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Model-Assisted Validation and Certification of AM Components

David Furrer
Pratt & Whitney

Sergei Burlatsky
Raytheon Technologies Research Center

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Outline

- Materials definitions in the Information Age (Industry 4.0)
- Product and process design approaches
- Approaches for component material requirements
- Testing and qualification planning

Traditional Engineering Materials Development and Definitions

- **Design Curves – Empirical; Data Driven**
- **Specifications**
- **Prints Notes**
- **Fixed Process Requirements**

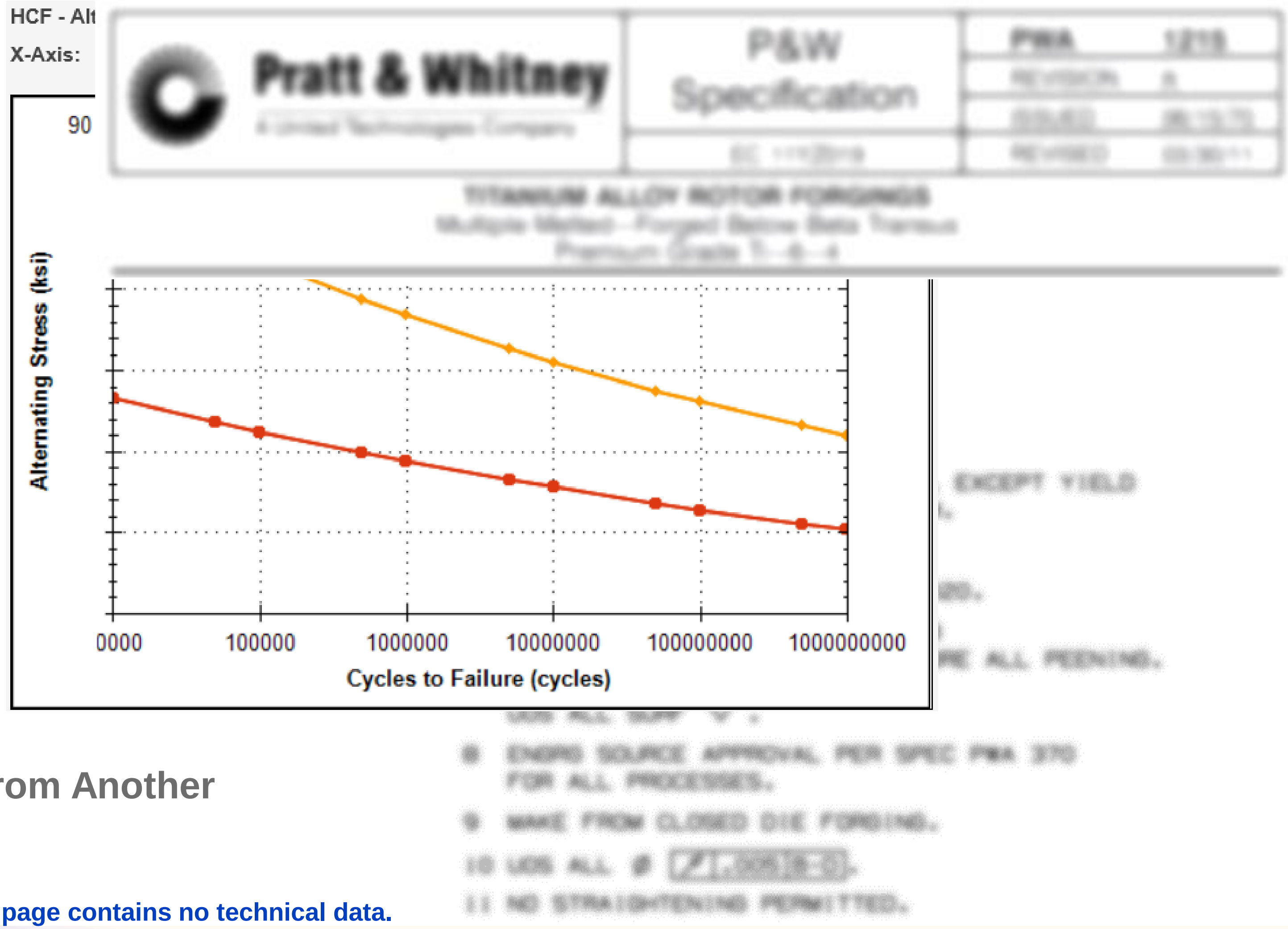
Material Equivalency - Material Pedigree - Application Space

Materials Definitions

Compilation of tools to define materials and establish equivalency

Traditionally:

- **Specification Documents**
- **Design Curves**
- **Drawing Notes**
- **Quality Standards**
- **Component Testing and Qualification Approaches**



Defining of Material Equivalency and Methods to Differentiate Material of One Controlled Pedigree from Another

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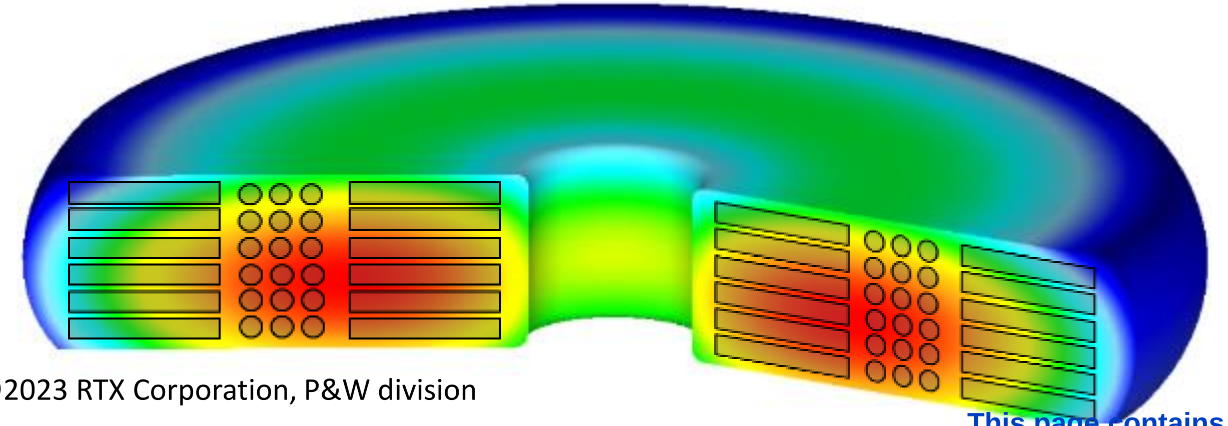
Specifications Defined Based on Statistical Minima*

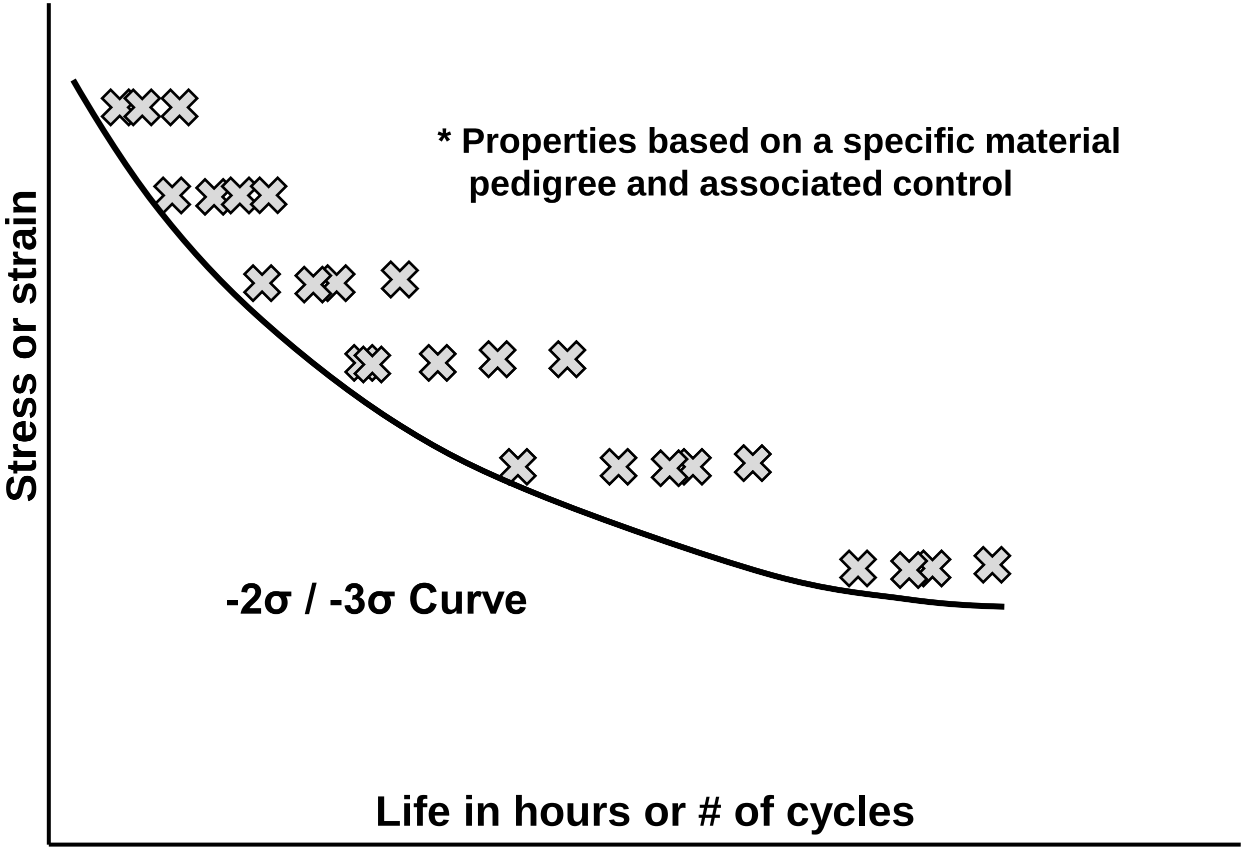
Material properties depend on processing path (manufacture and application)

Multiple components produced on manufacturing equipment

Test samples extracted from components using randomized locations, orientation, test conditions, etc.

Manufacturing path for components (pancakes, etc.) define range of pedigree space





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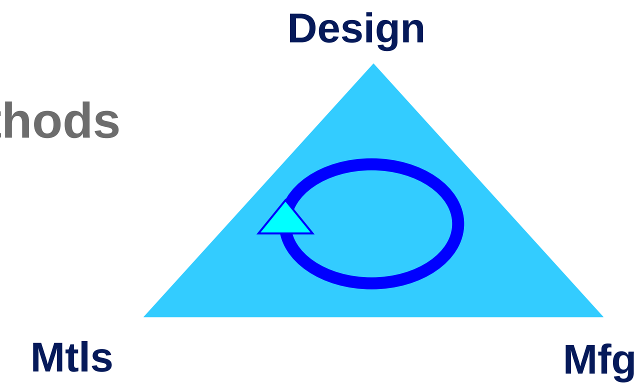
Materials & Product Engineering

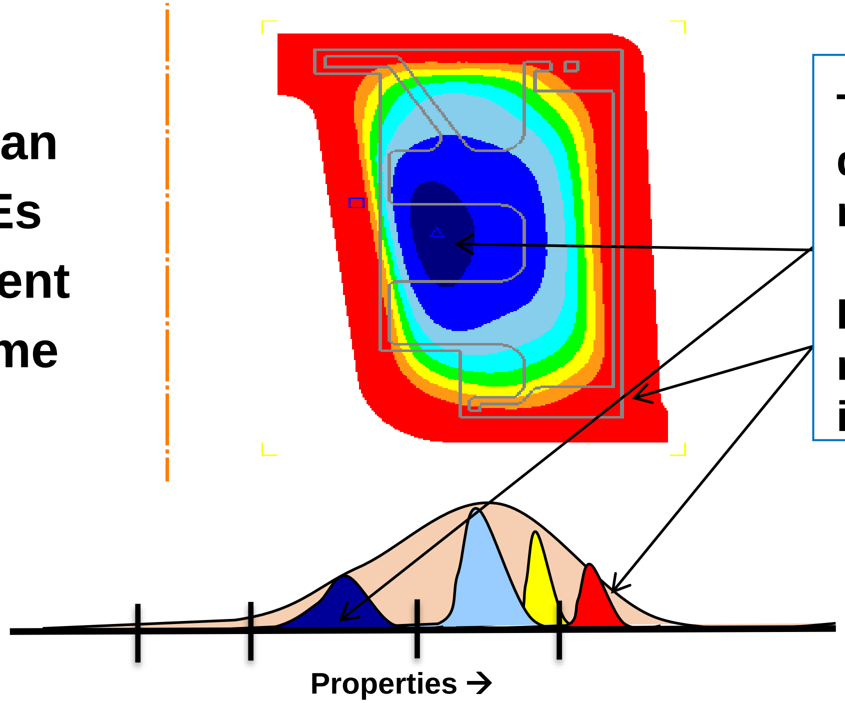
- Mechanical Properties → fn (chemistry and structure)
- Structure → fn (chemistry and processing)
- Processing → fn (component geometry)

Materials, Manufacturing Methods and Component Design are Strongly Coupled



Materials Definitions

Volumetric regions can be defined by SERVEs (Statistically Equivalent Representative Volume Elements)



True material capability and property distributions are controllable and reproducible; <u>not</u> "random variability".

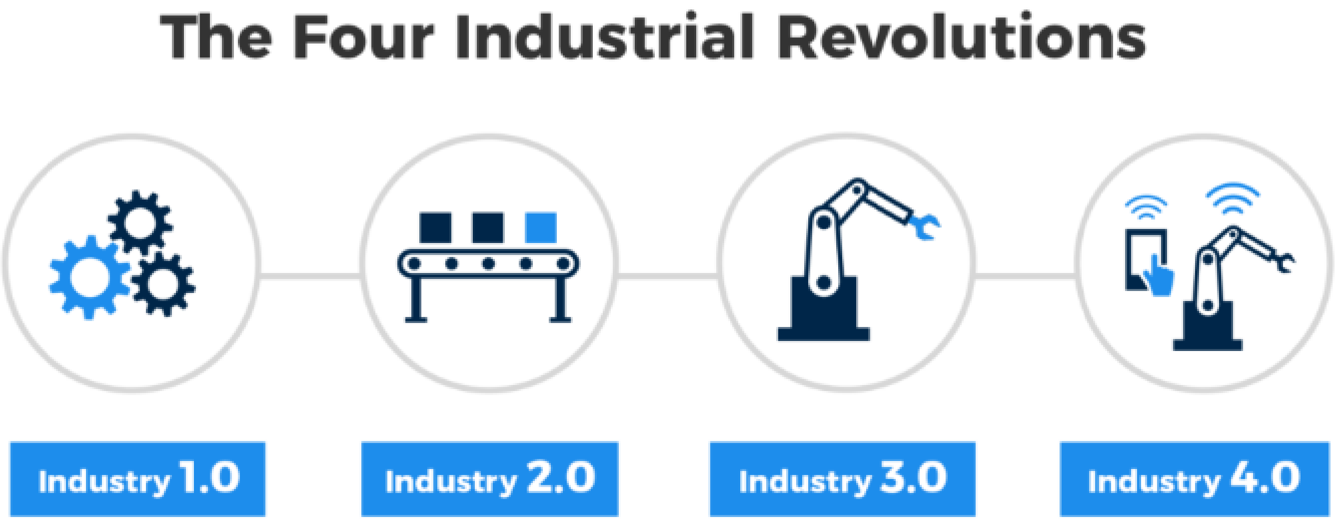
Properties are a fn (chemistry, microstructure, stain, cooling rate, etc.); i.e. pedigree.

Materials properties are path dependent and are often "location-specific". Engineering specifications often treat entire material volume as single, homogeneous property capabilities.

Modeling and simulation can help enhance material, process and component definitions

Industry 4.0

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



Framework for digital engineering, manufacturing, simulation, communication and optimization …. Including validation and certification

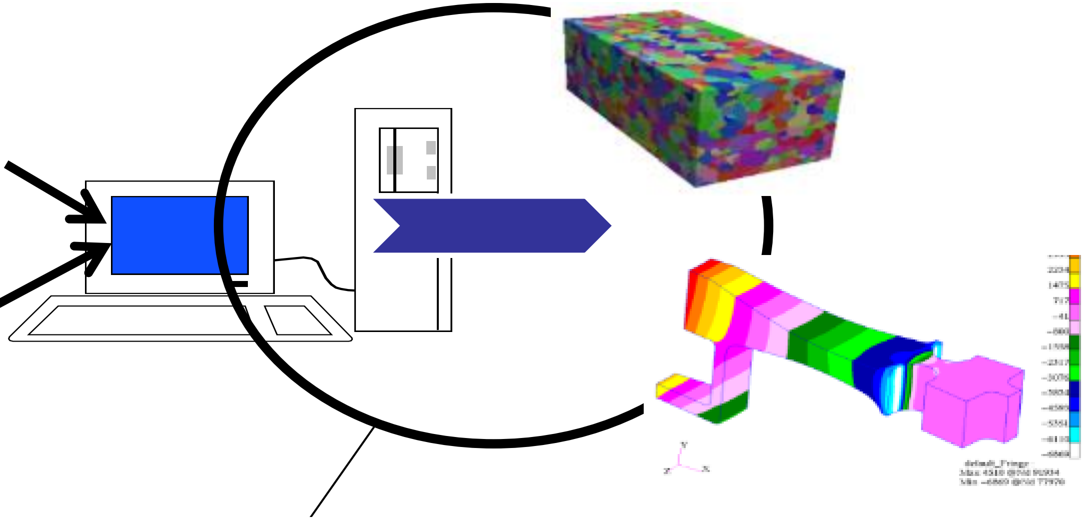
Integrated Materials & Process Modeling

Use of models to link design, producibility & component performance

Component Design

Model-based Mt'l definition

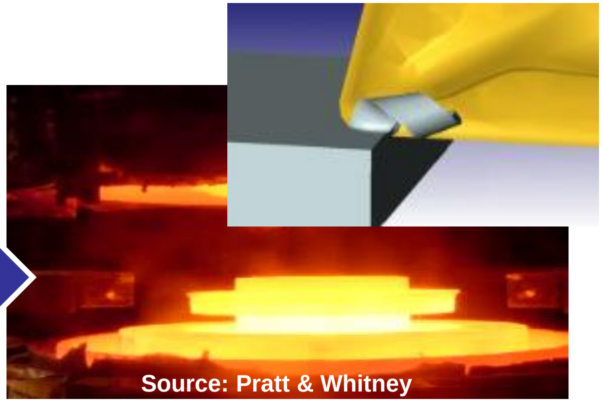
Model-based Mfg process definition

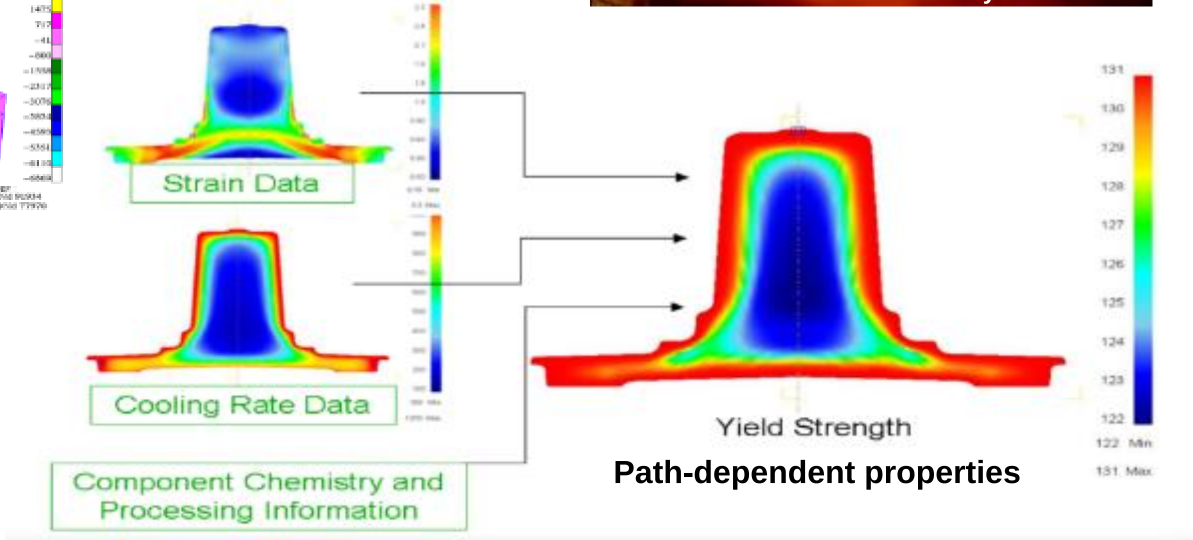


Parametric model includes local structure and properties

Component Manufacture

Model-based component definition





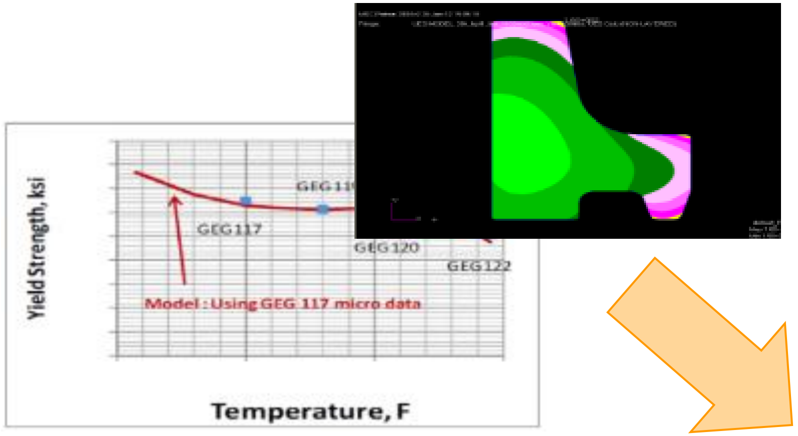
Path-dependent properties

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

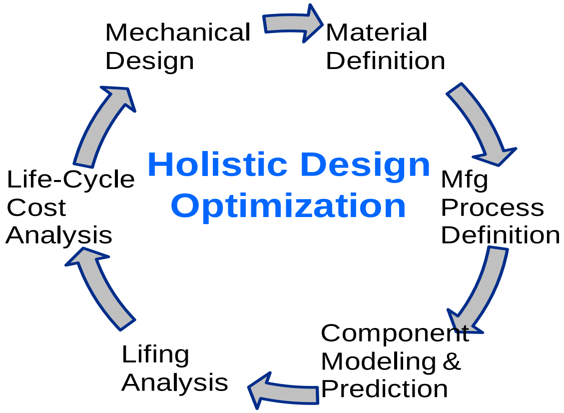
Probabilistic Property & Performance Predictions

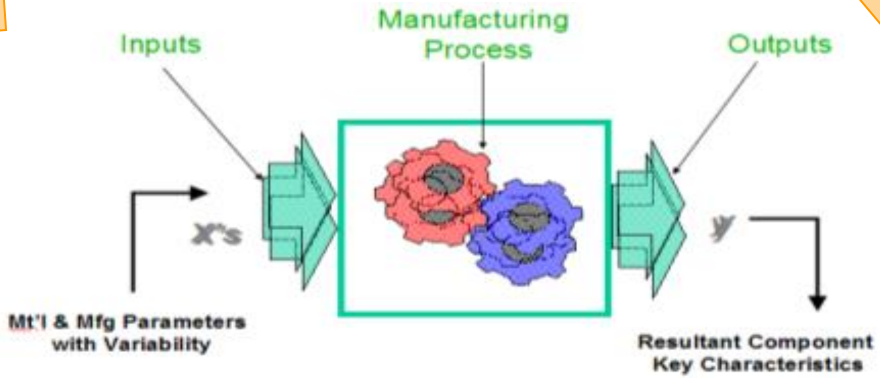
Material and manufacturing process modeling enables design for variation

Materials Modeling



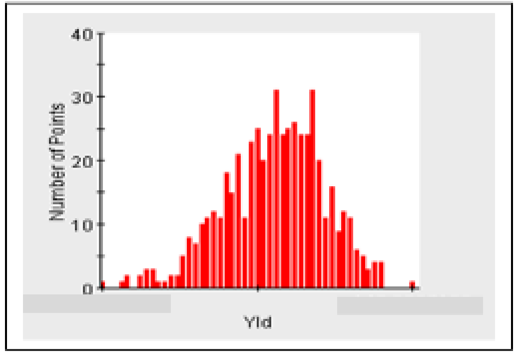
Development and Application of Physics-Based Models





Identification and Assessment of Material and Process Variability

Design for Variation



Predicted Material and Component Properties

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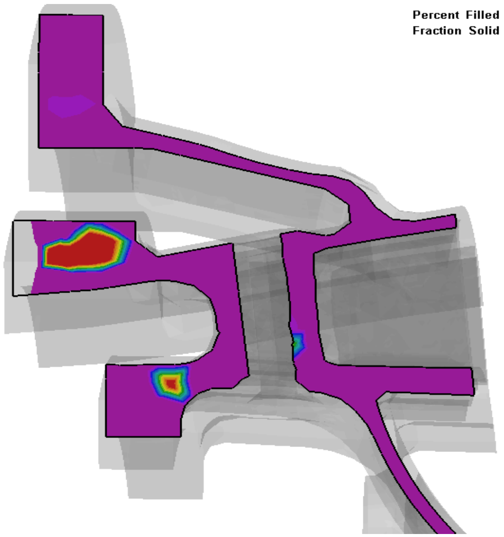
Model-Informed Process Controls and Product Testing

Engineered process controls and test location selection provides for efficient processes

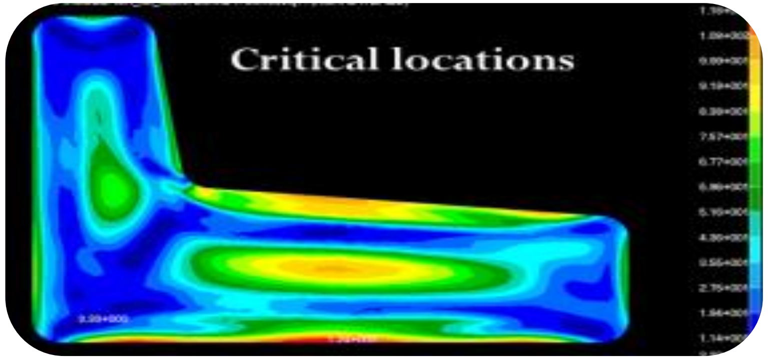
- **Modeling methods are guiding process control requirements**
- **Prediction of component location-specific attributes provide insight relative to test locations that are most sensitive to processing**
  - **Smart testing to minimize tests and maximize value**



Smart Testing

Engineered process controls and test location selection provides for efficient processes

Critical measurement locations from UQ perspective

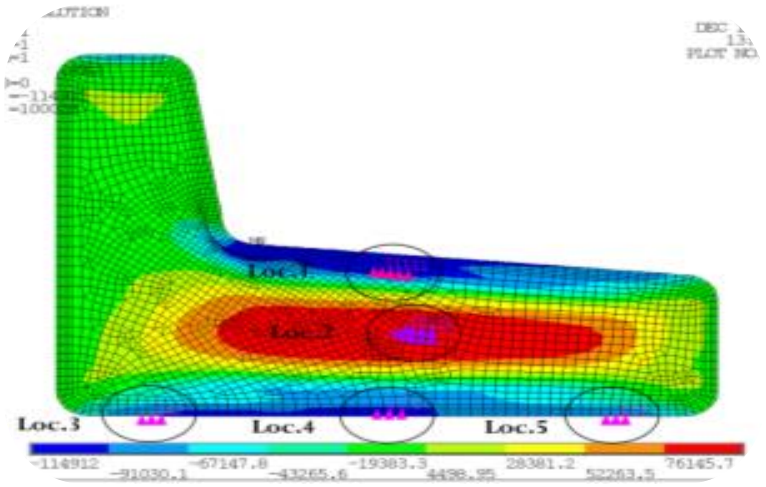


Measurement requirements :

- Locations (XYZ)
- Components (xx, yy, zz)
- Applied method and specifications
- Report data format

Test to confirm component capabilities versus model prediction

Continuous learning about material and process with Bayesian updating approach



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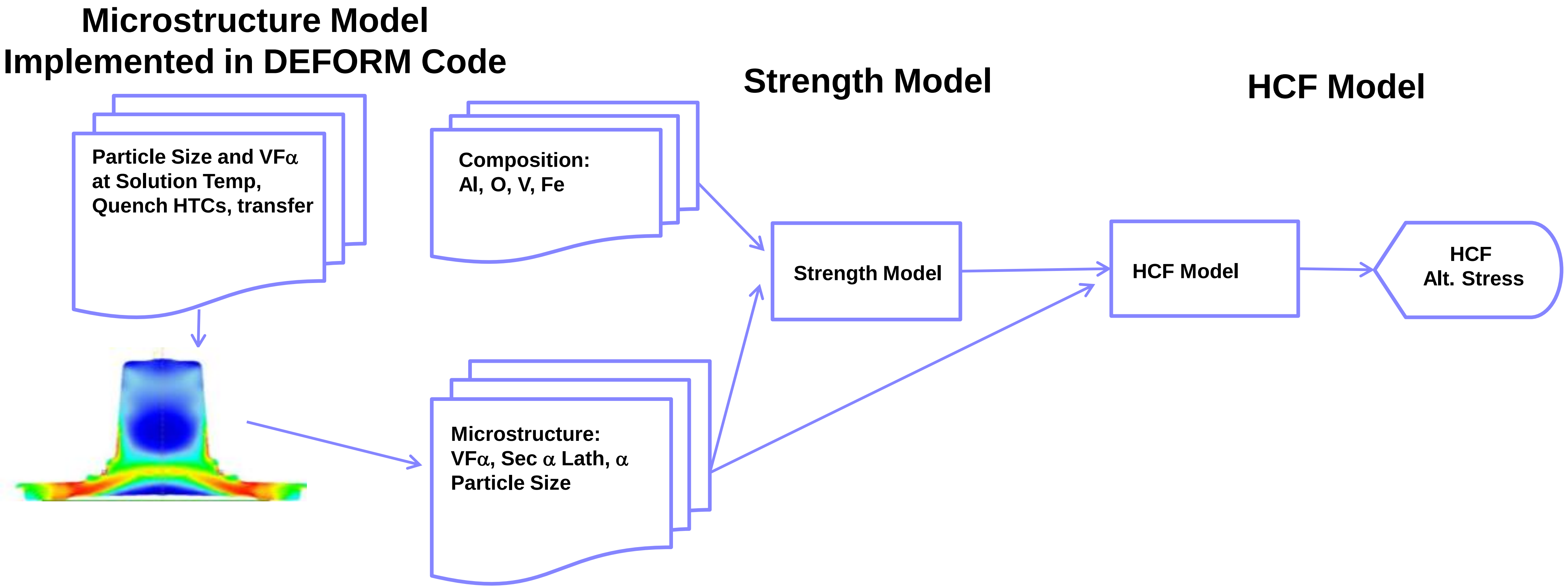
Model-Based Material Definition

MATERIAL – MICROSTRUCTURE – PROPERTY MODELS



Model-Based Material Definition Enabled Design and Lifing Optimization

Application of Additive Manufacturing

Mature

- Polymer tooling
- Demonstration hardware
- Visual Aids

Expand & Leverage

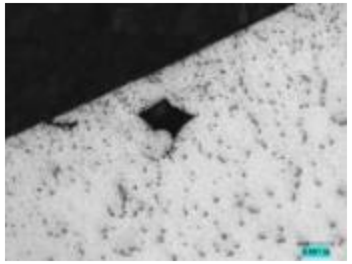
- Demonstration hardware
- Rig & test hardware
- Production hardware
- Tooling
- Certification

Develop

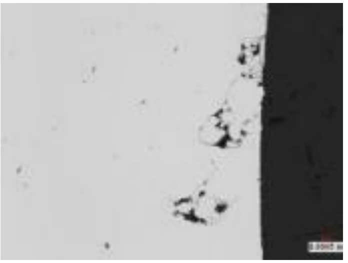
- Design system
- Material and process modeling data
- Process control capabilities

AM Certification and Qualification

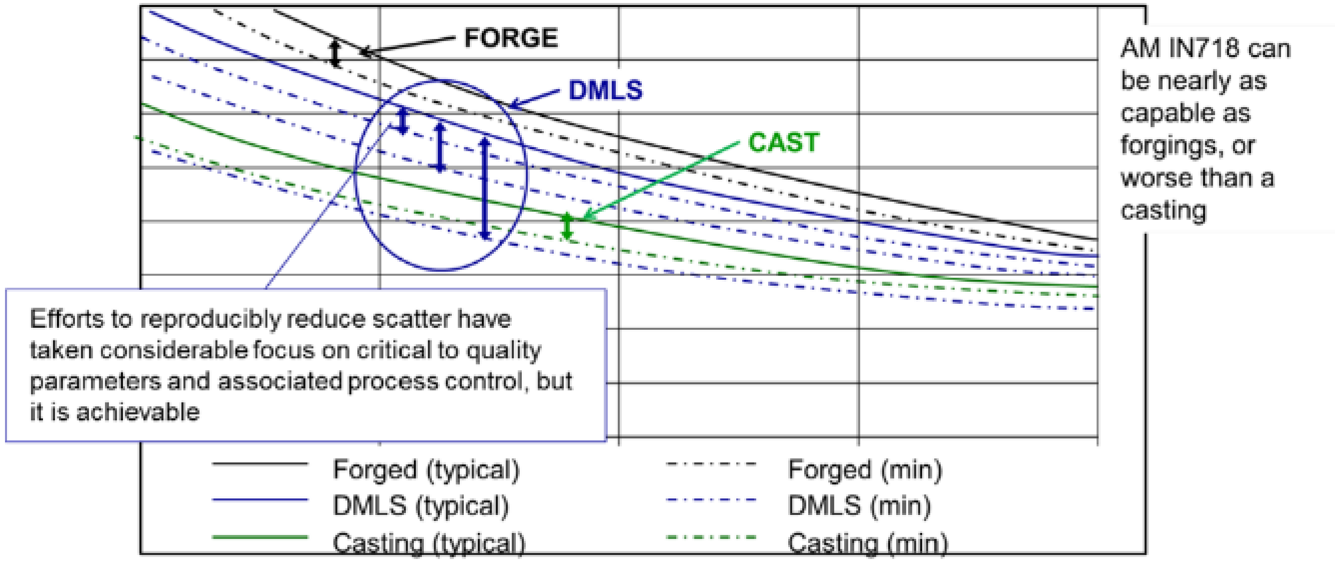
- Process defects
- Microstructure control
- Chemistry control
- Resultant property scatter
- Part-to-part/Batch-to-batch/ Machine-to-machine variability
- Powder handling and re-use
- Geometry control
- Surface finish



Lack of fusion



Partially sintered powder



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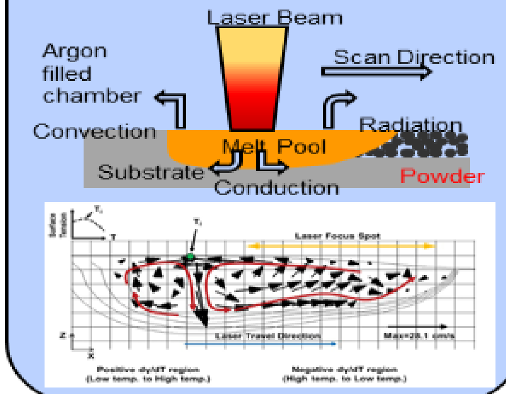
Laser Powder Bed Fusion Modeling Framework

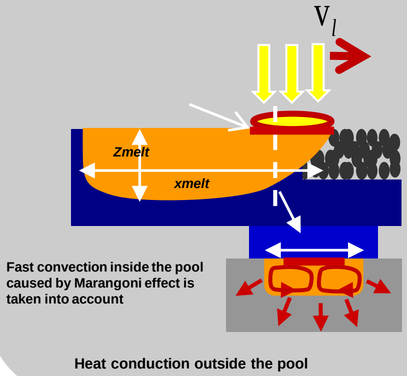
Integrated physics-based simulation of AM processes to predict part level distortion defects, microstructure and establish correlation to performance (fatigue)

In-situ sensing, monitoring and machine learning ← **Quantitative Process Relationships (fast acting modeling)** ← **Validated High Fidelity Physics Based Modeling** → **Predicted Properties**

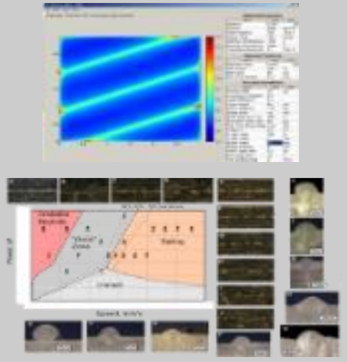
Heat source / Material interaction



Melt pool dynamics



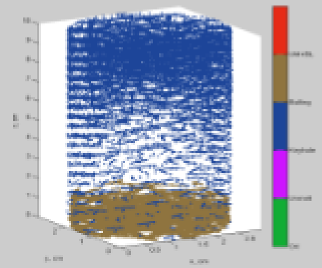
Bulk thermal history & Defects map



3D geometry representation

Fatigue life prediction

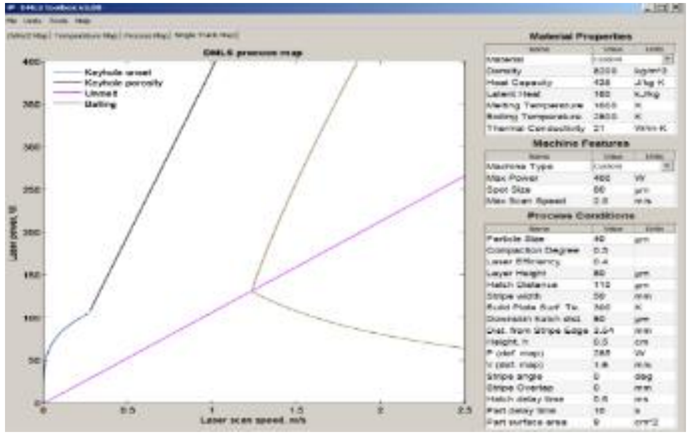
Process optimization



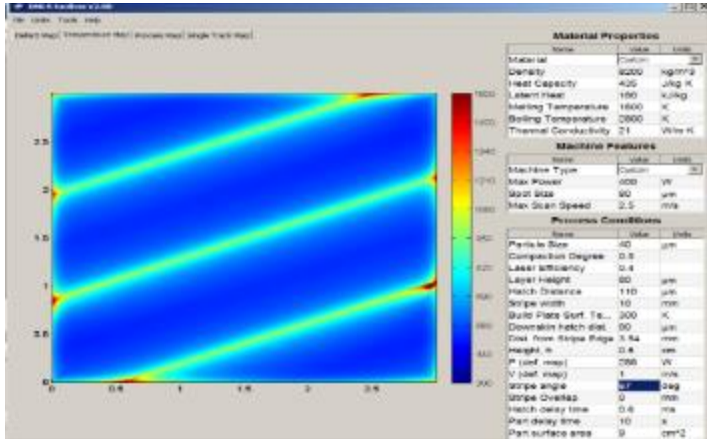
Model Input / Output

Model includes part geometry and location-specific processing path

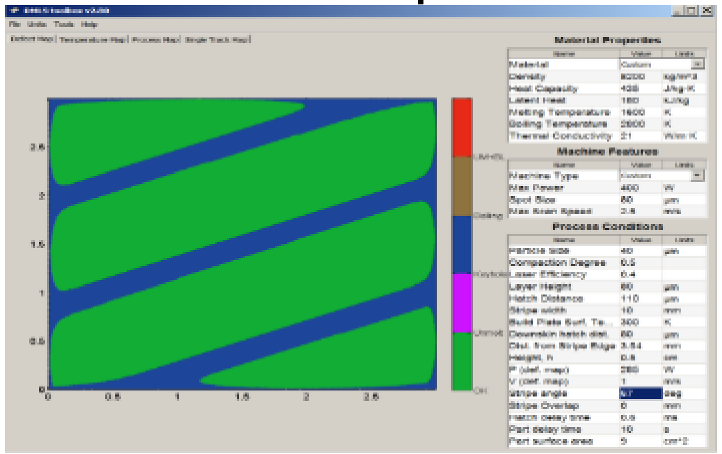
Single track map



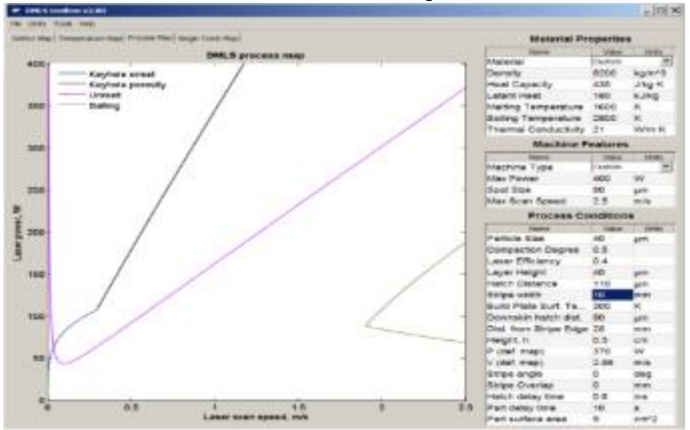
Temperature map



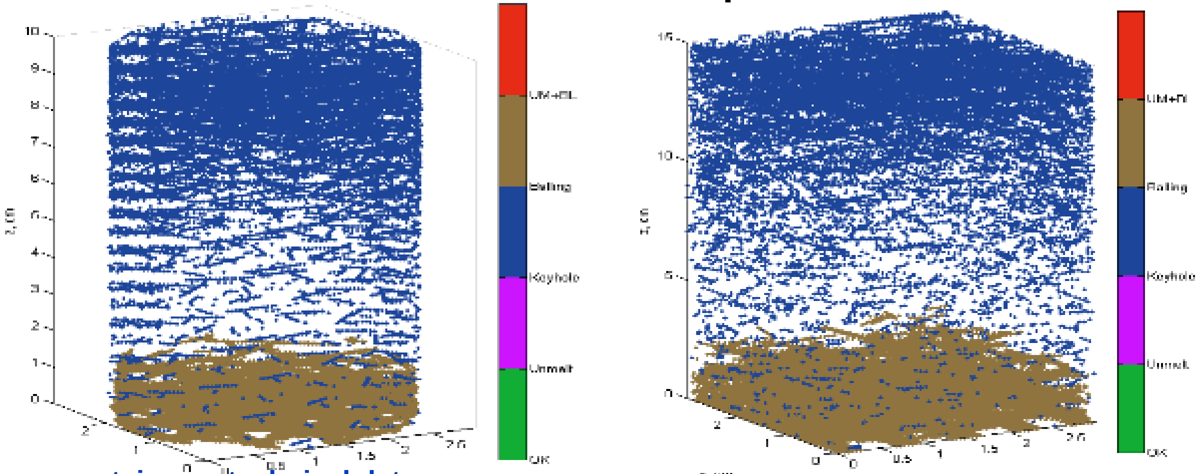
2D defect map



Process map



3D defect map



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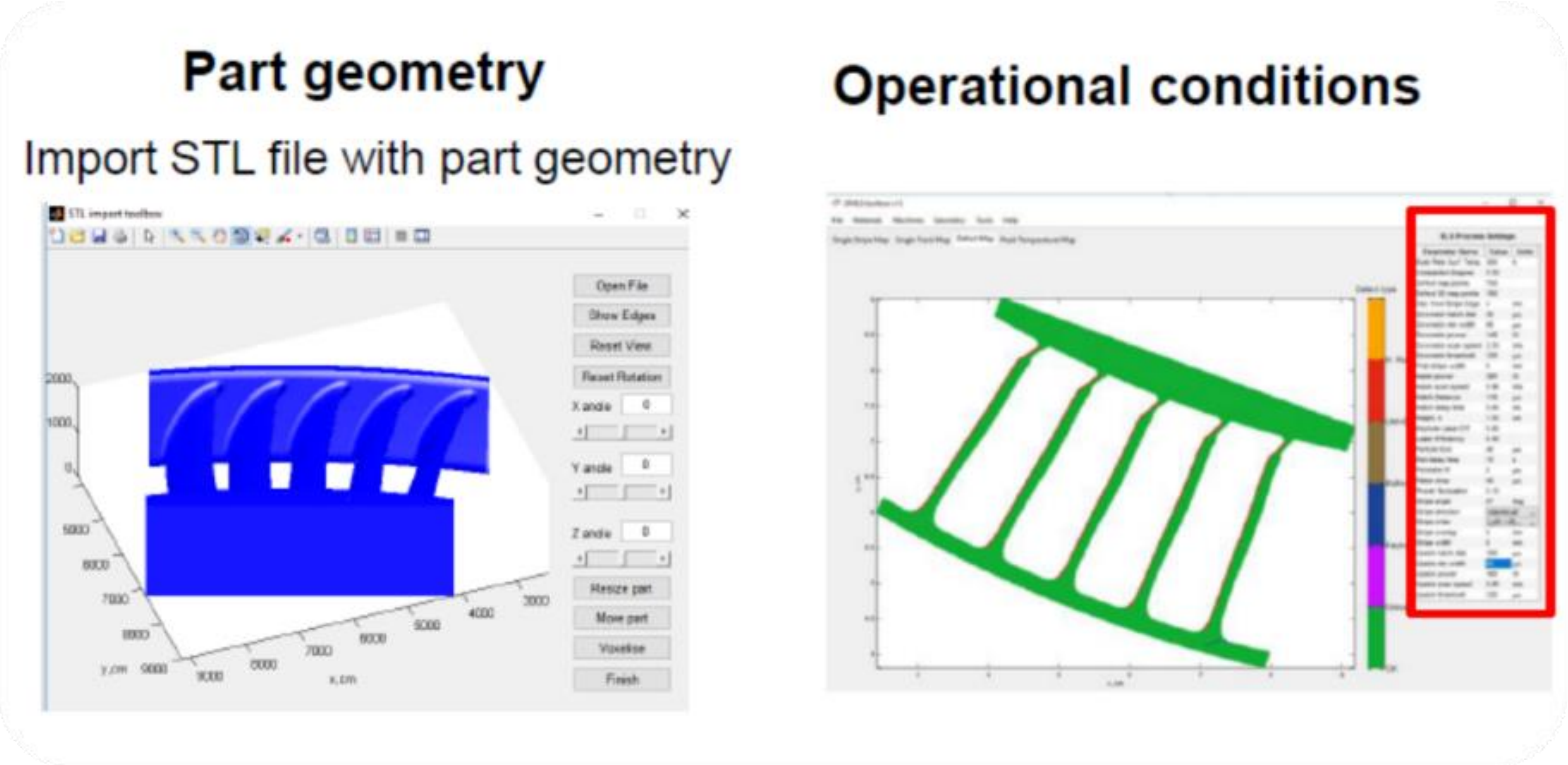
Modeling Applied to Component Configurations

Models provide optimal build paths (process operation conditions) for arbitrary geometries, build direction and bed loading density

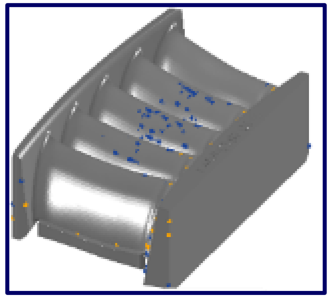


Additive Manufacturing Model Application

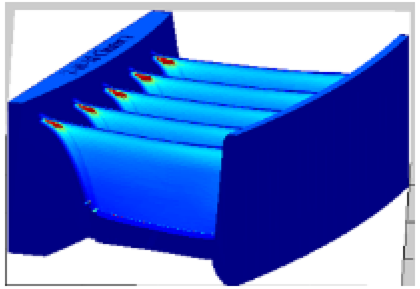
Component Model and Build Validation

STL part geometry

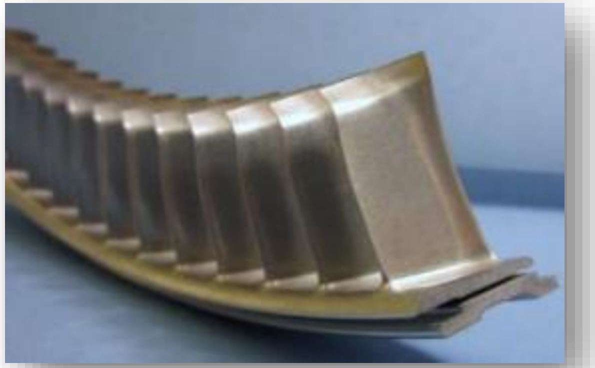
3D defect map



Surface roughness map



Final optimized built component



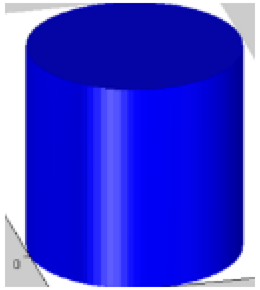
AM defect prediction model successfully applied to complex component build and final process design and control requirements

Physics-based fast acting tool for defects prediction

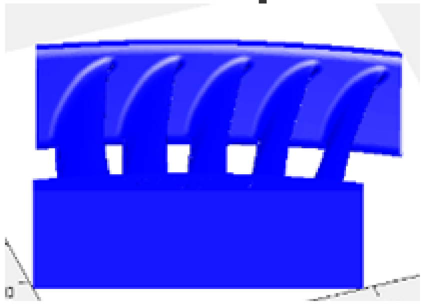
Analytical model-based approach does not require time-consuming simulations and extensive experimental calibration

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 (is not part, material and shape) calibration
- Calculation of 3D defect map for simple geometry takes ~ 7 s, for complicated geometry takes ~ 100 seconds on 4-core desktop

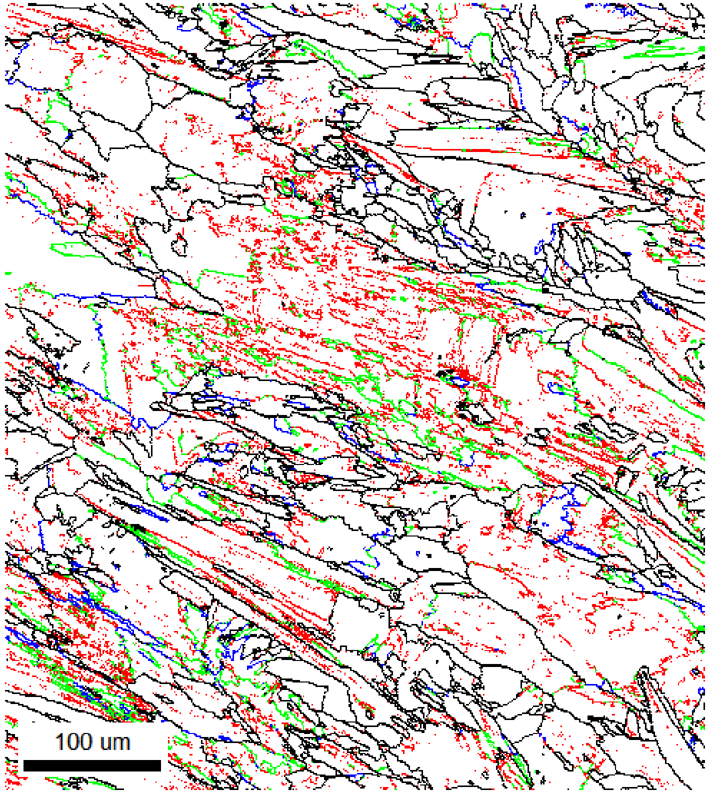


6 s



75 s

AM Material Microstructure Analysis and Control

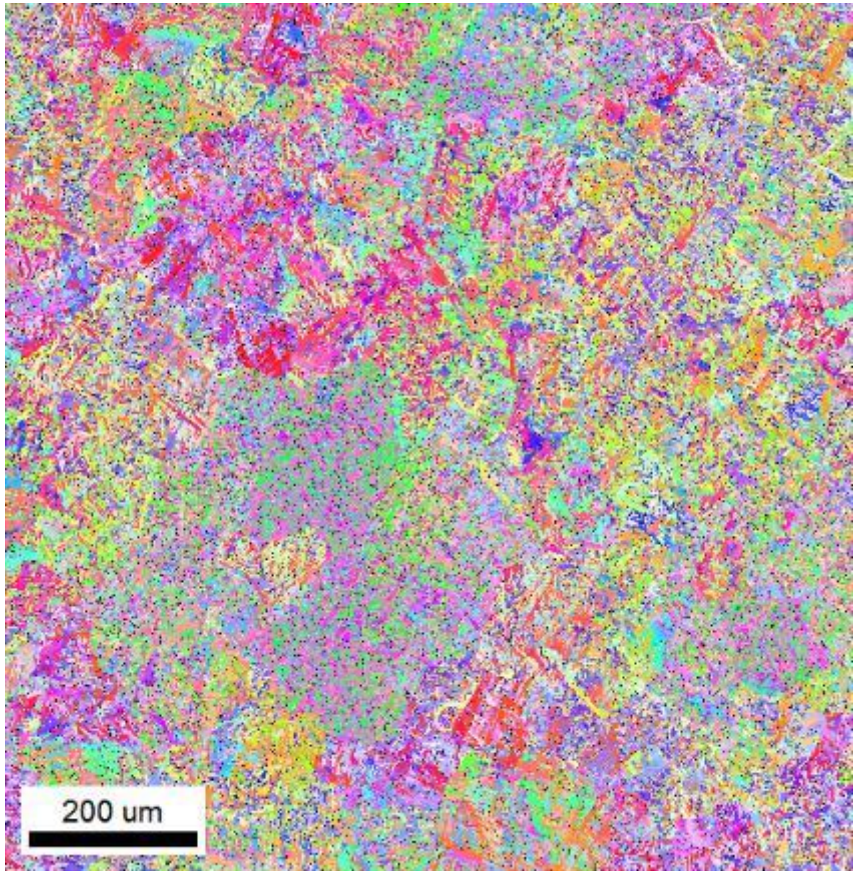


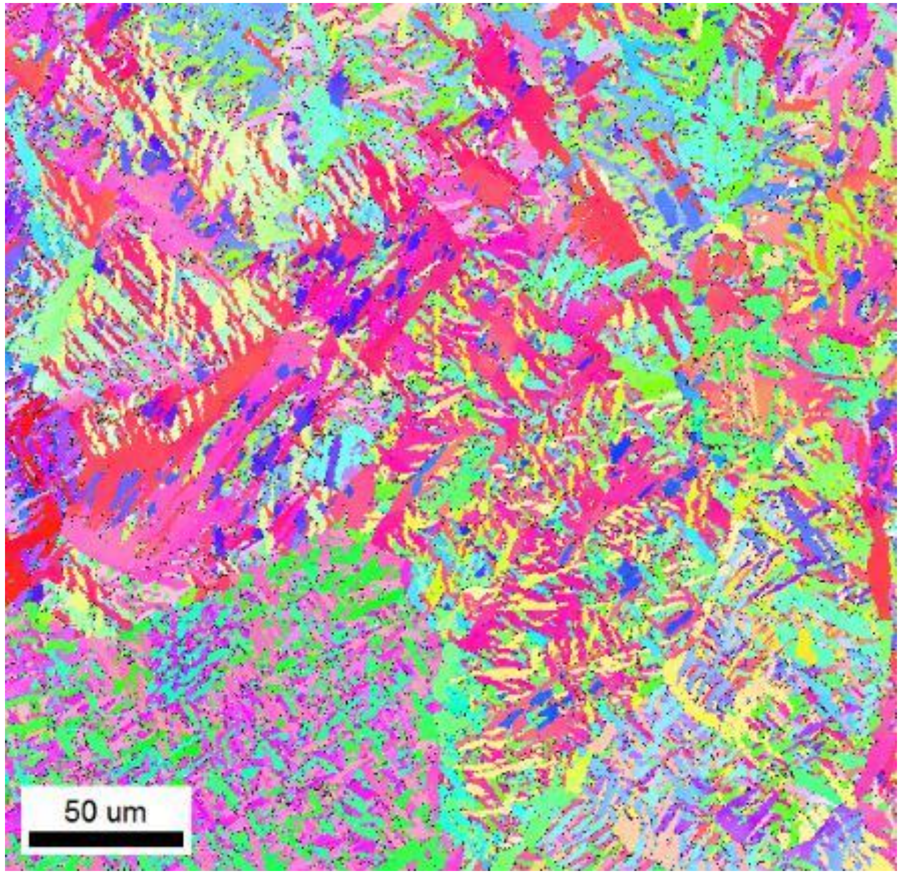
AM IN718 component microstructure

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

AM Material Microstructure Analysis and Control





EBM Ti 6-4 IPF Maps

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Machine Learning Methods: Enhanced Material Definitions

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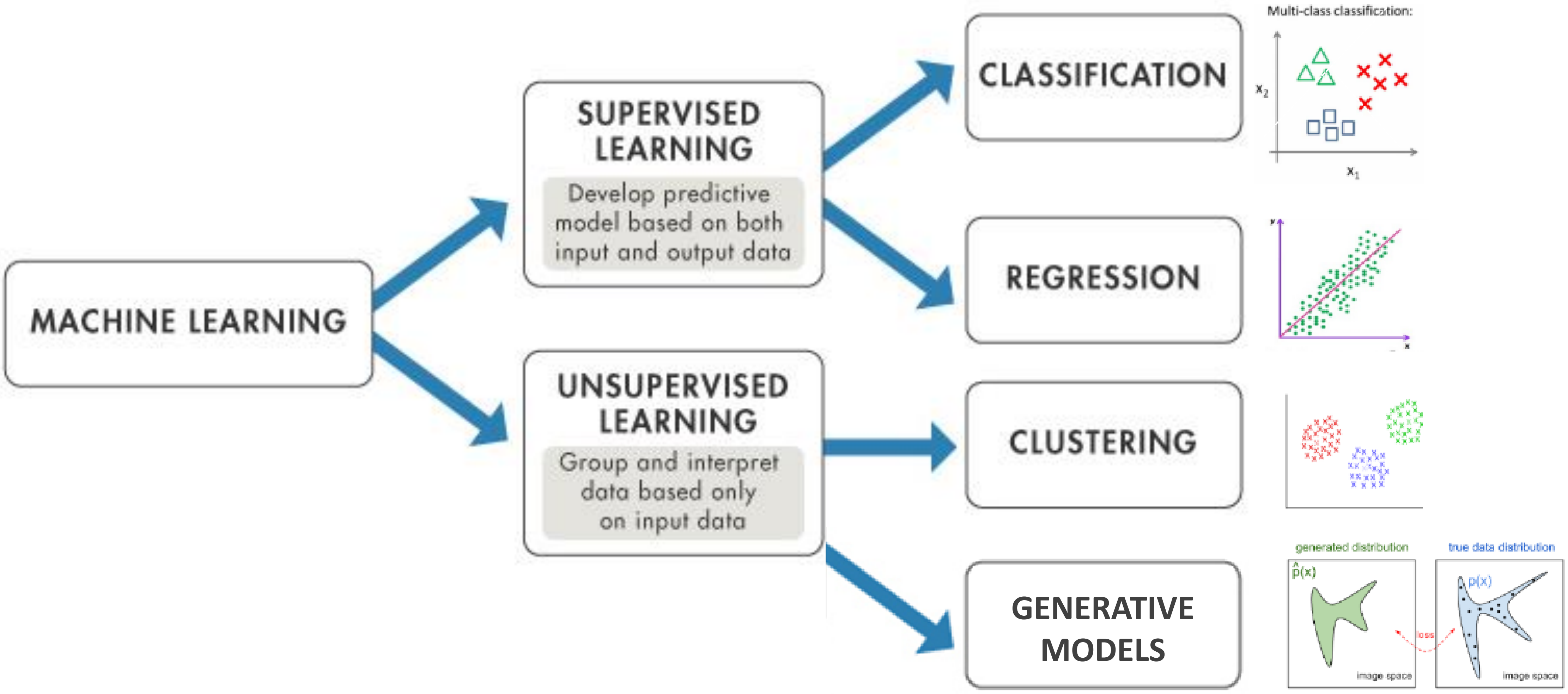

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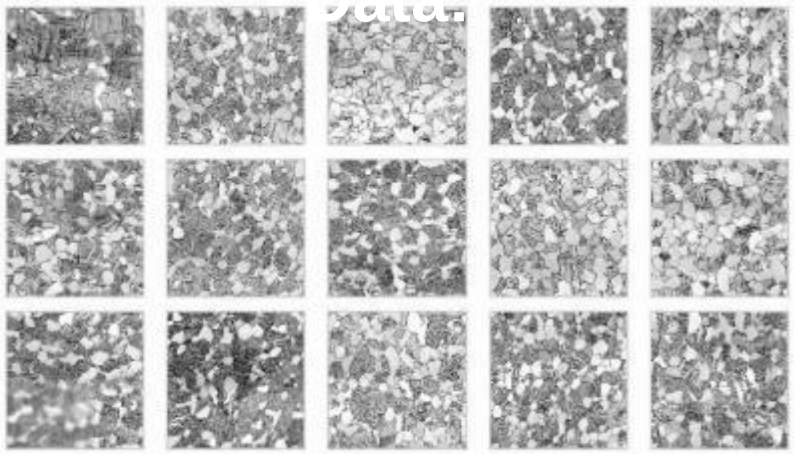
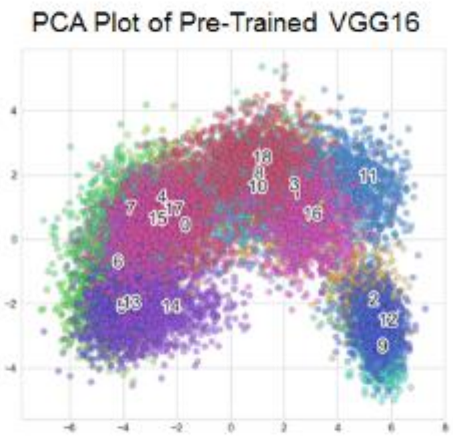
Machine Learning Providing New Understanding

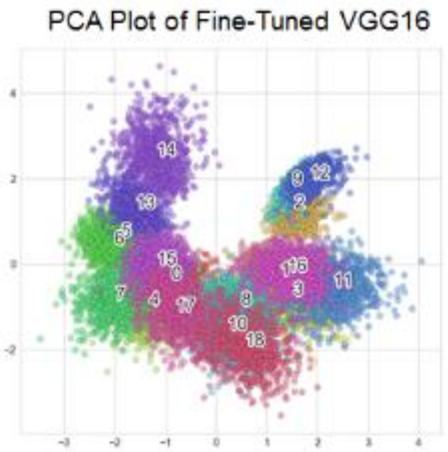
Microstructure data can be used to predict properties and classify materials

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

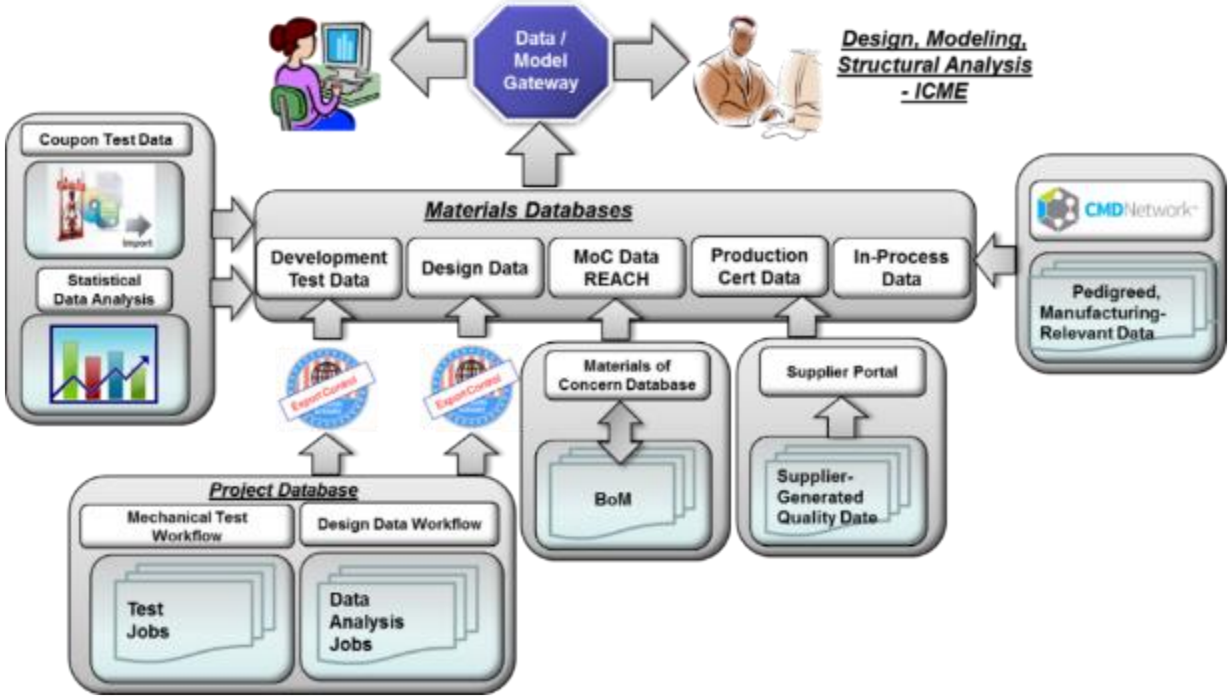
Industrial processes generate large amounts to data that produce digital thread elements

- **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



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

Conclusions and Take-Away

- **Integration of modeling, sensors and data analytics are providing significant benefits**
- **Model-based material and process definitions are becoming the new standard in holistic design, manufacturing and part/process validation and certification**