Quality and Additive Manufacturing...What You Need to Know and Learn
Shane Collins  4-14-17
Quality Concerns for Additive Manufacturing
Agenda

Introduction to Additive Manufacturing
Unique aspects of Additive Manufacturing
Significant Quality Concerns
Introduction to Additive Manufacturing
MB CalRAM Overview

- Founded in 2005 for Additive Manufacturing of metal components.
  - AS 9100 certified since 2006.
  - ITAR registered.
  - NADCAP accreditation in process
- Located in Ventura County in Southern California.
- Acquired by Insight Equity in 2014.
- Currently manufacturing structural flight hardware for two satellite producers with powder bed fusion.
Space Systems Loral Antenna Tower
Hundreds of parts per satellite, but each part is unique
Additive Manufacturing or 3D Printing

Standard Terminology for Additive Manufacturing Technologies

1. Scope
1.1 This terminology includes terms, definitions of terms, descriptions of terms, nomenclature, and acronyms associated with additive-manufacturing (AM) technologies in an effort to standardize terminology used by AM users, producers, researchers, educators, press/media and others.

2. Referenced Documents
2.1 ISO Standard.

3. Significance and Use
3.1 The definitions of the terms presented in this standard were created by this subcommittee. This standard does not purport to address all issues associated with the use of AM technologies. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use of additive manufacturing.

4. Additive Manufacturing Process Categories
4.1 The following terms provide a structure for grouping current and future AM machine technologies. These terms are useful for educational and standards-development purposes and are intended to clarify which machine types share processing similarities. For many years, the additive manufacturing industry lacked categories for grouping AM technologies, which made it challenging educationally and when communicating information in both technical and non-technical settings. These process categories enable one to discuss a category of machines, rather than needing to explain an extensive list of commercial variations of a process methodology.

- Binder jetting, m—an additive manufacturing process in which a liquid bonding agent is selectively deposited to join powder materials.
- Directed energy deposition, s—an additive manufacturing process in which focused thermal energy is used to fuse materials by melting as they are being deposited.
- Material extrusion, n—an additive manufacturing process in which material is selectively dispensed through a nozzle or orifice.
- Material jetting, n—an additive manufacturing process in which droplets of build material are selectively deposited.
- Powder bed fusion, m—an additive manufacturing process in which thermal energy selectively fuses regions of a powder bed.
- Sheet lamination, m—an additive manufacturing process in which sheets of material are bonded to form an object.
- Vat photopolymerization, s—an additive manufacturing process in which liquid photopolymer is in a vat is selectively cured by light-activated polymerization.

AM Process Categories
Material Jetting

- AM process in which droplets of build material are selectively deposited
  - Wax or Photopolymers
  - Multiple nozzles
  - Single nozzles
  - Includes
    - Objet
    - 3D Systems Projet
    - Stratasys Solidscape machines
    - Several Direct Write machines
    - XJET
    - Etc.

The Objet PolyJet Process
Vat Photopolymerization Process

- An additive manufacturing process in which liquid photopolymer in a vat is selectively cured by light-activated polymerization.
  - Stereolithography
  - DLP
  - Micro-SLA
Material Extrusion

- AM process in which material is selectively dispensed through a nozzle or orifice.
  - Based on Stratasys FDM machines
  - DIY community
Sheet Lamination

- An additive manufacturing process in which sheets of material are bonded to form an object.
  - Paper (LOM)
    - Using glue
  - Plastic
    - Using glue or heat
  - Metal
    - Using welding or bolts
    - Ultrasonic AM…
Binder Jetting

- AM process in which a liquid bonding agent is selectively deposited to join powder materials.
  - Zcorp
  - Voxeljet
  - ProMetal/ExOne
Directed Energy Deposition

DMG Mori

- AM process in which focused thermal energy is used to fuse materials by melting as they are being deposited
Powder Bed Fusion

- An additive manufacturing process in which thermal energy selectively fuses regions of a powder bed
  - SLS®, SLM®, DMLS®, EBM®, BluePrinter, etc.
  - Polymers, Metals & Ceramics
Conventional AM Prototype Uses

Rapid Prototyping
- Wind Tunnel Models
- Form-Fit-Function Models
- Experimental Rigs
- Desktop Models
Indirect AM for Production Applications

3D printed molds for sand casting using material jetting.

Surface repair using directed energy deposition. MIL-STD-3049

3D printed investment cast patterns using material jetting and vat photopolymerization.
# Production AM Platform Categories

<table>
<thead>
<tr>
<th>Process Technology</th>
<th>Polymers</th>
<th>Metals</th>
<th>Directed Energy Deposition</th>
<th>Hybrid DED/CNC</th>
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<tr>
<td>Polymer PBF</td>
<td>Ultem®</td>
<td>CoCrMo</td>
<td>Ti 6-4</td>
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## Production Materials

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## Applications

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<th>Ducts</th>
<th>Brackets</th>
<th>Fixtures</th>
<th>Composite Tooling</th>
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<tr>
<td>Brackets</td>
<td>Near Net Shape Parts</td>
<td>Part Preforms</td>
<td>Part Repair/Large Parts</td>
</tr>
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<td>UAV parts</td>
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</table>
Implementation Progress of High Density Nylon 12 Selective Laser Sintering (SLS)

- Nylon 12 SLS was first Additive Manufacturing (AM) process implemented; adoption is in early stages and use continues to grow.

Northrop Grumman
Oak Ridge Presentation

As of Oct 2013

<table>
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<td>Global Hawk</td>
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<td>Fire Scout</td>
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<tr>
<td>Special Programs</td>
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<td>223</td>
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</table>

Thousands of AM Parts Flying on NGAS Air Vehicles
Laser Sintered Nylon Parts for F/A-18 began ~ 2001

*About 20,000 parts made by laser sintering are already flying in military and commercial aircraft made by Boeing, including 32 different components for its 787 Dreamliner planes.

*Jerry Clark, Boeing
Early Examples of Metal Powder Bed Fusion for Production Applications

X-47B Air Mixer (2010)
Ti 6-4

Boeing 777 LED Light Housing (2006)
17-4 SS
AM Production Technology-Polymers

Laser Sintering

- EOS

Material Extrusion

- Stratasys Fortus
- 3D Systems
- Cincinnati BAAM
AM Production Technology-Metals

**Direct**

- Powder Bed Fusion
- Directed Energy Deposition

**Indirect**

- Metal Powder Consolidation
- And Sand Cast Patterns

ExOne

Voxeljet

Hybrid Systems
A Sampling of Metal Powder Bed Fusion Machines
When to Use Additive Manufacturing

- High Complexity
- Expensive Chips
- Schedule Reduction
- Low Volume

Tolerance by Feature
Barriers to Additive Manufacturing

1. 3D CAD Is Available
   - NO
   - YES
   - Interpret Drawings or 3D Scan
     - NO

2. Material and Process Standards Exists
   - NO
   - YES
   - Create Internal Specifications
     - NO

3. Design Allowable Database Exists
   - NO
   - YES
   - Non-Structural Point Specification
     - NO

4. Supply Chain Exists for the AM Process
   - NO
   - YES
   - Time to Develop Vendors
     - NO

5. Material Substitutions Are Allowed
   - NO
   - YES
   - AM Part Properties Equivalent to Wrought
     - NO

6. Design Change Authority Exists
   - NO

7. NDE Is Available for Technology
   - NO

8. Additive Manufacturing

Traditional Manufacturing
The Promise of Additive Manufacturing

Lightweight Structures

Competitive Advantage
Unique Quality Aspects of Additive Manufacturing

- Powder bed fusion
- Material extrusion
Metal Powder Bed Fusion Combines

- Welding
- Numerical Machine
- Powder Consolidation
- Control
- PBF
SDO Involved

Welding

Numerical Machine

Powder Consolidation

Control

AWS

SAE AMS-AM

ASME Y14.46

MPIF

SAE AMS-AM

PBF

NADCAP

NEPA

IEEE

ISO TC 44

ASTM

ISO TC 261
PBF Inputs Affecting Quality
Quality Concerns both Internal and with Supply Chain

- Digital product definition
- CAD Modification
- Support Generation
- Machine control software configuration management

- Pre-build checklist
- Install Platform
- Filling powder reservoir
- Recycle strategy
- Machine fitness

- Select alloy specific settings
- Load exposures
- Warm up build platform
- Start building process
- Document building process

- Clean process chamber
- Powder contamination control
- Empty collector reservoir
- Clean machine

- Stress Relief
- Remove parts from platform
- HIP
- Thermal Processing
- Coatings
- Witness coupon testing
Layer-wise Welding Produces Unique Microstructure

Beam power, Hatch space, Scan speed, Layer thickness

- Thin section OM show full density
- Mechanical properties meet specification minimum
- Create fixed baseline machine settings for Manufacturing Plan

OM top view after scan
PBF Parameters Determine Porosity and Part Buildability

- Powder Consolidation
- Microstructure Mechanical Properties
- Part Attributes
  - Thin Walls, Overhangs, Hollow Areas
  - Scan Strategy and Thermal Treatments
  - Exposure Parameters

PBF Parameters Determine Porosity and Part Buildability.
## Affect of Purge Gas on 17-4 SS Properties

### Nitrogen

<table>
<thead>
<tr>
<th>Temp</th>
<th>Yield (ksi)</th>
<th>ULT (ksi)</th>
<th>Elong %</th>
<th>R.A. %</th>
<th>S/N</th>
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<tbody>
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<td>LRH-Z</td>
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<tr>
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<td>LFH-Z</td>
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### Argon

<table>
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<th>ULT (ksi)</th>
<th>Elong %</th>
<th>R.A. %</th>
<th>S/N</th>
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<td>41</td>
<td>1-Z</td>
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<td>27</td>
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<td>122</td>
<td>165</td>
<td>29</td>
<td>41</td>
<td>3-Z</td>
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<tr>
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<td>123</td>
<td>166</td>
<td>27</td>
<td>33</td>
<td>4-Z</td>
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<td>Ave</td>
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<td>165.5</td>
<td>28.0</td>
<td>39.3</td>
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</tr>
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</table>

Observe the anisotropic behavior between tensile bars built in X,Y vs Z direction.
Powder Affects Part Quality

Particle size distribution, powder morphology, powder rheology

Recoater generating ceramic inclusions in used powder
• Used powder is allowed to be recycled.
• The proportion of virgin powder to used powder should be recorded on the component traveler with corresponding lot numbers.
• Component purchaser may specify number of times used powder can be recycled.
• Out of specification powder should be scrapped and no powder doping allowed.
• Stratification of virgin and used powder in the feed bin not recommended for production applications.
Internal Cavity Challenges with PBF

Small hole definition and remaining sintered particles.

Down-facing surfaces on internal channels. Internal supports would not be removable.
Powder Bed Fusion Supply Chain Management

Multiple OSP present part tracking challenges
Challenges with Material Extrusion

Bead turns prone to have porosity.

Small variation in diameter plastic filament can induce porosity between layers.
Significant Quality Concerns
No Standard AM Callouts

NOTES:
1. APPLICABLE STANDARDS/SPECIFICATIONS:
   ASME Y14.5M-1994, DIMENSIONING
   AND TOLERANCING.
2. MATERIAL: Ti-6Al-4V, BAR, ASTM B348,
   GRADE 5 OR PLATE, ASTM B265, GRADE 5.
   ALTERNATE MATERIAL: Ti-6Al-4V ELI
   (UNS R56401), BUILT BY ELECTRON BEAM
   MELTING PROCESS.
3. FINISH: TITANIUM ANODIZE PER SAE
   AMS2488, TYPE 2.
4. REMOVE ALL BURRS AND BREAK SHARP EDGES
   .01-.03.
5. UNLESS OTHERWISE SPECIFIED, MACHINED
   SURFACE FINISH SHALL BE 125 MICROINCHES.
   AFTER ALTERNATE ELECTRON BEAM MELTING
   PROCESS BEAD BLAST TO 125-150 RA
   MICROINCHES.
6. FEATURES AND DIMENSIONS NOT SHOWN ARE
   DETERMINED BY DATABASE FILE AM96G12.XXX.
   UNLESS OTHERWISE SPECIFIED, PROFILES
   SHALL BE WITHIN .010 BILATERAL TOLERANCE
   BOUNDARY FROM THE BASIC NOMINAL MODEL.
7. IDENTIFY PER MIL-STD-130. APPLY
   THE FOLLOWING TO THE BAG
   (CONTAINER) OR TAG, FASTEN TAG
   SECURELY. DO NOT MARK PART.
ASTM F42 Working to Develop Standards for AM

X-ray inspections per ASTM E 1742 – 2T sensitivity
AMS 2635 – Grade A
ASTM F42 Working to Develop Standards for AM
Questions
# Health and Safety in AM for Aerospace and Defense

<table>
<thead>
<tr>
<th>AM Process Categories</th>
<th>Feedstock Types</th>
<th>Health and Safety Impact</th>
</tr>
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<tbody>
<tr>
<td>Directed Energy Deposition</td>
<td>Metal wire, metal powders</td>
<td>Dust, fire and explosion</td>
</tr>
<tr>
<td>Material Extrusion</td>
<td>Polymer wire, gels, concrete</td>
<td>Vapors</td>
</tr>
<tr>
<td>Material Jetting</td>
<td>Liquid polymers</td>
<td>Vapors</td>
</tr>
<tr>
<td>Vat Photopolymerization</td>
<td>Liquid polymers</td>
<td>Vapors, skin irritation</td>
</tr>
<tr>
<td>Binder Jetting</td>
<td>Organic powders, metal powders, ceramic powders, polymer powders</td>
<td>Dust, fire and explosion</td>
</tr>
<tr>
<td>Powder Bed Fusion</td>
<td>Metal powders, polymer powders</td>
<td>Dust, fire and explosion</td>
</tr>
<tr>
<td>Sheet Lamination</td>
<td>Ceramic sheets, metal sheets</td>
<td>General H&amp;S</td>
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</table>
Is 3D Printing Safe – A Study at Penn State University

Presented at Solid Freeform Fabrication by Tim Simpson
Particle Counters and VOC Detection

- **TSI 8525 P-Trak Ultrafine Particle Counter**
  - Measures ultrafine particle concentrations (count/cm³) between 0.02-1.00 micrometer

- **TSI 9110 Aerotrak Portable Particle Counter**
  - Samples and separates particles into bin sizes

- **PPBRAe Plus Photoionization Detector (PID)**
  - Measures volatile organic compound (VOC) emission concentrations (ppb)

We thank Paul Kremer, Penn State Arch Engr, for use of equipment.
Particle Emissions from Material Extrusion 3D Printers

Charts are from Masters Thesis by William McDonnell
Volatile Organic Compounds

<table>
<thead>
<tr>
<th>Location</th>
<th>Plastic</th>
<th>Chemical Sampled</th>
<th>Primary VOC Concentration (ppm)</th>
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<tr>
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<td>PLA</td>
<td>Lactide</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
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<td>Lactide</td>
<td>0.07</td>
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<td>Lactide</td>
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<td>Styrene</td>
<td>0.028</td>
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<td>7</td>
<td>Polycarbonate</td>
<td>Caprolactam</td>
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</table>

- **Lactide** currently has no exposure limit.
- **Styrene** has a short-term exposure of 600 ppm and a time weight exposure of 100 ppm.
- **Caprolactam** has an exposure limit of 0.600 (ST) and 0.220 (TWS) ppm; inhalation can cause **dizziness, headaches, nosebleeds, vomiting, liver/kidney damage, confusion**.

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Figure 11. Fine Particle Concentrations in Environment 7 with and without Fan

Charts are from Masters Thesis by William McDonnell
From 3D Printers to Metallic Part Production

- Powder Bed Fusion
- Directed Energy Deposition
- Hybrid Systems
Typical AM Alloys
Titanium
- Ti 6Al-4V
- Ti 6-2-4-2
- TiAl
Aluminum
- AlSi10Mg
Steel
- Ni-Fe
- 17-4
- 316L
Nickel
- IN625
- IN718
- IN731

Typical AM Polymers
- PA-11
- PEI
- PEKK
- PEEK
Health and Safety Affects of Powders

Airborne Dusts
- Skin, eye and respiratory irritants

Chemical Hazards
- Reactive metal pairs and thermites

Combustible Dusts
- Fire
- Primary and secondary reactions

Imperial Refinery; Savannah, GA, 2008; from www.csb.gov

The explosion triangle: Airborne dust concentrations along with an oxygen rich environment and an ignition source.
Personal Protection for Handling Metal Powders

When to Wear

- Loading powder into machine
- Unloading finished parts
- Changing gas flow filters
- Sieving powder off line
- Mixing powders

Head and face shield
Respirator
Fire retardant fabric
Welding gloves
Fire retardant fabric
Conductive footwear with steel toe
Fire Codes for AM Powders

- NFPA 484 Standard for Combustible Metals
  - Aluminum, Titanium and Magnesium considered combustible

- NFPA 68 Standard on Explosion Protection by Deflagrating Venting
  - Ceiling blow out panel should be considered for aluminum and titanium

- NFPA 654 Standard for the Prevention of Fires and Dust Explosions from the Manufacturing, Processing and Handling of Combustible Particulate Solids
  - Keep all areas clean and free from spills
My Decade of Experience Working with Powder Bed Fusion

• Accidents have occurred when work instructions were not followed correctly.
  • Changing filters
  • Vacuum inside of chamber
  • Disengaging machine safety switches
• Accidents have occurred when ancillary equipment was not maintained properly.
  • Grounding straps on vacuums
  • Wearing of vacuum hose tips
  • Vacuums not cleaned out regularly and mixing powders
• Sieving equipment installed incorrectly
  • No proper ground
  • No inert gas atmosphere

• Handling of metal powder bed fusion feedstocks usually do not produce dust clouds.
  • Dust does build up on floors and tables in close proximity to machines over a few days and require consistent cleaning.
• Depending on the type of machine, filter changes can be dangerous.
• I’ve never been in or seen any fires more than a smoldering filter.
Other Safety Considerations for Metal Powders

Asphyxiation due to shield gas accumulation in work room
Drop hazard for build plates
Hand lacerations from support material removal
Formation of hydrogen gas during wire EDM process for aluminum
Remaining powder in supports or accumulated scrap powder ignited by sanding or grinding.
Questions