Factors Affecting Qualification/Certification - Evaluating the Criticality of Inherent Anomalies/Defects on the Fatigue Behavior of Additively Manufactured Ti-6Al-4V Parts

Projects sponsored by: Federal Aviation Administration (FAA)
Introduction

- **Project Title:** Factors Affecting Qualification/Certification - Evaluating the Criticality of Inherent Anomalies/Defects on the Fatigue Behavior of Additively Manufactured Ti-6Al-4V Parts
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  (See next slide for complete list of participants)
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- **Source of matching contribution:** Faculty time and graduate research assistant tuition
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Background

AM defects:

- Significantly reduce and introduce uncertainty to fatigue performance
- Pose great challenge for qualification/certification of AM parts

Muhammad, Nezhadfar, Thompson, Saharan, Phan, & Shamsaei, Int. J. Fatigue, 124 (2019) 188-204
Objective and Approach

- **Objective:** To quantify the detrimental effect of volumetric defects on mechanical properties of L-PBF Ti-6Al-4V Gr. 5

- **Approach:** Three steps are taken,

  I. Explore process windows by varying laser power, scan speed, and hatching distance
  
  II. Determine the criticality of volumetric defects on mechanical performance using specimens seeded with different defect types
  
  III. Take advantage of machine learning and simulations wherever applicable
Overall Scope

- AP&C Ti-6Al-4V Grade 5 powder (15-53 µm) was used as feedstock
Categorical defects feature, i.e., defect types (KHs, GEPs, LoFs), is indicative of processing condition.
Decision Tree for Defect Classification

Note: Reported accuracy is only for Ti-6Al-4V Grade 5 material fabricated using EOS M290

- Morphological parameters such as max. axis, aspect ratio, sphericity, extent, solidity, sparseness, roundness, elongation, and flatness were used for defect classification
The three defect types share overlaps of different degrees in the ranges of their morphological parameters; thus, employing only one or two parameters cannot uniquely determine a defect’s type.

The discriminating potential of a morphological parameter depends on the pair of defect types:
- Defect size (max. axis) best discriminates GEPs from KHS
- Roundness and sparseness best discriminate GEPs and KHSs from LoFs
A defect classification methodology incorporating multiple morphological parameters had been developed:
- >98% accuracy when implemented into decision tree
- >99% accuracy when implemented into artificial neural network
Note: X-ray computed tomography (XCT) was performed on vertical fatigue specimens with 5.5 μm voxel size

- 240 fatigue (16 x 15) and 96 tensile (16 x 6) specimens were fabricated
  - LoF: P-5%, P-10%, P-20%, H+5%, and H+20%
  - KH: P+30%V-20% and P+20%V-30%

- KH specimens were fabricated only in vertical orientation, while the recommended (R) and LoF ones were fabricated in vertical, diagonal, and horizontal orientations

<table>
<thead>
<tr>
<th>Defect Contents: Fatigue Specimens</th>
</tr>
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<tbody>
<tr>
<td>La: P^{10}V^{0}H^{0}</td>
</tr>
<tr>
<td>Lb: P^{20}V^{0}H^{0}</td>
</tr>
<tr>
<td>Lc: P^{0}V^{0}H^{+20}</td>
</tr>
<tr>
<td>Ld: P^{-5}V^{0}H^{0}</td>
</tr>
<tr>
<td>Le: P^{0}V^{0}H^{+5}</td>
</tr>
<tr>
<td>R: P^{0}V^{0}H^{0}</td>
</tr>
<tr>
<td>Ka: P^{+20}V^{30}H^{0}</td>
</tr>
<tr>
<td>Kb: P^{+30}V^{20}H^{0}</td>
</tr>
</tbody>
</table>

Energy density

\[ E = \frac{P}{Vht} \]

P: Laser power
V: Laser speed
h: Hatch distance
t: Layer thickness
Yield strength (YS) and ultimate tensile strength (UTS) of all specimens were almost comparable.

KH specimens had slightly higher strengths which might be attributed to the higher nitrogen content due to excessive energy input during fabrication.

LoF specimens had lower ductility due to larger number and larger size of defects causing an early failure.

Note: 6 vertical tensile specimens were tested for each condition.
- In vertical orientation, KH specimens exhibited better fatigue performance than recommended ones.
- LoF specimens exhibited worse fatigue performance for vertical and diagonal orientations.
- Fatigue lives of LoF specimens had more scatter than KH ones due to wide variation in shape, size, and location of the crack initiating defects.
Fatigue Fractography

- **LoF specimens**: all fatigue cracks initiated from either internal or near surface LoF defects
- **Recommended specimens**: all fatigue cracks initiated from internal or near surface LoF defects
- **KH specimens**: fatigue cracks initiated mostly from KH defects and rarely from LoF defects located at internal or near surface

Note: √area of crack initiating defects is shown on the top right side of the fractography images
Fatigue Behavior

- Defect sizes were measured using actual $\sqrt{\text{area}}$ of the defect
- The size of the fatigue crack initiating defects of recommended and KH specimens were comparable
- Mean of the crack initiating defects of LoF specimens were significantly larger compared to recommended and KH specimens
- Size of the defects explained the order of fatigue life
Summary

- Defect types shared different degrees of overlaps in the ranges of their morphological parameters.
- The defect classification methodology could provide >98% and >99% accuracy when implemented into decision tree and artificial neural network, respectively.
- KH specimens exhibited slightly higher tensile strength due to higher amount of nitrogen.
- KH specimens exhibited better fatigue performance due to smaller crack initiating defect sizes and slightly higher tensile strengths.
- LoF specimens exhibited scatter in fatigue behavior due to differences in crack initiating defect sizes.
Thank you for your attention!

- National Center for Additive Manufacturing Excellence (NCAME)