Aerospace Framework for Certification and Qualification for Advanced Manufacturing Technologies with Examples in Additive Manufacturing Using Ti-6Al-4V EB Powder Bed Fusion

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Abstract

While the materials, requirements, and service environments between aerospace and nuclear applications differ, there is much commonality including part criticality, service life, and use of nondestructive testing. Additionally, as small reactors are developed, annual production rates for nuclear parts will approach those for aerospace. This presentation will discuss a common framework used for certification and qualification, with examples on how it would be applied for an alloy in common between aerospace and nuclear, 316L, replaced with Ti-6Al-4V. This framework and the example will address feedstock, process development, design values, equipment & facility qualification, part qualification, and certification.

* 316L Laser Powder Bed Fusion Data Available on America Makes CORE

Certification & Qualification in AM

- Many Regulatory Bodies and Certifying Agencies Have Detailed Definitions
- All Engineered Products are Certified and Qualified to Some Extent
- My Basic Definitions
  - Certification – A component that meets design intent is fit for service in a system
  - Qualification – A properly manufactured component meets design intent
  - Part & Lot Acceptance – A part is equivalent to the qualified part

Related to Systems Engineering 'V'

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SUBSYSTEM REQUIREMENTS
- Loads
- Environmental Factors
- Margin of Safety
- Certification Criteria

COMPONENT REQUIREMENTS
- Criticality
- Part Envelope

COMPONENT DESIGN & ANALYSIS
- Geometry
- Stresses
- Material Selection
- Process Selection

CONSTRUCTION
- Stability
- Robustness
- Repeatability
- Producibility
- Characterized Properties
- Predictability of Performance
- Facility Qualification
- Machine/Process Qualification

COMPONENT TESTS
- Qualification Part Process, Lot and Part Acceptance
- Part Qualification Testing

SUBSYSTEM TESTS
- Special Subsystem Qualification Tests or Analytical Verification

USER ACCEPTANCE TESTS
- System Certification Testing and/or Analysis

Qualification & Certification Relationships

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Certification

Facility Qualification

- Quality System Approval
- Personnel Qualification

Machine Qualification

- Factory Acceptance Test (FAT)
- Installation Qualification (IQ)
- Operational Qualification (OQ)

Non-Print Process/Facility Qualification

- Feedstock
- Heat Treat
Machining
Chem Processing
- Nondestructive Testing
Coupon Testing

Requirements/Design/ Analysis

- System, Subsystem, and Part Requirements
- Design & Analysis Methods
Safety Assessment
Failure Modes & Effects
- Material Qualification (MQ)
Effects of Defects
Design Values

Pre-Production

Part/Performance Qualification (PQ)

- Process Conformance
- Part and Lot Acceptance
- Special 1st Article Tests (extra dimensions & NDT, part cut-up, correlation of part properties, etc.)
- Part, Subsystem, or System Functional Tests

PQ Approval
System Certification
Production Approval

Production

- Production Part Acceptance
- Production SPC Monitoring

Compare Lot Acceptance Results with Design Database

Certification and Qualification Taxonomy

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Term	Sub-Term	Simple Multi-Industry Description
System Certification (FAA Type Certification)		Demonstration through test and analysis that the overall system will meet requirements. Often involves full-scale test of system.
Production Certification (FAA Term)		Manufacturing facilities are capable of repeatably producing product per the approved Type certificate
Subsystem Qualification		Subsystem (avionics box, actuator, etc.) meets a series of general and subsystem-specific tests
Facility Qualification		Facility that makes feedstock, parts, post-processing has quality systems in place and processes that meet qualification requirements
Personnel Qualification		Proficiency of personnel operating equipment has been demonstrated
Machine Acceptance and Qual	Factory Acceptance Test (FAT)	Equipment works properly at equipment builder's facility
	Installation Qualification (IQ)	Equipment works properly at user's facility
	Operational Qualification (OQ)	Equipment produces material/parts with expected properties
Process Validation (PV)		Overall manufacturing chain and equipment makes parts that meet requirements (good for part families)
Part Qualification	Process Performance Qualification (PQ)	Parts produced repeatably meet performance requirements
Feedstock Qualification	Specification & 1st Source (Factory vs. Warehouse)	Feedstock meets requirements and feedstock that meets specification requirements produces material that meets requirements
Part Acceptance	Lot Acceptance	Data off equipment and lot coupons (mech, chem, met) pass
	Individual Lot Acceptance	Part specific tests (NDT, dimensional, hardness)

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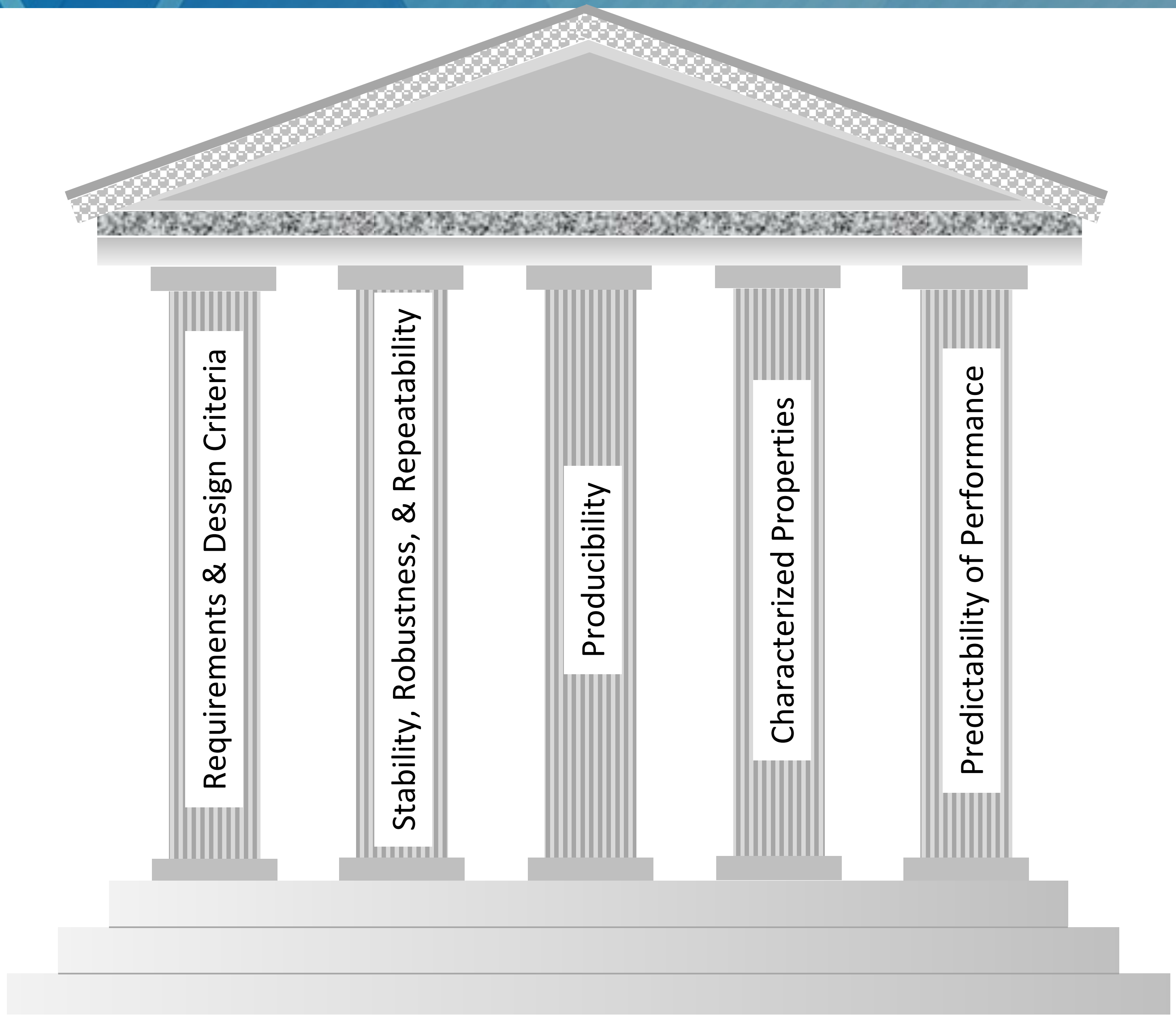
Certification

Certification Pillars



Jack Lincoln Aircraft Structural Integrity Framework

Requirements & Design Criteria

- Geometric – Volume, Interfaces
- Service – Loads, Number of Cycles, Temperature, Corrosion
- Knock-Down Factors (Temperature, Humidity, Surface Roughness, etc.)
- Margins of Safety
- Failure Mode and Effects
- Determination of Design Values
- Certification Method (Analysis, Test, or Both)
- Test Extent – Blurs Line with Qualification
  - Full System Containing Part
  - Subcomponent (Part Only)
  - Destruct and Extract Coupons

Stability, Robustness, and Repeatability

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- Production Parts That are Accepted Meet Requirements Demonstrated by Certification Parts
- Robustness – No Dramatic Property Changes with Minor Input Parameter Changes
  - Parameters Operator can Control (e.g., Laser Power, Travel Speed)
  - Parameters Operator cannot Control (e.g., Local Variations in Power Density, Humidity, etc.)
- Stability – Minimal Creep Over Time
  - Short Term (e.g., Bed Temperature Through Build)
  - Long Term (e.g., Over Part Production Span)
- Repeatability – Combination of Robustness and Stability with Respect to Final Product – Importance of Specifications for Feedstock, Processing, Post-Processing

Producibility

- Closely Related to Stability, Robustness, and Repeatability
- Part can be produced without excessive scrappage and rework
- Accounts for geometric complexity vs simple shapes
- Well within process size capability

Characterized Properties

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- Material Properties are Quantified
- Mechanical – Static (Tensile, Compression, Shear, Bearing), Dynamic, Durability – MMPDS is Excellent Guide
- Physical – CTE, Thermal Conductivity – MMPDS Contains Some
- Specialized – Wear, Friction
- Anisotropy – Look at Modulus
- Environmental Impacts (Temperature, Humidity, Surface Roughness, etc.)
- Surrogates – Hardness, Conductivity
- Ability to Nondestructively Inspect

Predictability of Performance

- Design Team confident that AM Material/Process combination will have the properties used for analysis
- Usually Not mean, median, or typical, but accounts for statistical variation
- Metallic Materials Properties Development and Standardization (MMPDS https://www.mmpds.org/) is Gold Standard
  - Static – A-Basis (99%/95% Confidence), B-Basis (90%/95% Confidence), S-Basis (99%) for More is Better
  - Typical Physical (More is Not Necessarily Better)
  - Some Durability, Damage Tolerance, Fracture
- MMPDS Standard very rigorous & challenging (Ref. Doug Hall presentation)
- Interim approach is developing part or part family specific values
- Need to account for NDT detectability limits/reliability for fatigue/fracture

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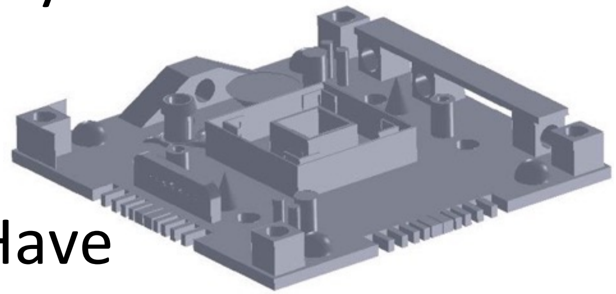
Qualification

Qualification

- Facility
  - Processes and controls in place (ISO-9000, AS-9100, etc.)
  - Not much different, If any, from other processes
- AM Machine
  - Far greater number of production machines requires different approach than wrought
  - Installation Qualification & Operational Qualification
- Material
- Performance/Part

Installation Qualification (IQ)

- Sometimes Called Site Acceptance Testing (SAT)
- Test Procedure, Program, and Pass/Fail Criteria Co-Developed by Printer Manufacturer and Printer Operator
- Performed by Printer Operator to Verify Printer Fit to Make Hardware (Reference AMS-7032, AWS D20.1)
- Surveys/Tests without Feedstock – Generally Same as FAT but May Have
  - Larger Range of Motion Unique to Intended Use
  - Energy Application Settings Unique to Intended Use
- Surveys/Tests with Feedstock - Generally Same as FAT but May Have
  - Material / Feedstock Unique to Intended Use
  - Geometries Unique to Intended Use
  - Parameter Combinations Unique to Intended Use
- May Add Heat Treatment, Along with Chemistry and Mechanical Testing



NIST Laser Powder Bed Fusion Artifact
(https://nvlpubs.nist.gov/nistpubs/jres/119/jres.119.017.pdf)

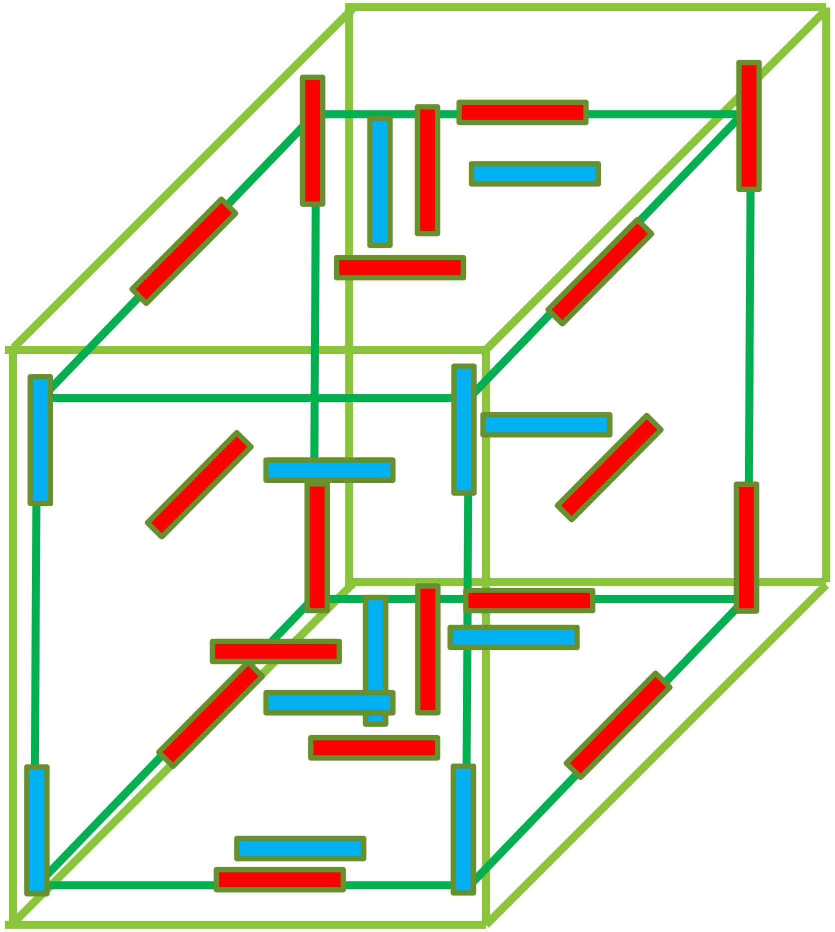
Machine Operational Qualification (OQ)

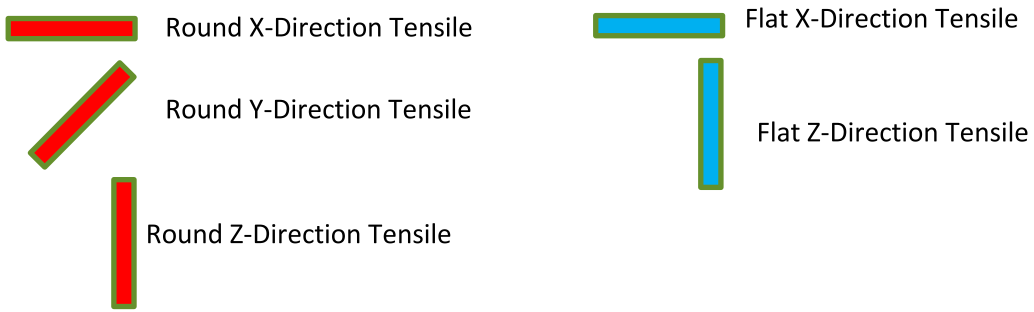
- AWS D20.1 and AMS-7032 are Existing Standards
  - Installation Qualification – Machine performs as machine builder expects
  - Operational Qualification – Machine produces material that meets material specification

- AMS-7032 Operational Qualification General Requirements
  - 3 Builds
  - 10 Tensile Tests/Direction/Build Covering Full Build Volume*DED
  - 3 Chemistry/Microstructure
  - 6 Horizontal and 6 Vertical Fatigue Recommended
  - NDT Coupons Per Material Specification
  - Coupons Meet Specification (NDT, Chem, Micro, Tensile) & T_{99} for Tensile w 1-Sample
  - Fewer Builds for Conditional and Non-Conditional Requalification

Machine Operational Qual Example Plan

- AMS7032 allows flexibility on build volume for DED processes





Build Lot	Feedstock Lot	Round Tensile from 12mm Diameter Cylinder			Flat Tensile from 1mm x 12mm Strip		Chemistry Microstructure
		X Direction	Y Direction	Z Direction	X Direction	Z Direction	
1	1	10	10	10	6	6	3
2	2	10	10	10	6	6	3
3	2	10	10	10	6	6	3
Total		**30**	**30**	**30**	**18**	**18**	**9**

Material Qualification (MQ)

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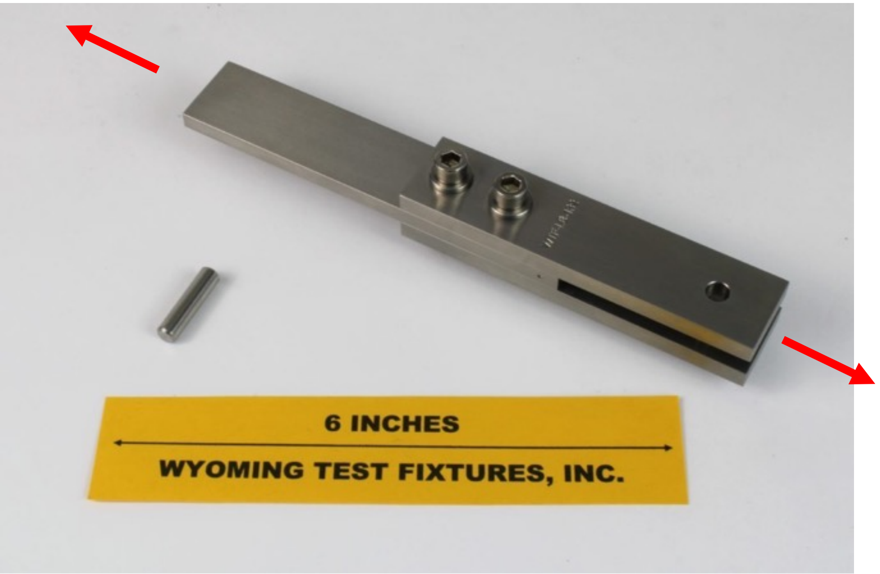
- Lots of overlap with process development/design allowables
- Variation with part geometry and build parameters
- Other Properties
  - Physical
  - Compression, Shear, Bearing
  - Fatigue, Fracture, Creep, etc.
- Some applications may require for each machine



Performance/Part Qualification (PQ)

- Validating that the part meets requirements
- Simple – Dimensional, NDT, Lot Acceptance (separate tensile, micro, chem coupons)
- Really complex – Full-scale test of part in service environment (landing gear component test)
- Middle
  - Additional dimensional, NDT, lot acceptance
  - Destructive sectioning of part and excising of mechanical, chemistry, and metallographic coupons

https://runwaygirlnetwork.com/2016/12/how-safran-landing-systems-tests-landing-gear-wheels-and-brakes/

Links Between Certification, Qualification, and Production

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- Tie Into Certification Pillars of Producibility and Predictability

Certification | Qualification | Production

Qualification Part:

- Manufacturing process for printer and part conform to those used to generate design values
- Geometry, tolerances, and surface finish meet those used in analysis and certification testing
- Test performance (loads, deflections, environmental exposure) meets subsystem requirements
- Microstructure and properties of excised coupons meet material specification

Production Parts:

- Manufacturing processes and plan conform to those used for the qualification part (fixed process)
- Lot acceptance coupon properties (tensile, chemistry, hardness, microstructure) meet those of material specification or part engineering
- Part acceptance inspections (volumetric NDT, surface NDT, dimensional, surface finish) meet part engineering and applicable material specifications
- Acceptable fraction of part and lot acceptance

Example – Ti-6Al-4V EB-PBF OQ

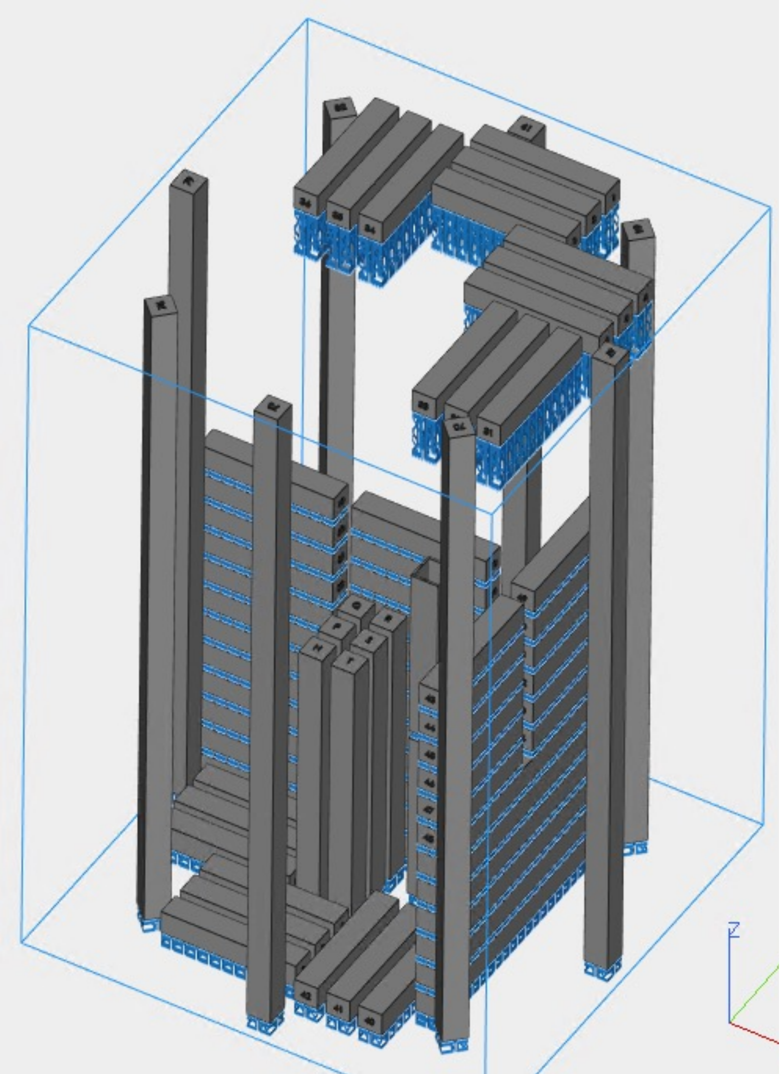
- See if a printer make and model different from that used to generate lot acceptance values for a material specification can meet AMS7032 (*Machine Qualification for Fusion-Based Metal Additive Manufacturing*) Operational Qualification (OQ) requirements
  - 1 feedstock lot, 1 thermal treatment run, 3 builds across volume
  - 30 total tensiles per lot acceptance orientation will all meeting lot acceptance minimums, and T_{99} > lot acceptance minimums
  - Composition and microstructure meet specification requirements
- Target specification
  - AMS7011 (*Electron Beam-Powder Bed Fusion (EB-PBF) Produced Preforms and Parts, Titanium Alloy, 6Al-4V, Hot Isostatically Pressed*)
  - Test data from a single printer make and model (ARCAM Q20+) meeting GAAM-18 requirements (minimum of 3 powder lots and 3 printers)

New Printer – JEOL JAM-5200EBM

- Print Volume – 250mm dia x 400mm tall
- Beam Output – 6kW
- Heating Capacity – 1100C
- Cathode Lifetime – 1500 hours
- He is Not Required
- First Printer in US Installed at Cumberland Additive in Pittsburgh
- Developing Capability of Refractory Alloys

Coupon Manufacture & NDT

- Reused TEKNA powder from a single lot that met AMS7015, with 0.16% O
- Build file encompassing entire volume of JAM-5200EBM (right)
- Coupons tested for evaluation received HIP per AMS7011, and the others retained for future use
- Radiographic inspection to notes of AMS7011, with all passing



0.5” x 0.5”

Composition Testing

- Met AMS7011 Requirements

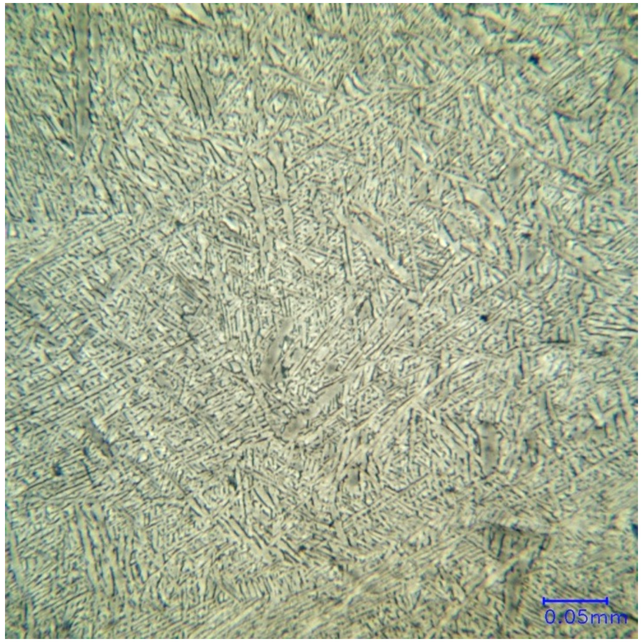
ELEMENT	AMS7011		COUPON									
	Min	Max	214-15C	214-61C	214-75C	215-15C	215-61C	215-75C	216-15C	216-61C	216-75C	Powder
C		0.08	0.01	0.02	0.02	0.01	0.02	0.02	0.01	0.02	0.02	<0.001
H		0.015	0.005	0.004	0.004	0.003	0.007	0.008	0.002	0.004	0.003	0.003
O	0.11	0.2	0.174	0.169	0.166	0.182	0.169	0.178	0.185	0.178	0.177	0.16
N		0.05	0.014	0.012	0.013	0.014	0.013	0.014	0.013	0.015	0.014	0.016
Ti			Remainder	Remainder	Remainder	Remainder	Remainder	Remainder	Remainder	Remainder	Remainder	Remainder
Al	5.5	6.75	6.01	6.11	6.02	6.07	5.98	6.05	6.02	6.04	5.99	6.47
V	3.5	4.5	4.13	3.99	4.09	4.18	4.08	4.06	4.15	4.06	4.1	4.08
Fe		0.3	0.17	0.23	0.17	0.17	0.2	0.16	0.17	0.17	0.17	0.25
Others		0.4	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	<0.10

Metallography

- Density below, although no minimum requirement in AMS7011
- Transformed beta microstructure
- No discontinuity larger than 20µm observed

ELEMENT	COUPON											
	214-15C	214-21M	214-61C	214-75C	215-15C	215-21M	215-61C	215-75C	216-15C	216-21M	216-61C	216-75C
Density	99.61	99.47	99.59	99.45	99.45	99.35	99.28	99.4	99.64	99.65	99.78	99.64

Brightness increased by 25% in PowerPoint



214-15

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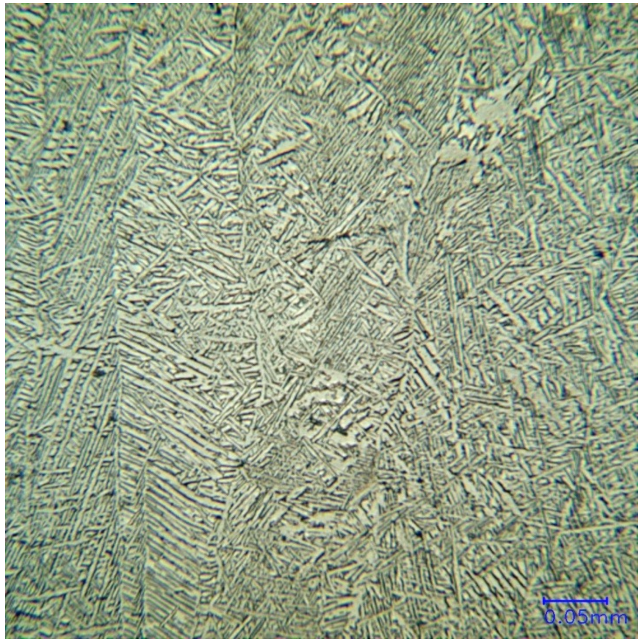

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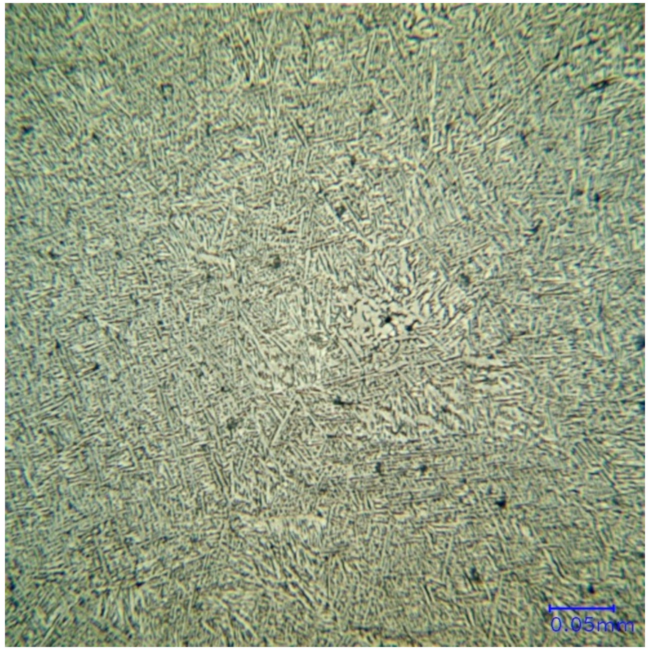

214-75

Tensile – Summaries & Statistics

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- All tests met minimums, with excellent ductility
- 8 of 9 T_{99} values met minimums, with Z-Direction TYS 1ksi below, meaning it meets 1-sample acceptance test with margin requirement
- 2-3ksi of anisotropy, versus 3-8ksi in AMS7011

X-Direction

Value	TUS (ksi)	TYS (ksi)	ELG (%)	RA (%)
Max	146	133	19	47
Min	140	119	14	34
Mean	142.5	124.8	17.1	41.7
Std Dev	1.76	2.56	1.12	3.25
n	30	30	30	30
T99	137	117	11	32
AMS-7011 Accept	130	112	9	n.a.

Y-Direction

Value	TUS (ksi)	TYS (ksi)	ELG (%)	RA (%)
Max	145	128	19	51
Min	139	121	14	38
Mean	142	124.2	17	44
Std Dev	1.75	1.79	1.43	3.55
n	30	30	30	30
T99	137	119	10	33
AMS-7011 Accept	130	112	9	n.a.

Z-Direction

Value	TUS (ksi)	TYS (ksi)	ELG (%)	RA (%)
Max	143	127	21	58
Min	138	121	17	47
Mean	140.8	123.3	19	53
Std Dev	1.59	1.56	1.03	2.66
n	30	30	30	30
T99	134	119	15	45
AMS-7011 Accept	133	120	10	n.a.

Conclusions and Recommendations

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Conclusions

- The ability to perform OQ on printer make and model different from that used to generate the specification minimum has been demonstrated for a given alloy & process combination.
- Ability for other alloy & process combinations needs to be demonstrated.

Recommendations

- Look at impact of adding 5200 dataset to current AMS7011 dataset on lot acceptance values
- Look at impact of additional 5200 printers/lots on 5200 T_{99} values
- Perform similar studies on other alloy & process specifications
- Since the acceptance values for several specifications are based on a single printer model, consider re-analyzing lot acceptance values at 5-year review date.
- Consider using 3 different printer models when generating initial lot acceptance values.

Presenter

Kevin T. Slattery, D.Sc is a Principal ADDvisor® at The Barnes Global Advisors. His primary expertise is in Metallic Additive and Metals Manufacturing, focusing on test program development, process and product verification, qualification, and certification. He is a 2020 Ambassador for America Makes, was part of the Materials Challenge Silver Medal team in the USAF Rapid Sustainment Office Additive Manufacturing Olympics, and a 2022 SAE Contributor of the Year Finalist. He led 7 first in the industry technology implementations, including the 1st metal additive manufacturing structural aircraft part. Prior to this, he was the Chief Scientist for AM and Metals in Boeing Research and Technology. He currently holds 40 US patents, with 13 applications pending.

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Thank you!

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