Materials TDT Talk:
An Evolving Perspective on AM Qual and Cert

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About Me

- B.S. Industrial & Systems Engineering, Auburn University, 2013
- M.S. Human Factors in Aeronautics, Florida Institute of Technology, 2017
- US Army Aviation and Missile Center, Redstone Arsenal
  - Co-op, Production Engineering, 2010-2013
- NAVAIR, Patuxent River Naval Air Station
  - Manufacturing & Quality, 2013-2016
  - Platform Stores Integration, Lead Systems Engineer, 2016-2019
- US Army Aviation and Missile Center, Redstone Arsenal
  - Production Engineering Lead for Improved Turbine Engine Program, 2019-2021
- NASA, Marshall Space Flight Center
  - M&P Lab, Additive Manufacturing & Digital Solutions Team, 2021-present
  - AM Qualification and Certification

Overview

- Capabilities and History of MSFC Additive Lab
- Qualified Material Processes
- Additive Manufacturing Control Plan
- Equipment and Facility Control Plan
- New AM Technology Knowledge Development Project

Capabilities and History of MSFC Additive Lab

- The lab has experience with about 30 different systems over the last 30 years
- NASA AM Objectives
  - Decrease production lead time & costs
  - Develop and Maintain Flight Certification Standards
  - Process development and characterization
  - Share knowledge and data in pursuit of smart vendor base & ensure agency remains a smart buyer
  - Design optimized components & test at relevant conditions
  - Appropriate Application
    - High complexity & difficult to manufacture
    - Low production rate
    - Long lead time & high cost

Metallic Additive Manufacturing

Concept Laser Xline 1000R (Retiring Soon)
In718
Build Volume: 630 x 400 x 500 mm

Image Credit: Velo3D

Velo3D Sapphire (Summer 2022)
In718
Build Volume: 315mm Ø x 400mm z

EOS M290 (Two Machines)
HR1, JBK75
Build Volume: 250 x 250 x 325 mm

EOS M100
Various Materials
Build Volume: 100 Ø x 95 mm z

Concept Laser Xline 2000R
In718
Build Volume: 400 x 800 x 500 mm

Concept Laser M1
In625/In718
Build Volume: 250 mm^3

Concept Laser M2
GRCop-42
Build Volume: 245 x 245 x 350 mm

DM3D Directed Energy Deposition
Various Materials

Polymer Additive Manufacturing

Stereolithography (SLA)

5000 SLA

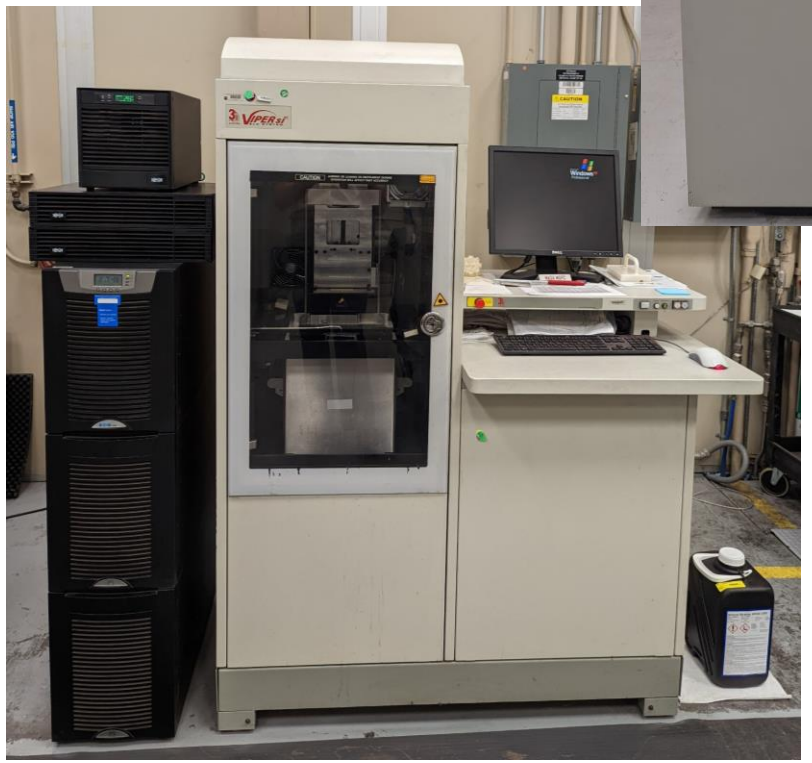
Somos Watershed 11122 XC

Build Volume: 20 in^3

Viper SLA

DMX Somos

Build Volume: 10 in^3



Fused Deposition Modeling (FDM)

AON M2+ (Summer 2022)

PEEK, PEKK

Build Volume: 450 × 450 × 565 mm

Stratasys Fortus 900

ABS, Polycarbonate, Ultem 9085

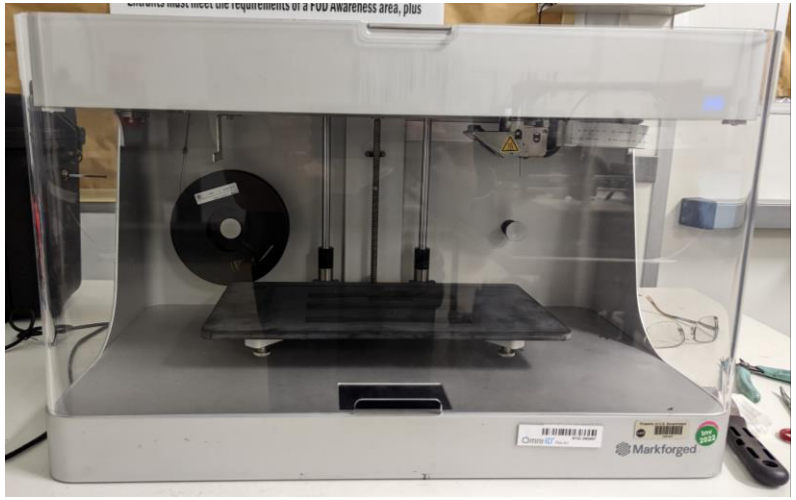
Build Volume: 914 x 609 x 914 mm

Markforged Mark Two

Carbon Fiber, Glass Fiber, Kevlar

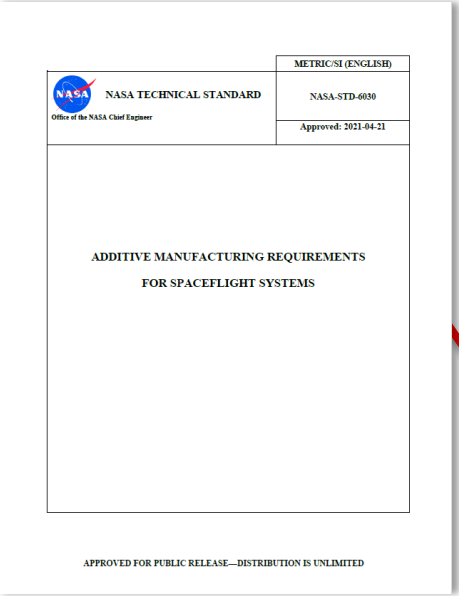
Build Volume: 320 x 132 x 154 mm

Image Credit: AON3D



NASA-STD-6030 Overview

- Why are qualification and certification important?
  - Ensure repeatability of process and part
  - Central to safe, flightworthy spaceflight hardware
- Walking the talk in lab
  - Stress test the requirements documents
  - Provide quality products to lab customers
- Adapt requirements to evolving technology
- Will be teaching class on NASA Approach to AM Q&C Methodology at end of August at The Aircraft Airworthiness & Sustainment Conference


NASA TECHNICAL STANDARD

Office of the NASA Chief Engineer

METRIC/SI (ENGLISH)

NASA-STD-6030

Approved: 2021-04-21

ADDITIVE MANUFACTURING REQUIREMENTS

FOR SPACEFLIGHT SYSTEMS

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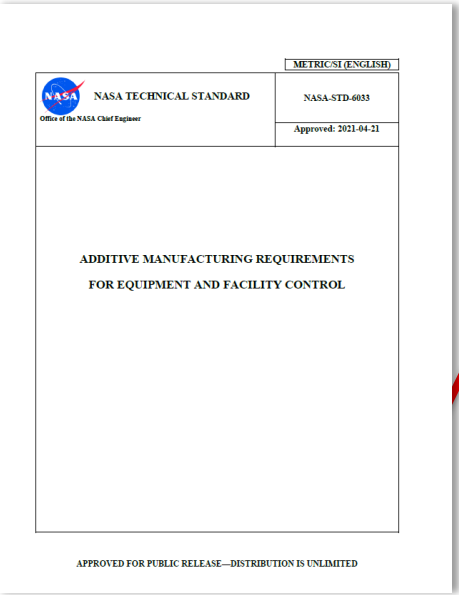
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NASA-STD-6033

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ADDITIVE MANUFACTURING REQUIREMENTS

FOR EQUIPMENT AND FACILITY CONTROL

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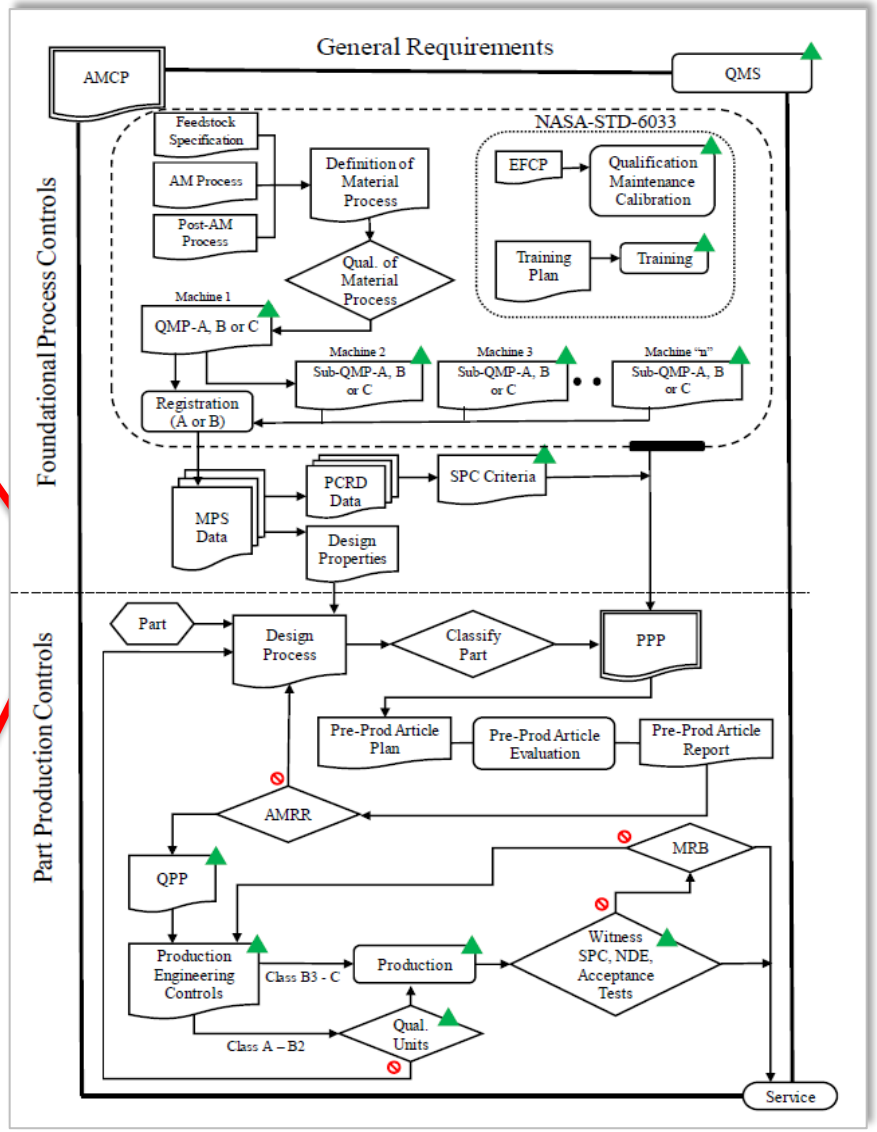
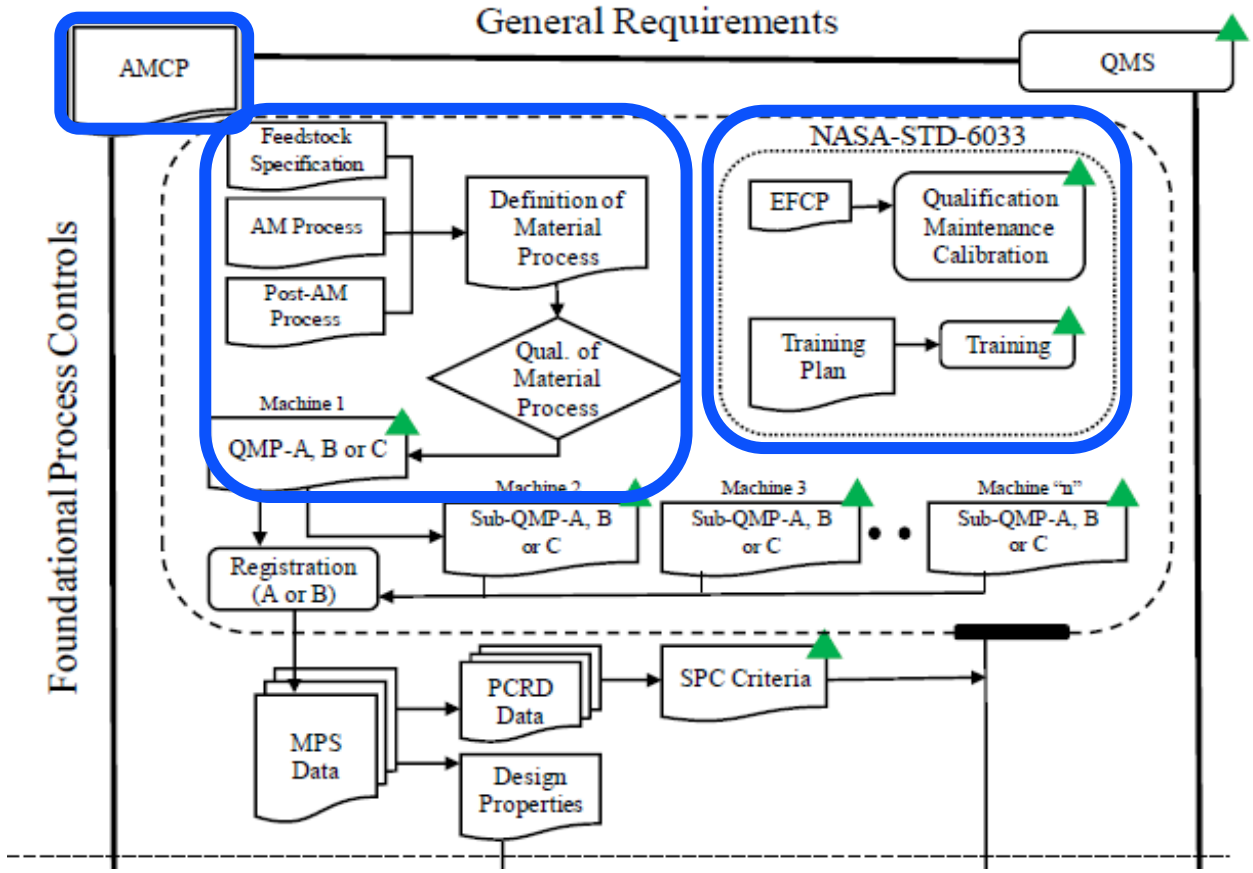


From NASA-STD-6030

Qualified Material Process Records

- Central to NASA-STD-6030 is qualifying a material process for each different machine and material combination
  - What are you building with?
  - How does your machine operate?
  - Post processing – what evolves your material state?
- Will review completed QMPs for lab capabilities
- QMPs for each machine/material combination in the lab are in development
  - Both metallic and polymer processes/materials
- Plans for future work also include development of an Additive Manufacturing Control Plan and Equipment and Facility Control Plan



From NASA-STD-6030

Stratasys Fortus 900 Ultem 9085 QMP

FDM Qualified Material Process Record

QMP Title:	QMP-MSFC-900mc-ULTEM (PEI) 9085
QMP Record Number:	QMP-MSFC-900mc-ULTEM (PEI) 9085_REV0
Check as applicable: x Master QMP ☐ QMP, based upon Master QMP: ☐ Customized QMP (Customized FDM Visual Inspection Typical Acceptable Anomalies & Unacceptable Defects Section)	
General Description: Fused Deposition Modeling (FDM) ULTEM (PEI) 9085	
RESTRICTIONS ON USE: QMP-C applicable only to parts classified as Class-C or Exempt per NASA-STD-6030	
QMP Approval Statement: All necessary data for qualification of this material and traceability to the requirements of NASA-STD-6030 Class C has been reviewed, judged acceptable, and archived.	
CEO Approval: Brian West	Date:

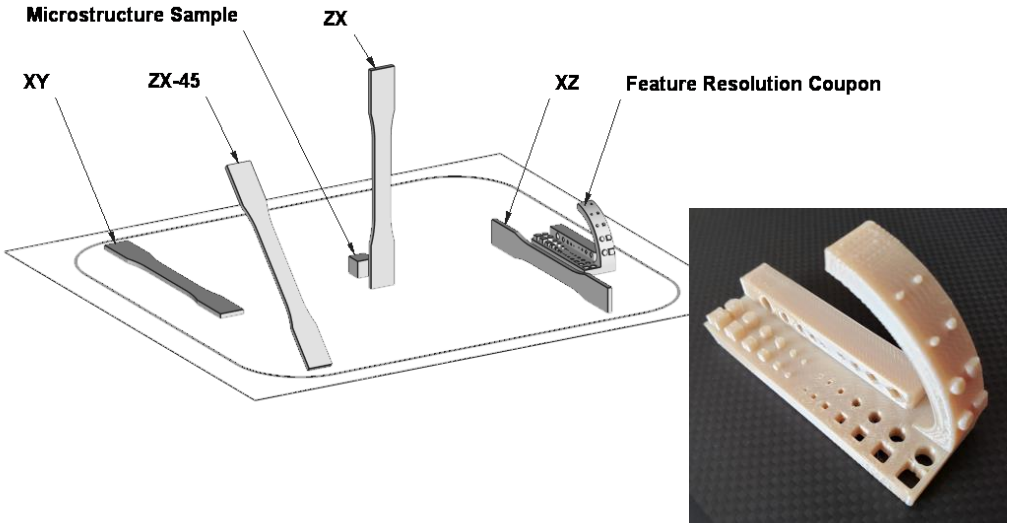
FDM Material Process Definition

Filament Feedstock	
Feedstock Specification:	STRATASYS ULTEM™ 9085 Certified Grade (CG) MDS_FDM_ULTEM9085_0921a.pdf
Material traceability:	ULTEM™ 9085 CG MFR Certificates of Analysis for both raw material and filament are supplied, documenting test results and identification to match filament manufacturing lot number to raw material lot numbers providing traceability from printed part per MSFC-SPEC-555 requirements

FDM Process Controls			
Machine ID:	900mc	Model/Model:	FORTUS 900mc
Serial Number:	L0444	Configuration Date:	5/3/2022
Slicer Software:	Insight 14.11	System Software:	3.32.3700.0
System/Slicer software updates shall be evaluated by the MSFC Additive Manufacturing team in order to fully understand the changes and impacts to the FDM process. If changes are deemed to be significant or not fully understood, a new Qualification Build shall be required to confirm test data remains in family and the FDM process performs as expected. For changes deemed insignificant, written justification shall be provided in order to document that a thorough review and impact assessment has been performed. This activity shall be logged and archived in a software revision log as a companion file to the approved QMP.			
Extruder Tip & Life:	T16 392 in^3 Maximum model material volume consumption		
Dew point limit:	N/A		
Build Plan/Toolpath File	.CMB		
Part Interior Style	Solid		
Contour Style	Single Contour		
Contour width	0.020 inch		

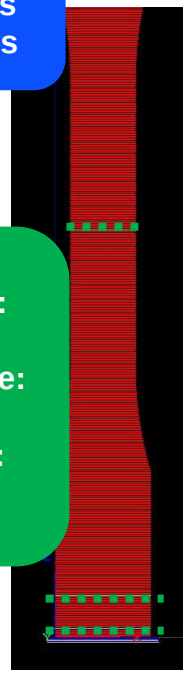
Other Topics

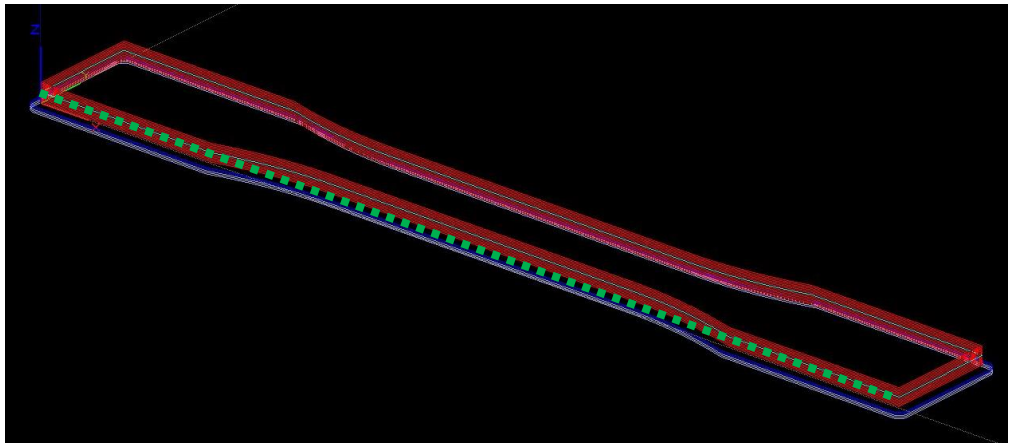
- Inspection Guide
- Tensile Data for Nominal and Thin Wall Parameters
- Comparison to NCAMP Reference Tensile Data

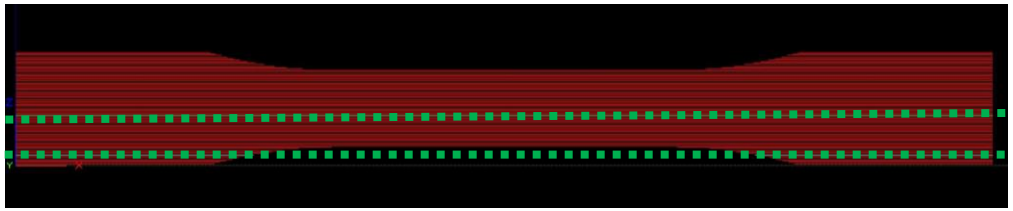


Qualifying Process Restarts

Short pause:
Ten minutes
Medium pause:
One hour
Long pause:
24 hours







Concept Laser M2 GRCop-42 QMP

L-PBF Material Process Record

Title: MP_BlueOrigin_ACO_M2_GRCop42
Record Number: MP_BlueOrigin_ACO_M2_GRCop42
General Description: Powder bed fusion GRCop42
Approval Statement: This document was developed as part of an Advanced Collaboration Opportunity between NASA Marshall Space Flight Center (MSFC) and Blue Origin. It draws comparisons to MSFC GRCop-42 data and NASA-STD-6030 requirements. It should not, however, be interpreted as a complete qualification to NASA-STD-6030 requirements.
CEO Review: Brian West — Date: 5/18/2022

L-PBF Metallurgical Process Definition

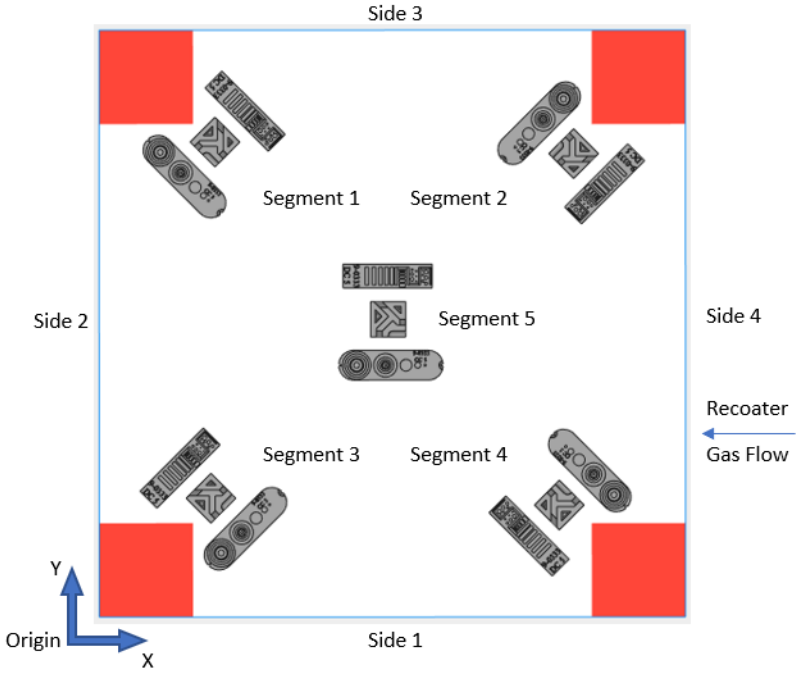
Powder Feedstock	
Feedstock Specification:	PAC GRCop42 Lot#: AMPGR42NASAAM21030
Reuse protocol:	No Reuse

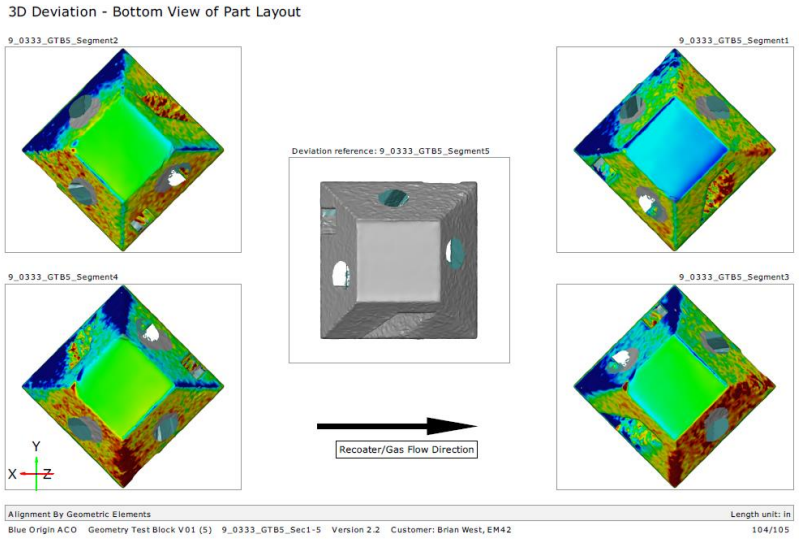
Powder Specification and Certifications

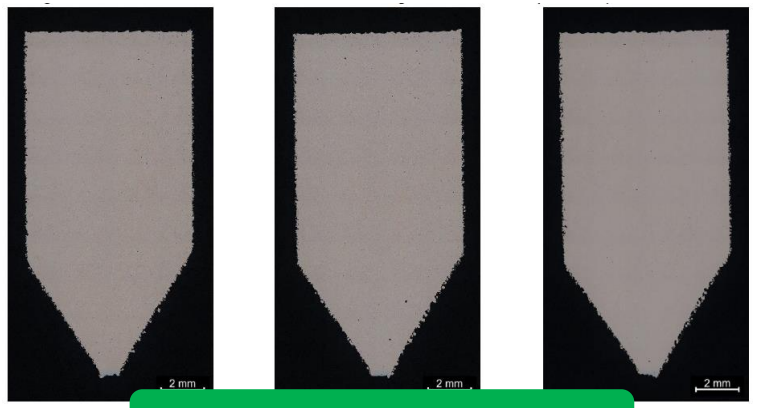
Powder procured IAW *GRCop-42 Alloy Gas Atomized Powder Specification, Rev 1-29, issued 7/22/2020*

Powder CoC available upon request.

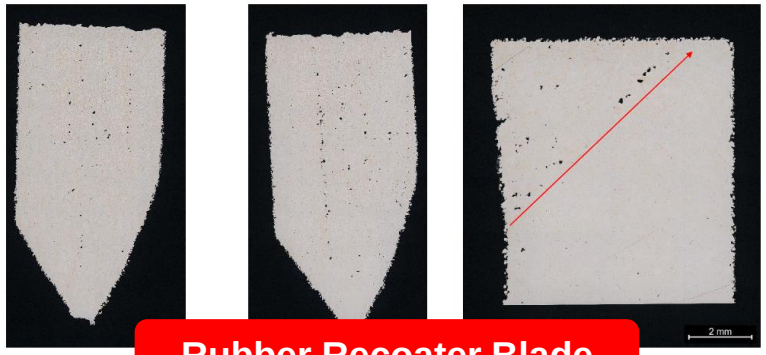
Fusion Process Controls			
Machine ID:	Concept Laser	Model/Model:	M2
Serial Number:	M2-2021-02-02	Configuration Date:	5/20/21 - 9/9/21
Slicer Software:	Materialize Magics	Software Version:	25.02
Recoater Configuration:	Steel Blade		
Build platform material:	Stainless steel, In 718 coating		
Preheat temperature:	None		
Nominal dosing range:	Variable		
Purge Gas composition:	Argon		
Argon gas flow:	60mm/s		
Oxygen limit:	Not directly controlled, but typically in ~0.01-0.05% range		
Humidity and Temperature controls:	Not measured/controlled		
Parameter File:	GRCop42_Material_Parameter	Hash:	N/A
Layer thickness:	30µm		
Other:	N/A		







Steel Recoater Blade



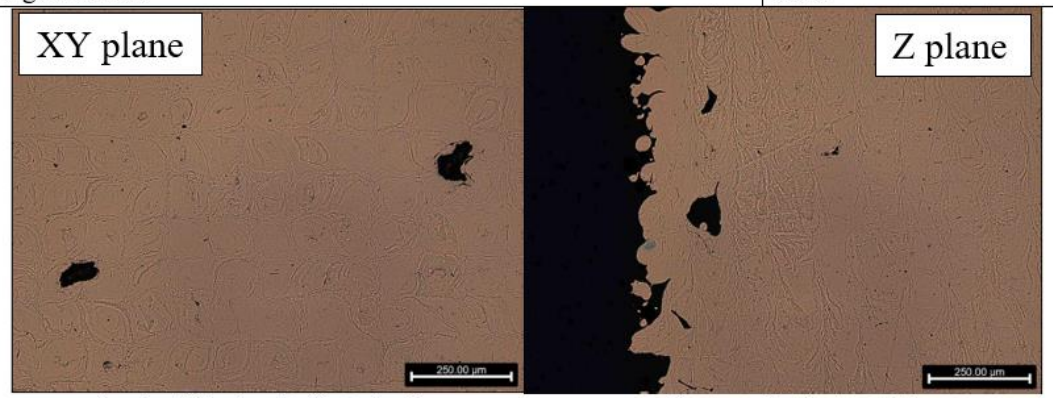
Rubber Recoater Blade

Mechanical Testing

1. Tensile
2. Tensile, Thin Walls
3. High Cycle Fatigue
4. Low Cycle Fatigue
5. Fracture Toughness
6. Fatigue Crack Growth Rate

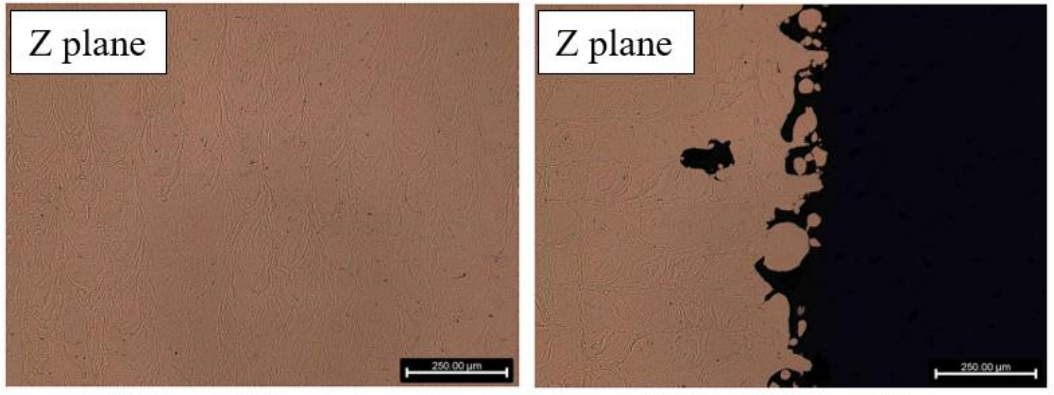
Concept Laser M2 GRCop-42 QMP

As-built Microstructure Evaluation:	
Plane	Z and XY Planes
Magnification	100x

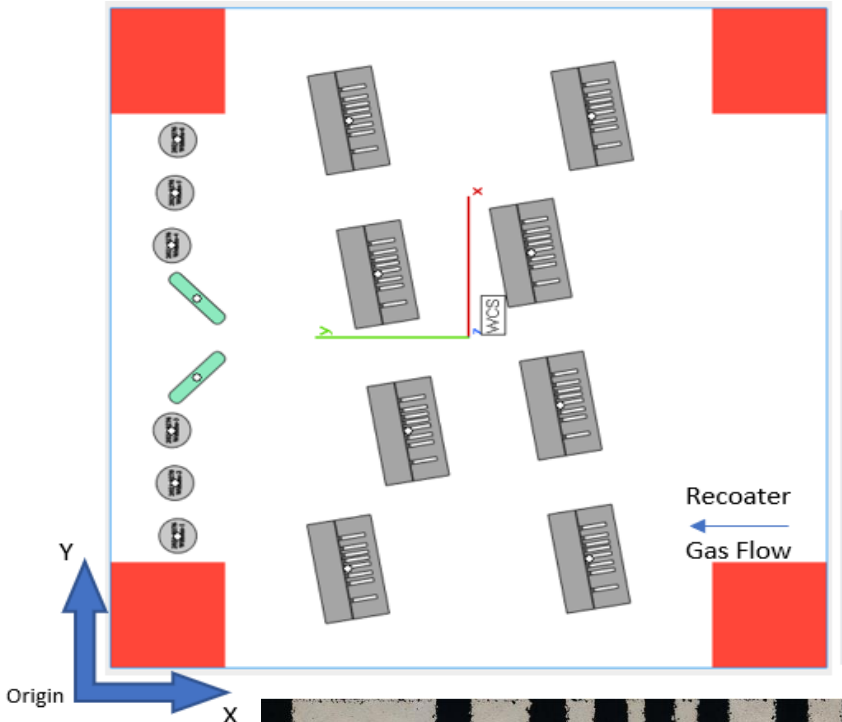


Lack of Fusion Defects in Core | Contour Defects at Edges

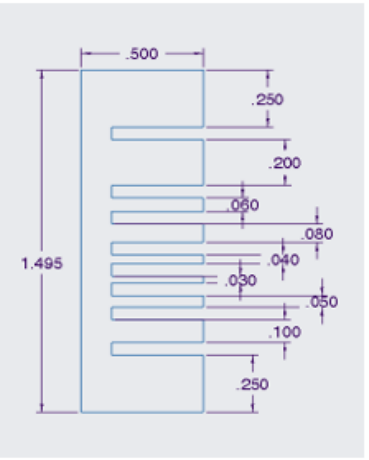
Heat-treated Microstructure Evaluation:	
Plane	Z Plane
Magnification	100x



No core defects noted | Contour Defects at Edges



Top View of Thin Specimens



Additive Manufacturing Control Plan

MSFC Technical Document EM42		
Additive Manufacturing Control Plan	EM40-AMCP-001	Revision [Draft]
	Document Date:	Page 1 of 6

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ADDITIVE MANUFACTURING CONTROL PLAN (AMCP)

EM40 – NONMETALLIC MATERIALS & ADVANCED MANUFACTURING DIVISION

Will define and govern lab policy and procedures for controlling our internal processes and serve as an AM team member handbook

Highlights of topic areas shown on the right

MSFC Technical Document EM42		
Additive Manufacturing Control Plan	EM40-AMCP-001	Re
	Document Date:	

TABLE OF CONTENTS

4.2. Unplanned Interruptions
4.3. Nondestructive Evaluation
4.4. Repair and Rework
4.5. Witness Testing
4.6. Serialization
4.7. Digital Thread
4.8. On-Machine Execution
4.9. Production Engineering Records
5. QUALIFIED MATERIAL PROCESS (QMP)
5.1. Process Development
5.2. Configuration Management
5.3. Feedstock
5.4. Build Process
5.5. Post-Processing
5.6. Subsequent Qualified Material Process (Sub-QMP)
6. PART PRODUCTION PLAN
6.1. Part-Specific Information
6.2. Part Classification and Associated Rationale
6.3. AM Part Production Summary
6.4. Witness Testing
6.5. Planned Interruptions
6.6. Post-Build Operations
6.7. Preproduction Article
6.8. End Item Data Package (EIDP) Information

Equipment & Facility Control Plan

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EQUIPMENT AND FACILITY CONTROL PLAN (EFCP)

EM40 – NONMETALLIC MATERIALS & ADVANCED MANUFACTURING DIVISION

Will define and govern AM lab equipment and facility, including machine qualification, maintenance, and calibration as well as operator training

Highlights of topic areas shown on the right

TABLE OF CONTENTS

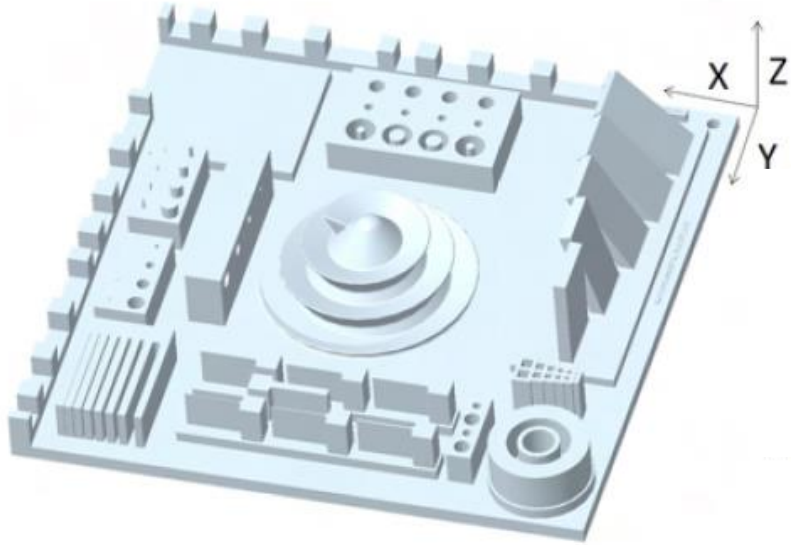
4.1. Feedstock Management
4.2. Digital Thread
4.2.2. Records Retention
4.3. Installation Controls
4.4. Operational Controls
4.4.1. Operational Procedures and Checklists
4.4.2. In Situ Monitoring
4.4.3. Configuration Management of AM Machines
4.4.4. Maintenance
4.4.5. Minimum Maintenance
4.4.6. Associated Equipment
4.4.7. Calibration
4.5. AM Machine Qualification
4.5.2. Establishing Initial Qualification
4.5.3. Reestablishing Qualification
4.6. Operator Certification
4.6.1. Training Program

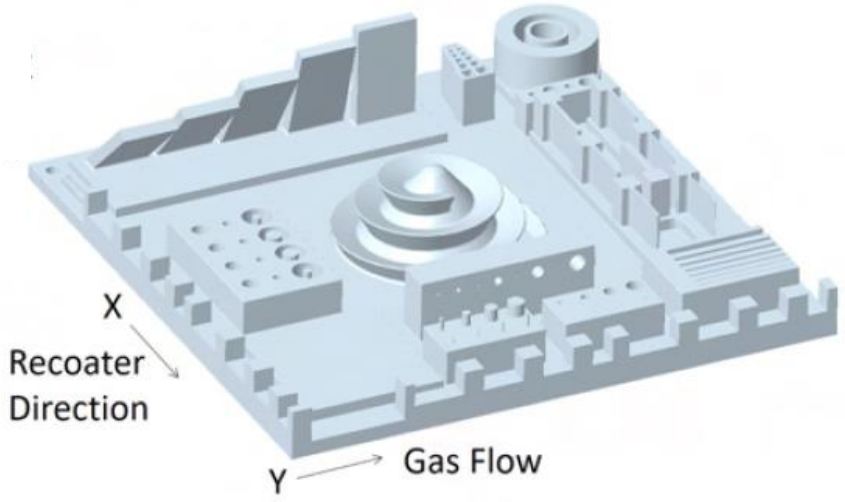
What's Next?

- Advanced Exploration Systems established an agency-wide team for AM Certification Support Team (AACT)
  - Develop "Smart Buyer" NASA workforce to ensure sustainable agency-wide AM certification
  - Advocate for critical AM tech advancement and capabilities across the agency, and cross-agency risk reduction
  - Provide centralized leadership for AM technical integration across the agency
- New AM Tech Knowledge Development Project
  - Focused on large-format, multi-laser technologies
    - SLM NXG XII 600, 12 lasers, Build Volume: 600 mm^3
    - Additive Industries MetalFAB1, 4 lasers Build Volume: 420 mm^2 x 400 mm z
    - AMCM M4K, 4 lasers, Build Volume: 450 mm^2 x 1000 mm z
  - Velo3D Sapphire Machine Lease at MSFC
  - Working with external partners for technical exchanges and metallurgical evaluation of new multi-laser powder bed fusion systems
  - Continually monitoring AM community for other areas of technology to research
    - Model-based tools
    - Generative design
    - Computational materials

New AM Tech Knowledge Development

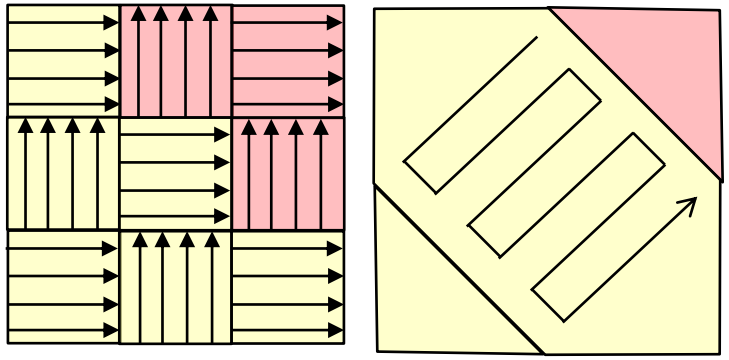
Part Name/ Number	Quantity	Details
Challenge part [Credit: P. Gradl et. al., NASA]	2	One shall be single laser (if possible), other shall be multi-laser*
Tensile specimens, ASTM E8/E8M	15	3 vertical, room temp 3 horizontal, room temp 3 vertical, high temp 3 horizontal, high temp 3 vertical, stitched*
High Cycle Fatigue (HCF) ASTM E466	9	3 vertical 3 horizontal 3 vertical, stitched*
High Cycle Fatigue (HCF) ASTM E466	3	3 vertical, as-built surfaces
Low Cycle Fatigue (LCF) ASTM E606/E606M	12	3 vertical, high strain 3 vertical, middle strain 3 vertical, low strain 3 vertical, stitched*
Promoted combustion rods	8	
Metallography bars	4	Remove one per build prior to stress relief
Laser quality specimens	One per laser source	



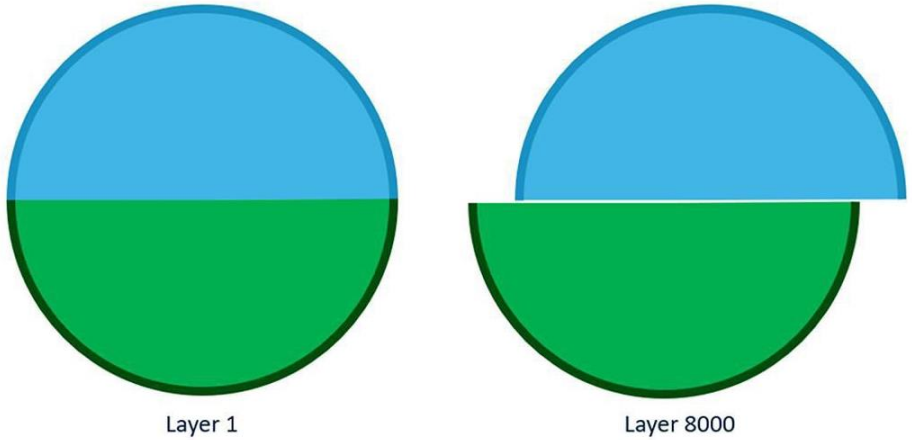


Multi-Laser Considerations

- Scan Strategies
- Laser Overlaps in Contour vs. Infill
- Laser Assignment
- Laser Alignment and Calibration
- Condensate or spatter interference with laser focus or intensity



Island Stripes



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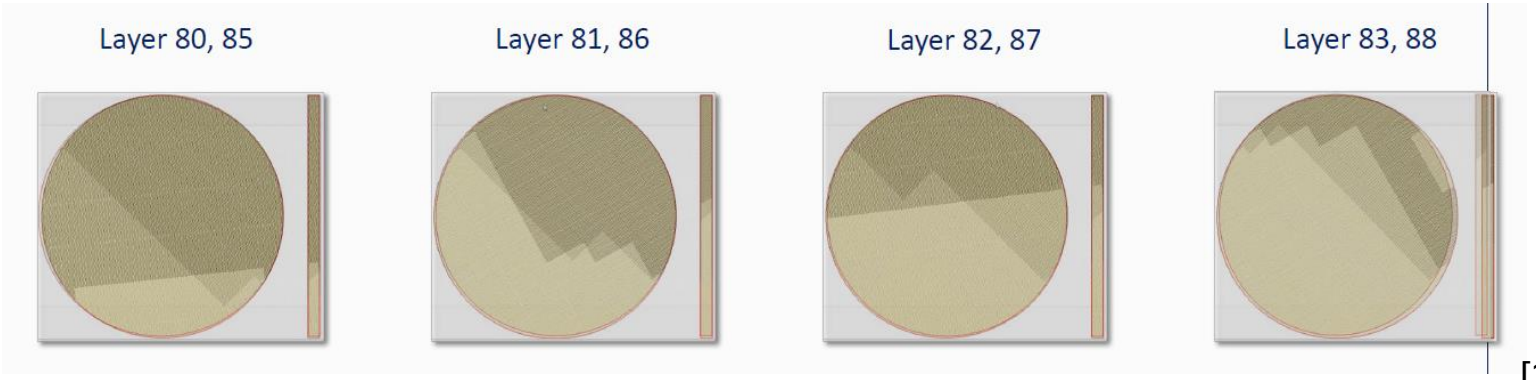

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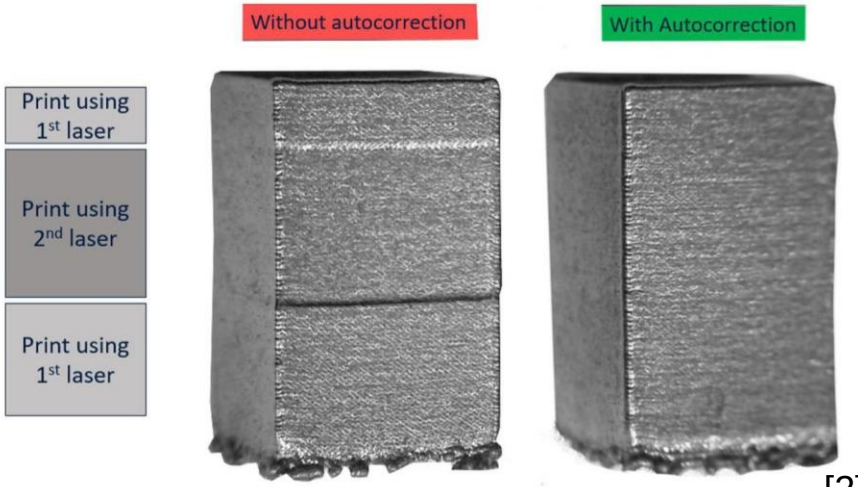

[2]

References
[1] Godfrey, Donald. SLM Solutions. Validation of Multi-Laser Printing Technology for Additive Manufacturing.
[2] Murphree, Zach. Velo3D. Why Pre-Build Calibration is Critical to Part Quality for Metal Additive Manufacturing. Quality Magazine. 2020-09-25. http://digital.bnpmedia.com/publication/frame.php?i=674814&p=&pn=&ver=html5&view=articleBrowser&article_id=3772591

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