Monitoring and Advanced Diagnostics to Enable AM Fundamental Understanding

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Ade Makinde & Prabhjot Singh
GE Global Research Center

Additive Industrialization at GE

- Different laser processes are in use internally
  - Powder bed
    - DMLM
    - E-BEAM
  - Wire-fed
  - Powder-fed
- Materials
  - Alloys (Al-, Fe-, Co-, Ni-, Ti, etc.) and Refractory metals
  - Ceramics
  - Polymers
- Aviation - High Volume Additive (1000s parts/year) Manufacturing Facility in Auburn, AL
- CATA, a corporate facility to drive innovation and implementation of advanced manufacturing technologies across GE in Pittsburgh, PA
- Additive development centers in each of the business

We are building parts that have been qualified & going into service

DMLM Process Development Fishbone Diagram

DMLD

Control of residual stress
Surface finish

Materials

Powder
- Mean Particle Size
- Particle Size Distribution
- Morphology
- Composition
- Porosity
- Flowability
- Packing density
- Material properties

Process/Machines

- Laser type (Wavelength, power)
- Laser spot Size / Variation
- Atmosphere & Inert gas flowrate
- Preheat temperature
- Preheat uniformity
- Humidity
- Material delivery
- Layer uniformity
- Residual stress build-up
- Powder handling & re-use

Heat Treatment/HIP

Metallurgy
- As-built microstructure
- HT temperature/ramp rate
- HT hold time
- HT atmosphere
- Phase formation

Surface finish
- Geom. fidelity
- LCF Life

Design

- Operating reqs.
- Feature resolution
- Feature geometry
- Tolerance reqs.

Process Planning

- Part orientation
- Path planner / Build preparation
- Scan-paths
  - Pattern
  - Power
  - Velocity
  - Layer thickness
- Support structure generation
- Operator

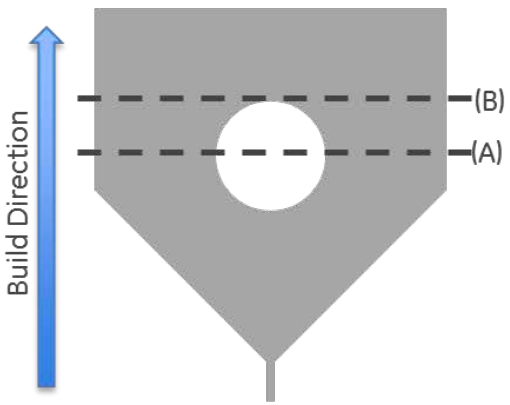
Post Processing (Surface finish)

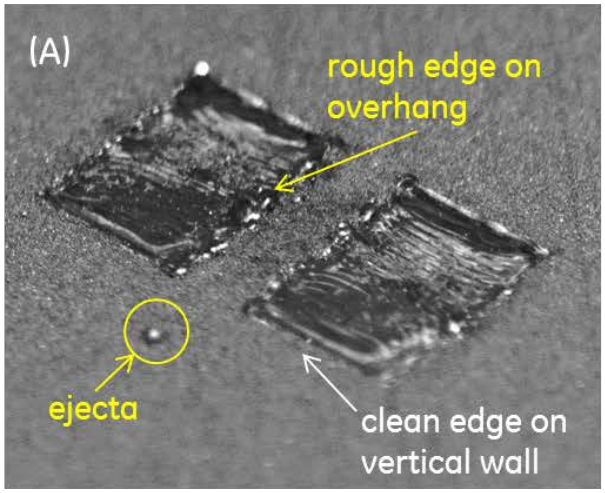
- Process method
- Final surface finish
- Material composition
- Feature fidelity
- Tolerances
- HIP

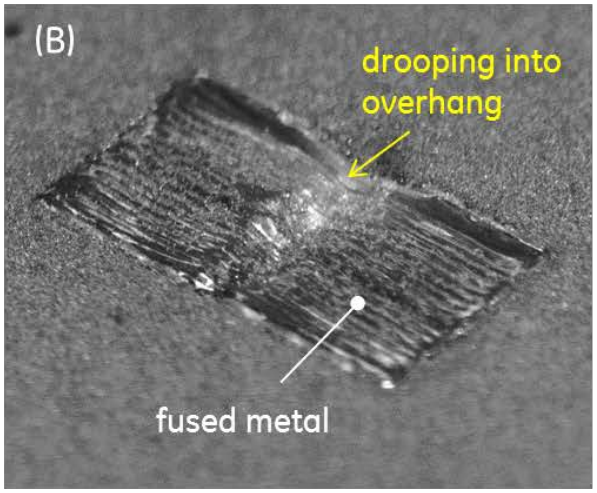
Distortion mitigation

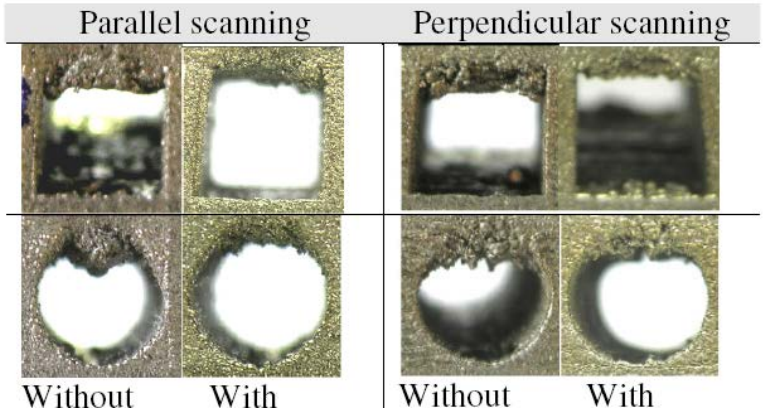
Porosity & surface finish

Process Issues









Meltpool control as a means to improving feature fidelity (Ref: KU, Leuven)

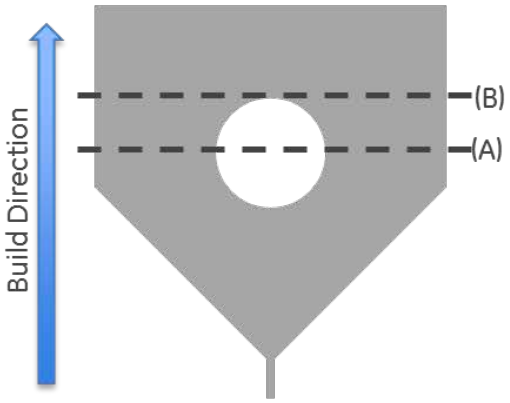
Types of sensors needed:

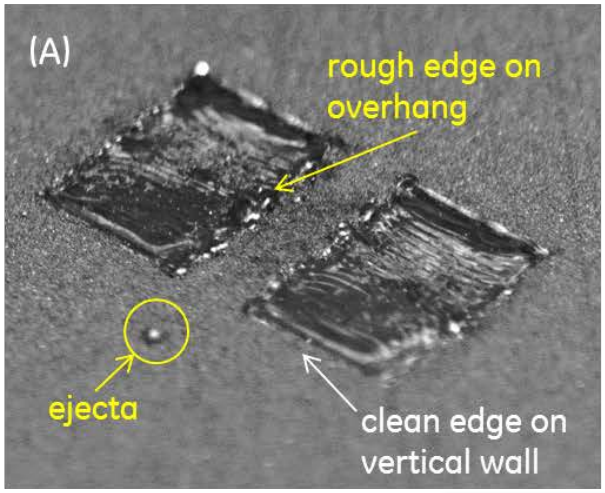
- High resolution cameras
- Melt-pool sensing
- Temperature sensors
- Humidity and moisture
- Gas flow
- Vibration
- Some method to look into the powder-bed

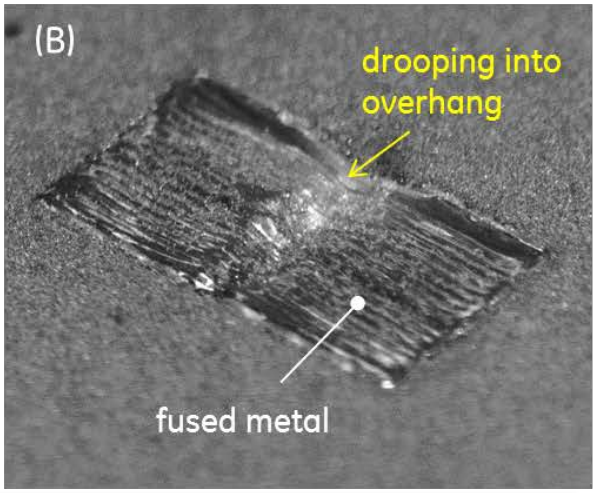
In-situ and Diagnostics Challenges in AM

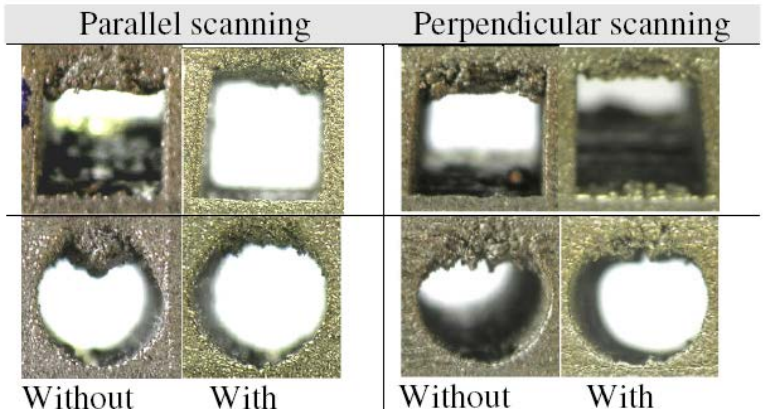
- High data rate collection needed
- Very large data sets; need efficient & fast data reduction algorithms
- Lack of sensors to capture the melting process in real time
- Control of thermal lensing
- In-situ look into the meltpool & powder bed
- Melt pool control
- High solidification rate (>1e5 K/s) thermodynamic database do not exist for microstructure modeling
- Non-uniformity of environmental conditions across the build chamber
- No ‘plug & play’: lack of access to machine process control information
- Large area with localized high temperature spots: challenge for infra red measurement systems
- Powder delivery & type of re-coater
- Cost of implementation of in-situ systems

Sensors Needed to Probe the AM Process









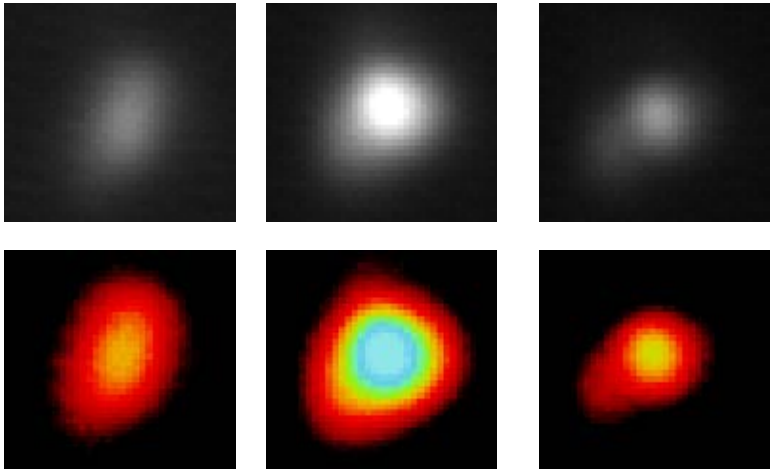
Melt pool control as a means to improving feature fidelity (Ref: KU, Leuven)

Types of sensors needed:

- High resolution cameras
- Melt-pool sensing
- Temperature sensors
- Humidity/moisture, O_2 sensors
- Gas flow
- Vibration
- Some method to look inside the powder-bed
- Stress cracking detection
- Packing density (re-coater)

Experimental Methods for In-Situ Monitoring

- Photodiodes to see variation in melt pool size with geometry
- High-speed imaging of the melt pool (10+ KHz)
- Close-loop control interface monitoring module integrated with laser signals
- Ultrasound (porosity & cracking detection in a ‘noisy’ environment)
- Infrared / pyrometer (thermography of a large area with localized hot zones a challenge)
- High energy X-rays (lab. level: for fundamental process understanding)



High speed imaging of the DMLM melt-pool

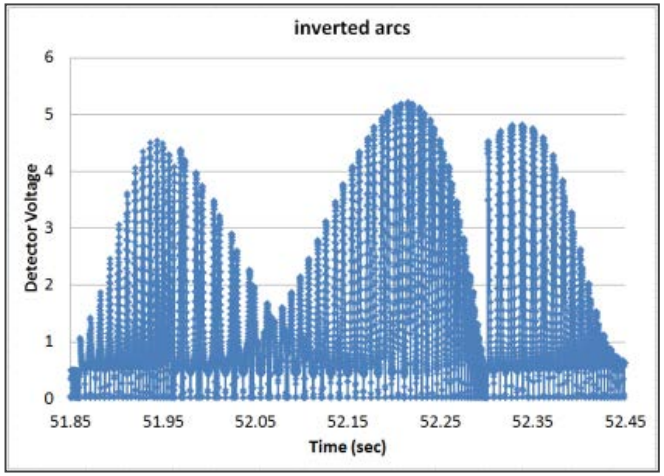
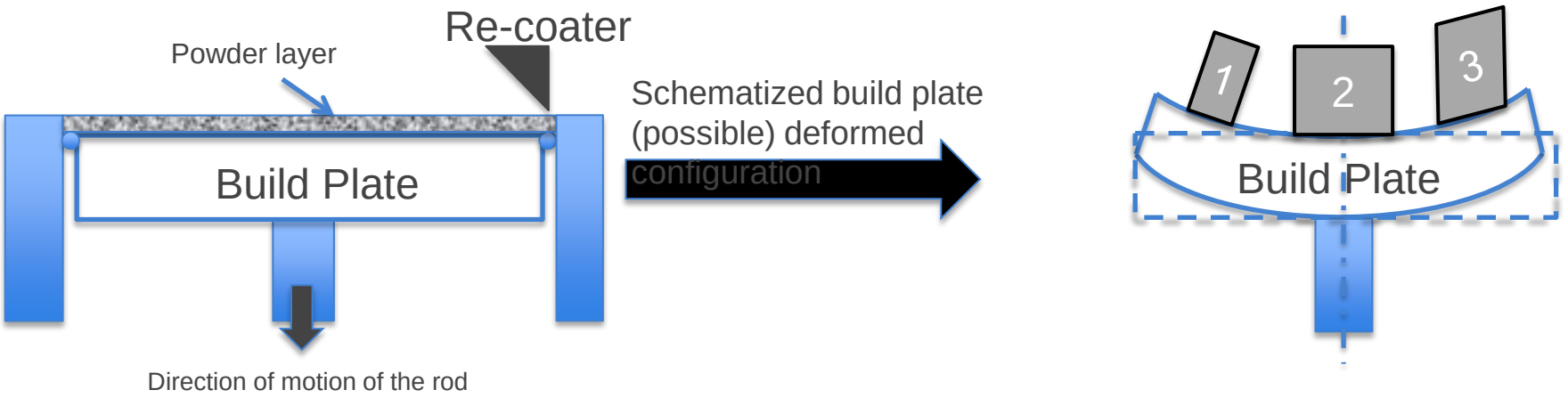


Photo-diode data showing variation in light intensity with geometry (higher at overhangs)

Integration of Uncertainty Analysis into Process Monitoring and Diagnostics: A Suggestion



- Variability in build surrounding conditions (heat transfer, laser spot size, thermal lensing, …) across the build plate & during the build affects the part
- Deterministic modeling is not good enough
- Powder packing from machine-to-machine (differences in re-coater, speed): thermal properties such as absorptivity & conductivity
- Powder re-use
- Need to use Bayesian hierarchical model (BHM) to compute and manage variability coupled with detailed physics-based models of melt-pool

Use of In-situ Measurements for Design Iteration, Inputs, Optimization, and Quality

- High fidelity physics model validation
- Use BHM to manage & control variability for integration into design practices
- Improves estimates of part life

- Understanding interaction between the different stages of the process: powder(size & distribution), laser, process parameters, part orientation, support structure, material properties (surface tension, viscosity, …), surface finish, distortion/residual stress, microstructure, …)

- Use BHM to develop fast, reduced order models incorporating new build and legacy data to update the uncertainty models for use in real time computations with integration into process monitoring

Appendix

References

- Measurement Science Roadmap for Metal-Based Additive Manufacturing - NIST 2013 Report
- Measurement Science Needs for Real-time Control of Additive Manufacturing Powder Bed Fusion Processes - NISTIR 8036
- Slotwinski *et al*, '*Porosity Measurements and Analysis for Metal Additive Manufacturing Process Control*', 2014, http://dx.doi.org/10.6028/jres.119.019
- J.-P. Kruth *et a*l, '*Feedback control of Selective Laser Melting*'
- GE internal reports