Joint Metal Additive Database Definition (JMADD)

5511.001

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Overview

- Project Call - Additive Manufacturing for High Temperature Metals
- Contract ID : FA8650-20-2-5700 P00007 (ACRN: AC, SUBCLIN: 000103)
- Technology Roadmap Swimlane Alignment : Materials
  - Materials – *M.1 Define Standard AM Material Requirements (M.1.2),* M.3 Develop AM Materials (M.3.1), *M.5 Establish DoD-wide AM data repository, M.6 Develop model-based approaches to accelerate materials and qual and cert*
  - Process – P.1 Develop and Validate NDE Capabilities, P.2 Establish Stable and Robust AM processes (P.2.1, P.2.2, P.2.3, P.2.4)
- Period of Performance: October 1, 2020, thru Oct 31, 2024
- Total funding: $4.24M
- Total Government Funding: $1.8M
- Total Cost Share: $2.44M
- Funding Organization: OSD ManTech

Overview – JMADD Project Team

America Makes
Brian Schmidt

NIAR (Wichita State University)
John Tomblin
Rachael Andrulonis
Royal Lovingfoss

PSU-CIMP3D (PennState Materials Research Institute)
Ted Reutzel

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EOS
Gregory Hayes
Ankit Saharan

Auburn University
Nima Shamsaei
Shuai Shao
Steve Taylor

Beehive Industries
Ryan O'Hara
Steven Ward
Charles Stansberry

Government Stakeholders

U.S. Army, U.S. Air Force, NASA, Federal Aviation Administration, United States Marine Corps, United States Navy

Public Advisory Committee

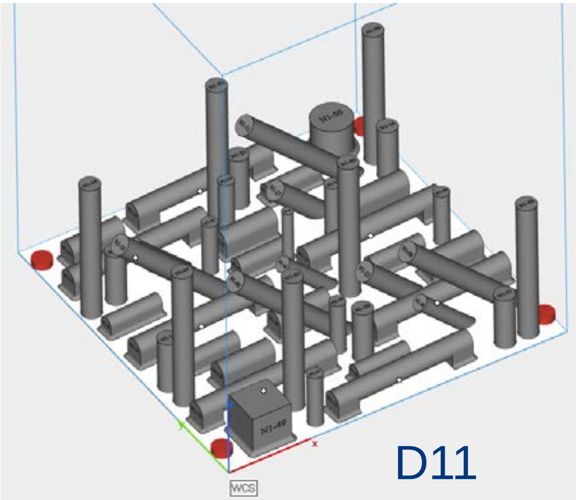
Embraer, Textron Aviation, Tekna, AP&C (A GE Additive Company), EWI, ASTM, Bombardier, Lockheed Martin, GE Additive, Northrop Grumman, Spirit AeroSystems, ATI, TBGA, SAE International

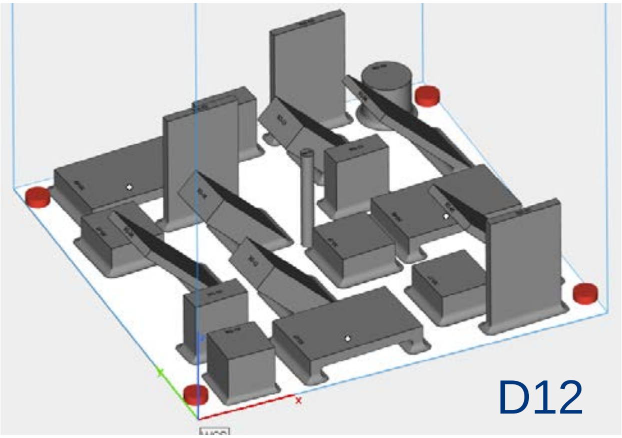
Project Objective

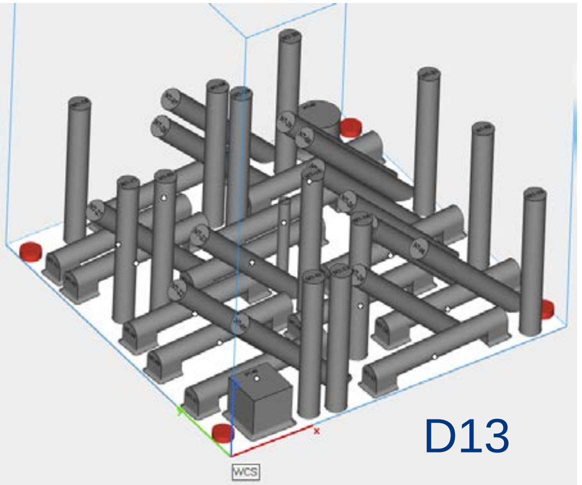
- To produce a set of publicly available statistically substantiated material property data of bulk material properties for metallic AM material with a corresponding material and process specification as well as a framework for future database development projects.
- The selection of a single material and process is necessary to manage the scope of such project, and to begin the work of identifying a standard process to develop material allowables and design data for Metal AM. The initial process and material combination for the scope of this project is Laser Powder Bed Fusion (L-PBF) of Ti-6Al-4V grade 5 alloy.
- The overall objective is to achieve B and A-basis (T90 and T99) design allowable data and establish a best practice for developing AM allowables and specifications that is publicly available for L-PBF of Ti-6Al-4V.

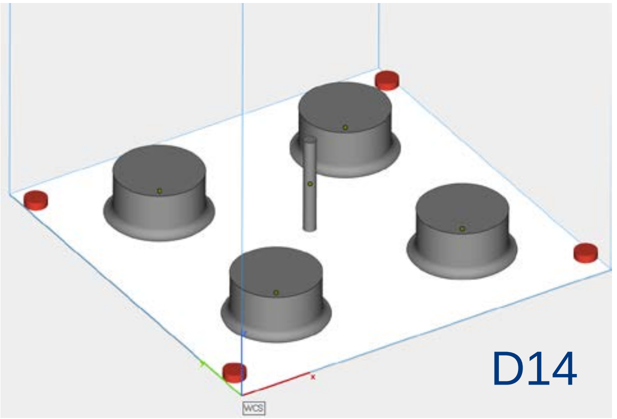
Task 2 Results – Qualification 1 (Virgin)

- Task 2 was initiated in December 2022 and will be completed in April 2024
- Machine architecture: EOS M290
- Three Ti-6Al-4V grade 5 powder suppliers (**AP&C, ATI, and Tekna**)
- Three fabrication sites: **(1) Beehive industries, (2) Boeing Commercial Airplanes, and (3) NIAR – Wichita State University**
- 19 feedstock lots total (10+ req'd)
- 10+ unique heats
- Lot release tensile test from each build
- Static, fatigue, RTA to 700°F ETA testing
- Physical testing
- Feedstock testing
- NDI by X-CT for a subset of specimens
- Four build designs
- Fully pedigreed data
- Site/site, run/run, lot/lot, and build design comparisons
- Microstructure evaluation
- All specimens are will be tested as-machined





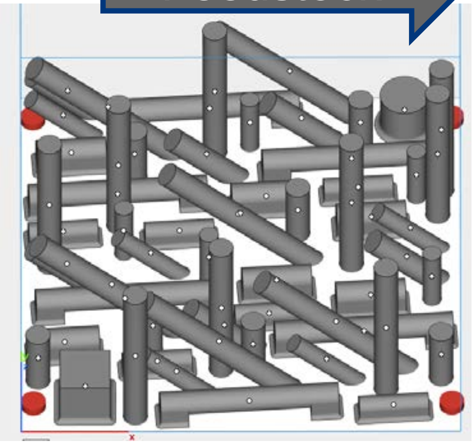




Qualification Process Chain

Build Design

Feedstock



Fabrication

Build Inspection

CLEAN

SR 700°C

SHIP

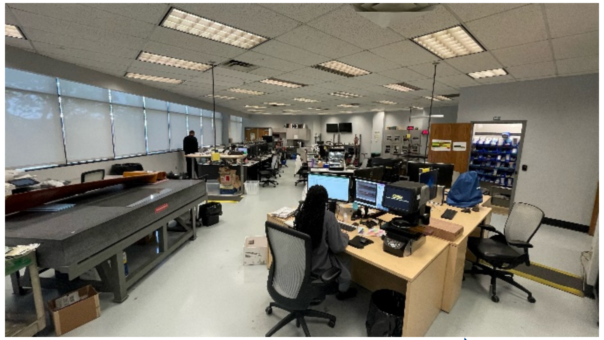
Wire-EDM

CLEAN

HIP

(200 MPa, 815°C)

Machining



Quality Control

Testing

Qualification Static Mechanical Tests

				Number of Lots x Number of Machines x Runs per Machine x Number of Specimens per build *(specimens per temperature) Test Temperature / Moisture Condition		
Build Orientation	**Test Type**	**ASTM Standard**	**Property**	**RTA (70°F/21°C)**	**ETA (300, 500, 700, 900°F, n=2)**	**Coupons Tested**
XY	Tension	ASTM E8, E21, E111	UTS, Yield, Modulus, and Elongation	5x3x2x4	1x3x1x8	144
ZX	Tension	ASTM E8, E21, E111	UTS, Yield, Modulus, and Elongation	5x3x2x4	1x3x1x8	144
Z45	Tension	ASTM E8, E21, E111	UTS, Yield, Modulus, and Elongation	5x3x2x4	-	120
XY	Compression	ASTM E9, E209, E111	Compressive Strength, Yield, and Modulus	3x3x2x3	1x3x1x8	78
ZX	Compression	ASTM E9, E209, E111	Compressive Strength, Yield, and Modulus	3x3x2x3	1x3x1x8	78
Z45	Compression	ASTM E9, E209, E111	Compressive Strength, Yield, and Modulus	3x3x2x3	-	54
XY	Shear	ASTM B769	Ultimate Shear Strength	3x3x2x3	1x3x1x8	78
ZX	Shear	ASTM B769	Ultimate Shear Strength	3x3x2x3	1x3x1x8	78
Z45	Shear	ASTM B769	Ultimate Shear Strength	3x3x2x3	-	54
XY	Bearing	ASTM E238	Yield and Bearing Strength	3x3x2x3	-	54
ZX	Bearing	ASTM E238	Yield and Bearing Strength	3x3x2x3	-	54
Z45	Bearing	ASTM E238	Yield and Bearing Strength	3x3x2x3	-	54
XY	Fracture Toughness	ASTM E399	Linear-Elastic Fracture Toughness	3x3x2x3	-	54
ZX	Fracture Toughness	ASTM E399	Linear-Elastic Fracture Toughness	3x3x2x3	-	54
Z45	Fracture Toughness	ASTM E399	Linear-Elastic Fracture Toughness	3x3x2x3	-	54

Qualification test matrix to be performed twice. Once for Task 2 and an additional time for Task 3 using virgin/reuse powder blend.

Qualification 1 Updates

- All Qualification 1 specimens have been fabricated and machined
- Of the approximately 1733 total specimens defined for Qualification 1 testing, 1599 specimens have been inspected and processed through QC to mechanical test.
- Testing for the fabricated, HIP, and machined specimens is ongoing. (Preliminary reduced data presented in the following slides)
- Test results from the blended reuse powder from all three fabricators were received from NSL Analytical (Test results will be presented in the following Task 3 results slides)
- “Before-blend reuse” powder will also be sampled and tested (powder testing is in process)
- Qualification dataset 1 generation to be completed by the end of April 2024.

Fabrication plan

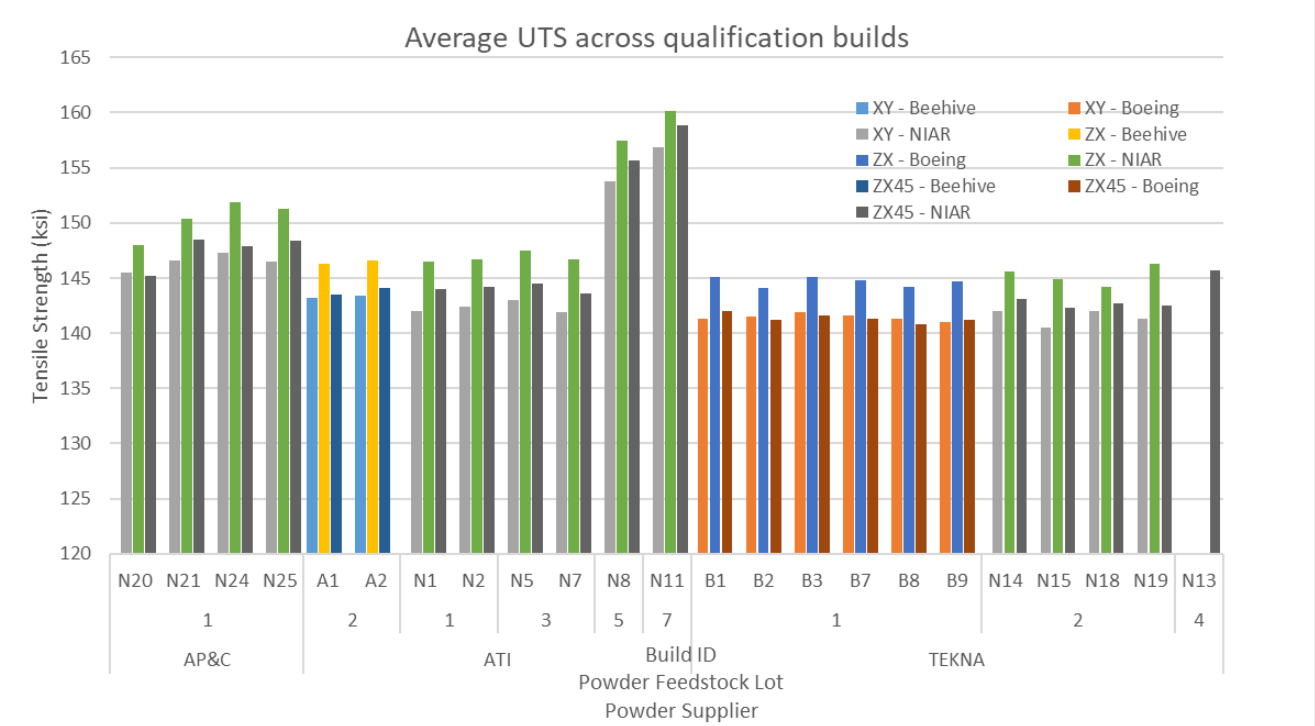
NIAR Q1 Fabrication				Beehive Q1 Fabrication				Boeing Q1 Fabrication			
Powder	Lot	Build Design	Build #	Powder	Lot	Build Design	Build #	Powder	Lot	Build Design	Build #
ATI	1	D11	N1	ATI	2	D11	A1	Tekna	1	D11	B1
			N2				A2				B2
		D12	N3			D12	A3				B3
			N4				A4			D12	B4
	3	D11	N5		4	D11	A5				B5
		D12	N6			D12	A6				B6
		D13	N7			D13	A7			D13	B7
	5	D11	N8		6	D11	A8				B8
		D12	N9				A9				B9
		D13	N10			D12	A10				
	7	D11	N11	AP&C	2	D11	A11				
		D12	N12				A12				
	8	D13	N13				A13				
Tekna	1	D11	N14			D12	A14				
			N15				A15				
		D12	N16				A16				
			N17			D13	A17				
		D13	N18				A18				
			N19				A19				
AP&C	1	D11	N20								
			N21								
		D12	N22								
			N23								
		D13	N24								
			N25								
Tekna	2	D12	N3-2								
		D13	N13-2								
	4	Thermal	N26								

Additional build completed

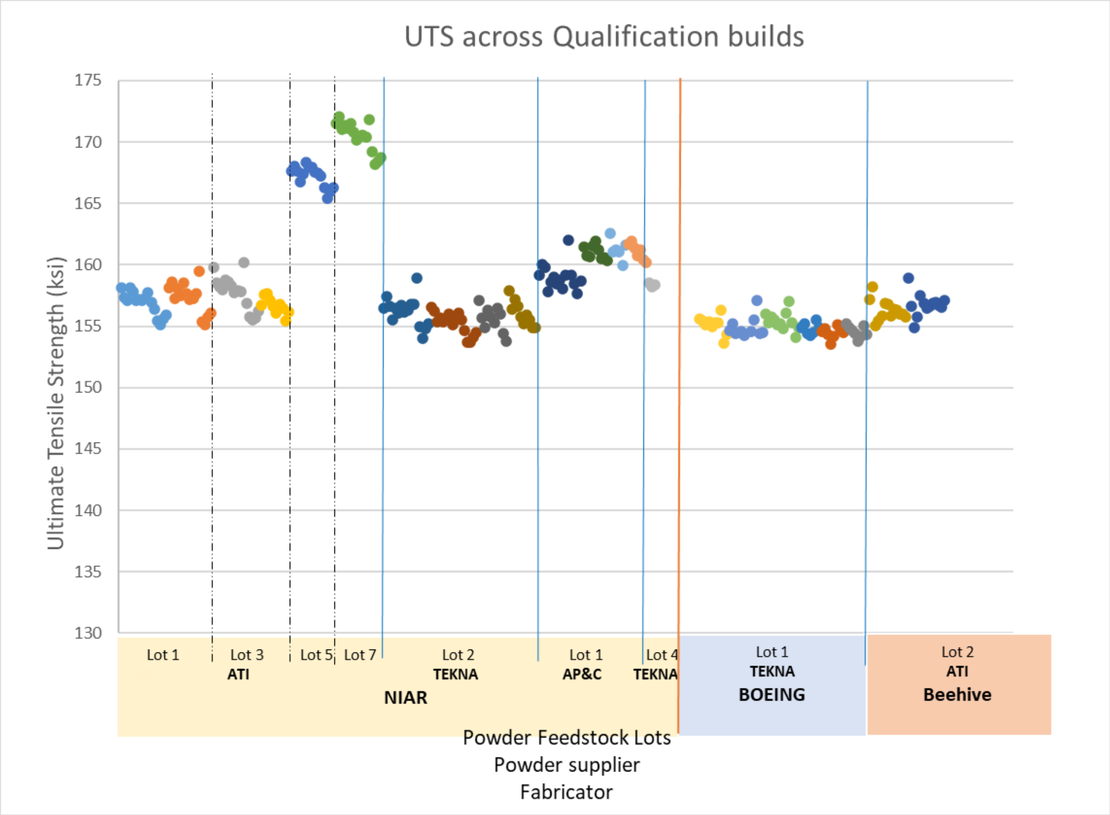
Fabricated | In process | # Build Failure

Qualification 1: ASTM E8 (Tension)

- Includes all 262 tested ASTM E8 specimens across 23 builds, across five ATI, three Tekna, and one AP&C powder lots.
- The data across most builds performed closely, except for build N8 and N11 which yielded higher results.
- Between the orientation data groups, ZX specimens averaged higher performance, followed by ZX45, then XY. Similar trends observed in the Prequalification studies.



Tension testing progress: 75% through



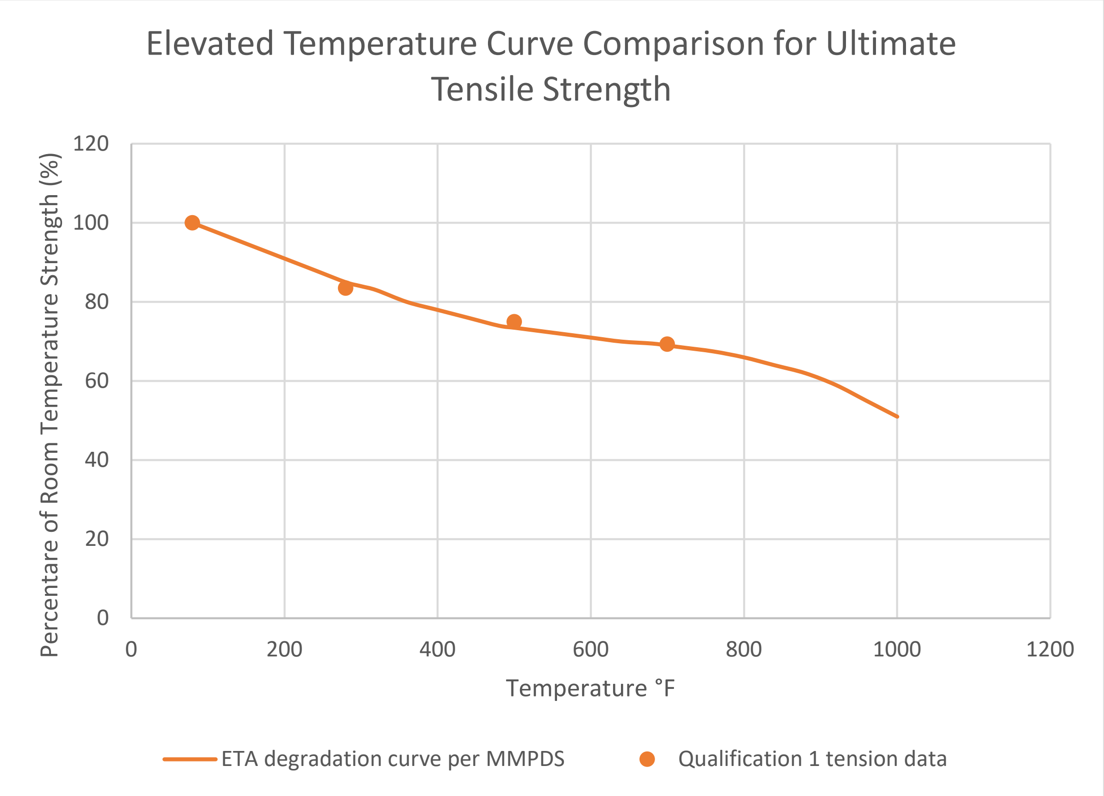
Data points specimen orientation sequence from left to right across each build: **ZX, Z45, then XY**

	Average	Standard Deviation	Coefficient of Variation (%)
0.2% Offset Yield Strength (ksi)	145.74	4.92	3.37
Ultimate Tensile Strength (ksi)	158.18	4.41	2.79
Modulus (Msi)	17.03	0.27	1.58
Percent Elongation at yield (%)	1.05	0.03	2.60
Percent Elongation at fracture (%)	13.95	0.77	5.53

Qualification 1: ASTM E21 (Elevated temp.)

- Eight specimens were tested at each elevated test temperature.
- ETA degradation curve was generated per MMPDS Figure 5.4.1.1.1. utilizing the Qual 1 average ultimate tensile strength of 158.35 ksi.
- Upon reviewing the gathered tension data, the percent knock down of the average UTS when the specimens were tested at elevated temperatures faired closely to MMPDS's temperature degradation curve knockdown (see table below).
- 900°F testing is in process.

ETA Percent Knockdown	300°F	500°F	700°F
MMPDS Figure 5.4.1.1.1.	16%	26.5%	31%
JMADD	16.52%	24.96%	30.65%



Blue texts in table are CoV's (%)

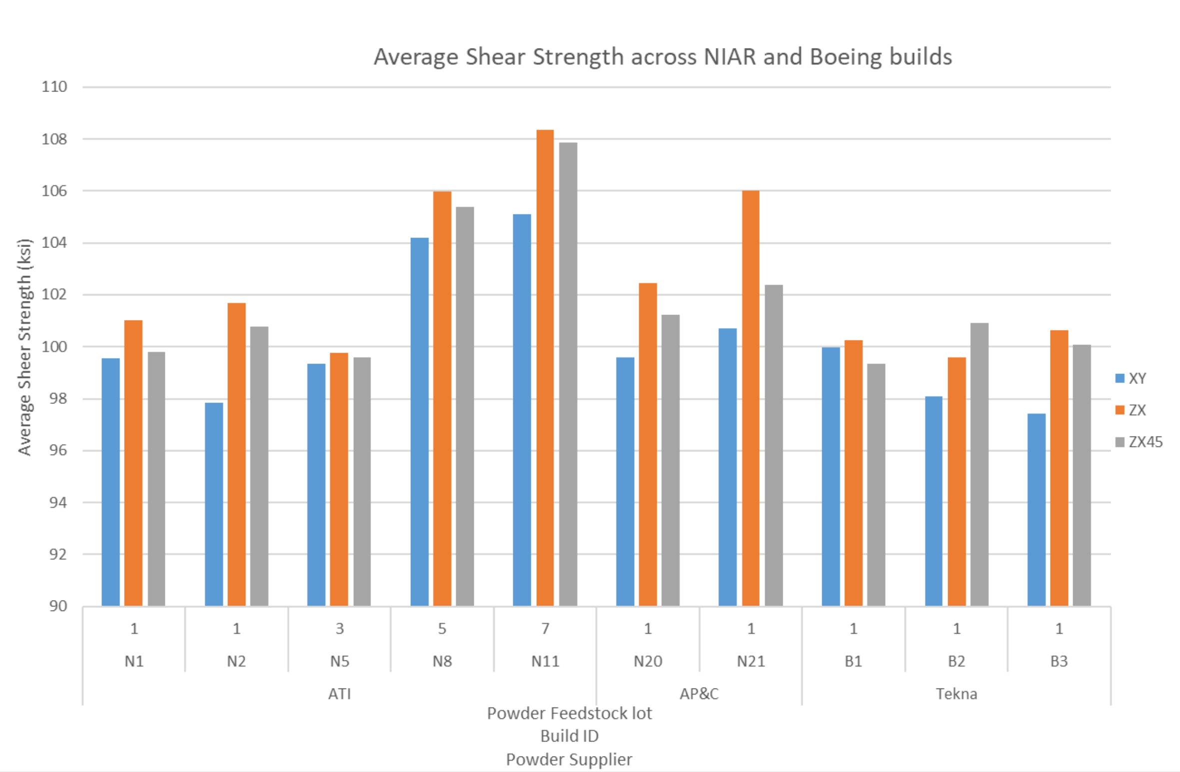
Test Temperature (°F)	0.2% Offset Yield Strength [ksi]		UTS (Ksi)		Young's Modulus (Msi)		Elongation at Yield (%)		Elongation at Fracture (%)	
RTA	145.88	3.51	158.35	2.91	17.03	1.61	1.06	2.72	14.02	5.28
300	116.32	4.43	132.19	1.54	15.85	1.42	0.93	3.64	14.65	5.77
500	99.50	3.14	118.82	2.54	15.20	1.66	0.85	1.56	13.82	4.62
700	91.02	4.26	109.81	3.62	14.26	3.16	0.84	1.29	12.47	6.75

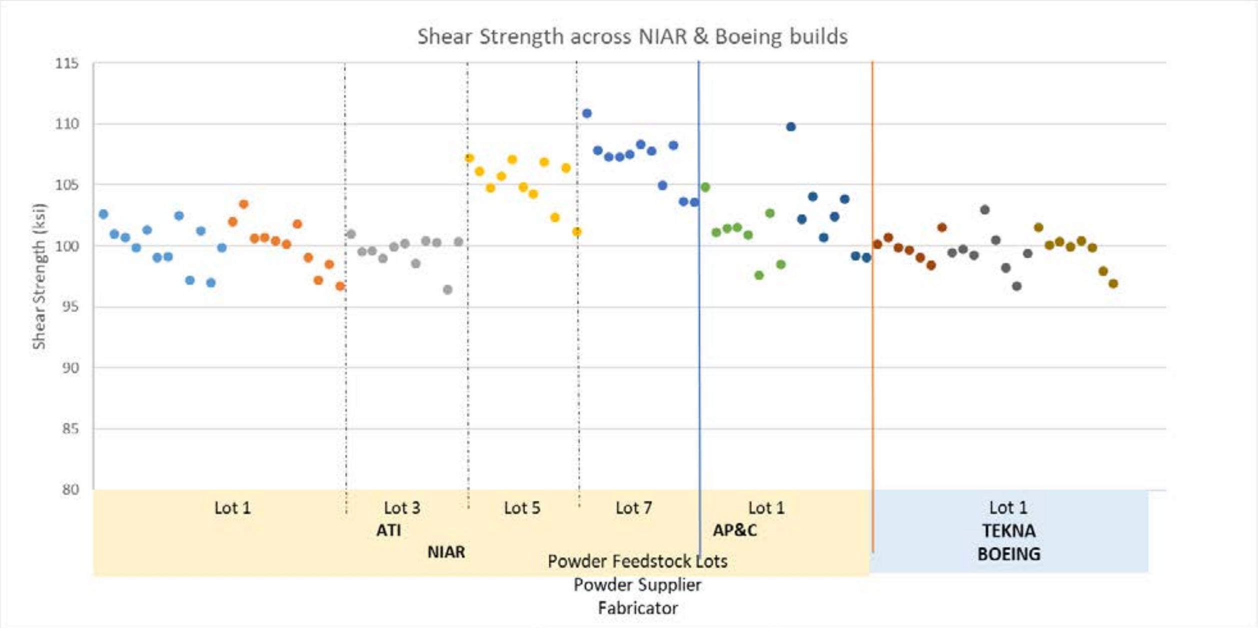
Elevated temperature curve was based off percentages provided in Figure 5.4.1.1.1 from MMPDS-17 Handbook

Elevated tension testing progress: 75% through

Qualification 1: ASTM B769 (Shear)

- Includes all 95 tested ASTM B769 specimens across 7 NIAR builds and 3 Boeing builds were tested.
- The data shows that specimens fabricated with ATI Lot 5 and Lot 7 yielded higher shear strength.
- Between the orientation data groups, ZX specimens averaged higher results, followed by ZX45, then XY specimens. Similar trends were observed in the prequalification studies.





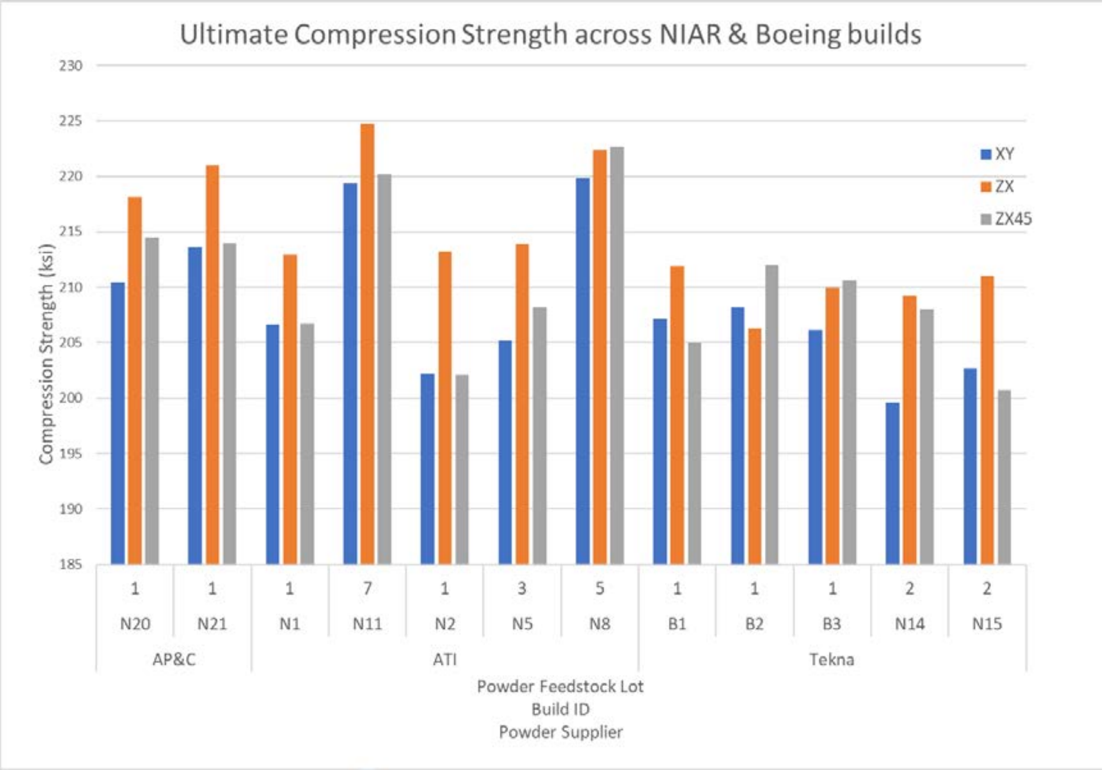
Data points specimen orientation sequence from left to right across each build: **ZX, Z45, then XY**

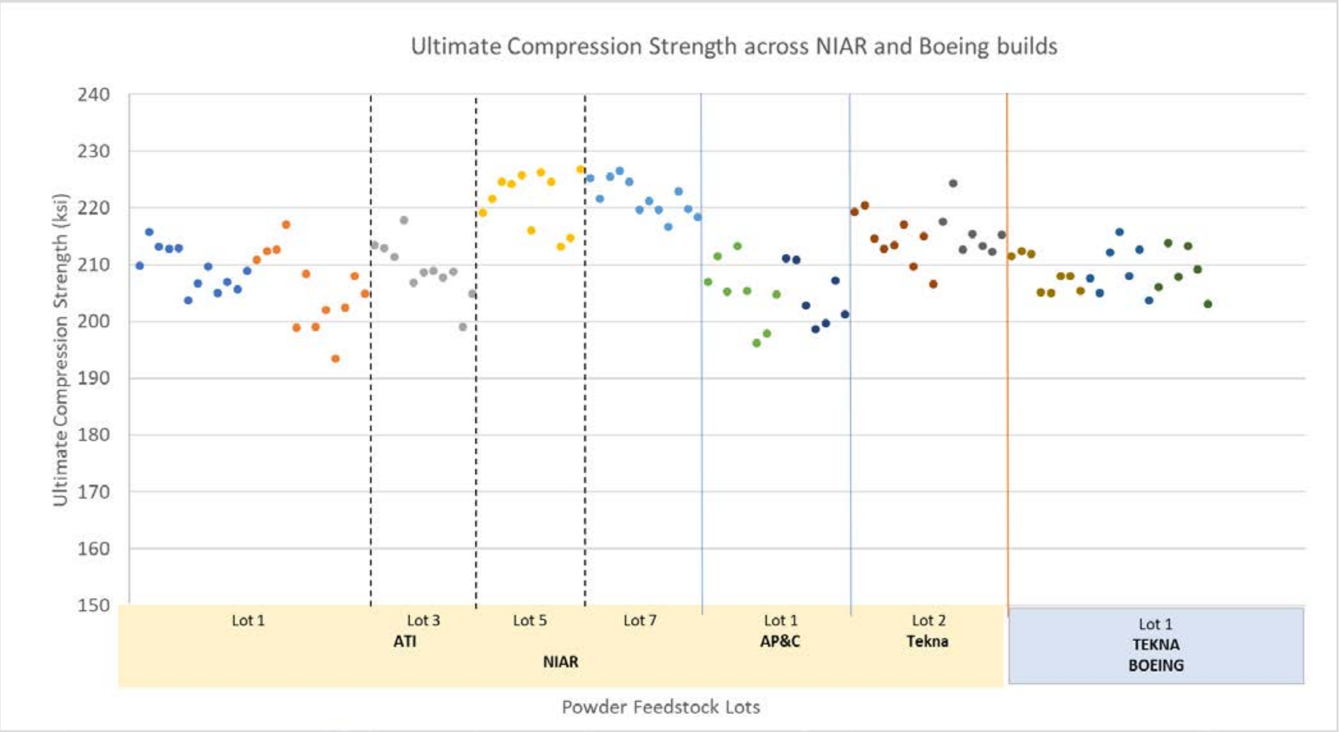
	Average Shear Strength (ksi)	Standard Deviation	Coefficient of Variation (%)
ZX	102.68	3.36	3.28
XY	100.41	3.18	3.17
ZX45	101.84	2.91	2.86

Shear testing progress: 65% through (Beehive test results to follow)

Qualification 1: ASTM E9 (Compression)

- A total of 95 specimens were tested, across 7 NIAR builds and 3 Boeing builds.
- There was a separation between the orientation data groups similar to the prequalification studies, with ZX and ZX45 specimens averaging higher UCS.
- The data also displayed the similar trend as E8 and B769 tests, where specimens fabricated with ATI Lot 5 and Lot 7 averaged higher UCS





Data points specimen orientation sequence from left to right across each build: **ZX, Z45, then XY**

	Ultimate Compression Strength [ksi]	0.2% Offset Yield Strength (ksi)	Compression Modulus (Msi)
Average	211.63	160.16	17.65
Standard Deviation	7.50	7.39	0.47
CoV [%]	3.54	4.61	2.68

Compression testing progress: 55% through (Beehive test results to follow)

Qualification 1: ASTM E209 (Elevated temp.)

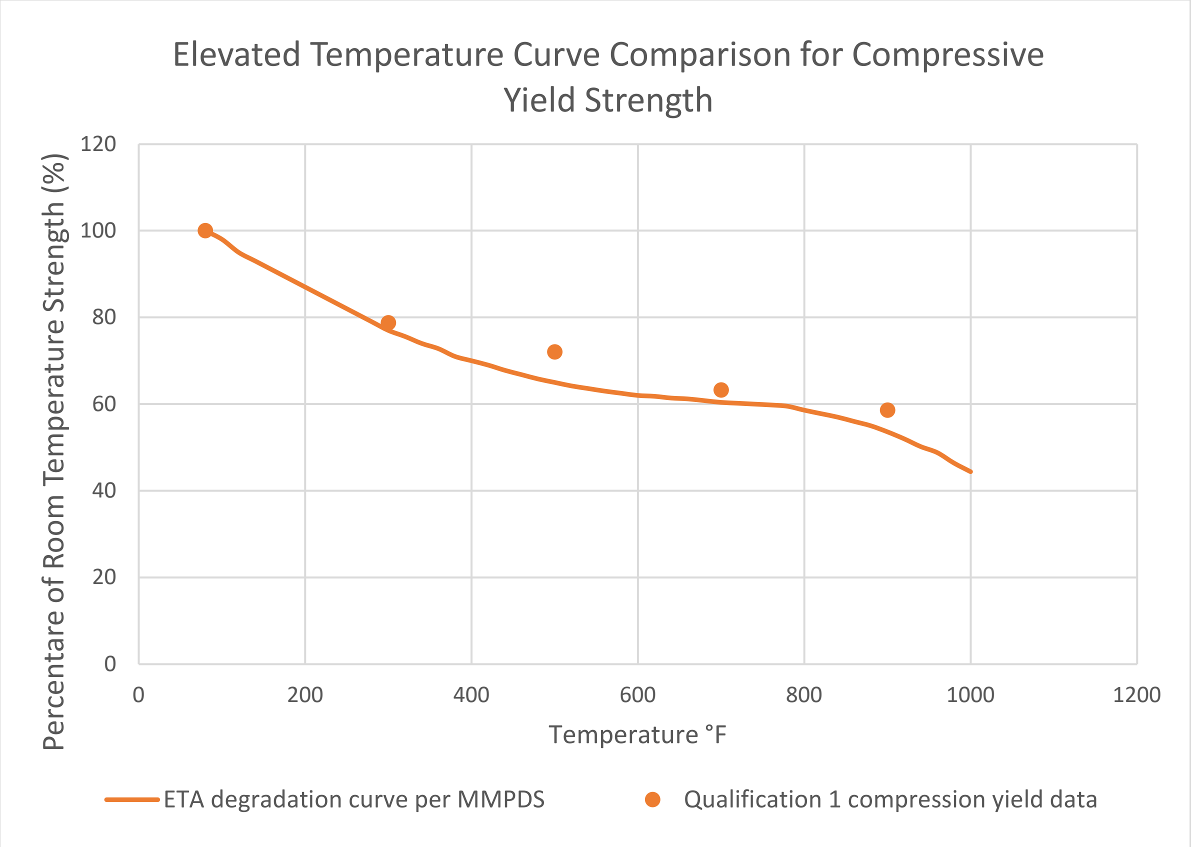
- Eight specimens were tested at each elevated test temperature.
- ETA degradation curve was generated per MMPDS Figure 5.4.1.1.2. utilizing the Qual 1 compressive yield strength of 160.16 ksi.
- Upon reviewing the gathered compression data, the percent knock down of the average compressive yield strength are slightly lower when compared to MMPDS's temperature degradation curve knockdown (see table below).

ETA Percent Knockdown	300°F	500°F	700°F	900°F
MMPDS per Figure 5.4.1.1.2.	23%	35%	39.6%	46.4%
JMADD	21.2%	27.9%	36.8%	41.4%

Blue texts in table are CoV's (%)

Test Temperature (°F)	Ultimate Compression Strength [ksi]		0.2% Offset Yield Strength (ksi)		Compression Modulus (Msi)	
RTA	211.63	3.54	160.16	4.61	17.65	2.68
300	183.51	2.80	126.18	3.61	17.46	3.37
500	183.41	2.73	115.42	6.21	15.76	3.57
700	167.70	3.17	101.27	5.06	15.08	4.60
900	145.58	3.04	93.84	3.93	13.74	13.85

Elevated compression testing progress: Complete

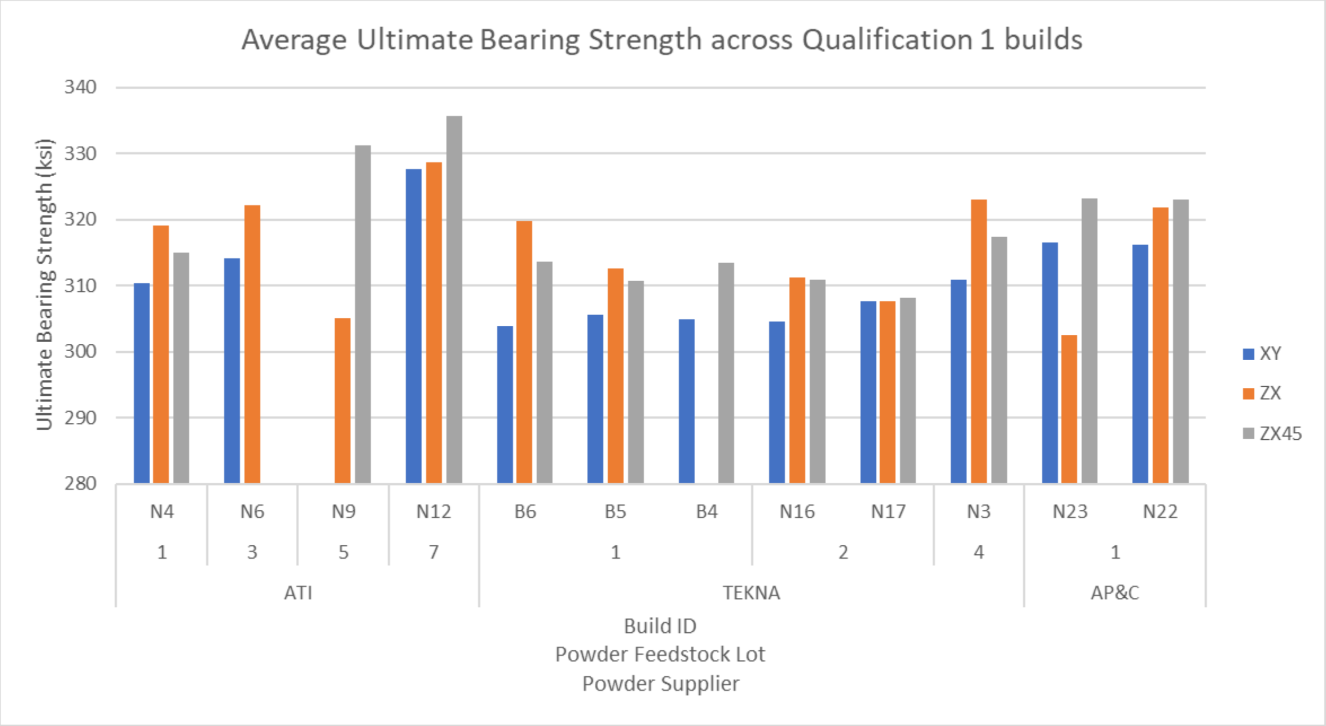


Elevated temperature curve was based off percentages provided in Figure 5.4.1.1.2. from MMPDS-17 Handbook

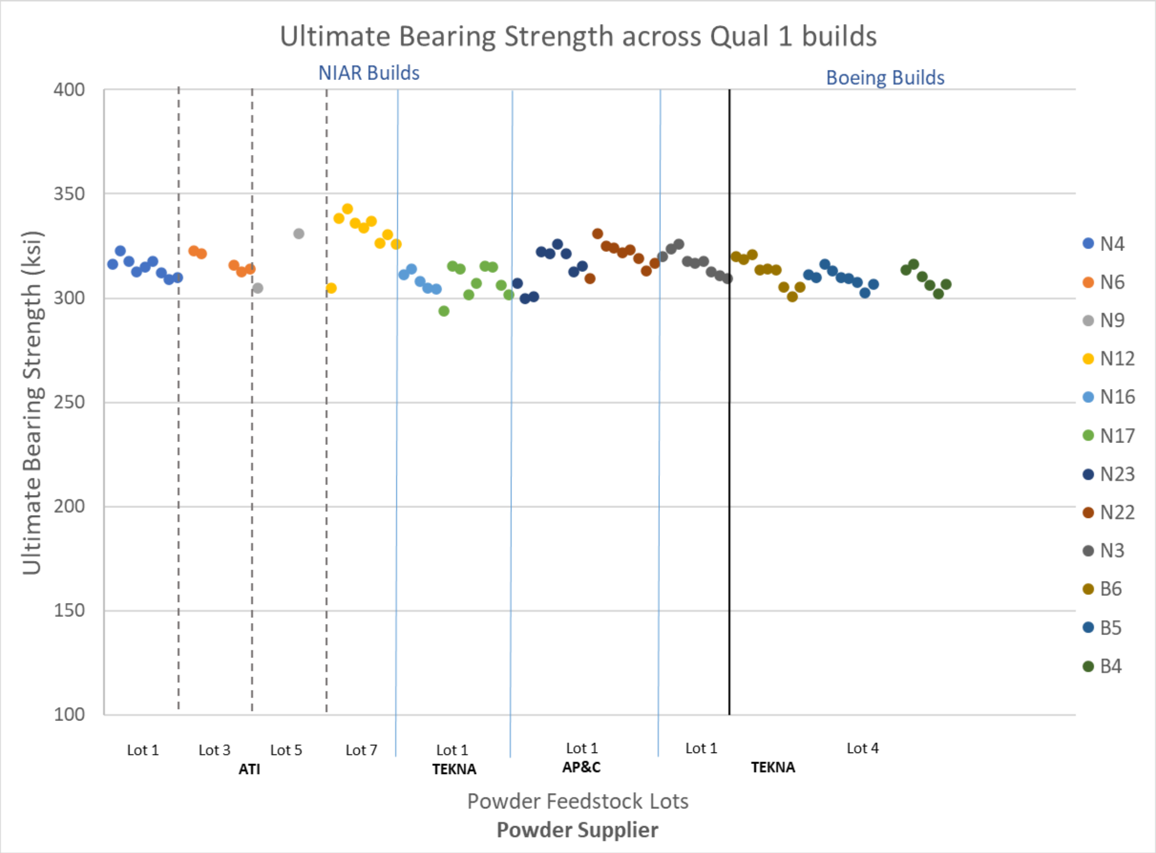
Qualification 1: ASTM E238 (Bearing)

America Makes — Driven by… NCDMM

- 90 bearing specimens (E/D=2.0) were tested across 9 NIAR builds and 3 Boeing Builds. (*E/D=1.5 will be tested in Qualification 2*)
- The data across builds performed similarly, except for build N9 and N12, which yielded higher results.
- This is attributed to the higher interstitial elements within the ATI powder Lot 5 and Lot 7.
- There was also a separation between the orientation data groups with ZX45 specimens averaging higher bearing strength, followed by ZX then XY specimens.



Bearing tests progress: 63% through (Beehive test results to follow)



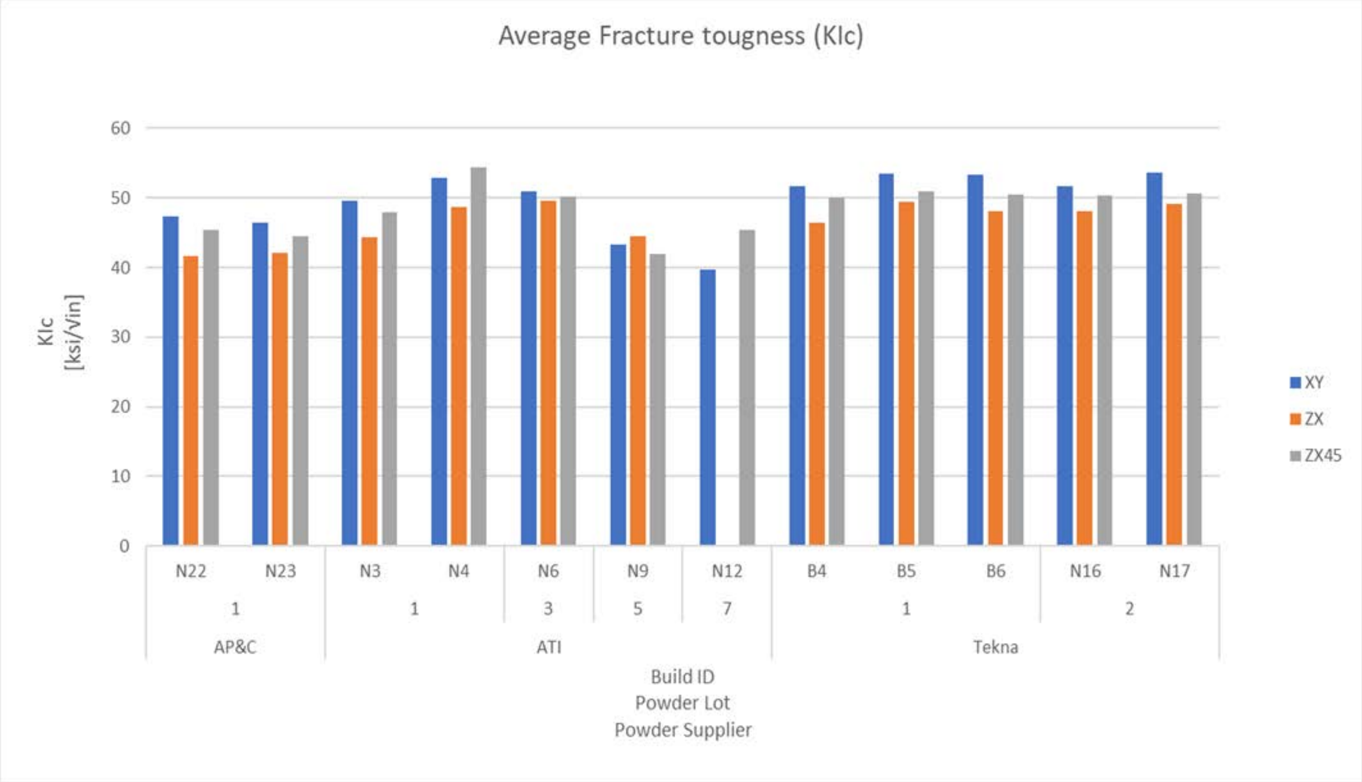
Data points specimen orientation sequence from left to right across each build: **ZX, Z45, then XY**

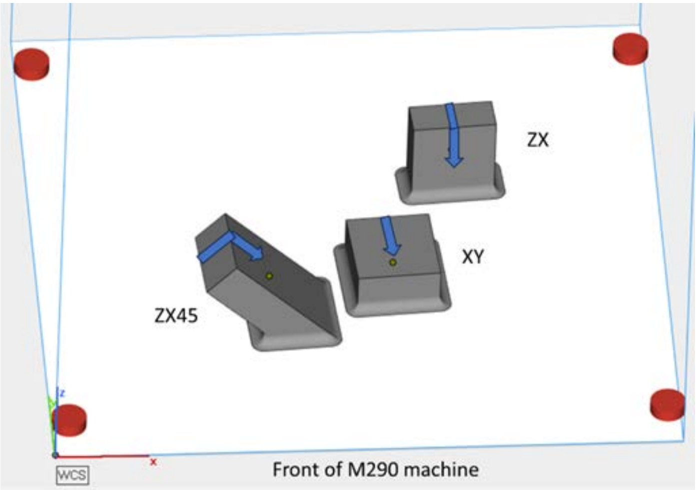
	Ultimate Bearing Strength (ksi)	2% Offset Bearing Strength (ksi)
Average	315.13	259.50
Standard Deviation	9.40	10.47
CoV [%]	2.98	4.03

Qualification 1: ASTM E399 (Fracture Toughness)

America Makes — Driven by… NCDMM

- 78 specimens were tested. (W=1 inch)
- The fracture toughness (K1C) values reported compare closely to those of conventionally manufactured Ti64, which ranges between 40 to 60 ksi√in (Kumar, Prakash, & Ramamurty, 2018).
- A separation between orientation data groups was observed, with XY orientation specimens yielding higher K1C values followed by ZX45, and then ZX. Similar trends observed by Kumar and Ramamurty (2019)
- Researchers also reported lower K1C when the configuration of the crack growth occurs parallel to the columnar prior beta grains formed along the laser tracks during printing





	KIc [ksi/√in]
Average	47.81
Standard Deviation	4.34
CoV [%]	9.09

Fracture toughness tests progress: 63% through (Beehive test results to follow)

Qualification 1: Powder elemental Composition

- Elemental composition acquired from their respective powder material certificates.
- Builds fabricated with ATI Lot 5 and Lot 7 contained higher amounts of interstitial elements (Oxygen, Carbon, and Nitrogen) which could explain the higher strength values.
- All measured elemental composition conforms to AMS 7015 and ASTM F2924 specifications.

NIAR will also be outsourcing work for bulk material elemental analysis (ICP-AES) in the final material state. (NSL Analytical).

Powder Supplier	ATI					Tekna			AP&C	AMS 7015	ASTM F2924
Powder Lot	1	2	3	5	7	1	2	4	1		
Element	Results/Measured (Weight percent)										
Aluminum	6.03	6.12	6.01	6.31	6.16	6.13	6.39	6.18	6.41	5.50 - 6.75	
Vanadium	4.02	4.06	4.12	3.94	3.86	4.05	4.23	4.06	4.03	3.50 - 4.50	
Iron	0.21	0.22	0.21	0.15	0.14	0.17	0.18	0.16	0.22	≤ 0.30	
Yttrium	< 0.0009	< 0.0009	< 0.0009	< 0.0009	< 0.0009	< 0.005	< 0.005	< 0.001	< 0.001	≤ 0.005	
Carbon	0.006	0.007	0.008	0.029	0.039	0.009	0.010	< 0.005	0.01	≤ 0.08	
Oxygen	0.149	0.142	0.145	0.178	0.19	0.12	0.13	0.12	0.14	0.11 - 0.20	≤ 0.20
Nitrogen	0.013	0.012	0.014	0.030	0.036	0.007	0.007	0.009	0.010	≤ 0.05	
Hydrogen	0.0009	0.0006	0.0010	0.001	0.0010	0.002	0.002	0.004	0.002	≤ 0.015	
Titanium	Balance	Balance	Balance	Balance	Balance	Balance	Balance	Balance	Balance	Balance	

ASTM B311

Test Setup Picture

- Boeing cubes were fabricated with Tekna powder and NIAR cubes were fabricated with ATI, AP&C, and Tekna powder.
- Test result shows that there is a consistency between all sites and powder feedstock used.
- Density from MMPDS per Table 5.4.1.0(c1):
    - 0.16 lb/in³ (4.43 g/cc)

		Specimen Density (lbm/in3)
Boeing	Average	0.15983
	Standard Deviation	0.00001
	CoV (%)	0.00638
NIAR	Average	0.15981
	Standard Deviation	0.00013
	CoV (%)	0.08269
Beehive	Average	0.15980
	Standard Deviation	0.00011
	CoV (%)	0.06623

ASTM E18

5 Top face indentations

5 Front face indentations

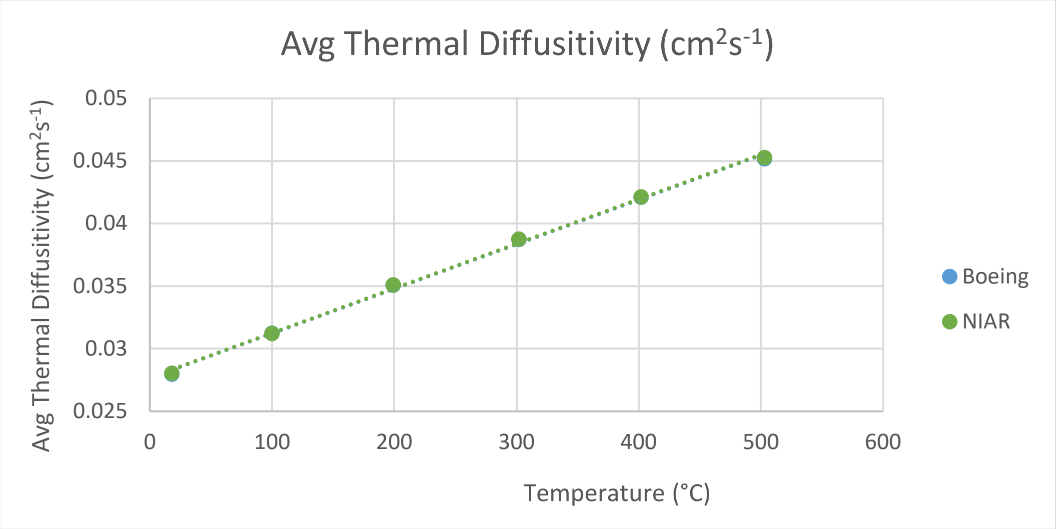
- 5 hardness tests performed on Front and Top of each density cube.
- Only one specimen tested from ATI lot 5.
- Upon reviewing the data, hardness values varied minimally across sites.
- Specimen from ATI lot 5 yielded highest hardness measurement. (which aligns with other static properties as ATI lot 5 had higher interstitials in powder lot.

Avg Combined Hardness (Rockwell C)	ATI						Tekna		AP&C	
	Lot 1	Lot 2	Lot 3	Lot 4	Lot 5	Lot 6	Lot 1	Lot 2	Lot 1	Lot 2
Average	36.95	37.79	37.32	38.05	38.89	39.78	37.02	37.58	37.67	37.98
Standard Deviation	0.81	0.84	0.86	0.88	-	1.31	0.99	0.83	1.10	0.76
CoV (%)	2.19	2.21	2.32	2.32	-	3.30	2.68	2.21	2.91	1.99

Static strength properties for ATI Lot 4, Lot 6, and AP&C lot 2 to follow

Qualification 1: Thermal Diffusivity and Conductivity

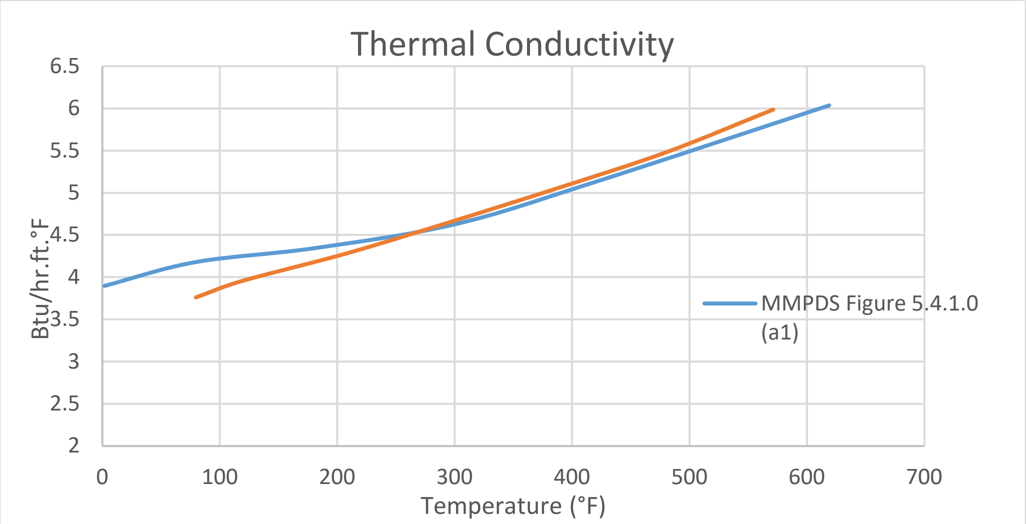
ASTM E1461



		Temperature (°C)					
		18	100	199	302	402	503
Boeing	Average (cm^2s^{-1})	0.0280	0.0312	0.0351	0.0387	0.0421	0.0452
	Standard Deviation	0.0001	0.0002	0.0002	0.0002	0.0002	0.0002
	CoV (%)	0.4932	0.5228	0.5890	0.4449	0.3680	0.4354
NIAR	Average (cm^2s^{-1})	0.0280	0.0312	0.0351	0.0388	0.0421	0.0453
	Standard Deviation	0.0004	0.0005	0.0006	0.0006	0.0006	0.0007
	CoV (%)	1.5891	1.5893	1.5878	1.4818	1.4964	1.4639

(Beehive test results to follow)

ASTM E1530 (NIAR results only)

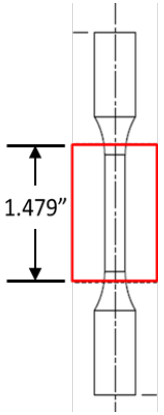


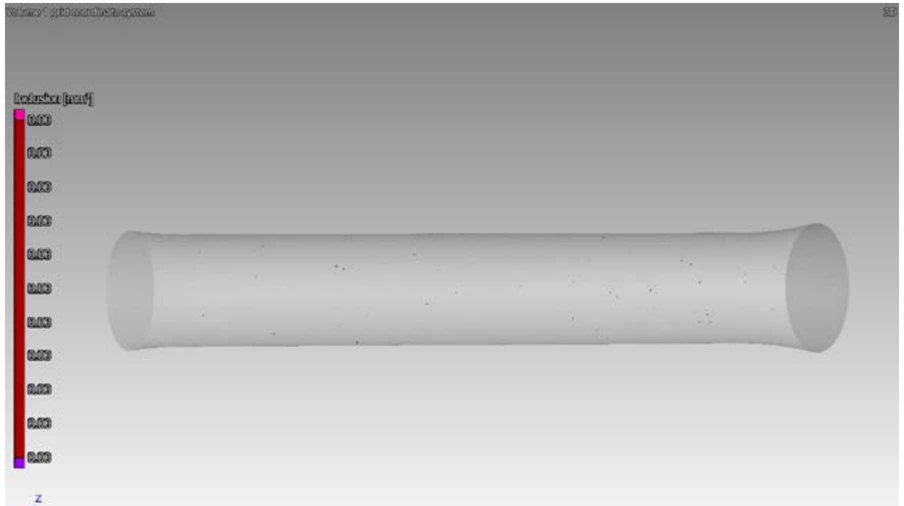
Mean specimen Temperature (°F)	Average BTU/h·ft·°F	CoV %
79.78	3.79	0.67
121.38	3.96	0.19
210.77	4.32	0.56
301.40	4.68	0.39
391.09	5.08	0.53
481.08	5.51	0.54
571.23	5.97	0.59

(Boeing and Beehive test results to follow)

Qualification 1: Representative CT Scan Results

- Parameters:
  - CT scan was carried out per NIAR's internal process: CP6190
  - 12 µm voxel size scan resolution.
  - Scan times averaged 5 hours and 30 minutes
  - Only a subset of Qualification specimens were selected for CT scan
- Results:
  - All CT scan data thus far for percent (%) porosity and inclusion are close to zero, ≤ 0.001%.





ASTM E8 scan area

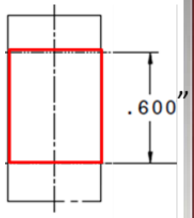
<u>Courtesy of Carnegie Mellon University (CMU):</u>

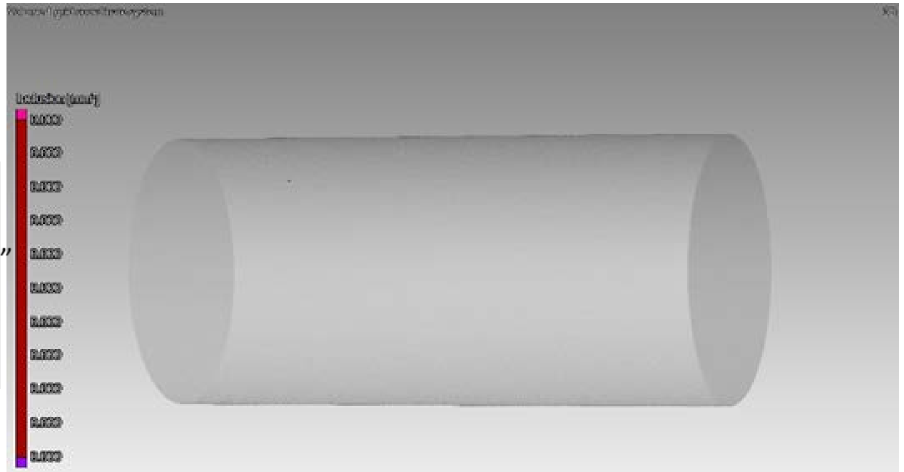
Supplemental CT scan data:

- Four NIAR specimens were supplied to CMU for additional CT scan data. (2 ZX, 1 ZX45, and 1XY orientation specimens.)
- CMU Voxel resolution range: 3.32 – 4.53 µm

Results:

- Pores of 60um in diameter were detected in one (XY specimen) of the four specimens submitted.
- XY specimen porosity percentage was 0.002%.
- Max volume of pores were 0.0003 mm^3
- Pores smaller than (voxel size)^3 were not detected in scans, therefore no pores with diameter larger than 13.8 um were detected in the other specimens.





ASTM E9 scan area

Note: Only a subset (216) specimens across test type will be CT scanned.
CT scan progress: 60% through

Task 3 Results

Qualification 2 (Virgin (50%) + Reuse (50%))

- Task 3 was initiated in July 2023 and will be completed in October 2024
- The qualification 1 test matrix is repeated for the qualification dataset 2
- The build designs, powder suppliers, and fabricators are identical to qualification 1
- The qualification 2 dataset will utilize 11 lots of blended (virgin + reuse) powder plus 8 lots of virgin powder for specimen fabrication.
- This yields a total of 60 builds across three fabricators:
  - 29 builds at NIAR
  - 24 builds at Beehive
  - 7 builds at Boeing

Qualification 2 Updates

- All qualification 2 fabrication is complete
- Elcan Industries has completed all sieving and blending work for all JMADD powder lots.
- All fabricated Qual 2 builds are now undergoing the necessary JMADD post-processing steps before final specimen machining.
- Testing for dataset 2 has begun (initiated December 19, 2023).
- Preliminary test results will be presented in the following slides

NIAR Q2 Fabrication			
ATI	1	R-D11	N27
ATI	1	R-D12	N28
ATI	1	R-D13	N29
ATI	3	R-D11	N30
ATI	3	R-D12	N31
ATI	3	R-D13	N32
ATI	5	R-D11	N33
ATI	5	R-D12	N34
ATI	5	R-D13	N35
ATI	7	V-D11	N36
ATI	7	V-D12	N37
ATI	8	V-D13	N38
ATI	9	V-D11	N39
ATI	9	V-D12	N40
ATI	10	V-D13	N41
ATI	12	V-D13	N42
Tekna	1	R-D11	N43
Tekna	1	R-D12	N44
Tekna	1	R-D13	N45
Tekna	3	V-D11	N46
Tekna	3	V-D12	N47
Tekna	3	V-D13	N48
AP&C	1	R-D11	N49
AP&C	1	R-D12	N50
AP&C	1	R-D13	N51
AP&C	3	V-D11	N52
AP&C	3	V-D12	N53
AP&C	3	V-D13	N54
Tekna	4	R-D14	N55

Beehive Q2 Fabrication			
ATI	2	R-D11	A20
ATI	2	R-D12	A21
ATI	2	R-D13	A22
ATI	4	R-D11	A23
ATI	4	R-D12	A24
ATI	4	R-D13	A25
ATI	6	R-D11	A26
ATI	6	R-D12	A27
ATI	6	R-D13	A28
ATI	9	V-D11	A29
ATI	9	V-D12	A30
ATI	10	V-D13	A31
ATI	11	V-D11	A32
ATI	11	V-D11	A33
ATI	11	V-D12	A34
ATI	11	V-D12	A35
ATI	12	V-D13	A36
AP&C	2	R-D11	A37
AP&C	2	R-D12	A38
AP&C	2	R-D13	A39
AP&C	3	V-D11	A40
AP&C	3	V-D12	A41
AP&C	3	V-D13	A42
Tekna	4	R-D14	A43

Boeing Q2 Fabrication			
Tekna	3	V-D11	B10
Tekna	3	V-D12	B11
Tekna	3	V-D13	B12
Tekna	1	R-D11	B13
Tekna	1	R-D12	B14
Tekna	1	R-D13	B15
Tekna	4	R-D14	B16

Fabricated (green)
In process (yellow)

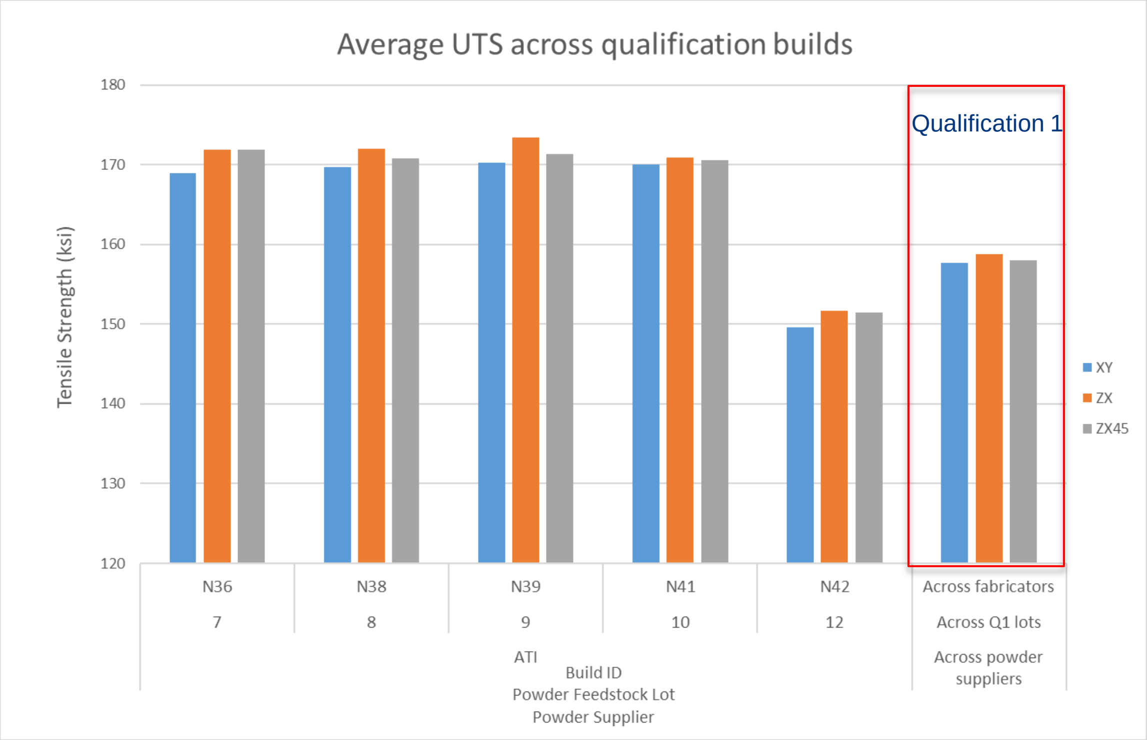
Qualification 2: (Reuse) Powder Testing Results

- Each lot of blended reuse powder from all fabricators were tested by NSL Analytical for elemental composition.
- “Before-blend reuse” powder was not tested prior to blending.
- NIAR is working on getting a PO and samples sent to NSL for further powder testing.

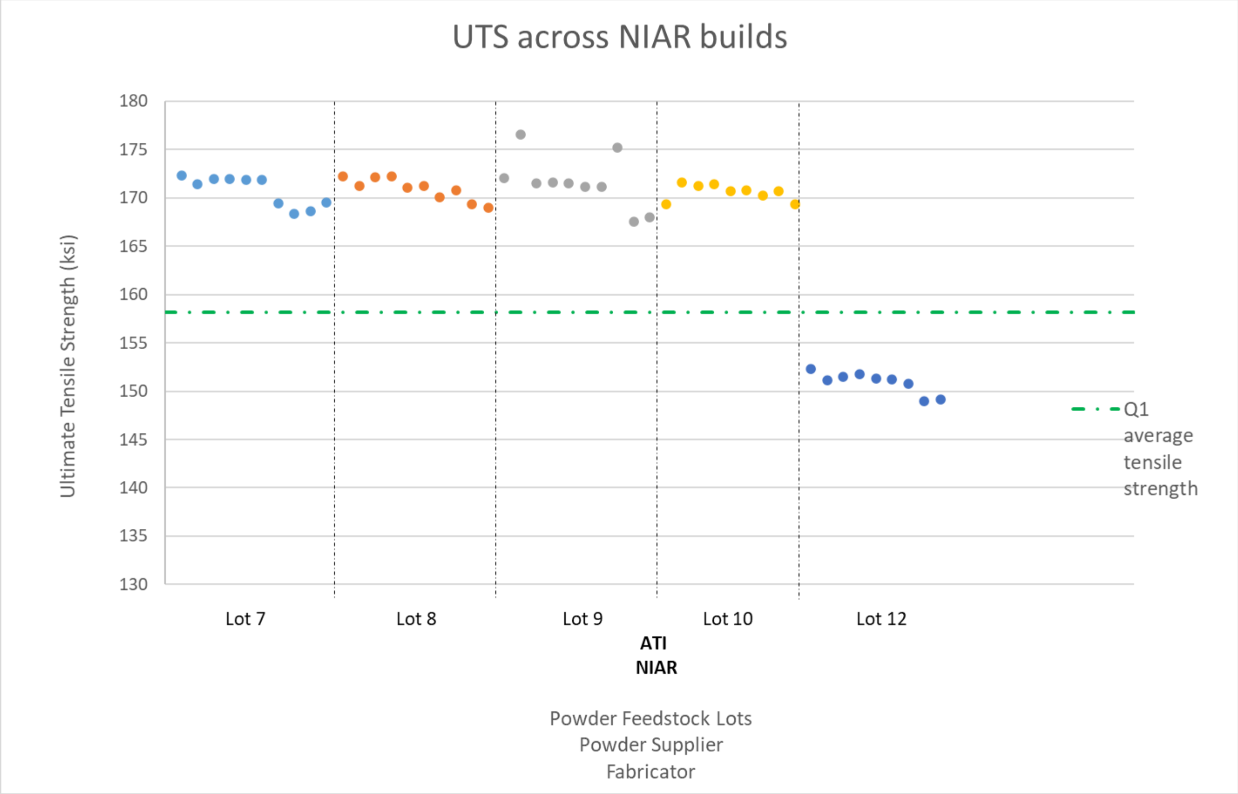
			CHEMICAL COMPOSITION (wt. %) - Ti BALANCE									
Supplier	Lot #	Powder state	Al	V	Fe	Y	C	O^2	N	H^2	OTHERS EACH	OTHERS TOTAL
AP&C	**Lot 1**	**Virgin**	6.41	4.03	0.22	< 0.001	0.010	0.14	0.0100	0.0020	< 0.10	< 0.40
		Reuse	6.48	4.04	0.22	< 0.001	0.016	0.15	0.0086	0.0017	< 0.05	< 0.10
	Lot 2	**Virgin**	6.31	3.96	0.2	< 0.001	0.010	0.14	0.010	0.0020	< 0.10	< 0.4
		Reuse	6.41	4.01	0.19	< 0.001	0.014	0.14	0.013	0.0016	< 0.05	0.027
Tekna	**Lot 1**	**Virgin**	6.13	4.05	0.17	< 0.005	0.009	0.12	0.0070	0.0020	< 0.05	< 0.05
		Reuse	6.32	4.26	0.19	< 0.001	0.010	0.14	0.0052	0.0029	< 0.05	< 0.10
	Lot 2	**Virgin**	6.39	4.23	0.18	< 0.005	0.010	0.13	0.0070	0.0020	< 0.05	< 0.05
		Reuse	6.37	4.17	0.19	< 0.001	0.010	0.16	0.0065	0.0022	< 0.05	< 0.10
	Lot 4	**Virgin**	6.18	4.06	0.16	< 0.001	< 0.005	0.12	0.0090	0.0040	< 0.02	< 0.05
		Reuse	6.32	4.07	0.17	< 0.001	0.006	0.14	0.0099	0.0037	< 0.05	< 0.10
ATI	**Lot 1**	**Virgin**	6.03	4.02	0.21	< 0.0009	0.006	0.149	0.013	0.0009		
		Reuse	6.13	4.05	0.20	< 0.0010	0.013	0.160	0.011	0.0010	< 0.05	< 0.10
	Lot 2	**Virgin**	6.12	4.06	0.22	< 0.0009	0.007	0.142	0.0120	0.0006		
		Reuse	6.26	4.13	0.19	< 0.001	0.008	0.140	0.0096	0.0010	< 0.05	0.036
	Lot 3	**Virgin**	6.01	4.12	0.21	< 0.0009	0.008	0.145	0.014	0.0010		
		Reuse	6.16	4.14	0.20	< 0.0010	0.010	0.160	0.012	0.0010	< 0.05	< 0.10
	Lot 4	**Virgin**	6.3	4.01	0.21	< 0.0009	0.006	0.16	0.0060	0.0009		
		Reuse	6.43	4.06	0.18	< 0.001	0.007	0.17	0.0065	0.0010	< 0.05	0.026
	Lot 5	**Virgin**	6.31	3.94	0.15	< 0.0009	0.029	0.178	0.030	0.0010		
		Reuse	6.35	3.96	0.15	< 0.0010	0.031	0.190	0.023	0.0011	< 0.05	< 0.10
	Lot 6	**Virgin**	6.22	3.86	0.15	< 0.0009	0.04	0.188	0.036	0.0009		
		Reuse	6.49	3.99	0.13	< 0.001	0.038	0.200	0.030	0.0011	< 0.05	0.037
AMS 7015 (Class A)			5.50 - 6.75	3.50 - 4.50	≤ 0.30	≤ 0.005	≤ 0.08	0.11 - 0.20	≤ 0.05	≤ 0.015	≤ 0.10	≤ 0.40
ASTM F2924								≤ 0.20				

Qualification 2: ASTM E8 (Tension)

- Includes all 48 tested ASTM E8 specimens across 5 NIAR builds, and across five ATI powder lots.
- The data across most builds performed closely, except for build N42 fabricated with ATI Lot 12 which yielded lower results.
- Specimen fabricated with ATI lot 7-10 yielded higher results when compared to the Qualification 1 average tensile strength.
- Between the orientation data groups, ZX specimens averaged higher performance, followed by ZX45, then XY. Similar trends observed in the Qualification 1 testing.



Tension tests progress: 10% through (Beehive and Boeing test results to follow)

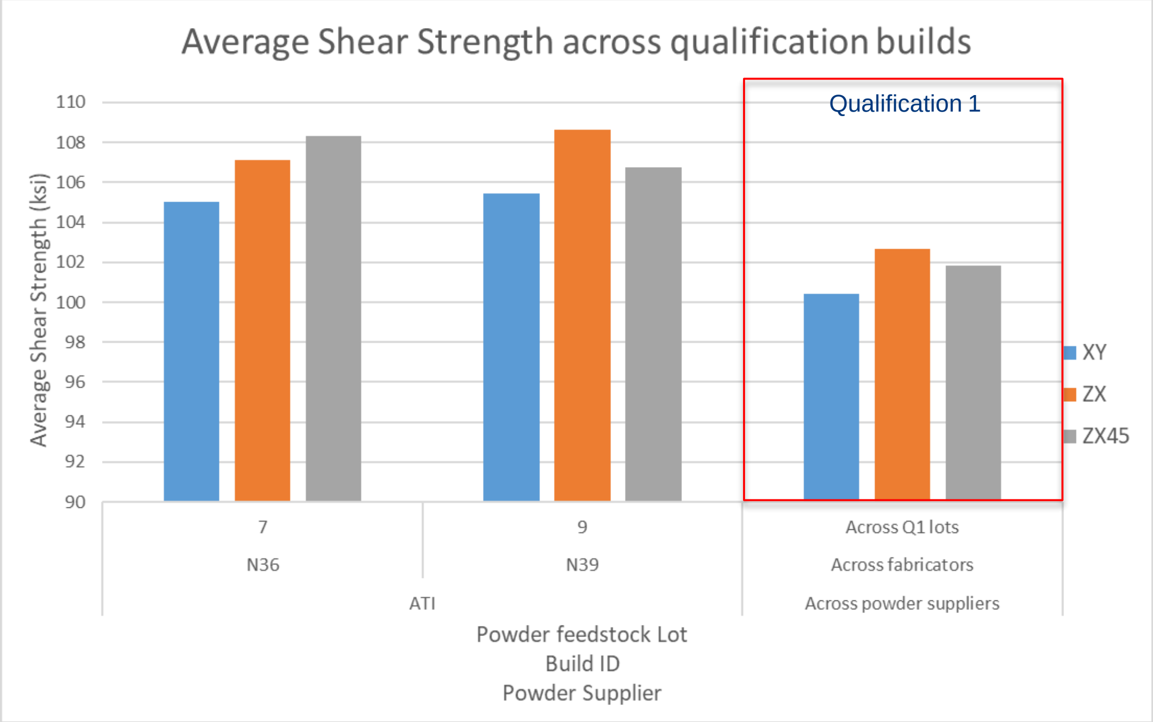


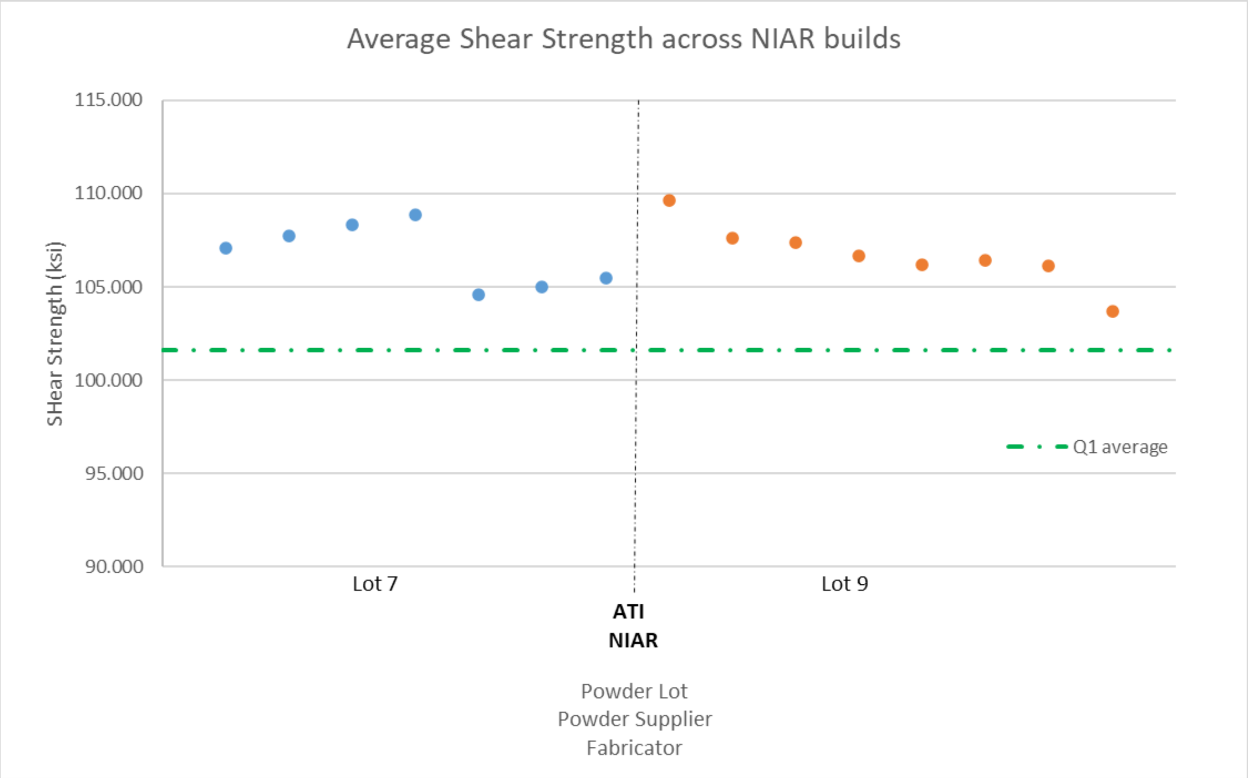
Data points specimen orientation sequence from left to right across each build: **ZX, Z45, then XY**

	Average	Standard Deviation	Coefficient of Variation (%)
0.2% Offset Yield Strength (ksi)	155.70	8.42	5.41
Ultimate Tensile Strength (ksi)	167.23	8.09	4.84
Modulus (Msi)	17.20	0.22	1.28
Percent Elongation at yield (%)	1.10	0.05	4.10
Percent Elongation at fracture (%)	13.49	1.72	12.78

Qualification 2: ASTM B769 (Shear)

- Includes all 15 tested ASTM B769 specimens across 2 NIAR builds, and 2 ATI powder lots.
- The data shows that specimens fabricated with ATI Lot 7 and Lot 9 yielded higher shear strength when compared to Qualification 1 average shear strength but faired closely across the two builds.
- Between the orientation data groups, ZX specimens averaged higher results, followed by ZX45, then XY specimens. Similar trends were observed in Qualification 1 testing.





Data points specimen orientation sequence from left to right across each build: **ZX, Z45, then XY**

	Shear Strength (ksi)
Average	106.73
Standard Deviation	1.63
CoV [%]	0.02

Compression tests progress: 5% through (Beehive and Boeing test results to follow)

Qualification 2: Powder elemental Composition

- Table below represents powder lots across presented Qualification 2 builds.
- Elemental composition acquired from their respective powder material certificates.
- Builds fabricated with ATI Lot 7 through 10 contained higher amounts of interstitial elements (Oxygen, Carbon, and Nitrogen) when compared to Lot 12, which could explain the observed higher strength values.
- All measured elemental composition conforms to ASTM F2924 specifications.

NIAR will be outsourcing work for bulk material elemental analysis (ICP-AES) in the final material state to NSL Analytical.

Powder Supplier	ATI					ASTM F2924
Powder Lot	7	8	9	10	12	
Element	Results/Measured (Weight percent)					
Aluminum	6.16	6.27	6.28	6.24	6.21	5.50 - 6.75
Vanadium	3.86	3.96	3.9	3.89	3.72	3.50 - 4.50
Iron	0.14	0.15	0.15	0.15	0.20	≤ 0.30
Yttrium	< 0.0009	< 0.0009	< 0.0009	< 0.0009	< 0.0009	≤ 0.005
Carbon	0.039	0.038	0.044	0.041	0.006	≤ 0.08
Oxygen	0.19	0.19	0.195	0.193	0.097	≤ 0.20
Nitrogen	0.036	0.039	0.035	0.034	0.012	≤ 0.05
Hydrogen	0.0010	0.0011	0.0008	0.0010	0.0013	≤ 0.015
Titanium	Balance	Balance	Balance	Balance	Balance	Balance

JMADD Metallography Discussion

- NIAR will be carrying out microstructure evaluations per MMPDS chapter 9 using the three main magnification levels for **both Qual 1 and Qual 2**:
  - **Macro-magnification:** To capture the extent and pattern of the largest features of the material structure. The magnification should be set to include numerous side-by-side deposition/fusion passes and numerous additive layers. This magnification should also be suitable for identifying patterns to the occurrence of flaws and their likely cause
  - **Nominal Magnification:** To provide a sound basis for the potential quantitative assessments of the microstructure such as grain size, grain morphology, average flaw size and/or flaw density. The images should contain a proper balance of feature size and quantity to allow for manual or automated methods of grain size or flaw shape detection.
  - **Local Feature Magnification:** To focus on smaller details that are significant to the microstructural characteristics. Examples of such features include grain boundary characteristics, precipitate structures, secondary phases, and other relevant features. It is also used to document the size and shape of flaws common to the material.

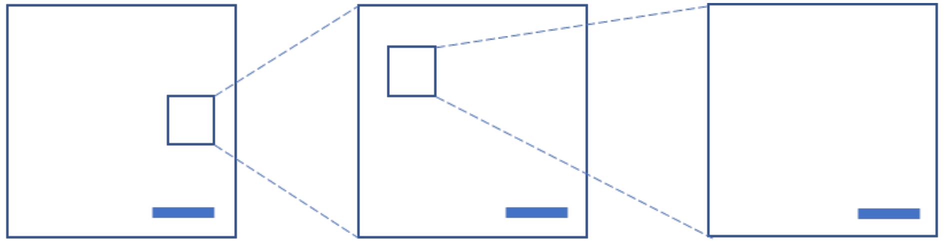


Figure 9.3.5. Three nested levels of image magnification

Photomicrograph images are in process

MMPDS chapter 9 is in draft and is not official content of the MMPDS Handbook

Summary

- Since TRX 2023:
  - Prequalification work completed
  - Qualification 1 fabrication complete
  - Dataset generation for qualification 1 in process
  - Qualification 2 fabrication completed, and testing is in process
- Takeaways
  - Mechanical properties across fabricators appear to perform closely (CoV’s ≤ 5%). The scatter trends are similar to Ti64 wrought products (MMPDS).
  - An increase in strength properties was observed when powder lots with higher interstitial elements were used for fabrication.
  - Elevated temperature test results are performing closely to MMPDS’s reported percent knockdown data.
  - A slight change in elemental composition was observed after powder blending namely the oxygen and aluminum contents.

Next steps

- Continue testing all specimens and analyzing reduced test results.
- Once Qualification 1 dataset is populated, statistical analysis for NCAMP B-basis allowable determination will begin. (Data will be shared with MMPDS for S/C-basis analysis concurrently)
- Qualification dataset 1 to be published at the end of April 2024.
- Continue post-processing and machining fabricated Qualification 2 specimens.
- Tested specimens will be outsourced for bulk material elemental analysis (ICP-AES) in the final material state.
- Continue to test, analyze, and populate qualification 2 dataset
- Final publications

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Backup/Appendix

Program Task 1 – Prequalification

- All prequalification work is **complete**
- Form Public Advisory Committee
- Perform Prequalification Studies
  - Perform Parameter Set Comparison Study (added)
  - Perform Orientation Down-Selection Study, informing build design considerations
  - Perform Site Comparison Study with all three fabrication machines
- Documentation
  - Develop specification framework
  - Develop Test Matrix and Test Plan
  - Create Feedstock, fabricated Additive Material, and Process specifications along with fabrication Process Control Document
- Specimen geometry and build design to support fabrication matrix
- Materials
  - Map out material requirements from build to lot and material supplier deliveries
  - Contract with and acquire powder from three material suppliers
- Trial fabrication for all build designs
- Define methods for powder retrieval and storage

Prequalification Studies

Parameter Set Comparison Study

- **Objective:** Used to characterize and compare microstructure quality of specimens fabricated using the two EOS stock parameters of interest.
- **Outcome:** All microstructural characterization as well as fatigue data shared by Boeing appears similar between the two parameter sets in the post-HIP state. Therefore, the EOS parameter set, Ti_Speed, with a 60 µm layer height, was chosen for qualification fabrication

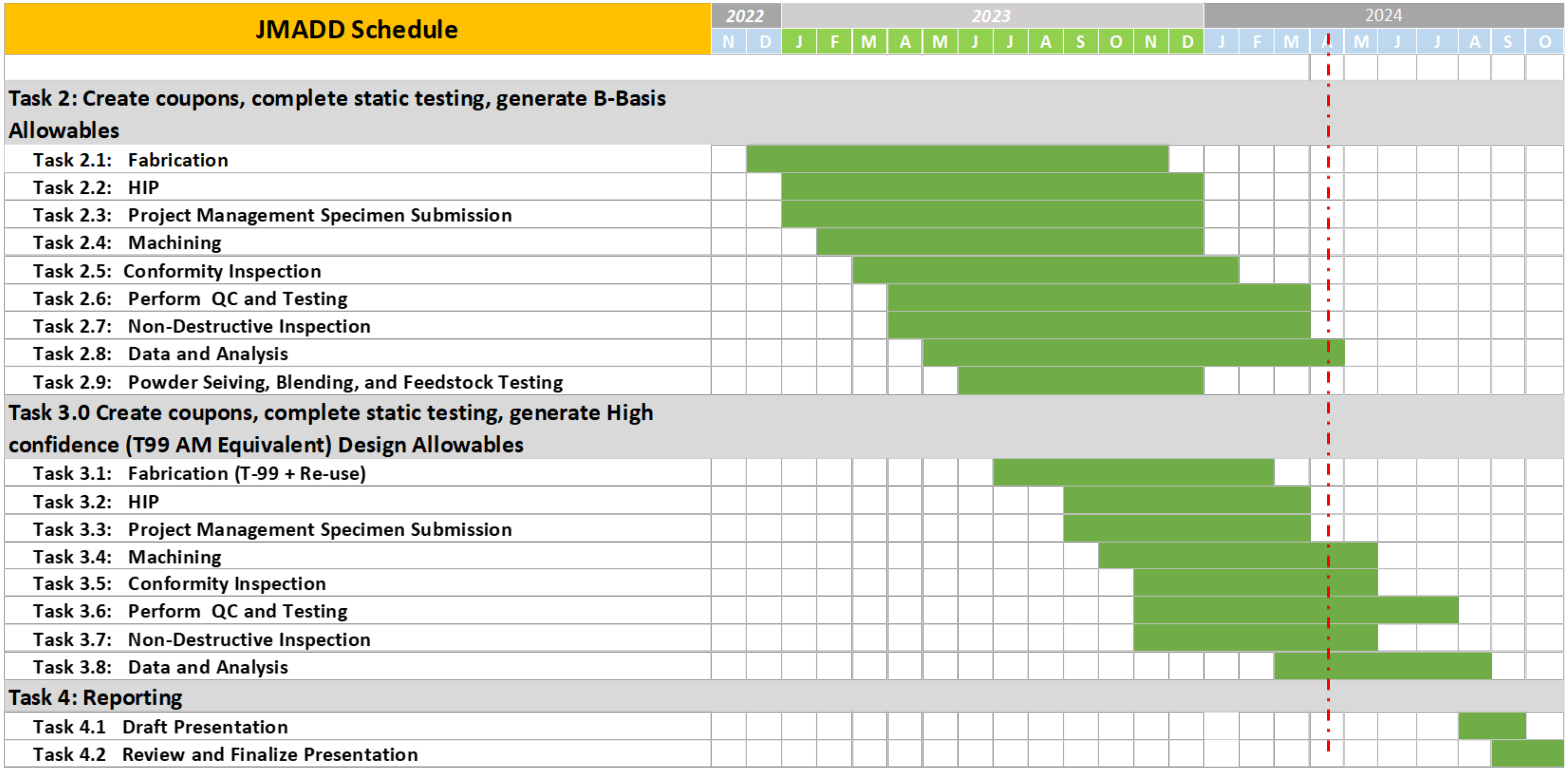
Orientation Down-Selection Study

- **Objective:** Primary focus on down selection of XY/YX, ZX45/ZY45, along with fab and test to confirm build design variables (min time intervals, specimen scaling, specimen spacing, build locations)
- **Outcome:** Mechanical and physical test data across builds and orientations faired closely, which helped finalize qualification build designs and specimen orientations.

Fabricator Site Comparison Study

- **Objective:** Compare build quality and test results from a common build design fabricated at each site following the defined JMADD process chain. Confirm acceptable quality of fabrication to support qual effort.
- **Outcome:** All sites were able to achieve good build quality while adhering to the defined JMADD process chain. Minor process chain variabilities across sites (i.e. build cleaning & powder recapture strategies) were documented in the JMADD PCD. Additionally, mechanical and physical test data also performed closely across sites.

Project Schedule

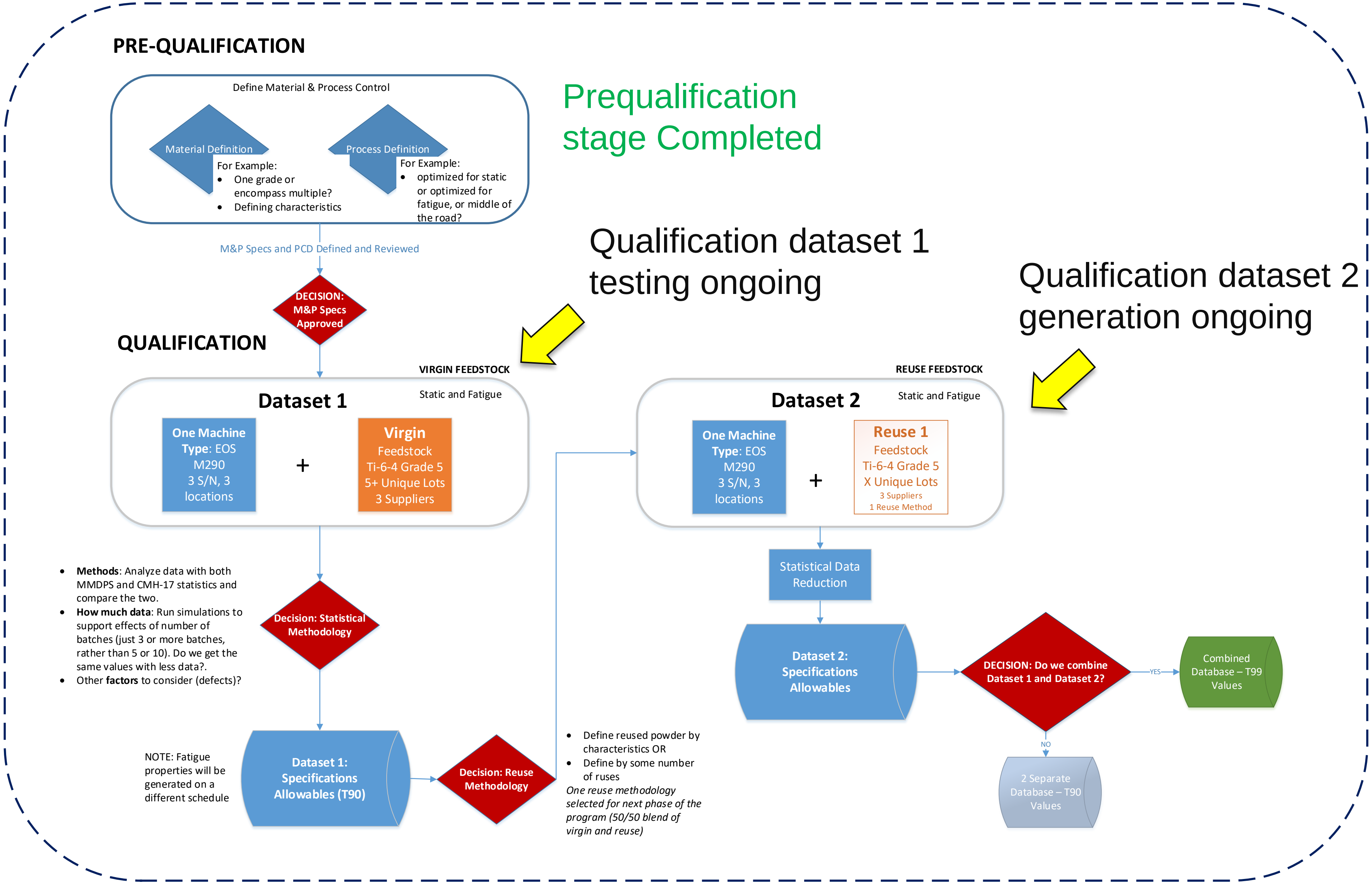


Program Task 2

Dataset 1 Generation (Virgin) (On-going)

- Fabricate and inspect specimens, perform post-processing, machining, testing, and generate T-90 allowables for static properties utilizing virgin powder (Initiated Nov 14, 2022)
  - Definition of powder reuse strategy for future work and review by the Public Advisory Committee and Government Technical Team.
  - Refine test plan and specifications before proceeding to Task 3.
  - Capture reuse powder. Sieve, blend, sample, and test powder for use in Task 3. Define feedstock specification based on virgin and reuse powder test results.
  - Review of Task 2 results by the Government Steering Committee.
  - Publish NCAMP B-Basis (T90) report.

Scope of Current JMADD Program



Qualification Cyclic Mechanical Tests

						Number of Heats x Number of Machines x Runs per Machine x Number of Specimens per build Test Temperature / Moisture Condition		
Build Orientation	Test Type	ASTM Standard	R-Value	Stress Levels	Property	RTA (70°F/21ºC)	ETA (600°F/316ºC)	Coupons Fabricated and Tested
XY	Fatigue LCF (4, 6)	ASTM E606/E466 (8)	T/C, T/T (-1, 0.5)	75%, 70%, 65%, 60%, 55%, 50%	Fatigue Strength, Residual	2x2x2x3 (1),(2)	1x2x2x3 (4)	36
ZX	Fatigue LCF (4, 6)	ASTM E606/E466 (8)	T/C, T/T (-1, 0.5)	75%, 70%, 65%, 60%, 55%, 50%	Fatigue Strength, Residual	2x2x2x3 (1),(2)	1x2x2x3 (4)	36
Z45	Fatigue LCF (4, 6)	ASTM E606/E466 (8)	T/C, T/T (-1, 0.5)	75%, 70%, 65%, 60%, 55%, 50%	Fatigue Strength, Residual	2x2x2x3 (1),(2)	1x2x2x3 (4)	36
XY	Fatigue HCF (4, 6)	ASTM E466	T/C, T/T (-1, 0.5)	45%, 40%, 35%, 30%	Fatigue Strength, Residual	2x2x2x3 (1),(3)	-	24
ZX	Fatigue HCF (4, 6)	ASTM E466	T/C, T/T (-1, 0.5)	45%, 40%, 35%, 30%	Fatigue Strength, Residual	2x2x2x3 (1),(3)	-	24
Z45	Fatigue HCF (4, 6)	ASTM E466	T/C, T/T (-1, 0.5)	45%, 40%, 35%, 30%	Fatigue Strength, Residual	2x2x2x3 (1),(3)	-	24

Notes:

1) Specimens for each build orientation and test type must come from at least two heats and two machines.
2) Will use 6 stress levels, 2 R-values, 2 coupons per stress level and R-value for RTA.
3) Will use 4 stress levels, 2 R-values, 3 coupons per stress level and R-value for RTA.
4) For ETA, will use 3 stress levels (40%, 50%, 60%) with 2 coupons per stress level at R-value of -1, will use 3 stress levels (60%, 70%, 80%) with 2 coupons per stress level at R-value of 0.5.
5) All coupons will be run with a frequency of 20 Hz.
6) Stress values will be determined by using static test data.
7) Runout will be 1 million cycles for LCF, 10 million cycles for HCF.
8) Specimen geometries included in Appendix 1 and Appendix 3 of NCAMP NTP.
9) LCF E606 will be run under strain control for the first 50,000 cycles at 5 Hz, then testing will switch to load control as defined by E466 at 20 Hz.

Dataset 2 Generation (Virgin + Reuse) (On-going)

- Fabricate and inspect specimens, perform post-processing, machining, testing, and generate T-99 allowables for static properties utilizing virgin+reuse blended powder (fabrication was initiated June 19, 2023).
  - Compare allowables generated from use of CMH-17 Stat and MMPDS statistical analysis.
  - Perform investigation of powder reuse dataset.
  - Review of Phase 2 results, acceptance by the Government Steering Committee.
  - Determine statistical grouping of powder reuse dataset.
  - Publish NCAMP A-Basis (T99) report