Factors Affecting Qualification/Certification - Surface Integrity of Additively Manufactured Ti-6Al-4V Parts

Project sponsored by: Federal Aviation Administration (FAA)
Introduction

- **Project Title:** Factors Affecting Qualification/Certification - Surface Integrity of Additively Manufactured Ti-6Al-4V Parts

- **Principal Investigator:** Nima Shamsaei
  
  (See next slide for complete list of participants.)

- **FAA Technical Monitor:** Kevin Stonaker

- **Source of matching contribution:** Faculty time and graduate research assistant tuition
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- The fatigue lives of L-PBF Ti-6Al-4V specimens in as-built surface are consistently shorter compared to the specimens with machined surface condition
- Fatigue cracks in specimens with as-built surface typically initiate from micro-notches on the rough surface
- In some cases, one or two volumetric defects, often gas entrapped pores, are also found near the crack initiation site
- The fatigue strength appears to decrease with the increase in surface roughness
Different surface treatments can improve fatigue life to different extents

Efficacy of surface treatments depends on the material and selected parameters

Insufficient machining depth may expose near-surface pores to the surface
Although standard surface parameters for as-built and half-polished specimens differ by almost a factor of two, fatigue lives of half-polished specimens did not improve.

Standard surface parameter could not capture the effect of surface texture on the fatigue behavior of AM parts.

### Surface Texture Parameters

<table>
<thead>
<tr>
<th>Surface Texture Parameter</th>
<th>As-built</th>
<th>Half-polished</th>
</tr>
</thead>
<tbody>
<tr>
<td>Line</td>
<td>Area</td>
<td>Line</td>
</tr>
<tr>
<td>Arithmetical mean height (Ra or Sa)</td>
<td>18.8 µm</td>
<td>19.8 µm</td>
</tr>
<tr>
<td>Root mean square deviation (Rq or Sq)</td>
<td>23.2 µm</td>
<td>24.5 µm</td>
</tr>
<tr>
<td>Maximum profile peak height (Rp or Sp)</td>
<td>62.8 µm</td>
<td>111.8 µm</td>
</tr>
<tr>
<td>Maximum profile valley depth (Rv or Sv)</td>
<td>58.7 µm</td>
<td>87.7 µm</td>
</tr>
</tbody>
</table>
The applicability of different non-destructive inspection (NDI) techniques to measure the surface texture of AM parts has not been thoroughly studied.

While x-ray computed tomography (XCT) can capture surface texture and subsurface volumetric defects, it is costly to use and the resolution may not be adequate.

Depending on the measurement technique employed, the calculated values of standard surface parameters may vary.
Objective & Approach

- **Objective**: Factors Affecting Qualification/Certification - Surface Integrity of Additively Manufactured Ti-6Al-4V Parts

- **Approach**: Four steps are taken,
  
  I. Explore the effect of key process variables and/or post-processing on surface and near-surface conditions
  
  II. Evaluate the effectiveness of NDI techniques to assess their capability of detecting material and manufacturing critical anomalies on the surfaces and near-surface
  
  III. Determine the combined effect of surface and near-surface defects on tensile behavior and fatigue life
  
  IV. Identify the key influencing defect features on tensile and fatigue properties and establish appropriate metrics for characterizing surface conditions
Task List

• TASK 1: Literature Review & Design of Experiment (DoE)
  1.1. Literature review
  1.2. DoE

• TASK 2: Fabrication & Surface Treatments of Specimens
  2.1. Fabrication of specimens with recommended infill parameters
  2.2. Fabrication of specimens with recommended contour parameters
  2.3. Surface treatments of specimens

• TASK 3: NDI
  3.1. Digital/optical microscope
  3.2. XCT
  3.3. Florescent penetrant inspection

• TASK 4: Mechanical Testing & Fractography
  4.1. Tensile & fatigue tests
  4.2. Fractography

• TASK 5: Data Analysis & Modelling
  5.1. Effectiveness of NDI techniques to detect surface/near-surface critical anomalies
  5.2. Surface/near-surface defect features – tensile behavior correlation
  5.3. Surface/near-surface defect features – fatigue life correlation
  5.4. Representative surface metrics for the tensile and fatigue behavior of AM parts

• TASK 6: Final Report
- AP&C Ti-6Al-4V Grade 5 powder (15-53 μm) was used as feedstock
- XCT, Keyence, Dektak, and SWLI were used to measure surface texture
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# DoE: XCT Coupons

<table>
<thead>
<tr>
<th>Condition</th>
<th>Laser order 1</th>
<th>Laser order 2</th>
<th>Laser order 3</th>
<th>P</th>
<th>V</th>
<th>h</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recommended</td>
<td>Infill</td>
<td>20 µm</td>
<td>0 µm</td>
<td>280</td>
<td>1200</td>
<td>0.14</td>
</tr>
<tr>
<td>LoF</td>
<td></td>
<td></td>
<td></td>
<td>252</td>
<td>1200</td>
<td>0.14</td>
</tr>
<tr>
<td>LoF</td>
<td></td>
<td></td>
<td></td>
<td>224</td>
<td>1200</td>
<td>0.14</td>
</tr>
<tr>
<td>LoF</td>
<td></td>
<td></td>
<td></td>
<td>280</td>
<td>1200</td>
<td>0.17</td>
</tr>
<tr>
<td>KH</td>
<td></td>
<td></td>
<td></td>
<td>364</td>
<td>960</td>
<td>0.14</td>
</tr>
<tr>
<td>KH</td>
<td></td>
<td></td>
<td></td>
<td>336</td>
<td>840</td>
<td>0.14</td>
</tr>
</tbody>
</table>

| No contour |                | N/A | N/A | N/A |
| Contour order | Offset, 20 µm | Offset, 0 µm | Infill |
| Contour order | Offset, 20 µm | Infill | Offset, 0 µm |
| Contour order | 0µm | Infill | Offset, 20 µm |
| Single contour | Infill | Offset, 20 µm | N/A |
| Single contour | Infill | Offset, 0 µm | N/A |
| Different offset | Infill | Offset, 40 µm | Offset, 20 µm |
| Different offset | Infill | Offset, 40µm | Offset, 0 µm |

- 14 different key process variables were considered

Unit: mm

Coupon colors correspond to different process parameters, which are shown using corresponding color in the table.
Results: Surface Texture of XCT Coupons

- Coupon without contour resulted in deepest surface valleys
- Infill process parameters (i.e., KH and LoF) did not significantly affect Sa and Sv values
### Results: Selection of Process Parameters

<table>
<thead>
<tr>
<th>Geometry</th>
<th>Orientation</th>
<th>Contour</th>
<th>Infill</th>
<th>Sa (µm)</th>
<th>Sv (µm)</th>
<th>Surface Treatment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solid</td>
<td>Vertical</td>
<td>No contour</td>
<td>Default</td>
<td>19</td>
<td>135</td>
<td>No</td>
</tr>
<tr>
<td>Solid</td>
<td>Vertical</td>
<td>Order of contours</td>
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<td>20</td>
<td>74</td>
<td>No</td>
</tr>
<tr>
<td>Solid</td>
<td>Vertical</td>
<td>Order of contours</td>
<td>Default</td>
<td>20</td>
<td>70</td>
<td>No</td>
</tr>
<tr>
<td>Solid</td>
<td>Vertical</td>
<td>Order of contours</td>
<td>Default</td>
<td>19</td>
<td>76</td>
<td>No</td>
</tr>
<tr>
<td>Solid</td>
<td>Vertical</td>
<td>1 contour</td>
<td>Default</td>
<td>20</td>
<td>88</td>
<td>No</td>
</tr>
<tr>
<td>Solid</td>
<td>Vertical</td>
<td>1 contour</td>
<td>Default</td>
<td>17</td>
<td>75</td>
<td>No</td>
</tr>
<tr>
<td>Solid</td>
<td>Vertical</td>
<td>Different offsets</td>
<td>Default</td>
<td>21</td>
<td>92</td>
<td>No</td>
</tr>
<tr>
<td>Solid</td>
<td>Vertical</td>
<td>Different offsets</td>
<td>Default</td>
<td>17</td>
<td>70</td>
<td>No</td>
</tr>
<tr>
<td>Solid</td>
<td>Vertical</td>
<td>Default</td>
<td>KH</td>
<td>19</td>
<td>79</td>
<td>No</td>
</tr>
<tr>
<td>Solid</td>
<td>Vertical</td>
<td>Default</td>
<td>KH</td>
<td>21</td>
<td>83</td>
<td>No</td>
</tr>
<tr>
<td>Solid</td>
<td>Vertical</td>
<td>Default</td>
<td>LoF</td>
<td>21</td>
<td>75</td>
<td>No</td>
</tr>
<tr>
<td>Solid</td>
<td>Vertical</td>
<td>Default</td>
<td>LoF</td>
<td>18</td>
<td>62</td>
<td>No</td>
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<tr>
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<td>Vertical</td>
<td>Default</td>
<td>LoF</td>
<td>20</td>
<td>93</td>
<td>No</td>
</tr>
<tr>
<td>Solid</td>
<td>Vertical</td>
<td>Default</td>
<td>Default</td>
<td>21</td>
<td>81</td>
<td>No</td>
</tr>
</tbody>
</table>

Note: *Green* shading indicates selected process parameters for fabrication of tensile and fatigue specimens

- Reported Sa and Sv values were obtained using SWLI
Objective & Approach

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## Overview of NDI Techniques

<table>
<thead>
<tr>
<th>Method</th>
<th>Advantages</th>
<th>Disadvantages</th>
<th>Cost</th>
<th>Scan Time</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Dektak</strong></td>
<td>- Measurements can be obtained quickly</td>
<td>- Requires continuous contact with the surface</td>
<td>~$10,000</td>
<td>2 Minutes</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Performs line scans not area</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Keyence</strong></td>
<td>- Measurements can be obtained quickly</td>
<td>- Glare can cause outliers in the data</td>
<td>~$60,000</td>
<td>6 Minutes</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Resolution is not as fine as other methods</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>SWLI</strong></td>
<td>- Measurement can achieve sub-nanometer precision in height</td>
<td>- Cannot read spiky or nonreflective asperities</td>
<td>~$200,000</td>
<td>40 Minutes</td>
</tr>
<tr>
<td><strong>XCT</strong></td>
<td>- Subsurface defects can be detected</td>
<td>- Scan time can be long</td>
<td>~$1,000,000</td>
<td>&gt;2.5 hours</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Requires heavy post processing</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Post-processing: XCT

- Surface topography was obtained by stacking line profiles.

Flow chart for XCT image processing:

- Stacked images (TIFF)
- Sub-image (TIFF)
- Blur image
- Binary
- Fill holes
- Line profile
- Stack
- Area profile
- Gaussian
- Surface maps

Implications from overhang structures:

With overhang structures:

- Sa = 19 µm, Sv = 58 µm, Sz = 142 µm
- 300 µm

Without overhang structures:

- Sa = 16 µm, Sv = 53 µm, Sz = 140 µm
- 300 µm

Flow chart:

- Surface topography was obtained by stacking line profiles.
Results: Surface Texture from the Matching Areas

- XCT surface topography with overhang structures showed similar results to other techniques.
- Dektak and Keyence showed lower roughness values compared to SWLI and XCT.
- Surface profile obtained from polished cross-section was similar to XCT profile, indicating XCT results are more representative of the true profile.
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DoE: Tensile and Fatigue Specimens

- 3 stress levels with 4 tests per level were chosen for each condition
- Geometries for D/M and S/M were oversized from outer diameter by 2 mm and 0.2 mm, respectively

<table>
<thead>
<tr>
<th>#Fatigue Specimens per Set</th>
<th>#Tensile Specimens per Set</th>
<th>Geometry</th>
<th>Orientation</th>
<th>Contour</th>
<th>Infill</th>
<th>Surface Treatment</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>6</td>
<td>Solid</td>
<td>Vertical</td>
<td>No contour</td>
<td>Default</td>
<td>No</td>
</tr>
<tr>
<td>15</td>
<td>6</td>
<td>Solid</td>
<td>Vertical</td>
<td>No contour</td>
<td>KH</td>
<td>No</td>
</tr>
<tr>
<td>15</td>
<td>6</td>
<td>Solid</td>
<td>Vertical</td>
<td>No contour</td>
<td>LoF</td>
<td>No</td>
</tr>
<tr>
<td>15</td>
<td>6</td>
<td>Solid</td>
<td>Vertical</td>
<td>Default</td>
<td>Default</td>
<td>No</td>
</tr>
<tr>
<td>15</td>
<td>6</td>
<td>Solid</td>
<td>Vertical</td>
<td>Default</td>
<td>KH</td>
<td>No</td>
</tr>
<tr>
<td>15</td>
<td>6</td>
<td>Solid</td>
<td>Vertical</td>
<td>Default</td>
<td>LoF</td>
<td>No</td>
</tr>
<tr>
<td>15</td>
<td>6</td>
<td>Solid</td>
<td>Vertical</td>
<td>1 contour</td>
<td>Default</td>
<td>No</td>
</tr>
<tr>
<td>15</td>
<td>6</td>
<td>Solid</td>
<td>Vertical</td>
<td>Different offset</td>
<td>Default</td>
<td>No</td>
</tr>
<tr>
<td>15</td>
<td>6</td>
<td>Solid</td>
<td>Vertical</td>
<td>Default</td>
<td>Default</td>
<td>S/M</td>
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<tr>
<td>15</td>
<td>6</td>
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<td>Default</td>
<td>Default</td>
<td>D/M</td>
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<tr>
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<td>Solid</td>
<td>Vertical</td>
<td>Default</td>
<td>Default</td>
<td>M/P</td>
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<tr>
<td>15</td>
<td>-</td>
<td>Tubular</td>
<td>Horizontal</td>
<td>Default</td>
<td>Default</td>
<td>Only P</td>
</tr>
<tr>
<td>15</td>
<td>-</td>
<td>Tubular</td>
<td>Horizontal</td>
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<td>15</td>
<td>-</td>
<td>Tubular</td>
<td>Vertical</td>
<td>Default</td>
<td>Default</td>
<td>No</td>
</tr>
</tbody>
</table>

Tensile specimens (ASTM E8)

Fatigue specimens

As-built tubular fatigue specimens

S/M: Shallow machining  
D/M: Deep machining  
M/P: Machining and polishing  
P: Polishing
Summary

- Variation in infill process parameters did not affect surface texture values
- Coupons without contour exhibited deepest surface valleys
- In general, Dektak and Keyence showed lower surface texture values compared to the SWLI and XCT
- The surface texture values obtained from the XCT were dependent on the specific method used for processing the raw data
- Surface profile obtained from the XCT was more representative of the true profile obtained from the polished cross-section
Thank you for your attention!

- National Center for Additive Manufacturing Excellence (NCAME)