GO BEYOND

Use of Modeling and Data to Design and Control AM Processes

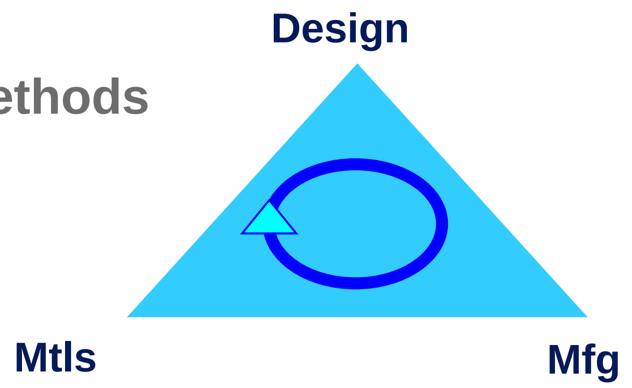
David Furrer
Pratt & Whitney

NIST Workshop
Empowering Small and Medium Size Enterprises Through Effective Additive Manufacturing Data Management
June 6 – 8, 2023
Gaithersburg, MD

Materials & Product Engineering

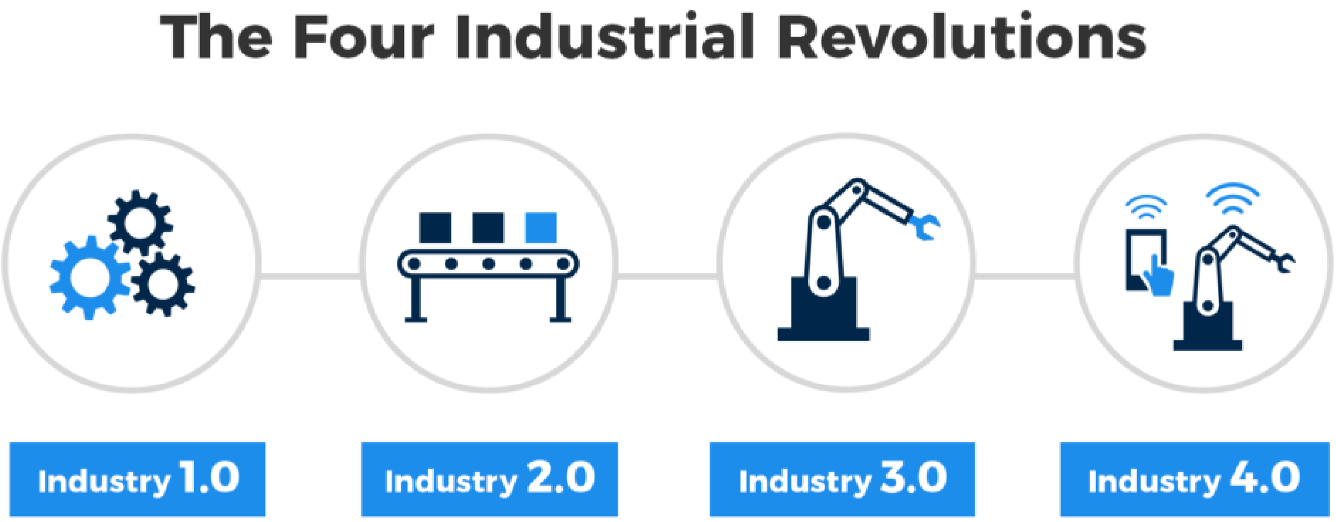
- **Mechanical Properties → fn (chemistry and structure)**
- **Structure → fn (chemistry and processing)**
- **Processing → fn (component geometry)**

Materials, Manufacturing Methods and Component Design are Strongly Coupled



Industry 4.0

Industry 4.0 is a true technology revolution and not a buzz-word term



Framework for digital engineering, manufacturing, big-data, modeling and simulation, communication and component optimization ….

Including qualification and certification

Model-Based Engineering

- **Current industry-wide effort focused on solid models with further incorporation of component-specific requirements**
- **Model-based material and process modeling emerging as a means to link materials and process information with component geometric design optimization**

D. U. Furrer, D. M. Dimiduk, J. D. Cotton, C. H. Ward, "Making the Case for a Model-Based Definition of Engineering Materials", *Integrated Materials and Manufacturing Innovation* (2017) 6:249–263, DOI 10.1007/s40192-017-0102-7 (http://link.springer.com/article/10.1007/s40192-017-0102-7).

Certification and Qualification

- **What does "Good" look like?**
- **What is the pragmatic "Engineering Design Intent"?**

- **Can we define an AM part sufficiently to establish an efficient, robust Testing Plan?**

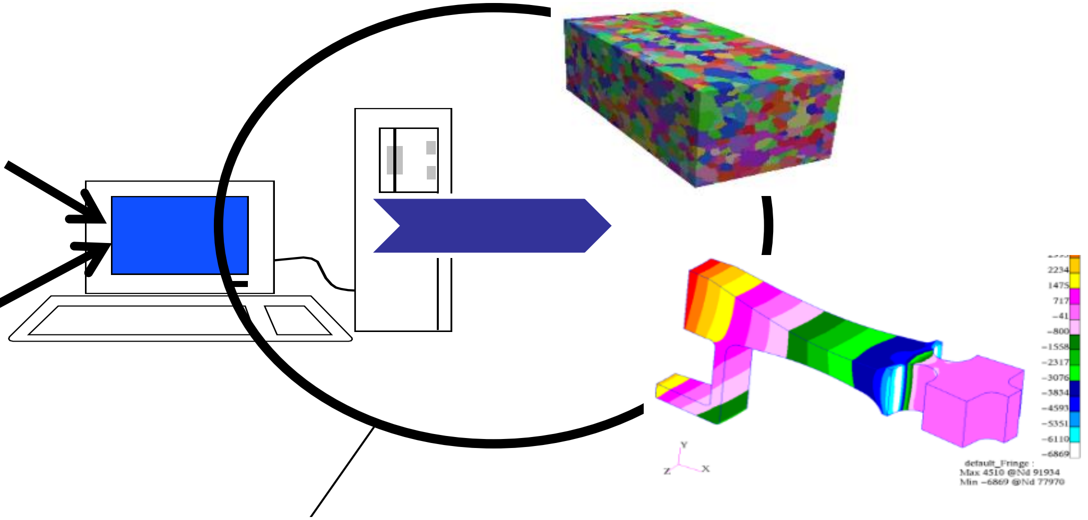
Integrated Materials & Process Modeling

Use of models to link design, producibility & component performance

Component Design

Model-based Mt'l definition

Model-based Mfg process definition

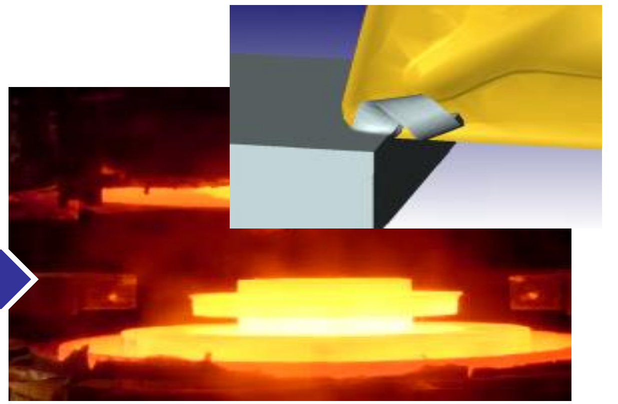


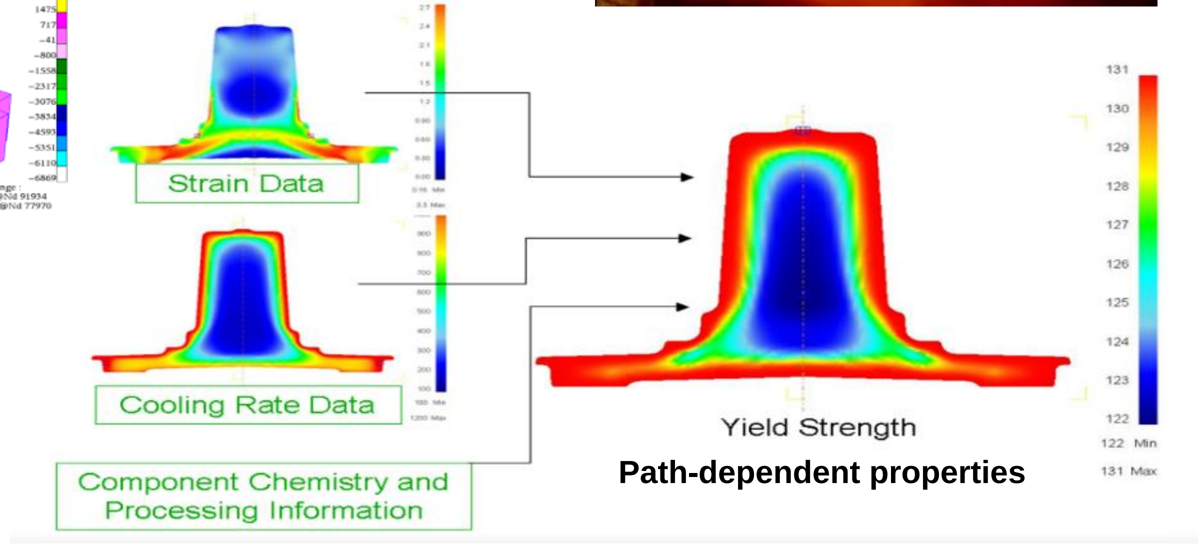
Parametric model includes local structure and properties

Utilization of Modeling to Predict Component Capabilities and Proactively Mitigate Producibility Risks

Component Manufacture

Model-based component definition



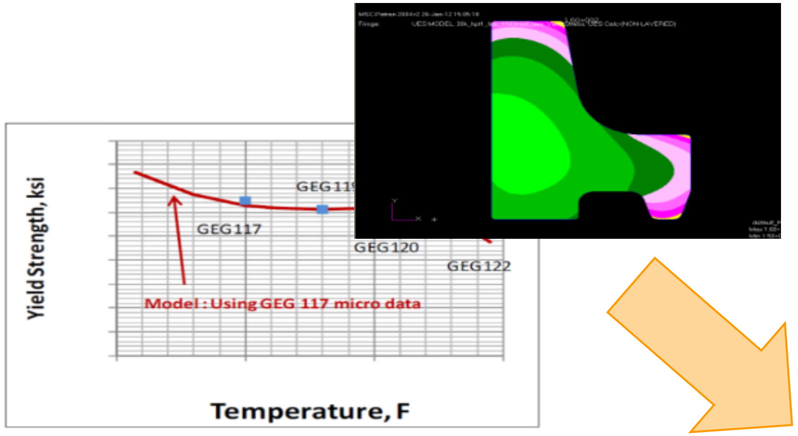


Path-dependent properties

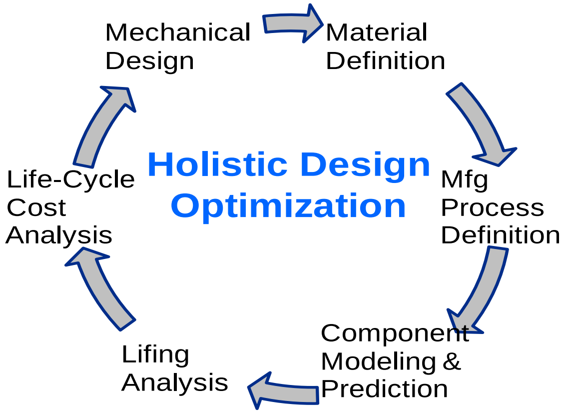
Probabilistic Property & Performance Predictions

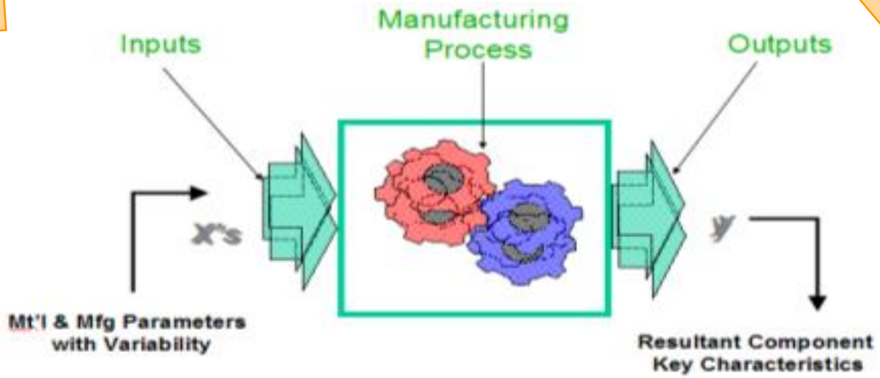
Material and manufacturing process modeling enables design for variation

Materials Modeling



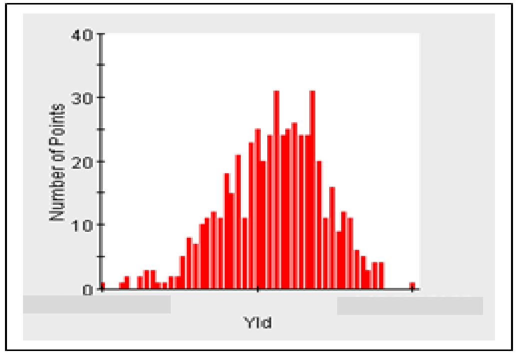
Development and Application of Physics-Based Models





Identification and Assessment of Material and Process Variability

Design for Variation



Predicted Material and Component Properties

D. Furrer and J. Schirra, "The Development of the ICME Supply-Chain: Route to ICME Implementation and Sustainment", *JOM*, volume 63, pages 42–48 (2011).

Model-Informed Process Controls and Product Testing

Engineered process controls and test location selection provides for efficient processes

- **Modeling methods are guiding process control requirements**
- **Prediction of component location-specific attributes provide insight relative to test locations that are most sensitive to processing**
  - **Smart testing to minimize tests and maximize value**

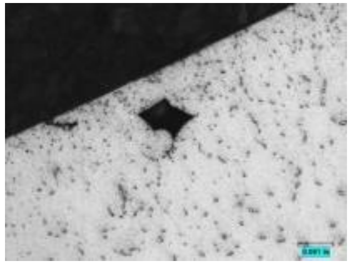
Test to confirm component capabilities versus model prediction

Continuous learning about material and process with Bayesian updating approach

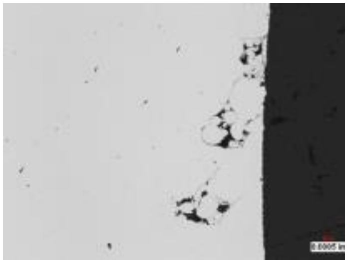
AM Certification and Qualification

The Devil is in the Details

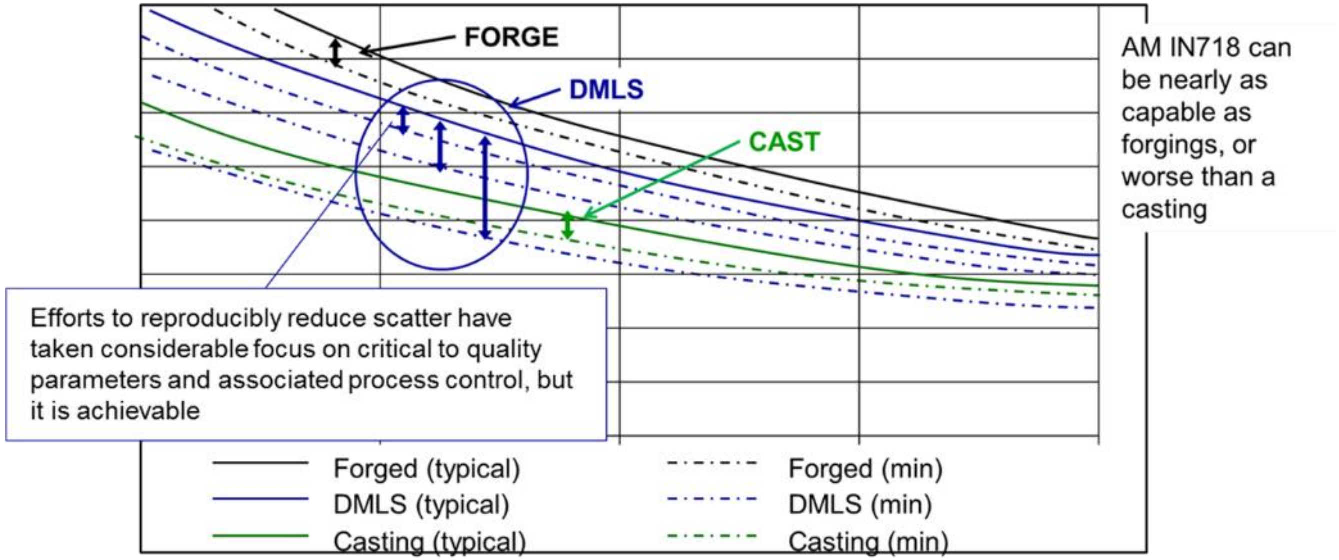
- **Process defects**
- **Microstructure control**
- **Chemistry control**
- **Resultant property scatter**
- **Part-to-part/Batch-to-batch/ Machine-to-machine variability**
- **Powder handling and re-use**
- **Geometry control**
- **Surface finish**



Lack of fusion



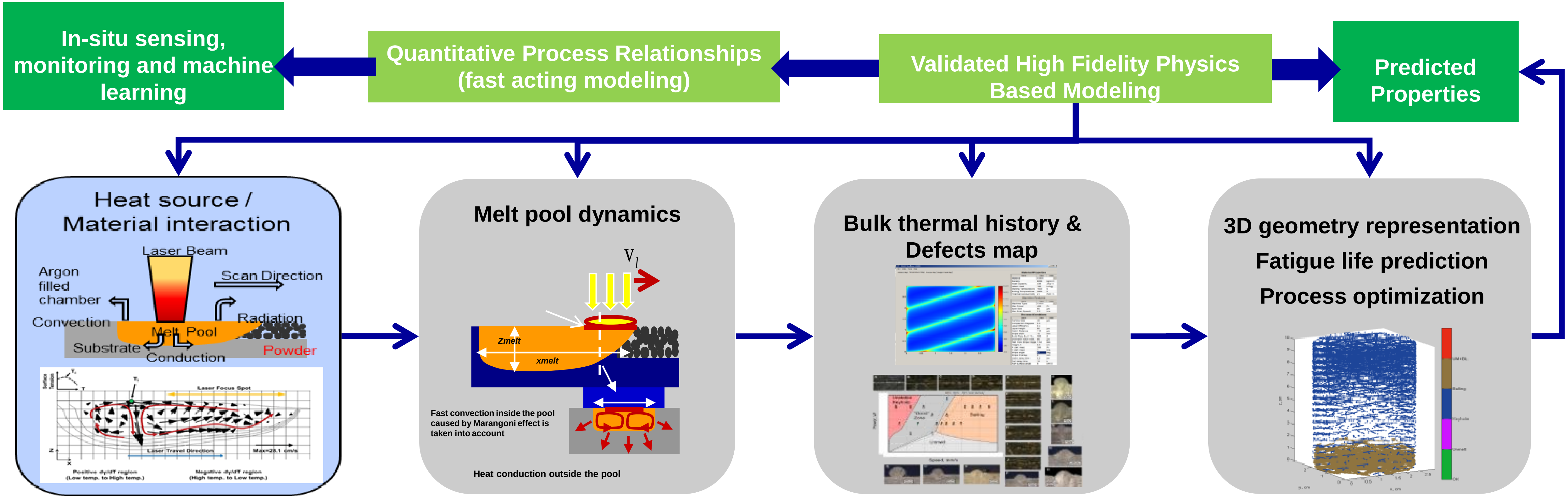
Partially sintered powder



No Technical Data Per the EAR or ITAR

Laser Powder Bed Fusion Modeling Framework

Integrated physics-based simulation of AM processes to predict part level distortion, defects, microstructure and establish correlation to performance (fatigue)

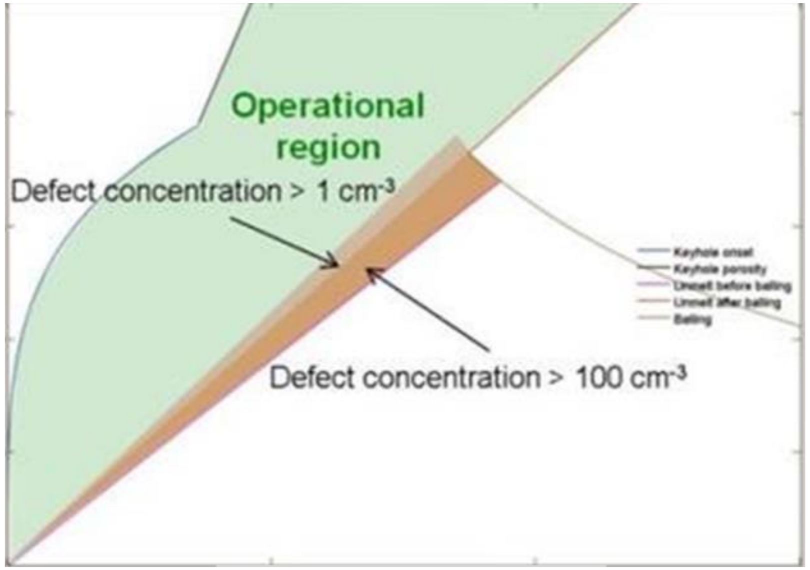


Model Integration with AM Process Design

Materials properties are manufacturing process path dependent

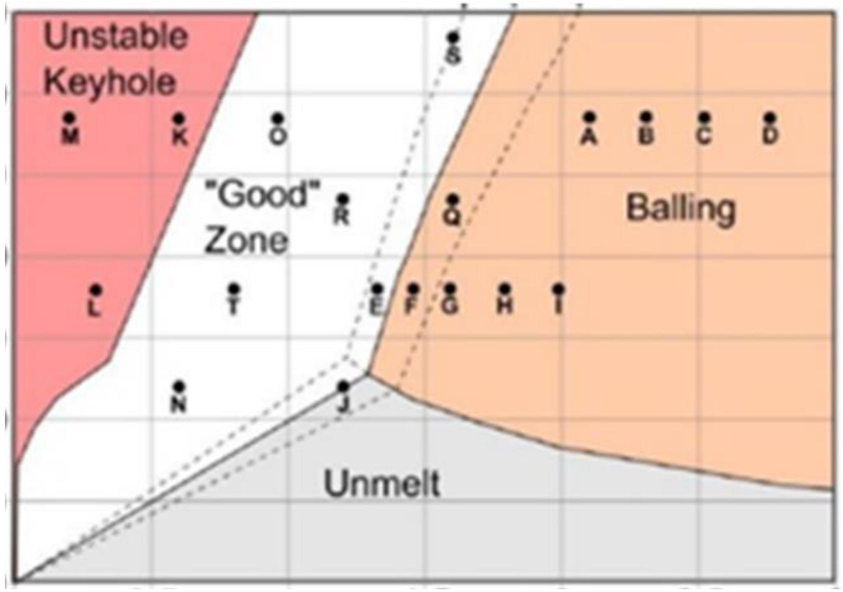
Process definition development

- Physics-based reasoning
- Materials and process design space redefined
- Defining process window based on build parameters, part geometry and process monitoring



Product data

- Specimen testing
- Component testing
- Process equivalent test specimens (PETS)

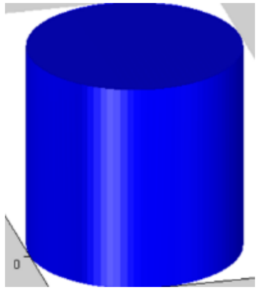


Physics-based fast acting tool for defects prediction

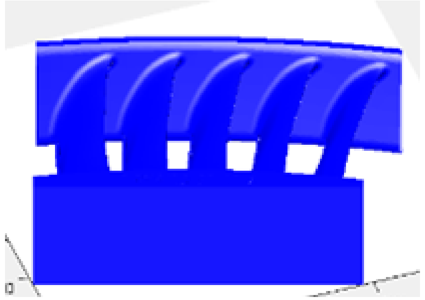
Analytical model-based approach are computationally efficient

Model capabilities and features

- Calculation of process map. Visualization of defect free/rich areas in P(laser power) – V (scanning rate) cross-section of multi-parameter space
- Calculation of 2D and 3D defect maps from first-principles with minimal and universal calibration
- Calculation of 3D defect map for simple geometry takes ~ 7 s, for complicated geometry takes ~ 100 seconds on 4-core desktop



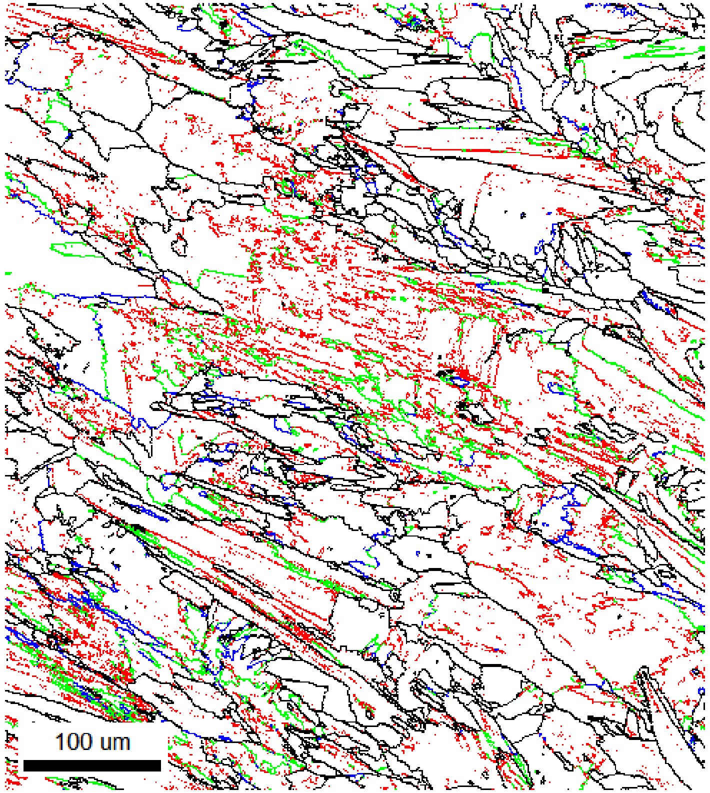
6 s



75 s

AM Material Microstructure Analysis and Control

AM IN718 component microstructure



Boundaries: Rotation Angle

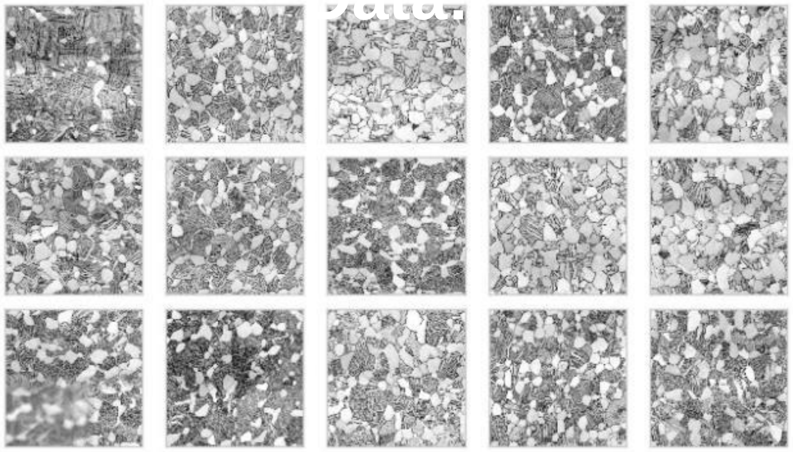
	Min	Max	Fraction	Number	Length
Red	2°	5°	0.338	41325	2.39 cm
Green	5°	10°	0.141	17204	9.93 mm
Blue	10°	15°	0.060	7300	4.21 mm
Black	15°	65°	0.462	56475	3.26 cm

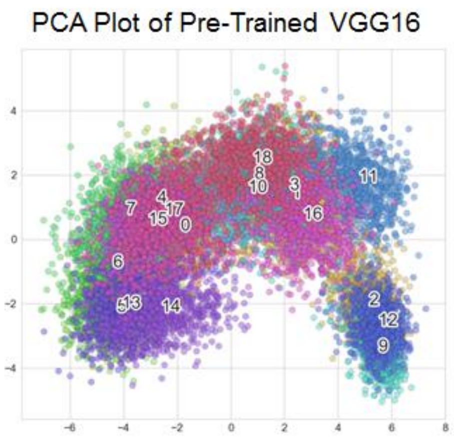
Machine Learning Providing New Understanding

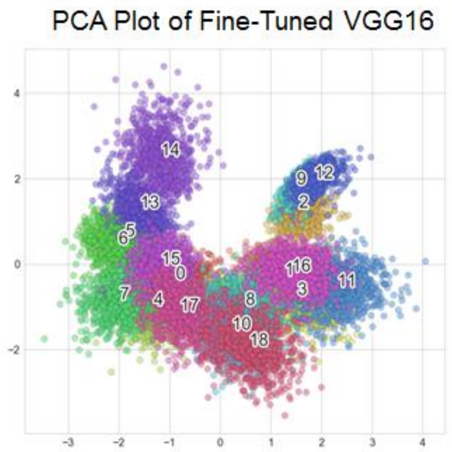
Microstructure data can be used to predict properties and classify materials

CLASSIFICATION

REGRESSION







Microstructure dataset can be collected with variation in manufacturing pedigree

Machine Learning models can be used to provide principal component analysis (PCA)

Predictive models can also be developed to guide testing and process control understanding

Immediate applications for:

- Visual similarity assessment / lookup
- Outlier detection
- Quality control
- Process development

Models are fast -- analyze 100's of images / second

ML Tools and Methods can be applied directly to manufacturing data as well as component properties.

Automated Data Capture and Analytics

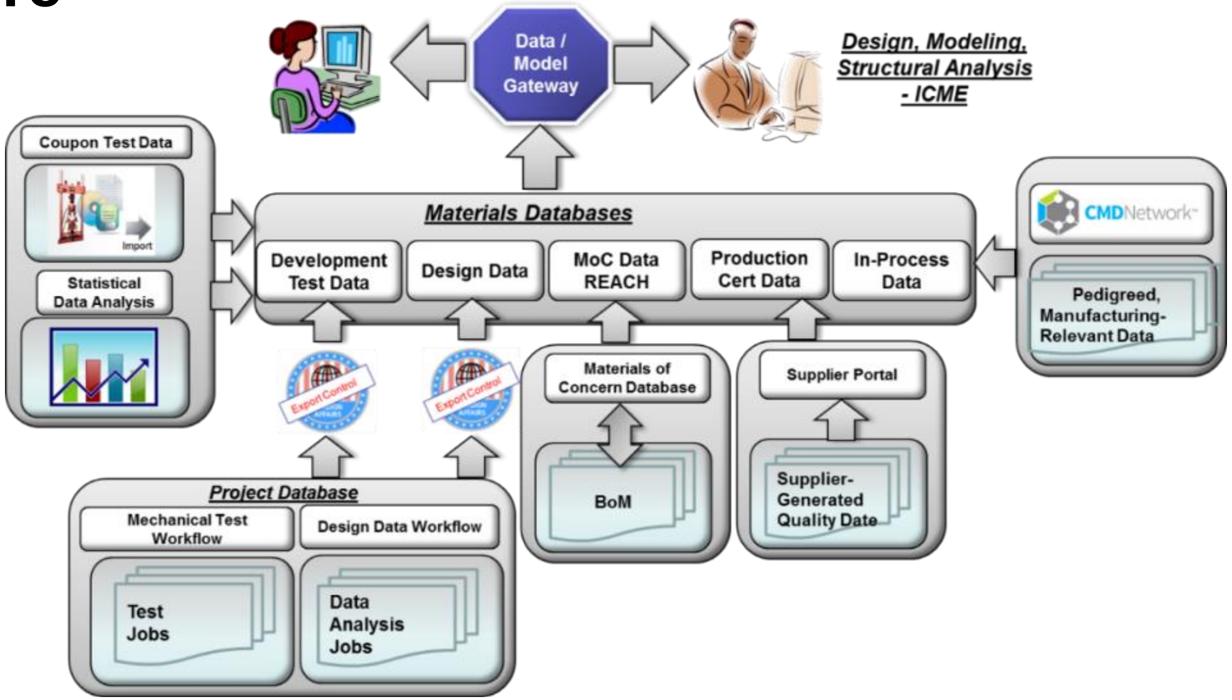
Industrial processes generate large amounts to data that produce digital thread elements

- **Industry 3.0 provided manufacturing automation and computerization**
- **Industry 4.0 provides simulation, automated capture of sensor data which enables real-time automated process monitoring and controls**
  - **Linkage of process data capture, data analysis and modeling**

Digital Data Management

Industry 4.0 requires a robust digital data infrastructure

- **Material and process pedigree capture**
- **Performance correlation to processing**
- **Model-based data capture and visualization activities**
- **Models used as Repository of Corporate Knowledge**



Zero Cost for Data Capture • Zero Data Loss • Data Availability for Analytics

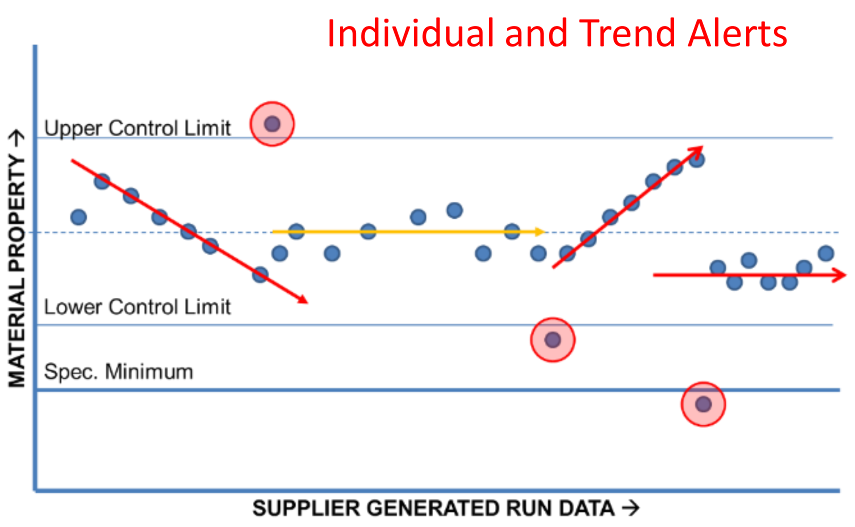
This page does not contain any export regulated technical data.

Automated Process Control – Monitoring and Trending

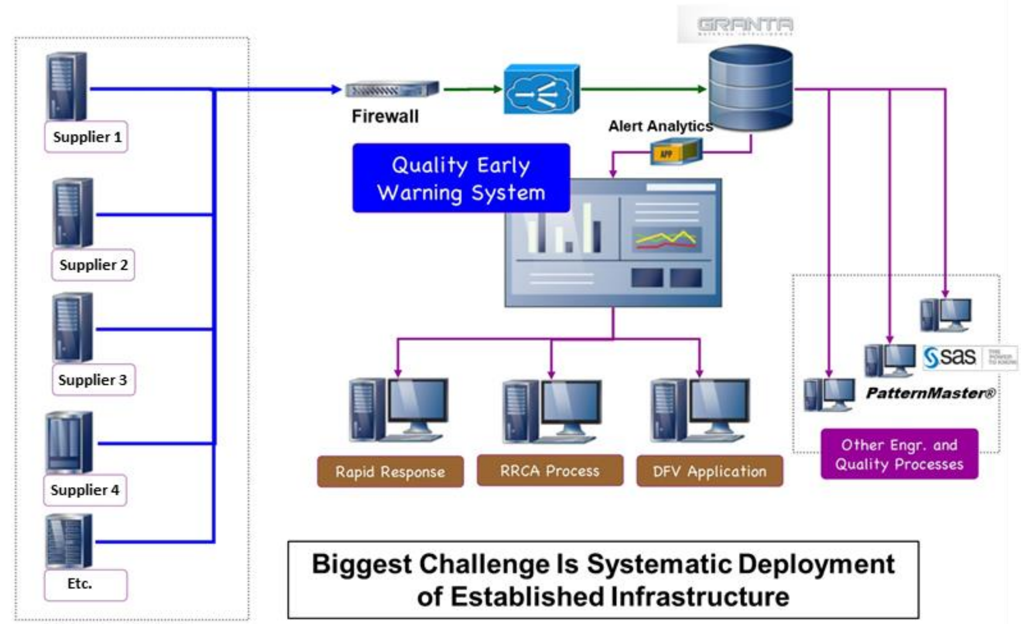
Industry 4.0 requires a robust digital data infrastructure

- **Integrated sensors and component testing provides means for adaptive process controls**
- **Data capture and analysis designed to trigger proactive intervention of issues**

Automated capture and analysis of supplier generated data



Quality Control and Monitoring



Rotors, Airfoils
Structural Castings

Data Capture and Creation of Knowledge

Opportunities for the Community

- **Standards for Digital Certificate of Conformance Data**
  - ASM Materials Data Management and Analytics Committee
  - Workshop on Industry Standard for Digital Certificates of Conformance
  - Potential Hierarchical Requirements Structure
    - Overarching Framework defining Digital Data Requirements and Linkage to Subordinate Specs (NEW)
    - Material, Process and Testing-Specific Specs Define Data Types and Associated Meta-Data (Enhancements of Current Specs)
- **Model-Based Material and Process Definitions**
  - Development, Validation and Deployment of Physics-Based Models
    - Microstructure, Properties, Defects, Residual Stresses, Distortion
  - NASA STRI being Launched for Model-Guided Rapid Qualification of AM Components
    - Tony Rollet (CMU) and Somnath Ghosh (JHU)

Conclusions and Take-Away

- Integration of modeling, sensors and data analytics are providing significant benefits in the era of Industry-4.0 and AM
- Models can guide process window development and control requirements
- Smart testing can provide faster and more informed product validation and certification

- Data management through data analytics and modeling tools provides for a more complete means of knowledge capture