FEAA128: Model Based Property Prediction of Ni-based Components Fabricated by Additive Manufacturing

PI: Sebastien Dryepondt & Mike Kirka

ORNL: Patxi Fernandez-Zelaia, Youseb Lee

Jiaho Cheng and Xiaohua Hu

Siemens: Anand Kulkarni, Kyle Stoodt, Jason Weissman

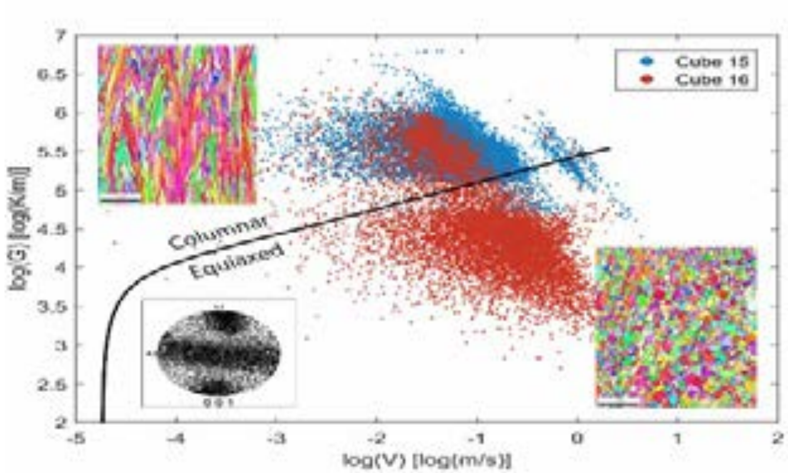
NETL program manager: Vito Cedro III

Background/Objectives

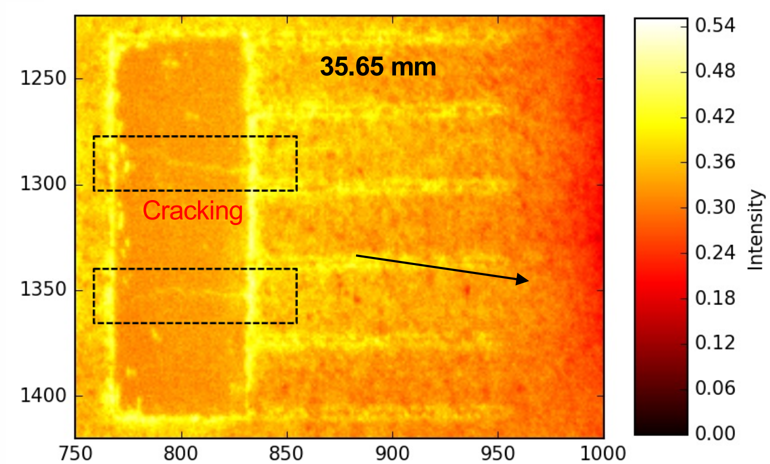
- Develop/**improve** physics-based simulation tools to describe all steps of the AM process
- Use simulation + real-time process monitoring to establish correlation between process-structure-property and "locally" control the alloy properties

Arcam Q10+

Grain structure prediction



In-situ Crack detection via Near IR In-situ



Improving Approach/Physic-Based Models For Process-Microstructure-Properties Correlation

✓ **Linking of Process to Microstructure**

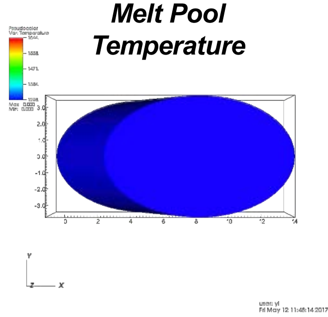
✓ **Linking of Microstructure to Performance**

Particle model

Process

Truchas (FVM)
Abaqus (FEM)

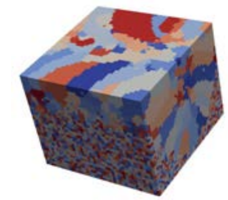
Melt Pool Temperature



New Point Net Beam Strategies

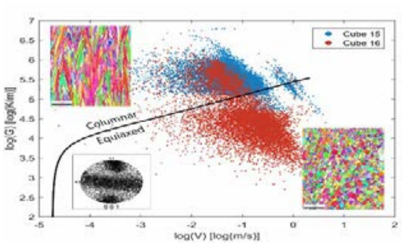
Melt Pool

FEM
DREAM 3D

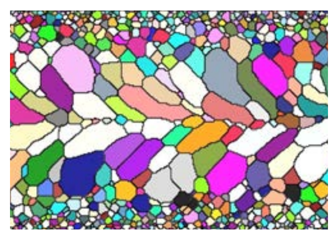


Crystal Plasticity

Microstructure



Analytical prediction
Kinetic Monte Carlo Model (KMC)



Performance

- Synthetic microstructure created based on the processing conditions
- Image analysis/Correlation statistics

- Synthetic microstructure being used for performance simulation

New Point Net Beam Strategies to Control Thermal Gradients, Solidification Rates and Microstructures

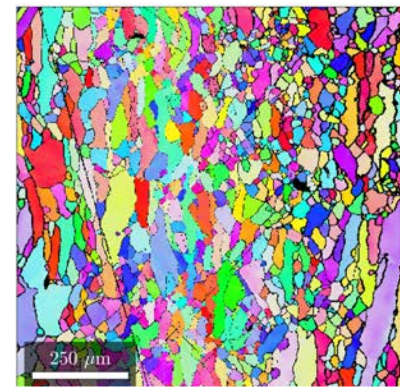
- **Physics is contained in heat transfer response**

Random

Square

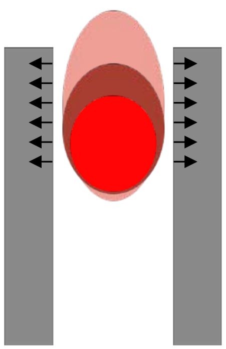
Random

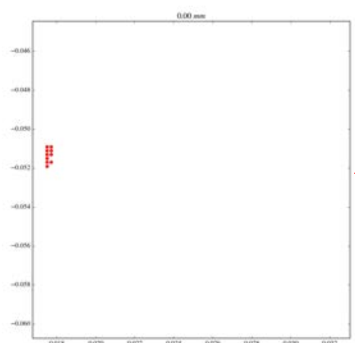
Square



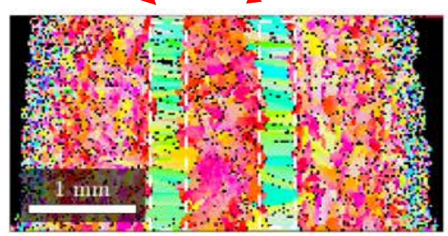
- **Mesoscopic texture control by changing melting sequence**

EBM282

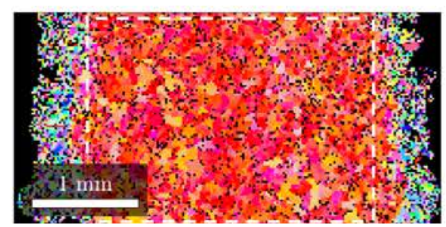




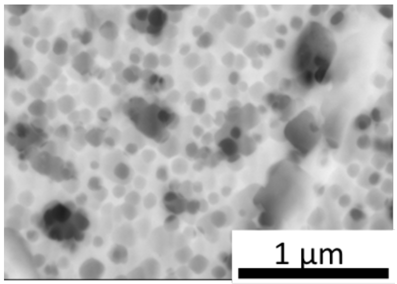
Melted last



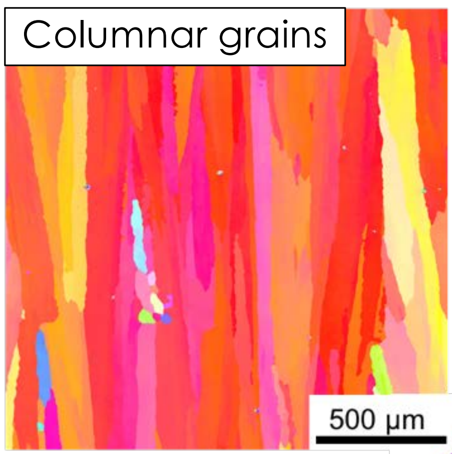
Standard

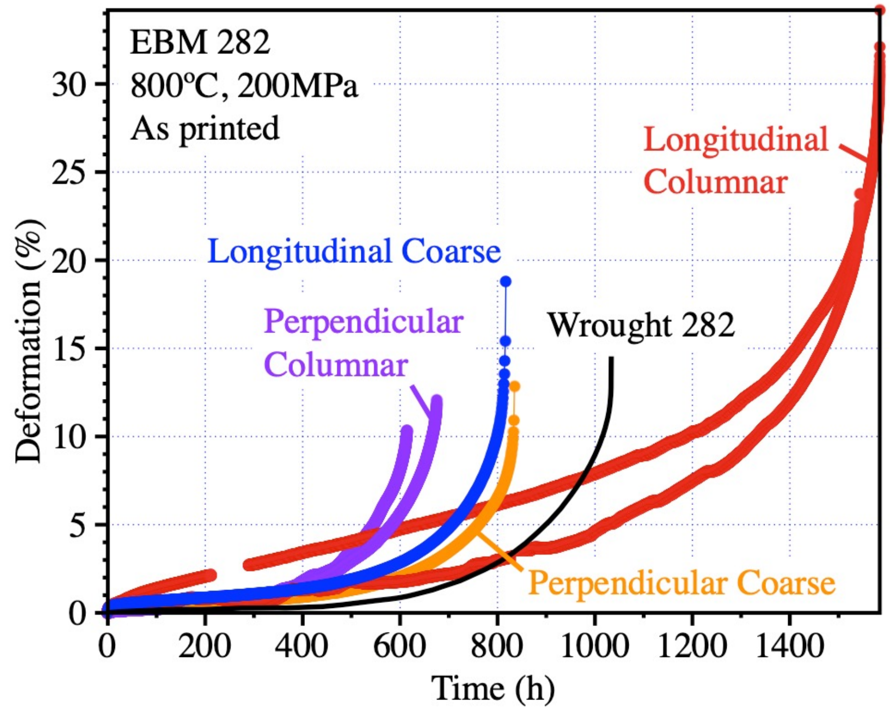


Controlling the Microstructure to Reduce EBM282 Creep Anisotropy at 800°C



As printed γ' strengthened
EBM 282
Ni-20Cr-10Co-8.5Mo-2.1Ti-1.5Al



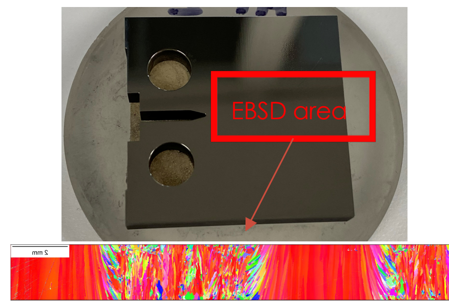


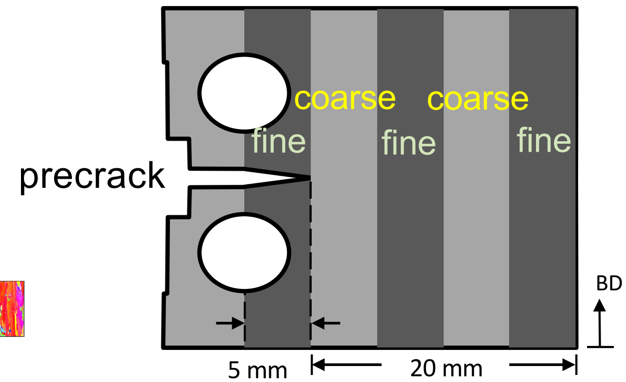
Same/better results at 750°C

Superior creep strength with columnar grains along the build direction (BD) but significant creep strength decrease perpendicular to BD

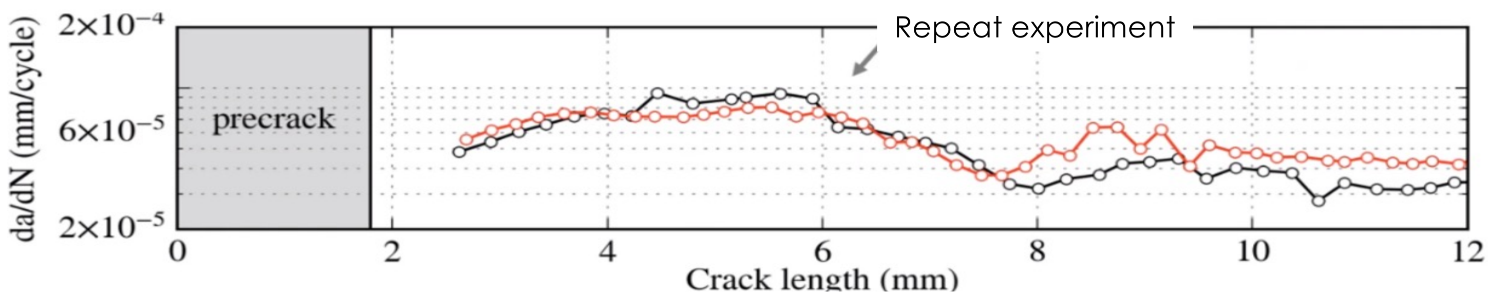
Variation of Fatigue Crack Growth in EBM 282 Composite Microstructure

Constant ΔK=20ksi*in$^{0.5}$ tests
Paris Law: $da/dN = C(\Delta K)^n$
Hence $da/dN = f($***microstructure alone***$)$

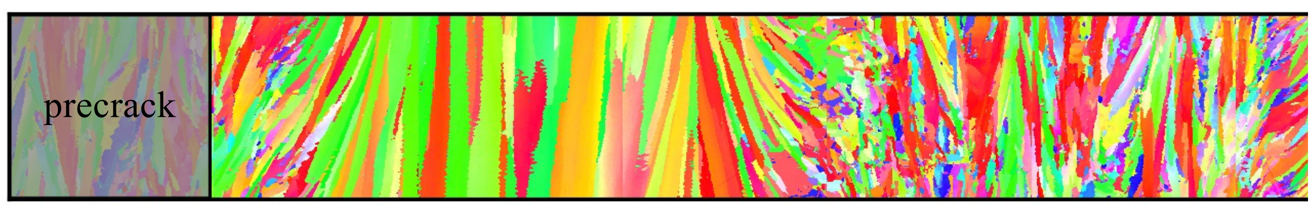




2X da/dN change across microstructures



'Composite' microstructure of EBM Haynes 282 coupon



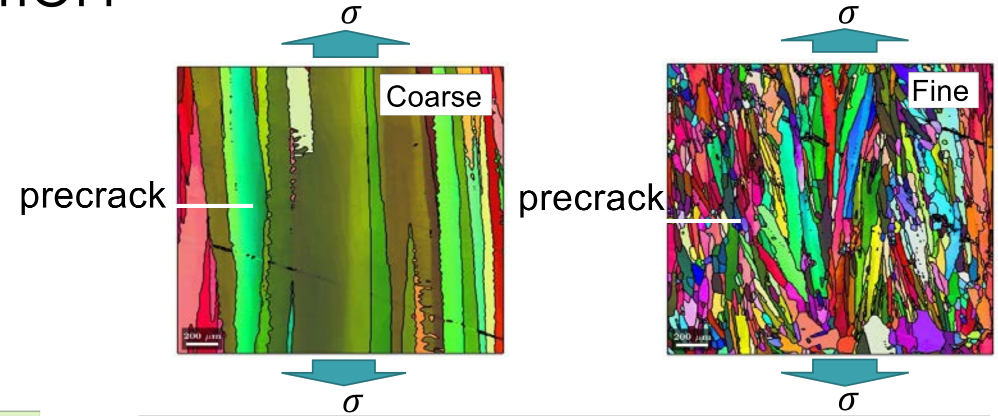
Coarse columnar grained region

Fine grained region

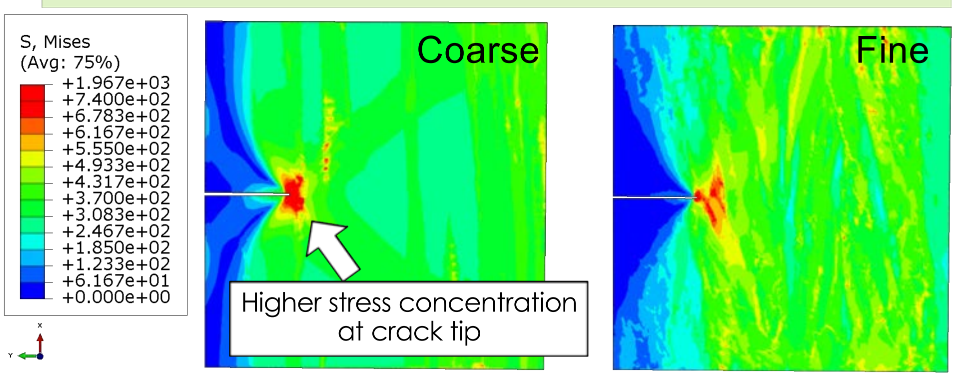
Crystal Plasticity Model Reveals Microstructure Influence on Fatigue Crack Propagation

- Crystal plasticity finite element model (CPFEM) predicts the effect of grain size, grain morphology and texture on the heterogeneous deformation in the microstructure

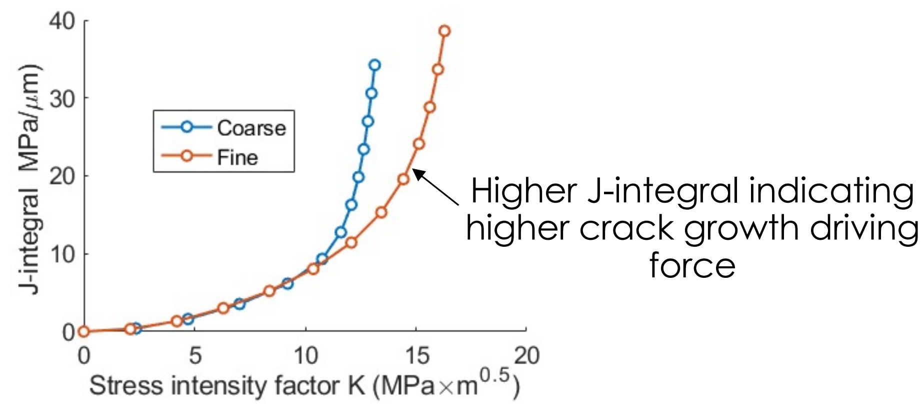
Simulated microstructure



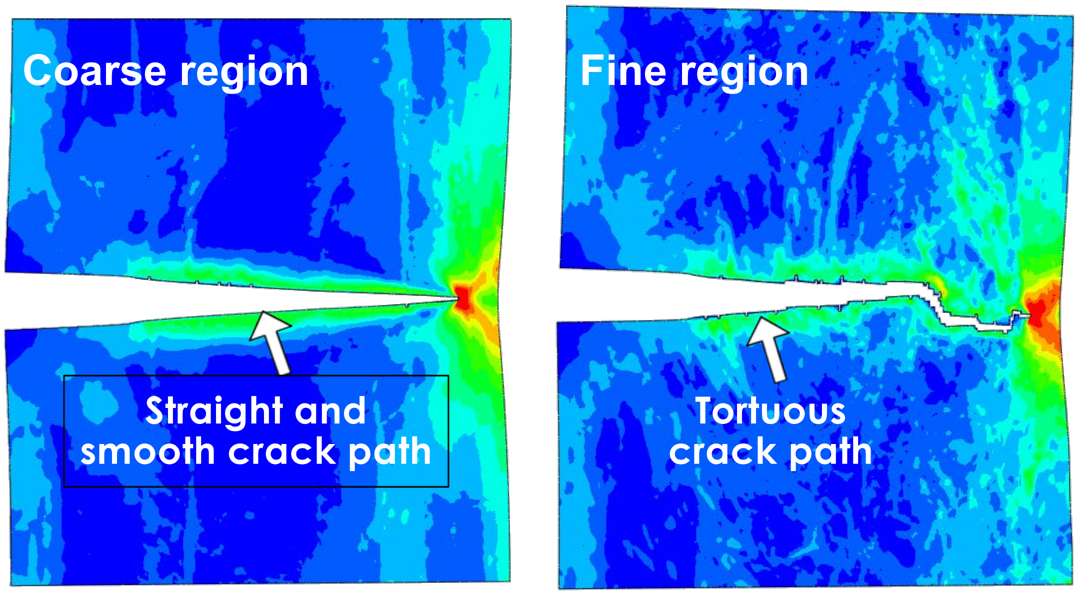
Distribution of stress under applied load of 320MPa



J-integral component along crack direction

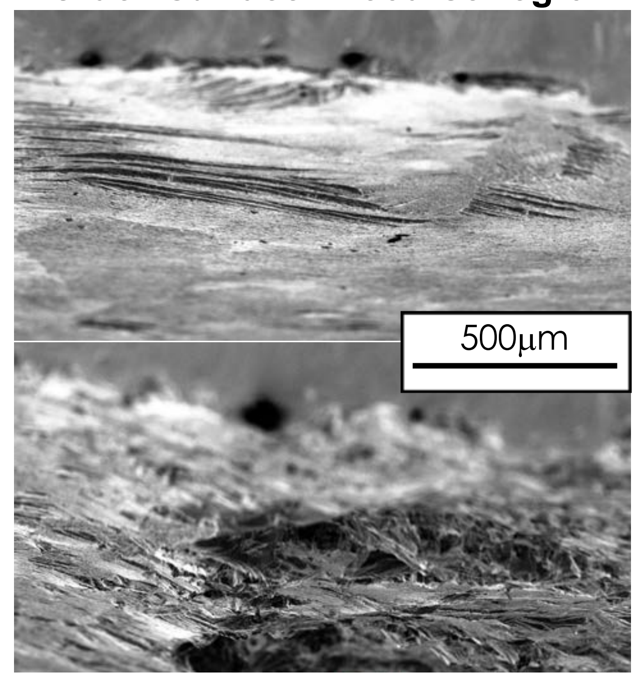


Crystal Plasticity Model Predicts Different Crack Propagation Paths for Coarse and Fine Regions



CPFEM simulated crack path

Crack surface in coarse region



Crack surface in fine region

Fractography of fatigue crack surfaces

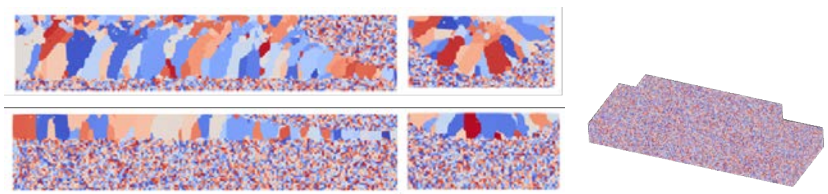
Demonstrate opportunity for local control of properties through microstructure control for complex components

Synthetic Microstructure to Accelerate Process-Microstructure-Performance Correlation

Process-Microstructure

Using Kinetic Monte Carlo Model

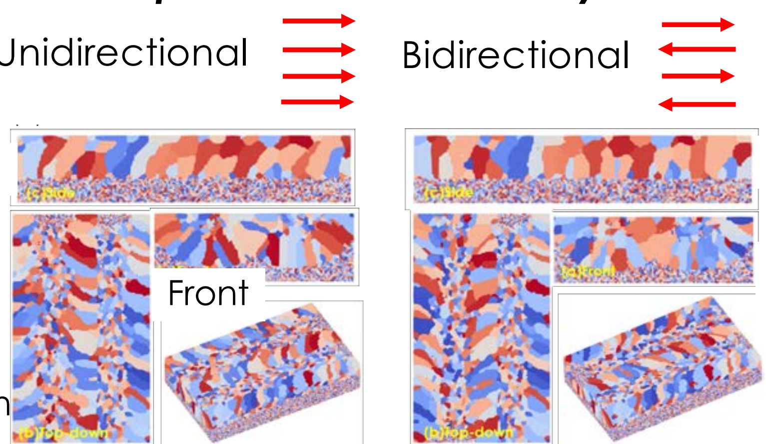
1.Melt Pool Shape



2.Scan pattern & 3.Geometry

Unidirectional

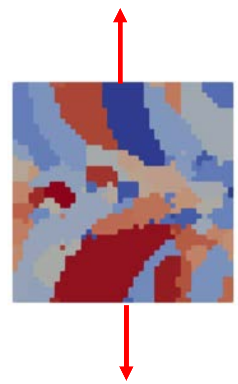
Bidirectional

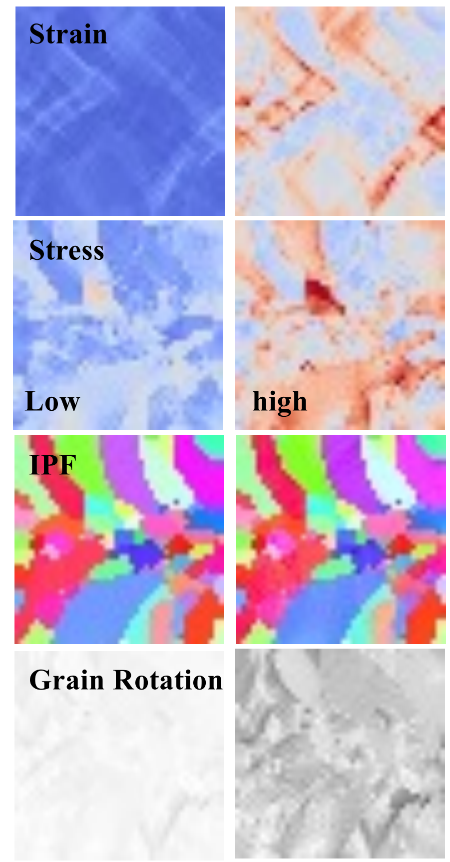


Microstructure-Performance

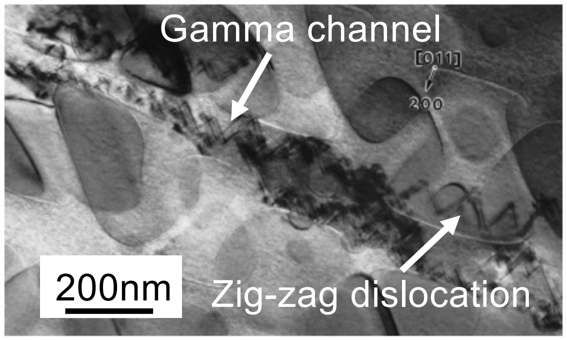
Conversion from KMC to FEM

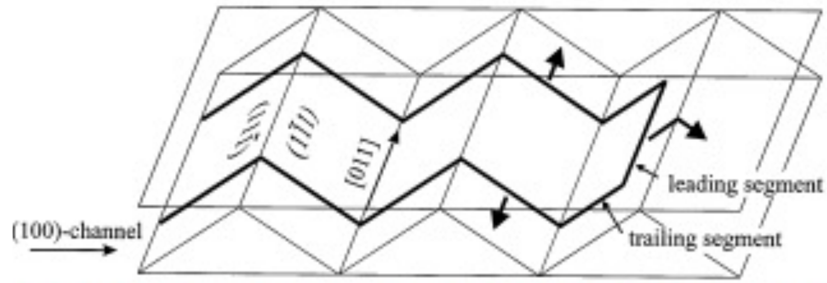
Uniaxial Loading





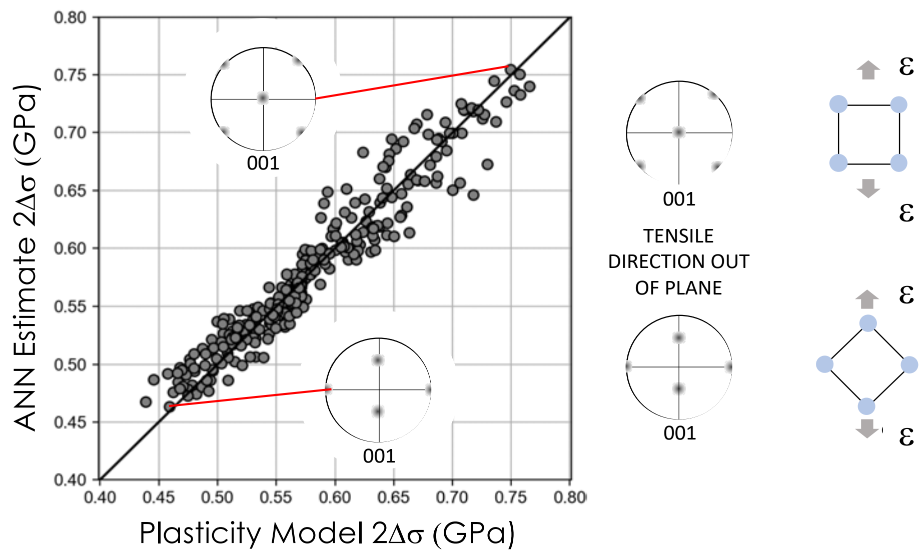
Machine Learning Surrogate Model for Emulating AM Ni-base Superalloy Viscoplastic Behavior



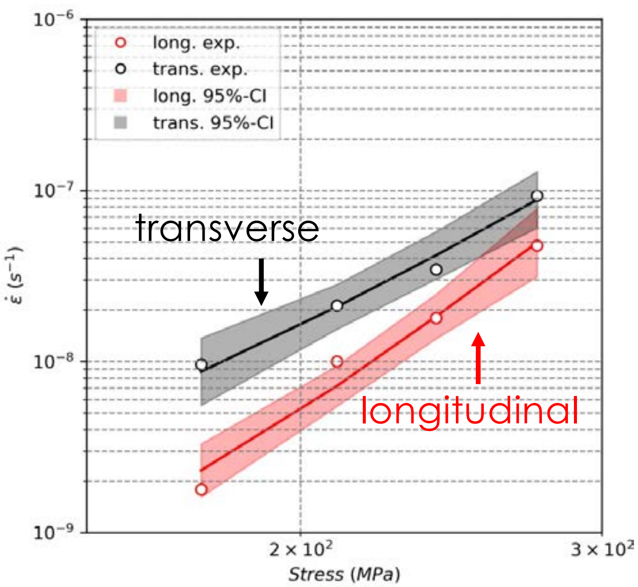


- Addition of cube slip systems in viscoplastic self-consistent (VPSC) code can explain observed mechanical anisotropy
- ANN emulates the VPSC model (or CPFEM model) to predict mechanical properties based on anisotropic crystallographic texture

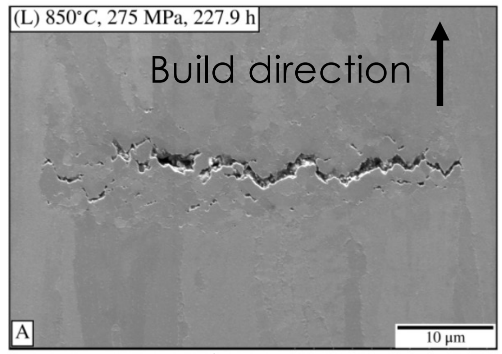
ANN model captures strength-texture dependence



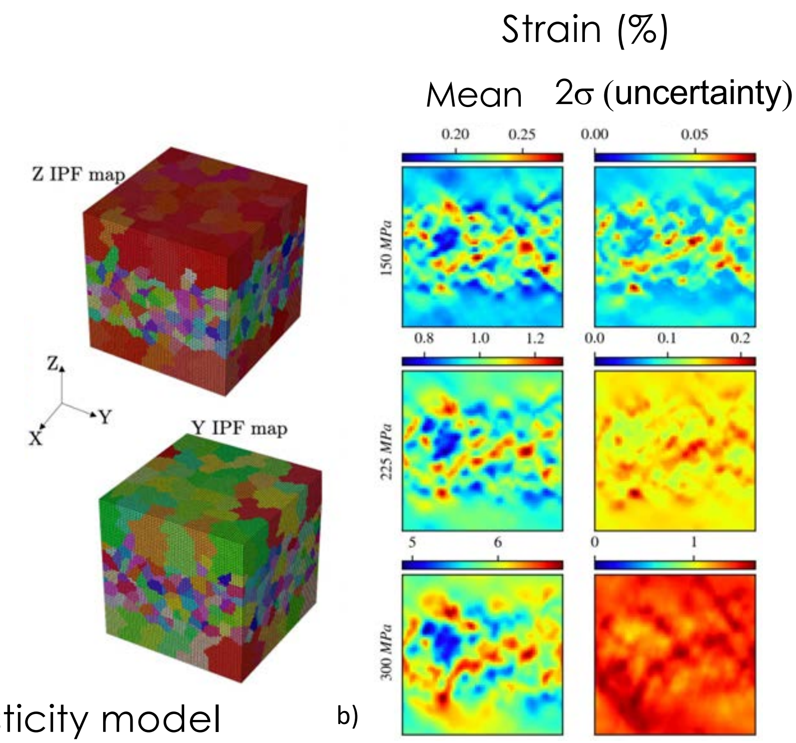
Equiaxed Grain Clusters Found in AM Microstructures Results in Local Strain concentration



Creep properties of EBM 738



AM materials can contain heterogenous 'stray grains' which crack during creep

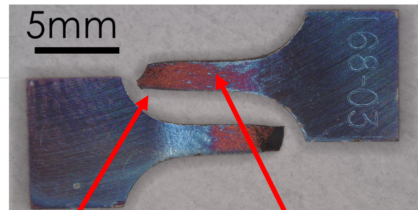


Crystal plasticity model

Creep properties anisotropy likely related to crystallographic texture and heterogenous stray grains leading to local stress concentration

Extract Maximum Constitutive Information From Experiments Utilizing Correlation Statistics

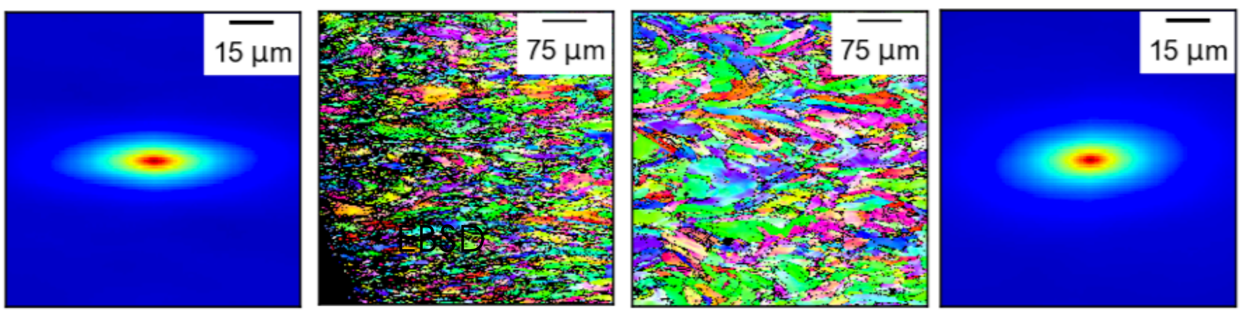
LPBF 316L
600°C tensile

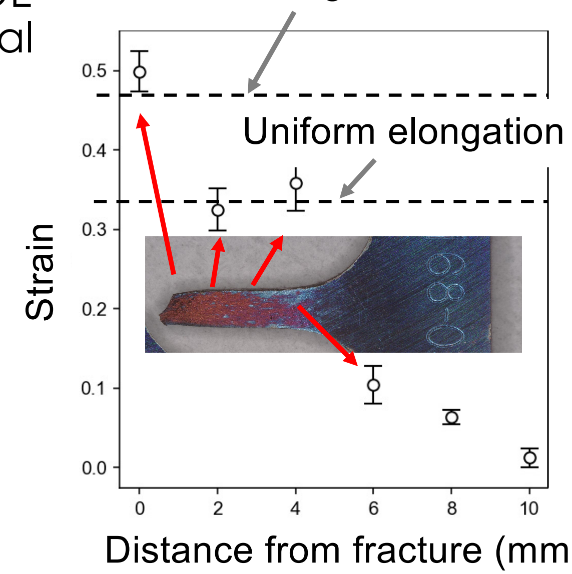


Collaboration with DOE
VTO Propulsion Material
Core Program

Autocorrelation
function

0 mm
4 mm

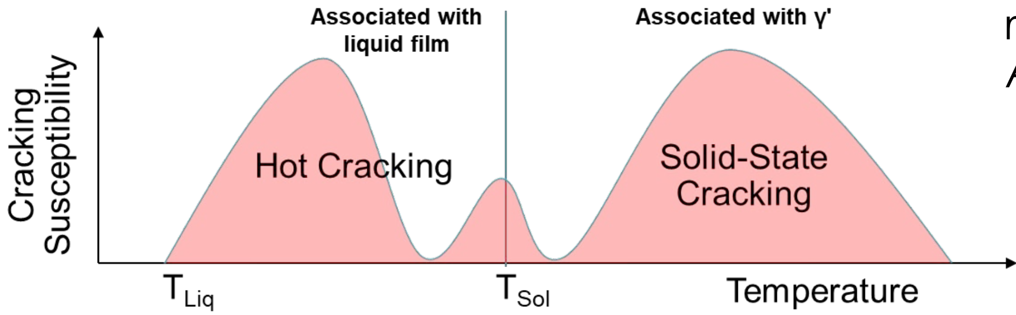




- Successful estimate of strain from microstructure
- Tools can be used for microstructure/properties or damage correlation for tensile, creep, fatigue, oxidation, etc.

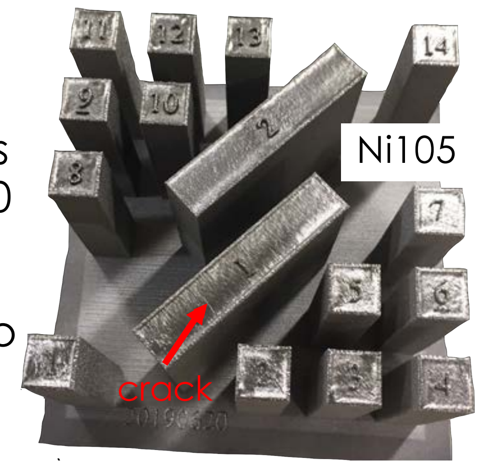
Understanding Crack Formation in High Gamma Prime Alloys for Crack-free Components

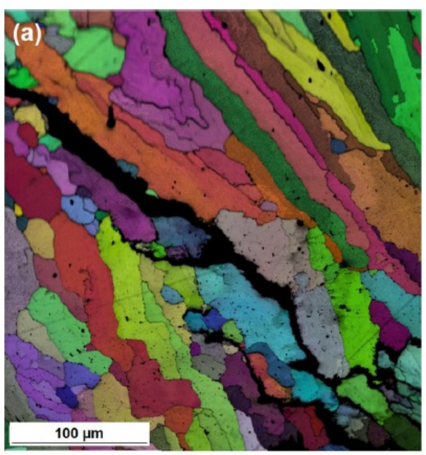
Crack Formation Modeling (EERE-AMO/FE)

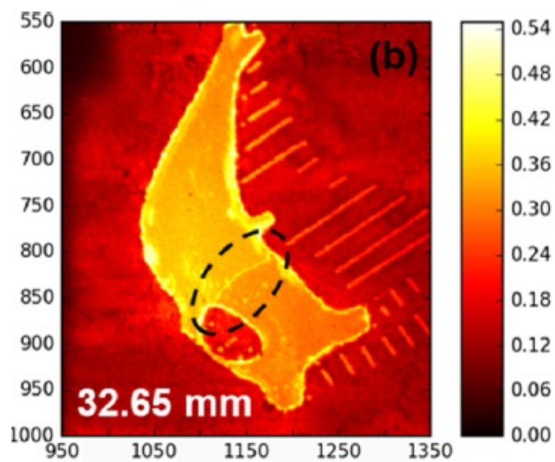


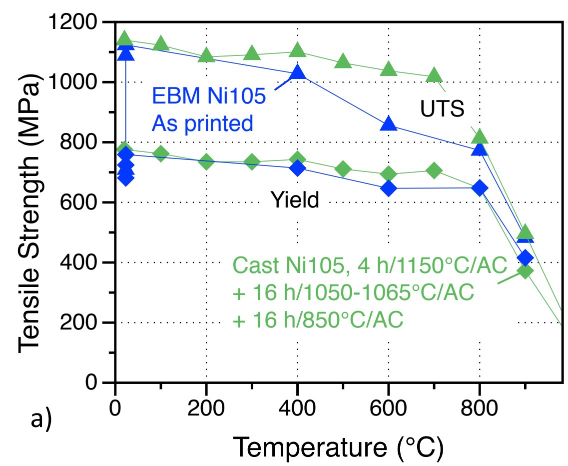
Looking at new alloys relevant for FE such as Alloy Ni105 or ABD-900

Very different crack pattern compared to CM247

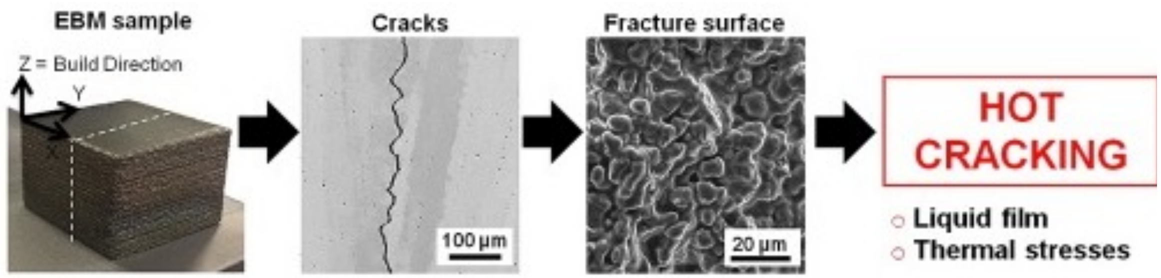






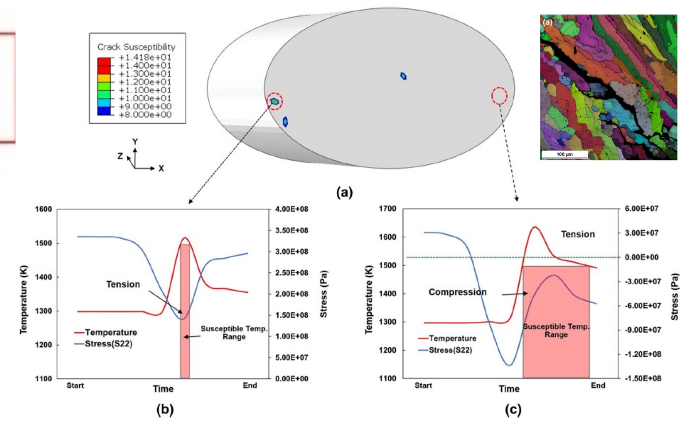


Cracking Prediction during AM Process



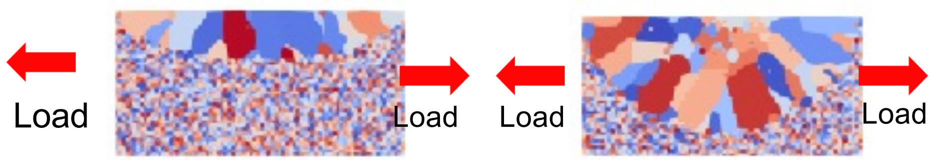
Chauvet, Edouard et al. "Hot cracking mechanism affecting a non-weldable Ni-based superalloy produced by selective electron Beam Melting." *Acta Materialia* 142 (2018): 82-94.

Hot cracking susceptibility



Lee, Y. S., Michael M. Kirka et.al. (2018)

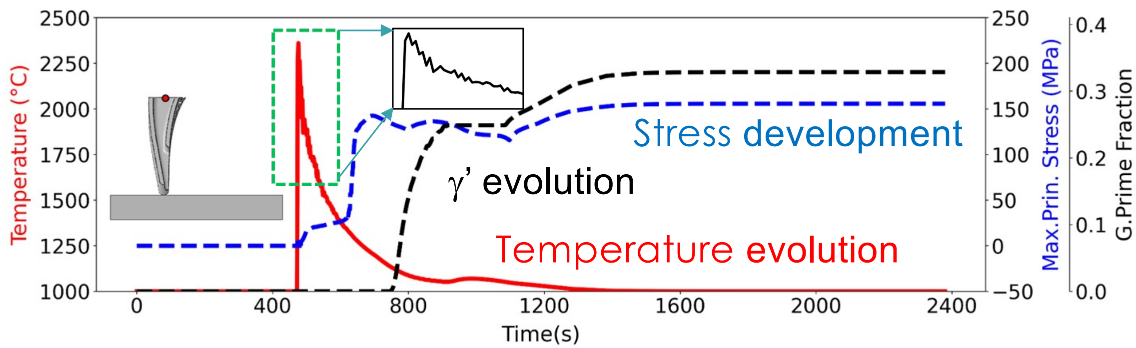
Grain morphology



Hot Cracking

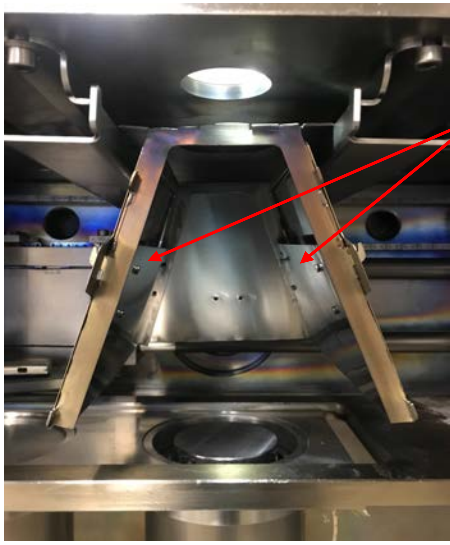
Solid-State Cracking

Complex blade geometry

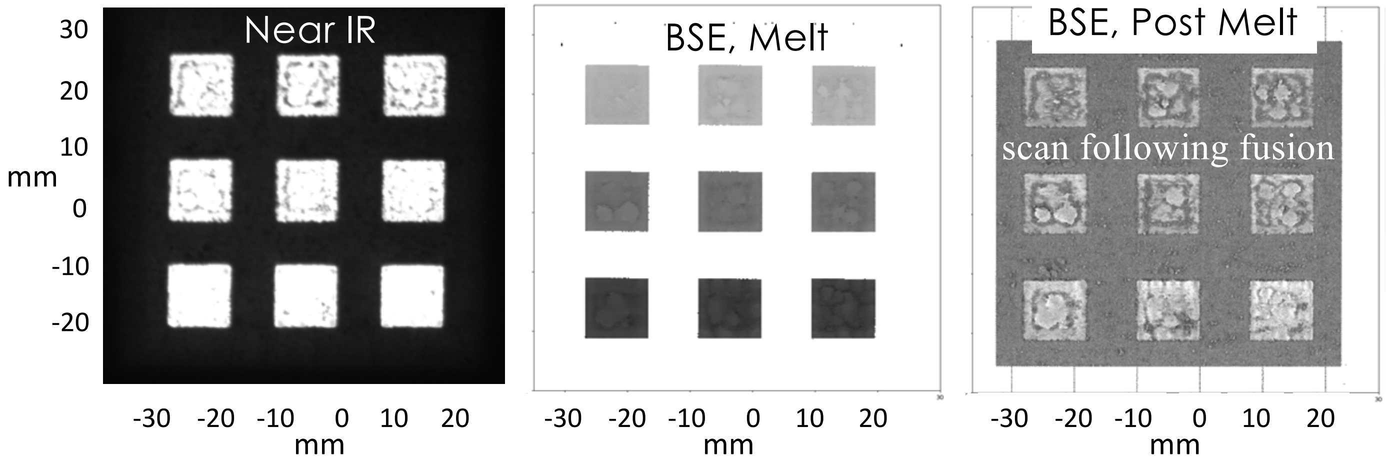


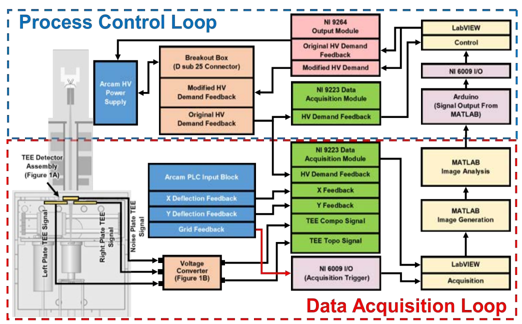
1. Thermal profile
2. Precipitation
3. Stress

Developing Advanced Sensor & Machine Learning Architecture for Near Real-Time Process Control



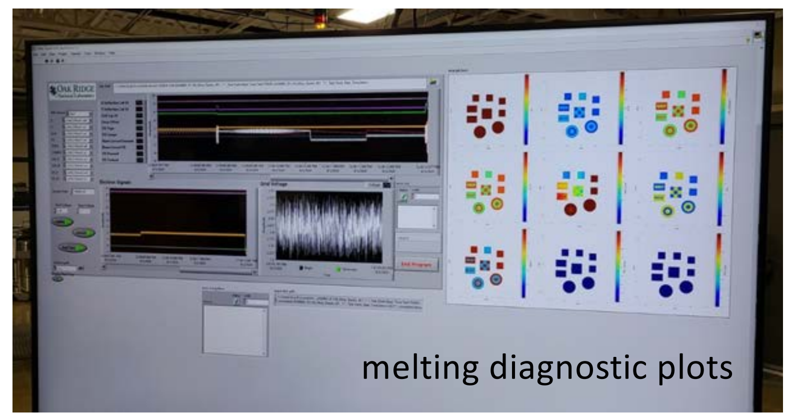
Stainless steel plates used as backscattered electron detectors (BSE)





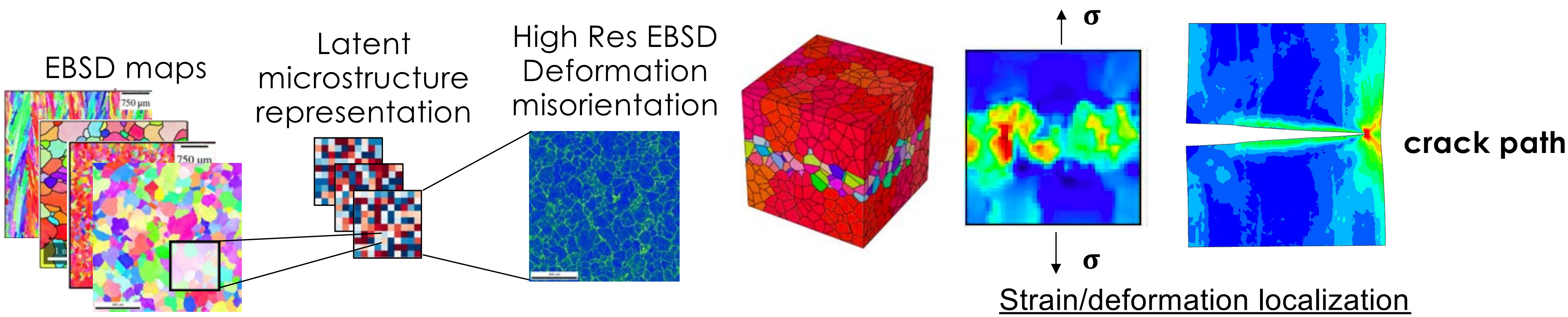
C. Ledford, M. Tung, C. Rock, T. Horn 2020

Real time process control



Conclusion/Future Work

- Significant progress in developing modeling/data analytics tools for process-microstructure-properties correlation



CNN architectures for learning stress-microstructural localization relationships

Strain/deformation localization estimates via FEA plasticity

- Add complexity to the synthetic microstructure i.e. precipitates
- Upgrade/modify tools for large scale AM
- AM Microstructure control for specific application (e.g. H)

Acknowledgment: "This material is based upon work supported by the Department of Energy Award Number DE-FEAA128."

Disclaimer: "This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof."