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

June 2016

Final Report

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SUMMARY REPORT: JOINT FEDERAL AVIATION ADMINISTRATION–AIR FORCE WORKSHOP ON QUALIFICATION/CERTIFICATION OF ADDITIVELY MANUFACTURED PARTS

The Federal Aviation Administration William J. Hughes Technical Center Aviation Research Division COR was Kevin Stonaker. Point of contact for questions regarding the workshop content – Michael Gorelik (Michael.gorelik@faa.gov)

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.

Additive manufacturing; 3-D printing; Rapid prototyping; Rapid manufacturing; Direct metal laser sintering; Selective laser melting; Direct metal deposition; Laser engineered net shaping; Metals; Alloys

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ACKNOWLEDGEMENTS

The author would like to acknowledge the following people and organizations who contributed to making the workshop a success either through their sponsorship, participation, or both:

The workshop organizers and sponsors:

- Michael Gorelik (FAA)
- Rollie Dutton (Air Force Research Laboratory [AFRL])

The senior management/leaders for their perspectives:

- Rich Jennings (FAA)
- Dale Carlson (Air Force)

The presenters:

- Michael Gorelik, Jim Kabbara, and Mark Freisthler (FAA)
- Rollie Dutton, Mary Kinsella, Jon Miller, John Brausch, Jeff Calcaterra, and Mike Hirsch (AFRL)
- Mick Maher (Defense Advanced Research Project Agency [DARPA])
- Karen Taminger and Kristin Morgan (NASA)
- Kevin Jurrens (National Institute of Standards and Technology)
- Elizabeth McMichael (Naval Air Systems Command)
- Jack Beuth and Tony Rollett (Carnegie Mellon University)
- 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)

In addition, the author would like to recognize and thank the DARPA Defense Sciences Office and Mr. Michael (Mick) Maher, the DARPA Open Manufacturing Initiative Program Manager, for supporting the author in providing facilitation services for this workshop.

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.
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<th>Description</th>
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<td>ACO</td>
<td>Aircraft Certification Office</td>
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<td>AFRL</td>
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<td>AM</td>
<td>Additive manufacturing</td>
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<td>AMNT</td>
<td>Additive Manufacturing National Team</td>
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<td>AWS</td>
<td>American Welding Society</td>
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<td>Code of Federal Regulations</td>
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<td>Defense Advanced Research Projects Agency</td>
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<td>DARWIN</td>
<td>Design Assessment of Reliability With Inspection</td>
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<tr>
<td>MIDO</td>
<td>Manufacturing Inspection District Office</td>
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<tr>
<td>MMPDS</td>
<td>Metallic Materials Properties Development and Standardization</td>
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<tr>
<td>MSFC</td>
<td>Marshall Space Flight Center</td>
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<tr>
<td>NAVAIR</td>
<td>Naval Air Systems Command</td>
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<td>NDE</td>
<td>Nondestructive evaluation</td>
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<td>NIST</td>
<td>National Institute of Standards and Technology</td>
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<td>OEM</td>
<td>Original equipment manufacturer</td>
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<td>OM</td>
<td>Open Manufacturing</td>
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<td>PMA</td>
<td>Parts manufacturer approval</td>
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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.

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 (FAA Sponsor – 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 AM processes to FAA employees and to review and discuss qualification and certification processes and needs related 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.
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 (MIDO), certification (AOC), 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 Research 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 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. 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, 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

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1 The intention is to make the presentations available for future reference, subject to distribution notices and restrictions.
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
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 Methods (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)

Day 3–September 3

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

<table>
<thead>
<tr>
<th>Government (non-FAA)</th>
<th>Name</th>
<th>Organization</th>
<th>Role</th>
<th>Comments</th>
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<td>Rollie Dutton</td>
<td>Air Force</td>
<td>co-host</td>
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<td>Dale Carlson</td>
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<td>Mary Kinsella</td>
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<td>Jon Miller</td>
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<td>John Brausch</td>
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<td>Jeff Calcaterra</td>
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<td>6</td>
<td>Mick Maher</td>
<td>DARPA</td>
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<td>7</td>
<td>Brad Cowles</td>
<td>Contractor</td>
<td>workshop facilitator</td>
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<td>8</td>
<td>Kevin Jurrens</td>
<td>NIST</td>
<td>presenter</td>
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<td></td>
<td>Liz McMichael</td>
<td>NAVAIR</td>
<td>presenter - remotely</td>
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<td>Kristin Morgan</td>
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<td>Karen Taminger</td>
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<td>Doug Wells</td>
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<td>Alan Pentz</td>
<td>NAVAIR</td>
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<td>William Herderich</td>
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<td>Ken Kopp</td>
<td>FAA</td>
<td></td>
<td></td>
</tr>
<tr>
<td>45</td>
<td>Anthony Flores</td>
<td>FAA</td>
<td></td>
<td></td>
</tr>
<tr>
<td>46</td>
<td>Bill Champion</td>
<td>FAA</td>
<td></td>
<td></td>
</tr>
<tr>
<td>47</td>
<td>Al Clifton</td>
<td>FAA</td>
<td></td>
<td></td>
</tr>
<tr>
<td>48</td>
<td>Brian Younce</td>
<td>FAA</td>
<td></td>
<td></td>
</tr>
<tr>
<td>49</td>
<td>Chinh Vuong</td>
<td>FAA</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Industry</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>50</td>
<td>Mark Shaw</td>
<td>GEA</td>
<td>industry panel</td>
<td></td>
</tr>
<tr>
<td>51</td>
<td>Dave Abbott</td>
<td>GEA</td>
<td>presenter</td>
<td></td>
</tr>
<tr>
<td>52</td>
<td>Jesse Boyer</td>
<td>P&amp;W</td>
<td>industry panel</td>
<td></td>
</tr>
<tr>
<td>53</td>
<td>Matt Crill</td>
<td>Boeing</td>
<td>industry panel</td>
<td></td>
</tr>
<tr>
<td>54</td>
<td>Brian Hann</td>
<td>Honeywell</td>
<td>industry panel</td>
<td></td>
</tr>
<tr>
<td>55</td>
<td>Craig Brice</td>
<td>Lockheed Martin</td>
<td>industry panel</td>
<td></td>
</tr>
<tr>
<td>56</td>
<td>Tom Chiang</td>
<td>Bell Helicopter</td>
<td>industry panel</td>
<td></td>
</tr>
<tr>
<td>57</td>
<td>Brian Thompson</td>
<td>GKN</td>
<td>industry panel</td>
<td></td>
</tr>
<tr>
<td>58</td>
<td>Russ Thompson</td>
<td>GKN</td>
<td></td>
<td>Day 2 only</td>
</tr>
<tr>
<td>Academia</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>59</td>
<td>Anthony Rollett</td>
<td>CMU</td>
<td>Day 1 only</td>
<td></td>
</tr>
<tr>
<td>60</td>
<td>Jack Beuth</td>
<td>CMU</td>
<td>Day 1 only</td>
<td></td>
</tr>
<tr>
<td>61</td>
<td>Steve Daniewicz</td>
<td>MSU</td>
<td></td>
<td></td>
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</tbody>
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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)

<table>
<thead>
<tr>
<th>Location</th>
<th>Site Attendees</th>
<th>AMNT</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Burlington</td>
<td>4</td>
<td>2</td>
<td>6</td>
</tr>
<tr>
<td>Chicago</td>
<td>3</td>
<td></td>
<td>3</td>
</tr>
<tr>
<td>Atlanta</td>
<td>2</td>
<td></td>
<td>2</td>
</tr>
<tr>
<td>DC</td>
<td>3</td>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td>San Antonio</td>
<td>1</td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Wichita</td>
<td>1</td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Kansas</td>
<td></td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Renton</td>
<td>3</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>Phoenix</td>
<td></td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Los Angeles</td>
<td>3</td>
<td></td>
<td>3</td>
</tr>
<tr>
<td>Hartford, CT</td>
<td>2</td>
<td></td>
<td>2</td>
</tr>
<tr>
<td>Ft Worth</td>
<td></td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>New York</td>
<td>1</td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Atlantic City</td>
<td>1</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Vandalia</td>
<td>2</td>
<td></td>
<td>2</td>
</tr>
<tr>
<td>Denver</td>
<td>1</td>
<td></td>
<td>1</td>
</tr>
</tbody>
</table>

27 9 36
## Table D-1. Federal Aviation Administration Roundtable Comments

<table>
<thead>
<tr>
<th>Category</th>
<th>Line Item</th>
<th>Comments–Sorted by Category</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>General Considerations for Additively Manufactured Parts</td>
<td>1 8</td>
<td>Very broad activity in government, industry, and academia</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1 21</td>
<td>Time frame to mature AM has been long</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1 23</td>
<td>Many similarities between AM and composites when they were being introduced</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1 35</td>
<td>Similarity to composites in many respects</td>
<td></td>
</tr>
<tr>
<td>Cost and Business Considerations for AM</td>
<td>2 2</td>
<td>Concern that barrier to entry for PMA type activity is low</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2 22</td>
<td>Intellectual property may be further stumbling block for progress in applications and certification</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2 24</td>
<td>High cost to understand the process beyond initial capital investment</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>2 28</td>
<td>Recognize that AM may prove to be an expensive process when all things are considered (data required, NDE, post-processing, etc.)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2 33</td>
<td>AM appears to be a niche process for specific applications: must meet business case, not for primary structures, etc.</td>
<td>3</td>
</tr>
<tr>
<td>Variation, Process Controls, and Quality Considerations</td>
<td>3 1</td>
<td>Concern with inherent variability in AM production and output</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3 4</td>
<td>Rich Jennings: “we don’t know what good looks like.”</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3 5</td>
<td>NDE: big issue both for new production and in-service inspection</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3 6</td>
<td>Highly variable material properties produced by AM processes</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3 7</td>
<td>Lack of standardized process controls and certification—more possible important control variables</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3 9</td>
<td>Treat AM processes at local machine level for control and qualification</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3 14</td>
<td>AM process defines part capability locally: how to capture like in part type design drawing</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3 15</td>
<td>Concern over all the unknowns about AM (also “Unknown-Unknowns”)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3 30</td>
<td>Frozen process approach seems desirable</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3 32</td>
<td>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</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3 38</td>
<td>AM seems immature at this point.</td>
<td></td>
</tr>
<tr>
<td>Part Applications and Criticality</td>
<td>4 10</td>
<td>Maybe expect more non-critical part applications. Need different checklist?</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4 11</td>
<td>Need to track lessons learned from non-critical parts</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4 13</td>
<td>Need to address application of AM processes to repair</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4 16</td>
<td>Repairs, sustainment, reverse-engineered parts, replacement parts are possibly a bigger risk with AM. Ref: Parts 121 and 145</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4 20</td>
<td>PMA applications believed imminent with AM processes</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4 36</td>
<td>May apply to electronics in near future? Need guidance here?</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4 45</td>
<td>Need to prevent PMA of AM parts – (order 8110.42 rev needed?)</td>
<td></td>
</tr>
<tr>
<td>Category</td>
<td>Line Item</td>
<td>Comments–Sorted by Category</td>
<td>Notes</td>
</tr>
<tr>
<td>----------</td>
<td>-----------</td>
<td>----------------------------</td>
<td>-------</td>
</tr>
<tr>
<td>Guidance, FAA Policy, and Interagency Collaboration for AM</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>3</td>
<td>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.</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>17</td>
<td>FAA behind “AM power curve?” No active research effort here within FAA</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>34</td>
<td>Current regulations can likely handle AM. Similarity to policy memo adds for composite materials</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>37</td>
<td>Need policy or guidance first that can be matured into an AC later.</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>40</td>
<td>Interim guidance first that can be matured into an AC later</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>41</td>
<td>Guidance to “applicants” would be beneficial to ensure complete compliance package is prepared</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>42</td>
<td>Need to define focal points for field offices to ensure communication with the AMNT</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>43</td>
<td>Building block approach still needs to be used for AM</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>44</td>
<td>What about “foreign authorities” and bilateral agreements regarding AM?</td>
<td>4</td>
</tr>
<tr>
<td>5</td>
<td>2</td>
<td>Current AM policy memo identifies AM applicants and parts, but need guidance on “what next.”</td>
<td>1</td>
</tr>
<tr>
<td>5</td>
<td>3</td>
<td>Guidance on NDE requirements for certification</td>
<td>1</td>
</tr>
<tr>
<td>5</td>
<td>4</td>
<td>Guidance regarding AM application to lower criticality parts—NSE.</td>
<td>1</td>
</tr>
<tr>
<td>5</td>
<td>5</td>
<td>Policy memo needed for non-critical parts</td>
<td>1</td>
</tr>
<tr>
<td>5</td>
<td>6</td>
<td>Consider need for policy on DER authority regarding AM parts</td>
<td>1</td>
</tr>
<tr>
<td>5</td>
<td>7</td>
<td>Need an FAA plan or roadmap for AM</td>
<td>1</td>
</tr>
<tr>
<td>5</td>
<td>9</td>
<td>Need process for interagency sharing on AM</td>
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</tr>
<tr>
<td>5</td>
<td>10</td>
<td>Any output from national team to assist AM assessments will be helpful</td>
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</tr>
<tr>
<td>Tools, Training, and Checklists for AM</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>12</td>
<td>Need focus on education and guidance for qualification/certification of AM processes—5 part certification process</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>25</td>
<td>Value to current AFRL AM checklist (Distribution A version)—need to distribute</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>27</td>
<td>Need for training relative to AM</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>29</td>
<td>Reiterate need for AM checklist(s)</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>31</td>
<td>Many unknowns regarding AM for regulators when they review these processes. Need standardized tools to assist.</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>39</td>
<td>FAA manufacturing engineers need training and background here specific to AM</td>
<td></td>
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<tr>
<td>6</td>
<td>1</td>
<td>AM checklist(s) needed with what questions to ask</td>
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<tr>
<td>6</td>
<td>8</td>
<td>Formal tool kit needed for AM conformity for applicants and regulators</td>
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Table D-1. Federal Aviation Administration Roundtable Comments (continued)

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

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

2. R. Jennings, FAA HQ, “FAA Management Perspective” (Note: speech; no presentation charts used.)
4. J. Brausch, AFRL, “Nondestructive Inspection Challenges for Additive Manufacturing”
5. J. Miller, AFRL, “Structural Materials Challenges to AF Implementation of AM”
10. S. Daniewicz, Mississippi State University, “Mechanical Behavior of Components Fabricated Using AM”
18. J. Kabbara, FAA, “FAA AM Certification Perspective and Go-forward Plans”

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 subgroup 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)

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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
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...

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

Encompasses many process types...
- Powder Bed Fusion
- Directed Energy Deposition
- Material Extrusion
- Vat Photopolymerization

...using various materials.
- Metals
- Polymers
- Composites
- Ceramics

Powder Bed Fusion

An additive manufacturing process in which thermal energy selectively fuses regions of a powder bed
**Directed Energy Deposition**

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

**Material Extrusion**

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

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

Material or Binder Jetting

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

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

AM Process and Material Types

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

- Metals
- Polymers
- Other
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

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
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

Source: Wohlers Associates

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

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

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

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

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”

Embedded Electronics for ISR and EW
Information and tracking in contested environments (A2/AD) is foundational to decision making and force projection
• 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

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

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 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
- ‘attributable’ 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

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DISTRIBUTION STATEMENT A. Approved for public release; distribution is unlimited.
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

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

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

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

AM Value to AFSC Manufacturing

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

Long-term outlook
- 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

Game-changers
- 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

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

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<td>Component Conformance/ Equivalency</td>
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<td>Fatigue &amp; Fracture</td>
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Dr. Lincoln’s Requirements

Producibility

Supportability

**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

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 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

**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 ProvidedForgings
  - Ti forging cost reduced due to competition

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  - Process simulation for design & control
  - Verification & Validation for qualification
  - Process-structure-property relationships
  - Develop digital thread for AM components
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”
“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.”

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
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

- 2009 AM Industry Roadmap
- America Makes / National Additive Manufacturing Innovation Institute
- Public-Private Partnership National AM Roadmap
- ASTM Committee F42 on Additive Manufacturing Technologies
- Standards Development
- NIST Workshop: Measurement Science for Metal-Based AM
- Substantial Collaborations and Stakeholder Interactions
- Precompetitive Technology Development
- Joint research, site visits, events, etc.

http://events.energetics.com/NIST-AdditiveMfgWorkshop
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 Input Materials
- Uncertainties in Equipment and Process Performance
- Uncertainties in the Final Parts
Uncertainties in Additive Manufacturing

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)

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

Recent ASTM standards

Powder flowability measurements
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
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

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

- 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.
- High fidelity infrastructure to support AM data management
- Fundamental building blocks of AM information

Metal Additive Manufacturing Testbed

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

- 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

- 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](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

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: ROBUST IN-SITU PROCESS MONITORING TECHNIQUES**

**STAKEHOLDERS & POTENTIAL ROLES**
- **AM Materials**
  - Characterization Data and Standards for Post Processing
  - Robust In-Situ Process Monitoring Techniques
  - Metal Design Allowables Database
- **AM Process and Equipment**
  - Non-Destructive Evaluation Techniques Optimized for Metals AM
  - Fast-In-Situ Measurements
  - Performance Capability Database for AM Technologies
- **AM Qualification and Certification**
  - Closed Loop Process Control
  - Standard Guidelines and Methods for Qualification and Certification
  - Shared/Standardized Third-Party Data Repository
- **AM Modeling and Simulation**
  - Expert System for AM Design
  - Validated Physics- and Properties-Based Models for AM
  - Standard Data Structures, Definitions, and Metrics for AM Models

**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
  - **Other**: Needed for AM to be a manufacturing tool

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

**OVERARCHING TARGETS**
- Maximized detection capabilities to qualify production with batch size of one

**MILESTONES AND RESULTS**

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

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
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

Contact Info

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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.cm.edu/me/people/jack-beuth.html
https://sites.google.com/site/beuthadditivelab/
https://engineering.cm.edu/next

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

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**
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.
Complex Mix of Inter-Related Process Variables

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

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

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

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 T64)
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 T64)

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 T64)
4. America Makes: Powder Property vs. Part Quality (EOS Arcam T64 CoCr)
5. CMU Alumnus Support (Richard Feiler): AM for Racing Car Applications (EOS, Multiple Alloys)
6. DOE: Microchannel Heat Exchanger Fabrication (EOS, Arcam)

TRL 4-7

Tech Transfer

Projects
1. Innovation Works and Carnegie Mellon: Start-up Funding

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 Laboratories 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

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

- U.S. AM Machine Maker Industry
  - Optomec, Ssiaky

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

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  - Kennametal, Bayer, TE Connectivity, Incodema 3-D, Stratronics, Alcoa

- U.S. AM Machine Maker Industry
  - Optomec, Ssiaky

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

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
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)

- 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

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
Supply Chain: Powders

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 or scrapped – problem with O₂ 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*
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
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

Contains unpublished results: please contact rollett@cmu.edu for any subsequent use

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
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

1: Extract keypoint descriptors
2: Obtain visual dictionary
3: Create microstructural signatures
Outcome: A microstructure classifier

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

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

- 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:

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.

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

Leonardo da Vinci: wrote in the 1500s that “among cords of equal thickness, the longest is the least strong”
Visualizing (Grain) Size Distributions

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

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

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 \( \rightarrow D[4,3] \)
  - 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

Results – Combined Histogram

Al Particle Size Distribution (Number Weighted)

Results – Combined CDFs

Normal Probability Scale

Deviation from log-normal at large sizes:
#20 has the most large particles,
#19 the fewest

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).

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**.
Porosity Size Distribution in 6.5-7.9 mm from Top Surface

Size Distribution of Spherical Porosity

Number of Pores vs. Pore Diameter (μm)

Probablity in % vs. log(Pore Diameter)

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

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

Chris Pistorius & Ming Tang
Materials Science and Engineering
PA-RAMP
Lack-of-fusion defect – scanning electron microscopy

Porosity/Density Prediction

Melt pool geometry

Melt pool overlap across layers

Comparison of model with literature data

Comparison with standard operating point

Carnegie Mellon University

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

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

NSF-DMREF
'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, 225³ 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)$_{hcp}$ | BCC direction / to (1120)$_{bcc}$ |
|----------------|----------|----------------------|-------------------------------|
| 1              | (110)    | (111)                |
| 2              | (110)    | (111)                |
| 3              | (110)    | (111)                |
| 4              | (110)    | (111)                |
| 5              | (011)    | (111)                |
| 6              | (011)    | (111)                |
| 7              | (011)    | (111)                |
| 8              | (011)    | (111)                |
| 9              | (101)    | (111)                |
| 10             | (101)    | (111)                |
| 11             | (101)    | (111)                |
| 12             | (101)    | (111)                |
Effect of Alpha Fraction, Columnar Beta, Strain Along z*

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

Effect of Beta Morphology, Strain Along z*

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
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**
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

Tensile Behavior: Wrought vs. AM

- Higher strength and less ductility/elongation compared to wrought


Effect of Size and Geometry

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

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 crack growth](image)

- Fatigue crack growth
- Initiation
- Propagation
- Final fracture

![Fatigue curve](image)

- Microstructure vs. cycles to failure
- Coarse vs. fine microstructure
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.


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

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


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

EBSD image of a single layer deposited by LENS

Microstructural tailoring for enhancing structural integrity

Anisotropy in SLM Parts

Stress-life approach

**Effects of Post-Processing on SLM Parts**

**SLM 17-4 PH SS**

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


---

**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

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.


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
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:


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

## Tensile Behavior: Common Trends

<table>
<thead>
<tr>
<th>Alloys</th>
<th>Ultimate Stress (MPa)</th>
<th>Yield Stress (MPa)</th>
<th>Elongation to failure (%)</th>
<th>AM Process</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Wrought DLD</td>
<td>Wrought DLD</td>
<td>Wrought DLD</td>
<td></td>
</tr>
<tr>
<td>316 SS</td>
<td>586</td>
<td>234</td>
<td>50</td>
<td>LENS</td>
</tr>
<tr>
<td>316L SS</td>
<td>480</td>
<td>170</td>
<td>40</td>
<td>Laser consolidation</td>
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<tr>
<td>404L SS</td>
<td>...</td>
<td>324</td>
<td>55</td>
<td>LENS</td>
</tr>
<tr>
<td>AISI H-13</td>
<td>1,725</td>
<td>1,462</td>
<td>12</td>
<td>LENS</td>
</tr>
<tr>
<td>CPM-9V</td>
<td>...</td>
<td>821</td>
<td>...</td>
<td>Laser consolidation</td>
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<tr>
<td>Ti-6Al-4V</td>
<td>931</td>
<td>827</td>
<td>10</td>
<td>LENS</td>
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<tr>
<td>TC-18</td>
<td>1,157</td>
<td>1,119</td>
<td>14</td>
<td>Laser melting deposition</td>
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<tr>
<td>IN-718</td>
<td>1,379</td>
<td>1,158</td>
<td>20</td>
<td>LENS</td>
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<tr>
<td>IN-625</td>
<td>834</td>
<td>614</td>
<td>37</td>
<td>LENS</td>
</tr>
<tr>
<td>IN-600</td>
<td>660</td>
<td>427</td>
<td>45</td>
<td>LENS</td>
</tr>
<tr>
<td>IN-690</td>
<td>725</td>
<td>450</td>
<td>44</td>
<td>DLF</td>
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<tr>
<td>IN-738</td>
<td>1,095</td>
<td>870</td>
<td>6.5</td>
<td>Laser consolidation</td>
</tr>
</tbody>
</table>

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


### 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**
No porosity was found on the fracture surface

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


Fracture Toughness

Significant anisotropy

HIP process can:

- reduce anisotropy
- Improve fracture toughness

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


As-built LENS

Annealed LENS

No difference between LENS as-built and annealed

Physical Events During Direct Laser Deposition (DLD)

Add discussion
Additive Manufacturing: Large Potential

- Actual parts are now being manufactured
- 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
Using AM for “Tailoring” Materials for Application

Premise:

- 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

Simulation of SLM Process (Thin Wall Build)

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)

### MSU Leads a National Consortium in Additive Manufacturing

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

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

- **CLF²**

#### 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 *Mechanical Behavior of Additive Manufactured Parts* approved
  - Spring 2016 in San Antonio, TX

- CAVS is a member of ‘America Makes’
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
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

• 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

Aircraft Ready for Tasking
Parts on Demand

Rapid Manufacture
Using AM Technology

Build Package Database

Ship Electrons, Not Part
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

<table>
<thead>
<tr>
<th>Manufacturing Process (foundation)</th>
<th>Specimen Count</th>
<th>Cost ($M)</th>
<th>Time (Yrs)</th>
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<td>Full-scale article</td>
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<td>100-125</td>
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<tr>
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<td>10-20</td>
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<tr>
<td>Sub-components</td>
<td>25-50</td>
<td>10-35</td>
<td>3</td>
</tr>
<tr>
<td>Elements</td>
<td>2000-5000</td>
<td>10-35</td>
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<tr>
<td>Coupons</td>
<td>5000-100,000</td>
<td>8-15</td>
<td>2</td>
</tr>
</tbody>
</table>

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


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 Incorporates 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.

Manage explosive train using additive manufacturing.

Command Locations

8 MAJOR SITES ~35,000 PEOPLE
33 PMAs ~4000 AIRCRAFT ~12,000 ENGINES

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

NAWCAD
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 HQ
Depot / Industrial Site (Fleet Readiness Centers)
Naval Air Warfare Center
Logistic Support Activity

Atsugi, Japan
Fleet Readiness Center

Lakehurst NAWC Aircraft Div
Patuxent River NAVAIR HQ, REOs NAWC Aircraft Div
Orlando NAWC Aircraft Div

North Island Fleet Readiness Center Southwest
China Lake NAWC Weapons Div
Point Mugu NAWC Weapons Div

Cherry Point Fleet Readiness Center East
Jacksonville Fleet Readiness Center Southeast

Orlando NAWC Aircraft Div

NAVAIR AM IPT
Across NAVAIR

Fleet Readiness Centers

- DEPOT LEVEL MAINTENANCE AND REPAIR (AIRFRAME, ENGINES, COMPONENTS AND SUPPORT EQUIPMENT)
- INTERMEDIATE LEVEL MAINTENANCE

Fleet Readiness Centers

- INSERVICE ENGINEERING AND LOGISTICS SUPPORT
- AIR LAUNCH AND RECOVERY REPAIRS

NAVAIR AM IPT
Across NAVAIR

Fleet Readiness Centers

- DEPOT LEVEL MAINTENANCE AND REPAIR (AIRFRAME, ENGINES, COMPONENTS AND SUPPORT EQUIPMENT)
- INTERMEDIATE LEVEL MAINTENANCE

NAVAIR AM IPT
Across NAVAIR

Fleet Readiness Centers

- INSERVICE ENGINEERING AND LOGISTICS SUPPORT
- AIR LAUNCH AND RECOVERY REPAIRS
NAVAIR Additive Manufacturing Initiatives

### Initiative #1 Projects
- Casting Replacements
- Structural Repair/Replacement
- ALRE/SE Components
- AM Tooling Process Standard
- Weapons and Energetics
- Complex Engine Components

**Candidate Parts**

### Initiative #2 Projects
- Material and Process Qualification
- Structural Analysis and Structural Certification
- Non-Destructive Inspection Methods
- Innovative Process Models

### Initiative #3 Projects
- 3D/Model Based Environment
- 3D Modeling and AM Digital Environment
- AM Data Architecture/Standards
- AM Build Package Development

### Initiative #4 Projects
- NAVSUP and DLA Supply Chain
- Cost Modeling and ROI
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.
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.
• BLUF – Additive Manufacturing will go through the same qualification/certification process as any other new process.
**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**

1. Identify Need
   - WS-STEP: Unfunded Project
   - Funded Project
   - Gap: Technology Need

2. Submit proposal to EZP

3. Preliminary Screening by AFLCMC/EZP

   - Any new/substitute materials, processes, and product forms impacting AW

   - Go to AW
   - Preliminary Evaluation (See Slide 2)

   - Gaps sent to AFRL

   - Proceed to AW

---

**AFLCMC... Providing the Warfighter’s Edge**
AFLCMC… Providing the Warfighter’s Edge

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

A. Preliminary Evaluation

1. Any new/substitute materials, processes, product forms submissions (See Slide 1)

2. Initial Evaluation by CET

Go

3. Enterprise Technology Process

Go

Further technology maturity required

Single WS use standard AW Process

B. Airworthiness Plan and Certification Basis Development

4. Develop Baseline Cert Reqs

5. Document WS unique Cert Reqs

6. Document Qualification Plan

7. MAAC Approval

C. BC Develop/Endorse

8. Update BC

9. BC Endorsed

Go

No Go

D. Certification Basis/Compliance Review

10. Execute Qual Plan

11. Compliance Reports

12. Compliance Report Approval


E. Implementation

Package Submittal Development Details (Slide 1)

- **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
• 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

• 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…
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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Motivation

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

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
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

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MSFC Requirement Document

- 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

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Certified AM Design State

Certified AM Part Production

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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

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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

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Process Control

- Four aspects of process control are levied by the document
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*
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

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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

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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
    - 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**

[Diagram showing the process control reference distribution (PCRD) and its interaction with QMP, AM design value suite, part builds, characterization builds, test specimens, PCWS, and first article/WS.]
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

**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

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

**NDE Results from Single Bead Experiments**

- 2016 deg. C
- 1702 deg. C
- 1554 deg. C
- 677 deg. C

- Semi-Solid
- Molten Pool
- Transition
- Transient Cool Down

10 in.

**Front View**

**Back View**

**NDE Image**
Thermally-Induced Distortion /Residual Stress

Residual Stress Modeling

- Stress dropped to near zero, no additional distortion
- 25 beads

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

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

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 EBF³

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)

Spacecraft Electronics, Sensors and Coatings

Printed Nanosensor

• 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.
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

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NASA GSFC
Additive Manufacturing and Risk Mitigation - A Regulatory Perspective

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 *)

<table>
<thead>
<tr>
<th>Failure Mechanism</th>
<th>% Failures (Aircraft Components)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fatigue</td>
<td>55%</td>
</tr>
<tr>
<td>Corrosion</td>
<td>16%</td>
</tr>
<tr>
<td>Overload</td>
<td>14%</td>
</tr>
<tr>
<td>Stress Corrosion Cracking</td>
<td>7%</td>
</tr>
<tr>
<td>Wear / abrasion / erosion</td>
<td>6%</td>
</tr>
<tr>
<td>High temperature corrosion</td>
<td>2%</td>
</tr>
</tbody>
</table>


• 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…

- Material equivalency (?)
- Use of conventional design and certification criteria (?)
- No New Regulations Required for AM (?)
- Risk of new material system introduction
- Historical lessons learned
- AM-specific rules and policies (?)

Level of Criticality
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)
Alaskan Directorate
Anchorage, AK
Renton, WA

Small Airplane Directorate (14 CFR Part 23)
Northwest Mountain
Great Lakes
Central

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

Western-Pacific
Hawthorne, CA

Southern
Atlanta, GA

Southwest
Fort Worth, TX

Rotorcraft Directorate (14 CFR Parts 27, 29)
Mike Monroney Aeronautical Center
Oklahoma City, OK

Great Lakes
Chicago, IL

New England
Boston, MA

FAA Headquarters
Washington, D.C.
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>
<thead>
<tr>
<th>Development Phase</th>
<th>Development Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modification of an existing material for a noncritical component</td>
<td>2 to 3 years</td>
</tr>
<tr>
<td>Modification of an existing material for a critical structural components</td>
<td>Up to 4 years</td>
</tr>
<tr>
<td>New material within a system for which there is experience</td>
<td>Up to 10 years. Includes time to define the material’s composition and processing parameters.</td>
</tr>
<tr>
<td>New material class</td>
<td>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).</td>
</tr>
</tbody>
</table>


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…”


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

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*

Inherent Anomalies Specific to PM Alloys

<table>
<thead>
<tr>
<th>Type</th>
<th>Description</th>
<th>Typical Elements</th>
<th>Size, Mil(^2)(*)</th>
<th>Avg.</th>
<th>Max.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Discrete chunky ceramic</td>
<td>Al, Mg, Zr, Ca, O</td>
<td>8</td>
<td>50</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Ceramic agglomerates</td>
<td>Al, Si, Mg, Ca, O</td>
<td>10</td>
<td>110</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Reactive agglomerates</td>
<td>Al, Zr, Cr, Ca, O</td>
<td>15</td>
<td>250</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Voids</td>
<td>Ar</td>
<td>&lt;2</td>
<td></td>
<td>--</td>
</tr>
</tbody>
</table>

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:
  o Part of Title 14 of the Code of Federal Regulations (CFR).
  o 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):
  o Part 21 – Certification Procedures for Products and Parts
  o Part 23 – Airworthiness Standards: Normal, Utility, Acrobatic and Commuter Airplanes
  o Part 25 – Airworthiness Standards: Transport Category Airplanes
  o Part 27 – Airworthiness Standards: Normal Category Rotorcraft
  o Part 29 – Airworthiness Standards: Transport Category Rotorcraft
  o Part 33 – Airworthiness Standards: Aircraft Engines
  o Part 35 – Airworthiness Standards: Propellers

FAA Certification/Approval/Authorization

FAA issues:
➢ Type Certificate (TC) – Part 23, 25, 27, 29 and 33
➢ Production Certificate (PC)
➢ 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)

- Applicants deviating from above may request special approval from FAA administrator.

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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

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Federal Aviation Administration

July 21, 2015 Additive Manufacturing Workshop
FAA Perspectives

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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/MIDO/FSDOs

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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-government 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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FAA, Design, Manufacturing, & Airworthiness Division  
Electrical & Mechanical Equipment Branch - AVS / AIR-133  
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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 than 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 than 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.
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

### General AM Standards
- **Terminology**
  - ASTM F2792-12a
  - ISO 17296-1
  - ISO/ASTM 52921-13

### Processes / Materials
- ISO 17296-2
- Qualification and Certification Methods
- Requirements for Purchased AM Parts
- Non-Destructive Evaluation Methods

### Test Methods
- ISO 17296-3
- Test Artifacts
- General Test Methods
- Performance Test Methods

### Design / Data Formats
- ISO 17296-4
- ISO/ASTM 52915-13
- Data Structures and Metrics for AM Models

### Top-Level AM Standards
- General concepts
- Common requirements
- Generally applicable

### AM Standards by Category
- **Material Category-Specific**
  - Metal Powders
  - Polymer Powders
  - Photopolymer Resins
  - Ceramics
  - etc.

- **Process Category-Specific**
  - Powder Bed Fusion
  - Material Extrusion
  - Binder Jetting
  - Directed Energy Deposition
  - etc.

- **Material-Specific Standards**
  - Material-Specific Size Specification
  - Material-Specific Chemical Composition
  - Material-Specific Viscosity Specification
  - etc.

- **Process-Specific Standards**
  - Process-Specific Performance Test Methods
  - Process-Specific Test Artifacts
  - System Component Test Methods
  - etc.

- **Application-Specific Standards**
  - Aerospace
  - Medical
  - Automotive
  - etc.

### Specialized AM Standards
- Specific to material or process category

### 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
- ASTM F2791-13, Standard Practice for Reporting Data for Test Specimens Prepared by Additive Manufacturing
- ASTM F3001-14, Standard Specification for Additive Manufacturing Titanium-6 Aluminum-4 Vanadium ELI (Extra Low Interstitial) with Powder Bed Fusion
- ASTM F3049-14, Standard Guide for Characterizing Properties of Metal Powders Used for Additive Manufacturing
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

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

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.
Questions and Discussion
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 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.

SAE AEROSPACE STANDARDS HISTORY – FROM 1916

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

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

2015

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

Engineering Meetings Board
Technical Standards Board
Engineering Education Board
Sections Board
Membership Services Board
Publications Board
Foundation Board of Trustees

Performance Review Institute

Aerospace Council

SAE BOARD OF DIRECTORS

Technical Standards
Board

Engineering
Meetings
Board

Sections
Board

Membership
Services
Board

Publications
Board

Foundation
Board of
Trustees

SAE ORGANIZATIONAL STRUCTURE: COUNCIL LEVEL

Technical Standards Committees

Aerospace Council

IVHM Systems Groups

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

Aerospace Council

Non-Metals & Related Processes
- AMS-CE Elastomers
  - AMS-P Polymeric Materials
  - AMS-P-17 Polymer Matrix Composites

Aerospace Materials Systems Group Committees
- AMS-CACRC - ATA/ATA/SAE Commercial Aircraft Composite Repair Committee
  - Repair Materials TG
  - Repair Techniques TG

Aerospace Council

Non-Destructive Evaluation
- AMS-A Preparation of Surfaces & Processes
  - AMS-M Infrared Thermography

Aerospace Council

Airworthiness
- AMS-E Systems & Process
  - Systems & Process

Aerospace Council

Aerospace Council
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
- Environmental Standards
- Structural Health Monitoring
- Composite Repair
- Additive Manufacturing
- Human Factors & Cockpit Design
- De-icing & Carbon Brake Oxidation
- Aircraft & Engine Health Monitoring
- Counterfeit Parts Avoidance
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

73 FAA TSOs
75 SAE docs

95 FAA ACs
236+ SAE docs

12 ICAO docs
30 SAE docs

58 EASA ETSOs
61 SAE docs

21 EASA AMCs
62 SAE docs
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
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.

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.
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

Baseline Materials

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

Directional Properties

Composite
- Discrete phases
- Anisotropic
- Inhomogeneous

Hybrid and Composite Materials

AMS-AM Today

Increasing Complexity

Future
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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FAA perspective on Additive Manufacturing values in MMPDS

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 develop their own design values for their specific products. (Note: per FAA policy only applicants have direct contact FAA. Suppliers 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 validate 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

<table>
<thead>
<tr>
<th>Prior to Purchase</th>
<th>After Purchase</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Stock Materials</strong></td>
<td><strong>Part Fabrication</strong></td>
</tr>
<tr>
<td><strong>Externally Engineered Material</strong></td>
<td><strong>Final Product</strong></td>
</tr>
<tr>
<td><strong>Internally Engineered Material</strong></td>
<td><strong>Final Product</strong></td>
</tr>
</tbody>
</table>

* 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 conduct 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.

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.
Application of Shared Database Approach To AM

Industry/Government Consortium

- Industry Material Spec
- Industry Process Spec
- Material Property Testing
- Statistical data reduction
- Approved Process for testing for Equivalency
- Published Material Allowables Tables

Individual Data User

- Industry Material Spec
- Company Specific Process Spec based on Industry Spec
- Reduced Material Property Testing

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 may 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.