Remaining Challenges & Progress in Additive Manufacturing

November 6th 2019

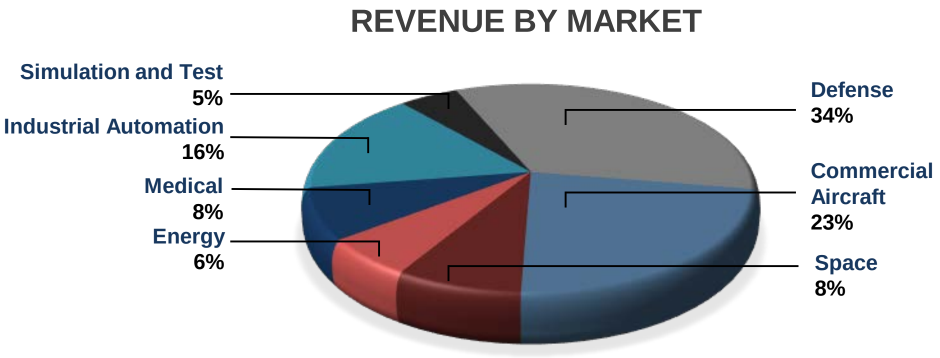
Overview

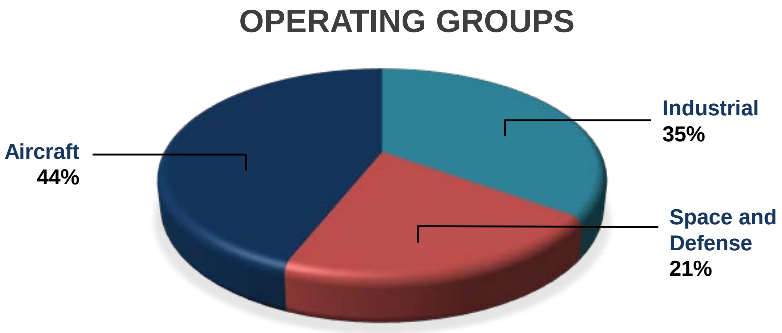
- Background
- Update on Moog's AM Experience & Current LPBF Current Status
- Remaining Challenges
- Summary

Moog – When Performance Really Matters ®

- Founded in 1951 by Bill Moog
- A worldwide designer, manufacturer, and integrator of precision motion control products and systems.
- Multi-national Company
  - Over 100 locations in 28 Countries
  - Over 11,500 Employees Worldwide
  - $2.7 Billion in Revenue (FY 2018)
- Traded on the New York Stock Exchange (MOG.A and MOG.B)

- 7 Markets:
  - Defense
  - Commercial Aircraft
  - Industrial Automation
  - Simulation & Test
  - Medical
  - Energy
  - Space
- 3 Reporting Segments:
  - Aircraft Controls
  - Space and Defense
  - Industrial Systems





Aircraft: Commercial & Military

Primary Flight Control Actuation System

1. Aileron Power Control Unit (PCU) and Remote Electronic Unit (REU) Assembly (x4)
2. Flaperon Actuator (x4)
3. Flaperon Control Module and Remote Electronic Unit (REU) Assembly (x4)
4. Inboard Spoiler Power Control Unit (PCU) (x4)
5. Outboard Spoiler Power Control Unit (PCU) (x6)
6. Spoiler Remote Electronic Unit (SREU) Assembly (x10)
7. Electromechanical (EM) Spoiler Actuator (x4)
8. Electric Motor Control Unit (EMCU) (x6)
9. Horizontal Stabilizer Trim Actuator (HSTA) Assembly (x1)
   - Resolver (HSTA)
   - Motor Brake (HSTA)
   - Lower Integrity Sensor (HSTA)
   - Upper Integrity Sensor (HSTA)
10. Elevator Power Control Unit (PCU) and Remote Electronic Unit (REU) Assembly (x4)
11. Rudder Power Control Unit (PCU) and Remote Electronic Unit (REU) Assembly (x3)

Spoiler Resolver (x14) *not shown*

Power-by-Wire Architecture

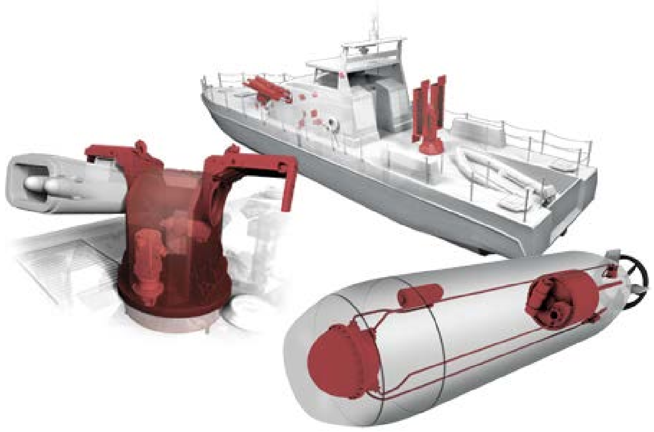
1. Leading Edge Flap Control Unit
2. Leading Edge Power Drive Unit
3. Asymmetry Brake
4. Outboard Position Sensor
5. Flaperon EHA
6. Horizontal Tail Electronic Control Unit

Space and Defense

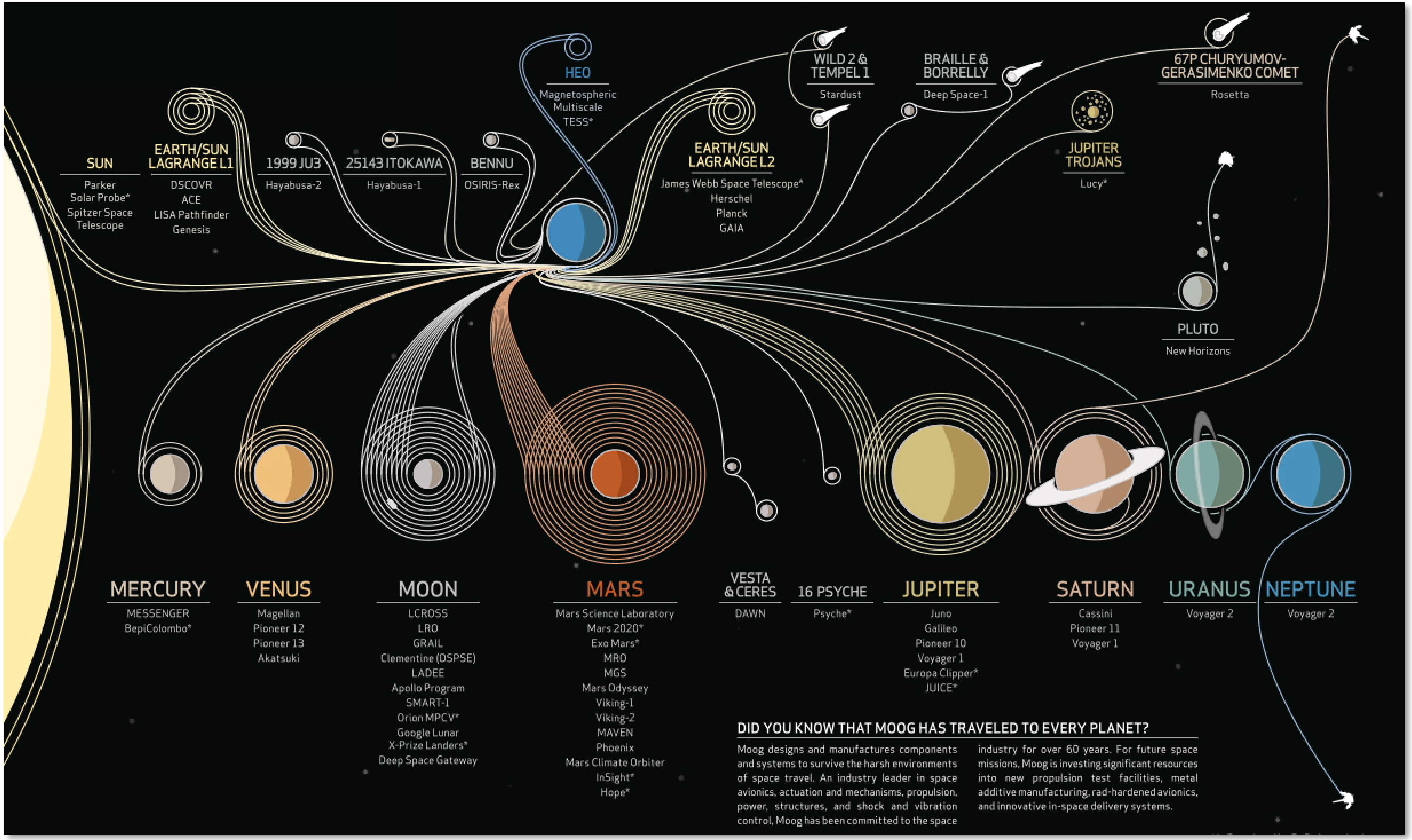
Air

Land

Sea

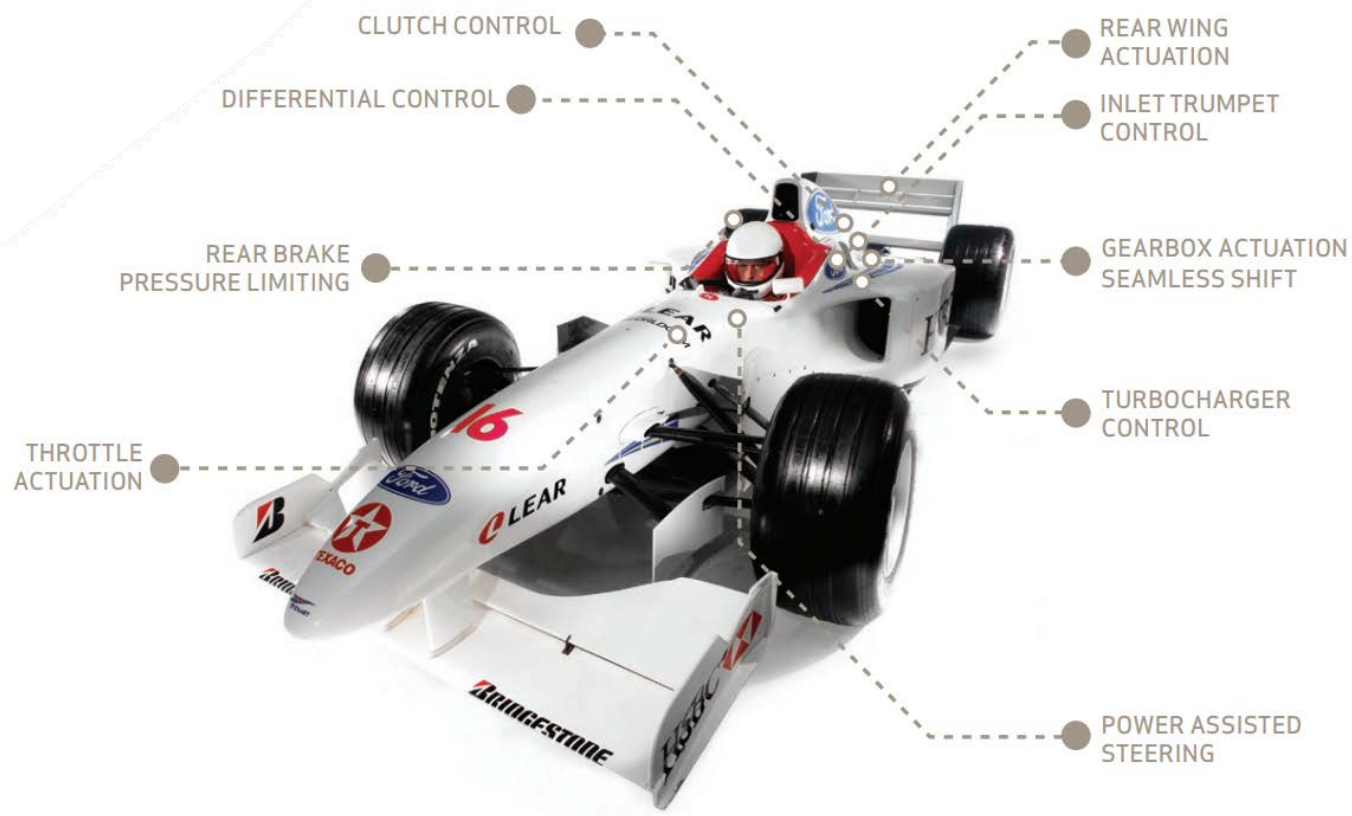


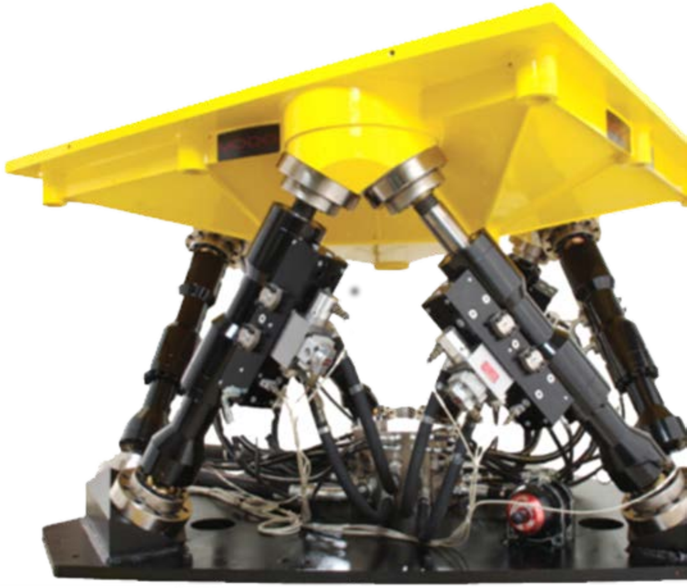
Moog in Space



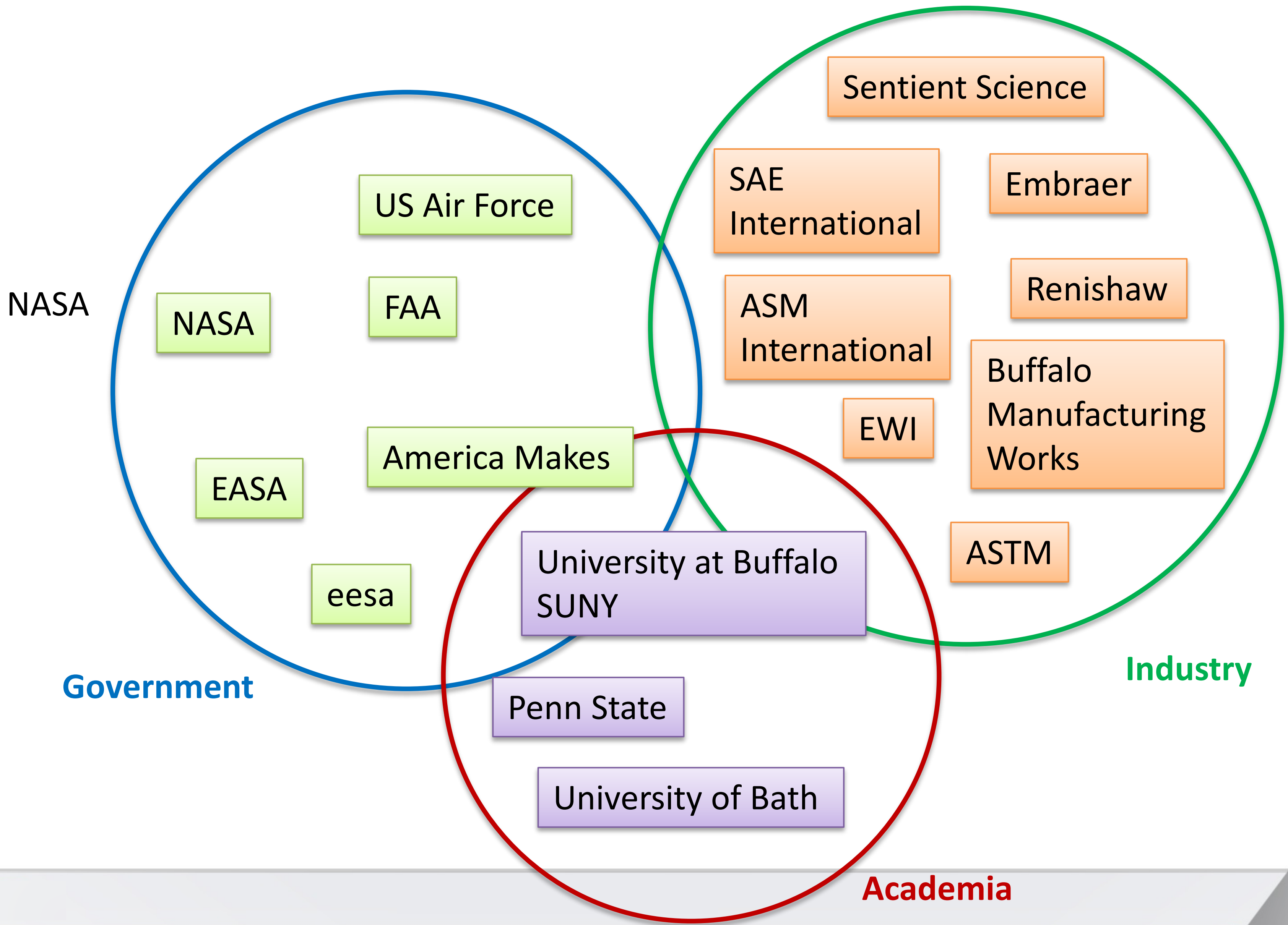
Industrial


MOOG


CLUTCH CONTROL
DIFFERENTIAL CONTROL
REAR BRAKE PRESSURE LIMITING
THROTTLE ACTUATION
REAR WING ACTUATION
INLET TRUMPET CONTROL
GEARBOX ACTUATION SEAMLESS SHIFT
TURBOCHARGER CONTROL
POWER ASSISTED STEERING



Research & Development Associations



UPDATE ON MOOG'S AM EXPERIENCE & CURRENT STATUS

Metal Additive at Moog

ATC
ADVANCED TECHNOLOGY CENTER

2013

Established Advanced Technology Center (ATC)

To Progress Additive Research and Development

2015

Acquired Linear AMS

Additive Service Bureau Capabilities

AMC
ADDITIVE MANUFACTURING CENTER

2018

Established Additive Manufacturing Center (AMC)

To Develop Additive Production Capabilities

Additive Enabled Solutions

MOOG SPACE AND DEFENSE GROUP

MOOG AIRCRAFT GROUP

MOOG INDUSTRIAL GROUP

Demand

AMC
ADDITIVE MANUFACTURING CENTER

Additive Development and Production

POWDER

TO

- Additive Engineering
- Additive Process
- Heat Treat
- Inspection
- Machining

PART

ATC
ADVANCED TECHNOLOGY CENTER

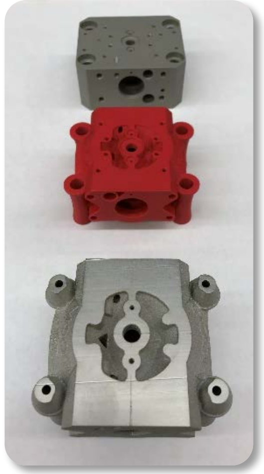
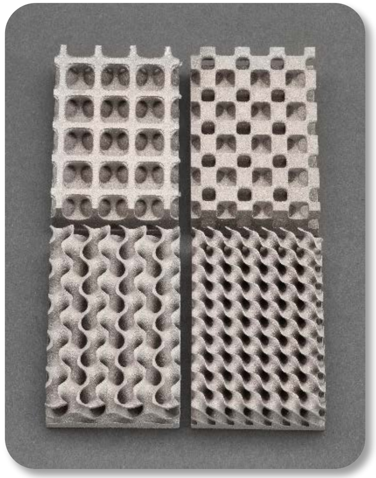
Research

Internal Customer

External Customer

ADDITIVE MANUFACTURING CENTER

Why Use Additive Manufacturing?

Faster Iteration	Custom Solutions	Reduce Weight	Parts Consolidation	Improve Performance
				

This document does not contain Technical Data or Technology as defined in the ITAR Part 120.10 or EAR Part 772

(12) Materials:

17-4 SS
316 SS
15-5 SS
Ti64
CPTi
Inconel 625
Inconel 718
Cu18150 Copper
GRCop84 Copper
Alsi10mg
F357 Alum
CoCr

(11) Machines:

(2) EOS M290
(3) EOS M280
(1) Renishaw AM500
(1) Renishaw AM250
(3) SLM280 (2X Laser)
(1) SLM280 (1X Laser)


M32104
VULCAN
VAC-AERO #3
• Vacuum Furnace: AMS 2750 Certified; Capable of 1.4x10-5 Torr; Gas Quench And Partial Pressures with Argon Gas
• Homogenization & Stress Relieving Of All Fe, Ni, Co, and Ti based alloys
• Annealing of Ti and Ti Alloys
• Solution Treating And Aging of PH Stainless Steels: 17-4, 15-5
• Solution Treating And Aging of Inconel 625 & 718
• Solution Treating Of Haynes 25, Hastelloy X, And Other Ni & Co Super Alloys
• Tempering of Maraging and Tool Steels
SPECIAL PROCESSES
AMC
MAXIMO ASSET# 108645
OPERATOR INTERFACE
VACUUM CONTROLLER
OVERTEMP CONTROLLER
HOT ZONE POWER
FRONT
BACK
HEAT TREAT

Moog Process Coverage Compliance Matrix

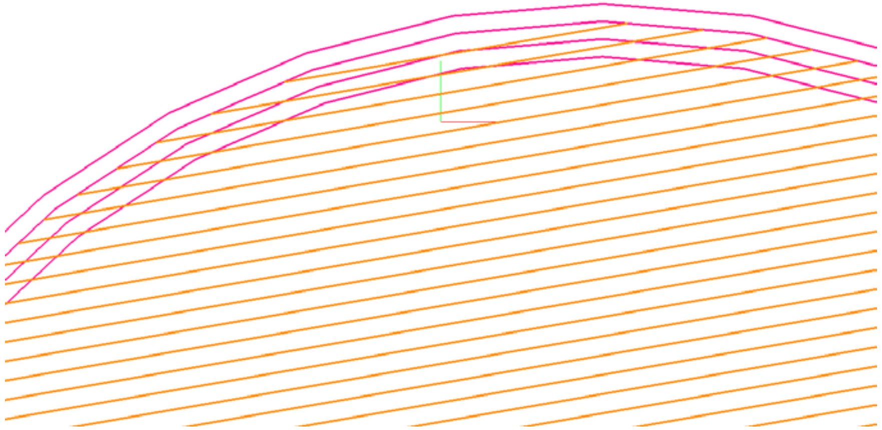
Common Industry Understanding or Acceptance of:	Al 2014 Cast *(common airframe alloy)*	AM Alloy *(airframe or engine alloy)*	MOOG Standards
Material and process specs	Yes	No / WIP	EMS45279:Ti, EMS45710:15-5, EMS52093: F357
Design allowables • Effect of Environment • Knock down factor	Yes	No / WIP	MRE43676:Ti MRE46017:15-5 MREXXXX: F357 in work
Capable NDI methods • Effect of surface finish	Yes	No / WIP	EPS47032
Characterization of material defect / anomalies types	Yes	No / WIP	MRE48189
Key manufacturing process control parameters and acceptable ranges	Yes	No / WIP	EPS42894 EPS50785
Effect of process parameters on microstructure and mechanical properties • Heat Treat • Hipping	yes	No / WIP	MRE43676:Ti MRE46017:15-5
Qualification / certification criteria	Yes	No / WIP	Point Certified Design/Process (2)

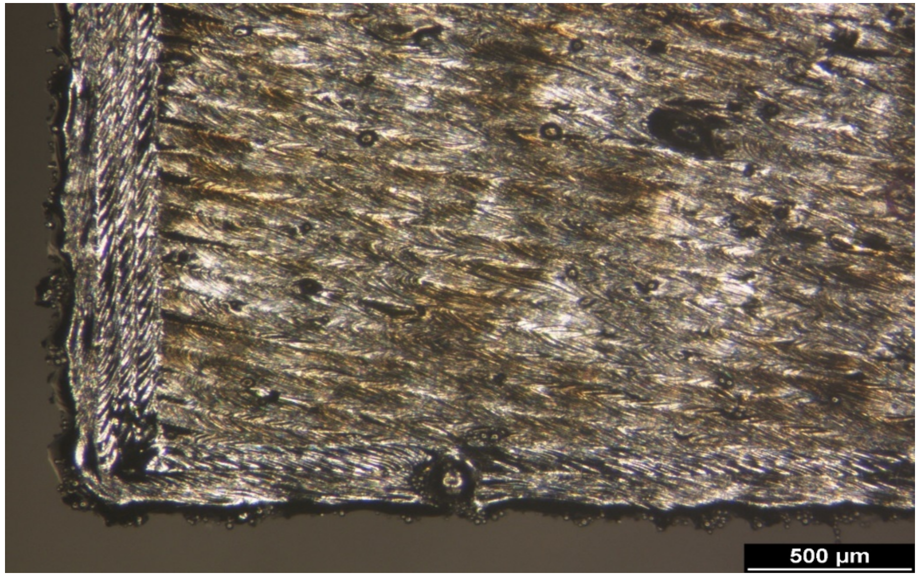
1. Table courtesy Jim Kabbara (FAA AM National Team Lead) taken from presentation by Chinh Vuong (FAA), presented to SAE Aerospace Standards Summit July 7, 2015
2. Near term plan – until appropriate standards are sufficiently mature

LPBF Process Controls are key to maintaining quality. Internal standards transitioning to industry standards

A Quick Review of LPBF Laser Welding

- A simple analogy…
  - Colouring in with a pencil
  - Volume and border
    - Interface is important





Laser Powder Bed Fusion is a form of welding

AM is more than just the AM Machine:

Build Stresses

Build Direction

Recoater direction

Build Plate Design

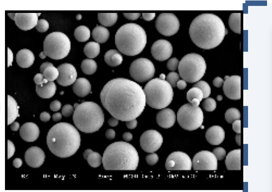
Supports

Machining allowances

AM Design rules 2.0

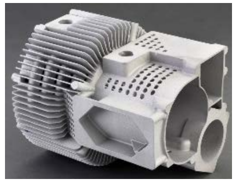
AM part Selection (Suitability criteria/ assessment)

Data Control and Verification

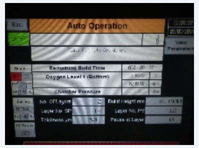


Powder Management

Includes: Specification, Sieving, reuse, handling, filling, removal



AM Design freedom/ constraints



AM Machine Parameters

AM Machine Control strategies

Build Verification

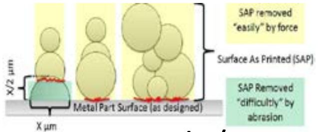
Finish Machining

3D scanning

AM part Costing

Stress relieve

EDM

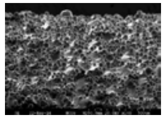


SAP Level I/II removal

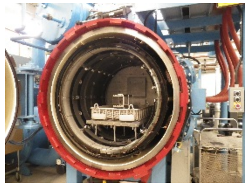
CT scan

Honing

Polishing

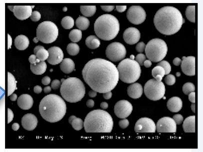


Contamination Control



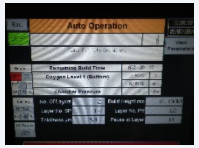
Heat Treat

Key Process Steps with Parameters



Powder Management

Includes: Specification, Sieving, reuse, handling, filling, removal

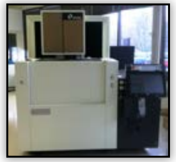


AM Machine Parameters

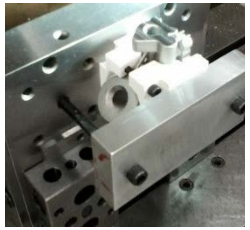
AM Machine Control strategies

Build Verification

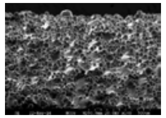
Stress relieve



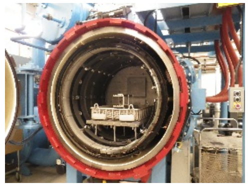
EDM



Finish Machining



Contamination Control



Heat Treat

Build Plate Design

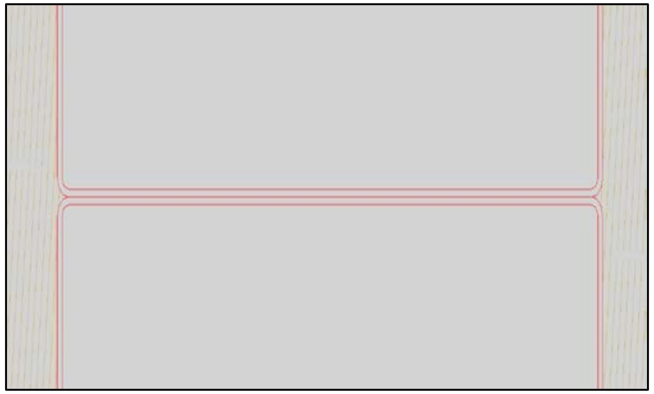
Supports

LPBF Process Parameters

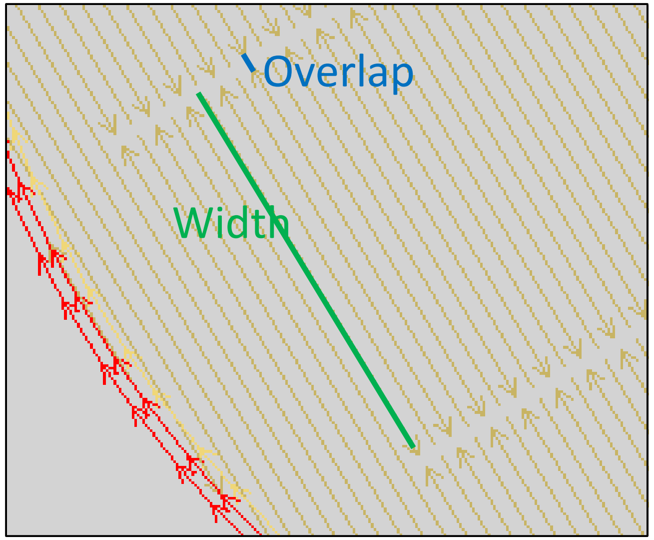
- Key & Variable Parameters (check/update between maintenance visits)
  - Laser Power
  - Scan Speed
  - Scan Spacing (volume and border)
  - *Volume/Border interface is critical*
  - Laser Spot Size (focus)
  - Scan Order (inside-out or outside-in)
- Key & Set Once Parameters
  - Gas flow speed
  - Chamber oxygen limits
- Set Once & Maintain Parameters (check/update during maintenance visit)
  - Part scaling values
  - Machine Calibration
    - X-Y Scan field
    - Laser power mapping
    - Global laser offset

LPBF Process Parameters - Examples

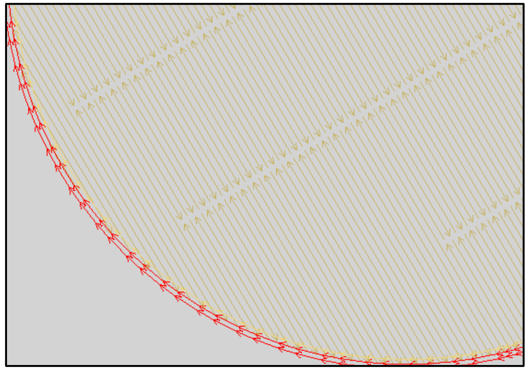
- **Blocked Path:**
  - Filters volume scans on thin walls



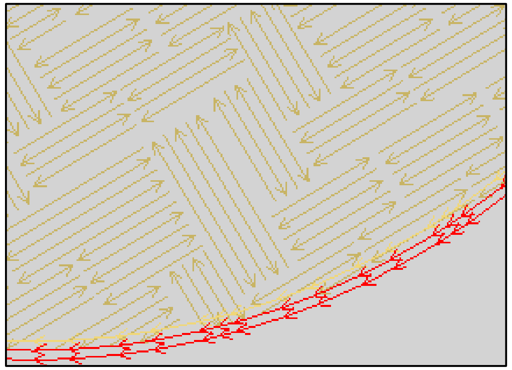
- **Stripe Width & Overlap:**



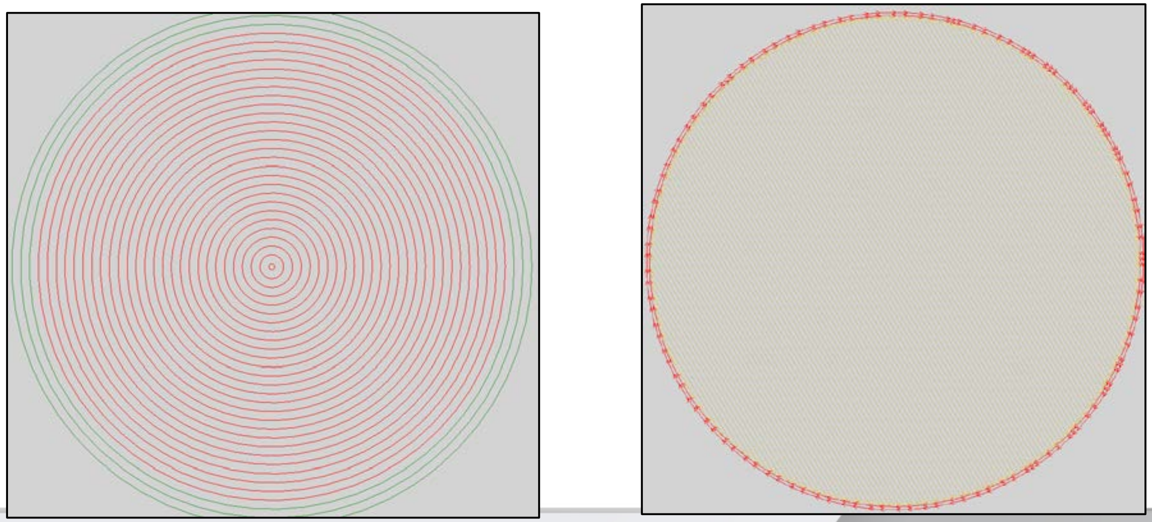
- **Volume Scan types:**



Stripes



Chessboard

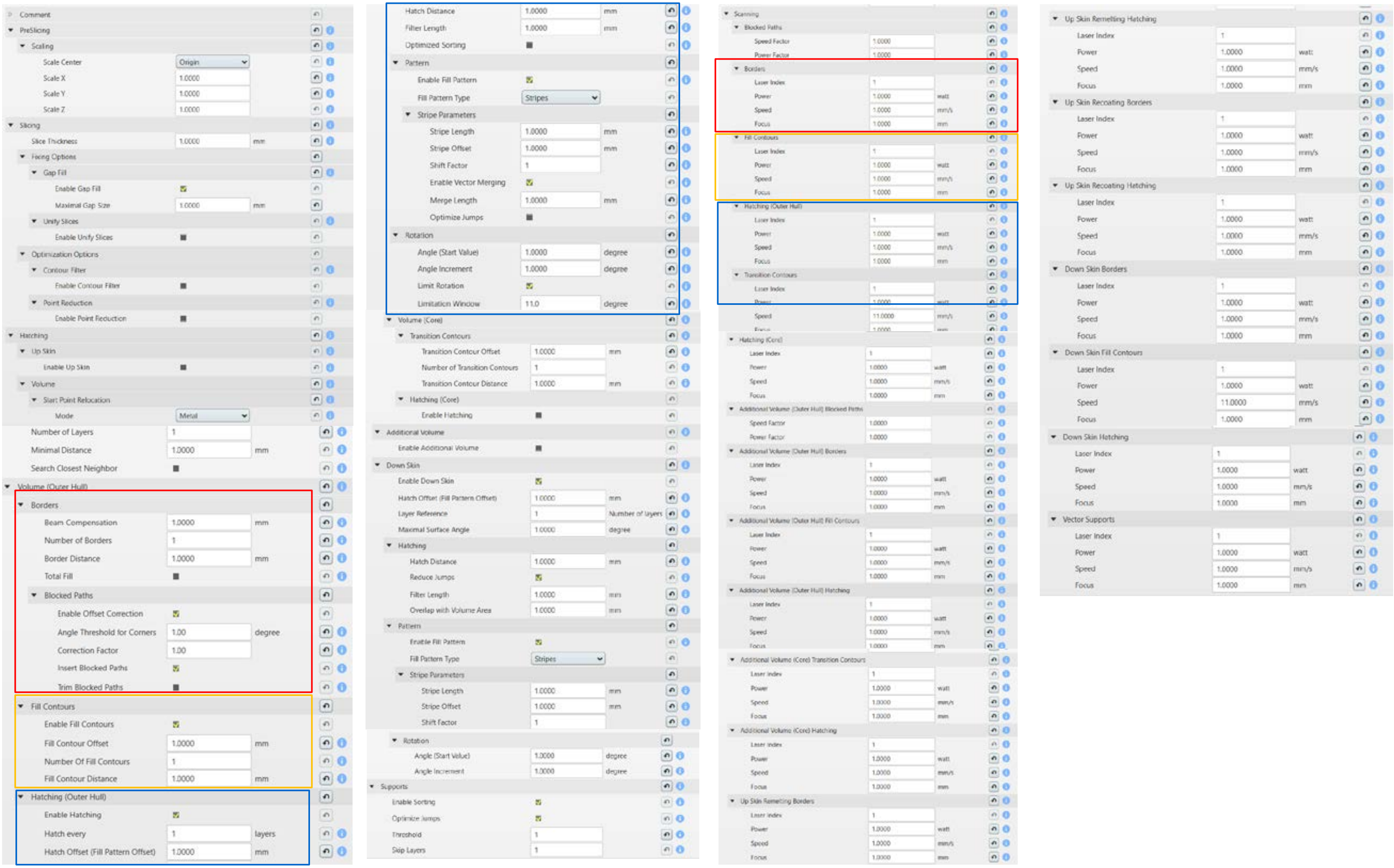


Total fill

Meander

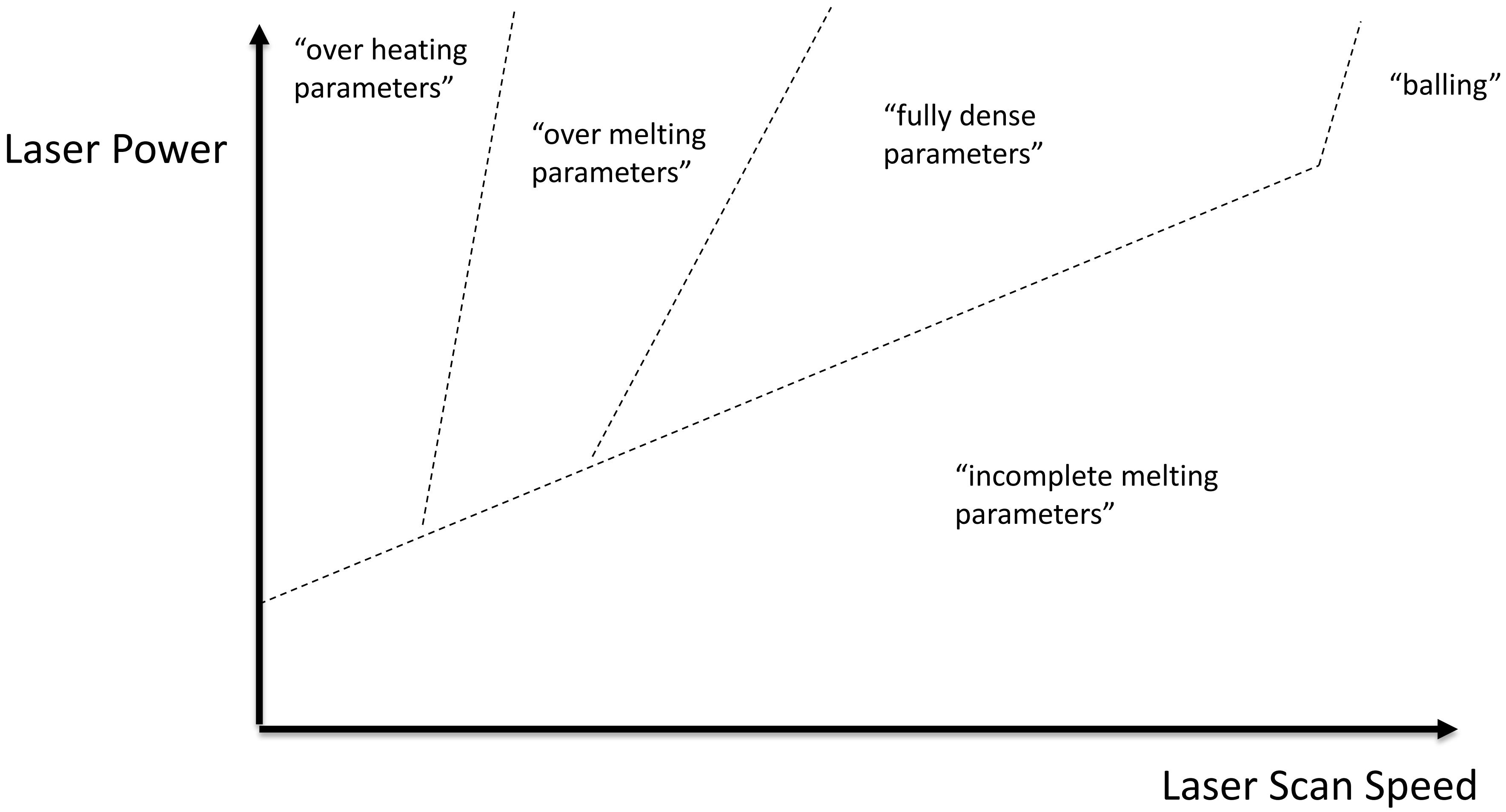
LPBF Process Parameters – Total Number Estimate

Typically 30 parameters are varied through multiple DOEs

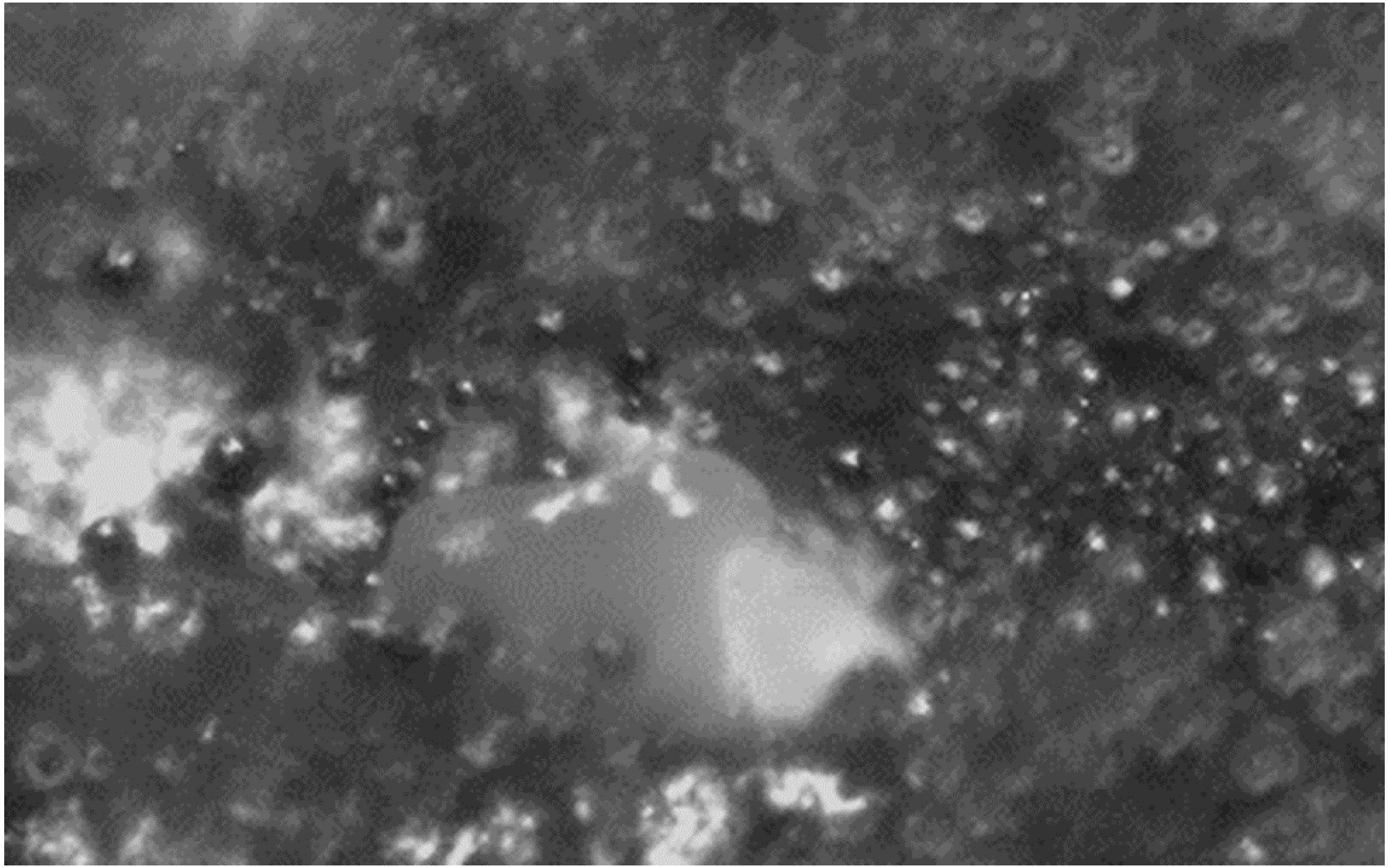


*300 - 400 Total parameters to vary depending on machine

Flaw Formation



Melt Pool Physics – LPBF Videos

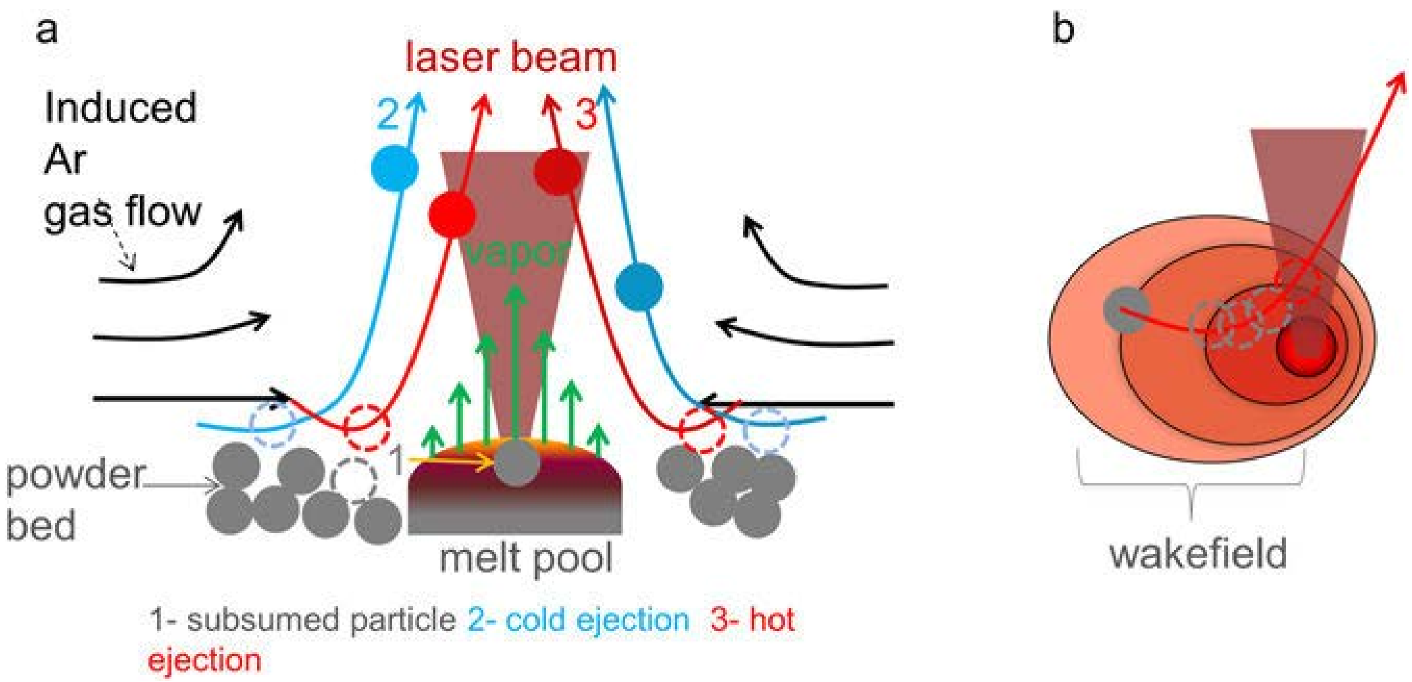


Metal vapor micro-jet controls material redistribution in laser powder bed fusion additive manufacturing

Sonny Ly, Alexander M. Rubenchik, Saad A. Khairallah, Gabe Guss & Manyalibo J. Matthews

http://www.nature.com/articles/s41598-017-04237-z

Melt Pool Physics – LPBF Videos



(a) Schematic depicting particle entrainment of the powder bed by an induced argon gas flow for a stationary laser beam. A vapor jet creates a low pressure zone which leads to an inward gas flow that entrains particles and leads to three distinct trajectories: particles with low vertical momentum are swept into the melt pool and subsumed (1), particles with higher vertical momentum but originating >2 melt pool widths away are swept into the trailing portion of the vapor jet and ejected as cold particles (3) and particles with roughly the same vertical momentum as (2) but originating closer to the point of laser irradiation (<2 melt pool widths) are swept into or near the laser beam itself rapidly heat and are ejected as incandescent, hot particles. (b) For a moving laser beam, a non-uniform jet stream wakefield is induced and extends 3–4 beam diameters away.

Metal vapor micro-jet controls material redistribution in laser powder bed fusion additive manufacturing
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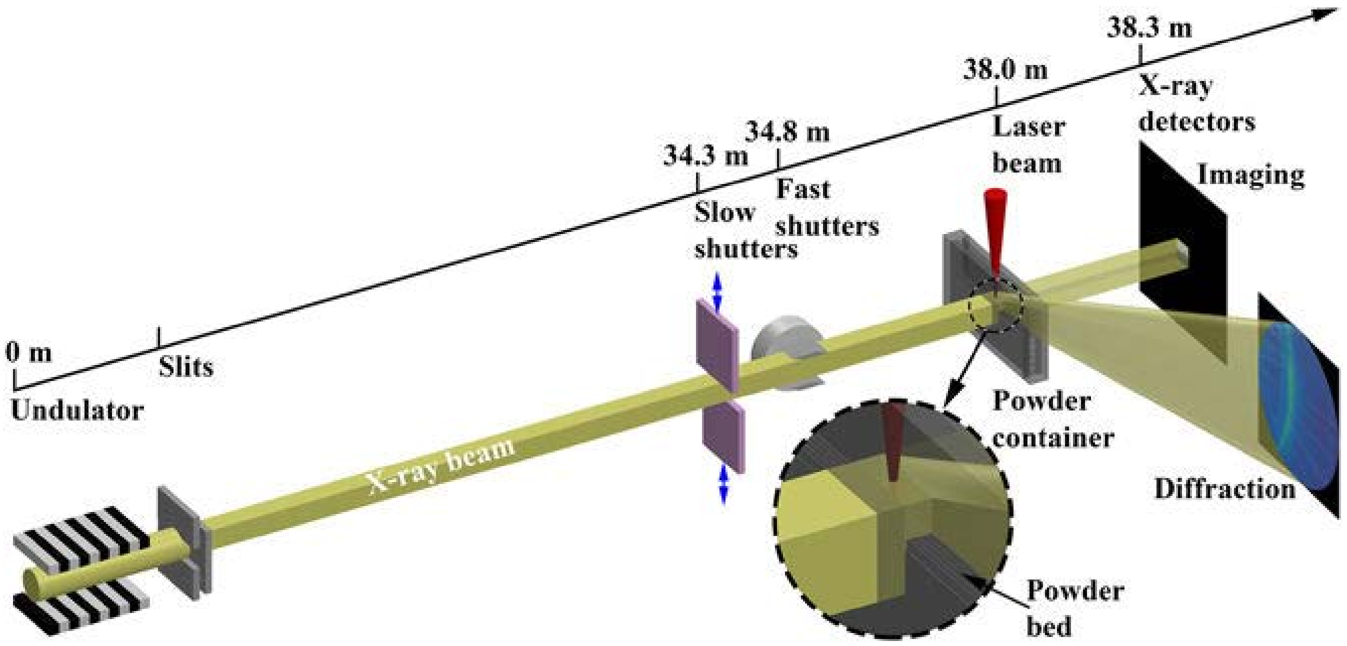
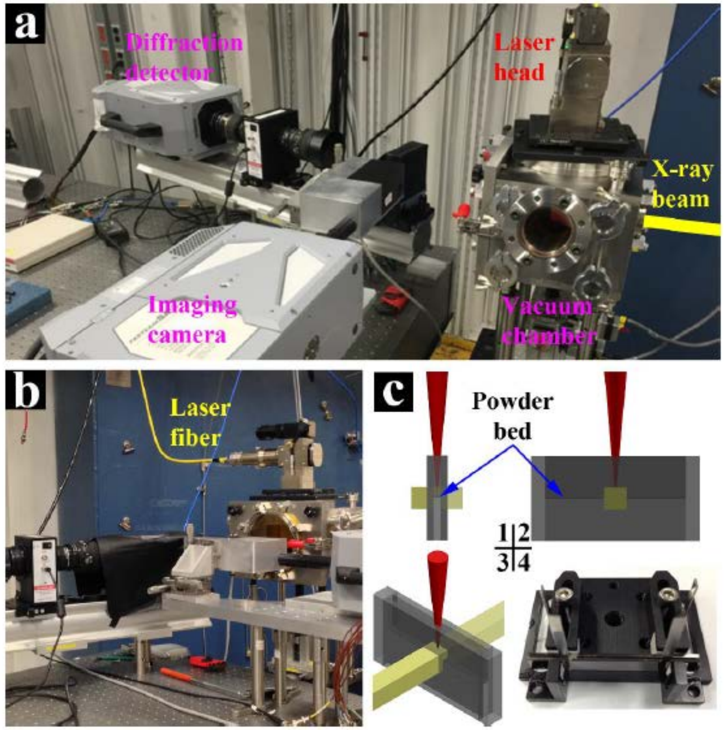
Melt Pool Physics – LPBF X-Ray Videos

- An example of real-time monitoring of LPBF process





Real-time monitoring of laser powder bed fusion process using high-speed X-ray imaging and diffraction
Cang Zhao, Kamel Fezzaa, Ross W. Cunningham, Haidan Wen, Francesco De Carlo, Lianyi Chen, Anthony D. Rollett & Tao Sun
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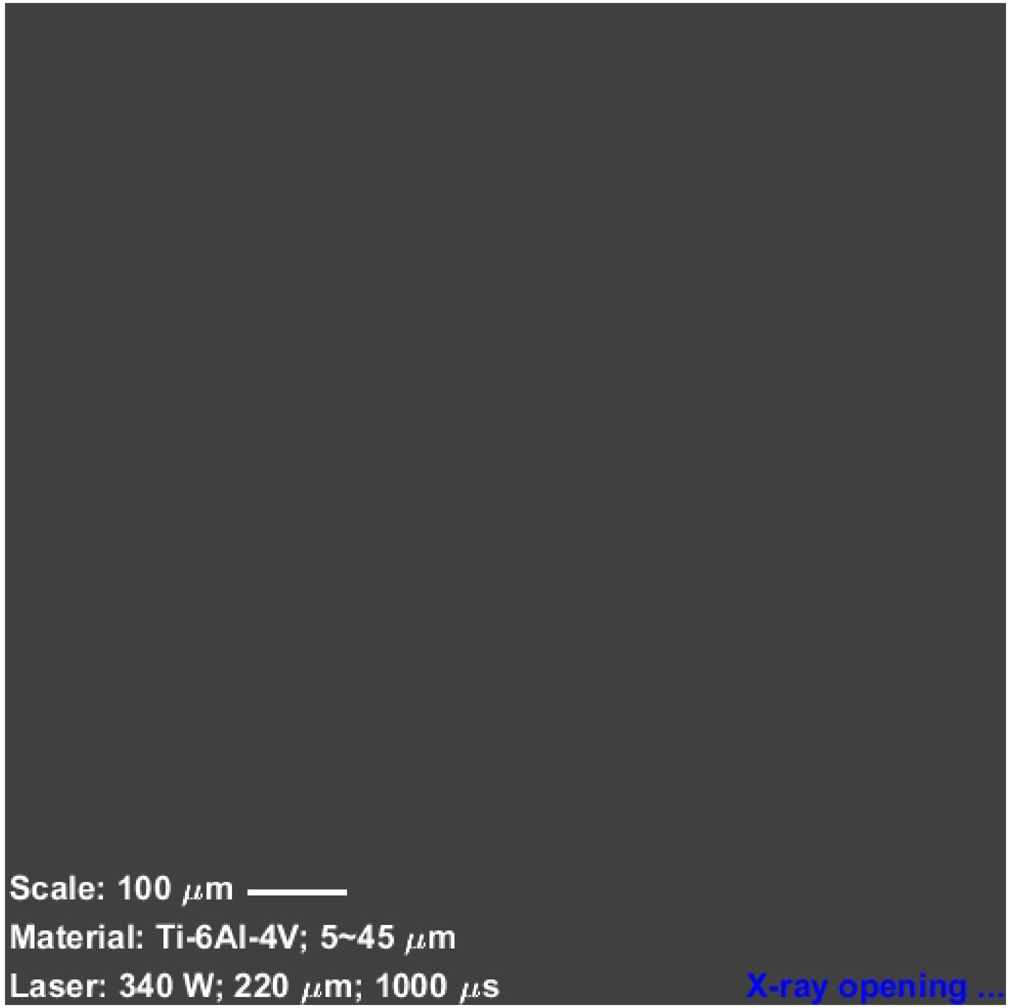

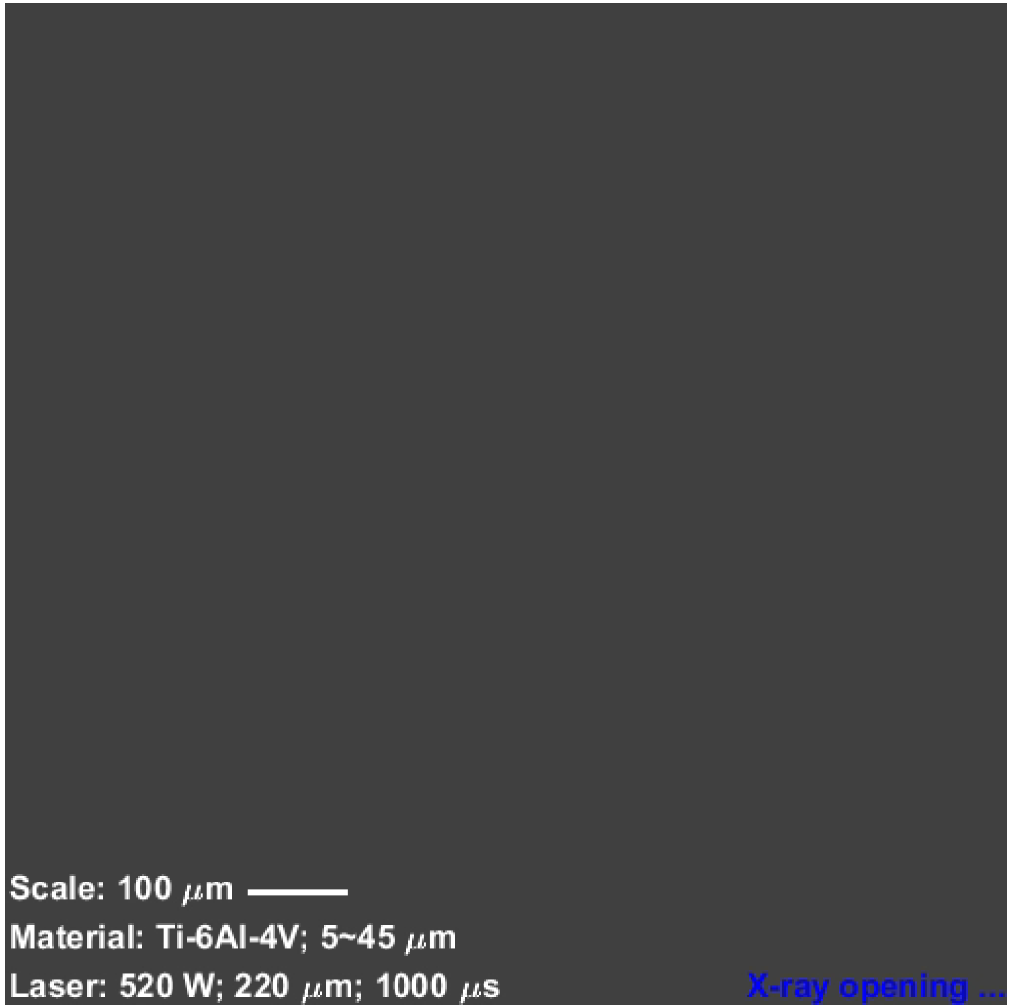

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http://www.nature.com/articles/s41598-017-03761

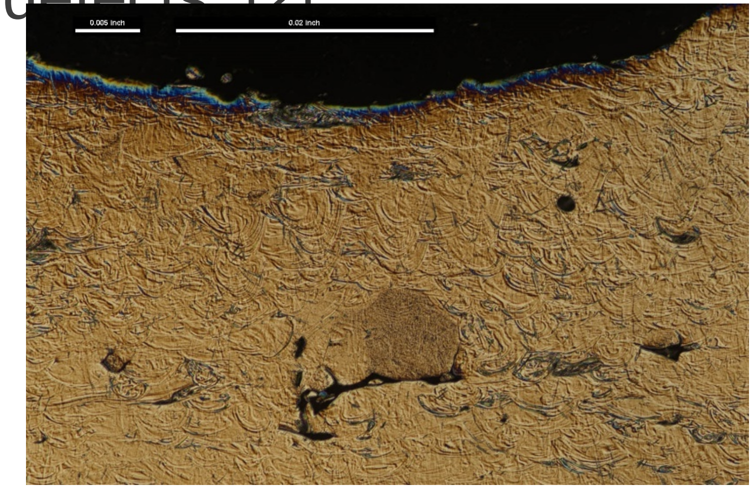
Formation of Stochastic Defects

Reasons to suspect spatter contributes to defects:

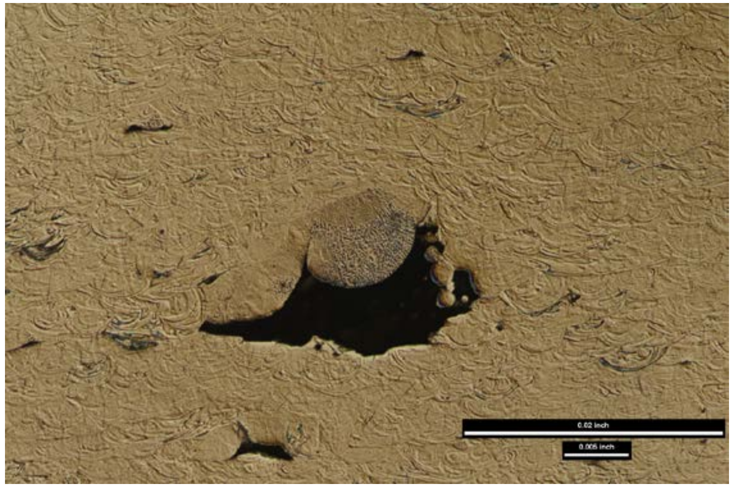
Builds produced with contaminated (large spatter) powder have lower tensile strength [1].

[1] (Liu, Y., Yang, Y., Mai, S., Wang, D. & Song, C. Investigation into spatter behavior during selective laser melting of AISI 316L stainless steel powder. Materials & Design 87, 797–806 (2015).)

Large particles with, odd microstructures, observed embedded by lack-of-fusion defects. [2]



Un-melted particle with approx. diameter of 187 um

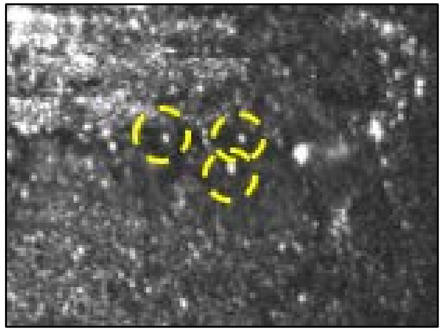


Un-melted particle with approx. diameter of 203 um

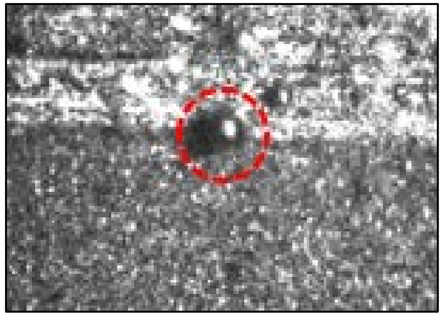
[2] Formation processes for large ejecta and interactions with melt pool formation in powder bed fusion additive manufacturing
Abdalla R. Nassar, Molly A. Gundermann, Edward W. Reutzel, Paul Guerrier, Michael H. Krane & Matthew J. Weldon, Scientific Reports volume 9, Article number: 5038 (2019)

Multi-particle collisions forms large agglomerate

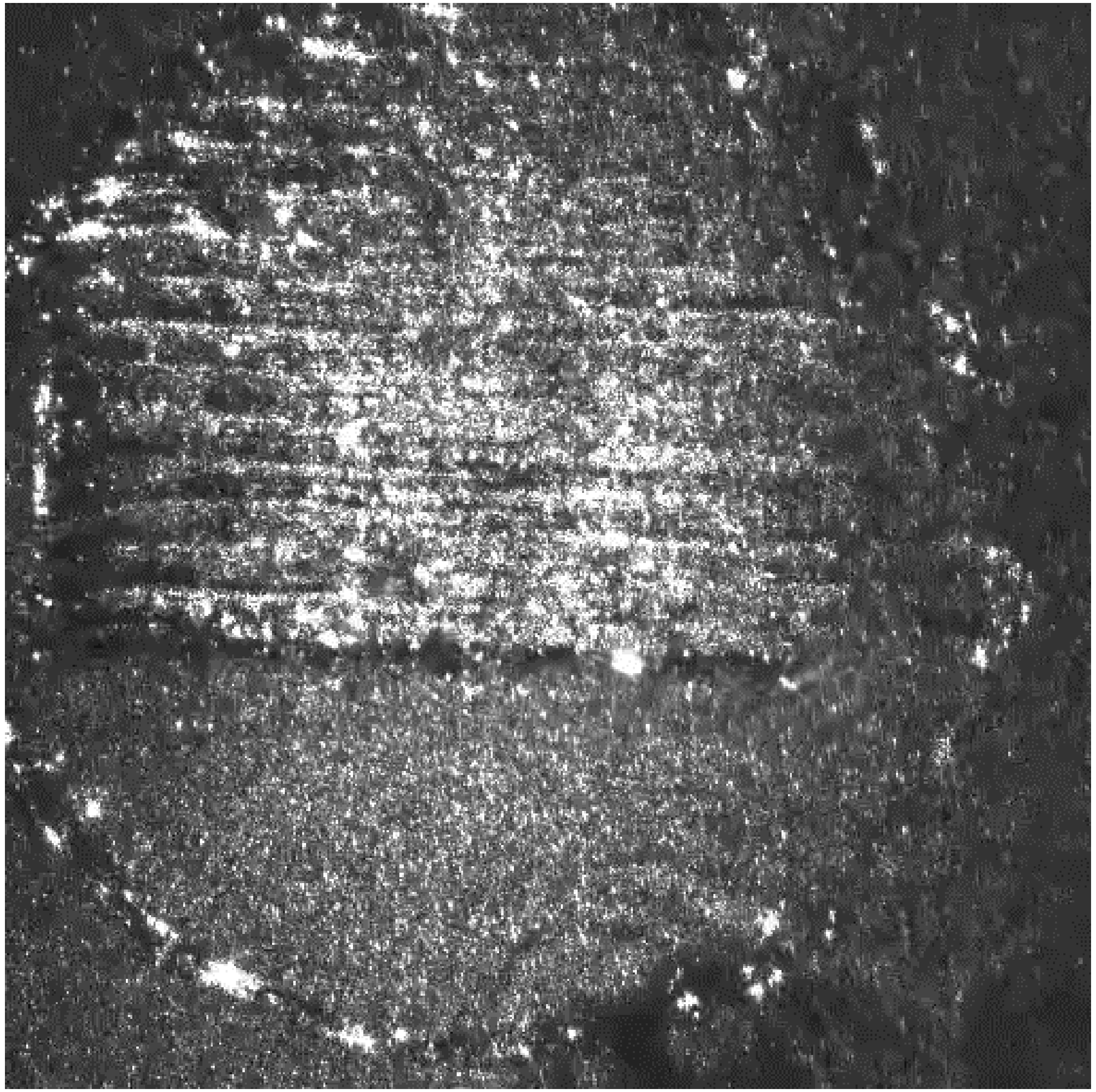
Three partially-molten particles are ejected:



Large agglomerate is formed:



*layer was completed using ideal processing conditions



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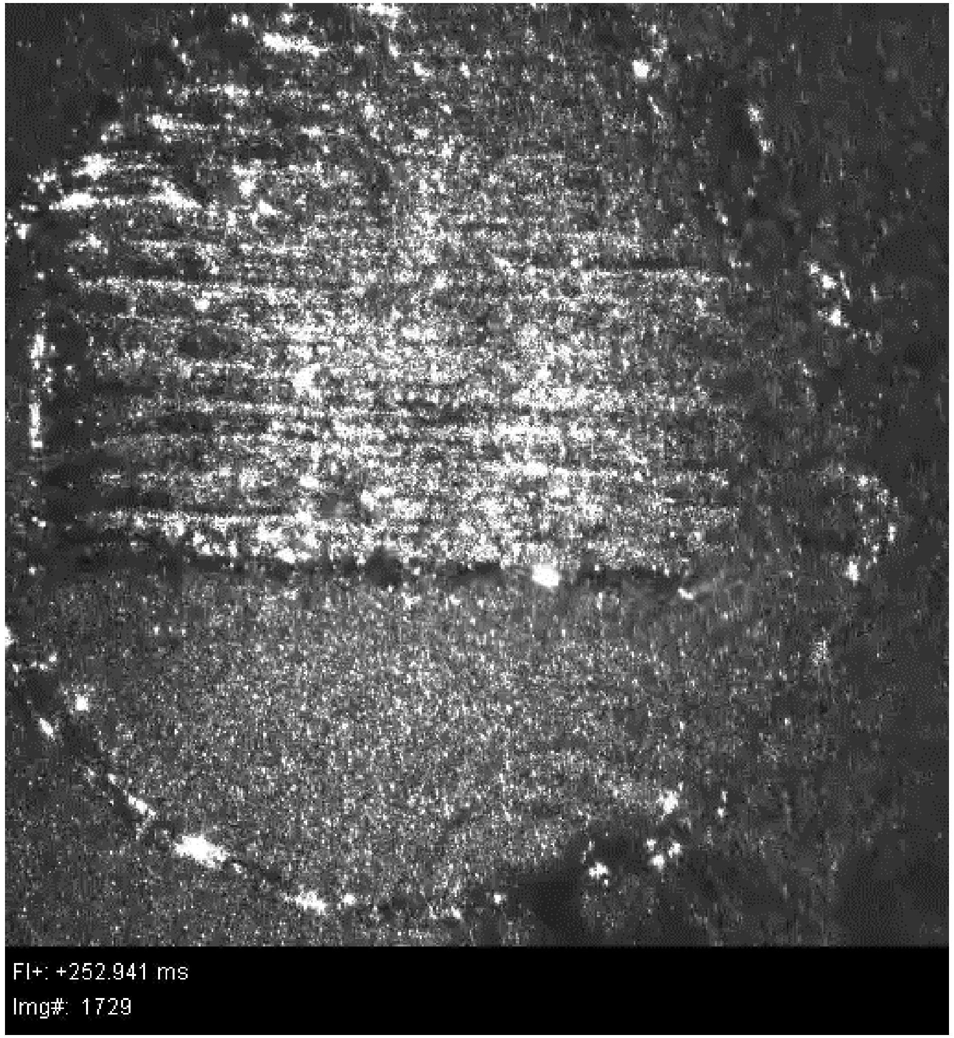
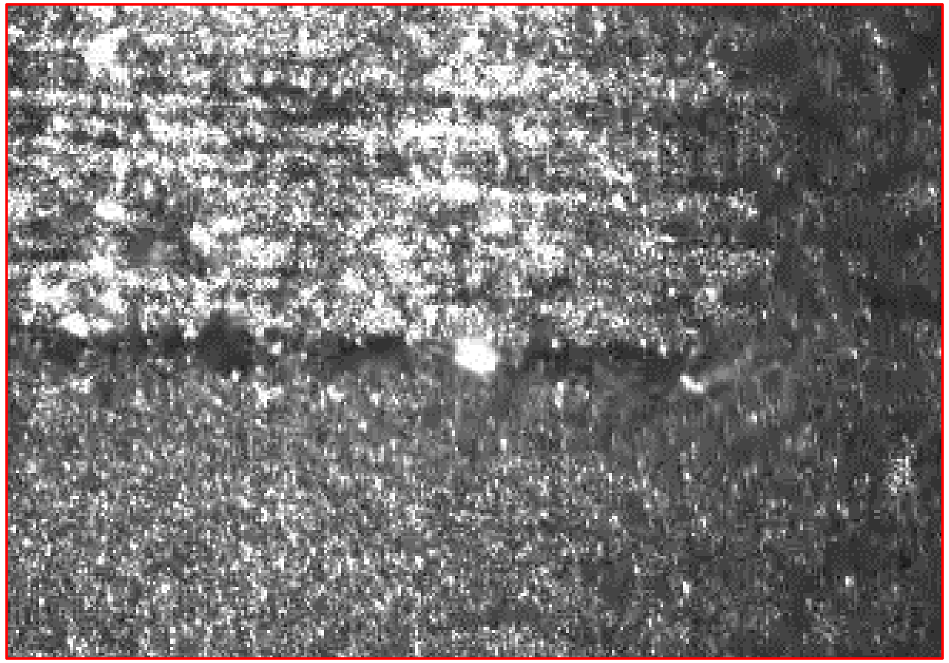




Slowed 10 frames per second

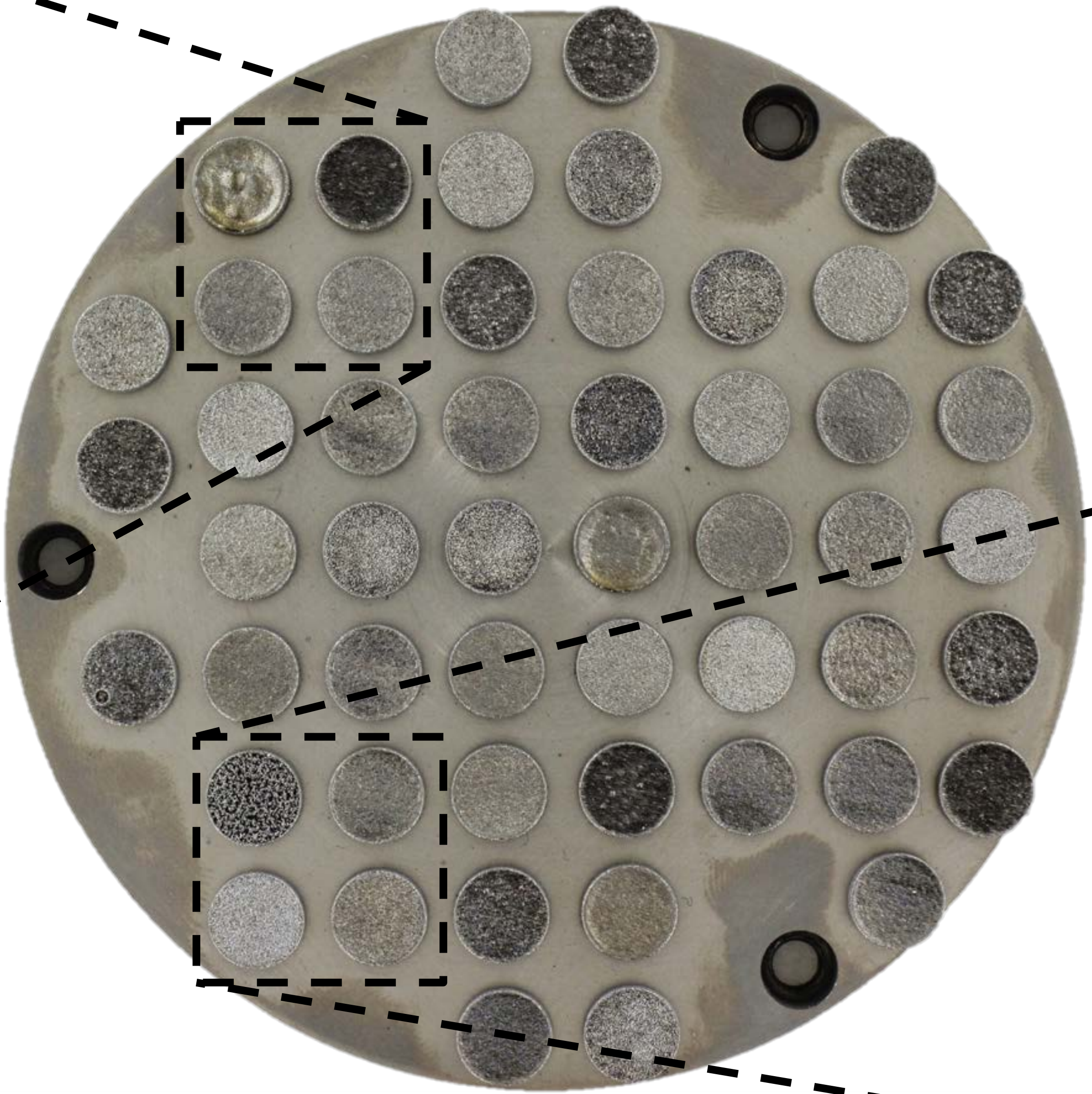
Build Flaws and Causes

- **Build flaw :** undesirable feature of the completed component which may be attributed to the previous processes. Examples include:
  - Agglomeration
  - Metallurgical or Gas pores
  - Keyhole Pores
  - In-Build thermal stress
  - Undermelt or Lack of Fusion
  - Contamination

Industry and Academia are working hard to understand AM process specific defect root causes and mitigations

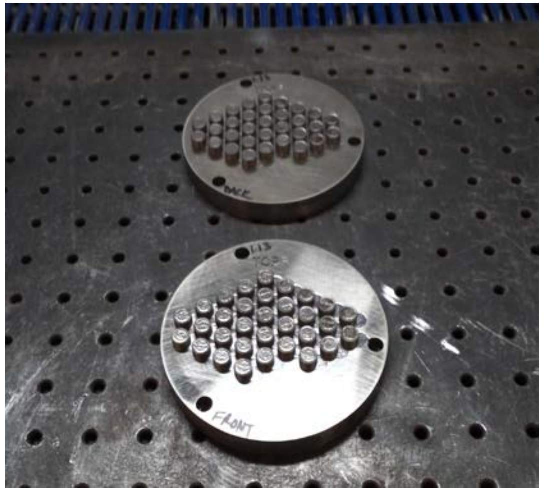
Laser Parameter Development Using DOE Methods

Extra high energy density



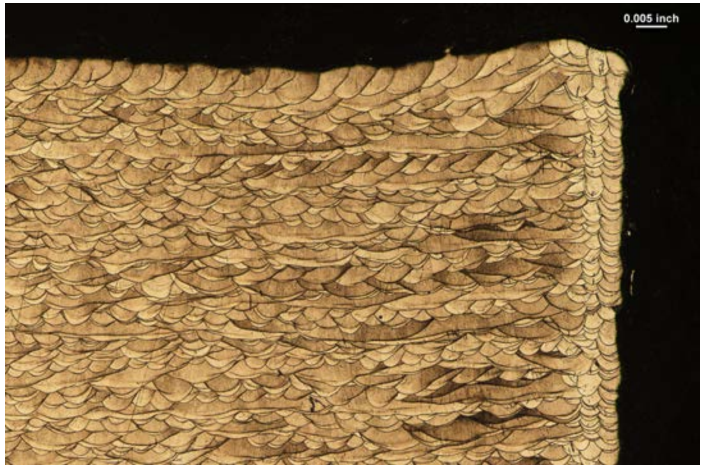
Really low energy density/very wide hatch spacing

Example DOE Results - Density



Initial Parameters

- Subsurface defects present
- Volume porosity higher than average



DOE Optimized Parameters

- Decreased max defect size
- Increased Density ~0.5 -

Max Defect Size:

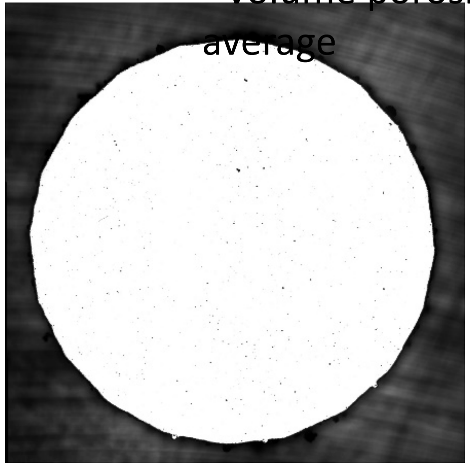
Front: 0.004"

Rear: 0.011"

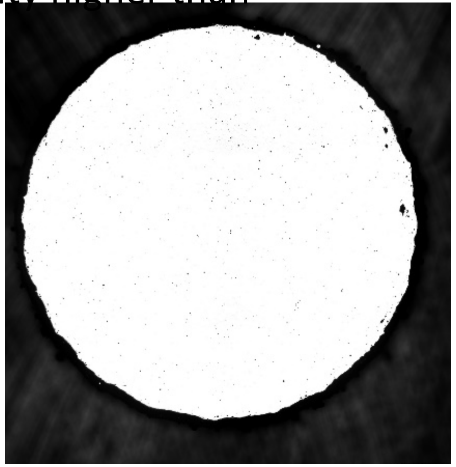
Density:

Front: 99.41%

Rear: 99.19%



Front



Rear

Max Defect Size:

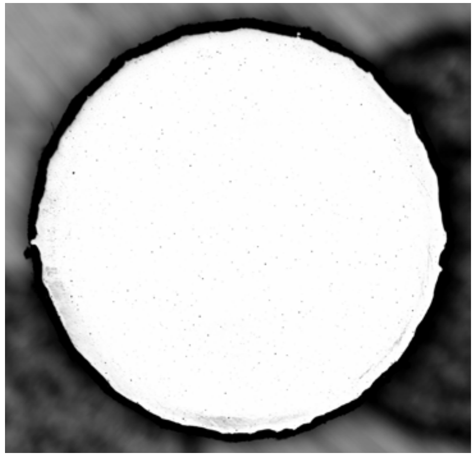
Front: 0.002"

Rear: 0.001"

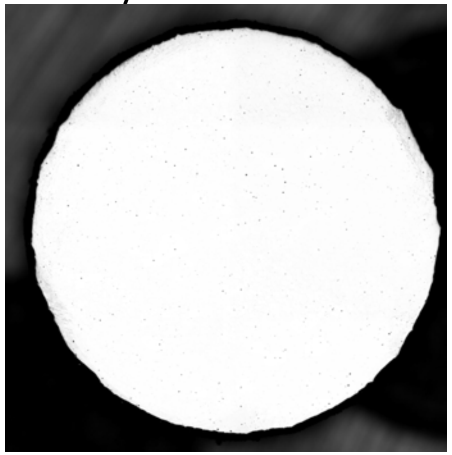
Density:

Front: 99.82%

Rear: 99.85%



Front

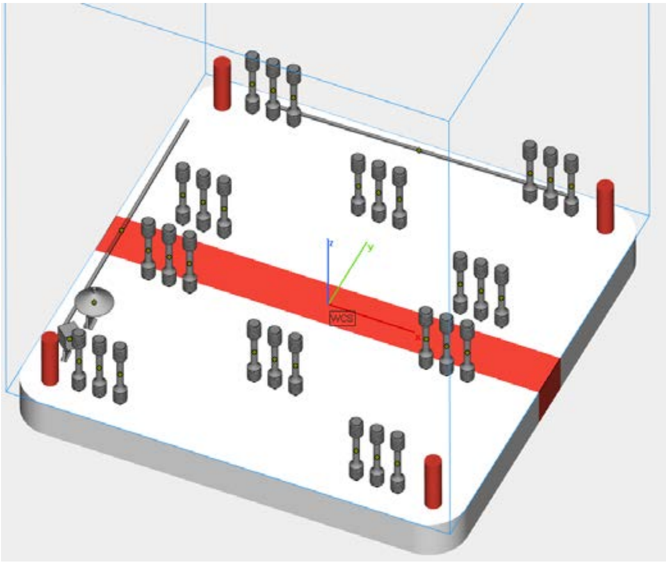


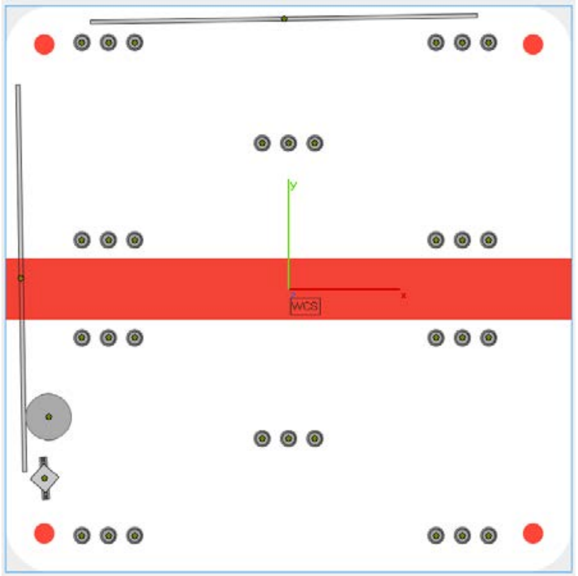
Rear

AM Parameter DOE – Tensile Properties

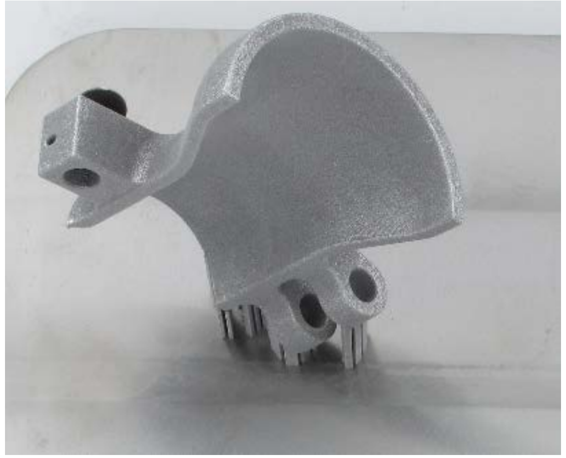
Optimizing for Elongation:

- 3 Parameter sets with 5 Samples per laser field
  - Solution heat treated
  - Precipitation Aged
- Parameters selected based on DOE interactions and lessons learned





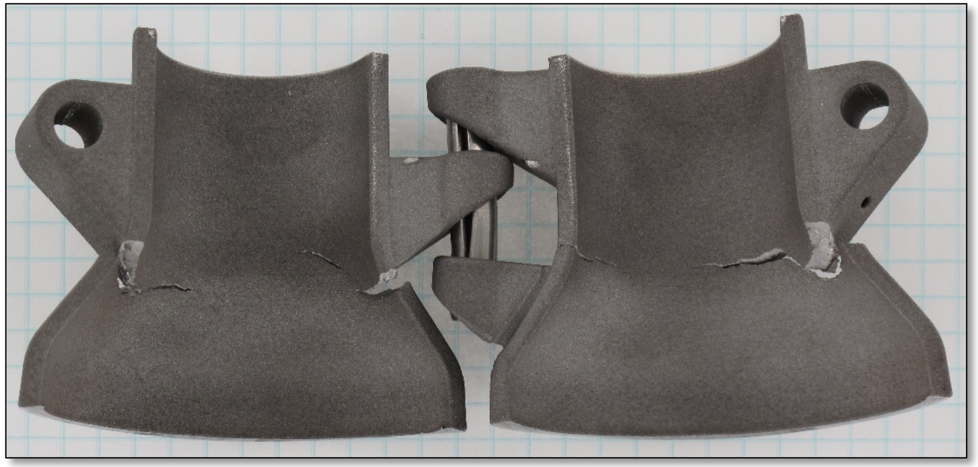
AM Design Process at Moog – Actuator Locking Collar



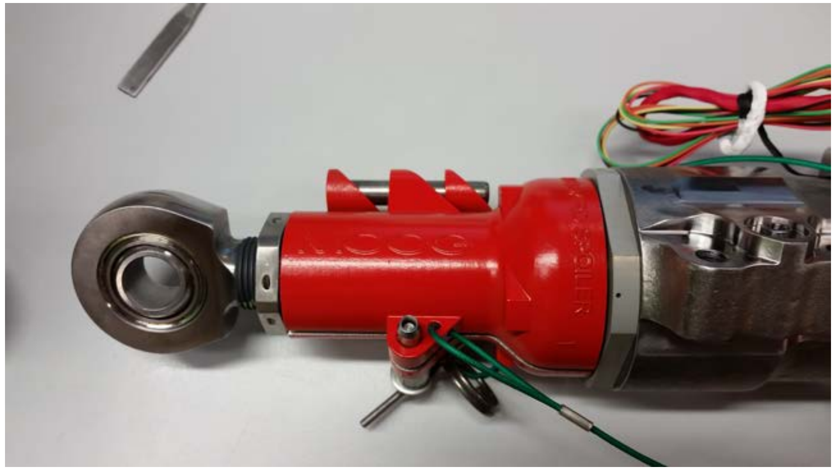
1. Initial Design Concept

2. Improved Design Concept

3. Design for Manufacturing



4. Assembly & Development Testing



4. Final Part

REMAINING CHALLENGES

Barriers for Utilizing Additive

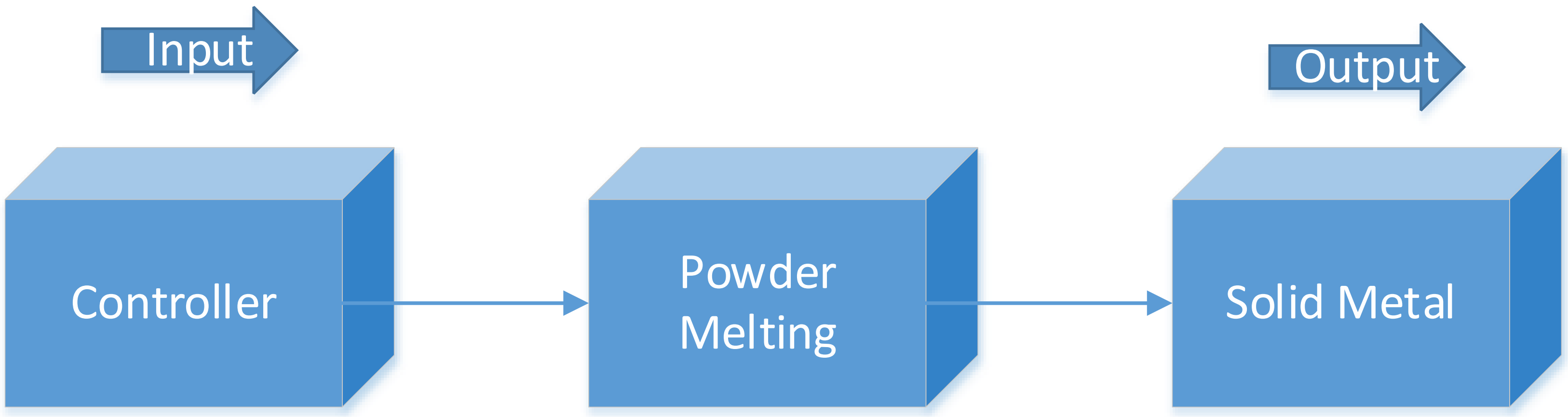
Design
- Awareness
- Time
- Robust Design Tools

Trust
- Reliable Inspection & NDT
- Machine Repeatability
- Process Control

Cost
- Machine Capability
- Faster Inspection
- Less Build Failures

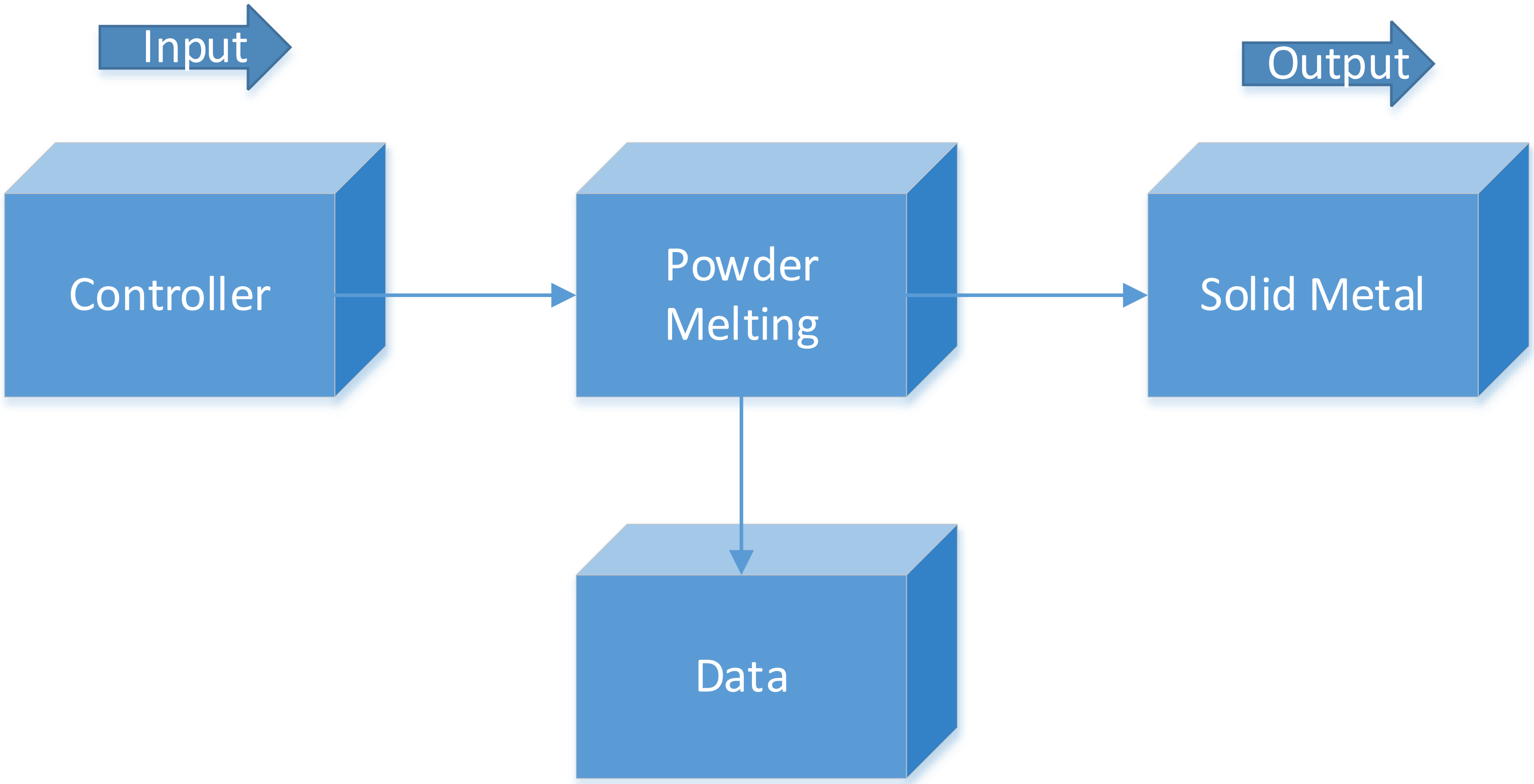
Open Loop (Current)

Generation 1 Machines



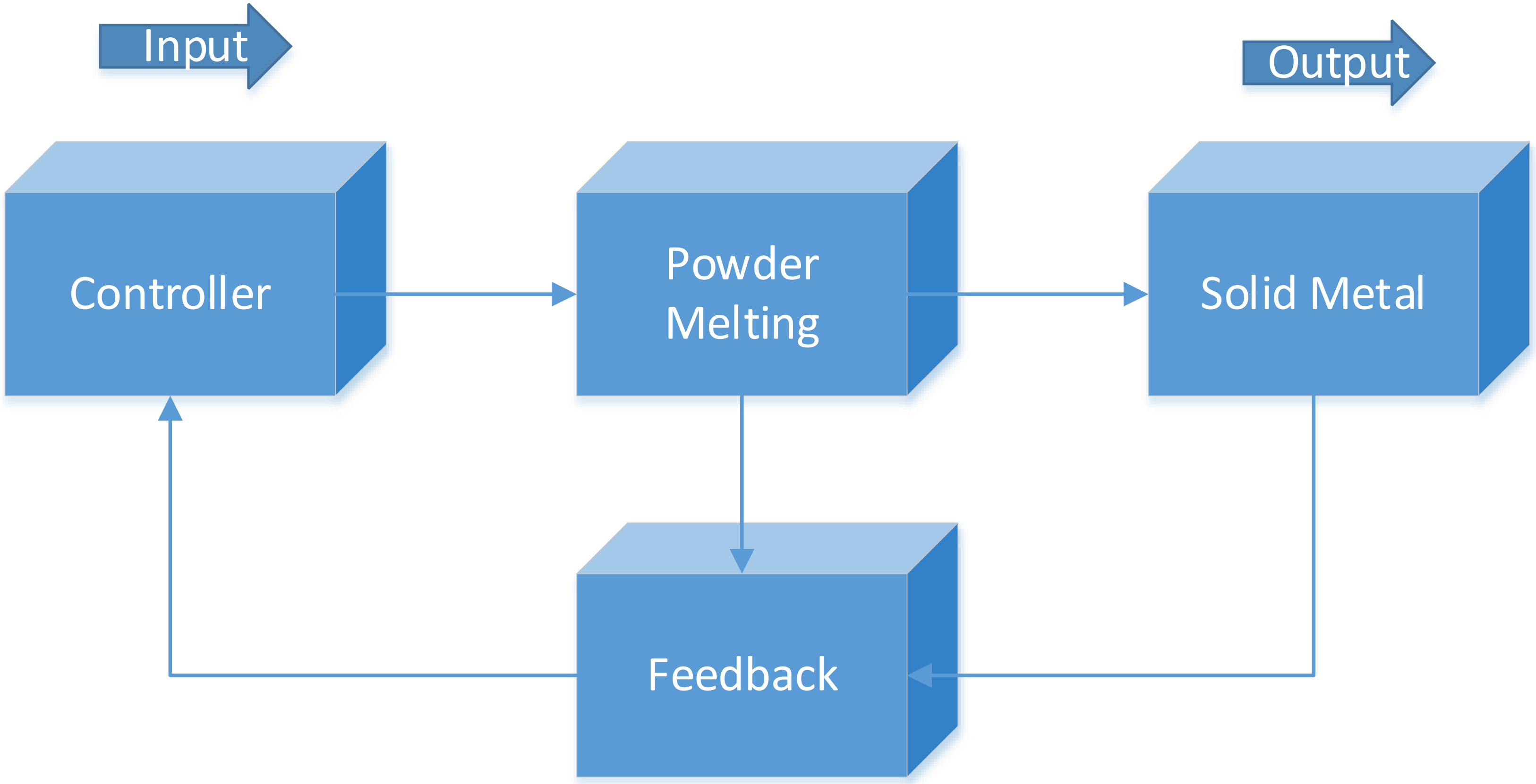
Melt Pool Monitoring (Emerging Now)

Generation 2 Machines

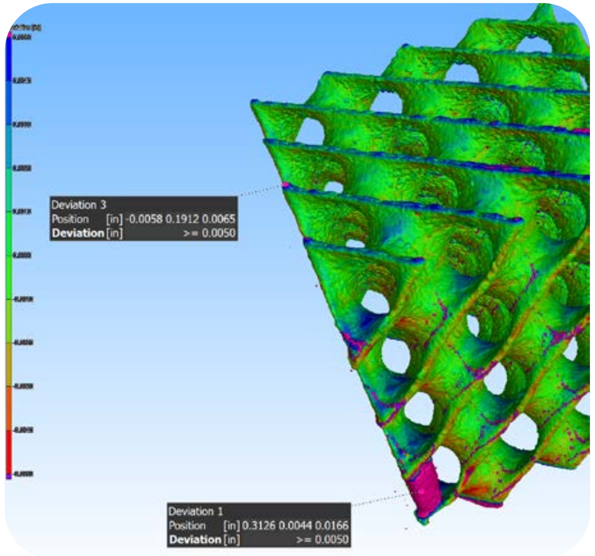


Closed Loop (Future in next 3-5 Years)

Generation 3 Machines

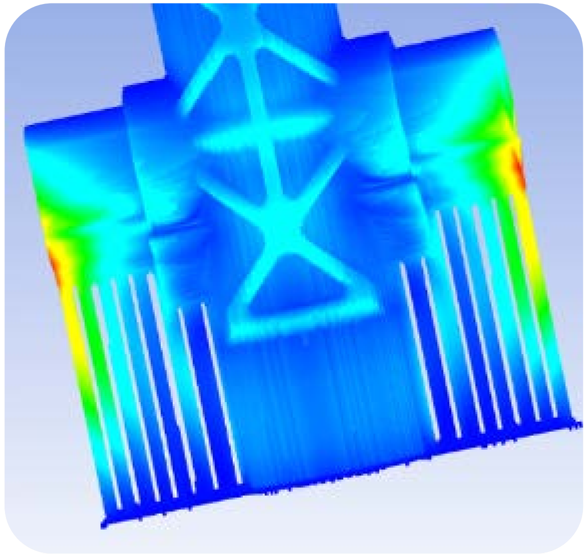


Remaining Part Production Challenges



Reliable and Cost Effective Inspection Methods Including NDT

Increased Repeatability of Additive Processes



Robust Design Analysis Tools

Common Industry Specifications

SUMMARY

Summary

- Reasons for using AM are clear
  - Potential applications can be quickly evaluated
- Process parameters are understood
  - Maturity linked to specific alloy
- Defect understanding is quickly emerging
- Process & equipment reliability is a challenge
- Inspection & NDT require development

Questions

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