Computational Tools for Additive Manufacture of Tailored Microstructure & Properties

Annual Project Meeting Presentation: Simulation Based Engineering

Raytheon Technologies Research Center
Team: Ranadip Acharya, Paul Attridge, Luke Borkowski, Brian Fisher, John Sharon, Alex Staroselsky, & Anthony Ventura

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Background & Introduction

**Purpose:** Establish computational tools to link AM parameters to material properties to enable parts with spatially varying microstructure for enhanced performance

Project seeks to demonstrate the application of computational methods & tools on microstructure evolution and prediction of mechanical behavior for nickel based superalloy parts.

**Current State:** use “standard parameters” to print parts with a homogenous microstructure; limited control over grain size, morphology, etc.

**Desired State:** a predictive thread of AM input parameters through to tailored property placement

**Challenge:** AM parts go through multiple steps, each with strong impact on finished part
Core Questions

Successful implementation of thread that links AM process parameters through to part performance requires answers to the following:

• What AM process parameters can be readily be controlled & modeled to manipulate deposit microstructure?
• Do differences in as-deposited microstructure get erased with post processing thermal treatments (e.g. stress relief)?

Motivating / Target Case Study for the Program

• AM of a turbine blade with coarse grains in the air foil and fine grains at the root
• Platform: Laser Powder Bed Fusion
• Material: IN718, Ni-superalloy

Experiences hottest temperatures; creep limited
Fatigue limited
Revolutionize hardware via additive manufacturing (AM)

- Process efficiency gains through new component design can be gained by rapid concept iteration as casting development cycle times are erased.
- Enhanced part lifetime/performance through AM enabled spatially varying microstructures.
- Upend part replacement supply chains with new processing developments impacting a large existing base including F-Class turbines.
- AM applicable to all Industrial Gas Turbines as well as derivative power generation systems such as aerospace turbines.

Gas Turbine Efficiency Gains Thru Rapid AM Design Iteration

Novel AM Enabled Tailored Mechanical Property

Cost Effective AM Enabled Part Design

Technology Transition To Supply Base

Conventional to AM Conversion

Product Development Cycle

Common Tool Sets

Product Deployment

Approved for Public Release
Project Outline & Status

Key Tasks & Progress

A. Models to link AM Process Parameters to As-Deposited Microstructure

B. Initial to Final Microstructure Evolution Correlation (Post Processing Effects)

C. Microstructure-Properties-Performance Model

D. Demonstration of Spatially Varied Microstructure Via AM

In Progress
Update: Link AM Parameters to Microstructure

Microstructure influenced by thermal history of the melt pool

Approaches to control melt pool solidification
1. Increase layer thickness → requires sufficient laser power
2. Laser scan path → need control over scan strategy

RTRC’s COTS powder bed systems are too limited in laser power to take advantage of Approach 1 so focus was placed on manipulating laser scan vectors.
Update: Link AM Parameters to Microstructure

Use an “Active Melt Pool” scan whereby the melt pool is active for longer time thus lowering cooling rate & making a flatter pool to promote a 2D microstructure for larger columnar grains

Standard or default scan strategy

Active melt pool scan strategy

CFD simulation of active melt pool shows that this scan strategy results in a wide and flat melt pool

Phase field simulations indicate active melt pool results in larger dendrites
Active melt pool technique experimentally validated to result in larger, more columnar like, grains.

CFD simulation provides thermal gradient $G$, & solidification speed $(R)$ that can be plotted on a microstructure solidification map.

Validation

EBSD scans of IN718 additive coupons made with default and active melt pool scan strategy

Active melt pool solidification primarily in the columnar zone. The top of the melt pool (orange zone) may be equiaxed but this is erased when the next layer during AM is processed.
Update: Microstructure Evolution Trends

Insights for Microstructural Evolution

While custom heat treatments could be employed to influence grain structure evolution, this work follows industry standard post-processing thermal treatments.

- Stress Relief (ASTM F3055)
- HIP (ASTM F3055)
- Solution + Age (AMS 5663M)

Track trends in the evolution of grain size, shape, and orientation distribution that are key inputs to the microstructure sensitive performance model.

Quantify grain size with EBSD

Quantify final grain size with EBSD

Approved for Public Release
**Update: Microstructure Evolution Trends**

Larger grains from active melt pool approach retained through post processing.

Overall, texture is random for both default & active melt pool (AMP) deposits in post processed state.

<table>
<thead>
<tr>
<th>Scan Strategy</th>
<th>Grain Size (µm)</th>
<th>Trends</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>As-deposit</td>
<td>Post Processed</td>
</tr>
<tr>
<td>Default</td>
<td>27</td>
<td>70</td>
</tr>
<tr>
<td>Active Melt Pool</td>
<td>44</td>
<td>365</td>
</tr>
</tbody>
</table>

**Scan Strategy**

- Default Scan
- Active Melt Pool

**Grain Size**

- As-deposit
- Post Processed

**Trends**

- ~2.5X increase in grain size, more equi-axed
- ~8X increase in grain size, elongated grains
Update: Microstructure Performance Models

Grain-scale simulations to predict global creep behavior governed by bulk grain & grain boundary mechanisms

- Additive IN718 modeled as a connected 2 phase system
  1. Grain Material modeled with crystal plasticity
  2. Grain Boundary Phase modeled by Norton’s Law

- Microstructure sensitivity → smaller grains means more grain boundary phase influence in the material response.
Work In Progress

- Model is de-bugged and operational with surrogate material calibration factors

- Model calibrated for time independent quasi-static tensile/compressive behavior

- Collection of time-dependent creep data for additively manufactured coarse grain and fine grain deposits are in progress & required for model calibration to predict creep performance.

![Graph showing Cauchy stress vs. logarithmic strain]
Update: Spatially Varied Microstructure Demo

Successfully printed a turbine blade surrogate with coarse grains in the air foil (creep resistance) and fine grains at the root (fatigue resistance)

Strategy
• Print blade using powder bed system with “default” parameters in the root & active melt pool scan strategy for the airfoil.

Key Accomplishments
• Retention of spatially tailored microstructure after full post processing (Stress relief → HIP → Solution → Age thermal treatments).
• No egregious defects such as cracks, pores, etc.

EBSD scan with random color assigned to individual grains

Active Melt Pool
Coarser grains
~365µm

Default Parameters
Finer grains
~70µm

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Preparing for Next Steps

Assembling the Full Framework Connecting Process-Structure-Properties-Performance

- Implementation with software packages common to industry

**Directions Beyond the Program**

Coordinate with AM platform providers to offer systems with features to enable more microstructural control

Methods to connect across the different models in the tool chain
Concluding Remarks

Summary

• Employed modeling to understand the impact of AM process parameters on the as-deposited microstructure → results in the ability to influence material properties & performance in 3D printed parts by intentionally adjusting scan vectors, laser power, speed, etc.

• Confirmation that spatially varied microstructure can be retained with post processing.

• Employed lessons learned to demonstrate AM of a turbine blade with spatially varying microstructure having coarse grains in the air foil for creep resistance and finer grains at the root for fatigue resistance.

Next Steps

• Finalize the microstructure sensitive property model for prediction of creep performance. Awaiting the collection of long duration (500+ hr) creep data for coarse and fine grain AM Ni-superalloy to use for model calibration.

• Complete program with documentation of all technical progress.
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