Overview of AM Modeling and Simulation Activities at MSFC

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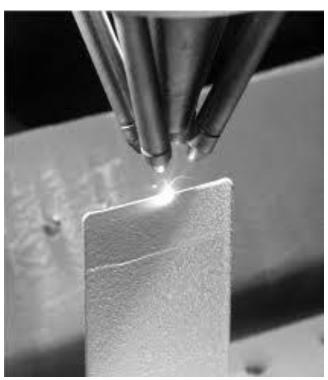
Outline

- Background
- AM Modeling Considerations
- NASA Materials Genome Initiative at MSFC
  - CIMJSEA
  - Additional Work & agency MGI
- AM In-Situ IR Inspection

Background

Introduction

- NASA has been conducting research on rapid prototyping and additive manufacturing (AM) for over 20 years at the Marshall Space Flight Center (MSFC) rapid prototyping lab; the lab is part of the National Center for Advanced Manufacturing and the MSFC Engineering Directorate Materials & Processes lab
- NASA is interested in metals AM for the development of spacecraft hardware, particularly for complex rocket engine components
    - AM is also being used by many other sectors of manufacturing that are seeking ways to gain efficiency in their process, build complex components, or achieve different materials and properties



AM Process Modeling Relevance

- Optimize material build parameters with reduced time and cost through modeling
  - Modeling as an alternative to DOE for process optimization
    - Develop process parameter – to – microstructure relationships
  - Increase understanding of build properties
    - Control as-built material properties, reduce post build treatments
- Capture and improve as-manufactured material deficiencies
  - Anomalies and internal defects
  - Predict areas of concern (fracture critical, high residual stress, difficult to manufacture, geometry changes – how to get to final desired geometry)
  - In-situ measurement and quality management and / or control
- Increase reliability of builds
- Decrease time to adoption of process for critical hardware
- Start process and microstructure evolution modeling of In718

AM Modeling Considerations

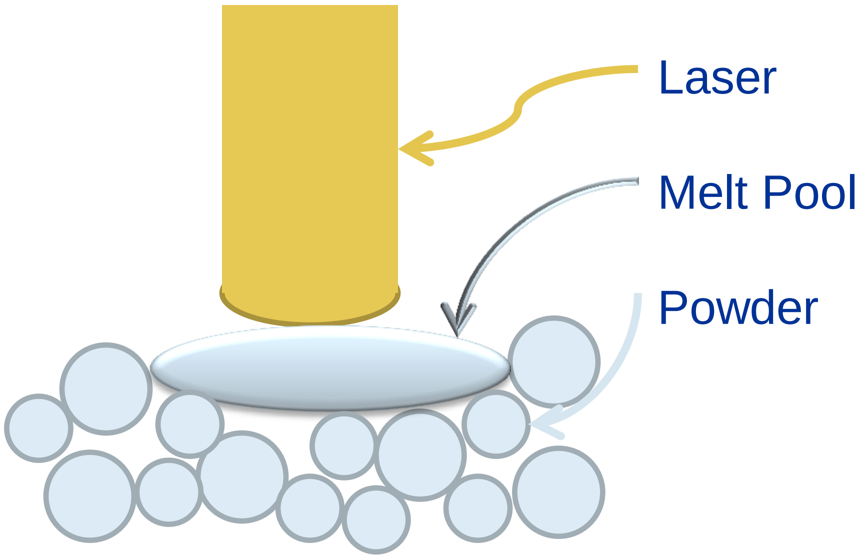
Component-Level Model

- Model layer-by-layer
- Desired results include component residual stresses and distortions
  - Consider material properties of powder, bulk; heat input, flux, thermal conductivity…
  - Consider restraints, build geometry

Line-Scan Model

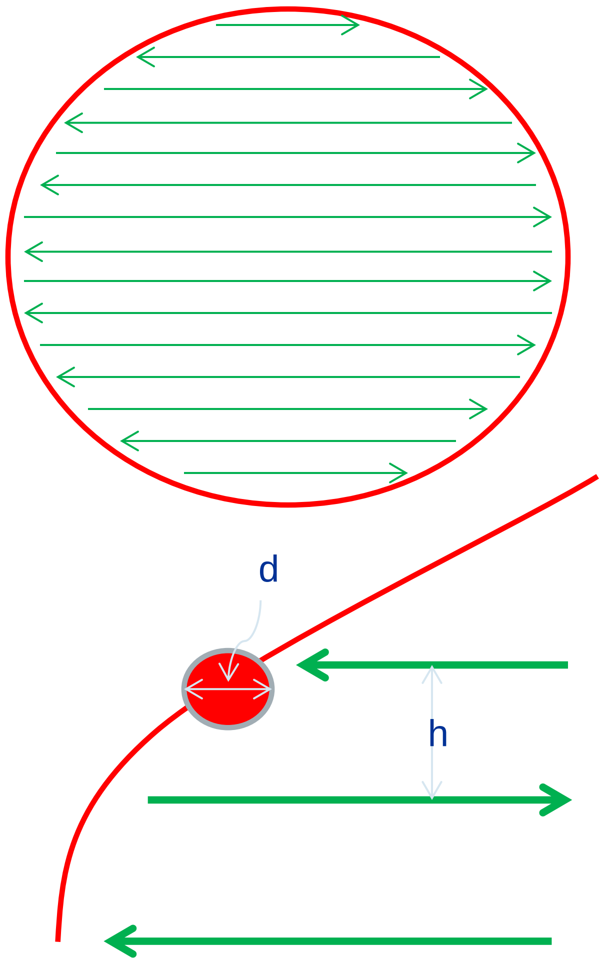
- Model each laser scan, similar to a welding model. Desired results include thermal history of component at any point on the build.

  - Need to consider absorption and conductivity as a function of powder / melt / solid / temperature.
  - Very high rates and differentials – very non-linear.
  - Very small area to consider – need ½ beam diameter cells near area of interest ~25-35 micron.
  - Possible to model laser interaction? Or just use heat flux assumption?



Line-Scan Model: Scan styles

- Two basic scan types in a typical part layer
  - Area scans
    - Also known as hatch or fill scans
    - Produce bulk of material in DMLS
    - Three critical parameters: beam speed (s, mm/s), spacing between individual passes of laser (h, mm), and laser power (P, W)
  - Line scans
    - Produce outer contours of parts and support structures
    - Area scans are made up of many line scans
    - Three critical parameters: beam speed (s, mm/s), beam diameter (d, mm), laser power (P, W)



This slide prepared by Dustin Lindley, Jacobs ESSSA Group, NASA MSFC

Some Notes

- Critical input parameters: laser power, beam speed, hatch spacing, beam diameter, layer thickness.
- Powder material:
  - **Inconel 718**, 625, aluminum, Ti-6-4
  - Powder particles 30-50 micron diameter
  - Powder layer thickness 45 micron
- Laser beam diameter ~50-70 micron; melt pool ~100-150 micron
- Heat input ~2-4 J/mm^2
- Some goals: to understand
  - Thermal history (leads into microstructure evolution model)
  - Residual Stress
  - Distortion
  - Porosity
  - Cracking

NASA Materials Genome Initiative at MSFC

MSFC MGI Task

- Process modeling through Applied Optimization and microstructure evolution modeling at the OSU as part of the Center for Integrative Material Joining Science for Energy Applications (CIMJSEA)
- Microstructure evolution model and Data Informatics with GRC
- AM Process Modeling & In-Situ Test at LaRC
- AM Macroscopic Material Properties Model from ARC
- MSFC ER43 Sinda/G modeling

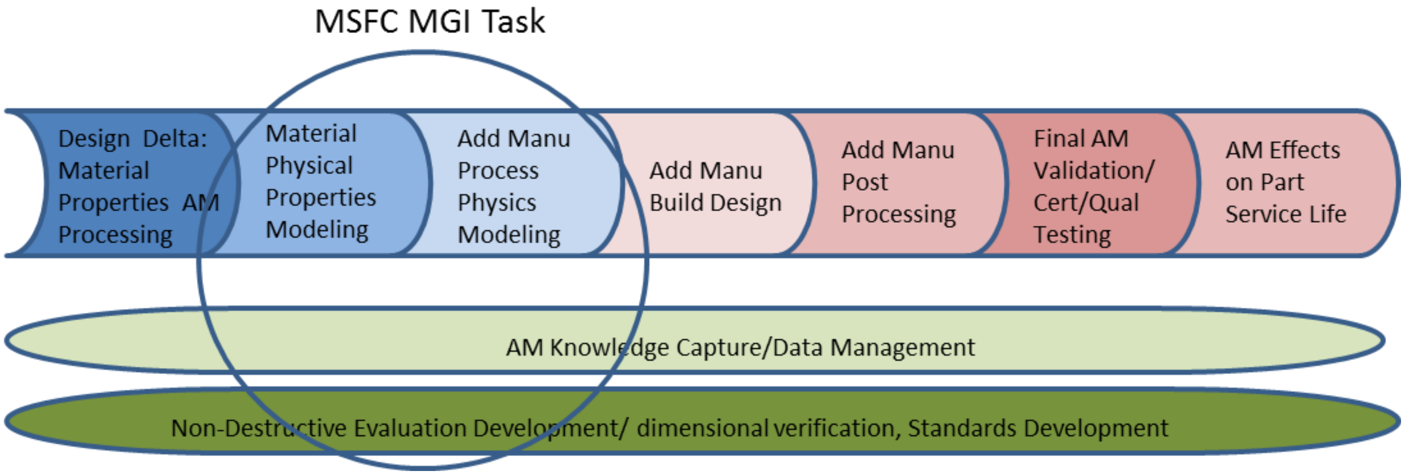


Image courtesy of Terri Tramel, MSFC EM42

CIMJSEA Project

- Goals of the project
  - Model microstructure evolution in a powder-bed additive manufacturing process, using thermal modeling from Applied Optimization and Simultaneous Transformation Kinetics modeling at OSU.
  - Validate model using metallography from coupons manufactured at MSFC using Cusing M2 powder-bed system and in-situ data acquisition from QM Meltpool.
- Objectives set for the first year
  - Build samples on Cusing M2 machine and record data using QM Meltpool. Share data and parameters with AO for calibration of powder-bed AM process model.
  - Conduct metallography on samples produced
  - Begin calibration and modeling of STK at OSU.
  - Project started June 2013

CIMJSEA

NSF I/UCRC Center for Integrative Materials Joining Science for Energy Applications

- Close the gap between material development and application - weldability
- Scientifically-based methodologies for assessing material weldability/joinability that span *nm* to *mm* scale
  - extending the life of material joints within the aging energy infrastructure
  - reduction of the time and cost of deploying advanced materials (bulk materials, hybrid, advanced) for the new energy infrastructure
- Develop next generation of materials joining engineers & scientists

Current members and membership costs

NSF I/UCRC Center for Integrative Materials Joining Science for Energy Applications

Welding Engineering Program

Current Members

1. Areva
2. Air Force Research Laboratory
3. American Eng. and Manuf.
4. Applied Optimization
5. Babcock & Wilcox
6. Cameron International
7. CompuTherm
8. Edison Welding Institute
9. Electric Power Research Institute (EPRI) (2)
10. ESI-Sysweld®
11. ExxonMobil
12. General Electric
13. Honda of America
14. ITW-Hobart
15. Lincoln Electric
16. Los Alamos National Lab (2)
17. NASA
18. Oak Ridge National Lab
19. PPL
20. Pratt& Whitney
21. Rolls Royce
22. Special Metals
23. SFP Works
24. ThermoCalc
25. Trinity Industries
26. Wolf Robotics

<u>Membership</u>

- Open to all US and foreign organizations
- Sharing of all project information
- Voting Membership
  - $45,000/yr
  - Designate 1 project supported by grad student
- Non-voting Membership
  - $25,000/year
  - Access to other project information

For more information, please contact the center director:

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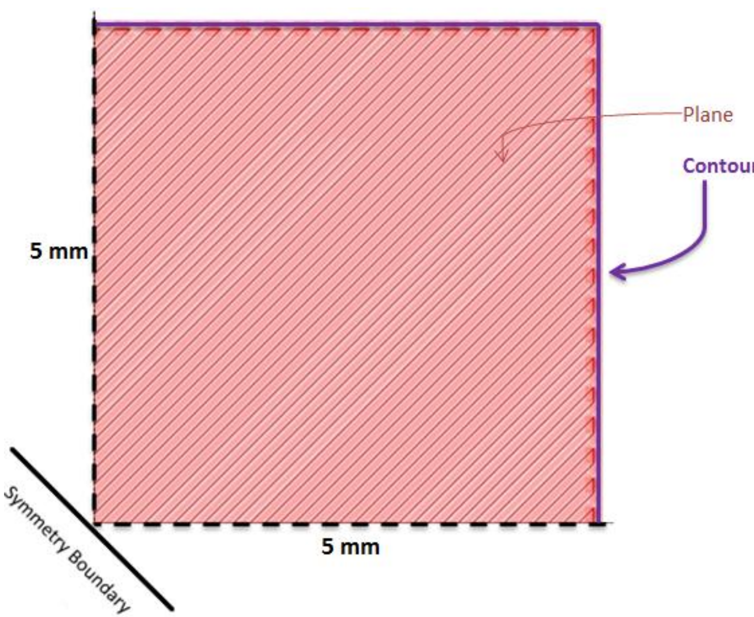
QM Meltpool Data

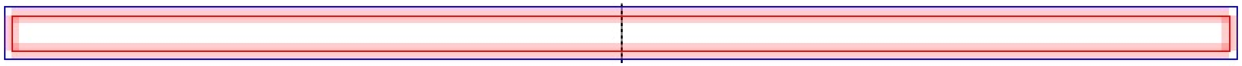
- QM Meltpool is Concept Laser GmbH in-situ quality mgt module
  - A high-speed IR Camera measures the integrated intensity of the IR radiation and captures images. Software determines from camera images how many pixels are within a threshold color level corresponding to molten material.
  - A Photodiode measures the brightness intensity of the melt pool.

Part	Layer	Contour	Diode Intensity	From Photodiode, average intensity value of contour trace
			Meltpool Intensity	From Camera, average integrated IR intensity of contour trace
			Meltpool Area	From Camera, average number of pixels above threshold color level during contour trace
		Plane	Diode Intensity	From Photodiode, average intensity value of bulk material / hatch scan
			Meltpool Intensity	From Camera, average integrated IR intensity of bulk material / hatch scan
			Meltpool Area	From Camera, average number of pixels above threshold color level during hatch scan



Single Track Builds

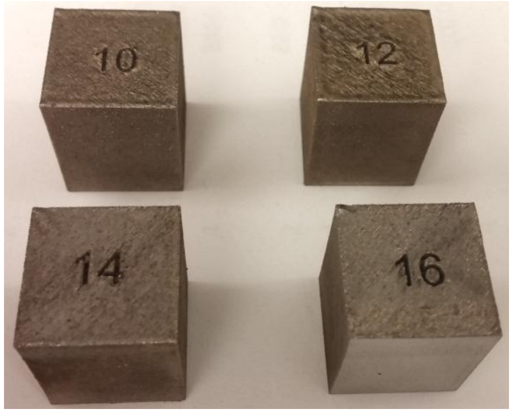
- Ultimately 3 cases of “single tracks”
  1.) Track on SS build plate with no powder
  2.) Track on SS build plate with 1, 2, 3 layers of powder
  3.) Track on In718 build with 1 – 10 layers of powder
- For single track, a continuous laser path is desired; Machine control only allows this for part contours (e.g. geometry perimeters)
  - “Single Track” geometry is therefore defined as a rectangle perimeter
- All samples have been built using In718 powder in the Concept Laser M2, and QM Meltpool data were compiled and provided to CIMJSEA members

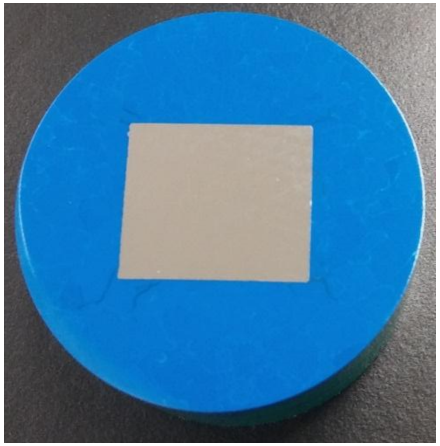


Red line is laser path, blue line is CAD OML geometry definition and red shade is presumed final track geometry

Coupon Builds

- Printed 15 mm x 15 mm x 15 mm cubes at 36 different parameter sets using In718 powder in the Concept Laser M2
- QM Meltpool data for all 36 samples were compiled and provided to CIMJSEA members
- Samples representing 8 parameter sets corresponding to single tracks have been mounted and polished; metallography forthcoming





Next Steps

- Examine weld bead geometry and provide data to AO
  - Image and record shape and geometry of weld "scallops"
- Examine microstructure to understand microstructural evolution to as-built condition
  - Record grain shape, size, orientation, EBSD
  - Compare bottom and top layers
- Measure and record micro-hardness over the height of the samples (build direction)
- Evaluate samples for porosity, cracking (inter-dendritic, liquation), dendrite arm spacing, TEM, Microprobe, etc. as determined by team after initial results reported
- Begin calibration and modeling of STK at OSU

Data Informatics

- NASA Glenn Research Center (GRC) maintains NASA Granta Material Intelligence (Granta MI) database for materials properties
  - Environmental restricted substances
  - EDSU Metallic Materials Data Handbook
  - Global Powder Metal Database
  - Material Universe
  - Metals Information for the 21st century
  - Metallic Materials Properties Development and Standardization
- MSFC build data
  - Parameter DOE’s (build parameters and heat treatments)
  - Build witness samples
  - External vendor witness samples
  - Typically tensile testing and metallography; LT and HT tensile, fracture, HCF, LCF, weld samples, etc. planned

AM Process Model & In-Situ Test at LaRC

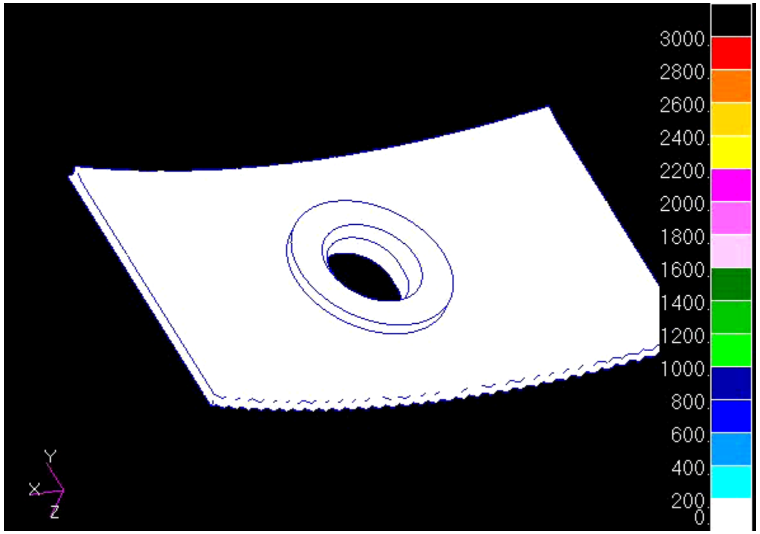
- NASA Langley Research Center is generating a model to include melt pool convection and mixing, and developing in-situ test methods to validate this model
  - Prediction of deposit shape (layer height and width), 3D thermal history, residual stress, and distortion
    - Residual stress distribution map for AM component to assist in mechanical testing configuration and component certification
    - 3D Thermal history results applied to commercial microstructural evolution models for microstructure prediction
    - Design alternative gradient microstructures that could be utilized to improve component behavior
  - Use available NDE methods to identify melt pool geometry and thermal gradients for selected deposition parameters
- Also performing mechanical tests on AM material to determine constitutive relationships for microstructural / mechanical response

AM Material Properties Model at ARC

- NASA Ames Research Center is developing computational methods for predicting macroscopic AM part properties and associated variability
  - Analytical and numerical models for determining probability distributions over macroscopic properties of AM components as functions of process and material parameters
    - For example, predict residual stress in the AM component
  - This allows exploration of additive manufacturing trade space, reduction in observed variability in part performance metrics
- Also informing the design of next-generation autonomous AM systems through a suite of new sensing modalities that will help to fully characterize the process in situ, and developing analytical reduced order physics models that will enable real-time adaptive control of laser and process parameters.
  - Allow quantitative sensing and control of the AM process

MSFC Thermal Analysis Branch MSC Sinda

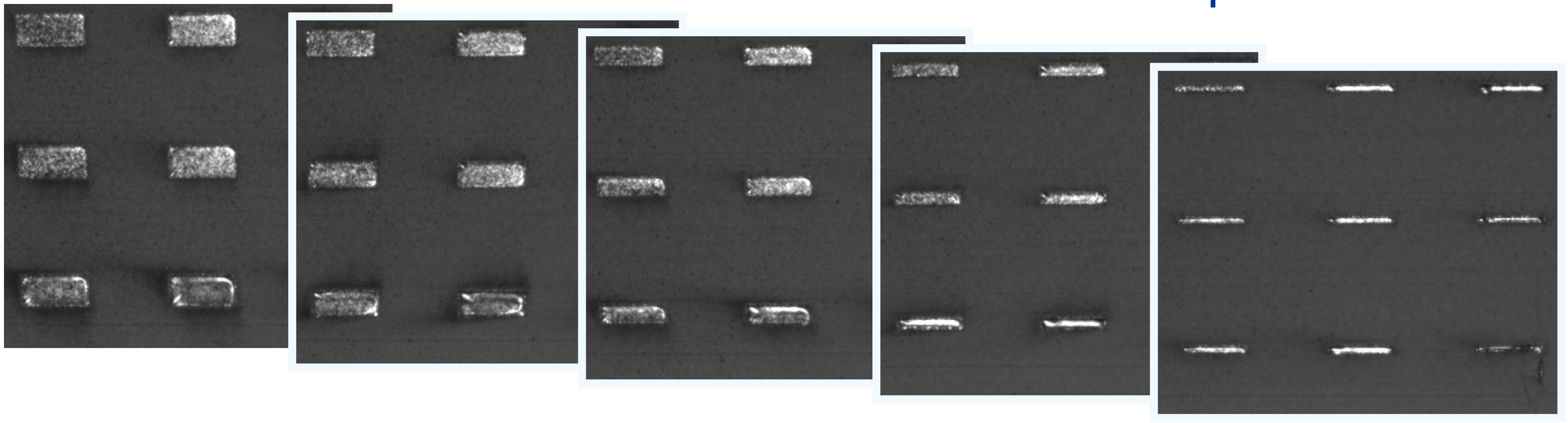
- MSC Sinda (Sinda/G) is a commercial finite difference code used by NASA for other problems regarding high thermal gradients and rates (e.g. rocket engine flow and combustion, welding)
- NASA MSFC Thermal analysis branch aims to develop an AM powder bed process model based on NASA work completed for modeling thermal transients in welding Shuttle observation port ring to the fuel pre-burner
  - Model temperature history of weld, residual stresses and distortion, cracking



AM In-Situ Infrared Inspection

AM Infrared Inspection – MSFC ER43

- Develop a real-time dimensional inspection technique and digital quality record for the AM process using IR camera imaging and processing techniques.
  - In-situ inspection of internal and external geometries
- IR camera(s) to image each layer
- Software to determine melted geometry from each Z-height layer using IR images
  - Develop algorithm to determine AM powder-sintered metal interface for each layer
- Reconstruct data into a 3D model to be used for inspection



Questions?

Acknowledgements:

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Other: Dustin Lindley