SAND2022-15143C

Sandia National Laboratories

Relevance of AM standards in highly leveraged, process-structure-property-performance (PSPP) applications

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ICAM 2022

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U.S. DEPARTMENT OF ENERGY | NNSA National Nuclear Security Administration

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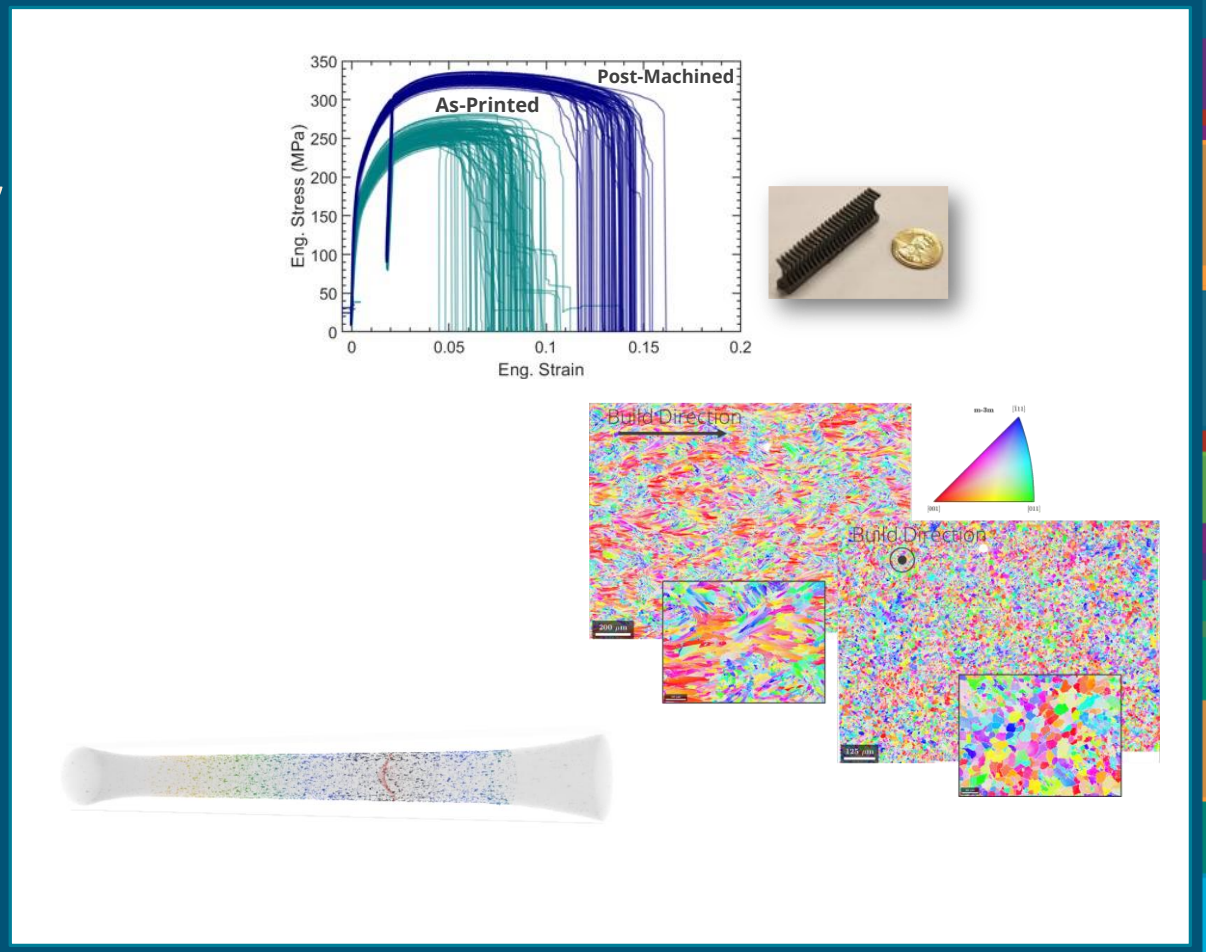
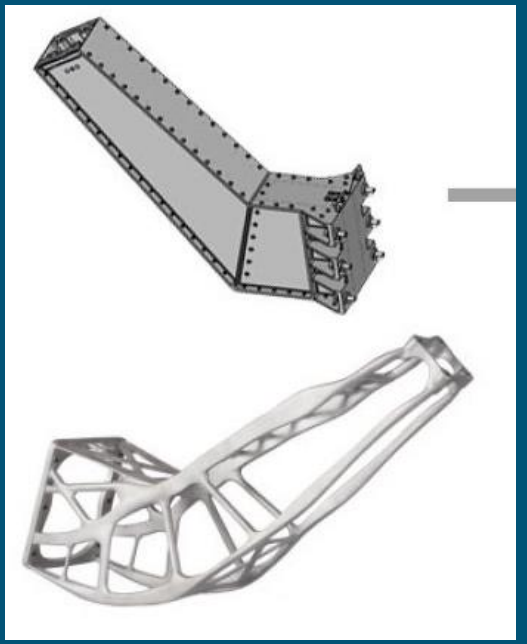
Topics

- Opportunities of additive manufacturing
- Existing standards landscape
- Introducing the “Cone of Uncertainty”
- Strategies to leverage standards



Opportunities of Additive Manufacturing

- Rapid product realization
- Assembly consolidation
- Complexity for “free”
- Highly optimized structures
- Alternate material properties
- Tailorable, engineered microstructure

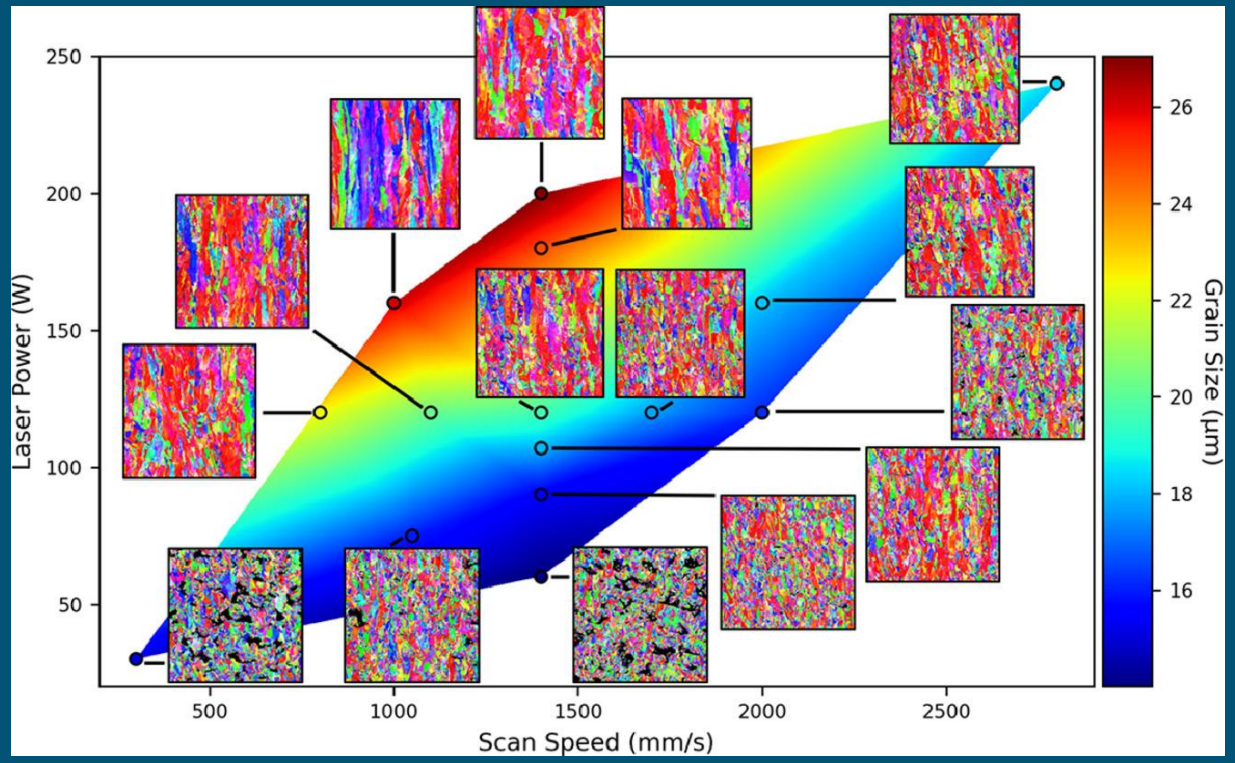


https://www.eos.info/en/

Process-Structure-Property-Performance (PSPP) Relationship

PSPP

- Established relationships between process variables and output
- Theoretical hypersurface across *n*-dimensional space for the *n* variables relating all controllable inputs
- Intentional placement of properties by varying process control for localized and tailored material response
- **Only as effective as our ability to reproduce it.**



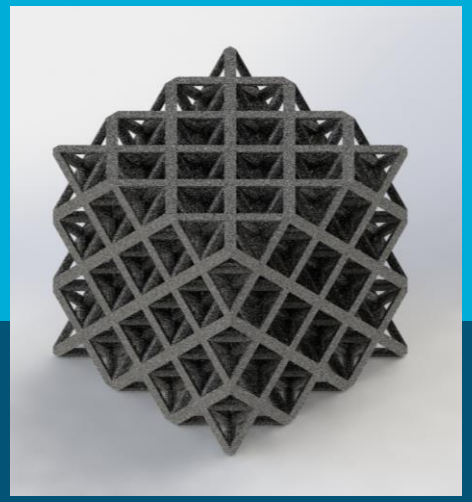
PSPP Example

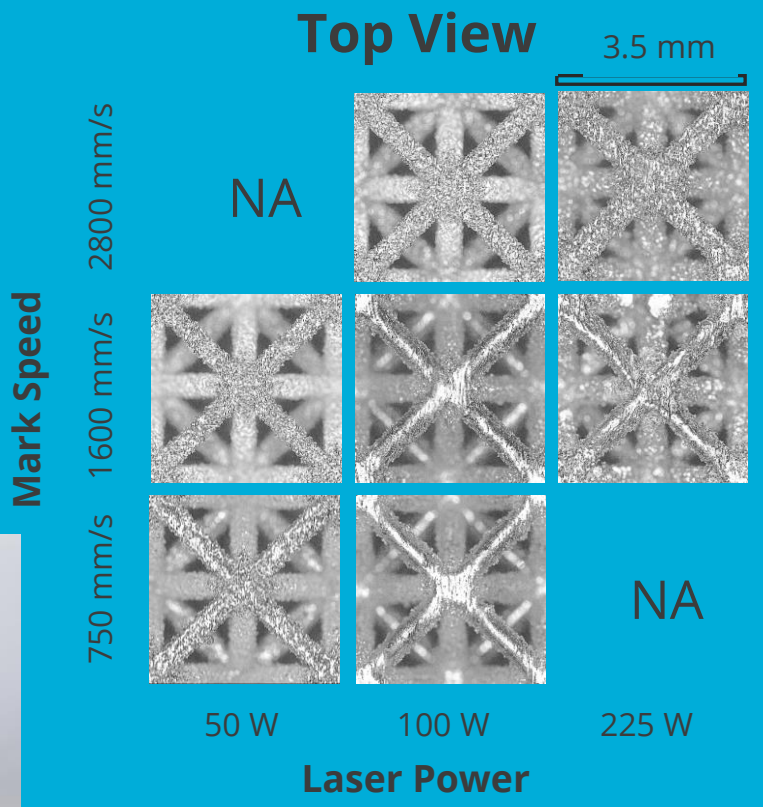
Metal Additive Manufacturing of Lattice Structures: A Study of Process Parameters and Mechanical Performance

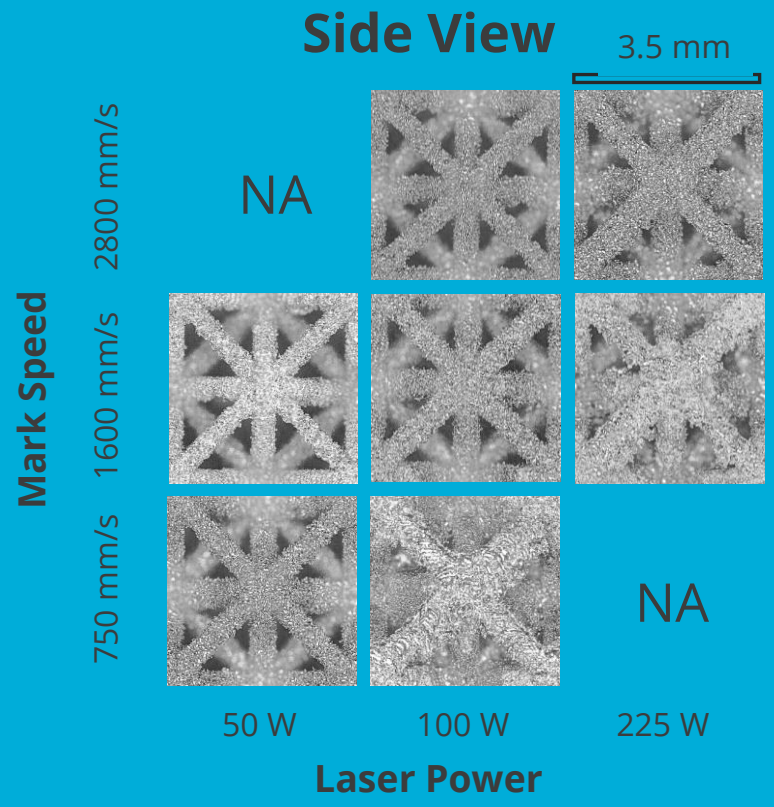
Characterization

- Strut Size
- Strut Uniformity
- Surface Quality
- Top View vs Side (Orientation)

Octet Truss
- FCC Lattice Type
- Lattice 20% Fill
- 3x3x3 Unit Lattice
- 10.5 mm Lattice Side Length







Scott Jensen*, Benjamin White, Anthony Garland, Michael Heiden, David Saiz, Brad Boyce, and Bradley Jared
Sandia National Laboratory, Albuquerque, New Mexico 87185

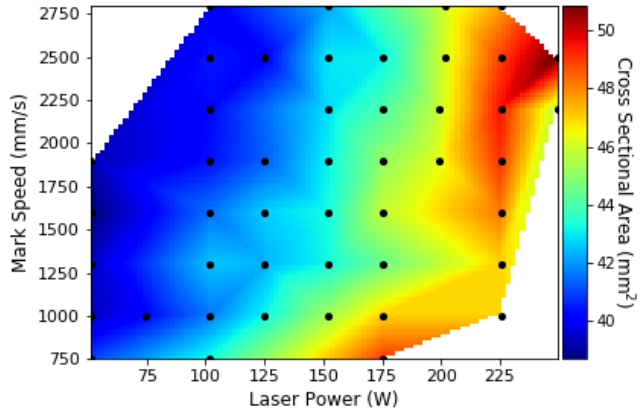
PSPP Example, Continued

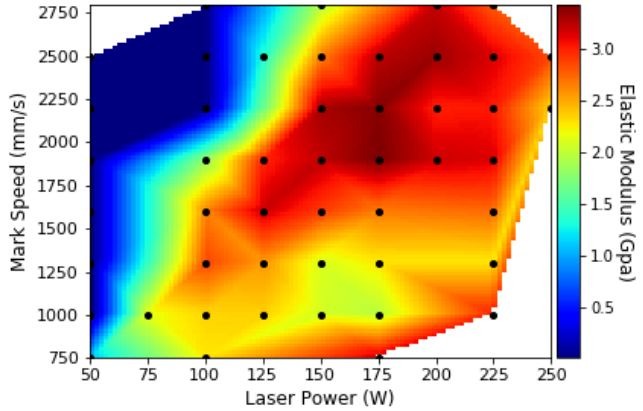
Metal Additive Manufacturing of Lattice Structures:
A Study of Process Parameters and Mechanical Performance

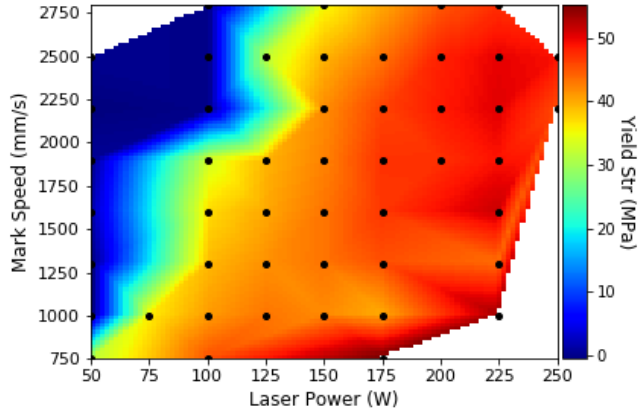
Strut Size

Mechanical Properties

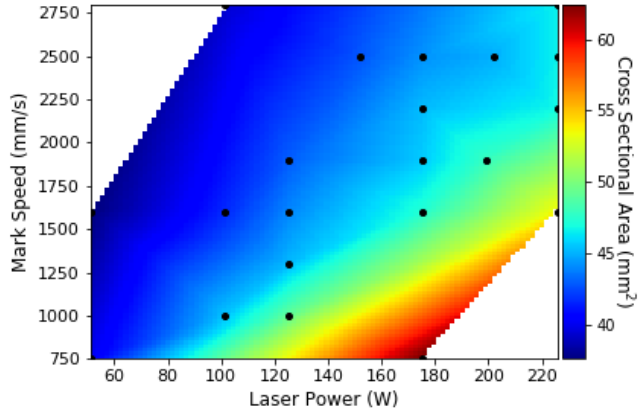
Top View

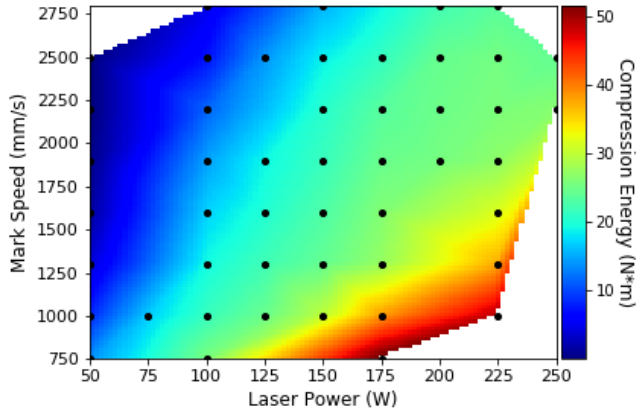


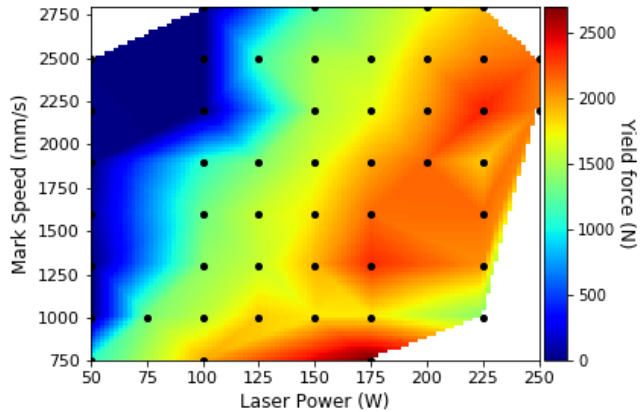




Side View







Existing Standards Landscape for AM

Several Standards Defining Organizations (SDOs) active

- ASTM, ISO, ASME, AWS, SAE, MPIF, NASA, DIN, IEEE, ANSI*, and others

Each organization operates within a particular domain or mission

- Some broad and expansive, others narrowly tailored
  - SAE: aerospace only (heavy emphasis on commercial aviation)
  - NASA: aerospace only (heavy emphasis on spaceflight)
  - MPIF: metal powder industry
  - ASME: mechanical design definition and communication
  - ASTM/ISO: sub-committees narrowly addressing various topics (testing, characterization, process, properties)

Some overlap exists between these SDOs

Existing Standards Landscape for AM

Standards frequently are:

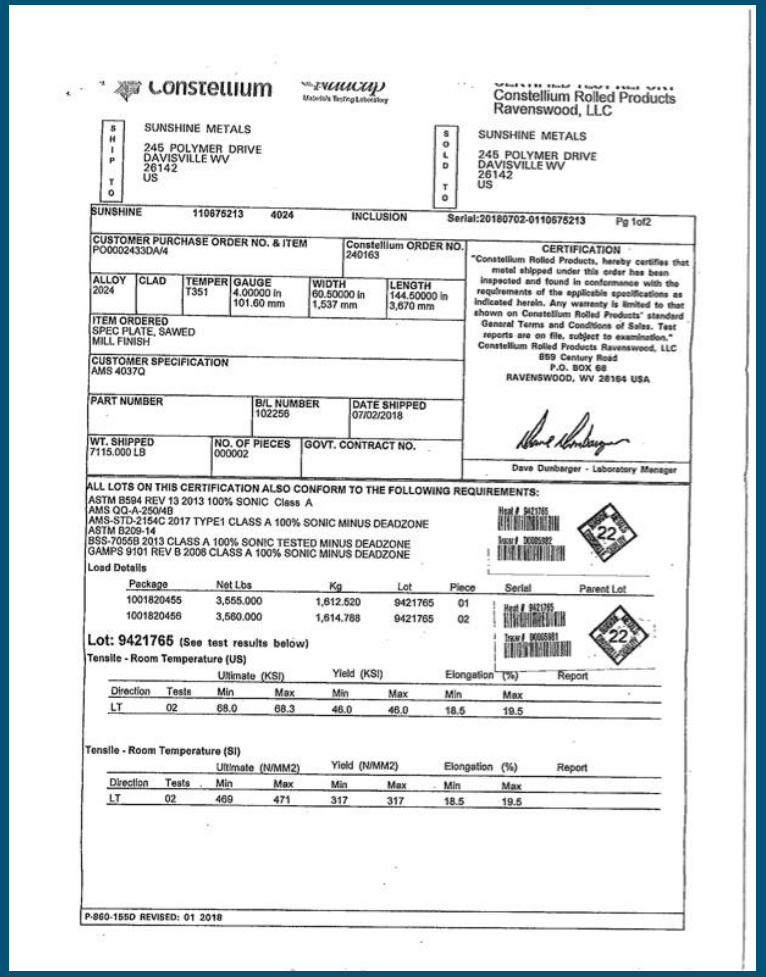
- Devoid of process-specific operational attributes and controls
  - Don’t tell you how to run your AM equipment
  - Don’t tell you what powder to use (frequently controlled for chemistry, but not PSD)
  - Post-build, thermal processing is an exception
- Accommodating to feedstock producers with less-restrictive chemistry reqts.
  - Commonly differentiate by grade/class on oxygen
- Leveraging narrowly applicable finished property acceptance metrics
  - Frequently room temperature tensile, defect size and spacing, and occasionally hardness

But standards aren’t meant to directly describe every application

Volumetric versus AM Materials Specifications

Precedent for Material Specifications

- ✓ **Volumetric** forming processes
- ✓ **Single-document material specifications** with monolithic properties
- ✓ **Testing** of stock represents material and subsequent parts
- ✓ **Wide applicability** for forms used in subtractive manufacturing



Constellium

Constellium Rolled Products
Ravenswood, LLC

SHIP TO: SUNSHINE METALS
245 POLYMER DRIVE
DAVISVILLE WV
26142
US

SOLD TO: SUNSHINE METALS
245 POLYMER DRIVE
DAVISVILLE WV
26142
US

SUNSHINE 110675213 4024 INCLUSION Serial:20180702-0110675213 Pg 1of2

CUSTOMER PURCHASE ORDER NO. & ITEM	Constellium ORDER NO.
PO0002433DA/4	240163

ALLOY	CLAD	TEMPER	GAUGE	WIDTH	LENGTH
2024		T351	4.00000 in 101.60 mm	60.50000 in 1,537 mm	144.50000 in 3,670 mm

ITEM ORDERED
SPEC PLATE, SAWED
MILL FINISH

CUSTOMER SPECIFICATION
AMS 4037Q

PART NUMBER	B/L NUMBER	DATE SHIPPED
	102256	07/02/2018

WT. SHIPPED	NO. OF PIECES	GOVT. CONTRACT NO.
7115.000 LB	000002	

CERTIFICATION
"Constellium Rolled Products, hereby certifies that metal shipped under this order has been inspected and found in conformance with the requirements of the applicable specifications as indicated herein. Any warranty is limited to that shown on Constellium Rolled Products' standard General Terms and Conditions of Sales. Test reports are on file, subject to examination."
Constellium Rolled Products Ravenswood, LLC
699 Century Road
P.O. BOX 68
RAVENSWOOD, WV 26164 USA

Dave Dunbarger - Laboratory Manager

ALL LOTS ON THIS CERTIFICATION ALSO CONFORM TO THE FOLLOWING REQUIREMENTS:
ASTM B594 REV 13 2013 100% SONIC Class A
AMS QQ-A-250/4B
AMS-STD-2154C 2017 TYPE1 CLASS A 100% SONIC MINUS DEADZONE
ASTM B209-14
BSS-7055B 2013 CLASS A 100% SONIC TESTED MINUS DEADZONE
GAMPS 9101 REV B 2008 CLASS A 100% SONIC MINUS DEADZONE

Load Details

Package	Net Lbs	Kg	Lot	Piece	Serial	Parent Lot
1001820455	3,555.000	1,612.520	9421765	01		
1001820456	3,560.000	1,614.788	9421765	02		

Lot: 9421765 (See test results below)

Tensile - Room Temperature (US)

Direction	Tests	Ultimate (KSI) Min	Ultimate (KSI) Max	Yield (KSI) Min	Yield (KSI) Max	Elongation (%) Min	Elongation (%) Max	Report
LT	02	68.0	68.3	46.0	46.0	18.5	19.5	

Tensile - Room Temperature (SI)

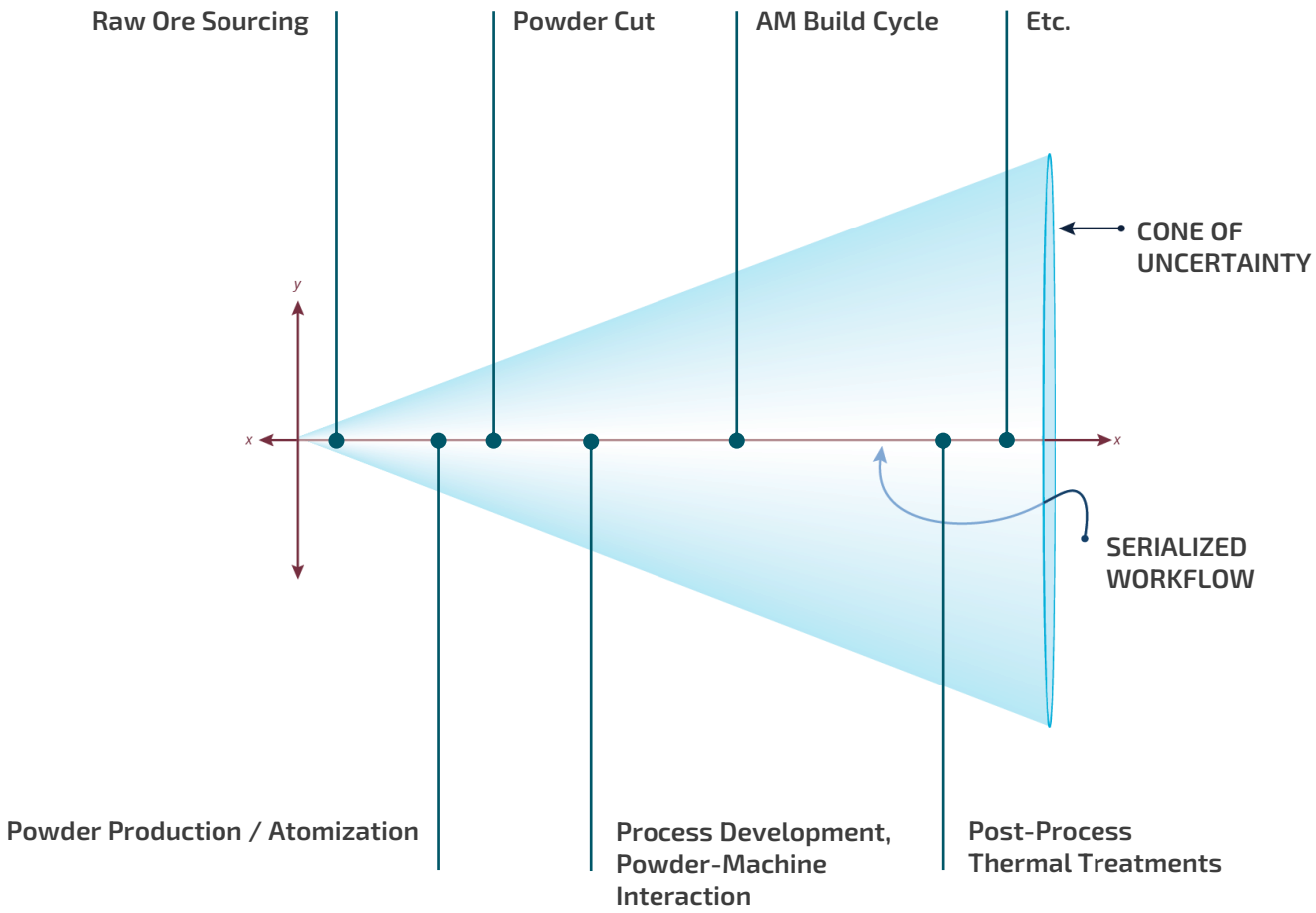
Direction	Tests	Ultimate (N/MM2) Min	Ultimate (N/MM2) Max	Yield (N/MM2) Min	Yield (N/MM2) Max	Elongation (%) Min	Elongation (%) Max	Report
LT	02	469	471	317	317	18.5	19.5	

P-860-155D REVISED: 01 2018

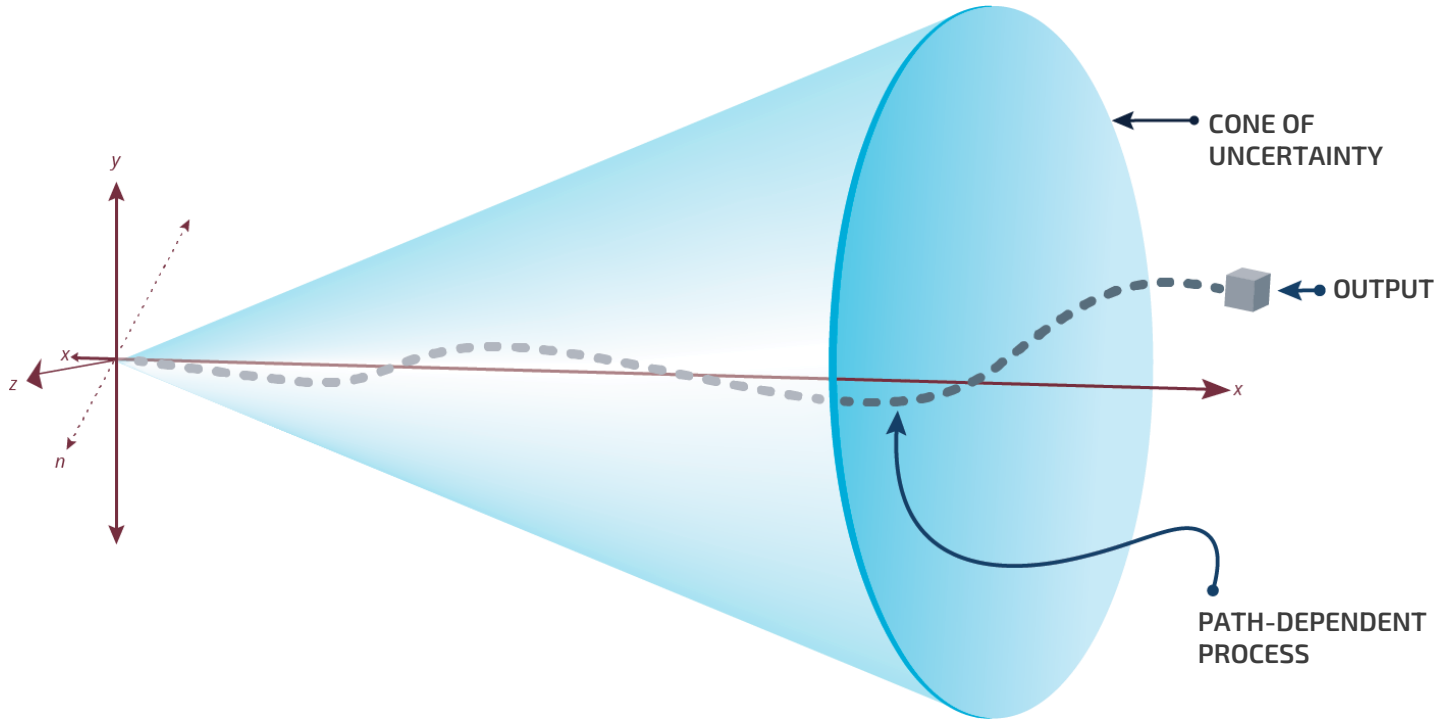
Problems with AM Paradigm

- ✗ **Lack of volumetric consistency**
- ✗ **Material specifications** need large safety factors with uncertainty
- ✗ **Witness coupons** may not represent part
- ? **Where is a material specification appropriate or useful?**

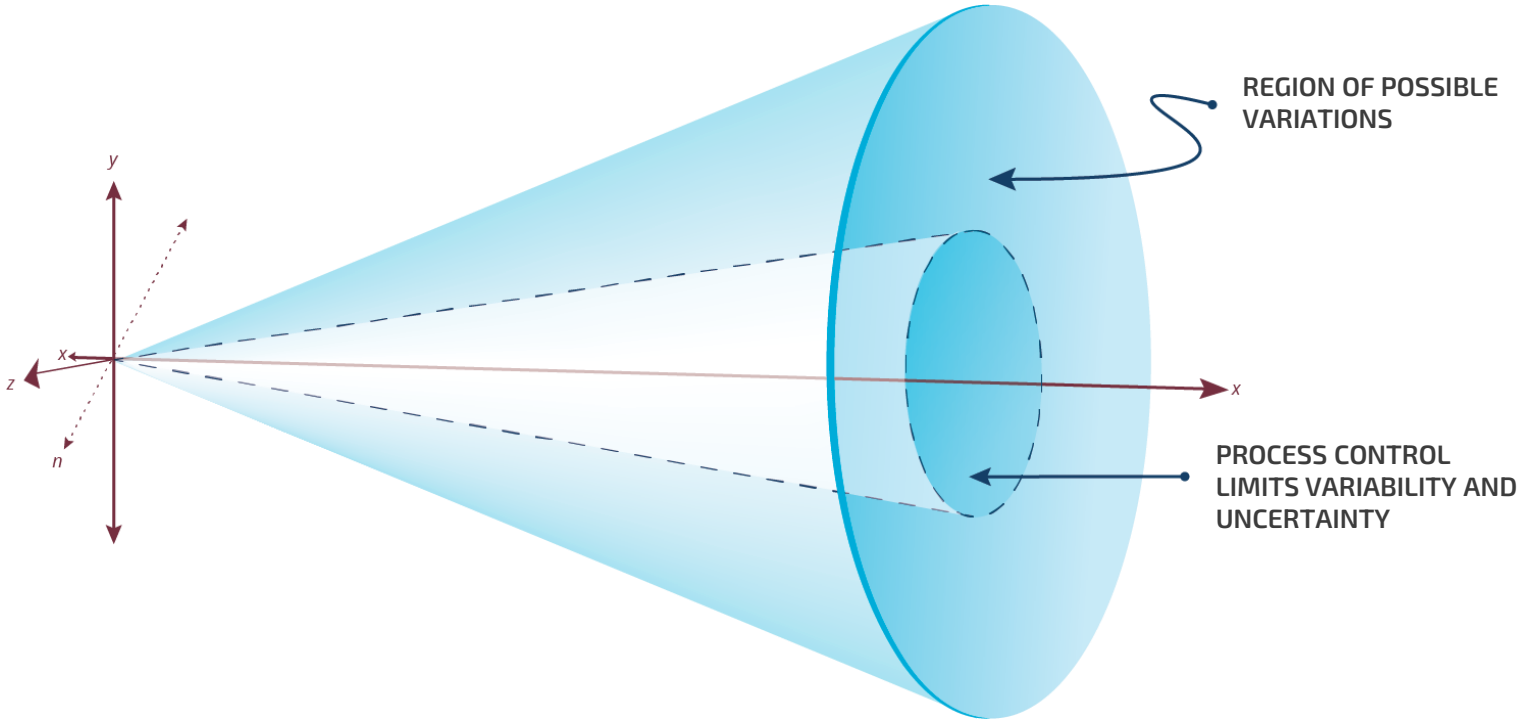
Cone of Uncertainty, ex: LPBF



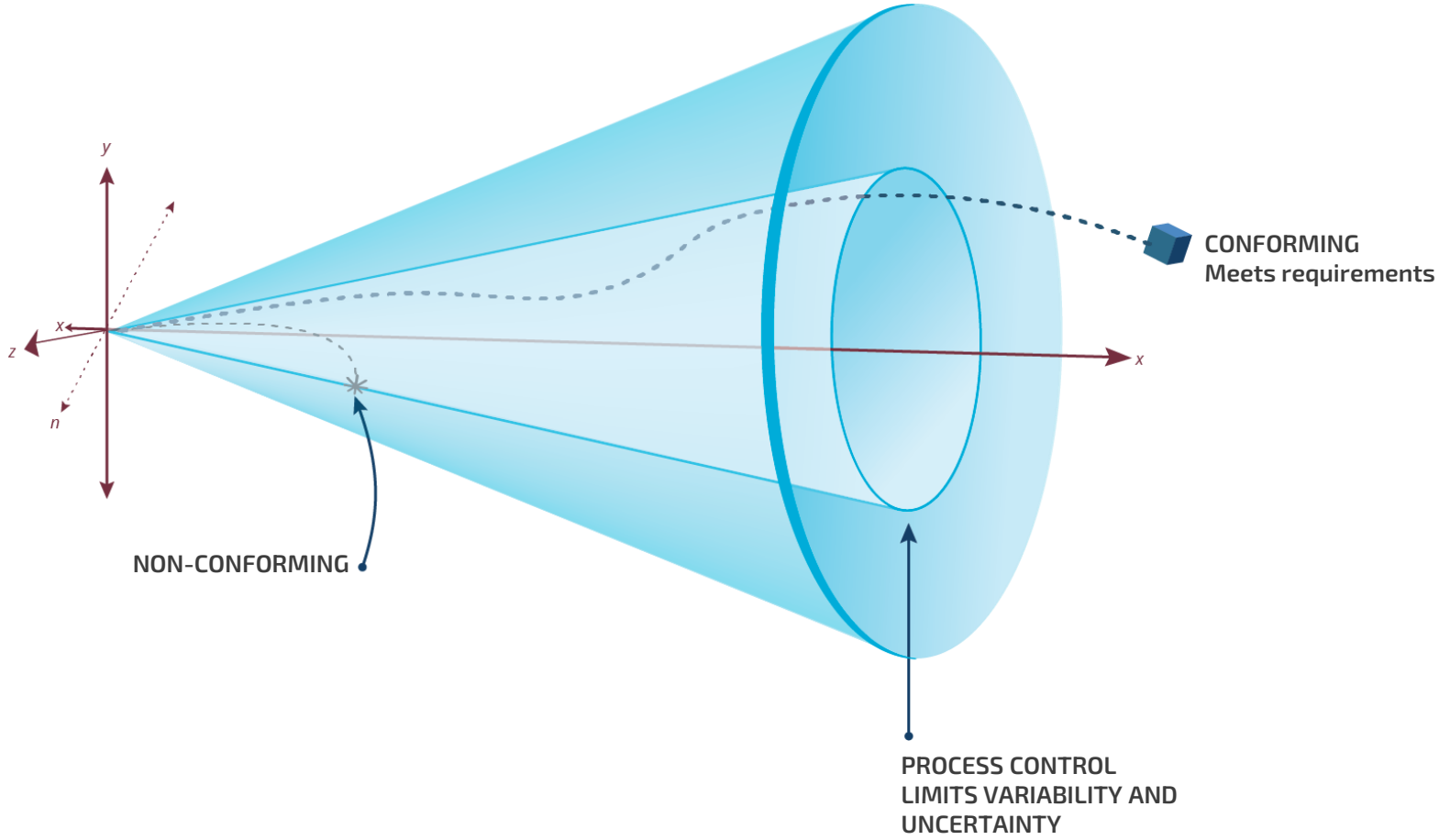
Cone of Uncertainty, Path Dependent Output



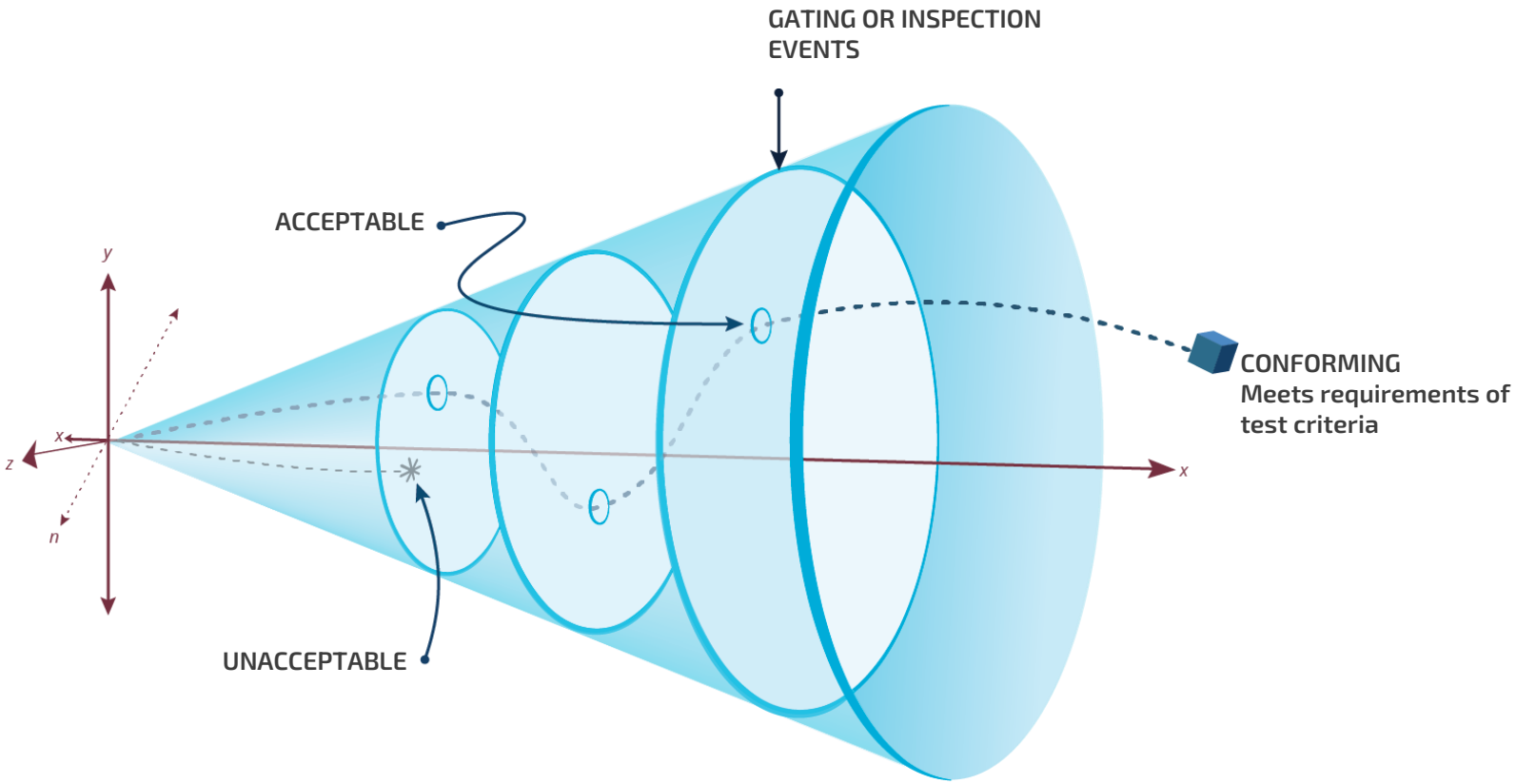
Effect of Process Control on Output Uncertainty



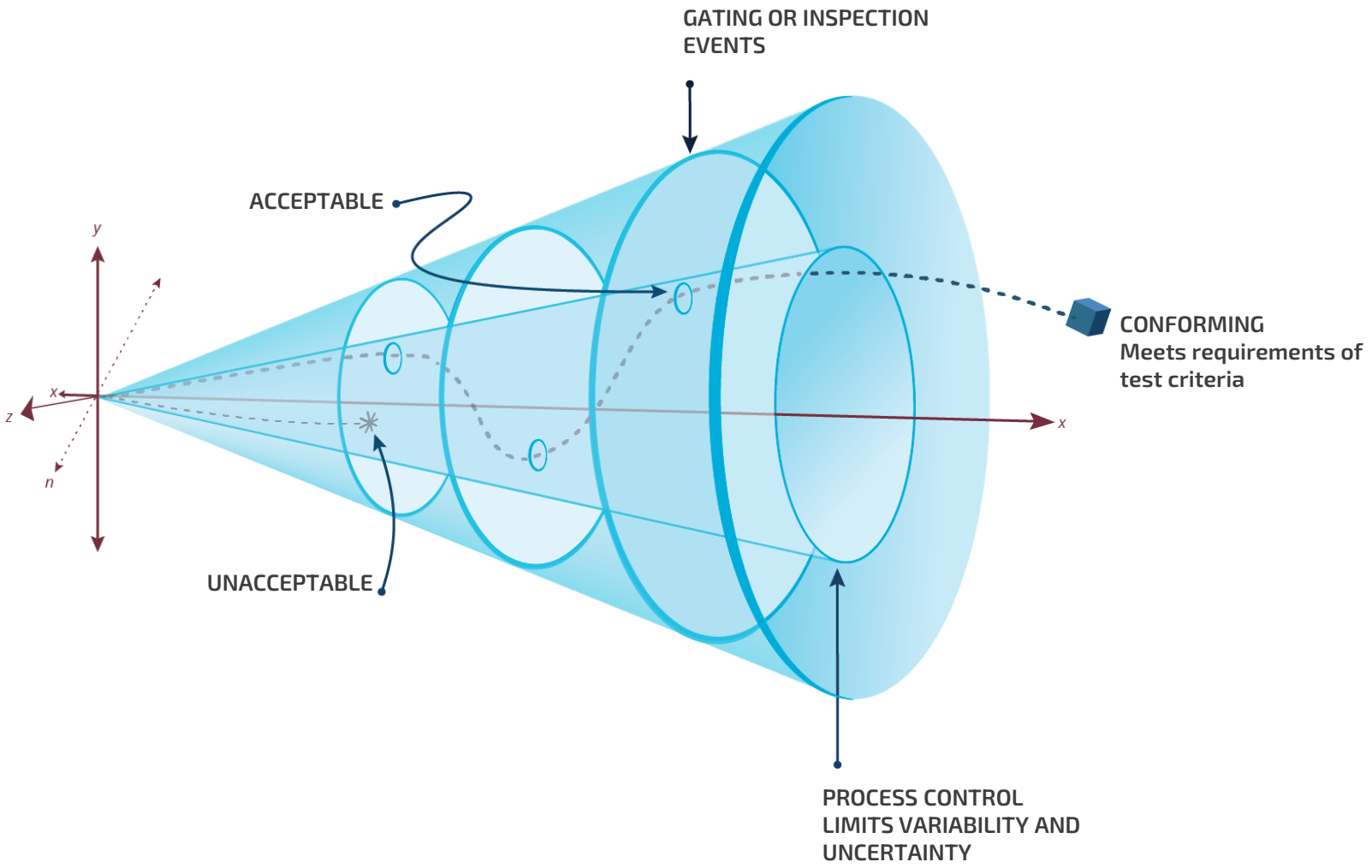
Effect of Process Control on Output Uncertainty



Acceptance Gating and Testing on Output



Balance of Both



Strategies for Standards: Process Control

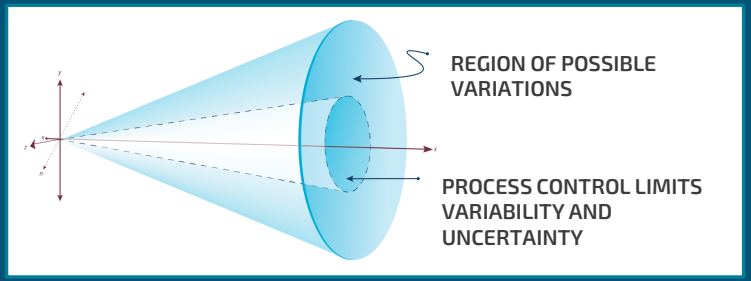
- **PSPP: Only as effective as our ability to reproduce it.**

- **Identification of KPVs**
  - Determine Key Process Variables (KPVs) that impact the process to develop robust understanding of AM workflow (What axes are appropriate on the cone of uncertainty)

- **Sensitivity Determination**
  - Using Manufacturing Process Window analyses, determine the tolerance to variability (How big does the cone of uncertainty expand for a particular step because of any one variable)

- **Cost-Benefit Analyses**
  - Undue process control may see diminishing returns on acceptable, requirements-conforming product. (Should acceptance tests be utilized)
  - E.g. powder PSD need be reproducible, but exacting precision and consistency is expensive to maintain. Can it be loosened?

Greater likelihood of fabricating conforming product.



Strategies for Standards: Acceptance Gating on Process

Developed AM Part

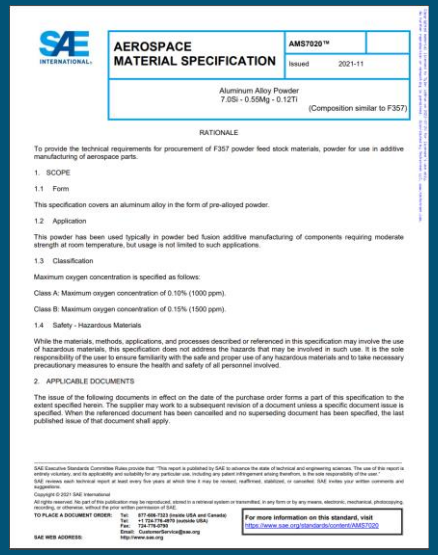
Need to Verify
Process Health and Reproducibility
During Production

Production AM Parts

Hypothetical Performance Requirements

- No Yield with Applied Force of 500 N
- Deflection no Greater than 10 mm During Service

AM Materials Specification Gate



SAE INTERNATIONAL

AEROSPACE MATERIAL SPECIFICATION

AMS7020™

Issued 2021-11

Aluminum Alloy Powder
7.0Si - 0.55Mg - 0.12Ti
(Composition similar to F357)

RATIONALE

To provide the technical requirements for procurement of F357 powder feed stock materials, powder for use in additive manufacturing of aerospace parts.

1. SCOPE

1.1 Form

This specification covers an aluminum alloy in the form of pre-alloyed powder.

1.2 Application

This powder has been used typically in powder bed fusion additive manufacturing of components requiring moderate strength at room temperature, but usage is not limited to such applications.

1.3 Classification

Maximum oxygen concentration is specified as follows:

Class A: Maximum oxygen concentration of 0.10% (1000 ppm).

Class B: Maximum oxygen concentration of 0.15% (1500 ppm).

1.4 Safety - Hazardous Materials

While the materials, methods, applications, and processes described or referenced in this specification may involve the use of hazardous materials, this specification does not address the hazards that may be involved in such use. It is the sole responsibility of the user to ensure familiarity with the safe and proper use of any hazardous materials and to take necessary precautionary measures to ensure the health and safety of all personnel involved.

2. APPLICABLE DOCUMENTS

The issue of the following documents in effect on the date of the purchase order forms a part of this specification to the extent specified herein. The supplier may work to a subsequent revision of a document unless a specific document issue is specified. When the referenced document has been cancelled and no superseding document has been specified, the last published issue of that document shall apply.

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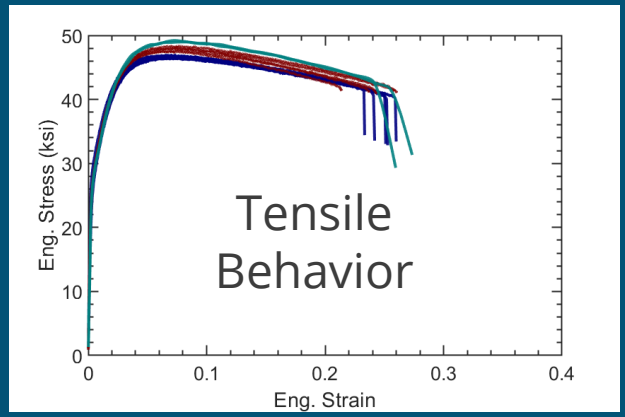
Required Witness Coupon Tests

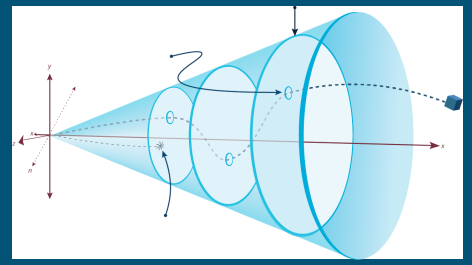


Strategies for Standards: Acceptance Gating on Process

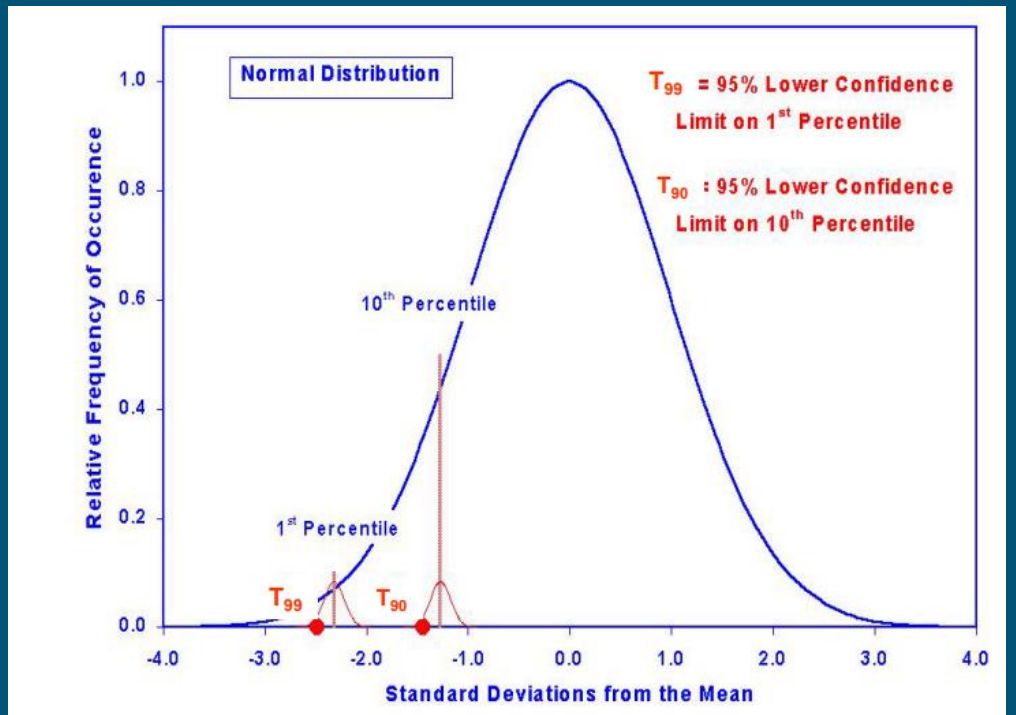
1. **Product is shown to meet requirements in Development**

2. **Process output is characterized and its variability bounded throughout Development**

3. **Sampling and testing strategy in (2) is continued into Production to demonstrate:**
   1. Machine calibration and health
   2. KPV consistency and interaction
   3. Lack of process anomaly



Witness sampling is not representative of the properties of the part itself, but only the coupon and is especially deficient to inform properties of a PSPP-leveraged process.



Doug Hall, MMPDS & Additive Metals Presentation, NIST-ASM International Additive Manufacturing Data Management Workshop October 28, 2020

Other Standardization Tools on Horizon

- In-situ process monitoring may enable greater control as a gating mechanism that ensures process consistency when combined with process control
- Powder feedstock reuse metrics for critical applications
- Feedstock production process controls for polymers (wire, powder, and pellet) and metals (wire)

Questions