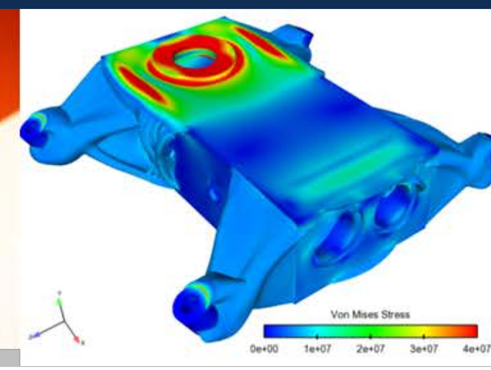
Exceptional service in the national interest



Monitoring and Advanced Diagnostics to Enable AM Fundamental Understanding

D. M. Keicher

Sandia National Laboratories

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Overview

- Challenges with AM
- Diagnostics
  - Closed-Loop Control Results
  - Failure Diagnostic Results
- Benefit to End User
  - AM CAD/CAM Concept
  - Feed-Forward Control
- Summary/Conclusions

Additive Manufacturing

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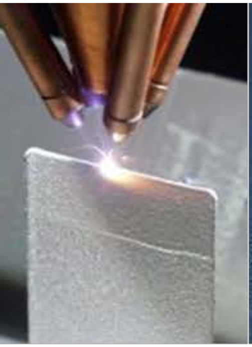
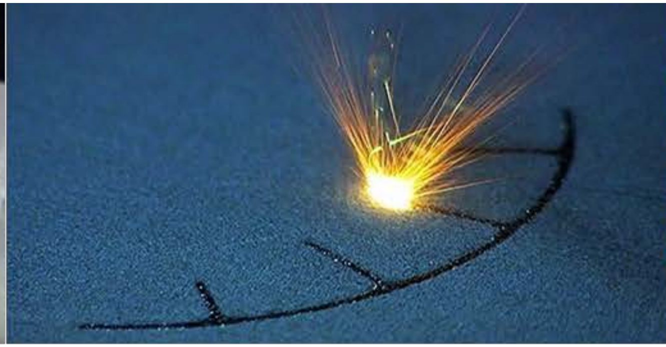
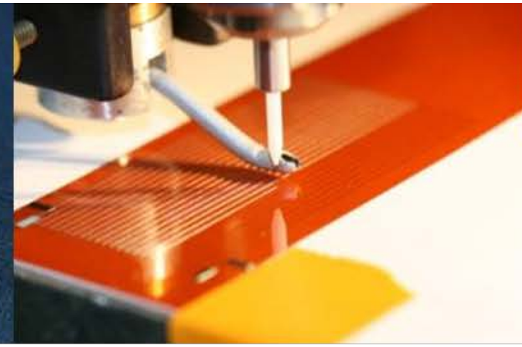
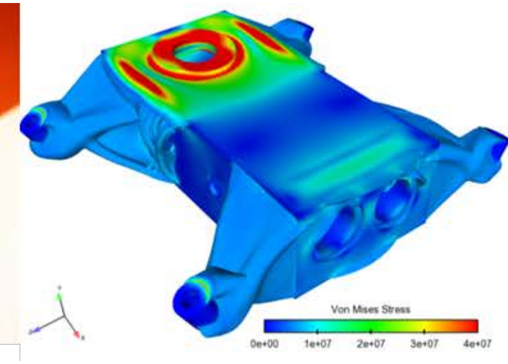








Challenges in Additive Manufacturing (AM)

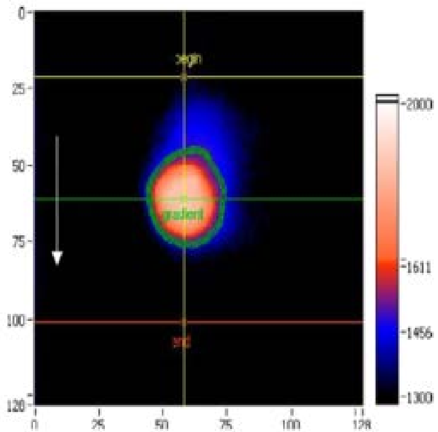
- Confidence in Integrity of AM Parts
- Need to Accelerate Integration of Model Based Processing into AM
  - Empirical approach no longer viable
- User Unfriendly Equipment
  - Unable to optimize processes
- Closed Architecture of AM Machines
- Variations in Feed Stocks
- Etc.

AM Specific Diagnostics Challenges

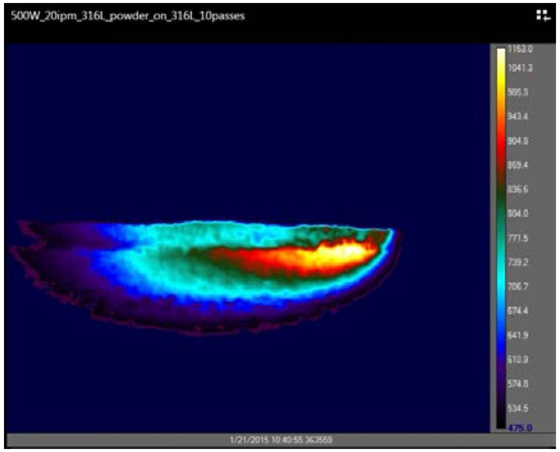
- What are we trying to accomplish
  - Detect occurrence of build defects
  - Provide a metric for quality control
  - Control dimensional accuracy
  - Enable platform independent printing
- Combination of process/system diagnostics needed

Examples of Potential Diagnostics

- Real-Time Spatially Resolved Defect/Geometry Detection
  - Open-Loop
    - Data collection/analysis for quality control
  - Closed-Loop
    - Data collection/analysis for real-time control
- System Diagnostics for Process Transfer
  - Beam spot size measurements
  - Laser power measurements
  - State of health monitors (i.e. optics)



Thermal image of coaxial view for LENS build



Thermal image of side view for LENS build

Example of Closed-Loop Process Control – LENS System

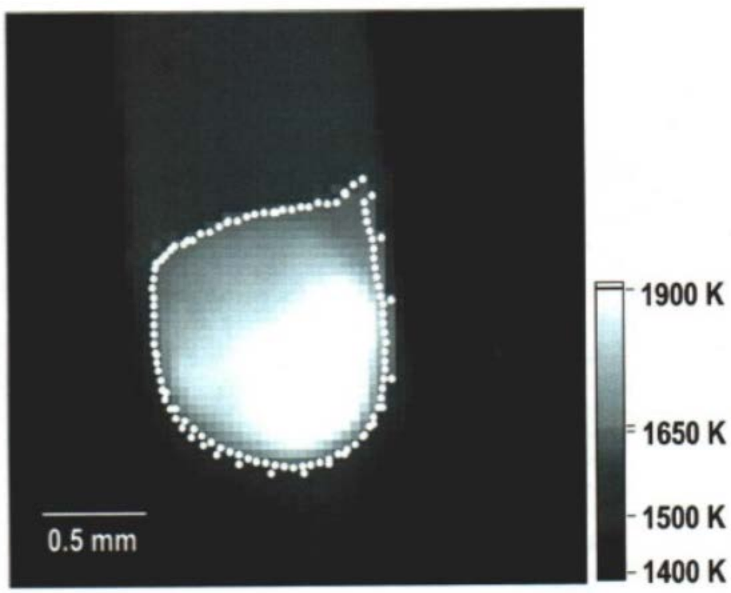


Figure 5: In-situ visible image of stainless steel 316 molten pool. Solidification area is outlined in white dots at 1650 K.

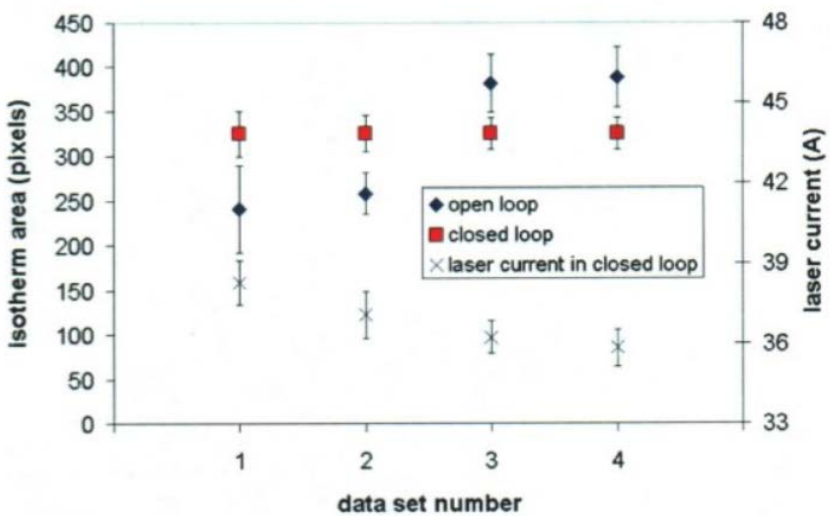


Figure 6: Comparison between open loop processing and closed loop processing with control of the isotherm area.

Closed loop process control enable process consistency but does not move away from empirical based process development.

Model Results for Melt Pool Control

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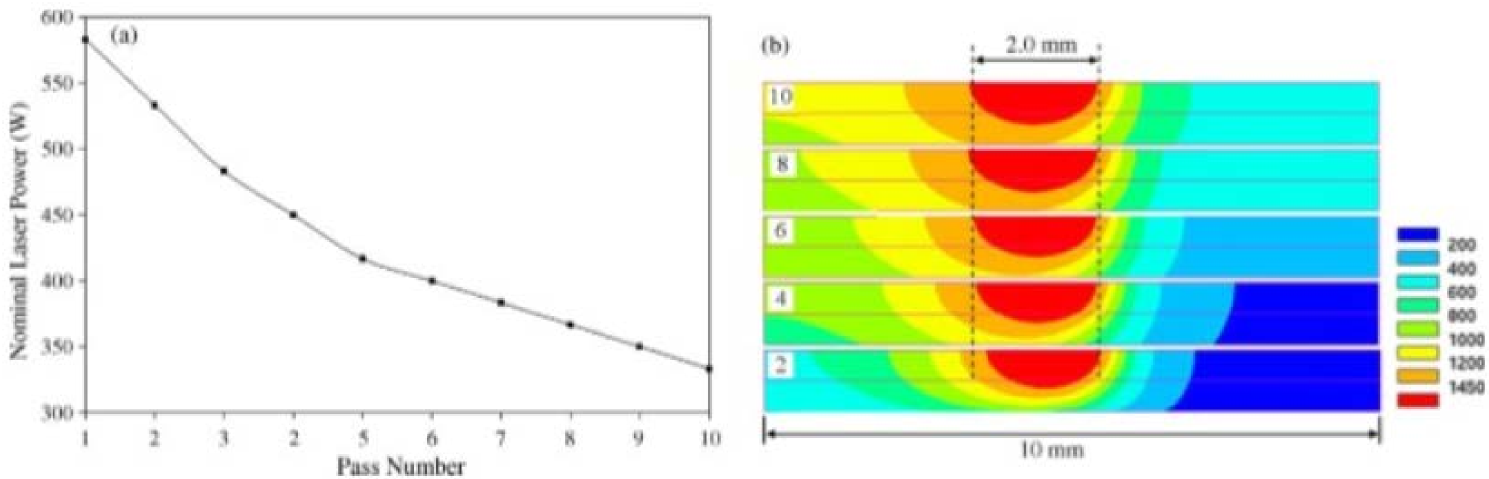
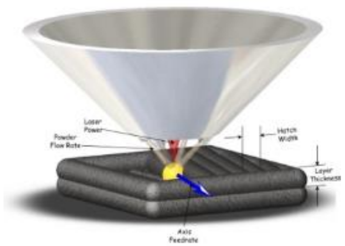


Fig. 5. (a) Nominal laser powers for each pass to achieve a steady molten pool size; (b) molten pool size and shape when the laser beam moves to the center of the part for layers 2, 4, 6, 8, and 10. The average size of the molten pool is 2.0 mm. The molten pool size is determined by the melting temperature of SS410 (1450 °C).

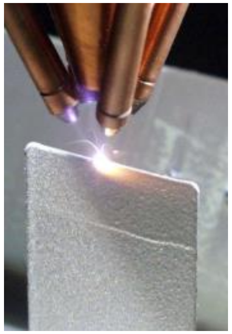
Process modeling able to replicate real world behavior of weld pool with and without closed loop process control.

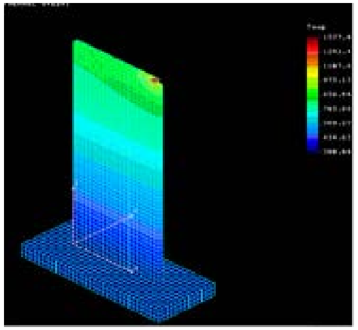
Prior LENS® Research

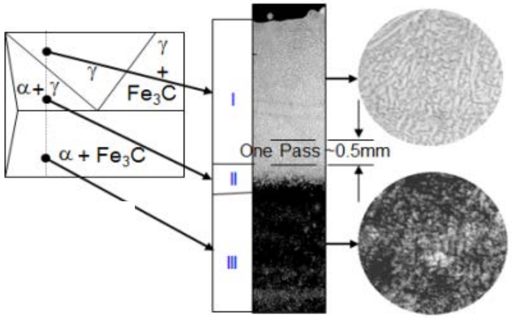


Graded composition demonstration

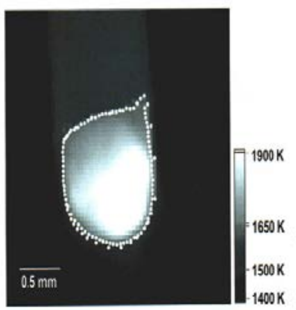
Process characterization/modeling

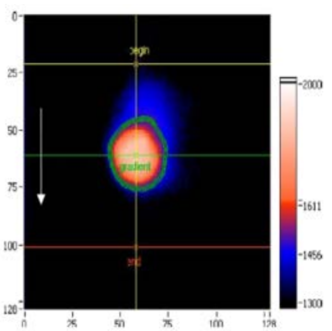






Part heats up during the build & heat flow changes -- so microstructure & properties in the top (I), middle (II), & base (III) of the part differ





Closed-loop process control

melt pool -> microstructure

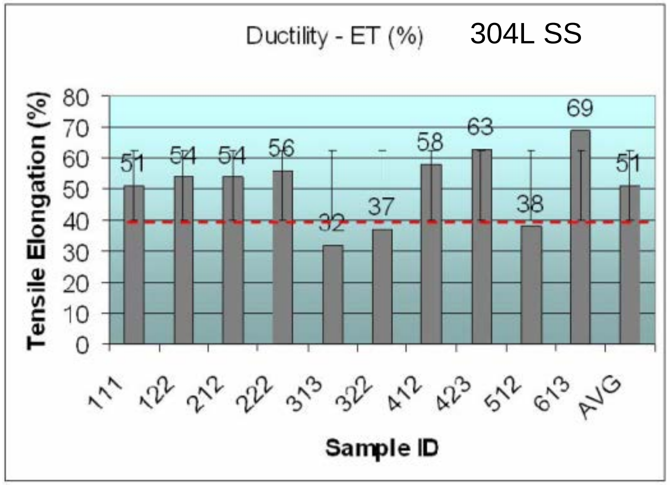
Variety of LENS® metals

Ti-6Al-4V
Aermet 100
Stainless 304L, 316L
tool steels
Inconel
graded NiTi

Potential advantages

- fully dense material
- strength up to 1.5x wrought material
- no loss of ductility
- graded materials
- add to exiting parts
- U.S. based supplier

LENS® materials properties

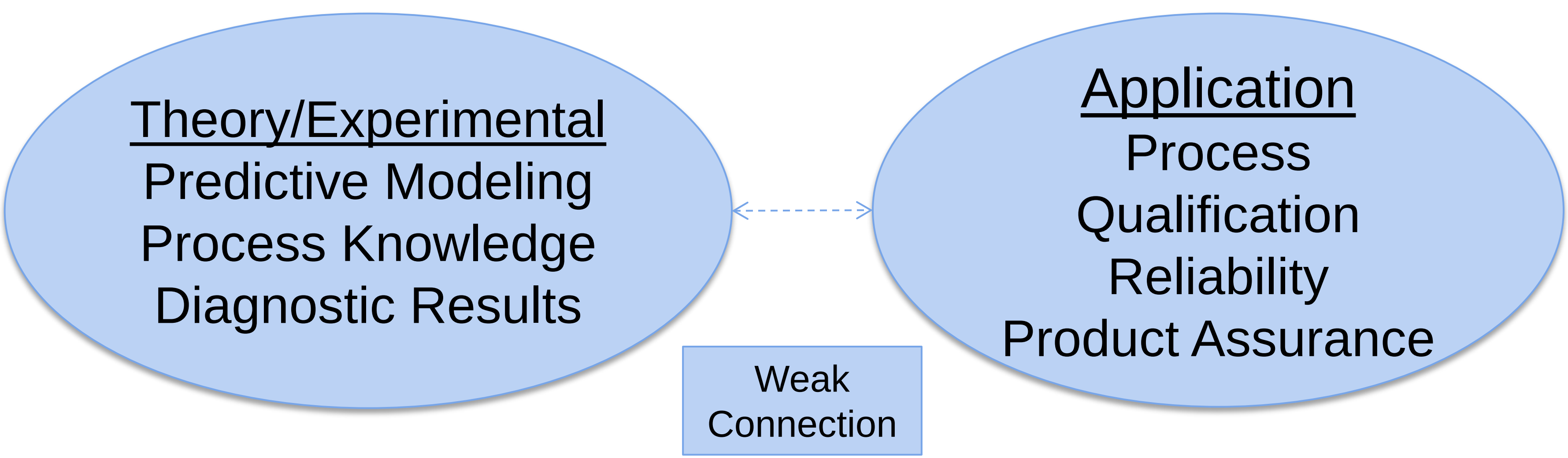


Potential for process based quality

- process monitors ID'd build flaws

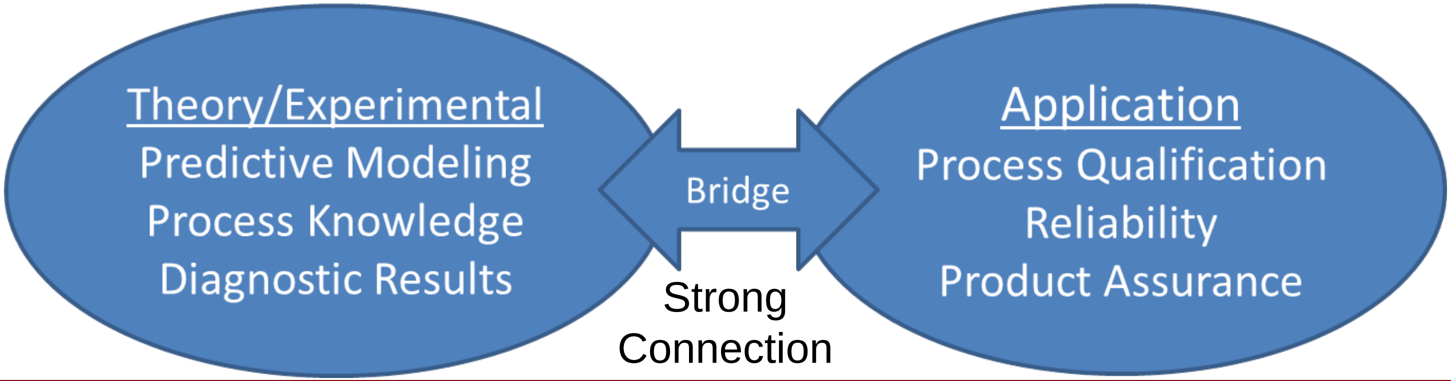
Current Approach to Additive MFG.

- Theory/Experiment Capabilities Disconnected from End User Application
- Efforts in Both Areas Important and Significant
- Opportunity Exists to Leverage Developments in Each Area to Accelerate Adoption of AM

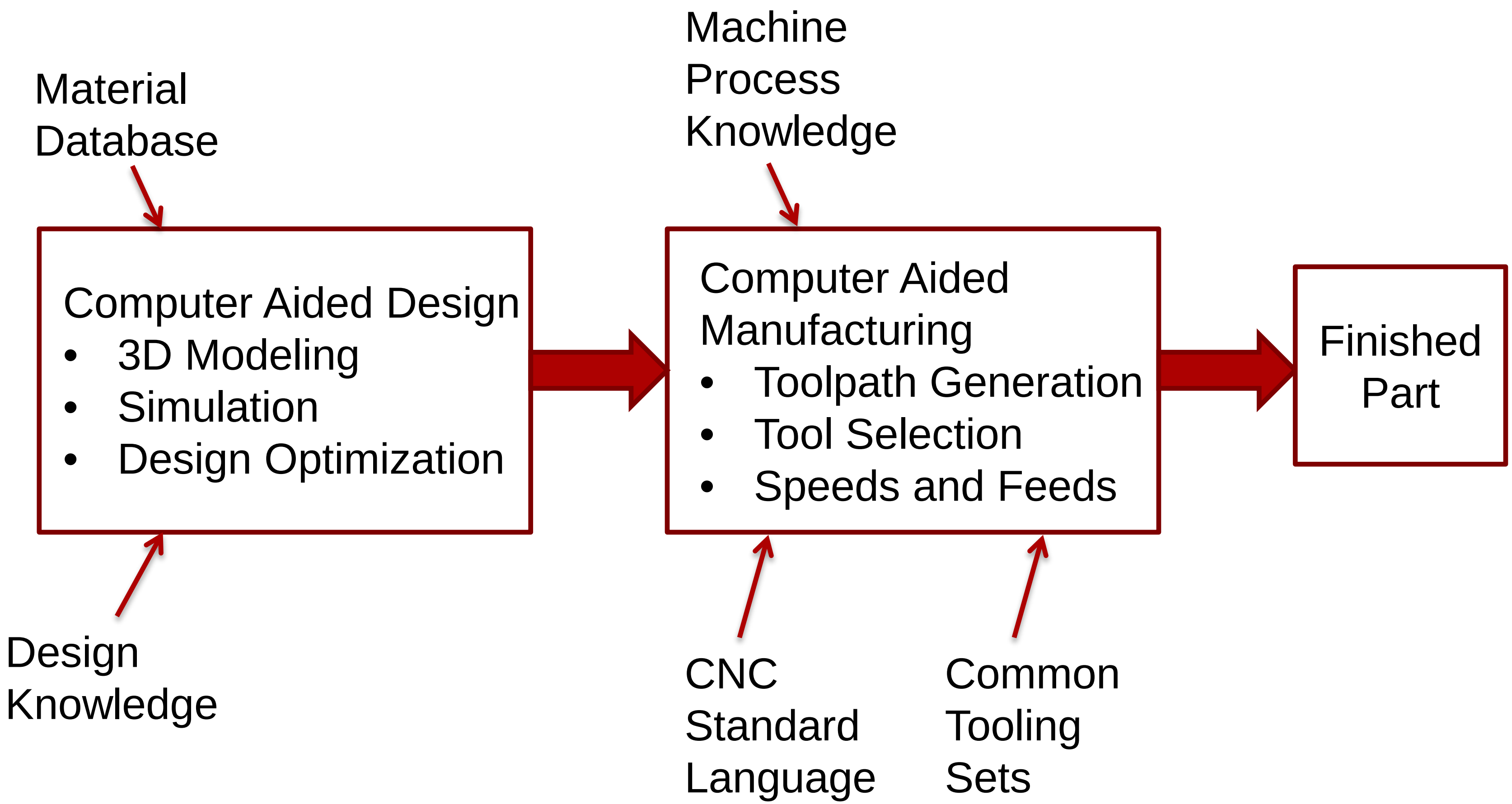


Vision for Additive MFG.

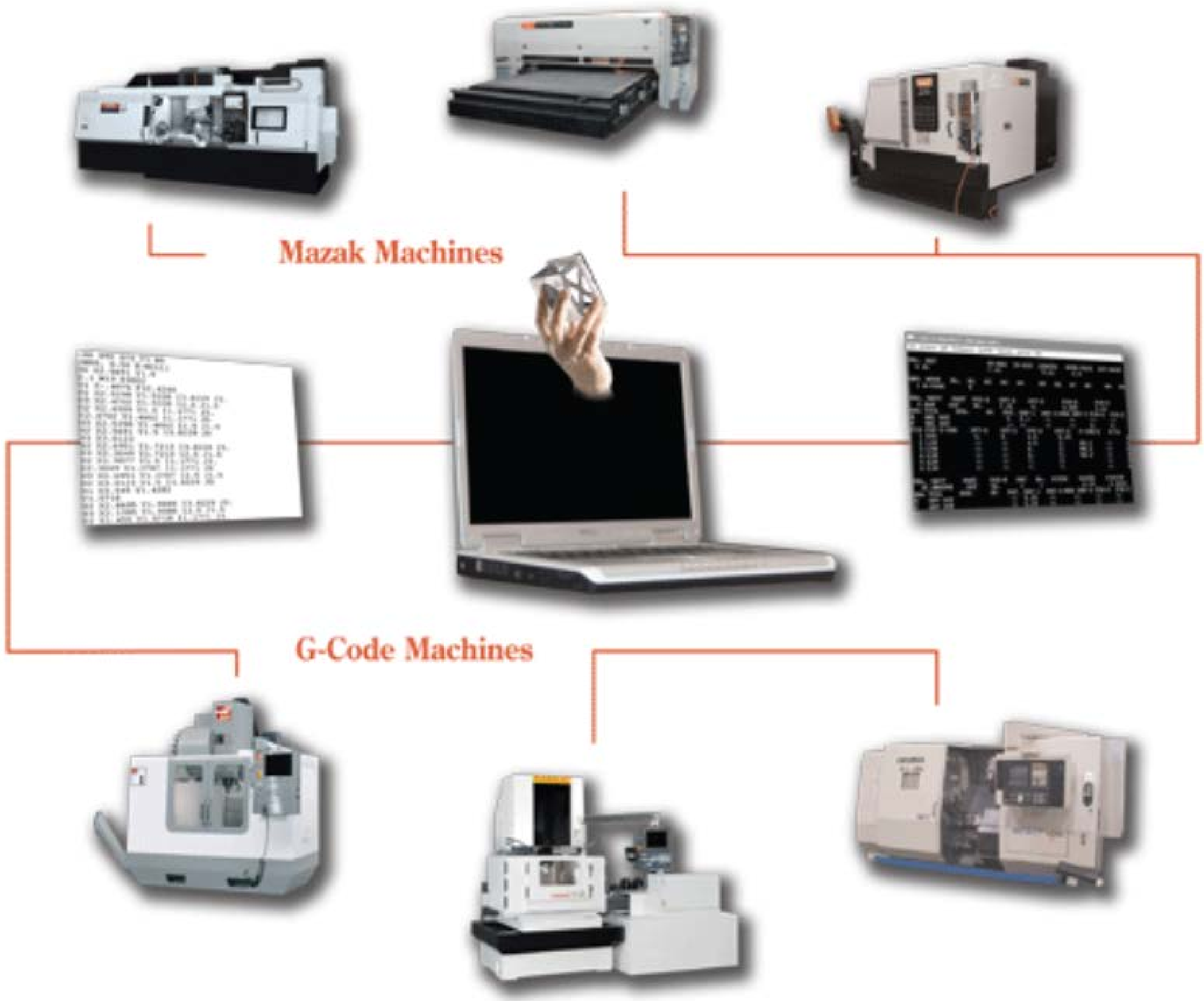
- Develop Tools to Provide Bridge Between Theory/Exp. And Application
- Model-Based Toolpath Generation Leverages Predictive Capability to Provide Feedforward Process Control
- Validation Provides Connection to Accelerate New Process Development
  - Model-based experiments lead new process development
    - New materials
    - Multi-materials
  - Fewer experiments needed to support new process validation



Traditional Manufacturing Approach
Computer Aided Design/Manufacturing
CAD/CAM

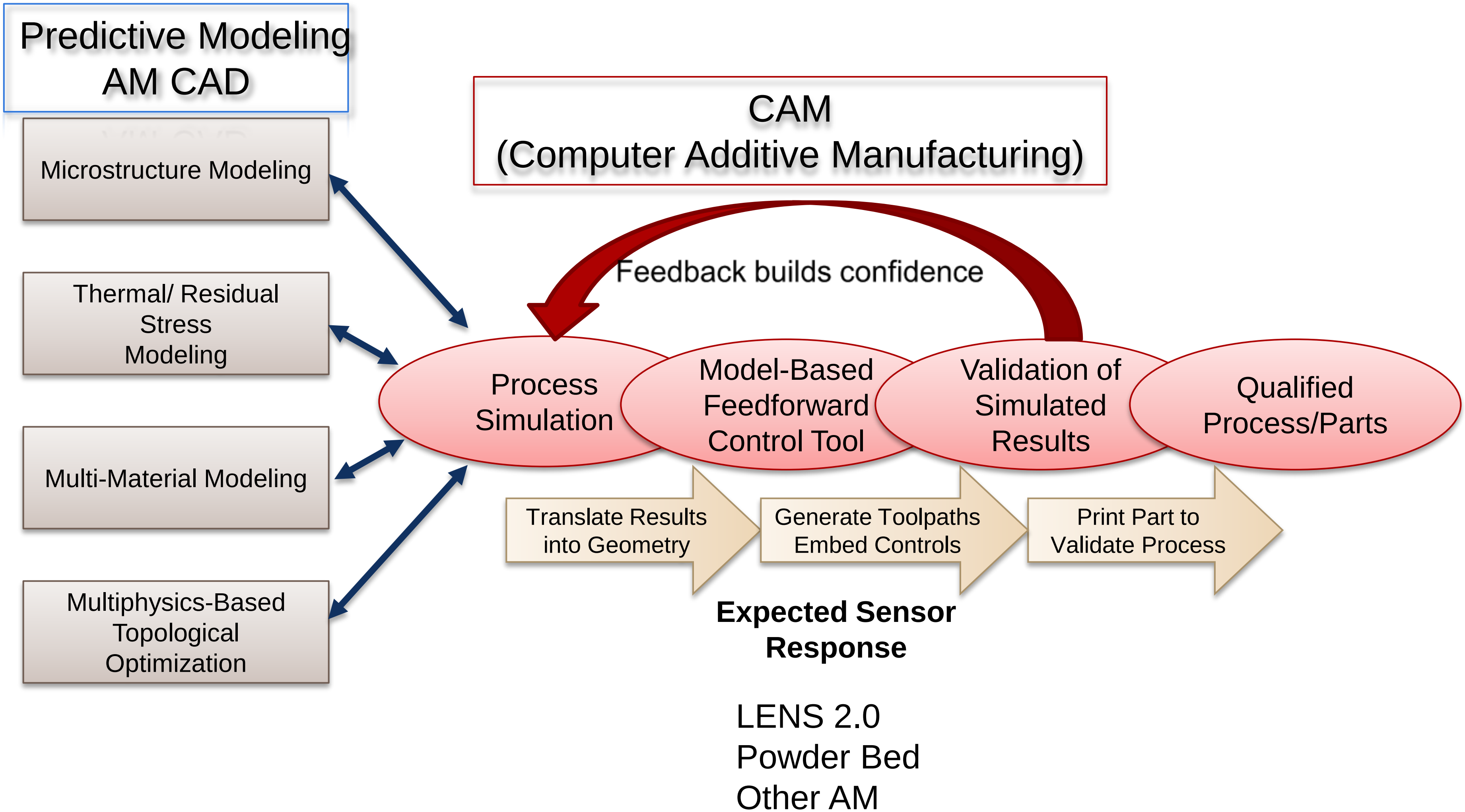


CAM System Machine Independent



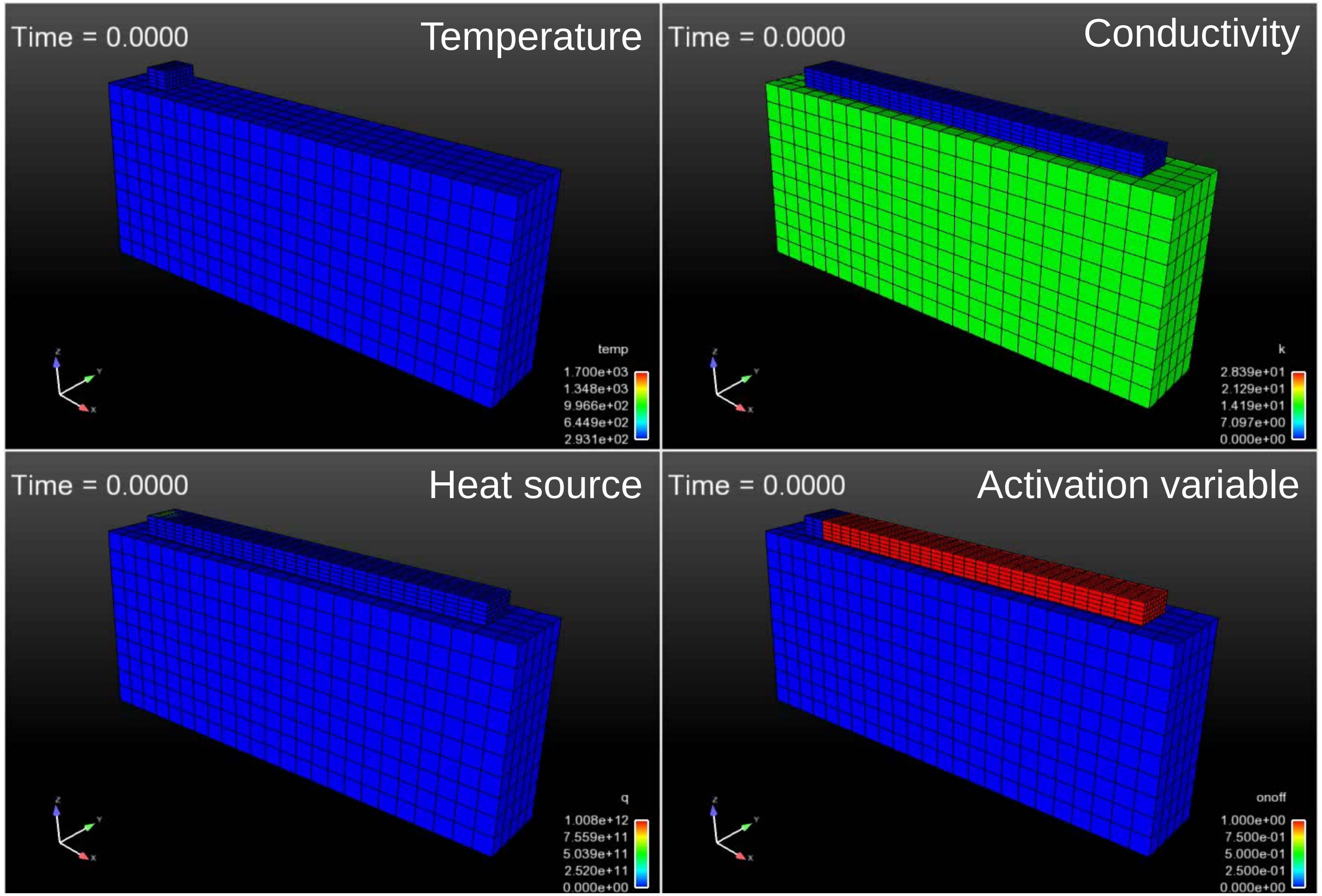
Vision – AM Super Highway

Model-Based Feedforward Control Provides Path for End-Users to Leverage Predictive Capabilities to Accelerate Development in AM



Coupled Aria/Presto Code for Moving Heat Source and Material Birthing

Courtesy of Lauren Beghini (8259) ECLDRD Project



Moving heat source model and material birthing allows us to build up material in a layer-by-layer fashion to simulate AM builds.

Coupling Thermal Data with Model for Prediction of AM Build Shape

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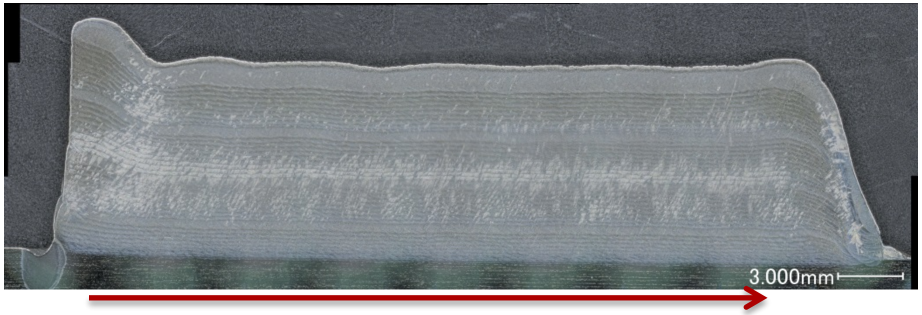
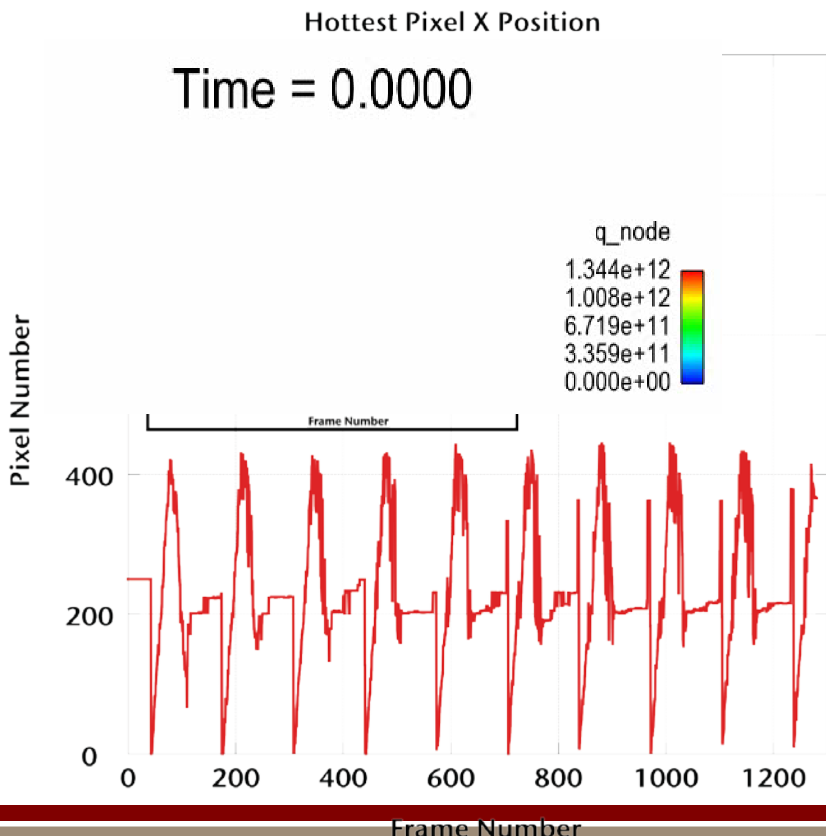
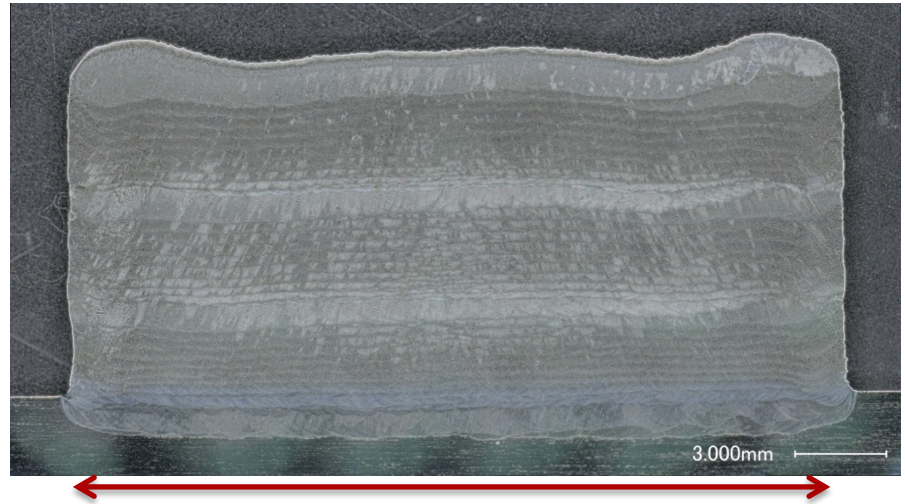


4 x 10 passes 1 direction

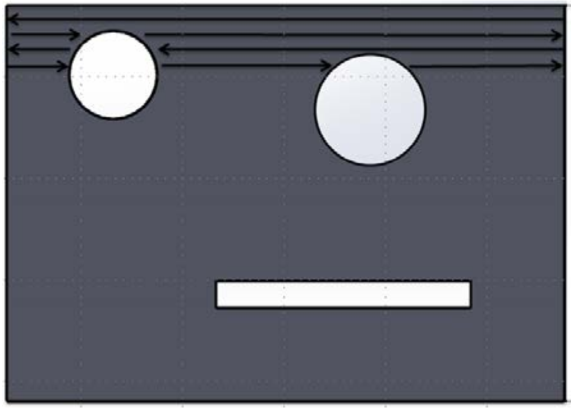




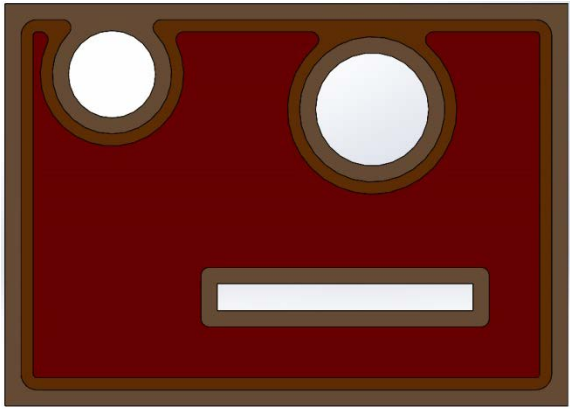
3 x 10 passes 2 direction

The thermal history provides data that can be used in the moving heat source model to predict the final geometry of a built part

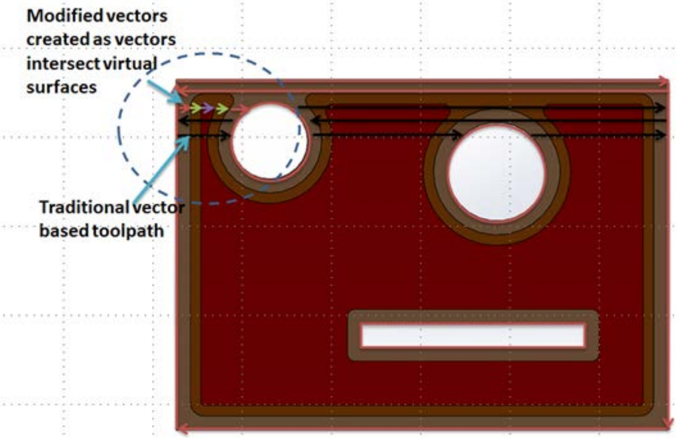
Moving from Simple Vectors to Vectors with Embedded Commands



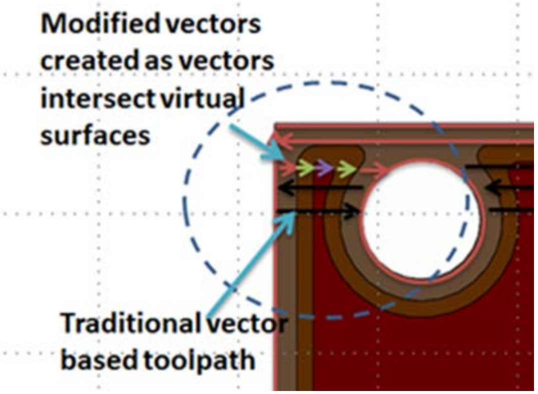
Current approach to generate toolpath for 3D printing



Conceptual isotherm map showing areas with constant temperature



Embedded surface provide features for slicer with assoc. proc. parameter



Vector associated with process parameters provide feedforward control

Benefit in AM CAD/CAM Approach

- Confidence in Integrity of AM Parts
  - Use Predictive Modeling Results to Generate Toolpaths to Drive Processes
  - Correlate Part Properties to Predicted Properties
  - Results – Improved Process Confidence
    - Streamline Development/Mfg
    - Enhance Component Design Space
- Accelerate Integration of AM Model Based Processing
  - Significant Opportunity to Advance Validity in AM
  - Demonstrate Leadership Role in Providing Certainty in AM
  - Virtual Prototyping Improves Speed in Process Development

Benefit in AM CAD/CAM Approach (cont.)

- User Unfriendly Equipment
  - Provide Process Knowledge to Overcome Steep Learning Curve
  - Post Processors Provide Vendor Specific Commands to Broad Range of Equipment
- Closed-Architecture of AM Machines
  - Select G-Code Standard to Launch AM-CAM Capability/Open Architecture Platform
  - Post-Processor can Adjust for Machine Differences
  - Provide Users with Edit Capability to Enable Open-Architecture System
  - Supports Embedded Process Control Commands

Benefit in AM CAD/CAM Approach (cont.)

- Variations in Feedstock Properties
  - Model-Based Prediction can Account for Feedstock Variability.
  - Predictive Capabilities Accelerates:
    - Elemental Blending of Materials
    - Development of Gradient Structures

Conclusions

- Developed Concept for Interface to Simulate AM Processes
- Developed Concept to Generate Toolpaths with Embedded Process Control Commands