Additive Manufacturing Using *FLOW-3D*

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FLOW Science

Topics for Discussion

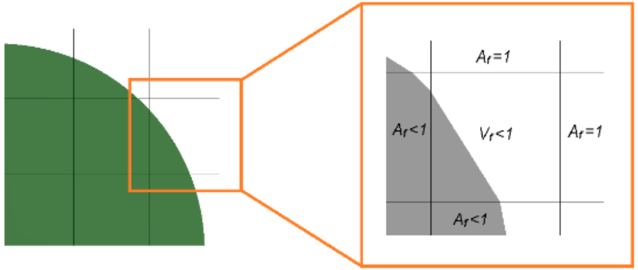
- ***Volume-of-Fluid* (VoF) Method**
- **Laser Welding**
- **Laser Powder Bed Fusion**
- **Multi-bed Layer Simulation**
- **DEM Model**
- **Direct Metal Deposition**

Some History

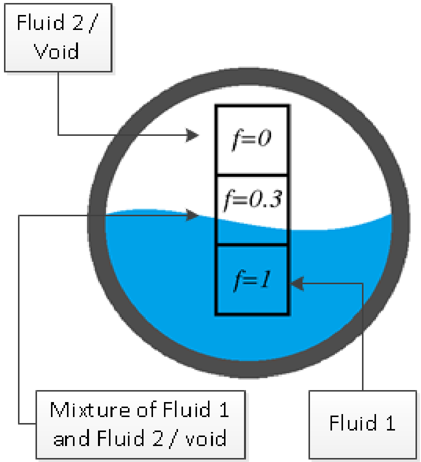
- **Founded in 1980 by Dr. C.W. "Tony" Hirt from the Los Alamos National Lab**
- ***FLOW-3D*® is a general computational fluid dynamics (CFD) software with superior abilities in predicting 3D transient flows with free surfaces**
- ***FLOW-3D* first released in 1985**
- **Two user interfaces**
  - ***FLOW-3D***
  - ***FLOW-3D* Cast**

Solver Uniqueness

- **FAVOR™**
- **Unique meshing advantage**
  - **Geometry can be added and removed without modifying the existing mesh**



- **Volume of Fluid (VoF) Method**
- **Uniquely suited to study free surface evolution**



TruVOF: ***FLOW-3D***’s Free Surface Modeling

- **A scheme to locate the surface**
- **An algorithm to track the surface as a sharp interface moving through a computational grid**
- **A means of applying boundary conditions at the surface**

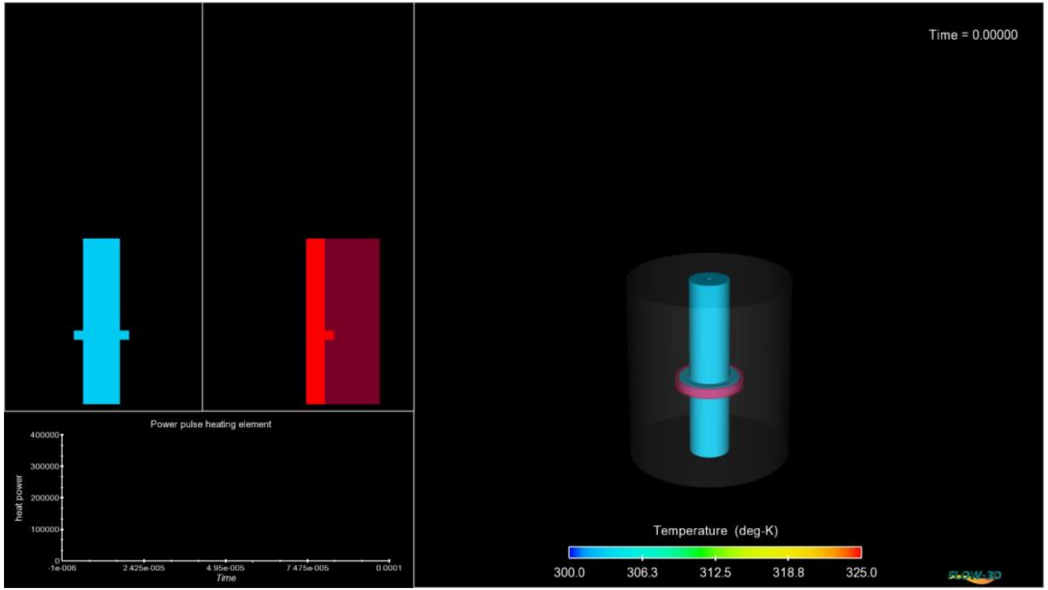
Advantages of one-fluid VoF method

Especially useful when the ratio of liquid to gas density is quite large!

VOF modeling

- Free surface flows
- Multiphase

- Free surface
- Surface tension
- Phase change
- Heat transfer



Example of fluid ejection using heating elements: heat impulse drives local phase change (fluid to gas) which in turns ejects a fluid droplet

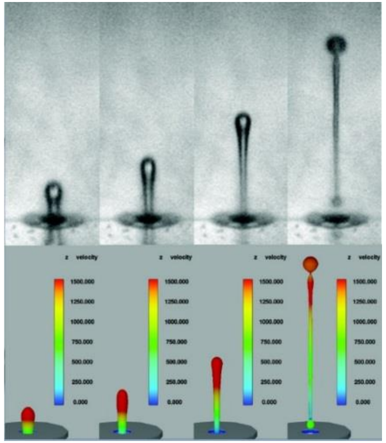
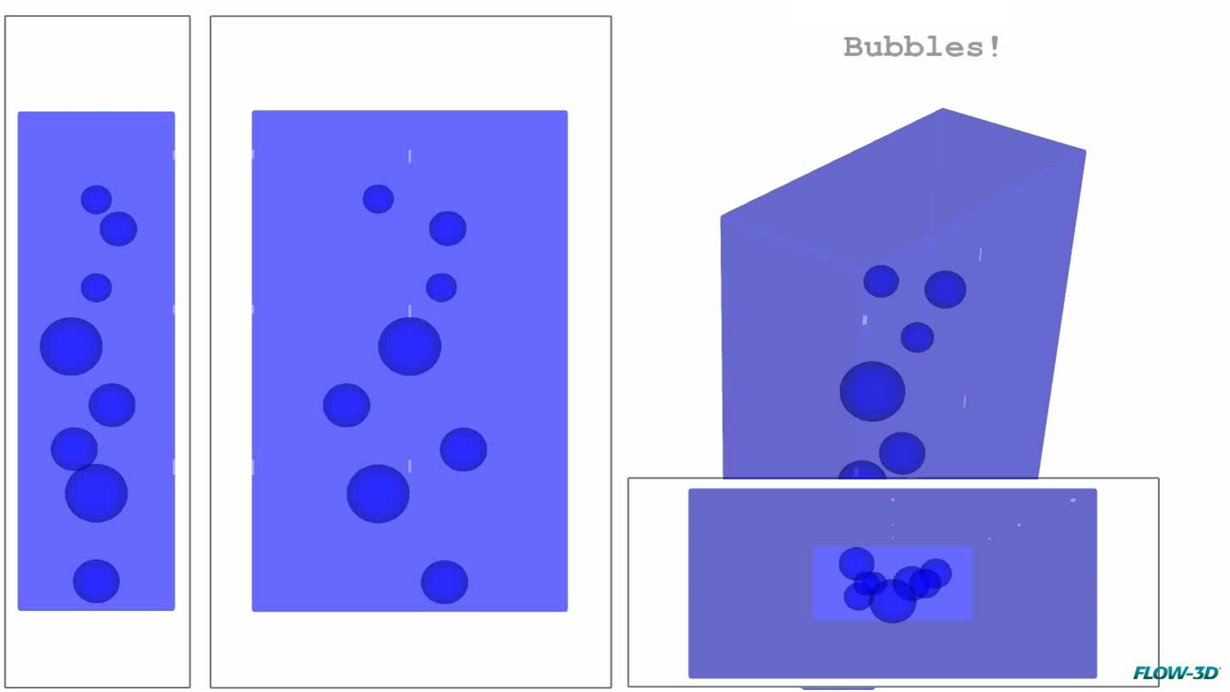


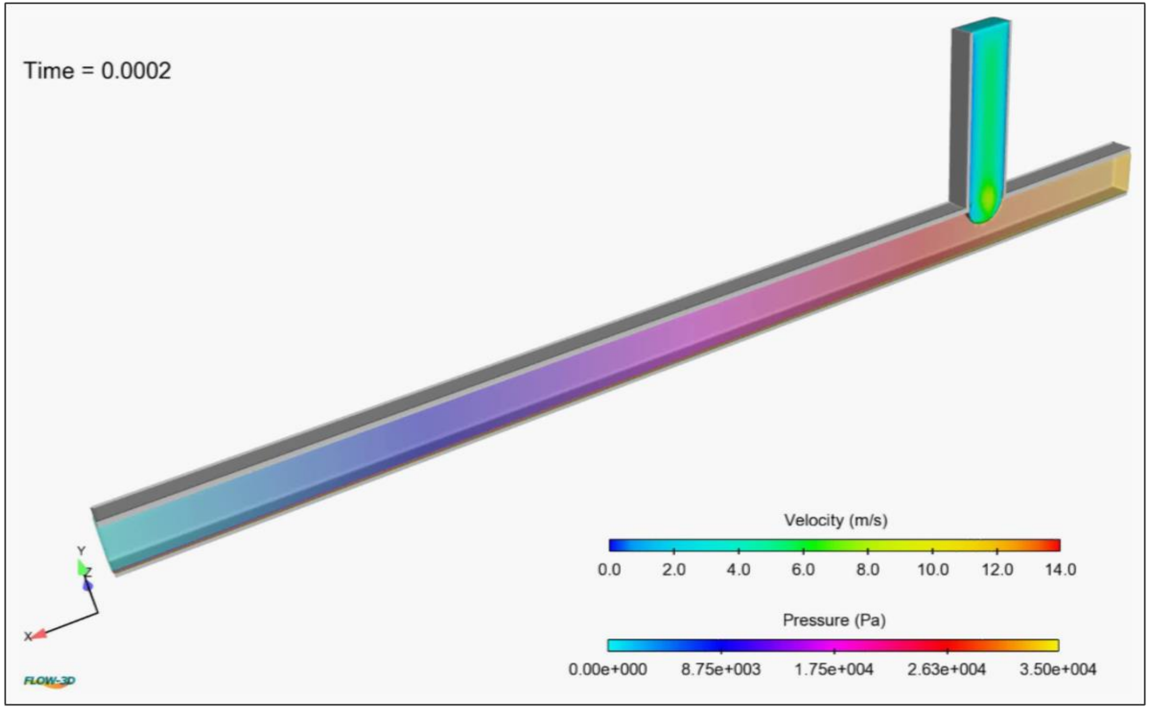
Image courtesy of Eastman Kodak

VOF modeling

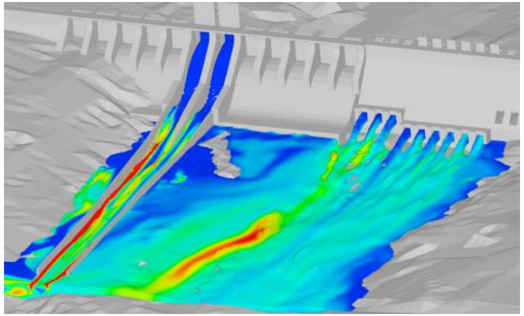


2 Fluid VOF Modeling

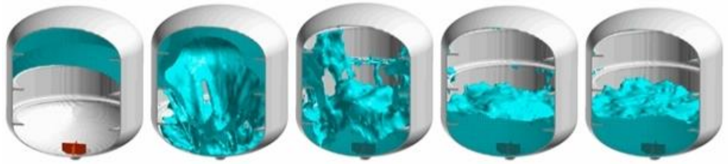
2 fluids VOF



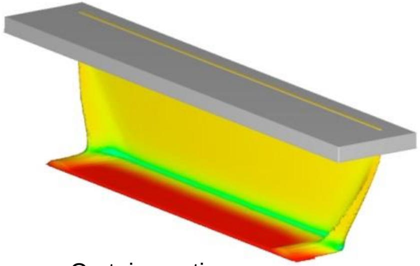
Application Areas



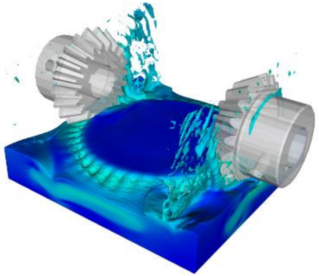
Air entrainment in dam flows



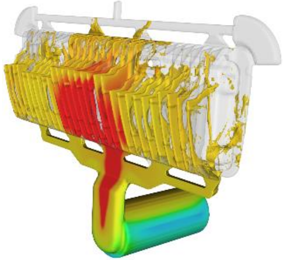
Propellant fuel sloshing



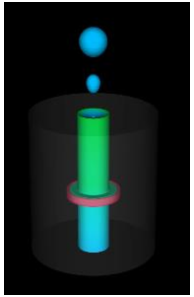
Curtain coating



An automotive differential

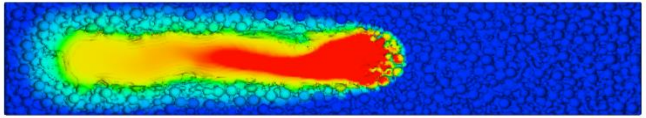


High Pressure Die Casting



Inkjet simulations

Powder bed fusion



A prelude to powder bed fusion

LASER WELDING

Relevant Physical Models

FLOW-3D®

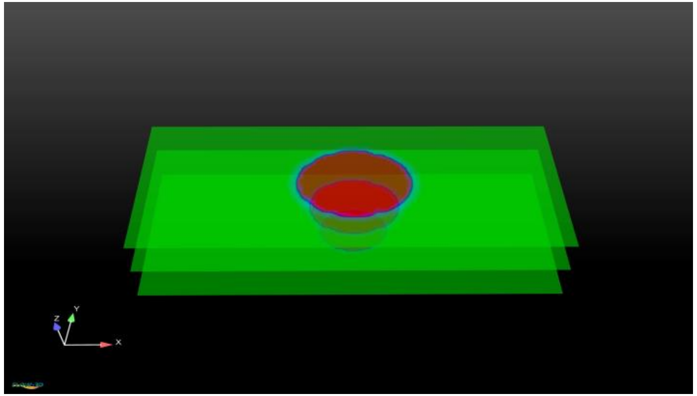
- **Viscous flows**
- **Heat transfer**
- **Solidification**
- **Phase change (vaporization)**
- **Density evaluation**
- **Surface tension**
- **Bubble/voids model**

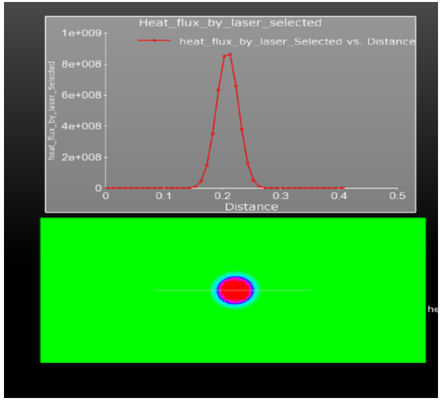
WEL Add-on Module

- **Heat flux produced by the laser**
- **Laser motion**
- **Evaporation pressure**
- **Shield gas**
- **Multiple laser reflections in keyhole**

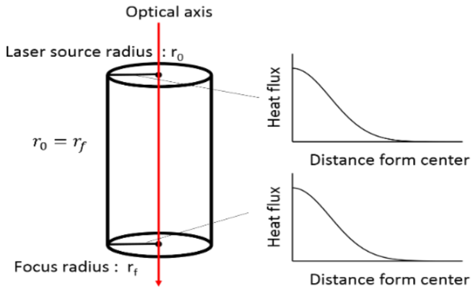
Features Laser/Heat Source

- **Specify the power output for multiple laser beams**
- **Flux distribution along the optical axis**
  - Can take cylindrical or conical distributions
- **Flux distribution along the beam diameter**
  - Can be constant or take a Gaussian distribution

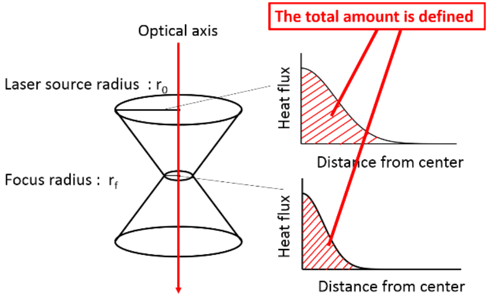




Laser beam profile and flux distribution



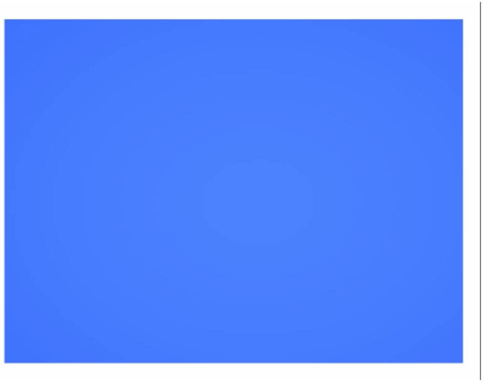
(a) Cylindrical distribution

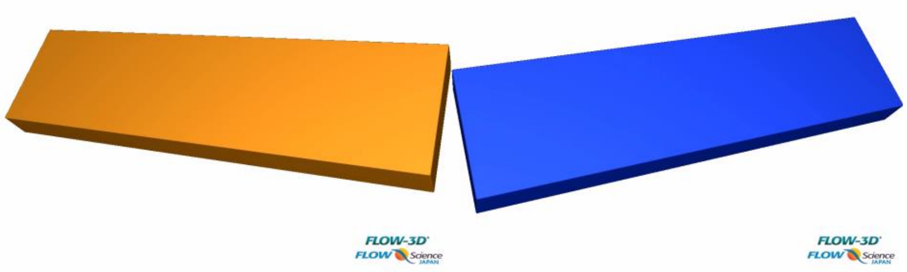


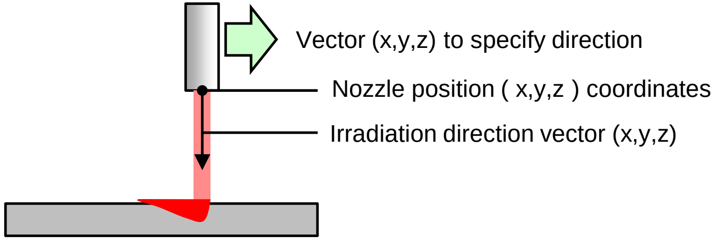
(b) Conical distribution

Features Laser Beam Motion

- **High degree of control**
  - Various shapes for laser beams
  - Specify independent motion for nozzle (laser source) and irradiation direction
    - Set using (x,y,z) coordinates and a velocity-time table
- **Motion can be input using a .csv file**



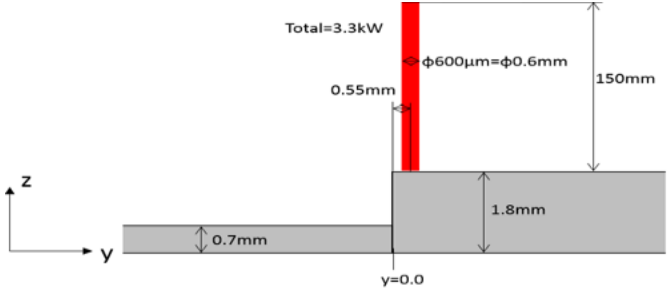




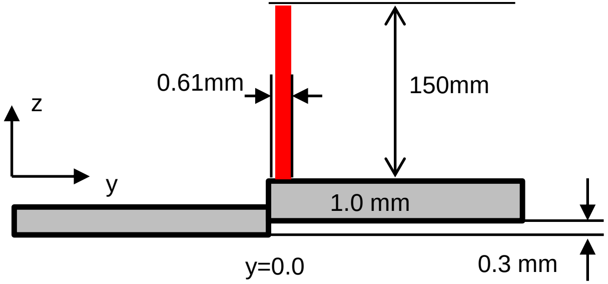
Case Study Shiloh Industries

***FLOW-3D* welding simulations show good agreement with experiments for welding joints**

Case	Power	Speed	Plate thickness
TM1	3300W	4.5 m/min	1.8 mm - 0.7 mm
TM5	3300W	4.5 m/min	1.0 mm - 0.7 mm

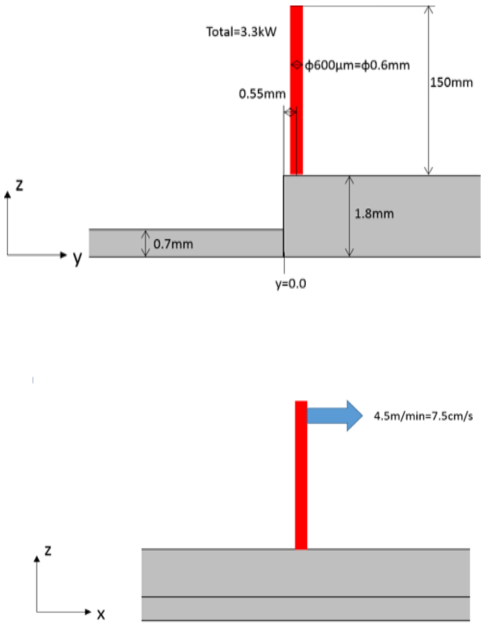


TM1



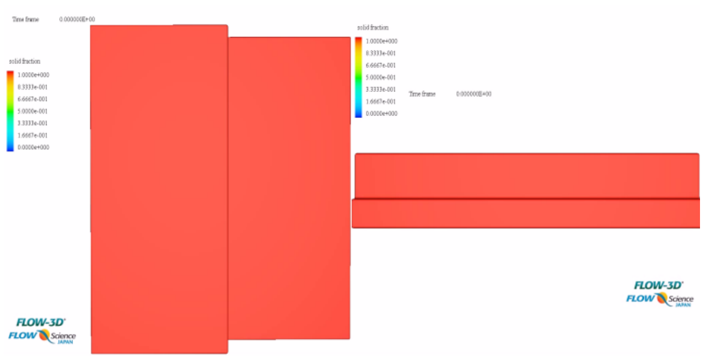
TM5

Case Study TM1 Welding

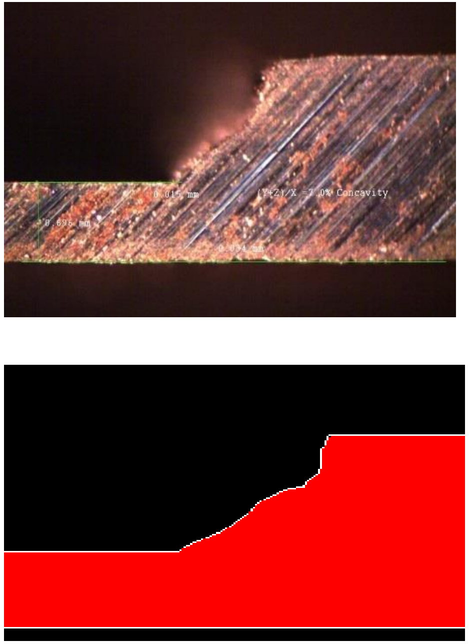


Schematic of the TM1 joint

TM1

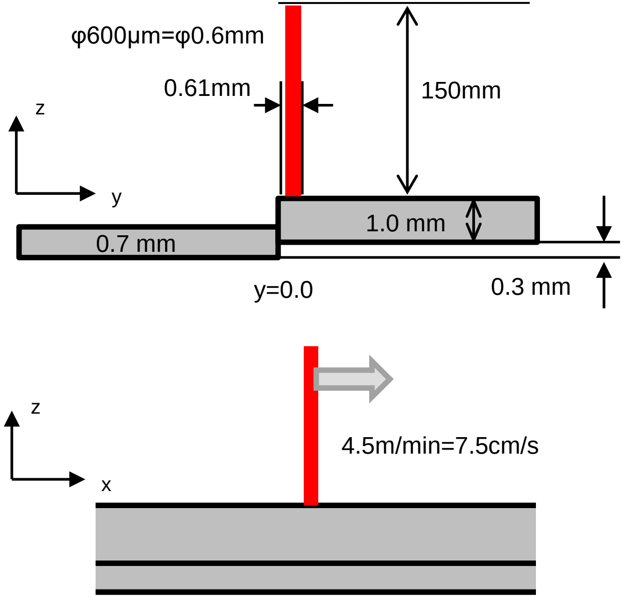


Simulation showing temperature profile



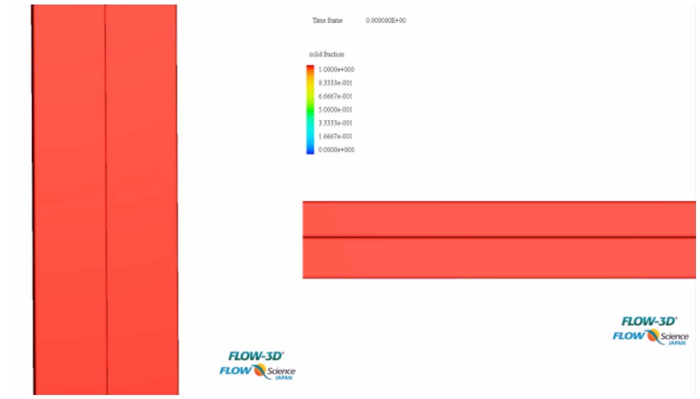
Comparison of weld sections in experiments (top) vs. simulation (bottom)

Case Study TM5 Welding

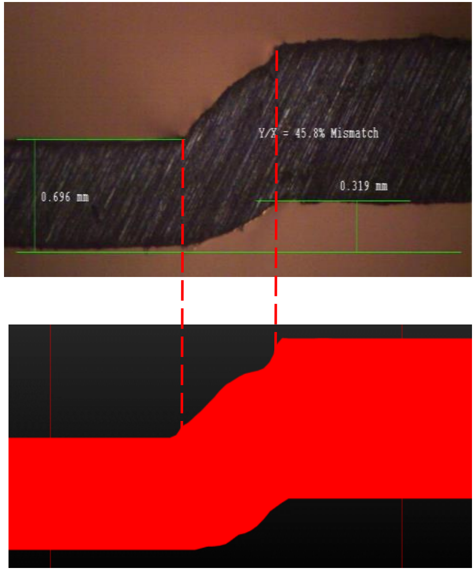


Schematic of the TM1 joint

TM5



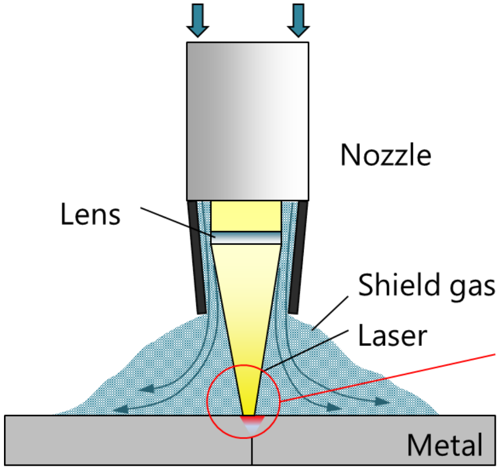
Simulation showing temperature profile



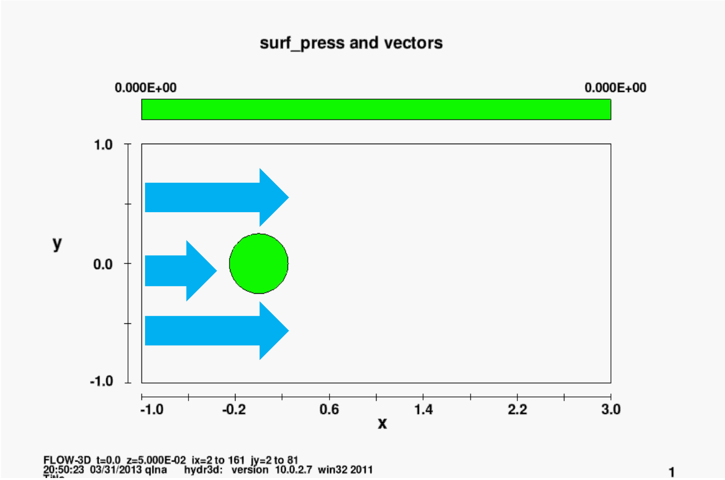
Comparison of weld sections in experiments (top) vs. simulation (bottom)

Features Shield Gas

Shield gas applies a dynamic vapor pressure on the melt pool surface



The behavior change due to the shield gas flow can be observed



Liquid droplet under vapor pressure

Features Evaporation Pressure

Critical in high laser power density applications

- An evaporation occurs at melt pool interface
- Exchange of mass and energy involved with phase change
- Exerted recoil pressures can cause further depression in the melt pool

There is no general equation defined for evaporation pressure. For this reason, we have the following model:

$$Ps = A\ exp\left\{B\left(1 - \frac{Tv}{T}\right)\right\}$$

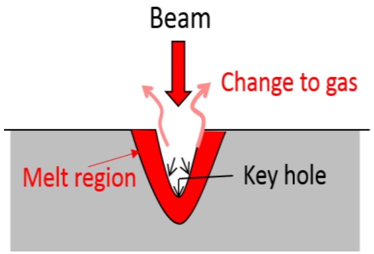
P_s : Evaporation pressure [Pa]

T_v : Boiling Point [K]

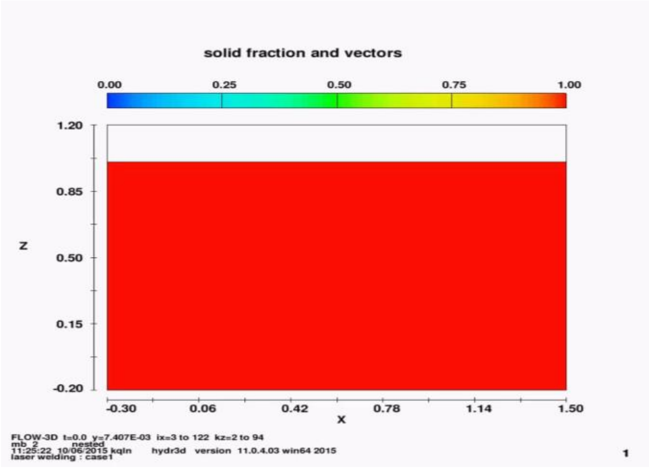
T : Temperature [K]

A : Coefficient [Pa]

B : Coefficient



Deep penetration laser welding

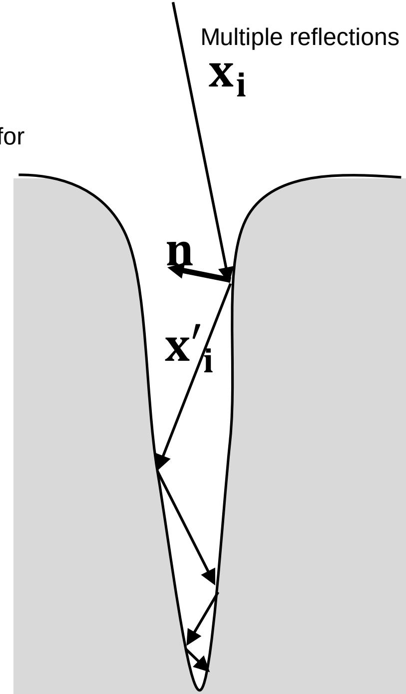


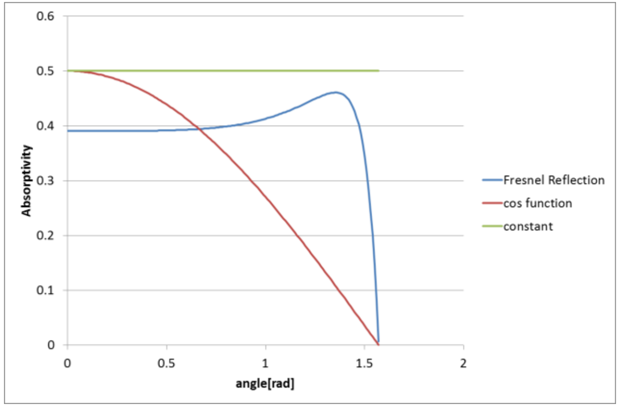
Features Multiple Reflections

The welding module can account for multiple reflections.

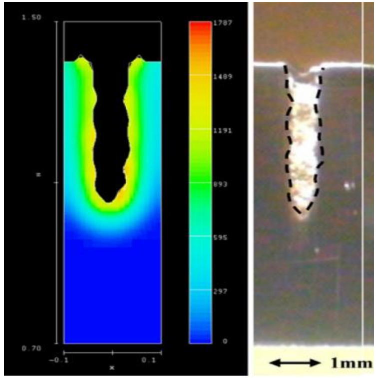
$$\mathbf{x}_i' = \mathbf{x}_i - 2(\mathbf{x}_i \cdot \mathbf{n})\mathbf{n}$$

Reflected vector calculation





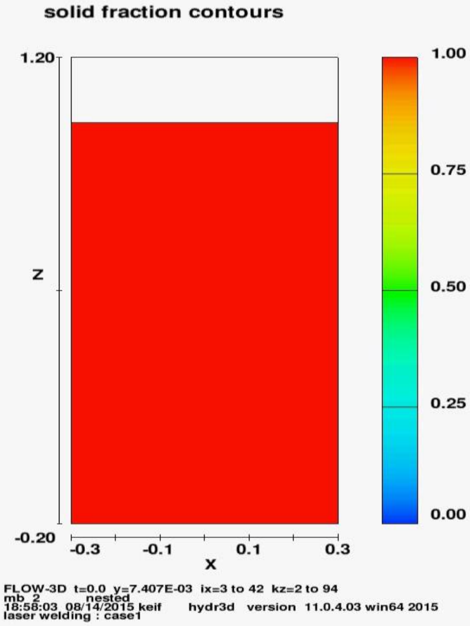
Absorption rate – angle of incidence



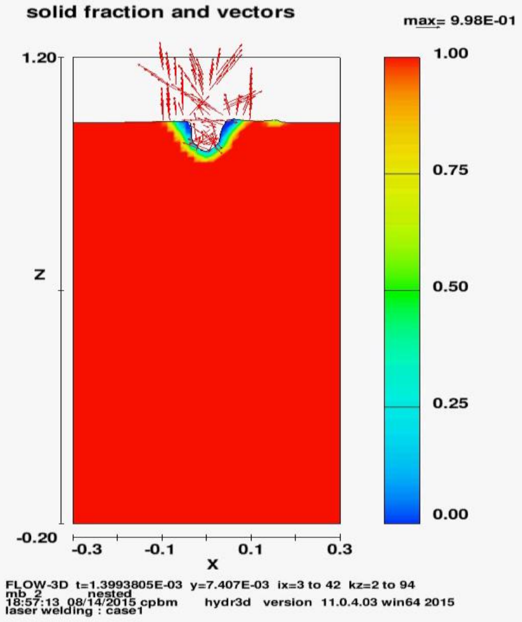
Simulation and experimental comparison of keyhole

Reference:
Jung-Ho Cho, Suck-Joo Na, 2006, Implementation of real-time multiple reflection and Fresnel absorption of laser beam in keyhole

Features Multiple Reflections



Multiple reflections - **Off**

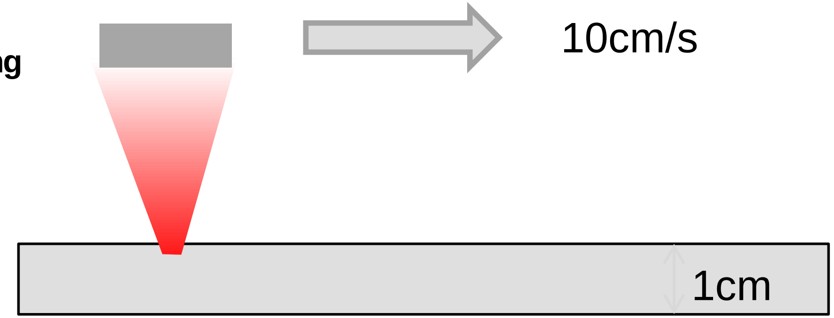


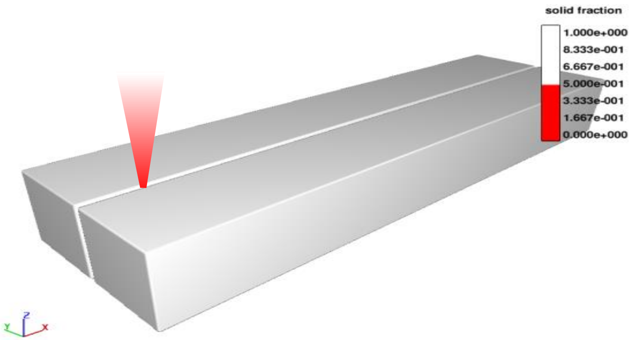
Multiple reflections - **On**

FLOW Science

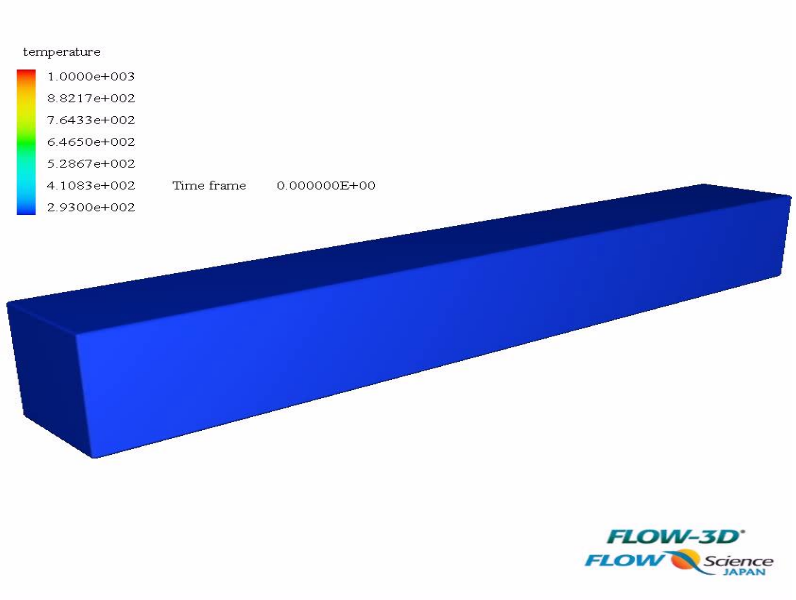
Deep Penetration Weld

- **Computational setup of a *FLOW-3D* deep penetration laser welding simulation of an aluminum plate**
- **Material properties of an aluminum alloy**
  - ρ=2.3g/cm3
  - μ=0.013poise
- **3D simulation**
  - Mesh=896,000 (dx=0.25mm)
  - T=0.5sec
- **Models used**
  - Surface tension
  - Heat transfer
  - Phase change (solidification, evaporation)
  - Evaporating pressure

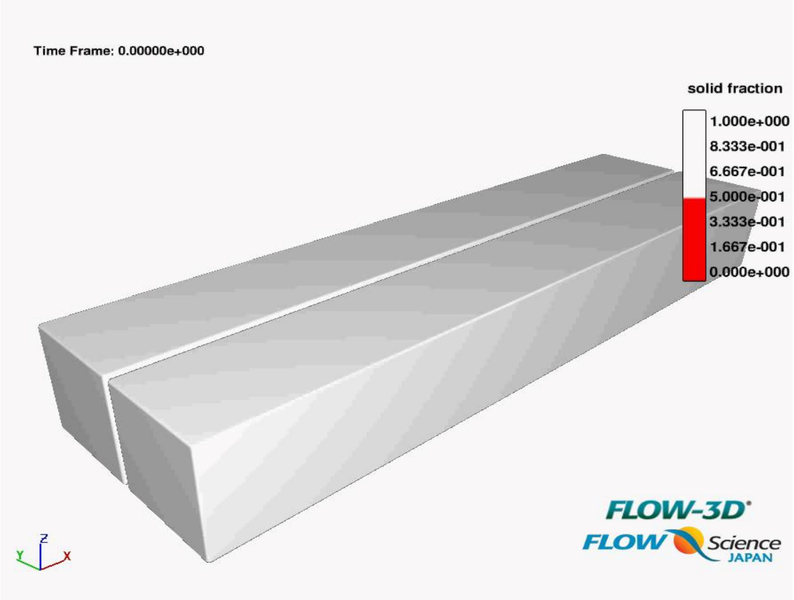




Deep Penetration Weld



Temperature contours in cross-section

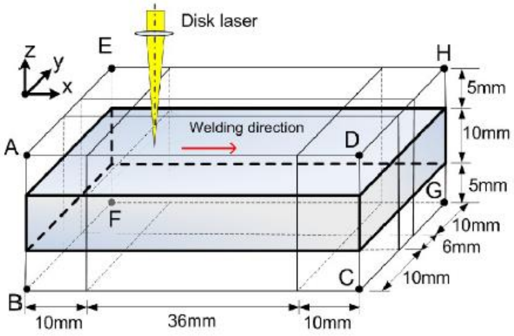


Solid fraction contours

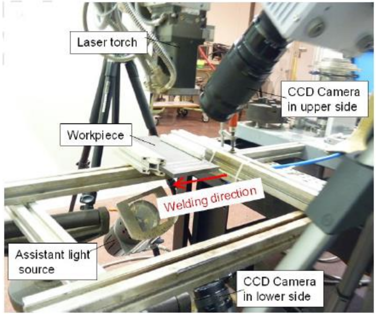
Case Study KAIST and BAM

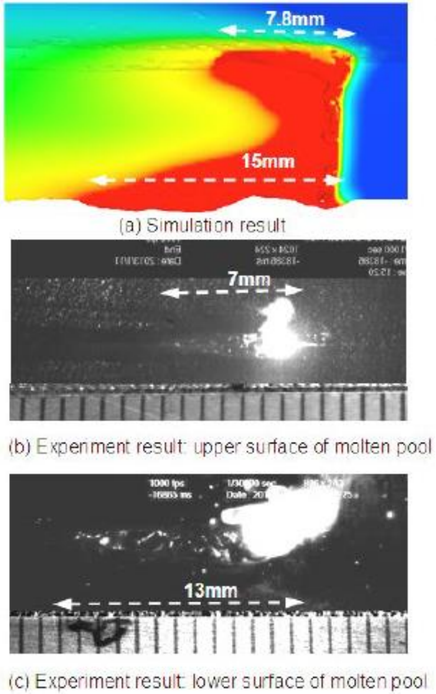
- **High laser power welding - Full penetration laser welding carried out on a 10mm steel plate using a 16kW laser**
- **Simulations and experiments show similar lengths for top (~7.5mm) and bottom (~14mm) molten pool formations**

Schematic of computation domain in ***FLOW-3D***



Experimental setup with CCD cameras observing both the top and bottom molten pool



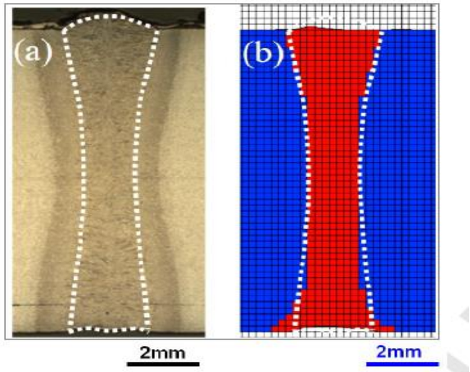


Simulation results (top) and experiments results (bottom) for melt pool lengths

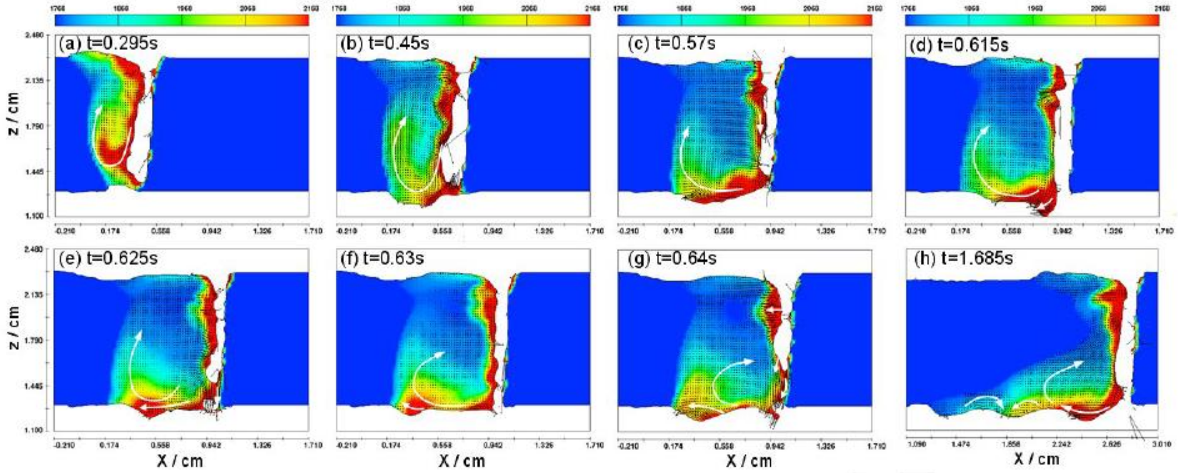
<u>Ref:</u> *Zhang, L.J., et. al., Numerical simulation of full penetration laser welding of thick steel plate with high power high brightness laser, Journal of Materials Processing Technology (2014)*

Case Study Deep Penetration Weld

- *FLOW-3D* predicts molten pool features in good agreement with experiments
- Lower surface of molten pool may be longer and more unstable than upper surface
- Simulations help identify possible reasons for transient flow field of molten pool – An outcome of the influence of gravity, recoil pressure and surface tension forces

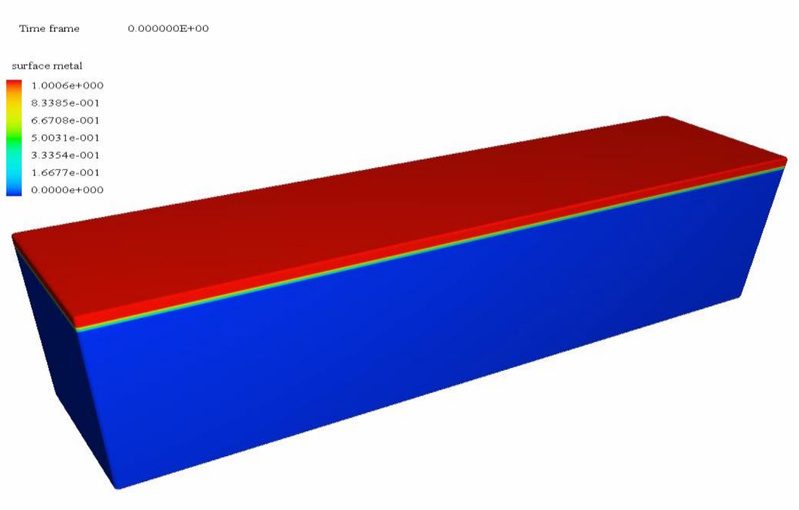


Comparison of weld cross section between (a) experiment and (b) simulation

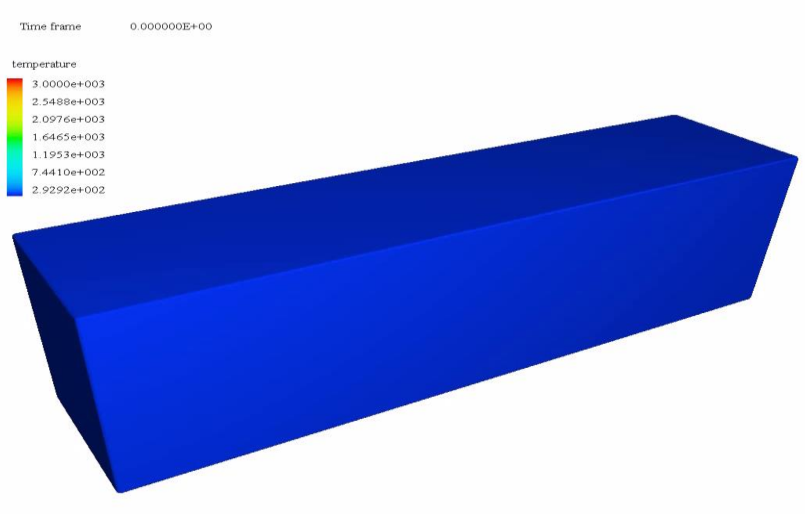


Simulation results of the flow pattern of lower molten pool

Porosity Formation



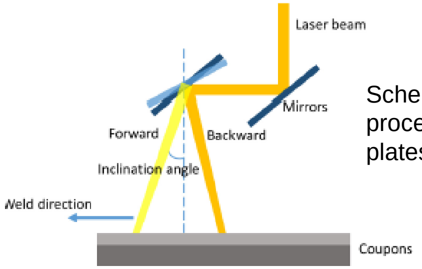
Bubble formation and flow pattern of the molten pool



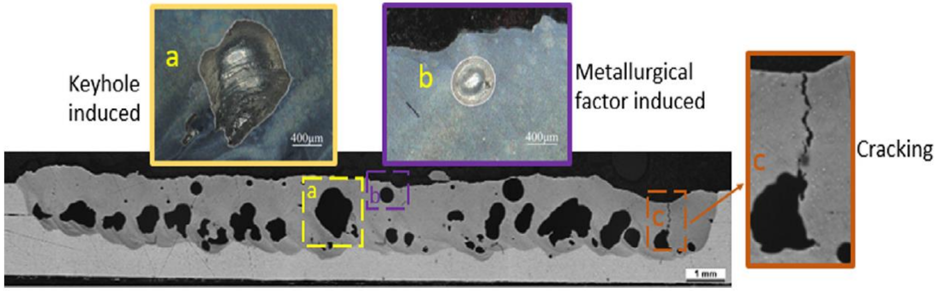
Temperature (K) contours in molten pool

Case Study GM and Shanghai University

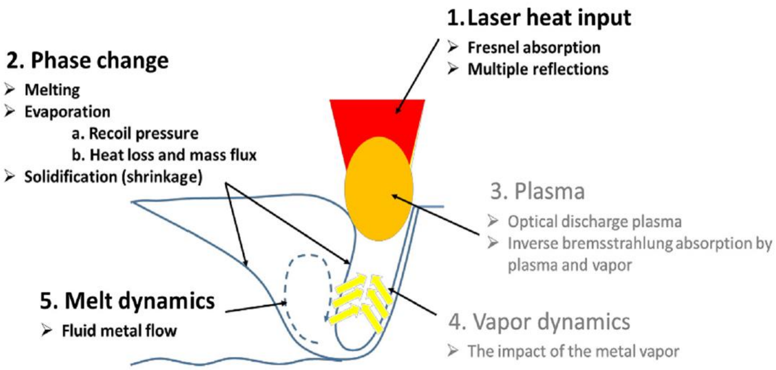
- **Study to determine the influence of welding speed and angle of inclination on porosity occurrence in keyhole welding**
- **Simulations provided recommendations to mitigate keyhole induced porosity occurrence**



Schematic of remote laser lap welding process on AA5182 1mm + 2mm plates. Beam spot diameter is 0.6mm



Weld porosity in laser-welded Al joint's cross section. Keyhole induced porosity occurs due to flow dynamics and can initiate cracking. Optimized process parameters can mitigate this kind of porosity.

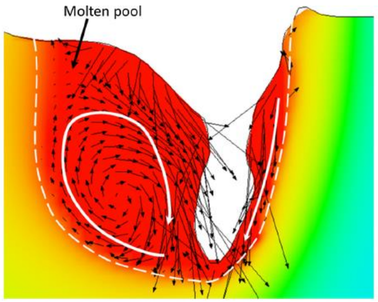


Major phenomena accounted for by ***FLOW-3D*** in simulating melt pool dynamics

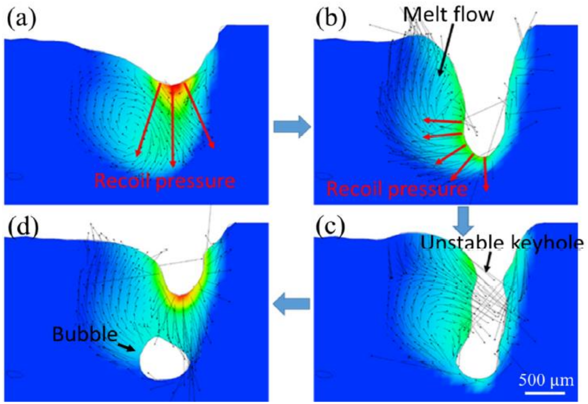
Ref: Numerical Study of keyhole dynamics and keyhole-induced porosity formation in remote laser welding of Al alloys, R. Lin et al., Int. J. Heat Mass Transfer, 108(2017) 244-256

Case Study Keyhole Porosity

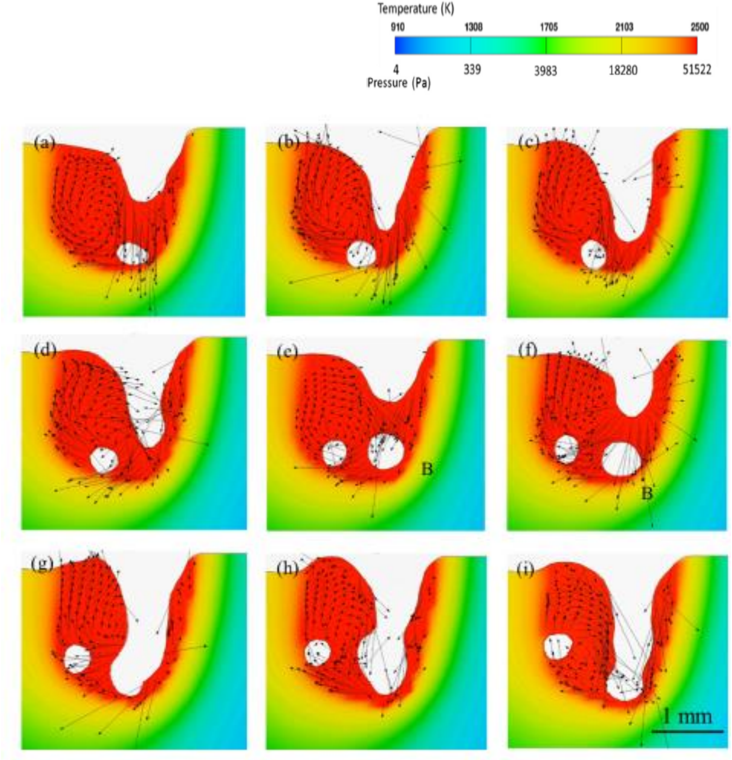
- **Unstable keyholes collapse and form bubbles/voids.**
- **Bubbles float to the back of melt pool and are trapped by the advancing solidification front results in porosity.**
- **If a bubble opens up to the keyhole again, no porosity occurs.**



Melt pool dynamics



Keyhole formation and collapse



Transient evolution of a melt pool and porosity occurrence

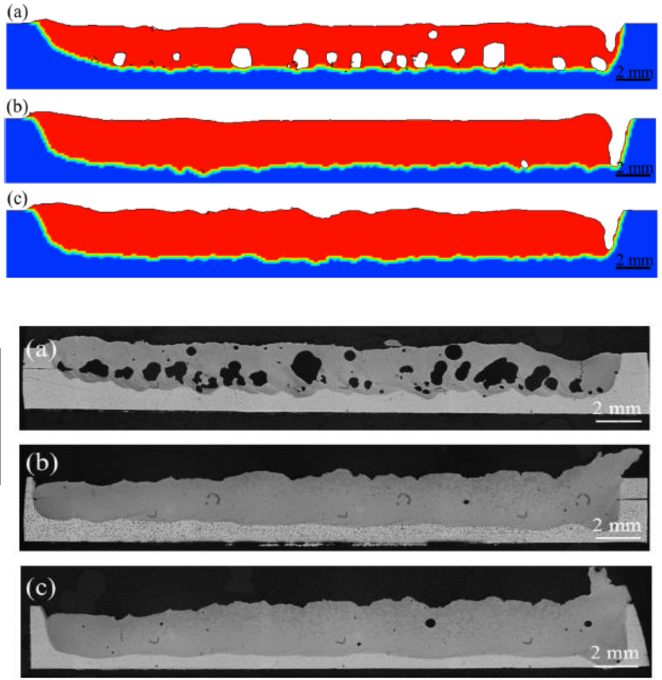
FLOW Science

Simulations vs Experiments

- **Parametric study**
  - Case (a): P = 2.5 kW, v = 3 m/min
  - Case (b): P = 5.0 kW, v = 10 m/min
  - Case (c): P = 6.0 kW, v = 12 m/min

- **Increasing weld speed results in decreasing porosity**

Case (a) to Case (c): Increasing scanning speed and laser power

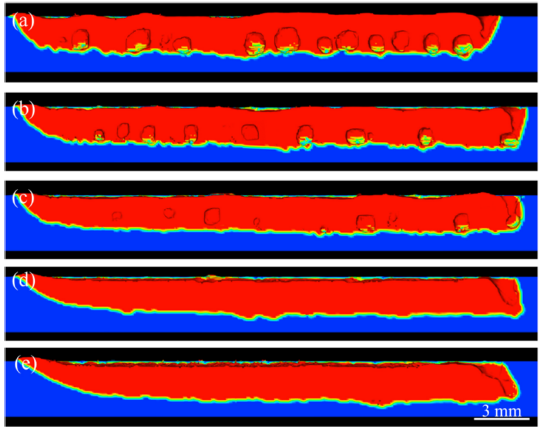


Distribution of porosity in longitudinal welding sections as seen in simulations (top) and experiments (bottom)

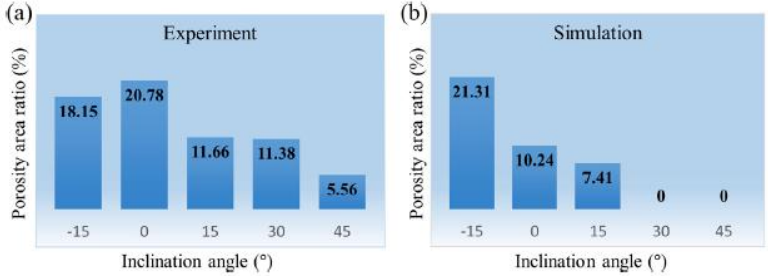
Simulations vs Experiments

- **Parametric study**
  - Case (a): 2.5 kW, 3 m/min and -15^0
  - Case (b): 2.5 kW, 3 m/min and 0^0
  - Case (c): 2.5 kW, 3 m/min and 15^0
  - Case (d): 3 kW, 3 m/min and 30^0
  - Case (e): 3 kW, 3 m/min and 45^0

Case (a) to Case (e): Increasing weld angle inclination



- **Increasing weld angle results in decreasing porosity**



Pore area percentage at different inclination angles as seen in (a) experiments and (b) simulation results.

Outcomes of the Study

- **With increasing laser power and welding speed**
  - Larger keyhole opening and little fluctuation in depth
  - Laser beam shines on front keyhole wall with minimal turbulence in rear molten pool
  - Minimizes porosity formation

- **With increasing laser beam inclination**
  - At large angles, laminar flow is observed in rear molten pool due to gravity and recoil pressure acting along similar directions
  - Minimizes porosity occurrence

- ***FLOW-3D* simulations gave a realistic understanding of the welding process and helped mitigate porosity formation!**

POWDER BED FUSION PROCESSES

Powder Bed Fusion – Physical Models

FLOW-3D®

- Viscous flow and turbulence
- Heat transfer
- Solidification
- Phase change (vaporization)
- Density evaluation
- Surface tension
- Bubble/voids model
- Thermal Stresses

+

DEM Add-on Module

- Discrete Element Method (DEM)
- Randomized distribution of particle bed
- Multiple particle species

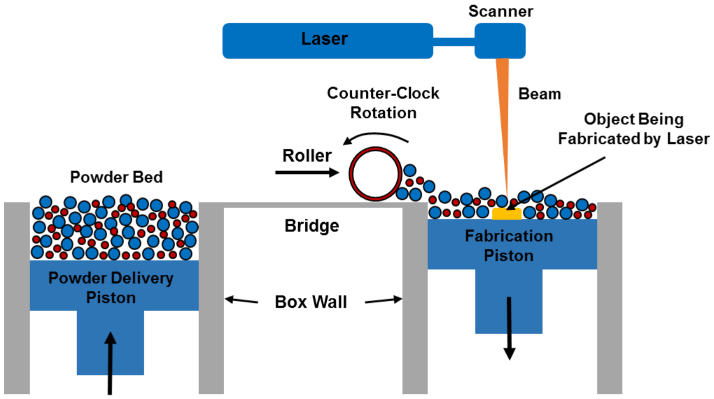
WELD Add-on Module

- Heat flux produced by the laser
- Laser motion
- Evaporation pressure
- Shield gas

Powder Bed Fusion Process

- **Sequence of a simulation setup**
  - Powder bed laying using DEM
  - Laser irradiation using WELD

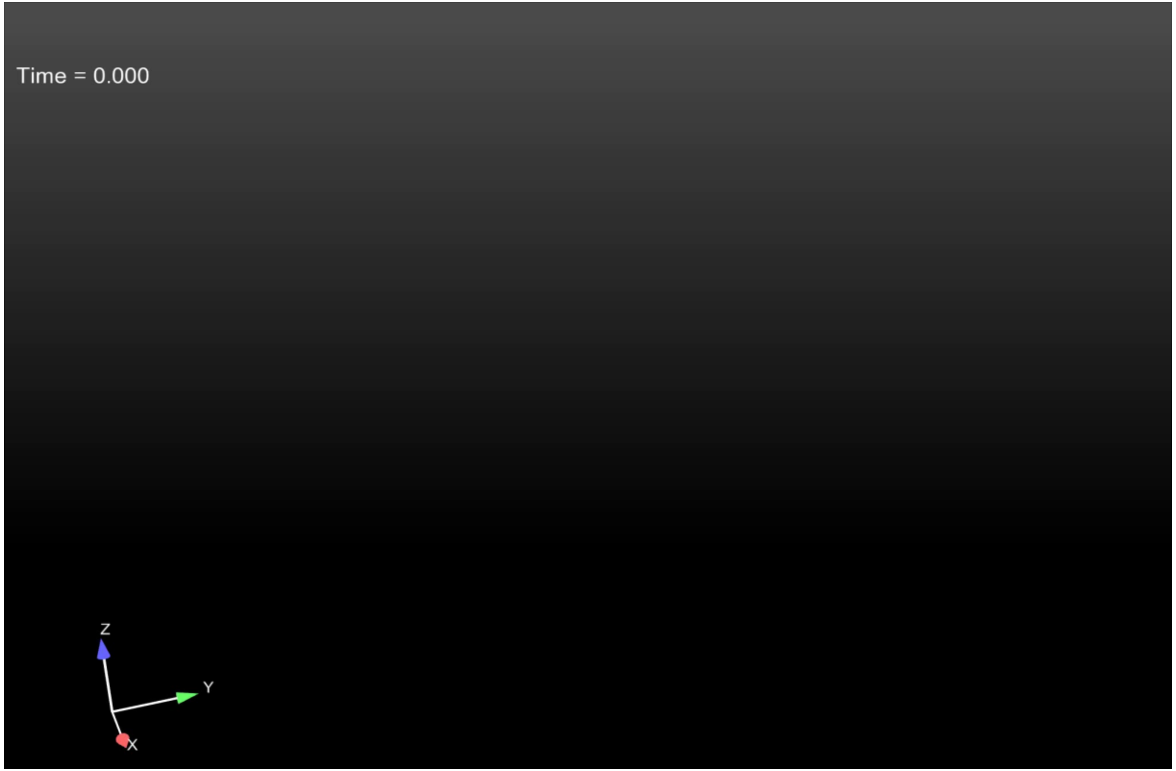
- **Additional analysis**
  - Thermal stress analysis using ***FLOW-3D***’s structural analysis interface



Schematic of a powder bed fusion process

Additive manufacturing in progress
Ref: https://3dprint.com/41790/zecotek-3d-print-powder/

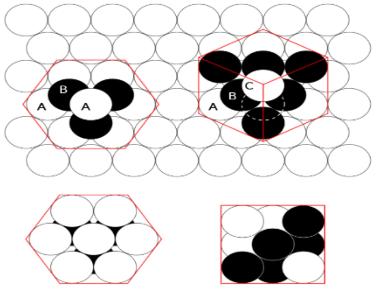
DEM – Bed Preparation (Powder Laying)



Particles are dropped to simulate the natural lamination process. Material used is Ni alloy (Inconel 718) with a particle diameter of 20μm

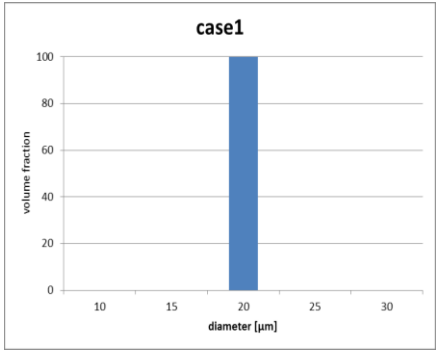
DEM – Particle Size Distribution

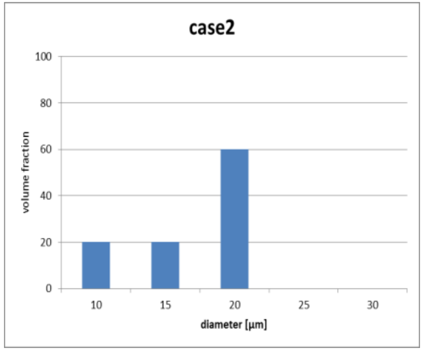
- **Three particle size distributions considered**
  - Case 1 with 20µm particles
  - Case 2 with 10, 15 and 20µm particles
  - Case 3 with 20 and 30µm particles
- **Total supply volume is same in each case**
- **Different particle radii result in different packing fractions**

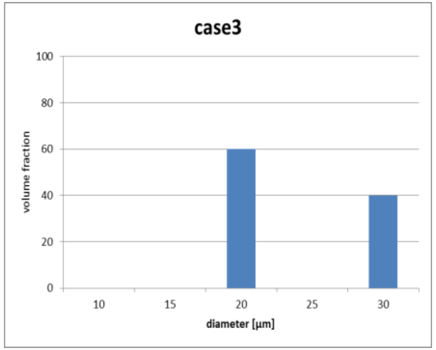


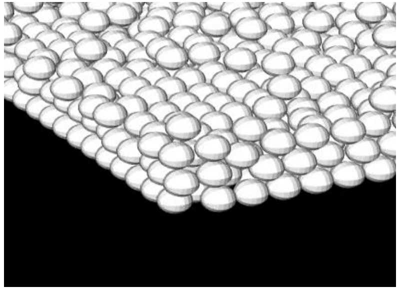
Hexagonal close-packed lattice | Face-centered cubic lattice

ref: Wikipedia



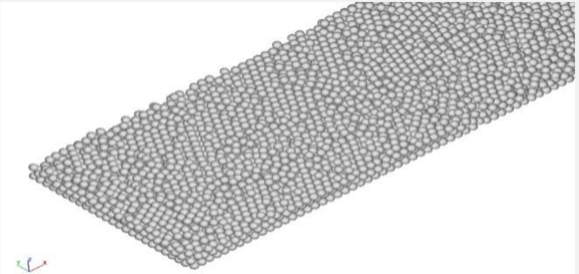
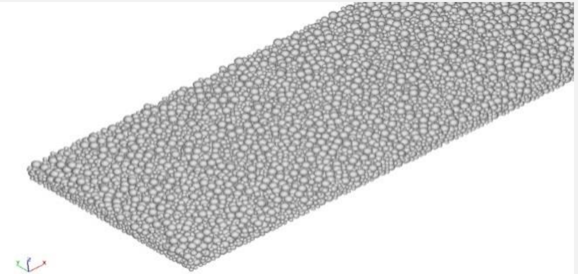
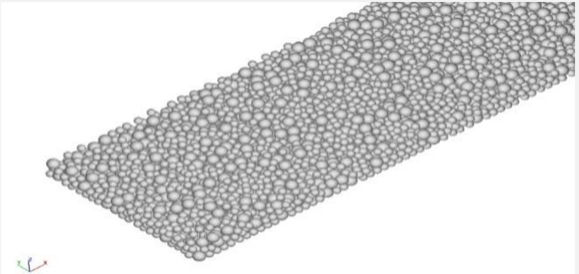
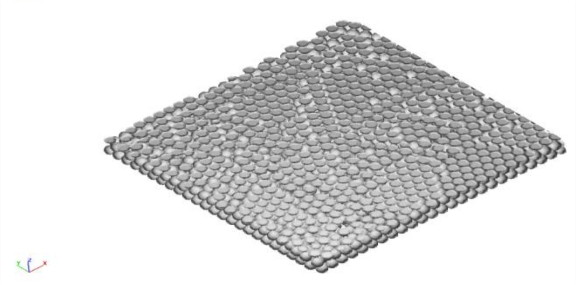
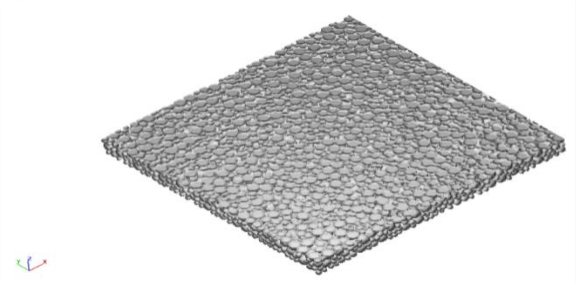
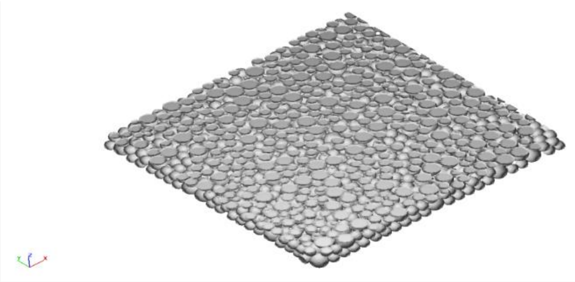




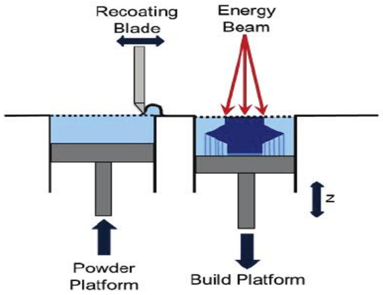


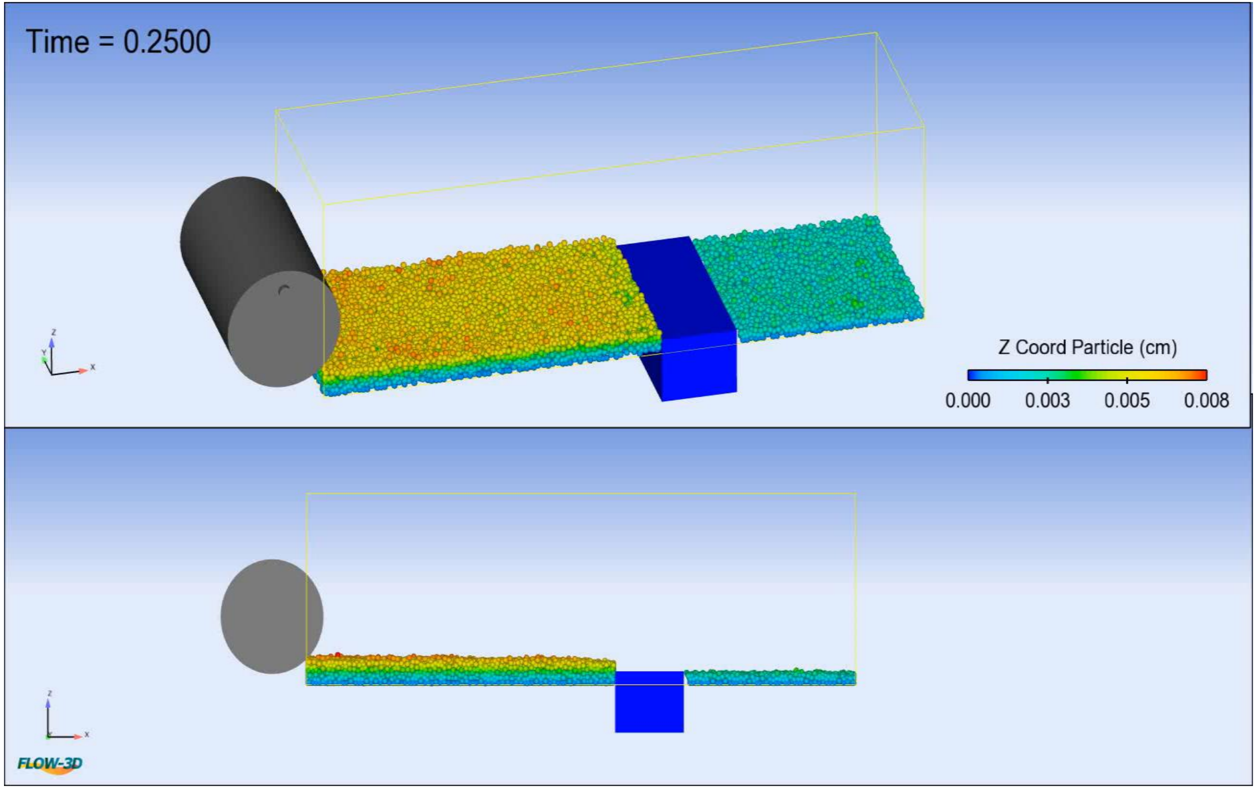
Base particle size of 20µm

Packing Fraction

Case1	Case2	Case3
		
		
69.7%	70.2%	67.3%

Powder Spreading



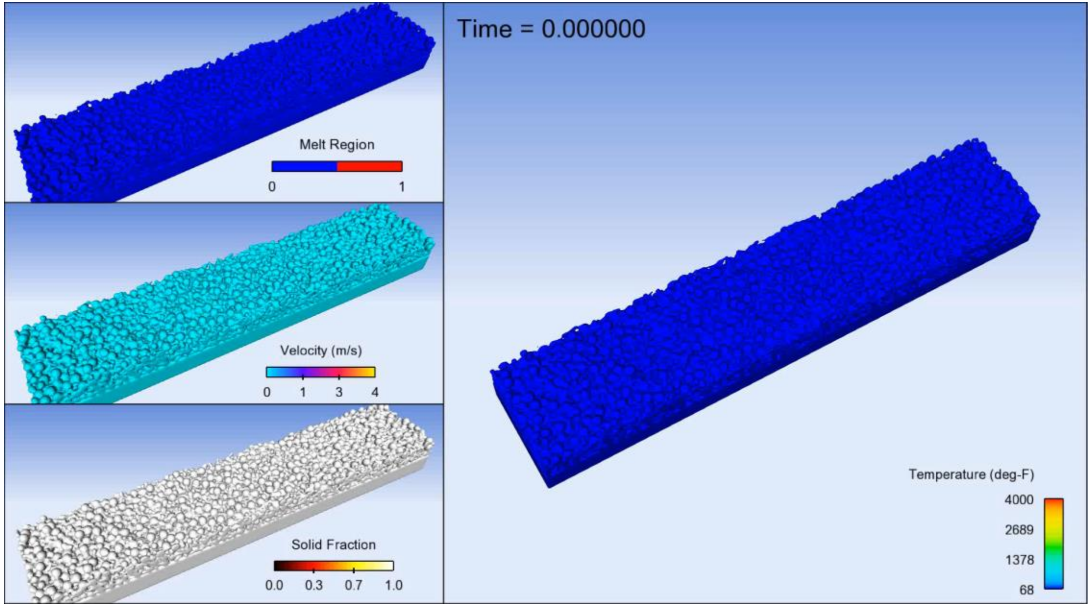


<u>Features of interest:</u>

1. Transfer of powder to build platform
2. Distribution of powder sizes transferred

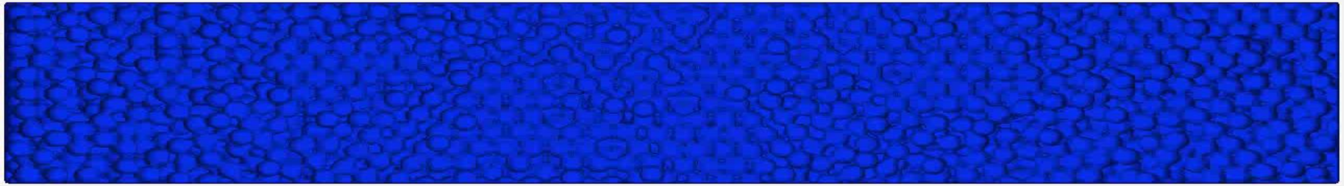
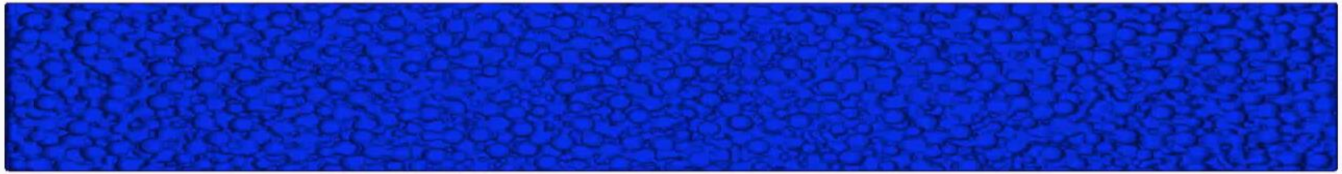
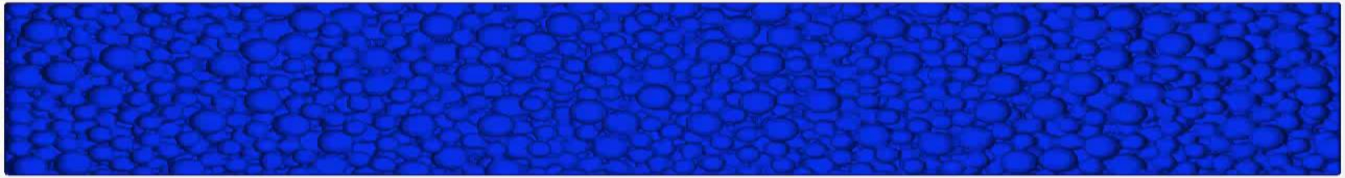
Weld – Laser Irradiation

- **Laser irradiation parameters**
  - Power output of 200W
  - Scanning speed of 3.0m/s
  - Spot radius of 100µm
- **20µm diameter particles simulated**
- **Analysis includes**
  - Melt region
  - Velocity of melt pool
  - Solid fraction
  - Temperature of melt pool

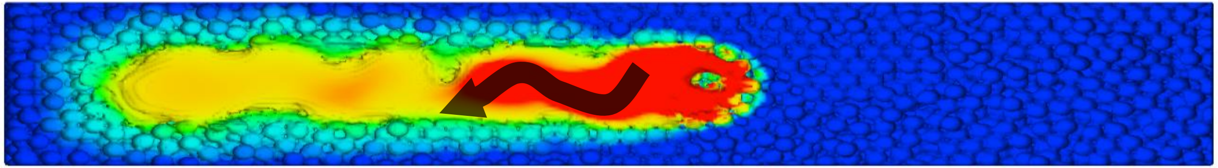
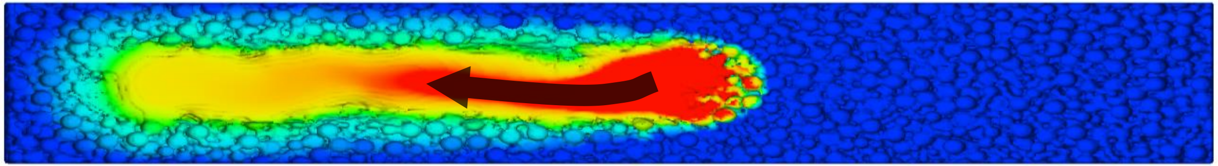
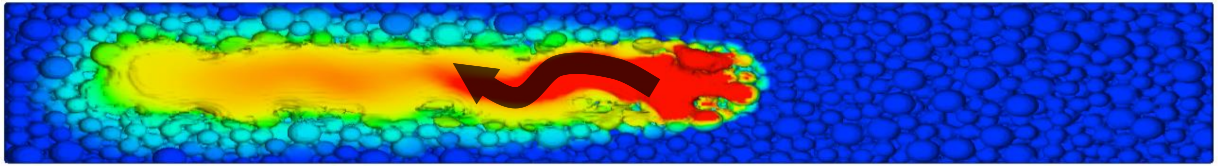


FLOW Science

Melt Pool Comparisons

Case	Temperature Contours
Case1	
Case2	
Case3	

Melt Pool Comparisons

Case	Temperature Contour
Case1	
Case2	
Case3	

Thermal Stress Analysis

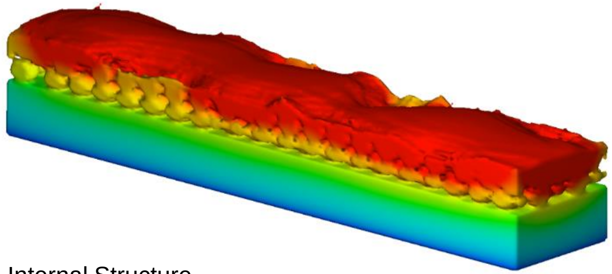
Results File

Pressure/Temperature Data
(Load Data)

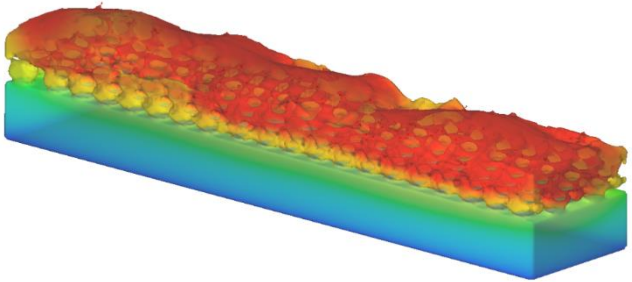
FEA packages

- NX Nastran
- MSC Nastran
- MSC MARC
- ABAQUS

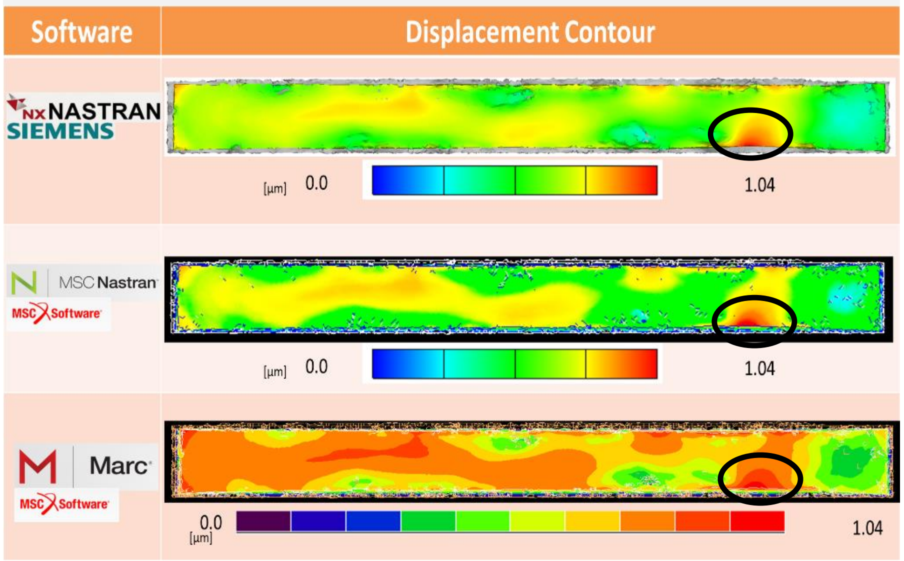
Fused particle bed



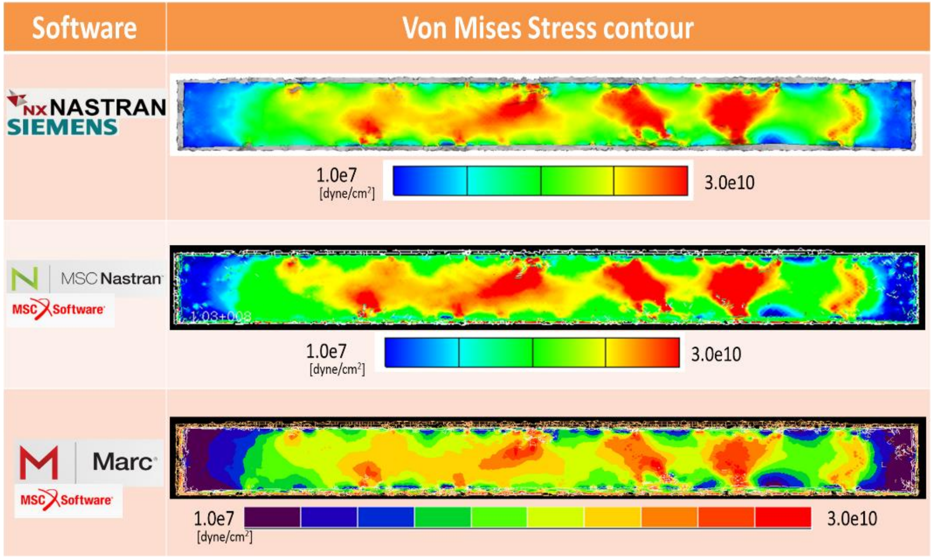
Internal Structure



Displacement & Thermal Stresses



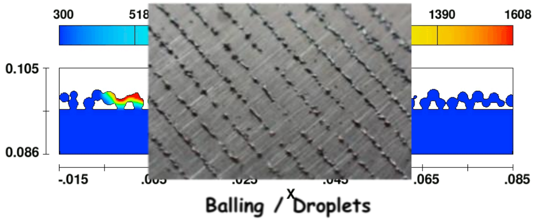
Displacement contours values showing good agreement among different FEA packages



Stress contours also showing good agreement among different FEA packages

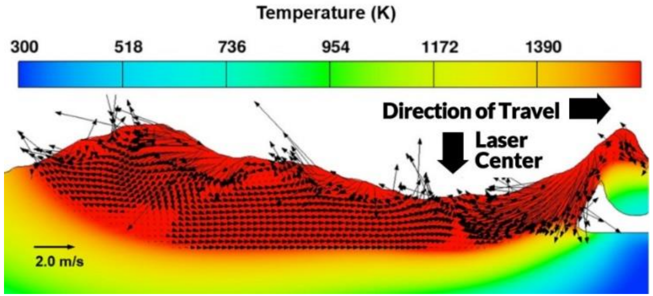
Case Study Balling Defects

Surface Defect



* Images from M. Jamshidinia, EWI, 2015.

- ***FLOW-3D*** is used to quantitatively study the effect of laser power, scanning speed and powder size distribution on the bead geometry and formation of balling defect.

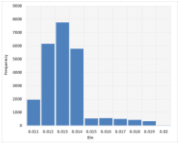


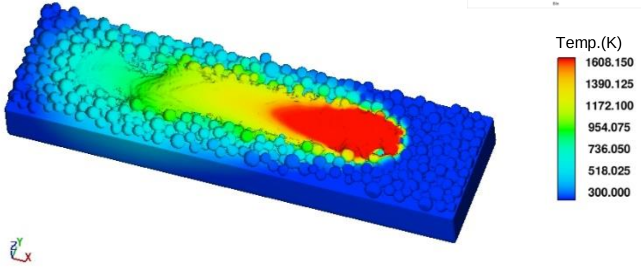
Longitudinal section view of heat transfer and fluid flow in the molten pool.

<u>Ref:</u> "Mesoscopic simulation of heat transfer and fluid flow in laser powder bed additive manufacturing", YS Lee, W Zhang, International Solid Free Form Fabrication Symposium, 1154-1165

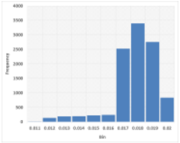
Effect of Particle Size Distribution

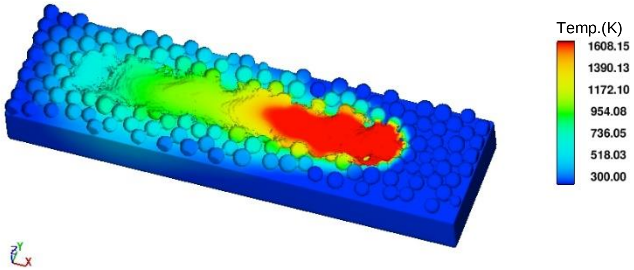
* PSD+





* PSD-





- Complete melting of particle at PSD+ due to higher small-particle fraction
- Smoother edge of molten pool

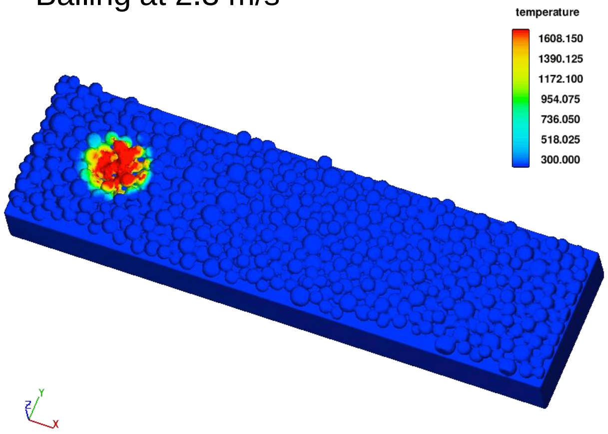
- Partial melting of particle at PSD- due to higher large-particle fraction
- Corrugated edge of molten pool

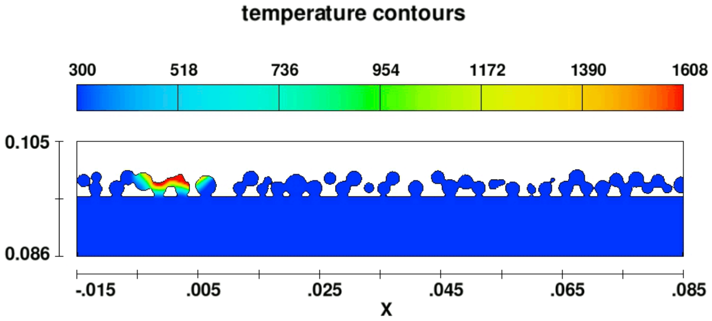
→ As expected, finer particles are beneficial for the surface finish, as indicated by the smoother contour of the molten pool.

** Scanning speed=1.1 m/s, laser power= 200W, packing density= 38%

Effect of Scanning Speed

* Balling at 2.3 m/s



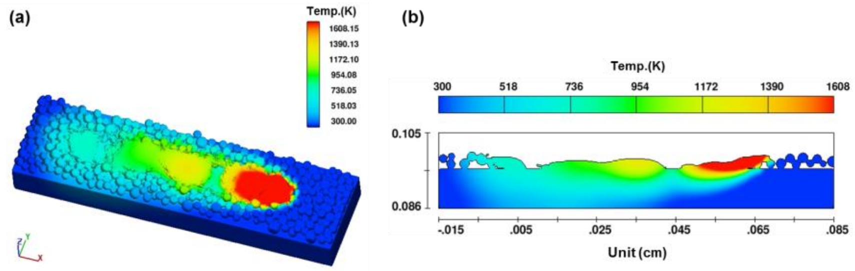


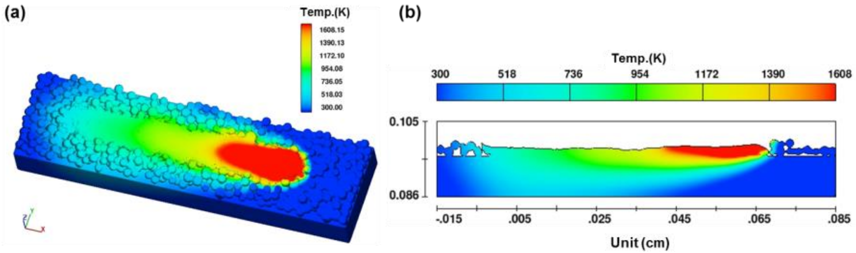
- A faster travel speed increases the likelihood of balling defects
  - Low heat input per unit length and shallow melting
  - Length to width ratio increases with scanning speed
- Rayleigh instability has been used to explain the break-up of molten pool into small islands

** Scanning speed=2.3 m/s, laser power= 200W, packing density= 38% and PSD+

Effect of Packing Density

* All conditions same except packing density





- Increasing the powder packing density not only reduces the formation of balling but also produces a smoother weld pool contour.

** Scanning speed=1.1 m/s, laser power= 150W, packing density= 38% and PSD+

Case Study Microstructure Prediction

- **<u>Overarching goal</u>: Understanding effect of solidification conditions on microstructure of IN718 fabricated by L-PBF**
  - 3D transient heat transfer and fluid flow model

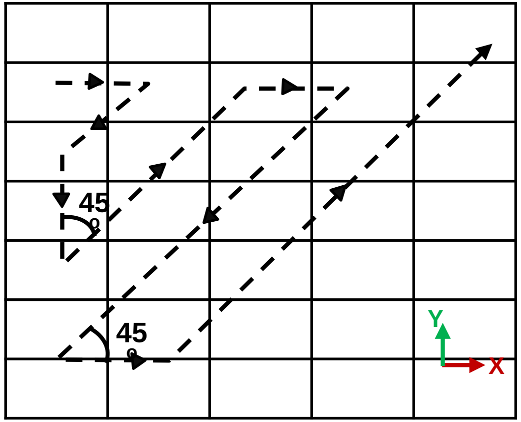
- **Focus of the present study:**
  - Laser melting of a single layer of powder particles
  - Consideration of laser scanning patterns
    - Actual scanning patterns used in fabrication are proprietary to the equipment manufacturing.
    - As a result, a "theoretical" scanning pattern is used in the simulation.

- **Process parameters: laser power, travel speed and scanning pattern**
  - Temperature dependent thermo-physical properties for IN718

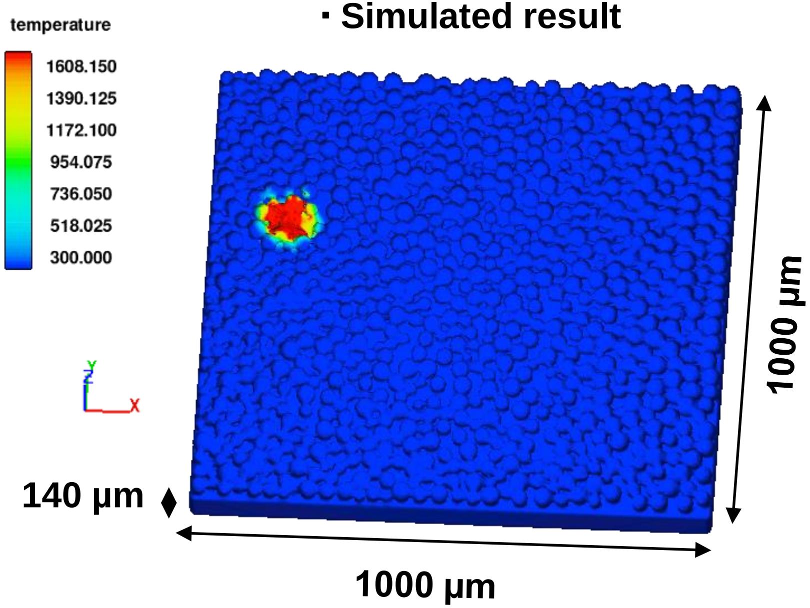
<u>Ref:</u> "Modeling of heat transfer, fluid flow and solidification microstructure of nickel-base superalloy fabricated by laser powder bed fusion", YS Lee, W Zhang, Additive Manufacturing 12, 178-188: http://dx.doi.org/10.1016/j.addma.2016.05.003

Simulation of Zigzag Scanning Pattern

▪ Scanning pattern

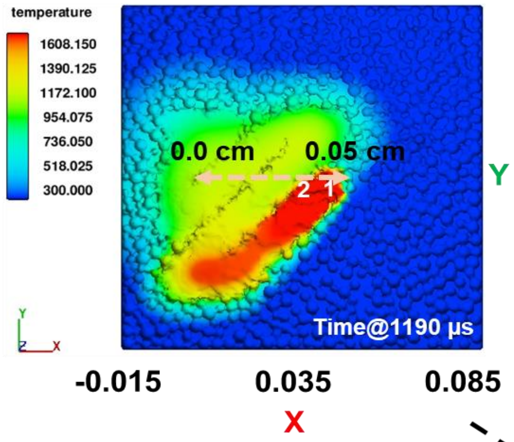


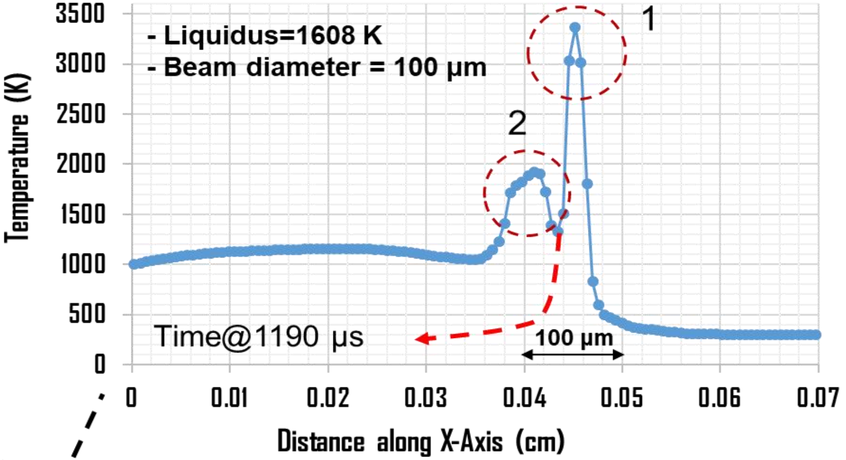
▪ Simulated result

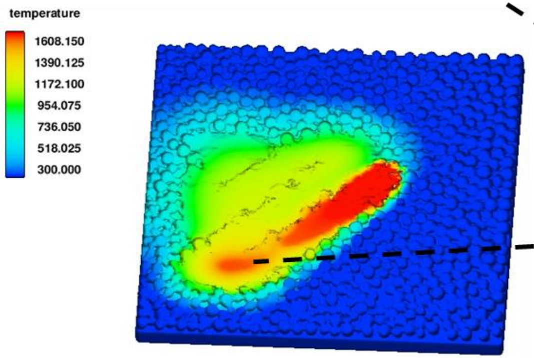


- Reheating is observed at the boundary of two successive beam paths.

Reheating and Remelting of Track

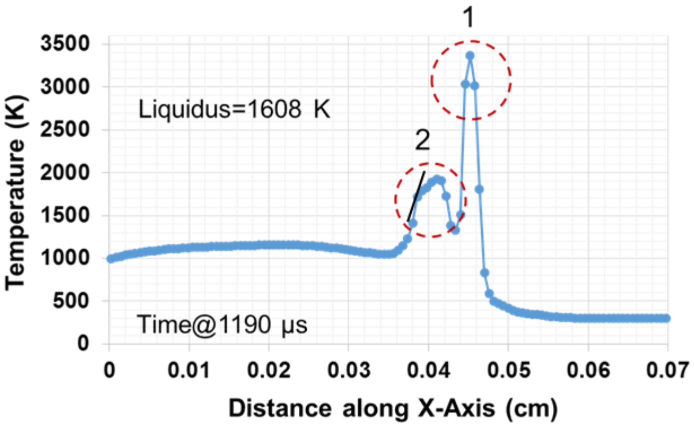






- **Top figures: Successive path can cause significant reheating of previous track (e.g., see Location 2)**
- **Left figure: Cooling rate is slower at the round corner**

Prediction of Primary Dendrite Arm Spacing

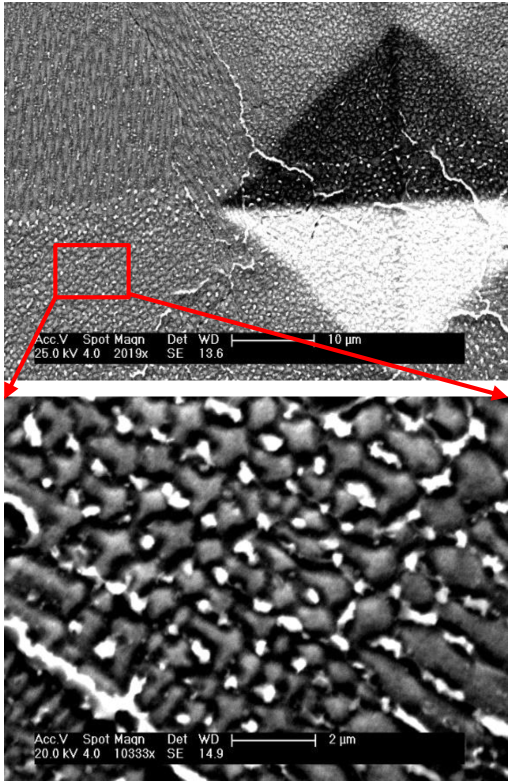


Location	Thermal Gradient, G	Solidification Rate, R
1	1.43E+06 (K/cm)	150 (cm/s)
2	3.50E+05 (K/cm)	150 (cm/s)

Location	Cooling Rate (G*R)	PDAS	
		Trivedi	Kurz-Fisher
1	2.14E+08 (K/s)	0.17 (μm)	0.23 (μm)
2	5.25E+07 (K/s)	0.35 (μm)	0.46 (μm)

Improvements needed:

- **Scanning speed is 150 cm/s in simulation (cf. 96 cm/s in experiment).**
- **R is assumed as scanning velocity. It varies from location to location in the melt pool.**



- **Measured PDAS: 0.9~1.8 μm**

Case Study Keyhole Effects in L-PBF

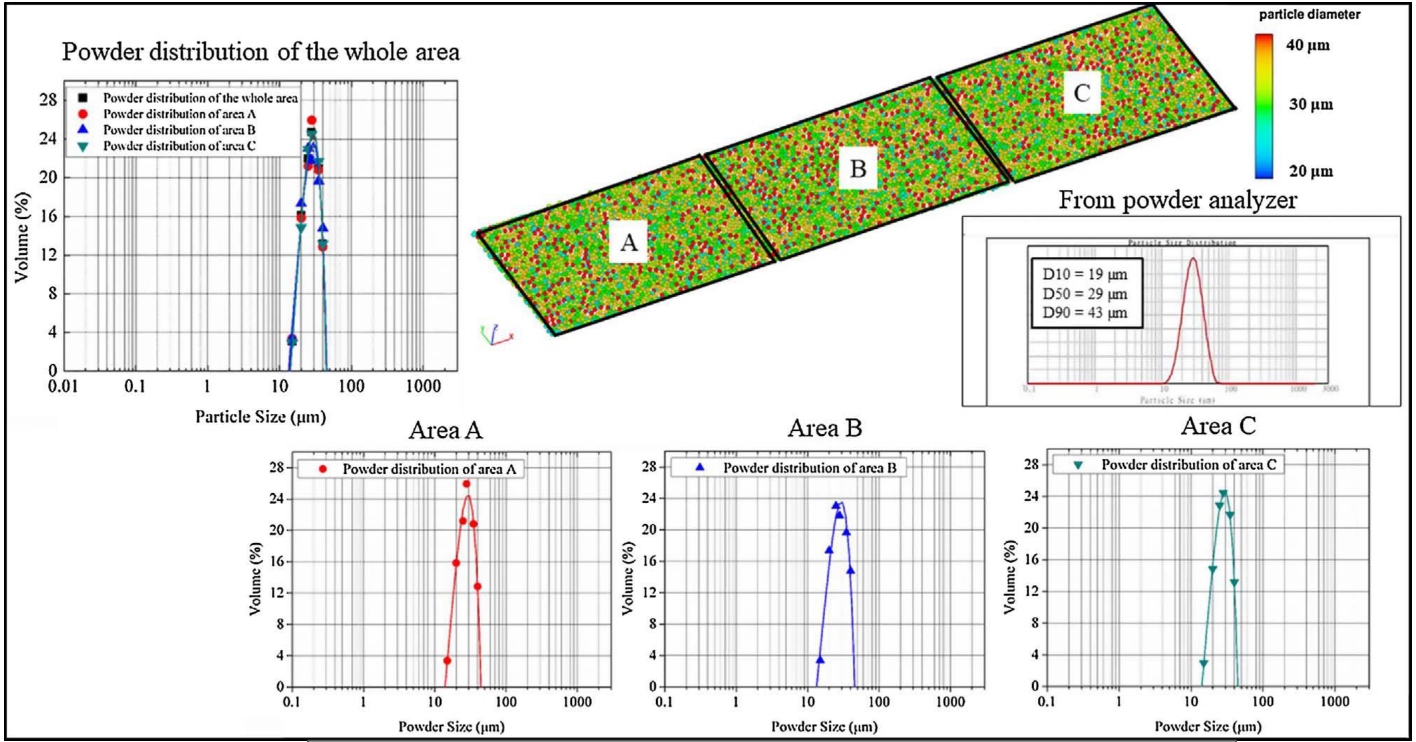
- **<u>Overarching goal:</u>** Investigating the melt-pool behavior of a randomly-distributed powder bed (H13) with keyhole formation by Nd-YAG laser
  - Discrete Element Method (DEM) used to simulate a randomly-packed powder bed
  - 3D transient heat transfer and fluid flow model that incorporated evaporation effects

- **Focus of the present study**
  - DEM validation by analyzing powder size aggregation
  - Laser melting model validation through comparison of melt pool temperature, melt pool dimensions and surface morphology.

- **Conclusions**
  - With evaporation, the melt pool dimensions are deeper and narrower, and the surface temperature is lower.
  - The surface morphologies with and without evaporation are totally different because of the recoil pressure triggered by the keyhole formation, which in turn affects the heat and flow behavior as evaporation occurred

<u>Ref:</u> *"Numerical modeling of melt-pool behavior in selective laser melting with random powder distribution and experimental validation, Wu, San, et. Al, Journal of Materials Processing Tech., 2017. DOI: https://doi.org/10.1016/j.jmatprotec.2017.11.032*

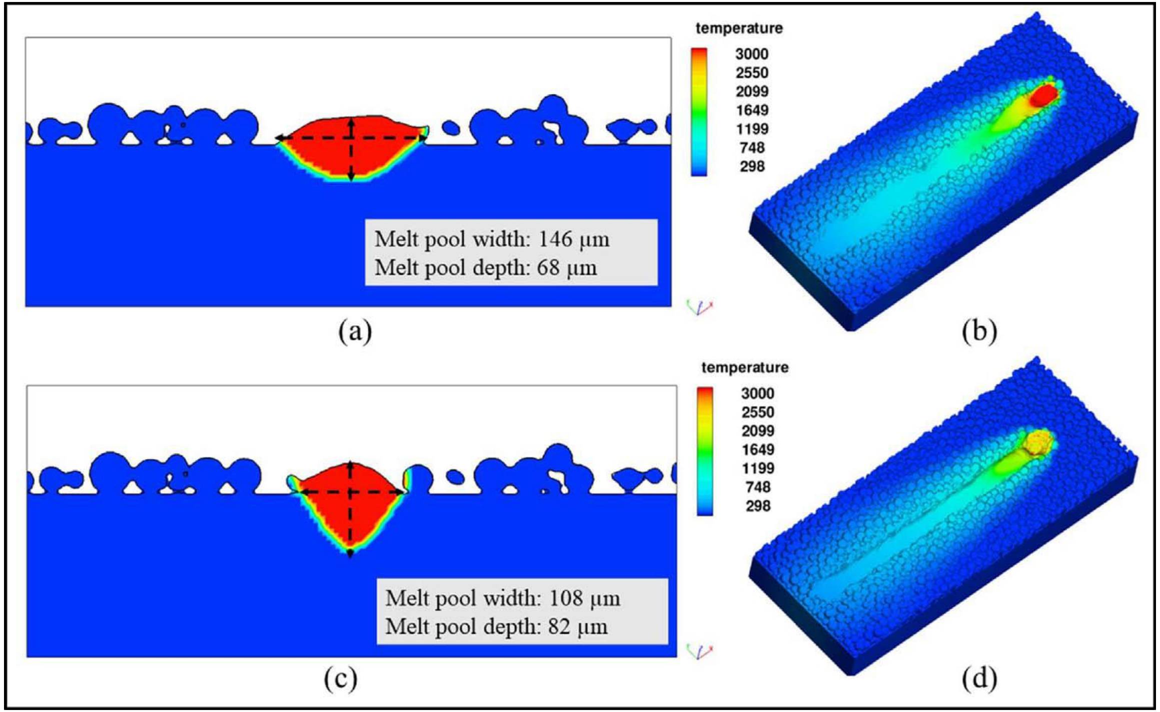
DEM Model Validation



Validation and examination of the powder-size distribution in Areas A, B, and C to determine if any size segregation occurs

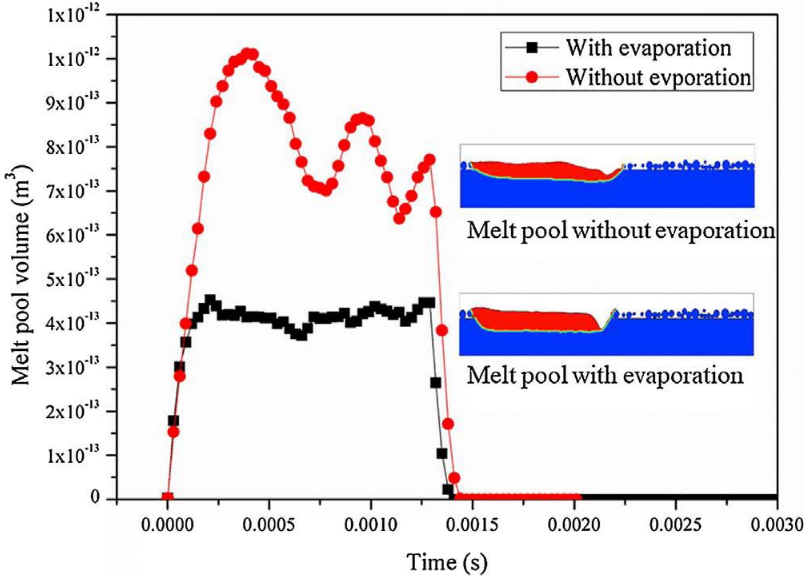
Effect of Evaporation in the Laser-Melting Model

(a) The melt pool is wide and shallow when neglecting evaporation, with
(b) the temperature of the melt pool overheating.
(c) The melt pool is narrow and deep when incorporating evaporation, in which
(d) the maximum temperature is 2676 K when evaporation occurs.

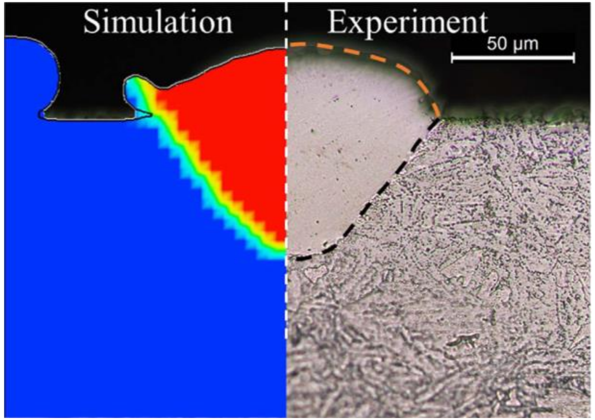


FLOW Science

Data Comparison



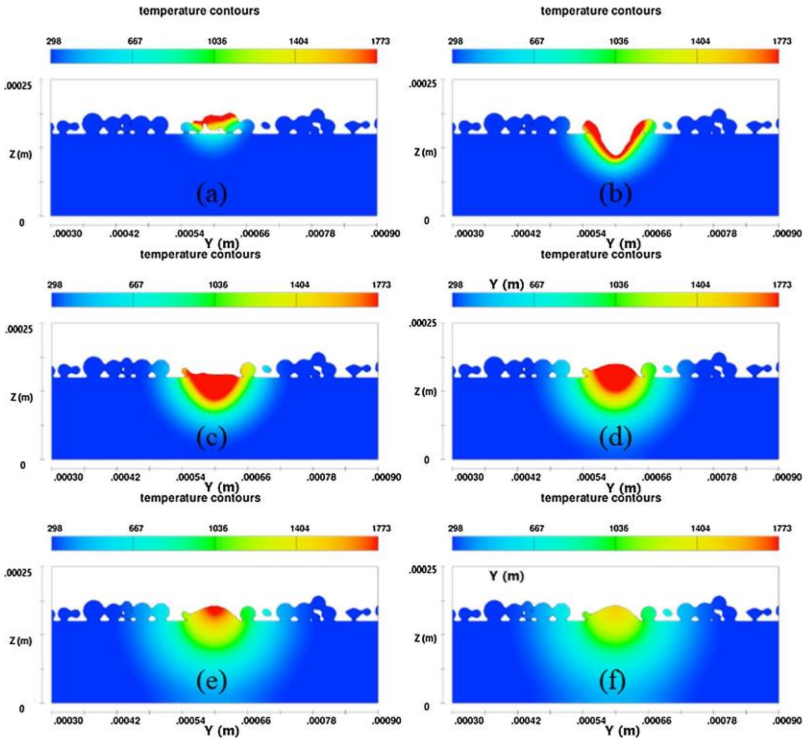
Comparison of melt pool volumes for the two cases

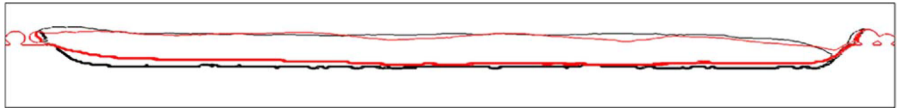


Validation of the melt-pool dimensions (black-dashed line) and the surface morphology (orange-dashed line)

Numerical Model Analysis

Temperature distributions during keyhole formation at (a) 0 s; (b) 50 microseconds; (c) 100 microseconds; (d) 150 microseconds; (e) 200 microseconds; and, (f) 250 microseconds.



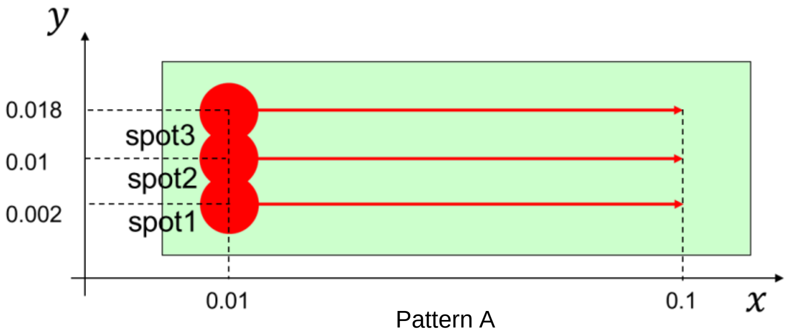


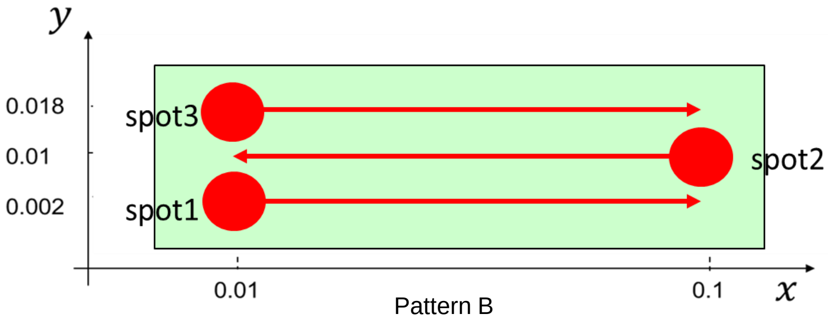
Cross-sectional illustration comparing the surface morphology and melt pool area with (black line) and without evaporation (red line)

MULTI-BED LAYER SIMULATION

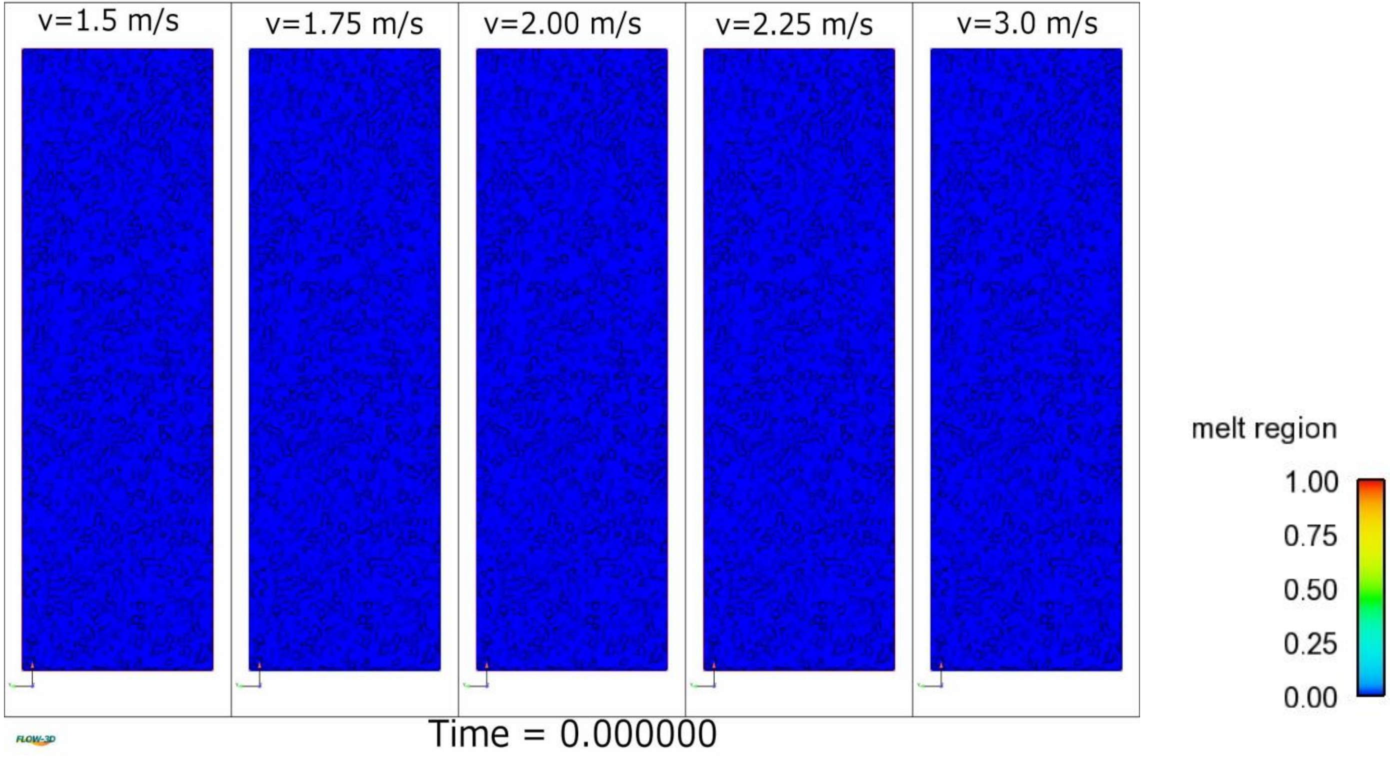
Scanning Speed & Strategy Study

- **Different scan strategies and scanning speeds were investigated to understand build quality**
- **Laser output of 200W and a spot radius of 0.005 cm used**
- **Scan strategy**
  - Pattern A
  - Pattern B
- **Scanning speeds**
  - 3.0 m/s
  - 2.25 m/s
  - 2.0 m/s
  - 1.75 m/s
  - 1.5 m/s

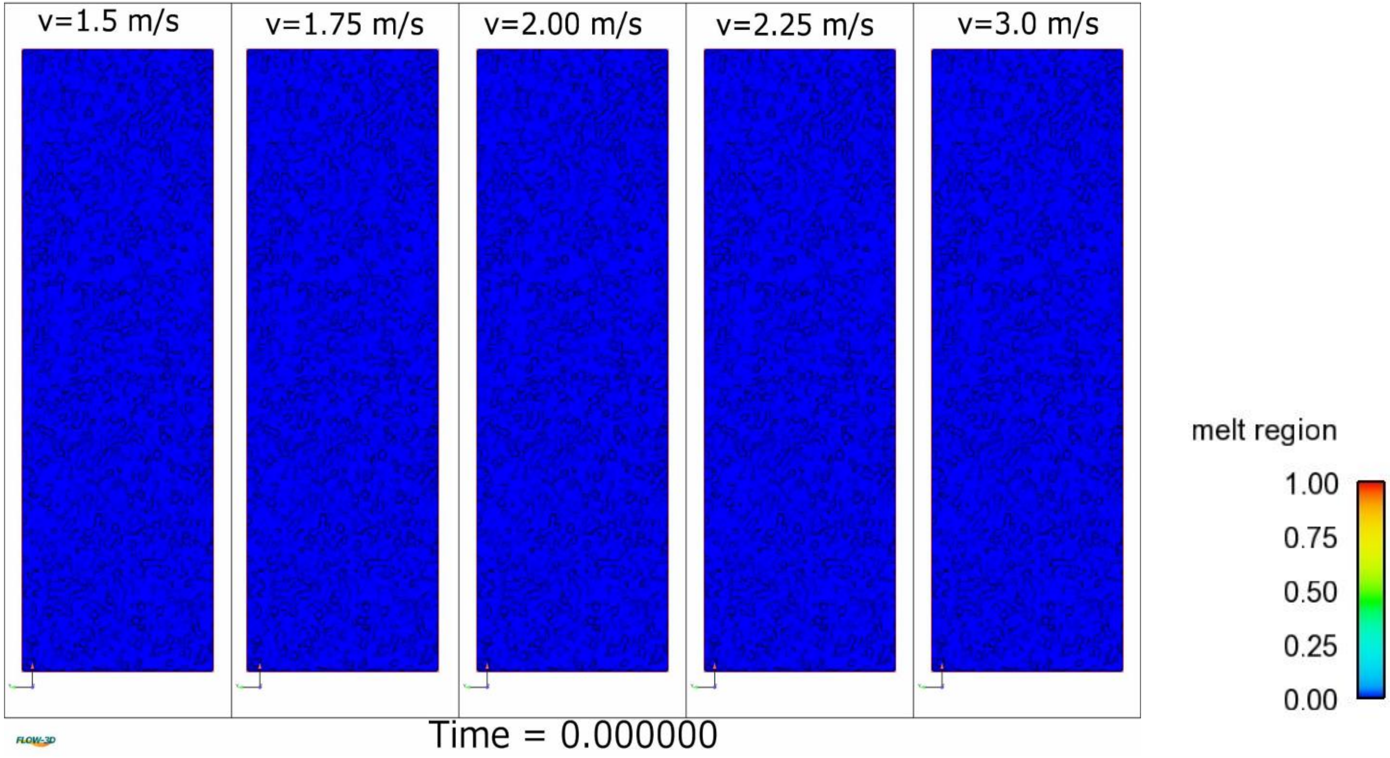




Results – Pattern A

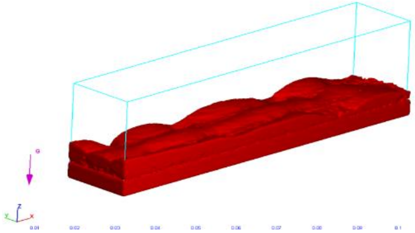


Results – Pattern B

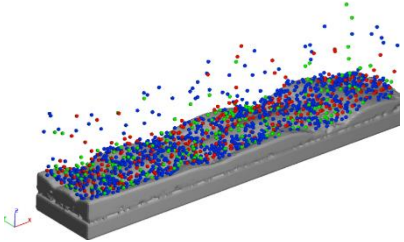


FLOW Science

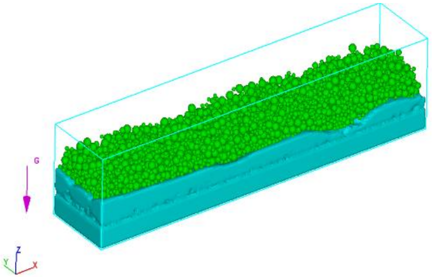
Performing a Multi-layer Build



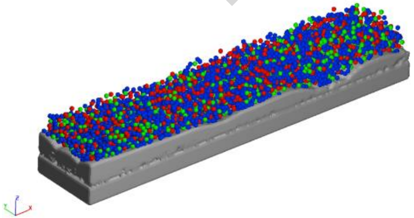
Data from the previous build layer is saved



Metal powder is dropped on the bed



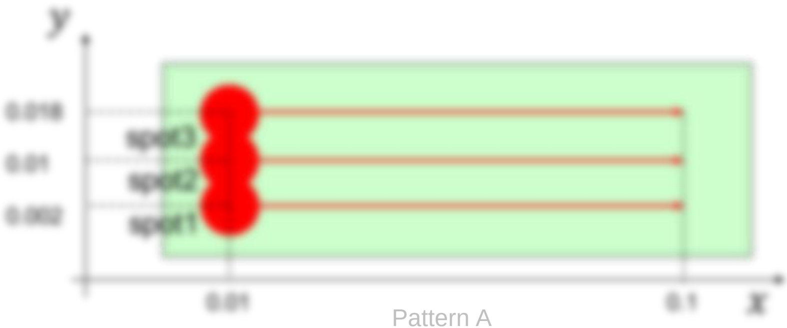
Simulations are performed on the new powder bed



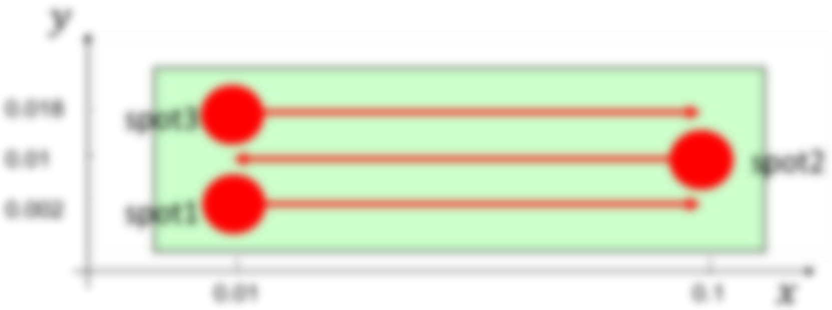
Another bed layer is formed

Process Parameters

- **Particle Distribution**
  - 10μm (20%)
  - 15μm (20%)
  - 20μm (60%)
- **Ni alloy (Inconel 718) properties used**
- **Laser output of 200W and a spot radius of 0.005 cm**
- **Scan strategy**
  - Pattern A
  - Pattern B
- **Scanning speed**
  - 1.5 m/s

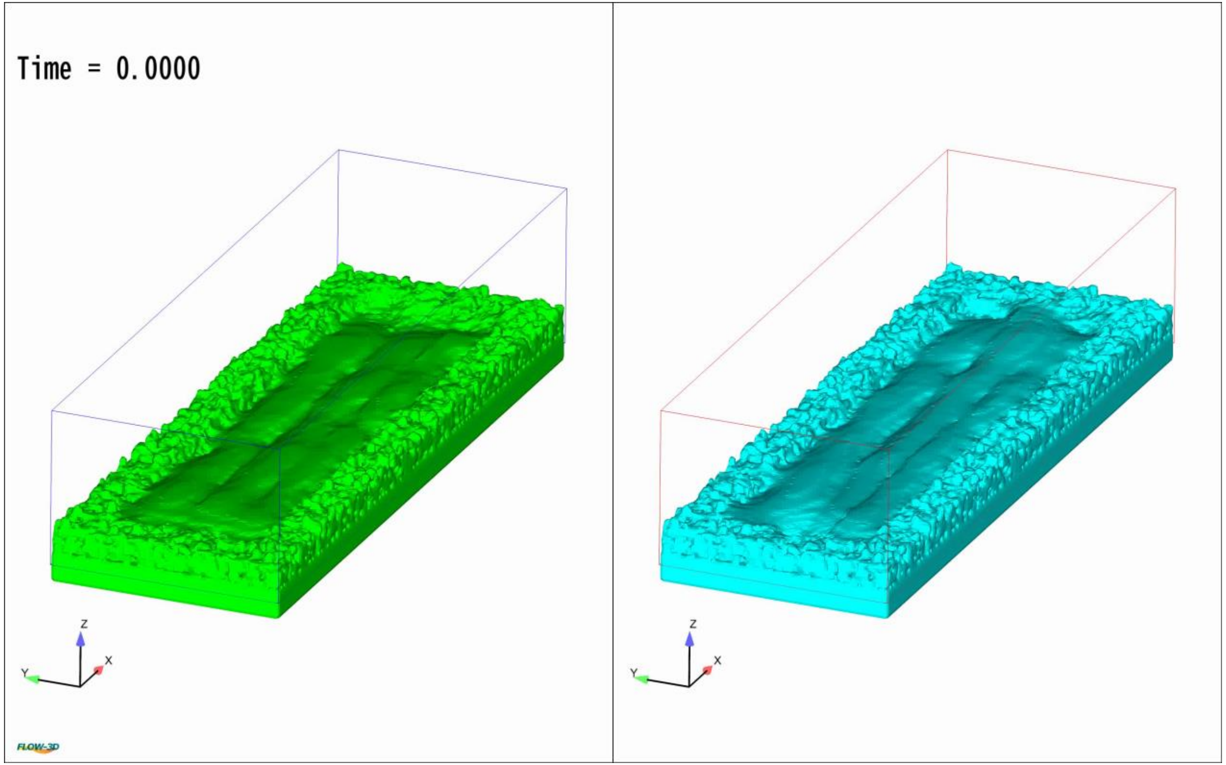


Pattern A



Pattern B

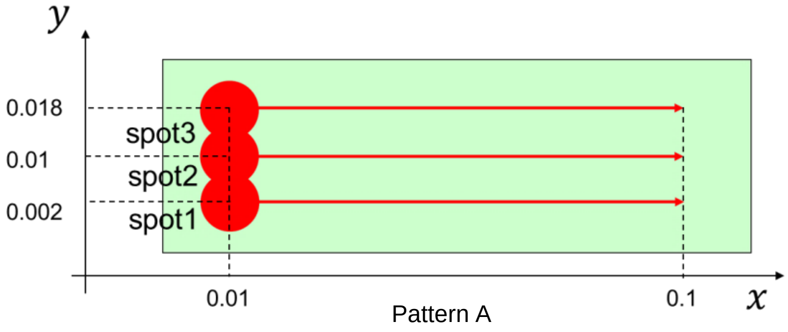
Bed Laying Animation

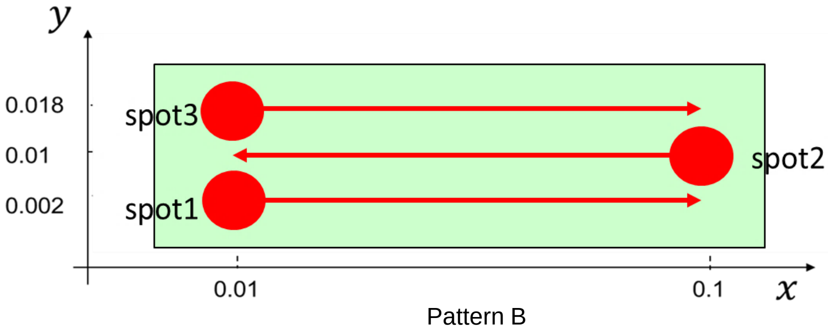


Powder bed laying on Pattern A vs. Pattern B

Process Parameters

- Particle Distribution
  - 10µm (20%)
  - 15µm (20%)
  - 20µm (60%)
- **Ni alloy (Inconel 718) properties used**
- **Laser output of 200W and a spot radius of 0.005 cm**
- **Scan strategy**
  - Pattern A
  - Pattern B
- **Scanning speed**
  - 1.5 m/s





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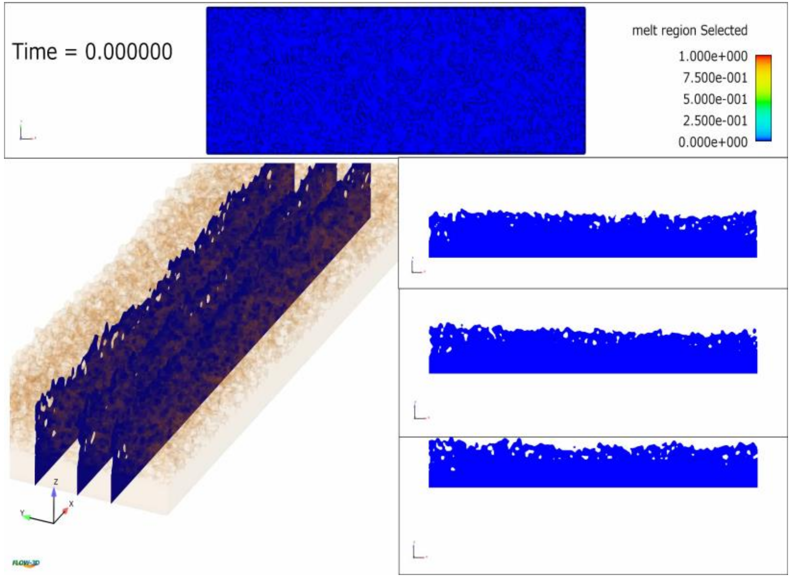
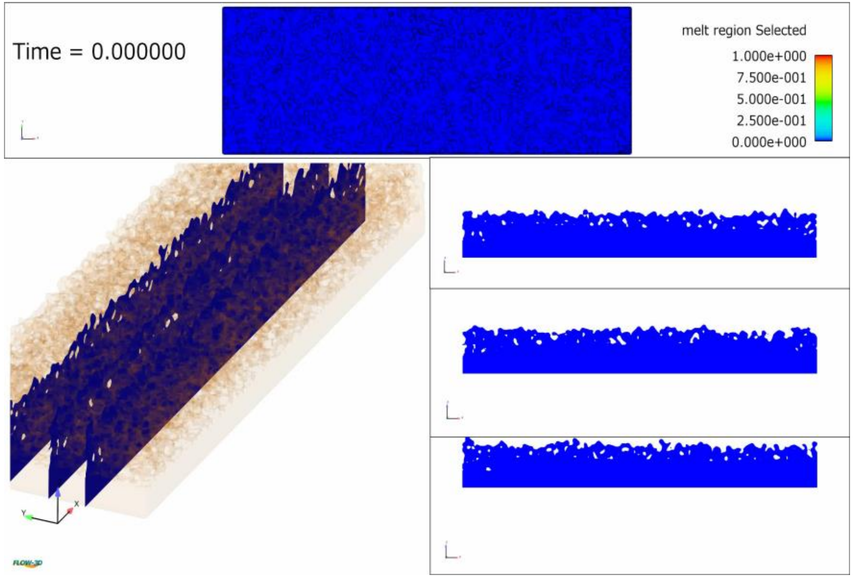
Different Scan Strategies



Pattern A – Multi layer build

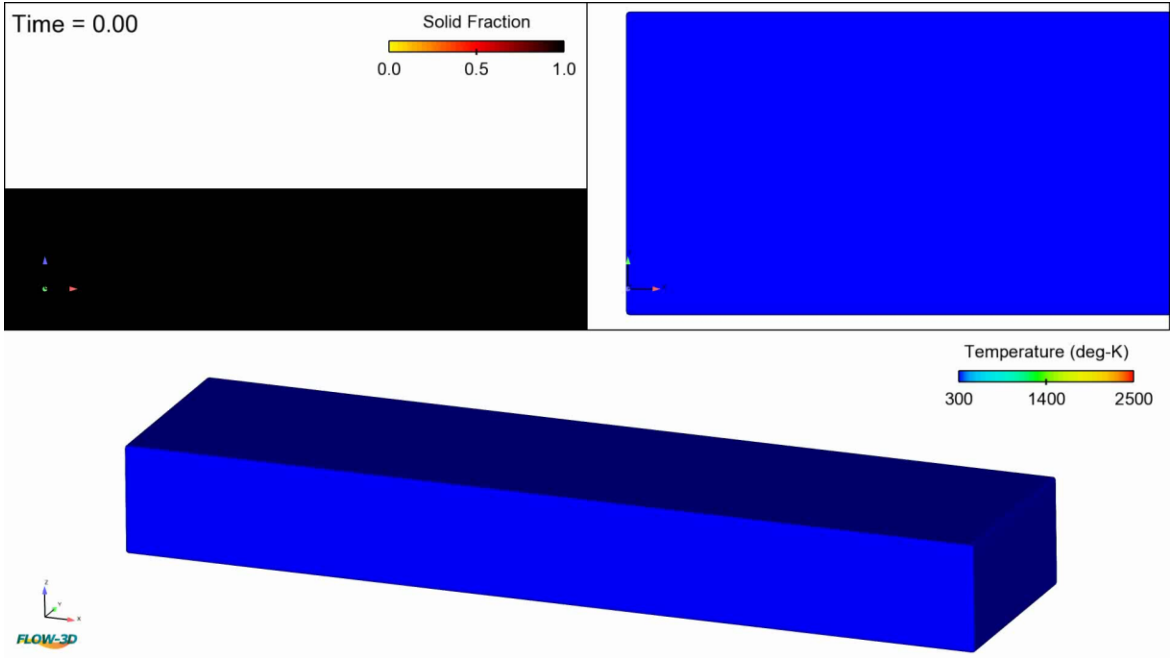


Pattern B – Multi layer build

DIRECT METAL DEPOSITION

Laser Metal Deposition – Single Layer

- 40 micron fluid particles injected at 500,000/s
- Laser power is 100W
- Scan speed is 1cm/sec
- Beam diameter is 2mm
- IN-718 material alloy

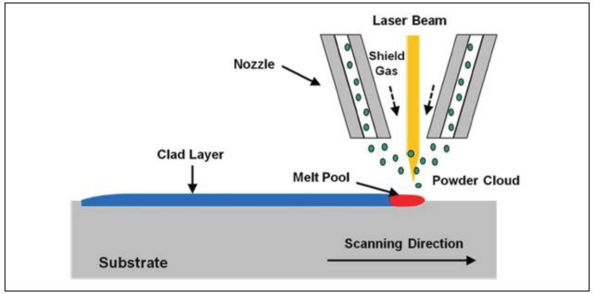


FLOW Science

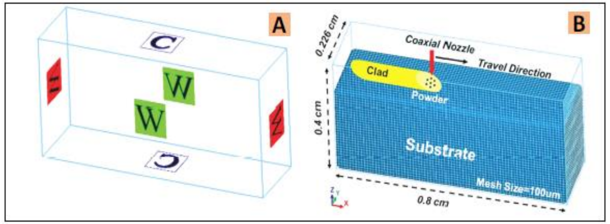
Case Study Ohio State University

- **Laser cladding of an IN718 laser single layer, single track deposit was studied to understand the effect of process parameters on**
  - Laser-powder-substrate interaction
  - Melt pool formation
  - Fluid convection and
  - Solidification

- **Complexities of the physical model simulated**
  - Absorptance of the laser beam that varies with material composition and temperature
  - Power losses by reflection, radiation, conduction and convection
  - Powder catchment efficiency defined as ratio between molten pool area and powder jet area
  - Surface tension varies with temperature and total surface-active sulfur
  - Columnar dendritic solidification arises due to influence of temperature gradient and solidification rate



Schematic of process using coaxial powder feed nozzle



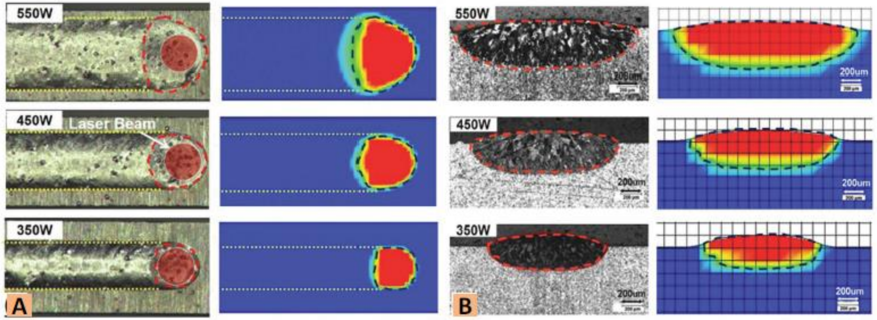
Boundary conditions and computational domain

<u>Ref:</u> "Simulation of Laser Additive Manufacturing and its Applications", PhD Thesis, Yousub Lee, OSU, 2015

Case Study Melt Pool Analysis

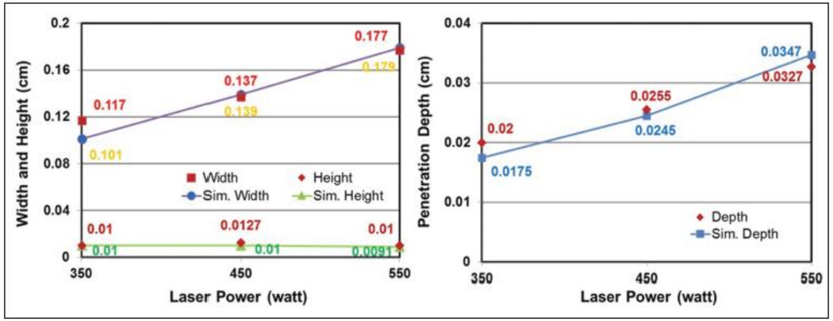
- **Parametric study**
  - **Laser power varied between 350W, 450W and 550W**
- **Simulations and experiments show good agreement for the shape and size of the laser clad**
- **Increasing laser power results in larger clad width and depth, but not height**

Top to bottom: Decreasing laser power



Top-down view of melt pool

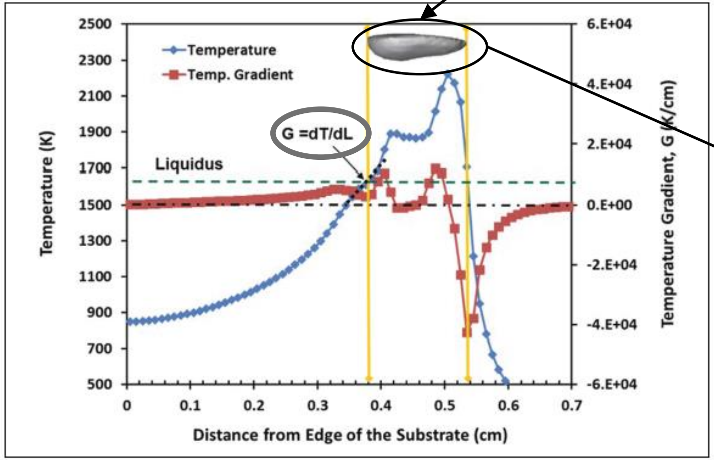
Cross-sectional view of melt pool



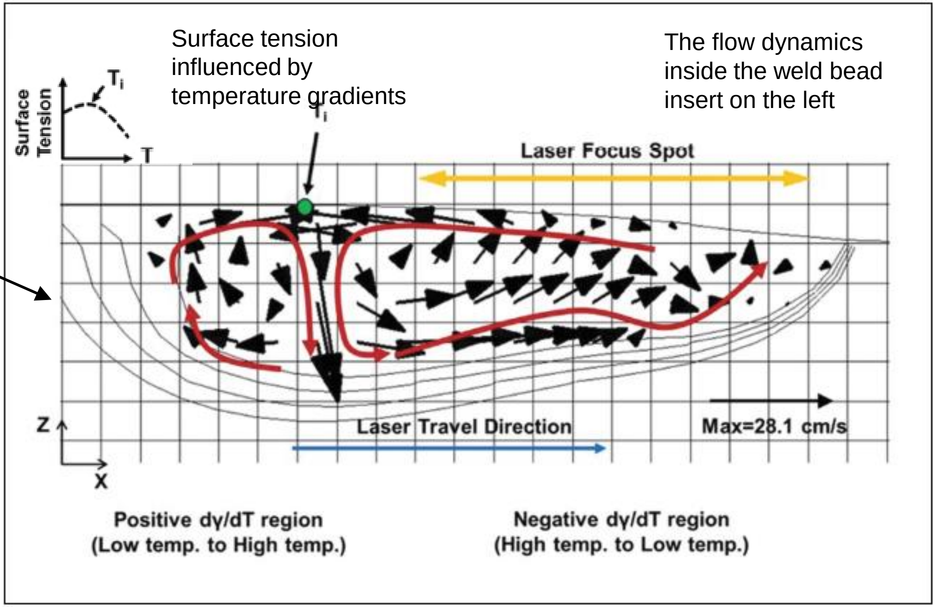
Plots for simulated and experimental laser clad dimensions

Case Study   Melt Pool Analysis

Weld bead



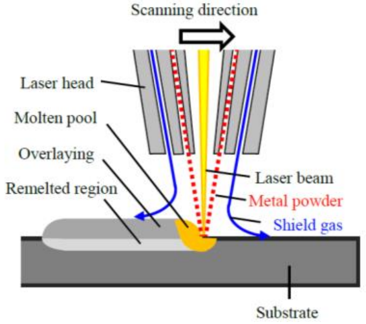
Quasi-steady state temperature profile and temperature gradient (G) along the weld pool centerline at time t = 0.43 s.



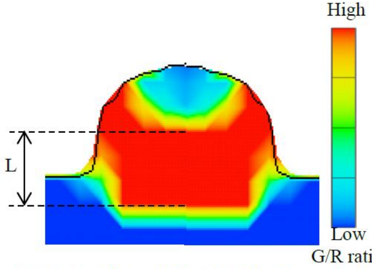
Longitudinal section view showing fluid flow and mixing in the laser clad melt pool and the location of laser focus spot. The green dot indicates the location of the weld pool surface with temperature, T_i , where surface tension gradient transitions from positive to negative.

Case Study Mitsubishi Heavy Industries

- **The researchers at Mitsubishi Heavy Industry had an interesting problem**
  - Single Ni-crystal blades used in gas turbines are damaged often
  - It's quite expensive to replace them, so repair is always preferable
- **Laser metal deposition can repair damaged blades**
  - However, the weld metal needs to have same crystal orientation as base metal
- **Objective**
  - To maximize growth of single crystal in weld metal
- **And how did they achieve that?**
  - Calibrate numerical parameters with experiments
  - Control thermal gradient and the solidification rate which depend on process parameters used



Schematic of LMD

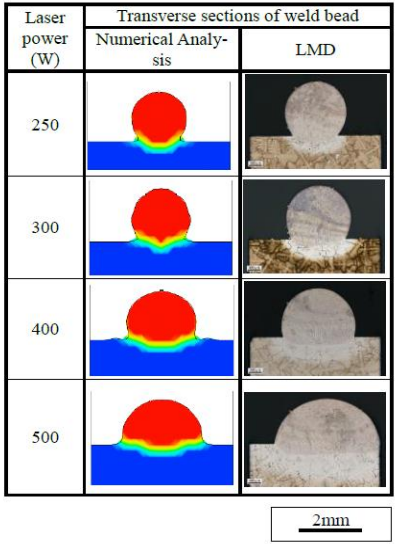


L: Single crystal orientation length in the melted region

Ref: "Mitsubishi Heavy Industries Technical Review Vol. 52 No. 4 (December 2015)

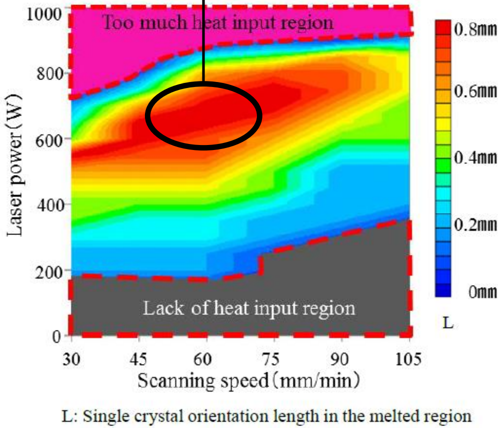
Case Study Laser Welding Repair

- **Calibrate numerical parameters with experiments**
- **Process parameter optimization**
  - Scanning speed
    - 30mm/min – 105mm/min
  - Laser power
    - 100W – 1000W
  - Powder feed rate
    - 1.2g/min – 2.0g/min
- **Optimum parameters achieved**
  - Laser power of 650 W, a scanning speed of 60 mm/min and a powder supply rate of 2g/min



Transverse sections comparison between numerical analysis and Actual LMD.

Sweet spot or rather sweet weld!



Dependence of single crystal orientation length in the melted region on LMD parameters

Questions or Comments

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