Metallic Additive Manufacturing Guidelines for Aircraft Design and Certification

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Technical Approach

Material Qualification
- Baseline Testing Applied to Increasingly Complicated Materials
- Expand Framework to Additional AM Technologies
- Perform Equivalencies to Demonstrate Framework

Factors Effecting Qualification
- Validate and Expand Processing Window
- FST Studies – Impact of Design
- Scaling – Specimen to Part Correlations
- Building Block – Application Specific Characterization

Pre-Qualification Considerations
- Static & Dynamic Property Behaviors
- Effect of Defects
- Machine to Machine Variability
- Within Chamber Variability
Overview

• Metallic qualification: JMADD Ti-6Al-4V LPBF Qual
• Expansion from metal qualification effort:
  • Feature-Level Building Block Study
  • Metal Additive Manufacturing Surface Feature Inspection
  • Equivalency: GE M2 Ti-6Al-4V LPBF
  • Investigation of Post-Processing Effects by Fatigue Curve Generation
Current JAMS Material and Process Investigations

Test Methods
- Handbook Development
- SDO Support

Dynamic Testing
- Ti 6-4 – M290
- Inconel 718 – M290
- Ti 6-4 – GE M2

Machining
- ULTEM9085 + Fortus 900mc
- ULTEM9085 Equivalent x2

Microstructure
- Parameter Mapping

Notching Methods
- Ti 6-4 Fatigue Curves

ULTEM9085 + Fortus 900mc

CCF Onyx + X7

FY18
FY19
FY20
FY21

Not in use for FAA programs
<table>
<thead>
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<th>Factors Effecting Qualification</th>
<th>Special Factors &amp; Equivalencies</th>
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<td>Establish Industry/Gov’t Steering Committee</td>
<td>Development of Statistical Guidelines</td>
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<td>Processing Window Expanse</td>
<td>Fabricated v. Machined</td>
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<td>Machine &amp; Material Variability</td>
<td>Test Methods</td>
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<td>Scaling &amp; Machining</td>
<td>Parameters Effects on FST</td>
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<td>Task 20/21a</td>
<td>JMADD: Powder Bed Fusion Qual EOS M290</td>
<td>Building Block</td>
<td>AM Roadmap</td>
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<td>Task 21b</td>
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<td>Metal</td>
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<td>Polymer + Metal</td>
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</table>

Joel White – Wichita State University, NIAR JAMS Technical Review – April 18, 2023
JAMS Metal AM Programs

• Current Programs:
  • JMADD Ti-6Al-4V laser powder bed fusion qualification
    • EOS m290 Ti-6Al-4V grade 5 – stress relief, HIP, machined state
    • Metal AM framework creation and A-basis allowable generation
  • Building Block – Feature level testing program

• Initiated 2023
  • Expanding Metal Framework to Additional Machine Types
  • Ti-6-4 JMADD Fatigue Curves
  • Metal Additive Manufacturing Surface Feature Inspection
JMADD Qual 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 NCAMP B and A-basis (T90 and T99) material allowable data and establish a best practice for developing AM allowables and specifications that is publicly available for L-PBF of Ti-6Al-4V.
**JMADD Expanded Qualification Framework**

### Project Includes:
- 3 Fabricators
- 3 Feedstock manufacturers
- Virgin and Reuse feedstock
- 10+ heats
- Gov’t steering committee (33 members)
- Public Advisory Committee (80 members)
- NCAMP spec and allowable generation
- Data submission for consideration by MMPDS
- All specimens in SR, HIP, machined state
- Fully pedigreed data
- ~3600 specimens total

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**SCOPE OF CURRENT JMADD PROGRAM**

**PRE-QUALIFICATION**
- Determine Material & Process Control
  - One grade or encompass multiple?
  - Setting characterization

**QUALIFICATION**
- Dataset 1: Specifications
  - Virgin Feedstock: 2 lots
  - Reuse Feedstock: 2 lots

**Dataset 2**
- Virgin Feedstock: 2 lots
- Reuse Feedstock: 2 lots

**Dataset 3**
- Virgin Feedstock: 2 lots
- Reuse Feedstock: 2 lots

**Dataset 4**
- Second Machine Type

**Dataset 5**
- Second Machine Type – different process parameters

**EXAMPLES OF EXPANSION**
- Static and Fatigue
- Static and Fatigue

**NOTE:** Fatigue properties will be generated on a different schedule

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**EXPANDING THE DATABASE – FUTURE WORK**

**EXPERIMENT: What are equivalence test requirements?**

**Dataset 3**
-Virgin/Reuse Feedstock: Ti-6-4 Grade 5

**Dataset 4**
- Virgin/Reuse Feedstock: Ti-6-4 Grade 5

**Dataset 5**
- Second Machine Type – different process parameters

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**CURRENT WORK**

**Dataset 1**
- Specifications
  - Allowables (T90)

**Dataset 2**
- Specifications
  - Allowables (T90)

**Dataset 3**
- Specifications
  - Allowables (T90)

**Dataset 4**
- Specifications
  - Allowables (T90)

**Dataset 5**
- Specifications
  - Allowables (T90)
JMADD Expanded Qualification Framework

**SCOPE OF CURRENT JMADD PROGRAM**

**PRE-QUALIFICATION**

- Entire Material & Process Control
- How to Employ:
  - Using data or even more data?
  - Establishing boundaries

**QUALIFICATION**

**Dataset 1**

- One Machine Type
  - EOS M290 3S/N, 3 locations
  - Specifications
  - Allowables (T90)

**Dataset 2**

- One Machine Type
  - EOS M290 3S/N, 3 locations
  - Specifications
  - Allowables (T90)

**REUSE FEDERATION**

- Virgin
  - Ti-6Al-4V Grade 5
  - Unique Lots 3
  - Suppliers 3

**Dataset 3**

- Second Machine Type
  - Specifications
  - Allowables

**Dataset 4**

- Second Machine Type
  - Specifications
  - Allowables

**Dataset 5**

- Second Machine Type
  - Specifications
  - Allowables

**EXAMINING DATA & PRIMARY TEST REQUIREMENTS**

**EXAMPLES OF EXPANSION**

- Static and Fatigue
- Static and Fatigue

**NOTE:** Fatigue properties will be generated on a different schedule.

**DECISION:**

- Do we combine Dataset 1 and Dataset 2?
  - Combined Database – T99 Values
  - Separate Database – T90 Values

**DECISION:**

- Is Dataset 3 statistically combinable to previous Database(s)?
  - Combined Database
  - Separate Databases

**PRE-QUALIFICATION DECISION:**

- Virgin/Reuse Feedstock
  - Ti-6Al-4V Grade 5
  - Unique Lots 3
  - Suppliers 1

**QUALIFICATION DECISION:**

- Reuse Methodology
  - M&P Specs and PCD Defined and Reviewed

**Dataset 1 Specifications Allowables**

- • Analyze data with both MMDPS and CMH-17 statistics and compare the two.
- • How much data:
  - Run simulations to support effects of number of batches (just 3 or more batches, rather than 5 or 10). Do we get the same values with less data?
- • Other factors to consider (defects)

**EXAMPLES OF EXPANSION**

- Static and Fatigue

**SCOPE OF CURRENT JMADD PROGRAM**

- Define Material & Process Control
  - For Example:
    - • Optimized for static or optimized for fatigue, or middle of the road?

**EXAMPLES OF EXPANSION**

- Static and Fatigue

**NOTICE:**

- Fatigue properties will be generated on a different schedule.

**31B-2: Expansion to second machine type**
NCAMP Additive Documentation Framework

- **NAMS** (additive material spec) includes fully defined key characteristics including chemistry, density, minimum tensile strength, grain size, porosity limit and surface finish.
- **NPS** is a material and machine agnostic L-PBF process spec.
- **Powder Spec** defines limits for feedstock material
- **PCD** includes line by line operational instructions and full post-processing conditions.
- **All specs will be posted publicly along with allowables generated from the program.**

All specifications have been reviewed by GSC and NCAMP DER
Qualification Process Chain

1. Build Design	2. Fabrication	3. Machining
4. Quality Control	5. Wire-EDM	6. HIP

Build Inspection

(200 MPa, 815°C)
Qualification 1 fabrication

- Qualification 1 fabrication began in Nov 2022.
- NIAR and Boeing fabricated 25 and 9 builds respectively for generation of the 1st of 2 datasets along with a third fabricator.
- NIAR’s builds N1-N25 have been fabricated. Complete 3/10.
- Build failures:
  - N3 – improper specimen .stl z-location. Files have been corrected.
  - N13 – argon pressure drop due to argon dewar valve malfunction.
- Additional powder was purchased to re-fabricate builds N3 and N13. Fabrication complete 3/24.
- Boeing completed all 9 qual build fabrications without failure.
- NIAR received Boeing builds B1-B9 3/7/23.
- 350 of the submitted 500 specimens have completed final machining and are in queue for QC and testing. Approx 1600 total defined for Qual 1 testing.
Prequalification Studies:
Orientation Down Selection Study Builds

G1 Specimen orientation study
G2
G3 Time between layer exposure study
G4
G5
G6 Specimen spacing study
G7
G8 Specimen Scaling study
G9
G10 Low Cycle Fatigue

Builds 9 and 10 were completed but photos were not taken prior to wire EDM of build plate.
Orientation Down Selection Study

ASTM E8 – Ultimate tensile Strength (UTS) across all builds

- Includes all 69 tested ASTM E8 specimens across nine builds (G1 through G9)
- All data groups fair closely, although there is visual separation between orientation data groups. ZY45 specimens showed highest results, followed by Z45, then ZX. Similar trends for HIP specimens were seen in the paper by Meier, et al. (2022)

<table>
<thead>
<tr>
<th>Property</th>
<th>Average</th>
<th>Standard Deviation</th>
<th>Coefficient of Variation (%)</th>
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</thead>
<tbody>
<tr>
<td>Ultimate Tensile Strength (ksi)</td>
<td>159.27</td>
<td>1.47</td>
<td>0.92</td>
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<tr>
<td>Modulus (Msi)</td>
<td>17.19</td>
<td>0.24</td>
<td>1.42</td>
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<tr>
<td>0.2% Offset Yield Strength (ksi)</td>
<td>147</td>
<td>2.02</td>
<td>1.38</td>
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<tr>
<td>Percent Elongation at yield (%)</td>
<td>1.05</td>
<td>0.01</td>
<td>1.05</td>
</tr>
<tr>
<td>Percent Elongation at fracture (%)</td>
<td>12.77</td>
<td>0.77</td>
<td>6.07</td>
</tr>
</tbody>
</table>


ASTM E9 – Ultimate Compression Strength across all builds

- A total of 30 specimens (0.5” diameter x 1.0” length) in different orientations across builds G1 and G2 were tested.
- Upon reviewing the gathered compression data, the results varied minimally across builds. However, there was a separation between the orientation data groups, with Z45 specimens showing the highest UCS, followed by ZX, and then XY specimens.
- On build G2, a single Z45 specimen outperformed all specimens, which resulted in a higher average for Z45 orientation specimens.

### Average Ultimate Compression Strength across all builds

<table>
<thead>
<tr>
<th>Build Number</th>
<th>G1 - XY, 245, ZX</th>
<th>G2 - 245, XY</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ultimate Compression Strength (ksi)</td>
<td>210.91</td>
<td>212.03</td>
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</tbody>
</table>

### ASTM E9 – Compression Data

<table>
<thead>
<tr>
<th>Property</th>
<th>Average</th>
<th>Standard Deviation</th>
<th>Coefficient of Variation (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.2% Offset Yield Strength (ksi)</td>
<td>160.57</td>
<td>3.95</td>
<td>2.46</td>
</tr>
<tr>
<td>Ultimate Compression Strength (ksi)</td>
<td>210.91</td>
<td>4.46</td>
<td>2.11</td>
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<tr>
<td>Modulus (Msi)</td>
<td>17.82</td>
<td>0.34</td>
<td>1.88</td>
</tr>
</tbody>
</table>
ASTM E466 – Low Cycle Fatigue data

- 50,000 cycles strain control; remaining load control. (R: -1 at RTA)
- Specimens at 70% stress level failed before a million cycles; most specimens tested at 50% and 60% stress levels survived. One Z45 failed at 646,545 cycles.
- Residual strengths matched static tensile data. Residual elongation at fracture is higher than static tensile tests.

<table>
<thead>
<tr>
<th></th>
<th>Average</th>
<th>Standard Deviation</th>
<th>Coefficient of Variation (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.2% Offset Yield Strength (ksi)</td>
<td>146.77</td>
<td>1.63</td>
<td>1.11</td>
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<tr>
<td>Ultimate Tensile Strength (ksi)</td>
<td>159.99</td>
<td>0.76</td>
<td>0.48</td>
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<tr>
<td>Modulus (Msi)</td>
<td>17.25</td>
<td>0.18</td>
<td>1.02</td>
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<tr>
<td>Percent Elongation at yield (%)</td>
<td>1.05</td>
<td>0.01</td>
<td>0.61</td>
</tr>
<tr>
<td>Percent Elongation at fracture (%)</td>
<td>17.23</td>
<td>0.76</td>
<td>4.39</td>
</tr>
</tbody>
</table>
Prequalification: Site Comparison Study

- All sites provided RTA and ETA UTS results with low variance – Coefficient of variation (CoV) below 2%
- 6% difference seen between highest and lowest performing RTA site and feedstock vendor
## Site Comparison Study

### ASTM E8 – Ultimate Tensile Strength across all sites (Continued)

<table>
<thead>
<tr>
<th></th>
<th>RTA NIAR</th>
<th>Auburn</th>
<th>Boeing</th>
<th>ETA NIAR</th>
<th>Auburn</th>
<th>Boeing</th>
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<tbody>
<tr>
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<td>AP&amp;C</td>
<td>TEKNA</td>
<td>AP&amp;C</td>
<td>TEKNA</td>
<td>AP&amp;C</td>
<td>TEKNA</td>
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<tr>
<td></td>
<td>149.84</td>
<td>1.50</td>
<td>144.11</td>
<td>1.77</td>
<td>141.57</td>
<td>1.15</td>
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<tr>
<td>Ultimate Tensile Strength (ksi)</td>
<td>162.19</td>
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<td>157.31</td>
<td>1.18</td>
<td>153.88</td>
<td>0.37</td>
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<tr>
<td>Young's Modulus (Msi)</td>
<td>16.80</td>
<td>2.39</td>
<td>16.29</td>
<td>2.20</td>
<td>16.85</td>
<td>1.34</td>
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<tr>
<td>Percent Elongation at yield (%)</td>
<td>1.07</td>
<td>2.36</td>
<td>1.04</td>
<td>2.91</td>
<td>1.04</td>
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<tr>
<td>Percent Elongation at fracture (%)</td>
<td>14.19</td>
<td>5.98</td>
<td>12.90</td>
<td>4.29</td>
<td>12.50</td>
<td>3.35</td>
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Ongoing Project: Building Block

• Project work ongoing throughout 2022, but consensus from sponsors and industry steering committee has not been reached.

• Scope options previously discussed:
  1) Define test methods for detail/element configurations for the purpose of defining structural feature design values/ performance debits.
     • Feature options for investigation include: thin walls, overhangs, roofs, holes/lugs, radii, which may be adjusted based on AM process type being investigated.
  2) Define test methods for detail/element configurations for the purpose of demonstrating manufacturing capability of certain features.
     • This would allow for certification of manufacturers to fabricate parts which include the feature types demonstrated.

• This project will be defined to work in conjunction with the Fatigue Curves project.
2023 New Projects

• Expanding Metal AM Qualification Framework to Additional Machine Types
• JMADD Fatigue Curves
• Surface Feature Inspection
Expanding Metal AM Framework to Additional Machine Types

• PoP: 18-24 months

• Background: Feedback from Industry, the Public Advisory Committee, and the Government Steering Group all have commented that while the decision to limit the initial database to a single machine architecture is well understood and supported, further expansion to include machine agnostic standards and specifications so that additional machines are qualified is critical to move the industry forward.

• Objectives: Develop a robust equivalency approach for metals including static and dynamic properties. Perform an equivalency on a different (secondary) laser powder bed fusion machine architecture that is capable of processing Ti-6Al-4V alloy.
Expanding Metal AM Framework to Additional Machine Types

**Scope**

- The project will establish and utilize a NCAMP metal AM equivalency process to act as a pathfinder machine to machine equivalency within the same process type (LPBF)
- Expand the baseline specification framework to include machine-agnostic process specifications and standards
- Specification documents from JMADD program will be leveraged but investigation into definition of a performance-based printed material specification (leveraging JMADD NAMS) will be performed.
  - Characterize “intermediate requirements with associated responses” in an effort to achieve the performance based spec requirements (such as thermal post processing to achieve desired microstructure)
  - This will further enable additive machines with same AM process type to leverage baseline database.

**System**
- EOS M290

**Architecture**
- Single laser PBF

**Broader Type of machine**
- LPBF (multi-laser)
Machine Equivalency: Approach

• Utilize established NIAR GE M2 machine, specifications, process definition, and framework to define and conduct a metal AM equivalency to JMADD dataset.
  • NIAR - owned GE M2 Series 5 LPBF machine (single or dual laser capability)
  • Established JMADD LPBF-specific Process Specification
  • JMADD post-processing chain definition as starting point
  • Leverage NCAMP composites equivalency framework and JMADD NCAMP metal AM qualification framework to generate a metal AM equivalency method
  • Utilize JMADD Additive Material Spec (final material characterization) as starting point for performance-based spec definition

• Generate and execute a fully defined equivalency methodology for comparison to JMADD dataset

Deliverables: A deliverables report documenting the equivalency framework and results, including statistical equivalency comparison between the Concept Laser M2 data and the baseline EOS M290 qualification.


Ti-6-4 JMADD Fatigue Curves

- **PoP**: 24 months
- **Background**: A significant difference exists between bulk material allowables and alternative post processing. Fatigue curves are commonly used to show performance debits for alternatives in material or part definition. Clarifying data and guidelines are needed to enable industry use. No public database showing the different fatigue curve debits for alternate post processing operations exists for any AM alloy.

**Objectives**: Leveraging the JMADD program, which is developing bulk material allowables, this task will generate fatigue curves for the as-fabricated and additional alternate post-processing conditions for comparison back to JMADD fatigue values.

**Deliverables**: Fatigue Curves, Report documenting lessons learned and guidelines

*It is noted that a change in heat treatment/post-processing is generally considered a material change for the output material. Instead of creating a B or S-basis property dataset for these new materials, a fatigue curve approach was recommended to specifically capture fatigue performance effects from alternate post-processing methods.*
After bulk material allowables have been generated (JMADD), fatigue curves must be created to enable design of parts based off of differing surface finish and post-processing, such as stress relief and HIP. Additional curves may be generated in industry to provide characterization of knock-downs for other part features.

Three conditions for fatigue curves were defined for generation:
1. Machined and Vacuum/Inert Stress Relief (No HIP)
2. As Printed, Vacuum/Inert Stress Relief (No HIP)
3. As Printed, Vacuum/Inert Stress Relief and HIP

Additional or alternate option:
4. Machined, VSR and 100 MPa HIP (Potential GAMAT)
5. Machined and HIP (no Stress Relief)

Knockdowns and behavior associated with each iterations above will be generated.

JMADD test plan and specifications will be leveraged to ensure resulting data aligns with methodology used in the original JMADD qualification Program.
Approach

- Create common mixed build design for fabrication and performance comparison across builds (8 builds)
- Fabricate specimens from single material lot and vendor
- Post-process and machine per test matrix definition
- Generate RTA fatigue curves for comparison to JMADD baseline
- Include E8 static tensile lot release specimen on each build

<table>
<thead>
<tr>
<th>Vendor</th>
<th>Lot</th>
<th>R-Ratio</th>
<th>Stress Levels</th>
<th>Orientation</th>
<th>DV</th>
<th>Finish</th>
<th>Condition</th>
<th>Specimens per SL</th>
<th>ZX Specimens</th>
<th>XY Specimens</th>
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</thead>
<tbody>
<tr>
<td>AP&amp;C</td>
<td>A</td>
<td>-1</td>
<td>S</td>
<td>XY</td>
<td>#1</td>
<td>Machined</td>
<td>VSR</td>
<td>12</td>
<td>60</td>
<td></td>
</tr>
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<td></td>
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<td></td>
<td>ZK</td>
<td>#1</td>
<td>Machined</td>
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<td>#2</td>
<td>AF</td>
<td>VSR</td>
<td>12</td>
<td>60</td>
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<td></td>
<td></td>
<td></td>
<td>ZK</td>
<td>#3</td>
<td>AF</td>
<td>VSR + HIP</td>
<td>12</td>
<td>60</td>
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</tr>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>XY</td>
<td></td>
<td>GAMAT*</td>
<td>Machined HIP or SR+100 HIP</td>
<td>12</td>
<td>60</td>
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<td></td>
<td>ZK</td>
<td></td>
<td>GAMAT*</td>
<td>Machined HIP or SR+100 HIP</td>
<td>12</td>
<td>60</td>
<td></td>
</tr>
</tbody>
</table>

Total Specimens: 240 XY, 120 ZX, 360 Total Specimens

*As-fabricated Z45 specimen limitation due to specimen radius down-skin angle
Metal Additive Manufacturing
Surface Feature Inspection

• **PoP**: 18 months

• **Background**: Fatigue design values are significantly impacted by the as-fabricated surface condition and must be characterized when present on fatigue sensitive components. These surfaces are not able to be inspected using traditional surface inspection methods such as Fluorescent Penetrant Inspection (FPI) and therefore rely on the use of fatigue design value debit factors. This practice has successfully been applied on many certified LPBF parts, and yet questions remain concerning the lack of inspectability of these surfaces. The inspection concern is routed in the uncertainty related to manufacturing flaws, such as cracks, which may exceed the design value debits determined for as-printed surfaces.

• **Objectives**: The specific research goal is to understand whether the combination of as-printed surface design values and bulk material inspection methods such as X-Ray or CT-scan are sufficient to assure the material properties of fatigue sensitive LPBF components.
Metal Additive Manufacturing
Surface Feature Inspection

**Overall Research Question:**
Is the combination of as-printed surface design values and bulk material inspection methods, such as X-Ray or CT-scan, sufficient to assure the material properties of fatigue sensitive LPBF components?

**Task 1: Fracture Mechanics Analysis**
Analysis used to understand the fatigue and fracture coupon test results

**Task 2: Establish Representative Coupon**
Coupon used establish detectability by inspection

**Task 3: Bulk Material NDI Capability Study**
- What, if any, bulk material NDI methods are effectively able to determine size and location of manufactured features/flaws?

**Task 4: Surface Feature NDI Capability Study**
- What, if any, surface feature NDI methods are effectively able to determine size and location of manufactured features/flaws?
Near Term Tasks

JMADD:
• Complete B-basis dataset and perform statistical analysis
• Initiate A-basis/reuse fabrication and test

New Projects:
• Confirm FAA objectives and defined scope for each project
• Establish steering committees for each new project
• NIAR to complete development of NCAMP Metal AM Equivalency framework
• NIAR finalizing Fatigue Curves Test and Fabrication plan
Looking Forward

• **Benefits to Aviation**
  • JMADD creates much-needed baseline allowables and specifications for adoption by industry
  • JMADD establishes a qualification & equivalency framework enabling further expansion (machines, materials, AM process types, post-processes)
  • Follow-on programs answer key questions driven by industry need
  • Programs create experience and datasets needed for guidance and standards development and output

• **Future Needs**
  • Demonstrate scalability of AM qualification framework to new materials, machines, and process types
  • Finalize and demonstrate equivalency method to additional machines within material and process type
  • Guidance to define features and tests enabling research continuing up the building block pyramid

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