Achieving "Just Press Print" for Metal Additive Manufacturing

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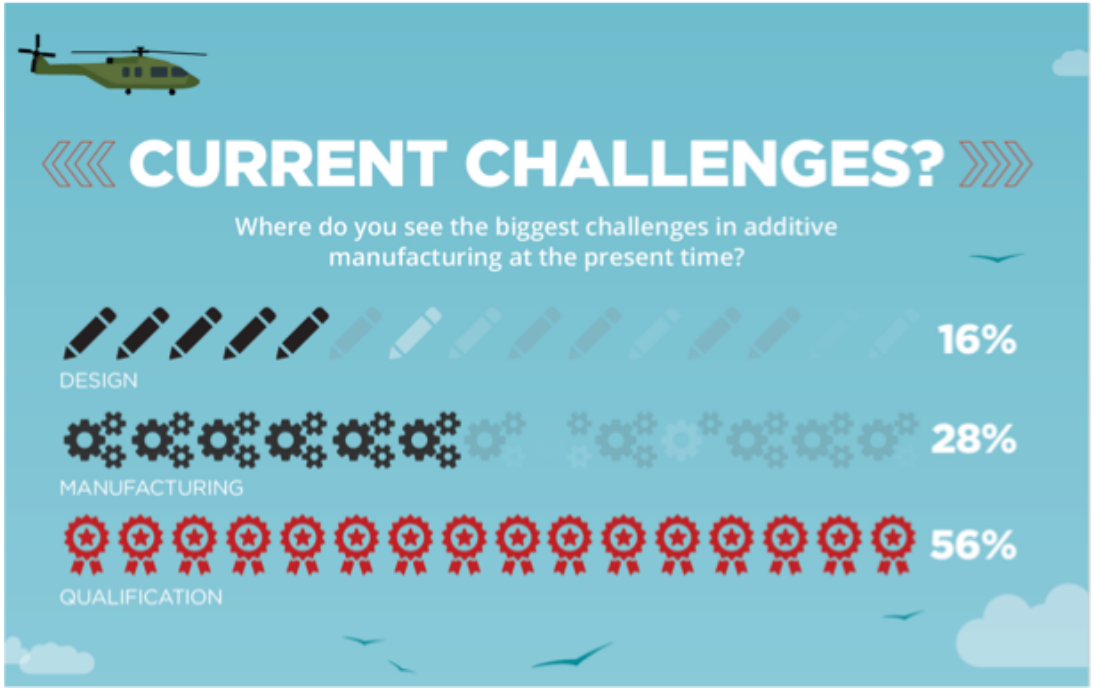
Today, there are still barriers to adoption of metal additive manufacturing technology

- 56% of manufacturers surveyed indicated that **uncertain quality** of the final product is a barrier to adoption of AM
- FAA very concerned about process variability and defects that cause fatigue failures
- Success requires an experience base
- Limited science base

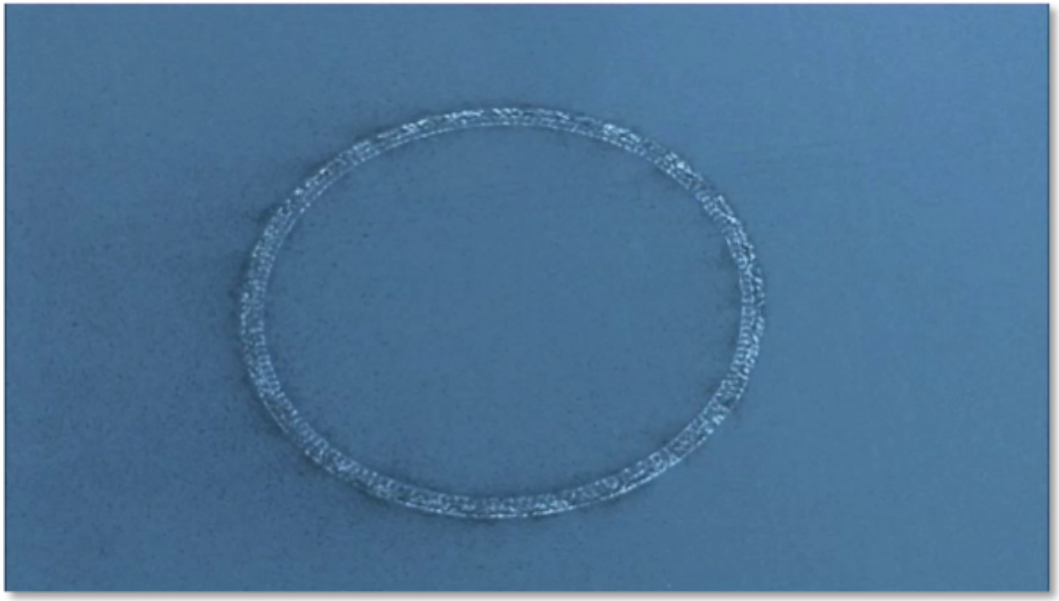


http://bit.ly/2hMibdi

The challenge is to replace the experience-based approach with a science-based, automated approach that can be implemented in real manufacturing environments

Why is qualification such a challenge for laser-based metal powder-bed fusion additive manufactured parts?

- The physics of the process is quite complex
- Process optimization is costly and time consuming (only have partial control)
- Material and part quality changes if there is a change in:
  - Geometry
  - Orientation
  - Feedstock material
- But, despite these issues, AM offers exquisite control of the process
- **The challenge is to harness this control to produce qualified parts**



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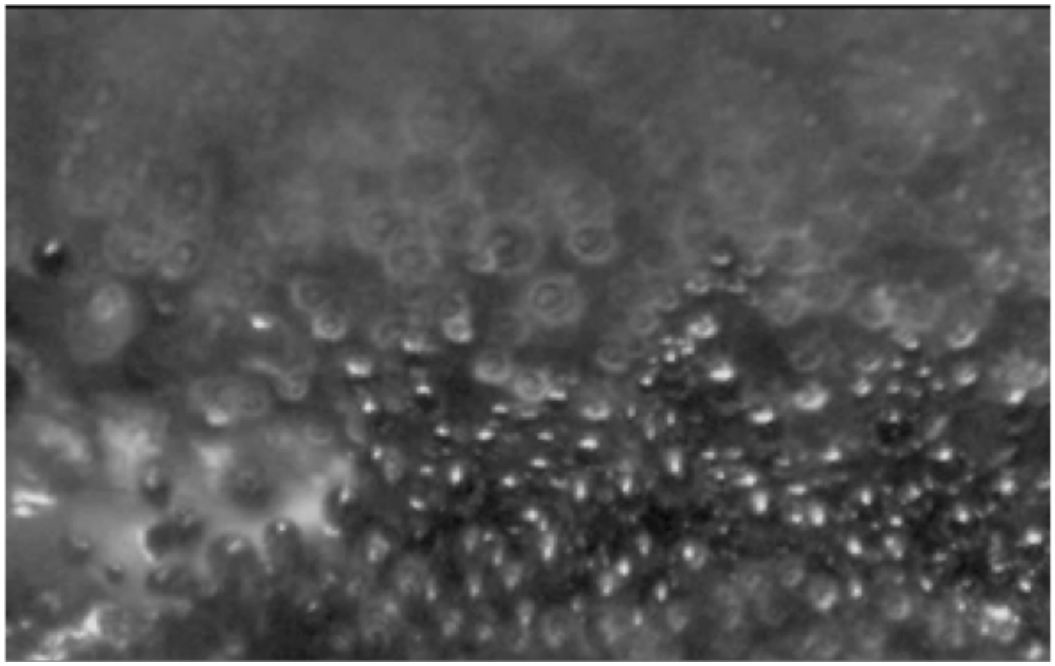
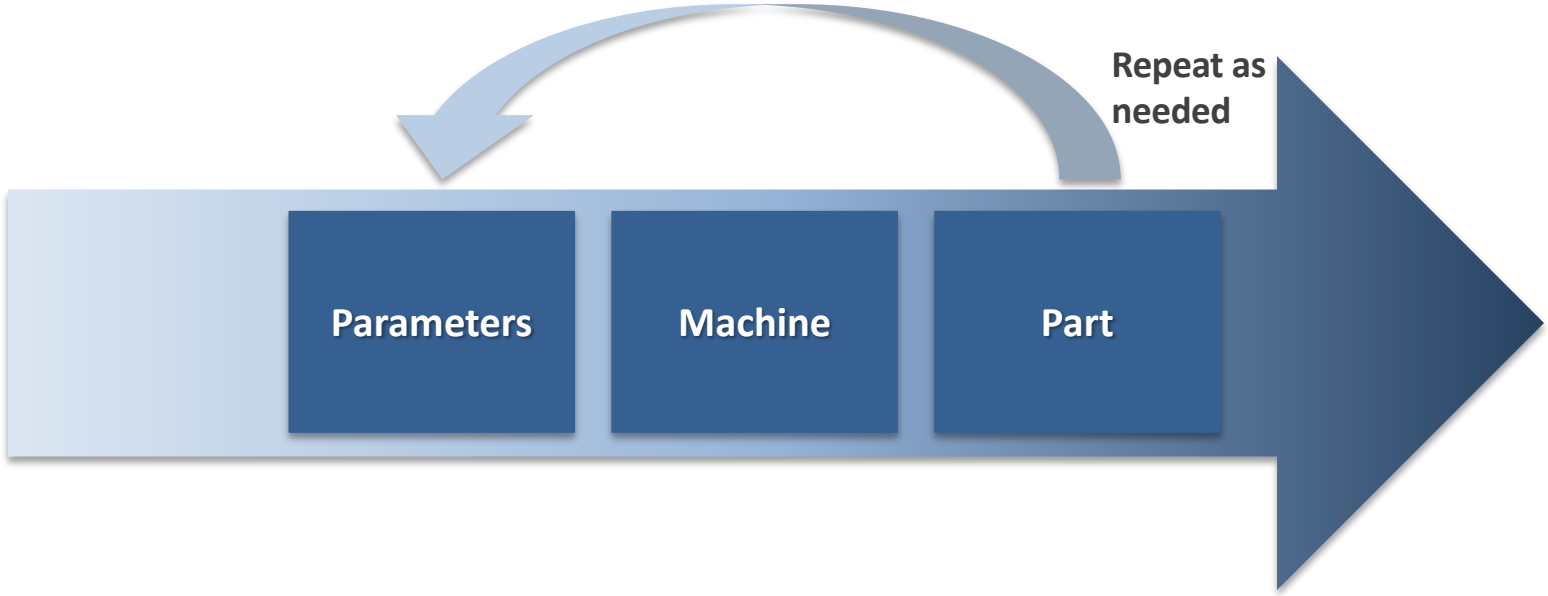


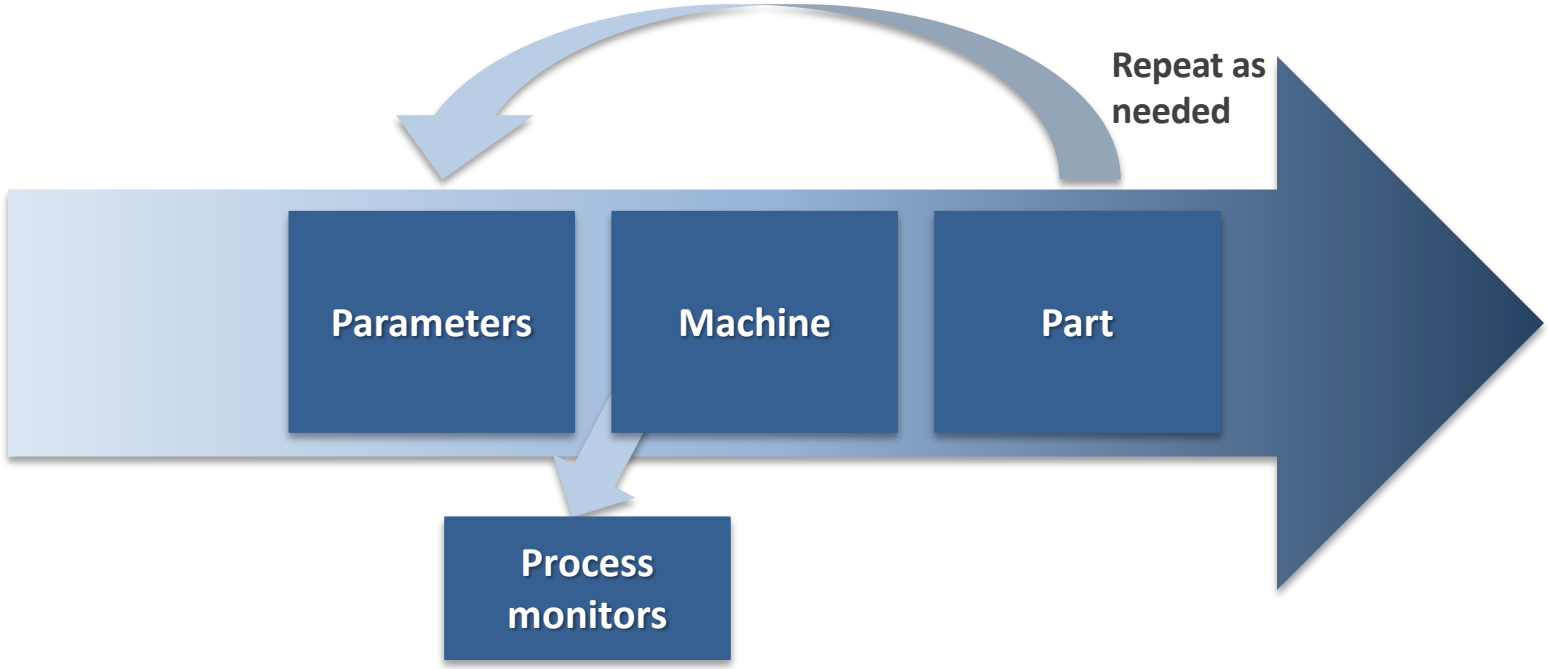
S. Ly et al. 2017, Nature Communications (in press)

Currently, there is no closed-loop control, only Edisonian iteration



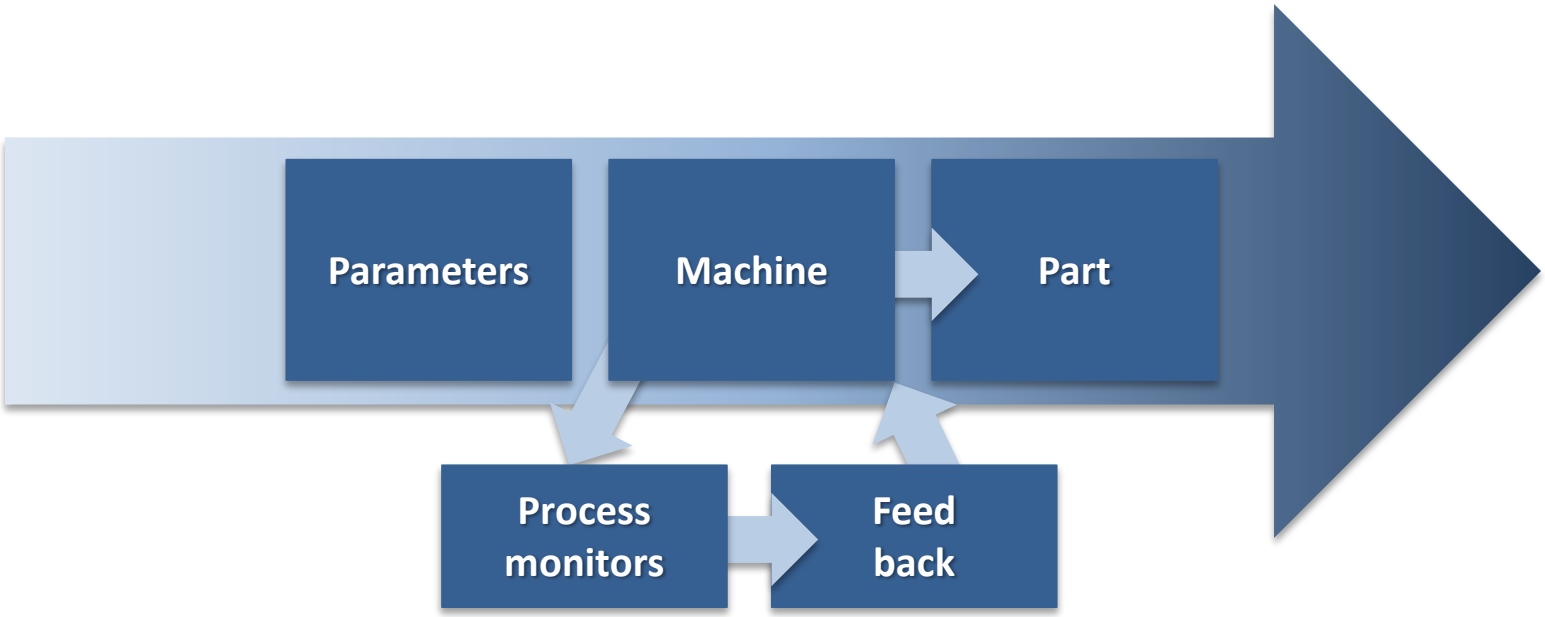
After many iterations, an acceptable part can be made

The approach being taken by some is to incorporate process monitoring, but is still open loop



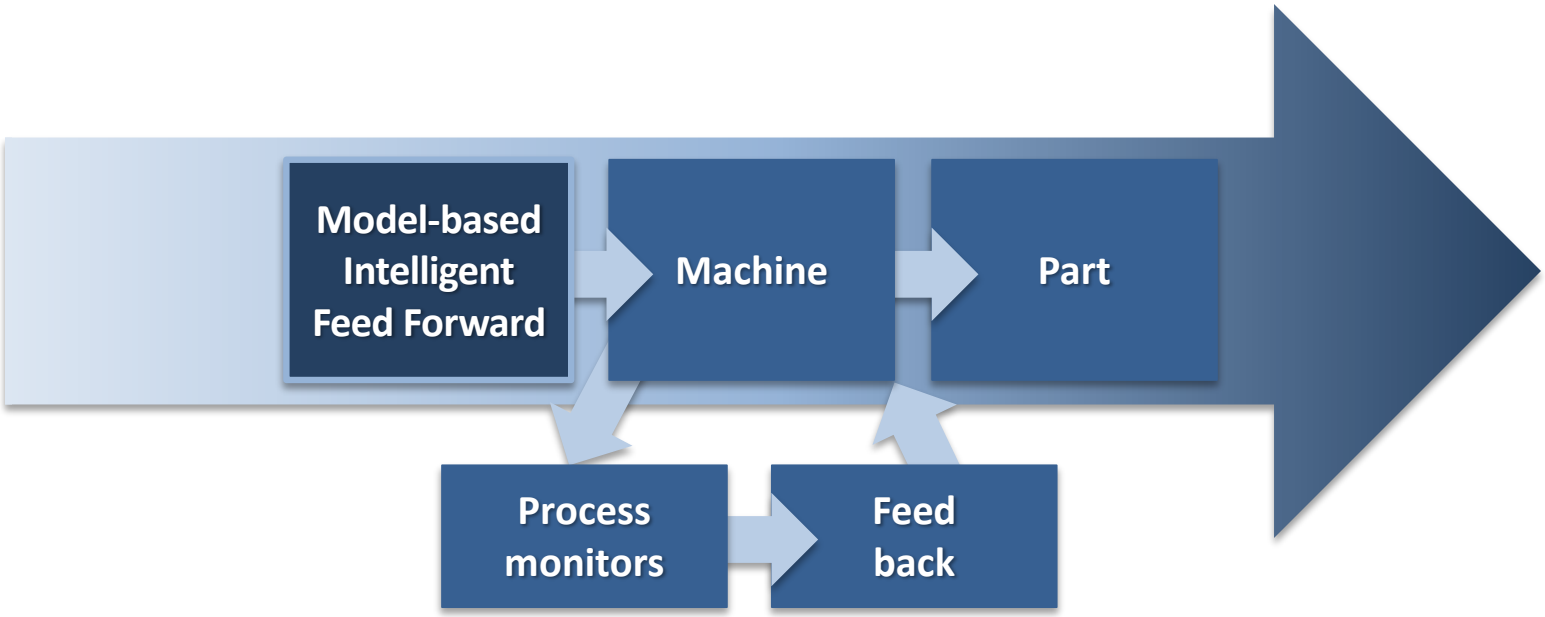
Fewer iterations, but still inefficient

Feedback control is the next step



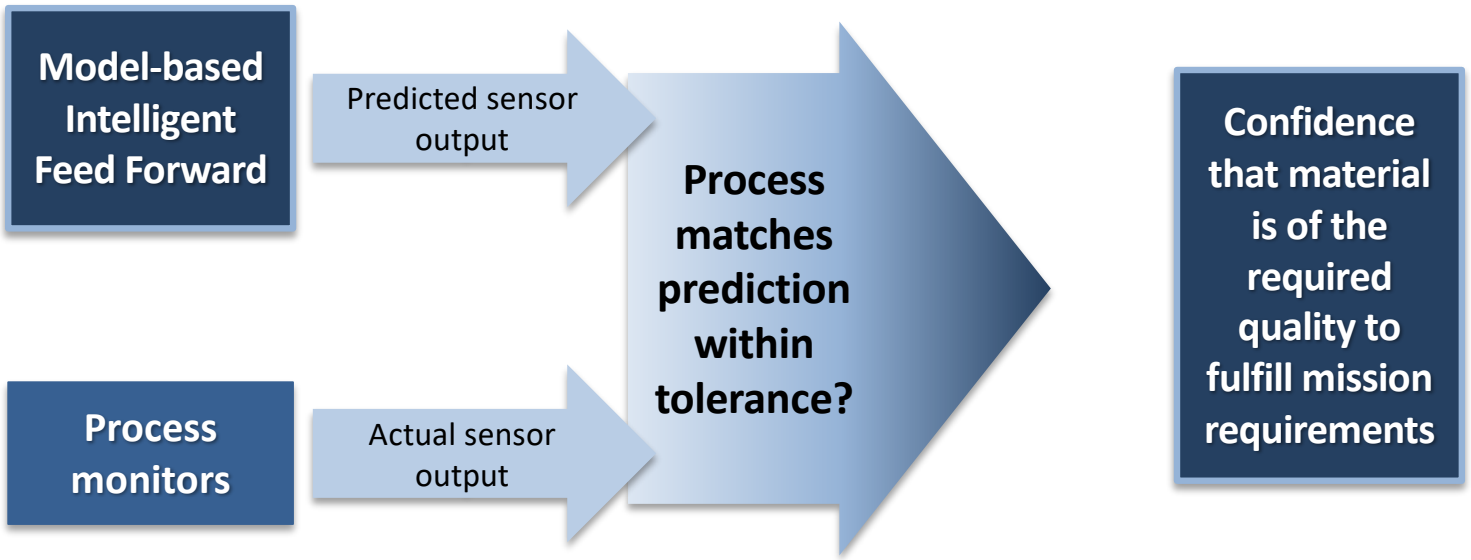
Works when parameters are close to optimal

Vision—Closing the loop with Intelligent Feed Forward (IFF)



IFF puts a narrow band on parameters and approaches "First time right, every time right"

IFF can provide a basis for qualifying parts



Feed-forward adaptive process control has the greatest potential for removing the dreaded variability associated with AM

IFF provides access to two additional classes of defect mitigation strategies

Common geometries and scanning

- Core
- Contour
- Up skin
- Down skin
- Top surface
- Hatch
- Scanning strategy
- Laser parameters

Pre-programmed

Scan

- Keyhole
- End or track
- Lack of fusion
- Fractional island scans
- Other scan strategy induced issues

Power and speed mapping

Part-specific geometry

- Thin walls
- Arbitrary inclined downward surfaces
- Unsupported overhangs
- Internal channels
- Residual stress
- Lattices

Voxel-by-voxel control

Today

With IFF

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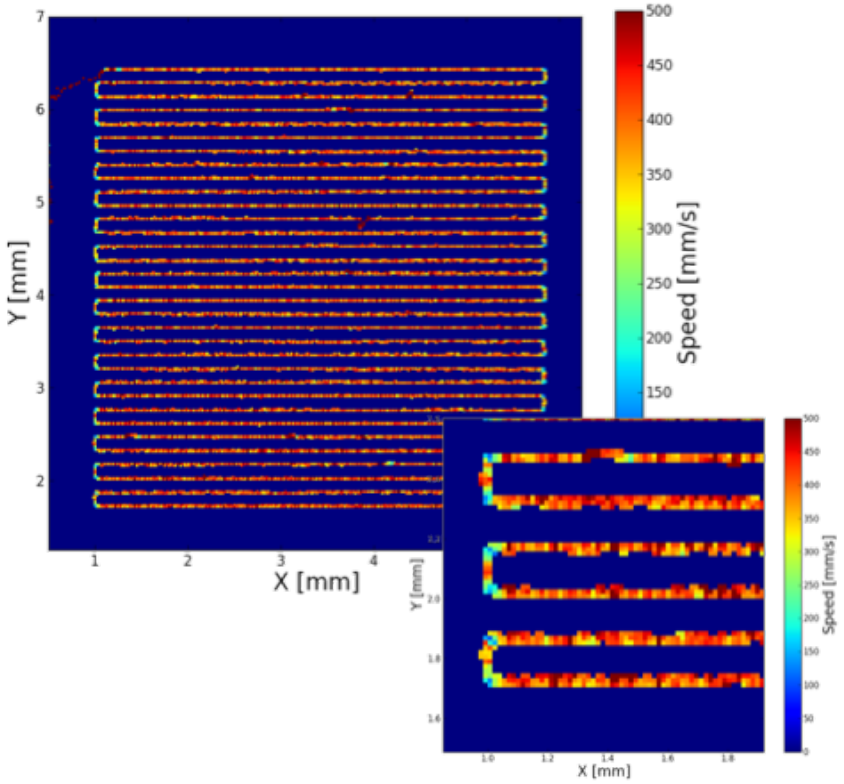
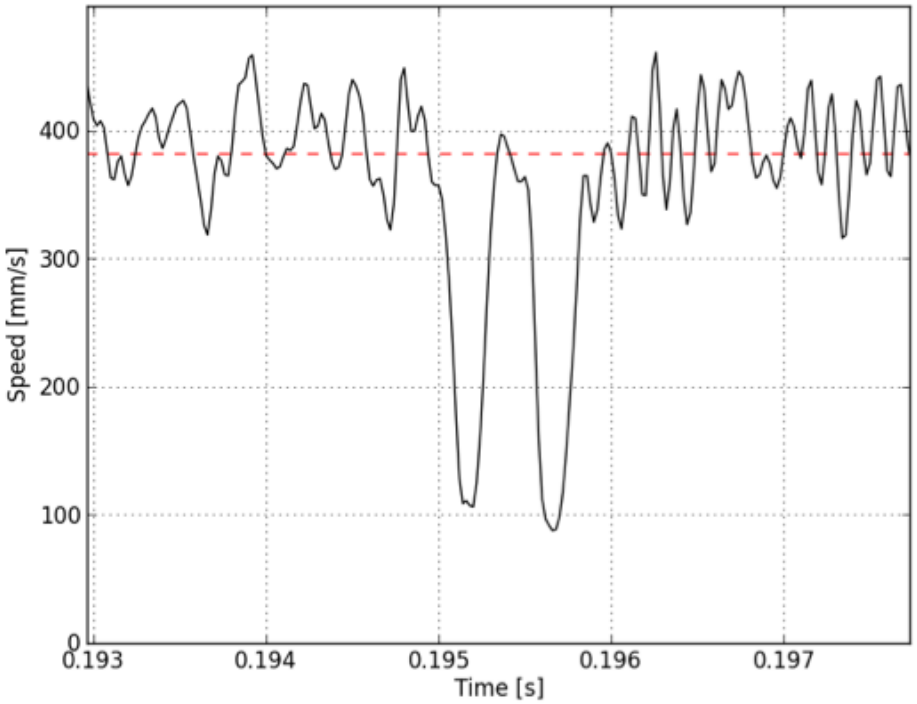
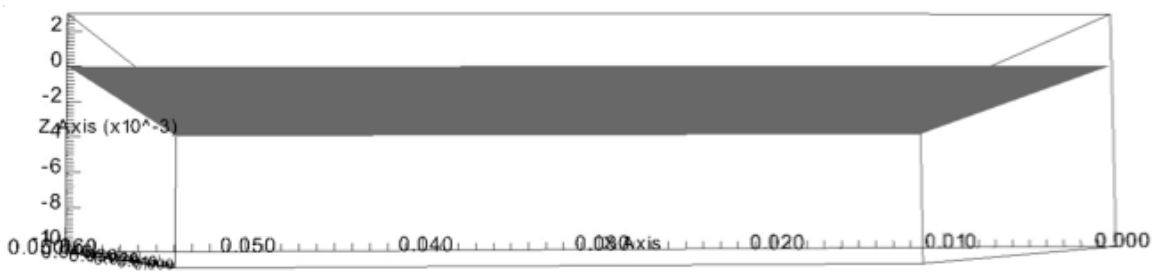
The serpentine island scanning strategy almost ensures the presence of keyhole defects at each turn around



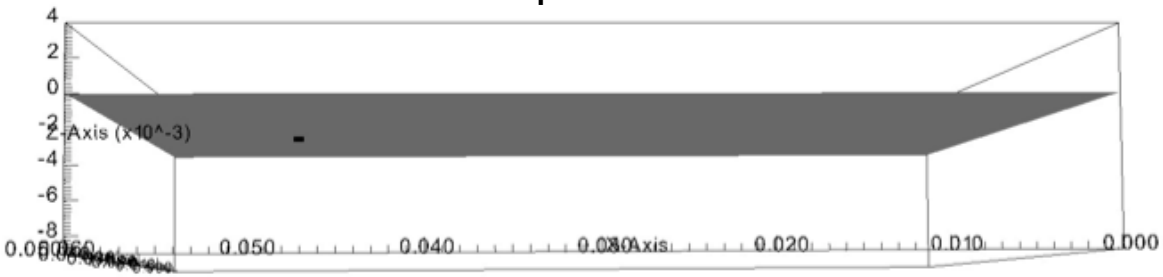


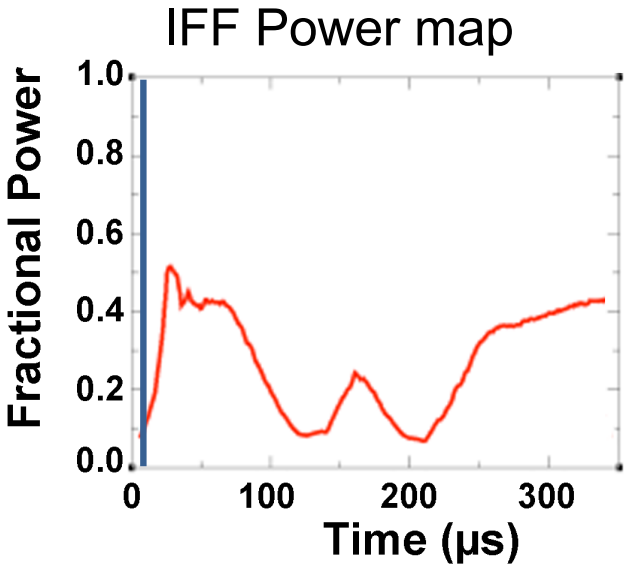
ALE3D has prescribed a power map that mitigates corner turning defects

Pore forming at turn-around at constant power & speed



ALE3D optimizes laser power to achieve user pre-assigned depth & scan speed

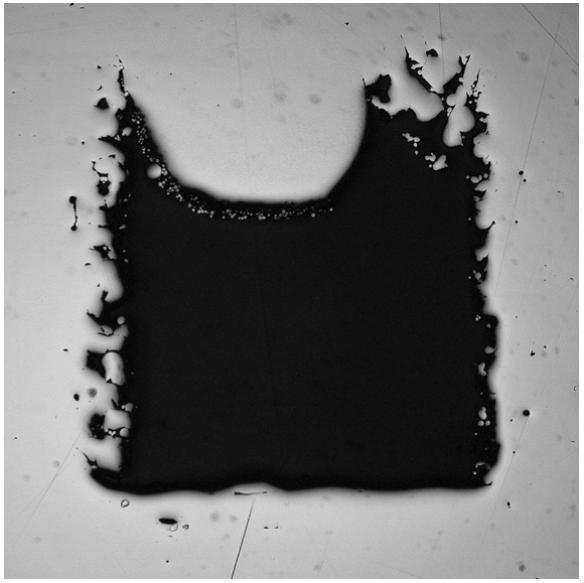




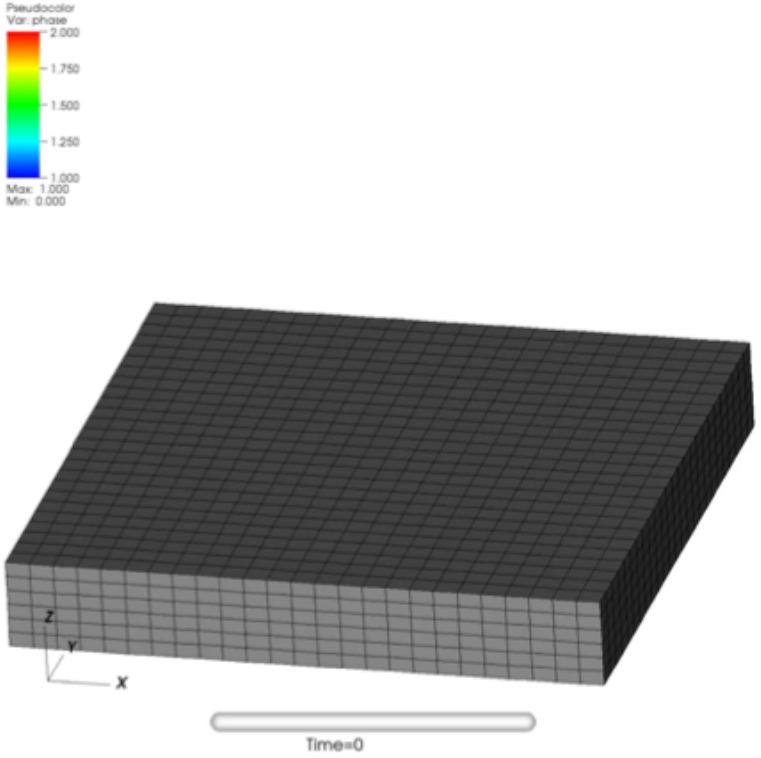
ALE3D informed intelligent feed forward tightens control over build process quality

Diablo simulations predict over melting in the overhang region

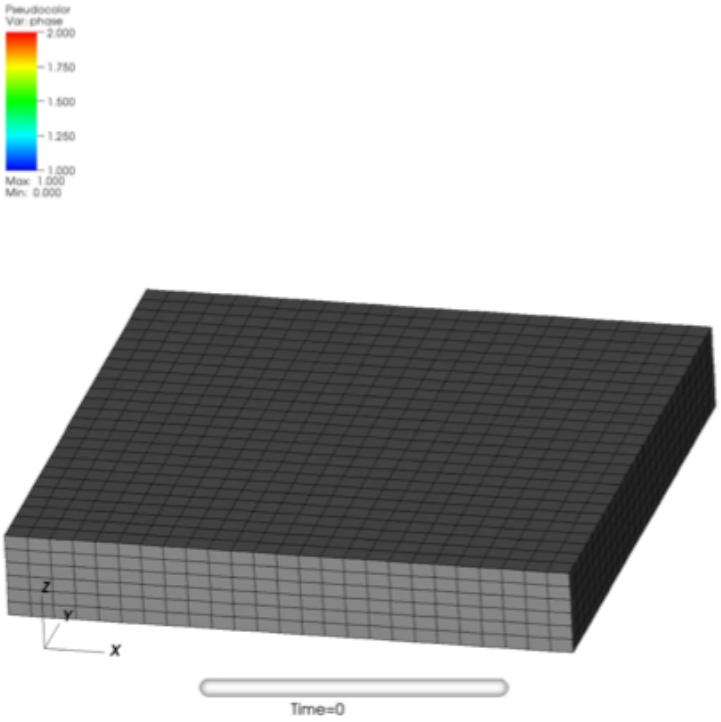
High laser power:
Full density / dross

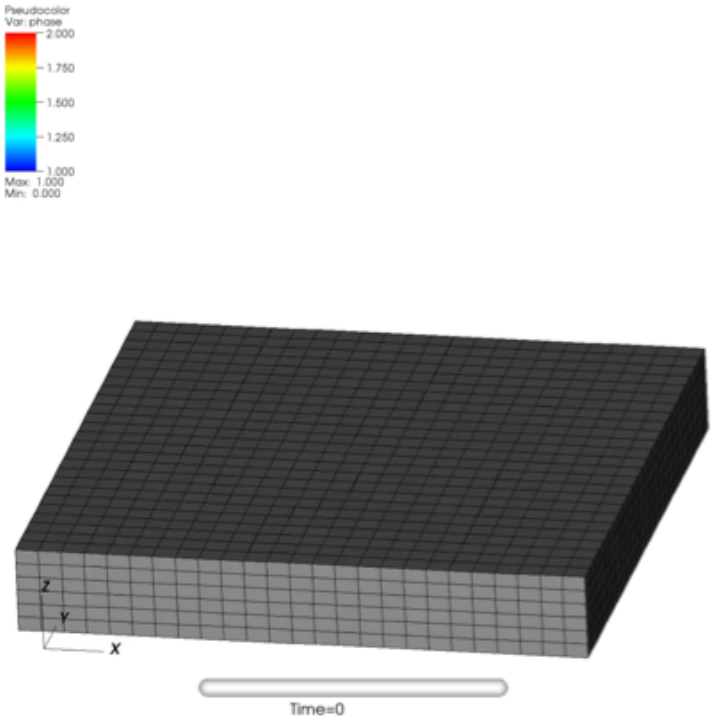


Experimental observation of “dross” formation in overhang regions



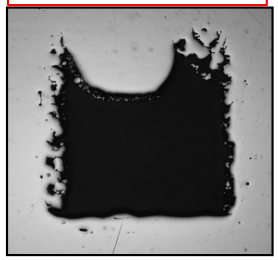
By changing the laser power in our Diablo code, we can mitigate the excessive melting in the overhang



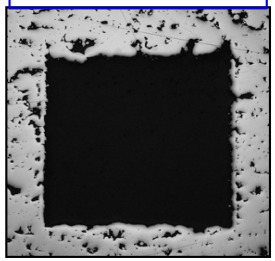


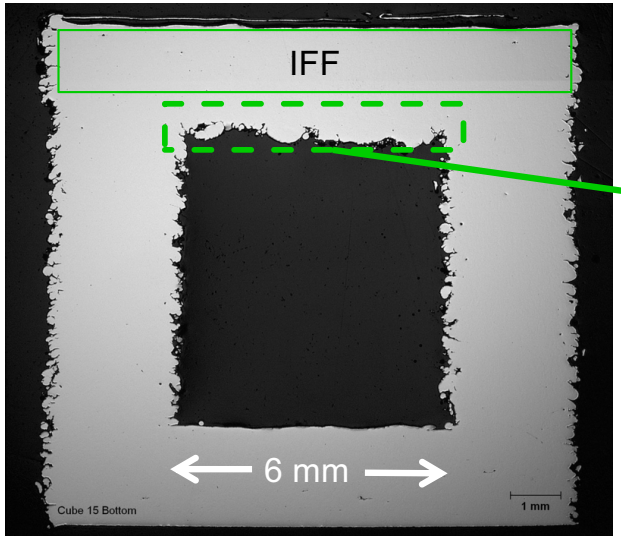
IFF has been successfully demonstrated at LLNL to address the overhang defect problem

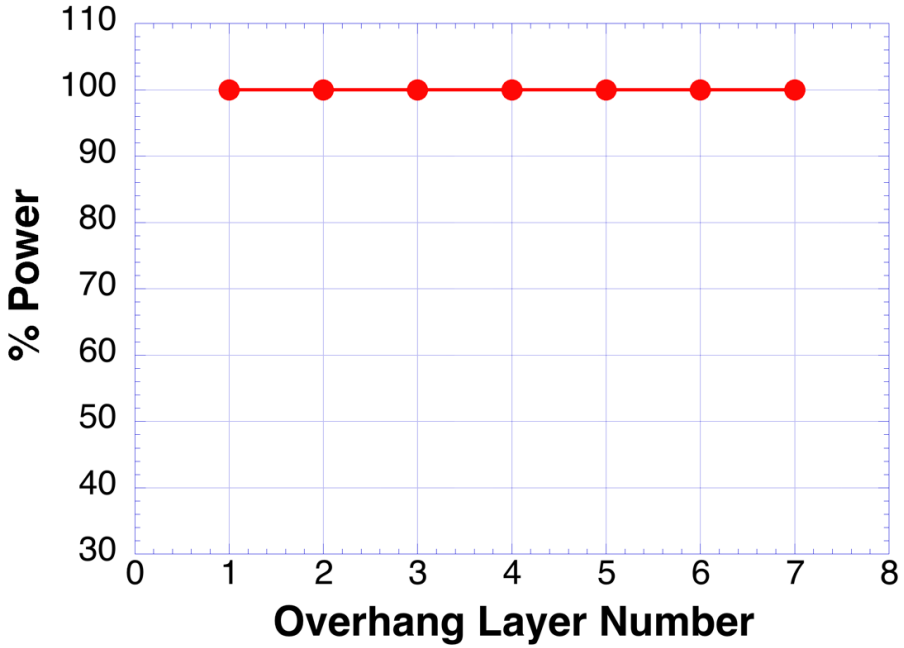
No mitigation



Uniform power reduction



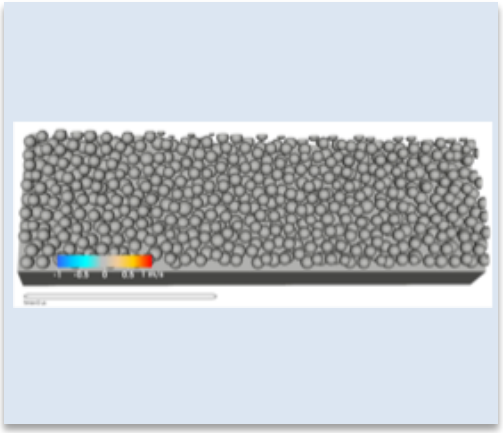




This demonstrates the potential for IFF

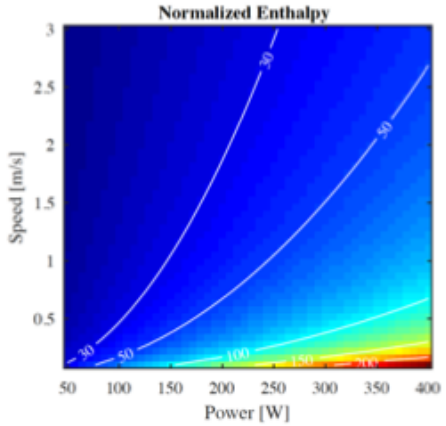
The challenge: LPBF is a multi length scale and multi time scale problem

Physics-based models



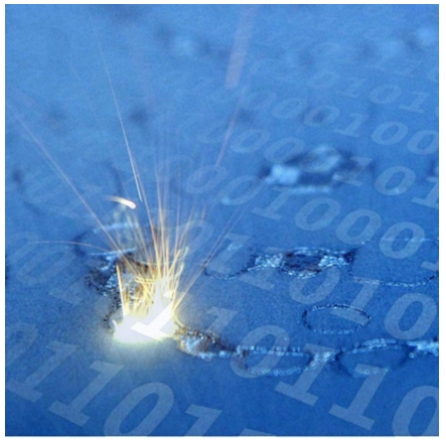
IFF v1.0

Ultrafast surrogates



IFF v2.0

AI and machine learning

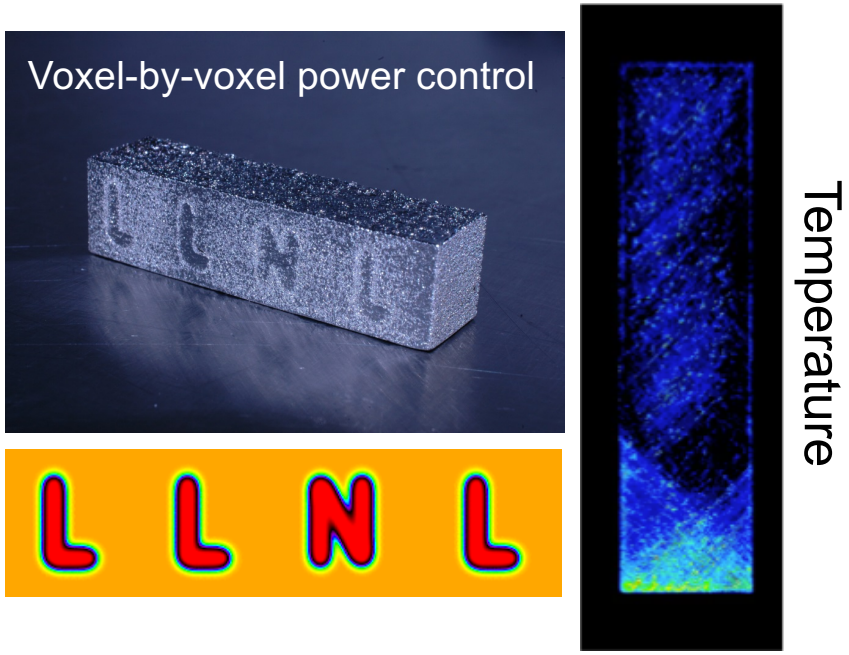


IFF v3.0

Development of ultrafast surrogates will be the key to wide application of IFF

The intelligent feed-forward approach, when successfully developed, will enable “right every time” production

- The approach is meant to be agnostic to feedstock material, machine, and geometry
- It will replace the current experience base with a science base
- Will help establish a "digital thread" to accommodate the large amounts of data (including in situ sensor data) that come with the AM process
- The challenge is to develop the ultrafast surrogate models for the process that follow all of the laser scan paths through all the layers for the entire part



In ten years’ time, we believe that every metal additive manufacturing machine will have intelligent feed forward capability, enabling “just press print” for metal additive manufacturing

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