Computational Materials for the Design and Qualification of Additively Manufactured Components

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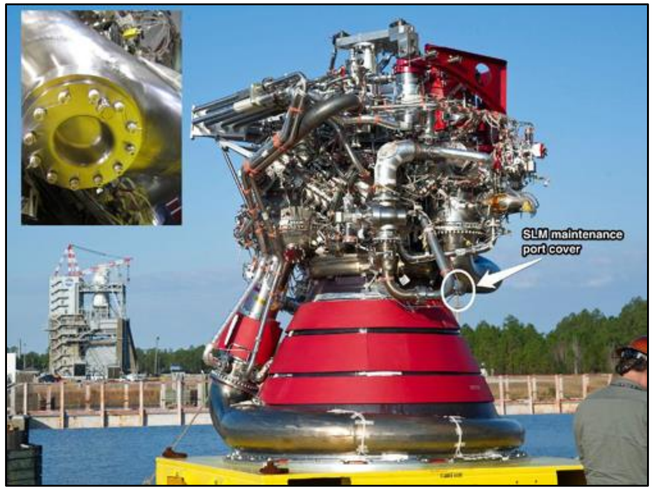
Additive Manufacturing

Selective Laser Melting (SLM)



Space Exploration

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

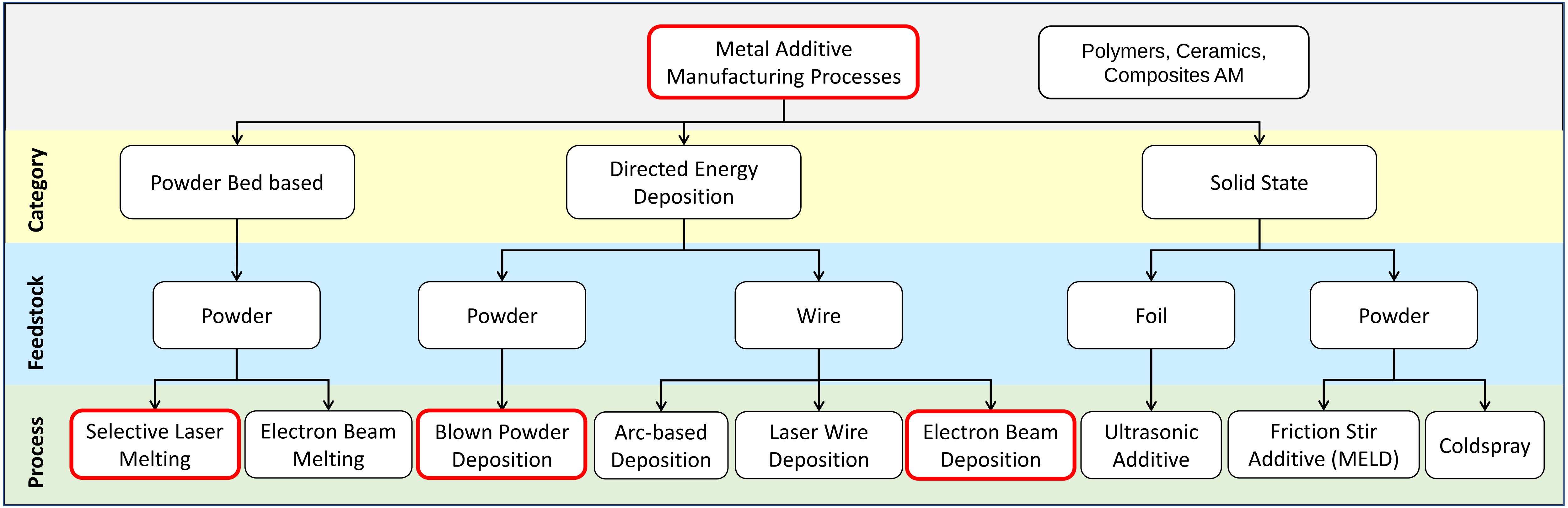
- Rocket Engine, Launch Vehicle
- Airframe

Directed Energy Deposition (DED)

Aeronautics Research

Computational Materials for Design and Qualification of AM Components

AM Processes

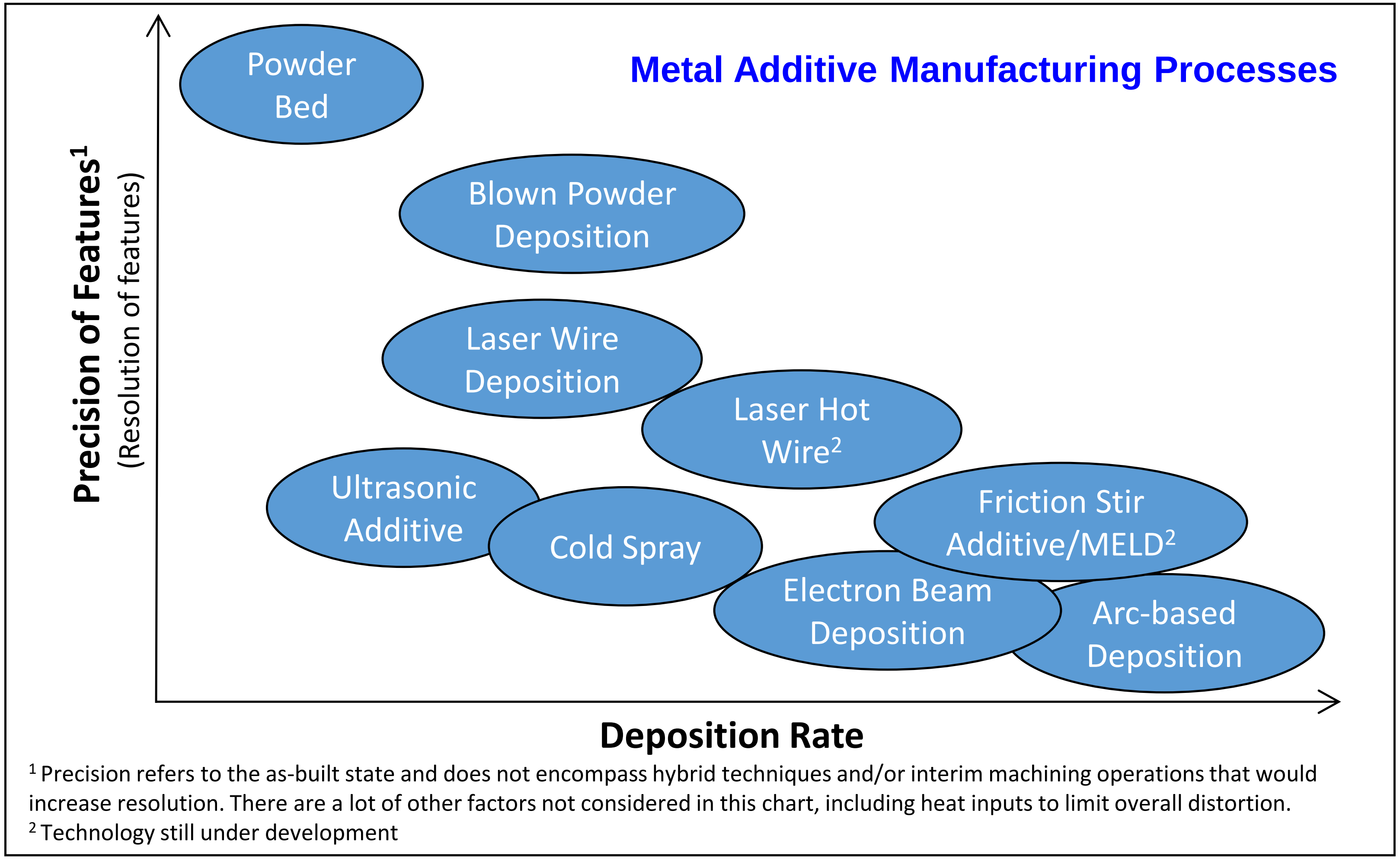


Other metal AM processes are being developed: binder-jet, material extrusion, vat photopolymerization, hybrid methods

Based on Ref:

- Ek, K., “Additive Manufactured Metals,” Master of Science thesis, KTH Royal Institute of Technology (2014).
- Gradl, P., Brandsmeier, W., Calvert, M., et al., “Additive Manufacturing Overview: Propulsion Applications, Design for and Lessons Learned. Presentation,” M17-6434. 1 December (2017).
- ASTM Committee F42 on Additive Manufacturing Technologies. Standard Terminology for Additive Manufacturing Technologies ASTM Standard: F2792-12a. (2012).
- Gradl, P.R., Greene, S.E., Protz, C., Bullard, B., Buzzell, J., Garcia, C., Wood, J., Osborne, R., Hulka, J. and Cooper, K.G., 2018. Additive Manufacturing of Liquid Rocket Engine Combustion Devices: A Summary of Process Developments and Hot-Fire Testing Results. In *2018 Joint Propulsion Conference* (p. 4625).

AM Processes



Paul Gradl, MSFC

- 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

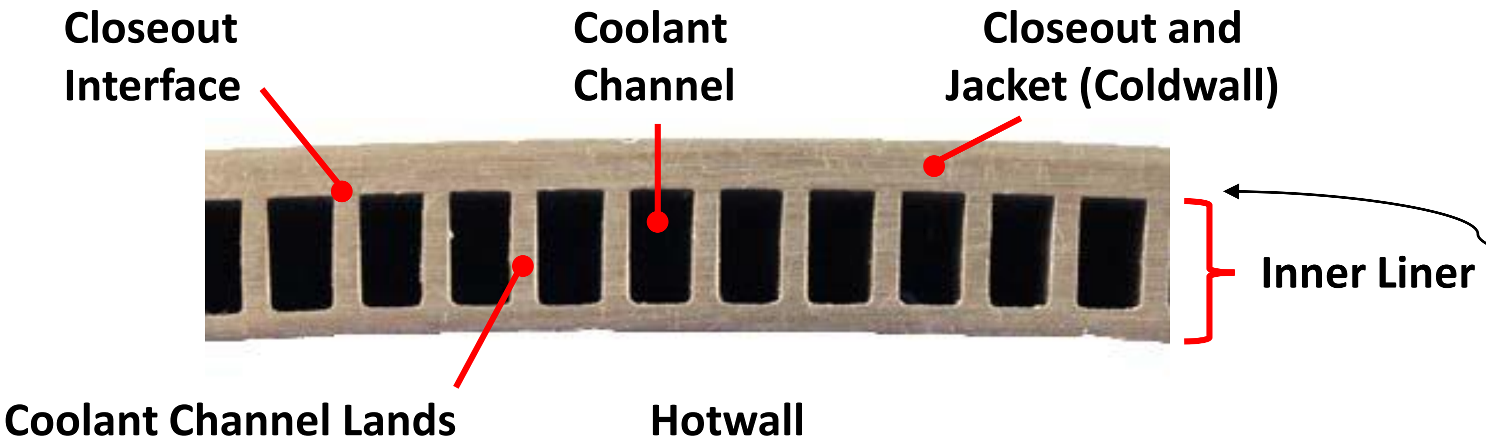
★ GE Leap Engine Fuel Nozzle

- Designed for AM
- Part count reduced from 20 to 1
- Reduced weight by 25%
- 5x lifetime
- Certified part, manufacturing ~40k per year

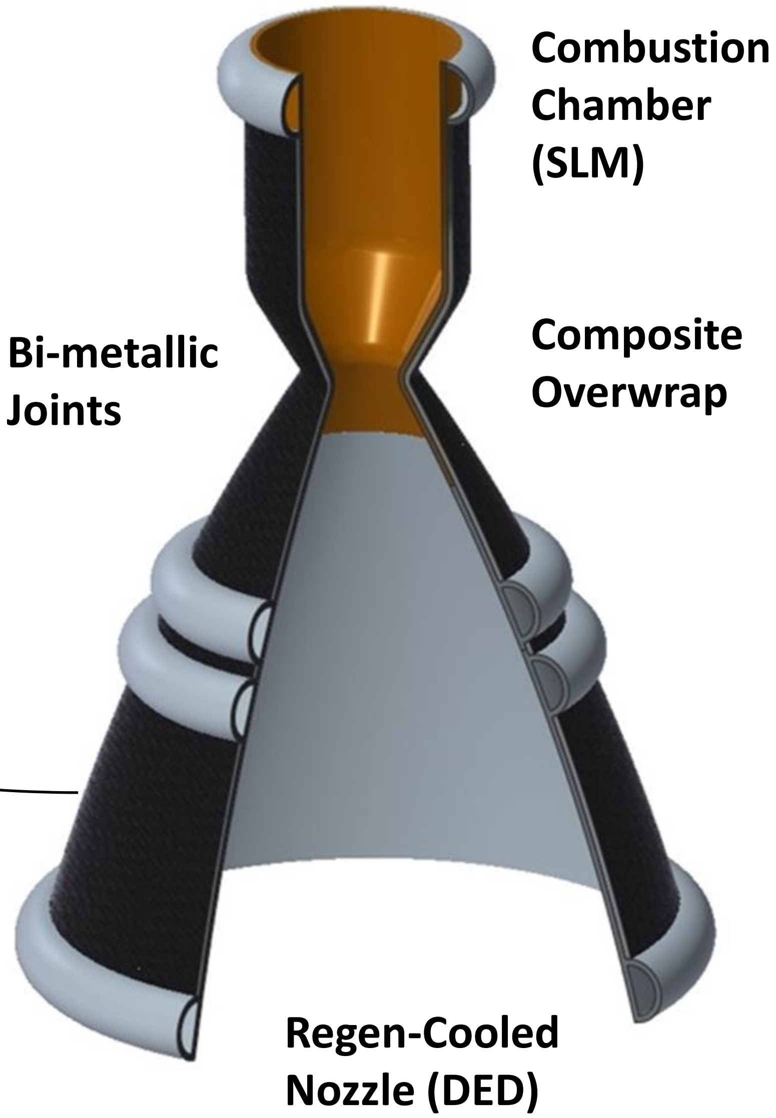
RAMPT

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



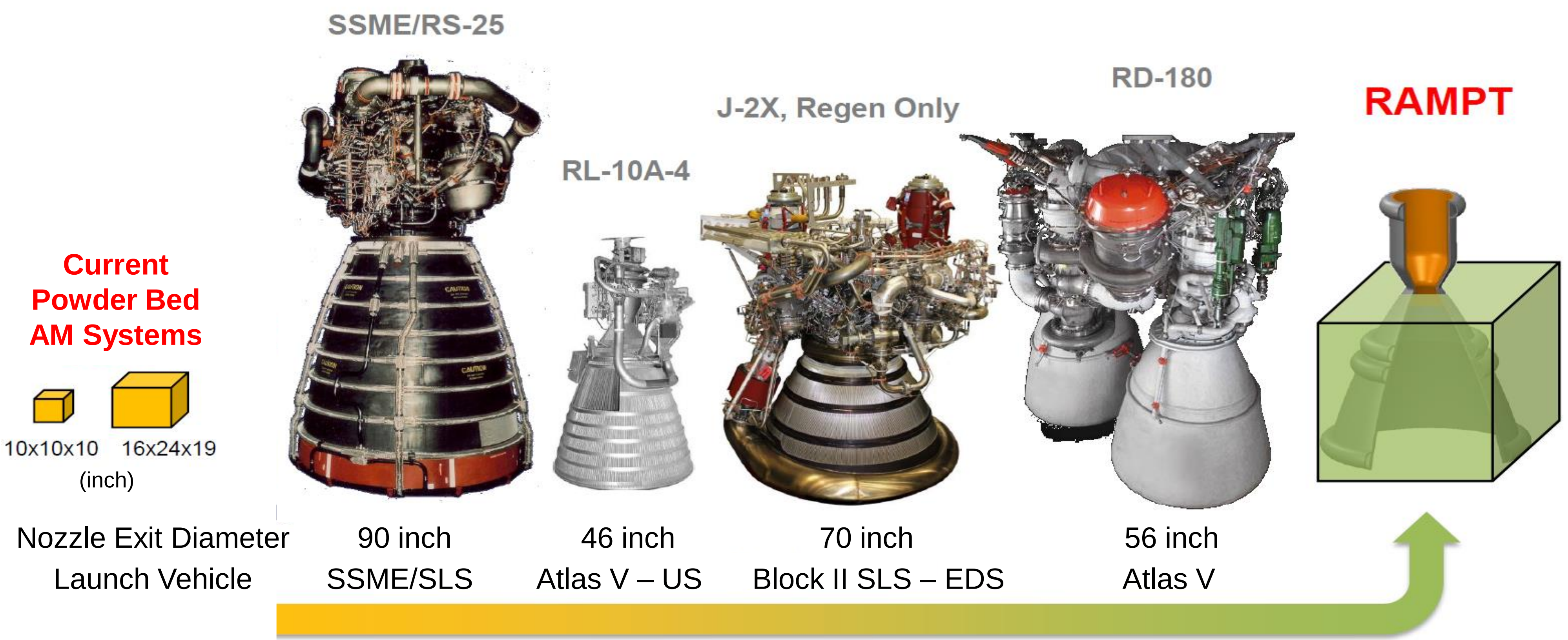
Thrust Chamber Assembly (TCA)



RAMPT

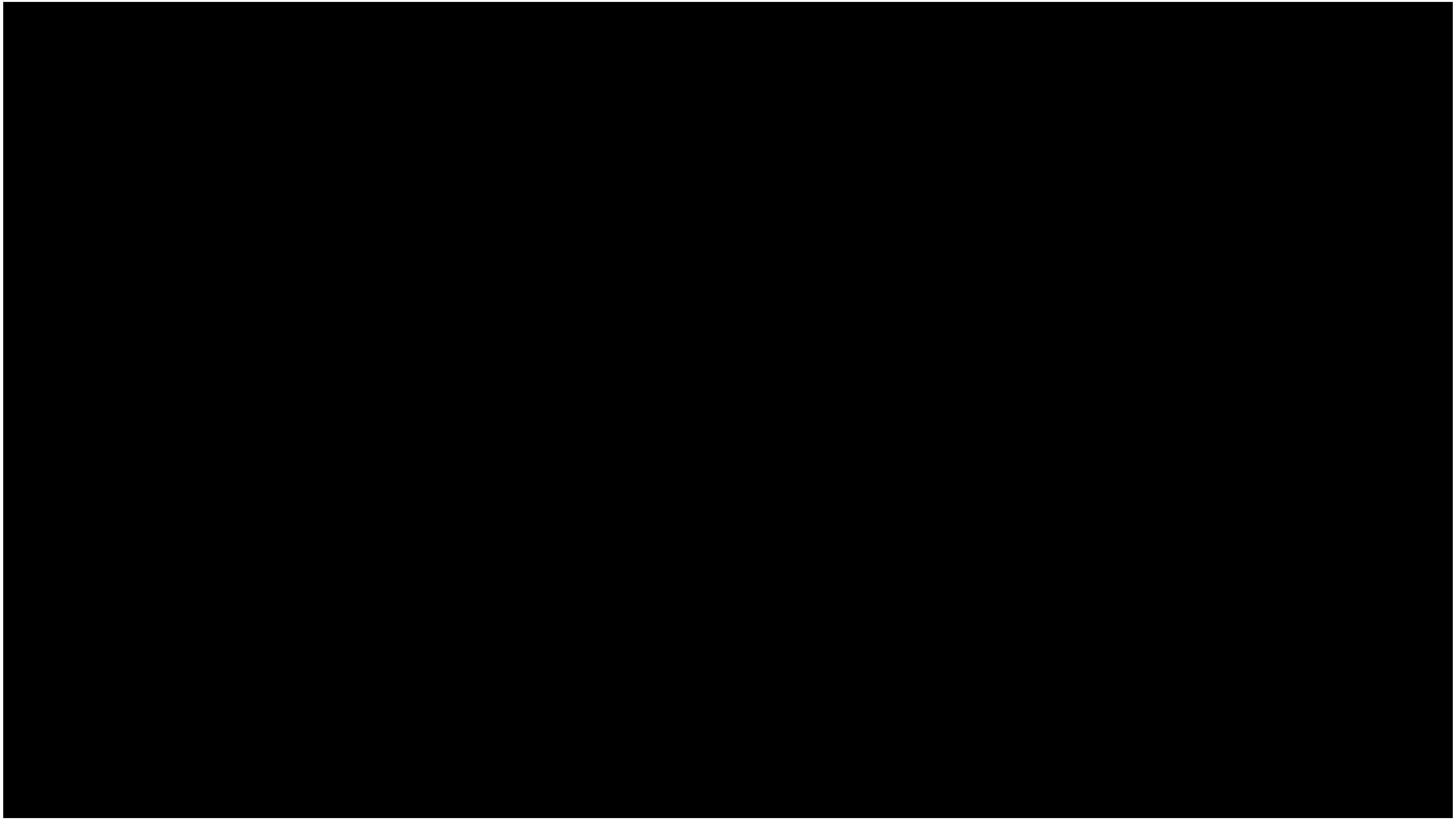
Focus on the TCA addresses:

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



Nozzle Exit Diameter	90 inch	46 inch	70 inch	56 inch
Launch Vehicle	SSME/SLS	Atlas V – US	Block II SLS – EDS	Atlas V
Fuel Mixture	LOX/LH2	LOX/LH2	LOX/LH2	kerosene/LOX (dual chamber)
Thrust	2100 kN	100 kN	1300 kN	4150 kN

Hot-Fire Testing

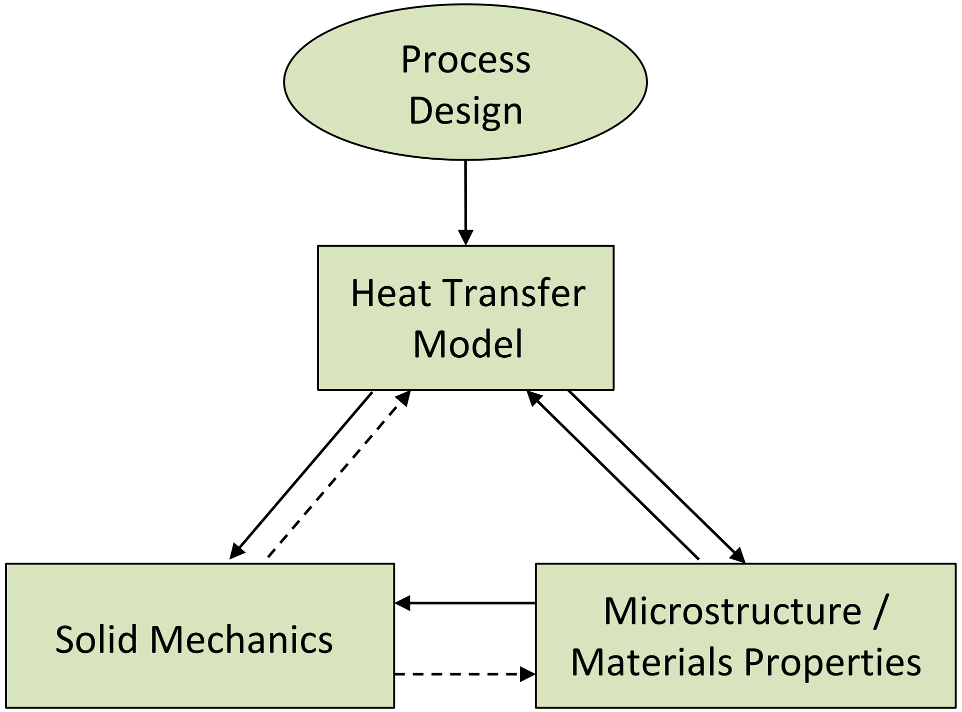


Computational Process Modeling

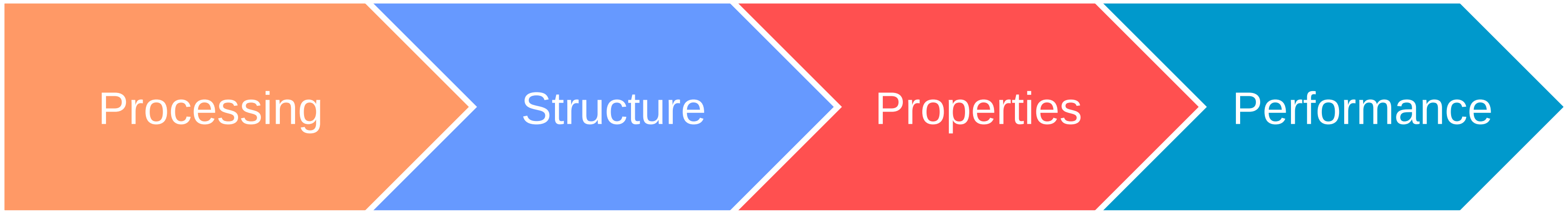
Physics-based modeling of the additive manufacturing (AM) process contributes to the following:

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

Heat transfer during the process drives the formation of the microstructure and residual stress

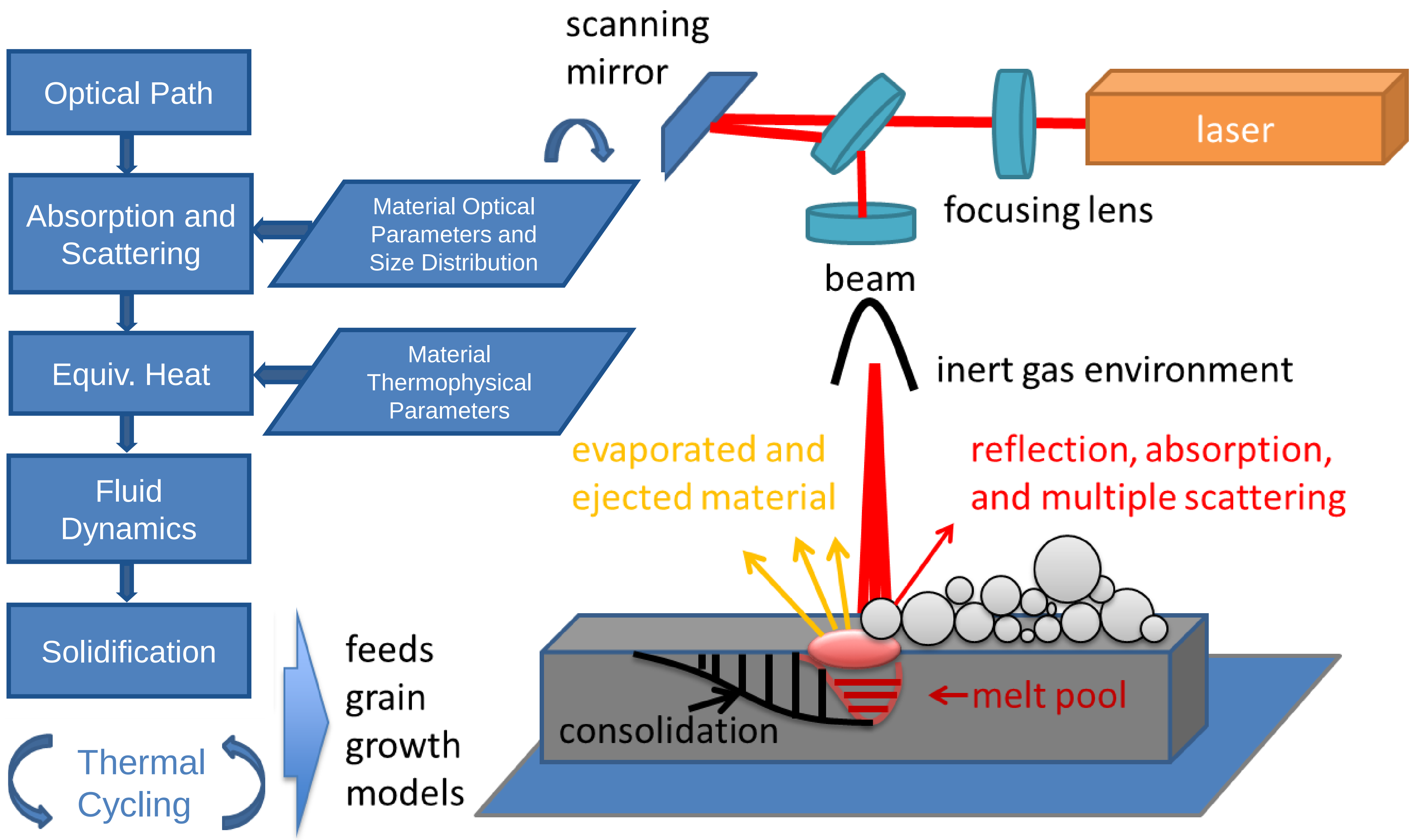


Note: Dashed lines represent insignificant coupling which is generally ignored



Selective Laser Melting

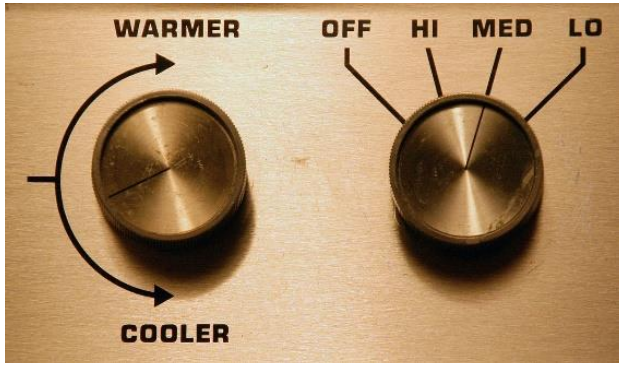
Process Modeling Activities



Process Parameters

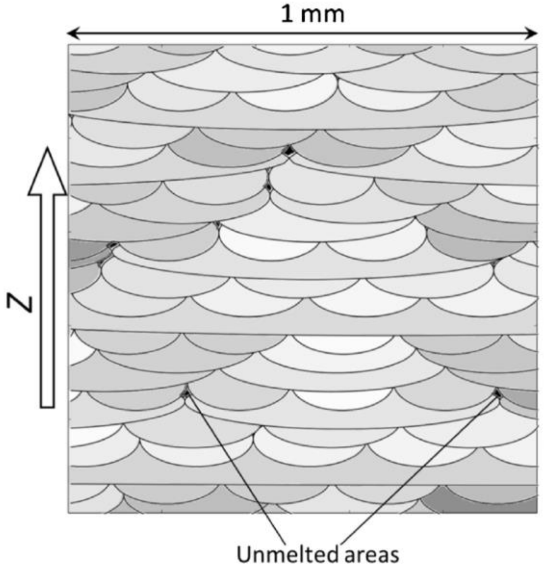
Selective Laser Melting Process Design Space

Machine Parameters		Manufacturing Parameters		Feedstock Properties	
Laser Power	Chamber Atmosphere	Part Geometry	Part Orientation	Composition	Powder Shape
Laser Speed	Chamber Airflow	Scan Strategy	Support Structures	Avg Powder Size	Thermal Properties
Laser Spot Size	Build Plate Properties	Feature Size	Local Properties	Powder Size Distribution	Recycled
Hatch Spacing	Powder Bed Temperature				
Layer Thickness	Layer Rotation				

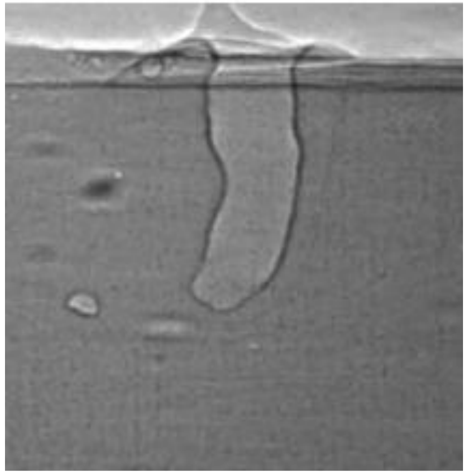


Process Design: Porosity

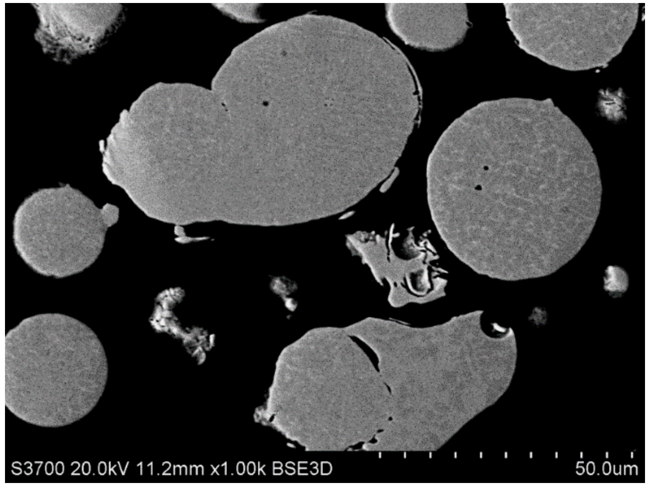
Lack of Fusion



Keyholing



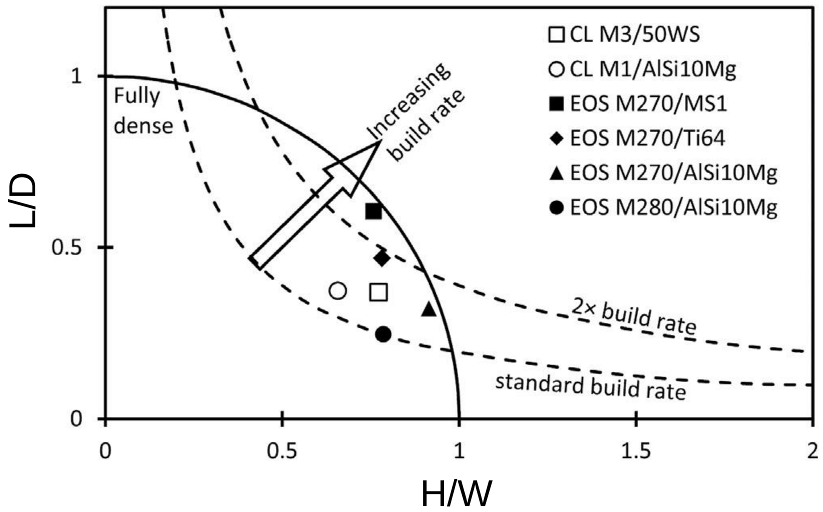
Trapped Gas Inherited From Powder



Criterion for complete melting

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

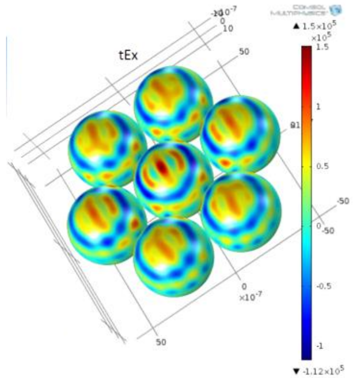
with hatch spacing (H), layer thickness (L), and melt pool width (W) and depth (D)

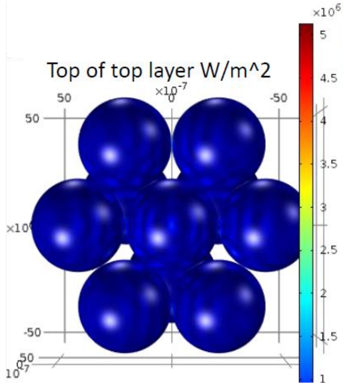


Multiscale Thermal Analysis

Fine Scale ~1 µm (powder spheres)

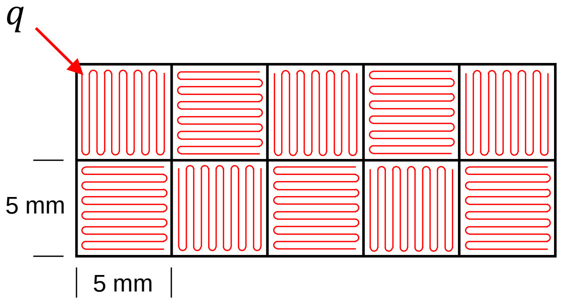
- Melt pool analysis
- Physics: electromagnetic scatter, heat conduction, fluid flow, surface tension, vapor pressure, phase change
- Provide heat input model (q) for thermal analysis



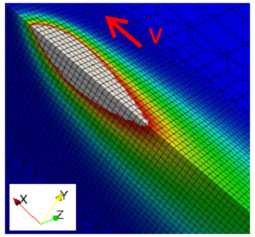


Intermediate Scale ~1 mm (scan path)

- 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



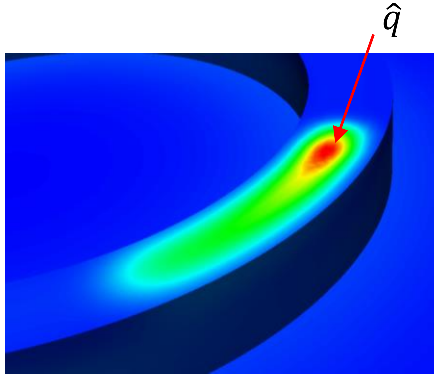
Top View (e.g. ‘chess’ scan strategy)



Single Track Analysis (symmetry model)

Large Scale ~1 m (build path)

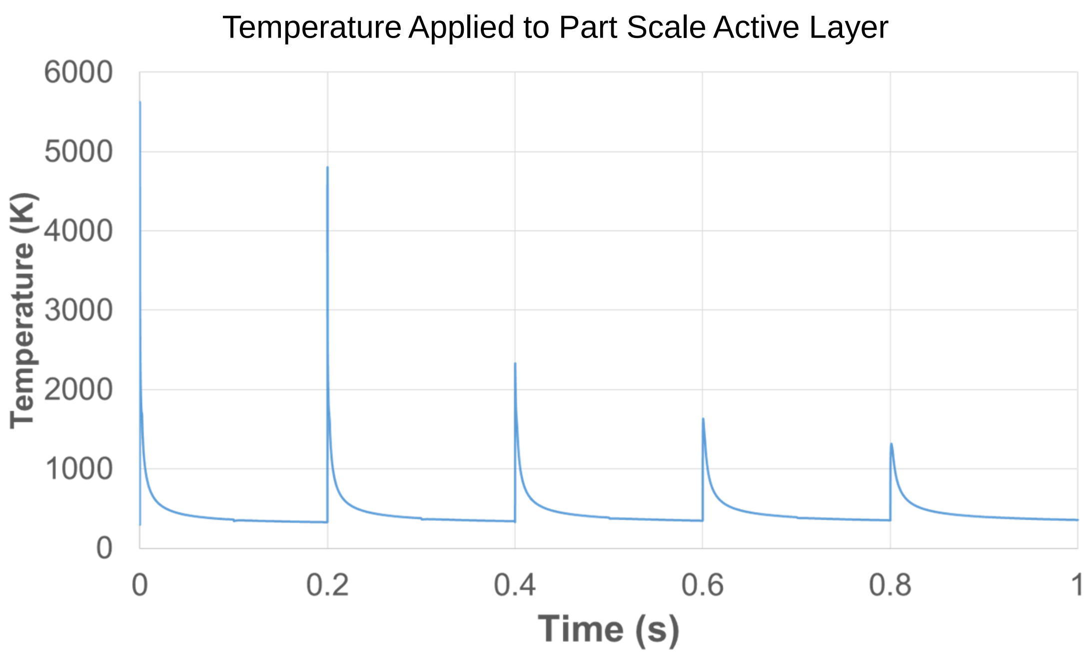
- Thermal analysis of section/part
- Physics: conduction, convection, radiation, phase change
- Model build path with moving heat source $\hat{q}$
- Provide thermal history for section/part

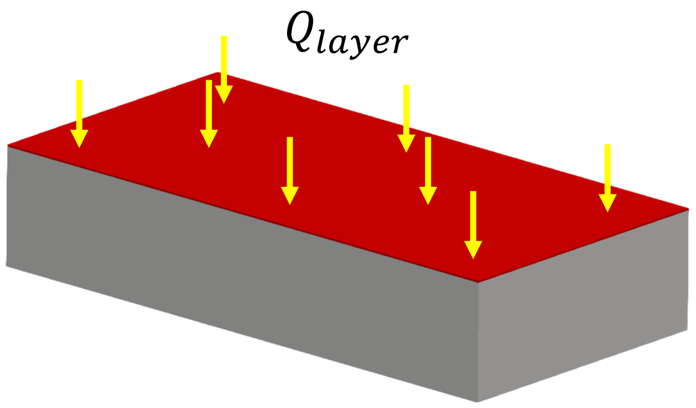


Cylinder Wall

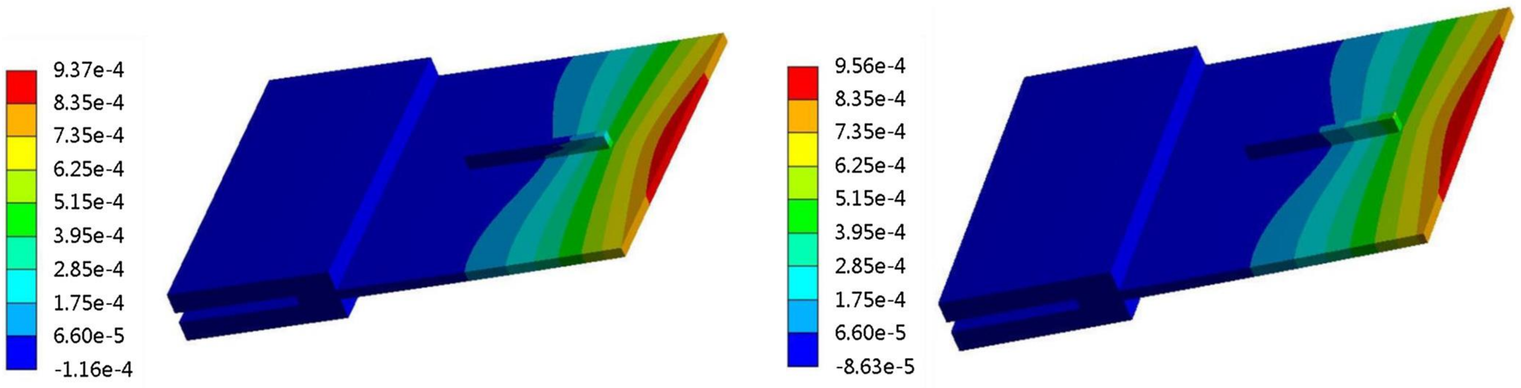
Residual Stress

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





Volumetric heating applied layer-by-layer



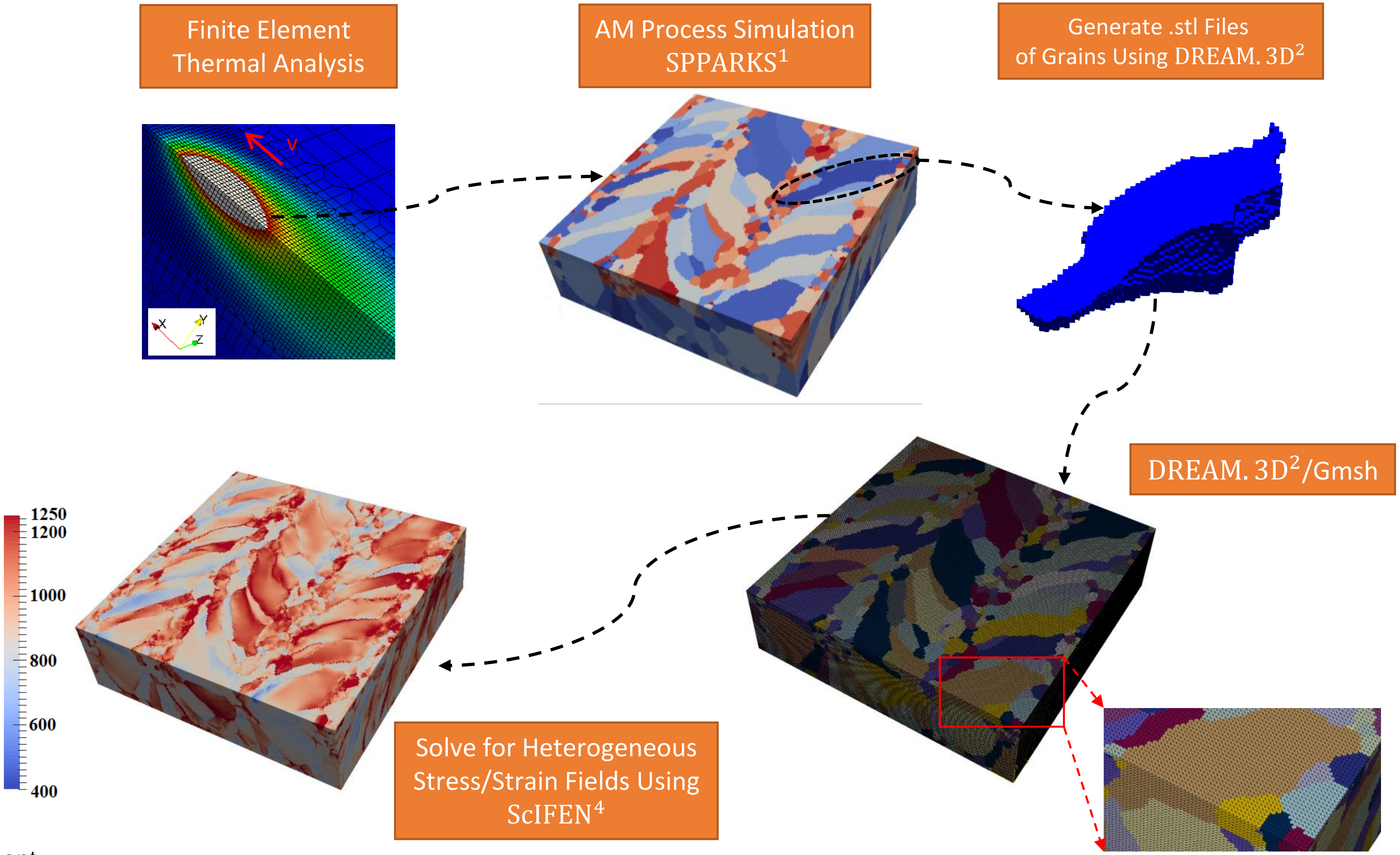
Vertical residual distortion (m) for a five layer line deposit by detailed process simulation (left) and the modified inherent strain method (right)
X. Liang et al./Additive Manufacturing 23 (2018) 147-486

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

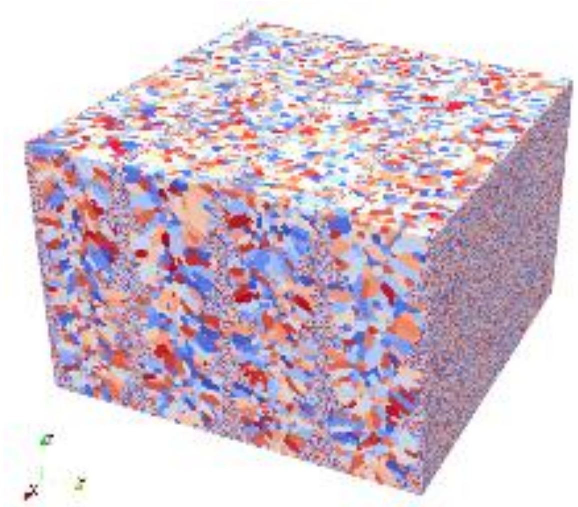
2) Develop reduced-order PSP model which links process parameters to properties

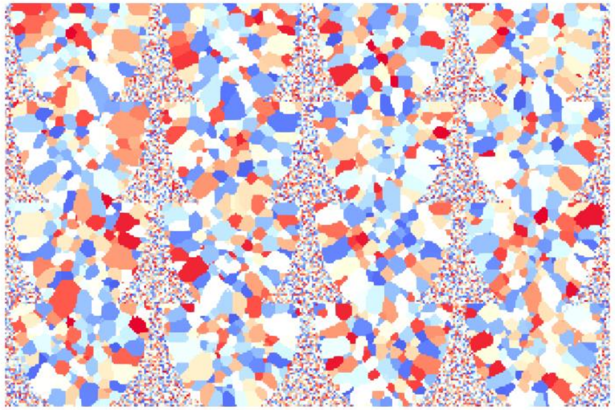


PSP Framework

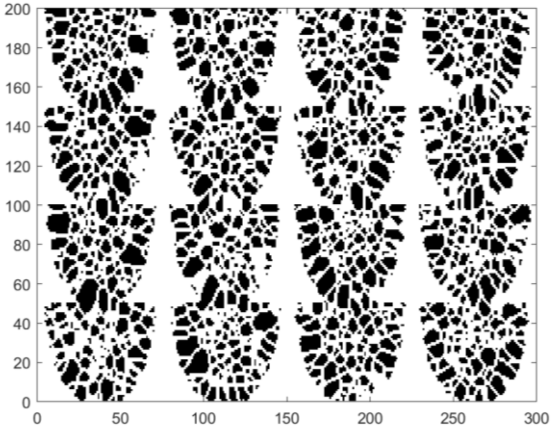
SPPARKS microstructure → compute 2-point statistics

Kalidindi, Georgia Tech University

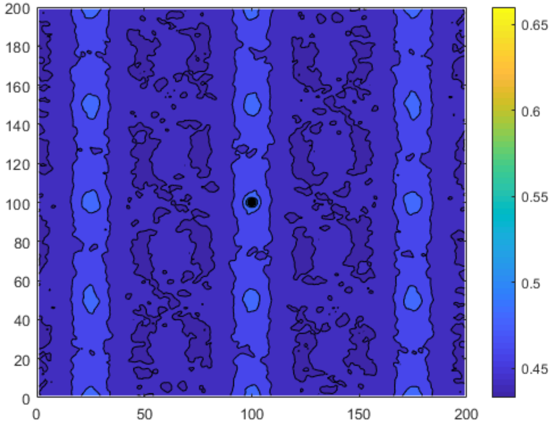




Simulated Microstructure Slice at X=110



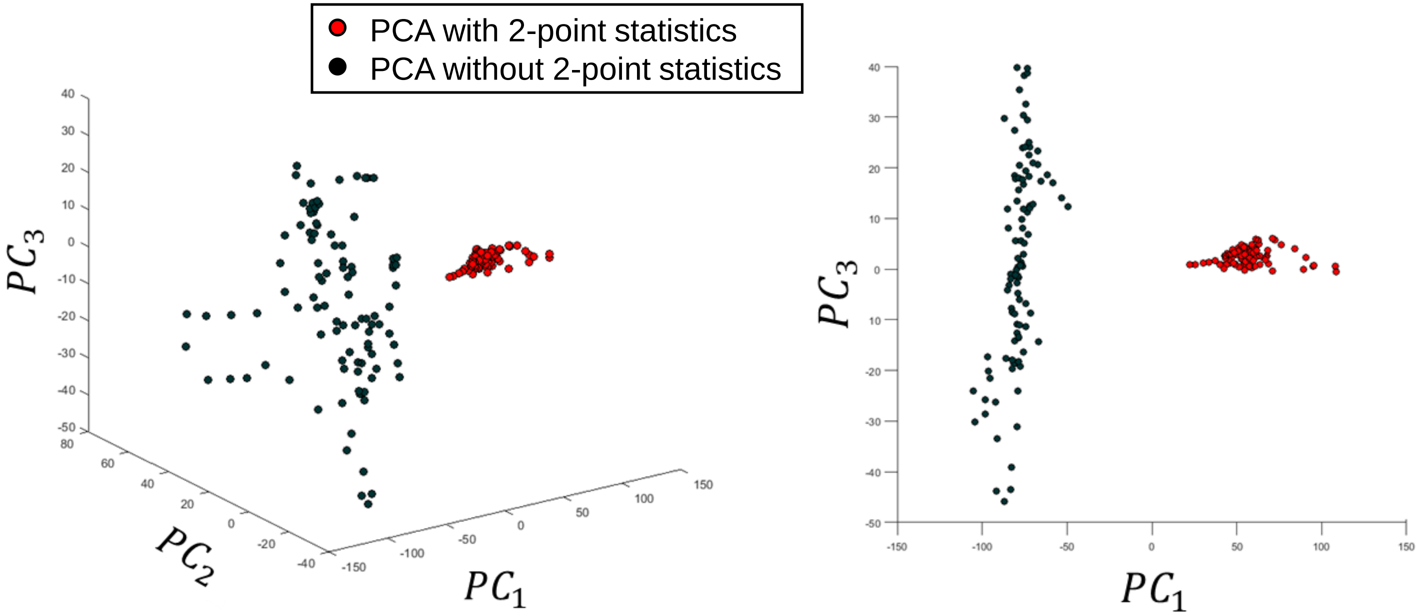
Binary Image Depicting Cell Boundaries



Auto Correlation with Cutoff=100

Why use 2-point statistics

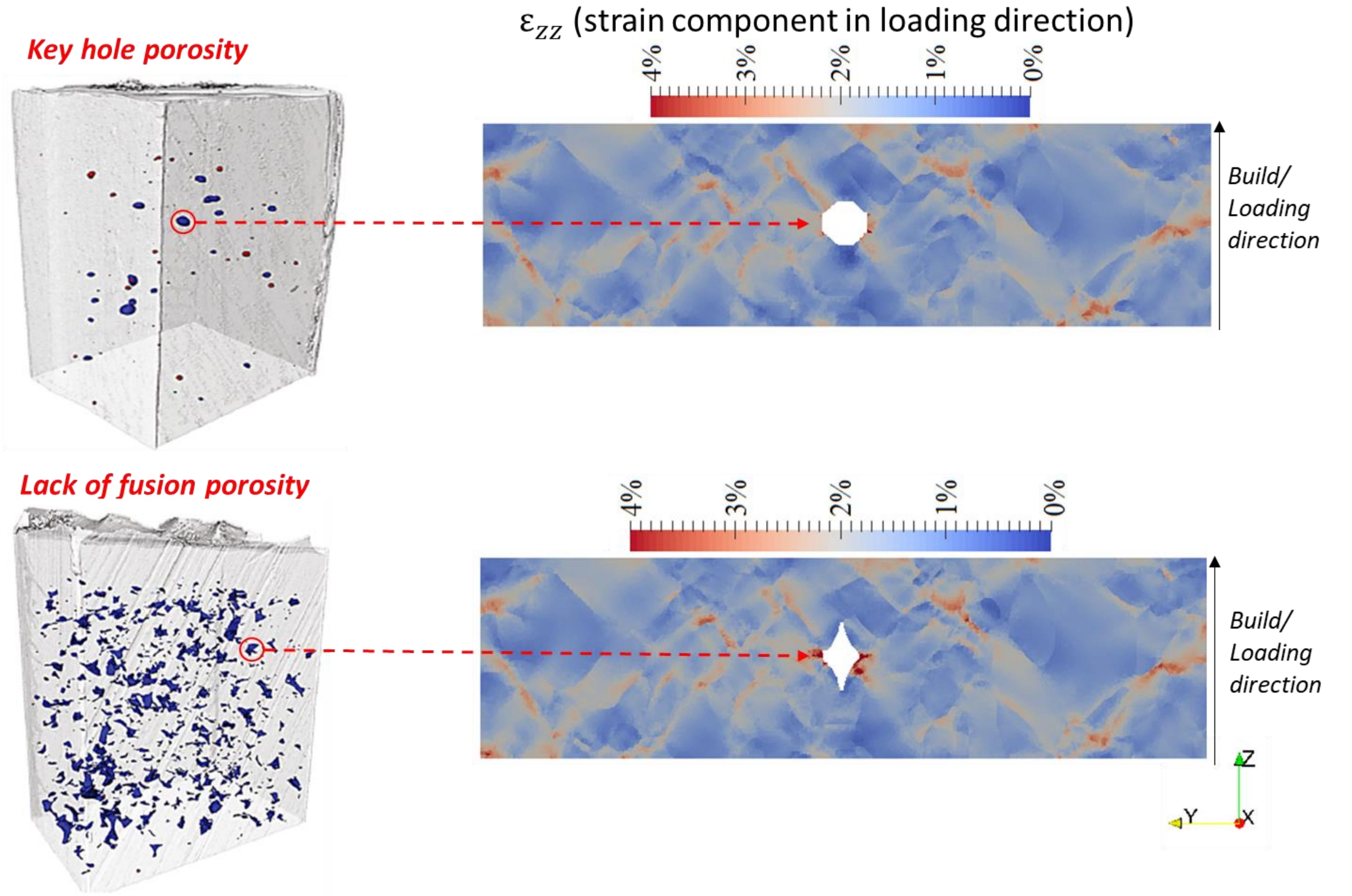
- Principle Component Analysis (PCA)
- Each point represents a two-dimensional slice taken from the same 3D microstructure
- Total of 100 slices from a single 3D microstructure



PSP Framework

Incorporate Defects

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



Process Monitoring

Process Monitoring Supports:

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

In-Situ Sensors:

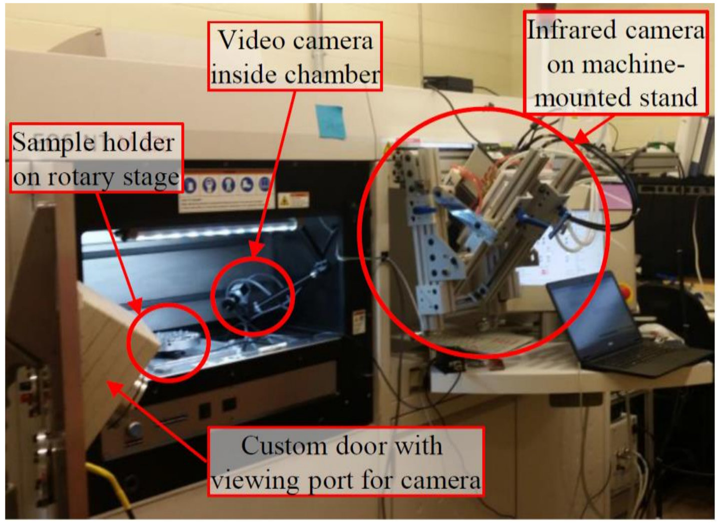
- Thermal, Optical, Profilometry, Acoustic

Synchrotron Measurements:

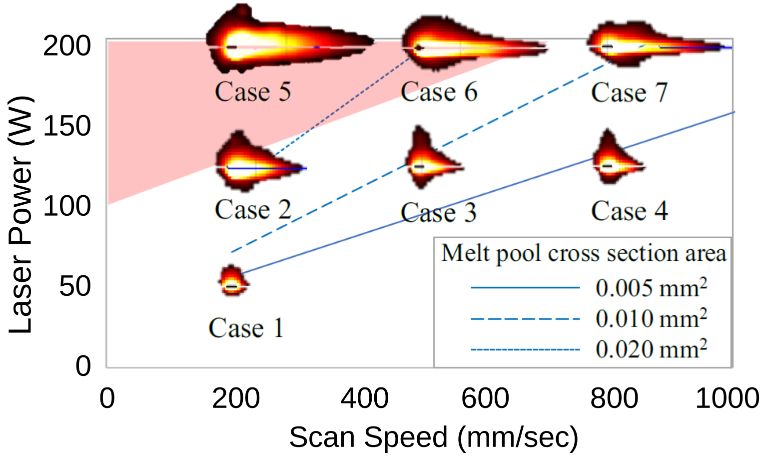
- Dynamic X-ray Radiography (DXR) at the Advanced Photon Source

Benchmark Data:

- AM Bench
- AFRL AM Challenge Series

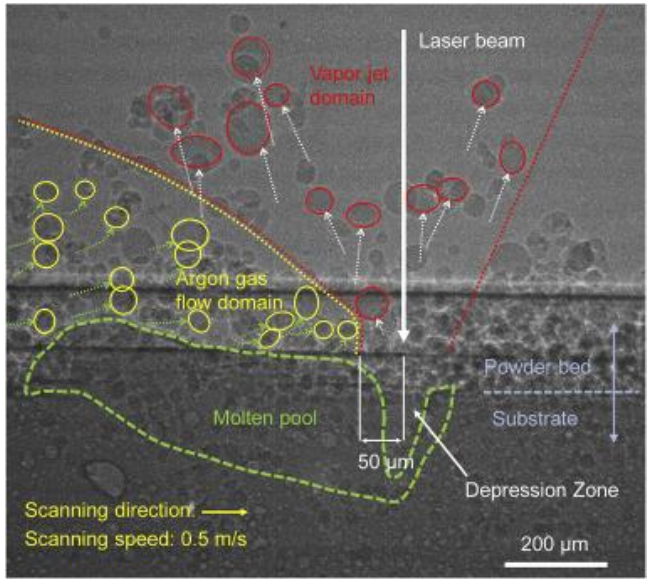


Camera Systems Heigel, NIST 2017



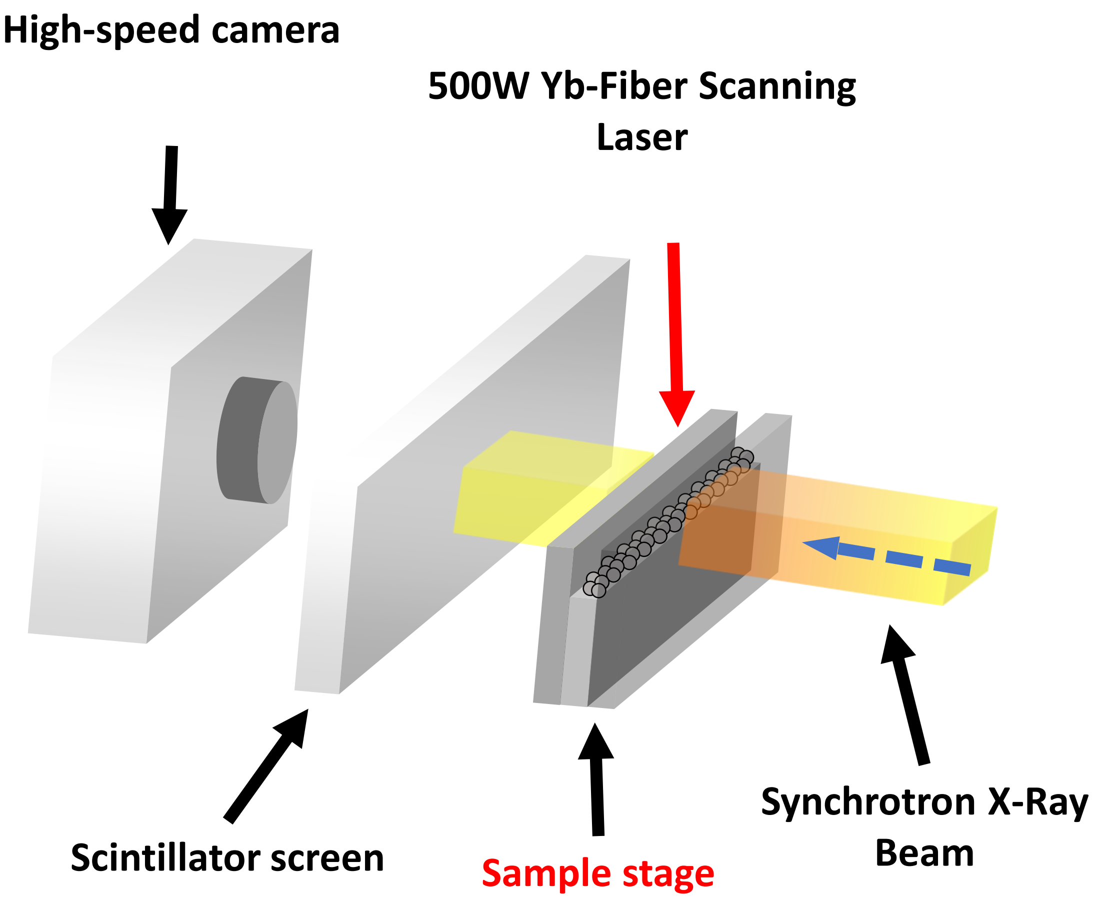
Melt Pool Surface Images

Argonne Advanced Photon Source



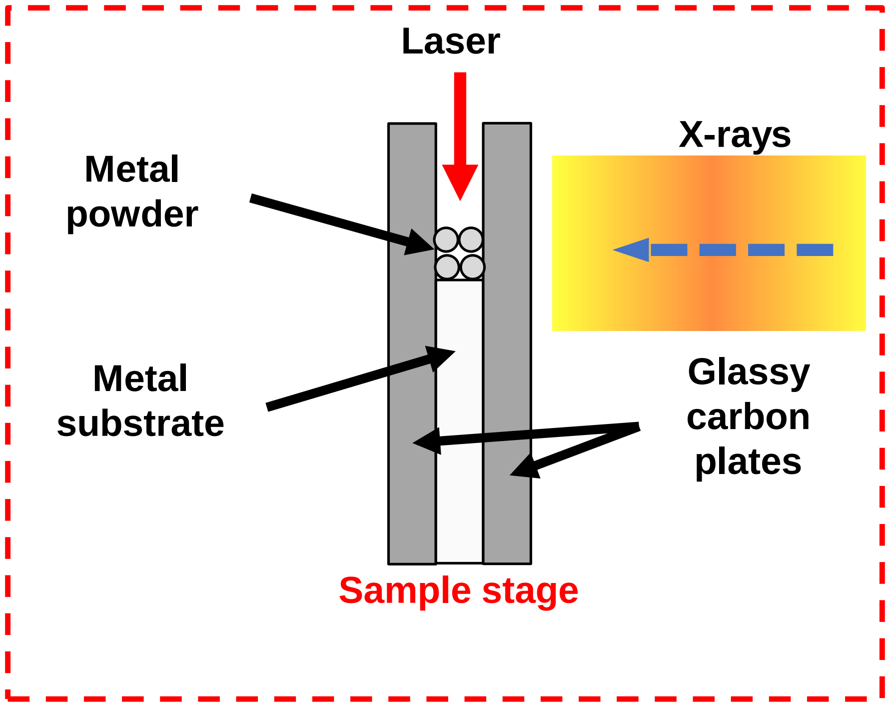
DXR Image Guo, 2018

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

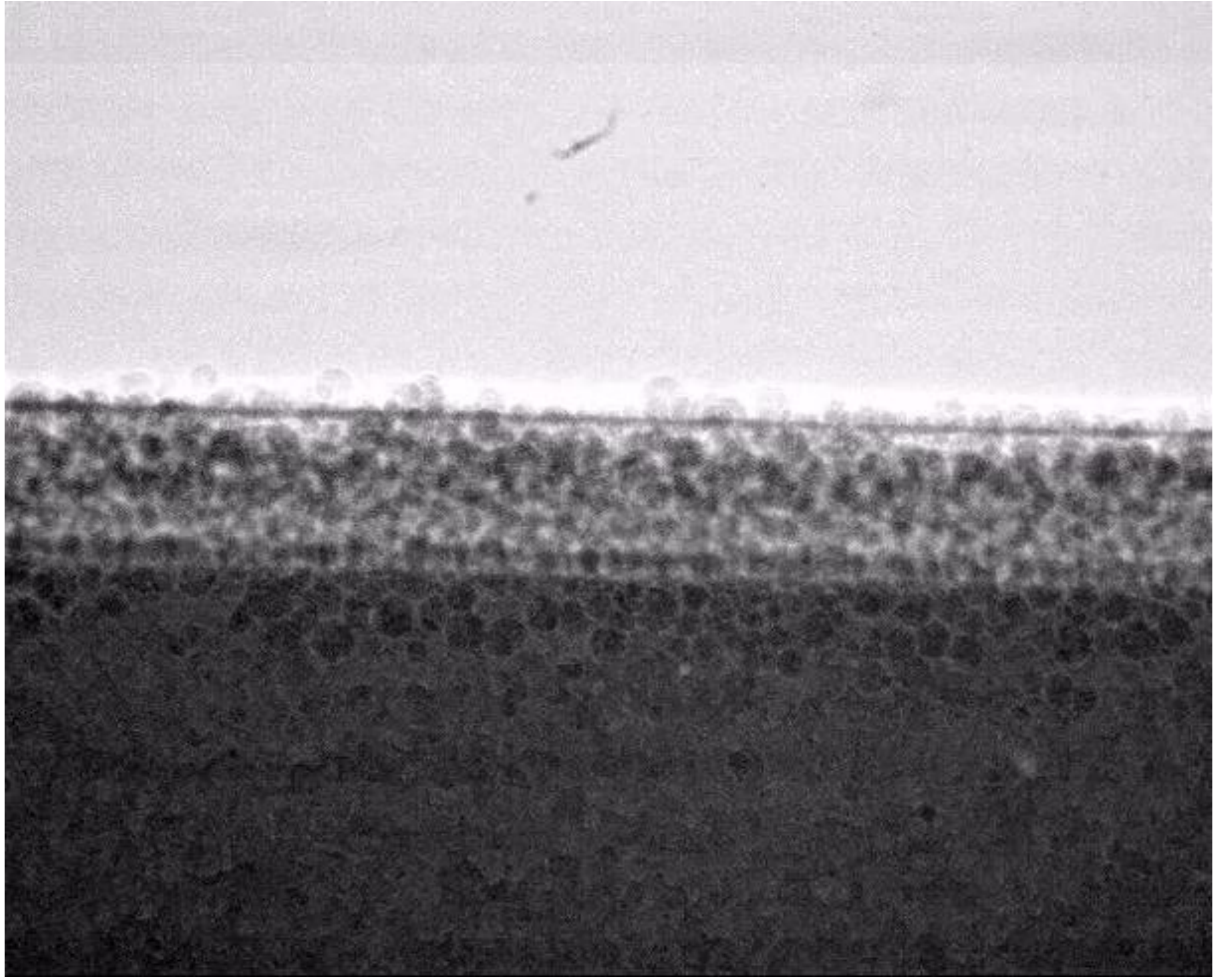


APS, 32ID-C
Tao Sun, Cang Zhao,
Kamel Fezzaa and Haidan Wen

Sun et al. (2017), *Scientific Reports,* **6** 3702

Dynamic X-Ray Radiography

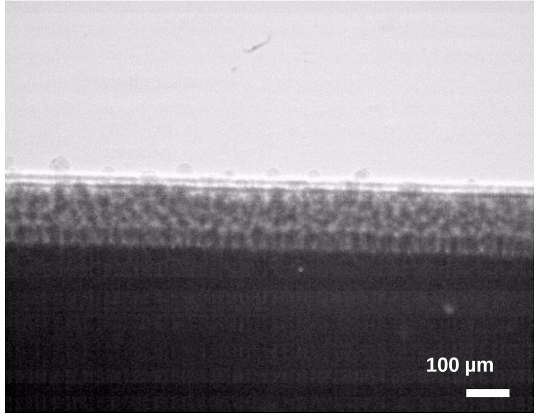
X-ray Vision of Metallic Powder-Bed AM



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



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.

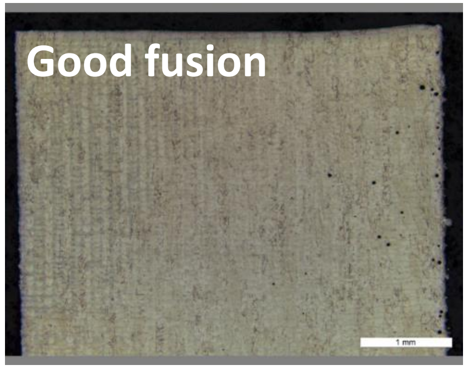
Goal

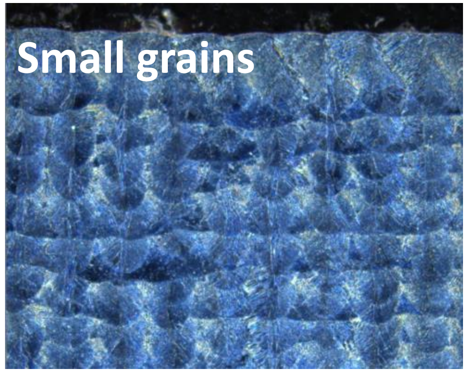
Use computational models to streamline parameter development for the XLINE machine

Approach

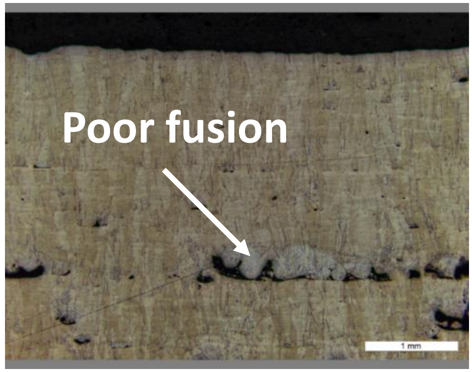
Predict the scan speed for various XLINE power settings to produce a similar melt pool depth as the M2

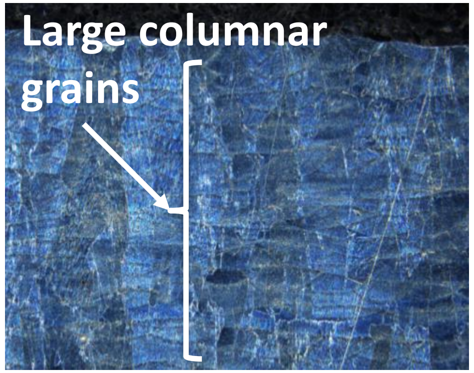
M2 Machine:
Power 180 W, Scan Speed 600 mm/s, Hatch 4 mm





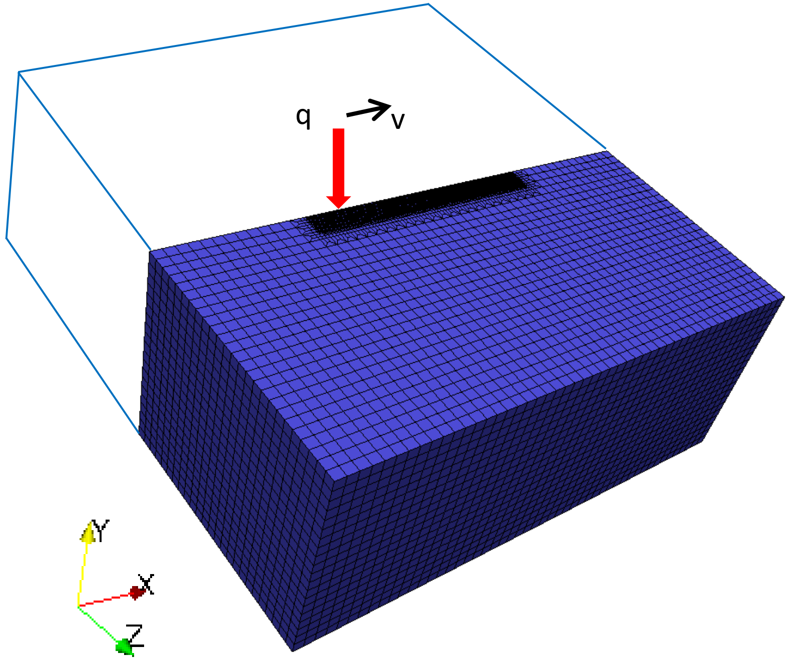
XLINE Machine:
Power 180 W, Scan Speed 600 mm/s, Hatch 4 mm





Case Study: Parameter Selection

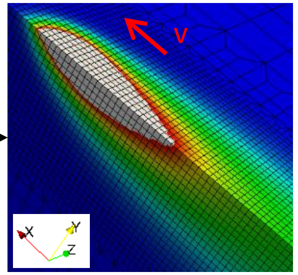
Symmetric model for a single scan track



- 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.**

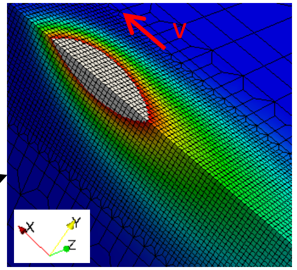
M2: w=54um

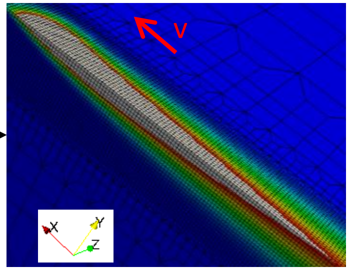
Power (W)	Scan Speed (mm/sec)	Depth (mm)	Width (mm)
180	600	0.034	0.108



XLINE: w=100 um

Power (W)	Scan Speed (mm/sec)	Depth (mm)	Width (mm)
180	300	0.035	0.152
250*	520	0.034	0.155
400	1000	0.033	0.163
500	1200	0.035	0.171
600	1500	0.034	0.175
945	2500	0.034	0.185

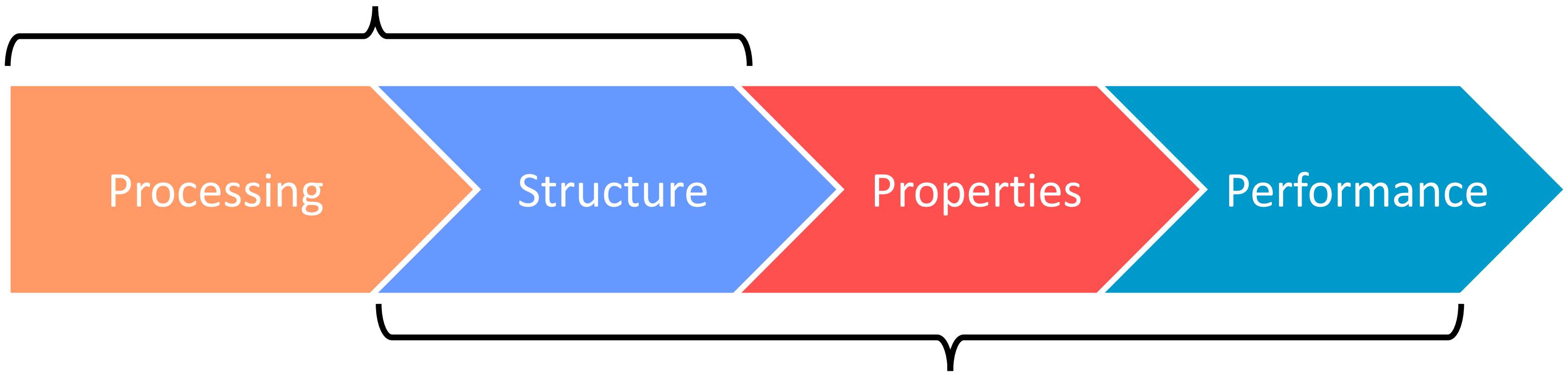




* The power and scan speed established for the XLINE are 250 W and 500 mm/sec.

Concluding Remarks

Main focus of several research programs



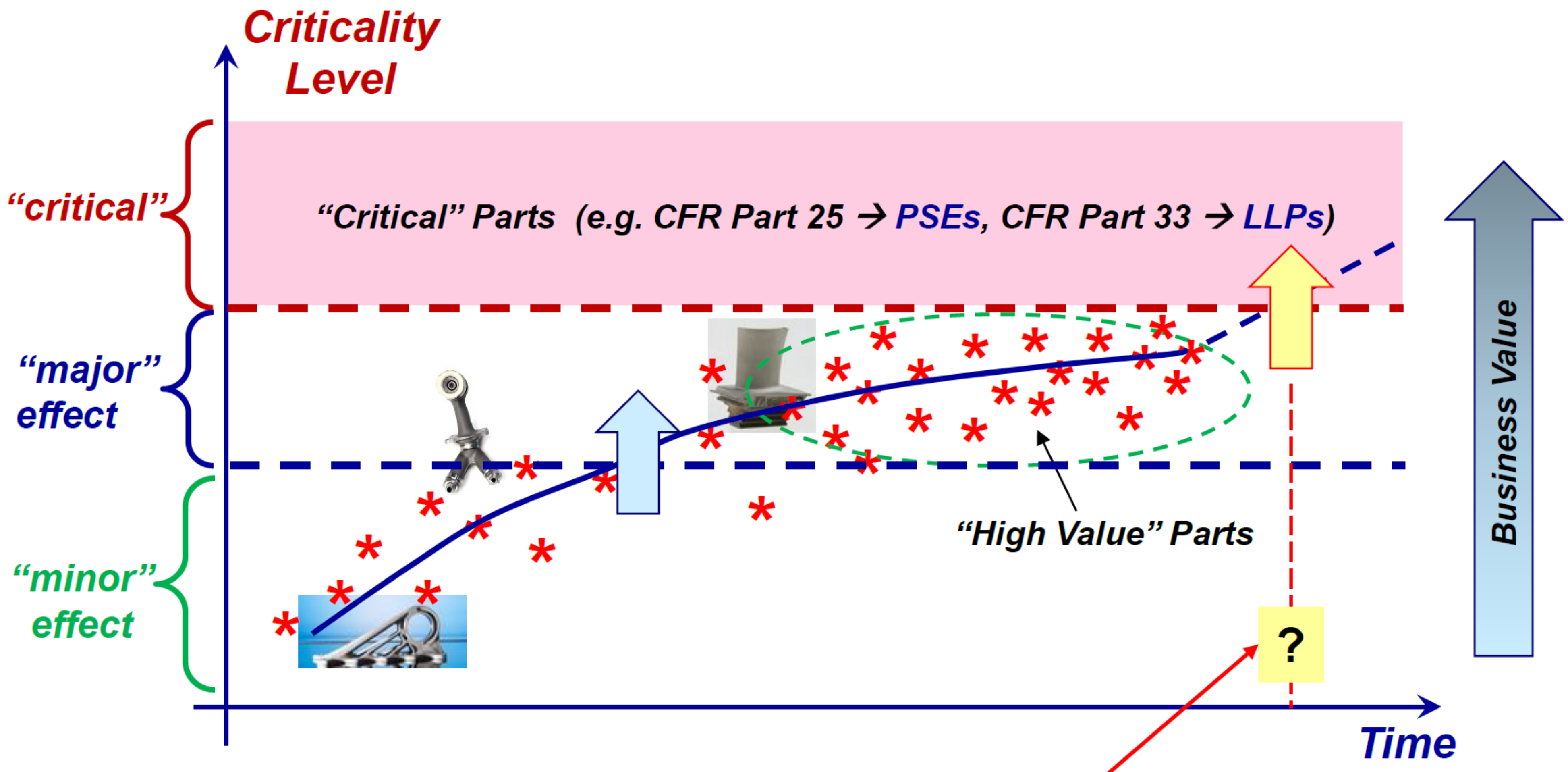
More work needed in this area:

- 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



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

Courtesy of Michael Gorelick, FAA

Acknowledgements

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Joshua Fody, NASA Langley Research Center

Eddie Schwalbach, Air Force Research Laboratory

Tao Sun, Argonne National Laboratory

Kevin Wheeler, NASA Ames Research Center

Surya Kalidindi, Georgia Tech University

Thank you for your attention.