EXTREME VALUE ANALYSIS OF DEFECTS ON AM PARTS

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A research with the support of RUAG Space, Product Unit Structures
Summary of the presentation

- **Introduction & motivation**
- **Extreme value analysis for CT scans**
  1. Sampling strategies;
  2. Analysis in terms of volumes;
  3. Geometric features of extreme defects;
- **How to reduce CT scan effort**
  5. Choice of the threshold;
  6. Minimum material volume to be scanned;
- **Application to component**
  7. Prospective application onto a component;
- **Conclusions**
Defects have a large influence on the fatigue limit. They can be treated as short cracks according to Murakami’s projected root area and described by the Kitagawa diagram.

- Fatigue properties of AM are very similar to those of standard processes;
- Large reduction of fatigue resistance for as-built samples (they can be modeled as equivalent surface defects);
- Intrinsic variability of the fatigue limit due to several factors (process/microstructure).
the fatigue is controlled by the **extreme values** of the population of defects **not** by the average dimension

analysis of extremes based on **extreme value sampling** at the end of the 90’s

ESIS P11-02
ASTM E2283-03
**Statistics of extremes strategies**

### Peaks-over-threshold

In a given volume, all the defects over a certain threshold are considered.

- no standard (but good books);
- all the measurements above \( u \) are treated;
- **Exponential distribution** \((d \to \infty)\);
- Extrapolated distribution for the maximum defect in a given volume is the **Gumbel distribution**

### Block maxima

In a given volume, only the largest defect is considered.

- considered in ASTM E2283-03;
- it is applied very naturally with polished sections;
- a bit ‘innatural’ to pick up the maximum defect in a given sub-volume.
- **Gumbel distribution** \((d \to \infty)\)
Activity

- CT scans for a series of specimens that were provided by RUAG Space, Product Unit Structures,
  together with a component were analyzed with CT scans at ESA;
- Analysis with the statistics of extremes with POT method.

<table>
<thead>
<tr>
<th>Name</th>
<th>Print direction</th>
<th>N</th>
<th>$V_{\text{max}}$</th>
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</tr>
<tr>
<td>V26</td>
<td>vertical</td>
<td>20871</td>
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</tr>
</tbody>
</table>

At the beginning only the data in the gage length were considered.
A comparison on defect size $V$ and $\sqrt[3]{V}$ is done considering only the gage volume. Some difference among the specimens.

- Above a threshold of 0.075 mm, the flaw distribution of the exceedances is an exponential;
- this corresponds to the well established results for inclusions in steels ($V_{area}$ is a Gumbel)
1. Fix a threshold for the volume: \( u = 0.075 \)

2. Calculate the mean excess: \( \mu = \text{mean}(3\sqrt{V} - u) \)

3. Return period of the defect exceeding \( u \) in a bigger volume: \( T = \frac{V_c}{V_s} \cdot n_u \)

4. Define the maximum defect with return period \( T \) in terms of diameter and volume:

\[
d_{\text{max},T} = \mu \cdot \log T + u \\
d_{\text{max}} \in \text{LEVD} \left\{ \lambda = d_{\text{max}}, \delta = \mu \right\}
\]
Predictions of maximum defects have been compared with maximum defect detected on the entire specimen (not only the gage length).

Considering the low number of defects used in the estimation of maxima (only those in $V_g$), the prevision is quite good.
Defects $\rightarrow$ fatigue

From Murakami we know that:

$$\Delta K = 0.65 \cdot \Delta S \cdot \sqrt{\pi \sqrt{\text{Area}}}$$

The projection along the stress direction (PZ) can then be used to define the $\sqrt{\text{Area}}$ parameter, essential for the Kitagawa diagram.

In order to perform good estimations of the fatigue life, the extreme value analyses have to be carried out on the $\sqrt{\text{Area}}$ parameter.
POT on $\sqrt{A}$

Even considering $\sqrt{A}$, distributions are very similar, except for U25 and V26. Once again, only the defects in the gage volume are taken into account.

![Exp. probability plot]

POT threshold: $\sqrt{A_{th}} = 100\mu m$

The analysis of Varea confirms that the exponential fit can be adequate.
Summary of the application

• Comparison of the specimens considering the area of defects perpendicular to specimen axis;
• Important defects have $\sqrt{A} > 100 \, \mu m$ (final flat part of Kitagawa diagram);

threshold $u$ has a meaning also from the point of view of Kitagawa diagram (only defects exceeding 100 $\mu m$ are detrimental)
1) Our estimates of maximum defects from a small material volume are really precise?

2) How much effort do we have to spend (scanning time, material volume) for obtaining good estimates if we had to estimate the maximum defect on a big component?
The reference distribution obtained by ‘Block maxima’ sampling a much larger material volume has been estimated through the POT by taking different values of $u$. The threshold varies from $u=100 \, \mu m$ to $u=150 \, \mu m$ and $200 \, \mu m$.

The estimations based on the two POTs described are in line with the maxima found, and in particular the estimation is very accurate fixing $u=150 \, \mu m$, while using $u=100 \, \mu m$ we underestimate the real maxima. No further improvement for $200 \, \mu m$. 

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**Block Maxima on defect area**

Introduction & motivations

Extreme value analysis

CT scan optimization

Applications
Specimen F3H was tested considering two CT resolutions:

- **High resolution**: pixel size 15 μm;
- **Low resolution**: pixel size 30 μm.

The goal is to verify if decreasing the resolution some time needed for CT could be saved, without losing in accuracy when describing the extreme defect distribution.

- Distribution of POT is almost the same!
- Significant time saving from 7.5 h to 2.3h!
Minimum material volume

Monte Carlo simulations have been performed in order to understand the influence of this variability, sampling 3, 5 or 10 subvolumes of the 15 ones and fitting the exponential distribution on the exceedances over the threshold $u$.

- **3 subvolumes**
- **5 subvolumes**
- **10 subvolumes**

For
- $u = 100 \, \mu m$
- $u = 150 \, \mu m$
The distribution matters!

Even if the two maxima are not perfectly in line with the estimation, both the LEVD and the composed distribution found by statistic of extremes on a volume equal to $7.5 \, V_{gage}$ (the whole volume divided by 2, the return period of these points) yields a good prevision.
Bracket parts

Two small parts of the component were analyzed by CT: QM1 and QM2.

Their volumes are:
- $V_{QM1} = 15500 \text{ mm}^3$
- $V_{QM2} = 3870 \text{ mm}^3$

Application of the previous ‘rules’ was successful.
CT scans of the component reveal that, apart from internal volumetric defects, there are regions of sub-surface pores.

If we treat them as a 2-D crack:

\[ \sqrt{\text{area}}_{sup} = 650 - 790 \ [\mu m] \]
Prospectively, this is the scenario for fatigue assessment considering average strength of AlSi10Mg

The sub-surface defects appear to be more detrimental than the internal ones.
In this presentation I have discussed some applications of the statistics of extremes to AM parts:

- it has to be used because fatigue strength is controlled by the maximum defect in a given volume;
- features and methods developed in the ‘90’s for inclusions are still valid and it is worth adopting that wide background (e.g. ASTM E2283-03);
- It looks that the ‘Peak Over Threshold approach’ is the most simple to apply for CT scan measurements;
- It is possible to determine the minimum requirements for the scan of a component (threshold, minimum volume) that also allow to reduce the effort of defect sampling;
- prospective application to fatigue is very simple through the Kitagawa diagram.
Essential references


The authors would like to acknowledge the support of RUAG Space, Product Unit Structures, Zurich (CH)
Overview of Fatigue and Damage Tolerance Performance of Powder Bed Fusion Alloy N07718

William Campbell
NASA MSFC
Huntsville AL

William Tilson
Jacobs ESSSA Group
Huntsville AL

ASTM/NIST Workshop on Mechanical Behavior in Additive Manufactured parts

May 4, 2016
MSFC PBF Capability

- Selective Laser Melting (SLM)
  - Heat source is a 200 W laser
- Concept Laser M1 Cusing SLM machine
  - 250 x 250 x 250 mm³ build volume
SLM 718 Post-Processing

- Stress Relief: 1065°C for 1.5 hours; furnace cool.
- HIP: 1165°C, 100 MPa, 3-4 hours
- Solution (AMS 5664): 1066°C for 1 hour; air cool.
- Age (AMS 5664): 760°C for 10 hours; furnace cool to 650°C; treat for total of 20 hours.

As-built microstructure

Heat treated microstructure
Typical Build Properties

- Typical tensile witness test curve for SLM 718.
  - Ultimate Tensile Strength: ~ 1380 MPa
  - Yield Strength: ~ 1170 MPa
  - Fracture Elongation: > 20%
Defective Build

- A build of test specimens was produced; all indications were that the build was successful.
- Witness tensile testing revealed lower than expected material properties.
Defective Build

- Metallographic examination revealed lack of fusion defects in the material.
- Source was eventually determined to be a clogged ventilation duct that was allowing combustion by-products to settle on the powder bed.
- “Reference” data – Low Stress Ground, R = -1, Defect-free build
Low Cycle Fatigue of SLM 718

- Compare to build with defects – slightly lower fatigue life

Plotted fits are power-law fits of the form $Y = ax^b + c$
Low Cycle Fatigue of SLM 718

- Defect-free build with as-built surface finish; fatigue life even lower

Plotted fits are power-law fits of the form $Y = ax^b + c$
Low Cycle Fatigue of SLM 718

- As-built surface finish, with defects; surface finish has more effect than internal defects.
High Cycle Fatigue of SLM 718

• Key Variables
  • Orientation
    • Z – loading axis perpendicular to powder bed plane.
    • XY – loading axis parallel to powder bed plane.
    • 45° – loading axis 45° from powder bed plane.
  • Surface Finish
    • Low Stress Ground – ASTM E466 finishing procedure
    • As-Built – Surface finish from the SLM machine
  • Temperature
    • Room Temperature (RT) – nominal lab conditions, 70-75°F
    • Liquid Nitrogen (-320°F)
- Low stress ground; minimal effect from orientation
- “Reference” data – Low Stress Ground, Room Temperature, R = 0.1
High Cycle Fatigue of SLM 718

MMPDS reference curve is wrought N07718 bar stock, heat treated to AMS 5662, from MMPDS-08 Figure 6.3.5.1.8 (f). Plotted fits are power-law fits of the form $Y = ax^b + c$.

- Z-oriented, As-built surface finish; decreased fatigue life
- 45°-oriented, As-built surface finish; similar fatigue life, 45° tend to be rougher than Z
- Z-oriented, lathe-turned surface finish; quicker machining turnaround, slight decrease in life from low stress ground.
- Z-oriented, Tumbled then Electropolished; investigated for part finishing.
High Cycle Fatigue of SLM 718

- Z Oriented, Tumbled then Chem Milled; investigated for part finishing.
High Cycle Fatigue of SLM 718

- Fatigue life decreases with increasing surface roughness.

- Low stress ground
- As-built
- Tumbled & Electropolish
- Tumbled & Chem Mill
- Tests in LN$_2$ (-320$^\circ$). Some increase in life for as-built surfaces; more increase for low stress ground.
- Identical builds were procured from three third-party SLM vendors; one build was provided by MSFC.
- The specimens were heat treated per MSFC guidance, although allowances were made for vendors with existing mature processes.
- A series of comparison testing was done to evaluate the quality of the material.
- Z-oriented, low stress ground surface finish; compared to M1 and wrought reference curves
- Z-oriented, “as-provided” surface finish; compared to M1 and wrought reference curves
Fatigue Crack Growth Results

• Round Robin Results
  • 3 specimens from each build
  • Z-XY test orientation
  • Post-processing same as fatigue specimens

• Testing Methodology
  • Tested according to ASTM E647
    • “Standard Test Method for Measurement of Fatigue Crack Growth Rates”
  • R = 0.1 and R = 0.7 data shown
  • Compression pre-cracking procedure (CPC)
Compression Pre-Cracking

- Compression-compression loading used to generate a crack at the notch root of a c(T) specimen.
- May produce more conservative threshold and near-threshold crack growth rates.
- Following CPC procedure detailed by Newman and Yamada.
Fatigue Crack Growth

- Wrought Inconel-718 alloy obtained from Boeing-Rockwell. Tested using the ASTM LR test method and CA loading.
• Wrought Inconel-718 alloy obtained from Boeing-Rockwell. Tested using the CPLR test method and CA loading.

Fatigue Crack Growth

- SLM 718 M1 Machine included as a reference. This data is not part of the Round-Robin.
- Produced using ASTM LR and CA loading.
Fatigue Crack Growth

- MSFC Round-Robin data. Consistent with M1 data.
Fatigue Crack Growth

- Lab B - Higher observed growth rates than M1 data.
Fatigue Crack Growth

- Lab C - Consistent with M1 data.
Fatigue Crack Growth

- Lab D - Consistent with M1 data. CPLR only.
• Only Lab B had any distinction from the M1 data.
Fatigue Crack Growth

- Wrought Inconel-718 alloy obtained from Boeing-Rockwell. Tested using the ASTM LR test method and CA loading.

Fatigue Crack Growth

- Wrought Inconel-718 alloy obtained from Boeing-Rockwell. Tested using the CPLR test method and CA loading.
• Higher observed growth rates compared to wrought 718 near-threshold.
• MSFC - Consistent with M1 data.
- Lab B - Consistent with M1 data.
Fatigue Crack Growth

- Lab C - Lower crack growth rates near-threshold compared to M1 data. More closely follows Newman data.
Fatigue Crack Growth

- Lab D - Lower crack growth rates near-threshold compared to M1 data. More closely follows Newman data.
Fatigue Crack Growth

- MSFC & Lab B: Consistent with M1 data
- Lab C & Lab D: Consistent with Newman data
Fracture Toughness Results

• Round Robin
• SLM 718
  • Stress relief, HIP, ASM 5664 Heat Treatment
• ASTM E1820
  • J-R vs $\Delta a$
  • Legend lists $J_{IC}$ value obtained from ASTM E1820
Fracture Toughness Results

M1 Machine

$J_{IC} = 92.7$
$J_{IC} = 98.2$
$J_{IC} = 89.1$
$J_{IC} = 79.5$

$J$ (KPa•m)

$\Delta a$ (mm)
Fracture Toughness Results

M1 Machine

- Fits are power law regression line specified in ASTM E1820.
- Fits of highest and lowest $J_{IC}$ value obtained from M1 machine for reference.
Fracture Toughness Results

Round Robin - MSFC

- $J_C = 98.2$
- $J_C = 79.5$
- $J_C = 111.7$
- $J_C = 103.2$

$J$ (KPa•m) vs. $\Delta a$ (mm)
Fracture Toughness Results

Round Robin - Lab B

$J$ (KPa m) vs $\Delta a$ (mm) plot for different $J_C$ values:
- $J_C = 98.2$ (dashed blue line)
- $J_C = 79.5$ (solid green line)
- $J_C = 81.6$ (circle green markers)
- $J_C = 84.6$ (triangle green markers)
Fracture Toughness Results

Round Robin - Lab C

- $J_C = 98.2$
- $J_C = 79.5$
- $J_C = 99.4$
- $J_C = 106.0$

$J$ (KPa$\cdot$m)

$\Delta a$ (mm)
Fracture Toughness Results

Round Robin - Lab D

\[ J (\text{KPa} \cdot \text{m}) \]

\[ \Delta a (\text{mm}) \]
Fracture Toughness Results

Round Robin - All Labs

J (KPa-mm)

Δa (mm)
FINAL TECHNICAL PROGRAM

WORKSHOP ON MECHANICAL BEHAVIOR OF ADDITIVE MANUFACTURED COMPONENTS

Sponsored by ASTM Committee E08 on Fatigue and Fracture in conjunction with the National Institute of Standards and Technology (NIST).

May 4-5, 2016
Grand Hyatt San Antonio
San Antonio, TX

Workshop Organizers: Steve Daniewicz, Mississippi State University
Nima Shamsaei, Mississippi State University
Nik Hrabe, NIST
Nick Barbosa, NIST

WEDNESDAY, MAY 4, 2016
*separate registration is required for Wednesday and Thursday

8:00 AM
Opening Remarks
Steve Daniewicz, Mississippi State University

8:15 AM
Additive Manufacturing in the Context of Structural Integrity
Michael Gorelik, FAA

8:45 AM
Reliability of Mechanical Behavior in Metallic Additively Manufactured Parts Used in Critical Applications
Doug Wells, NASA Marshall

9:15 AM
Ti-6Al-4V for Orthopaedic Implants in Fatigue
Mukesh Kumar, Zimmer-Biomet

9:45 AM BREAK

10:15 AM
Fracture Mechanics and Nondestructive Evaluation Modeling to Support Rapid Qualification of Additively Manufactured Parts
Craig McClung, Southwest Research Institute (SWRI)
10:45 AM
**Extreme value analysis of defects on AM parts**
Steffano Beretta, Politecnico di Milano

11:15 AM
**Fatigue Life Manipulation of SLM® Parts**
Wadim Reschetnik, Paderborn University

11:45 AM  **LUNCH**

1:15 PM
**Advanced Characterization of Additively Manufactured Materials, including Synchrotron–based 3D X-rays**
Anthony Rollett, Carnegie Mellon University

1:45 PM
**Effects of HIP Processing on Additively Manufactured, Titanium Materials Produced Using an Electron Beam – Directed Energy Deposition Process**
Hank Phelps, Lockheed Martin Aeronautics

2:15 PM
**Overview of Fatigue and Damage Tolerance Performance of Powder Bed Fusion Alloy N07718**
William Tilson and William Campbell, NASA Marshall

2:45 PM  **BREAK**

3:00 PM
**Presentation of NEEDS and BARRIERS from pre-workshop survey**
Nik Hrabe, NIST

3:30 PM
**Expert Panel leads discussion of NEEDS and BARRIERS**
Expert Panelists:
Bob Klein, Stryker
John Slotwinski, Johns Hopkins Applied Physics Laboratory (APL)
Gautam Gupta, 3D Systems
Craig McClung, Southwest Research Institute (SWRI)

4:30 PM
**Entire group prioritizes NEEDS and BARRIERS**

5:00 PM  **CLOSE 1st Day**
THURSDAY, MAY 5, 2016
*separate registration is required for Wednesday and Thursday

8:00 AM
Opening Remarks
Nik Hrabe, NIST

8:15 AM
Ongoing challenges in additive manufacturing of fatigue resistant materials
Nima Shamsaei, Mississippi State University presented by: Jutima Simiriwong, Mississippi State University

8:45 AM
Breakout Sessions generate STRATEGIES for identified NEEDS and BARRIERS

10:00 AM   BREAK

10:30 AM
Breakout Sessions prepare summaries of their discussions

11:00 AM
Breakout Sessions present summaries

11:45 AM
Closing Remarks
Steve Daniewicz, Mississippi State University

12:00 PM   CLOSE Workshop
Ti-6Al-4V for Orthopedic Implants in Fatigue

Mukesh Kumar
Zimmer-Biomet

WORKSHOP ON MECHANICAL BEHAVIOR OF ADDITIVE MANUFACTURED COMPONENTS

Sponsored by ASTM Committee E08 on Fatigue and Fracture in conjunction with the National Institute of Standards and Technology (NIST).

May 4-5, 2016
Grand Hyatt San Antonio
San Antonio, TX
What does the Orthopedic Industry do

In the business of restoring mobility by replacing damaged bone / cartilage with metallic implants that

– Must survive years
– In a hostile (corrosive) environment
– (osseo) integrate with the surrounding bone to transmit 5-8 X body weight
– Under fatigue conditions
Titanium and Porous Structure

• Why do we need this porous structure
  – Bone – Implant Interface
    • Transmit load

• Animal
• Human
Animal Studies
Human – Retrieval Analysis
Porous Beaded Structure - Notch
Orthopedic Industry and Additive Manufacturing

Additive Manufactured Implants now available
   – Acetabular shells
   – Spinal Implants

Low fatigue environment
Some Surgical Cases

Some clinical cases ....

  – To get an idea of loads involved
    • Imagine your own anatomy

Why Additive Manufacturing makes perfect sense

Imagine the following work flow
  Image (sometimes the contralateral side)
  Create CAD
  Make Implant / Bone Model / Fixtures and Guide

In many cases - Time is of the essence
18 year old patient
osteosarcoma of the proximal humerus

Expandable proximal humeral implant with a Compress stem

Failed allograft

CUSTOM IMPLANT NOT FDA CLEARED

CUSTOM IMPLANT NOT FDA CLEARED
• Bilateral Triflanges

IMPLANT NOT FDA CLEARED
IMPLANT NOT FDA CLEARED
• Mid shaft Tibia

IMPLANT NOT FDA CLEARED
• Mid shaft femur

IMPLANT NOT FDA CLEARED
Work flow

What do we do today
- Scan of bone
- Evaluate contralateral side if available
- Design implant with surgeon (truly one of – so surgeon prescription)
- Surgeon approval
- Machine implant from bar stock
- Coat implant with porous structure
- Clean / passivate / package / sterilize

What we want to do
- Based on scan
  - 3D Print
  - Can print the porous structure
  - No need to program CNC machines
  - No issues of tolerance match ups
- Clean / passivate / package / sterilize

Can we define what we need to get Additive Manufactured Implant more main stream
Some Functional Requirements

The Patient

- All age groups
  - Young and Old

- Activity level
  - Sedentary and Active
    - And this can change with time

- Body Mass
  - And this definitely changes
Some Functional Requirements

Must be similar to ASTM F136

– Why?
  • We know ASTM F136 works
    – Maybe unnecessarily high
  • Surgeons have a comfort
What are we looking for ...

- What heat treatment regimen can provide fatigue properties in excess of wrought material?
- How does the fatigue property change if there is semi-sintered loose powder on the "as built" surface?
  - Is there a way to simulate the decrease in fatigue from the presence of such semi-sintered surface particle clusters and thus help define acceptance criteria for such clusters?
- Design rules - recognizing that porous structures are essential features in orthopedic implants, but the presence of porous structures create stress risers and reduce fatigue properties, what design rules could be followed to help create a higher fatigue strength implant
Questions?
Fracture Mechanics and Nondestructive Evaluation Modeling to Support Rapid Qualification of Additively Manufactured Parts

ASTM Workshop on Mechanical Behavior of Additive Manufactured Components
May 4, 2016
San Antonio, Texas

Craig McClung, Michael Enright, John McFarland, Jonathan Moody
Southwest Research Institute

Irving Gray, Joe Gray
NDE Technologies, Inc.
Acknowledgments

• Funding for this SBIR effort provided by the US Air Force Research Laboratory
  ➢ Andrew Nauss, AFRL Program Monitor for Phase I
  ➢ Bill Musinski, AFRL Program Monitor for Phase II
Motivation

• Additive Manufacturing methods can produce defects
• NDE may be required to ensure structural integrity
• Key questions:
  Ø What size defects can be found in a complex part?
  Ø What size defects matter to structural integrity?
• Simulation modeling can be used to answer these questions without expensive physical testing
  Ø NDE simulation can determine what size defects can be found
  Ø Fracture mechanics simulation can determine what size defects matter to structural integrity
  Ø Coupled simulations can determine the impact of NDE reliability on fracture risk
Method:
Integrated NDE and Fracture Risk Models
Overview

• Defect Morphology
  - Identify anomaly types associated with DMLS additive manufacturing processes

• POD Curve Simulation
  - Link NESSUS with XRSIM to generate location-specific POD curves

• Fracture Risk Simulation
  - Link NESSUS/XRSIM-generated POD curves with DARWIN to predict risk of fracture with inspection

• Application Example
  - Illustrate generation of location-specific POD curves and fracture risk assessment for actual component (engine mount)
Representative AM Defects

Low Energy- Lack Of Fusion

High Energy- Keyhole Porosity
Simulating Non-Destructive Inspections Using XRSIM

- XRSIM simulates the application of X-Rays to a component to identify defects
- The intensity of the simulated X-Ray images is dependent on a number of factors
  - Equipment
    - Inherent filtration of x-ray tube, eddy current lift off and coil tilt, broad band center frequency
  - Setup
    - Placement of the central axis of the x-ray tube, orientation of the UT probe, scan variation in lift off and probe tilt
  - Signal Noise
  - Flaw morphology
    - Size, shape, position & orientation in the part
XRSIM Defect Detection Based on Contrast Values

- XRSIM provides virtual images that simulate the X-Ray NDE method
- Human detection of a defect is dependent on contrast values
  - Contrast is based on the image intensity at a defect versus the intensity of the surrounding image
Simulating POD Curves Using Probabilistic Analysis

- The contrast value associated with a single defect size is modeled as a random variable.
- The threshold contrast value at which a defect can be detected by a human is also modeled as a random variable.
The POD values for each anomaly size can be used to construct the full POD curve.
POD Curve Simulation
Using NESSUS and XRSIM

• Create a response surface model
  ➢ Relates contrast values with XRSIM input variables

• Propagate NDI random variables through response surface
  ➢ Result: PDF of contrast values

• Create a probabilistic model (PDF) of human contrast detection threshold
  ➢ Based on detect/no detect data

• Obtain POD curve
  ➢ Achieved by comparing contrast PDF with contrast threshold PDF at each anomaly size
Process for Constructing Contrast Response Surface

- Identify ranges of XRSIM input variables
- Generate a table of XRSIM input data using design of experiments (DOE) approach in NESSUS
- Generate training data for each set in DOE table using XRSIM
- Construct a Gaussian Process response surface fit to the contrast training data using NESSUS

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<th>Upper</th>
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<td>Detector signal w/ grain diffraction</td>
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<td>Spherical porosity</td>
<td>μm</td>
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<td>200</td>
</tr>
</tbody>
</table>
Linking XRSIM/NESSUS with DARWIN

- Input Random Variables
  - Part thickness
  - Detector signal
  - Spherical pore size

- XRSIM
  - Part thickness
  - Detector signal
  - Spherical pore size
  - Contrast values
  - Detect/no detect data
  - POD versus
    - pore size
    - part thickness

- NESSUS
  - Part thickness
  - Detector signal
  - Spherical pore size

- DOE Input File
  - Part thickness
  - Detector signal
  - Spherical pore size

- DOE Results File
  - Part thickness
  - Detector signal
  - Spherical pore size

- POD File
  - POD versus
    - pore size
    - part thickness

- DARWIN
  - Risk of Fracture With Inspection
Application Example: Additive Manufacturing

- Actual engine mount developed under DARPA project (DMLS AM process, Ni 718 Alloy)
XRSIM Input Variables

• Geometry complexity implies
  - Multiple orientations of the part
  - Several kilovoltage settings

• POD data assumes application of an inspection protocol where kilovoltage and orientations are fixed

• Key parameters controlling contrast
  - Part thickness
  - Pore size
  - Detector signal (grey scale)
  - Contrast noise
Detectability Maps from XRSIM at Several Orientations
Probabilistic Model of Human Detectability Contrast Threshold

- Threshold value estimated based on 100 XRSIM results and corresponding detect/no detect data from NDE Technologies
- Detection does not follow a strict rule based on a single threshold value, so threshold modeled as a random variable
- Maximum likelihood used to estimate threshold mean and standard deviation, assuming normal distribution: Mean=183, Stdev=41
Probability of Detection Curves

• Deterministic input variables:
  - Part thickness
  - Pore size

• Random input variables:
  - Detector signal: Uniform (10,14000)
  - Contrast noise: Normal (0,79)
  - Contrast threshold: Normal (183,41)

• POD curves were computed using Monte Carlo simulation combined with conditional expectation
  - POD = Probability [Contrast > Contrast threshold]
Location 1 Results

**Orientation 1**  \( \text{Thickness} = 8.1 \text{ mm (0.319 in)} \)

**Orientation 2**  \( \text{Thickness} = 45.45 \text{ mm (1.79 in)} \)

Beyond range of RSM applicability (1mm to 35mm)
Influence of NDI on Manufacturing Anomaly Distribution
Summary

- **Part thickness**
- **Detector signal**
- **Spherical pore size**

- **Contrast values**
- **Detect/no detect data**

- **POD versus**
  - pore size
  - part thickness

**DMLS**

- **CAD Model**
- **Part Thickness File**

**DOE Input File**

**XRSIM**

- **DOE Results File**

**NESSUS**

- **Pod File**

**DARWIN**

- **Risk of Fracture With Inspection**
Continuing Tasks

- Automate POD curve creation in XRSIM
- Automate transfer of location-specific POD curves from XRSIM to DARWIN
- Implement inverse calculation of critical initial crack size in DARWIN and transfer to XRSIM
- Verification and validation
Potential Future Extensions

• Use the integrated XRSIM-DARWIN modeling system to optimize NDE scan plans

• Combine with ICME models of the AM process (including models of microstructure and defect formation) to optimize the AM process itself
Role of Material Properties

- The fracture risk simulations also depend on known/assumed values of material properties (e.g., FCG).
- The uncertainties in these properties could be included as another random variable in the fracture risk simulations.
- The material properties will be functions of the local microstructure, which will depend on the manufacturing process and the location/orientation within the part.
Effects of HIP Processing on EB-DDED Additively Manufactured Ti-64 Materials

Hank Phelps
Jeff Langevin
Adam Sutton
Outline

- Background on EB-DED
  - Process
  - Flaw Types
  - Potential Applications
- Hot Isostatic Press Process
  - Why Considered
  - Benefits
- Impacts on Mechanical Properties
- Summary
- Conclusions
EB-DED Process

NC Path Planning and Deposition

Near-shape Article

Machine Part
Examples of Discontinuities

- Inclusions
- Deposit
- LOF
- Porosity, Voids
- Substrate

Indications Measured from 0.0066” – 0.0255” for this specific Clipping Plane

0.060”

0.030”
Potential Applications

- Vertical Tail
  - Root Rib
  - Aft Spar
  - Leading Edge Spar

- Canopy Bowframe
- Flaperon Spar
Planned EB-DED Process Flow

1. Deposit
2. Machine
   - Inspection
   - Configuration
3. UT
4. Heat Treat
5. CT
6. Weld
7. Repair
8. Machine Final
9. Inspect Final
Alternative Process Flow

Add HIP to
1) Avoid Weld Repairs
2) Develop Confidence
3) Convert CT to Focused RT

Deposit → HIP → Machine Inspection Configuration → UT → Heat Treat → Weld Repair → RT → Machine Final → Inspect Final

1) Avoid Weld Repairs
2) Develop Confidence
3) Convert CT to Focused RT
Refining Microstructure of Additive Manufacturing Materials to Improve Non-Destructive Inspections (NDI)(4034.001)
# EB-DED Preforms

<table>
<thead>
<tr>
<th>Condition</th>
<th>Process</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline</td>
<td>EB-DED + BA</td>
</tr>
<tr>
<td>HIP</td>
<td>EB-DED + HIP + BA</td>
</tr>
</tbody>
</table>

![Image of EB-DED Preform]
Tensile Results

Typical HIP Results as Percentage of BL Property

- % of BL Value
- X
- Y
- Z

- TUS
- TYS
- Elong

Fracture Toughness

Average Fracture Toughness vs Orientation

Specimen Orientation

Ksi-(Inch)^0.5

80  90  100  110

YX  XY  ZX

BL  HIP

Spec Min

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Approved for Public Release 1/28/2016. PIRA AER201601008
Strain Life Results (R=-1.0)

Run Out
Fatigue Crack Growth Results

YZ Orientation
R=0.05
HHA

Fatigue Crack Growth Rate

ΔK

Longer Life

BL-YZ-01
BL-YZ-02
HIP-YZ-01
HIP-YZ-02
UT Inspection Results

**HIP**

**BL**

Transducer: 0.75” Diameter, 5 MHz, 6” Focus Immersion

Note – Lg LOF Result of Process Breakdown

0.45” x 1.6”

0.35” x 0.95”
## Summary

<table>
<thead>
<tr>
<th>Property</th>
<th>Effect of HIP</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Tensile</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>UTS</td>
<td>• X/Y &lt; 2% Z Equivalent</td>
<td>Reduced Scatter</td>
</tr>
<tr>
<td>Yield</td>
<td>• X/Y &lt; 5% Z &lt; 1%</td>
<td></td>
</tr>
<tr>
<td>Elongation</td>
<td>• Increased 11 to 22%</td>
<td></td>
</tr>
<tr>
<td>Fracture Toughness</td>
<td>• No Impact</td>
<td></td>
</tr>
<tr>
<td>Strain Life</td>
<td>• Supports Existing Design Curve</td>
<td></td>
</tr>
<tr>
<td>Fatigue Crack Growth</td>
<td>• Supports Existing Design Curve</td>
<td></td>
</tr>
<tr>
<td>Ultrasonic Inspection</td>
<td>• Improved Inspectability</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• No Rejectable Indications</td>
<td></td>
</tr>
</tbody>
</table>
Conclusions

• **EB-DED Process Capable of Producing Large Aerospace Components**
  – High Build Rates
  – Internal Material Quality Still an Issue

• **Hot Isostatic Pressing**
  – Capable of Closing & Healing Internal Flaws
  – Minimal In-Plane Strength Reduction Offset by Lower Scatter
  – Improves Out of Plan (Z Direction) Strength
  – No Other Significant Property Impacts
  – Recommended for Inclusion for Critical Components
Acknowledgements

• Mike Mesick – LM NDI Level III
• Scott Stecker – Sciaky
• Andy Mugnaini – Sciaky
Fatigue Life Manipulation of SLM® Parts

Wadim Reschetnik,
Richard Grylls, Benjamin Bauer,
Hans Albert Richard, Gunter Kullmer

Direct Manufacturing Research Center
Paderborn University – Germany
SLM Solutions NA, Inc.
Agenda

1. Additive Manufacturing – Selective Laser Melting - SLM®
   • SLM Solutions NA, Inc.
   • Selective Laser Melting System SLM® 280\textsuperscript{HL} and 500\textsuperscript{HL}
   • Qualified Materials

2. Project Fatigue Life Manipulation
   • Direct Manufacturing Research Center – DMRC
   • Motivation and Aims of the Project

3. Experimental Investigation
   • Setup and Testing Methods
   • Fatigue properties of SLM® materials
   • Fatigue Life Manipulation by Notches

4. Conclusion
1. Additive Manufacturing - Selective Laser Melting - SLM®

SLM Solutions NA, Inc.
Formerly: HEK GmbH • MCP HEK Tooling GmbH • MTT Technologies GmbH

Achieve fast, safe, and cost-efficient complex metal parts with Selective Laser Melting® additive manufacturing technologies.
1. Additive Manufacturing - Selective Laser Melting - SLM®

SLM Solutions Group AG – a deep rooted 3D printing heritage

Since 1970
Rapid Prototyping

1998-2002
Development of SLM Technology

2003
Fiber Laser Technology

2006
First company to process aluminum and titanium.

2007
400 Watt Laser Technology

2009

2011
Hull-Core Technology

2013
Multi-laser technology & automated powder handling devices.

2015 onwards
Drive industrial application of 3D metal based printing technology.

Note: History of SLM Solutions Group and its predecessors
Source: Company information
1. Additive Manufacturing - Selective Laser Melting - SLM®

SLM® 280 HL

- 35% faster than the competition with twin-laser technology
- 280 x 280 x 350 mm build envelope
- Built-in 400 W laser
- Option to add 1 additional 400 W (twin) or 1000 W (duo) laser
- Ideal for medium to high volume part production
- Closed-loop powder handling
- Patented bi-directional powder recoater movement
- Upgraded process control
- Open software architecture and system parameters
- Optimized gas flow and recirculation

**Build Speed**: 20 – 45 ccm/h
**Layer Thickness**: 20 – 75 / 100 μm
**Operational Beam Focus**: 80 – 120 / 700 μm
**Dimensions in mm (B x H x T)**: 1800 x 1900 (2400) x 1020
**Weight**: approx. 1000 kg
1. Additive Manufacturing - Selective Laser Melting - SLM®

SLM® 500HL

The flagship system for larger complex metal parts.

- 500 x 280 x 365 mm build envelope
- 2 standard 400 W lasers
- Option to equip 4x 400 W (Quad Laser Technology)
- Lasers may be used independently or parallel in the build process
- Closed-loop powder handling
- Patented bi-directional powder recoater movement
- Adapter for higher platform temperatures
- Open software controls
- Optimized gas flow and recirculation

Build Speed: 55 | 105 ccm/h Twin | Quad
Layer Thickness: 20 – 75 μm
Operational Beam Focus: 80 – 150 μm
Dimensions in mm (B x H x T): 5200 x 2700 x 2800 (incl. PRS & PSX)
Weight: approx. 3100 kg
1. Additive Manufacturing - Selective Laser Melting - SLM®

**SLM® 500 HL**

- Dense parts from most metals
  - Fully functional
  - Blaze structures
  - Assembly bulky
  - Tolerant details

**DMRC**

Wadim Reschetnik
May 4, 2016 • Grand Hyatt San Antonio • San Antonio, Texas, USA
Qualified Materials

- Continuous development of different materials. Certification due to customers needs and requirement.

- Material data is available on a separate attachment. System parameters are available for the following materials:

<table>
<thead>
<tr>
<th>Qualified Materials</th>
<th>Stainless Steel: 316L (1.4404)</th>
<th>17-4 (1.4542)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tool Steel:</td>
<td>Maraging (1.2709)</td>
<td>H13 (1.2344)</td>
</tr>
<tr>
<td>Titanium:</td>
<td>Ti Al6 V4</td>
<td>Ti Al6 Nb7</td>
</tr>
<tr>
<td>Aluminum:</td>
<td>AlSi10Mg</td>
<td>AlSi12</td>
</tr>
<tr>
<td>Cobalt Chrome:</td>
<td>CoCr28Mo6 (ASTM F75)</td>
<td></td>
</tr>
<tr>
<td>Inconel:</td>
<td>625</td>
<td>718 738</td>
</tr>
</tbody>
</table>
2. Project Fatigue Life Manipulation

Direct Manufacturing Research Center – DMRC

- Institution of the faculty of mechanical engineering at the Paderborn University
- Flexible and very interdisciplinary structure
- Collaboration of 9 different chairs and a large number of industrial partners
- Funded by the State Government of North Rhine-Westphalia, industrial partners and public sources
- All project topics are guided by industry partners

Research  Materials  Machines  Service providers and end-users

- UNIVERSITÄT PADBERN
- Evonik Industries
- EOS
- E-MANUFACTURING SOLUTIONS
- Baker Hughes
- Boeing
- John Deere
- Eisenhüttenwerk

- Heraeus
- SLM Solutions GmbH
- The LEGO Group
- Siemens
- H&H Innovation & H&H Smart Products
- KRAUSE

- voestalpine
- Stratasys
- LIEBHERR
- Parker
- Phoenix Contact
- SCHWARZ

- Stükenjürgen
- bp blue production
- Centroplast Engineering plastics GmbH

* = Founding member
2. Project Fatigue Life Manipulation

Direct Manufacturing Research Center – DMRC

- Research fields in Laser Sintering, Fused Layer Modeling & Laser Melting

- Material and process qualification: LM.fatigue, LM, LS, FLM

- Design for AM: Design Rules, Tolerances, Lightweight design

- Business development, Costs, Applications, Function Integration, Machine development
2. Project Fatigue Life Manipulation

Motivation
• Technical components are subjected to various stresses
• Responsible for the limited service life

Main Goal
• Extending the total life time of components
• Using advantages of additive manufacturing
• Ingenious configuration of
  • Notch form
  • Notch position
  • Notch orientation

Schematic illustration of notch form, notch position and notch orientation for lifetime manipulation
2. Project Fatigue Life Manipulation

**Major measure for lifetime modification**
- Lifetime under fatigue loading is divided into crack initiation and fatigue crack propagation
- "Jump" in $\alpha-N$-diagram and shorten the lifetime
- Switching between fatigue crack propagation and crack initiation phase
- Initiating effect at each notch

*Schematic illustration of lifetime manipulation caused by notches*
3. Experimental Investigation

Experimental setup for fracture mechanics

\[ U = R \Omega \cdot I_0 = \rho \cdot \frac{l}{A} \cdot I_0 \]

- **U** = voltage
- **R**\( \Omega \) = resistance
- **I_0** = supply current
- **\rho** = specific material resistance
- **l** = length of specimen
- **A** = cross sectional area
3. Experimental Investigation

Testing Methods

- mechanical load
- cyclic stress intensity factor at the crack

\[ \Delta K_1 = \Delta \sigma \cdot \sqrt{\pi \cdot a \cdot Y_I} \]

\[ \Delta \sigma = \text{cyclic loading stress} \quad a = \text{crack length} \quad Y_I = \text{geometry factor} \]
3. Experimental Investigation

Fatigue properties of SLM® materials

Ti-6-4

\( R = 0.1 \)

- as-built
- heat treated
- conventionally processed material

Heat treatment significantly improves the fatigue crack growth performance
3. Experimental Investigation

Fatigue Life Manipulation by Notches – Lifetime Phases

- Specimen with notch (diameter Ø=1mm) in crack path
- Unnotched specimen without notch in crack path

- Initiation phase
- End of hole
- Crack growth phase

Graph showing crack length [mm] against load cycle [N] for unnotched and notched specimens.
3. Experimental Investigation

Fatigue Life Manipulation by Notches – Unnotched Specimen

![Graph showing crack length vs. load cycle for Ti-6-4 with R = 0.1]

- **Crack length** \( a \) [mm]
- **Load cycle** \( N \)
- **Material**: Ti-6-4
- **Ratio**: \( R = 0.1 \)
3. Experimental Investigation

Fatigue Life Manipulation by Notches – One Hole with different Diameter

Ti-6-4

\[ R = 0.1 \]

Notch diameter has no significant influence on the total fatigue lifetime
3. Experimental Investigation

Fatigue Life Manipulation by Notches – Row of Holes

- No re-initiation after growing at the first hole
- Force increasing
- Deformed notches due to manufacturing process

Row of notches has significant influence on the total fatigue lifetime
3. Experimental Investigation

Fatigue Life Manipulation by Notches – Elongated Notches

- No re-initiation after growing at the first elongated notch

![Graph showing fatigue life manipulation](image)

- Ti-6-4
- $R = 0.1$

- Unnotched Specimen
  - d0_R2
  - d0_R3
  - d0_R4

- Notched Specimen
  - A2
  - A3
3. Experimental Investigation

Fatigue Life Manipulation by Notches – Elongated Notches

- No re-initiation after growing at the first elongated notch
- Even after 10mil. cy.

![Graph showing crack length vs. load cycle](image)

- Ti-6-4
  - $R = 0.1$

- Unnotched Specimen
  - $d_0$ _R2_
  - $d_0$ _R3_
  - $d_0$ _R4_

- Notched Specimen
  - A2
  - A3
3. Experimental Investigation

Fatigue Life Manipulation by Notches – Elongated Notches

- No re-initiation after growing at the first elongated notch
- Even after 10mil. cy.

- force increasing

![Graph showing crack length vs. load cycle for Ti-6-4 with Notched Specimen A2 and A1, where $R = 0.1$.]
3. Experimental Investigation

Fatigue Life Manipulation by Notches – Elongated Notches

- Comparison of different specimens with elongated notches – width 1 mm
- Notches lead to initiation effect
- This initiation effect increases with the number of notches
- But this effect is limited by the residual cross-section area of the specimen

→ The fatigue lifetime manipulation is possible and influenced by the number, size, form and position of the notches
4. Conclusion

- Numerous experimental investigations were conducted on different SLM®-processed materials like titanium alloy and stainless steel.
- Only a part of the results was presented.
- Results show that the fatigue life (decrease or increase) can be manipulated by notches.
- Significant crack growth retardation occurs if the crack initiation phase, caused by notches, plays a significant role in the total lifetime.
- Taking the titanium alloy as an example, a significant lifetime extension can be achieved by using a row of notches.
- Additive manufacturing offers the possibility to produce structures that have a longer fatigue lifetime.
Fatigue Life Manipulation of SLM® Parts

THANK YOU FOR YOUR ATTENTION


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E-mail : reschetnik@fam.upb.de
Advanced Characterization of Additively Manufactured Materials, including Synchrotron–based 3D X-rays


With help from many others, especially John Siemon, Yanar Cagatay, Jaakko Suni (Alcoa Tech. Center) & Xianghui Xiao (APS)

Support:
America Makes
NSF
PA-RAMP
Adv. Photon Source
DOE
NIST
NASA
DOE-NNSA

Contains unpublished results: please contact rollett@cmu.edu for any subsequent use

www.cmu.edu
Outline

• NextManufacturing Center at CMU; process model
• Quantitative prediction of microstructure: reduced order model to predict porosity
• Advanced characterization, e.g., 3D tomo (CT), HEDM
  – 3D High Energy x-ray Diffraction Microscopy (HEDM)
  – Pore size distributions, powder particle sizes, statistical presentation of data.
• Machine vision for microstructure
• Summary
Metals AM

- CMU NextManufacturing Center
  - Broad AM group at Carnegie Mellon
  - Many inter-related projects with significant contributions
  - Strong emphasis on genomic approach
  - Brings together the AM ecosystem in the region

- Process Mapping Overview
  - Broad approach to process understanding

- Within 5 years AM users will be able to:
  - Vary microstructure spatially within parts
  - Monitor and control the process
  - Choose from a wide variety of powders
  - Eliminate or design for porosity
  - Design the process as they design a part (including cost estimates)
Melt pool geometry

Comparison of model with literature data

Porosity/Density Prediction

Comparison with standard operating point
Synchrotron Computed Tomography

• The Advanced Photon Source (APS) at Argonne National Laboratory provides high energy x-rays with high brilliance (flux)

• Synchrotron source is useful for computed tomography (CT):
  – Sample size (up to 2 mm diameter at 2BM)
  – Resolution (0.65 µm)
  – **Short scan times** (2-6 mins)
  – Terabytes of data; **long times** required to a) reconstruct each 3D image and b) analyze the results (e.g., segmentation)
Advanced Synchrotron Capabilities: CT+HEDM

- Recently NF- & FF-High Energy Diffraction Microscopy (HEDM) experiment at 1-ID on AM Ti-6-4
- 3D microstructure and orientation information with Near-Field mode
- 3D residual stress distribution via Far-Field mode
- Capability for in situ loading during CT, NF and FF; RAMS loading system developed by AFRL
- Schuren et al. (2015), 'New opportunities for quantitative tracking of polycrystal responses in three dimensions', COSSMS, 19 235.
Porosity Measurement via CT


• Aim was to characterize porosity size and shape distributions as a function of processing conditions

• Used computed tomography at the Advanced Photon Source at the Argonne Natl. Lab. In Chicago

• High energy x-rays permit rapid measurement (a few minutes per mm\(^3\) sample volume) at high resolution (minimum pore size ~ 1 \(\mu m\)), which is suitable for pores ranging up to 100 \(\mu m\).

• About 100 sample volumes can be measured per 24 hours of beamtime at 2BM (at APS), which uses “pink” radiation (parallel beam, limited range of energies, very high intensities). Each volume is of order 1 mm\(^3\) with a resolution of approx. 1 \(\mu m\). Substantial help from Xianghui Xiao (APS) is gratefully acknowledged.

• The void content of any material is particularly important with respect to fatigue resistance. Fatigue cracks typically start from voids in preference to other microstructural features (after manufacturing defects and corrosion pits).
CT on Beamline 2BM at APS

Time used: 3-5 minutes per volume
Data: approx. 0.2 Tbytes per volume
Software used for analysis:
tomopy
ImageJ
Avizo

Beamline and Facilities: Beamline 2BM

Introduction
The 2BM beamline offers measurement capabilities for x-ray microtomography, x-ray topography and x-ray microdiffraction. X-ray microtomography and x-ray diffraction instruments are installed on separate optical tables for independent operation with fast switch over time. Optically-coupled high-resolution CCD system is used for microtomography and topography with up to 1 micron spatial resolution. X-ray microdiffraction setup consists of KB microfocusing mirrors (~3 micron minimum spot), four-circle Huber diffractometer, high-precision translation sample stage, two orthogonally-mounted video cameras for viewing sample, fluorescence detector (Si drift diode) and diffraction detector (a scintillation detector or a CCD).

Three different levels of monochromatization are available. Conventional monochromatic x-rays from a double-bounced Si (111) crystal monochromator (DGM, D(EED=1E+4), wide band-pass monochromatic x-rays from a double multilayer monochromator (DMM, E/E=1+4E-2) and pink beam. The available x-ray range is from 5 keV to 30 keV. The lower limit is due to the x-ray windows and the upper limit is due to the critical angle of the x-ray mirror. Two different coatings (Cr and Pt) for the x-ray mirror allow either 20 keV or 30 keV energy cutoff.

Beamline Scientists:
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Francesco De Carlo: decarlo@aps.anl.gov, 630 252-0145.
Beamline post-doc:
Yangshen Pan: pan@aps.anl.gov, (630) 252-6935

Techniques
- X-ray Tomography

Optical Components:

<table>
<thead>
<tr>
<th>Component</th>
<th>Distance from Source/Description</th>
<th>Installed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Filter assembly</td>
<td>23.2 m</td>
<td>05/1998</td>
</tr>
<tr>
<td>Hor. and vert. slits</td>
<td>23.5 m</td>
<td>26 µm reproducibility 05/1998</td>
</tr>
<tr>
<td>Vert. deflecting mirror</td>
<td>24.9 m</td>
<td>0.15 deg. plane w/2 coatings (Cr, Pt) 12/1997</td>
</tr>
<tr>
<td>Double multilayer mono</td>
<td>27.4 m</td>
<td>Unfocussed 05/2009</td>
</tr>
<tr>
<td>Hor. and vert. slits</td>
<td>48.3 m</td>
<td>25 µm reproducibility 02/1997</td>
</tr>
</tbody>
</table>

Beamline Configurations

- White Beam: (2BM-A) Beam at sample: 50 x 3 mm 2 (hor x vert), uncollimated
- Pink Beam: (2BM-B) Beam at sample: 50 x 3 mm 2 (hor x vert), uncollimated
- Monochromatic (multilayer) (2BM-B) Beam at sample: 25 x 4 mm 2 (hor x vert), E = 0.5-33 keV, d(E/E) < 10^-2

Detectors

<table>
<thead>
<tr>
<th>Detector</th>
<th>Manufacturer</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertex</td>
<td>Roper, Photometrics</td>
<td>Peltier cooled CCD camera</td>
</tr>
<tr>
<td>Coolscan HQ</td>
<td>PCO</td>
<td>Scintillator Point Detector</td>
</tr>
<tr>
<td>PCO Edge</td>
<td>PCO</td>
<td>CMOS</td>
</tr>
<tr>
<td>PCO Ditisar</td>
<td>PCO</td>
<td>CMOS</td>
</tr>
<tr>
<td>Biotron</td>
<td></td>
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<tr>
<td>Ion Chambers</td>
<td></td>
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<tr>
<td>2-BM-B X-ray Optics</td>
<td>HS-MI nikon, University of Chicago design</td>
<td></td>
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<tr>
<td>2-BM-B X-ray Optics</td>
<td></td>
<td></td>
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<tr>
<td>Ancillary Equipment</td>
<td>Monopositioning system</td>
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</tr>
</tbody>
</table>
**X-ray Computed Tomography (XCT)**

- Conventional methods for porosity analysis inadequate
  - Archimedes
  - Metallographic analysis
- **XCT**: Constructs 3D model from a series of 2D radiographs
  - Contrast generated by difference in X-ray absorption as they travel through a material
- Provides information on size, morphology, and spatial distribution in 3D
- Most lab-scale XCT instruments have limited resolution (~25 µm)
- **Synchrotron source offers significantly better resolution (~1 µm), scan time**

Microstructure in Ti-6Al-4V

- Illustrate lamellar microstructures observed.
- **Five Ti-6Al-4V samples** (3 cm diameter, 1.5 cm height cylinders) were fabricated on Arcam EMB System at NC State
- **Beam velocity was varied to create melt pool areas corresponding to 1X, 2X, 4X, 1/2X, 1/4X of the “nominal” melt pool area**
- 1 x 1 x 15 mm imaging samples were cut from the bulk, and contour-bulk interface. CT-scans were taken from top ~ 8 mm of each sample
- CT on 2-BM beamline with 100 keV pink beam (parallel box beam), absorption mode; help from Xianghui Xiao (APS) acknowledged.
- Objective was to **characterize different types of porosity observed in AM metals**, and begin to **supplement process maps with intrinsic defect properties**
Ti-6Al-4V microstructure

- Standard microstructures are based on heat treatment in the two-phase range; this gives a mix of primary $\alpha$ and Widmanstätten $\alpha+\beta$.
- Despite the high cooling rate ($\sim 10^6 \text{ /s}$), the $\beta$ structure is columnar and the transformation gives either martensite or acicular $\alpha$.
- Variations in thermal history can give rise to significant transitions in microstructure. This example documents the variation in a Ti-6Al-4V build, which shows a martensitic microstructure near the top and a basketweave microstructure (or tempered martensite) towards the base.
**Ti-6Al-4V**

Increasing Melt Pool Area

Cunningham *et al.* (2016) *JOM, 68* 1-7
Ti-6Al-4V

Porosity Size Distribution in 6.5-7.9 mm from Top Surface

Size Distribution of Spherical Porosity

Tutorial: probability plots show straight line for normal distr. Plots made with R package, open source, www.r-project.org

Quantifying the pore size distribution enables understanding of how it varies with conditions, and eventually control. Crucial for fatigue resistance

Donegan et al. (2013) Acta mater. 61 5595; application of peaks-over-threshold for quantifying tails

Carnegie Mellon University
Ti-6-4 Sample 5B, contour-bulk interface: Intentionally porous
Powder Characteristics vs. Flow Behavior

- Gas-atomized powder generally display a log-normal size distribution\(^1\)
- Log-normal distribution will appear linear on adjusted cumulative probability plot

- Deviation from log-normal suggests sudden change in distribution (sieving)
- AlSi10Mg powder does not deviate from log normal
- EOS Ti-6Al-4V does not follow this trend

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\(^1\) O.D. Neikov, Chapter 5 - Atomization and Granulation, In Handbook of Non-Ferrous Metal Powders, edited by Neikov et al., Elsevier, Oxford, 2009, Pages 102-142
Powder Distribution vs. Flow

Distributions

Flow measurements on a Freeman Rheometer
Propeller driven into a beaker full of powder
Confined flow effectively measured
Contrast with free flow with a Hall Cup
An automatic and objective system for finding relationships between microstructures

- Using machine vision and machine learning techniques, we automatically harvest, store, and compare microstructural image data.

DeCost and Holm, *Computational Materials Science* 110 (2015) 126–133
Outcome: A microstructure classifier

- Given “training” micrographs divided into classes, we can classify new micrographs automatically and with high accuracy.

  - Applications: Process analysis, control and qualification; archiving; statistical analysis; finding correlations between structure and processing.

  - 5-fold cross-validation on 15 microstructures per class (105 total)

    ⊳ A score of ‘15’ indicates perfect classification of validation images into the correct class:

DeCost and Holm, *Computational Materials Science* 110 (2015) 126–133
Summary

• Understanding microstructure is important during every step in the additive manufacturing process. If you do not understand the details of the process, it is entirely possible to have a problem because of defects such as voids.

• Location of the voids relative to the surface is very important.

• This challenge can be addressing by combining
  – Measurement of powders and defects, especially pores: analysis with extreme value statistics, link to powder flow
  – Advanced characterization 3D microscopy with high energy synchrotron x-rays e.g. tomography of voids
  – Demonstrated ability to predict incomplete melting (and keyholing)
  – Development of micro-mechanical models for materials
Reliability of Mechanical Behavior in Metallic Additively Manufactured Parts for Critical Applications

Doug Wells
NASA MSFC
Huntsville AL

ASTM/NIST Workshop on Mechanical Behavior in Additive Manufactured parts

May 4, 2016
AM Reliability Challenges

There is more to AM than manufacturing

*AM machines create a unique material product form – typically purview of the foundry or mill*

**Subtractive Forging Process**

1. Ingot Making  
2. Cutting  
3. Heating  
4. Forging  
5. Heat Treating  
6. Machining  
7. Inspection  
8. Delivery with CoC

**Additive SLM Process**

1. Powder Making  
2. Printing  
3. HIPing  
4. Heat Treating  
5. Machining  
6. Inspection  
7. Final Part

As the ‘mill’, the AM process must assure manufacturing compliance throughout the build process and material integrity throughout the volume of the final part.
AM Reliability Challenges

• AM responsibility serving as the material mill gives rise to additional reliability concerns
  – Low entry cost compared to typical material producers
  – New players in AM, unfamiliar with the scope of AM, lacking experience
  – Fabrication shops not previously responsible for metallurgical processes
  – Research labs converting to production

• AM machines operate with limited process feedback!
  – Reliability depends upon the quality and care taken in every step of AM operations => rigorous and meticulous controls
Two primary opportunities to ensure AM reliability

1. In-Process Controls, (Control what you do)
   - Understanding fundamentals of the process
   - Knowing the process failure modes (pFMEA)
   - Identifying observable metrics and witness capabilities
   - Meticulous process scrutiny
   - *Future to provide detailed process feedback for post-process evaluation, eventually closed-loop controls.*

2. Post-Process Evaluation (Evaluate what you get, NDE)
   - Extensive subject, ASTM E07 and many partners involved
   - Not covered in this discussion

Part reliability rationale comes from sum of both in-process and post-process controls, weakness in one must be compensated in the other
The AM Process: Concept to Part

**Concept**
- Design for Powder Bed Fusion
  - Build box limitations
  - Self-supporting design
  - Powder and Support removal
  - Finishing allowances
  - Surface texture requirements

**Build Lot Execution**
- Platform selection
- Recoater selection
- Powder selection
- Build parameters
- Build data collection
- Post-build
  - Powder removal
  - Platform removal

**Equipment**
- Calibration
- Maintenance
- Equipment Vendor
- Software versions

**Structural Assessment**
- Material Properties

**Model Processing**
- File formats
- Support integration
- Platform layout
- Part build orientation
- Lot acceptance

**Part Classification**
- Consequence of failure
- Build complexity
- Structural margins

**Model Quality**
- Integrity of solid
- Model checking
- Version control

**Component Development Plan**
- Planning for all operations from Concept to Part
- Written prior to handoff from design to build

**Feedstock**
- Virgin Powder
  - Qual control spec
  - Certification/analysis
- Recycled Powder
  - Sieving
  - Environment control
  - Re-use limitations

**Blend Lot**
- Chemistry
- Mixing
- Distribution

**Build Vendor**
- Quality system
- Qualification

**Raw Part Inspection**
- Visual
- Radiography or CT
- Metallurgical
- Dimensional

**Thermal Processing**
- Part and lot acceptance articles
- Stress relief
- HIP
- Solution treat or anneal
- Precipitation age

**Finishing Operations**
- Machining
- Bead/grit blast
- Peening
- Honing/polishing
- Etching
- Cleaning

**Final Inspection/Acceptance**
- Dimensional
- Surface texture
- Final part PT, ET, UT, CT
- Lot acceptance test/result
- Process certification records

**Part**
The AM Process: Concept to Part

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Structural Assessment
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  - Powder selection
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  - Build data collection
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Part
• Systematic and controlled execution of AM processes is required to achieve requisite mechanical reliability

• Standardization of AM processes is actively pursued by private industry, government organizations, and standards development organizations worldwide.
  – ASTM F42, ISO collaboration
    • Only SDO with open, published AM standards
  – SAE AMS-AM
  – AWS

• NASA works with SDOs to bring open industry standards to AM

• Currently available open industry standards do not levy sufficient controls for spaceflight applications
Standardization for AM Mechanical Reliability

- Draft NASA MSFC Standard
- Current methodology for AM reliability for critical applications
  - Space Launch System
  - Commercial Crew Program

Aerojet Rocketdyne RS-25

SpaceX SuperDraco
Draft NASA MSFC Standard implements four fundamental aspects of process control for AM:

- Each aspect of process control is essential to the production of critical AM parts with reliable mechanical behavior.
- Discussion here focuses on process control fundamentals for production of mechanically reliable AM materials.
Foundation: Qualified Metallurgical Process

• Draft NASA MSFC Standard identifies AM as a unique material product form and requires the metallurgical process to be qualified on every individual AM machine.
• While aspects of this foundation are present in, for example, ASTM F3055 (IN718 AM spec), rigor, qualification, and traceability are currently lacking.
Qualified Metallurgical Process (QMP)

- Feedstock control or specification
- AM machine parameters, configuration, environment
- As-built densification, microstructure, and defect state
- Control of surface finish and detail rendering
- Thermal process for controlled microstructural evolution
- Mechanical behavior reference data
  - Strength, ductility, fatigue performance
Qualified Metallurgical Process (QMP)

- As-built densification, microstructure, and defect state
- Thermal process for controlled microstructural evolution
Reference parts:
Metrics for surface texture quality and detail rendering
Overhanging, vertical and horizontal surface texture, acuity of feature size and shape

Qualified Metallurgical Process (QMP)

• Reference Parts
• Control of surface finish and detail rendering
• Critical for consistent fatigue performance if as-built surfaces remain in part
Foundation: Qualified Metallurgical Process

- Mechanical behavior reference data
  - Strength, ductility, fatigue performance
  - Process Control Reference Distributions (PCRD)
- Establish and document estimates of mean value and variation associated with mechanical performance of the AM process per the QMP
  - Will evolve with lot variability, etc.
- Utilize knowledge of process performance to establish meaningful witness test acceptance criteria
Foundation: Qualified Metallurgical Process

Types of AM build witness specimens

- Metallurgical
- Tensile (strengths and ductility)
- Fatigue
- Low-margin, governing properties

What is witnessed?

- Witness specimens provide direct evidence only for the systemic health of the AM process during the witnessed build
- Witness specimens are only an in-direct indicator of AM part quality through inference.
Types of AM build witness specimens

- Metallurgical

Example acceptance criteria - as-built state:
- Weld penetration depth and shape
- Grain nucleation patterns
- Porosity
- Lack of fusion / Cracks

Example acceptance criteria - final state:
- Grain size
- Expected phases or carbide sizes
- Grain boundary cleanliness
- Porosity
- Lack of fusion / Cracks
Types of AM build witness specimens

• Metallurgical

Example acceptance criteria - final state:
• Grain size
• Expected phases or carbide sizes
• Grain boundary cleanliness
• Porosity
• Lack of fusion / Cracks
Types of AM build witness specimens

- Mechanical
  - Move away from spot testing for acceptance against 99/95 design values or specification minimums
  - Evaluate with sufficient tests to determine if the AM build is within family
  - Compromise with reasonable engineering assurance
  - Proposed
    - Six tensile
    - Two fatigue

Evaluate against the PCRD of the QMP

- Ongoing evaluation of material quality substantiates the design allowable
- Only plausible way to maintain design values
Example of AM build witness specimen evaluations

Nominal process is **blue**, off nominal in **red**

**Two (2) witness tests per build**

Random draw from nominal process 10 times

Process shift hard to discern

**Six (6) witness tests per build**

Random draw from off-nominal process, 10 times

Process shift discernable with analysis of mean and variation
Simulation is used to evaluate small sample statistical methods for witness specimen acceptance

Design acceptance criteria for the following:

- Keep process in family
- Minimize false negative acceptance results
- Protect the design values witnessed
- Protect the inferred design values
AM process controls cannot be meaningfully implemented without oversight and integration with strong Quality Management System
- Example, SAE AS9100

Mechanical reliability in AM cannot be established until:
- Process is defined and understood
  - Concept to Part
- Failure modes identified
- QMS engaged to monitor process and defeat failure modes

Standardization is key to developing a consistent approach
To ensure mechanical reliability in AM:

- Requires thorough understanding and control of the process - Just as would be expected from a mill, foundry, or manufacturing house
- Requires sufficient process standardization to produce reliable parts in a routine fashion
- Requires quality management systems be in place
- Requires In-Process controls
  - Start with a solid foundation
    - Qualified metallurgical Process
  - Ensure mechanical reliability
    - Process witnessing, statistical evaluations
- Requires Post-Process controls
  - NDE
  - Proof testing
  - Etc.
Additive Manufacturing at MSFC

Thank You
Witness for Statistical Process Control

QMP

Characterization builds

Part builds

PCWS consistent with PCRD

Test Specimens

First Article/WS

Design and Analysis

Compatibility

PCRD

AM Design Value Suite