Flaw Generation in Laser Powder Bed Fusion (L-PBF)

AMC Meeting at EWI

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Outline

- L-PBF process: Defects
- Literature Review
- Problem and Objectives
- Experiments
  - Category 1: Open-to-Surface Flaws
    - Minimum width
    - Machine settings
    - Length effect
    - Walls effects
    - Beam Offset
    - Clustered Flaws
  - Category 2: Embedded Flaws
- Summary
- Future Study
L-PBF process: Defects

- Laser powder-bed fusion (L-PBF) processes are actually a lengthy welding process.
  - Quality of components produced by L-PBF is affected by the quality of each single track.
L-PBF process: Defects

- The common types of defects in PBF processes:
  - Porosity
  - Lack of Fusion
  - Balling
  - Cracking
  - Delamination
  - Anisotropy in microstructures (and mechanical properties)
  - Surface roughness!

- Calibration in non-destructive inspection (NDI)
  - Development of the know-how for producing these defects would be beneficial.
Moylan et al.: “the minimum feature size achievable on this system in stainless steel is between 0.5 mm and 0.25 mm”.

Manfredi et al.: “recommended machine setting”

Yang et al.: the influence of scanning strategy (hatch vs. contour) on dimensional accuracy

Minev E.: the influence of slicing and stair-stepping effect on dimensional accuracy
Problem and Objectives

- **Problem:** How to create a defect with/at a desired
  - Geometry
  - Dimension
  - Location

- **Objectives**
  - Evaluate capabilities of a laser powder-bed fusion (L-PBF) process in producing defects
  - Develop the know-how
Experiments

- **Equipment:**
  - EOS M280 with 400W laser at EWI (SN 1349)

- **Material:**
  - Nickel Alloy Inconel 718

- **Flaw categories:**
  - Category 1: Open-to-Surface flaws
  - Category 2: Embedded flaws
Experiments- Category 1

- **Category 1: Open-to-Surface Flaws**
  - Several notches were produced with
    - Width (µm): 40, 80, 120, 160, 280, 400, 600, 1000
    - Depth (µm): 100, 200, 500, 1000

- **Flaw measurement**
  - Notches built transverse to coupon length
  - Each specimen sectioned along the dashed line

Depth: 1000 µm
`Category 1: Open-to-Surface Flaws`

- Depth: 100 um
- Depth: 200 um
- Depth: 500 um
- Depth: 1000 um
Experiments- Category 1

Category 1: Open-to-Surface Flaws

- Depth:
  - Shallower notches have mostly irregular cross section (notch wall).
  - Deeper notches have smoother cross section, but smaller widths (40, 80, 120 um) fused in these cases.
  - Depth oversize was on the range of ±50 um, except in the fused cases.

- Width:
  - An increase in width was accompanied by a decrease in error.
  - Width oversize decreased by an increase in width.
  - Width oversize was changed to undersize at 280 um.
Category 1: Open-to-Surface Flaws

- Lesson learned
  - 160-280 um was the range of minimum width that could be reliably produced by the current L-PBF machine.
  - Less accurate measurement due to the edge effect (irregular and round edges) on unpolished surfaces.
  - A change in design of coupons was needed.
Category 1: Open-to-Surface Flaws (new design)

- Dimension:
  - Length (mm): 6 mm
  - Depth (um): 500 um
  - Width (um): 40, 80, 120, 160, 280, 400, 600, 1000
- Top surface of each specimen polished to remove roughness and allow measurements.
Experiments - Category 1

Category 1: Open-to-Surface Flaws (new design:#1)

- A trend similar to that of the previous experiment was observed between notch width and oversize.
- Notches with width of 40 um fused along length.
Category 1: Open-to-Surface Flaws (machine settings)

<table>
<thead>
<tr>
<th>Machine setting</th>
<th>Skywriting</th>
<th>Hatching</th>
<th>UpDown Skin</th>
<th>Pre Contour</th>
<th>Post Contour</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample #</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
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- Not a considerable difference, except irregularity in edges and corners.
Category 1: Open-to-Surface Flaws (machine settings)

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- Larger deviation in width
- Sharper walls at width ≥ 280 um
Category 1: Open-to-Surface Flaws (machine settings)

- Reduced oversize in widths ≤ 160 um
- Sharper edges
* Category 1: Open-to-Surface Flaws (machine settings)

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- Notches with width < 160 um (by design) were not possible to fabricate reliably.
Experiments- Category 1

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Notches with all widths are oversized.

w = 160 um @ #6
Experiments- Category 1

- **Category 1: Open-to-Surface Flaws/ machine settings**
  - Lesson learned: the recommended settings to reduce dimensional error in open-to-surface flaws:
    - Skywriting: ON
    - Hatching: ON (rotation)
    - UpDown Skin: ON
    - Pre-contour: OFF
    - Post-contour: OFF
Category 1: Open-to-Surface Flaws (other studies)

- a) Walls Effect:
  - Rectangles with different sizes (200-1000 um)
  - No new information

- b) Length Effect:
  - Different lengths at a fixed width (160-280 um)
  - not a meaningful influence of length on width
Experiments - Category 1

Category 1: Open-to-Surface Flaws (ongoing studies)

- c) Clustered Flaws: notches with
  - The same width
  - Different distances
- Beam offset
  - 1\textsuperscript{st} iteration: 4 levels of beam offset
  - 2\textsuperscript{nd} iteration: 6 levels of beam offset.

1\textsuperscript{st} iteration 2\textsuperscript{nd} iteration
Category 2: Embedded flaws

- Dimension:
  - Height (mm): 0.2, 0.4, 0.6, 0.8
  - Width (mm): 0.2, 0.4, 0.6, 0.8, 1, 1.5, 2
  - Distance (along buildup direction): 10 mm
- Notches built in one specimens
- Specimen cut at middle of 10 mm length and cut surface polished to remove roughness and allow measurements

Fused completely in all widths (except at w=1.5 mm).
Experiments- Category 2

**Category 2: Embedded flaws**
- Large under-sizing in height
- Notch with a 0.2 mm-height fused completely.

Fusion at lower height, and longer width
Category 2: Embedded flaws

- **Height:**
  - Average height undersize: 190-270 um, with uncertainty from 20-90 um.
  - Complete fusion for heights smaller than 0.2 mm and smaller than 0.4 mm in some cases.

- **Width:**
  - Larger width (>0.4 mm) increases possibility for partial or complete fusion at small heights (<0.4 mm)
  - Average width oversize: ± 20 um, with uncertainty from 40-400 um.
  - Smaller height and width seems to be fabricated with less uncertainty.

- **Ongoing study**
Summary

- Shallower notches have mostly irregular cross section (notch wall). Deeper notches have smoother cross section, but smaller widths (40, 80, 120 um) fused in these cases.
- An increase in width was accompanied by a decrease in error. 160-280 um was the range of minimum width that could be reliably produced by the current L-PBF machine.
- Activation of skywriting, rotational hatching and UpDown skin could lower mismatch between designs and actual sizes of flaws. Pre and post contours resulted in the fusion of narrow widths or an increased oversize, respectively.
Summary

◆ All embedded flaws with different heights showed larger under-sizing in height. Flaws with 0.2 m height were completely fused.

◆ Larger width (>0.4 mm) increased possibility for partial or complete fusion at small heights (<0.4 mm)

◆ Smaller height and width seems to be fabricated with less uncertainty.
Future Study

- Continuation of the ongoing studies
  - Optimized beam offset
  - Minimum width/distance in clustered flaw
  - Height undersize in embedded flaws

- Validation of the current results through additional case-studies

- Development of a relationship between nominal and actual sizes of flaws
EWI is the leading engineering and technology organization in North America dedicated to developing, testing, and implementing advanced manufacturing technologies for industry. Since 1984, EWI has offered applied research, manufacturing support, and strategic services to leaders in the aerospace, automotive, consumer electronic, medical, energy, government and defense, and heavy manufacturing sectors. By matching our expertise to the needs of forward-thinking manufacturers, our technology team serves as a valuable extension of our clients’ innovation and R&D teams to provide premium, game-changing solutions that deliver a competitive advantage in the global marketplace.

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During scanning a certain time is needed to accelerate the mirrors to the desired speed. This is due to inertia of mirrors used for scanning. During this time laser beam cover some distance in which speed is not constant hence more energy is applied at the edges of the part than the inside of the part.

If skywriting option is selected,

- the mirror is accelerated already before the start of the part so that it has reached the desired speed before the beginning of exposure. Laser is switched on at the start of the part.
- Similarly retardation phase begins at the part end where the laser is switched off.
Hatch Pattern

- Four choices for hatch pattern selection are generally available:
  - along x
  - along y
  - both in xy
  - alternating in xy
Up/Down Skin

- **Up-skin**: The layer above which there is no area to be exposed, is termed up-skin, and is built in three layers.
- **Down-skin**: The layer below which there is no exposed area is called down-skin, and is built in two layers.
- **Core**: The rest of the part is termed core or in-skin.

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Scanning Strategy

- Hatch operation fills the interior region of the scanned area with a series of parallel tracks.
  - regular structures with bulky geometries
- Contour operation scans along the outer contour of the scanned area.
  - better defines the part boundaries and improve the surface finish of the final structures
- Edge operation performs a single track scanning
  - regions with small dimensions, such as the sharp tip of the triangular area.

Yang, Li, Haijun Gong, Samuel Dilip, and Brent Stucker. "An investigation of thin feature generation in direct metal laser sintering systems."
Beam Offset

- If the controller commanded the beam center to the edges of the feature’s geometry, the parts would be too large because the beam would fuse a small amount of powder on the free side of the geometry equal to the radius of the beam spot.

- To compensate for this, the controller uses a beam offset that positions the beam center toward the material side of the feature by an amount equal to the beam radius.