant capital equipment investment. Benefits cited included improved durability, weight savings, and lower cost compared to traditionally manufactured fuel nozzles. The precedents set here are significant: comprehensive due diligence is required in design; materials selection; process development and control; machine qualification; material/part characterization; and quality assurance. The application must meet requisite business case metrics.

All of the industry panel participants are actively working metal AM. The overall main message was that current processes for design, manufacturing, materials, and quality are applicable for AM at the high level, but they must be followed rigorously. Additional requirements specific to AM may be required in the future. No shortcuts.

4.3 RESULTS OF THE FAA ROUNDTABLE

The Day 3 session was limited to government only and included approximately 45 participants. The workshop facilitator recorded 55 comments during the roundtable event. These were subsequently grouped into seven categories for further consideration. The complete listing of comments, sorted into the seven categories, is presented in appendix D.

The seven categories are somewhat arbitrary, but it appears that these groupings facilitate more efficient consideration of the roundtable results. Results and conclusions are summarized below for each of the seven categories:

1. General Considerations for Additively Manufactured Parts: FAA participants recognized that there is broad activity in AM in government, industry, and academia. They cited that the development time frame has been long. The notable conclusion was that there are similarities between additively manufactured parts and composites (specifically organic matric composites) during their introduction because the material/process/part is closely integrated for both classes of materials.

2. Cost and Business Considerations for AM: Cost and business considerations produced mixed reactions. There is a concern that the “barriers to entry” to make aerospace parts with structural metals have been greatly reduced. However, it was recognized that development and certification of AM parts will have high cost beyond capital investment. The notable conclusions are:

    a. Barrier to entry may be low for PMA-type activity in terms of capital investment required.
    b. There will be significant costs to understand and characterize AM processes for specific applications and to adequately address quality, NDE, process control, and characterization. These considerations may offset, or possibly exceed, direct process cost benefits.

3. Variation, Process Controls, and Quality Considerations: Many participants cited inherent variability with AM processes; lack of standards for process controls and qualification; and perception that AM, in general, is still relatively immature as a manufacturing technology for aerospace metal parts. The notable conclusions are:

    a. Potential for high variability in AM processes requires treating AM processes at local machine level, addressing important control variables (there are many), and establishing standardized process controls and certification procedures.
    b. A frozen process approach seems desirable, but output and variability must be demonstrated.
    c. Part capability may have to be defined or specified locally (as in zoning of parts).
    d. Current AM processes have been developed and exercised by experts. There is significant risk when non-expert practitioners or organizations use AM for aerospace parts.

4. Part Applications and Criticality: Participants cited the need to track "lessons-learned" from non-critical parts and to expect more non-critical part applications. More concern was expressed over AM applications to aftermarket and repair than to new type certifications. The notable conclusions are:

   a. Repairs, sustainment, and reverse-engineered replacement parts pose significant risk (Ref: Parts 121 and 145).
   b. PMA applications (as in approval requests to the FAA) are believed imminent.
   c. Order 8110.42 for PMA applications needs to be reviewed using AM processes.

5. Guidance, FAA Policy, and Interagency Collaboration for AM: This category had the largest number of entries, indicating high interest and concern here by FAA participants. They expressed the general need for a defined path forward, from process parameter definition and control to regulatory roles and responsibilities, and associated support tools and guidance documents for application to AM. The notable conclusions are:

   a. Current regulations can likely handle AM, with policy memo adds similar to what was done with composites.
   b. Need interim policy memos or issue papers/guidance for AM that can be matured into Advisory Circulars later, if needed.
   c. Guidance is needed for "Applicants" to ensure complete compliance packages are prepared before submittal.
   d. Consider the need for policy review regarding Designated Engineering Representative authority relative to AM.
   e. Guidance is needed regarding AM for lower criticality parts (i.e., no safety effect [NSE]).
   f. An FAA plan or roadmap for AM is needed. This should consider the need for FAA research and define help from the AMNT.
   g. Need a process or policy for interagency sharing regarding AM.
   h. Need to define or clarify policy regarding foreign authorities and bilateral agreements on AM.

6. Tools, Training, and Checklists for AM: Several participants cited the need for training and standardized "tool kits," especially checklists, for AM qualification and certification. The notable conclusions are:

   a. Checklists are needed: the AFRL checklist described during the workshop could be a start, possibly modified for FAA use.
   b. A formal tool kit is needed for both applicants and regulators.
   c. Training specific to AM is needed for qualification/certification, especially for FAA manufacturing engineers.

7. Standards and Specifications: Participants were surprised at the lack of specific standards for AM materials and processes because there was a desire to see such standards to support qualification/certification reviews. In general, it was recognized that, in addition

to general standards and specifications for AM, application-specific standards and specifications will certainly be required. The notable conclusions are:

a. Output is needed from various standards groups, because these are often referenced for FAA regulations or policies.
b. Standards and specifications are a priority-need for fatigue-limited applications.
c. The expectation is that applicants who bring forward AM parts for qualification/certification will have supporting standards and specifications.

4.4 CONCLUSIONS REGARDING THE WORKSHOP

Many specific observations and conclusions were drawn from the workshop, based on the technical presentations, industry panel, and final day FAA roundtable. This section is intended to summarize results and conclusions regarding the workshop itself and its objectives:

- The educational objective of the workshop was fully met: AFRL and agency presentations comprehensively introduced AM methods, materials, applications, challenges, and current status. The industry panel was informative regarding plans and near-term applications. NIST and the standards groups presented current status and future plans. A significant number of FAA employees involved in certification attended and benefitted directly; and many of the presentations could serve as excellent reference sources for others.

- The objective to benchmark qualification/certification efforts and initiate collaboration with other agencies was also met, with the exception that follow-up with the Navy is required because of postponement of their participation. The Air Force, NASA, and DARPA programs were all reviewed. These reviews detailed applications, research, and current thinking regarding qualification/certification. In addition, current activities in standards and specifications were reviewed and consortia groups and their efforts were identified. The means or plans for follow-up to establish true collaboration were not addressed here.

- The objective to introduce the AMNT to the regional and field offices of the FAA was also met. Introductions and face-to-face contacts were established. Perspectives were interchanged. The charter of the AMNT was presented and discussed. Workshop results will facilitate development and successful dissemination of the detailed AMNT plan and roadmap in the near future.

- The FAA roundtable was successful. The issues, concerns, and requests that surfaced during the roundtable comprehensively represented the presentations and industry panel results, as well as the experiences and expectations of the FAA participants. These results, when categorized and summarized, provide a clear summary of concerns and requests for guidance, policy, training, tools (e.g. checklists), communication, and reference material for future use.

This was an information-intensive workshop that required full attention at all times from the participants. The attendee participation and attention were excellent. Overall, the workshop objectives were fully met. Workshop results will be useful for future planning and actions regarding qualification and certification of additively manufactured aerospace parts.

5. RECOMMENDED NEXT STEPS

The workshop was successful in meeting its objectives. The following actions are recommended in the near term to ensure the results of the workshop are effectively utilized:

1. The presentations made during the workshop should be collected and archived in an accessible location for use by FAA employees. Their value will diminish with time as they become outdated, but in the near term they provide useful educational and reference information.

2. The FAA AMNT should review results of the workshop for use in construction or refinement of their roadmap and plans. It was clear that many FAA participants would like additional education, guidance, policy, and tools to address AM qualification/certification issues. The workshop presented a unique opportunity to identify and document these needs. Two specific recommendations are made:

   a. Development of near-term action plans to address immediate needs, such as checklists and guidance memoranda.
   b. Development of longer-term plans consistent with an agency-level roadmap on certification of additively manufactured parts.

3. The best means for future communication and collaboration within the FAA regarding AM should be determined. Person-to-person contact was established between the AMNT and regional- and field-office personnel. The most effective way to sustain that communication and the preferred means for information dissemination and exchange should be established. This may prove especially important as requests for qualification/certification of AM parts materialize, and as checklists, guidance and policy memos, etc., develop within directorates. The specific recommendation is to develop a "Communication Plan for AM," encompassing the needs of both the technical community and FAA management.

6. SUMMARY

The FAA and AFRL jointly sponsored a workshop to address the qualification and certification of AM parts, focused on those using structural metal alloys. There was broad interest and participation. Presentations and an industry panel covered the technology, programs, and challenges represented and the current and planned efforts to establish standards and specifications. Many useful results and conclusions were generated, which have been summarized and organized for future use. The FAA AMNT was introduced and relationships established within the FAA and with other agencies and organizations.

Results and presentations from the workshop will be made available for future reference and used to guide FAA development of detailed plans and roadmaps in the near future. These plans will address training and education; guidance and policy; and appropriate tools or references needed to meet the qualification and certification challenges posed by this technology.

APPENDIX A—WORKSHOP AGENDA

Joint FAA–Air Force Workshop
On Qualification/Certification of Additively Manufactured Parts
Co-sponsored by FAA Chief Scientist (M. Gorelik) and AFRL/ManTech (R. Dutton)

September 1–3, 2015
Venue: Tec^Edge
(http://wbi-icc.com/centers-services/tecedge-icc)
5000 Springfield Street, Dayton, OH

Workshop facilitator: Brad Cowles, Cowles Consulting, LLC
Dress code: business casual

Note to all presenters: Due to the tight workshop schedule, presentation time limits will be strictly enforced; please allow a few minutes for Q&A within the allocated time window.

Day 1 – September 1

8:15–8:30	Introductions (All)
8:30–9:00	Workshop overview and objectives (R. Dutton/AFRL and M. Gorekil/FAA)
9:00–9:15	FAA Management Perspective (R. Jennings/FAA HQ)
9:15–10:30	AFRL AM Seminar (M. Kinsella, J. Miller/AFRL)
10:30–10:45	Break
10:45–12:15	AFRL AM Seminar–cont. (J. Brausch, M. Kinsella, J. Miller/AFRL)
12:15 – 1:00	Lunch (catered on site)
1:00–1:45	AFRL Research & Future AM (J. Miller/AFRL)
1:45–2:45	NIST Perspective on AM K. Jurrens/NIST)
2:45–3:15	AM Current Capabilities and Process Mapping Methods Methods tied to Qualification (Prof. J. Beuth/CMU)
3:15–3:30	Break
3:30–4:00	Microstructure in AM (Prof. A. Rollett/CMU)
4:00–4:30	Mechanical Behavior of Components Fabricated Using AM (Prof. S. Daniewicz/MSU)
4:30–5:00	Summary of Day 1/Discussion (B. Cowles/All)
6:45–…	Team Dinner–Texas Roadhouse (Fairborn, OH)

Day 2 – September 2

8:00–8:15	Coffee, introductions
8:15–8:30	USAF Senior Leader Perspective (D. Carlson/USAF)
8:30–9:15	DARPA OM Overview (M. Maher/DARPA)
9:15–9:45	NavAir AM Certification Perspective (L. McMichael/NavAir)–via telecon
9:45–10:15	Air Force AM certification perspective (M. Kinsella/AFRL)

10:15–10:30	Break
10:30–11:15	NASA AM Certification Perspective and AM R&D (K. Morgan/MSFC and K. Taminger/LaRC)
11:15–12:00	FAA AM Certification Perspective and Go-Forward Plans (J. Kabbara, M. Gorelik/FAA)
12:00–12:30	Lunch (catered on site)
12:30–3:00	Industry Perspective on AM–Panel session (moderated by B. Cowles and M. Gorelik) • Bell Helicopter (T. Chiang) • Boeing (M. Crill) • GE Aviation (M. Shaw) • GKN Aerospace (B. Thompson) • Honeywell Aerospace (B. Hann) • Lockheed Martin (C. Brice) • P&W (J. Boyer)
3:00–3:15	Break
3:15–4:45	Overview of AM Standards Development • ASTM F42 and ASME Y14.46–K. Jurrens, NIST (30 min) • SAE AM committee–D. Abbott, GEA (15 min) • MMPDS–M. Freisthler, DAA (30 min) • AWS standards–J. Calcaterra, AFRL (15 min)
4:45–5:00	Meeting wrap-up/discussion
5:00	Adjourn (for general audience)

<u>Day 3</u>–<u>September 3</u>

8:30–9:30	Summary of workshop observation and go-forward plans (M. Gorelik/ R. Dutton/B. Cowles)
9:30–11:30	FAA round table (AMNT + site representatives) Government attendance based on interest • Feedback from the sites • Additional discussion re. AMNT work plans, roadmap outline etc. • Engagement with external organizations, training requests etc.
11:30	Adjourn

APPENDIX B—WORKSHOP ATTENDEES

Table B-1. List of attendees for Sept 1–3 2015 Additive Manufacturing Workshop/Dayton, Ohio

		Name	Organization	Role	Comments
	Government (non-FAA)	13			
1		Rollie Dutton	Air Force	co-host	
2		Dale Carlson	Air Force	keynote – Day 2	
3		Mary Kinsella	Air Force	presenter	
4		Jon Miller	Air Force	presenter	
5		John Brausch	Air Force	presenter	
6		Jeff Calcaterra	Air Force	presenter	
7		Mick Maher	DARPA	presenter	
8		Brad Cowles	Contractor	workshop facilitator	
9		Kevin Jurrens	NIST	presenter	
		Liz McMichael	NAVAIR	presenter - remotely	rescheduled
10		Kristin Morgan	NASA	presenter	
11		Karen Taminger	NASA	presenter	
12		Doug Wells	NASA	attendee	
13		Alan Pentz	NAVAIR	attendee	
	FAA	36			
14		Rich Jennings	FAA	keynote – Day 1	
15		Tim Mouzakis	FAA		
16		Dan Kerman	FAA		
17		Mark Boyer	FAA		
18		Jo-Ann Theriault	FAA		
19		Antonio Cancelliere	FAA		
20		Ian Lucas	FAA		
21		Paul Craig	FAA		
22		Chandra Ramdoss	FAA		
23		Mauricio Kuttler	FAA		
24		Michael Sullivan	FAA		
25		Carlos Morales	FAA		
26		Mark Freisthler	FAA	presenter	
27		Melanie Violette	FAA		
28		Tung Tran	FAA		
29		Tyler Feeley	FAA		
30		Steve Litke	FAA		
31		Shawn Malekpour	FAA		
32		Christopher Richards	FAA		
33		Andreas Rambalakos	FAA		
34		Rob Capezzuto	FAA		
35		William Herderich	FAA		

Table B-1. List of attendees for Sept 1–3, 2015
Additive Manufacturing Workshop/Dayton, Ohio (continued)

		Name	Organization	Role	Comments
36		Penelope Trease	FAA		
37		Robert Grant	FAA		
38		Michael Gorelik	FAA	co-host	
39		Jim Kabbara	FAA	presenter	
40		Robert Cook	FAA		
41		Ken Hutcherson	FAA		
42		Mark James	FAA		
43		Kevin Stonaker	FAA		
44		Ken Kopp	FAA		
45		Anthony Flores	FAA		
46		Bill Champion	FAA		
47		Al Clifton	FAA		
48		Brian Younce	FAA		
49		Chinh Vuong	FAA		
	Industry	9			
50		Mark Shaw	GEA	industry panel	
51		Dave Abbott	GEA	presenter	
52		Jesse Boyer	P&W	industry panel	
53		Matt Crill	Boeing	industry panel	
54		Brian Hann	Honeywell	industry panel	
55		Craig Brice	Lockheed Martin	industry panel	
56		Tom Chiang	Bell Helicopter	industry panel	
57		Brian Thompson	GKN	industry panel	
58		Russ Cochran	Boeing	attendee	Day 2 only
	Academia	3			
59		Anthony Rollett	CMU		Day 1 only
60		Jack Beuth	CMU		Day 1 only
61		Steve Daniewicz	MSU		

APPENDIX C—WORKSHOP DEMOGRAPHICS AND FEDERAL AVIATION ADMINISTRATION REPRESENTATION

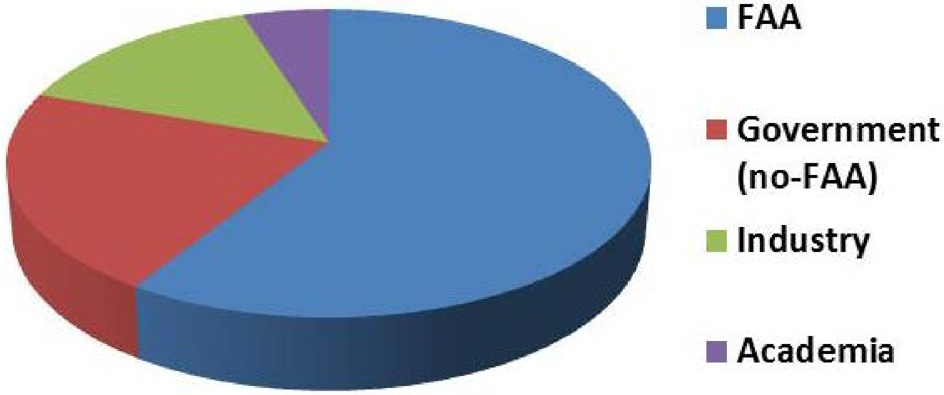


Figure C-1. Federal Aviation Administration Chief Scientific and Technical Advisors Workshop Demographics

Table C-1. Federal Aviation Administration Chief Scientific and Technical Advisors Workshop Attendees (September 1–3, 2015)

	Location	Site Attendees	AMNT	Total
1	Burlington	4	2	6
2	Chicago	3		3
3	Atlanta	2		2
4	DC	3	2	5
5	San Antonio	1		1
6	Wichita	1		1
7	Kansas		1	1
8	Renton	3	1	4
9	Phoenix		1	1
10	Los Angeles	3		3
11	Hartford, CT	2		2
12	Ft Worth		1	1
13	New York	1		1
14	Atlantic City	1	1	2
15	Vandalia	2		2
16	Denver	1		1
		27	9	36

APPENDIX D—FEDERAL AVIATION ADMINISTRATION ROUNDTABLE COMMENTS

Table D-1. Federal Aviation Administration Roundtable Comments

Category	Line Item	Comments–Sorted by Category	Notes
		General Considerations for Additively Manufactured Parts	
1	8	Very broad activity in government, industry, and academia	
1	21	Time frame to mature AM has been long	
1	23	Many similarities between AM and composites when they were being introduced	
1	35	Similarity to composites in many respects	
		Cost and Business Considerations for AM	
2	2	Concern that barrier to entry for PMA type activity is low	
2	22	Intellectual property may be further stumbling block for progress in applications and certification	
2	24	High cost to understand the process beyond initial capital investment	2
2	28	Recognize that AM may prove to be an expensive process when all things are considered (data required, NDE, post-processing, etc.)	
2	33	AM appears to be a niche process for specific applications: must meet business case, not for primary structures, etc.	3
		Variation, Process Controls, and Quality Considerations	
3	1	Concern with inherent variability in AM production and output	
3	4	Rich Jennings: “we don’t know what good looks like.”	
3	5	NDE: big issue both for new production and in-service inspection	
3	6	Highly variable material properties produced by AM processes	
3	7	Lack of standardized process controls and certification–more possible important control variables	
3	9	Treat AM processes at local machine level for control and qualification	
3	14	AM process defines part capability locally: how to capture like in part type design drawing	
3	15	Concern over all the unknowns about AM (also “Unknown-Unknowns”)	
3	30	Frozen process approach seems desirable	
3	32	Current AM processes developed and exercised by experts—what happens when manufacturing transitions to other shops and non-experts? Especially on mass-produced, high volume parts	
3	38	AM seems immature at this point.	
		Part Applications and Criticality	
4	10	Maybe expect more non-critical part applications. Need different checklist?	
4	11	Need to track lessons learned from non-critical parts	
4	13	Need to address application of AM processes to repair	
4	16	Repairs, sustainment, reverse-engineered parts, replacement parts are possibly a bigger risk with AM. Ref: Parts 121 and 145	
4	20	PMA applications believed imminent with AM processes	
4	36	May apply to electronics in near future? Need guidance here?	
4	45	Need to prevent PMA of AM parts – (order 8110.42 rev needed?)	

Table D-1. Federal Aviation Administration Roundtable Comments (continued)

Category	Line Item	Comments–Sorted by Category	Notes
		Guidance, FAA Policy, and Interagency Collaboration for AM	
5	3	Need defined path forward—from process parameter definition and control, to regulatory roles and responsibilities—need support tools for application to AM. Need guidance documents for short term.	
5	17	FAA behind "AM power curve?" No active research effort here within FAA	
5	34	Current regulations can likely handle AM. Similarity to policy memo adds for composite materials	
5	37	Need policy or guidance first that can be matured into an AC later.	
5	40	Interim guidance first that can be matured into an AC later	
5	41	Guidance to "applicants" would be beneficial to ensure complete compliance package is prepared	
5	42	Need to define focal points for field offices to ensure communication with the AMNT	
5	43	Building block approach still needs to be used for AM	
5	44	What about "foreign authorities" and bilateral agreements regarding AM?	4
5	2	Current AM policy memo identifies AM applicants and parts, but need guidance on "what next."	1
5	3	Guidance on NDE requirements for certification	1
5	4	Guidance regarding AM application to lower criticality parts–NSE.	1
5	5	Policy memo needed for non-critical parts	1
5	6	Consider need for policy on DER authority regarding AM parts	1
5	7	Need an FAA plan or roadmap for AM	1
5	9	Need process for interagency sharing on AM	1
5	10	Any output from national team to assist AM assessments will be helpful	1
		Tools, Training, and Checklists for AM	
6	12	Need focus on education and guidance for qualification/certification of AM processes—5 part certification process	
6	25	Value to current AFRL AM checklist (Distribution A version)—need to distribute	
6	27	Need for training relative to AM	
6	29	Reiterate need for AM checklist(s)	
6	31	Many unknowns regarding AM for regulators when they review these processes. Need standardized tools to assist.	
6	39	FAA manufacturing engineers need training and background here specific to AM	
6	1	AM checklist(s) needed with what questions to ask	1
6	8	Formal tool kit needed for AM conformity for applicants and regulators	1

Table D-1. Federal Aviation Administration Roundtable Comments (continued)

Category	Line Item	Comments–Sorted by Category	Notes
		Standards and Specifications	
7	18	Need to achieve standards and specifications for AM material/parts, especially for fatigue-limited parts	
7	19	Need output from NIST and standards groups because these are often the references for FAA regulations or policies.	
7	26	Surprising lack of specific standards for AM materials and processes	
		Notes:	
	1	Was cited as key expectation from AMNT or FAA offices	
	2	Item could also be categorized under “Variation, Process Controls, and Quality Considerations”	
	3	Item could also be categorized under “Part Applications and Criticality”	
	4	Item could also be categorized under “Standards and Specifications”	
	5	Comments captured by facilitator during roundtable. Concurrently projected to ensure of intent.	
		Minor editing and consolidation performed post-meeting	

AM = Additive Manufacturing; PMA = parts manufacturer approval; NDE = nondestructive evaluation; AC = Advisory Circular; AMNT = Additive Manufacturing National Team; DER = designated engineering representatives; AFRL = Air Force Research Laboratory; NIST = National Institute of Standards and Technology

APPENDIX E—LIST OF PRESENTATIONS

1. M. Gorelik, FAA, and R. Dutton, AFRL, “Opening Remarks”
2. R. Jennings, FAA HQ, “FAA Management Perspective” (Note: speech; no presentation charts used.)
3. M. Kinsella, AFRL, “Additive Manufacturing Overview–FAA Workshop.”
4. J. Brausch, AFRL, “Nondestructive Inspection Challenges for Additive Manufacturing”
5. J. Miller, AFRL, “Structural Materials Challenges to AF Implementation of AM”
6. J. Miller, AFRL, “Structural Materials: AM Research and Strategy”
7. K. Jurrens, NIST, “NIST Measurement Science for Additive Manufacturing”
8. J. Beuth, Carnegie Mellon University, “AM Current Capabilities and Process Mapping Methods Tied to Qualification”
9. A. Rollett, Carnegie Mellon University, “Microstructure in AM”
10. S. Daniewicz, Mississippi State University, “Mechanical Behavior of Components Fabricated Using AM”
11. D. Carlson, USAF ASC/EN, “Joint FAA-Air Force Workshop on Qualification/Certification of Additively Manufactured Parts: AFLCMC Propulsion Perspective”
12. M. Maher, DARPA, “Additive Manufacturing in the Open Manufacturing Program”
13. E. McMichael, NAVAIR, “NAVAIR Additive Manufacturing”
14. J. Calcaterra, AFRL, “Air Force AM Certification Perspective”
15. K. Morgan, NASA-MSFC, “NASA AM Certification Perspective”
16. K. Taminger, NASA-LaRC, “NASA’s Additive Manufacturing Technology Development Activities”
17. M. Gorelik, FAA, “Additive Manufacturing and Risk Mitigation—A Regulatory Perspective”
18. J. Kabbara, FAA, “FAA AM Certification Perspective and Go-forward Plans”
19. K. Jurrens, NIST, “AM Process Related Tolerance Specification Issues”
20. D. Abbott, GE, “SAE AM Committee”
21. M. Freisthler, FAA, “FAA Perspective on Additive Manufacturing Values in MMPDS”
22. M. Hirsch, AFRL, “Overview of AM Standards Development: AWS”

Note: Presentations 3, 4, 5, 6, 11, 12, and 22 had “Distribution C” notices, which limited their distribution. “Distribution A” versions, suitable for public release with unlimited distribution, were provided by AFRL for presentations 3, 5, and 6.

APPENDIX F—FACILITATOR COMMENTS

The workshop summary was intended to represent the proceedings and results of the workshop in a complete and objective manner. This appendix offers a brief set of comments from the facilitator Bradford A. Cowles as an experienced observer of qualification and certification processes. They represent the opinions of the author.

- Workshop Comments: The workshop was productive and met its objectives. The format was effective; content was both comprehensive and focused to meet the objectives; and participation was outstanding. The successful outcome is attributable to detailed agenda planning and preparation, including the pre-workshop interaction with presenters and the industry panel and broad pre-workshop coordination within the FAA. This pre-work and interaction was critical to ensure focus on objectives and a common understanding of time and logistical constraints of the workshop itself.

- Qualification/Certification of Additively Manufactured Parts as a workshop topic: It was clear that this is a timely topic of exceptional interest. Extensive efforts have been underway for several years in industry, government, and academia. However, very little focused effort has been undertaken to specify qualification or certification requirements, especially any special considerations or expectations associated with additive manufacturing (AM). Exceptions may be the current efforts to develop standards and specifications, though most of these appear to be general in nature and will not reduce the requirement for material, process, and application-specific procedures and specifications. In addition, the Defense Advanced Research Projects Agency Open Manufacturing Initiative has two programs addressing “rapid qualification of AM processes,” though these are focused on early maturation of the technology, which is somewhat pre-certification.

- Additive Manufacturing National Team (AMNT): Establishing this team is, in the opinion of the author, an excellent action by the FAA. This team has the charter to address, in large measure, the previous comment: namely the qualification/certification requirements specific to AM. In addition, the team can provide proactive identification of appropriate guidance and policy actions in a timely manner and ensure two-way communication of such across the distributed FAA. This team might also identify appropriate potential FAA research projects that are not covered by other agencies or industry.

- Industry Working Group or Sub-Committee for AM: This was mentioned during discussion of the AMNT and is apparently under consideration by the FAA. In the author’s opinion, this is an excellent idea and should be pursued in the near term. The following is an historical example. The FAA's Titanium Rotating Components Review Team was formed following the Sioux City, Iowa accident in 1989. Their report, which was issued in December 1990, contained 11 recommendations in several major areas, including: Titanium Melt Processes, Manufacturing Inspections, In-Service Inspections, Design Methods & Advisory Material (including Damage Tolerance), and Research and Development topics. As a result, the Aerospace Industry Association’s Rotor Integrity

Sub-Committee (RISC), an industry working group chartered by the FAA, was established to assist the FAA in implementing these recommendations. RISC was responsible for developing draft materials for several FAA Advisory Circulars addressing both manufacturing-induced and inherent material anomalies for safety-critical parts, and defining several strategic research and development topics that ultimately resulted in development of the Design Assessment of Reliability With Inspection (DARWIN®) code and validation of its methodologies based on combined original equipment manufacturers' (OEMs') field and manufacturing experience. In addition, a working sub-group of RISC, Rotor Manufacturing project, was created following the Pensacola accident in 1996 and focused on developing a manufacturing Lessons Learned database and industry report. The Engine Titanium Consortium was set up separately as a research and development consortium headed by Iowa State University to develop enhanced nondestructive evaluation (NDE) inspection methods, funded by FAA grant money. [Note: information for this historical perspective on RISC provided by M. Gorelik].

Collectively, the efforts of these committees have generated industry standards and guidance for titanium defect and risk assessments; manufacturing; NDE methods and requirements; and supporting risk analysis tools, specifically DARWIN. The concepts and methods have been extended and now include powder metallurgy nickel super alloy applications. Formation of these committees was reactive, but there is an opportunity to establish a similar FAA and industry working group in a proactive manner. It appears there would be high interest in participation, though it should be noted that near-term production and aftermarket applications of AM are currently limited. Still, such a committee would develop as needed over time, as was the case with the historical example.

- Risk Assessment of AM Parts: The presentations and industry panel indicated that current high-level engineering and quality processes are applicable to AM parts, and in general are regarded adequate if adjusted for the specific material/process/parts and rigorously executed. It was generally noted that AM parts represent highly integrated product of the material, specifics of the process, and the part itself (size, geometry, build plan, etc.). What were not brought out were requirements for any special considerations for assessment of structural performance of AM parts. Specifically, measurement and quantification of defect species and other volumetric or location-specific risks in AM parts, including the stress state; service environment; handling damage; surface finish or post-process capability; and NDE capability, by location within the part. Risk and consequence of failure will depend on the application, but it seems obvious that, for AM parts, this risk will be location-dependent within the part. In the author's opinion, there should be near-term focus on such risk assessment, or zoning, of AM parts. This could possibly be simplistic in nature or involve a more complex assessment of the entire part. One applicable tool to do this is already operational and in general use: DARWIN. The input distributions for defects, NDE capability, etc., are not established and would pose a challenge. However, this represents a focused challenge that would produce a quantitative result, useful when application risk warrants its use.

- Input Material Quality and Control for AM Processes: This topic was partially addressed in presentations and by the industry panel. In the author's opinion, this should be a near-term focus for standards development, industry, and probably the AMNT. Powder quality specifications, procedures, and control for AM use will likely be critical to part quality, because it directly affects both the process and outcome. Specifications or guidelines for powder handling and re-use will be a critical aspect for quality assurance of AM parts. Experience with nickel superalloys, titanium, and other structural alloys has been almost entirely with all-inert handling, with established guidelines for revert and reuse. Input material controls for AM use did not seem to have the same rigorous attention, except when manufacturers imposed them.

- Input Material Suitability for AM: This topic received surprisingly little attention; the most came from GE during the industry panel. Some alloy selection attributes will be different for AM than for conventional processes, because AM is essentially a controlled welding and re-solidification process, with multiple cycles of melting and re-solidification for most of the material. There has been a lot of AM work using Ti6-4, and a significant amount using INCO718. Both are workhorse alloys and are widely used in many product forms. Neither has been optimized for AM. Both have exhibited defect generation under AM processes and sometimes microstructural anisotropy. CoCr alloy, however, seems to respond well to AM, reportedly with minimal defect generation and minimal anisotropy. Many current alloy selections for AM seem based on commonality of use in other processes and availability in powder or wire form for AM. In the future, input materials will surely evolve and may even be optimized for AM as applications and experiences grow; there is no doubt that the AM alloy universe will expand. Meanwhile, alloy selection may prove critical to ensure high-integrity parts, and it should certainly be possible to classify or rate alloys for suitability for AM. A process to do this, like standard testing for machinability or weldability, would seem useful. This might be linkable to NDE or other quality assurance requirements.

- Consideration of Process Interruptions: This may prove to be a non-issue, but it seems likely that economic pressures will eventually drive acceptance of parts where process interruptions have occurred. This may be attributable to machine causes, aberrations with the part build, operator-induced stoppages, or other causes. Whatever the cause, consideration of how to disposition such parts will likely be an issue as soon as significant volume manufacturing is initiated. This could go on the "checklists" initially, but may need some specific attention in the future.

- Part Criticality Classification Criteria for AM: There are several classifications for part criticality, depending on system and application. In the Air Force, for example, classifications resulting from damage tolerance assessments include "fracture, mission, and durability critical." In the FAA, there are terms for "life limited parts," (from Title 14 Code of Federal Regulations [CFR] Part 33)," primary structural elements (PSE) (from 14 CFR 25), "no safety effect (NSE)," and presumably others. The types of critical parts differ as a function of the system application, but all determine whether special considerations must be applied. In a Day 2 presentation, Dr. Gorelik showed a chart with expected AM target parts illustrated. It showed expected evolution of AM applications over time, from low-risk (NSE parts) to “Sub-Critical” and “High-Value” parts. However, development costs and qualification/certification requirements for AM may actually drive attention to the “high-value” parts initially. It would seem beneficial to identify a standard means to determine part criticality for AM applications and possibly tie that criticality to qualification and certification requirements. This may be especially useful to help address part qualification/certification applications that are eventually proposed by non-OEM entities.

This was a great workshop that I believe met all its objectives. Much came out of it, which has hopefully been summarized in an informative and actionable manner. Hopefully, these additional comments are also regarded as constructive in nature.

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

Co-sponsored by FAA Chief Scientist (M. Gorelik) and

AFRL / ManTech (R. Dutton)

September 1-3, 2015

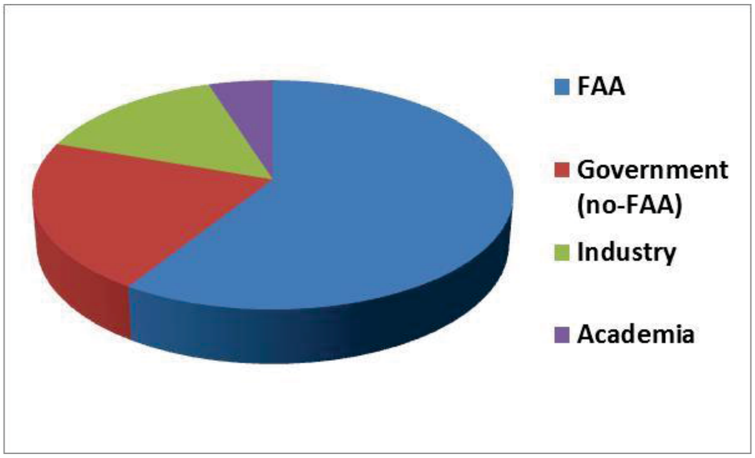
TecEdge Facility, Dayton, OH

Workshop facilitator: Brad Cowles, *Cowles Consulting, LLC*

Workshop Objectives

- **Educating FAA workforce in the area of AM technology**
- **Benchmarking qualification / certification efforts of other agencies, and promoting inter-agency collaboration**
- **Establishing a stronger linkage between the AMNT and regional offices (ACOs, MIDOs)**

Workshop Demographics



FAA CSTA Workshop Attendees (Sept 1-3, 2015)

	Location	Site Attendees	AMNT	Total
1	Burlington	4	2	6
2	Chicago	3		3
3	Atlanta	2		2
4	DC	3	2	5
5	San Antonio	1		1
6	Wichita	1		1
7	Kansas		1	1
8	Renton	3	1	4
9	Phoenix		1	1
10	Los Angeles	3		3
11	Hartford, CT	2		2
12	Ft Worth		1	1
13	New York	1		1
14	Atlantic City	1	1	2
15	Vandalia	2		2
16	Denver	1		1
		27	**9**	**36**

Emerging Technology Considerations

AM ➔
- ❑ New material systems
- ❑ New manufacturing technologies
- ❑ …

"Since its emergence 25 years ago, additive manufacturing has found applications in industries ranging from aerospace to dentistry and orthodontics… and is poised to exceed $3B by 2016 …" (Wohlers 2011).

Motivation

One of the FAA Priority Initiatives: *Risk-Based Decision Making*

Build on safety management principles to proactively address emerging safety risks…"

Agenda Review – Day 1

8:15am	**Introductions (All)**
8:30	Workshop overview and objectives (R. Dutton / AFRL and M. Gorelik / FAA)
9:00	FAA Management Perspective (R. Jennings / FAA HQ)
9:15	AFRL AM Seminar (M. Kinsella, J. Miller / AFRL)
10:30	*Break*
10:45	AFRL AM Seminar – cont. (J. Brausch, M. Kinsella, J. Miller / AFRL)
12:15pm	*Lunch (catered on site)*
1:00	AFRL Research & Future AM (J. Miller / AFRL)
1:45	NIST Perspective on AM (K. Jurrens / NIST)
2:45	Current Capabilities and Process Mapping Methods tied to Qualification (Prof. J. Beuth / CMU)
3:15	*Break*
3:30	Microstructure in AM (Prof. A. Rollett / CMU)
4:00	Mechanical Behavior of Components Fabricated Using AM (Prof. S. Daniewicz / MSU)
4:30	Summary of Day 1 / Discussion (B. Cowles / All)
6:45 - …	Team Dinner – *Texas Roadhouse (Fairborn, OH)*

Agenda Review – Day 2

8:00 am	**Coffee, introductions**
8:15	USAF Senior Leader Perspective (D. Carlson / USAF)
8:30	DARPA OM Overview (M. Maher / DARPA)
9:15	NavAir AM Certification Perspective (L. McMichael / NavAir) – via telecon
9:45	Air Force AM certification Perspective (M. Kinsella / AFRL)
10:15	**Break**
10:30	NASA AM Certification Perspective and AM R&D (K. Morgan / MSFC and K. Taminger / LaRC)
11:15	FAA AM Certification Perspective and Go-forward Plans (J. Kabbara, M. Gorelik / FAA)
12:00 pm	**Lunch (catered on site)**
12:30	Industry Perspective on AM - Panel session (moderated by B. Cowles and M. Gorelik)

- *Bell Helicopter (T. Chiang)*
- *Boeing (M. Crill)*
- *GE Aviation (M. Shaw)*
- *GKN Aerospace (B. Thompson)*
- *Honeywell Aerospace (B. Hann)*
- *Lockheed Martin (C. Brice)*
- *P&W (W. Brindley)*

Agenda Review – Day 2 (cont.)

3:00 **Break**

3:15pm **Overview of AM Standards Development**

- **ASTM F42 and ASME Y14.46 – K. Jurrens, NIST (30 min)**
- **SAE AM committee – D. Abbott, GEA (15 min)**
- **MMPDS – M. Freisthler, FAA (30 min)**
- **AWS standards – J. Calcaterra, AFRL (15 min)**

4:45 **Meeting wrap-up / discussion**

5:00 ***Adjourn (for general audience)***

Agenda Review – Day 3

(government only)

8:30 **Summary of workshop observation and go-forward plans**

(M. Gorelik / R. Dutton / B. Cowles)

9:30 **FAA round table (AMNT + site representatives)**

Government attendance based on interest

- **Feedback from the sites**
- **Additional discussion re. AMNT work plans, roadmap outline etc.**
- **Engagement with external organizations, training requests etc.**

11:30 ***Adjourn***

Benchmarking Government Efforts in AM

- **Most major US government agencies have been involved in AM roadmaps development and R&D *over the past 5-10 years***
  - **NSF, ONR, DARPA, NIST, NIH, USAF, NavAir, NASA, FDA etc.**
- **Examples of funded activities (DoD) – *partial list***
  - **Metallic AM Inspection Benchmarking for AF**
  - **Manufacturing Variability Quantification for Aerospace**
  - **DARPA Open Manufacturing**
  - **Metallic AM for Liquid Rocket Engines**
  - **AM of Ceramic Cores for Airfoils**
  - **Direct Part Mfg of HT Thermoplastic Composites**
  - **Sustainment Opportunity Assessment & Risk-based Decision Tree**

> $50M R&D Investment

Part of FAA Strategy – Leveraging Investments and Expertise of Other Government Agencies

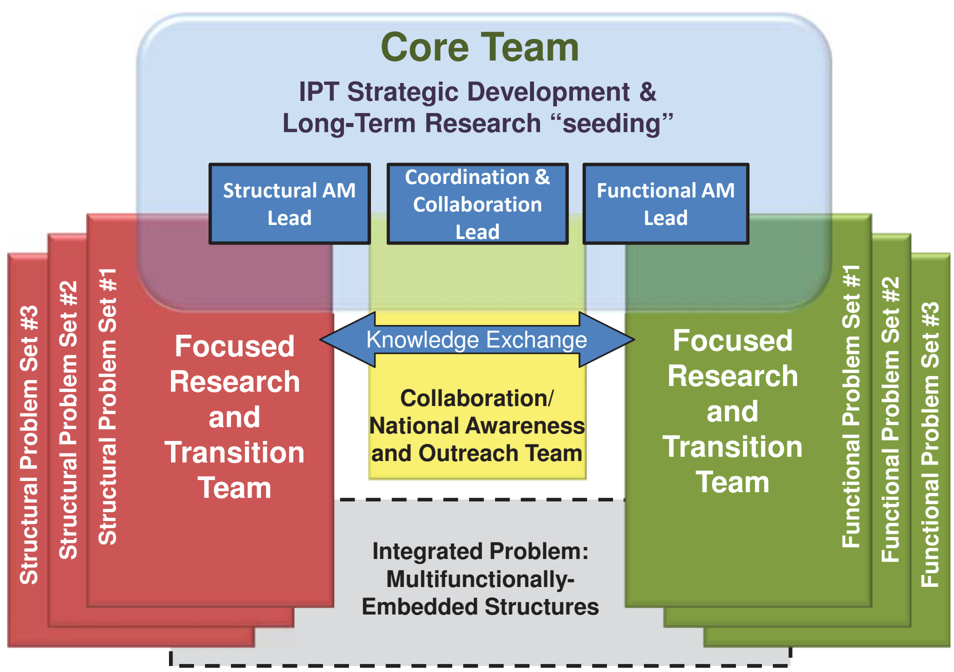
Additive Manufacturing

May 2015

Mary E. Kinsella, PhD
Materials and Manufacturing Directorate
Air Force Research Laboratory

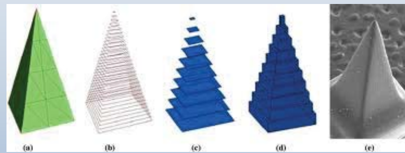
Integrity ✭ Service ✭ Excellence

Additive Manufacturing IPT Concept



Additive Manufacturing Overview

Build a part by *adding* material layer by layer from a CAD file…



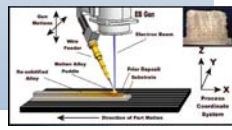
emeraldinsight.com

…vs. *subtracting* material from a larger form, e.g., machining.

ctemag.com

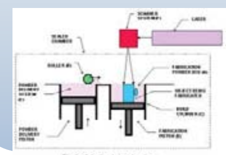
Encompasses many process types…

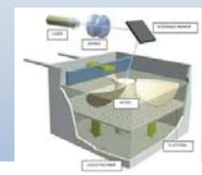
- Powder Bed Fusion
- Directed Energy Deposition
- Material Extrusion
- Vat Photopolymerization
- Material Jetting
- Binder Jetting
- Sheet Lamination



…using various materials.

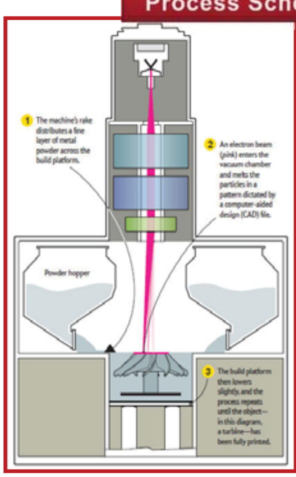
- Metals
- Polymers
- Composites
- Ceramics





Powder Bed Fusion

Process Schematic



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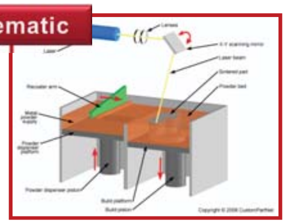
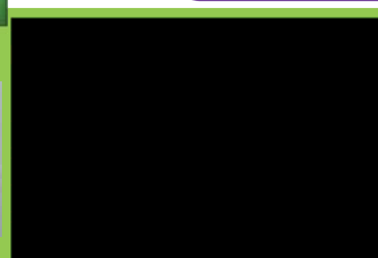


Equipment

Work in Process

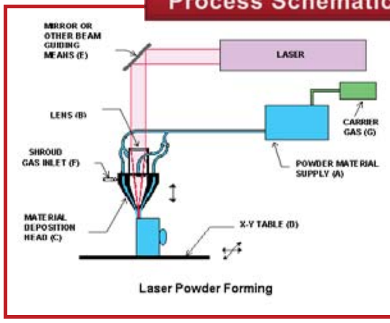


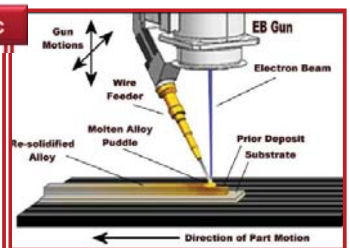
An additive manufacturing process in which thermal energy selectively fuses regions of a powder bed

Finished Parts

Directed Energy Deposition

Process Schematic





Equipment

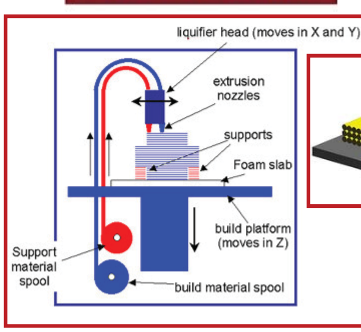
An additive manufacturing process in which focused thermal energy is used to fuse materials by melting as they are being deposited

Work in Process

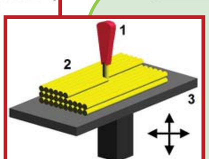
Finished Parts

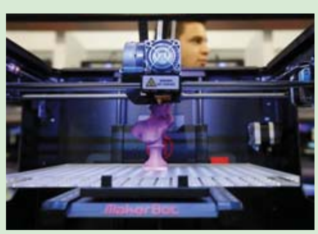
Material Extrusion

Process Schematic



Work in Process

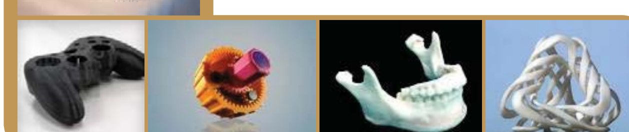




Equipment

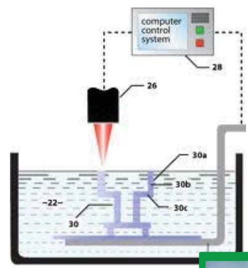
An additive manufacturing process in which material is selectively dispensed through a nozzle

Finished Parts



Vat Photopolymerization

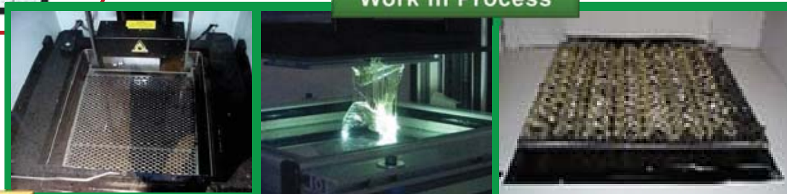
Process Schematic



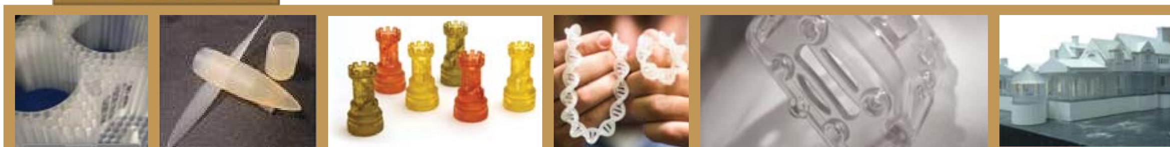
An additive manufacturing process in which liquid photopolymer is selectively cured by light-activated polymerization

Equipment

Work in Process



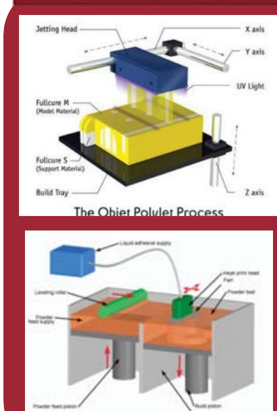
Finished Parts



Material or Binder Jetting

An additive manufacturing process in which droplets of material are selectively deposited, or bonding agent is deposited onto powder

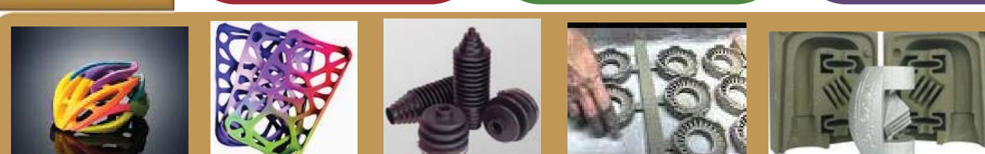
Process Schematic



Work in Process

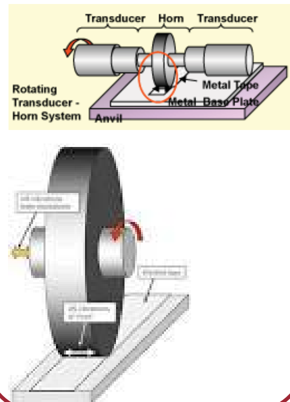
Equipment

Finished Parts

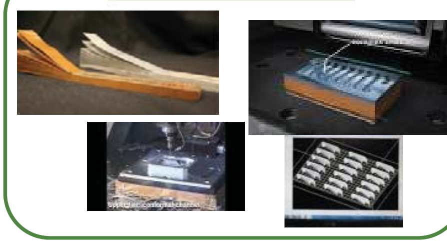


Sheet Lamination

Process Schematic



Work in Process

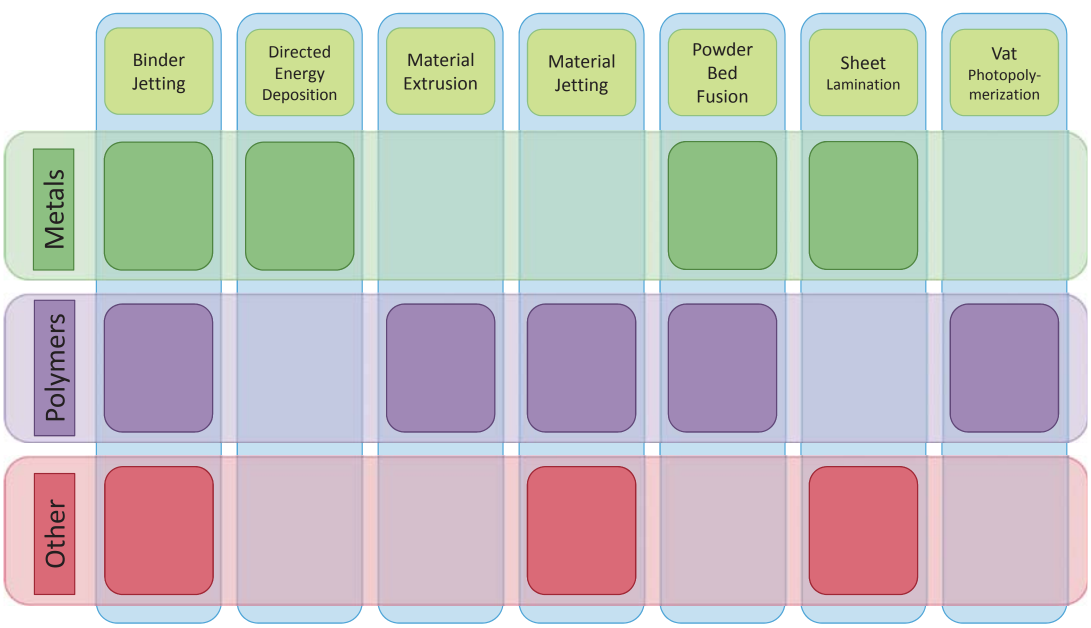


An additive manufacturing process in which sheets of material are bonded to form an object

Equipment

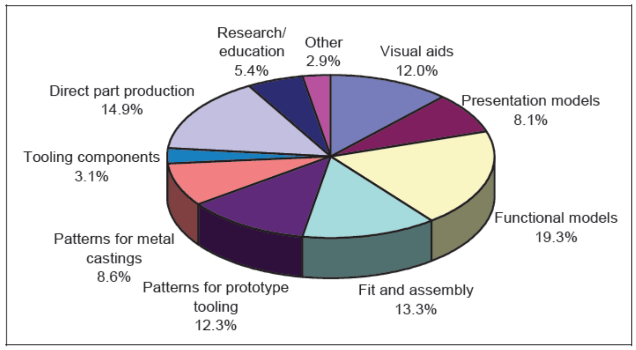
Finished Parts

AM Process and Material Types



Uses for AM: Research, Development, Manufacturing

- **Prototypes**
- **Design Iteration**
- **Form-Fit Models**
  - **Fit checks**
  - **Aesthetics**
- **Tooling, e.g.,**
  - **Casting Cores**
  - **Composite Layup Tools**
  - **Fixtures and Templates**
  - **Masks**
- **Education & Training Aids**
- **End Use Parts**



Source: Wohlers Associates, Inc.

Bioprinted kidney vascular tree prototype, courtesy of York Technical College

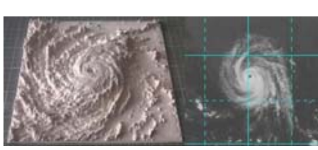
Packaging insert (left) molded using a porous tool (right) made on an FDM machine, courtesy of Stratasys

Heat exchanger, courtesy of Within Technologies

Exploration of AM Applications by Sector

- Architecture and Construction
  - Architectural models, construction materials
- Arts and Entertainment
  - Unique, complex geometries; custom figures and toys
- Aerospace
  - Satellites, airframes, engine components, conformal/ integrated electronics
- Automotive
  - Concepts, custom parts for limited production, spares
- Medical
  - Implants, surgical models, tools, bio materials for tissues, organs
- Maker community

Maker Faire WHITE HOUSE June 18 2014

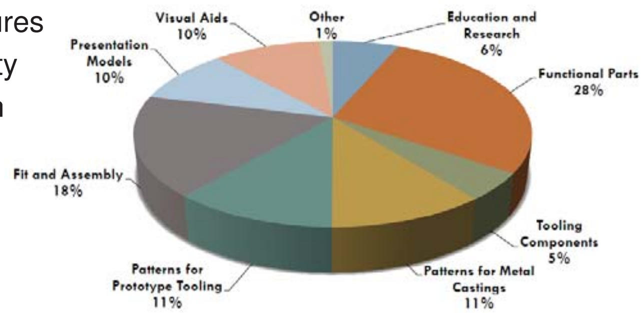


Aerospace Applications of AM

- Aerospace Community
  - Practically all sectors are actively evaluating AM:
    structure, propulsion, space, munitions, electronics, human system
  - Depending on application, a variety of implementation paths are possible:
    tooling, prototypes, design iteration, production parts
  - Some aspect of **Material, Process** and **Component Qualification** is required for nearly every implementation path

- AM Aerospace Opportunities
  - Functionally-embedded structures
  - Expanded geometric complexity
  - Required component re-design
  - Low production quantities
  - Mass customization
  - Non-critical parts

Source: Wohlers Associates



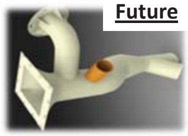
AF Opportunities for Structural AM

Expanded Component Geometries

Multiple component families geometries are constrained by conventional manufacturing capabilities, including ducting, fuel nozzles, heat exchangers and turbine airfoils

Today

Future

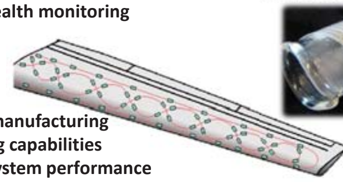


Potential for
- Part Consolidation
- Lead-Time Improvements
- Performance Benefits

Functionally-Embedded Structures

Embedding devices within structure could enable improved communication, real-time structural health monitoring, …

- **Reliable, integrated electronics printed directly on structure**
- **Conformal antennas adapted into load-bearing structure**
- **Distributed electronics for flight-control feedback and structural health monitoring**



Potential for
- Simplified manufacturing
- New sensing capabilities
- Improved system performance

Unintended Spares and Obsolescence

Re-manufacture of components with obsolete manufacturing routes are expensive and have long lead times due to tooling requirements associated with conventional processing approaches

Current Issues:
- Long Tooling Lead Times
- Low Production Volumes
- Material Substitution Re-certification

Potential for
- Improved Lead Times
- Reduced Cost (LRP)

Component Repair

Repair rather than replacement of end-of-life components could drastically reduce the AF sustainment burden but viable repair technologies are difficult to tailor to aerospace requirements

Current Issues:
- Current components NOT designed FOR repair
- Unvalidated repair processes and inspection requirements

Potential for
- Repair-able components
- Reduced Sustainment Burden

How could AM Electronics Impact the AF?

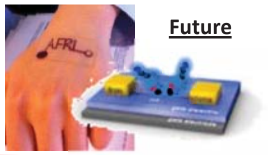
Human System and Cognition

Human Performance limits capability in MANY Military Missions
….and New Technologies are Needed to Sense, Assess and Augment the "Man-in-the-Loop"

- Information Overload
- Missed Intelligence
- Threat/Danger Missed

Today

Future



Embedded Electronics for ISR and EW

Information and tracking in contested environments (A2/AD) is foundational to decision making and force projection

- **Communication (conformal apertures)**
- **Distributed electronics for feedback and structural health monitoring**
- **Reconfigurable Electronics**

Integrated Power for Autonomous Ops

Energy limits operational capabilities and mission impact for large time and distances scenarios

Issues:
- **Cost & Weight**
- **Scale-up**
- **Durability**

Integrated Power harvesting, storage, and management

Expected 1.5X – 3X increase in flight endurance.

Survivable Electronics

Precision effects with smaller, low profile munitions pressing requirement for current and future platform effectiveness

- **Robust electronics in extreme environments (shock, vibration, thermal)**

Benefits and Challenges

AF Benefits:
- Reduced lead time and cost for small production runs
  - → Aircraft Availability & Sustainment Affordability
- Mass customization and enabling geometric complexity
  - → Adaptive Warfighter & Energy Efficiency
- Weight reduction via part consolidation/material substitution
  - → Reduced Sustainment Burden & Energy Efficiency

Technical Challenges:
- Unquantified material quality with undefined **inspection protocols** to meet aerospace structural requirements
- Highly variable **material properties** and and lack of statistical databases for design
- Lack of standardized **process controls** typically required for structural applications
- Inadequate cost models for representation of **post-processing requirements**
  - Inspection, Machining, and Heat Treatment

Why AM Implementation Is a Challenge

- **Structures Bulletin: Substitution with AM**
  - NOT RECOMMENDED without significant testing and AFRL/RX support
- **Considerations for Implementation of AM**
  - Demonstrated Process Controls
  - Nondestructive Evaluation & Quality Assurance
  - Post-Deposit Processing & Residual Stress Management
  - Statistically-Based Mechanical Property Database
- **Challenge: How to statistically ensure material integrity for design with**
  - continually-changing, local processing environment with changes in geometry and process parameters (similar to welding)
  - lack of *constrained* process controls
  - stochastic formation of difficult-to-inspect weld-type defects
  - post-deposit distortion and residual stress
  - undefined post-processing requirements, lack of POD for NDI

Staged Implementation Potential of AM

An AFRL Perspective

Now…
- early design prototypes
- process implements (fixtures, tooling)
- polymeric applications (ducting, brackets)

Soon…
- niche AM applications
- reduced-life or 'safe-life' components
- 'attritable' applications (RPVs, munitions)

Later…
- full-life, non-critical structural applications
- embedded electronics/sensors

Far-Term…
- fracture-critical hardware …?
- hybrids and graded materials …?

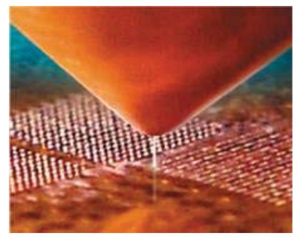
How to Shortcut the Timeline
- **Design for AM**
- **Quantify Risk**
- **Quantify Mfg Variability**
- **Develop Cost Models**

What are "niche AM apps"?
- **Component Redesign**
- **Complex Geometry**
- **Non-critical Hardware**
- **Small Lot Production**
- **Short Life Applications**

AFRL Additive Manufacturing Strategy

- Develop Risk-Quantification Tool for Substitution and Implementation of AM technologies in AF Systems
- Conduct Targeted Research to Inform the Qualification of Additive Materials and Processes
  - Process monitoring and sensing
  - NDE and material characterization
  - AM-tailored material development
  - Component demonstration

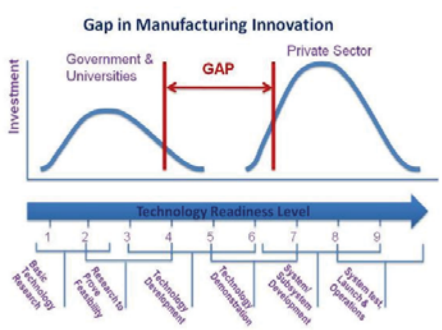
- Advance AM Capabilities via Modeling & Simulation
  - Process simulation for design & control
  - Verification & Validation for qualification
  - Process-structure-property relationships
  - Develop digital thread for AM components



America Makes
National Additive Manufacturing Innovation Institute

- *A Defense-wide Manufacturing S&T team-led, Multi-agency collaboration between industry, government and universities*
- *Public-private partnership*

- Shared facilities open to industry
  - Especially attractive to small businesses
- Enabling technology transition and commercialization
- Addressing Technology Readiness Level (TRL) / Manufacturing Readiness Level (MRL) 4-7
  - Bridge the gap in Manufacturing Innovation
- Educational outreach and workforce development



A Model for Subsequent Manufacturing Innovation Institutes

The Air Force Qualification Pathway and its Challenges for AM

Integrity ★ Service ★ Excellence

Additive Manufacturing & Repair Panel
2015 CTMA Partners Meeting
27 May 2015

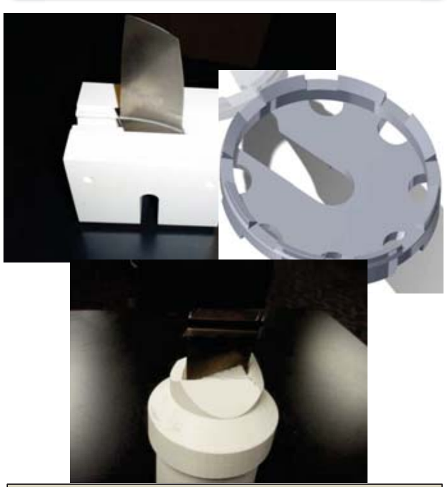
Mary E. Kinsella, PhD.
AFRL/RXMS
Air Force Research Laboratory

U.S. AIR FORCE

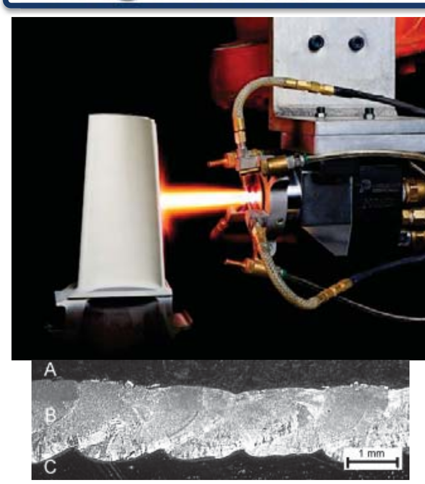
AM Value to AFSC Manufacturing

AF SUSTAINMENT CENTER

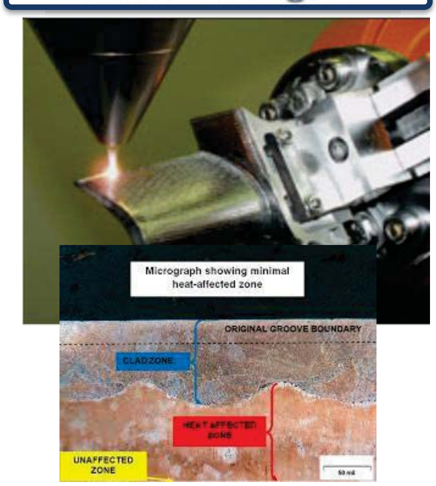
Immediate value	Long-term outlook	Game-changers



- Hybrid tooling /fixtures integrated with metal sub-components
- Rapid prototyping for form, fit, and function
- Electrically Conductive & ESD Tooling Applications



- Manufacture of metal fixtures, masks, and jigs for repair process.
- Manufacture of DMSMS components.
- Manufacture of non-rotating and structural aircraft components
- Electronics and Conformal Antennas and Sensors



- Effective dimensional metallic Restoration of Propulsion Items
- Better microstructural control
- Manufacture of parts On-Demand
- Near Net Form Castings & Extrusions - POD

AM as A Ready-for-Use Technology

Coating of Blades and Engine Components

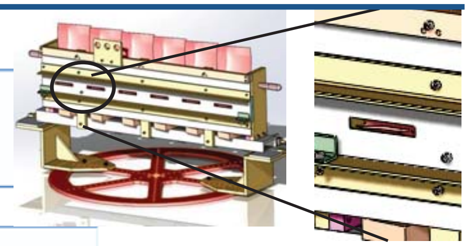
- Leading edge dimensional restoration, complex repairs, hard-facing and corrosion/heat resistant coatings

Specialized Masking

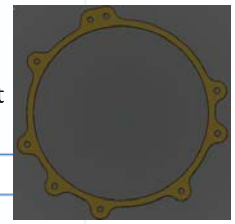
- Thermal spray/painting requires intricate masking techniques – mask cannot interfere with spray path
- Shot peening masking is also required which permits shot to be applied at precise angles and small areas.

Complex tooling fixtures take time to manufacture

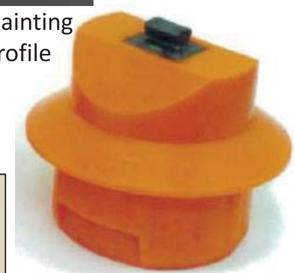
- Plasma/HVOF spray fixtures often have long lead times for manufacture. Special tooling is hard to machine!
- Print On-Demand Tooling will reduce production lead times



Plasma spray Shadow mask



Gearbox painting Mask profile



Shot peening Mask fixture

The big picture: Improve existing processes by implementing hard masking.

How do we get from drawing/concept to manufactured component in the least amount of time?

A fundamental change in how fixtures are designed and how we do repairs (repair approval) must precede this added technology!

Process Qualification Requirements

Qualification of processes and certification of components used on AF systems requires that components meet or exceed the following criteria, regardless of the manufacturing process used:

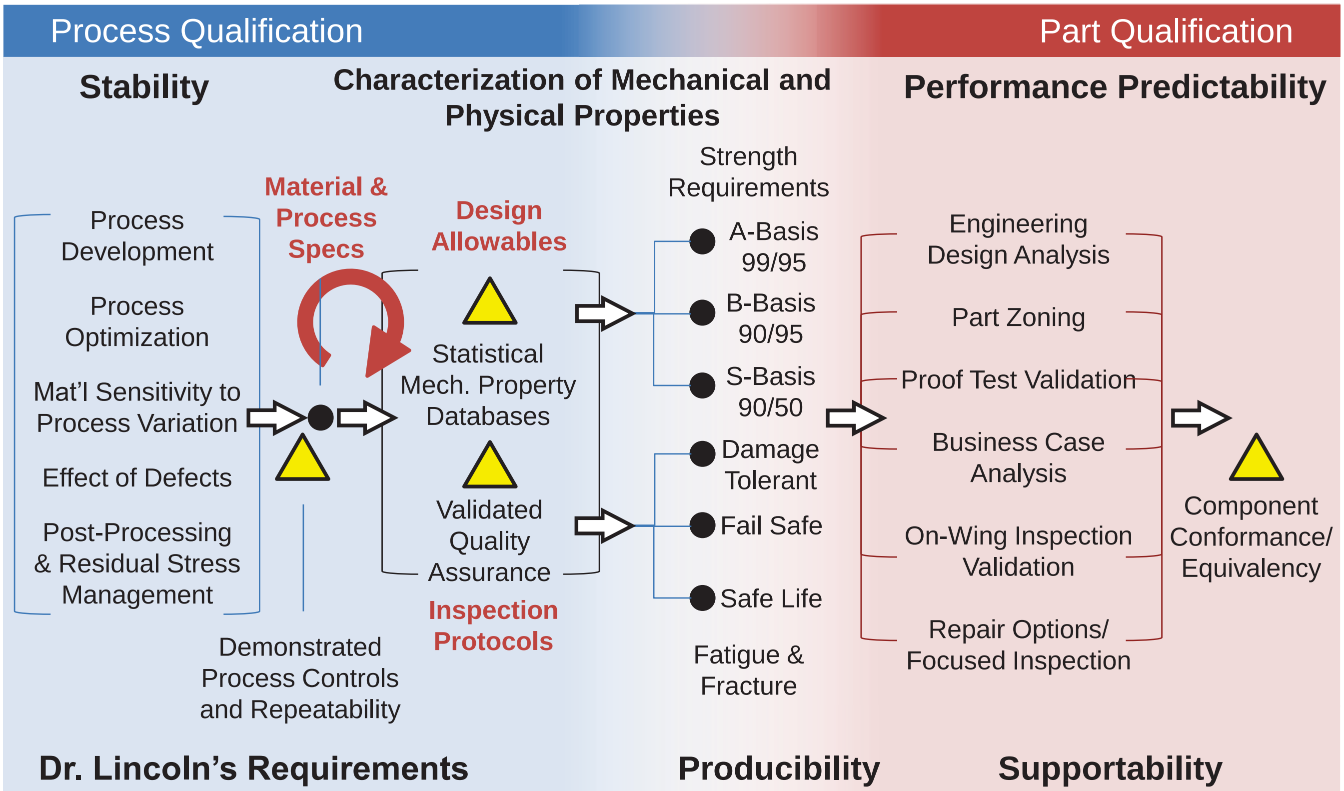
- Airframe or engine specifications
- AF system requirements and structural integrity policies/procedures
- Drawing compliance
- Conformance to material specifications
- Justifiable and attractive business case

All manufacturing processes (including AM) also must demonstrate:

- Stability – no suitable public specs exist, very few OEM-based, mostly internal
- Producibility – most AM vendors/OEMs have not demonstrated reproducibility
- Characterized Mechanical and Physical Properties – limited non-proprietary data
- Predictability of Performance – insufficient component-level testing
- Supportability – undefined in-field inspection and/or repair processes

Challenges for qualifying AM processes and certifying AM components arise due to a lack of reproducibility and a lack of a governing process specification.

Qualification Pathway: New Materials and Processes



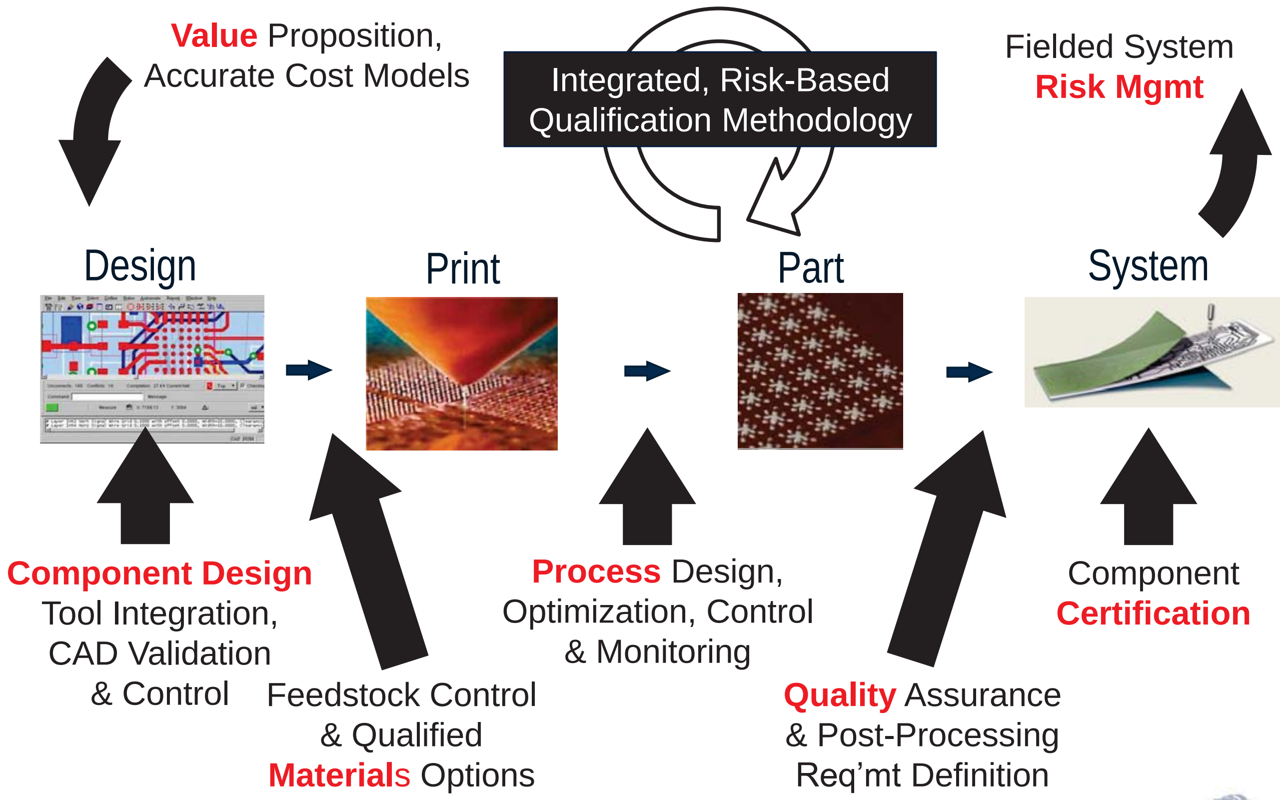
Why AM Implementation Is a Challenge

- **Structures Bulletin: Substitution with AM**
  - **NOT RECOMMENDED without significant testing and AFRL/RX support**
  - **Bulletin to be appended with position paper on critical AM considerations**
- **Considerations for Implementation of AM**
  - **Demonstrated Process Controls**
  - **Nondestructive Evaluation & Quality Assurance**
  - **Post-Deposit Processing & Residual Stress Management**
  - **Statistically-Based Mechanical Property Database**

How to statistically ensure material integrity for design with

1. **continually-changing, local processing environment with changes in geometry and process parameters (similar to welding)**
2. **lack of *constrained* process controls**
3. **stochastic formation of difficult-to-inspect weld-type defects**
4. **post-deposit distortion and residual stress**
5. **undefined post-processing requirements, lack of POD for NDI**

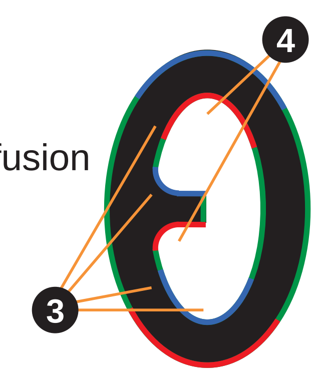
Additive Manufacturing: Challenges to AF Implementation

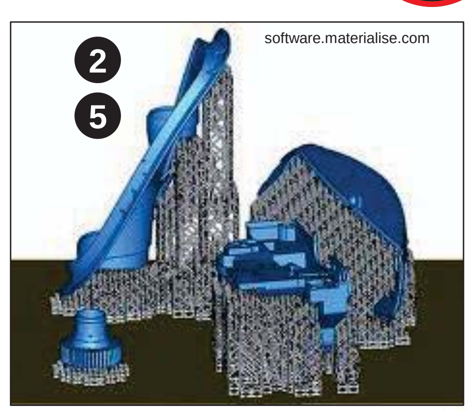


AM Challenges to AF Implementation: *Design*

Mechanical Design Approach

- Process regularly produces what would be considered defects in conventional processes: porosity and lack of fusion
- Anisotropic & variable mechanical properties
- Design is not "unconstrained by manufacturing"
- There are "AM design rules" that are different than conventional manufacturing design rules
- Undefined AM Limitations
  1. Min/Max Wall Thicknesses
  2. Complexity
  3. Wall Pitch, Radii
  4. "Overhangs", "Ceilings"
  5. Support Structures

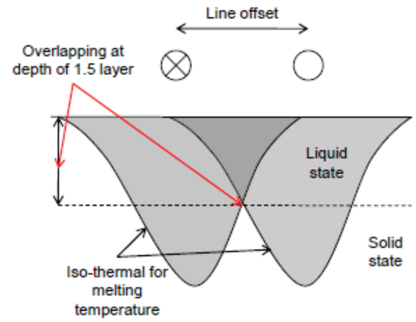


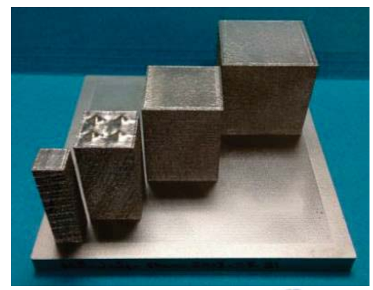


AM Challenges to AF Implementation: *Print*

AM Processing

- Range of process parameters
  - Current, speed, hatch spacing
  - Laser/beam focus and offset
  - Contour, passes, turning point
  - Empirical corrections, scaling factors
  - Surface temperature, environment
  - Qualitative calibration procedures
    - recalibration frequency, inconsistent maintenance procedures
  - Powder recyclability procedures
- Pseudo-Empirical Black Boxes to control process
- Manufacturing variability is unknown & a major consideration:
  - two parts, same fixed process, different structure

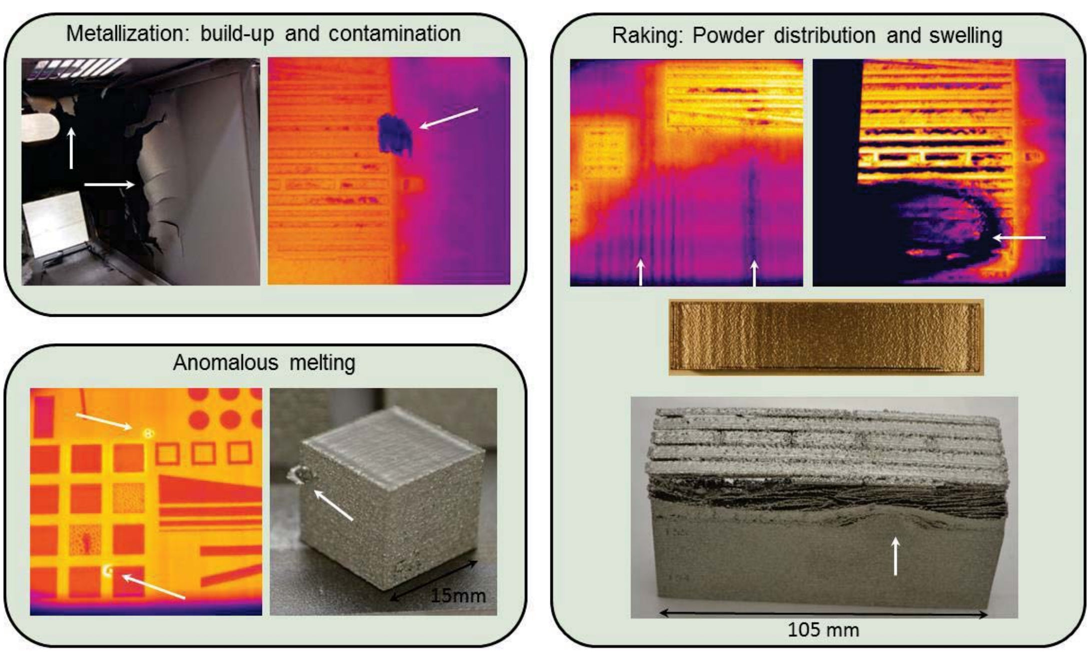




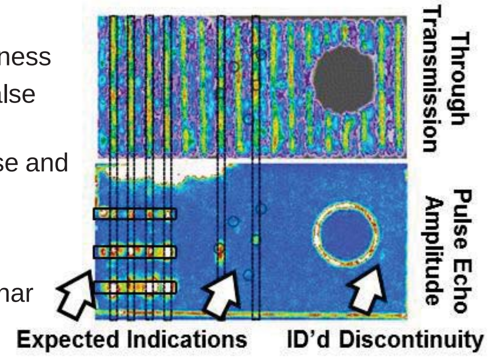
AM Challenges to AF Implementation: *Print*

AM Powder Bed Fusion

- Examples of process-induced defects



AM Challenges to AF Implementation: *Part Inspection*



Surface Finish

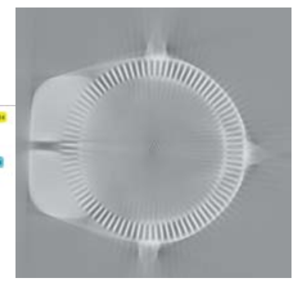
- As-deposited and porous surface finish reduces inspection effectiveness
  - Fluorescent Penetrant: High background fluorescence and false positives
  - Ultrasonics: Poor coupling of sound into substrate from coarse and non-planar surfaces.

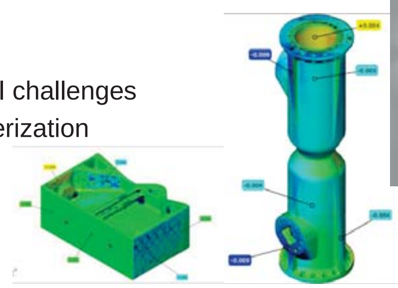
Micro/Macro Structure

- EBAM Ti-6Al-4V Beta Anneal heat treat results in coarse and columnar microstructures.
  - Limits effective inspection depth to < 1 inch to detect 3/64" FBH
  - Result: process layup & post-deposit sequence re-design required

Complex Geometries

- Limits inspectability of 100% part volume
- Computed Tomography of Powder Bed, Ni and Ti
  - X-ray scattering challenges – thick vs. thin wall challenges
  - Need technique qualification and flaw characterization tools/algorithms





High Propensity for Flaw Generation

- Distributed/linear porosity and incomplete fusion

AM Challenges to AF Implementation: *System*

Certification

- Proof testing
  - Viable means to assure material quality with sufficient design analysis
  - Only for suitable applications/components
- Component performance equivalency to material data
  - Generally, lack activity in this area
  - Very thin walls & complex geometries limit ability to excise test specimens
- How to certify component
  - Certify by similarity? Similar to what?
  - Certify by analysis? With what tools?
  - Sub-scale testing? How to justify?
  - Full scale test? Expensive.

In-Field Inspections

- unknown inspection tools
- post-processing affects inspectability
- increased inspection burden?

F-15 Pylon Rib Insertion Success Story

Issue: -7075 Al Forging, Pylon Rib, Corrosion Fatigue Cracking
-Decision to move to Ti 6-4 forging already made
Long lead time for Ti forging ~1 year

Solution: -Replace with Ti 6Al-4V Additive
-To meet urgent need for aircraft in depot
- Quality issues lessened because of high margin for Ti in this application.

RX Role: -Provided Technical Leadership to Acquisition
-Executed Technology Demonstration Project
-Worked Attachment Issues (bushings, fasteners,etc...)

Results: -Additive Substitution Certified for use in Structural Application!
-Parts Manufactured and Qualified although 3-5X over forging
-Prior to Insertion on AC, Aluminum Industry Provided Forgings
-Ti forging cost reduced due to competition

AFRL Additive Manufacturing Strategy

- Develop Risk-Quantification Tool for Substitution and Implementation of AM technologies in AF Systems
- Conduct Targeted Research to Inform the Qualification of Additive Materials and Processes
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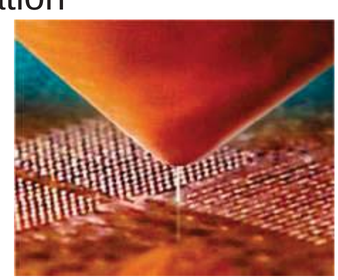
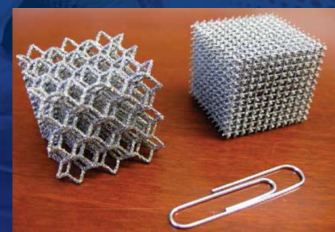


NIST Measurement Science for Additive Manufacturing



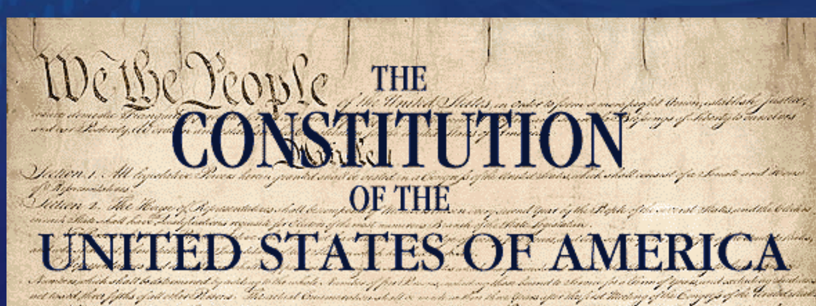
Kevin Jurrens
Deputy Chief, Intelligent Systems Division
Engineering Laboratory
National Institute of Standards and Technology
U.S. Department of Commerce

NIST
National Institute of Standards and Technology
U.S. Department of Commerce

The History of Standards in the U.S.

"Uniformity in the currency, weights, and measures of the United States is an object of great importance, and will, I am persuaded, be duly attended to."

George Washington, State of the Union Address, 1790



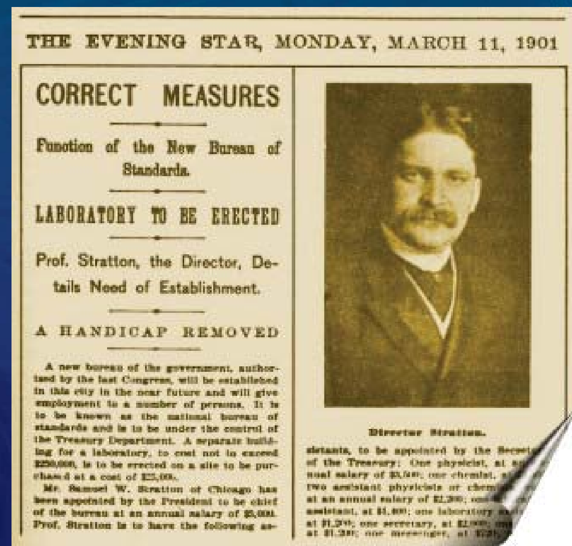
Article I, Section 8: "The Congress shall have the power to…*fix the standard of weights and measures"*

Founding Charge of the National Bureau of Standards (1900)

"It is therefore the unanimous opinion of your committee that no more essential aid could be given to

- manufacturing
- commerce
- the makers of scientific apparatus
- the scientific work of Government
- schools, colleges, and universities

than by the establishment of the institution proposed in this bill."



THE EVENING STAR, MONDAY, MARCH 11, 1901

CORRECT MEASURES

Function of the New Bureau of Standards.

LABORATORY TO BE ERECTED

Prof. Stratton, the Director, Details Need of Establishment.

A HANDICAP REMOVED

A new bureau of the government, authorized by the last Congress, will be established in this city in the near future and will give employment to a number of persons. It is to be known as the national bureau of standards and is to be under the control of the Treasury Department. A separate building for a laboratory, to cost not to exceed $250,000, is to be erected on a site to be purchased at a cost of $25,000.

Mr. Samuel W. Stratton of Chicago has been appointed by the President to be chief of the bureau at an annual salary of $5,000. Prof. Stratton is to have the following as-

Director Stratton.

sistants, to be appointed by the Secre[illegible] of the Treasury: One physicist, at [illegible] nual salary of [illegible]; one chemist, [illegible] two assistant physicists or chem[illegible] at an annual salary of $2,200; [illegible] assistant, at $1,800; one laboratory [illegible] at $1,200; one secretary, at [illegible] at $1,200; one messenger, at [illegible]

House Committee on Coinage, Weights and Measures, May 3, 1900, on the establishment of the National Bureau of Standards (now NIST)

NIST's Mission

- To promote U.S. innovation and industrial competitiveness by advancing **measurement science, standards**, and technology in ways that enhance economic security and improve our quality of life

engineering laboratory

Unique Role of NIST Research Laboratories

- Emphasis on infrastructural metrology and non-proprietary, standardized metrology methods that address a broad class of measurement challenges
- Emphasis on rigorous and generic procedures to characterize measurement uncertainty that comply with international standards
- Long-term commitment, expertise, and neutrality essential for harmonized and unbiased national and international standards
- Leverage NIST core competences in measurement science, rigorous traceability, and development and use of standards -- as well as specific expertise in measurements and standards for manufacturing systems, processes, and equipment

➢ **Measurements and Standards**

Primary Outputs of NIST Research Laboratories

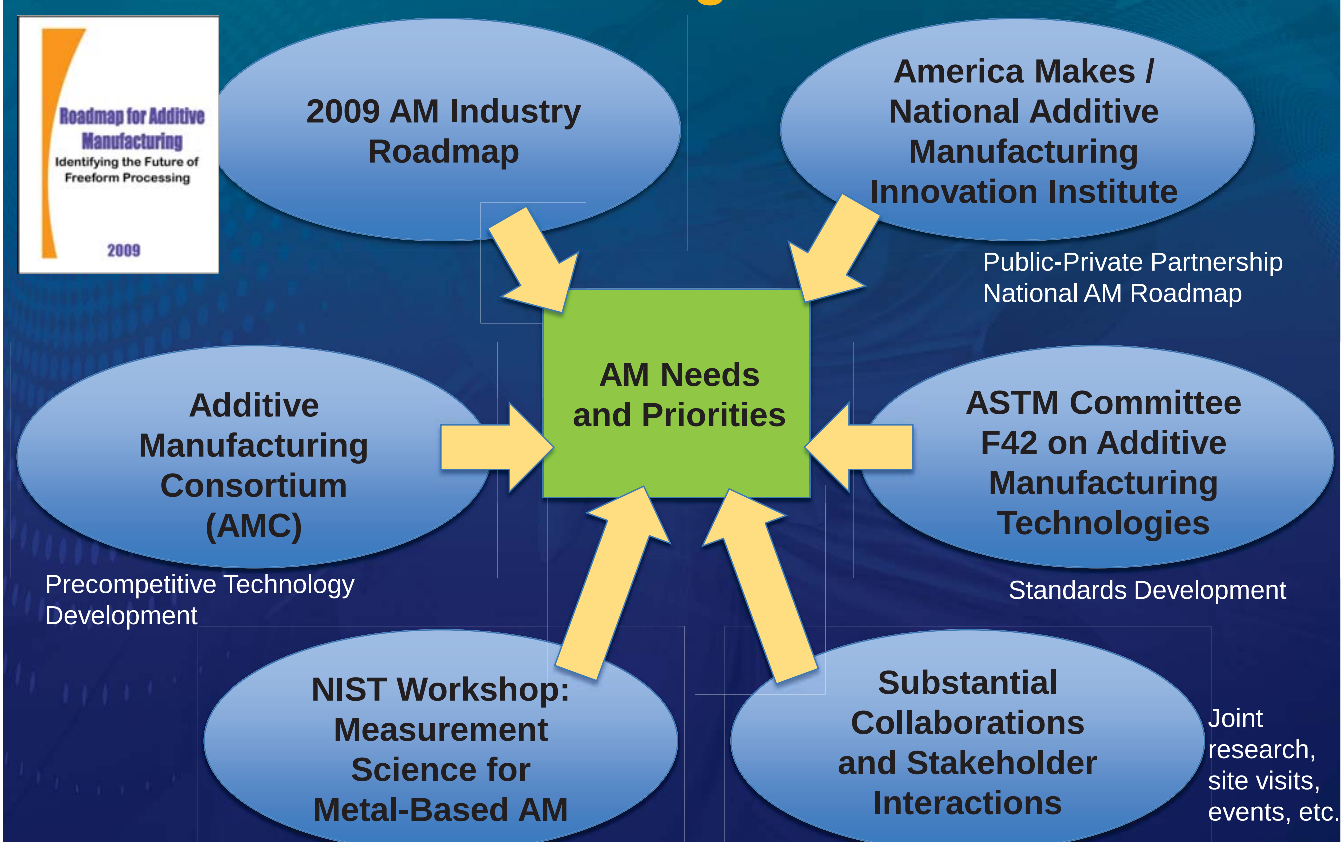
- Measurement methods
- Performance test methods and metrics
- Documentary standards
- Standard reference data
- Standard reference materials
- Calibration services
- Technology transfer: technical publications, industry workshops, collaborations

Why Focus on Additive Manufacturing?

- Technology advances, events, and media visibility have generated much emphasis on AM, including attention at the highest levels of corporate management and the federal government
- Much synergy and momentum – the AM industry is poised for growth, innovations, and new products
- Examples:
  - Publicity in mainstream media (e.g., 3D Printing, "Maker Movement")
  - AM industry roadmaps
  - AM industry consortiums and collaborations
  - America Makes: National Additive Manufacturing Innovation Institute
  - AM standards: ASTM, ISO, ASME, SAE/AMS, AWS, others
  - Federal emphasis on manufacturing

Interest and Opportunities in Additive Manufacturing Continue to Grow

Additive Manufacturing Needs and Priorities



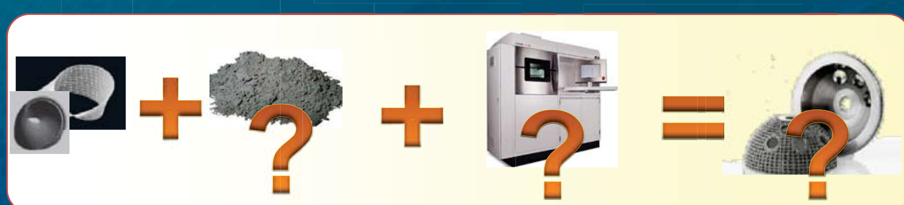
Needs, Priorities, and Action Plans (Dec. 2012)
http://events.energetics.com/NIST-AdditiveMfgWorkshop

engineering laboratory

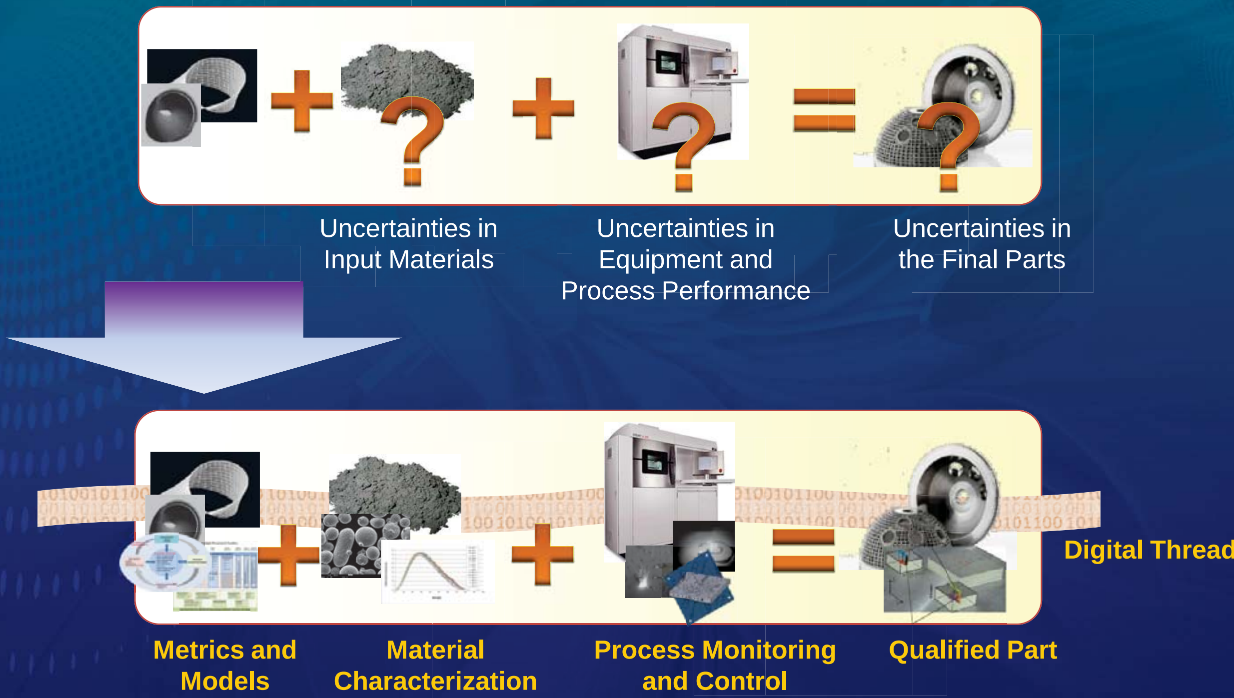
Barriers that Prevent Broad Adoption of Metals-Based Additive Manufacturing

- Limited material types and unknown / non-uniform properties
- Lack of process repeatability and inconsistent system performance
- Consensus protocols and test data for qualification and certification do not exist
- Insufficient part accuracy without significant post-processing
- Insufficient surface finish (e.g., for contoured surfaces)
- Fabrication speed too slow / costs too expensive
- Build volumes / part size too small
- Current AM data formats define approximated geometry
- Many needs for AM standards (materials, process, machine, quality)
- Need for improved non-destructive evaluation methods for complex defects and part geometry
- Requirements for post-processing (e.g., heat treatment, surface treatment, support removal, finish machining)
- Lack of AM-specific design tools / design guidelines

Uncertainties in Additive Manufacturing



Uncertainties in Additive Manufacturing



Measurement Science and Standards
Drive Innovation and Reduce Risk of Adoption

Measurement Science for Additive Manufacturing (MSAM)

Four research thrusts:

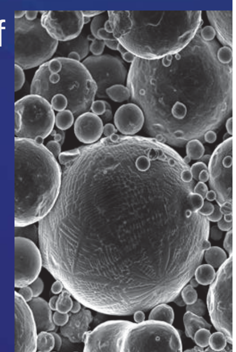
- Characterization of Additive Manufacturing Materials
- Real-Time Control of Additive Manufacturing Processes
- Qualification of Additive Manufacturing Materials, Processes, & Parts
- Additive Manufacturing Systems Integration

Program focuses on metals-based AM

One of Four Programs in the NIST Engineering Laboratory Advancing Essential Measurement Science and Standards for Smart Manufacturing

Characterization of AM Materials

- Methods to characterize powder and finished part materials
  - Powder properties used in modeling
    - Dimensional – particle size, size distribution, morphology
    - Mechanical – friction, flowability/spreadability and their variation as function of dimensional properties
    - Thermal – conduction, diffusion, reflectance, latent heat and their variation as function of dimensional properties
  - Finished part material properties
    - Mechanical – tensile, fatigue as function of direction
    - Microstructure – phases, grain structure, distribution of precipitates and voids



- Correlations between powder characteristics and part material
- Correlations between process parameters and microstructure
- Materials database
- Round robin studies (to populate material database)

Powder Characterization

Measurement methods

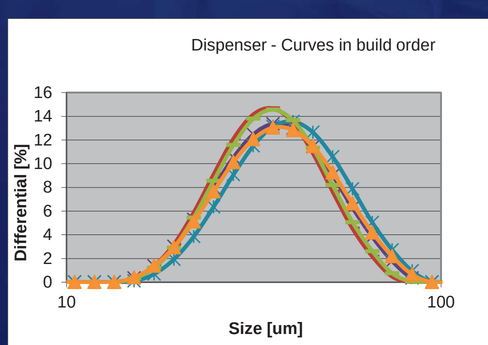
- SEM (size, morphology),
- Quantitative X-Ray Diffraction (chemical composition),
- Laser Diffraction (size distribution), X-Ray Computed Tomography (morphology),
- X-Ray Photoelectron Spectroscopy (elemental chemical states)

Powder bed density measurements

Recent ASTM standards

- ASTM F3049-14 Standard Guide for Characterizing Properties of Metal Powders Used for Additive Manufacturing Processes
- ASTM F3122-14 Standard Guide for Evaluating Mechanical Properties of Metal Materials Made via Additive Manufacturing Processes

Variability of nominally identical powder, effects of powder reuse / recycling

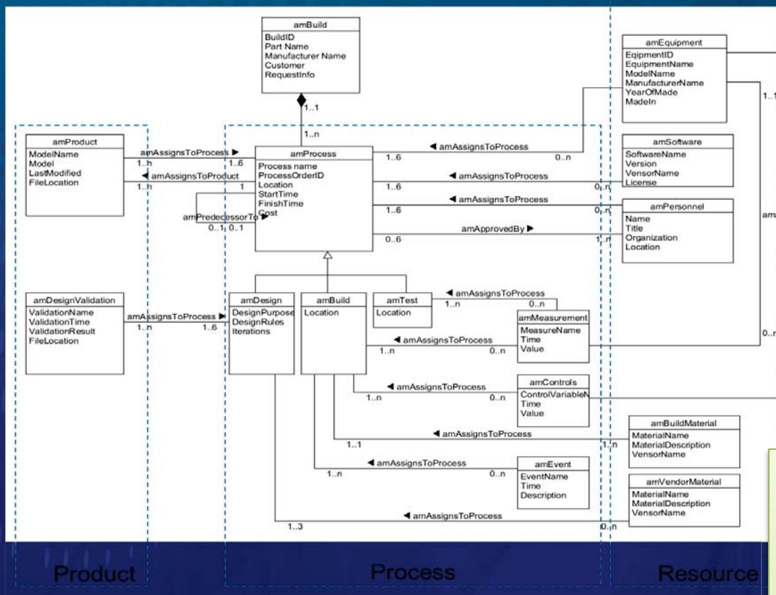


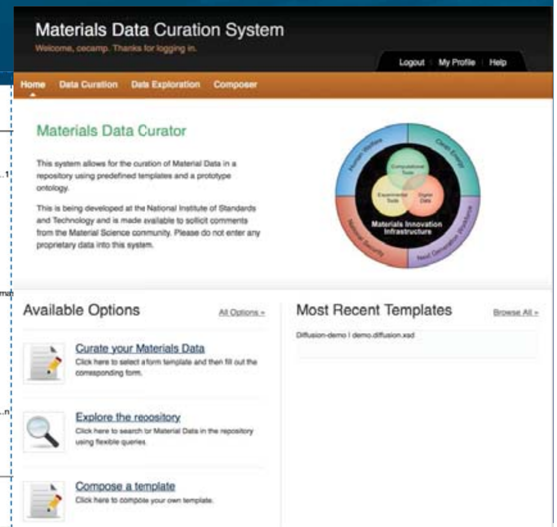
Powder flowability measurements

Test03_Crop.mp4

AM Material Pilot Database

Leveraging Material Genome Initiative tools and America Makes Data Working Group efforts





- Written in python Django
- Backed by MongoDB
- SPARQL Query interface
- XML-based Schema
- Ability to store templates
- Schema management tools
- REST API interface
- Features in progress: Schema composer and Links to Dspace repository

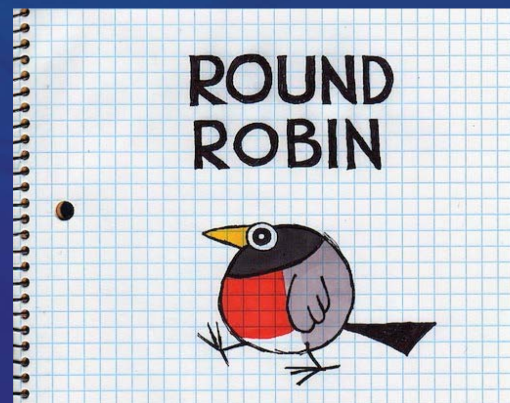
Motivation for Round Robin Studies

- Roadmapping efforts identify Round Robin studies as high priority need for AM
- ASTM F42/ISO TC261 joint plan for standards development lists Round Robin studies in the highest category affecting all of AM
- **Data and Qualification**

engineering laboratory

Round Robin Definition (informal)

- Study coordinator sends control to multiple participants
- Participants perform a task on the control following a defined procedure
- Participants return the outcome of the task to coordinator
- Coordinator/statistician analyze results
- Top down approach to uncertainty assessment

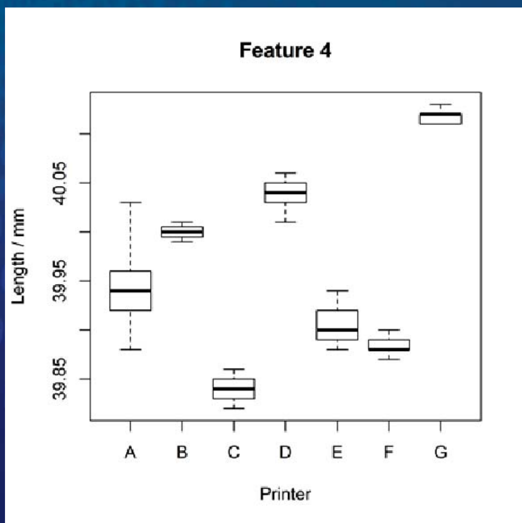


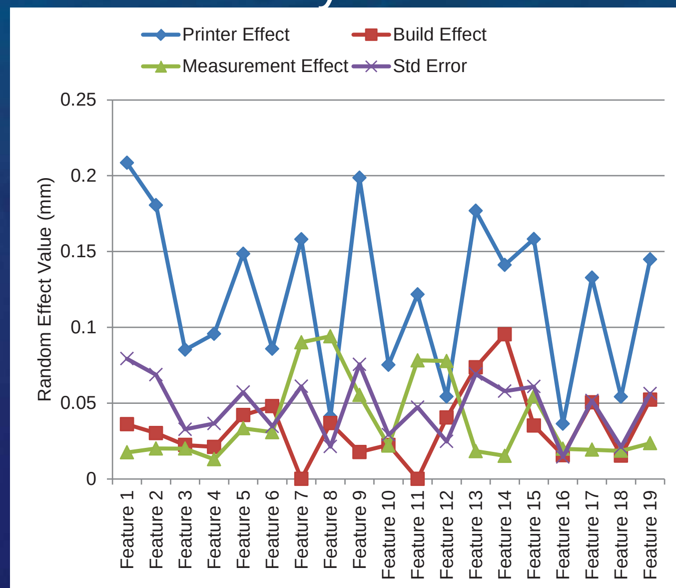
AM Round Robin Studies

	NIST MakerBot	NIST CoCr	EWI IN625	CIRP Stainless	NIST IN625
# Participants	6	8	2 labs, 3 machines	7	7
Machine Types	Replicator G; Replicator 2, Replicator 2x	5 EOS M270, 1 EOS M280, 2 Arcam	EOS M270	Laser Beam Melting	5 EOS M270, 1 EOS M280, 1 SLM 250
Material	PLA, ABS	Cobalt-Chrome alloy	Inconel 625	Stainless Steel S15500	Inconel 625
Measurements	Geometry	Tension (x-direction only), Microstructure	Tension, Load controlled fatigue (HCF), Strain controlled fatigue (LCF) Microstructure	Tension, Compression, Porosity	Tension (x-direction only)
Focus	Pilot test for geometry measurements	Learn more about conducting Round Robin Studies	Develop Manufacturing Plan; Seed data for S-basis design allowables	Understand scientific basis for variations based on system technology, position, orientation, software and user experience	Seed data for AM materials database

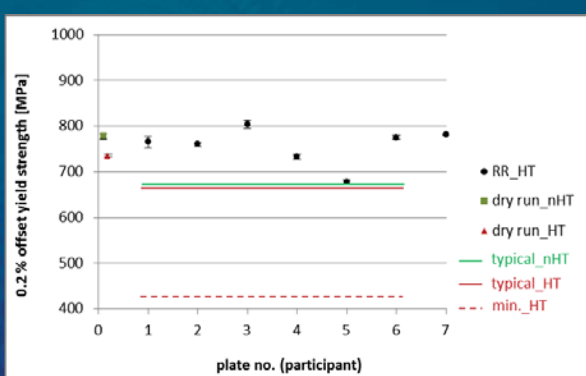
Round Robin Results—MakerBot

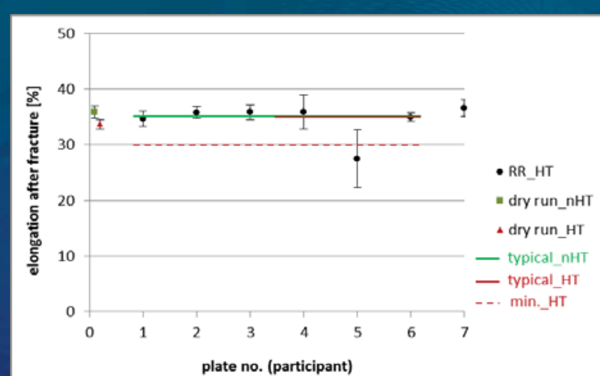
- “Printer effects” dominate variability

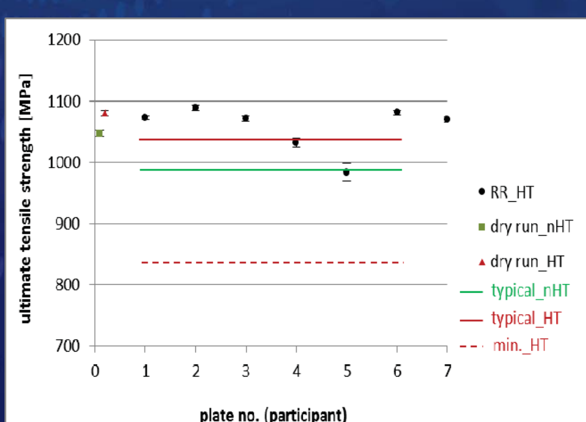


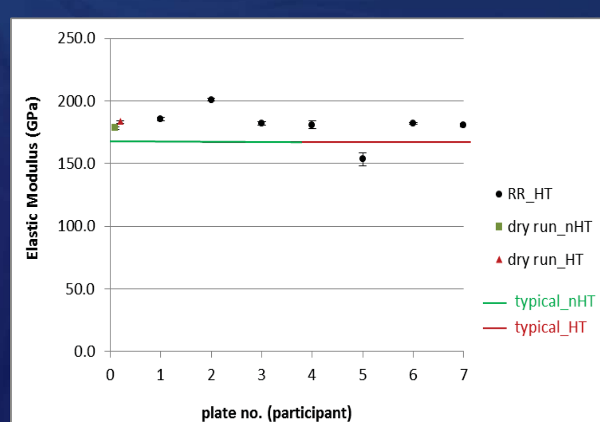


Sample results from IN625 Round Robin study









General Lessons Learned So Far – Results

- Between laboratory variation significantly larger than within laboratory (or between build) variability
- Unknown variables exist between laboratories (even with similar materials) that are not adequately controlled by the manufacturing plan
- More to be gained by increasing the number of participating laboratories than by increasing the number of samples manufactured by each lab
- Prescribe procedures rather than values for setting certain machine parameters???

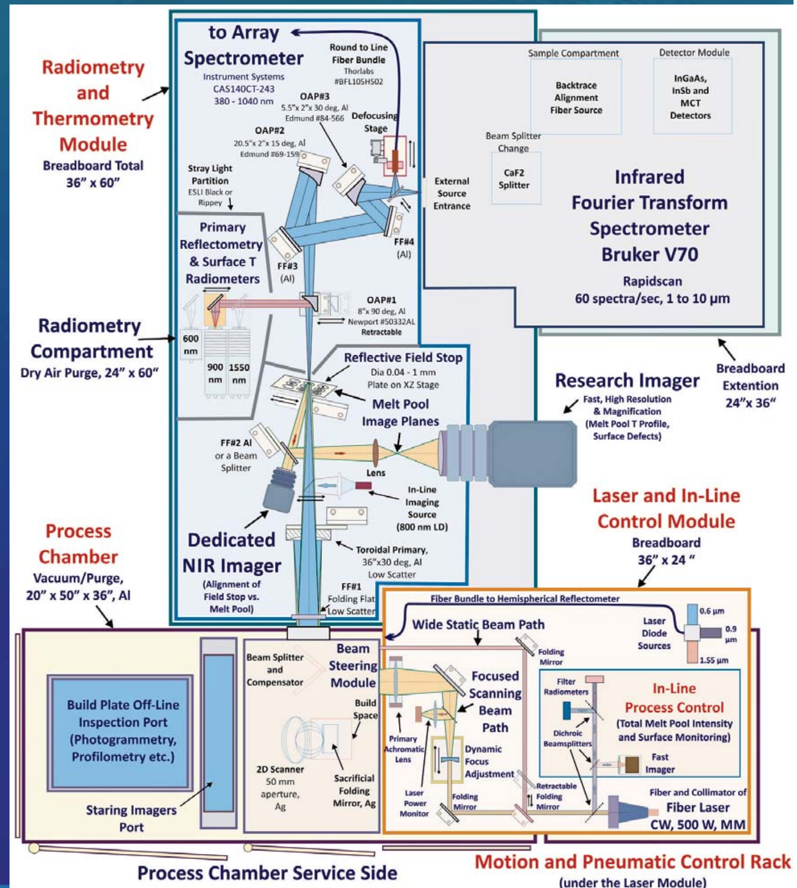
General Lessons Learned So Far – Procedures

- Manufacturing plan is vitally important
  - Joint development of manufacturing plan is valuable but time consuming
  - Manufacturing plan requires much more than merely machine parameter settings
  - Common procedures mean the experiment is limited by the least capable machine/laboratory
- Participants should return meta-data as well as built samples

Real-Time Monitoring and Control of AM processes

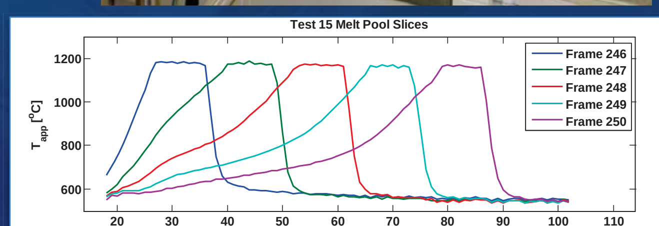
Improve the repeatability of AM processes by:

- Identifying critical process measurands
- Developing measurement systems and methods used for these measurands
- Developing AM Metrology Testbed
- Developing plant model linking process inputs, process signatures and final part characteristics
- Developing control strategies using these models

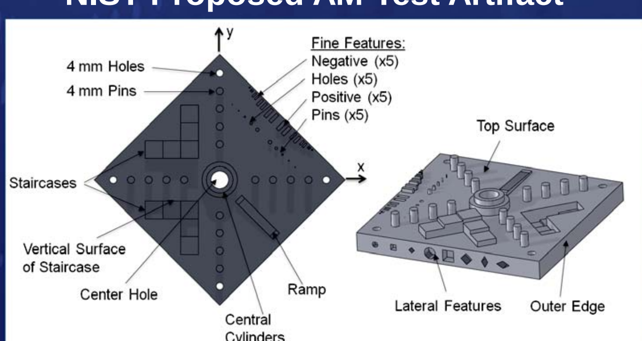


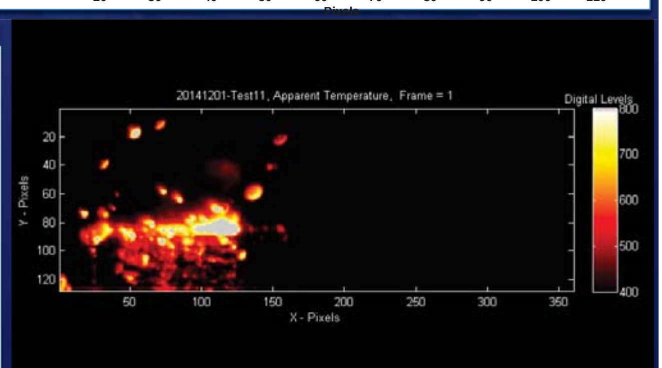
Qualification for Additive Manufacturing Materials, Processes, and Parts

- Explore round robin testing as an option to reduce or distribute the cost of statistical based qualification
- Provide reference data (temperature, microstructure, residual stress) to allow validation of physics-based models of powder bed fusion processes, a necessary step for model-based qualification
- Develop pre-process and post-process measurement methods for performance characterization of AM machines and critical components



NIST Proposed AM Test Artifact





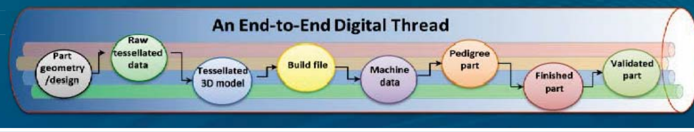
Systems Integration for Additive Manufacturing

High fidelity infrastructure to support AM data management

Fundamental building blocks of AM information

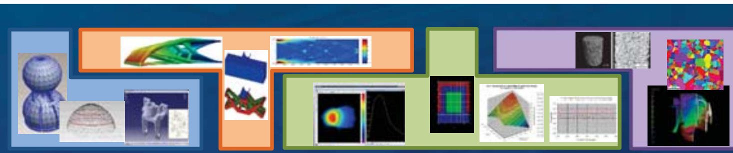
Verification and Validation

to promote information integrity through an end-to-end digital thread and supporting infrastructure.



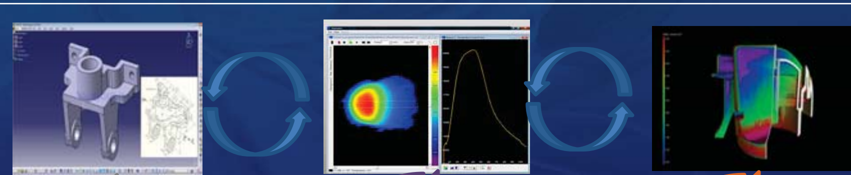
Composability

to leverage inter-domain dependencies and support the reuse, feedforward and feedback of information.



Interoperability

to identify and characterize interfaces between domains and support the flow and transparency of information.

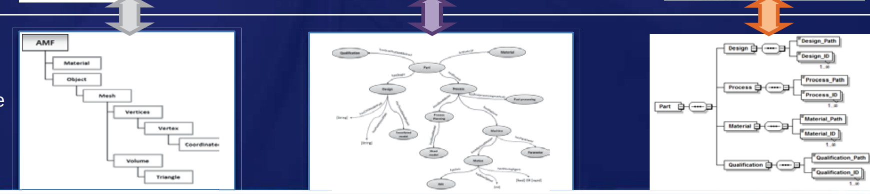


Modularity

to create domain-specific and format-independent definitions throughout the design-to-product transformation.

Metrics/Models

to characterize and describe AM geometry, materials, parts, and processes.



Metal Additive Manufacturing Testbed

EOS M270

- Direct Metal Laser Sintering (DMLS)
- Build volume: 250 mm x 250 mm x 215 mm
- Metal powders: stainless steel, titanium, Inconel, aluminum, cobalt-chrome
- Powder size: 5 micron to 60 micron, with 30 micron median (for stainless steel)
- Layer thickness: 20 micron (for stainless steel)
- Laser: Yb-fiber, 200 W, 1060 – 1100 nm wavelength
- Nitrogen or argon build environment
- Safety interlocks, built-in oxygen sensors, and warning system

ExOne M-Lab

- Binder jetting process
- Build volume: 40 mm x 60 mm x 35 mm
- Metal powders: stainless steel, bronze, tungsten

Optomec MR-7 (FY16 arrival)

- Laser Engineered Net Shaping (LENS)
- Build volume: 300 mm x 300 mm x 300 mm
- Metal powders: stainless steel, titanium, Inconel, aluminum, tool steel, copper
- Dual powder feeders for gradient materials
- Deposition rate: up to 100 g/hr
- Laser: IPG fiber, 500 W
- Argon build environment
- Thermal imager and melt pool sensor

AM Measurement Science Leadership

- Conducted Roadmapping Workshop: Measurement Science for Metal-Based Additive Manufacturing (Dec 2012) with 88 AM experts
  - http://events.energetics.com/NIST-AdditiveMfgWorkshop

  - ➢ Build upon prior AM roadmaps
  - ➢ Actionable plans: what's needed and how to get there – beyond just a list of research needs
  - ➢ Foundation for ASTM F42 strategic plan
  - ➢ Detailed input for America Makes national AM roadmap
  - ➢ Consensus needs and priorities to influence the national research agenda

Workshop Results

- Plenary Talks, Industry Panel, Moderated Break-Out Groups
  - AM Materials
  - AM Processes and Equipment
  - AM Modeling and Simulation
  - Qualification and Certification of AM Materials, Processes, and Products
- Workshop Final Report and AM Measurement Science Roadmap
  - Summary of results, including recommendations, presentation slides, white papers, break-out group results, etc.
  - Actionable plans: beyond a list of research needs
  - Addresses one slice of overall AM roadmap; to be integrated with America Makes national AM roadmap

http://events.energetics.com/NIST-AdditiveMfgWorkshop/index.html

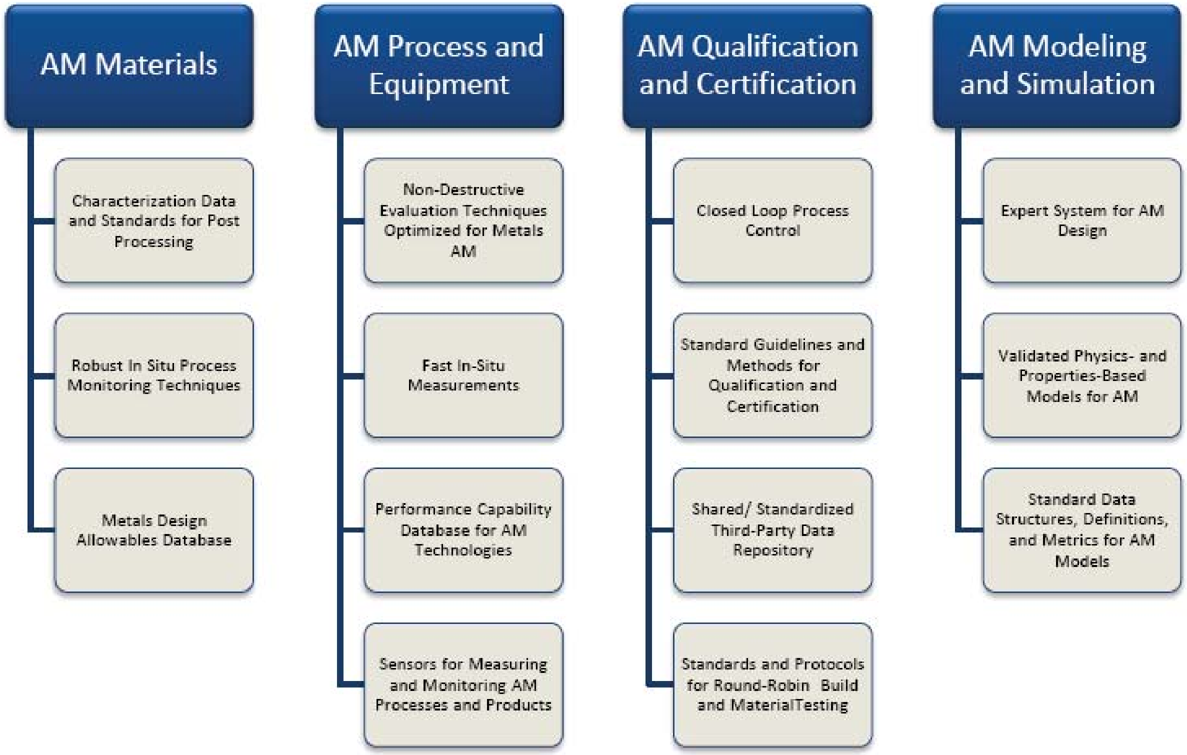


Figure E-2. Important Technology and Measurement Challenges for Additive Manufacturing

FIGURE 2-2. ROADMAP ACTION PLAN: ROBUST IN-SITU PROCESS MONITORING TECHNIQUES

BARRIER: In-situ process monitoring techniques for material and product defects are currently not robust and lack key capabilities (e.g., high-speed video and high-speed thermograph for deposition of materials, real-time measurement, and in-situ detection of processing anomalies leading to discontinuities, such as thermal gradients, voids, and inclusions). Feedback control for composition and microstructure, and sensor integration is not attainable with current black box controllers.

APPROACH SUMMARY: Identify, develop, and implement process monitoring, NDE, and in-process measurement techniques to enable maximum detection of material defects.

	ROADMAP ACTION PLAN	MILESTONES AND RESULTS	OVERARCHING TARGETS
1–2 years	• Identify and implement existing process monitoring technologies, identify constraints and limits, and resolve measurement capabilities • Collect and analyze critical data	• Implementation of process monitors on existing AM platforms • Identification of limits of existing sensor/process monitoring equipment • Correlation of NDE and mechanical testing to	• Maximized detection capabilities to qualify production with batch size of one
3–5 years	• Correlate NDE data with destructive testing • Identify existing, alternate, and in- process measurement techniques not being investigated that are capable of scaling with AM processes • Identify and develop techniques for real- time	• Identification of alternatives that address the gaps of existing process monitoring technologies • Implementation of these new technology detection limits • Correlation to NDE and mechanical testing • Demonstration of the ability to collect and	
5+ years	• Use data to drive modeling efforts • Correlate modeling with process measurement to enable robust process control (e.g., vision system identifies a defect/pore, process control system corrects and eliminates defects)	• Demonstration of direct correlation between process monitoring, control, and NDE	

STAKEHOLDERS & POTENTIAL ROLES

- **Industry/AM Users:** Aerospace, biomedical, oil and natural gas industry: Identify needed material and mechanical properties
- **Industry/AM Providers:** Open up software and collaborate with researchers to implement and support these techniques
- **Academia:** Conduct basic research and analysis
- **Standards Committees:** Evolve standards along with the technology
- **Government:** Support standards development; Coordinate and facilitate cooperation among NIST, Oak Ridge, NASA, DOE, DOC, NSF, NIH, DARPA;

Resources (i.e., neutral source)

RELATIVE IMPACTS

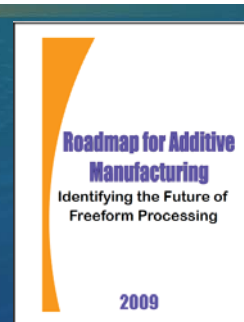
LOW—HIGH

- ◆◆◆ **Improves product quality:** Eliminate defects; Have an intimate and unprecedented understanding of component quality
- ◆◆◆ **Reduces costs:** Scrap, raw materials; Reduce capital investments in forming/shaping
- ◆◆◆ **Accelerates innovation:** For example, making available the data needed to develop techniques for designing micro-structuring
- ◆◆◆ **Enhances industry competitiveness:** Lower lead times (e.g., batch size one production)
- ◆◆◆ **Faster product development time:** Eliminate need for tooling
- N/A **Other:** Needed for AM to be a manufacturing tool

Several Other AM Roadmaps

- 1998 NCMS Rapid Prototyping Roadmap
- 2009 NSF/ONR Roadmap for Additive Manufacturing
- America Makes National AM Roadmap
- Federal Agency Roadmaps: DOD, NASA, etc.
- Country-Specific Roadmaps, e.g.,
  - United Kingdom
  - Australia
  - South Africa

2009 AM Industry Roadmap



- Roadmap Development Workshop sponsored by National Science Foundation (NSF) and Office of Naval Research (ONR)
- Expert participants from AM system vendors, industry users, technology suppliers, academia, government
- Focused on needs, priorities, and a research roadmap for AM over next 10-12 years
- Roadmap recommends several high-priority developments that are needed to advance the AM industry; grouped in the following categories:
  - Research
  - Education and Outreach
  - Development and Community
  - National Testbed Centers

A Sampling of Recommended Developments Identified in the 2009 AM Industry Roadmap

- Process-structure-property relationships for each material and process
- Closed-loop and adaptive AM systems with feed-forward and feedback capabilities
- A much better understanding for the basic physics and chemistry of AM processes
- Conceptual design methods to aid designers in defining and exploring design spaces enabled by AM
- A new foundation for CAD systems that overcomes limitations in representing very complex geometries and multiple materials
- Sustainable (green) materials to reduce environmental impact, including recyclable, reusable, and biodegradable materials
- University courses and materials, and training programs for industry practitioners
- Development and adoption of robust standards for AM
- Establishment of a national testbed center to leverage equipment and serve as a highly visible showcase facility (or network of facilities)

Additive Manufacturing Consortium (AMC)

Consortium Priority Needs*

- Property Database
- Quality Control
- Distortion Control
- Equipment Development
- Feedstock / Input Materials
- Design Rules
- Standards
- Process Modeling / Optimization
- AM Knowledge Base

* Focus: precompetitive technology development

America Makes – National Additive Manufacturing Innovation Institute

America Makes

NIST Contributions

- Assisted with initial solicitation (by DoD/AFRL)
- NIST serves on Technical Advisory Board (TAB):
  - Kevin Jurrens, Engineering Laboratory
  - Phil Wadsworth, Manufacturing Extension Partnership
  - Function: technical guidance, project selection, program reviews, coordination of federal interests and activities
- Teaming with technical projects (NIST collaborators paired with America Makes funded projects)
- AM Roadmap Advisory Group
- AM Data Schema Advisory Group
- Technical collaborations with America Makes and NIU for NIST MSAM awards (kick-off events Dec. 2013)

GO Additive – Government Organization for Additive Manufacturing

- Existing mechanism to foster communication, coordination, and collaboration among federal agencies and organizations
- Open to any government employee with an interest in additive manufacturing; voluntary memberships on open, revolving door basis (~70 current members)
- Three current "Communities of Interest" formed:
  - Strategy and Leveraging
  - Technical Data
  - Qualification and Certification
- Information shared through GO Additive restricted portal on OMB MAX.gov system
- Chair: Jennifer Fielding, AFRL

engineering laboratory

CMU Workshop: Certification of Metal Additive Manufacturing

- Held June 19, 2015, with 25 invited participants
- Focus on improved understanding of issues involved in certifying metal AM parts and systems for use in airframes and engines for civil aviation
- Final report available, with results and recommendations in 3 key areas:
  - Shared Materials Databases
  - Certification
  - Standards for AM Processes and Materials

Open Questions Raised at Workshop

- What are the commonalities and differences among the qualification / certification approaches used in the different application areas? (i.e., for certifying bodies such as FAA, FDA, NASA, DOD, DOT, etc.)
- Could the qualification requirements for AM materials, processes, and parts be consistent across the application areas? Why or why not?
- What role (if any) does predictive modeling have in current qualification / certification approaches? How could predictive modeling play a larger role in the future?
- What would a material or process specification for AM look like? (what is the necessary content?)
- How can the respective stakeholders best come together to share technical ideas and solutions? (what mechanism will make this happen?)

Proposed Key Factors for Progress

- Definitions of terms
  - at a minimum: documented, public, widely disseminated
  - should terms be consistent across application areas?
  - do we need consensus agreement?
- Clear definition of AM qualification requirements (from each application perspective)
- Identification of priority needs and development of key standards for reference by AM qualification procedures
- Method for down-selecting and studying the impacts of variations in (numerous) material and process inputs on final part outcomes (many variables, frequent changes)
- Established mechanism(s) for sharing technical ideas and solutions
- Demonstration of reduced risk through increased knowledge and test data, new predictive capabilities, and accurate and repeatable AM processes

Final Thoughts

- Manufacturing is changing
- New types of measurement and standards needs exist
- NIST is addressing those needs with Smart Manufacturing programs, including one on Additive Manufacturing
- AM allows U.S. manufacturers to make innovative and complex parts that are difficult or impossible to make with conventional manufacturing techniques
- While AM has great potential, it also has challenging problems that limit its current adoption by U.S. industry
- Working with a variety of partners, NIST measurement science research provides needed standards and methods to qualify AM materials and processes for demanding applications

NIST Partnering Strategies

- Planning and Roadmapping Workshops
- Testbeds, Facilities, and Tools
- Standards Engagement
- NIST Sponsored Events
- Cooperation Mechanisms
- Other Tech Transfer Mechanisms

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Questions and Discussion

AM Current Capabilities and Process Mapping Methods Tied to Qualification

Jack Beuth

Professor, Department of Mechanical Engineering
Director, NextManufacturing Center
Carnegie Mellon University
CEO, Tolemaic Systems

Web pages:
http://www.cmu.edu/me/people/jack-beuth.html
https://sites.google.com/site/beuthadditivelab/
https://engineering.cmu.edu/next

Carnegie Mellon

Direct Metal Additive Manufacturing

- Laser and Electron Beam Powder Bed Fusion Processes
- EOS Laser Process Shown to the Left
- Processes Are Very Complicated but They Can be Understood

AM Research at Carnegie Mellon

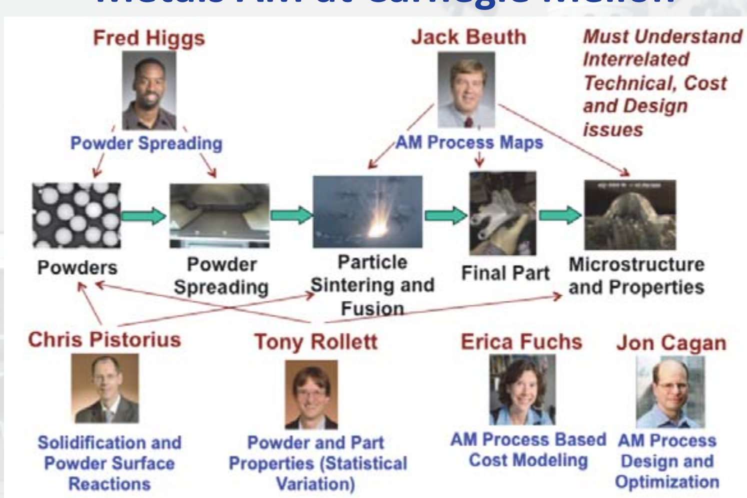
Carnegie Mellon

CMU NextManufacturing Center

Exploring the manufacturing genome through additive processing

- Over 20 Faculty Across Campus
- AM is a ***Testbed*** for Developing New Methods for Advanced Manufacturing

Metals AM at Carnegie Mellon



Carnegie Mellon

CMU NextManufacturing Facility

- Metals
  - **(2) Arcam S12 Electron Beam Metal Machines**, fully upgraded with the multi-beam option
  - **EOS M290 Laser Sintering Metal Machine**, with all available material parameter sets
- Polymers
  - Objet350 Connex Multi-Material 3-D Printer
  - (2) Stratasys Dimension Elite FDM Machines
  - Multiple Cube Pro Maker Machines
- Metrology
  - Freeman Tech Powder Rheometer
  - Infinite Focus G4 with Real 3D Surface Measurement
  - GF Machining Solutions AC Progress VP3 Wire EDM Machine



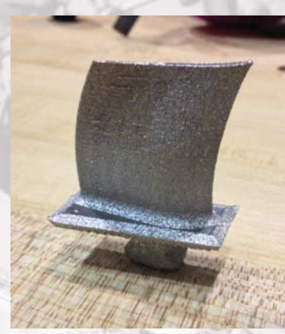
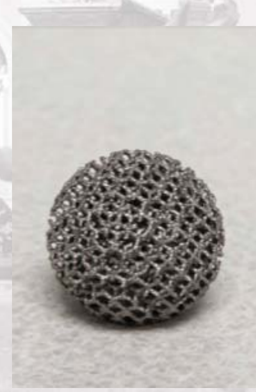




We Allow Industrial Partners to Use our Equipment on a fee basis and we also offer training on AM equipment

AM Part Examples

- Compressor Blade (generic version from GE)
  - Arcam vs. EOS
  - Surface Finish
  - Warping of Planar Section for EOS
- CMU Meshed Sphere
  - Arcam Fabricated
  - EOS Versions were Scraped by Spreader Blade

State of the Art and Process Mapping

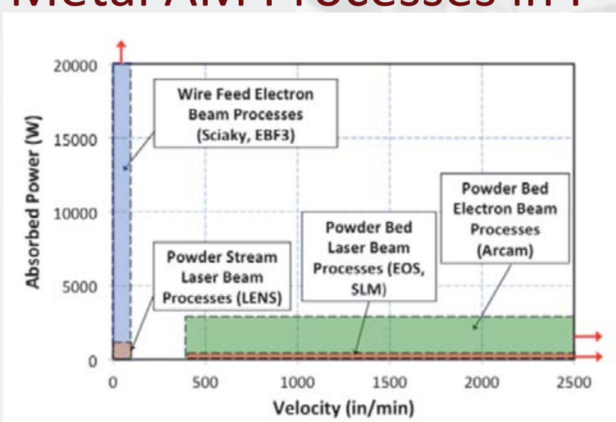
State of the Art for Direct Metal AM

- You can print most 3-D shapes directly out of metals
  - Close to 100% dense, features down to 200 microns (EOS)
  - Build Volumes Approx 10”x10”x8”
  - Parts can take 4-8-24 hours (or more) to build
  - AM is for Real: GE fuel nozzle and other AM-fabricated parts are going into commercial jet engines, which are very conservatively designed
- Current processes were developed to allow shapes to be built
  - Other process outcomes are important when making components

Our Research

- Our Patent Pending *Process Mapping* Technology Uniquely Maps the Dependence of Process Outcomes *(deposition rate, porosity, microstructure, precision, surface finish etc.)* in terms of Identified Primary Process Variables *(beam power, travel speed, layer thickness, background temperature, local geometry)*
- Customers can develop their own "recipes" for part fabrication
- Step through a series of geometries from single beads to components to component features
- Can map modeling results or experiments – we are defining limited numbers of experiments to run to characterize a process

Direct Metal AM Processes in P-V Space



- We are mapping all direct metal processes across 6 alloy systems
  - Approach is the same, results are different but many results are analogous
  - Our start-up company, **Tolemaic Systems**, is developing software to take users step-by-step through process mapping their machines
  - Our work can help any direct metal AM machine user get the most out of their substantial investment in machine, maintenance, tech support, etc.

Process Map Impact on Aerospace Qualification

Current Practice

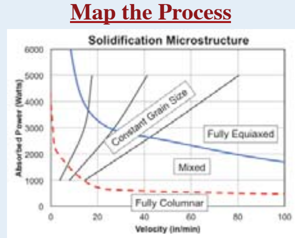
Complex Mix of Inter-Related Process Variables →

Trial and Error Experiments
1. High Cost – In Aerospace $Millions to Qualify One Process to Make One Part
2. Long Times: Years to Qualify a Process
3. Each Machine Can be Different

Process Mapping

Identify Primary Process Variables
1. Beam Power
2. Beam Travel Speed
3. Material Feed Rate
4. Background Temperature
5. Local Geometry

→ **Map the Process**



Final Goal

Process Outcomes
1. Part Geometry
2. Surface Finish
3. Microstructure and Properties
4. Flaws
5. Precision

- Process Mapping Quickly Points Users to Optimal Process Variable Combinations
- Backed by 12 Fundamental and Tech Transfer Research Projects Funded by NSF, ONR, NIST, America Makes, the State of Pa and Others

Current Projects

(Jack Beuth with Rollett, Fuchs, Higgs, Pistorius, Cagan)

***Fundamental* Projects Establishing Process Mapping Methods**
1. **NSF:** Integrating Melt Pool Geometry and Microstructure Control (Sciaky Ti64)
2. **NSF:** Process Mapping Across Alloy Systems (EOS Arcam, Ti64 IN718)
3. **NIST:** Process Mapping of Laser Powder Bed AM (IN625 Stainless Steel)
4. **NIST/Am Makes:** Process Mapping of Defects (Arcam EOS Ti64)
5. **ONR:** Mapping of Microstructure Control for High Temperature Deposition (EOS Arcam Ti64)
6. **CMU MechE:** AM Process Design Optimization (All Processes and Alloys)

→

TRL 4-7 *Tech Transfer* Projects
1. **Pa RAMP:** Deposition of Aluminum Alloys (EOS Arcam)
2. **America Makes:** Thermal Imaging and Integrated Melt Pool Geometry and Microstructure Control (LENS Sciaky Ti64)
3. **America Makes:** Process Mapping of Powder Bed Processes (EOS Arcam Ti64)
4. **America Makes:** Powder Property vs. Part Quality (EOS Arcam Ti64 CoCr)
5. **CMU Alumnus Support (Richard Feiler):** AM for Racing Car Applications (EOS, Multiple Alloys)
6. **DOE:** Microchannel Heat Exchanger Fabrication (EOS, Arcam)

→

***Tolemaic Systems, LLC* Software Development Projects**
1. **Innovation Works and Carnegie Mellon:** Start-up Funding

- Current Fundamental, Tech Transfer and Business Projects

Collaborators

University Collaborators
Wright State Univ, North Carolina State Univ, University of Louisville, Penn State Univ, Case Western Reserve Univ, University of Texas at El Paso

National Laboratory and Other Government Facilities
NASA Langley, NIST, ORNL, Walter Reed Army Medical Center, Robert C. Byrd Institute

Aerospace Industry
GE Aviation, GE Global Research, Pratt & Whitney, United Technologies Research Center, Lockheed Martin, CalRAM

Powder Production Industry
ATI Powder Metals, Ametek Specialty Metal Products, Carpenter Powder Products, TIMET

Medical Implant and Device Industry
Medical Modeling, Fineline Prototyping

U.S. AM Machine Maker Industry
Optomec, Sciaky

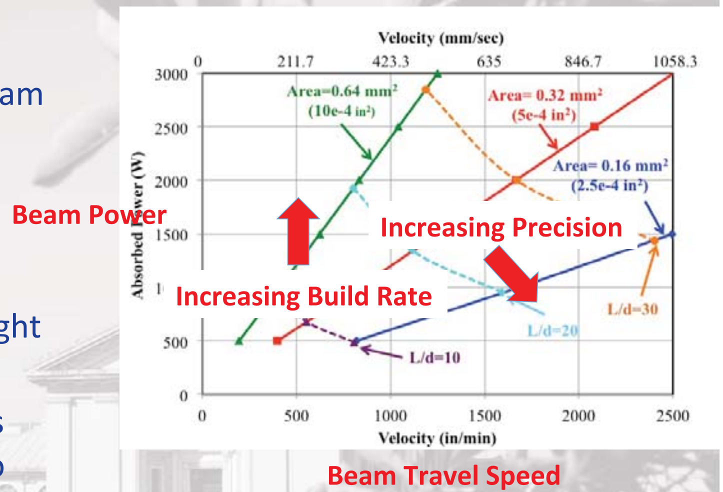
Other Industries
Kennametal, Bayer, TE Connectivity, Incodema 3-D, Stratonics, Alcoa

- 6 Universities, 5 Laboratories, 20 Companies on funded projects, with 10+ more who are interested

Guiding Process Changes

Build Rate vs. Precision

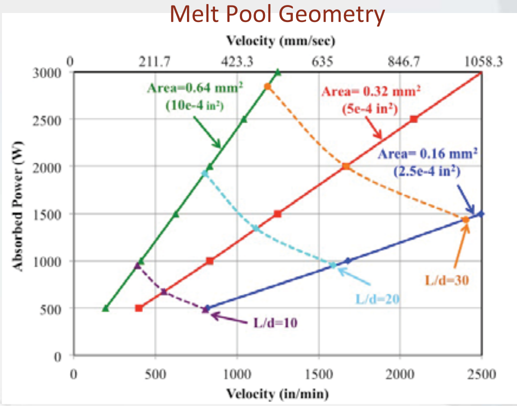
- Beam Power vs. Beam Travel Speed Map for Arcam Electron Beam Process
- Build Rate Scales with Power
- Process Precision Scales with Melt Pool Size (Straight Lines)
- Can Stay on Straight Lines while Increasing Power to Maintain Precision and Increase Build Rate
- Process Design Interface Under Development



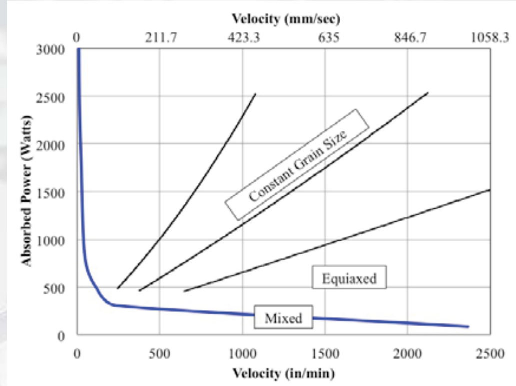
Feedforward Microstructure Control

Linking Melt Pool Geometry to Microstructure

Melt Pool Geometry



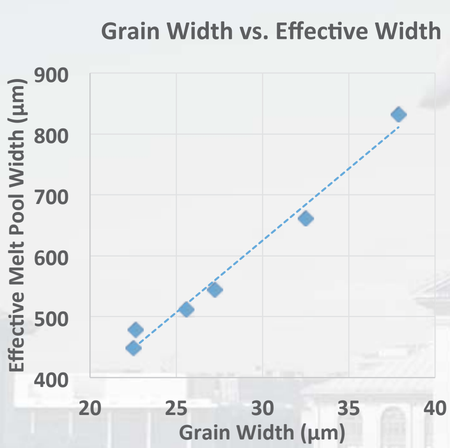
Solidification Microstructure

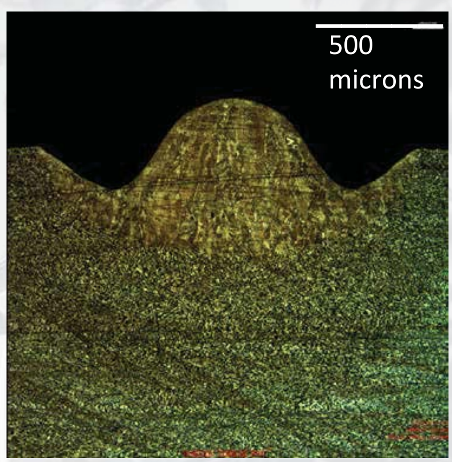


- Finite element simulations for a single geometry (feature), deposition rate, background temperature (above is for Ti64 Single Beads in Arcam)
- Key Insight: Melt pool size and cooling rate are linked

Carnegie Mellon

Melt Pool Width vs. Grain Width for Single Beads





For Arcam process

Grain width scales with Melt Pool Width

Number of grains per width is constant approx. 21

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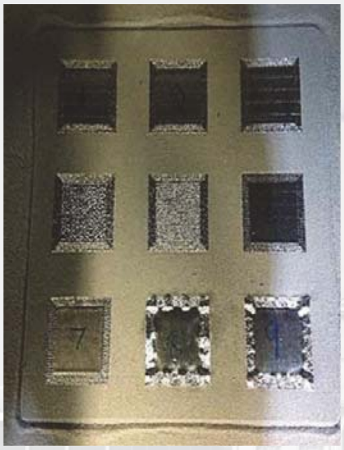
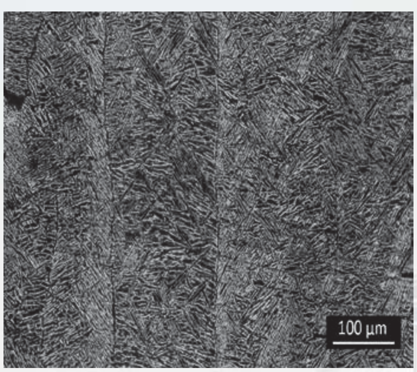
Multi-layer Pad (Solid Build) Tests

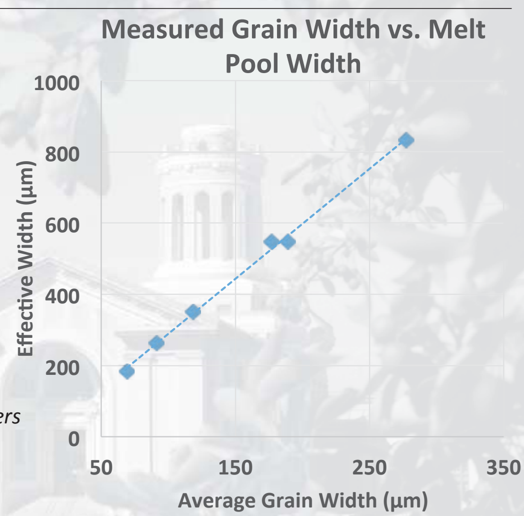


- Test blocks of size 30x30x20 mm are built with different beam currents and speed functions, one of them includes the nominal build parameters on Arcam S12

Melt Pool Width vs. Prior Beta Grain Width(Pads)



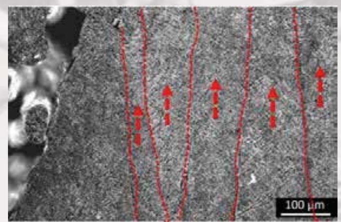
Cross-Section Micrograph of the block built with parameters yielding increased prior beta grain width



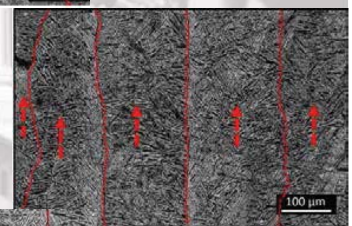
- *No trace of individual layers or individual melt pools in the final part*
- Columnar grains grow through layers
- Number of grains per effective width is ~ 3
- Decrease in number when compared to single beads **– but still a constant!**

Specifying Microstructure in Solid Builds

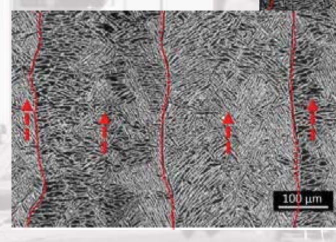
- Material Microstructure Determines Mechanical Properties
- Opportunity to Specify Microstructure and Properties on a Point-by-Point Basis in a Component
- We Understand How to Do This via Point-by-Point Changes in Process Variables: *a breakthrough result*
- Also Being Applied in Real-Time Control Systems



Bulk Raster
Average β width = 91 µm



Bulk Raster
Average β width = 177 µm



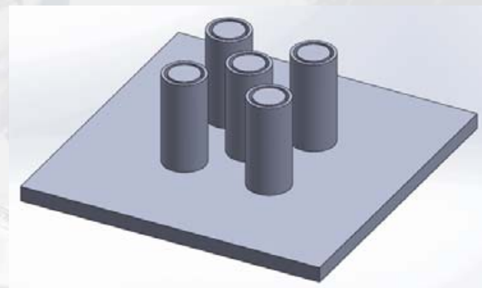
Bulk Raster
Average β width = 277 µm

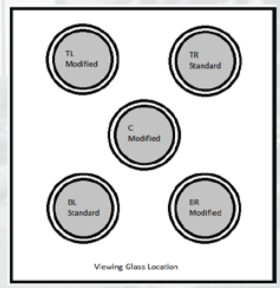
Feedback Control of Microstructure

Real-Time Microstructure Control

(with U. Texas El Paso)

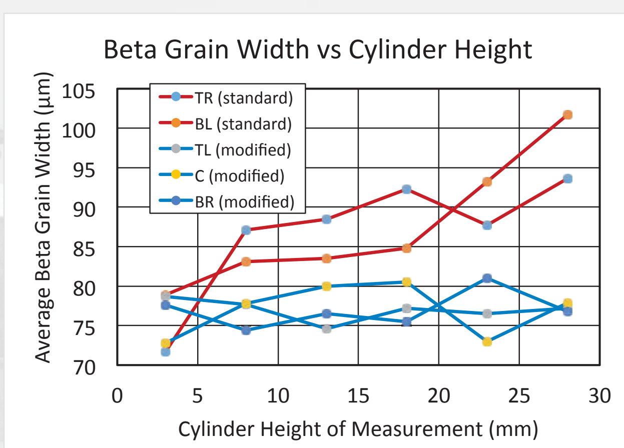
- Current Processes have Little or No Process Sensing and Control
- Arcam Process Typically Has Temperatures Drift Higher as a Part is Built (from UTEP)
- This Causes Microstructural Features to Change from the Bottom to the Top of the Part
- Control Procedure
  - 5 Cylinder Builds, 3 Modified, 2 Standard, All 30mm Tall
  - Thermal Imaging at 5mm Increments used to Control Beam Power

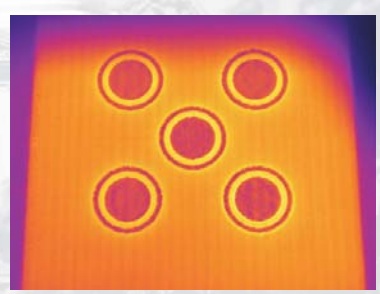




Real-Time Microstructure Control

- Standard Cylinders Both Show Steady Increases in Average Beta Grain Size with Part Height Location
- Modified (Controlled) Cylinders Show Essentially Constant Beta Grain Size Through the Height
- *A breakthrough result*





IR Image from UTEP

Supply Chain: Powders

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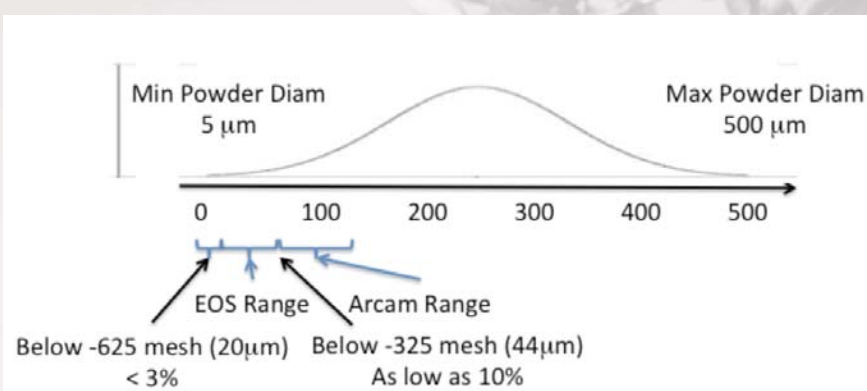
AM Powders
(with NC State)



- Current AM processes use only a fraction of the powder produced
- Ti64 Powder Costs: Arcam: $255/kg EOS: $617/kg
- Unused powder may be recycled <u>or scrapped</u> – problem with O_2 content
- We are working with NC State to allow some use of larger diam powders if an application allows it – can substantially decrease cost: *a recent breakthrough result from NCSU*

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Summary

- Our process mapping work is addressing multiple issues of importance to process qualification methods
- Broad AM Group at Carnegie Mellon
- *Qualification Methods have to Take into Account Where AM will be in the near future:*
  - Users not confined to default process variables
  - Users will be able to locally control microstructure and other outcomes up-front in the design process
  - Process monitoring and feedback control is coming
  - Even current machines are not limited to current powder types

Carnegie Mellon University

Microstructure in Additive Manufacturing

A.D. (Tony) Rollett

Ross Cunningham, Tugce Ozturk, Suraj Rao, Ming Tang, Chasen Ranger, Chris Pistorius, Elizabeth A. Holm, Jack Beuth, with help from many others

Support:
America Makes
NSF
PA-RAMP
DOE
NIST
NASA
DOE-NNSA

Prototype Heat Exchanger

GE Engine Brackets

Outline

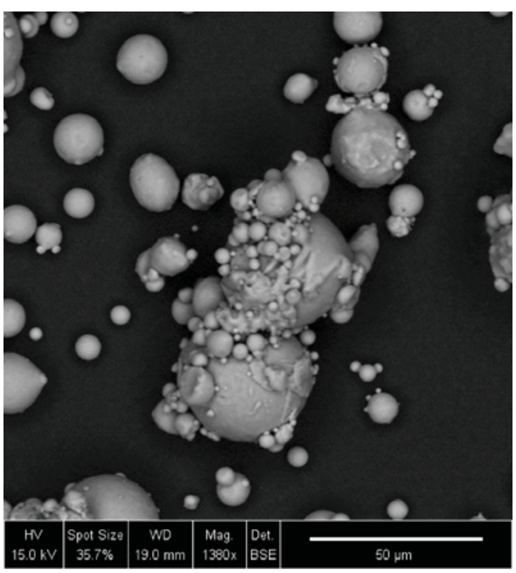
- The challenge of microstructure
- Machine vision/learning for microstructure
- Extreme value analysis, for, e.g. powder size
- Advanced characterization, e.g. 3D tomo
- Reduced order model to predict porosity
- Microstructure-Properties simulation
- Summary

Projects, Support: Why a University?

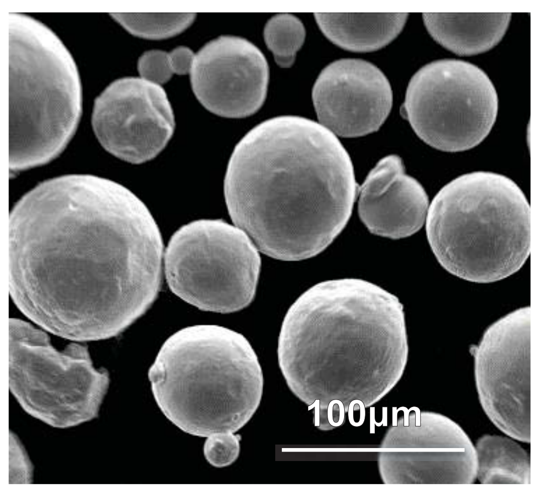
- Novel Ti alloys via AM: Natl. Science Foundation (NSF)
- Advanced High Temp. Heat Exchangers: DOE
- Powder Study: America Makes
- 3D Microstructure, mechanical response in SS: DOE-NNSA
- Processing-Microstructure-Properties in Al: Pennsylvania and Alcoa (complete).

- Why work with universities? From the perspective of certification, university research advances measurement, develops new understanding, **trains people**. Crucially, we try to get answers to problems before the question comes up!

Microstructural Challenges: Raw Materials

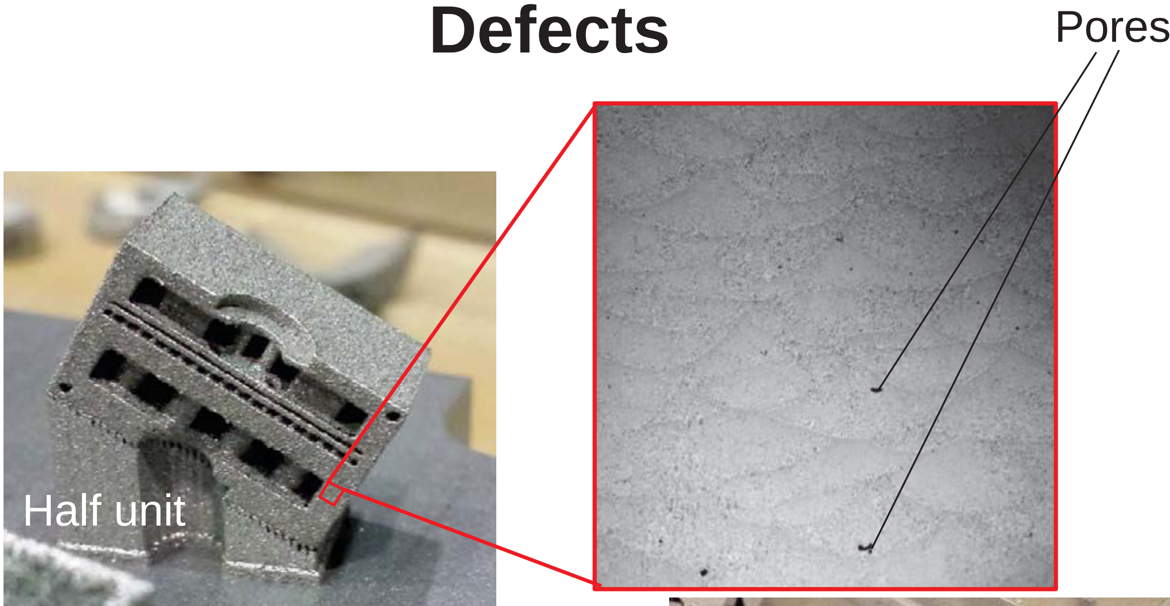


aluminum powder

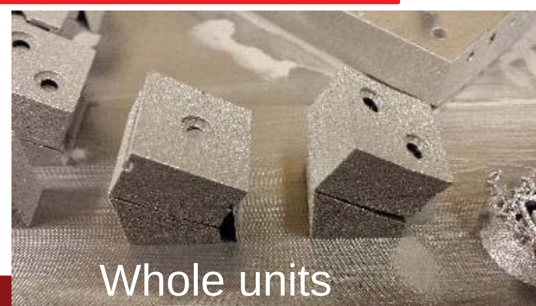


Ti64 powder

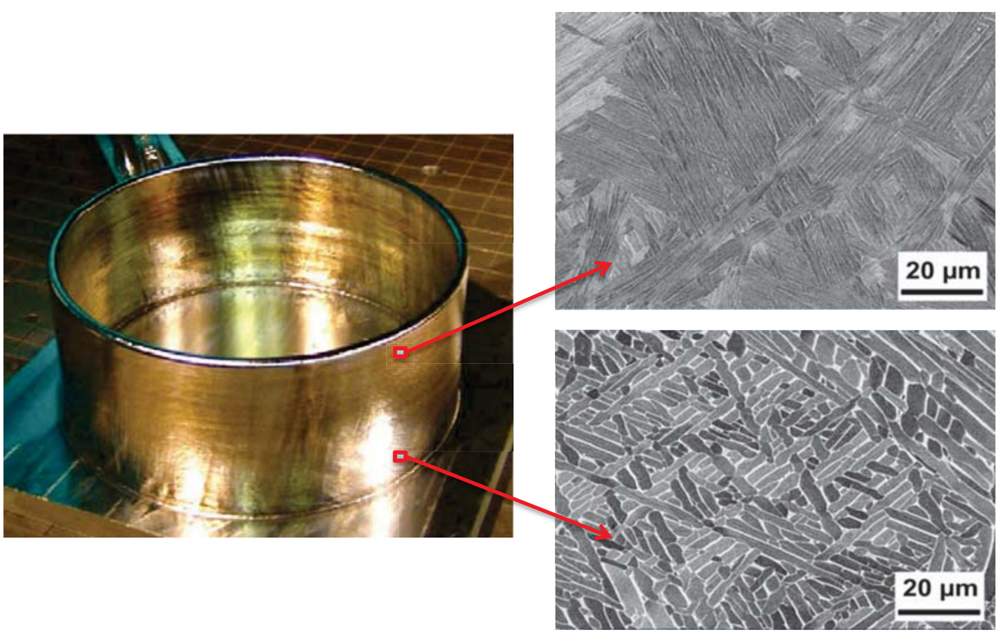
Microstructural Challenges: Defects



Prototype heat exchanger for high temperature service (> 700 ° C)



Microstructural Challenges: Process control



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Microstructural Image Data: Computer vision for autonomous image classification

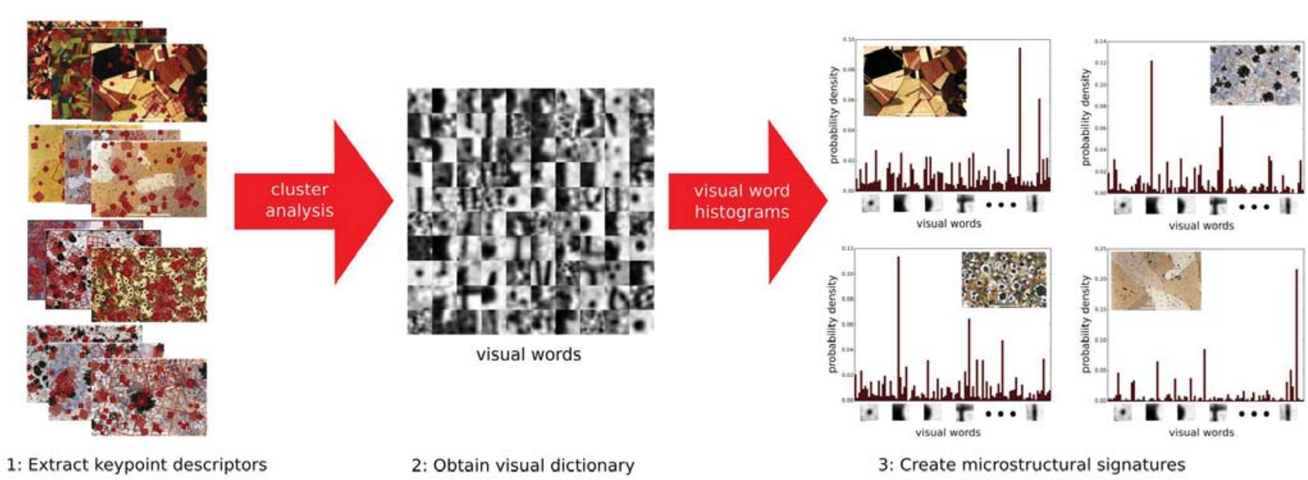
Brian L. DeCost, Elizabeth A. Holm
Materials Science and Engineering

NSF

An automatic and objective system for finding relationships between microstructures

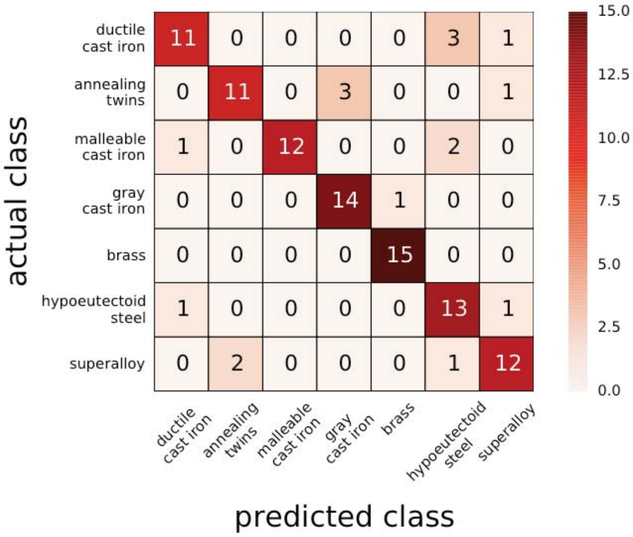
- Using machine vision and machine learning techniques, we automatically harvest, store, and compare microstructural image data.

Bag of visual features microstructure representation



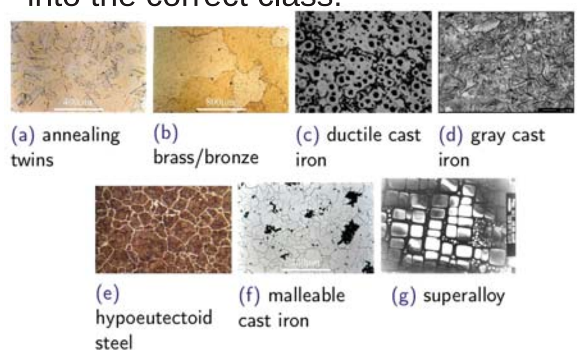
Outcome: A microstructure classifier

- Given "training" micrographs divided into classes, we can classify new micrographs automatically and with high accuracy.



- 5-fold cross-validation on 15 microstructures per class (105 total)

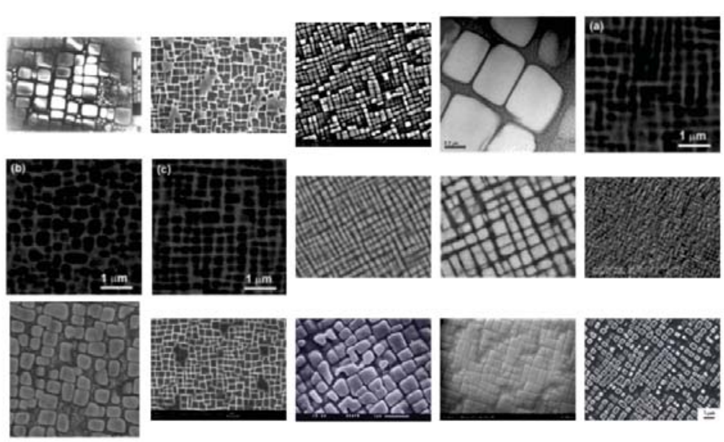
∴ A score of '15' indicates perfect classification of validation images into the correct class:



- **Applications:** Process analysis, control and qualification; archiving; statistical analysis; finding correlations between structure and processing.

Goal: Make decisions based on the full spectrum of microstructural information

- Microstructure depends on processing and controls performance.
- Most processing and performance models use only simple microstructural parameters (grain size, precipitate volume, etc.).
- Microstructural image data utilizes the full spectrum of microstructural information to inform materials and process models.



Qualify superalloy processing routes based on microstructural outcome?

- **Main point: by keeping all available data (not just microstructures), we can apply data analytics to overcome issues with inadequate data volume.**

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Extreme value analysis: Al-10Si-Mg Powders

Suraj Rao, Ross Cunningham
& A.D. (Tony) Rollett
Materials Science and Engineering

PA-RAMP

www.cmu.edu

Extreme Values: Historical Development

Leonardo da Vinci: wrote in the 1500s that "among cords of equal thickness, the longest is the least strong"

APPLICATION OF THE THEORY OF EXTREME VALUES IN FRACTURE PROBLEMS*

BENJAMIN EPSTEIN

Coal Research Laboratory, Carnegie Institute of Technology

In this paper it is shown that the theory of extreme values is pertinent to the treatment of certain aspects of the fracture or break-down of materials used in modern technology. An attempt is made to integrate some of the results scattered through the technical literature.

J. Amer. Statistical Assoc., **43**:243, 403-412 (1948).

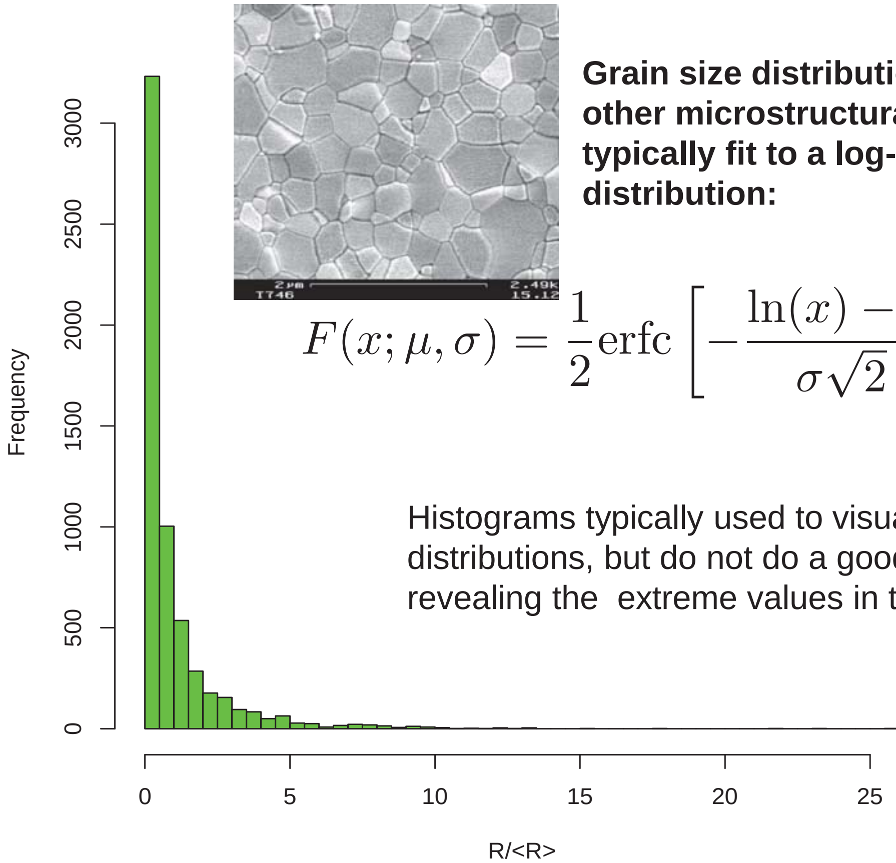
[2] F. T. Peirce, "Tensile Tests for Cotton Yarns V. 'The Weakest Link'—Theorems on the Strength of Long and of Composite Specimens," *Journal of the Textile Institute*, Transactions, *17*, 355 (1926).

[3] W. Weibull, "A Statistical Theory of the Strength of Materials," *Ing. Vetenskaps Akad. Handl.*, No. 151 (1939); "The Phenomenon of Rupture in Solids," *Ibid.*, No. 153 (1939). See also John Tucker, "Statistical Theory of the Effect of the Dimensions and Method of Loading upon the Modulus of Rupture of Beams," *Proceedings of the American Society of Testing Materials*, *41*, 1072 (1941).

[4] N. Davidenkow, E. Shevandin and F. Wittman, "The Influence of Size on the Brittle Strength of Steel," *Journal of Applied Mechanics*, *14*, No. 1, A63–67 (1947).

[5] T. A. Kontorova, *J. Tech. Phys. U.S.S.R.*, *10*, 886 (1940); J. I. Frenkel and T. A. Kontorova, "A Statistical Theory of the Brittle Strength of Real Crystals," *J. Phys. U.S.S.R.*, *7*, 108 (1943).

Visualizing (Grain) Size Distributions



Grain size distributions (or many other microstructural features) are typically fit to a log-normal distribution:

$$F(x;\mu,\sigma) = \frac{1}{2}\mathrm{erfc}\left[-\frac{\ln(x)-\mu}{\sigma\sqrt{2}}\right] = \Phi\left[\frac{\ln(x)-\mu}{\sigma}\right]$$

Histograms typically used to visualize the distributions, but do not do a good job of revealing the extreme values in the distribution.

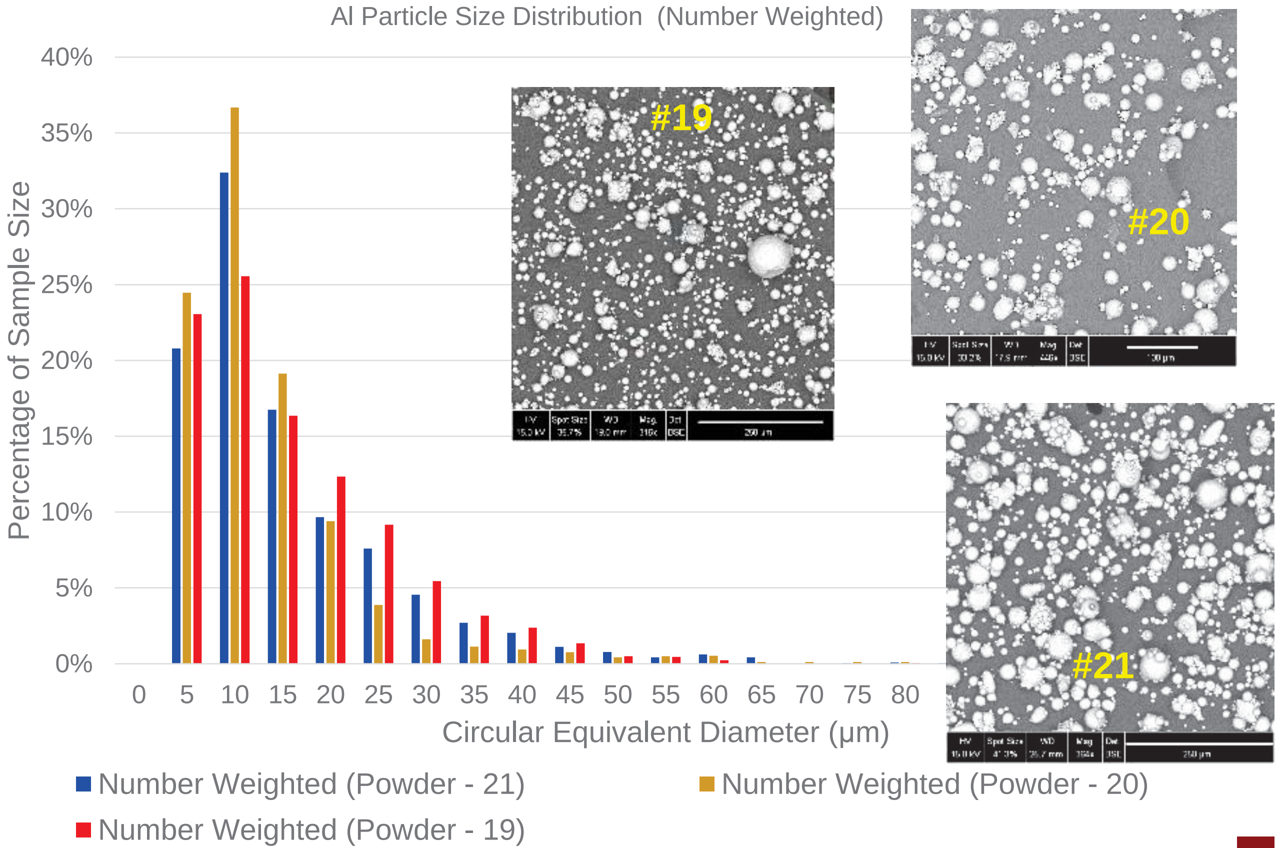
Statistical Data Viewpoint

- "Average" Types
  - Number average
  - Area average
  - Volume average
- Horiba Instrument
  - Mean → D[4,3]
  - Volume Average (or)
  - De Brouckere mean diameter

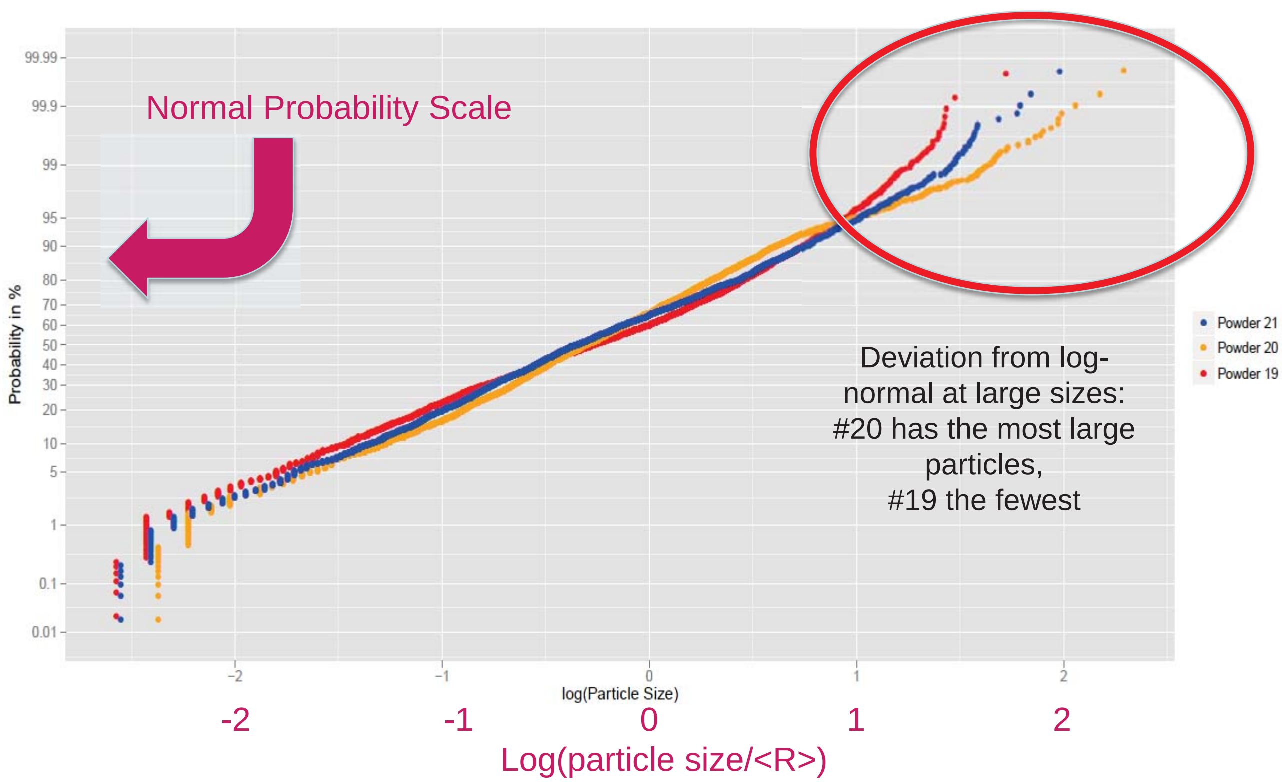
- Three different Al-10Si-Mg powders examined; also a virgin, unused powder.
- Mostly optical transmission microscopy (TOM) used to count *individual particles*

http://www.horiba.com/fileadmin/uploads/Scientific/eMag/PSA/Guidebook/pdf/PSA_Guidebook.pdf

Results – Combined Histogram



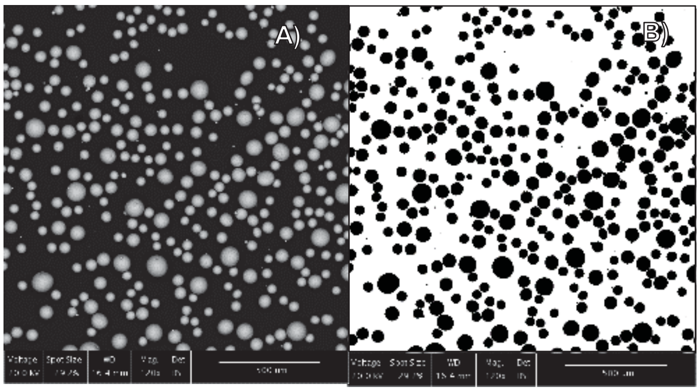
Results – Combined CDFs



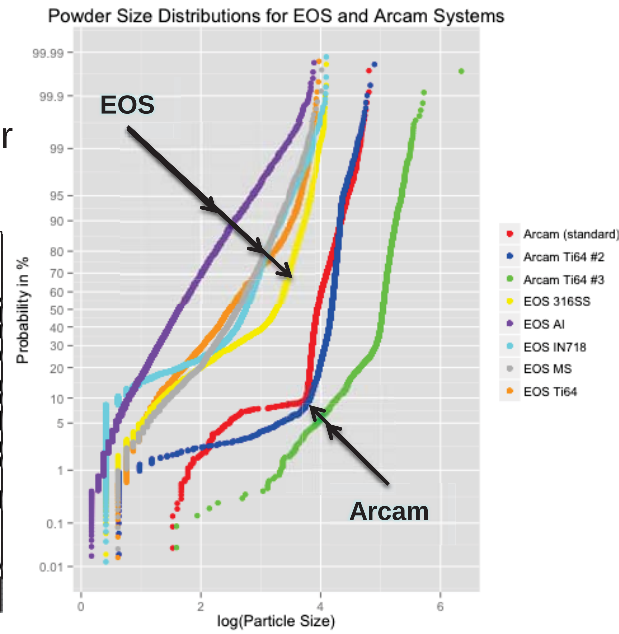
2D vs. 3D: "Comparison … distributions …in three and two dimensions …", Tucker *et al*. *Scripta materialia* **66** (2012) 554

Relating Powder Characteristics to Flow Behavior

- Characterize powder via SEM and image analysis software (imageJ)
- Relate powder properties to rheological behavior from Freeman FT4 Rheometer (Higgs)



(A) SEM image of Arcam Ti-6-4 powder.
(B) Thresholded image for analysis (imageJ).



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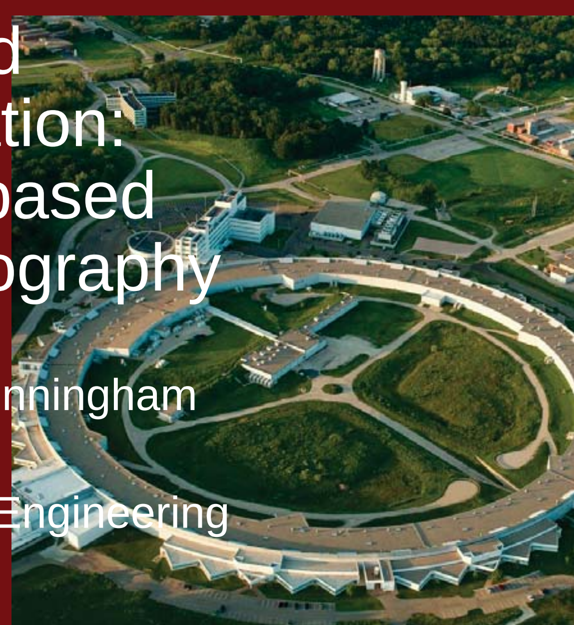
Advanced Photon Source
Argonne National Laboratory

Carnegie Mellon University

Advanced Characterization: Synchrotron-based Computed Tomography

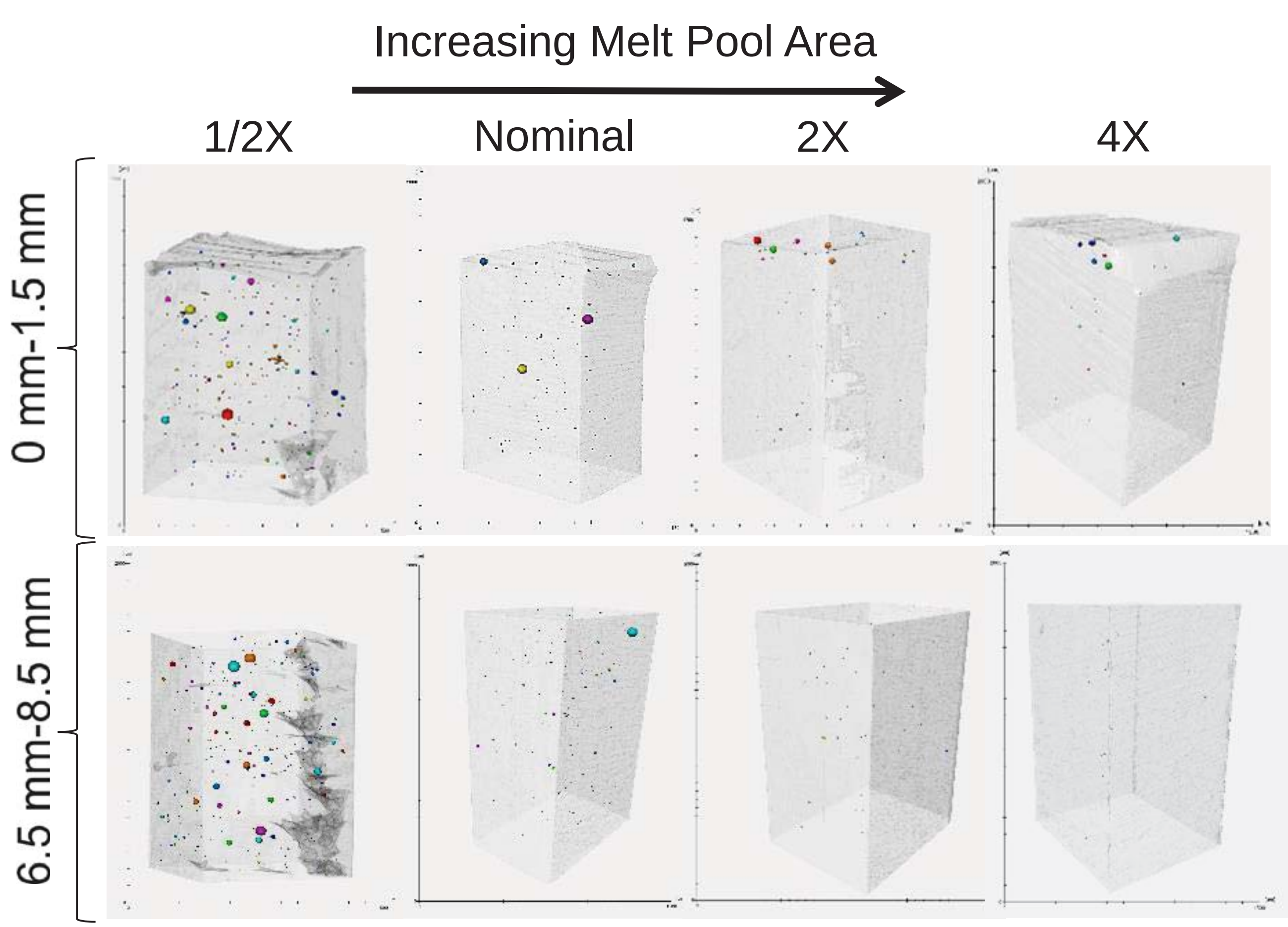


Tugce Ozturk, Ross Cunningham & A.D. (Tony) Rollett
Materials Science and Engineering

NSF, AM, PA-RAMP

Experiment at 2-BM Beamline

- **Five Ti-6-4 samples** (3 cm diameter, 1.5 cm height cylinders) were fabricated on Arcam EMB System at NC State
- **Beam velocity was varied to create melt pool areas corresponding to 1X, 2X, 4X, 1/2X, 1/4X of the "nominal" melt pool area**
- 1 mm x 1 mm x 1.5 cm imaging samples were cut from the bulk, and contour-bulk interface. CT-scans were taken from top ~8 mm of each sample
- CT on 2-BM beamline with 100 keV pink beam, absorption mode; help from Xianghui Xiao acknowledged.
- Object was to **characterize different types of porosity observed in AM metals**, and begin to **supplement process maps with intrinsic defect properties**



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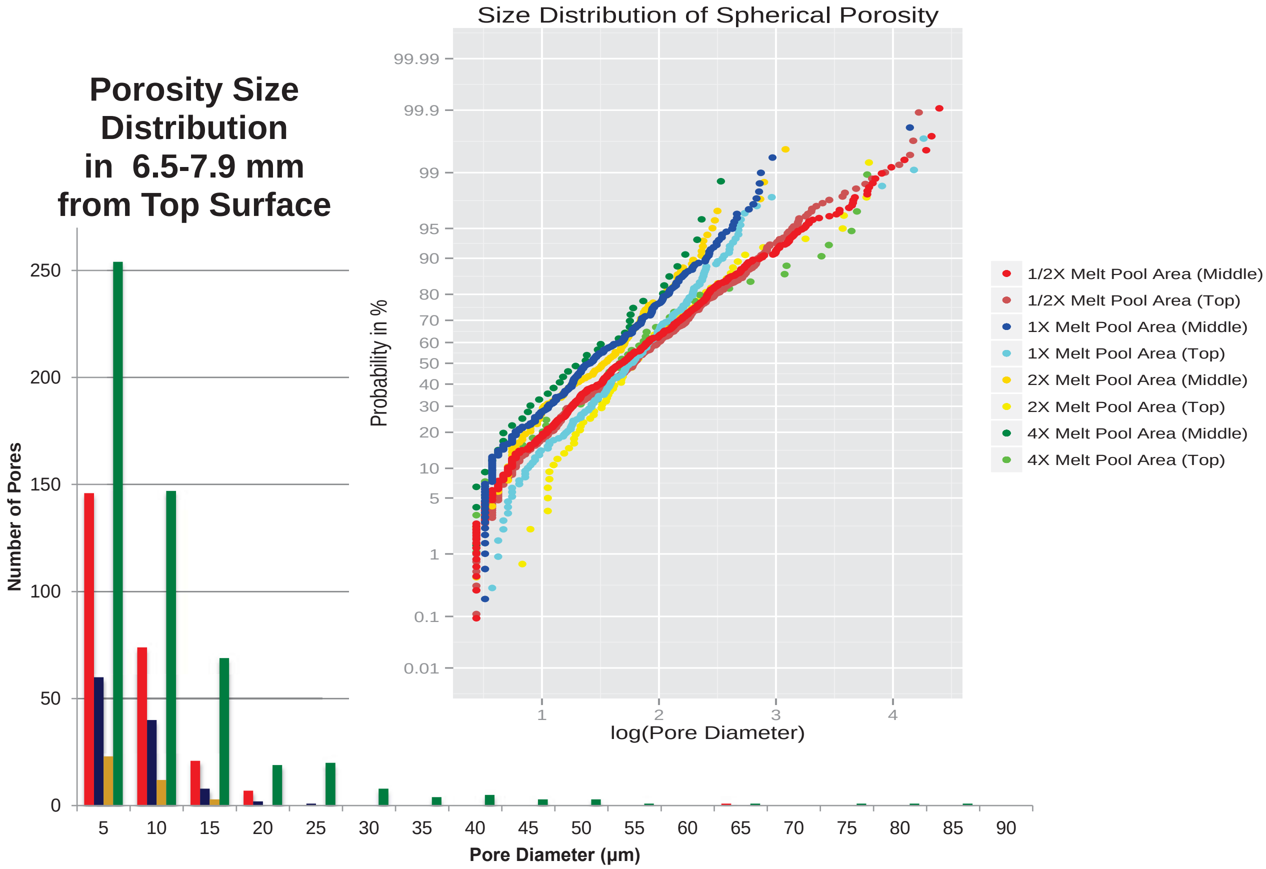
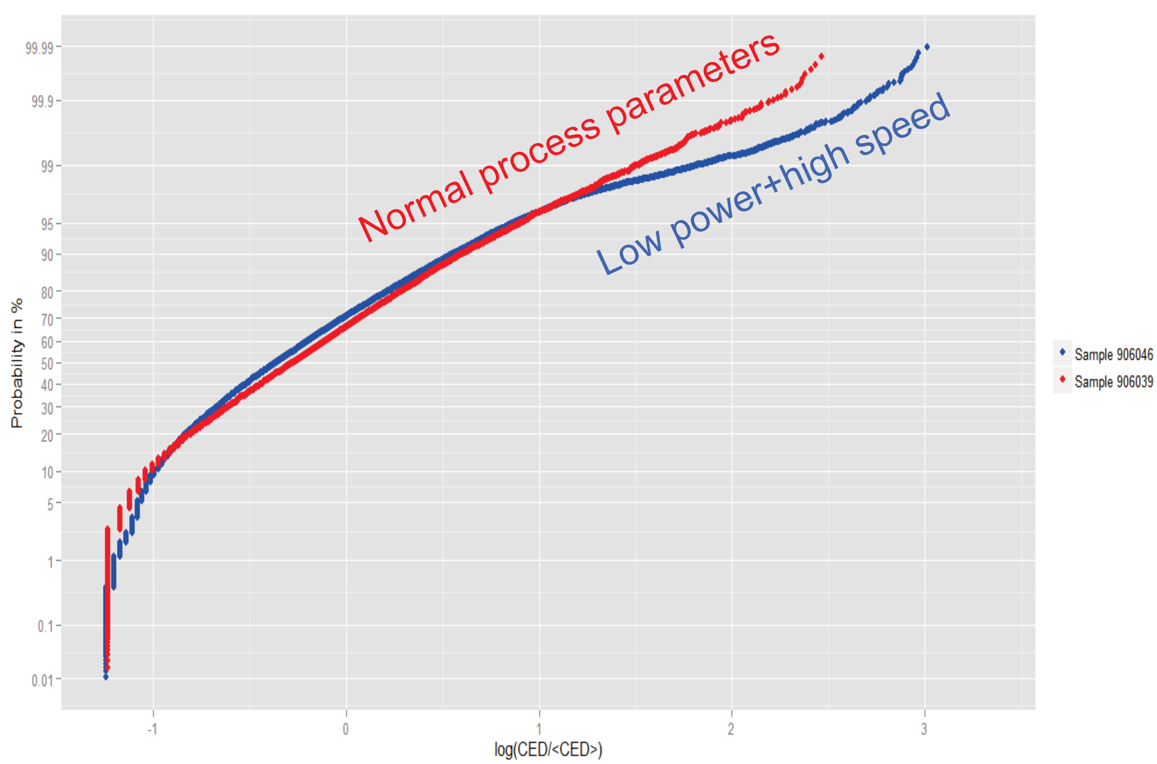


Ea



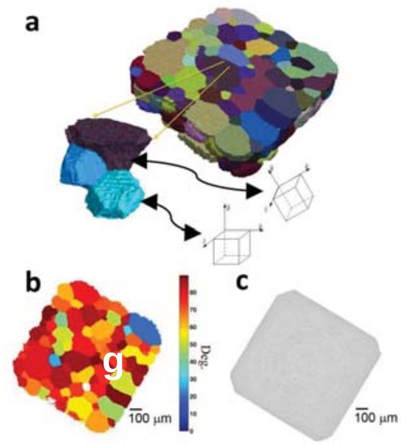
#39:

Fra

Three different process conditions, with very different void populations

Advanced Synchrotron Capabilities: CT+HEDM

- Recently completed **High Energy Diffraction Microscopy (HEDM)** experiment at 1-ID on AM Ti-6-4
- **3D microstructure and orientation information** with Near-Field mode
- **3D residual stress distribution** via Far-Field mode
- **Capability for** in situ **loading during CT, NF and FF; RAMS loading system developed by AFRL**



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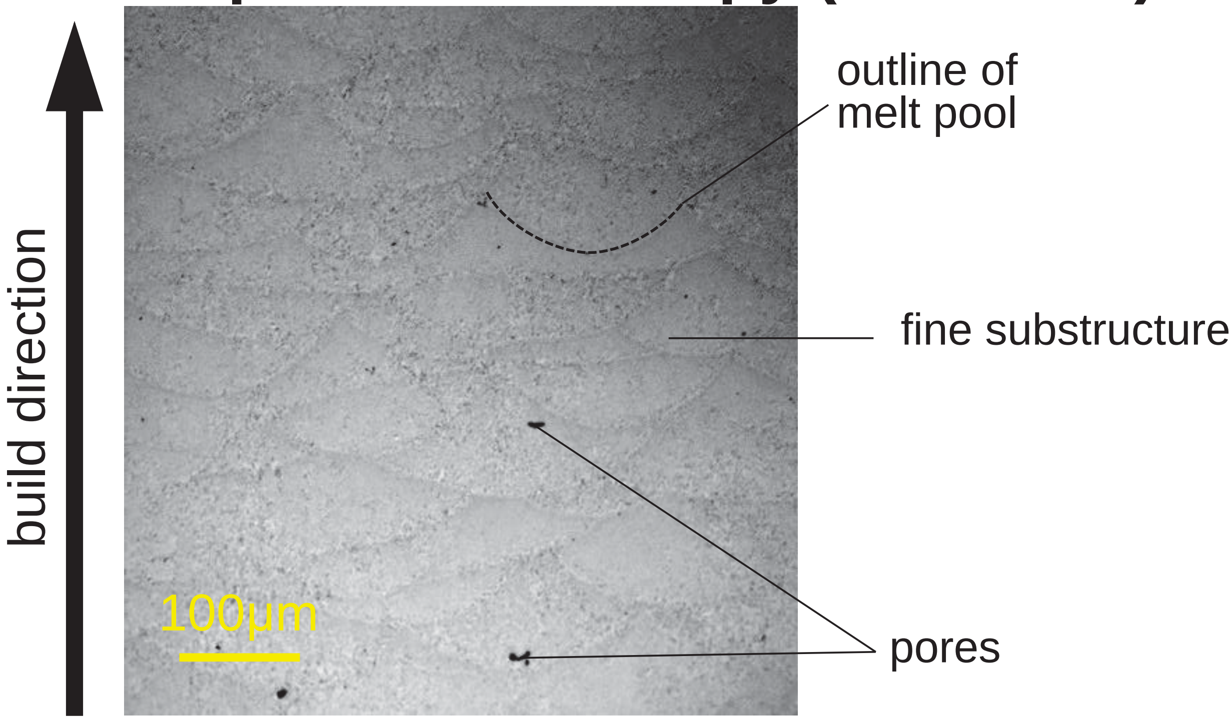
Advanced Characterization: Solidification Microstructures in Al-10Si-Mg

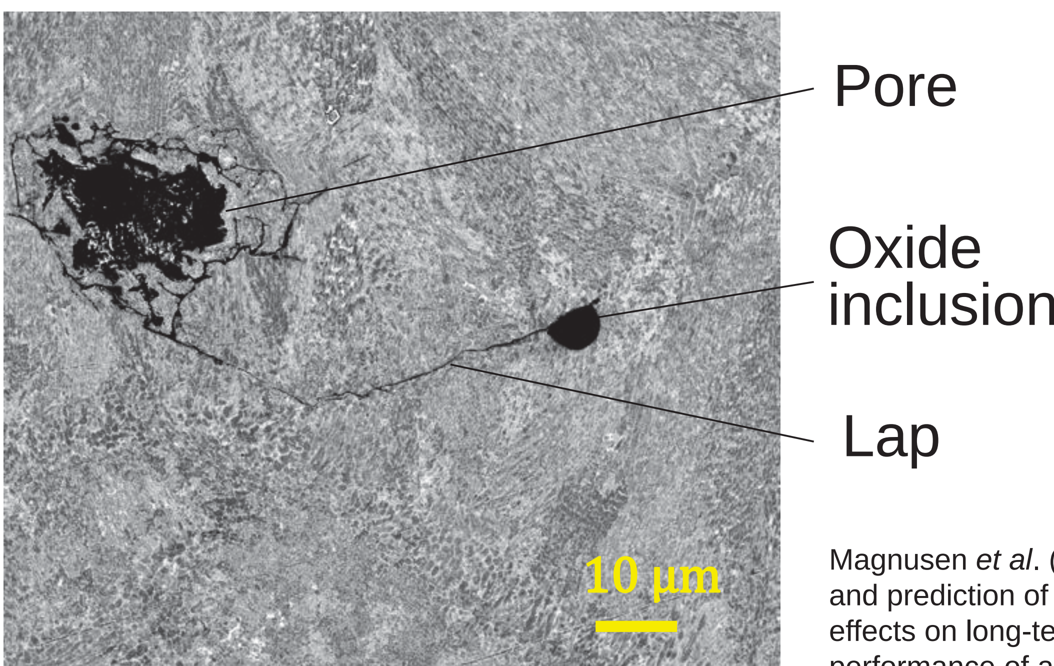
Chris Pistorius & Ming Tang
Materials Science and Engineering

PA-RAMP

Solidification microstructure - side-view – optical microscopy (unetched)



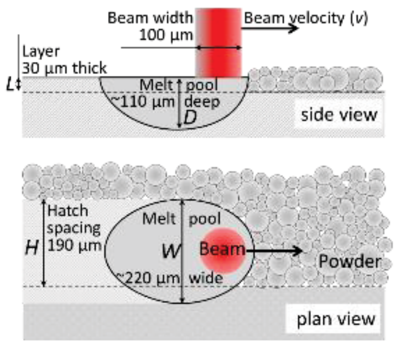
Lack-of-fusion defect – scanning electron microscopy



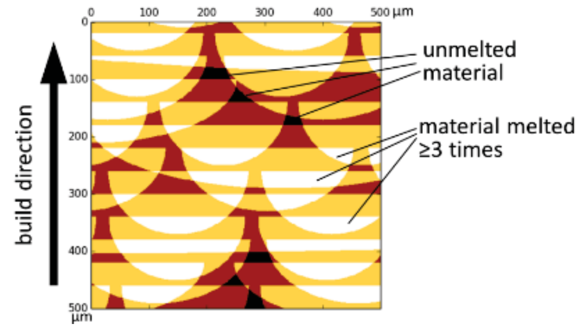
Backscattered electron image

Magnusen *et al*. (1997). Analysis and prediction of microstructural effects on long-term fatigue performance of an aluminum aerospace alloy. *Intl. J Fatigue*, **19** (Supp. 1), S275-S283.

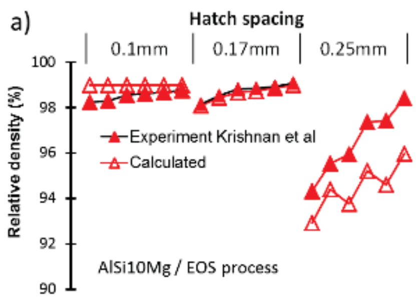
Porosity/Density Prediction



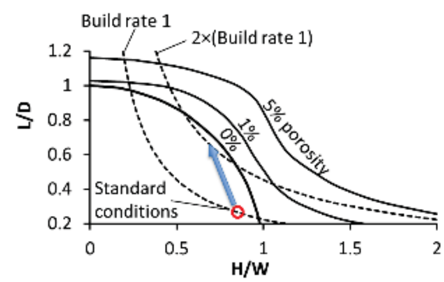
Melt pool geometry



Melt pool overlap across layers



Comparison of model with literature data



Comparison with standard operating point

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Microstructure Analysis, Synthetic Representation and Micromechanical Modeling of Additively Manufactured Ti Alloys

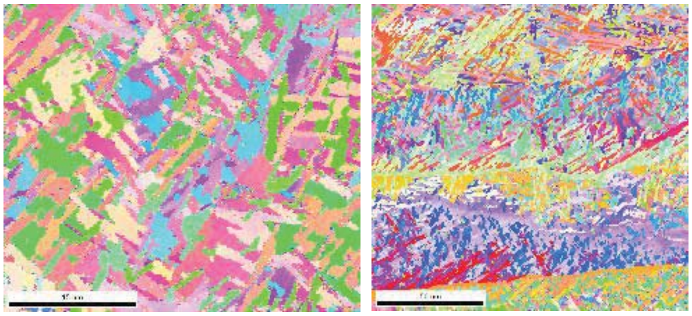
Tugce Ozturk, Ross Cunningham,
Anthony Rollett
Materials Science and Engineering

NSF-DMREF

www.cmu.edu

2-PHASE AM REPRESENTATIVE TI STRUCTURES
-- Effect of Microstructural Features on Mechanical Behavior --

‘How do the microstructural features such as the β-grain size, α-colony size and the relative volume fractions affect the overall mechanical response of Ti alloys



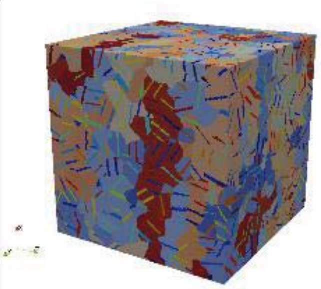
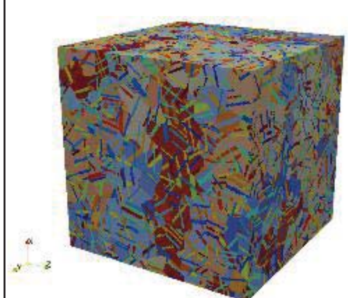
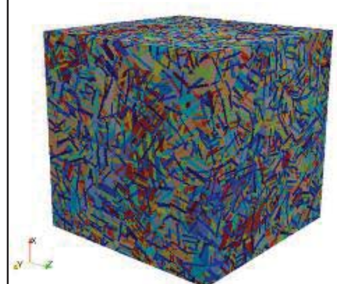
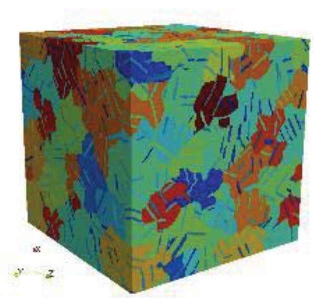
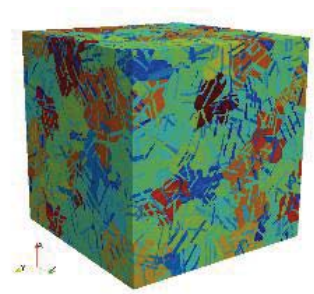
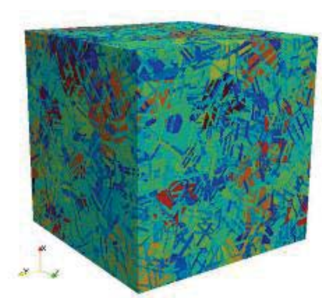
EBSD orientation maps of an additively manufactured near α Ti alloy (same sample, different scaling). Average β size is 100 microns and average α size is few microns.

- Based on the sensitivity study and the EBSD maps, 225^3 statistically representative microstructures are created with varying β (BCC) size-morphology and α (HCP) fractions.
- α particles → higher hardening parameters
- BCC to HCP transformation in Ti alloys (Burgers OR)

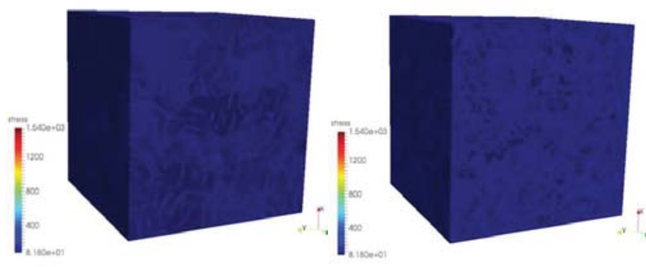
  (0001)*hcp* || {011}*bcc*

  [1120]*hcp* ||⟨111⟩*bcc*

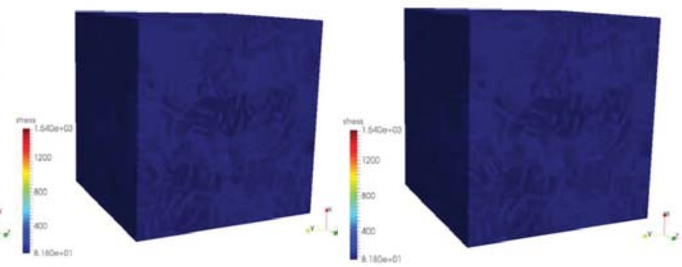
Variant number	BCC plane // to $(0001)_\alpha$	BCC direction // to $[11\bar{2}0]_\alpha$
1	(110)	$[\bar{1}1\bar{1}]$
2	(110)	$[1\bar{1}\bar{1}]$
3	$(1\bar{1}0)$	$[11\bar{1}]$
4	$(1\bar{1}0)$	[111]
5	(011)	$[11\bar{1}]$
6	(011)	$[\bar{1}1\bar{1}]$
7	$(01\bar{1})$	$[\bar{1}11]$
8	$(01\bar{1})$	[111]
9	(101)	$[\bar{1}11]$
10	(101)	$[11\bar{1}]$
11	$(\bar{1}01)$	$[1\bar{1}1]$
12	$(\bar{1}01)$	[111]

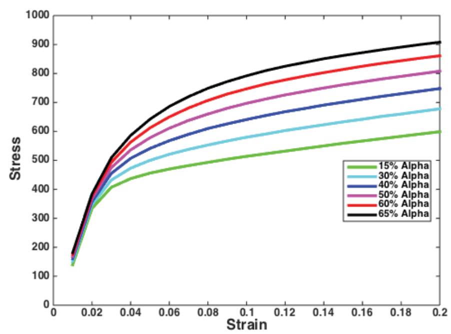
	15% Alpha	40% Alpha	65% Alpha
Columnar beta matrix			
Equiaxed beta matrix			

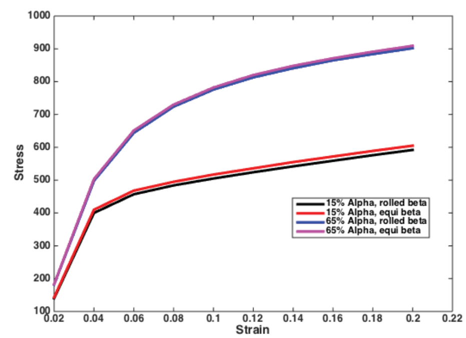
Effect of Alpha Fraction, Columnar Beta, Strain Along z*



Effect of Beta Morphology, Strain Along z*







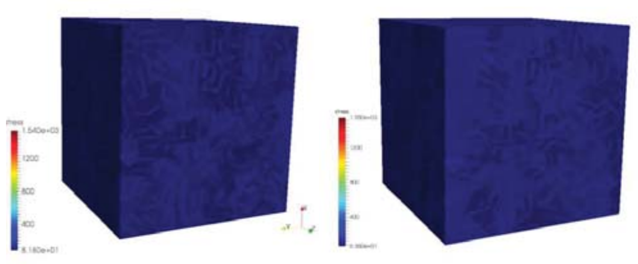
Effect of Alpha Fraction

As the alpha fraction increases, so does the overall strength.

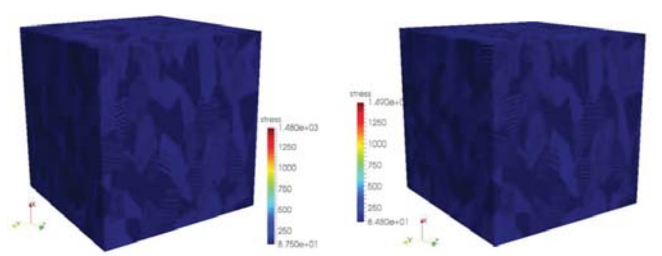
Effect of Beta Morphology

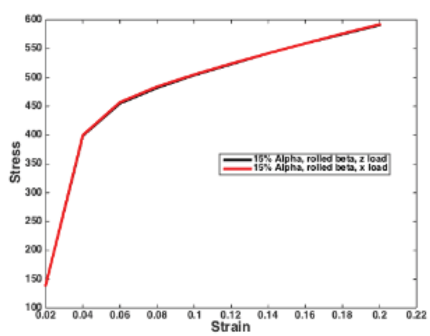
As the alpha fraction increases, β morphology effect diminishes for random textured β matrix.

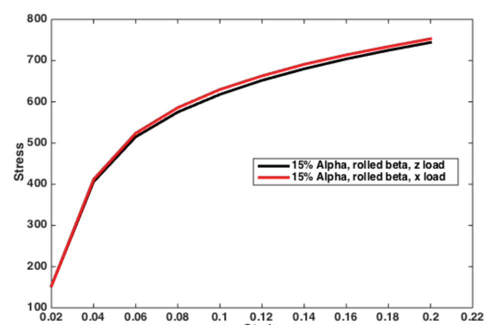
Effect of Loading Direction, Strain Along z vs. x (15% Alpha, Random texture)



Effect of Loading Direction, Strain Along z vs. x (15% Textured Alpha)







Effect of Loading Direction

- For textured (preferred rolling direction orientation) columnar β matrix, loading along the rolling direction decreases the strength.
- For the random texture, alpha dominates the response and effect of beta morphology is inconclusive.

Summary

- Understanding microstructure is important during every step in the additive manufacturing process.
- CMU addressing this challenge by combining
  - Computer vision, machine learning for microstructural image classification
  - Measurement of powders and defects, especially pores: analysis with extreme value statistics
  - Advanced characterization 3D microscopy with high energy synchrotron x-rays e.g. tomography of voids
  - Demonstrated ability to predict incomplete melting
  - Modeling of mechanical response using realistic representations of 3D multi-phase microstructures

Mechanical Behavior of Additive Manufactured Materials

Steve R. Daniewicz
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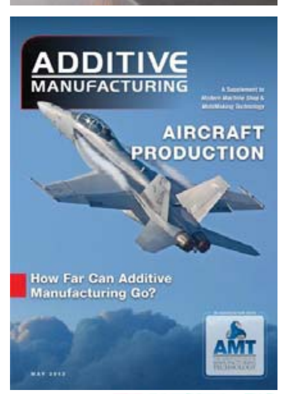
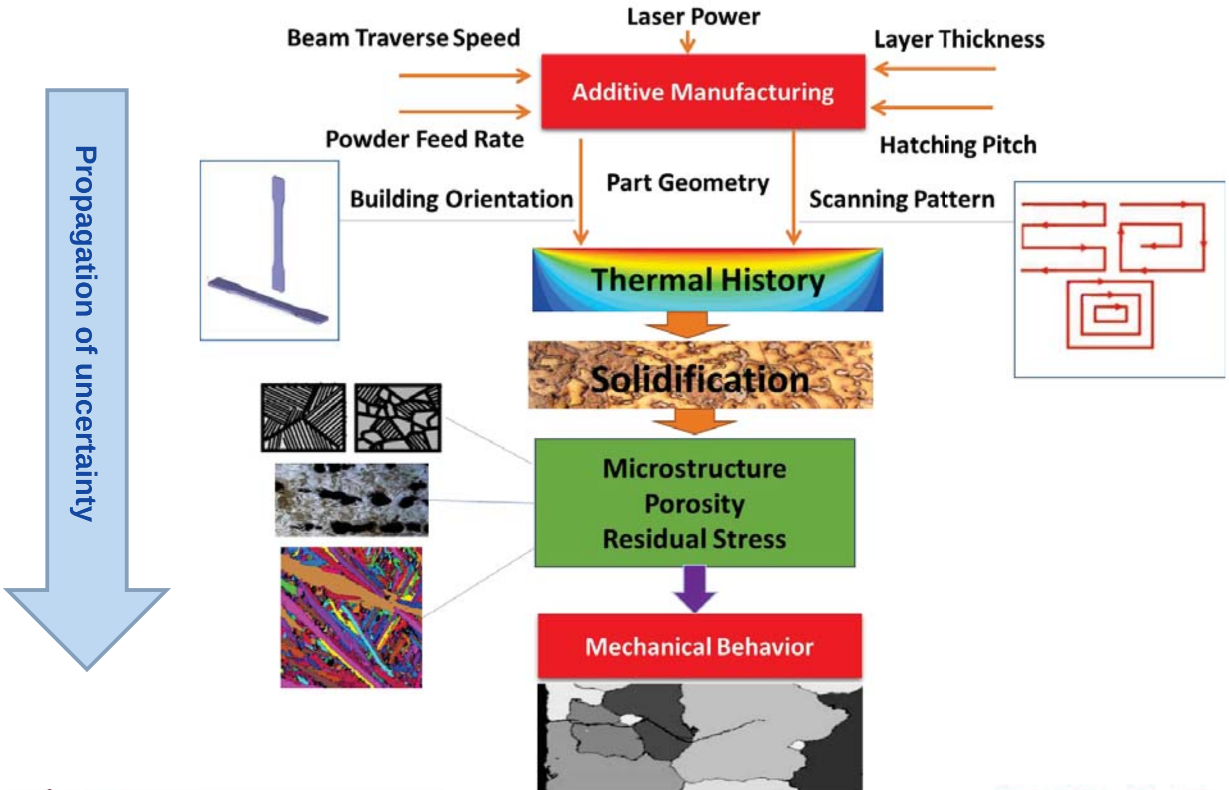
Joint FAA – Air Force Workshop
01 Sep 2015

Motivation for Adopting Additive Manufacturing

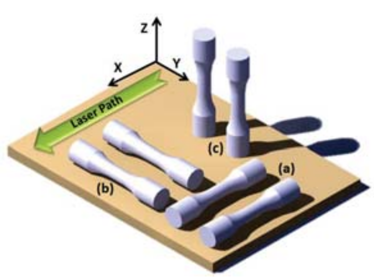
- Convert assemblies to integral parts
- Customize parts for specific applications
- Fabricate complex geometries
- Repair expensive parts
- Manufacture in remote locations
- Fabricate parts on demand
- Reduce weight and cost of parts
- Create "tailored" properties
- **Mechanical performance of AM parts need to be understood and certified**

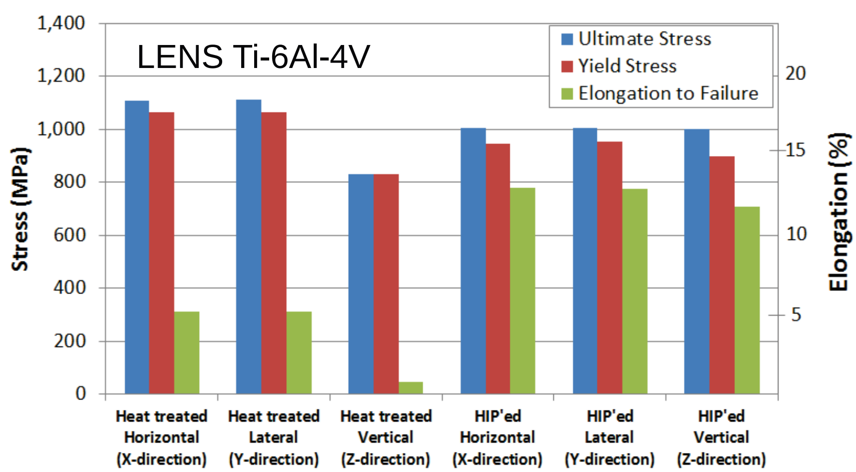


Additive Manufacturing Process



Tensile Behavior: Building Orientation

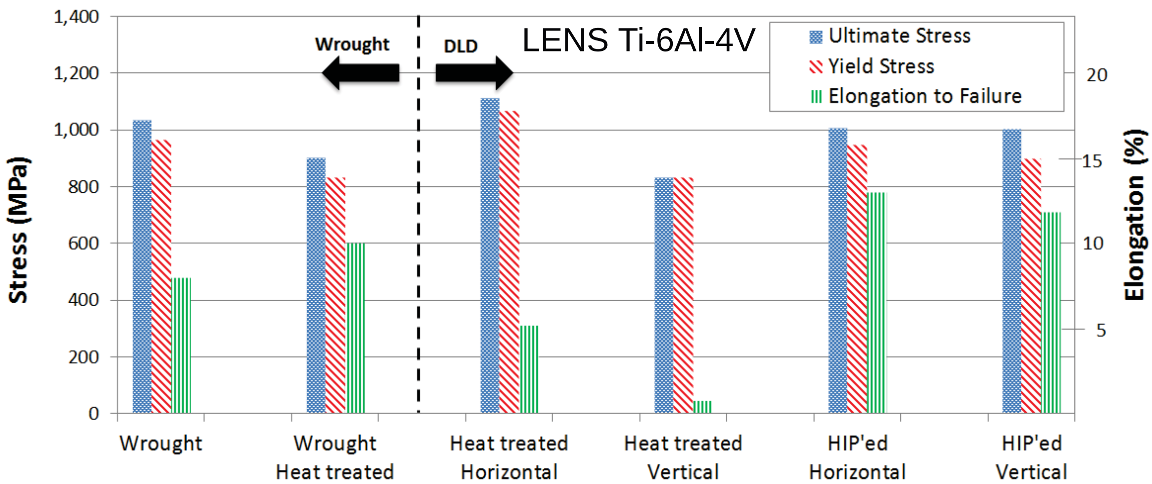




- No difference between X and Y specimens as the tool path rotated 90° between each layer
- Significant anisotropy between vertical and horizontal builds
- Post build heat treatment did not help
- Hot isostatic pressing (HIP) removed anisotropy and increased elongation, but reduced strength

P.A. Kobryn, S.L. Semiatin, Mechanical properties of laser-deposited Ti-6Al-4V, Solid Free. Fabr. Proceedings. Austin. (2001) 179–186.

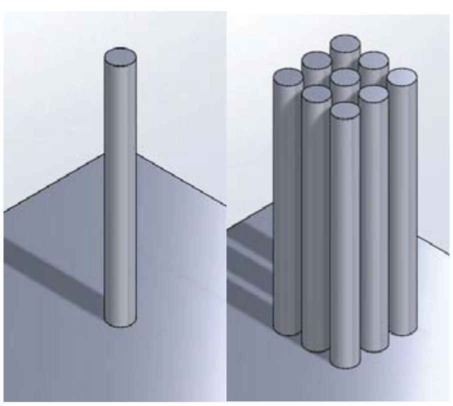
Tensile Behavior: Wrought vs. AM

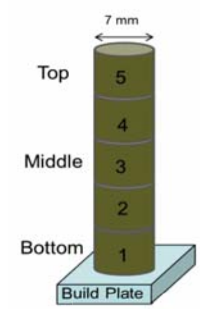


- Higher strength and less ductility/elongation compared to wrought

P.A. Kobryn, S.L. Semiatin, Mechanical properties of laser-deposited Ti-6Al-4V, Solid Free. Fabr. Proceedings. Austin. (2001) 179–186.

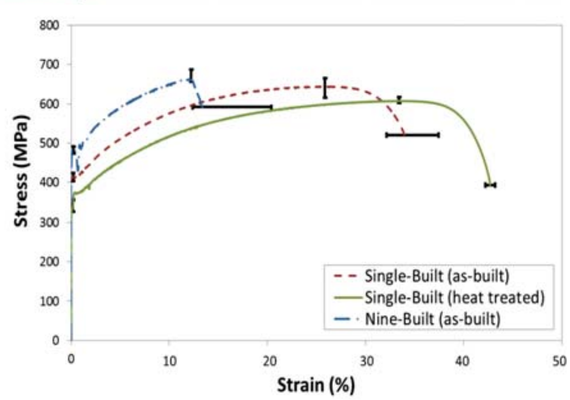
Effect of Size and Geometry





Yield Stress (MPa)		
Single-Built (as-built)	Single-Built (heat treated)	Nine-Built (as-built)
408	307	480
384	306	477
350	301	475
390	321	485
410	322	487

LENS 316L SS



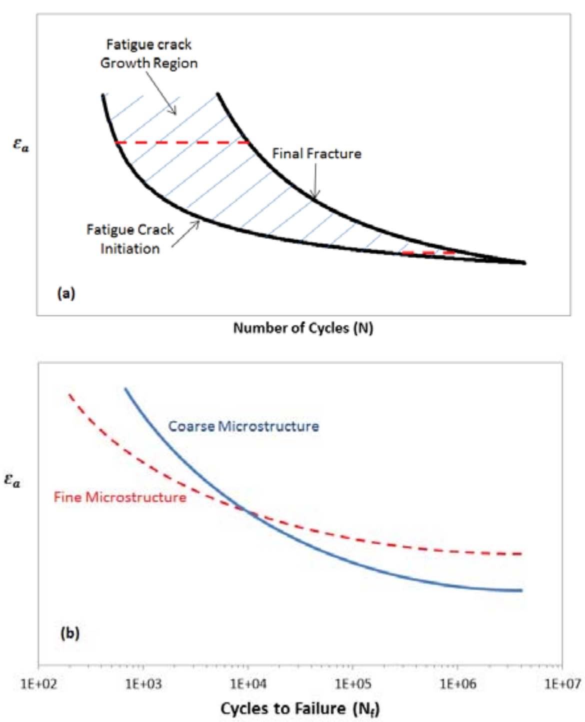
- Process and design parameters should be adjusted depending on part's dimensions/geometry
- Mechanical properties vary within the parts

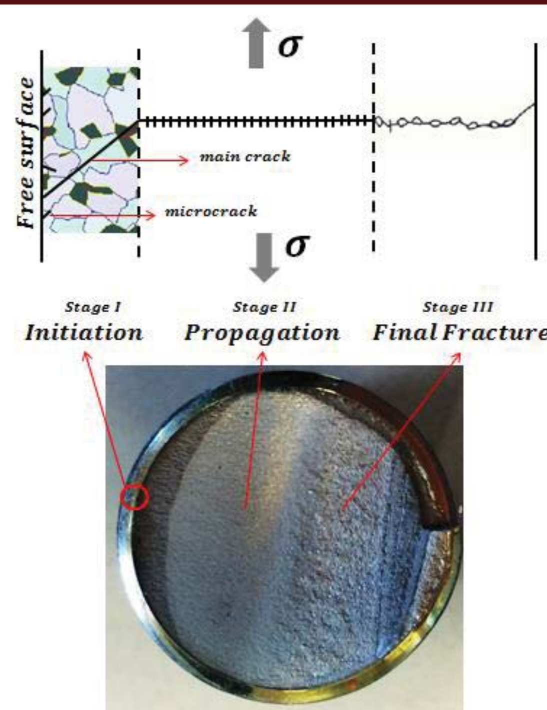
Yadollahi, A., Shamsaei, N., Thompson, S.M., Seely, D., 2015, "Effects of Time Interval and Heat Treatment on the Mechanical and Microstructural Properties of Direct Laser Deposited 316L Stainless Steel," *Materials Science and Engineering A*, **644**, pp. 171-183.

Monotonic Tensile Behavior: Summary

- Significant directionality (anisotropy) in strength
- AM parts have higher strength but lower ductility
- Post build processes (e.g. machining, heat treatment) can be used to increase ductility and reduce directionality
- Process parameters should change with part size and number
- AM parts are not homogeneous; as microstructure and mechanical properties vary within part

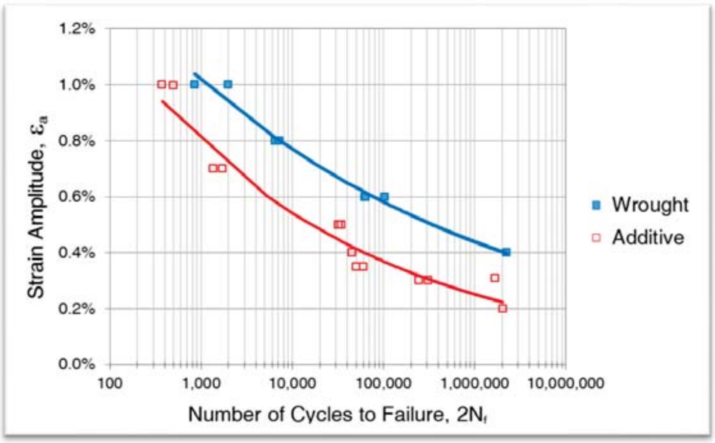
Fatigue: Background





Fatigue of AM Ti-6Al-4V

Strain Life Curve: Wrought & LENS Ti-6Al-4V



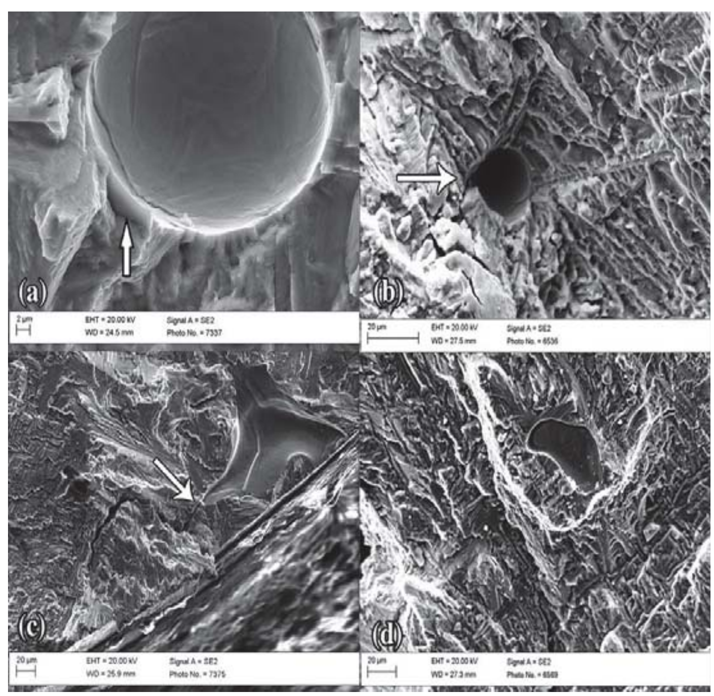
- **An order of magnitude** shorter fatigue lives for AM samples as compared to wrought samples.
- Such shorter fatigue lives may be related to the lack of ductility as well as presence of defects in AM samples.

Sterling, A.J., Torries, B., Lugo, M., Shamsaei, N., Thompson, S.M., 2015, "Fatigue Behavior of Ti-6Al-4V Alloy Additively Manufactured by Laser Engineered Net Shaping," _56th AIAA/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference_ Kissimmee, FL.

Porosity in AM Ti-6Al-4V

Fatigue life decreases with presence of:

- Larger pores
- Near-surface pores
- Closely-packed pores (pore density)
- More irregularly-shaped pores



- Some porosity introduced by partially melted (un-melted) particles
- Very little correlation was found between the number of pores and fatigue life of specimens

Sterling, A.J., Torries, B., Lugo, M., Shamsaei, N., Thompson, S.M., 2015, "Fatigue Behavior of Ti-6Al-4V Alloy Additively Manufactured by Laser Engineered Net Shaping," _56th AIAA/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference_ Kissimmee, FL.

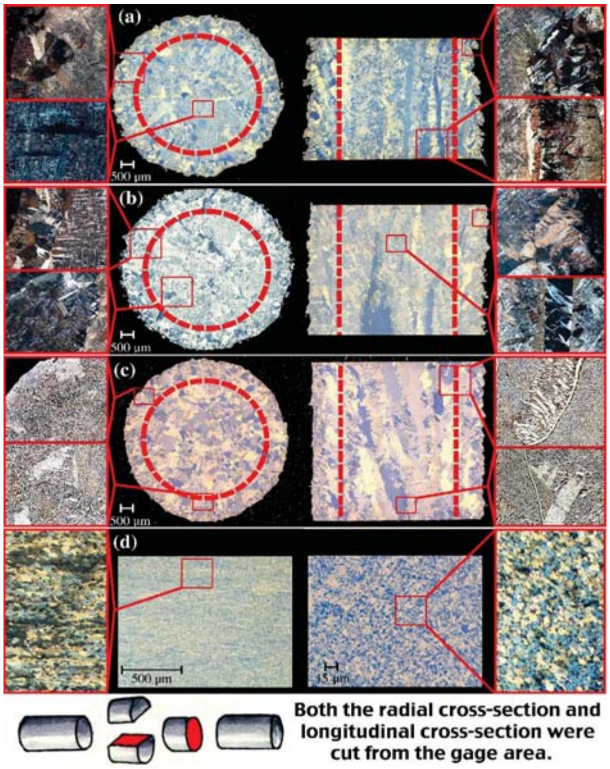
Effect of Heat Treatment on AM Ti-6Al-4V

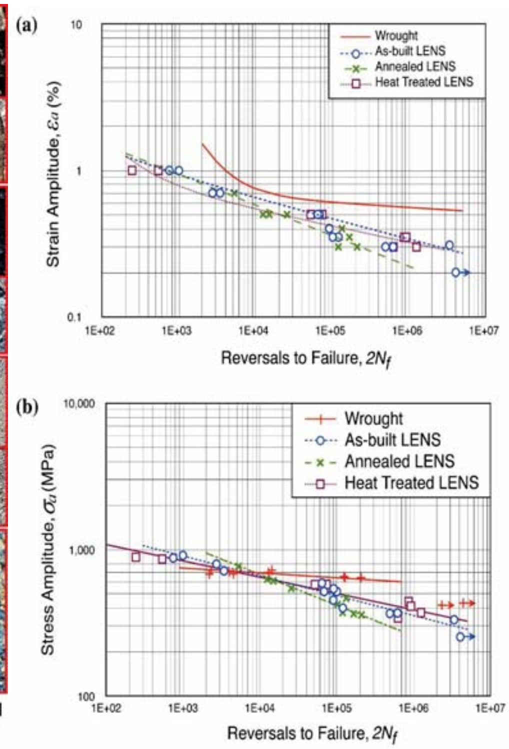
As-built

Annealed below β-transus temperature

Heat treated above β-transus temperature

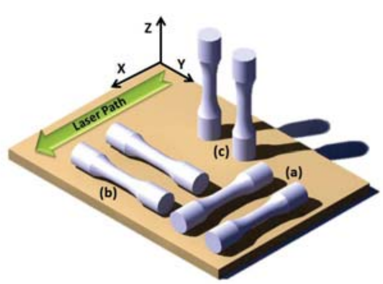
Wrought

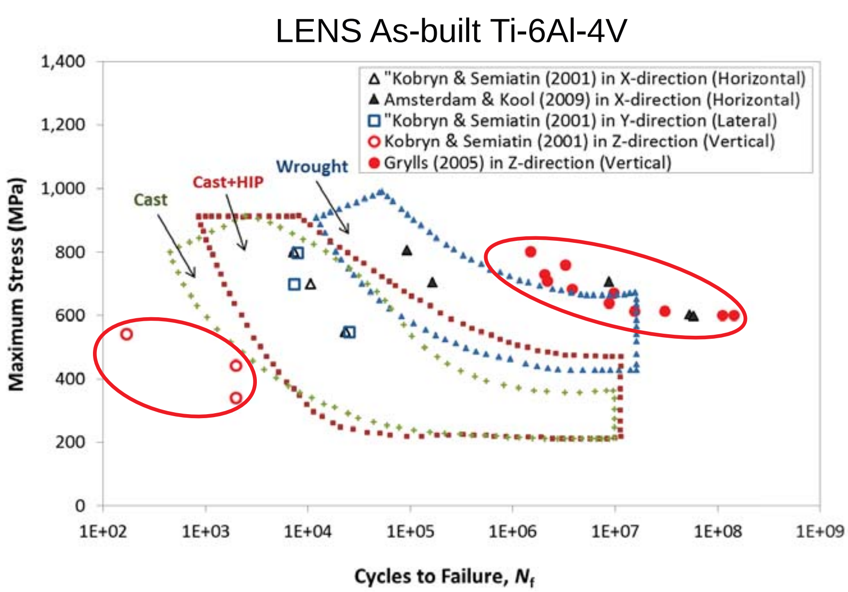




Sterling, A.J., Torries, B., Lugo, M., Shamsaei, N., Thompson, S.M., 2015, "Fatigue Behavior of Ti-6Al-4V Alloy Additively Manufactured by Laser Engineered Net Shaping," *56th AIAA/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference* Kissimmee, FL.

Anisotropy Effect on Fatigue Behavior of AM Parts





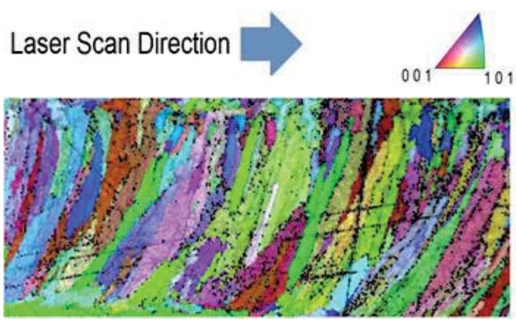
- Significant anisotropy effects
- Different process parameters results in different mechanical behavior
- Lack of process/testing standardization causes variability in results

Post-Processing via HIP

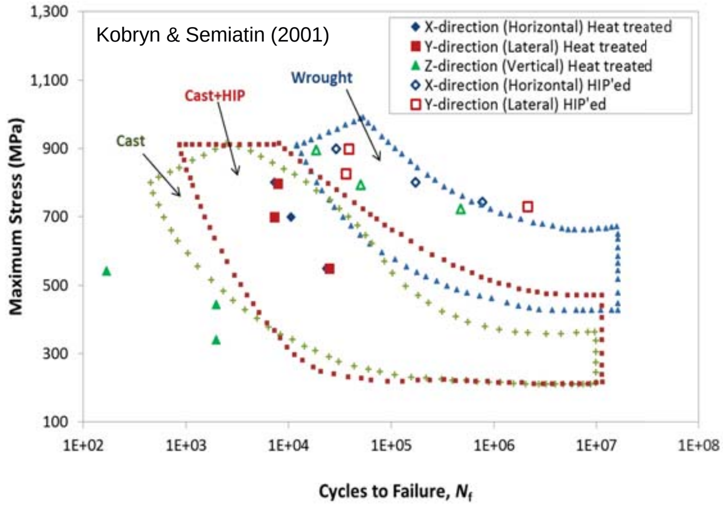
Hot Isostatic Pressing (HIP)

- reduce anisotropy
- improve fatigue resistance

However, any targeted microstructural features (a known benefit of AM) are removed

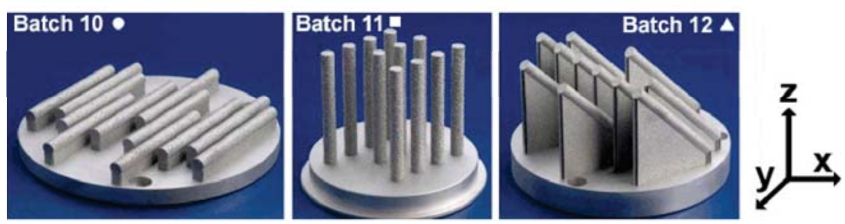


LENS Ti-6Al-4V

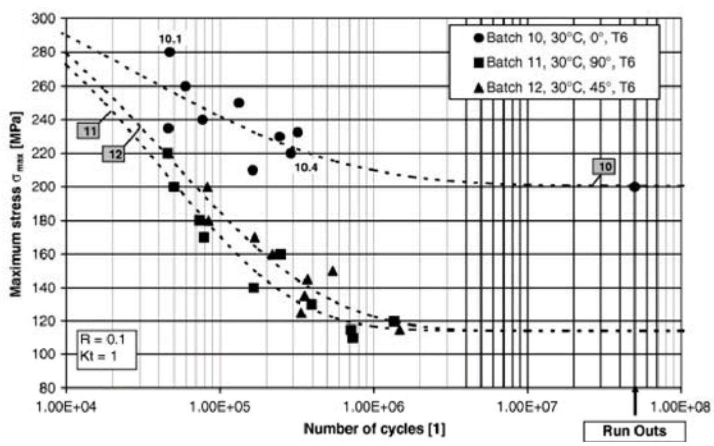


- EBSD image of a single layer deposited by LENS
- Microstructural tailoring for enhancing structural integrity

Anisotropy in SLM Parts

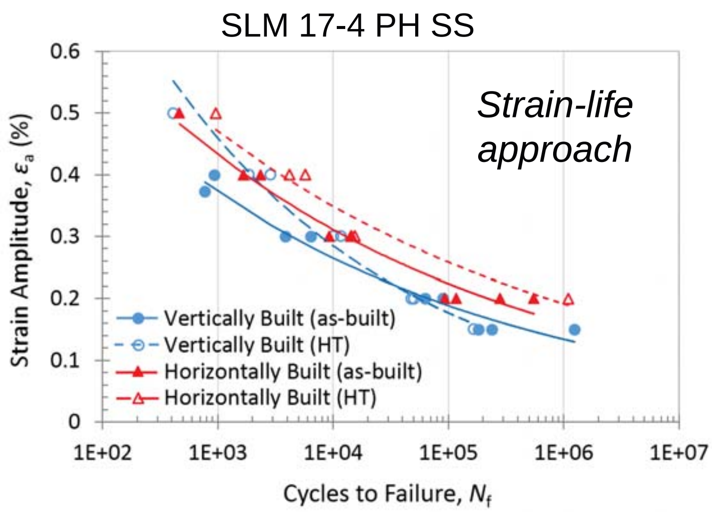


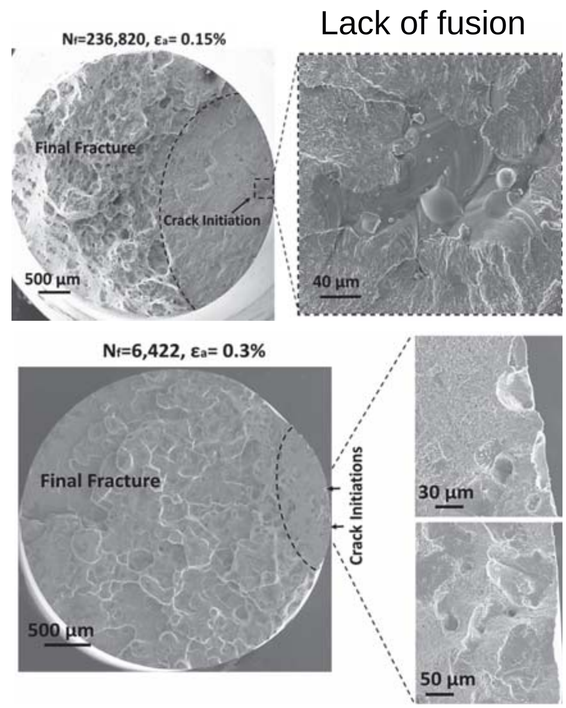
Stress-life approach



Brandl, E., Heckenberger, U., Holzinger, V., & Buchbinder, D. (2012). Additive manufactured AlSi10Mg samples using Selective Laser Melting (SLM): Microstructure, high cycle fatigue, and fracture behavior. Materials & Design, 34, 159-169.

Effects of Post-Processing on SLM Parts

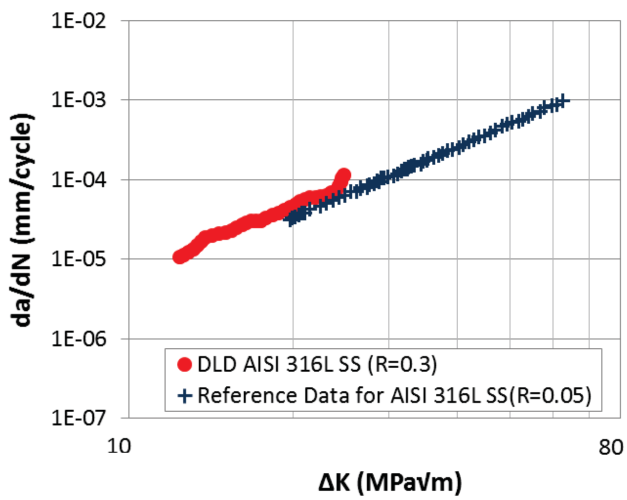




- **Significant anisotropy**
- **Cracks initiate from near surface defects**
- **Heat treatment:**
  - **did not reduce anisotropy**
  - **but, improved fatigue resistance**

Aref Yadollahi, Nima Shamsaei, Scott M. Thompson, Alaa Elwany, Linkan Bian, Fatigue Behavior of Selective Laser Melted 17-4 PH Stainless Steel, Solid Free. Fabr. Proceedings. Austin. (2015).

Fatigue Crack Growth Behavior in AM Parts

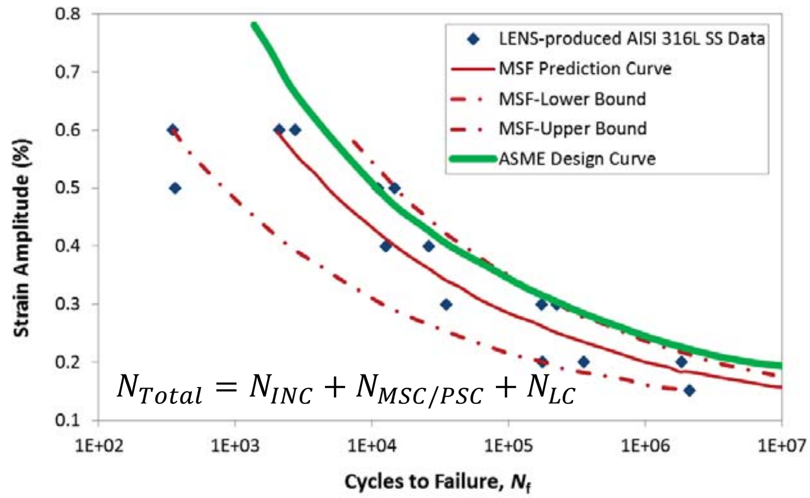


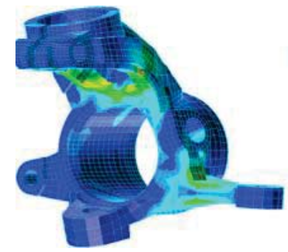
- Crack growth resistance of AM parts may be superior to wrought materials if appropriate process and design parameters are utilized
- In general, fatigue crack growth resistance of AM parts is not well understood

P. Ganesh, R. Kaul, G. Sasikala, H. Kumar, S. Venugopal, P. Tiwari, et al., Fatigue Crack Propagation and Fracture Toughness of Laser Rapid Manufactured Structures of AISI 316L Stainless Steel, Metallogr. Microstruct. Anal. 3 (2014) 36–45.

Microstructure-Sensitive Fatigue Model

LENS 316L SS





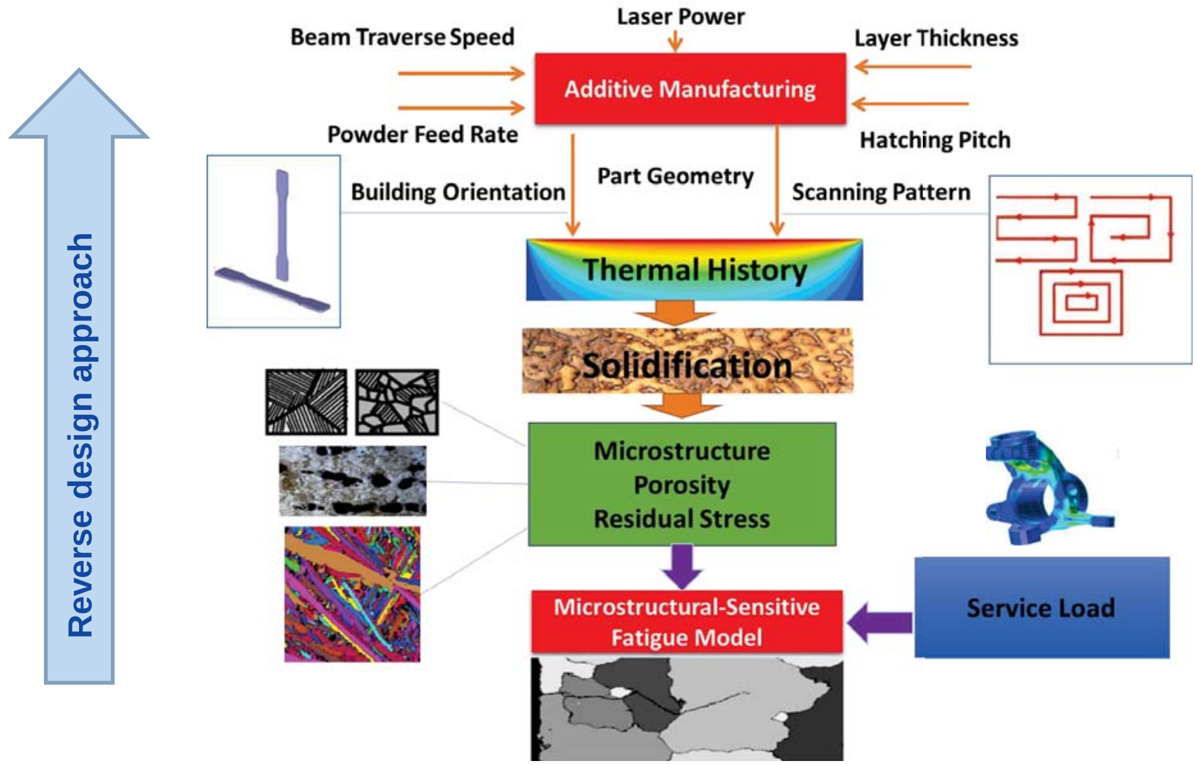
- Fatigue behavior of AM parts mainly depends on the microstructure resulting from processing and design parameters
- A **microstructure-sensitive fatigue model** that can incorporate microstructural features may be appropriate for modeling the fatigue behavior of AM parts
- ***Both*** stress and strength vary within the AM part

Y. Xue, A. Pascu, M.F. Horstemeyer, L. Wang, P.T. Wang, Microporosity effects on cyclic plasticity and fatigue of LENS-processed steel, Acta Mater. 58 (2010) 4029–4038.

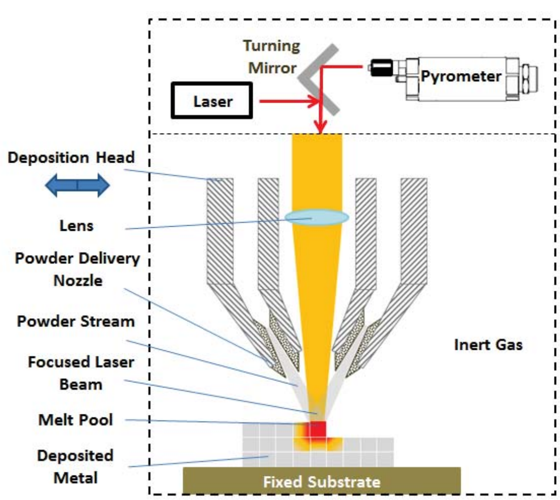
Fatigue Behavior: Summary

- Significant directionality
- Cracks initiate from pores, un-melted powder particles, and at regions with lack of fusion
- Post build treatments can reduce anisotropy and improve fatigue resistance; however, it removes any benefits gained from anisotropy
- Microstructure-sensitive fatigue models can be developed and calibrated for AM parts – reflecting the microstructural effects on fatigue behavior
- Depending on manufacturing and post-manufacturing process parameters, fatigue of AM parts can be superior or inferior to traditionally-manufactured parts
- Extensive research needed to better understand process-property-performance relationships for AM materials

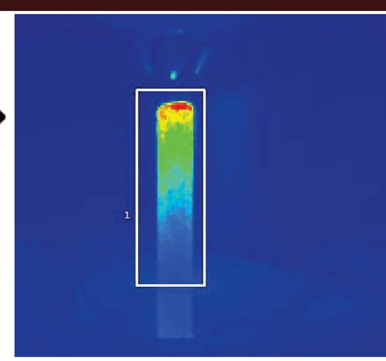
Application Driven Design for Additive Manufacturing



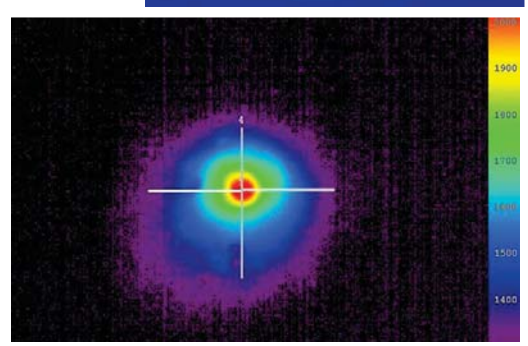
In-Situ Thermal Monitoring and Control



Thermal profile of part



Molten pool temperature distribution



Thermography Benefits

- Quantify cooling rates, thermal history
- Real-time part quality/features control

Ongoing Challenges

- Residual stresses and distortion
- Surface finish
- Is there an endurance limit for AM materials?
- Quantification of uncertainty in AM processes
- Certification/Standards
- In-situ- and post-quality control
- Fatigue behavior under torsion and multi-axial loading (possible benefits of directional properties)
  - Should we use HIP for all products? Post-processing?
  - Process/design optimization may be a better approach in minimizing defects

Questions?

Please contact:

Steve R. Daniewicz
daniewicz@me.msstate.edu

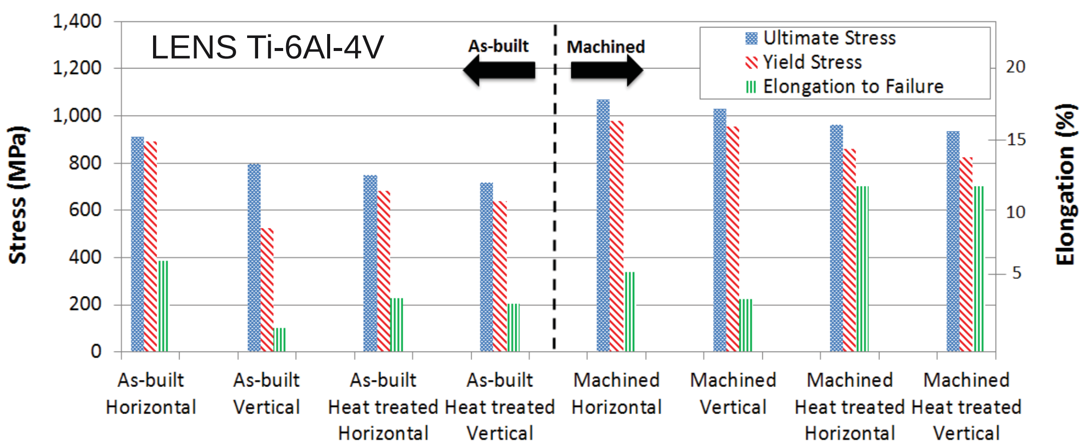
This presentation has been based on the following articles:

Scott M Thompson, Linkan Bian, Nima Shamsaei, Aref Yadollahi. **An overview of Direct Laser Deposition for additive manufacturing; Part I: Transport phenomena, modeling and diagnostics.** Additive Manufacturing. Vol. 8, pp. 36-62.

Nima Shamsaei, Aref Yadollahi, Linkan Bian, Scott M Thompson. **An overview of Direct Laser Deposition for additive manufacturing; Part II: Mechanical behavior, process parameter optimization and control***.* Additive Manufacturing. Vol. 8, pp. 12-35.

Back Up Slides

Tensile Behavior: Effect of Machining



- Machining removes the outer surface and improves strength and ductility
- Specimen core has mostly columnar microstructure parallel to loading direction
- Residual stresses can be removed by the post build machining
- Machining also reduces the effects of building orientation

Alcisto, J. et al. Tensile Properties and Microstructures of Laser-Formed Ti-6Al-4V. *Journal of Materials Engineering and Performance*, 20, (2010) 203–212.

Tensile Behavior: Common Trends

Alloys	Ultimate Stress (MPa)		Yield Stress (MPa)		Elongation to failure (%)		AM Process
	Wrought	DLD	Wrought	DLD	Wrought	DLD	
316 SS	586[1]	758[1]	234[1]	434[1]	50[1]	46[1]	LENS
316L SS	480[*2]	540-560[3]	170[*2]	330-345[3]	40[*2]	35-43[3]	Laser consolidation
404L SS	…	655[1]	276[1]	324[1]	55[1]	70[1]	LENS
AISI H-13	1,725[1]	1,703[1]	1,448[1]	1,462[1]	12[1]	1-3[1]	LENS
CPM-9V	…	1,315[3]	…	821[3]	…	>2[3]	Laser consolidation
Ti-6Al-4V	931[‡1]	896-1,000[‡1]	855[‡1]	827-965[‡1]	10[‡1]	1-16[‡1]	LENS
TC-18	1,157[‡5]	1,147-1,188[‡5,6]	1,119[‡5]	1,095[‡5,6]	14[‡5]	4.5-5.75[‡5,6]	Laser melting deposition
IN-718[3]	1,379[†1]	1,400[†1]	1,158[†1]	1,117[†1]	20[†1]	16[†1]	LENS
IN-625	834[1]	931[1]	400[1]	614[1]	37[1]	38[1]	LENS
IN-600	660[‡1]	731[1]	285[‡1]	427[1]	45[‡1]	40[1]	LENS
IN-690	725[4]	665[3]	348[4]	450[3]	41[4]	49[3]	DLF
IN-738	1,095[4]	1,200[3]	950	870[3]	6.5[4]	18[3]	Laser consolidation

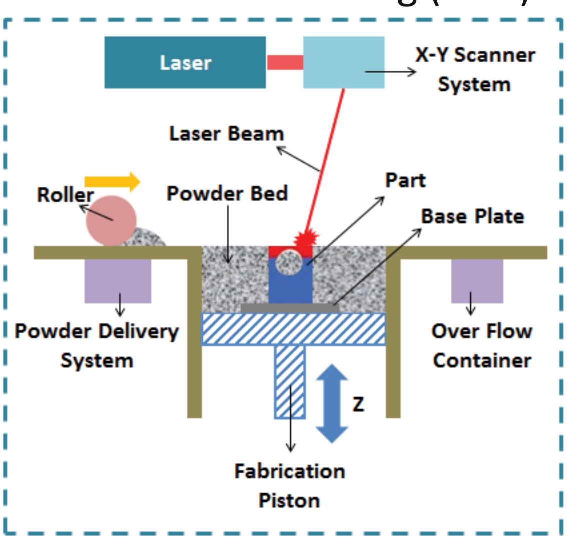
[*] Hot finished-annealed.
[‡] Annealed.
[†] Solution treated and annealed.

[1] C. Selcuk, Laser metal deposition for powder metallurgy parts, Powder Metall. 54 (2011) 94–99.
[2] ASM Handbook, ASM Handbook Volume 3, Alloy Phase Diagrams., Mater. Park. OH ASM Int. (1992).
[3] L. Costa, R. Vilar, Laser powder deposition, Rapid Prototyp. J. 15 (2009) 264–279.
[4] Nickel, Cobalt, and Their Alloys, ASM International, 2000.
[5] Y. Wang, S. Zhang, X. Tian, H. Wang, High-cycle fatigue crack initiation and propagation in laser melting deposited TC18 titanium alloy, Int. J. Miner. Metall. Mater. 20 (2013) 665–670.
[6] Z. Li, X. Tian, H. Tang, H. Wang, Low cycle fatigue behavior of laser melting deposited TC18 titanium alloy, Trans. Nonferrous Met. Soc. China. 23 (2013) 2591–2597

Laser Based Additive Manufacturing

Powder Bed Fusion

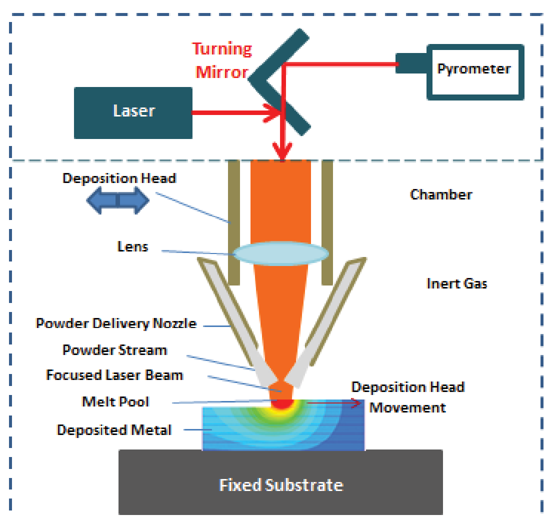
Selective Laser Melting (SLM)



- *Good surface finish*
- *High precision*
- *Very complex geometries*

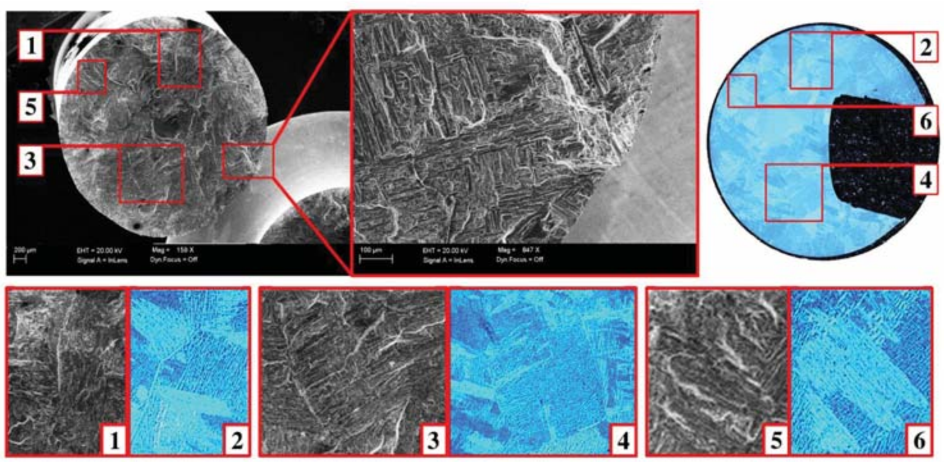
Direct Laser Deposition

Laser Engineered Net Shaping (LENS)



- *Multi material feeding*
- *High build rates*
- *Parts repair*

Failure Mechanisms of Heat Treated AM Ti-6Al-4V



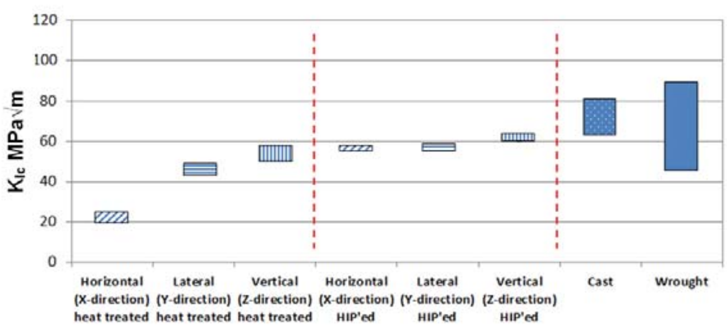
No porosity was found on the fracture surface

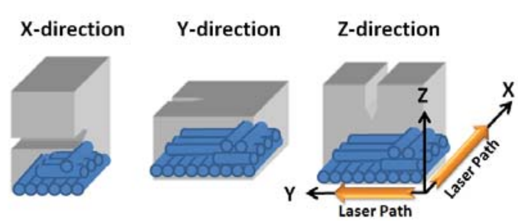
Currently under investigation to find the underlying microstructure on crack initiation and propagation sites

Sterling, A.J., Torries, B., Lugo, M., Shamsaei, N., Thompson, S.M., 2015, "Fatigue Behavior of Ti-6Al-4V Alloy Additively Manufactured by Laser Engineered Net Shaping," _56th AIAA/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference_ Kissimmee, FL.

Fracture Toughness

LENS Ti-6Al-4V





Significant anisotropy

HIP process can:

- reduce anisotropy
- Improve fracture toughness

P.A. Kobryn, S.L. Semiatin, Mechanical Properties of Laser-Deposited Ti-6Al-4V, Solid Free. Fabr. Proceedings. Austin. (2001) 179–186.

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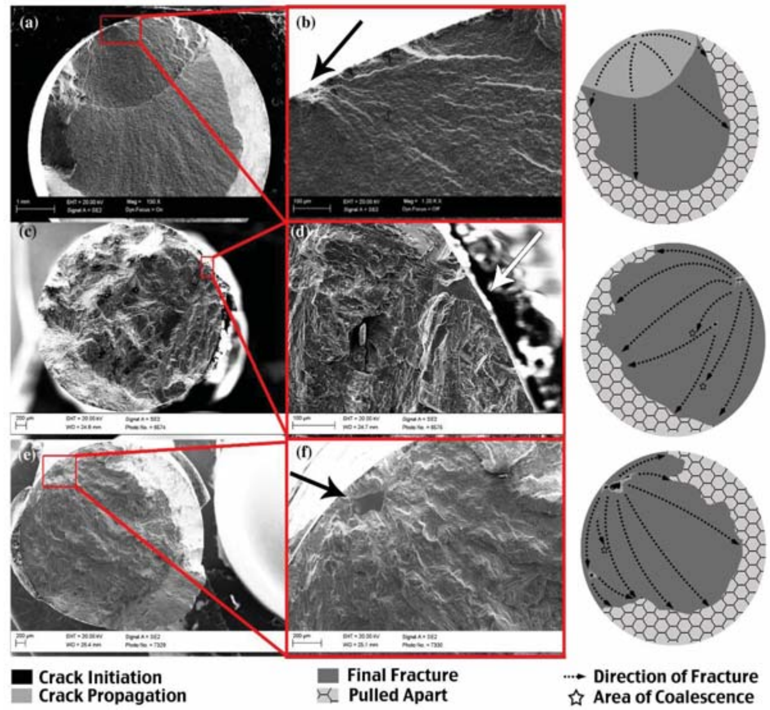
Failure Mechanisms of Wrought and AM Ti-6Al-4V

Wrought Ti-6Al-4V

As-built LENS

Annealed LENS

No difference between LENS as-built and annealed



Sterling, A.J., Torries, B., Lugo, M., Shamsaei, N., Thompson, S.M., 2015, "Fatigue Behavior of Ti-6Al-4V Alloy Additively Manufactured by Laser Engineered Net Shaping," _56th AIAA/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference_ Kissimmee, FL.

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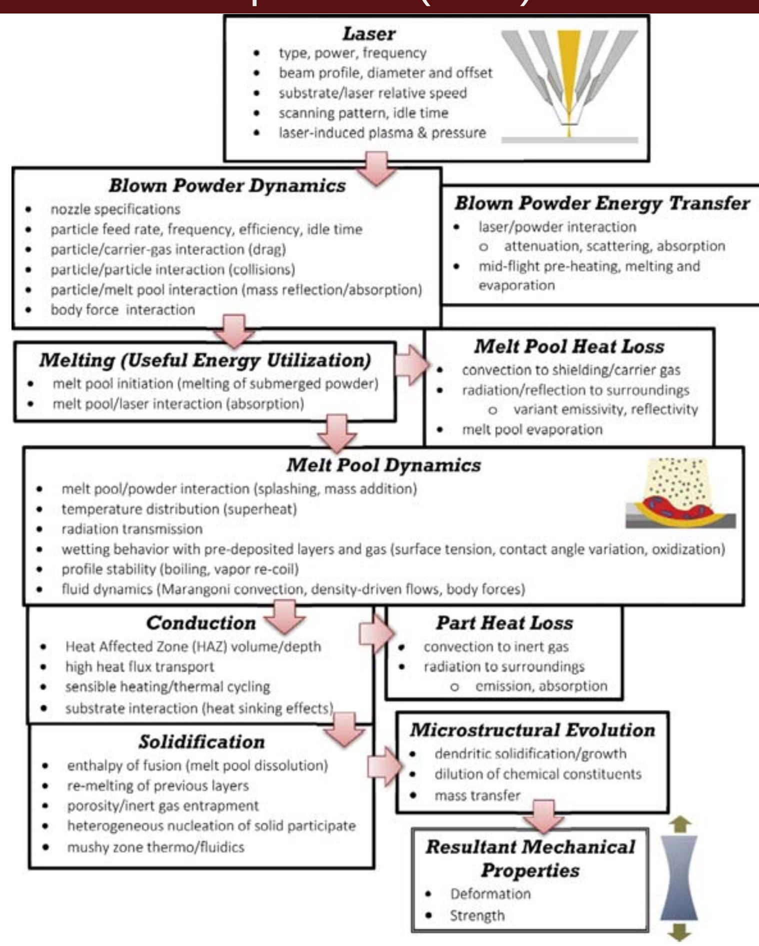
Physical Events During Direct Laser Deposition (DLD)

Add discussion



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Additive Manufacturing: Large Potential

- Actual parts are now being manufacturing
- **Don't fly with them yet!**

Facilities at Mississippi State

Direct Laser Deposition (DLD)

- OPTOMEC LENS 750 w/ 1 kW laser and multi-camera thermal monitoring
- Multi-powder feeder for functional-grading

Laser Powder Bed Fusion

- 400 W system to-be-installed at CAVS
- Thermal monitoring system to-be-installed

Materials characterization equipment

- Mechanical testing (fatigue, tension, etc.)
- Microstructural characterization
  - EBSD, Microscopy, X-Ray tomography

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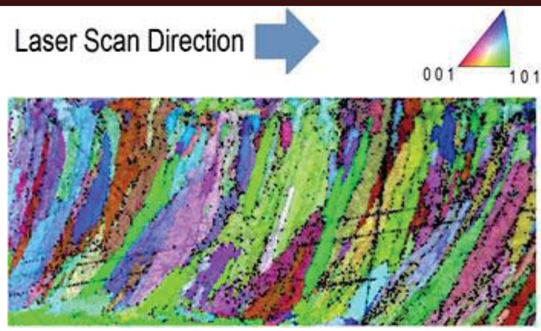
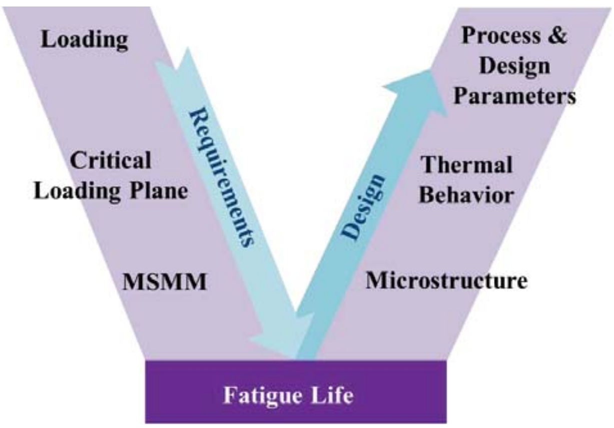
CAVS

Using AM for “Tailoring” Materials for Application



EBSD image of a single layer from LENS Ti-6Al-4V



Premise:

HPC

- Quantify service environment and potential loading
- Use a microstructurally-sensitive mechanical model (MSMM) to predict part performance virtually
- Optimize microstructure and determine a target thermal history
- Determine process/design parameters to produce parts via additive manufacturing

- **Build actual part for service**

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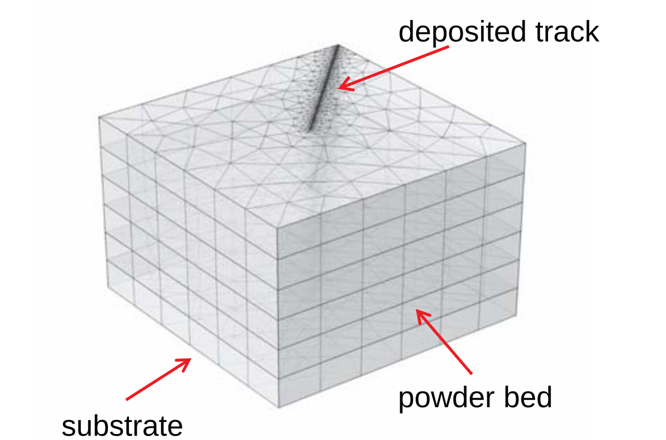
CAVS

Simulation of SLM Process (Thin Wall Build)

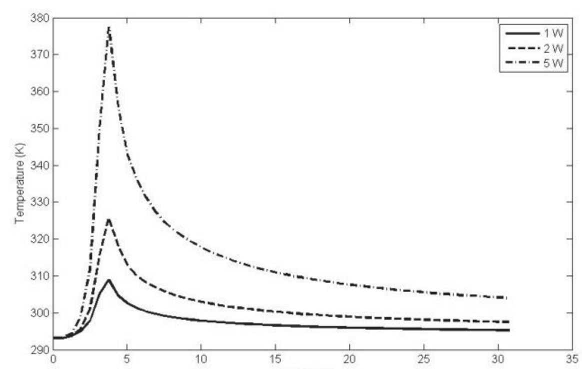
COMSOL



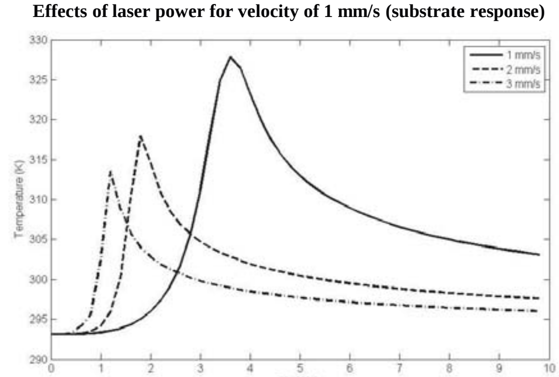
Fluid dynamics, solidification, high heat flux diffusion, microstructural evolution

Time scale ~ 10-100 μs (10-100 million time steps)
Space scale ~ 1 μm (resolution smaller than laser)

Masoomi, M., Elwany, A., Shamsaei, N., Bian, L., Thompson, S.M., 2015, “An Experimental-Numerical Investigation of Heat Transfer during Selective Laser Melting,” *2015 Annual International Solid Freeform Fabrication Symposium - An Additive Manufacturing Conference*, Austin, TX.



Effects of laser power for velocity of 1 mm/s (substrate response)



Effects of laser velocity for laser power of 2 W (substrate response)

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MSU Leads a National Consortium in Additive Manufacturing

Medium-to-Large Industry	Government
Caterpillar, Inc. (Peoria, IL & Corinth, MS) John Deere (Moline, IL) Eaton Aerospace Group (Jackson, MS)	NASA Marshall Space Flight Center (Huntsville, AL) Oak Ridge National Laboratory (Oak Ridge, TN) Air Force Research Laboratory (Dayton, OH) Federal Aviation Administration (Washington, DC)
Small Industry	***Academia***
Rapid Prototype + Manufacturing (Avon Lake, Ohio) HBM-nCode Federal LLC (Starkville, MS) Hol-Mac Corporation (Bay Springs, MS) Optomec (Albuquerque, NM) Taylor Machine Works, Inc. (Louisville, MS)	Mississippi State University (Starkville, MS) Georgia Institute of Technology (Atlanta, GA) Texas A&M University (College Station, TX) University of Arizona (Tucson, AZ) University of Toledo (Toledo, OH) Carnegie Mellon University (Pittsburg, PA)
Stratonics, Inc. (Lake Forest, CA) Simufact-Americas (Plymouth, MI) Mechanics & Materials Consulting, LLC (Flagstaff, AZ) Predictive Design Technologies (Starkville, MS)	***Not-For-Profit Organizations*** ASTM International (West Conshohocken, PA) SAE Fatigue Design & Evaluation Committee (Detroit, MI)

CLF²

Consortium on Laser Freeform Fabrication of Engineered Products with Enhanced Structural Integrity

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AM Part Certification

- ✓ MSU is collaborating with ASTM Committee F42 on Additive Manufacturing Technologies and ASTM Committee E08 on Fatigue and Fracture to develop standards.
- ✓ ASTM E08 workshop entitled <u>*Mechanical Behavior of Additive Manufactured Parts*</u> approved
  - Spring 2016 in San Antonio, TX
- ✓ CAVS is a member of 'America Makes'

America Makes
National Additive Manufacturing Innovation Institute

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CAVS offers…..

- Expertise: fatigue, heat transfer, solidification, process parameters optimization, uncertainty quantification
- Experimental capabilities: *thermally-monitored/controlled* LENS and in the process of buying SLM, uniaxial and multiaxial fatigue load frames, X-ray CT, SEM, ……
- High performance computing (HPC) for high-fidelity simulations
- Mechanical and microstructural characterizations
- “Design for AM” approaches for application-tailored parts and AM product development

MISSISSIPPI STATE UNIVERSITY™

NAVAIR Additive Manufacturing

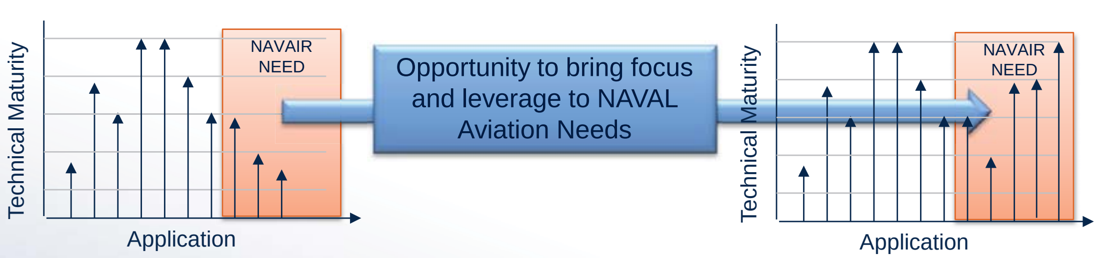
Presented to:

Presented by:

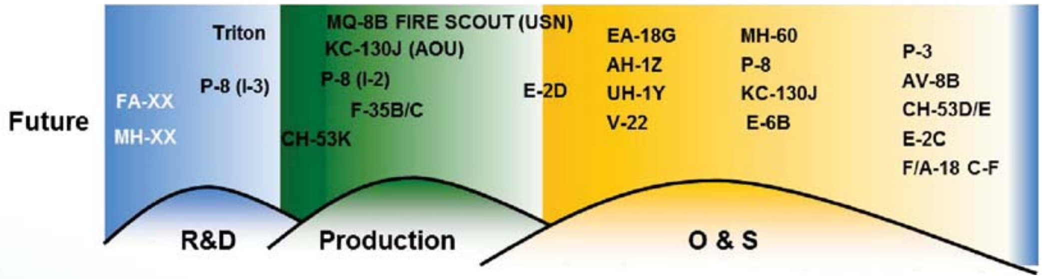
Ms.Elizabeth McMichael
Dr. William Frazier

Opportunity

- Clear understanding of our "Applications" can/will drive interest and promote opportunity for teaming.
- Defense Industry Applying AM today, some applications to Naval Aviation.
- Our Objectives are to Leverage and Expand AM Across our Portfolio
  - Drive Action Thru Clear Goals
  - Decompose Goals to Tangible Work
  - Maximize Partnerships
  - Focus Work on a Few but Critical Capabilities
- Goals are designed to *accelerate* the introduction of AM.



Naval Aviation Transition



Transition to next generation of Weapon Systems

- Maintenance and logistics requirements
- Open Architectures
- Integrated Weapons Systems
- Rapid Acquisitions
- More Lead System Integrator (LSI)

- Shorten the acquisition and support timeline
- Broaden the industrial supply base
- Improve/extend life limited parts
- “Parts on demand” at every FRC
- Industrial workforce that can use AM
- Logistics workforce than can plan for AM

Manage Associated Challenges

Example of Need

Problem Statement: The Navy’s inventory of aircraft is being pressed into service beyond their design life. As a result, components fail that were never expected to be repaired or replaced. With no replacements available in the supply system, long lead times develop for the repair or manufacture.

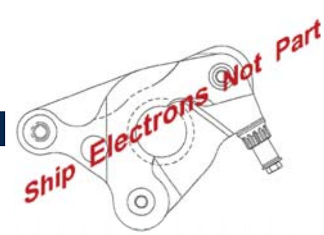
Broken Part

Reverse Engineer
if necessary

Build Package Database

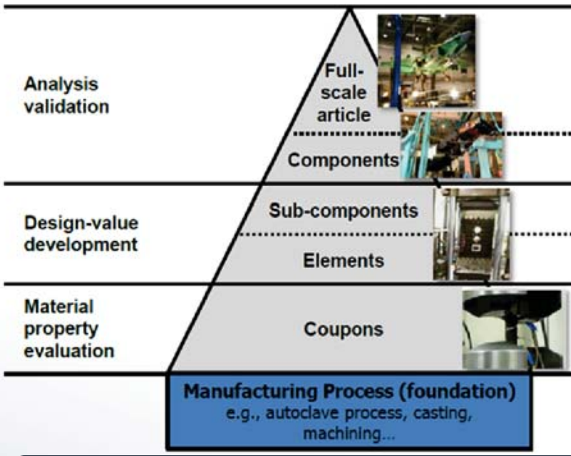
Aircraft Ready for Tasking
Parts on Demand

Rapid Manufacture
Using AM Technology



Major Challenge: Qualification & Certification

- Typical Aircraft Qualification/Certification Path
  - Range is determined by extent of new material, process and technology being introduced; and the amount of iterations.
  - Rotor and UAV platform costs are lower, large transport costs can be higher



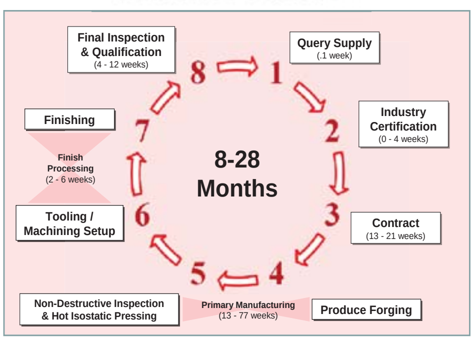
Level	Specimen Count	Cost ($M)	Time (Yrs)
Full-scale article	2-3	100-125	4
Components	10-30	10-20	3
Sub-components	25-50	10-35	3
Elements	2000-5000	10-35	3
Coupons	5000-100,000	8-15	2

Risk of unplanned cost and schedule impacts causes barrier to manufacturing innovation

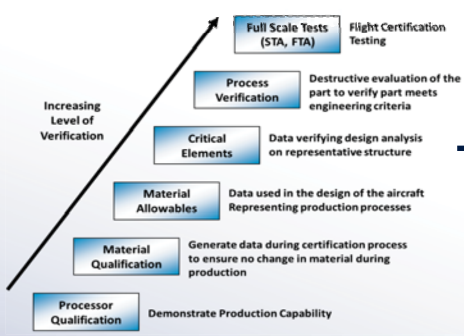
Ref. Mick Maher, DARPA "Open manufacturing," SAMPE, Nov 13, 2012

Changing the Paradigm *Accelerated AM* Implementation

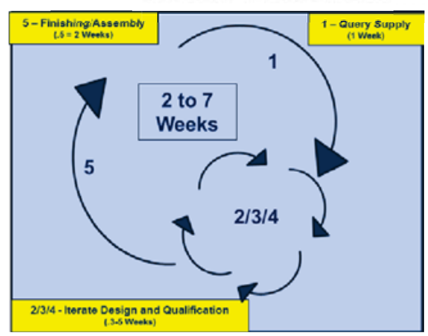
Current Process



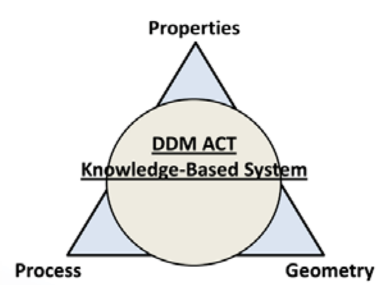
- **Linear Building Block Qualification Process**
- **Engineer Confidence based upon Statistically Substantiated Test Data**



On-demand Vision State



- **Design Process <u>Incorporates</u> Qualification/Certification**
- **Engineering Confidence based upon Validated Integrated Models and Simulation Tools.**



NAVAIR Transformative Goals

- Manufacture and qualify a Flight Critical Component at an FRC with minimal "touch labor"
- Make AM the preferred process for making tools at the FRCs
- Buy AM parts and tooling from DLA and NAVICP
- Manufacture and qualify a flight worthy AM "meta-material" integrating structural and sensor components
- Produce and qualify a rotating component with PHM-capable embedded sensors
- Build an AM printed explosive train with initiating, booster/timing, and main charge elements
- Development cost estimating methodology and should-cost for AM.
- Establish a NAVAIR AM capability for training, prototyping, process development, and standardization of AM.

Execute change necessary to rapidly leverage additive manufacturing for delivery of warfighter capability.

Manufacture and qualify a flight critical, non-proprietary component at an FRC with minimal "touch" labor using additive manufacturing.

Manufacture explosive train using additive manufacturing.

COMMAND LOCATIONS

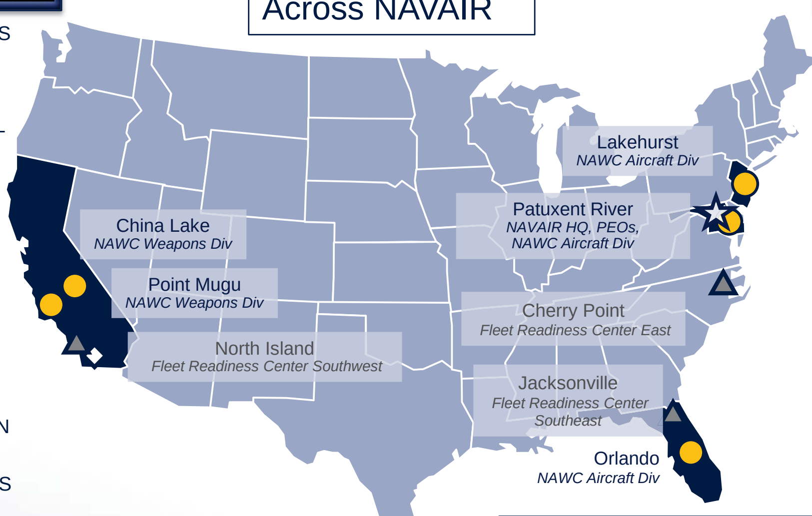
8 MAJOR SITES ~35,000 PEOPLE

33 PMAs ~4000 AIRCRAFT ~12,000 ENGINES

NAWCWD
WEST COAST HUB

- AIR-TO-AIR WEAPONS
- AIR-TO-GROUND WEAPONS
- MISSILES / FREEFALL WEAPONS
- ENERGETICS
- ELECTRONIC WARFARE SYSTEMS
- LAND AND SEA RANGES
- LIVE FIRE TESTING
- SYSTEM INTEGRATION
- PLATFORM / WEAPON INTEGRATION
- SYSTEM OF SYSTEMS (5TH GEN)

NAVAIR AM IPT Across NAVAIR



NAWCAD
EAST COAST HUB

- AIR VEHICLES
- PROPULSION AND POWER
- AVIONICS AND SENSORS
- CREW SYSTEMS
- AIRCRAFT LAUNCH AND RECOVERY EQUIPMENT / SUPPORT EQUIPMENT
- SHIP INTERFACE AND SUPPORT SYSTEMS
- HUMAN PERFORMANCE / SIMULATOR SYSTEMS
- TRAINING SYSTEMS
- PLATFORM / STORE INTEGRATION
- FLIGHT TESTING
- TEST RANGE
- PLATFORM MODIFICATIONS

☆ NAVAIR HQ
△ Depot / Industrial Site (Fleet Readiness Centers)
● Naval Air Warfare Center
◇ Logistic Support Activity

△ Atsugi, Japan
Fleet Readiness Center

COMFRC
FLEET READINESS CENTERS

- INSERVICE ENGINEERING AND LOGISTICS SUPPORT
- AIR LAUNCH AND RECOVERY REPAIRS
- DEPOT LEVEL MAINTENANCE AND REPAIR (AIRFRAME, ENGINES, COMPONENTS AND SUPPORT EQUIPMENT)
- INTERMEDIATE LEVEL MAINTENANCE

NAVAIR Additive Manufacturing Initiatives

#1 - Field AM Parts

Initiative #1 Projects

- Casting Replacements
- Structural Repair/Replacement
- ALRE/SE Components
- AM Tooling Process Standard
- Weapons and Energetics
- Complex Engine Components
- ⋮
- Industry/DoD/Other

Candidate Parts

#2 – Demonstrate Rapid Qualification/Certification

Initiative #2 Projects

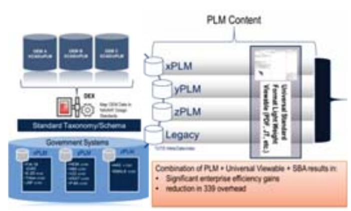
- Material and Process Qualification
- Structural Analysis and Structural Certification
- Non-Destructive Inspection Methods
- Innovative Process Models
- ⋮
- Industry/DoD/Other

NAVAIR Additive Manufacturing Initiatives

3 – Utilize "Digital Thread" across NAE

Initiative #3 Projects

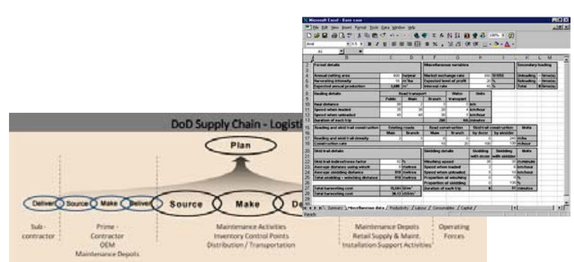
- 3D/Model Based Environment
- 3D Modeling and AM Digital Environment
- AM Data Architecture/Standards
- AM Build Package Development
- ⋮
- Industry/DoD/Other



4 – Update Business and Acquisition Processes

Initiative #4 Projects

- NAVSUP and DLA Supply Chain
- Cost Modeling and ROI
- ⋮
- Industry/DoD/Other



Industry/Academia Partnership and Collaboration

- AM Parts
  - Non-flight critical/flight critical parts
  - AM Enabled Designs
  - Alternative Materials
  - Meta-materials
  - Complex Engine components
- Rapid Qualification/Certification
  - AM material & process standards
  - Process models, controls, and sensors,
  - Process-microstructure-property data generation / management
  - NDI
- "Digital Thread"
  - 3D/MBE/PLM and AM requirements
  - Configuration Management
  - Security
- Business and Acquisition
  - Strategies to enable AM for suppliers
  - Data rights and IP
  - Cost modeling

Concluding Remarks

- AM is a disruptive, transformative technology that will profoundly impact NAVAIR.
- We are leaning forward in the implementation of AM in support of naval aviation weapon systems.
- We are more than willing to challenge extant assumptions and paradigms.
- We seek opportunities to partner with you in order to overcome the technical, business, administrative and policy issues limiting AM's full implementation.

Air Force AM Certification Perspective

Integrity ★ Service ★ Excellence

2 Sep 2015

Jeff Calcaterra, PhD
Structural Materials Evaluation Team
Materials Integrity Branch
System Support Division
Materials and Manufacturing Directorate

AFRL

Acknowledgements

- **Mike Froning (AFLCMC/EZP) gave me almost every slide for this presentation.**
- **Certification is an AFLCMC responsibility. Per new Airworthiness Bulletin, AFRL will participate in certification process for M&P issues.**

AFRL

Overview

- **BLUF – Additive Manufacturing will go through the same qualification/certification process as any other new process.**

Air Worthiness Bulletin

Change Evaluation Team

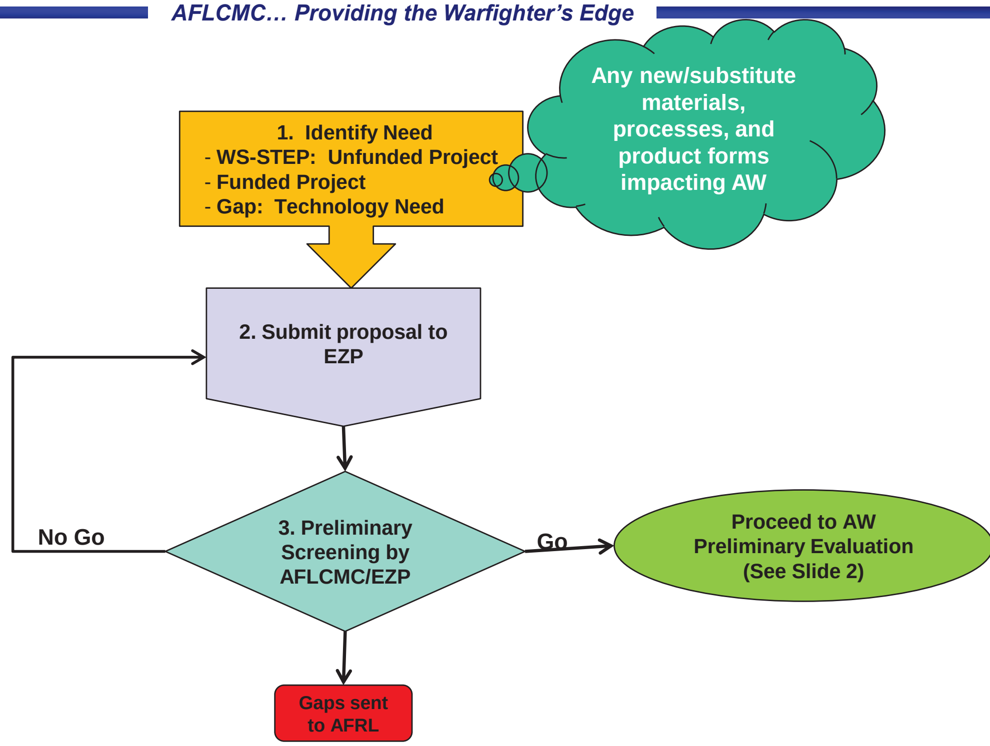
1. Purpose: This bulletin describes the process for deploying new or substitute materials, processes, and product form(s) on currently certified weapon systems/mission design series (MDS). The process described in this bulletin shall be applied to proposed materials, processes, or product forms that have been assessed by a weapon system's Chief Engineer (CE) as having an impact to the airworthiness of that weapon system.

3. Change Evaluation Team (CET): An integrated team of subject matter experts will be established encompassing AFLCMC, Air Force Research Laboratory (AFRL), and if appropriate, stakeholders such as commercial industry with knowledge of the new or substitute materials, processes, and/or product form(s) in question. The CET is responsible for coordination with the MDS CE Delegated Technical Authority (DTA) and associated Director of Engineering DTA for impacted systems to identify unique requirements.

Change Evaluation Team AFRL Participation

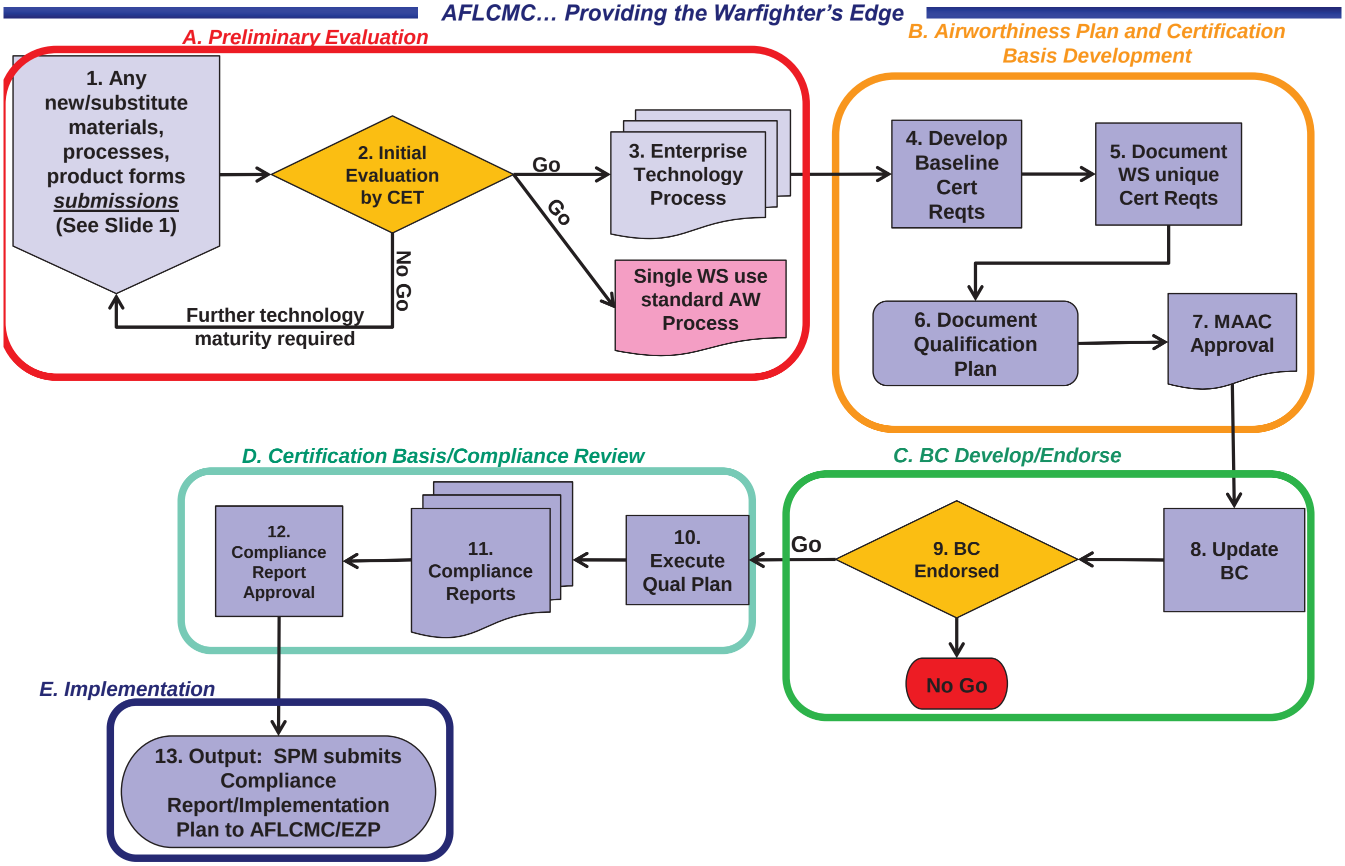
- **AFRL/RX participation is decided by AFRL/RX Chief Engineer**
  - The current process is that RX will provide a technology SME and a systems support SME

Package Submittal Development



Alternative Materials, Processes and Product Forms Airworthiness Bulletin Process - Overview

AFLCMC… Providing the Warfighter's Edge



Package Submittal Development Details (Slide 1)

AFLCMC… Providing the Warfighter's Edge

- **Step 1: Identify the need and/or gap for any new or substitute materials, processes, and product forms impacting Airworthiness**
  - Unfunded requirements documented within Weapon System Sustainment Technology Enterprise Program (WS-STEP)
  - Funded requirements by DLA, AFSC, AFNWC & AFLCMC organizations
- **Step 2: Submit proposal(s) to AFLCMC/EZP**
  - EZP will provide standardized format and process for proposal submission(s) to address the five entrance criteria factors…
    - Stability
    - Producibility
    - Characterized Mechanical & Physical Properties
    - Predictability of Performance
    - Supportability
- **Step 3: AFLCMC/EZP will conduct a preliminary screening to ensure the proposal package is complete and ready to proceed to the AW process**
  - Go: Addresses AW five primary factors entrance criteria (AW Bulletin)
  - No Go: Does not meet entrance criteria – send back to Team for updates
  - No Possible Solutions: Gaps sent to AFRL

AWB Process

- **Stability, Producibility, Mechanical & Physical Properties, Predicability of Performance and Supportability is determined based on the unique aspects of the technology**
- **For AM, these five characteristics are based on:**
  - **Process Control (including post processing)**
  - **Statistically Valid Mechanical Properties**
  - **Qualified NDE**
  - **Residual Stress Management**

AFRL

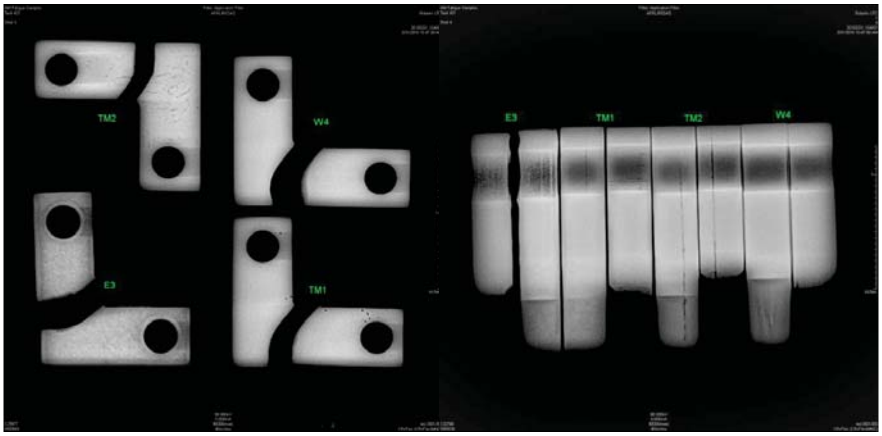
AWB Process

- **After the Change Evaluation Team completes its process, the engineering authority for any program still has to certify AM for use on their system.**
- **It is expected that any AM process will have unique controls that will be dependent on the application.**
- **There is no blanket approval process for AM – just like welding, brazing, thermal spray, etc…**

AFRL

AWB Process

- **Built in skepticism for AM**
  - **Most organizations don't seem to grasp the level of control needed for these processes.**



The authors in this peer reviewed paper concluded TM was superior to W or E because it had "better" microstructure and mechanical properties

Overview of Flight Certification Methodology for Additive Manufacturing

Mission Assurance Challenges

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Douglas Wells, MSFC
Materials & Processes (EM)
douglas.n.wells@nasa.gov
256-544-3300

Motivation

Photo: SpaceX

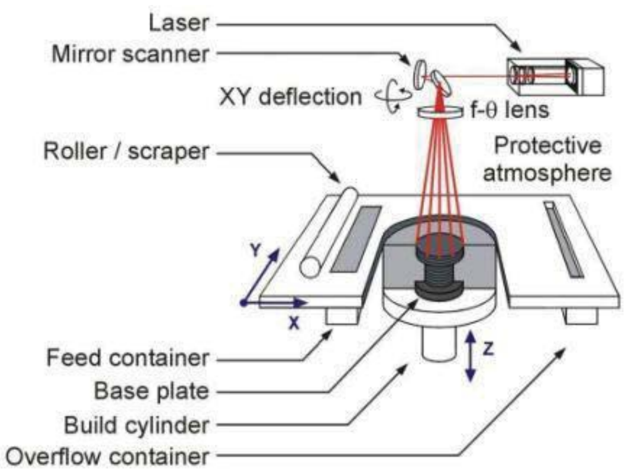
Commercial Crew Program
SpaceX's SuperDraco Thruster
Launch planned for 2017

Photo: NASA

Space Launch System
NASA's RS-25 core stage engine
Certification testing 2020

Requirement choices dictate how we embrace, foster, and protect the technology and its opportunities

Powder Bed Fusion Process



NASA Approach to AM Requirements

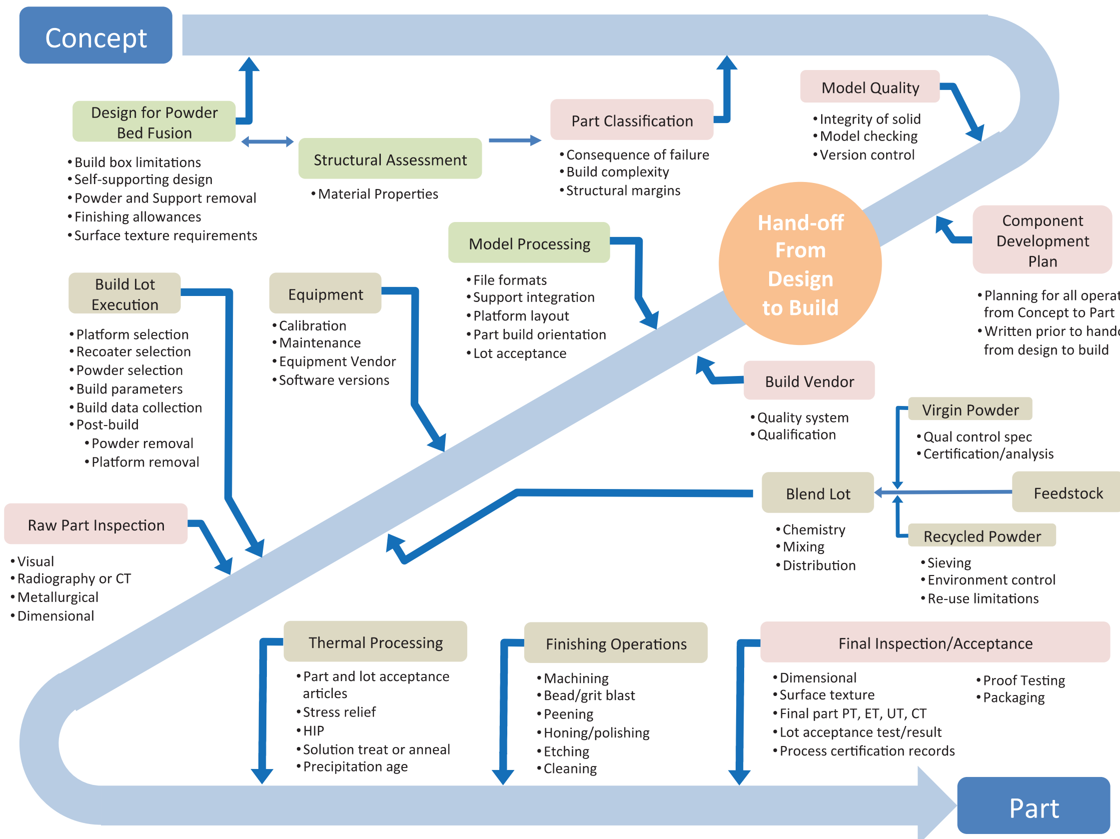
1. Develop a Center-level (MSFC) requirement
   - Allows for more timely release (targeting November 2015)
   - Review circle much wider than common
     - NASA Centers and NESC (Materials, Structures, NDE, Reliability)
     - Partners (Lockheed Martin, Aerojet Rocketdyne, SpaceX, Boeing)
     - Industry (P&W, Raytheon)
     - Certifying Agencies (FAA, USAF, NAVAIR, AMRDEC)

2. Revise as needed / Levy as required

1. Watch progress of standards organizations and other certifying Agencies

1. Incorporate AM requirements at an appropriate level in Agency specifications
   - Incorporate necessary detail, or
   - Refer to center document or industry standard

The AM Path: Concept to Part



Informational Briefing Only – Does not represent an official NASA Policy on AM Certification

MSFC Requirement Document

National Aeronautics and Space Administration

MSFC-STD-xxxx
REVISION: DRAFT 1
EFFECTIVE DATE: Not Released

George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama 35812

EM20

MSFC TECHNICAL STANDARD

Engineering and Quality Standard for Additively Manufactured Spaceflight Hardware

DRAFT 1 – JULY 7, 2015

This official draft has not been approved and is subject to modification.
DO NOT USE PRIOR TO APPROVAL

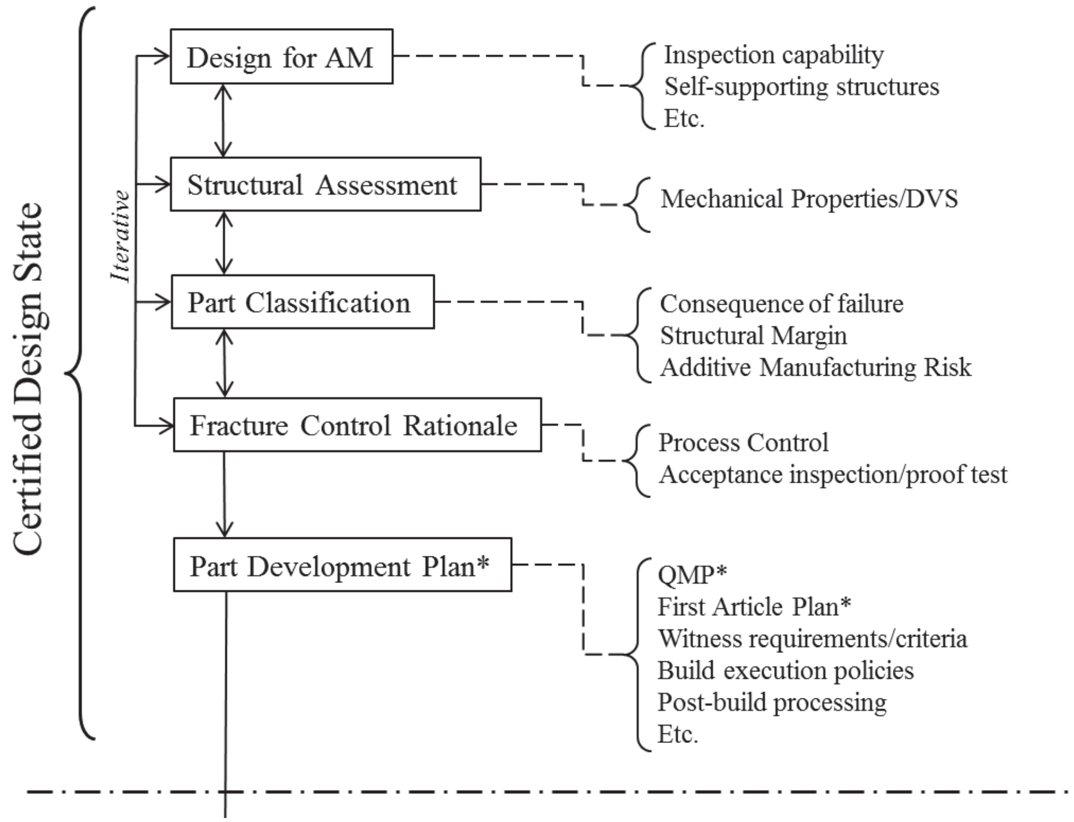
CHECK THE MASTER LIST—
VERIFY THAT THIS IS THE CORRECT VERSION BEFORE USE

THIS STANDARD HAS NOT BEEN REVIEWED FOR EXPORT CONTROL RESTRICTIONS
DRAFT VERSIONS DISTRIBUTED FOR REVIEW ARE NOT TO BE DISSEMINATED

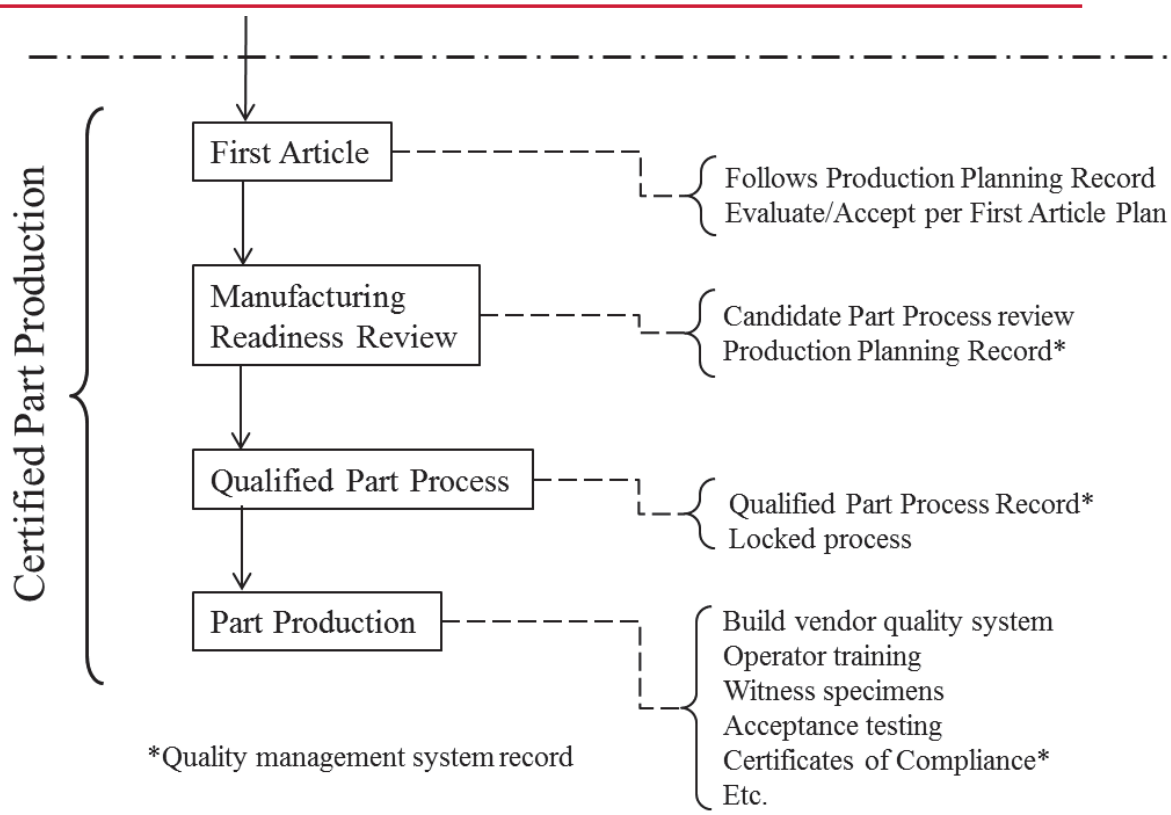
- Governing Standards
- Design for AM
- ***Part Classification***
- Structural Assessment
- ***Fracture Control***
- Qualification Testing
- Material Properties
- ***Process Controls***
  - ***Metallurgical***
  - ***Part***
  - ***Equipment Vendor Controls***
  - ***Vendor – Design and Build***

Informational Briefing Only – Does not represent an official NASA Policy on AM Certification

Certified AM Design State



Certified AM Part Production



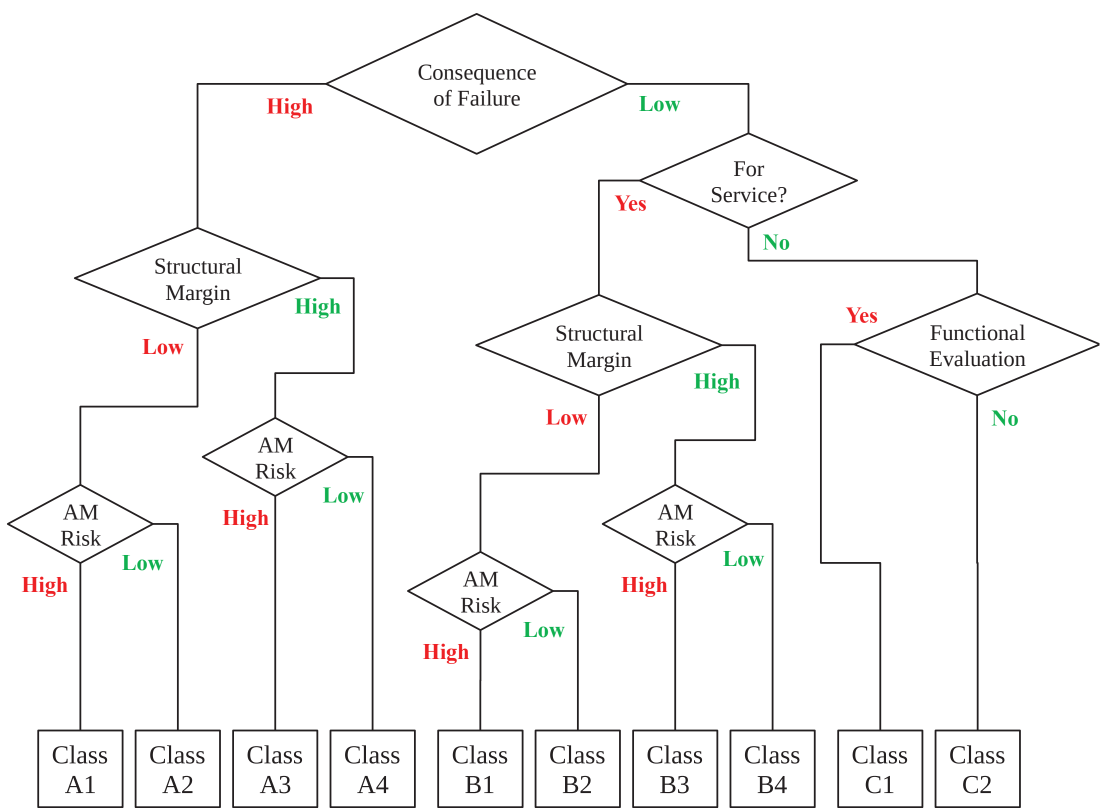
*Quality management system record

Informational Briefing Only – Does not represent an official NASA Policy on AM Certification

Part Classification

- ❖ All AM parts are placed into a risk-based classification system to help customize requirements
- ❖ Three decision levels
  - Consequence of failure (High/Low) {Catastrophic or not}
  - Structural Margin (High/Low) {strength, HCF, LCF, fracture}
  - AM Risk (High/Low) {build complexity, access, inspectability}
- ❖ Part classification highly informative for relating part risk
- ❖ Classification informative for fracture control evaluations

Part Classification Tree



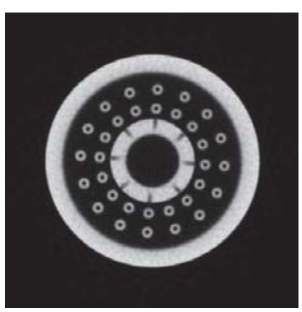
Fracture Control

- Fracture control holds key responsibility for AM mission assurance
  - Control of rogue flaws remains significant challenge
    - Open-loop process
    - In-situ monitoring still in development
  - Post-build non-destructive evaluation challenged by complex AM geometries
  - Fracture control experts will be expected to distill, interpret, and make recommendations regarding mission assurance risks for AM flight parts

Process Control

- Four aspects of process control are levied by the document

Metallurgical Process Control



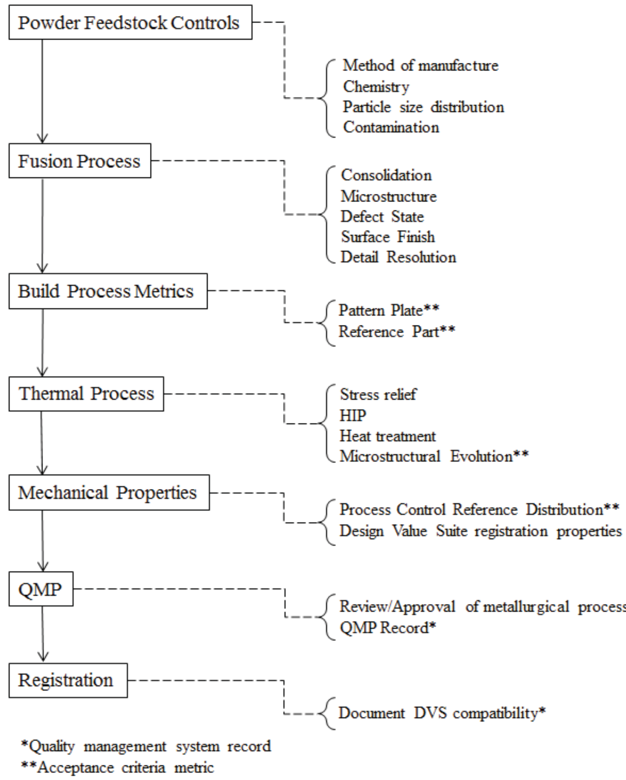
Part Process Control

Equipment Process Control

Build Vendor Process Control

Metallurgical Process Control

- Powder Feedstock Controls
- Fusion Process
- Build Process Metrics
- Thermal Process
- Mechanical Properties
- Qualified Metallurgical Process



Part Process Control

- Part Process governs all operations needed to produce a given part to a defined part process
- Includes every step in part production:
  - Qualified Metallurgical Process
  - Build layout
  - Witness specimens and testing
  - Powder removal
  - Platform removal
  - Thermal processing
  - Final machining operations
  - Surface improvement
  - Inspections
  - Part acceptance requirements
- Once established, locked, and approved, the sequence is considered a ***Qualified Part Process***

Equipment Process Control

- AM-related equipment requires proper calibration and maintenance, like all process-sensitive equipment
- Scope of such equipment calibration and certification remains to be determined
  - Mechanical
  - Electronic
  - Optical
  - Software
- How to allow for updates to improve machine performance?
  - Not common for any flight process-sensitive system

Vendor Process Control

- Design vendor
  - Provides the part design and associated CAD
    - CAD model file controls
    - CAD model checking
    - STL file generation
- Build Vendor
  - Developing criteria for approved build vendor list
  - Requires S&MA audit and approval
  - Quality systems in place, e.g. AS9100
  - Manages machine quality control program
  - Electronic file control, part interaction (support structures)
  - Feedstock handling, part handling, nonconformance system
  - Management of aerospace flight quality hardware and process
  - User training and skill requirements
  - Safety protocols

Knowledge Gaps and Risks

- *Requirements will not mitigate AM part risks to an equivalent level as other processes for some time to come.*
- Known unknowns needing investment
  - Unknown failure modes, limited process history
  - Open loop process
  - Feedstock specifications and controls
  - Thermal processing
  - Process parameter sensitivity
  - Mechanical properties
  - Part cleaning
  - Welding of AM materials
  - AM surface improvement strategies
  - NDE of complex AM parts
  - Electronic model data controls
  - Equipment faults, modes of failure
  - Machine calibration / maintenance
  - Vendor quality approvals

Take-Aways

- Certified AM Design
  - Classification of parts
  - Fracture Control holds key responsibility for Mission Assurance
- Certified AM Part Production
  - Qualified Metallurgical Process
    - Feedstock, fusion process, thermal process
  - Qualified Part Process
    - Part development plan
    - Process control witness tests
  - Equipment Process Control
    - Calibration, maintenance
    - Fitness for service declaration
  - Vendor Controls
    - Quality processes
    - Operator training

Back-up

Metallurgical Process Control

- Metallurgical Process Constituents
  - Feedstock controls
    - Chemistry
    - Powder morphology (PSD, shape, atomization methods)
  - Fusion process controls
    - Machine type
    - Parameters: laser power, speed, layer thickness, hatch width, etc.
    - Chamber atmosphere
  - Thermal processing controls
    - Governs microstructural evolution
    - As-built through recrystallization
    - Final densification
- When finalized and locked as a process, a ***Qualified Metallurgical Process*** **(QMP)** is established and referenced for use in part processes

Requirements Approach

- Typical scenario used to control critical processes
  - Broad Agency-level standards provide requirements
    - NASA-STD-6016 Materials
    - NASA-STD-5012 Propulsion Structures
    - NASA-STD-5019 Fracture Control
  - *Which call* process or quality standard controls product, for example:
    - AWS D17.1 Fusion Welding for Aerospace Applications
    - SAE AMS 2175 Classification and Inspection of Castings
    - SAE AMS 4985 Ti-6-4 Investment Castings
  - *Which call* considerable collections of "Applicable Documents"
- Additive manufacturing standards currently very limited
  - Lacking standardization is a universal, industry-wide issue, not just NASA
  - Mainly ASTM, Committee F42 on Additive Manufacturing
    - F3055 Standard Specification for Additive Manufacturing Nickel Alloy (UNS N07718)with Powder Bed Fusion
    - F2924 for Ti-6-4, F3001 for Ti-6-4ELI, F3056 for In625
  - Other Standards organizations in planning
    - SAE AMS, AWS
- NASA required to develop government requirements to balance AM opportunities and risks.

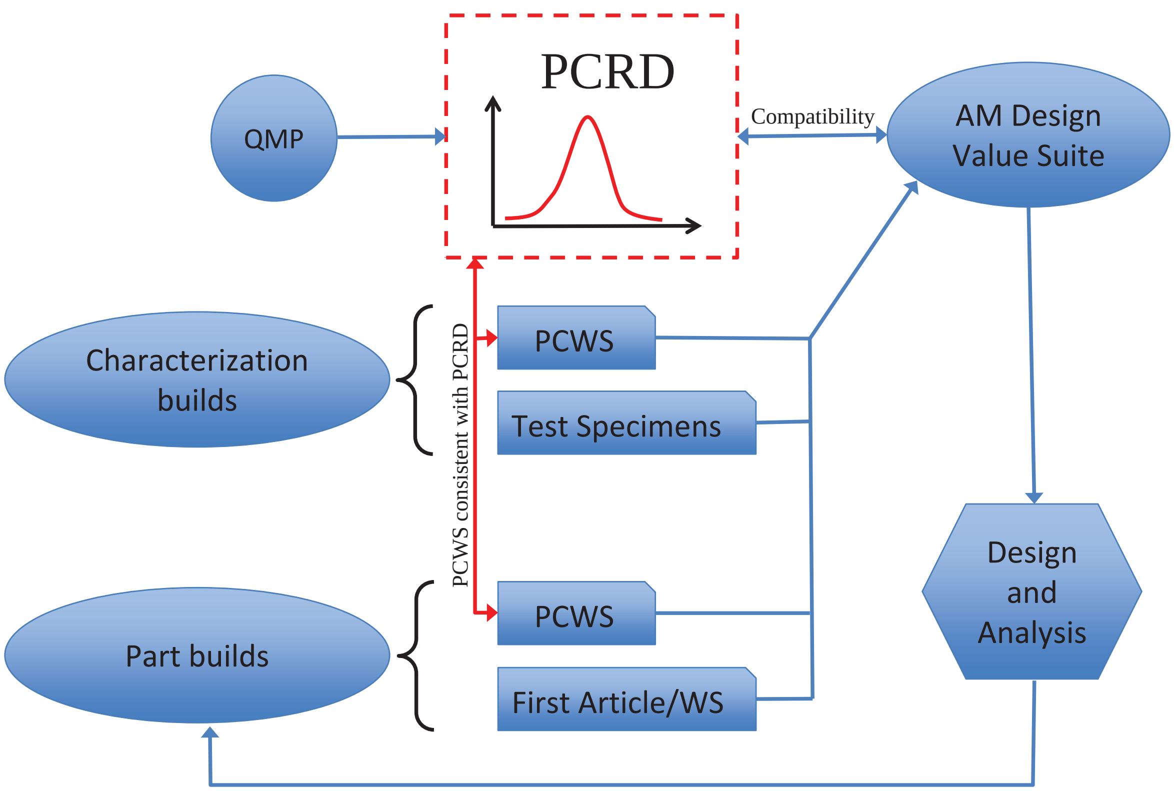
Part Development Plans

- Part Development Plans (PDPs) document the implementation and interpretation of the requirements for each AM part
- Companion to drawing
  - Intended as a configuration controlled document, enforced by the drawing to convey process controls and requirements
  - Must capture all requirements not within drawing notes
- Content varies with extent of approved internal specifications available for drawing call-out
- Content varies with part classification
- Example Content:
  - Part classification and rationale
  - Witness sampling requirements and acceptance criteria
  - First article evaluations and re-sampling periods
  - Build orientation, platform material, and layout
  - Special cleaning requirements
  - Repair allowance, Inspection requirements, critical dimensions

Material Properties

- Material properties often confused with certification
  - Certification >> material properties
- Highly "localized user" process requires different thinking
- Shift emphasis away from exhaustive, up-front material allowables intended to account for all process variability
- Move toward ongoing process monitoring with thorough, intelligent witness sampling of each build
- Hybrid of Statistical Process Control and CMH-17 approach for process-sensitive composite material equivalency
- Utilize a QMP to develop a *Process Control Reference Distribution* (PCRD) of material properties that reflects not the design values, but the actual mean and variability associated with the controlled AM process
- Enforce suite of design values compatible with PCRDs
- Accept parts based on comparison to PCRD, not design values
- PCRDs are continuously updated, design suite must be monitored and determined judiciously early on
- Allows for adoption of new processes without invalidating large allowables investments

AM Certification – Material Properties



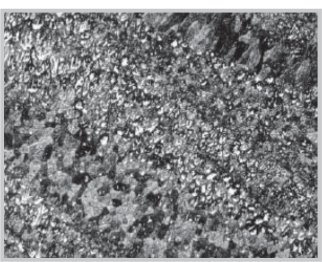
NASA's Additive Manufacturing Technology Development Activities

Karen M. B. Taminger
Materials Research Engineer, Adv. Materials & Processing Branch
NASA Langley Research Center

FAA-Air Force Workshop on Qualification/Certification of Additively Manufactured Parts

September 1-3, 2015

NASA's AM Technology Development Activities



- **AM Process Development Activities**
  - Electron Beam Freeform Fabrication
- **NASA Development Applications for Metal AM**
  - Aircraft
  - Space

Electron Beam Freeform Fabrication (EBF³) Process

Basics

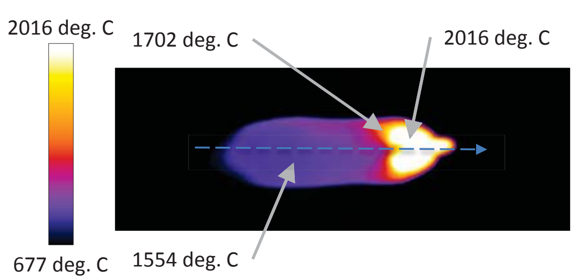
- Layer-additive process to build parts using CNC techniques
- Electron beam melts pool on substrate, metal wire added to build up part
- LaRC has ground-based and portable systems
- Alloys demonstrated: Ti-6-4, 2xxx Al alloys, 316 SS, In625, In718, Cu

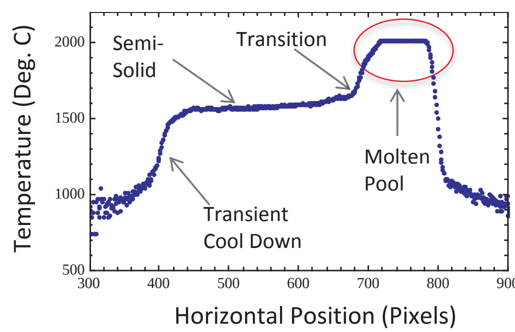
Sample parts built using EBF³ using Ti-6-4 (top) and 2219 Al (bottom)

Benefits

- Near-net shape parts minimize scrap & reduce part count
- High energy efficiency and feedstock usage efficiency
- Efficient design improves weight, assembly time, performance
- Intricate, complex geometries, functionally graded parts & structures
- Cross-cutting technology with numerous potential applications

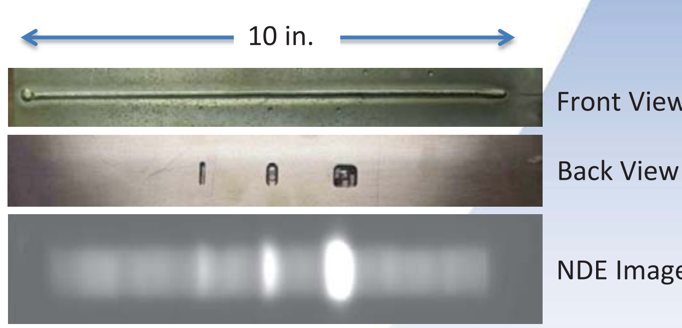
Thermal Monitoring During EBF³ Deposition





- Thermal imaging using near-IR cameras provides real-time information during EBF³ deposition
- Melt pool region used for process control
- Transient cool-down region used for internal flaw detection
- Next step is correlating transient signals with types of defects

NDE Results from Single Bead Experiments

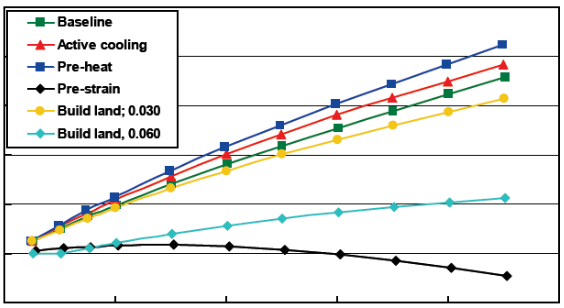


Thermally-Induced Distortion /Residual Stress

Residual Stress Modeling

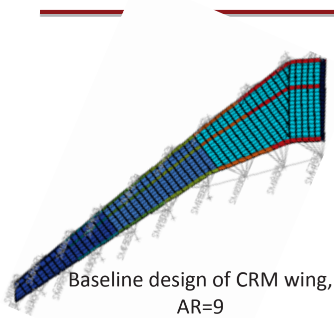
Localized heat induces distortion and residual stress, similar to that observed during welding

Experiments for Distortion Control

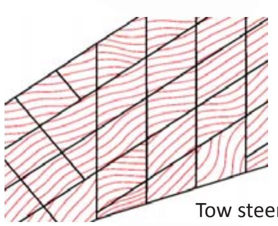


- Thermal control
  - Process control to minimize excess heat input
  - Deposition paths can be designed to distribute heat across part
  - Preheating/active cooling during deposition
- Mechanical constraint during deposition
  - Clamp close to deposition to constrain distortion
  - Elastic pre-strain baseplate in opposite direction
  - Build lands or thicker baseplate material
- Part design
  - Two-sided parts built with a flip table can offset distortion
- Traditional stress relief
  - Periodic thermal stress relief heat treatments (requires removal from chamber)
  - Vibratory stress relief practices common for welding

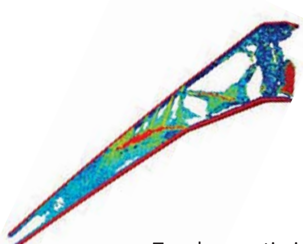
Passive Aeroelastic Tailored Structural Design



Baseline design of CRM wing, AR=9



Tow steered skins



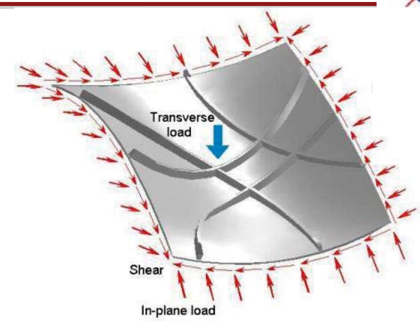
Topology optimization

Goal: Aeroelastically tailored wing structures with increased aspect ratio and reduced weight by 20-25%

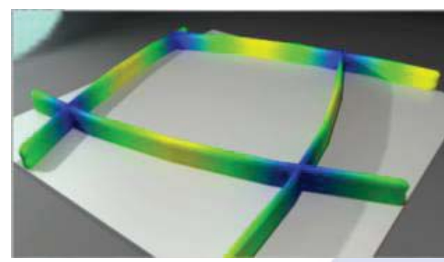
- Aeroelastic tailoring of materials and structures are being considered for broad design space
  - Bend/twist coupling can be achieved using internal structure reorientation
  - Curvilinear stiffeners, blending of spars and ribs enable modification of moments of inertia (I or J)
  - Functionally graded or tow steered composite engineered materials enables changing moduli (E or G)
- Design/analysis tools
  - Parametric studies (in-house)
  - Topology optimization (in-house)
  - Curvilinear stiffener and SpaRibs (VA Tech, Dr. Rakesh Kapania)
  - Multidisciplinary optimization (Univ. of Michigan, Dr. Quim Martins)
  - Analytical evaluations being performed in NASTRAN
- Next: build structural test article for static loads and ground vibration testing to validate FEM analyses
- Future: build dynamically scaled model for wind tunnel or flight testing to evaluate flutter and GLA performance

Integrated Metallic Fuselage Design and Functionally Graded Materials

- Engineered materials coupled with tailored structural design targeting 25% weight reduction and improved performance
- Multi-objective optimization:
  - Structural load path
  - Acoustic dampening in fuselage
  - Durability and damage tolerance
  - Reduced weight
  - Materials functionally graded to satisfy local design constraints
- Additive manufacturing using new alloys enables unitized structure with functionally graded, curved stiffeners
- Weight reduction by combined tailored structural design and designer materials



Design optimization tools developed at VA Tech through NRA contract

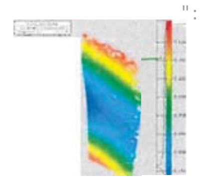


High toughness alloy at stiffener base for damage tolerance, transitioning to metal matrix composite for increased stiffness and acoustic damping

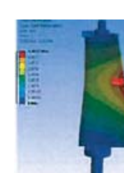
Non-Metallic Gas Turbine Engine Through AM

- Evaluate emerging materials and manufacturing technologies that will enable fully non-metallic gas turbine engines
- Assess the feasibility of using AM technologies to fabricate gas turbine engine components
  - Fiber reinforced polymer composites fabricated using FDM
  - High temperature ceramics / CMC's using binder jet process
  - Fabricate prototype components and test in engine operating conditions
- Conduct engine system studies to estimate the benefits of a fully non-metallic gas turbine engine design in terms of reduced emissions, fuel burn and cost

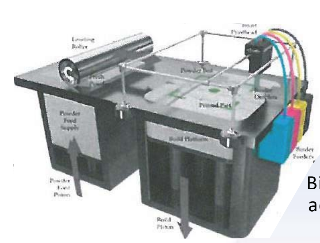
Polymer Vane Configuration in Cascade wind tunnel rig



Digital Image Correlation Measurements



Finite Element Analysis



Binder jet process was adapted for SiC fabrication

Functionally Graded Rocket Engine Components

Application:

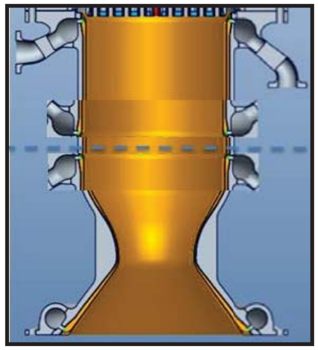
- U.S. liquid rocket engine manufacturers are experimenting with AM techniques for next generation rocket engine components

Design Considerations:

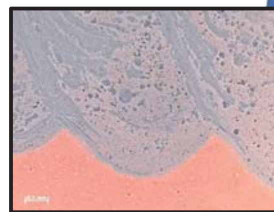
- Use of combination of additive manufacturing processes takes advantages of benefits of each
- Intricate copper combustion chamber and nozzle produced by SLS
- Grading from copper to nickel to deposit a structural jacket and manifolds using EBF^3

Sustainability Benefits:

- Rapid manufacturing turn-around enables more design/test iterations for optimizing nozzle geometry
- Potential to reduce full scale injector cost by nearly an order of magnitude (~90% reduction) and enhance performance through designs customized to additive manufacturing processes
- Successful hot-fire tests will infuse AM into US rocket engine industrial base (scheduled for Jan. 2016)



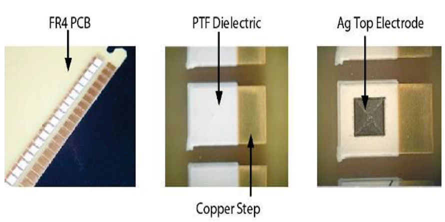
Schematic of integrated SLM copper/EBF^3 Inconel nozzle

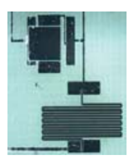


Microstructure of EBF^3 In625 direct deposited onto Cu base

SLM GRCop 84 chamber and nozzle after HIP

Spacecraft Electronics, Sensors and Coatings



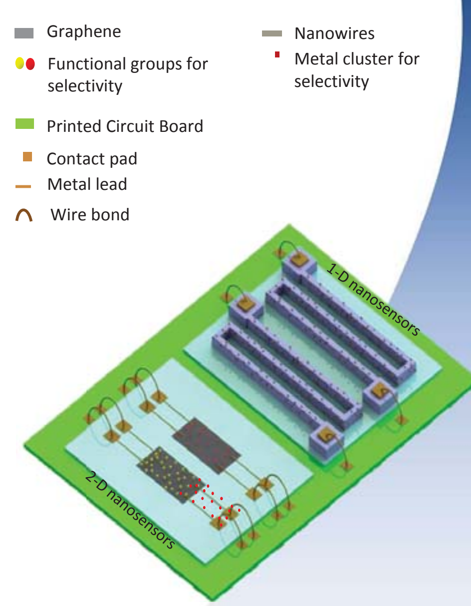


Printed RC filter

Multi-layer deposition, Polyimide dielectric and Ag deposited onto Cu pads to make a simple capacitor

- Aerosol jet printing of various circuit building blocks: crossovers, resistors, capacitors, chip attachments, EMI shielding.
- Nanosensors printed directly on a daughter board for chemical detection
- Super-black nanotechnology coating: Enable Spacecraft instruments to be more sensitive without enlarging their size. Demonstrated growth of a uniform layer of carbon nanotubes through the use of Atomic Layer Deposition.

Printed Nanosensor

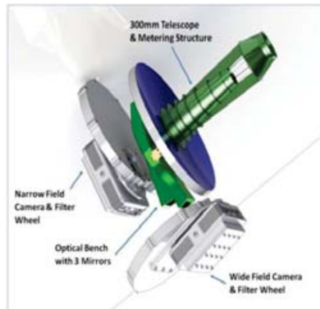


Spacecraft Instruments and Components

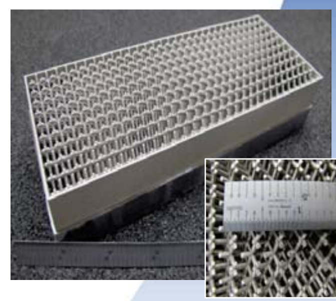
- GSFC's first AM part for instrument prototype/possible flight use (FY12) - Titanium tube - in a tube – in a tube for cryo thermal switch for ASTRO-H
- First to fly AM component in space (FY13) – battery case on suborbital sounding rocket
- Miniaturizing telescopes: Use DMLS to produce dimensionally stable integrated instrument structures at lower cost
- Integrated core-and-face-sheet optical bench material
  - Features tailored alloy composition to achieve desired coefficient of thermal expansion
- Component-level radiation shielding via DMLS

Battery Case

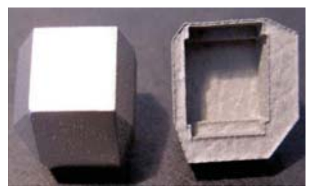
Cryo Thermal Switch for ASTRO-H



0.3m Telescope via DMLS



CubeSat-class 50-mm (2") imaging camera/instrument -mirrors and integrated optical-mechanical structures- manufacturing with 3D-printed parts



Optical bench core material sample

Additive Manufacturing and Risk Mitigation - *A Regulatory Perspective*

Federal Aviation Administration

Presented at:

FAA-AF Additive Manufacturing Workshop

September 1-3, 2015

Dayton, OH

Presented by:

Michael Gorelik, Ph.D.

FAA Chief Scientific and Technical Advisor

for Fatigue and Damage Tolerance

What Causes Failures?

Frequency of Failure Mechanisms *)

Failure Mechanism	% Failures *(Aircraft Components)*
☆ Fatigue	55%
Corrosion	16%
Overload	14%
Stress Corrosion Cracking	7%
Wear / abrasion / erosion	6%
High temperature corrosion	2%

*) Source: *Why Aircraft Fail, S. J. Findlay and N. D. Harrison, in Materials Today, pp. 18-25, Nov. 2002.*

- ***One of most challenging material / design requirements***
- ***Expect this trend to continue for metallic materials***

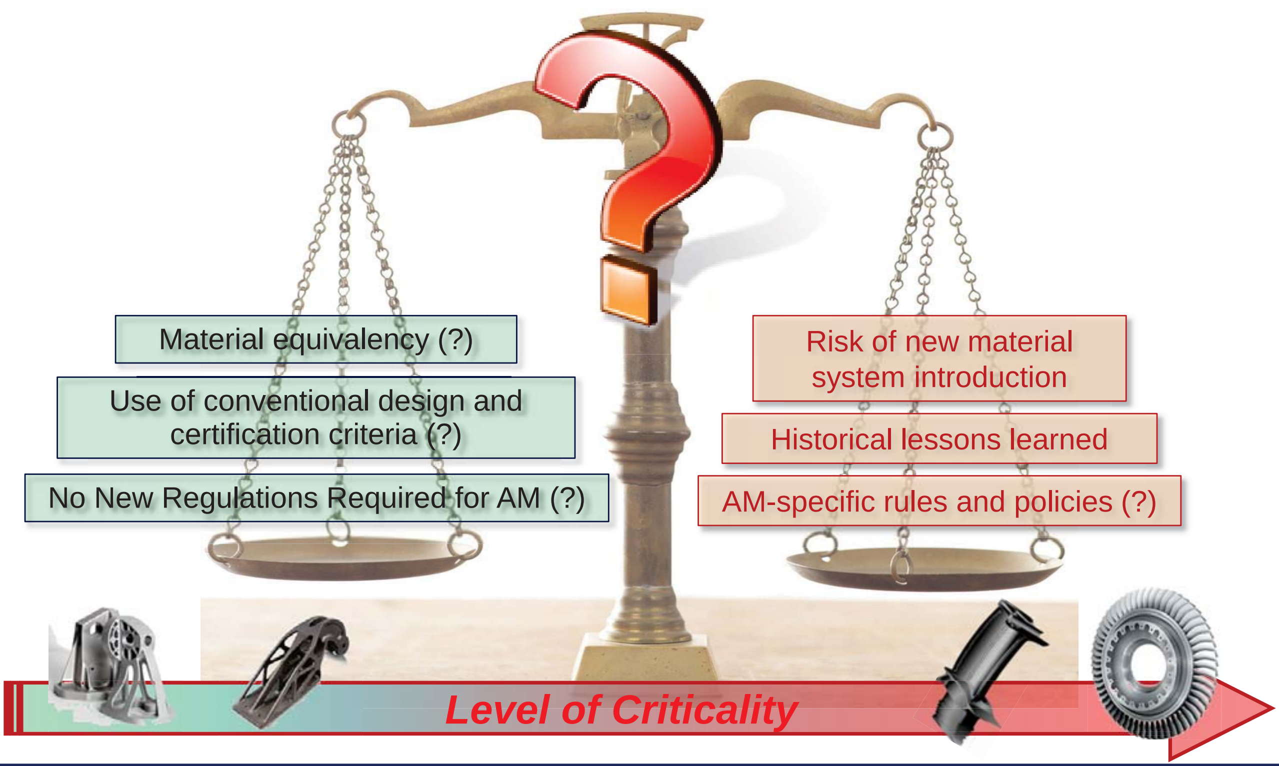
Technology Transition Criteria

- USAF performed a ***study of the successful transitions of structural technologies*** **from the laboratory to EMD**
  - *EMD = Engineering and Manufacturing Development*
- **It was found that *five factors constituted a common thread* among these successes:**
  - **Stabilized material and/or material processes**
  - **Producibility**
  - **Characterized mechanical properties**
  - **Predictability of structural performance**
  - **Supportability**

"A deficiency in any one of the factors could constitute a fatal defect "

Source: Dr. Jack Lincoln, Structural Technology Transition to New Aircraft, USAF.

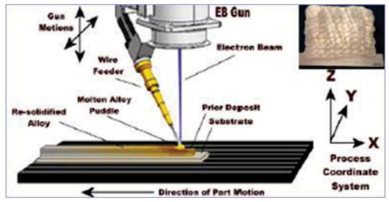
Finding The Right Balance…

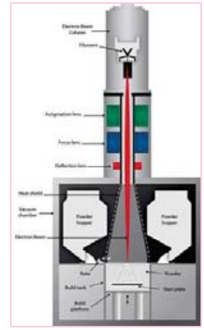


Federal Aviation Administration

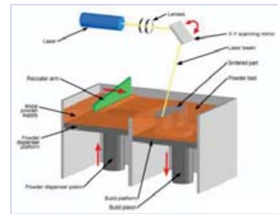
Diversity of AM Processes and Application Domains

By Source of Material:
Powder vs. Wire





By Source of Energy:
Laser vs. E-Beam



New Type and Production Certificates	Repair and Overhaul (MROs)	Aftermarket Parts (PMAs)

FAA Regulatory Environment

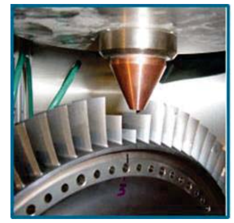
Transport Airplane Directorate
(14 CFR Part 25)

Small Airplane Directorate
(14 CFR Part 23)

Engine and Propeller Directorate
(14 CFR Parts 33, 35)

Rotorcraft Directorate
(14 CFR Parts 27, 29)

Business Drivers for AM

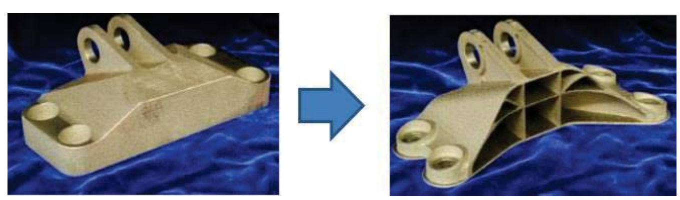


- Part count reductions
- Producibility / machinability issues
  - *e.g. thin-wall castings*
- More complex geometric designs
  - *Weight reduction*
  - *Design optimization*
- Single Source alternatives
- Production of low volume / legacy parts
- PMA business model (reverse engineering)
- Low barrier to entry for smaller businesses

- **Business Drivers can be good *Predictors* of *Technology Trends***
- **Be ware of hype – *just because something can be made using AM, doesn't mean it makes sense…***

Topological Optimization Using AM

- "*Complexity for Free…*"



- ***… But is it really?***
  - High number of Kt features
  - Inspectability challenges
  - Location-specific properties
  - Surface quality of hard-to-access areas
    - may need to live with as-produced surface

Need a Realistic Assessment of Technical Challenges / Risks Associated with a Business Case

From Non-Critical to Critical

- **Typical new aerospace alloy development and introduction timeline – *10 to 15 years***

➢ **However**

TABLE 2.2 Typical Development Times for New Materials

Development Phase	Development Time
Modification of an existing material for a noncritical component	2 to 3 years
Modification of an existing material for a critical structural components	Up to 4 years
New material within a system for which there is experience	Up to 10 years. Includes time to define the material's composition and processing parameters.
New material class	20 to 30 years. Includes time to develop design practices that fully exploit the performance of the material and establish a viable industrial base (two or more sources and a viable cost).

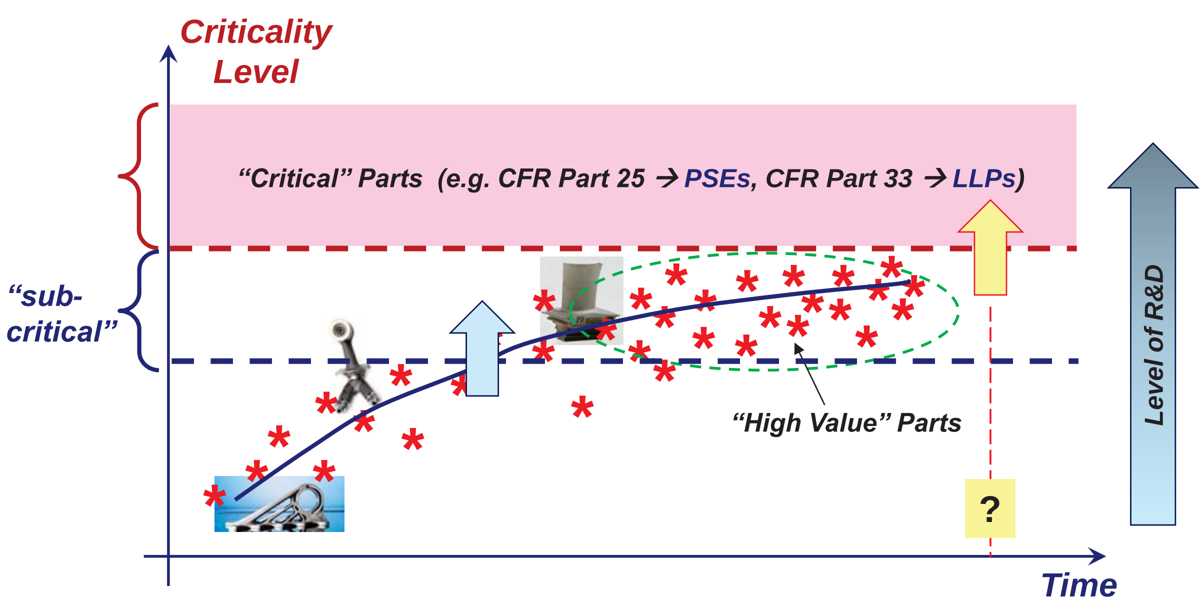
SOURCE: R Schafrik, GE Aircraft Engines, briefing presented at the National Research Council Workshop on Accelerating Technology Transition, Washington, D.C., November 24, 2003.

Example

"The *outcome* of Rawfeed (*an R&D program*) will be a *specification for a process to additively manufacture Class 1 titanium structures*, such as engine hangers, wing spars and gear ribs… expensive, critical parts…"

Reference: *Rolling Key To Additive-Manufacture Of Critical Structures*, Aviation Week & Space Technology, Nov 10, 2014.

Evolution of Criticality of AM Parts



Aggregation of parts at "sub-critical" levels may result in non-trivial *cumulative* risk impact

“History is a Vast Early Warning System”

Norman Cousins

Federal Aviation Administration

Lessons Learned – Powder Metallurgy

FLIGHT INTERNATIONAL, 11 October, 1980, pg 1413

… The US Navy grounded its 13 F-18s following the crash of a TF-18 in England on September 8 (see Flight, September 20, page 1177), following an inflight failure of one General Electric F404 engine. The cause of the accident was the disintegration of the low-pressure turbine (LPT) disc in the right-hand (No 2) engine.

- **…This event strongly influenced the direction of P/M superalloy technology, especially as-HIP**
- **A plausible explanation for the failure - *turbine disk contained a large undetected material flaw*…**

> ➢ **Shortly after the F/A-18 crash, the production of as-HIP P/M superalloys *decreased dramatically***

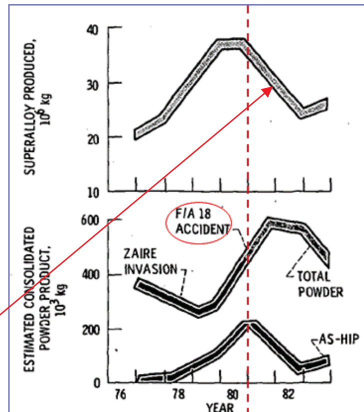


Figure 2. - Superalloy production.

Reference: “P/M Superalloys – A Troubled Adolescent?”, R. L. Dreshfield and H. R. Gray, NASA Technical Memorandum 83623, 1984.

Inherent Anomalies *Specific to PM Alloys*

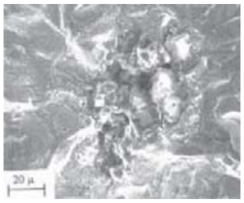
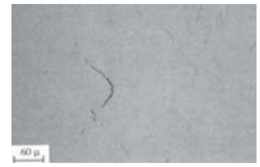


Table I. Major Types of Defects in HIP Rene' 95

Type	Description	Typical Elements	Size, Mils^2(*) Avg.	Max.
1	Discrete chunky ceramic	Al, Mg, Zr, Ca, O	8	50
2	Ceramic agglomerates	Al, Si, Mg, Ca, O	10	110
3	Reactive agglomerates forming PPB	Al, Zr, Cr, Ca, O C, Ca, Fe	15	250
4	Voids	Ar	$\angle 2$	--



Inherent Anomalies in AM Alloys…

- **Lack of fusion..?**
- **Micro-cracking due to residual stresses..?**
- **Porosity..?**
- **Other..? (“known unknowns”)**

…Need to be Understood, Characterized and Managed

Lessons Learned Summary - *Preliminary*

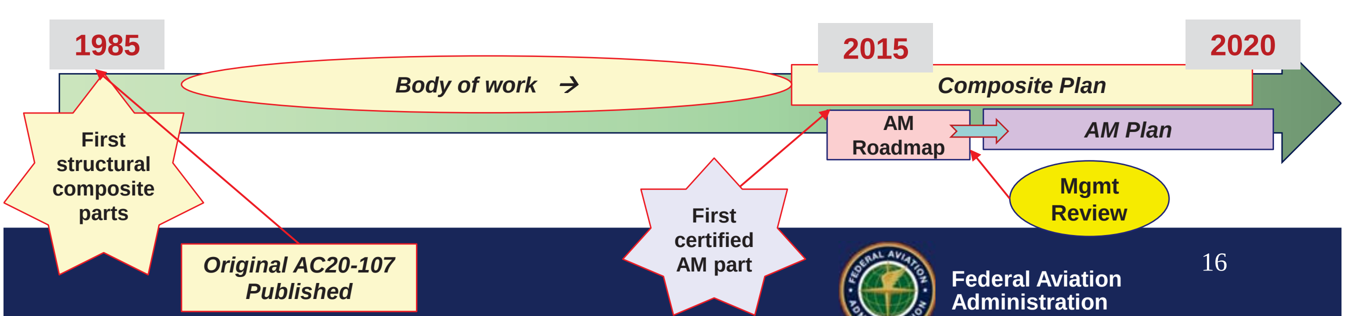
- **Early failures in high-criticality applications have a major impact on new technology**
- ***Scale-up challenges – transitioning from well-controlled development environment to full-scale production***
- **Good understanding of the key failure modes and material anomalies is crucial**
  - **And needs to be connected to manufacturing process controls and NDI methods**
- **Initially believed to be an innocuous material system change, subject to conventional design criteria…**
  - **… Ended up giving rise to a new *probabilistic* lifing framework used for both military and commercial certification**
  - **Highlights importance of managing uncertainty and variation**

Development of AM Roadmap

- **Benchmarking of other agencies and consortia roadmaps**
- **Inter-agency collaboration**
- **Industry outreach**
- **Engagement with standards organizations**
- **Formation of the FAA-chartered industry working group (*under discussion*)**
- **One of the key outcomes – recommendations for the National AM Plan**
- **Timeline – aim at developing a draft by the next year's AM Workshop**

Benchmarking of Composites Timeline

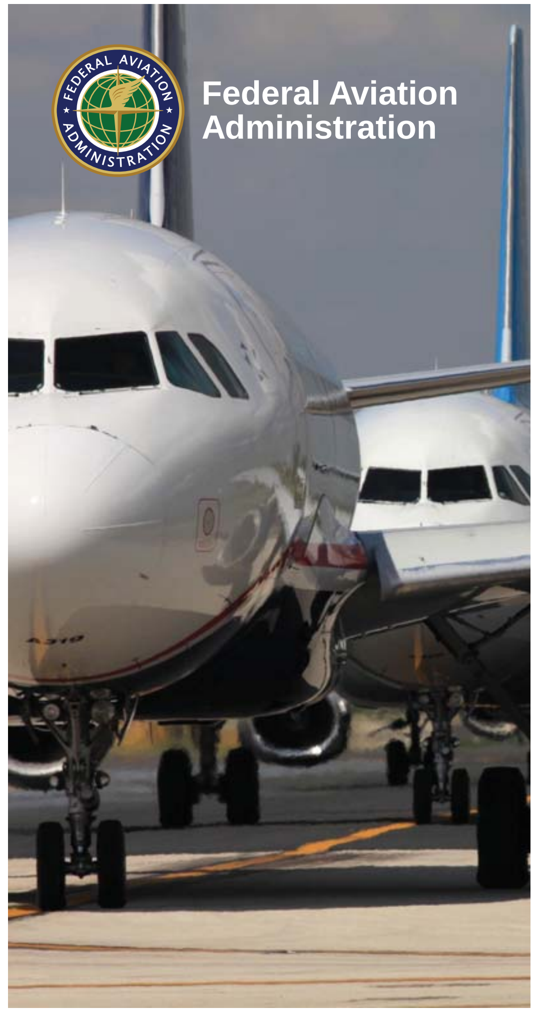
- **Composites**
  - One of the first composite applications (Part 25):
    - ➢ Horizontal tail stabilizer (Boeing) – *circa 1985*
  - 30 years of manufacturing, design and field experience
    - ➢ *Hundreds of certified structural / safety critical parts*
  - Over $15M in FAA R&D investments
- **Additive Manufacturing (metals)**
  - No field experience (commercial); very limited military
    - *one metal AM part (non-structural) certified to date by FAA*
  - No industry-level material or process specs
  - First available FAA R&D funds → *FY17*



Summary

- Most of the engine and aircraft OEMs are evaluating / developing / implementing AM technology
- FAA is starting to work on developing AM roadmap
- Most major OEMs and agencies support risk-based decision making approach, including "system-level" considerations:
  - Manufacturing process controls and specs development
  - Identification and characterization of key failure modes and anomalies
  - Lifing system and certification criteria
  - IPQA and NDI methods
- *Significant opportunities for industry and agencies collaboration*
  - ➢ Should be leveraged to effectively manage resources and risk of AM introduction across Aerospace

Additive Manufacturing Workshop



FAA Perspectives

By: Jim Kabbara

Date: Sept 2, 2015

Outline

- AM Challenges to FAA
- Key FAA Definitions
- Regulatory Requirements
- Roadmap to certification
- AM National Team
  - FAA Activities

Challenges of AM to FAA

- **Current regulations are written to traditional aircraft manufactures and operators:**
  - Applicants are persons or organizations who produce aircraft, engines or propellers.
  - The FAA is not staffed to interact directly with individual suppliers or manufacturers who are not applicants.

Key FAA Definitions

- **Applicant:** Person or persons seeking to certify a product.
- **Product:** An aircraft, aircraft engine, or propeller.
- **Type Design** consists of the drawings and specifications, and a listing of those drawings and specifications, necessary to define the configuration and the design features of the product shown to comply with the requirements of the part of the subchapter applicable to the product.
- **Production approval:** A document issued by the FAA to a person that allows the production of a product in accordance with its approved design and approved quality system, and takes the form of a **production certificate (PC)**.

Federal Regulations

- **The Federal Aviation Regulations are:**
  - Part of Title 14 of the Code of Federal Regulations (CFR).
  - Prescribed by the Federal Aviation Administration (FAA) governing all aviation activities in the United States.

- **Regulations that apply to the certification of specific products (aircraft, engines and propellers):**

Similar Requirements:
  - Part 21 – Certification Procedures for Products and Parts
  - Part 23 – Airworthiness Standards: Normal, Utility, Acrobatic and Commuter Airplanes
  - Part 25 – Airworthiness Standards: Transport Category Airplanes
  - Part 27 – Airworthiness Standards: Normal Category Rotorcraft
  - Part 29 – Airworthiness Standards: Transport Category Rotorcraft

  - Part 33 – Airworthiness Standards: Aircraft Engines
  - Part 35 – Airworthiness Standards: Propellers

FAA Certification/Approval/Authorization

FAA issues:

- **Type Certificate (TC) – Part 23, 25, 27, 29 and 33**
- **Production Certificate (PC)**

Part / Components:
- **Parts Manufacturer Approval (PMA)**
- **Technical Standard Order Authorization (TSOA)**

For Applicants to build certified product they need two FAA certificates

Type Certificate:

An applicant is issued a Type Certificate once they have demonstrated through test and analysis that the type design data (drawings, specifications and other documents needed to describe a design) meets all relevant regulatory requirements.

Production Certificate:

An applicant is issued a Production Certificate once their manufacturing facilities are capable of repeatable producing product per the approved Type Certificate.

PMA / TSOA

Applicants may receive Production Approval (PMA), Authorization to build TSO parts (TSOA).

- **PMA (Part 21, Subpart K)**

  Is a combined design and production approval for modification and replacement articles. It allows a manufacturer to produce and sell these articles for installation on type certificated products.

- **TSOA (Part 21, Subpart O)**

  It allows a manufacturer to produce and sell these articles that meet minimum performance set by Technical Standard Order (TSO).

  - ✓ Applicant still must show that PMA/TSO component meets the TC requirements prior to installation

Roadmap to Certification

To receive aircraft certification, applicants may use one of the three prong approaches;

- **Applicants provide full material documentation and data.**
  - ✓ **Applicants are required to show that materials brought into their facilities were purchased under documented controls**
  - ✓ **Applicants are required to show that their processes used to fabricate regulated products are under documented control**
  - ✓ **Applicant must show thorough testing in order to satisfy the statistical requirements defined in the regulations**
    - **Testing must account for the sources of variation introduced by both the materials and fabrication methods used to produce the product.**
- **Applicants submit with their application letter certifying that MMPDS data is used is the design of aircraft /components (No further showing)** — **Not Yet Applicable for AM**
- **Applicants deviating from above may request special approval from FAA administrator.**

FAA AM National Team, AMNT

Directorates
- ✓ Mark Freisthler (TAD)
- ✓ Dan Kerman (E&PD)
- ✓ Mark James (SAD)
- ✓ Bob Grant (RD)
- ✓ Tim Mouzakis (E&PD)

Headquarters
- ✓ Jim Kabbara (Team Lead)
- ✓ Robert Cook

CSTAs
- ✓ Michael Gorelik (F&DT)
- ✓ Terry Khaled (Metallurgy)

Flight standards
- ✓ Rusty Jones

Tech Center
- ✓ John Bakuckas
- ✓ Kevin Stonaker
- ✓ Dave Gallela

FAA Activities (AM National Team)

- Participate in government and industries sponsored initiatives to provide guidance on issues pertaining to certification and continued airworthiness of AM
- Evaluate current FAA policy and guidance to insure the safe implementation of these technologies
- Develop policy and guidance as needed to prepare *ACOs/MIDOs/FSDOs*

FAA Activities Out-Reach (Cont'd)

- Industry Associations
  - Currently AMNT members are participating in
    - ✓ Additive Manufacturing Innovation Institute (NAMII)
    - ✓ ASTM F32 committee on Additive
  - Metallic Material Properties Development Standardization (MMPDS)
    - ✓ Development of Equivalency design approach (Task 9)
  - Seeking GAMA and AIA support to establish industries-governments Additive Working Groups to help in the development of industry material, process specs and industry best practices
    - ASTM, SAE, etc.
    - OEM

My Contact Information

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Information Slides

Material Specifications

- **§ 2X.603 (Materials)**
  - The suitability and durability of materials used for parts, failure of which will adversely affect safety, must:
    - ✓ Be established by experience or test
    - ✓ Conform to approved specifications
    - ✓ Take into account the effects of environmental conditions

- **FAA acceptable material specifications for AM have not been developed at this time. These specifications are needed to support inclusion of these materials in MMPDS and FAA regulation**

Process Specifications

- § 2X.605 (Fabrication methods)
  - The methods of fabrications used must produce a consistently sound structure
    - ✓ If a fabrication process requires close control to reach this objective, the process must be performed under an approved process specification
    - ✓ Each new aircraft fabrication method must be substantiated by a test program.
- Each manufacturer will need to develop process specifications for their specific fabrication method.

Material Design Properties

- **§ 2X.613 (Material strength properties and material design values)**
  - Strength properties must be based on testing of materials meeting approved specifications to establish design values on a statistical basis
    - ✓ Design values must be chosen to minimize the probability of structural failure.
      - Single load path structures must meet a 99% probability with 95% confidence statistics
      - Redundant load path structures must meet a 90% probability with 95% confidence statistics

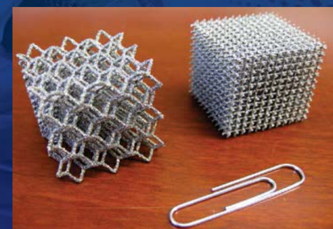
Material Requirements for Engines

- **Part 33 (Engines) regulations have different requirements then parts 23, 25, 27 & 29**
  - § 33.15 "The suitability and durability of materials used in the engine must:
    - ✓ Be established on the basis of experience or tests, and
    - ✓ Conform to approved specifications that ensure their having the strength and other properties assumed in the design data.
  - No mention of process and design values requirements as there are in the other parts of the regulations. Subpart E,("Design and Construction; Turbine Aircraft Engines") contain design related requirements.

Material Requirements for Propellers

- **§ Part 35 (Propellers) regulations also have different requirements then parts 23, 25, 27 & 29.**
- **§ 35.17 ("Materials and manufacturing methods") state;**
  - "The suitability and durability of materials used in the engine must:
    - ✓ Be established on the basis of experience, test or both, and
    - ✓ Account for environmental conditions expected in service.
  - All materials and manufacturing methods must conform to specifications acceptable to the Administration.
  - The design values of properties of materials must be suitably related to the most adverse properties stated in the material specification for applicable conditions expected in service.

Additive Manufacturing Standards Development



Kevin Jurrens
Deputy Chief, Intelligent Systems Division
Engineering Laboratory
National Institute of Standards and Technology
U.S. Department of Commerce

NIST
National Institute of Standards and Technology
U.S. Department of Commerce

Unique Role of NIST Research Laboratories

- Emphasis on infrastructural metrology and non-proprietary, standardized metrology methods that address a broad class of measurement challenges
- Emphasis on rigorous and generic procedures to characterize measurement uncertainty that comply with international standards
- Long-term commitment, expertise, and neutrality essential for harmonized and unbiased national and international standards
- Leverage NIST core competences in measurement science, rigorous traceability, and development and use of standards -- as well as specific expertise in measurements and standards for manufacturing systems, processes, and equipment

➢ **Measurements and Standards**

NIST Influence on AM Standards

- Identify needs and priorities through workshops and industry meetings
- Develop technical basis for standards through measurement science research
  - Draft content and starting point for standards development
- Serve on standards committees, e.g.,
  - ASTM Committee F42 on Additive Manufacturing Technologies
  - ISO Technical Committee 261 on Additive Manufacturing
  - ASME Y14.46 on GD&T for Additive Manufacturing
- Coordination, facilitation, and communication roles

Role of Additive Manufacturing Standards

- Standards can be used for (among others):
  - specifying requirements
  - communicating guidance
  - documenting best practices
  - defining test methods and protocols
  - documenting technical data
  - accelerating the adoption of new technologies
- Certifying bodies typically reference publicly available standards in their procedures
- Standards development in the U.S. is conducted through voluntary participation and consensus
  - ➢ Companies and agencies must participate to impact the priorities and content of standards!

ASTM Standards Committee F42

- ASTM Committee F42 on Additive Manufacturing Technologies established in January 2009 to address high-priority standards needs
- Initiated by diverse group of experts from Society of Manufacturing Engineers (SME), Rapid Technologies & Additive Manufacturing community
- F42 subcommittees formed for :
  - *Terminology*
  - *Test Methods*
  - *Materials and Processes*
  - *Design (including data formats)*
  - *Environment, Health, and Safety*
  - *U.S. Technical Advisory Group (TAG) to ISO TC 261*
- Current F42 roster: ~315 members; 22 countries represented (approx. 1/4 of roster from outside the U.S.)
- Status: 11 approved standards; 20+ work items under development
- http://www.astm.org/COMMITTEE/F42.htm

Types of ASTM Standards

- Standards can be of several forms, with different types of content and levels of rigor:
  - Standard Specification
  - Standard Test Method
  - Standard Practice
  - Standard Guide
  - Standard Classification
  - Standard Terminology
- ASTM technical committees address a wide variety of technology and advanced manufacturing areas
  - e.g., homeland security applications, emergency response robotics, automated guided vehicles, robotic manipulators, 3D vision systems, sustainable manufacturing, additive manufacturing, etc.

NIST Contributions to ASTM F42

- Substantial technical presence and leadership
  - Vice-Chair of Test Methods Subcommittee
  - Member of F42 Executive Committee, tasked to lead the strategic planning for F42
  - Leadership of technical task groups
  - New standards activities based on NIST research
  - Member of U.S. Technical Advisory Group to ISO TC261
  - ASTM / ISO: Joint Plan for AM Standards Development
- Developed strategic approach and vision for AM standards, focused on maximizing impact

ASTM F42 Procedures

- Two formal meetings per year (joint with ISO TC261):
  - Winter (Jan/Feb) in the U.S.
  - Summer (June/July) in Europe/Asia
- Standards developed through task groups
- New task groups formed based on common needs and interests
- Much development happens between meetings, using teleconferences, web meetings, etc.
- Draft documents from task groups are balloted within Subcommittee first, then full Committee
- ASTM ballot process: Every person has a voice
  - Negative votes must be resolved, withdrawn, or determined non-persuasive by majority vote

Formal Agreement Established between ASTM F42 and ISO TC261

- Formal collaboration established between ASTM and ISO (first of its kind!) for joint development of AM standards
- Will result in co-branded ISO and ASTM standards (same content, no need for future harmonization)
- Procedures for how ASTM and ISO will cooperate and work together in a practical sense are defined in the “Joint Plan for Standards Development”

July 2015 Update: CEN Committee

- CEN Technical Committee 438 on Additive Manufacturing established
- First meeting July 2015, co-located with ASTM F42 and ISO TC261 meetings
- Agreed to adopt ISO/ASTM standards, leading to now co-branded ISO / ASTM / CEN standards
- High Impact: CEN standards are mandated for use within European members, and corresponding national standards must be withdrawn

ASTM F42 and ISO TC 261: Agreement on Guiding Principles

- **One Set of AM Standards** – to be used all over the world
- Common roadmap and organizational structure for AM standards
- Use and build upon existing standards, modified for AM when necessary
- For efficiency and effectiveness, ISO TC 261 and ASTM F42 should **begin** the work together and in the same direction
  - Emphasis on **joint** standards development

➢ Joint Plan for AM Standards Development

Primary Drivers for the AM Standards Strategic Planning

- Improve usability and maximize future impact of the entire set of AM standards
  - Prevent overlap and contradiction among AM standards
  - Ensure that future AM standards work together as an integrated and cohesive set
  - Improve usability and acceptance for future users of all types (novice and expert)
- Meet current and future needs, while avoiding problems (e.g., harmonization) faced by standards groups in other areas

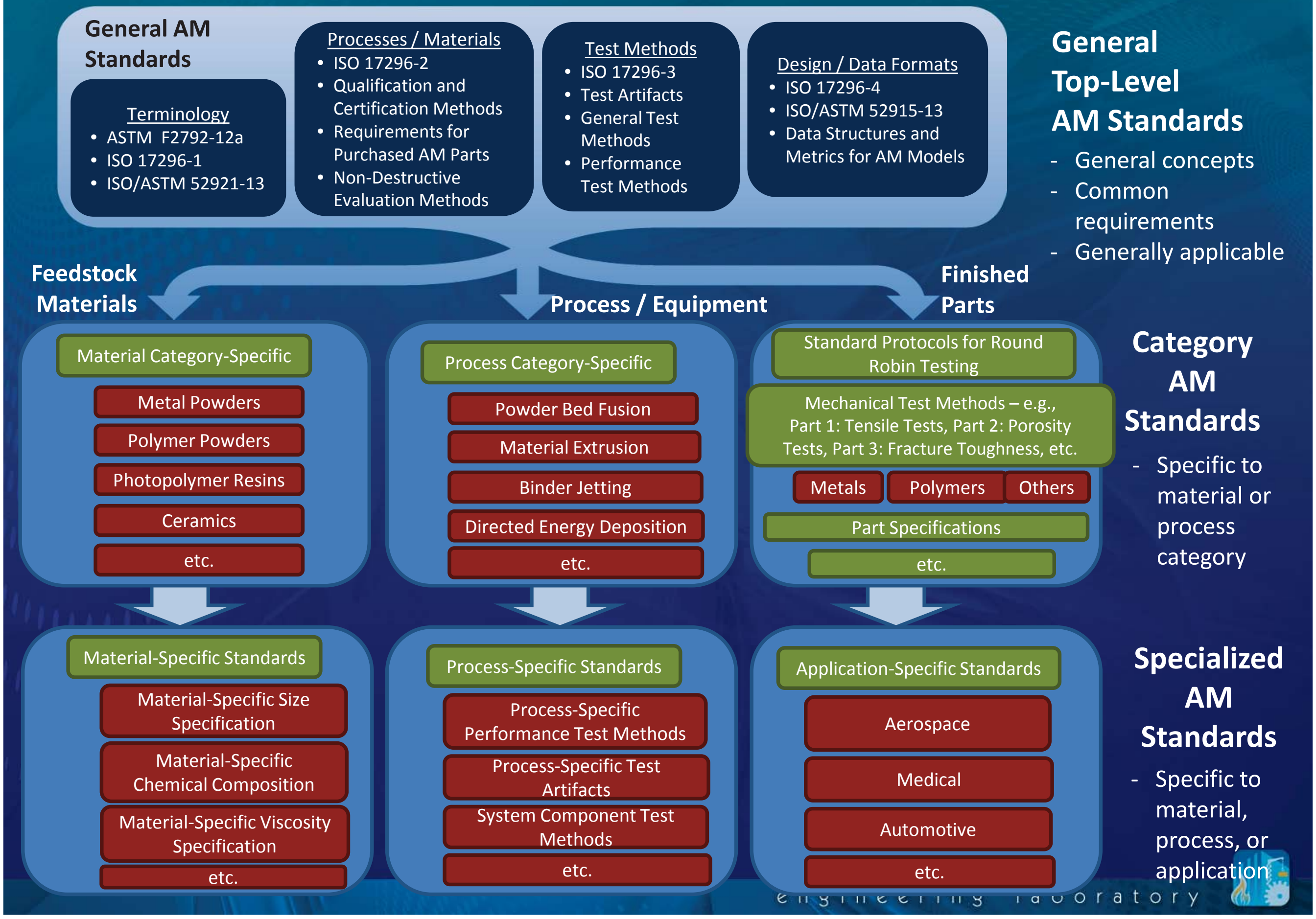
Key Questions for the Future of AM Standards

- Five years from now, what AM standards need to be in place to meet our application needs?
- What benefits or impacts will these future standards have for AM users, vendors, and technology providers?
- What steps can we take now to ensure that AM standards achieve the biggest future impact?

Organizational Structure of AM Standards

- Accommodates perspectives and requirements from both ISO TC261 and ASTM F42
- Augments ongoing bottom-up approach with a top-down strategic view
- Defines multiple levels and a hierarchy of AM standards:
  - General standards: general concepts, common requirements, generally applicable
  - Category standards: specific to a material category or process category
  - Specialized standards: specific to a material, process, or application

Structure of AM Standards



Usage Guidelines

- Modularized standards are intended
- Hierarchy of standards exists to reduce duplication:
  – Parent-child relations between levels (from top to bottom)
  – Characteristics pass from parent level to child level (upon reference)
  – Child level standards can modify or augment the characteristics as needed for the specific use
- Key question relevant to the 3 paths:
  – Does the developed standard specify/evaluate 1) Feedstock Materials, 2) Process/Equipment, or 3) Finished Parts?

Benefits of Strategic Approach

- Efficient - reduces potential for redundancies and incompatibilities
- Consistent – reduces potential need for future harmonization of contradictory standards
- Organized – prioritization and planning of standards development is easier, overall structure gives guidance to the working groups, and relationships between standards are clear
- Maintains current bottom-up approach and supplements with top-down, big-picture perspective

Approved AM Standards To-Date

- ASTM F2792-12a, Standard Terminology for Additive Manufacturing Technologies
- ISO/ASTM 52921-13, Standard Terminology for Additive Manufacturing Coordinate Systems and Test Methodologies
- ISO/ASTM 52915-13, Standard Specification for Additive Manufacturing File Format (AMF) Version 1.1
- ASTM F2791-13, Standard Practice for Reporting Data for Test Specimens Prepared by Additive Manufacturing
- ASTM F2924-14, Standard Specification for Additive Manufacturing Titanium-6 Aluminum-4 Vanadium with Powder Bed Fusion
- ASTM F3001-14, Standard Specification for Additive Manufacturing Titanium-6 Aluminum-4 Vanadium ELI (Extra Low Interstitial) with Powder Bed Fusion
- ASTM F3055-14, Standard Specification for Additive Manufacturing Nickel Alloy (UNS N07718) with Powder Bed Fusion
- ASTM F3056-14, Standard Specification for Additive Manufacturing Nickel Alloy (UNS N06625) with Powder Bed Fusion
- ASTM F3091-14, Standard Specification for Powder Bed Fusion of Plastic Materials
- ASTM F3049-14, Standard Guide for Characterizing Properties of Metal Powders Used for Additive Manufacturing
- ASTM F3122-14, Standard Guide for Evaluating Mechanical Properties of Metal Materials Made via Additive Manufacturing Processes

Joint Development of AM Standards by ASTM F42 and ISO TC261

Current Joint Groups

- Terminology – harmonization of existing terminology standards
- Standard test artifacts
- Requirements for purchased AM parts
- Design guidelines
- Specification for extrusion-based AM of plastic materials
- Practice for metal powder bed fusion to meet rigid quality requirements
- Specific design guidelines for powder bed fusion
- Qualification, quality assurance, and post processing of powder bed fusion metallic parts
- Nondestructive testing for AM parts

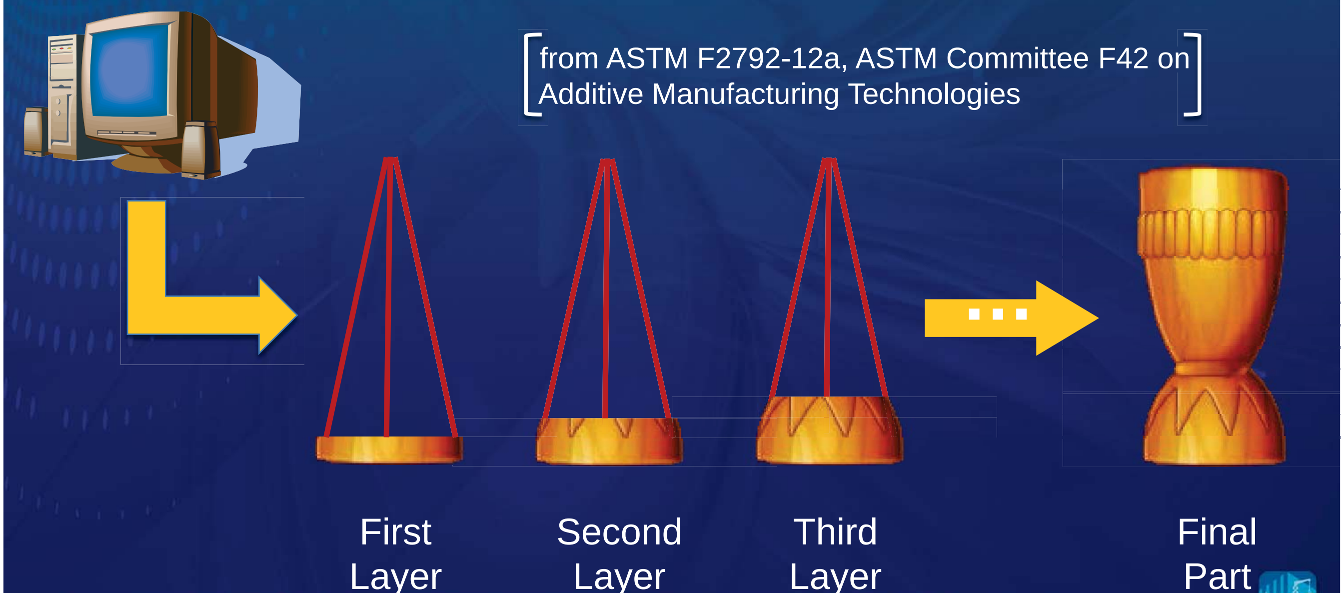
Candidates for Future Joint ASTM / ISO Groups

- Standard protocols for round robin testing
- Test methods for characteristics of feedstock materials
- Specifications for metal powder handling, storage, safety, etc.
- Test methods for mechanical properties of finished AM parts
- Qualification methods: material, machine, process, operator, etc.
- Quality standards and methods: pre-process, in-process, post-process
- Material recycling (re-use) guidelines

Standard Terminology

- Definitions of many standard terms are agreed upon, for example:
  - Additive Manufacturing (AM) is the process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies.

[from ASTM F2792-12a, ASTM Committee F42 on Additive Manufacturing Technologies]



Common Synonyms for *Additive Manufacturing*

- 3D Printing (media favorite)
- Layered Manufacturing
- Freeform Fabrication
- Direct Part Manufacturing
- Direct Digital Manufacturing
- Rapid Prototyping
- Several others – each system vendor uses a trademarked term

Additive Manufacturing is an umbrella term for a set of processes and technologies developed over the past 25+ years

Additive Manufacturing Materials and Processes

- Variety of Material Types:

  Polymers, ceramics, metals, composites, paper, etc.

- Variety of Material Forms:

  Filaments, resins, powders, sheets, rods, etc.

- Variety of Processes:

  Many systems: different approaches, different materials, different capabilities, different purposes

  - ASTM Committee F42 defines seven standard process categories

Seven Standard AM Process Categories

- Material Extrusion
- Vat Photopolymerization
- Material Jetting
- Binder Jetting
- Sheet Lamination
- Powder Bed Fusion
- Directed Energy Deposition

[from ASTM F2792-12a, ASTM Committee F42]

ASME Y14.46 Standards Committee

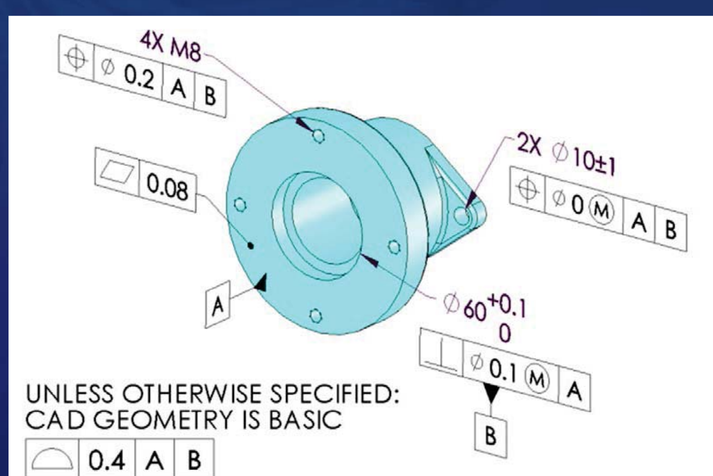
- New committee formed in 2015 to address aspects of Geometric Dimensioning & Tolerancing (GD&T) that are unique to additive manufacturing
- Builds on long-standing expertise and several GD&T standards developed by ASME Y14 committee
- Charter: Specific to Additive Manufacturing (AM), develop and standardize dimensioning and tolerancing methods, systems, and indications within engineering product definition digital data sets to promote uniform practices
- Standards will include data package requirements, part definition, process specific definition, and verification and conformance to specifications

Geometric Dimensioning & Tolerancing (GD&T)

- Language for communicating geometric tolerance specification and design intent between:

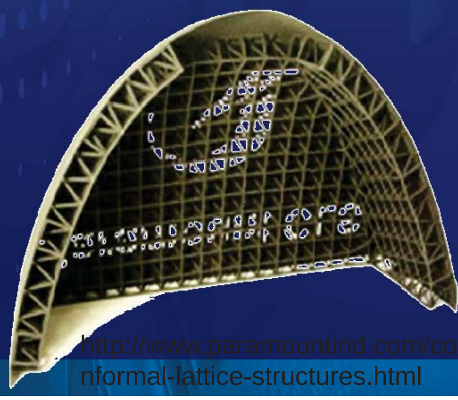
  Designers – Manufacturers

  Designers – Inspectors

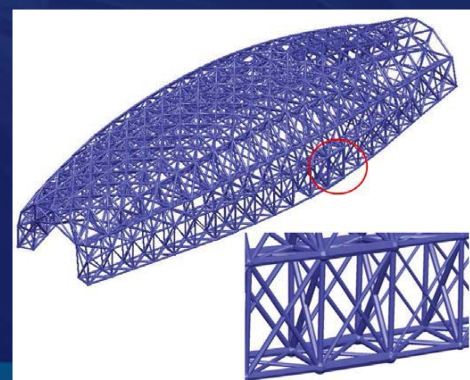


Case 1: Tolerancing Specification Issues Highlighted by AM Parts

- Some specification issues are not specific to AM processes, but heightened by AM capabilities
  - Features are feasible in other processes, but have no appropriate means of specification
  - These features are brought to attention because of the capabilities of AM processes

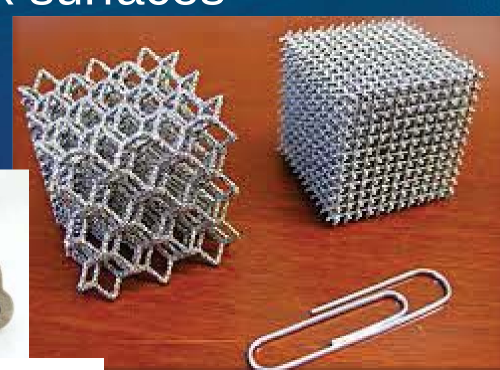


http://www.paramountind.com/conformal-lattice-structures.html



Tolerancing Specification Issues Highlighted by AM

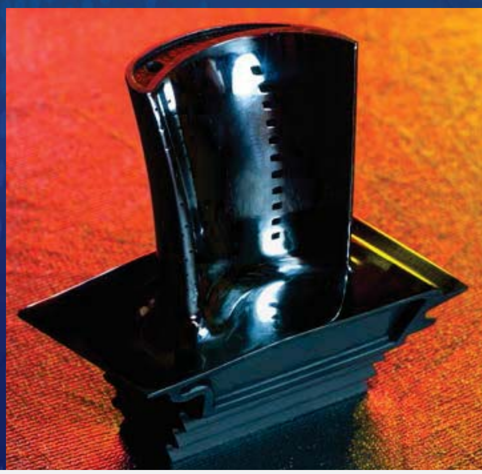
- Tolerancing free-form complex surfaces
- Topology optimized shapes
- Internal features

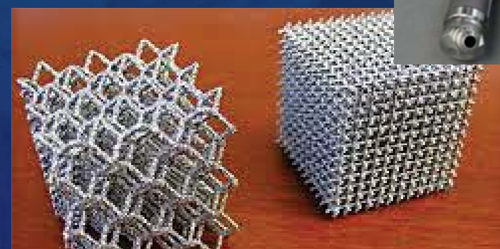


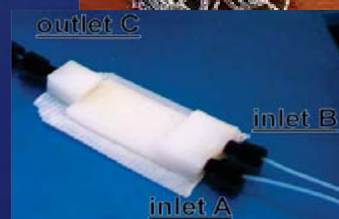
Functional need to specify tolerances to free-form complex features

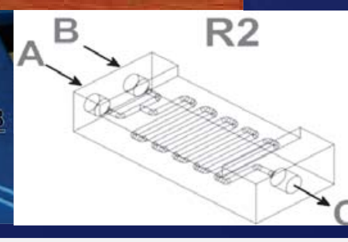
Tolerancing Specification Issues Highlighted by AM

- Internal features
  - Patterns
  - Functional features (cooling channels, fluid flow, etc)









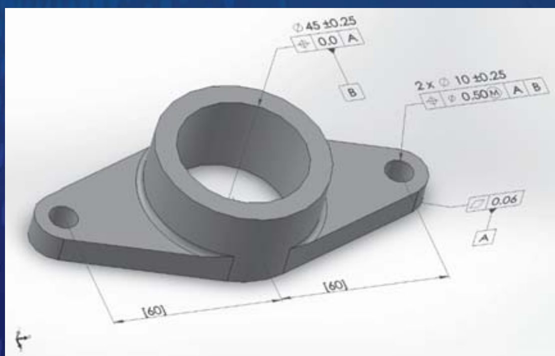
Functional need to specify tolerances to patterns and internal features

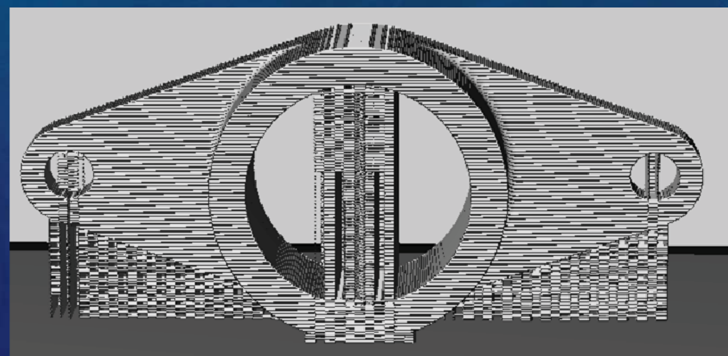
Case 2: Tolerancing Specification Issues Specific to Additive Manufacturing

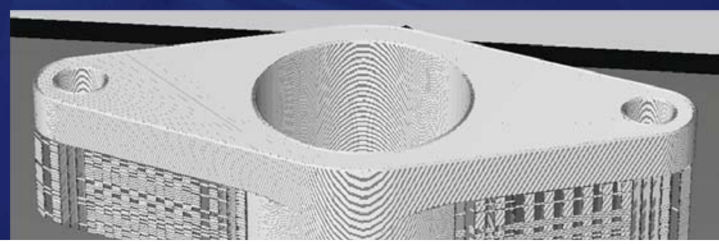
- Some specification issues can only be addressed with specific knowledge about the manufacturing process
  - Involves both product geometry (features) and best practices from manufacturing processes (rules, material modifiers, etc.)
  - Similar to:
    - Composites
    - Castings/forgings

AM Process Related Tolerance Specification Issues

- Build direction
- Support structures



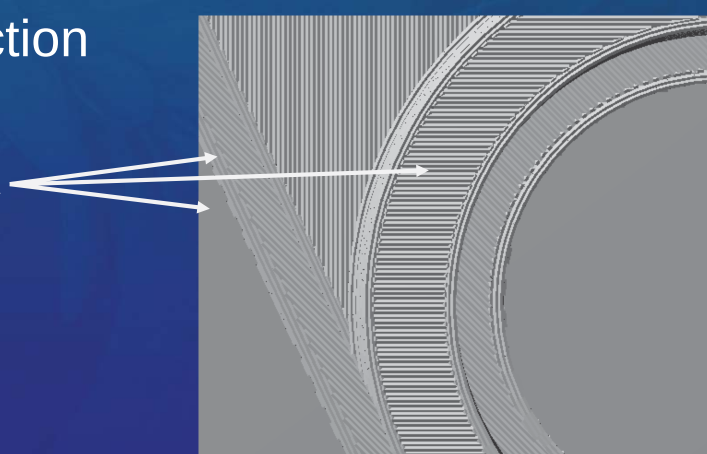




Build direction has a significant impact on post-processes and characteristics of the product

AM Process Related Tolerance Specification Issues

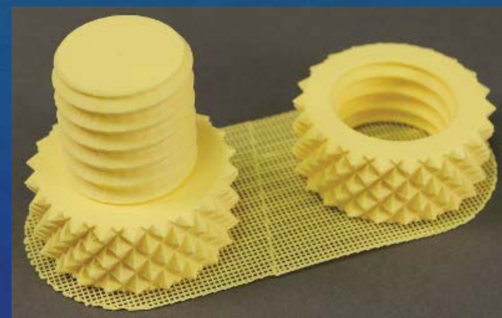
- Specifying layer thickness
- Scan\track direction

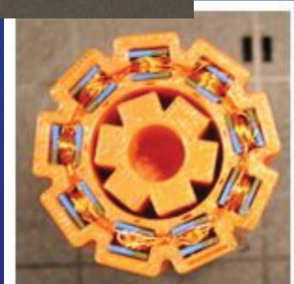


Scan\track direction causes specific properties in the AM product

Tolerance Specifications

- For multi-materials/functionally graded materials
- For as-built assemblies





Embedding Electro-Magnets

NIST Contributions to ASME Y14.46

- Vice-Chair of Y14.46 committee
- Much expertise in dimensional metrology, quality inspection, design systems, standard data representations, and GD&T
- Currently leading development of the committee charter and scope
- Coordination with ASTM F42 (specifically F42 Design subcommittee)
- Next meeting: October 20, St. Petersburg, FL

NIST Perspectives on AM Standards

- NIST will continue to support AM measurement science research and standards development
  - Standards efforts to-date have focused mostly on ASTM F42 and the corresponding interactions with ISO TC261 due to activity since 2009
- Primary motivations:
  - usability and impact of the resulting standards
  - one set of standards: consistent, cohesive, non-contradictory, non-overlapping, integrated
  - prevent duplication of effort and results
- Coordination, communication, and cooperation are necessary among AM users, standards bodies, and regulatory agencies
  - AM Standards Coordination Event: Oct. 7-8, Penn State Univ.

Contact Info

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Intelligent Systems Division
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National Institute of Standards and Technology (NIST)
100 Bureau Drive, MS 8230
Gaithersburg, MD 20899

www.nist.gov/el/isd

engineering laboratory

Questions and Discussion

SAE INTERNATIONAL

SAE AEROSPACE – AMS-AM ADDITIVE MANUFACTURING COMMITTEE

Joint FAA –Air Force Workshop
Dayton, OH
September 1-2, 2015

Dave Abbott, Chair
AMS-AM Committee

Who I Am

David H. Abbott

- Chair, SAE AMS-AM
- Principal Engineer, GE Aviation
- BS and MS Welding Engineer, OSU
- 20+ years experience in Additive Manufacturing
- One of four founders, AeroMet Corporation

AGENDA

1. SAE OVERVIEW
2. SAE AEROSPACE STANDARDS PROGRAM
3. STANDARDS DEVELOPMENT PROCESS

SAE OVERVIEW

SAE International is a global body of scientists, engineers, and practitioners that advances self-propelled vehicle and system knowledge in a neutral forum for the benefit of society.

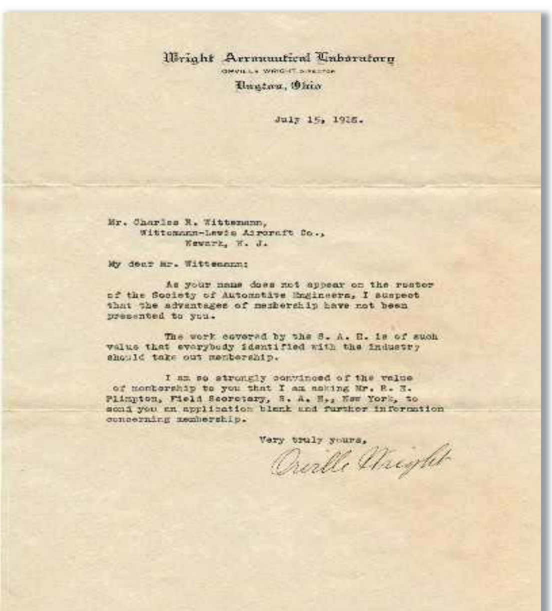
SAE International is a not-for-profit, non-lobbying technical organization and membership association with 138,000 members in over 100 countries.

Aerospace

Commercial Vehicles

Automotive

SAE AEROSPACE STANDARDS HISTORY – FROM 1916



Wright Aeronautical Laboratory
Orville Wright Director
Dayton, Ohio

July 15, 1918.

Mr. Charles R. Wittemann,
Wittemann-Lewis Aircraft Co.,
Newark, N. J.

My dear Mr. Wittemann:

As your name does not appear on the roster of the Society of Automotive Engineers, I suspect that the advantages of membership have not been presented to you.

The work covered by the S. A. E. is of such value that everybody identified with the industry should take out membership.

I am so strongly convinced of the value of membership to you that I am asking Mr. R. S. Plimpton, Field Secretary, S. A. E., New York, to send you an application blank and further information concerning membership.

Very truly yours,
Orville Wright

The Wright Brothers

"The work covered by the SAE is of such value that everybody identified with the industry should take out membership."
Orville Wright, 1918

SAE Standards History – and Future …..

1905

2015

SAE formed in 1905 to promote safety and common practices for the emerging automobile market

↓

SAE charter expanded in 1916 to incorporate aeronautics

↓

1st SAE Aerospace Standard, 1917

↓

Mil Spec reform transferred over 1500 specifications to SAE, late 1990's

↓

SAE Aerospace Standards Europe office opened in London in 2007

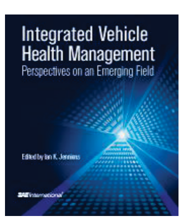
↓

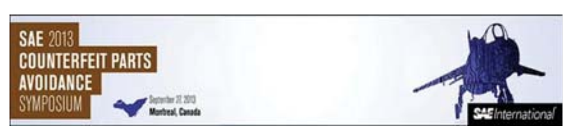
Acquisition of TechAmerica and ARINC Industry Activities Standards Programs, 2013

↓

The Future: 2015…**AMS-AM**

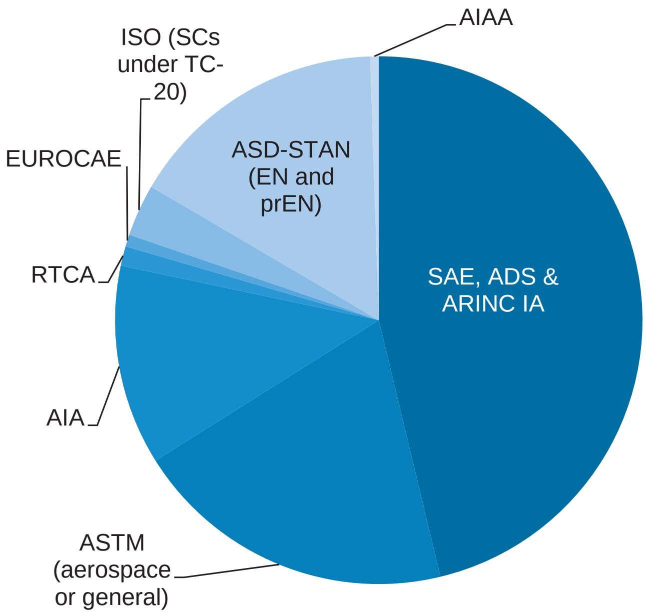
SAE AEROSPACE PORTFOLIO





SAE AEROSPACE STANDARDS PROGRAM

THE AEROSPACE STANDARDS LANDSCAPE: SAE GLOBAL LEADERSHIP



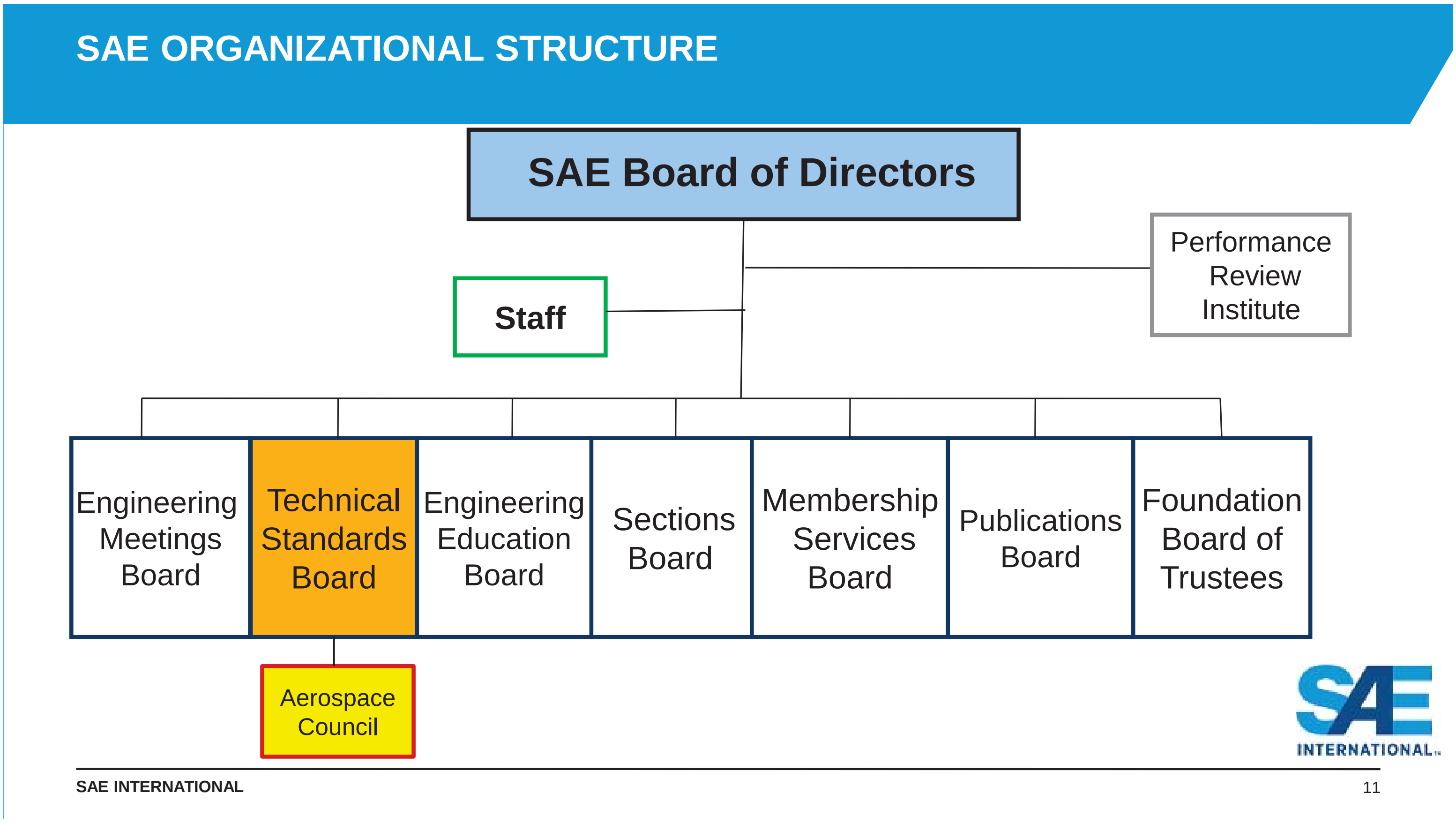
8500+ standards

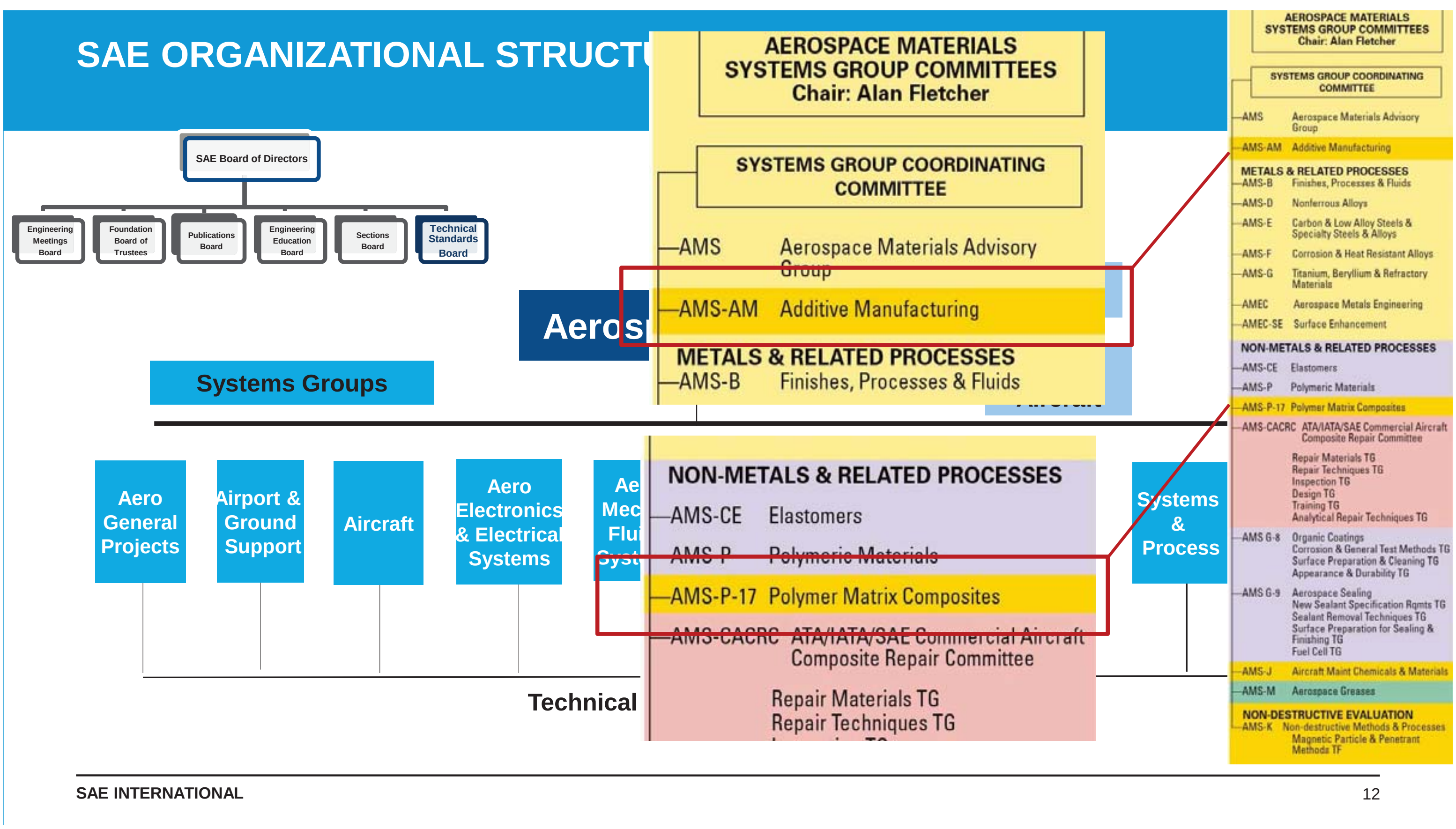
150+ committees, subcommittees, and task groups

11000+ global participants

Civil and Military

applications addressed


SAE ORGANIZATIONAL STRUCTURE
SAE Board of Directors
Staff
Performance Review Institute
Engineering Meetings Board
Technical Standards Board
Engineering Education Board
Sections Board
Membership Services Board
Publications Board
Foundation Board of Trustees
Aerospace Council
SAE INTERNATIONAL
SAE INTERNATIONAL
11


SAE ORGANIZATIONAL STRUCTU
SAE Board of Directors
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Engineering Education Board
Sections Board
Technical Standards Board
Aeros
Systems Groups
Aero General Projects
Airport & Ground Support
Aircraft
Aero Electronics & Electrical Systems
Systems & Process
Technical
AEROSPACE MATERIALS SYSTEMS GROUP COMMITTEES
Chair: Alan Fletcher
SYSTEMS GROUP COORDINATING COMMITTEE
AMS Aerospace Materials Advisory Group
AMS-AM Additive Manufacturing
METALS & RELATED PROCESSES
AMS-B Finishes, Processes & Fluids
AMS-D Nonferrous Alloys
AMS-E Carbon & Low Alloy Steels & Specialty Steels & Alloys
AMS-F Corrosion & Heat Resistant Alloys
AMS-G Titanium, Beryllium & Refractory Materials
AMEC Aerospace Metals Engineering
AMEC-SE Surface Enhancement
NON-METALS & RELATED PROCESSES
AMS-CE Elastomers
AMS-P Polymeric Materials
AMS-P-17 Polymer Matrix Composites
AMS-CACRC ATA/IATA/SAE Commercial Aircraft Composite Repair Committee
Repair Materials TG
Repair Techniques TG
Inspection TG
Design TG
Training TG
Analytical Repair Techniques TG
AMS G-8 Organic Coatings
Corrosion & General Test Methods TG
Surface Preparation & Cleaning TG
Appearance & Durability TG
AMS G-9 Aerospace Sealing
New Sealant Specification Rqmts TG
Sealant Removal Techniques TG
Surface Preparation for Sealing & Finishing TG
Fuel Cell TG
AMS-J Aircraft Maint Chemicals & Materials
AMS-M Aerospace Greases
NON-DESTRUCTIVE EVALUATION
AMS-K Non-destructive Methods & Processes
Magnetic Particle & Penetrant Methods TF
SAE INTERNATIONAL
12

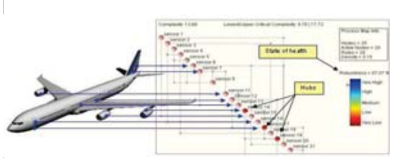
SAE AEROSPACE COUNCIL

Global Strategy and Oversight

- Agusta Westland
- Airbus
- All Nippon Airways
- A4A
- AVIC
- BAE Systems
- The Boeing Company
- Bombardier Aerospace
- CAPE
- CIRA
- COMAC
- European Aviation Safety Agency
- Embraer
- Federal Aviation Administration
- Fed Ex
- GE Company
- Gulfstream Aerospace
- Honeywell Aerospace
- Lockheed Martin
- Lufthansa Technik
- NASA
- Northrop Grumman
- Pratt & Whitney
- Rolls-Royce
- United Aircraft Corporation
- U.S. Department of Defense
- Wichita State University

KEY SAE AEROSPACE STANDARDS ACTIVITIES

Materials



Structural Health Monitoring

De-icing & Carbon Brake Oxidation

Counterfeit Parts Avoidance

Additive Manufacturing

Environmental Standards

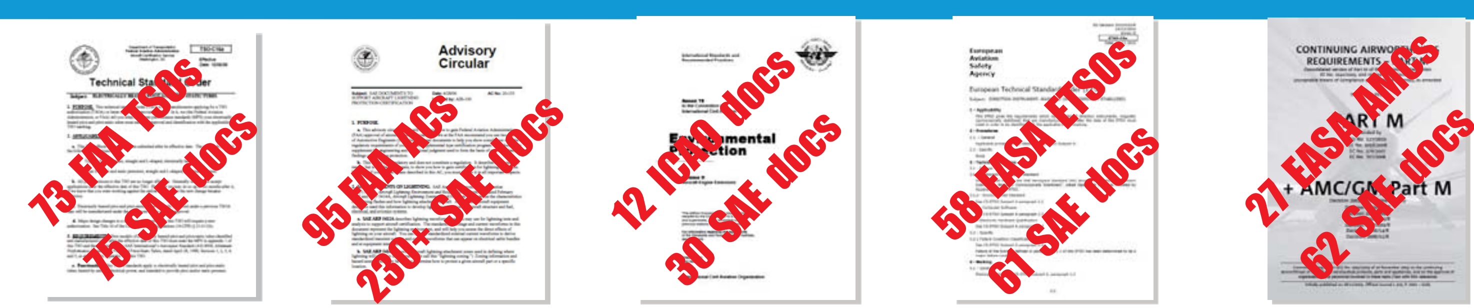
Composite Repair

Human Factors & Cockpit Design

Aircraft & Engine Health Monitoring

ONE FORUM, ONE STANDARD

REGULATORY REFERENCES TO SAE STANDARDS FOR AIRCRAFT CERTIFICATION



Example FAA TSO
Mandatory compliance

Example FAA AC
Guidance material

Example ICAO Annex
Mandatory compliance

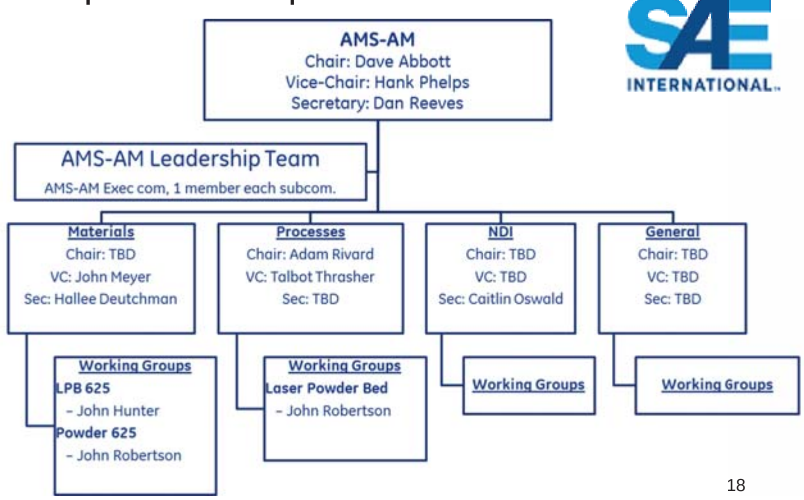
Example EASA ETSO
Mandatory compliance

Example EASA AMC
Guidance material

SAE AMS-AM COMMITTEE ON ADDITIVE MANUFACTURING

SAE AMS-AM Committee

- Inaugural meeting July 21-22, 2015 in Atlanta, GA.
  - 60+ in attendance, 20+ online
  - Reviewed draft agenda
  - Created subcommittees and initiated specification process
- Currently:
  - 150+ registered members
  - 4 Subcommittees
  - 1 sponsored specification
    - LPB 625
  - 2 proposed specifications
    - LPB 625 Powder Feedstock
    - LPB Process



Charter

Scope:

…to develop and maintain aerospace material and process specifications …for additive manufacturing, including precursor material, additive processes, system requirements and materials, pre-processing and post-processing, non-destructive testing and quality assurance.

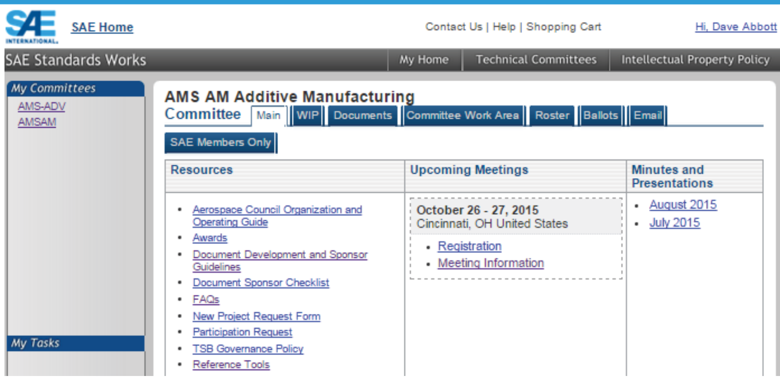
…the committee will collaborate with "other standards" organizations such as MMPDS, ASTM Committee F42 on Additive Manufacturing, AWS D20, Nadcap Welding Task Group, America Makes, CMH-17, and regulatory authorities such as FAA and EASA.

Charter

Objectives:

- **…develop Aerospace Material Specifications (AMS) for the procurement of additive precursor and manufactured materials … When applicable, ensure the material specification is tied to the appropriate shared material property database.**
- **Publish recommended practices and/or specifications for processing and fabrication of end products from AM materials.**
- **Provide a forum for the exchange of technical information related to additive manufacturing.**
- **Further the adaptation of industry sponsored material specifications through coordination with MMPDS, ASTM, AWS, Nadcap, other AMS committees and associated organizations.**
- **Coordinate requirements for publishing data in shared material property databases with MMPDS Emerging Technology Working Group for new metallic materials and CMH-17 for new composite materials.**
- **Establish a system to ensure material specifications are controlled and traceable.**

SAE AMS-AM Standards Works



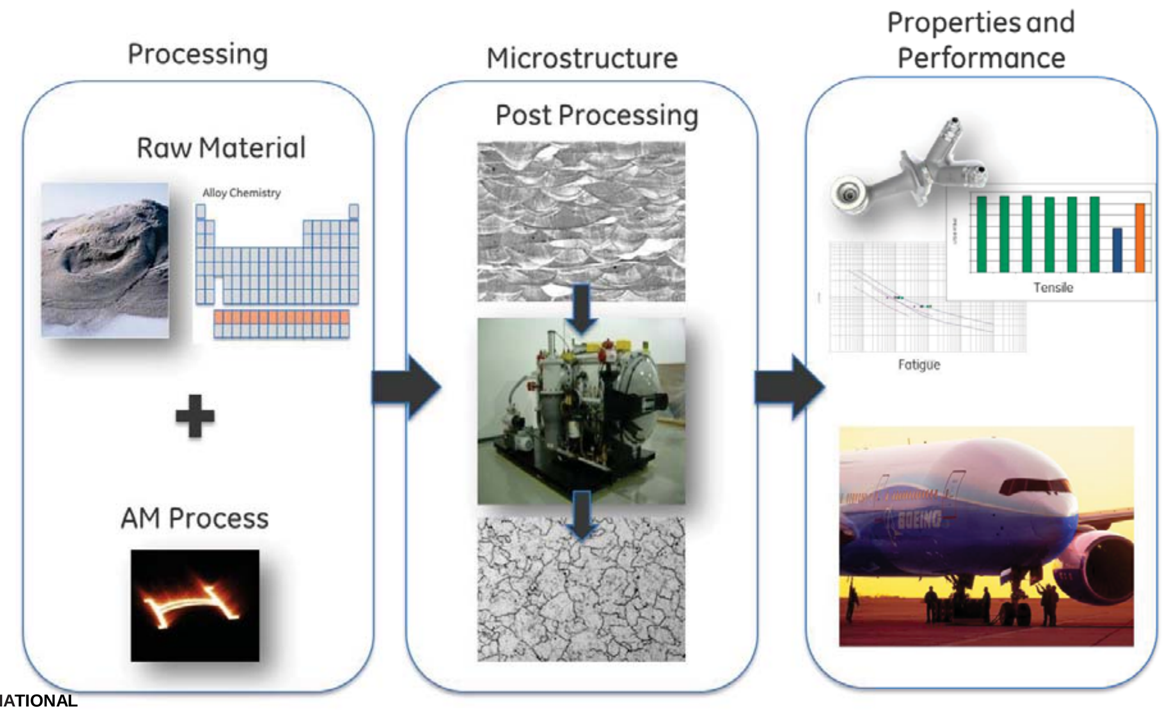
http://works.sae.org
Bookmark this site!

- All SAE technical committees use SAE standards works in the management of the committee.
- All useful documents, drafts, minutes, roster are accessed in Standards Works
- The site is secure owing to the nature of the material
- Committee processes – initiating documents, storing data, communicating, balloting, streamlined to allow fast and easy time-to-market

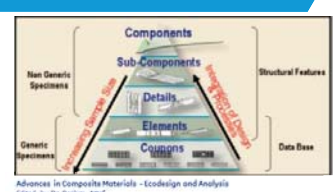
Starting Approach

- Establish framework.
- Start off easy.
- Be focused.
- Cover entire process, i.e., feedstock through service.
- Be specific.
- Low hanging fruit first to establish procedures/approach.
- Keep eye on future direction
  - increased complexity (isotropic->anisotropic->composite)
  - additional areas (software, informatics, analytics, process control)
  - trends (modeling, simulation, virtual testing)

Additive Manufacturing Process Basics

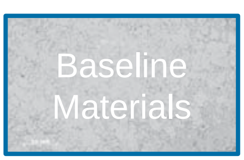


Increasing Degree of Complexity…



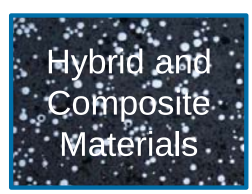
AM Materials

Commodity
- Response to Heat Treatment
- Equiaxed
- Homogeneous



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

Composite
- Discrete phases
- Anisotropic
- inhomogeneous



AMS-AM Today → Future

Increasing Complexity

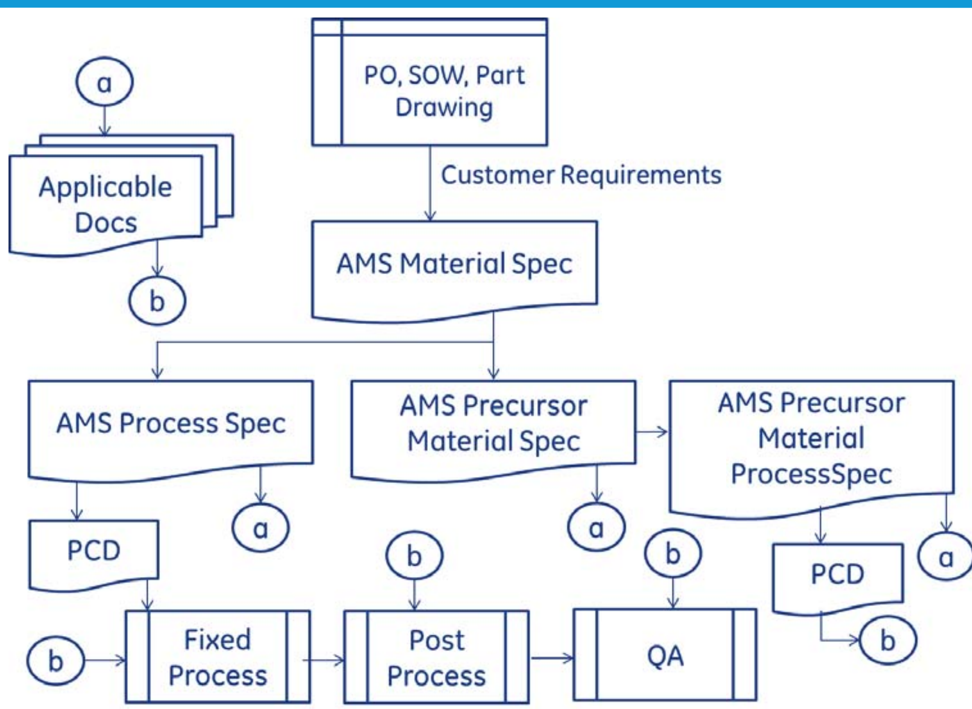
Specification Hierarchy

Material Specification … material requirements

- → **Process Specification**
- → **Feedstock Material Specification**
  - → **Feedstock Process Specification**

- **Hierarchical**
- **Defines requirements and establishes controls**

Flowchart – Specification Hierarchy



2015 Fall Semi-annual Meeting

- When: October 26-27, 2015
- Where: GE Aviation Learning Centre
  Cincinnati, OH
- Who: Open registration

Register online at www.sae.org.

QUESTIONS?

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Rhonda.joseph@sae.org

FAA perspective on Additive Manufacturing values in MMPDS

CSTA training

By: Mark Freisthler

Date: September 1, 2015

FAA Regulatory Requirements as they relate to Additive Manufacturing

- **Agenda**
  - FAA involvement with MMPDS
  - Differences between Stock materials whose values are currently published in MMPDS and AM Materials
  - Research addressing process intensive metallic materials (AM) within MMPDS
  - Comparison of AM and Composite materials
  - AM and Equivalency Testing Approach
  - Why is FAA following equivalency approach

Basic Material Requirements

- **Regardless of Material type the following basic regulations apply:**
  – Any material being used to manufacture parts whose failure would adversely affect safety must conform to an approved material specification.
  – Each new fabrication process must be substantiated by test and controlled by an approved process specification.
  – Material strength properties must be based on enough tests of materials meeting approved specifications to establish design values on a statistical basis.

Challenges of AM to FAA

- **Current regulations are written to traditional aircraft manufactures and operators:**
  – Applicants are persons or organizations who produce aircraft, engines or propellers.
  – The FAA is not staffed to interact directly with individual suppliers or manufacturers who are not applicants.
  – There are provisions in the regulations for providers of specific parts (TSOs and PMAs). However, the applicant will still be responsible for showing how TSO/PMA parts are fully compliant to the regulations before installation.

FAA Approaches to Additive Manufacturing

- Existing regulations equally apply to all AM parts.
  - Individual applicants (Boeing, Airbus, etc…) can developed their own design values for their specific products. (Note: per FAA policy only **applicants have direct contact FAA.** **S**uppliers and manufacturers need to work with applicants)
  - Work through SAE and ASTM to develop industry standards and FAA recognized organizations such as **MMPDS** to derive an acceptable process for determining material allowables. This approach will still require some testing by applicants to validated these values for their application. (This is the approach being taken by AGATE, NCAMP and CMH-17 for composite materials.)

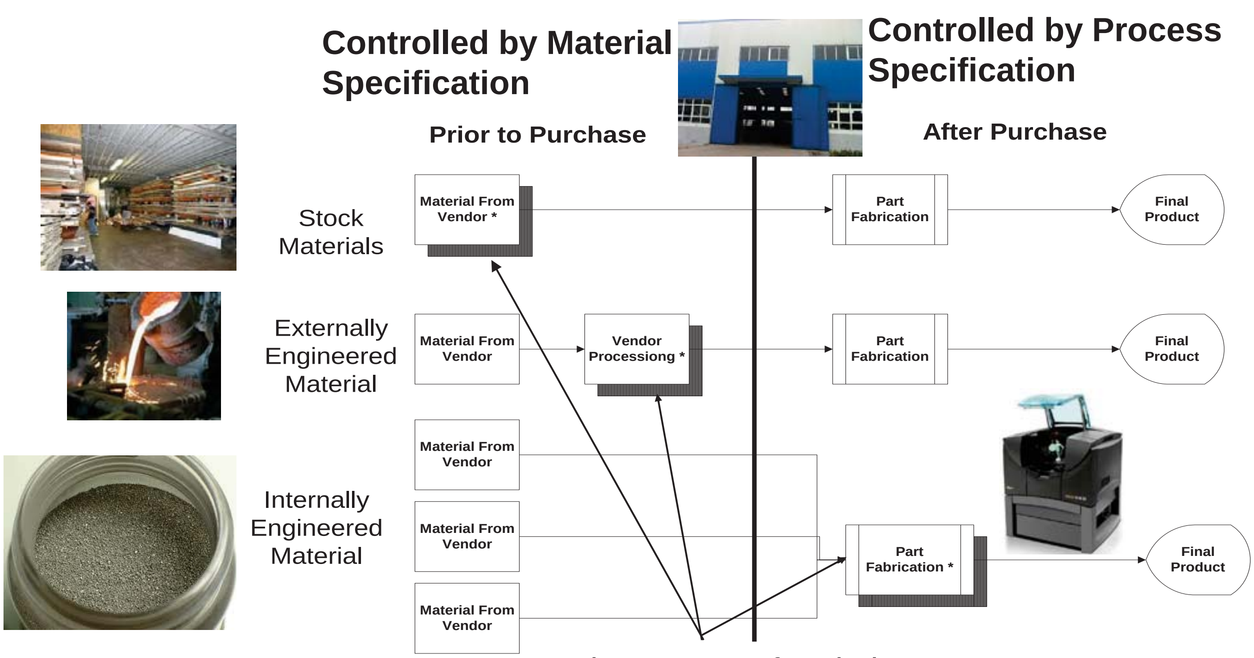
FAA involvement with MMPDS

- The Metallic Materials Properties Development and Standardization (MMPDS) handbook is the direct replacement of the Air Force sponsored MIL-HDBK -5
- In 1990 the Air Force policy was to move to industry standards.
- As a result of Air Force policy the FAA organized a new industry/government consortium to develop and maintain MIL-HDBK-5, now renamed MMPDS.
- The FAA retains the chairmanship of MMPDS, contracts with Battelle to be the secretariat of MMPDS, and have representatives on Government Steering Committee.

Design Values (Allowables) Considerations

- **Stock Materials –** **Common processes and procedures may be followed (such as MMPDS).**
- **Externally Engineered Materials –** **Variability is generally introduced during vendor processing and may vary depending on the part the vendor is producing.**
- **Internally Engineered Materials –** **The final material form is actually produced on-site with most of the variability being introduced during part fabrication. (Sources such as CMH-17, AGATE, NCAMP supplemented with applicant validation testing during the part fabrication phase)**

Major Sources of Variation

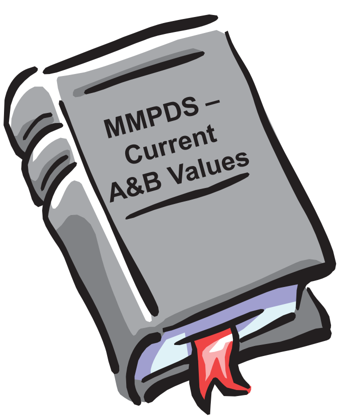


* Major Source of variation.

FAA sponsorship of MMPDS's AM Activities .

- **FAA initiated a research task, In coordination with the MMPDS organization, to develop processes and procedures which would allow the publication of design information relevant to "highly process dependent" metallic materials. The basic assumptions in this task:**
  - Design values and guidance for highly process dependent materials will be kept separate from current well established materials properties in MMPDS.
    - It was agreed by the MMPDS consortium to look into developing a separate volume for process intensive materials.
  - All values published in MMPDS will meet current regulatory requirements.
    - Industry material specifications will be required.
    - A standard suite of mechanical properties will be published.
    - Material allowables published will be statistically derived from submitted test data.
  - Guidance for acceptable use of data published for "process intensive materials" will be provided in the handbook.
    - It will be assumed that potential data user will need to perform some testing to validate that their internal processes supports the published MMPDS values.

Process Intensive materials Volume



Current handbook will remain unchanged to insure continued acceptance of Stock material values.

FAA Report for Process Intensive materials would contain unique data submission requirements and expanded data user guidance not contained in current MMPDS.

FAA support of New Volume

- **While the ultimate goal is to publish new "Highly Process Dependent" volume, current research in developing this volume will be captured in a FAA technical report. Contents of the report will include:**
  - Proposed outline for new volume
  - Data submission requirements
  - Analytical procedures for statistically deriving material allowables.
  - Guidance to potential allowables users on how to validate the applicability of published values to their internal manufacturing processes.
  - The statistical tool for potential allowables users to conduct "equivalency" testing (assumes shared data base approach is adopted.
- **FAA would support publication of new volume once key elements outside of MMPDS control are available:**
  - **Industry available material specifications (SAE, ASTM?) which controls the materials that may be purchased**.
  - Industry available process controls (either published in material specification or separate processing documents).
  - Associated FAA guidance (policy, ACs, DER/AR training) to implement AM approach.

The FAA position is based on experience with other "High Process Intensive" materials (composites)

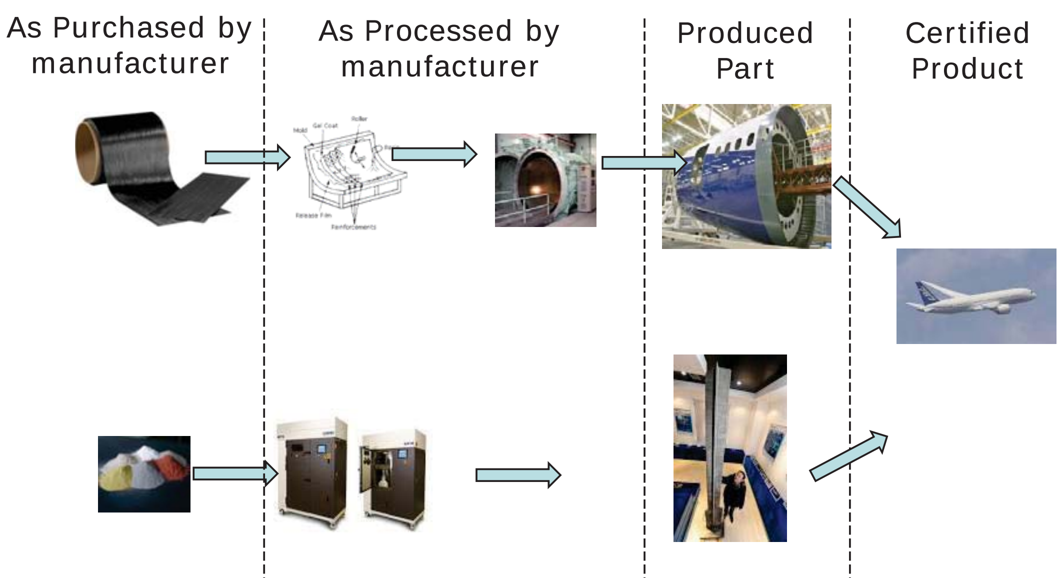
- In many ways there are parallels between Additive Manufactured Materials and Composite Materials.
  - The final material behavior not established until part fabrication.
  - In order to create base material for testing base material properties some non-company specific processing requirements are needed.
  - NCAMP/CMH-17 have a process established which allows individual companies to validate that allowables published by those organizations are valid for their specific application.

Shared Database Approach

The Shared Database approach being used for composite was:

- developed by a joint NASA/FAA Advanced General Material Transport Experiments (AGATE) program
- AGATE with continued FAA support has evolved into the National Center for Advanced Materials Performance (NCAMP)
- FAA policy is to acceptable NCAMP specifications and associated allowables when applicants follow NCAMP procedures
- NCAMP process is being incorporated into CMH-17.

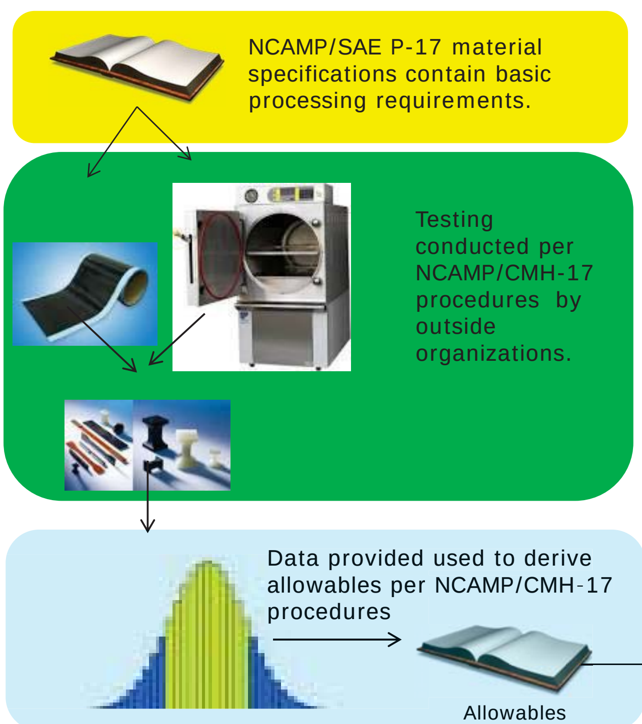
Composites & Metallic Additive Manufacturing Materials Have Similar Production Requirements



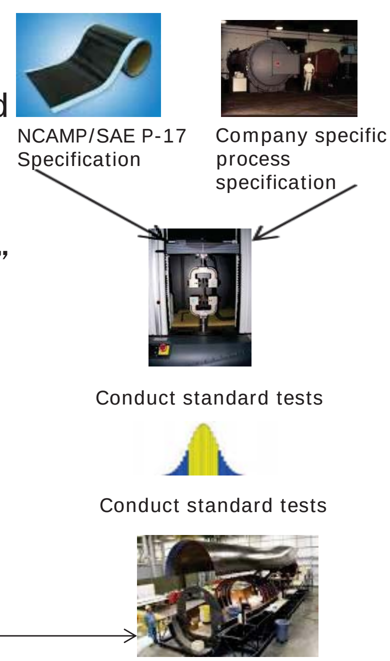
Equivalent Database Approach

- Using approved material specifications and a representative process, data is generated for a given material.
- Allowables are derived using data provided and approved statistical tools.
- Applicants intending to use published allowable need to conducted a reduced test program to validate that their internal manufacturing processes yield equivalent results (statistically speaking).

Simplified Shared Database Approach

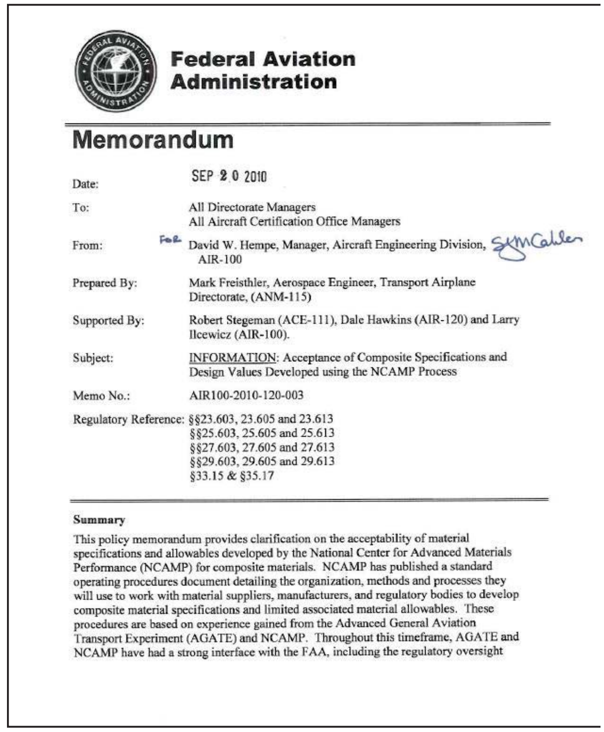


Applicants who want to use published allowables need to conduct "equivalency" Test program to validate that their interval process has the same statistical distribution.



FAA Policy on NCAMP Values

- **The FAA released a policy on the acceptability of the NCAMP (shared database) methodology.**
  - NCAMP specifications and associated allowables are accepted by the FAA as long as NCAMP procedures are followed.



Federal Aviation Administration

Memorandum

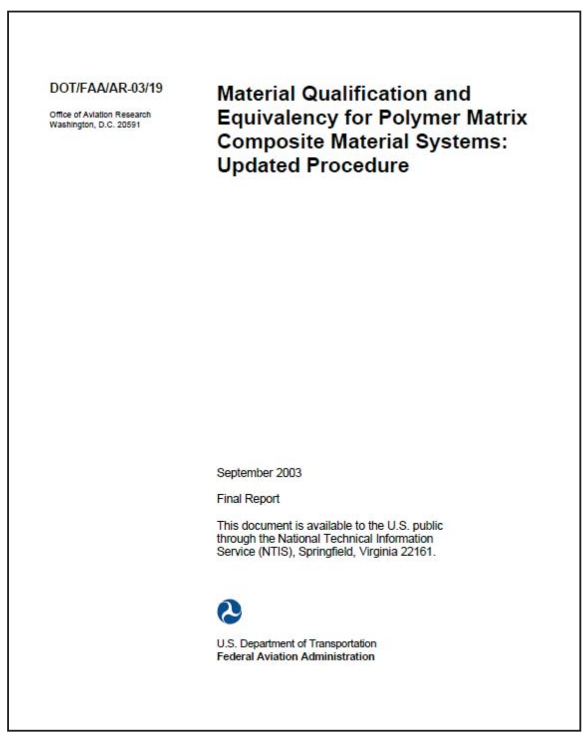
Date:	SEP 20 2010
To:	All Directorate Managers All Aircraft Certification Office Managers
From:	For David W. Hempe, Manager, Aircraft Engineering Division, AIR-100
Prepared By:	Mark Freisthler, Aerospace Engineer, Transport Airplane Directorate, (ANM-115)
Supported By:	Robert Stegeman (ACE-111), Dale Hawkins (AIR-120) and Larry Ilcewicz (AIR-100).
Subject:	INFORMATION: Acceptance of Composite Specifications and Design Values Developed using the NCAMP Process
Memo No.:	AIR100-2010-120-003
Regulatory Reference:	§§23.603, 23.605 and 23.613 §§25.603, 25.605 and 25.613 §§27.603, 27.605 and 27.613 §§29.603, 29.605 and 29.613 §33.15 & §35.17

Summary

This policy memorandum provides clarification on the acceptability of material specifications and allowables developed by the National Center for Advanced Materials Performance (NCAMP) for composite materials. NCAMP has published a standard operating procedures document detailing the organization, methods and processes they will use to work with material suppliers, manufacturers, and regulatory bodies to develop composite material specifications and limited associated material allowables. These procedures are based on experience gained from the Advanced General Aviation Transport Experiment (AGATE) and NCAMP. Throughout this timeframe, AGATE and NCAMP have had a strong interface with the FAA, including the regulatory oversight

FAA Technical Report

- **FAA has published a technical report providing details on Equivalency Testing requirements.**
  - Current report is for Composite materials and will need to revised to metallic materials.
  - http://www.tc.faa.gov/its/worldpac/techrpt/ar03-19.pdf



DOT/FAA/AR-03/19

Office of Aviation Research
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Material Qualification and Equivalency for Polymer Matrix Composite Material Systems: Updated Procedure

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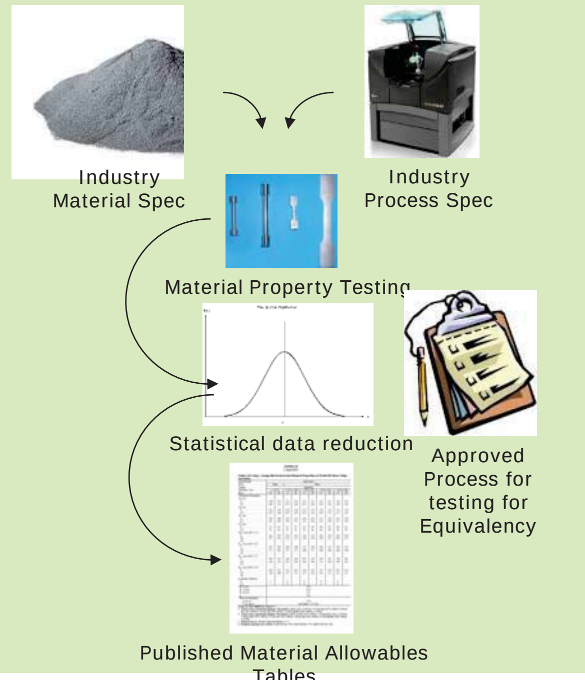
Final Report

This document is available to the U.S. public through the National Technical Information Service (NTIS), Springfield, Virginia 22161.

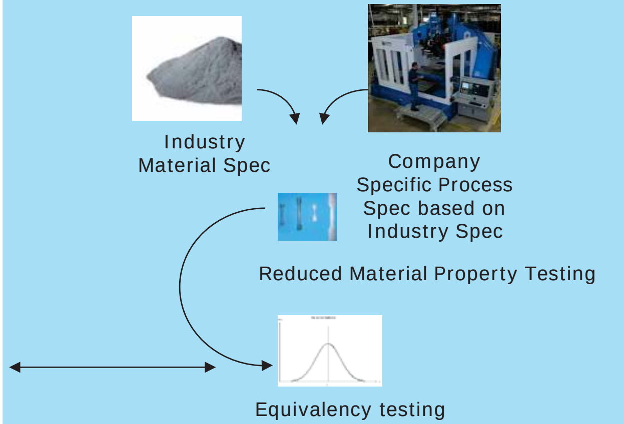
U.S. Department of Transportation
Federal Aviation Administration

Application of Shared Database Approach To AM

Industry/Government Consortium



Individual Data User



If statistical analysis validates that a company's processing of the base material results in the same scatter and distribution in the final material form the company my use the published allowables in their design.

Approach to AM

Standard Organizations (SAE/ASTM)

- Approved industry material Specification
- Accepted industry process specification

Mat'l Handbook Org (MMPDS)

- Data acceptance Criteria
- Standardized test procedures and matrixes
- Standardized Statistical tools
- Standardized procedures for conducting equivalency testing
- Means of publishing and distributing allowable tables

Individual Company Seeking to use Published Allowables

- Purchase materials per Material Specifications
- Develop internal process specification which is in line with industry specification
- Conduct reduced equivalency test program per standardized procedure using standardized test methods and procedures
- Perform equivalency analysis per standard procedure.
- If equivalency is validated company may use published table in design.

Why is FAA following this approach?

- When it comes to material allowable development FAA policy is only get directly involved with “applicants” (manufacturers of aircraft, engines or propellers).
- Development of an industry/government consortium path which allow the publication of AM design values outside an active FAA program.
- The FAA is looking to take advantage of experience gained from other materials with similar concerns.