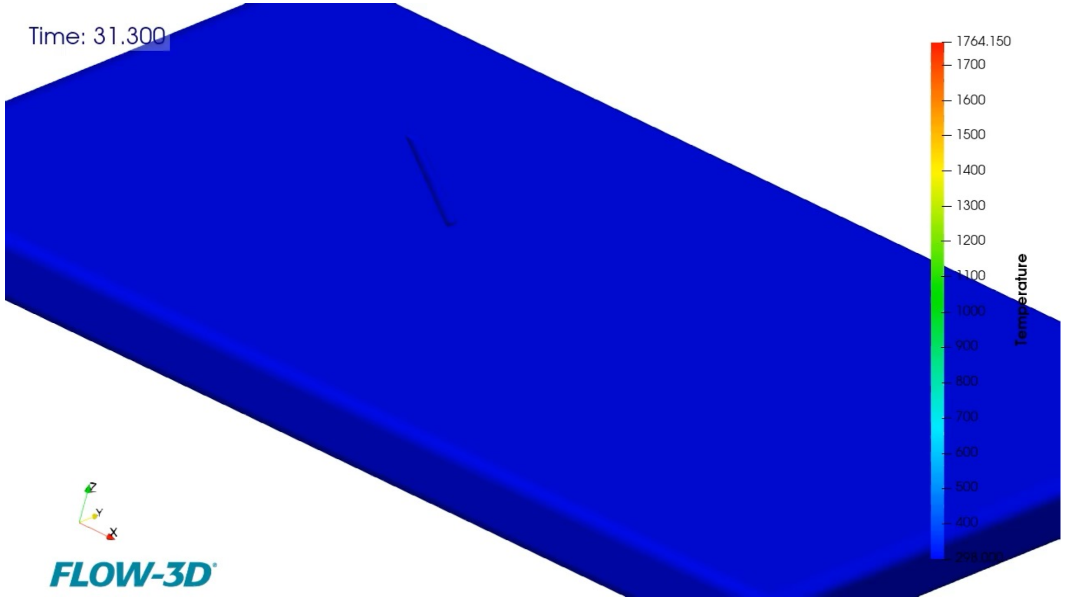
Hardness Prediction by Incorporating Heat Transfer and Molten Pool Fluid Flow in a Multi-pass, Multi-layer Weld for Onsite Repair of Grade 91 steel



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Outline

- Background
- Overarching goal and motivation
- Critical literature review
- Experimental data and model setup
- Multi-bead deposition results and validation
- Future work

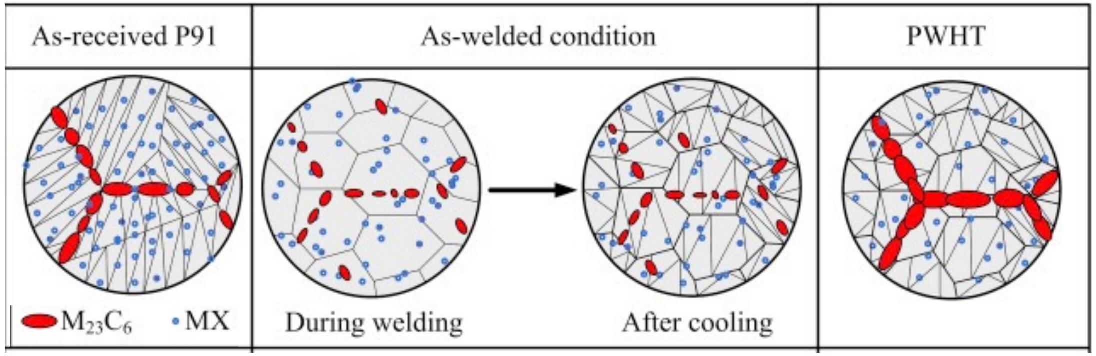
Background

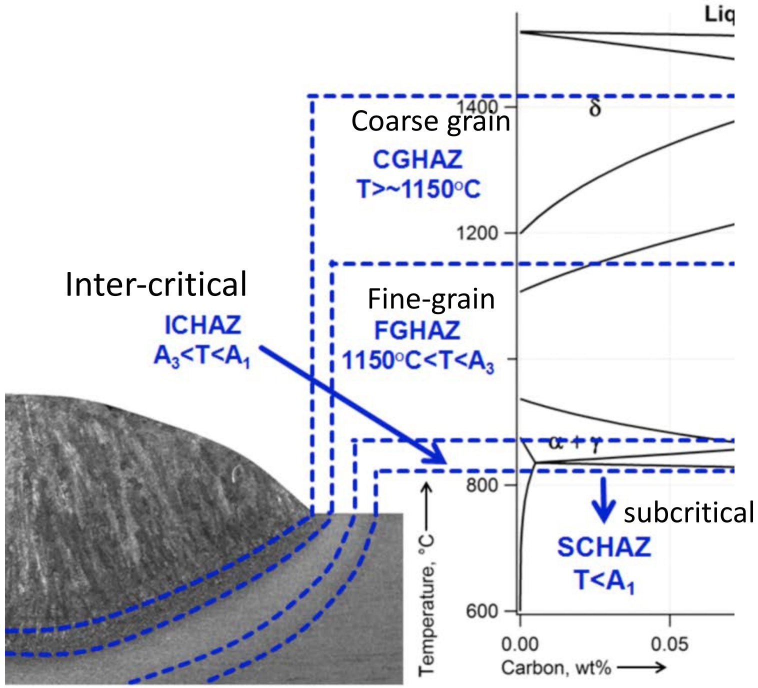
- Creep strength enhanced ferritic steels (CSEFs): Grade 91 steel

  Based on 9Cr-1Mo-V alloy

  Used in current fleet of power generation plants

  Grade 91 weldment in service -- Type IV failure in FGHAZ and ICHAZ





HAZ region in Grade 91 weldment (Parker & Siefert, 2015)

Tempered martensite with fine, dispersed precipitates such as MX and $M_{23}C_6$

During welding, base metal microstructure is altered and can be difficult and expensive to recover by post weld heat treatment (PWHT)

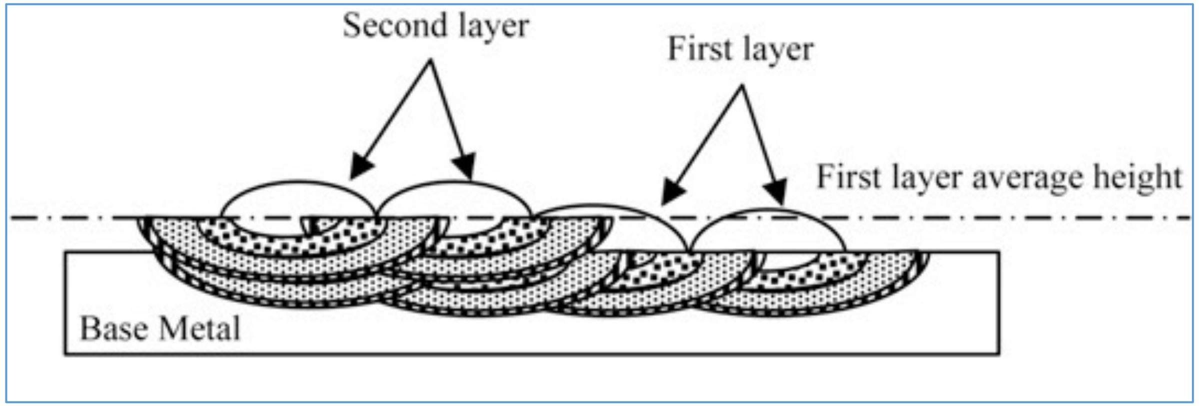
Repair of these welds – coordinating both welding and PWHT to repair failed parts in field are difficult as access is limited

Technical needs – in-field welding procedure which does not require PWHT

Background (cont.)

- Temper bead welding (TBW)

  Heat input from welding utilized to temper the hard microstructure for improving toughness.



Weld deposit at a location

Welding heat affecting the undesired microstructure in heat-affected zone (HAZ)

Achieving purpose of PWHT; easier application in field

Bead placement is crucial for a successful temper bead welding

Overarching goal & motivation

Grade 91 steel repairs

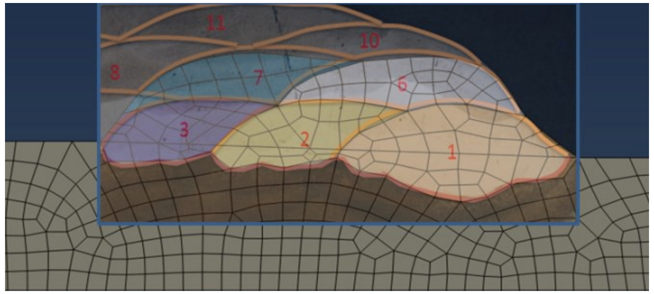
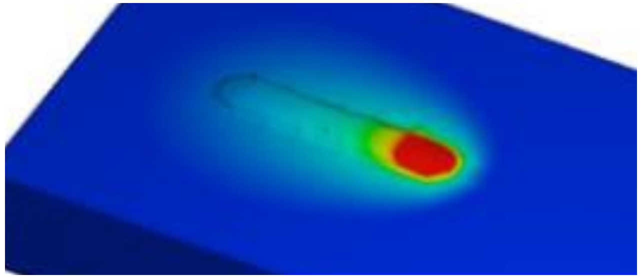
- Limited knowledge of their weld repairability
- Trial and error procedure to optimize microstructure and joint properties -- Time-consuming and expensive

Numerical model comes handy

Developing a model to enhance **predictive capability** of hardness and microstructure by incorporating heat transfer and molten pool flow:

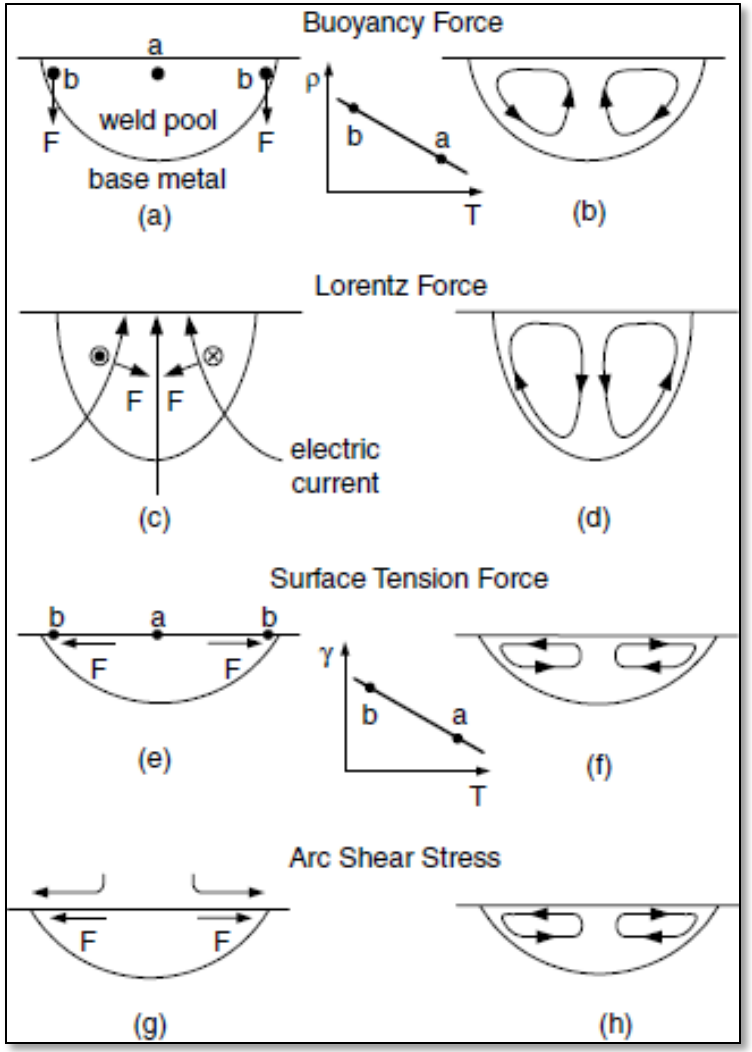
1. Model multi-bead deposition
2. Calculate thermal profile of each point on base material (i.e., substrate)
3. Consider tempering kinetics to predict hardness
4. Validate model including comparing predicted hardness with experimental values

Critical lit. review: Multi-pass, multi-layer deposition

Models in the literature	**Model developed in this research**
Finite element method (FEM) based	Molten pool based
Prebuild mesh based on known bead geometries or simplified shapes  Bead shapes are prerequisite	No assumption of bead shape.  Example of laser directed energy Deposition(DED) with blown power
* Ignored convective flow * Ignored defect formation	* Consider convective flow * Consider defect formation
Model-pool-based model considers convective flow and defect formation, enhancing its predictive capability than FEM-based model	

Critical lit. review: Why consider molten pool flow ?

- Molten pool convection
  - Marangoni – Surface tension gradient
  - Electromagnetic (will be included later) – Lorentz force
  - Buoyancy – Density gradient
  - Momentum from mass transfer – Globular transfer
- Hot and cold liquids mix up due to convective flow
- Effects of convection
  - Reduces peak temperature and temperature gradient inside molten pool
  - Changes bead shape and size, and thermal profile in the HAZ



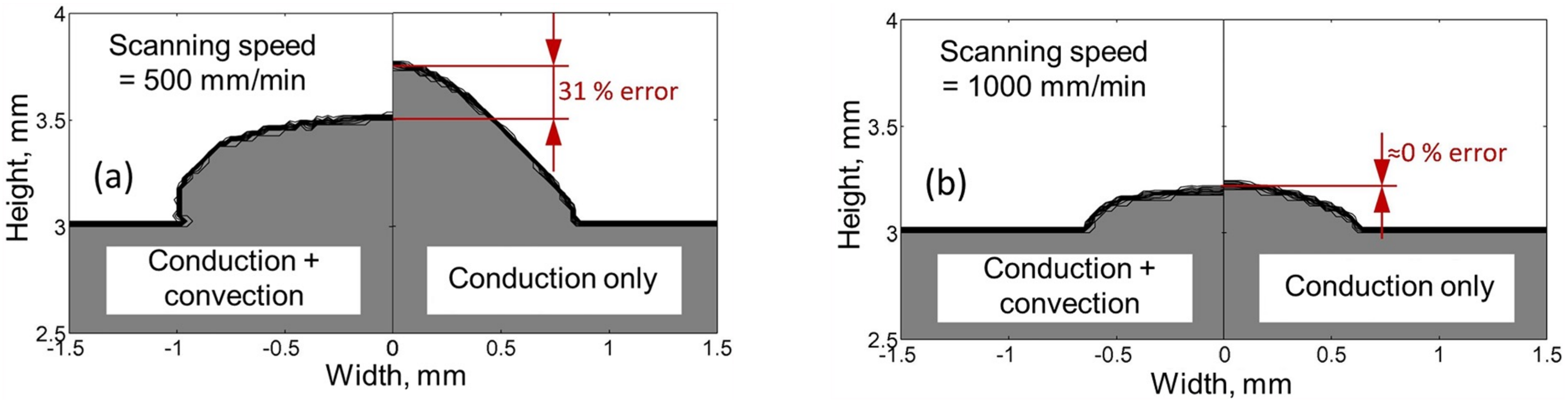
Driving forces for weld pool fluid flow behavior. (Wei et al., 2021)

Considerations in modeling molten pool flow

Incorporating conduction & convection in modeling is 10 times more computationally expensive than only heat conduction

- When can molten pool flow convection be neglected?
  - When Peclet number >> 1 , molten flow is critical in affecting heat transfer
  - Recently analysis shows scanning speed in additive manufacturing (AM) determines the Peclet number

$$\mathrm{Pe}_L = \frac{Lu}{\alpha}$$



(Arrizubieta et al., 2017)

At high scanning speeds (e.g., 1000 mm/min), molten pool solidifies rapidly, and there is insufficient time for convective flow to mix the hot and cold liquids

In this model, scanning speed = 100 mm/min, Peclet number >> 1 and it is thus essential to consider molten pool flow

Literature review on modeling of tempering

- **Most models based on analytical solutions:**
  - Johnson–Mehl–Avrami–Kolmogorov (JMAK) equation (Lu et al., 2018)

    $$\phi = 1 - \exp\left(-(kt)^n\right)$$ ϕ is the extent of tempering k, n – JMAK parameters

  - Hollomon-Jaffe parameter – Directly relating tempering parameters to hardness

    fn(Hardness) = T(C + log(t)) C – material property

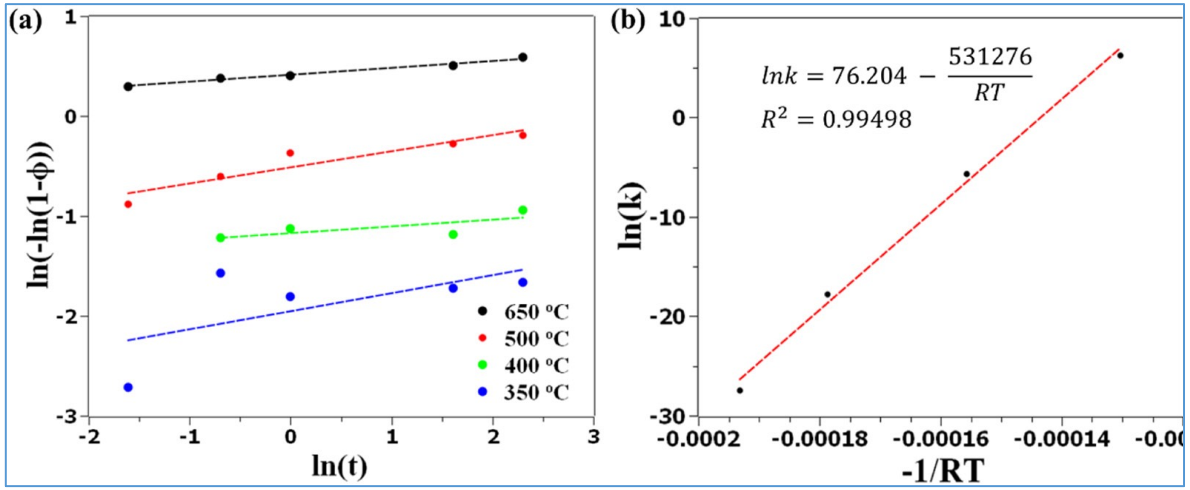
  - Simply peak temperature (Zhang, 2016)

    $\phi = fn(T_P)$ Linear fitting of ϕ vs tempering temperature

- **Prerequisite:** tempering kinetic parameters extracted from isothermal tempering experiments

$$\phi(t) = 1 - \exp\left[-\sum_{i=1}^{m}\left(k_0 \exp\left(-\frac{Q}{RT_i}\right)(\Delta t)\right)^n\right]$$

where ϕ(t) is the extent of tempering after time t=mΔt, Δt is the time step size



- **Output**
  - Hardness based on extent of tempering

$$\phi = \frac{H_{BM} - H}{H_{BM} - H_\infty}$$

Experimental data

- Limited experimental data on Grade 91 repair and tempering
- Experimental data available for tempered bead welding of low alloy steel
- Multi-bead deposition of stainless-steel (309L) filler wire over low alloy steel (SA-533) substrate

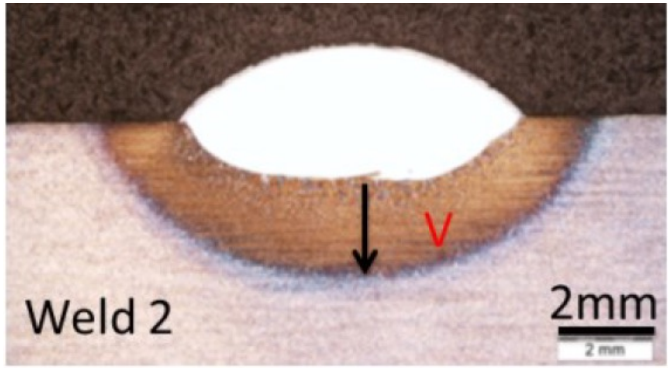
(Zhang, M.S. Thesis, The Ohio State University, 2016)

Gas tungsten arc welding (GTAW)

Welding parameters	
Voltage (V)	10.5
Current (A)	171
Wire feed speed (mm/s)	22.9
Wire diameter (mm)	0.89
Travel speed (mm/s)	1.69
Heat input (J/ mm)	1060

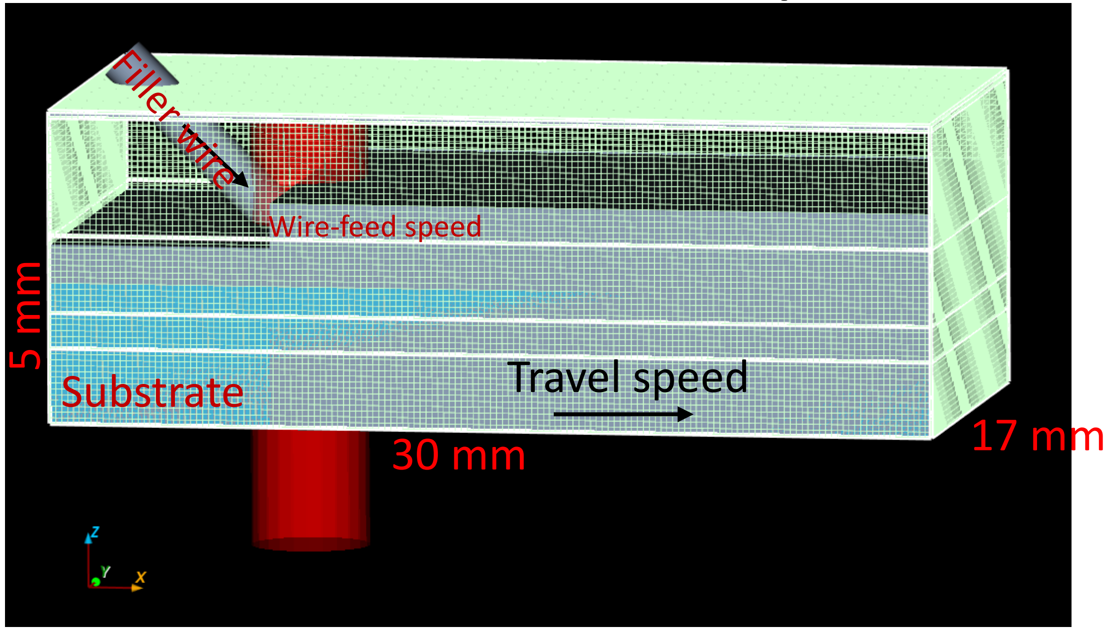
H_{BM} = 480 HVN
H_{∞} = 220 HVN

Single bead

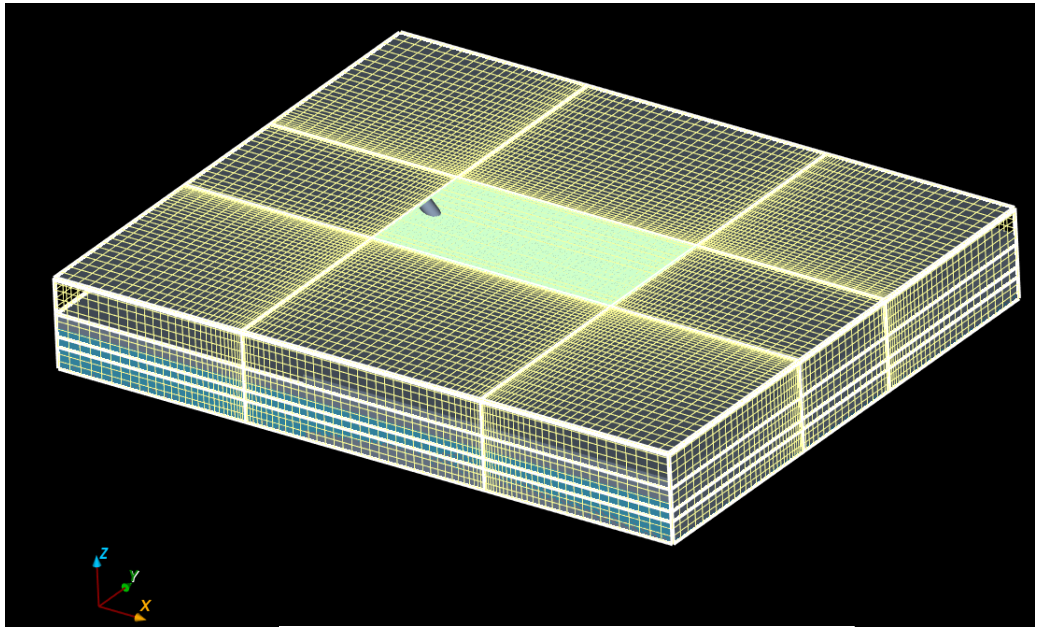


Multiple bead

Setup of molten pool model



Mesh block for deposition



Thermal diffusion block

Cell size – 0.02 cm
Number of cells for mesh block – 675,750

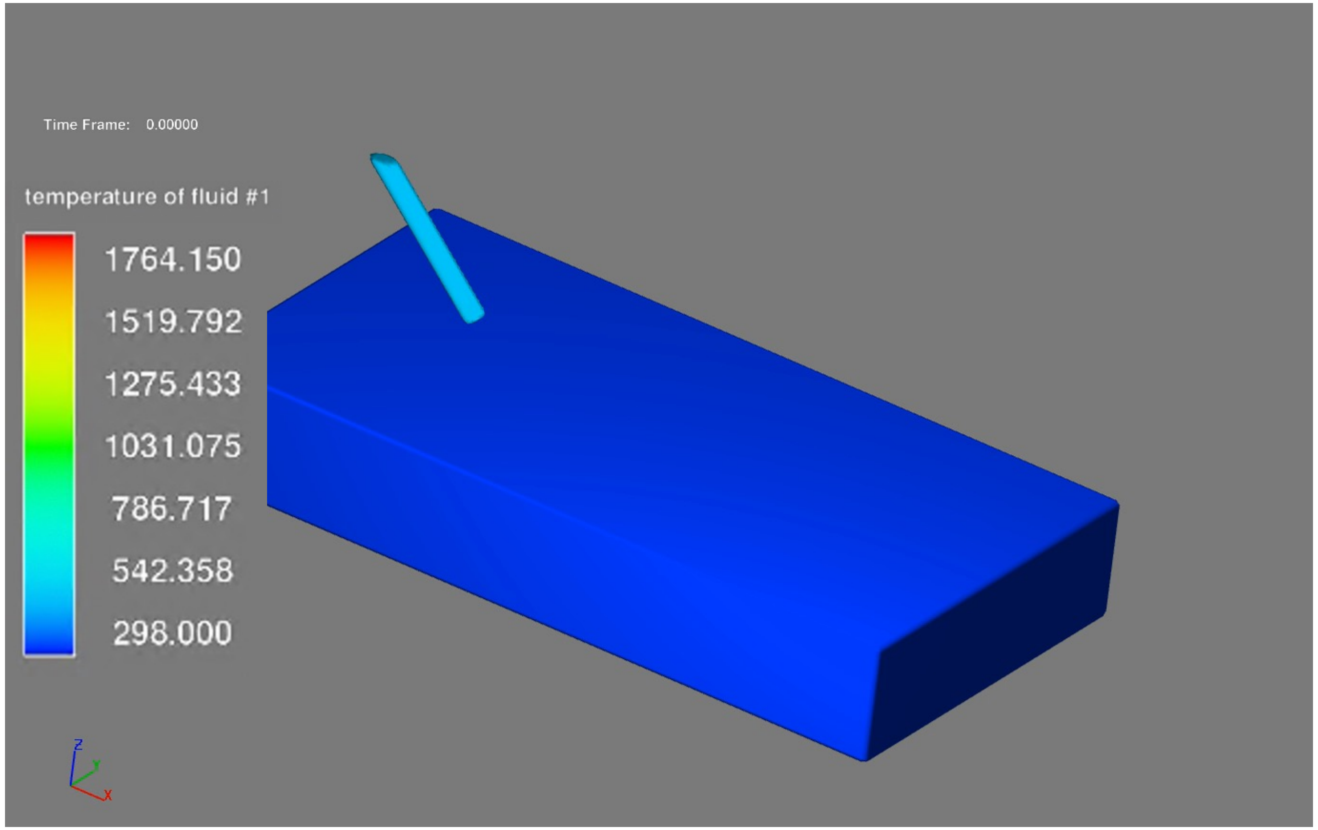
Cell size – 0.08 cm
Number of cells for thermal block – 97,565

How does the model work?

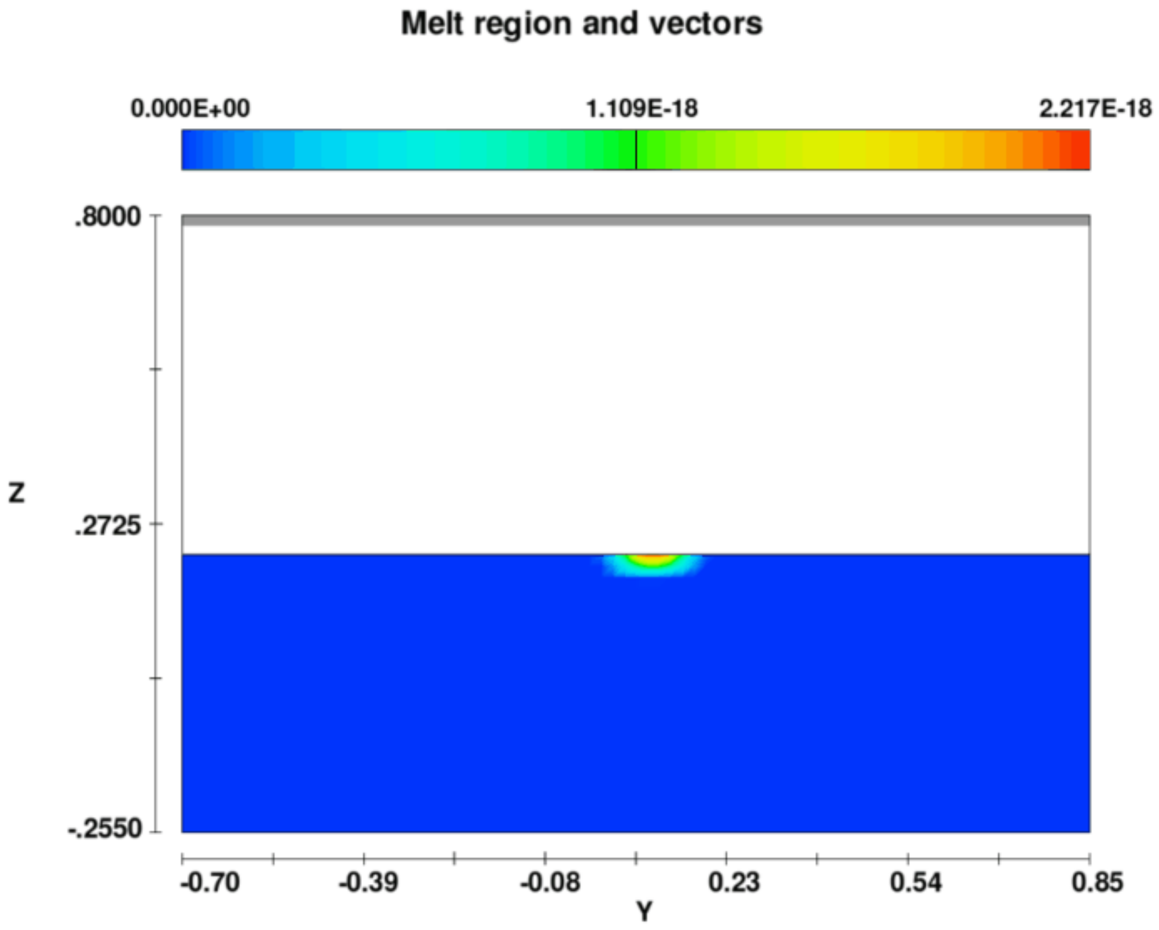
1. Based on Flow-3D software, which uses Volume of Fluid (VOF) method to track molten pool free surface
2. Heat source is stationary and has a Gaussian distribution
3. Substrate (base) is moving
4. Wire-feed is coming down inclined at 45° angle
5. Wire melts due to heat and gets deposited on substrate

Single bead deposition Wire-DED

3-D View



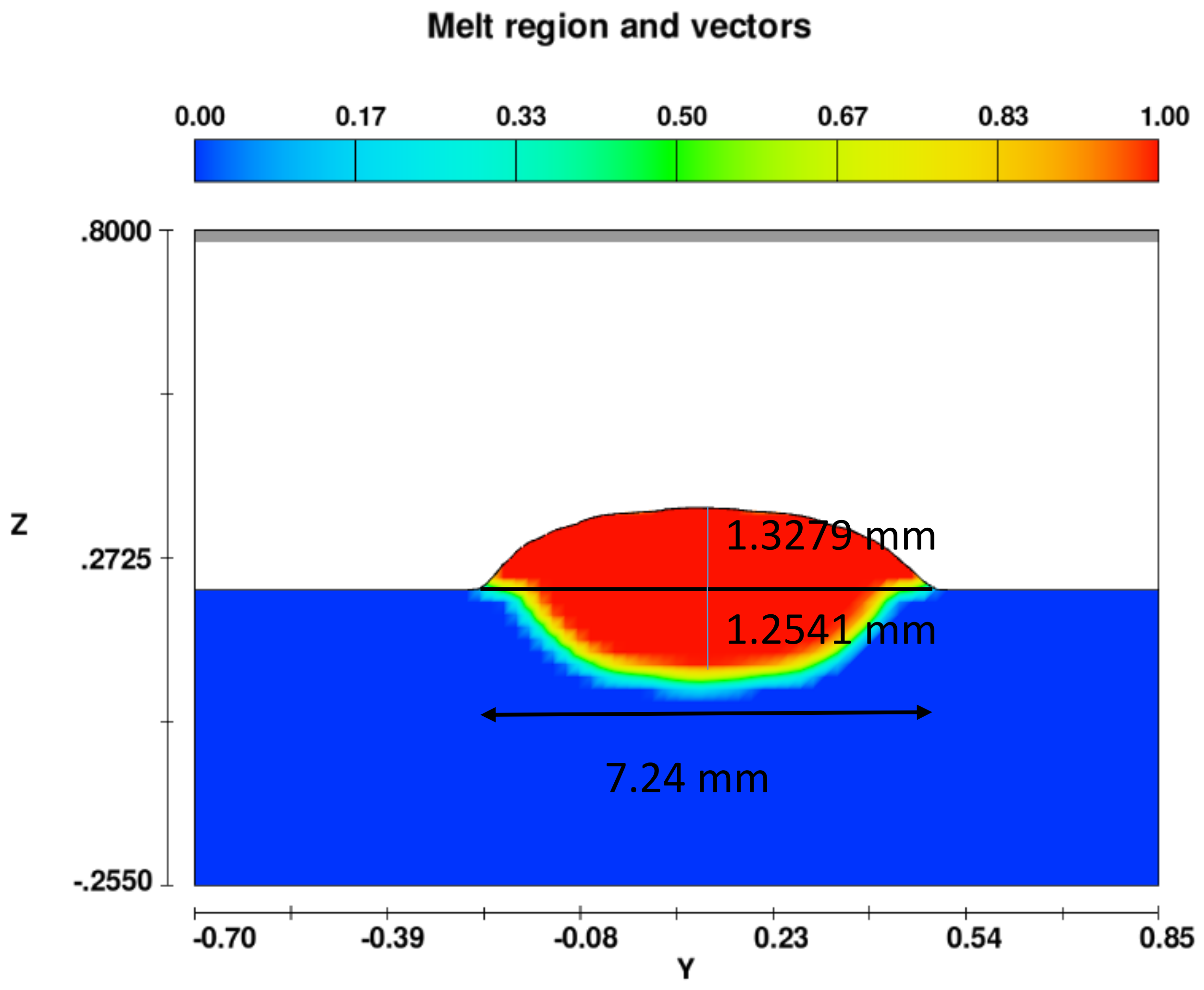
Transverse cross-section view

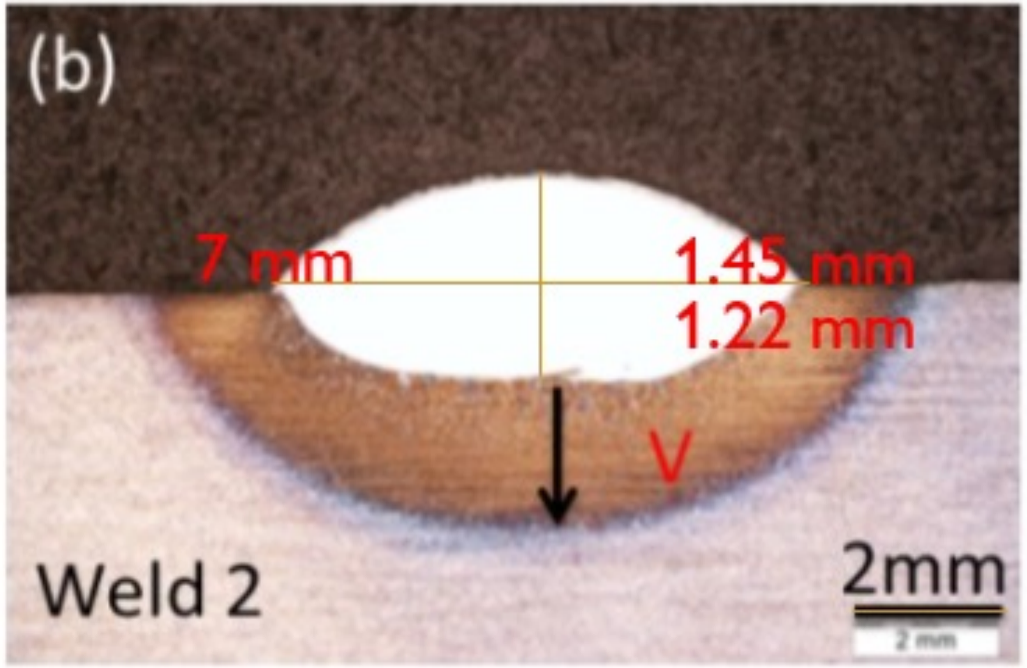


Molten pool represented by red contour

Bead evolution

Comparison with experimental data



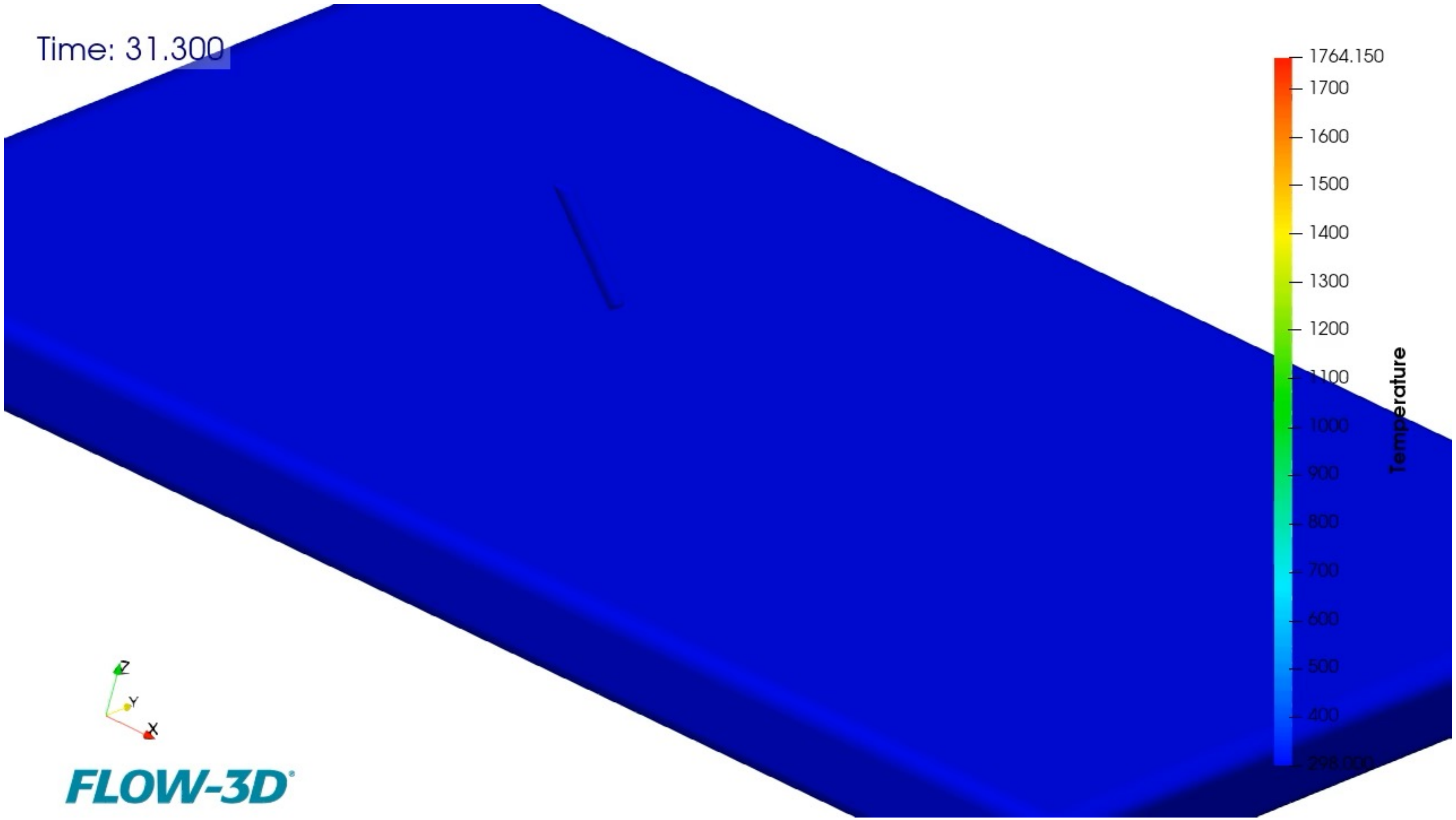


	Exp. (mm)	Comp. (mm)	Error
Deposited height	1.45	1.33	8.42%
Melt depth	1.22	1.25	2.79%
Melt Width	7.00	7.24	3.42%

Multi-pass, multi-layer deposition

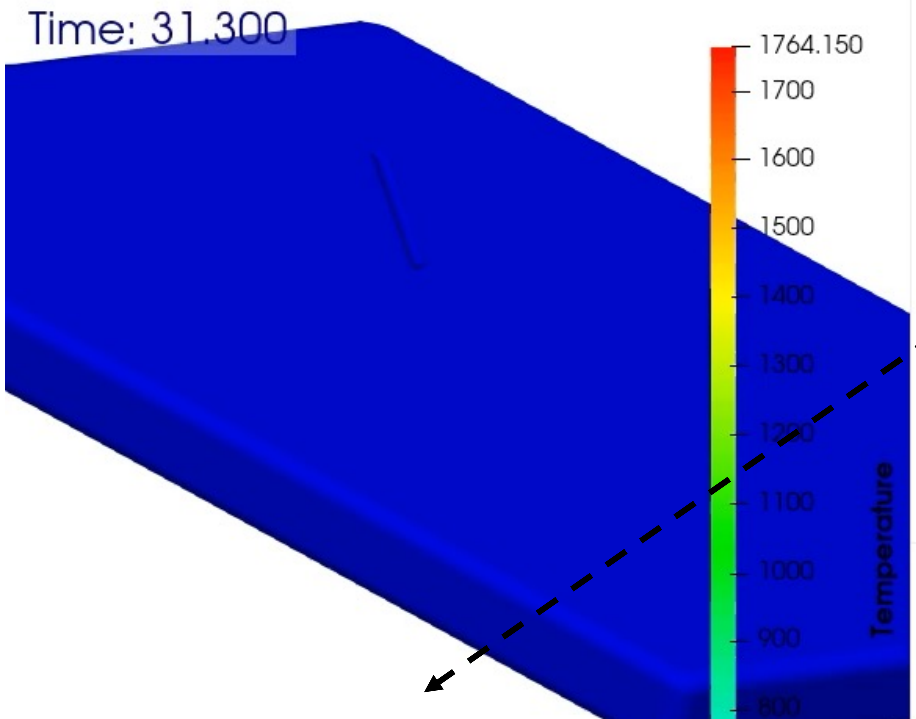
- Three bead deposition
- To keep the simulation time short:
  - Each layer deposited for 7 s
  - Cooling time between beads also set for 7 s
- Second bead getting deposited at the right edge of first bead (5mm offset way from the center of first bead)
- Third bead being deposited between the first and second bead in the next layer (2.5 mm offset the center of first bead)

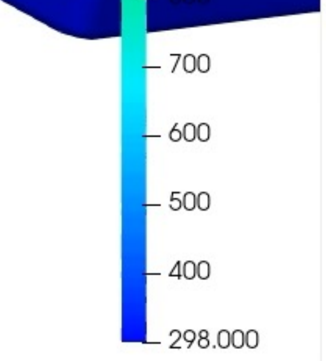
Temperature (K)

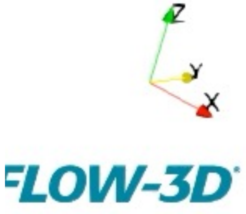


Molten pool represented by red contour

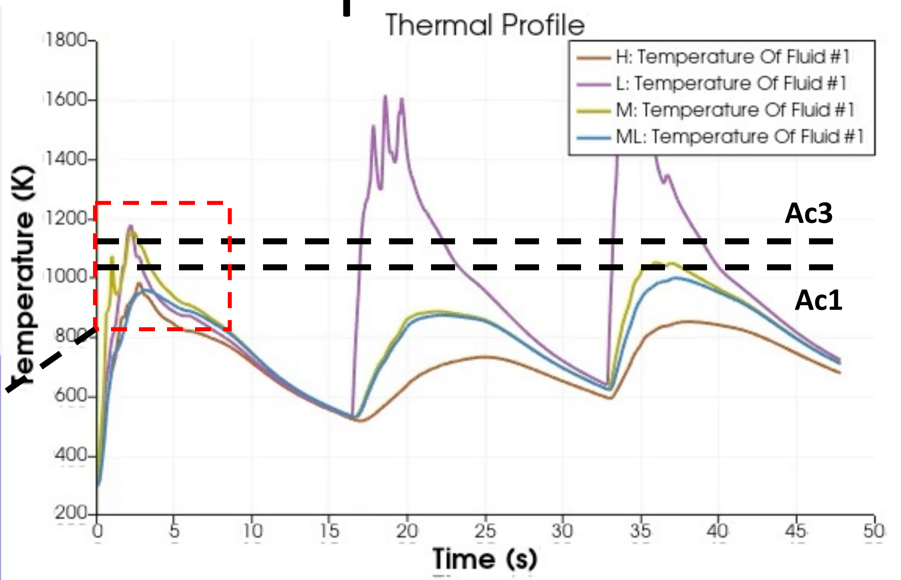
Thermal profile

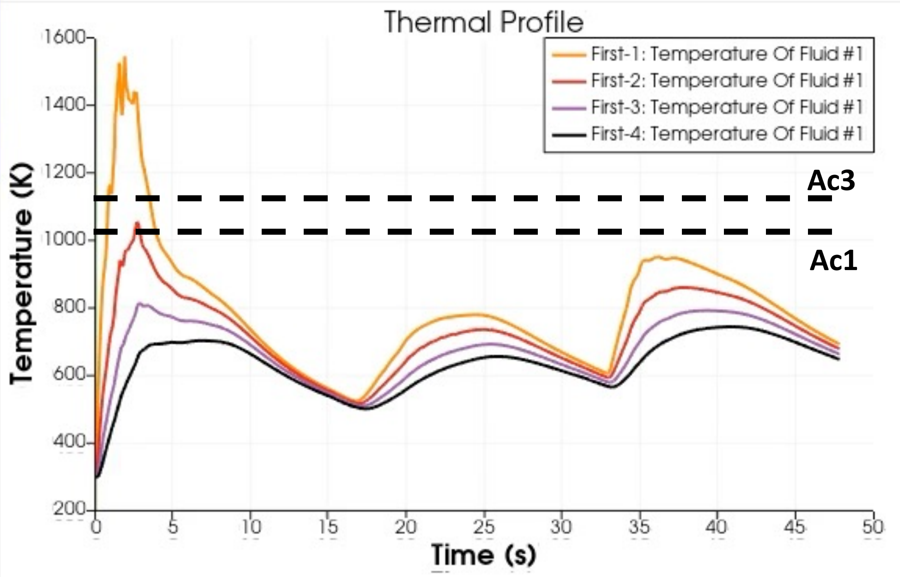




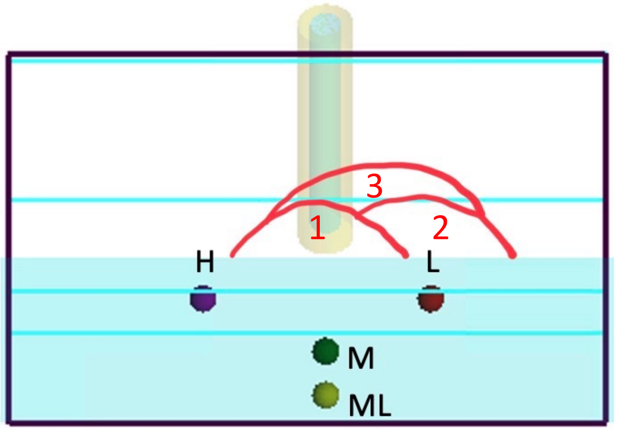


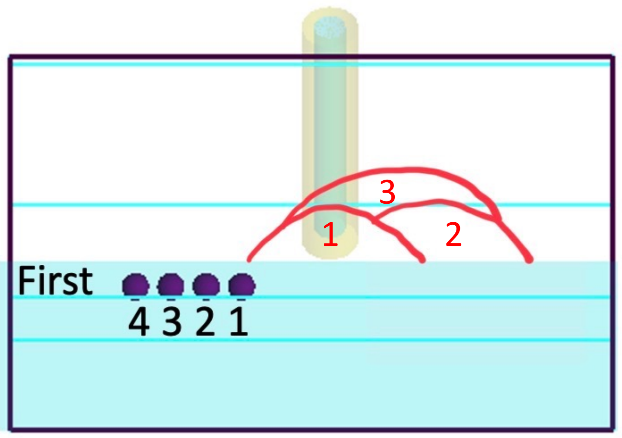
Probes located near weld start and thus not heated to high temperatures in the first bead





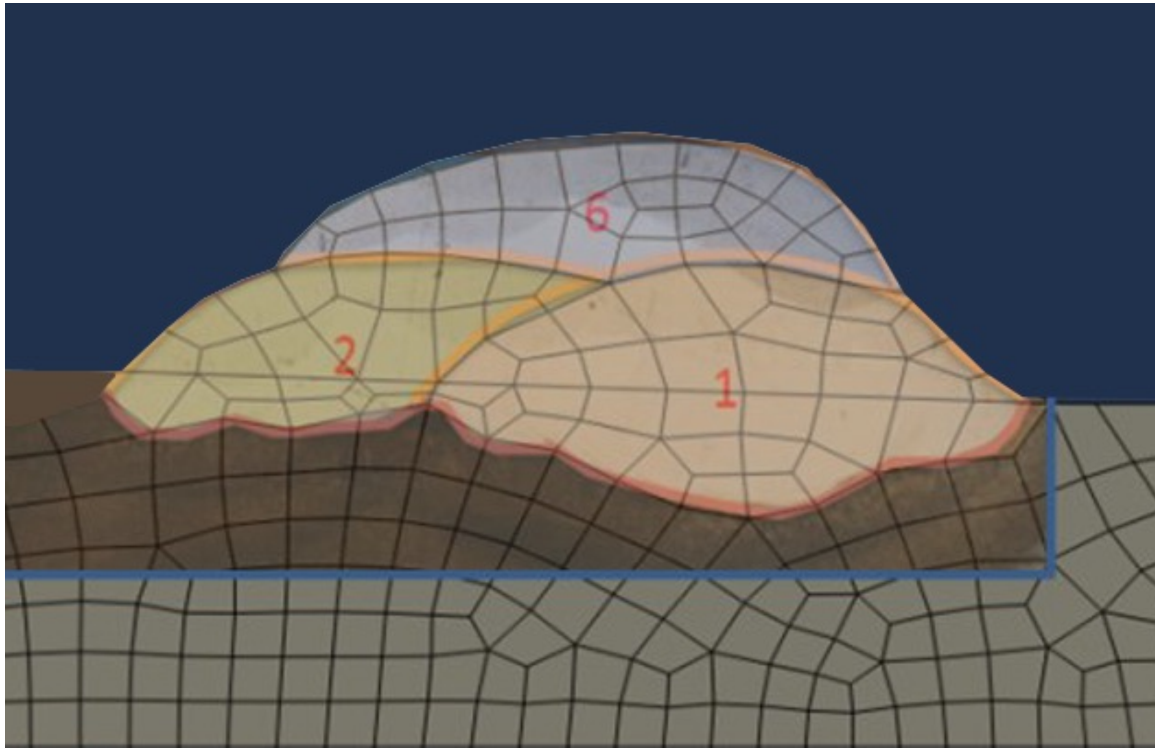
Probe location shown on cross-section



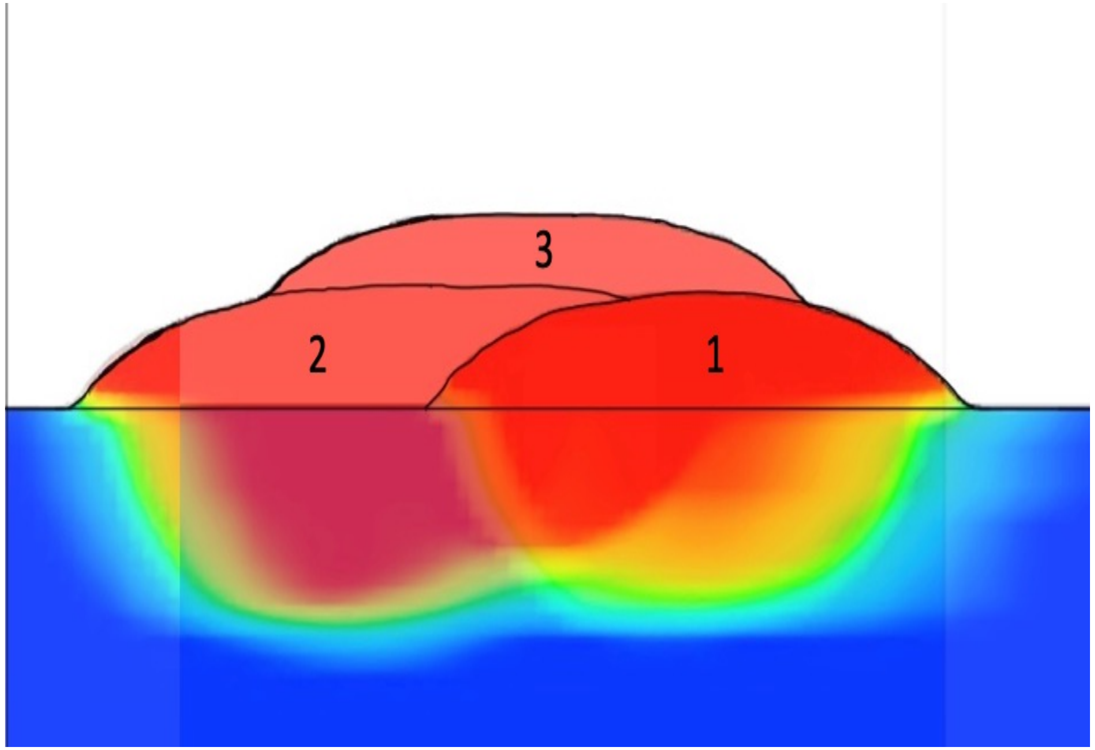


Comparison with experimental bead shapes

Experimental



Computational



- Predicted bead shapes consistent with those observed experimentally
- As the molten pool model does not require the bead shape as an input, it can be readily used to study how welding parameters and bead placement affect the thermal profiles

Preliminary results for hardness prediction

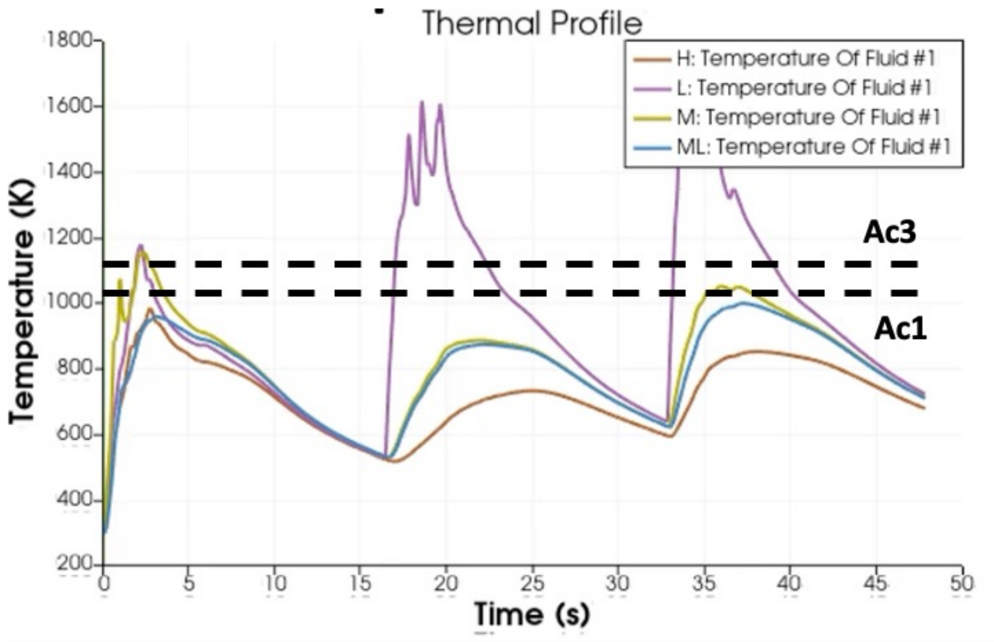
- For simplicity, the extent of tempering is assumed to depend on peak temperature only
- Using the thermal profile computed at the monitoring locations, the hardness is calculated:

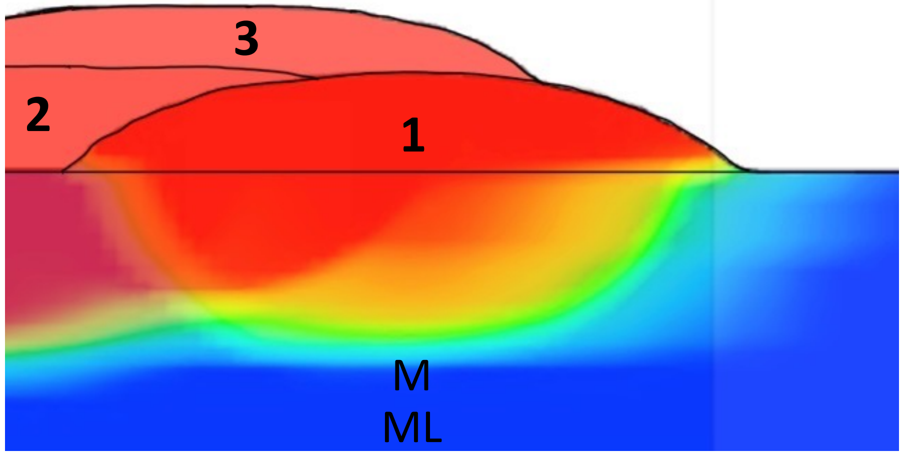
$$\phi = 0.0015T - 0.3888$$

$$\phi = \frac{H_{BM} - H}{H_{BM} - H_{\infty}}$$

H_{BM} = 480 HVN
H_{∞} = 220 HVN

Probe	ϕ	Predicted hardness(HVN)	Experimental hardness(HVN)
M	1	220	260
ML	1	220	220





Summary

- ✓ Molten pool model for multi-pass multi-layer deposition (2 layers, and 3 passes) without inputting deposited bead macrograph *a priori* has been developed
  - ✓ Comprehensive treatment of physics including melting of filler wire, and molten pool convection, etc.
- ✓ Thermal profiles computed in the weld beads and substrate
- ✓ Hardness prediction tested using a simplified tempering model

Future Work:

Thermal profile for each point on base material

Hardness mapping in area of concern (SCHAZ, ICHAZ, and FCHAZ)

Extending model for Grade 91 steel

Acknowledgments

- Research funded by U.S. Department of Energy, DE-FE0032067
- Thanks to Dr. Xuesong Gao and Prof. Boian Alexandrov of the Ohio State University for helpful discussions

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Thank You !!