Computational Materials for the Design and Qualification of Additively Manufactured Components

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Additive Manufacturing

Potential of Additive Manufacturing (AM)
• Significantly reduced manufacturing time and cost
• Increased manufacturing capability
• Increased design complexity

Realizing the Potential of AM Design
• Topology optimized structures
• Location specific/gradient microstructures
• Multi-material systems
• Multi-functional systems

Qualification of Fracture-Critical AM Components
• Rocket Engine, Launch Vehicle
• Airframe

Computational Materials for Design and Qualification of AM Components
Other metal AM processes are being developed: binder-jet, material extrusion, vat photopolymerization, hybrid methods.
AM Processes

Precision of Features

(Precision refers to the as-built state and does not encompass hybrid techniques and/or interim machining operations that would increase resolution. There are a lot of other factors not considered in this chart, including heat inputs to limit overall distortion.

Technology still under development

Cold Spray
Friction Stir Additive/MELD

Deposition Rate

Metal Additive Manufacturing Processes

Powder Bed
Blown Powder Deposition
Laser Wire Deposition
Cold Spray
Electron Beam Deposition
Arc-based Deposition
Laser Hot Wire
Ultrasonic Additive

Complexity of Features
Scale of Hardware
Material Physics
Speed of Process
Cost/Schedule
Material Properties
Internal Geometry
Availability
Powder Usage
Qualification of AM Components

Challenges with additive manufacturing
- Consistency
- Defect control
- Long and costly qualification process

Complex process-structure-property (PSP) relationship for AM
- Cannot be established by testing and empirical relationships alone
- Computational modeling is needed

Challenges for adoption of computational materials towards qualification
- How to adopt modeling and simulation methods under current rules and regulations
- Necessary validation and verification (V&V) efforts

GE Leap Engine Fuel Nozzle
- Designed for AM
- Part count reduced from 20 to 1
- Reduced weight by 25%
- 5x lifetime
- Certified part, manufacturing ~40k per year
Rapid Analysis & Manufacturing Propulsion Technology

Develop and advance large scale manufacturing and composite overwrap technologies to reduce design and fabrication cycles, reduce cost, and improve performance.
Focus on the TCA addresses:

- ~50% of the engine cost
- >50% of weight
- significant portion of the development schedule

**Launch Vehicle**
- **Nozzle Exit Diameter**:
  - 90 inch: SSME/SLS
  - 70 inch: Block II SLS – EDS
  - 56 inch: Atlas V

**Fuel Mixture**
- LOX/LH2: 2100 kN
- LOX/LH2: 100 kN
- LOX/LH2: 1300 kN
- kerosene/LOX (dual chamber): 4150 kN

**Current Powder Bed AM Systems**
- 10x10x10 (inch)
- 16x24x19 (inch)
Hot-Fire Testing
Physics-based modeling of the additive manufacturing (AM) process contributes to the following:

- Process Design/Optimization
- Defect Formation/Mitigation
- Certification
- Component Design

Heat transfer during the process drives the formation of the microstructure and residual stress.
Selective Laser Melting

Process Modeling Activities

- Optical Path
- Absorption and Scattering
  - Material Optical Parameters and Size Distribution
- Equiv. Heat
  - Material Thermophysical Parameters
- Fluid Dynamics
- Solidification
- Thermal Cycling

Scanning mirror
- laser
- focusing lens
- inert gas environment
- evaporated and ejected material
  - reflection, absorption, and multiple scattering
- feeds grain growth models
  - melt pool
  - consolidation
Selective Laser Melting Process Design Space

Machine Parameters
- Laser Power
- Laser Speed
- Laser Spot Size
- Hatch Spacing
- Layer Thickness

Manufacturing Parameters
- Part Geometry
- Part Orientation
- Scan Strategy
- Support Structures
- Feature Size
- Local Properties

Feedstock Properties
- Composition
- Powder Shape
- Avg Powder Size
- Thermal Properties
- Powder Size Distribution
- Recycled

Build Plate Properties
- Chamber Atmosphere
- Chamber Airflow
- Build Plate Properties
- Powder Bed Temperature
- Layer Rotation

Layer Rotation

Layer Thickness

Part Geometry

Part Orientation

Scan Strategy

Support Structures

Feature Size

Local Properties

Chamber Atmosphere

Chamber Airflow

Build Plate Properties
Process Design: Porosity

Lack of Fusion

Keyholing

Trapped Gas Inherited From Powder

Criterion for complete melting

\[ \left( \frac{H}{W} \right)^2 + \left( \frac{L}{D} \right)^2 \leq 1 \]

with hatch spacing (H), layer thickness (L), and melt pool width (W) and depth (D)
**Multiscale Thermal Analysis**

**Fine Scale ~1 µm (powder spheres)**
- Melt pool analysis
- Physics: electromagnetic scatter, heat conduction, fluid flow, surface tension, vapor pressure, phase change
- Provide heat input model ($q$) for thermal analysis

**Intermediate Scale ~1 mm (scan path)**
- Thermal analysis using scan strategy
- Physics: conduction, convection, radiation, phase change
- Model ‘squares’ with moving heat source $q$
- Provide equivalent heating ($\hat{q}$) for large scale

**Large Scale ~1 m (build path)**
- Thermal analysis of section/part
- Physics: conduction, convection, radiation, phase change
- Model build path with moving heat source $\hat{q}$
- Provide thermal history for section/part
Residual Stress

- Incorporate single track thermal analysis for part scale predictions
- Utilize layer-by-layer approach and modified inherent strain method for efficiency

Vertical residual distortion (m) for a five layer line deposit by detailed process simulation (left) and the modified inherent strain method (right)

X. Liang et al./Additive Manufacturing 23 (2018) 147-486
PSP Framework

Data science-based approach to develop reduced-order models that establish process-structure-property (PSP) relations for AM

1) Implement high-fidelity framework for characterizing property attributes with respect to process parameters and defects

2) Develop reduced-order PSP model which links process parameters to properties

Finite Element Thermal Analysis

AM Process Simulation SPPARKS¹

Generate .stl Files of Grains Using DREAM. 3D²

DREAM. 3D²/Gmsh

Solve for Heterogeneous Stress/Strain Fields Using ScIFEN⁴
SPPARKS microstructure $\rightarrow$ compute 2-point statistics

Why use 2-point statistics

- Principle Component Analysis (PCA)
- Each point represents a two-dimensional slice taken from the same 3D microstructure
- Total of 100 slices from a single 3D microstructure
PSP Framework

Incorporate Defects

- Equivalent microstructure
- Equivalent pore volume fraction
- 1% global strain applied
- Observation: High strain localization for the irregularly shaped pore

Key hole porosity

Lack of fusion porosity

$\varepsilon_{zz}$ (strain component in loading direction)
Process Monitoring

Process Monitoring Supports:
- Quantitative measures during the build process
- Validation of modeling and simulation
- Process and part qualification

In-Situ Sensors:
- Thermal, Optical, Profilometry, Acoustic

Synchrotron Measurements:
- Dynamic X-ray Radiography (DXR) at the Advanced Photon Source

Benchmark Data:
- AM Bench
- AFRL AM Challenge Series

Argonne Advanced Photon Source

DXR Image

Guo, 2018

Scan Speed (mm/sec) Laser Power (W)

<table>
<thead>
<tr>
<th>Scan Speed</th>
<th>Laser Power</th>
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<tr>
<td>0</td>
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<tr>
<td>200</td>
<td>50</td>
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<tr>
<td>400</td>
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<td>150</td>
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<tr>
<td>800</td>
<td>200</td>
</tr>
<tr>
<td>1000</td>
<td>250</td>
</tr>
</tbody>
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Camera Systems

Heigel, NIST 2017

Melt Pool Surface Images

Guo, 2018
Dynamic X-Ray Radiography

Provides 2D high-speed, in-situ observation of dynamic behavior of powder and melt pool under scanning laser beam
- Up to 200kHz time resolution
- 2 µm pixel resolution
- 24 keV x-rays

Tony Rollet et al, Carnegie Mellon University

APS, 32ID-C
Tao Sun, Cang Zhao,
Kamel Fezzaa and Haidan Wen

Sun et al. (2017), Scientific Reports, 6 3702
X-ray Vision of Metallic Powder-Bed AM

Keyhole Mode Melting

Laser scan across the x-ray beam

- Frame rate: 45 kHz
- Exposure: 100 ps
- Laser power: 300 W
- Scan speed: 0.3 m/s
- Laser spot: ~100 µm
- Material: Ti-6Al-4V

Tony Rollet et al, Carnegie Mellon University
Case Study: Parameter Selection

Problem
Marshall Space Flight Center is using Concept Laser M2 and XLINE SLM systems to build space flight hardware. Process parameters for the M2 machine are established, but material produced by the newer XLINE machine showed unacceptable quality.

Goal
Use computational models to streamline parameter development for the XLINE machine

Approach
Predict the scan speed for various XLINE power settings to produce a similar melt pool depth as the M2
Symmetric model for a single scan track

- Predict scan speeds for various XLINE powers to produce similar melt pool depths as the M2. Key difference is the beam width.
- MSFC spent 6 months experimenting with various parameters. With the modeling data, the XLINE process parameters were established in 3 weeks.

### M2: $w=54$um

<table>
<thead>
<tr>
<th>Power (W)</th>
<th>Scan Speed (mm/sec)</th>
<th>Depth (mm)</th>
<th>Width (mm)</th>
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<tbody>
<tr>
<td>180</td>
<td>600</td>
<td>0.034</td>
<td>0.108</td>
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### XLINE: $w=100$ um

<table>
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<th>Scan Speed (mm/sec)</th>
<th>Depth (mm)</th>
<th>Width (mm)</th>
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<td>180</td>
<td>300</td>
<td>0.035</td>
<td>0.152</td>
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<tr>
<td>250*</td>
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<tr>
<td>945</td>
<td>2500</td>
<td>0.034</td>
<td>0.185</td>
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* The power and scan speed established for the XLINE are 250 W and 500 mm/sec.
Concluding Remarks

Main focus of several research programs

- Processing
- Structure
- Properties
- Performance

More work needed in this area:
- Effect of microstructure on properties
- Effect of defects
- Fatigue
- Material characterization
- Validated non-destructive investigation
- Corrosion / environmental effects

Not everything has to be derived from first principles
- A meaningful combination of physics-based and empirical models can be used
- “Big Data” may provide an alternative approach
Concluding Remarks

“Critical” Parts (e.g. CFR Part 25 → PSEs, CFR Part 33 → LLPs)

“Critical”

“Major” effect

“Minor” effect

“High Value” Parts

Transition to “safety-critical” applications in aviation will occur sooner than initially expected

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