A Workshop on Predictive Theoretical and Computational Approaches for Additive Manufacturing:

Additive Manufacturing Scalability, Implementation, Readiness, and Transition

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United Technologies Research Center

United Technologies Research Center

United Technologies

Business units in 2015

UTC Building & Industrial Systems

Sikorsky

Otis

UTC Climate, Controls & Security

Pratt & Whitney

UTC Aerospace Systems

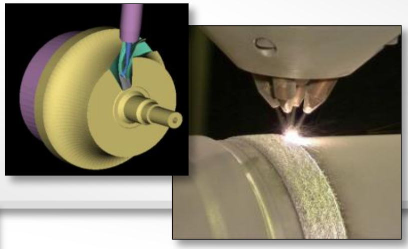
UTRC…UTC's Innovation Engine

Defining what's next

Define new frontiers…

AIS
Autonomous
& intelligent systems

Advanced manufacturing

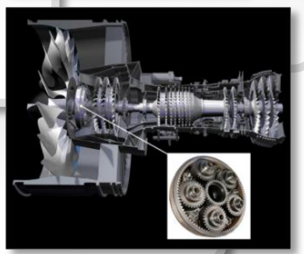


Big data

Co-develop new technologies…

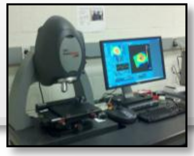
Next Gen
centrifugal

GTF
lubrication



Solve tough problems…

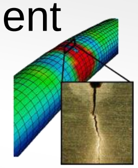
Materials
characterization



Surface topology
and wear analysis

Measurement
science

Digital imaging
strain analysis



Failure
analysis

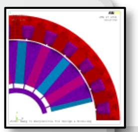
Scattering
to measure
residual stress

Serve as hub for technical interchange…

Tech
scouting

Rare
Earth
Magnets

REM
workshops



Leverage global network of innovation…

Monetize UTC intellectual property…

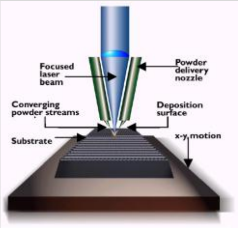
Alternative
markets

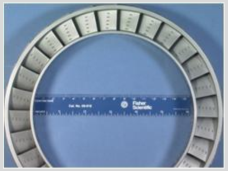
New
business models

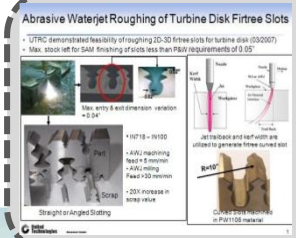
UTRC Develop Multi-Physics, Multi-Scale Models for Advanced Manufacturing Technologies

Process modeling pursued to improve product quality, performance and cost

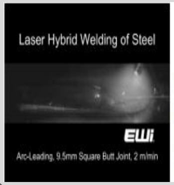
Additive Mfg: LPBF, LPDF, EBM …







Advance Abrasive Water jet Tech: No distortion, no heat affected zone

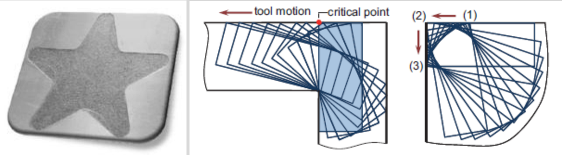


WAAM & Laser Hyper Welding: High productivity AM or welding

Ultrasonic Mach. : Inconel super alloy

Abrasive machining

Electrical discharge milling

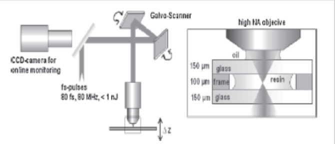


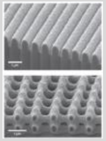
On-Line Hardening

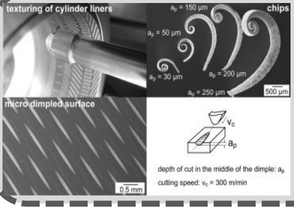
- **Control distortion**
- **25% reduction in cost**
- **20% reduction in time**

On-line inspection

Laser Nano Manufacturing







Micromachining: Micro-texturing of the surface using modeling.

Outline

- Are there drivers to integrate computational simulation and advanced optimization methodologies (AOM) to enable unique AM design?
- What opportunities exist for public-private-partnerships to advance HPC capabilities for AM?
- How will those partnerships benefit from advancements?
- Do processing standards change with an analytical and mechanistic model approach to implementation of full scale additive manufacturing?

Photo source: http://www.aviation.dla.mil/externalweb/userweb/AviationEngineering/Engineering/valueengineering/AFCAT/castandforged.asp

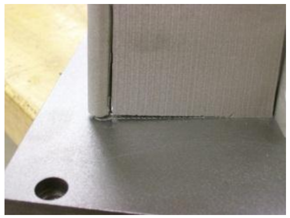
Process dependent design and materials
=
Different outcomes by process and properties

Design for the cold spray process

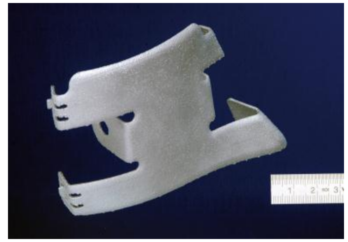
Design for direct metal laser sintering (DMLS)

Drivers to Integrate Computational Simulation & AOM

- Major challenges in AM Process
  - Distortion

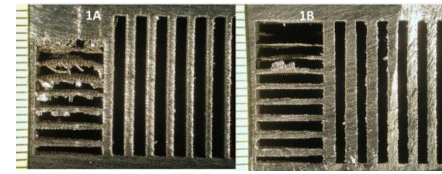


Aluminum



Titanium

Steel

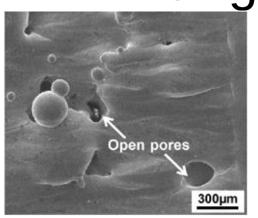


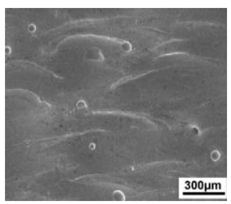
http://www.gecapital.com/webinar-assets/pdf/3dprinting-capital.pdf

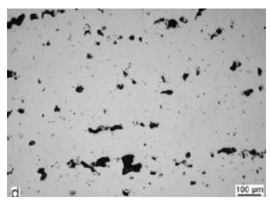
http://www.ilt.fraunhofer.de/content/dam/ilt/en/documents/product_and_services/laser_material_processing

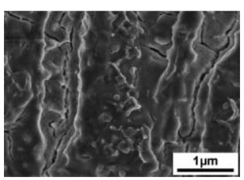
Lappeenranta University of Technology
Faculty of Technology, LUT Metal Technology
BK10A0401 Bachelor's thesis and seminar

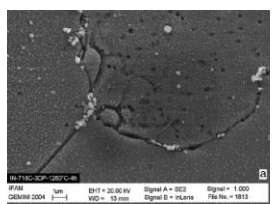
  - Origination of defects & microstructure and their effect on fatigue



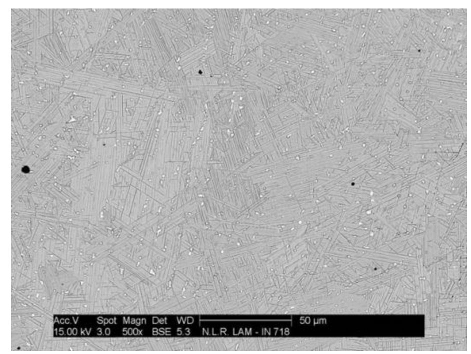




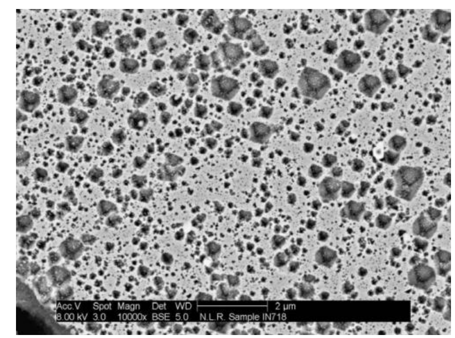




Defects



Microstructure of Longitudinal cross-section of the build



Microstructure grains

- *At what point are properties more influenced by defects than by the microstructure (grain size, grain orientation, anisotropy, …)*
- *To what extent does the initial microstructure from additive processing impact the properties of the final post processed component ?*

Drivers to Integrate Computational Simulation & AOM

How to get the best possible product by leveraging and integrating every tool at our disposal to define the most critical parameters?

Near term development and integration

Long term development and integration

Material Models for:
- Powder characteristics and representation;
- Physical properties;
- Thermal mechanical behavior;
- Metallurgy and Rheological;
- Layout of functional grading in materials

Process Physics:
- Multi-physics simulation of AM process
- Energy source representation and interaction parameters;
- Possible onset and propagation of defects
- Part specific control of defects,
- Interfacial characteristics

Design:
- Part geometry
- Support structure
- No support structure

Processing of Geometric Model:
- Slicing and path generation
- Optimize process through designed experiments
- Tailoring of process characteristics for desired properties

Equipment Environment as model input:
- Machine motion/scan parameters;
- Chamber process atmosphere;
- Shape and characteristic angle of deposit
- In-process monitoring
- Closed loop feed back

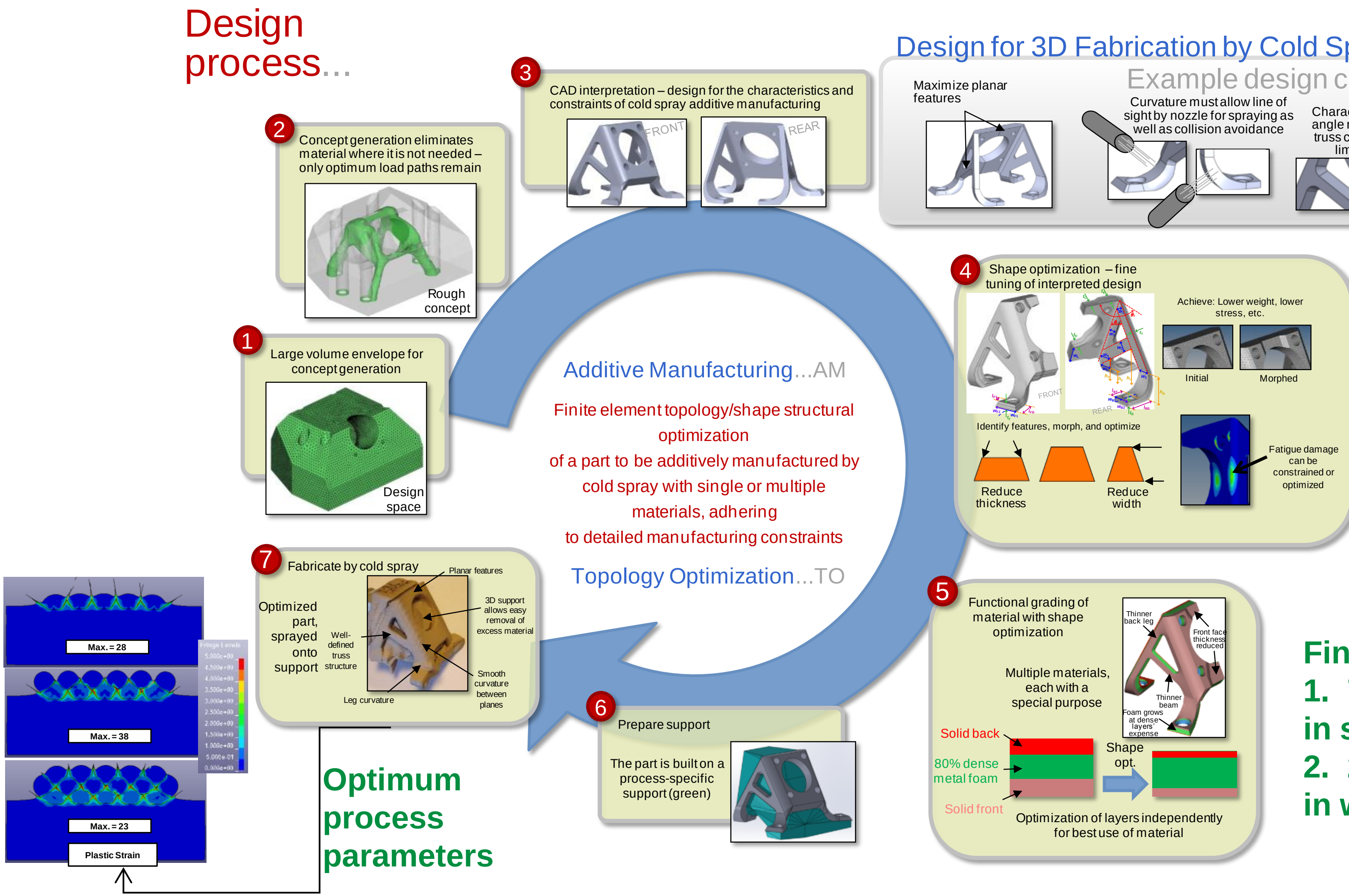
- ***Prediction of first part right process parameters***
- ***Optimization of:***
  - *Process parameters*
  - *geometrical accuracy,*
  - *mechanical and metallurgy properties,*
  - *building time and cost*

Drivers to Integrate Computational Simulation & AOM

- Interconnected needs
  - Design part for the AM manufacturing process
  - Engineer materials for the design
  - Specify / optimize process parameters (Process Map) for material properties and design
- Computational tools
  - Part design and analysis – FEA, CFD, Level set, multi-physics analysis
  - Manufacturing characteristics – CAD, morphing
  - Material properties – Multi-scale simulations
- Optimization
  - Linked codes
  - Simultaneous consideration of design, manufacturing, and materials

Drivers to Integrate Computational Simulation & AOM

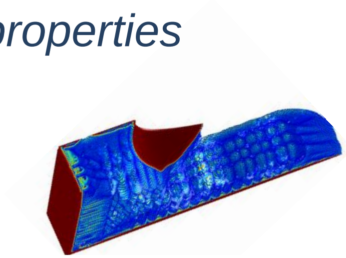
- *Enabling “the Design Freedom” or design for functionality*
- *Part weight reduction*
- *Use of nature inspired structures*
- *developing advanced materials with tailored properties;*

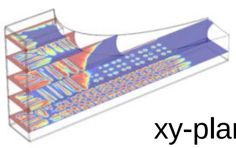


Final design:
1. **75% reduction in stress**
2. **20% reduction in weight**

HPC Modeling and Simulation Capabilities are Essential for AM Large Scale Modeling

Standards for HPC collaborations between Universities, National Laboratories and industry are needed to advance the AM large scale modeling of microstructure and material properties

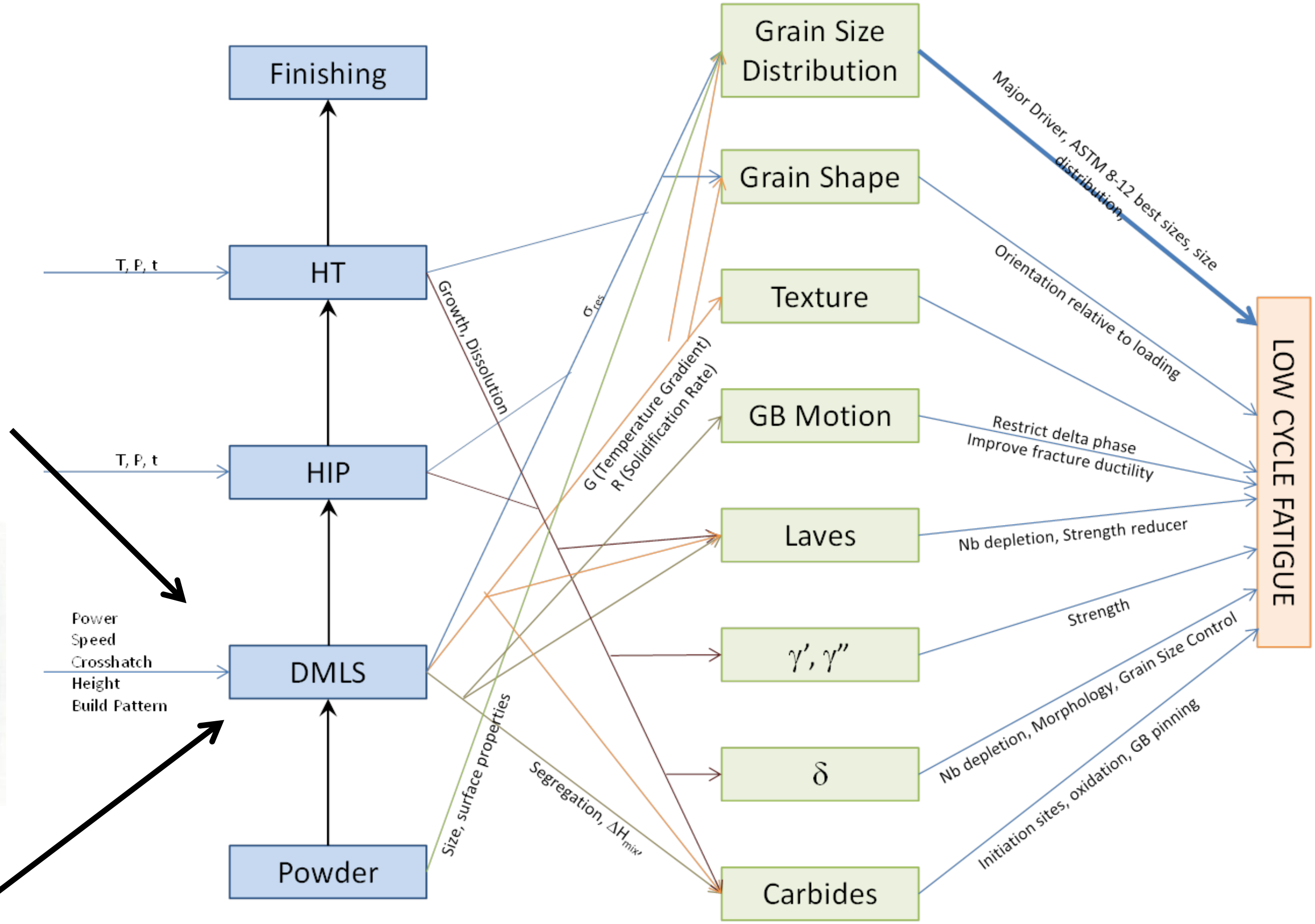




xy-plane

3D dendritic growth predicted using 8 CPUs computational time **one month**

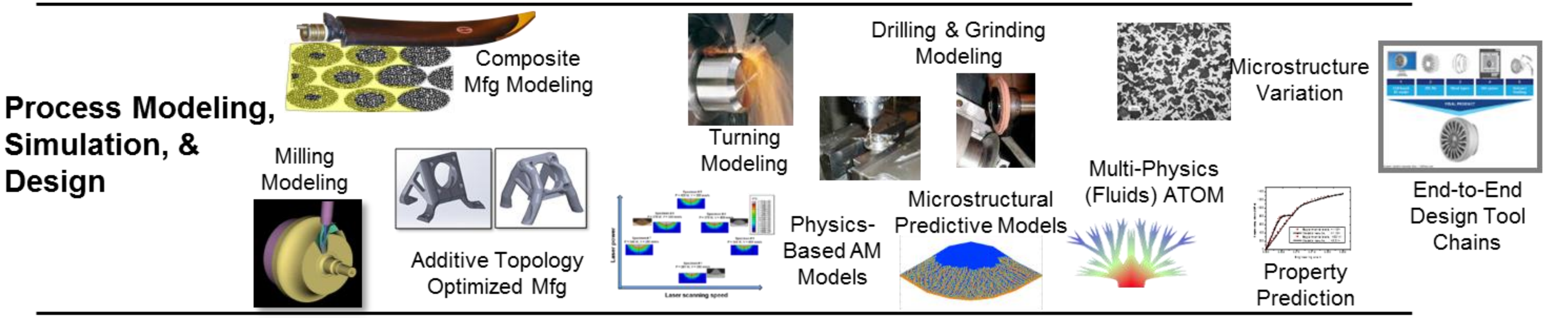
3D dendritic growth predicted for large scale using 768 GPUs with 768 CPUs for a time period of 100 seconds (Shibuta et al. JOM 67 (8) 2015)



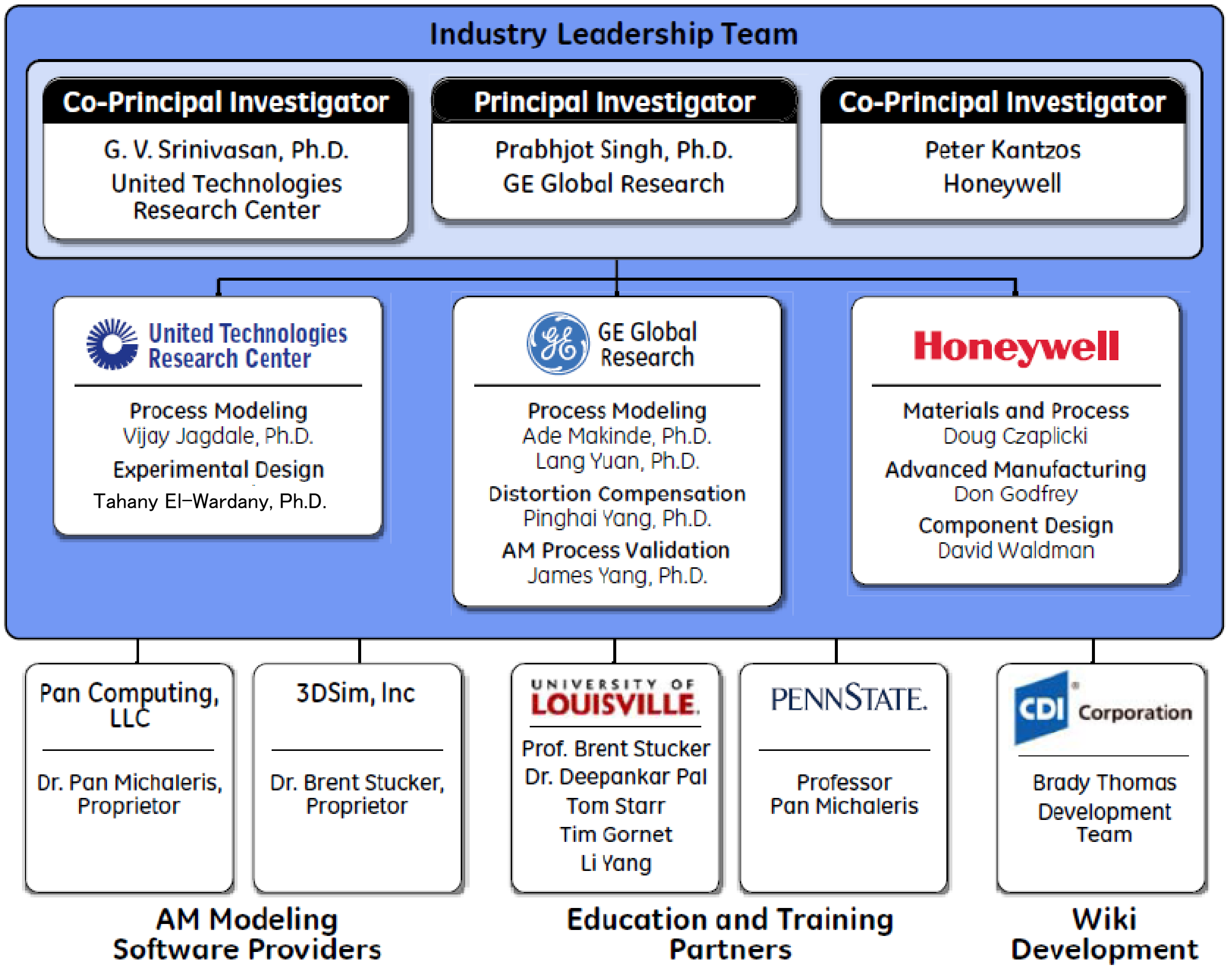
Opportunities for Public-private-partnerships to advance HPC capabilities for AM

What opportunities exist for public-private-partnerships to advance HPC capabilities for AM

- *Allows the introduction of different additive manufacturing constraints during the design stage of parts that will be produced by AM.*
- *Augments the computation of different multi-scale phenomena and enable smoother coupling between them for large scale modeling that predicts material properties and mechanical behavior.*
- *Facilitate the development and execution of high fidelity models of complex features such as microstructure evolution during rapid solidification during AM.*
- *Integrated computational material Engineering (ICME)*
- *Large data managements*
- *Technology transfer to Supply Chain / Aftermarket*



Opportunities for Public-private-partnerships to advance HPC capabilities for AM



Joint industry leadership

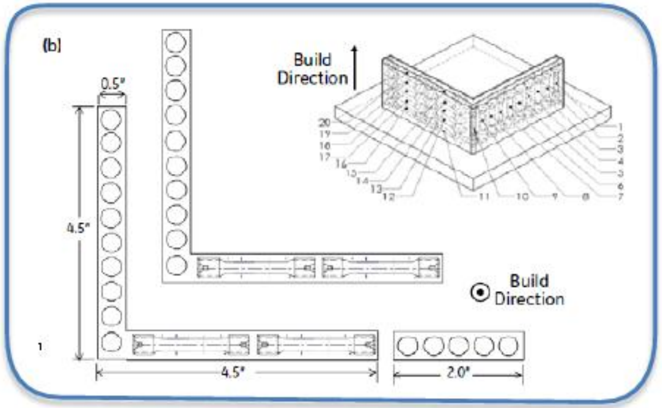
- As-built materials properties (Ni-alloys)
- Validation & testing of software via experimentation

- Distortion prediction
- Distortion compensation
- Wiki of AM best practices
- Education outreach

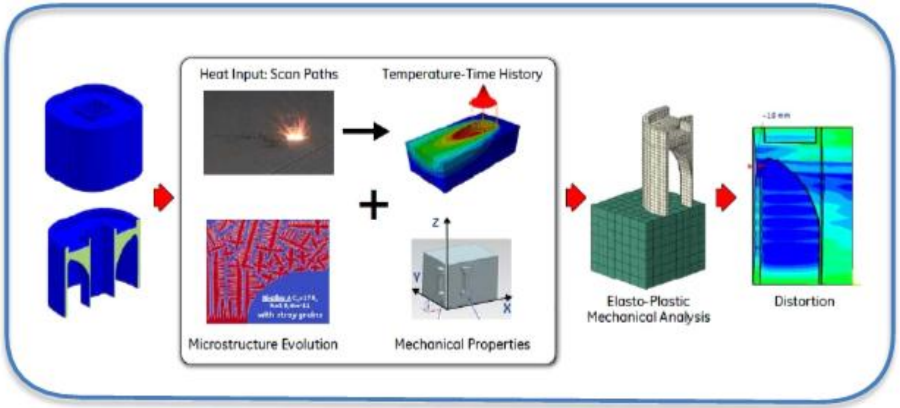
America Makes
National Additive Manufacturing Innovation Institute

Technical Approach

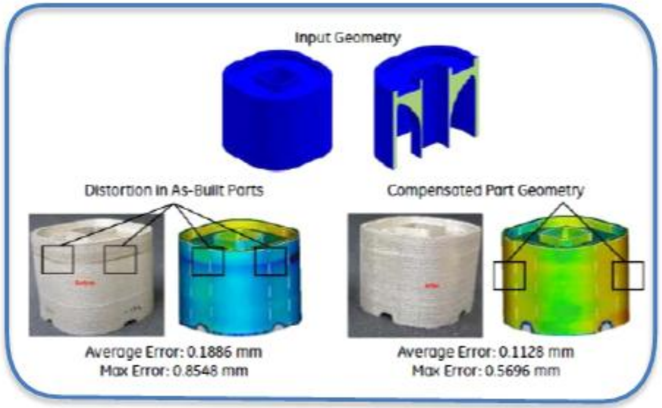
Example geometries



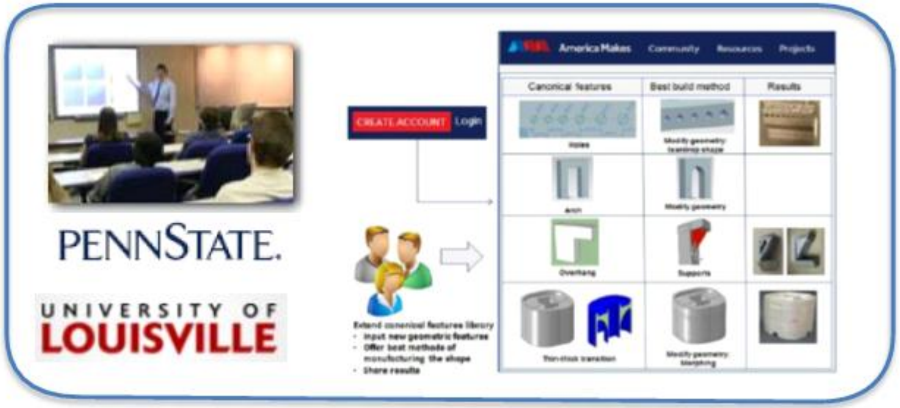
Task 2: Directional as-built material properties; IN625, IN718, IN718+



Tasks 1& 2: Validation & testing of thermo-mechanical models by Pan Computing & 3DSIM using canonical features. Test parts from NAMII members welcome



Task 3: Part compensation to reduce distortion

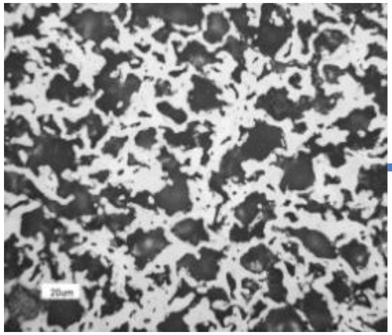


Tasks 4 & 5: Knowledge sharing – wiki & academic courses

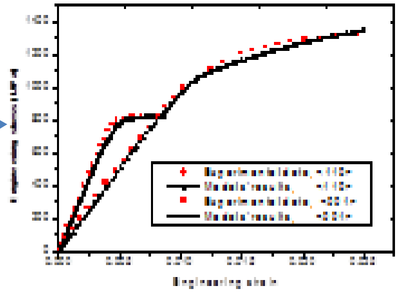
America Makes
National Additive Manufacturing Innovation Institute

Partnerships Future benefits from advancements

- Develop mechanistic understanding of materials behavior during layered manufacturing to enable unique design optimization.
- Partnership with software industry to generate new commercial off the shelf tools that can be applied for microstructure and mechanical property prediction.
- Develop preliminary design curves for new materials with minimum experimental cost;
- Linking materials and process models to support probabilistic design capabilities leading for process certification and first part right notion.

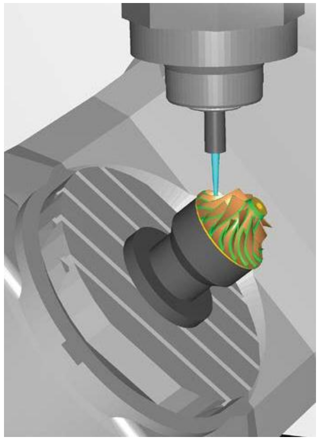


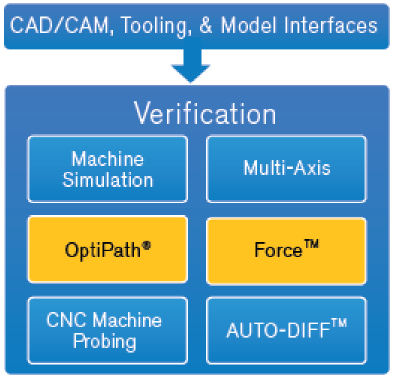
Microstructure Variation



Property Prediction

Fast act properties prediction

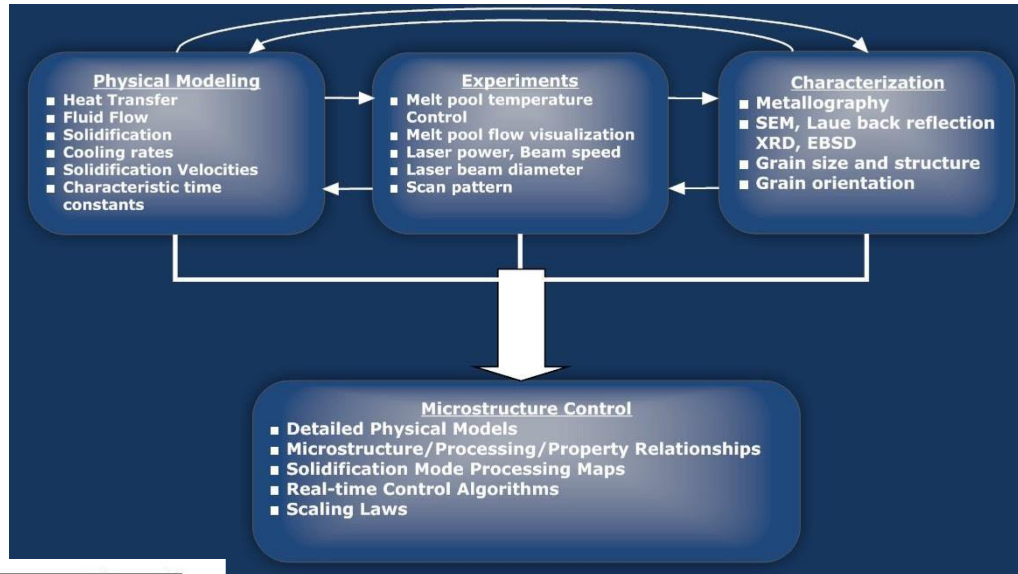




CGTECH / UTRC collaboration

Future Processing Standards

Do processing standards change with an analytical and mechanistic model approach to implementation of full scale additive manufacturing?

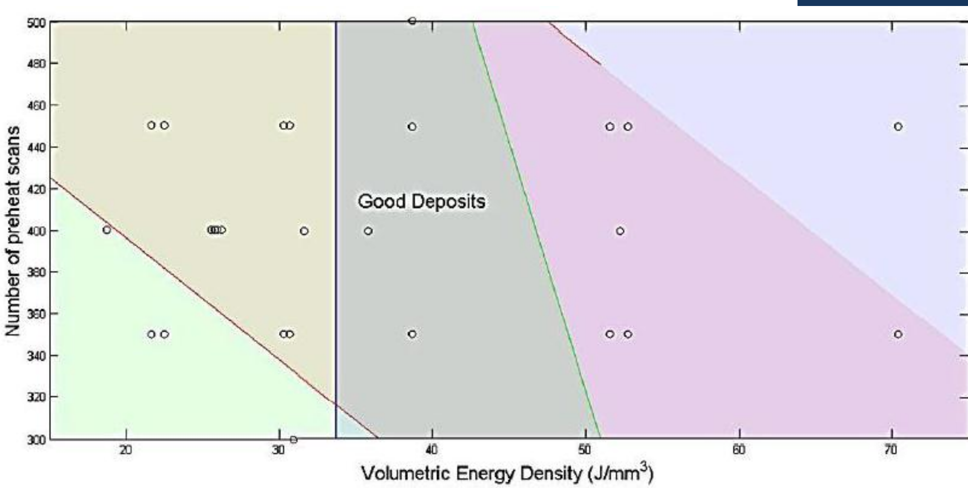


Process Standard will change:

1- The standards will reflect the mechanical property models developed to support materials, processing properties relationships and specifics in AM component design

2- inclusion of physics based model in the process frame work lead to the production of first part right

2- For real time feed back control of the process analytical model is required



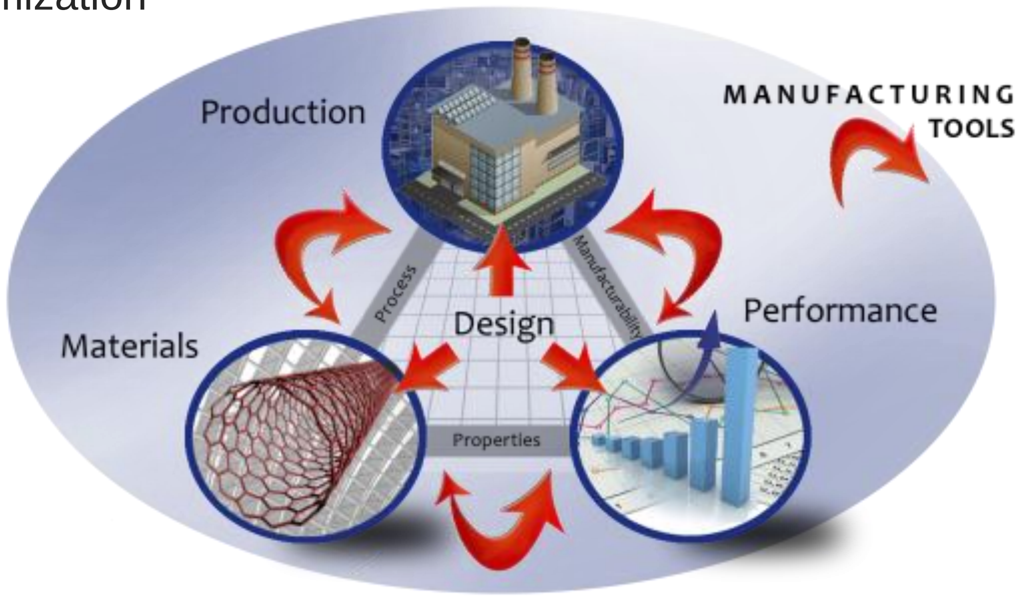
Fast Predefined process parameters based on analytical models

Coupled flow-thermal-microstructural modeling of the scanning laser epitaxy process, Ranadip Acharya et. al., TMS 2013.

Summary

Evolving Additive Manufacturing Paradigm Requires

- Integrate computational materials engineering
- Optimize with physics-based additive manufacturing models
- Enable topology optimization by additive manufacturing
- Implement concurrent hybrid processes
- Process monitoring, online inspection, feedback control
- Virtual manufacturing workflow optimization



Design Space to Integrate Properties, Process, and Manufacturability