Boeing Additive Manufacturing Capacities and Application in The Field

RAM XII Training Summit
11/13-14, 2019, Huntsville, AL

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Boeing Phantom Works

Agenda:

Introduction: AM Technology Overview
Technology Development
AM Printers/Capabilities, Design Guides/Specifications
Leveraged Technology Development

Committee F42 on Additive Manufacturing Technologies

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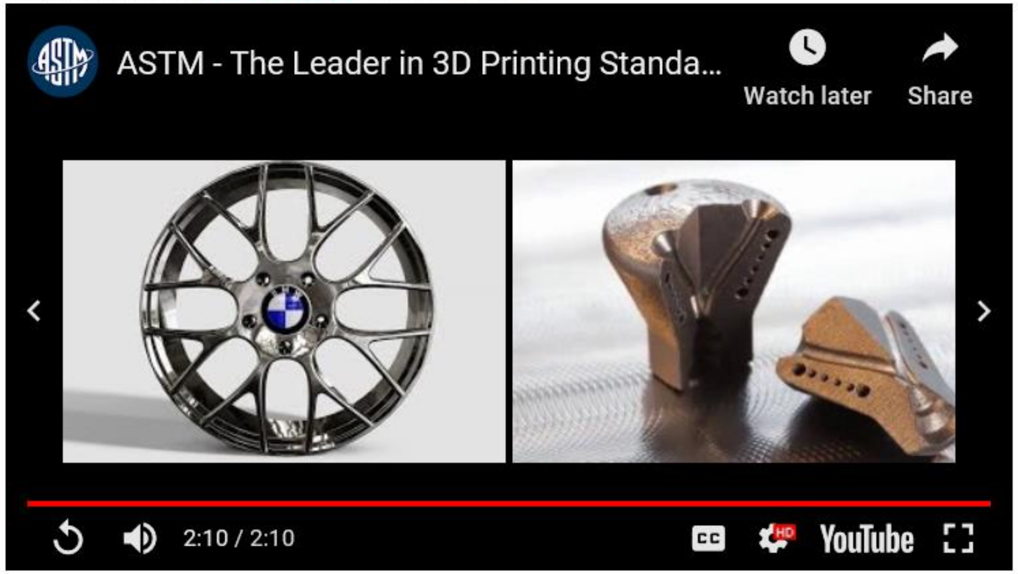
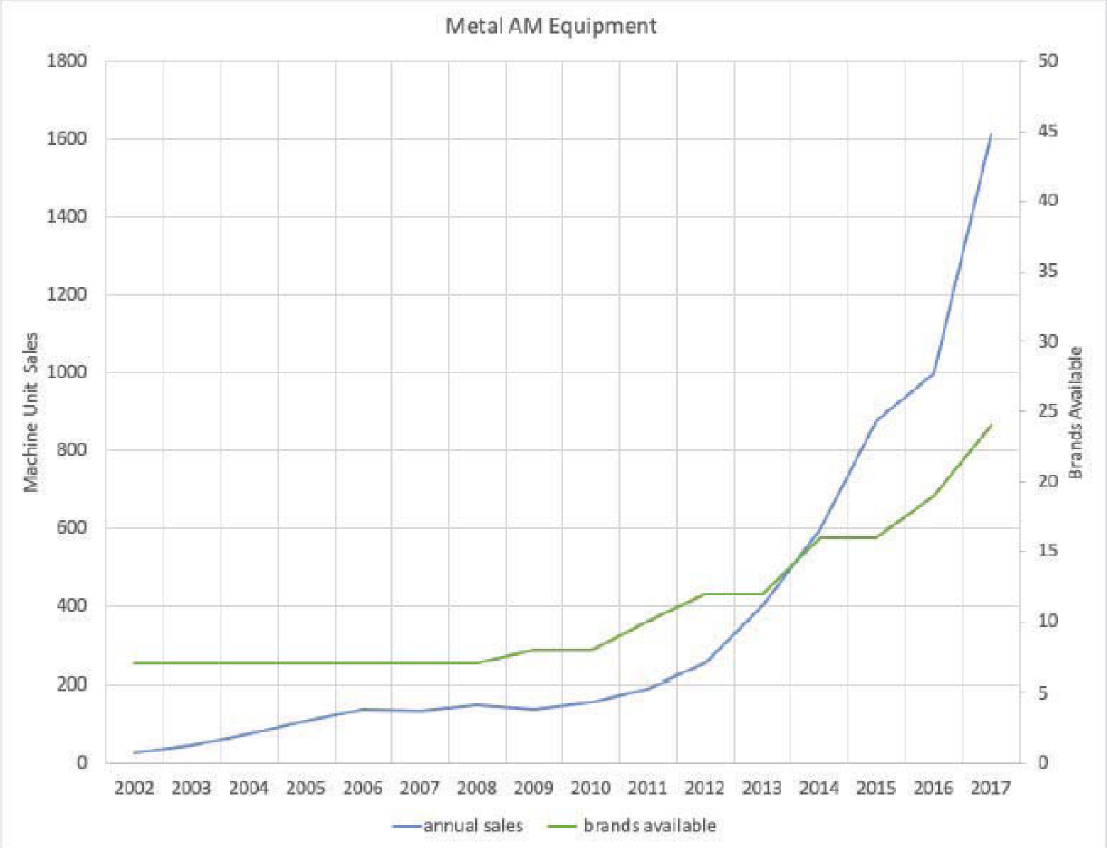
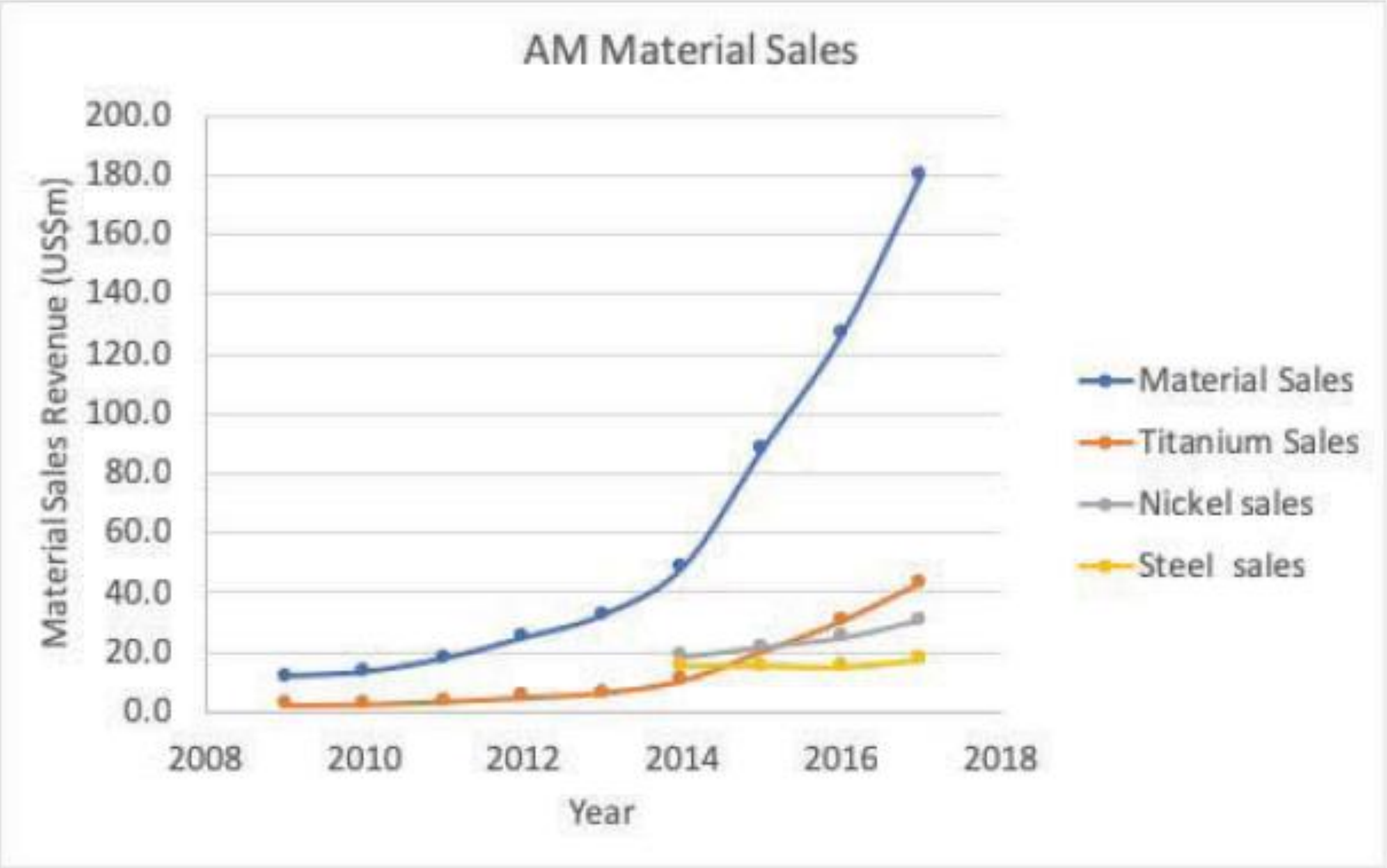


ASTM Committee F42 on Additive Manufacturing Technologies was formed in 2009. F42 meets twice a year, usually in the Spring and Fall (US & non-US, respectively), with about 150+ members attending two days of technical meetings. The Committee, with a current membership in excess of 725, has 8 technical subcommittees; all standards developed by F42 are published in the Annual Book of ASTM Standards, Volume 10.04 . Information on the F42 subcommittee structure, portfolio of approved standards, and Work Items under development, is available from the List of Subcommittees, Standards and Work Items below. These standards will play a preeminent role in all aspects of additive manufacturing technologies.


Metal AM Equipment
Machine Unit Sales
Brands Available
1800
1600
1400
1200
1000
800
600
400
200
0
50
45
40
35
30
25
20
15
10
5
0
2002 2003 2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015 2016 2017
annual sales
brands available

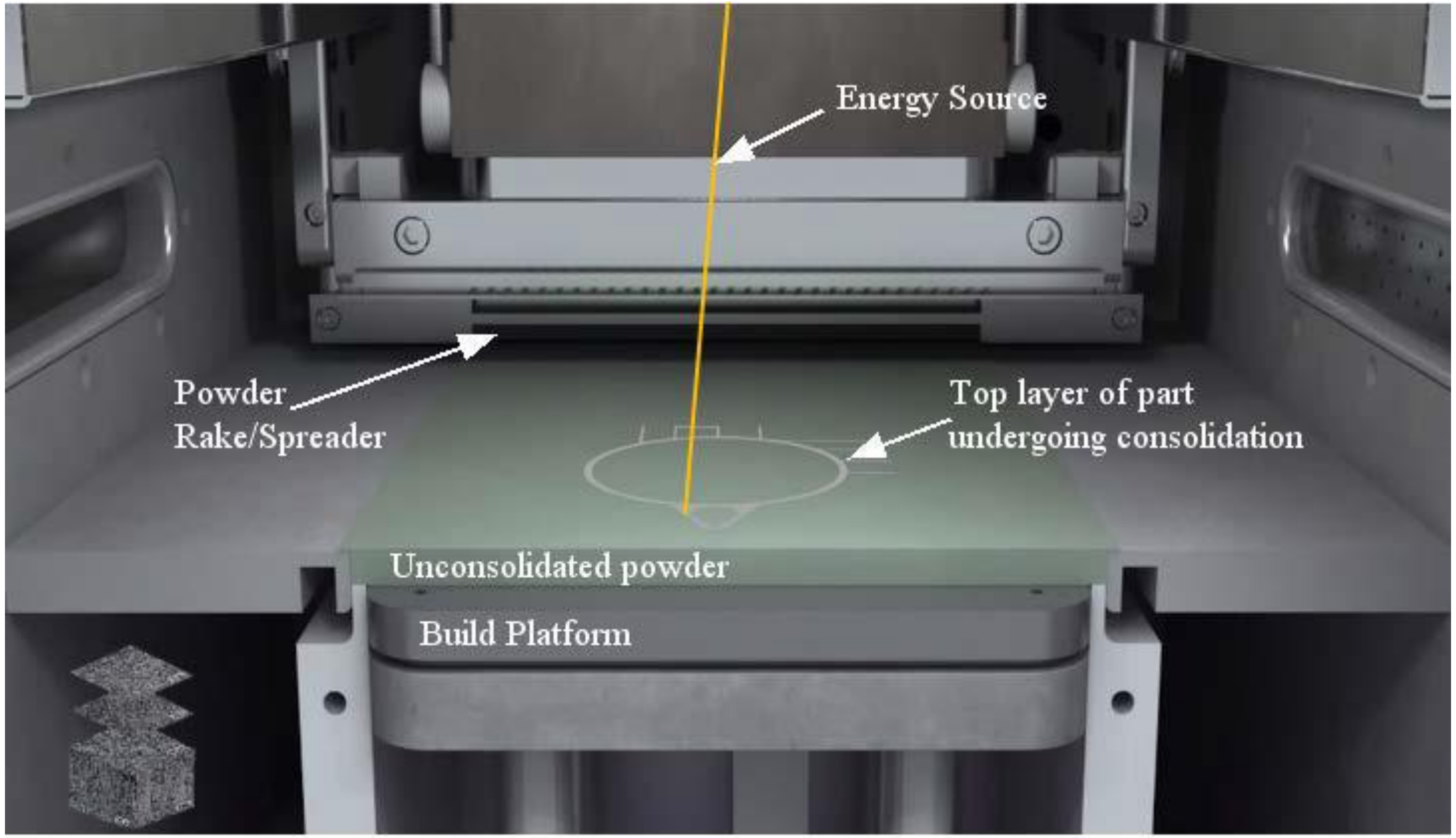

AM Material Sales
Material Sales Revenue (US$m)
200.0
180.0
160.0
140.0
120.0
100.0
80.0
60.0
40.0
20.0
0.0
2008
2010
2012
2014
2016
2018
Year
Material Sales
Titanium Sales
Nickel sales
Steel sales

AM Technology	Build Speed (g/hr)	Build Volume (cm^3)	Build Density	Surface Finish	Smallest Feature size (mm)	Geometric accuracy* (+/- in mm)
L-PBF	40	2,500	99%+	Good	0.1	0.1
EB-PBF	200	25,000	99%+	Moderate	0.5	0.5
Small Puddle DED	100	100,000	99%+	Moderate	1.0	1.0
Large Puddle DED	1000	varies	99%+	Poor	3.0	3.0
BJP	2400	2,500	50-65%	Best	0.1	0.1
Metal Material Extrusion	6000	100,000	100%	Poor	12.5	12.5

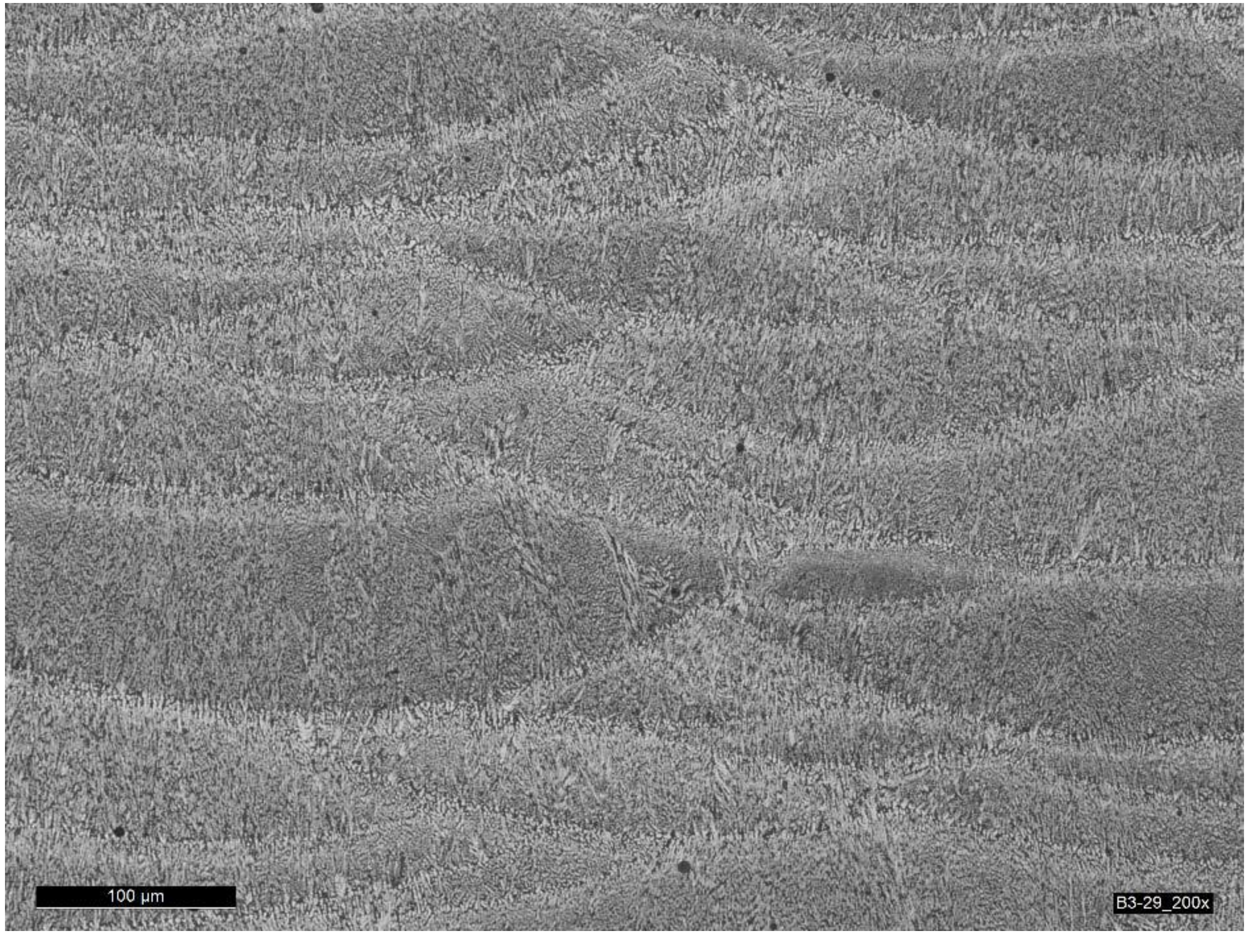
*Accuracy listed as typical machine hardware capabilities. Finished component accuracy is dependent on a number of other process factors.

Powder Bed Fusion

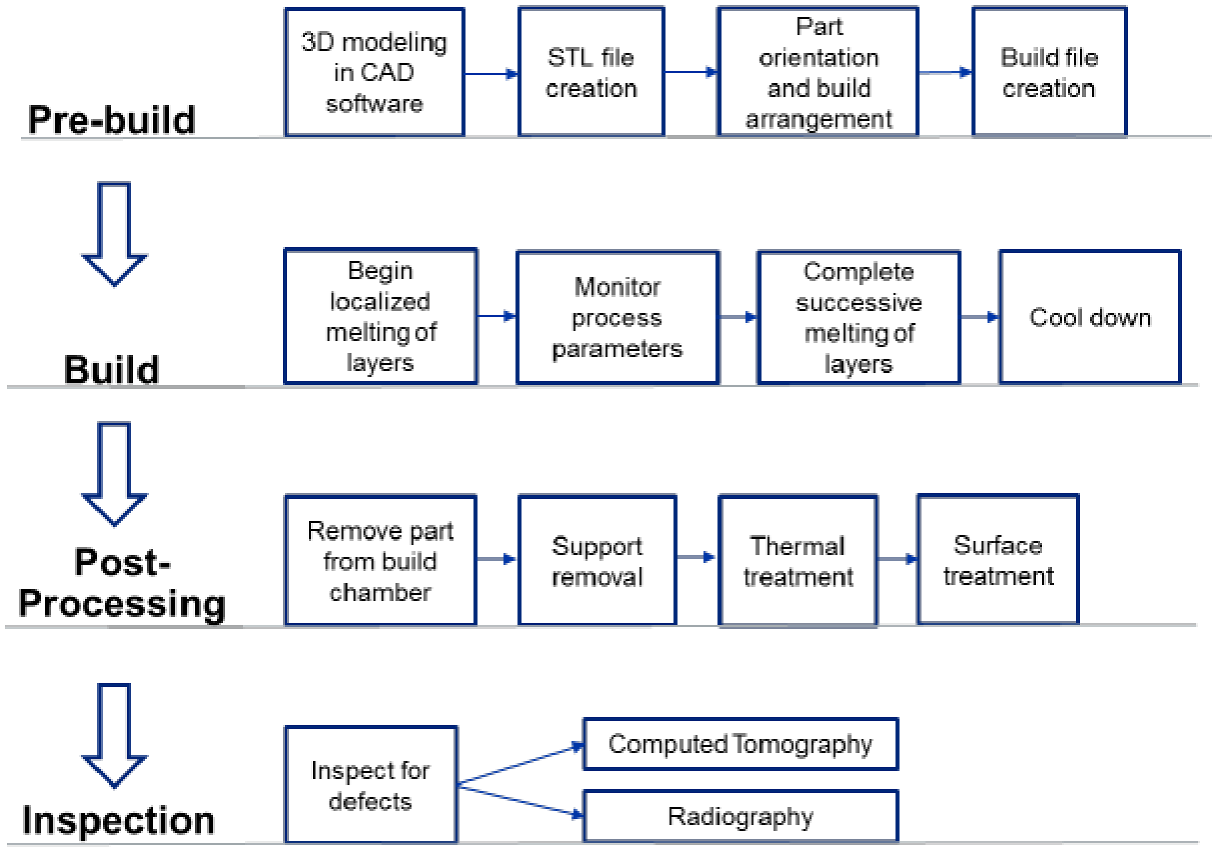
Powder bed fusion (PBF) is a process in which thermal energy selectively fuses regions of a powder bed. In most implementations, a roller, spreader, or rake spreads powder evenly over a build platform. The material used is often a spherical powder 10 to 100 microns in diameter (0.004” to 0.040”). The energy source is then applied through electrical or mechanical control to melt the powder in regions directed by computer control to make a part. There are 2 main types of powder bed fusion industrially available: laser and electron beam.



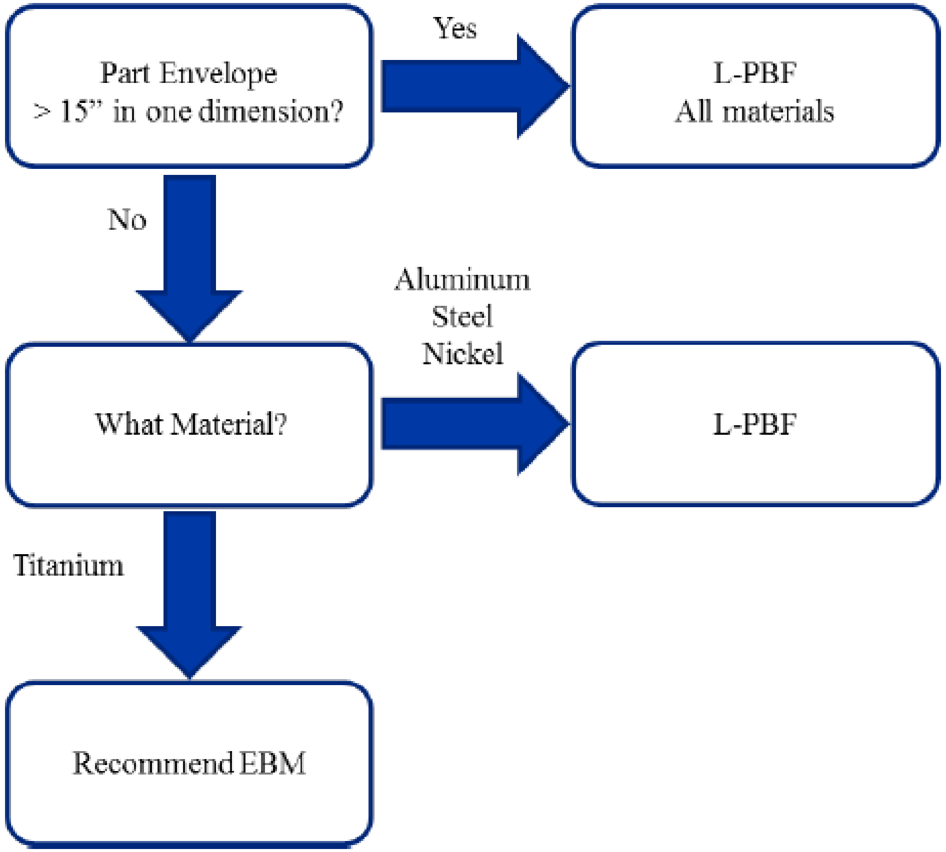
Powder Bed Fusion Overall View



Powder Bed Fusion Build Layer Detail

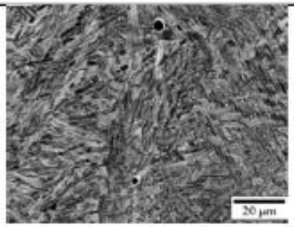
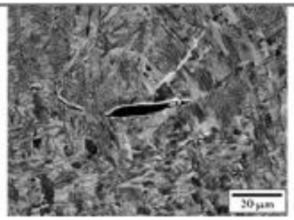
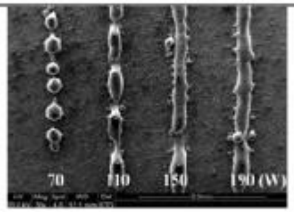
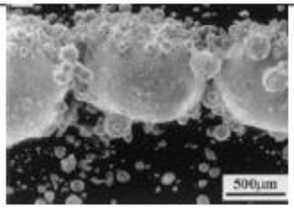
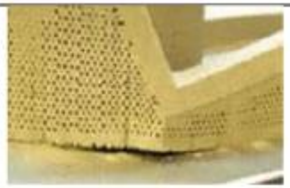


Powder Bed Fusion Build Flow Chart



Powder Bed Fusion Triage

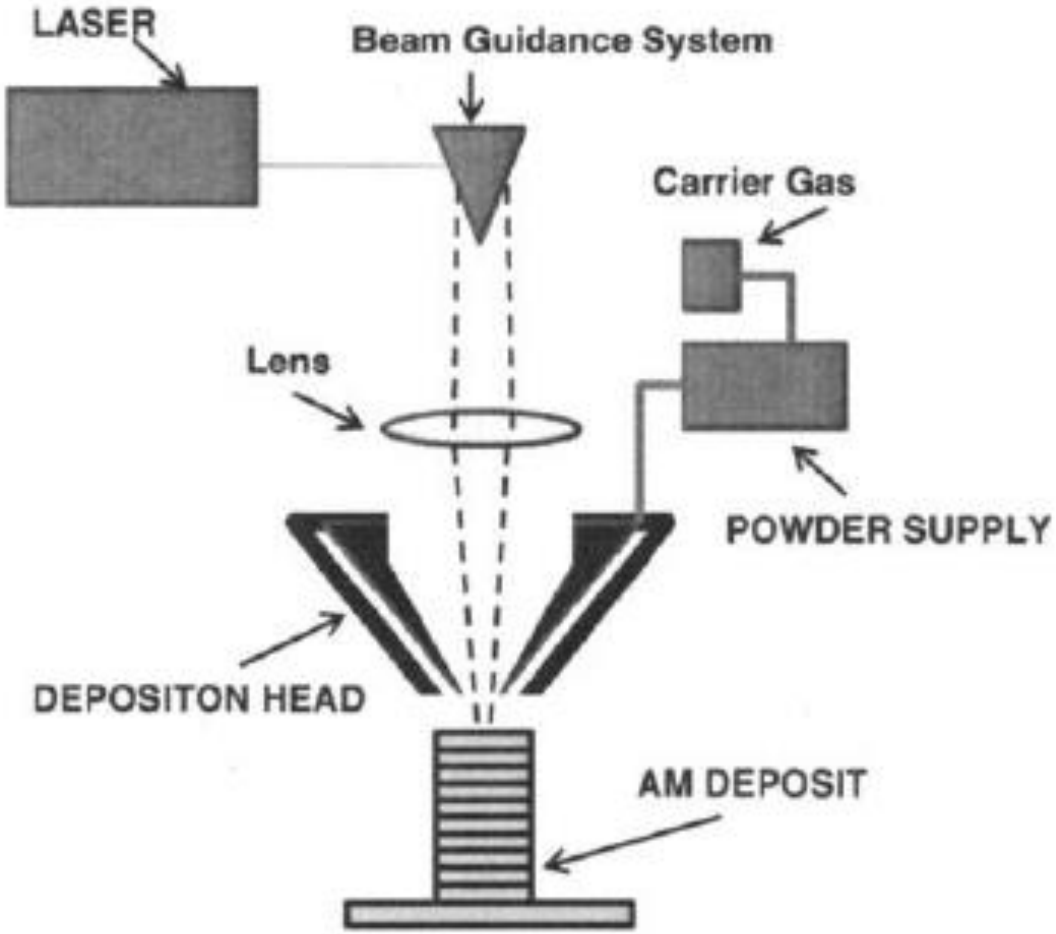
Typical AM Build Flaws

Material Discontinuity	Photo	Description	Typical Sizes
(Gas) Pores		Entrapped gas pores within the bulk of the material. Material dependent.	~9.9 μm (electron beam-PBF) 5–20 μm (laser-PBF)
(Elongated) pores		Lack of fusion pores in between layers of the AM process.	50–500 μm
Balling		Molten material is not a flat layer, but instead creates large spherically shaped particles on the surface.	Part dependent — theoretically up to the length of the part.
Unfused powder		The melt pool varies in size and unfused powder is present.	Satellite powder clumps: 100–150 μm.
Cracking		Cracks can be within the component or more commonly, a disconnection of the part from the baseplate is seen.	Parts on bed: residual stress in the range of materials yield strength. Parts removed from bed: deformation may occur without heat treatment or further processing.

Directed Energy Deposition (DED) – (including Hybrid)

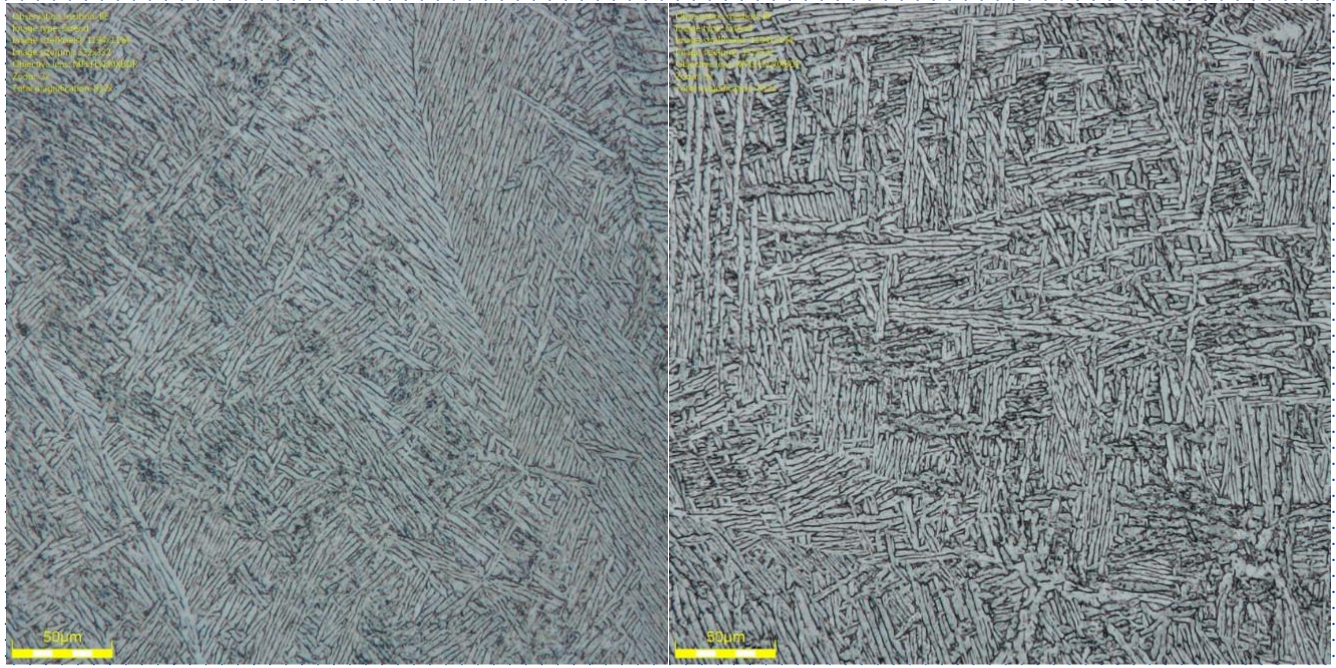
Directed energy deposition is most similar to conventional welding wherein a process in which focused thermal energy is used to fuse materials by melting as they are being deposited. The implementations of this set of technologies is perhaps the most widely varying with different feed sources (powder or wire) and energy supply, laser, electron beam, plasma, and kinetic motion. Machines are built on both industrial robot arms as well as gantry systems like in ME.

DED: POWDER FEED



DED: POWDER FEED IN-SITU INSPECTIONS

Technology Evaluated	Source	Details	Outcome
Acoustic Microscopy	X-wave Innovations, Inc	Difficult path towards production hardened technology. Vibrations experienced during manufacturing interfere with measurements.	Eliminated in 1st down-select.
Acoustic Emissions	Iowa State University	Preliminary testing on powder bed was shown. Sensitivity for inspection is not adequate enough at this time.	Eliminated in 1st down-select.
Air Coupled Ultrasonics	Boeing internal, University of Illinois in Chicago	Current technology does not meet sensitivity and resolution requirements. Large wave and poor penetration.	Eliminated in 1st down-select.
Non-linear Ultrasonics	University of Illinois in Chicago	Difficult path towards production hardened technology. Currently only contact method.	Eliminated in 1st down-select.
EMAT	Innerspec, Boeing internal	Preliminary testing is to be performed with EMAT, but initial assessment allowed for additional consideration. SEMAT eliminated in down-select due to safety concerns.	Eliminated in 2nd down-select.
Laser Ultrasonics	Intelligent Optical Systems	Preliminary testing was performed with LFMT and DMG Mori samples.	Down select candidate.
Melt Pool Monitoring	Purdue University	Preliminary testing at Purdue shows technique could be a viable process monitoring technique in combination or in place of NDT structural assessments.	Down select candidate.

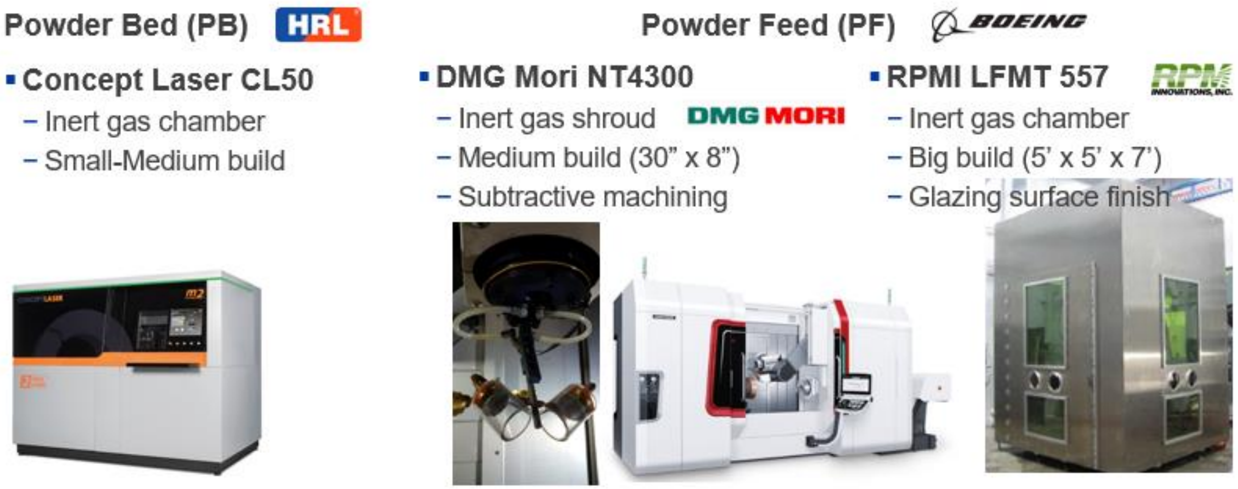


Ti-6Al-4V Microstructure: Conventional (left) vs Additive Manufacturing (Right)

Technology Overview

Potential Maintenance Burdon Introduced by Technology:
Army aviation platforms such as AH-64, and CH-47 have numerous parts that can be dropped in replaced by additive manufactured parts for enhanced maintenance and in support of continued operation in the field.

Description of Proposed Cost Match Strategy:
RDDT and EATTS programs and Boeing internal IRAD could be used to cost match a development program to mature the additive manufacturing technology for in-field application.



Technology Development

Develop in-field AVIM AVUM level Additive Manufacturing capabilities with powder sources and machine processes that cover a wide range of structural materials (steel, titanium, aluminum and nickel based alloys) that will meet dropped-in replacement/repair for AH-64 and CH-47 parts

Development Tasks (Include Current TRL)

TRL 1 for powder materials for in the field applications
TRL 0 for in-field 3D printing machines
TRL 0 for in-field 3D printing processes including software/modeling

Step 1: Identify parts for AH-64 and CH-47
Step 2: Match Powder Alloys that match parts and requirements
Step:3: Implement Demonstration for modular kits of in-field 3D printing machine, etc. including the operators in the field (see Demonstration approach & platforms below)

Risks and Mitigating Actions:
Describe major risks and mitigation approaches related to the development of the technology: The size 3D printing machine kit may limit the AM capability for dropped-in replacement parts availability

Timeline and Milestones:

Provide an expected timeline with major milestones and TRL for the development of the technology..

Technology Development

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Demonstration Approach:
Describe the proposed approach to demonstrate the technology: partnership with 3D printing companies to develop suitable size 3D printing machines including processes and software and powder supply for lab, Integration and field demo testing. Comprehensive training of 3D printing machine kit operators in the field.

Target Demonstration Platform(s):
Describe target demonstration platform(s): Airframe, Rotor, Flight Control and Drive system parts for AH-64 and CH-47.

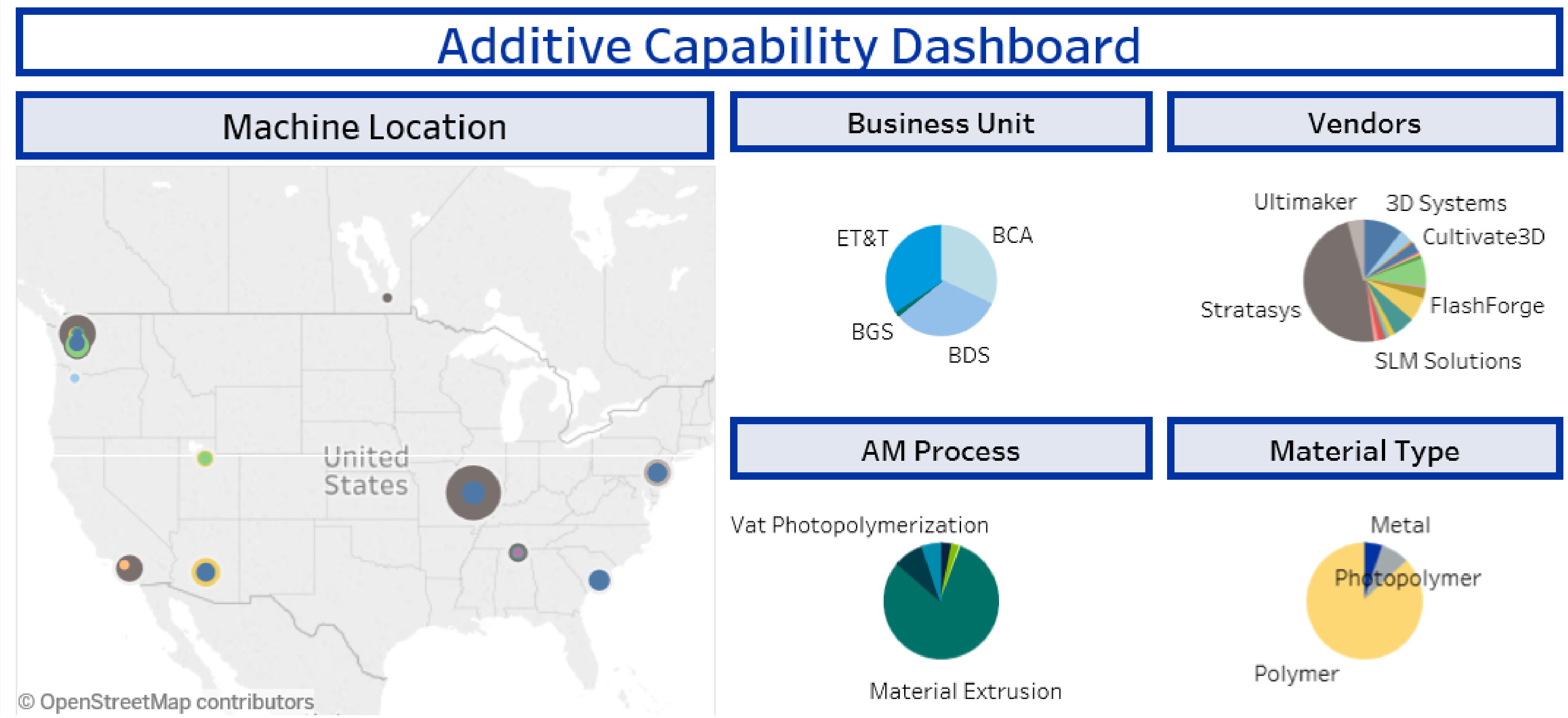
Platform Integration Requirements:
Describe requirements for the integration of technology into aircraft or ground based sustainment elements: comprehensive plan for field integration require demo and transition.

Milestone	Milestone Description(TRL)
#1	TRL 5 Lab Demo (1.6 years)
#2	TRL 6 Integration Demo (0.8 year)
#3	TRL 7 Field Demo (0.8 year)

Indicate Areas of Impact

Does this technology directly support	✓	If yes, provide short rationale
Mobile and capable field maintenance ➢ Minimized logistics footprint ➢ Maintainability in austere and distributed operational environments ➢ Responsive supply chain ➢ Other	✓	Additive Manufactured parts provide tremendous saving in cost and schedule in the field maintenance compared with conventionally manufactured parts & greatly minimize logistics footprint and highly enhance responsive supply chain.
Minimum cost ➢ Lifecycle ➢ Deployment to austere and distributed environments	✓	While meeting performance requirements and reducing O&S cost, additive manufactured parts in the field ultimately prolong life cycles.
Common sustainment architecture that is interoperable across DoD ➢ Common design elements and maintenance practice/procedures such as MOSA/FACE/OSACBM/SAE6268 ➢ Other	✓	Additive manufactured parts in the field for Army rotorcraft can be readily adopted for and applied across DoD for common design elements and maintenance practice/procedures due to common aerospace process and material requirements.

Boeing AM Printers/Capabilities, Design Guides and Specifications



AM Printers / Capacities (An Example)

Process/Material	Build Envelope XYZ inches
Stereolithography	
Semi-Flex Watershed	20 x 20 x 23
Heat Resistant Prototherm	20 x 20 x 23
Hi Impact NeXt	20 x 20 x 23
Formlabs Grey	5.7 x 5.7 x 6.9
Formlabs Tough	5.7 x 5.7 x 6.10
Formlabs Flexible	5.7 x 5.7 x 6.10
Formlabs High Temperature	5.7 x 5.7 x 6.10
Formlabs Durable	5.7 x 5.7 x 6.10
Plastic Laser Sintering	
EOS PA-2200 Nylon 12	26 x 13 x 22
ALM Aluminum Filled N12	12 x 10 x 16
ALM Carbon/GlassLite N12***	12 x 10 x 16
ALM Mineral Fiber Fill N12***	12 x 10 x 16
Neat Nylon 11	12 x 10 x 16
BMS8-401 Fire Retardant N11	12 x 10 x 16
Direct Metal Laser Sintering	
Maraging	9 x 9 x 8
15-5 Stainless	9 x 9 x 8
15-5 Stainless	11 x 11 x14
17-4 Stainless	9 x 9 x 8
Cobalt Chrome	9 x 9 x 8
Bronze	9 x 9 x 8
Ti-6al4v	11x 11 x 14
Fused Deposition Modeling**	
ABS-M30	36 x 24 x 36
Ultem	36 x 24 x 36
Multi-Jet Modeling	
Digital Materials	19 x 15 x 7.9

Internal AM Specifications

Manufacturing Documentation (Metal)

Copy

- SCGPS 28007 POWDER BED LASER MELTING PROCESS FOR MANUFACTURING ALUMINUM PARTS (ADDITIVE MANUFACTURING)
- SCGPS 28009 POWDER BED ELECTRON BEAM FUSION PROCESS FOR FABRICATING TITANIUM PARTS (ADDITIVE MANUFACTURING)
- SCGMS 10067 ALUMINUM POWDER FOR POWDER BED LASER MELTING (ADDITIVE MANUFACTURING)
- HBMS-06-003, Preforms, Titanium 6Al-4V, Electron Beam Deposited Powder

Manufacturing Documentation (Thermoplastics)

- SCGPS 28008 SELECTIVE LASER SINTERING PROCESS FOR MANUFACTURING THERMOPLASTIC PARTS (ADDITIVE MANUFACTURING)
- BAC5692, LASER SINTERING (LS) OF THERMOPLASTIC PARTS
- BMS8-401, THERMOPLASTIC LASER SINTERING (LS) RESINS
- HMS16-1292, Nylon, Plastic Selective Laser Sintering Compound [material spec]
- HP15-166, Selective Laser Sintering (SLS) of Nylon Materials [process spec]
- MMS5070, FDM Filament, Polycarbonate/Polyetherimide Based [material spec]
- PS14309, Process Spec for FDM of Thermoplastic Parts [process spec]
- BAC5950, Fused Filament Fabrication of Thermoplastic Parts [process spec]
- XBMS8-401B-01, THERMOPLASTIC LASER SINTERING (LS) RESINS [material spec]
- BMS8-430, Fused Filament Fabrication (FFF) Material [material spec]

Internal AM Specifications (Examples)

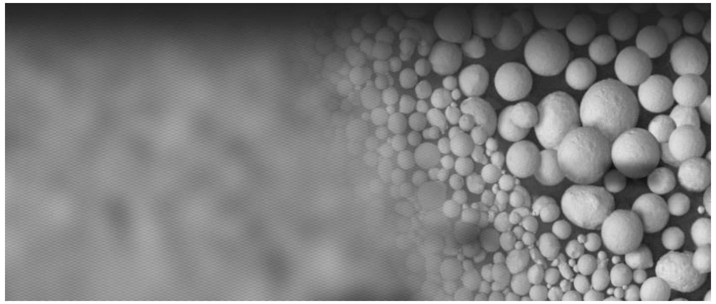
- Design
  - Selected Laser Sintering (SLS) Design Guide for Commercial Applications D6-85910
  - Fused Filament Fabrication (FFF) Design Guide D950-11693-1
  - SLS Design Guidelines STL 2003A013
- AM Powder Bed Fusion
  - Titanium Material BMS 7-419 (Ti-6-4)
  - Titanium Material BAC 5674 (Ti-6-4)
  - Aluminum Material BAC 5673 (AlSi10Mg)
- AM Powder Feed
  - Titanium Material BMS 7-361 (Ti-6-4)
  - Titanium Material MMS 1237 (Ti-6-4)

Examples: Gear Manufacturing Process

- **Traditional Manufacturing**
  - Foundry Melt
  - Ingot / Bar
  - Forging
  - Machining
  - Heat Treat / Carburize
  - Heat Treat / Harden
  - Final Grind
  - Shot Peen
  - Inspection

CarTech photo

- **Additive Manufacturing**
  - Foundry Melt
  - Powder
  - AM (Near Net Form)
  - Hot Isostatic Press (HIP) (maybe)
  - Heat Treat / Harden
    - (Case Treatment for Ti only)
  - Final Grind
  - Shot Peen
  - Inspection



CarTech photo

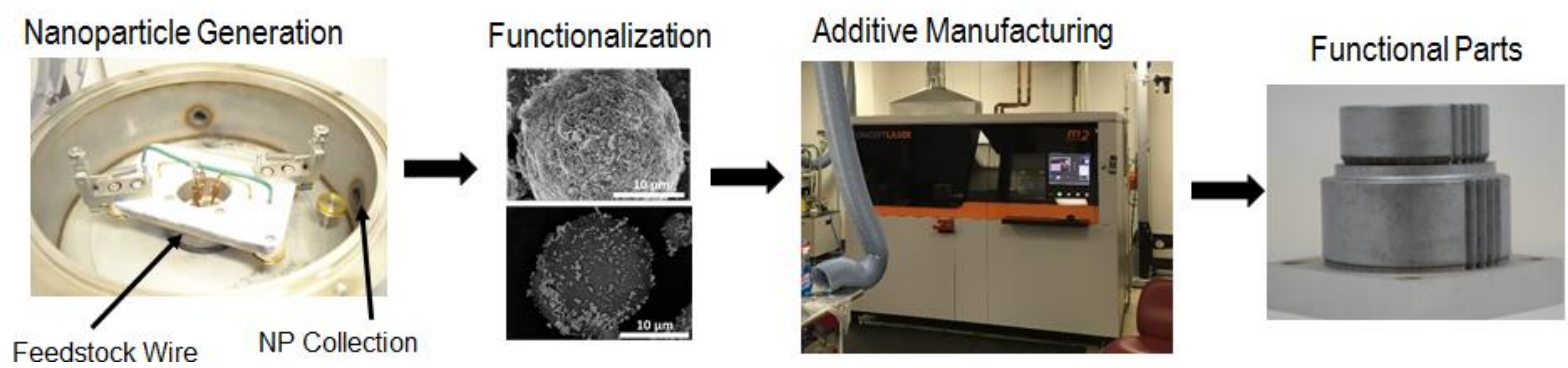
Examples: Gear AM MATERIALS

Steel Common Name	**Specifications**	**Atomized Commercially Available**	**Atomized S (Typical)**
AISI 8620	AISI 8620	YES*	0.025
AISI 9310	AISI 9310	YES	0.025
Pyrowear 53 X53	AMS 6308	NO	-
AISI 52100 100Cr6	ASTM A295	YES*	0.025
Pyrowear 675	AMS 5930	NO	-
M50 NIL	AMS 6278	NO	-
Ferrium C61	AMS 6517	YES	-
Ferrium C64	AMS 6509	YES	-
20MnCr5	SAE 5120	YES*	0.006
16MnCr5	SAE 5115 DIN 1.7139	YES	0.040

* Stock item from at least one supplier

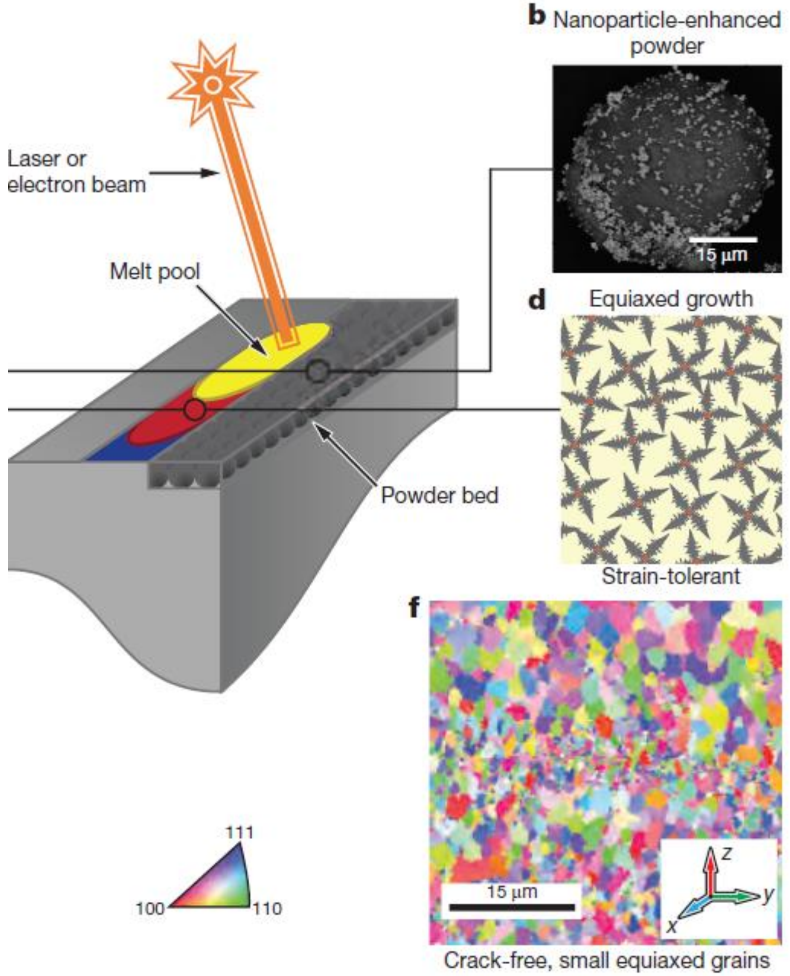
Gears | Steel | AM — Approach

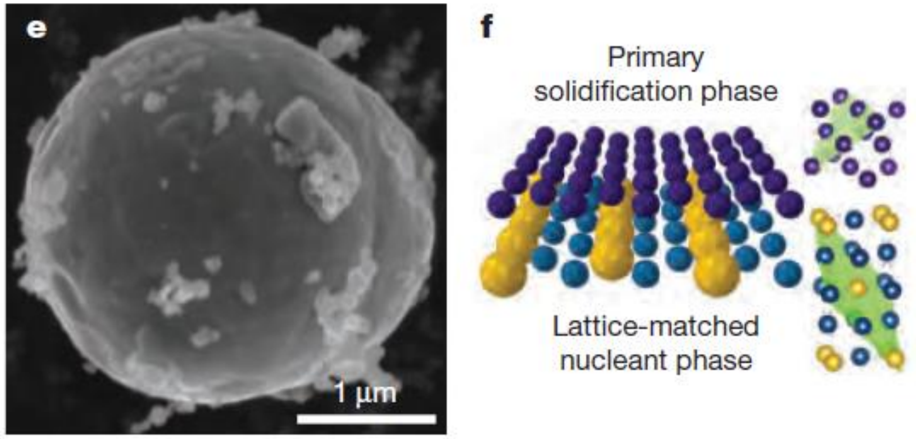
- **Nanoparticles / composition changes**
  - identified to alter solidification and microstructure
- **Nanoparticles assembled on conventional additive feedstock material**
- **AM Materials Processing**
  - using commercial off the shelf equipment
- **Final parts**
  - produced with targeted microstructure for enhanced mechanical properties



Gears | Steel | AM — Approach

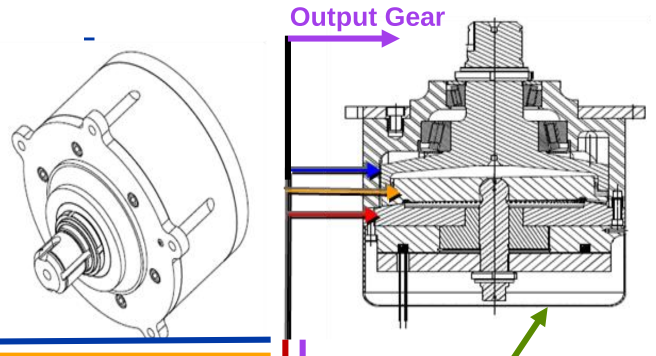
- **Nano-functionalized Approach**
  - GOAL — mimic effect seen in original research work with Maraging steels where borides effect **grain refinement without degradation of fracture toughness**.
  - NPs are **lattice matched to the FCC iron** predicted to be the **initial solidification phase**. It is to provide an **epitaxial condition** allowing **equi-axed grain formation**, and coherence in the matrix to act as **pinning points** (borides) to control microstructure during subsequent heat treatments.

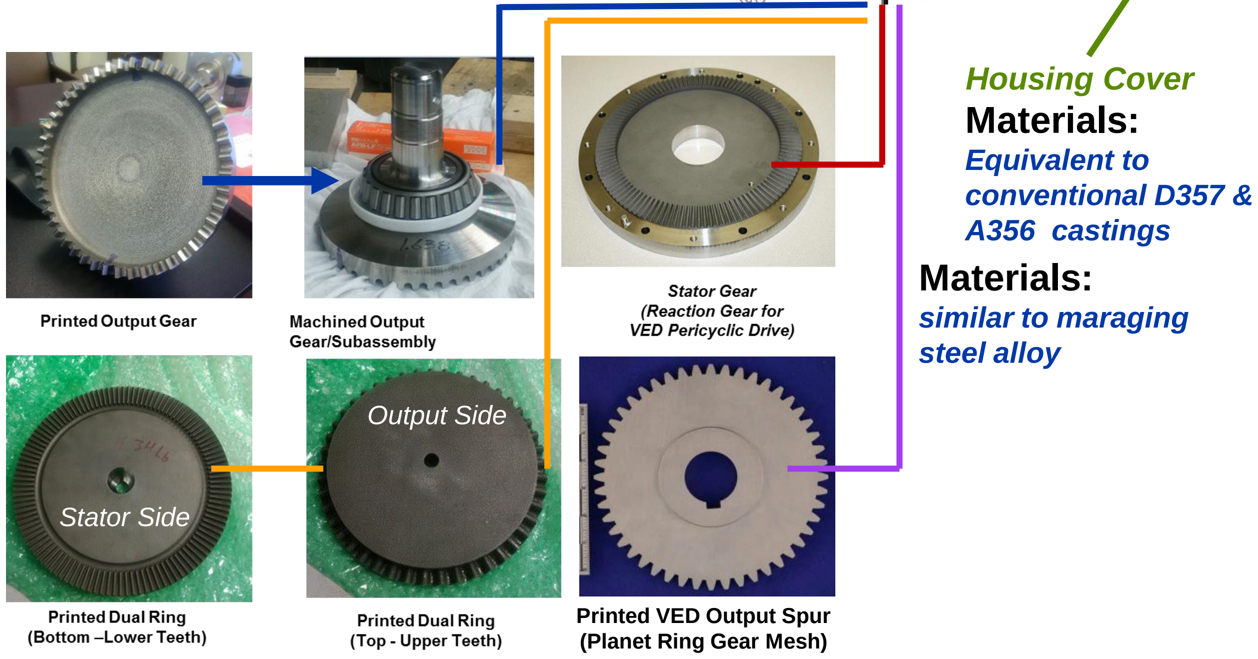




Leveraging of Tech Developments

- **AVSAT/NGRT**





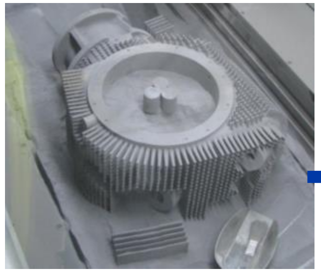
Virtual Elliptic Drive Development

– Other Programs, Etc.
  - RDDT Program (ADD)
  - EATTS Task Order-9 Composite Sump System Program (ManTech)

- **Boeing Internal IRAD**
  - AH-64 / CH-47 Engine Nose Gearboxes
    - Aluminum Powder Materials
    - Titanium Powder Materials
    - Steel Powder Materials

Equivalent to conventional to D357 & A356 castings

Engineering Model



AM Build – In Machine

Completed

First 3D Printed Gbx Hsg (Amaero)

Second 3D Printed Gbx Hsg (Poly-Shape)

Third 3D Printed Gbx Hsg (Amaero)

Summary

Introducing ASTM F42 Committee on Additive Manufacturing

AM Technology Overview and Development

Boeing AM Printers/Capabilities

Boeing AM Design Guides/Specifications

Leveraged Technology Development including Nano-functionalized Approach of AM Powder Bed Process