Building a Digital Twin of Additive Manufacturing

Presented by: Gerald Knapp

Collaborators

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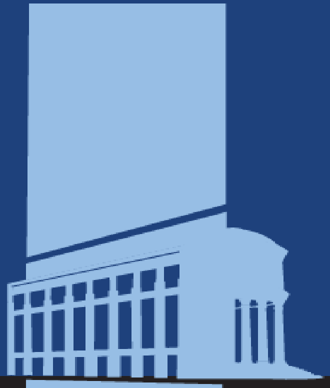


NEUP Nuclear Energy University Programs
U.S. Department of Energy

PennState
College of Earth
and Mineral Sciences

Department of Materials
Science and Engineering
CHANGE THE WORLD

11/08/2017

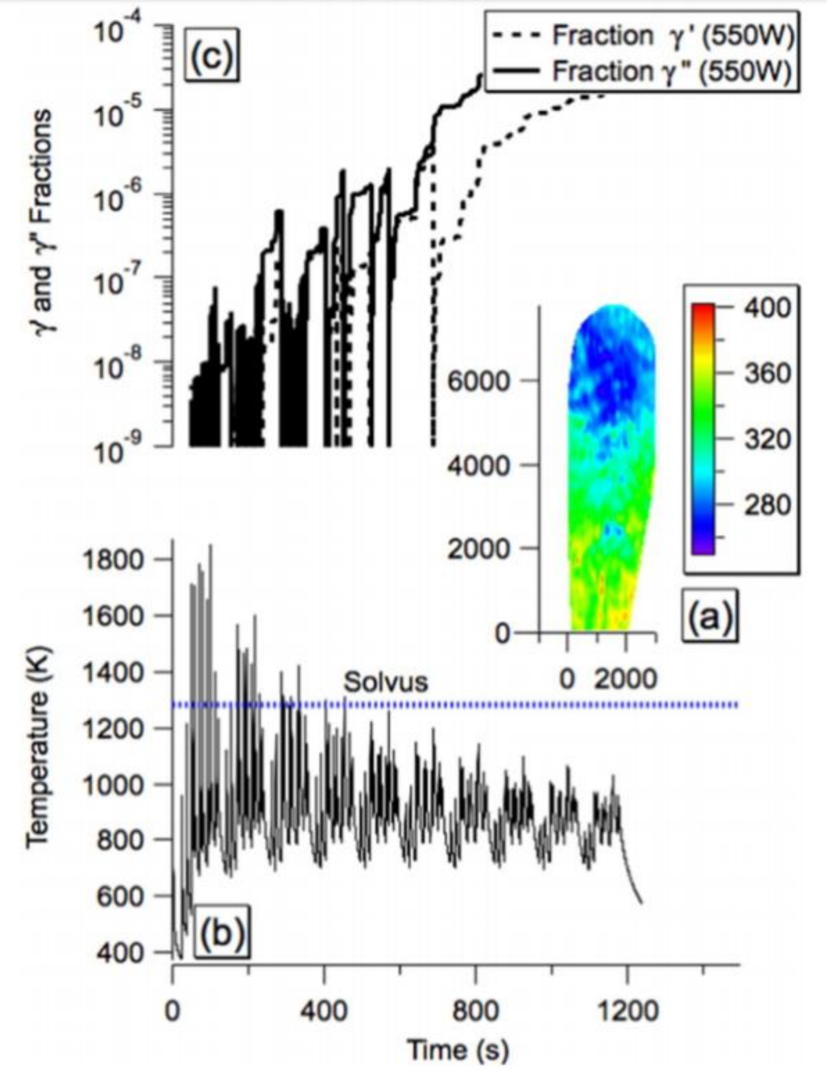
Motivation

- Additive manufacturing is a big step in digital manufacturing
- Fewer limitations on part design leads to innovation
- But…it also leads to diverse processing conditions
- Having tools to aid in the design of parts is critical to having defect-free, structurally sound parts

Digital Twins

- Creation of a digital twin will enable forward prediction and back-calculation of necessary input parameters
- Need to understand the phenomenon associated with the process

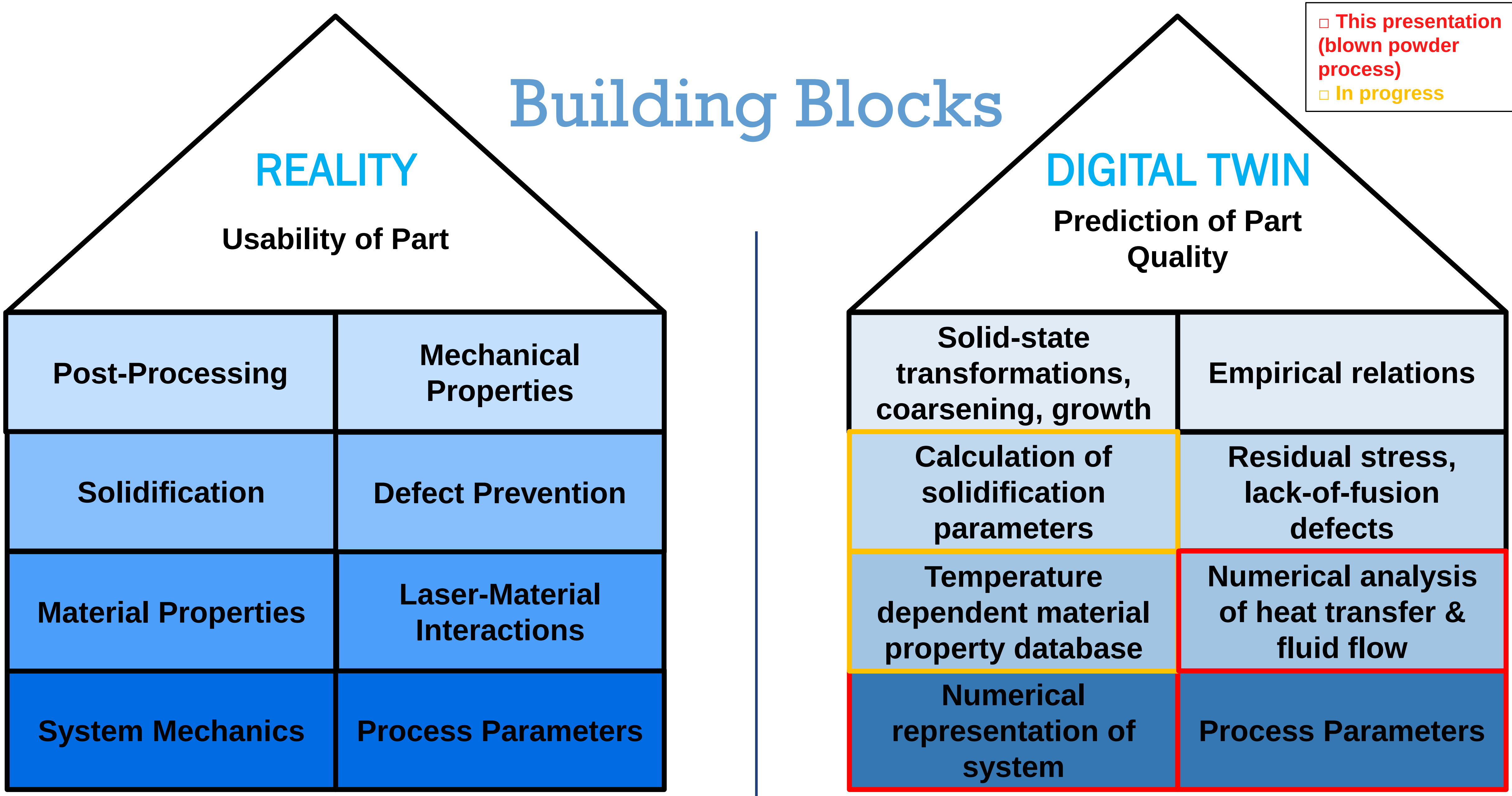
Inconel 718



T. DebRoy, W. Zhang, J. Turner, S.S. Babu, Building digital twins of 3D printing machines. *Scripta Materialia*, 2016.

- □ This presentation (blown powder process)
- □ In progress

Building Blocks



REALITY

Usability of Part

Post-Processing	Mechanical Properties
Solidification	Defect Prevention
Material Properties	Laser-Material Interactions
System Mechanics	Process Parameters

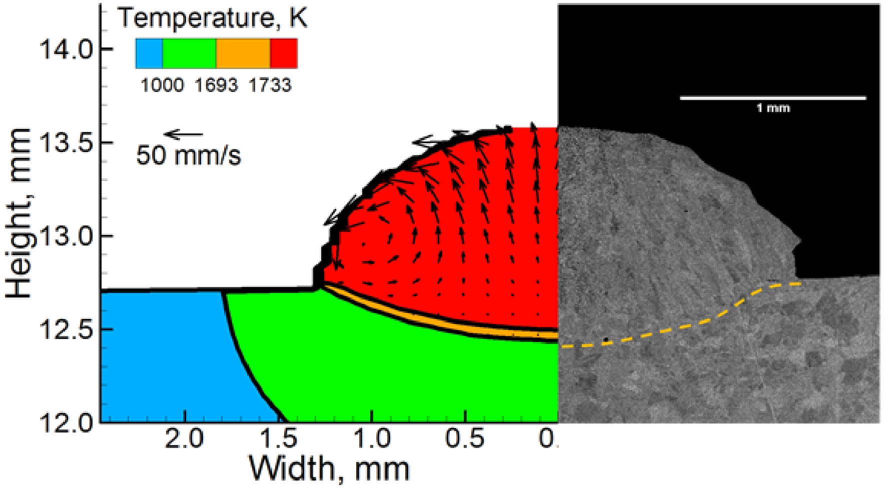
DIGITAL TWIN

Prediction of Part Quality

Solid-state transformations, coarsening, growth	Empirical relations
Calculation of solidification parameters	Residual stress, lack-of-fusion defects
Temperature dependent material property database	Numerical analysis of heat transfer & fluid flow
Numerical representation of system	Process Parameters

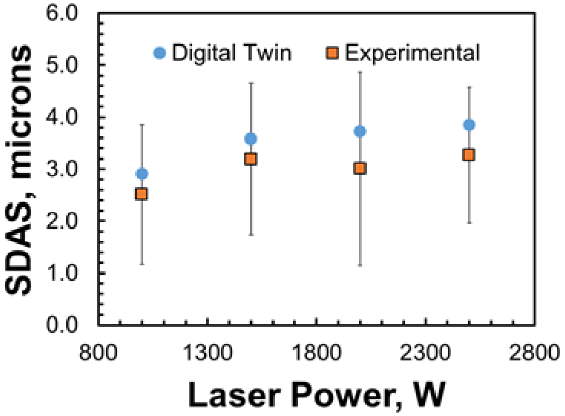
Overview – Predicting Product Properties

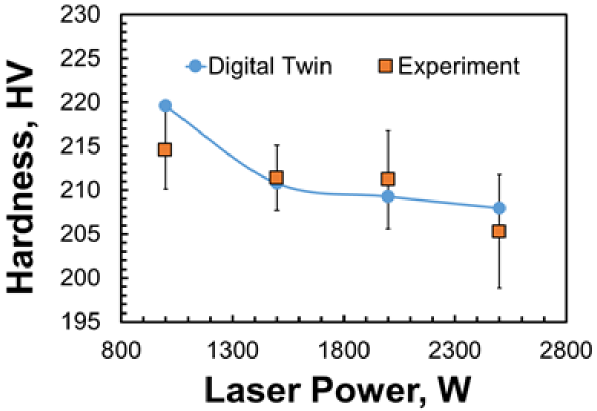
Temperature and Velocity Fields



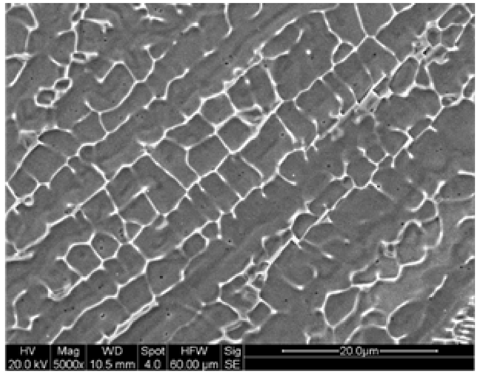
Digital Twin

Physical Experiment

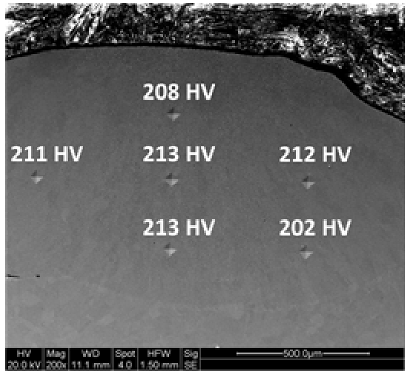




Microstructure



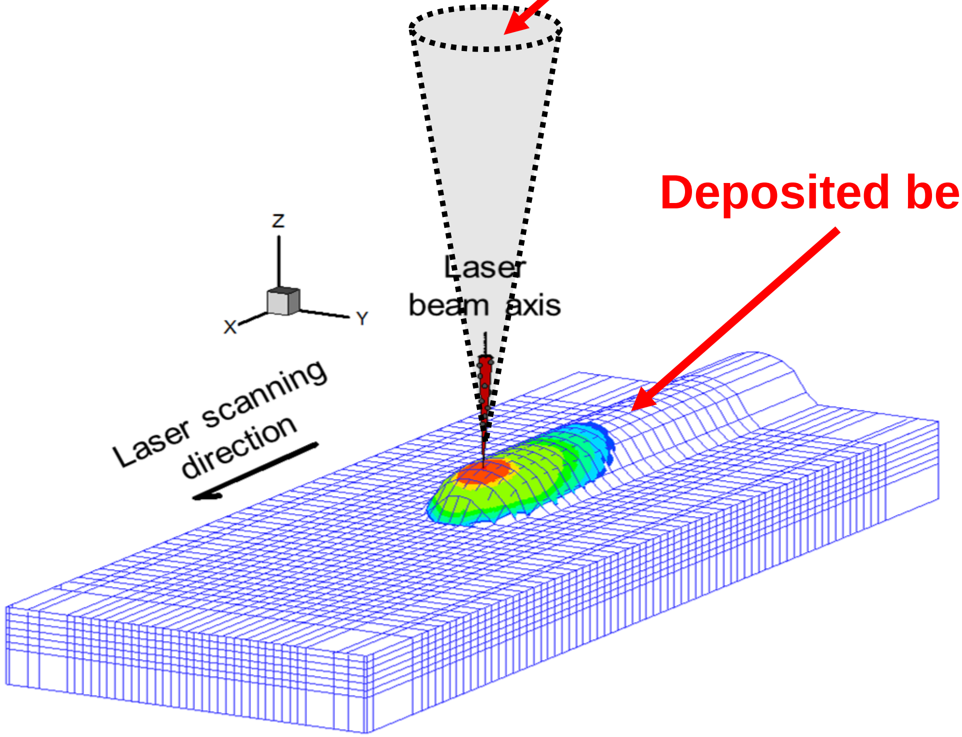
Properties



G.L. Knapp, T. Muhkerjee, J.S. Zuback, H.L. Wei, T.A. Palmer, A. De, T. DebRoy. Building blocks for a digital twin of additive manufacturing. Acta Materialia, 2017, vol. 135, pp. 390-399.

Directed Energy Deposition

- Powder-blown process
- Allows for faster build rates than powder bed processes
- Material deposits on a substrate from nozzle coaxial to the laser



Powder stream

Deposited bead

Numerical Model: Bead Shape

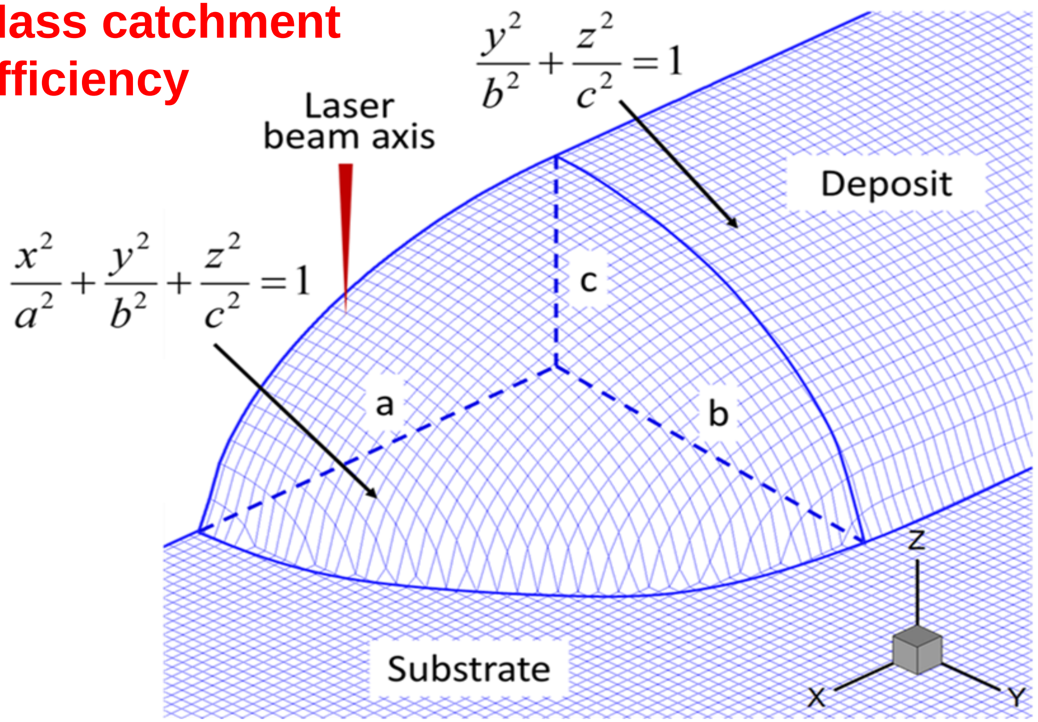
Term based on laser intensity distribution

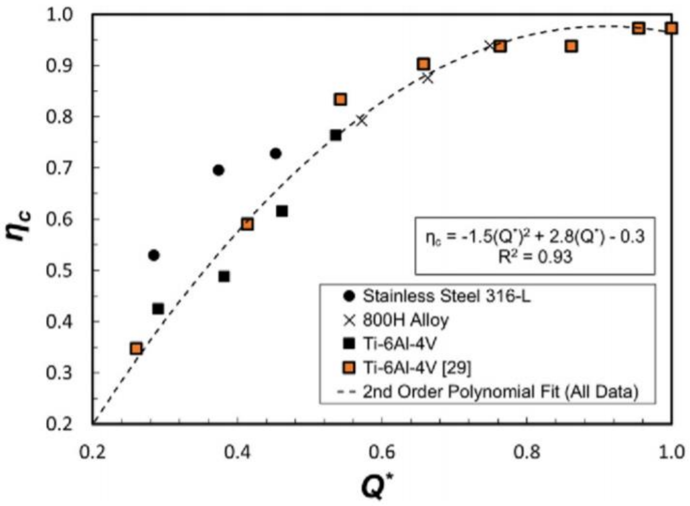
Mass catchment efficiency

$$a = b$$

$$b = f_m r_b \sqrt{\eta_c}$$

$$c = \frac{2\dot{m}\sqrt{\eta_c}}{\pi f_m r_b v_s \rho}$$





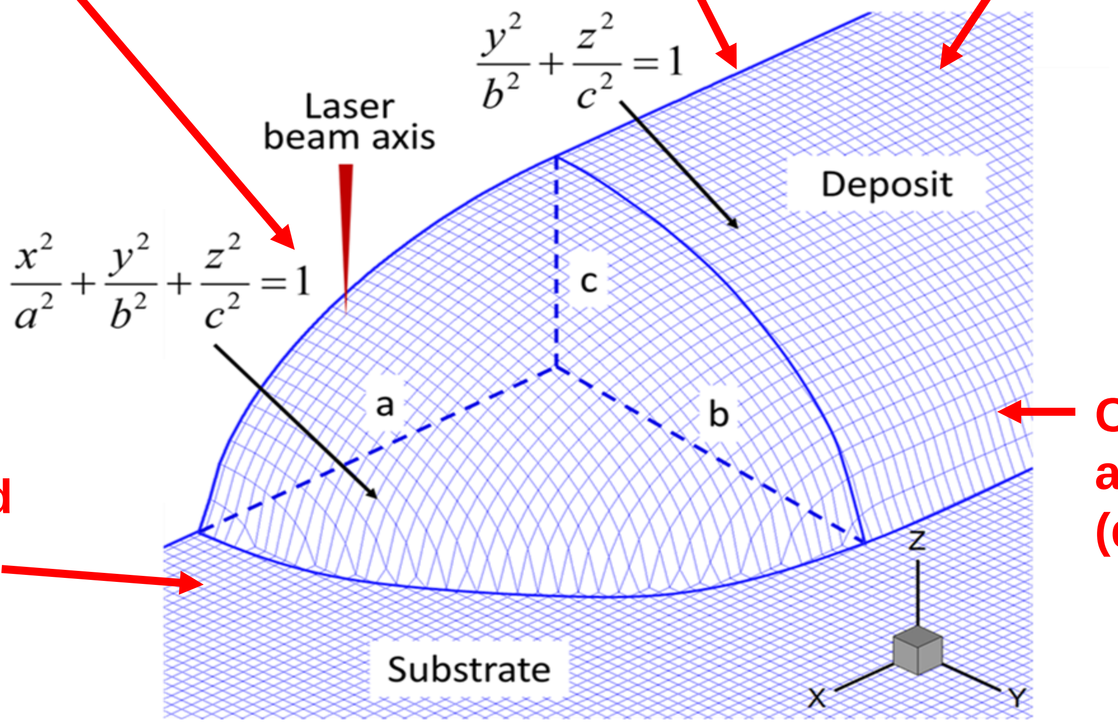
$$Q = \frac{\left(P/v_s\right)^{2/3}}{(C_P \Delta T + L)^{2/3}}$$

Numerical Model

$$a = b$$

$$b = f_m r_b \sqrt{\eta_c}$$

$$c = \frac{2\dot{m}\sqrt{\eta_C}}{\pi f_m r_b v_s \rho}$$



Knapp *et al*. Acta Materialia, 2017.

Boundary of active cells defined by paraboloid

Symmetry plane (for single bead)

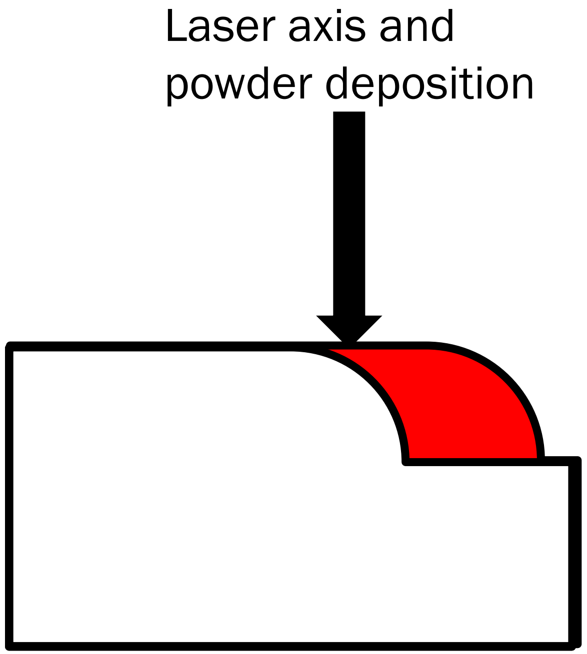
Constant geometry is assumed for deposited bead

Cells outside of shown mesh are considered inactive (dummy grids)

Boundary conditions applied at interface between dummy grid and active grids

Heat source modeling

- Combination of surface heat and volumetric heat source
- Powder is heated in-flight
- Remaining laser power goes to surface of deposit

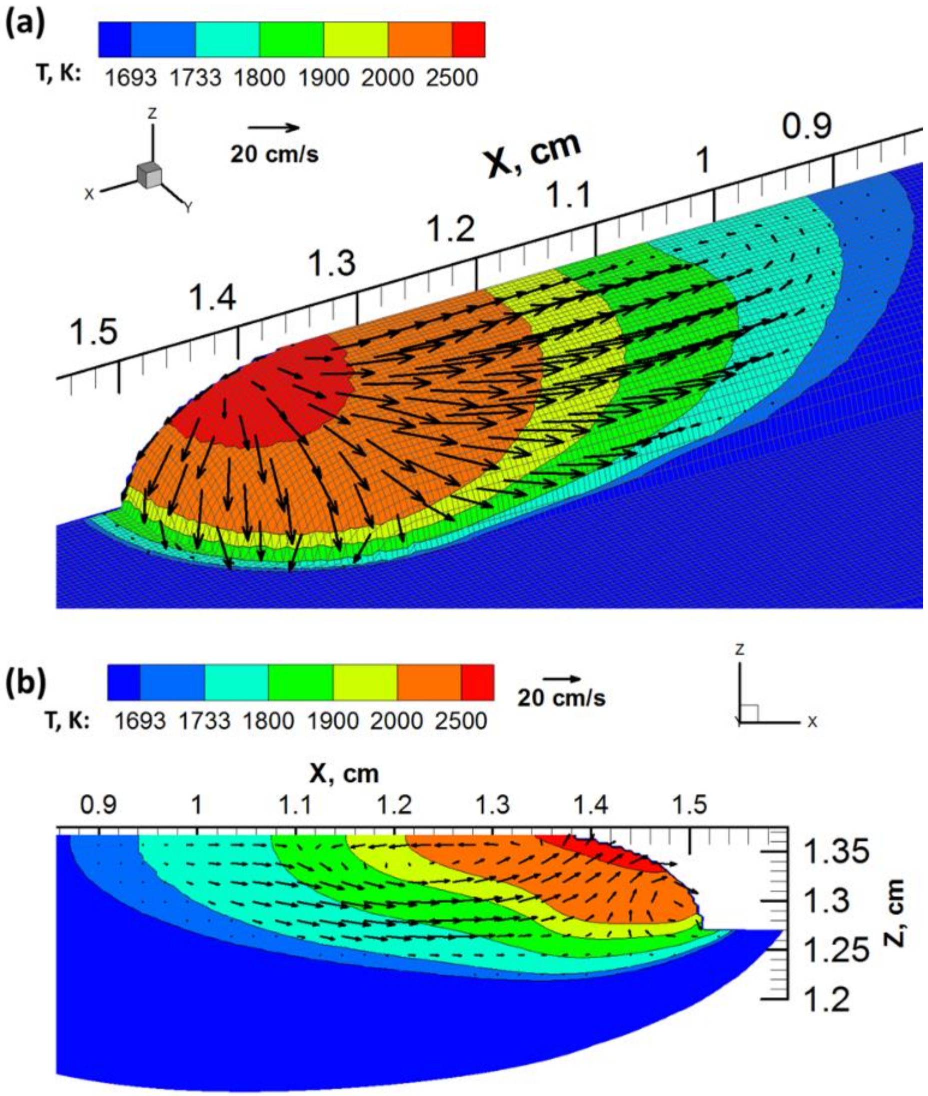


Computational Resources

- Rectangular grid: 250 x 30 x 20 (2.5cm long deposit, single pass)
- Grid points: 150,000
- Five constitutive equations (enthalpy, x/y/z velocity, pressure): 750,000 equations per iteration
- Iterate at each time step: 7,500,000 – 75,000,000 equations
- Typical CPU speed: 2-3GHz (~10^9 operations/second)
- Typically can solve each time step in ~1 second
- Solve single pass in ~2 minutes

Heat transfer and Fluid flow simulations

- Convection carries fluid from the front to the back of the molten pool
- Largely driven by surface tension gradients (Marangoni stresses)

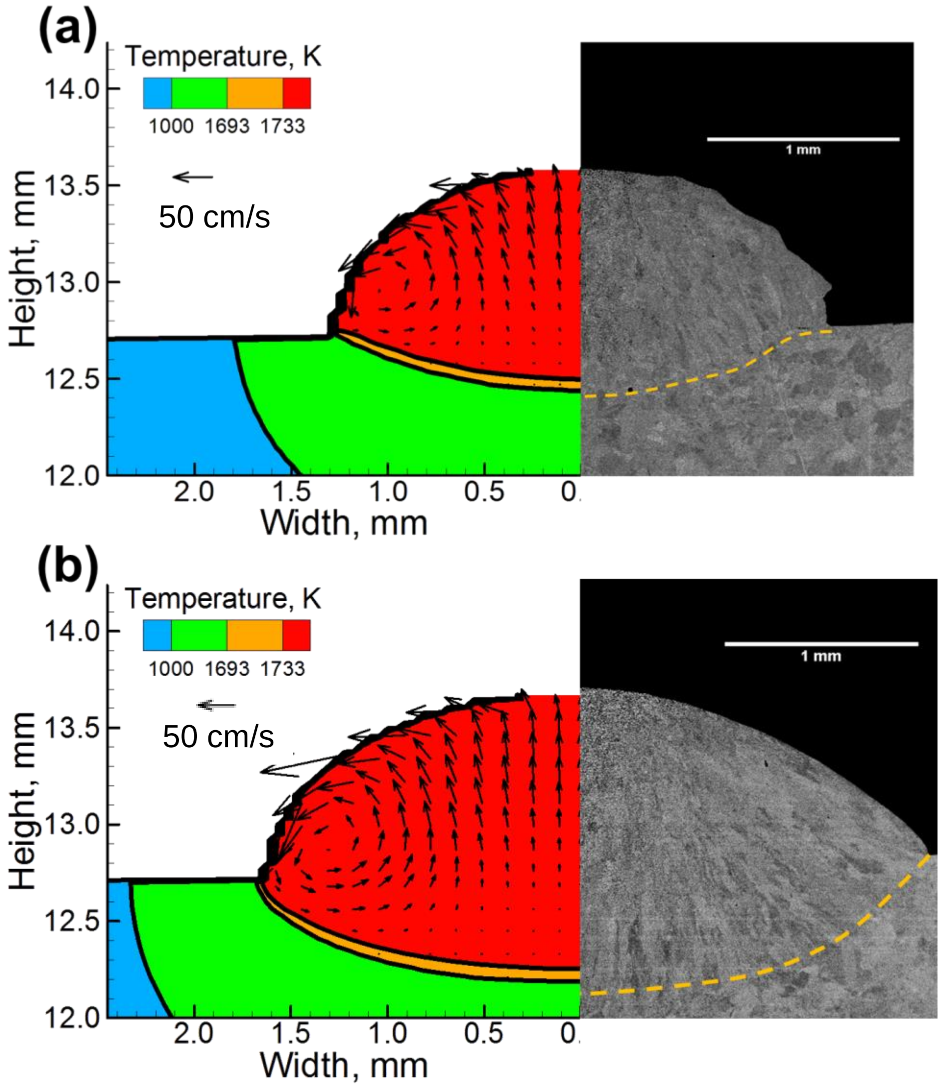


Temperature and velocity distributions on the curved shaped deposit for stainless steel 316L at 2500 W, 10mm/s. Scanning direction is along the +x-axis.

Comparison with real geometry

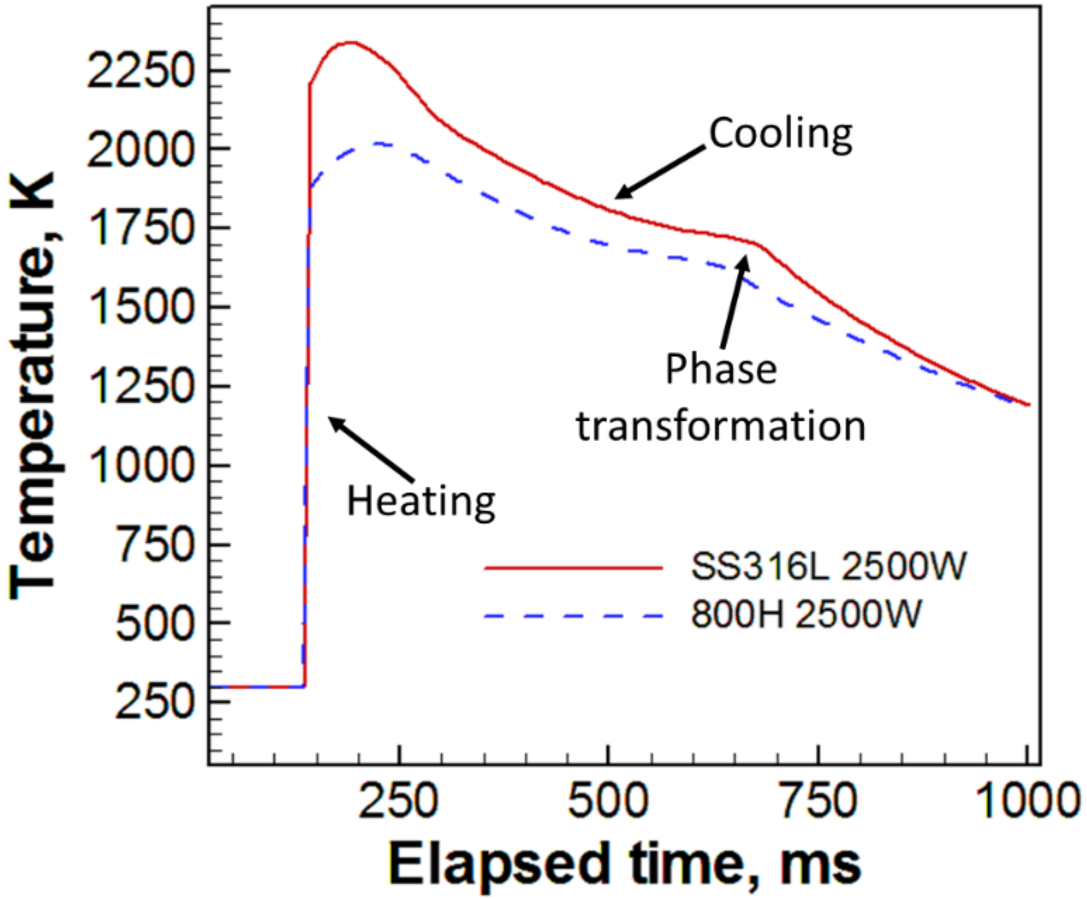
- Penetration depth is measured experimentally for SS 316
- Increased power allows more material to be melted, larger bead to form

$$Q = \frac{\left(P/v_s\right)^{2/3}}{\left(C_P \Delta T + L\right)^{2/3}} \Rightarrow \eta_c = f(P)$$



Comparison of the calculated deposit shape and size with experimental macrograph at the transverse cross section of the build for stainless steel 316L at (a) 1500 W and (b) 2500 W laser power.

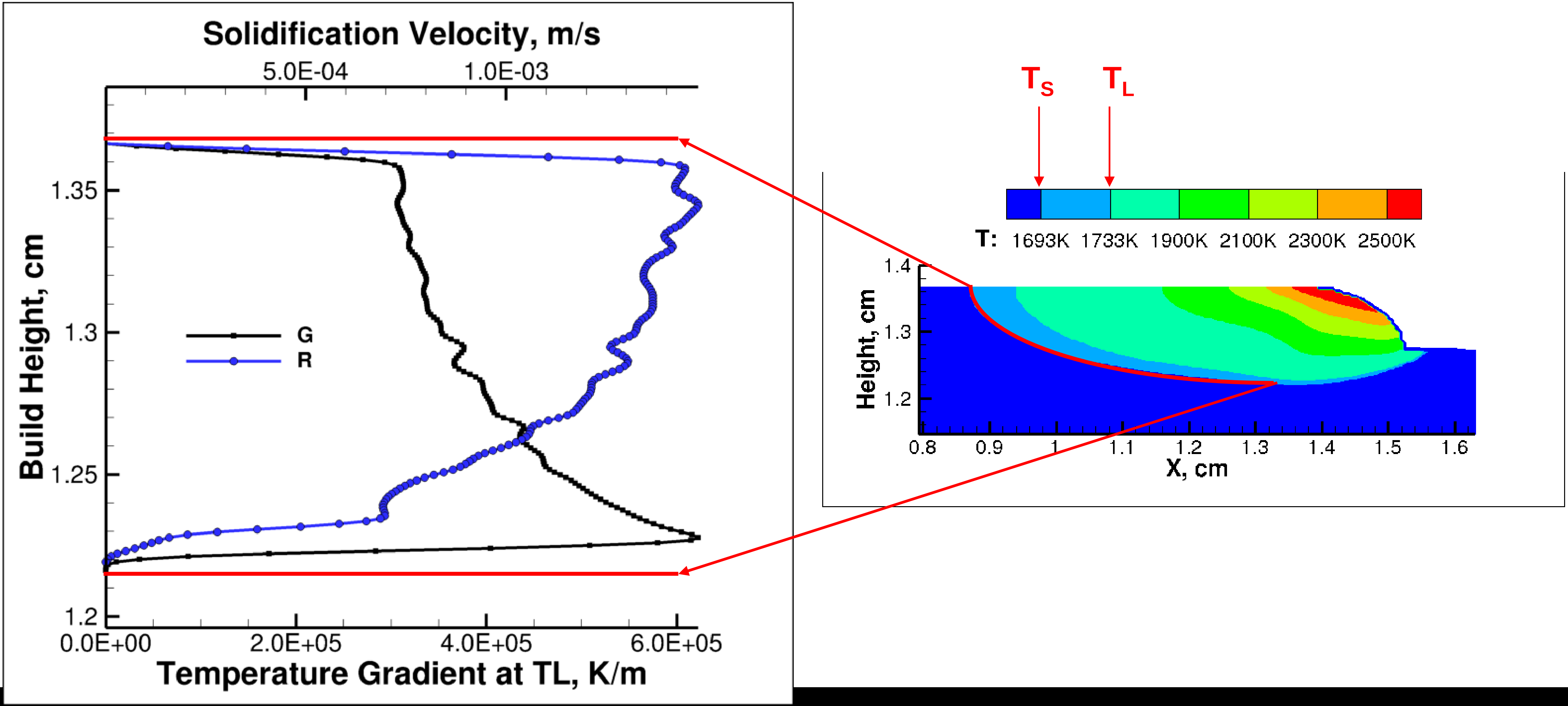
Thermal history



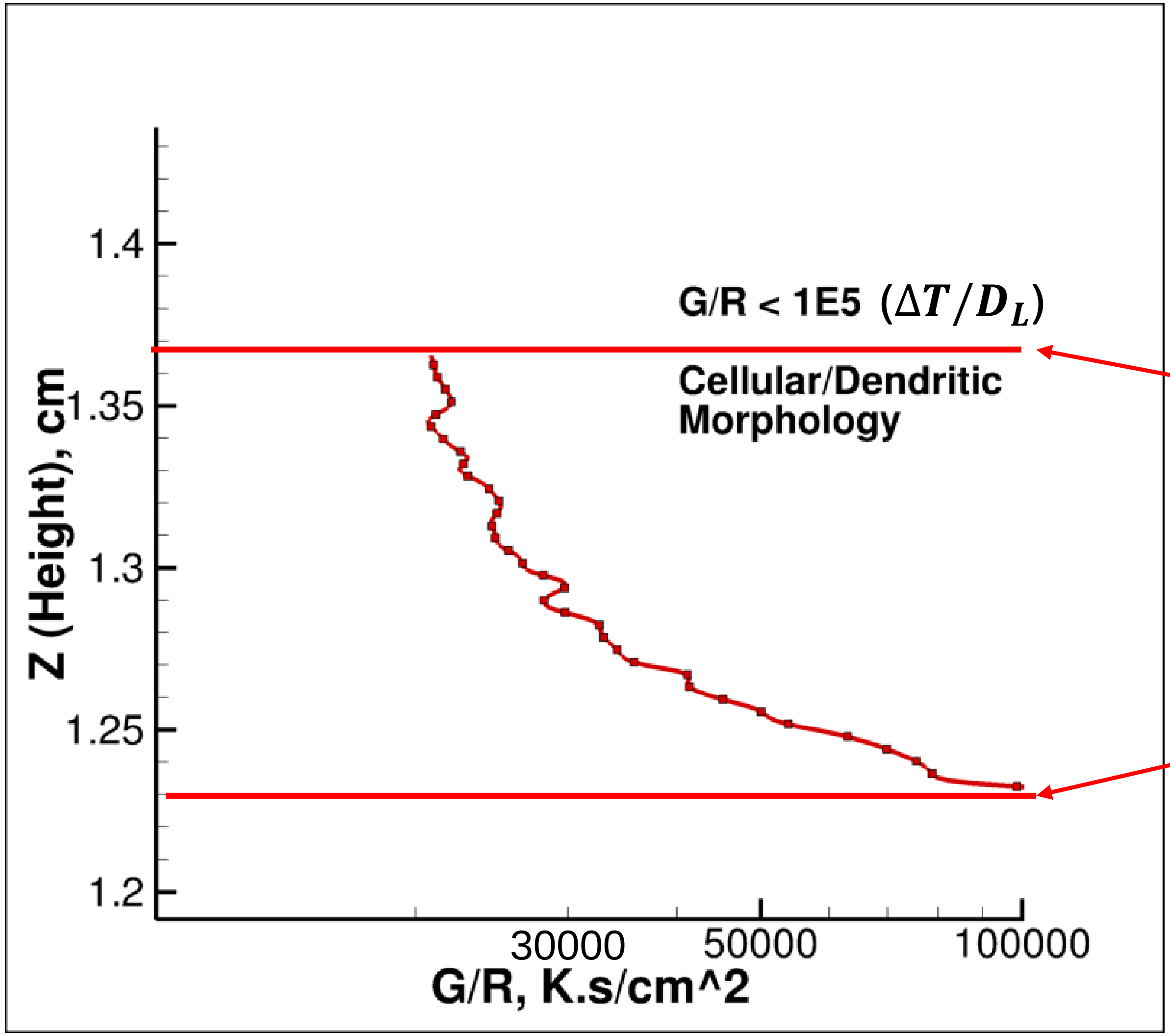
Simulated thermal history for a single deposit of stainless steel 316L and 800H at 2500W

- From numerical analysis, thermal histories can be extracted for each point
- Essential to calculating solidification parameters, temperature gradient (G) and solidification velocity (R)
- Enables coupling to residual stress/distortion model

Solidification parameters (G and R)

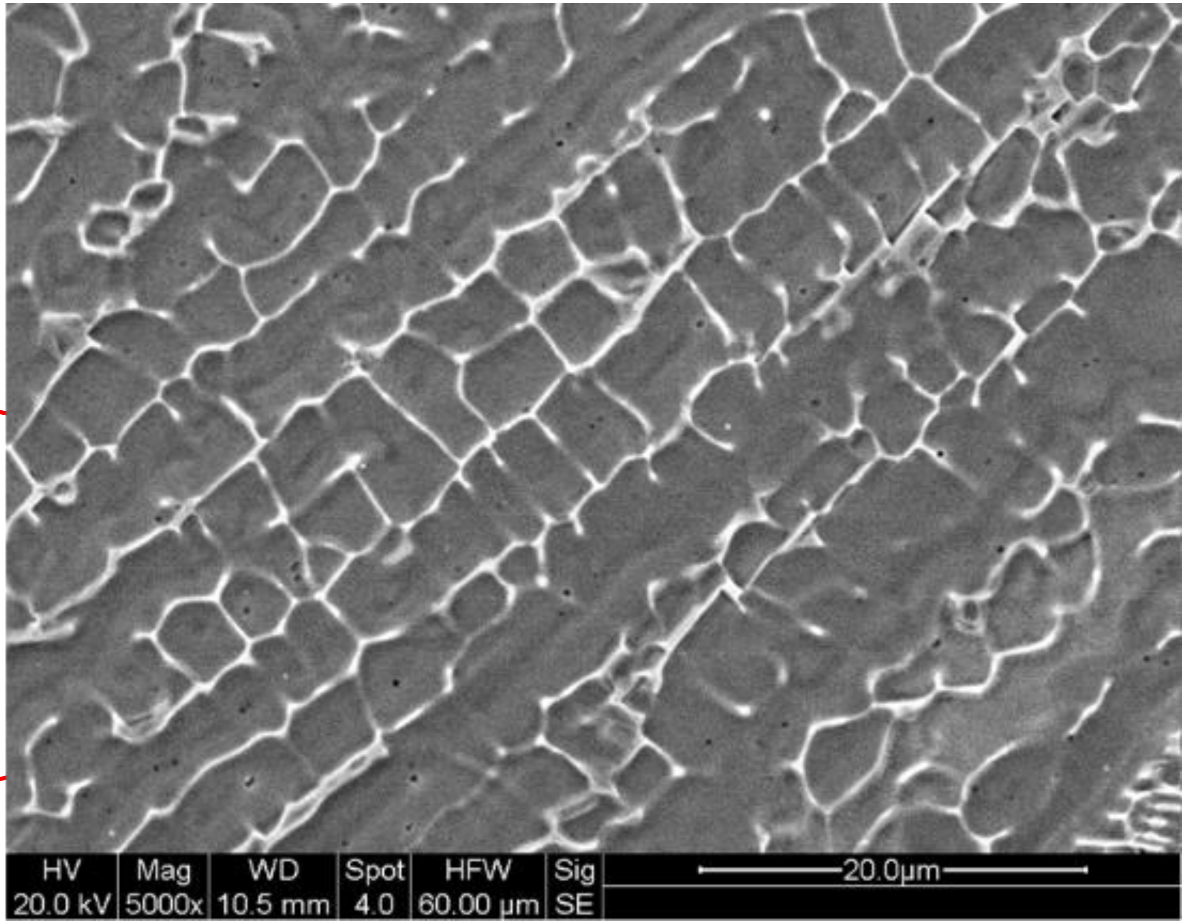


Solidification parameters (G/R)



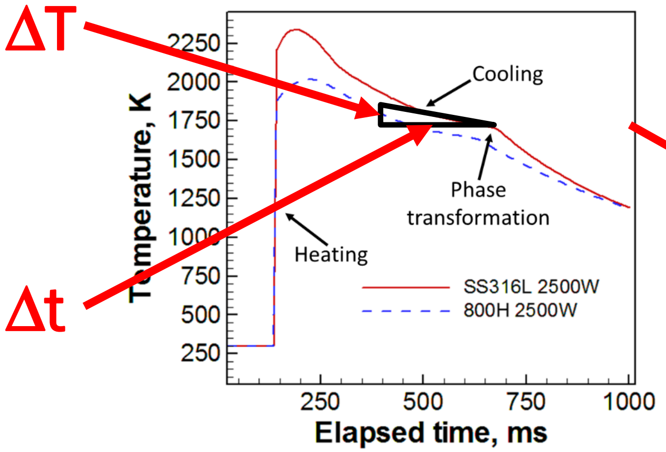
G/R < 1E5 $(\Delta T / D_L)$

Cellular/Dendritic Morphology

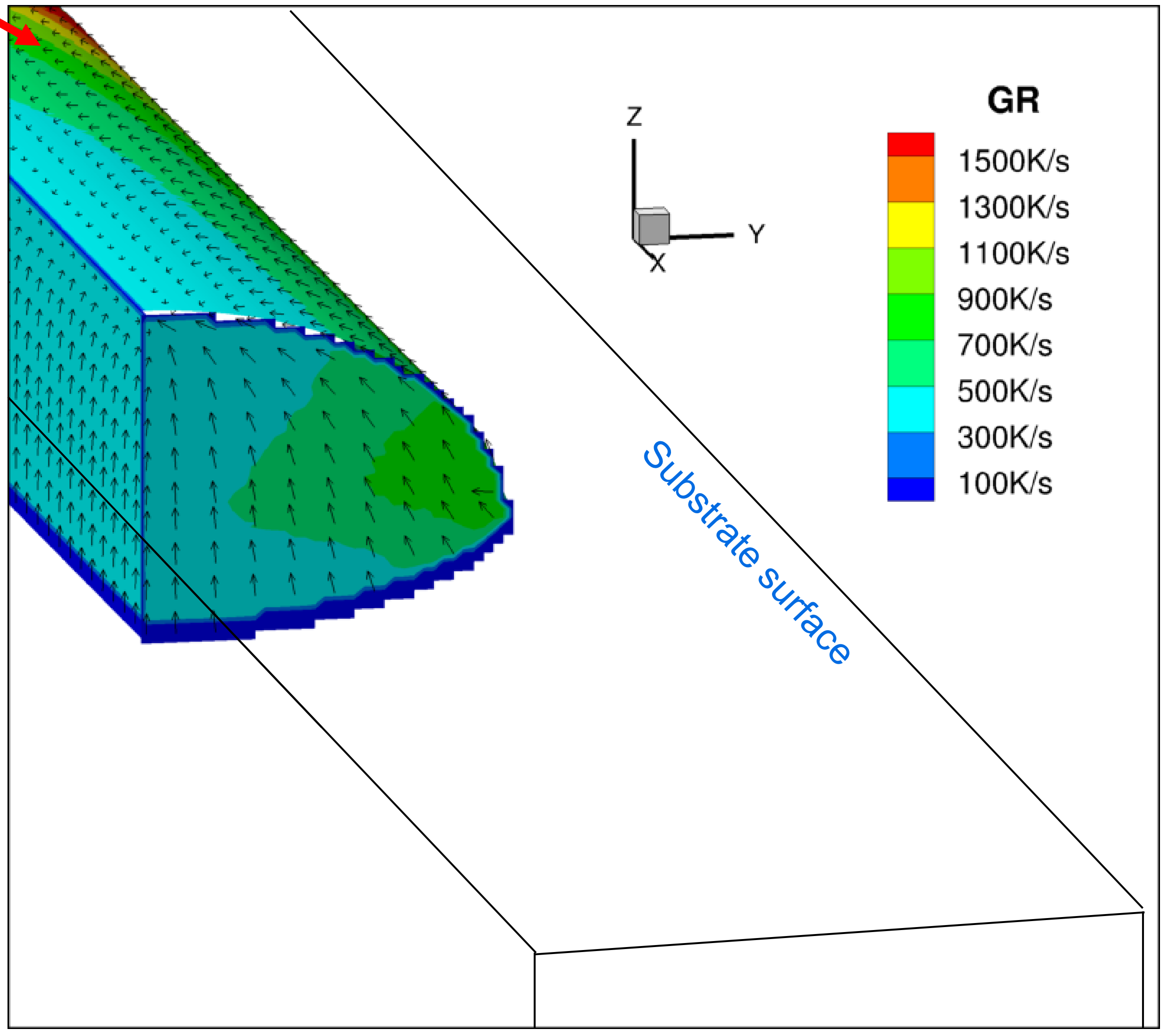


SEM micrograph of dendrites in SS316L manufactured at 2500W, 10mm/s

Cooling Rates



Calculate ΔT/Δt for each point



- Spatial variations of solidification parameters occur in all three dimensions
- Simple case studies need to be used to validate before using for larger-scale applications

Product property calculations

$$\lambda = 50 * (GR)^{-0.4}$$

$$\lambda \equiv SDAS\ in\ \mu m$$

$$\sigma_y = \sigma_0 + K_Y(\lambda)^{-0.5}$$

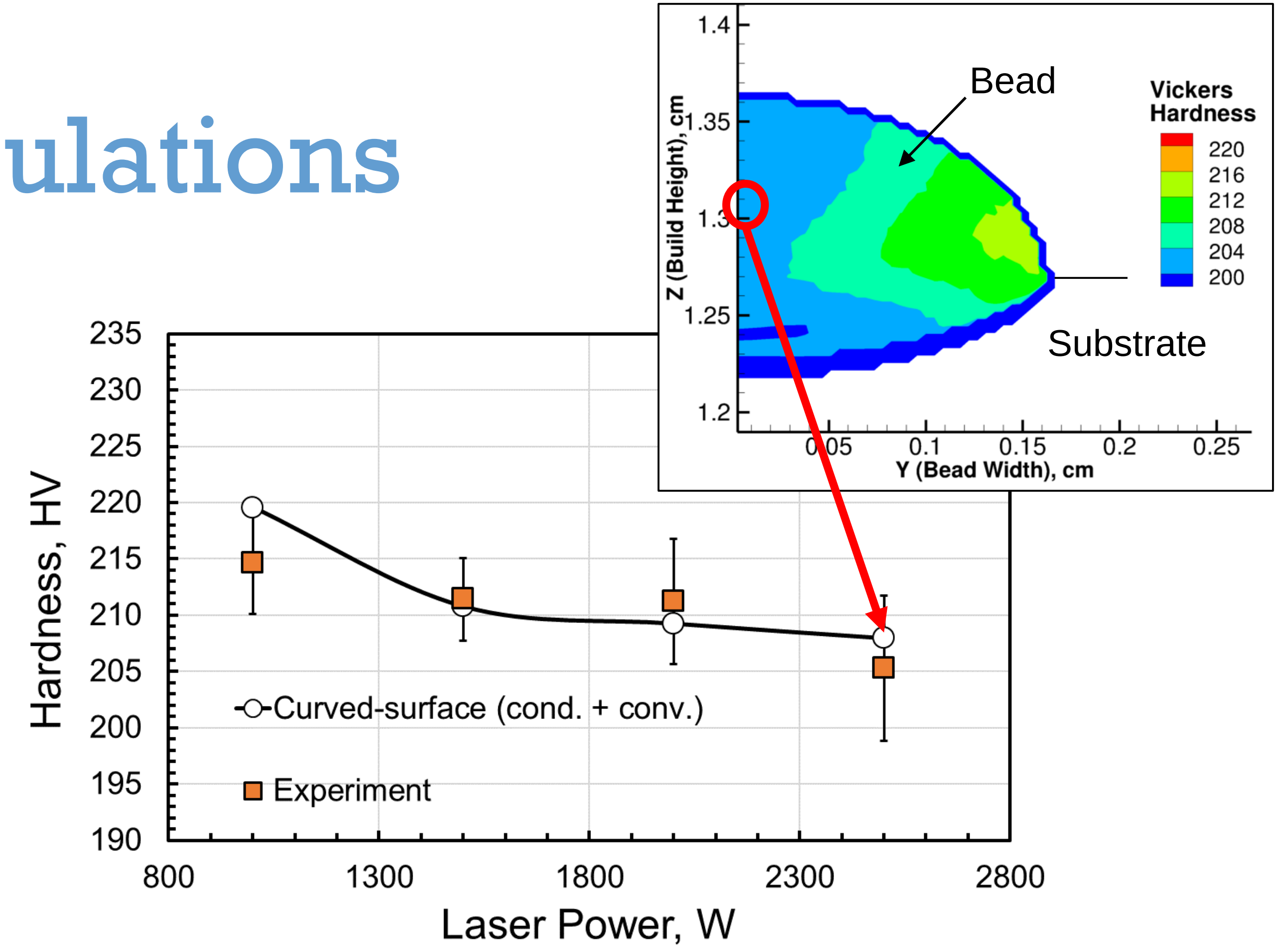
For SS 316

$\sigma_0 = 240MPa$

$K_Y = 279MPa.\mu m^{0.5}$

$$H_v = 3\sigma(0.1)^{2.25-m}$$

For SS 316 $\mathrm{m} = 2.5$

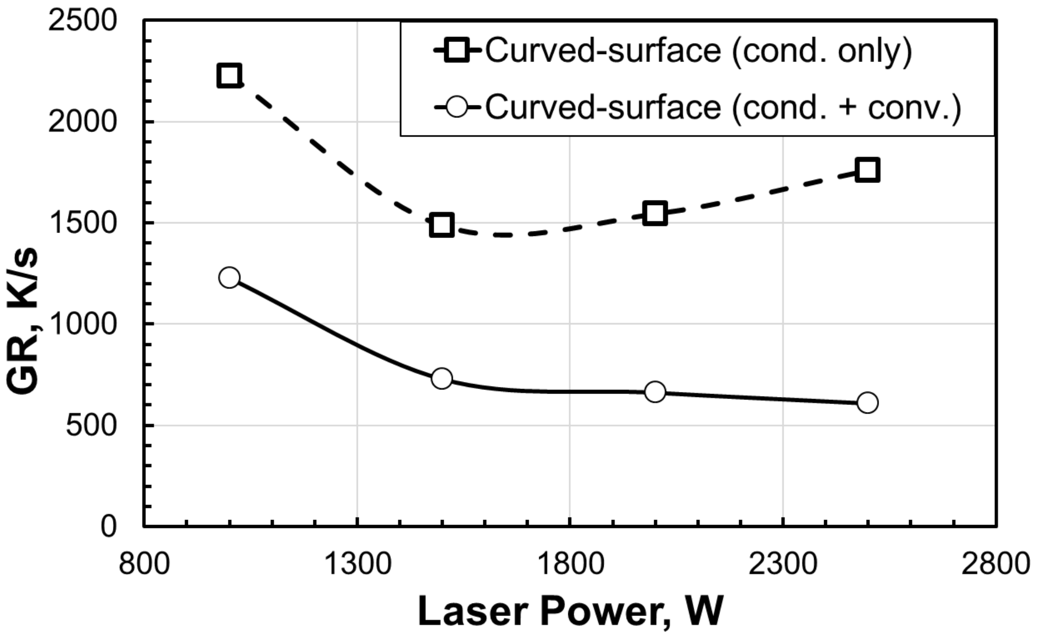


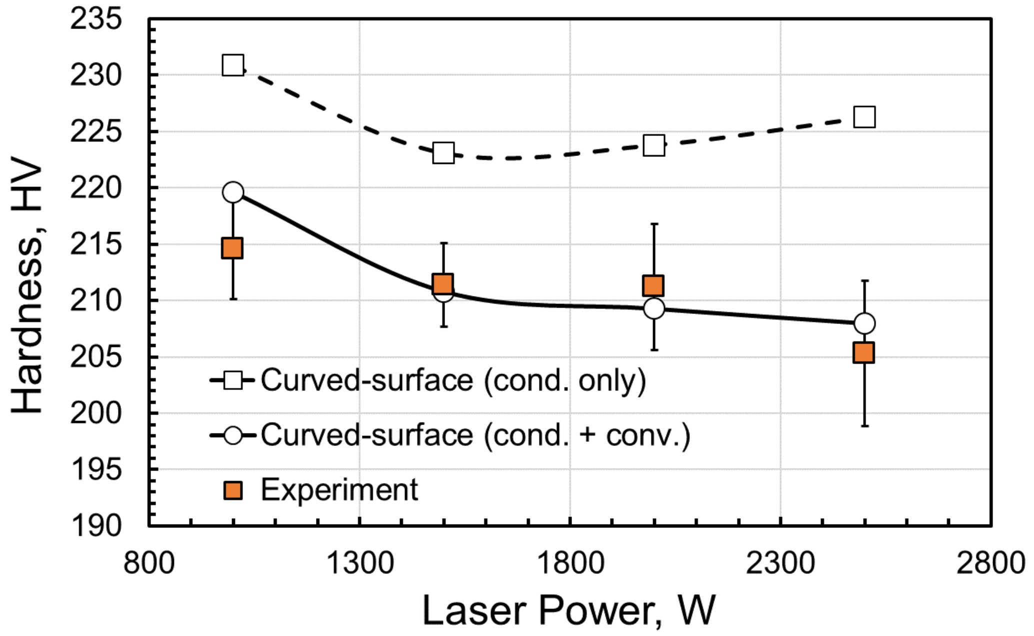
H. Yin, S.D. Felicelli, Dendrite growth simulation during solidification in the LENS process, Acta Mater. 58, no. 4 (2010) 1455-1465.

V. Manvatkar, A. De, T. DebRoy, Heat transfer and material flow during laser assisted multi-layer additive manufacturing, J Appl. Phys. 116, no. 12 (2014) 124905.

Importance of Fluid Convection

Ignoring fluid convection can lead to over-prediction of cooling rates, and thus miscalculation of mechanical properties.





Conclusions

- A number of building blocks for a digital twin of additive manufacturing have been validated
- Transient temperature fields are important, especially for evaluating critical solidification parameters
- Spatial variations in values can be seen
- In simpler alloys, general microstructural features can be predicted that can't be known from an equilibrium phase diagram
- Framework set for building of more complex digital twins