High-speed and High-quality Field Welding Repair Based on Advanced Non-destructive Evaluation and Numerical Modeling

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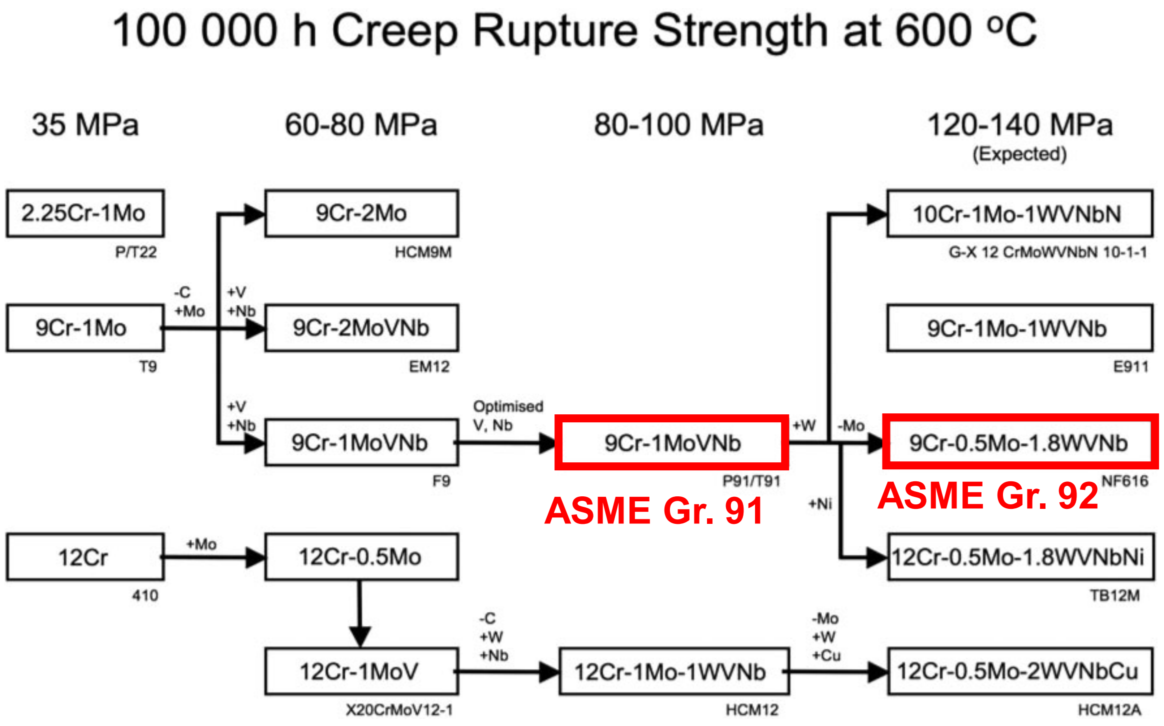
Presentation outline

- Background and Objectives
- Research Status and Accomplishments
- Summary and Conclusions

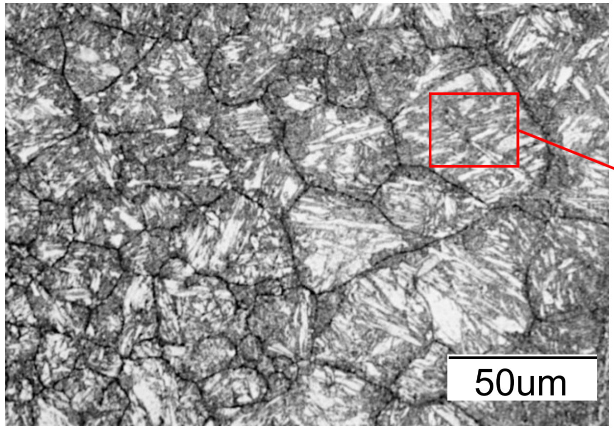
Creep Strength Enhanced Ferritic (CSEF) Steels

- Owing to its high creep-rupture strength, Grade 91 (9Cr-1MoVNb) steel is one of the most-widely used materials in structural components such as tubing, piping, and headers in the current fleet of fossil plants
- Grade 92 steel, having a higher creep strength than Grade 91 with addition of tungsten (W) and reduction in Molybdenum (Mo), is increasingly used in plant components



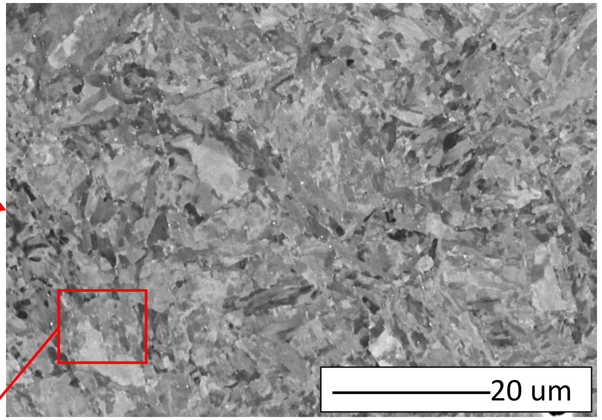
H. Cerjak and E. Letofsky: Sci. Technol. Weld. Join., Vol. 1, pp. 36–42 (1996)

Engineered Base Metal Microstructure



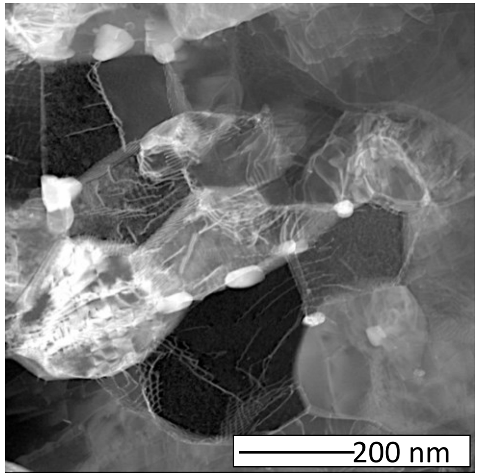
Optical Microscopy

Prior austenite grain boundaries



Scanning Electron Microscopy

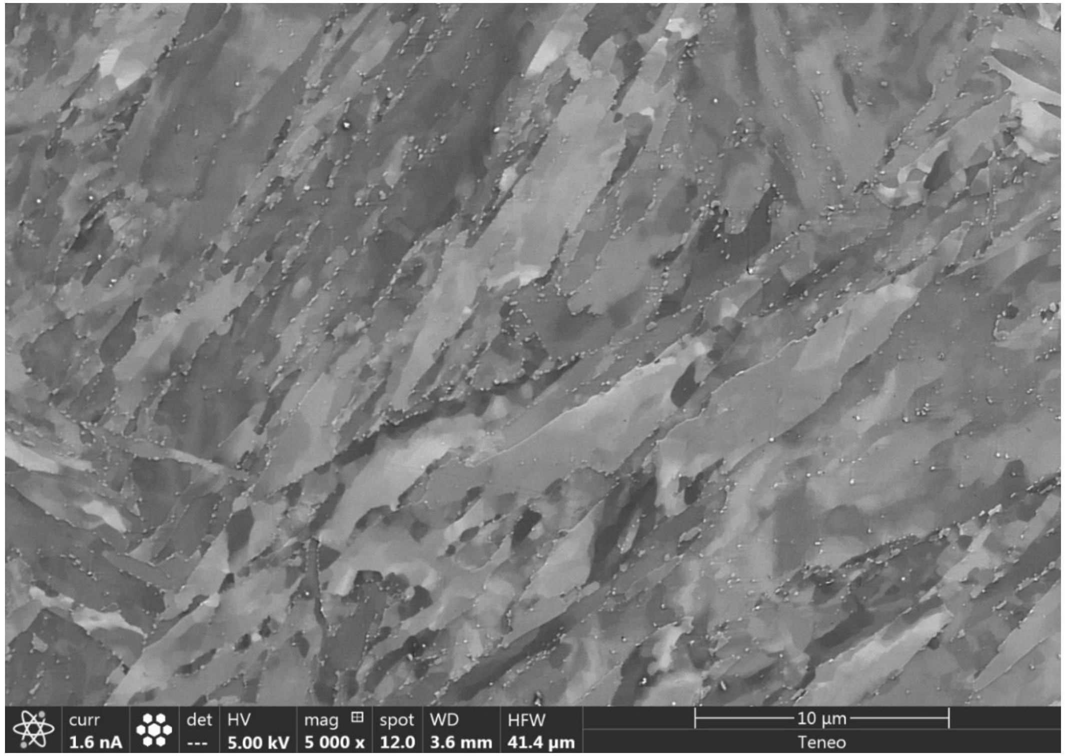
Tempered martensite



Transmission Electron Microscopy

Subgrains and precipitates

Grade 91



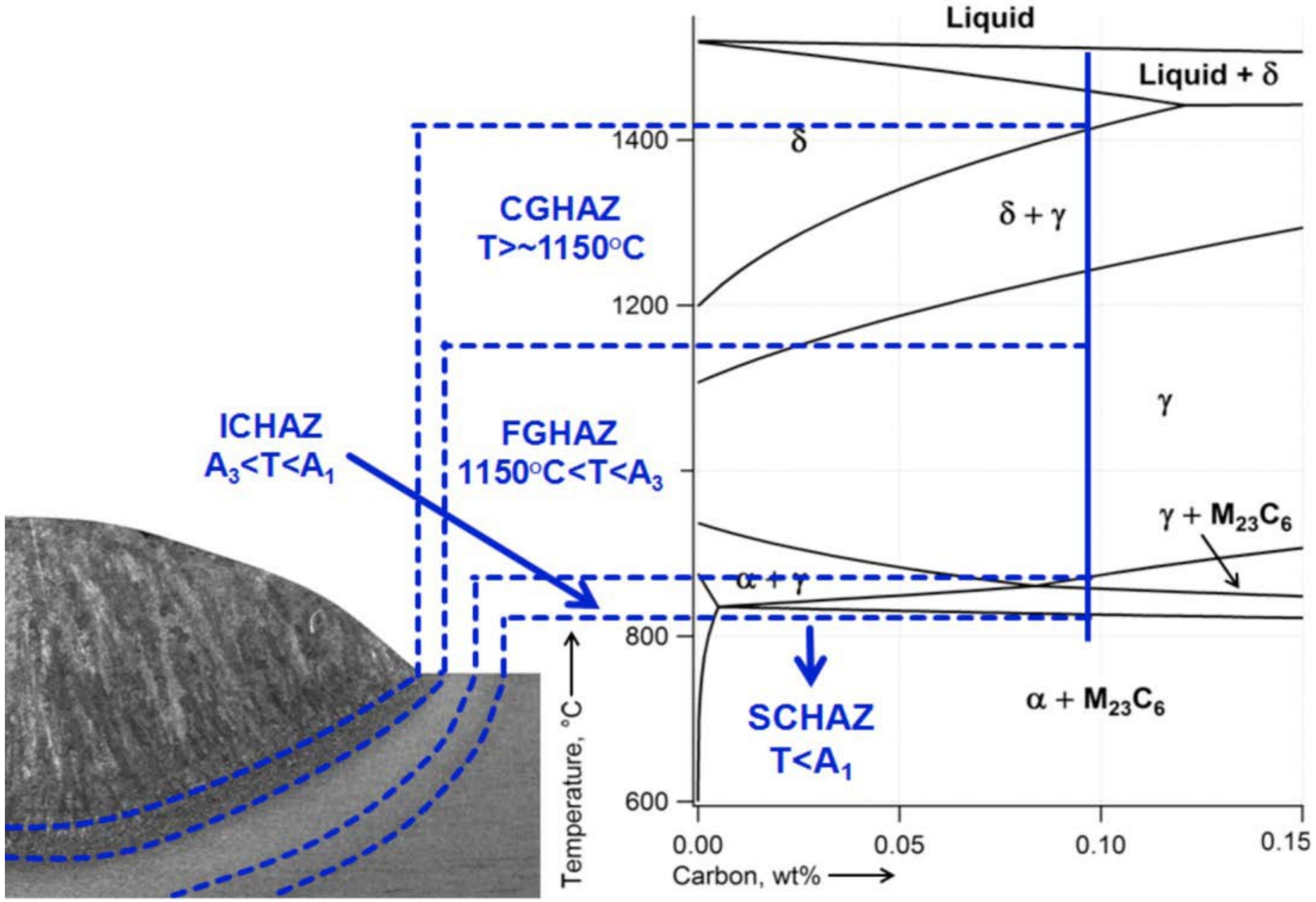
Grade 92

- Tempered martensite
- Carbide precipitation along PAGB and martensite laths

H.C. Whitt, Ph.D. Dissertation, The Ohio State University, 2019.
R. Johnson, M.S. Thesis, The Ohio State University, 2021.

Formation of Deleterious Microstructure

- Heat treatment at a temperature close to A1 (e.g., 760 °C or 1400 °C) is essential to obtain the tempered martensite microstructure
- Microstructure deleterious to mechanical properties can form if temperature is not maintained
  - Temperature too high (e.g., between A1 and A3) can lead to formation of ferrite (α)
  - Temperature too much lower than A1 can lead to untempered martensite



Literature Review of Temperbead Welding Techniques and Considerations for Grade 91 Components. EPRI, Palo Alto, CA, October 2012. 1026505.

Industry Needs and Project Objectives

- **Technical gaps:**
  - How to ensure field welding repair onto Grade 91 or 92 worked properly?
  - How to optimize welding parameters to reduce formation of deleterious microstructure?
- **Specific objectives**:
  - Developing a non-destructive evaluation (NDE) technique incorporating machine learning which can be used for reliable inspection of detrimental microstructure before and after welding
  - Significantly improving the fidelity and predictive capability of computational model for multi-pass, multi-layer welding by incorporating molten pool dynamics and metallurgical transformation kinetics
  - Training graduate and undergraduate students on NDE and welding applications related to fossil energy

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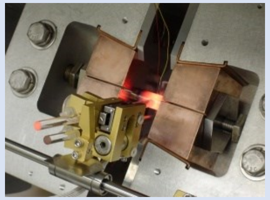
Overview of Research Tasks

Task 1.0 – Project Management and Planning	Task 2.0 – Fabrication of Weld Coupons
Task 3.0 – Gleeble Physical Simulation	Task 4.0 – Microstructure and Hardness Characterization
Task 5.0 – Non-Destructive Evaluation	Task 6.0 – Physics-based Models
Task 7.0 – Reporting	

CSEF steels:
- Grade 91
- Grade 92

Data generation

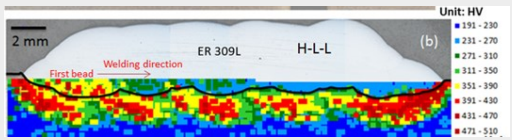
- **Fabrication of weld coupons**
- **Gleeble physical simulation**
- **Microstructure & hardness characterization**

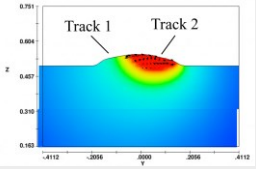


Data analysis

- **Non-destructive evaluation with machine learning**
- **Physics-based models**

Detect and control of microstructure



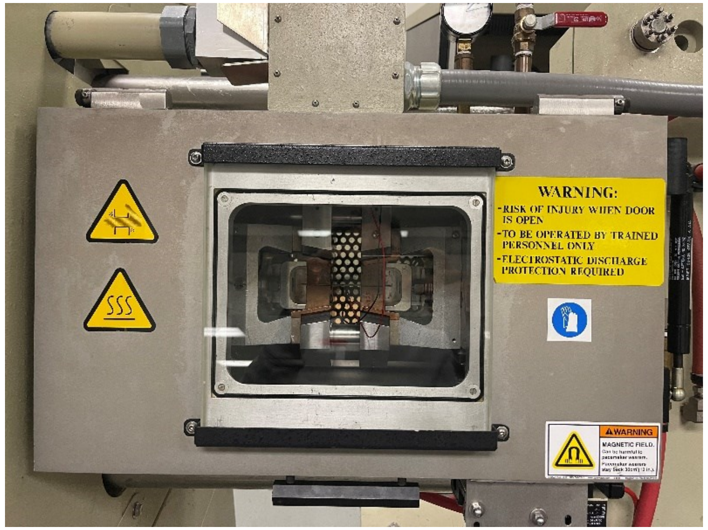


Task 3.0 - Gleeble Physical Simulation for Grade 91 and Grade 92 steels

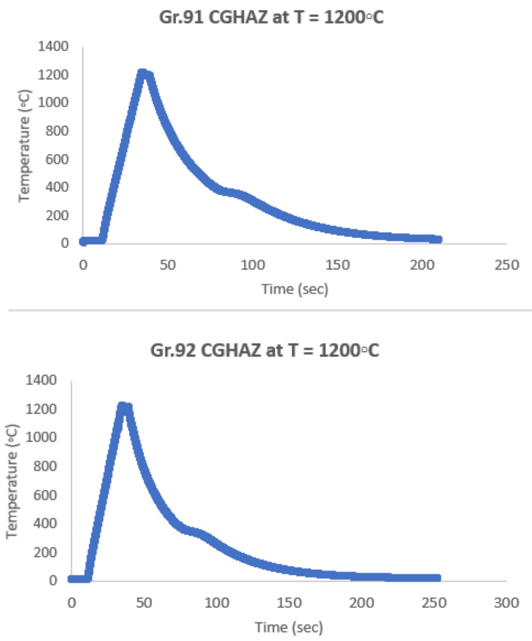
- Gleeble used to produce weld HAZ microstructures i.e., CGHAZ, FGHAZ, and ICHAZ
- Hardness (HV) survey ongoing for all HAZ microstructures in both tempered and non-tempered conditions

Sample Material	CGHAZ Temp range	FGHAZ Temp range	ICHAZ Temp range
Grade 91	T (1200°C) > 1150°C	1150°C > T (1100°C) >870°C	1150°C > T(875°C) >870°C
Grade 92	T (1200°C) >1150°C	1150°C >T (1100°C) >920°C	1150°C >T (940°C) >920°C

Temperature ranges used for Gleeble Simulation

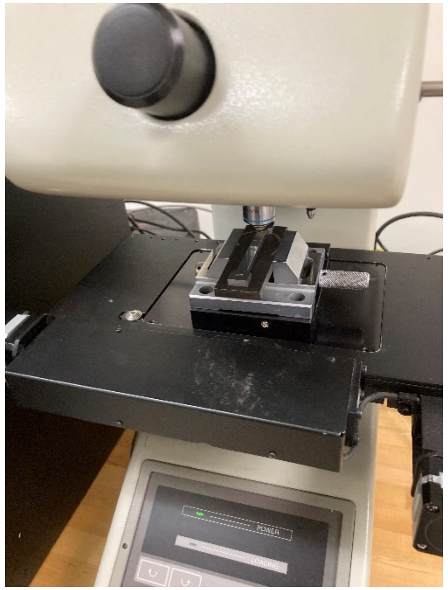


Actual testing in Gleeble

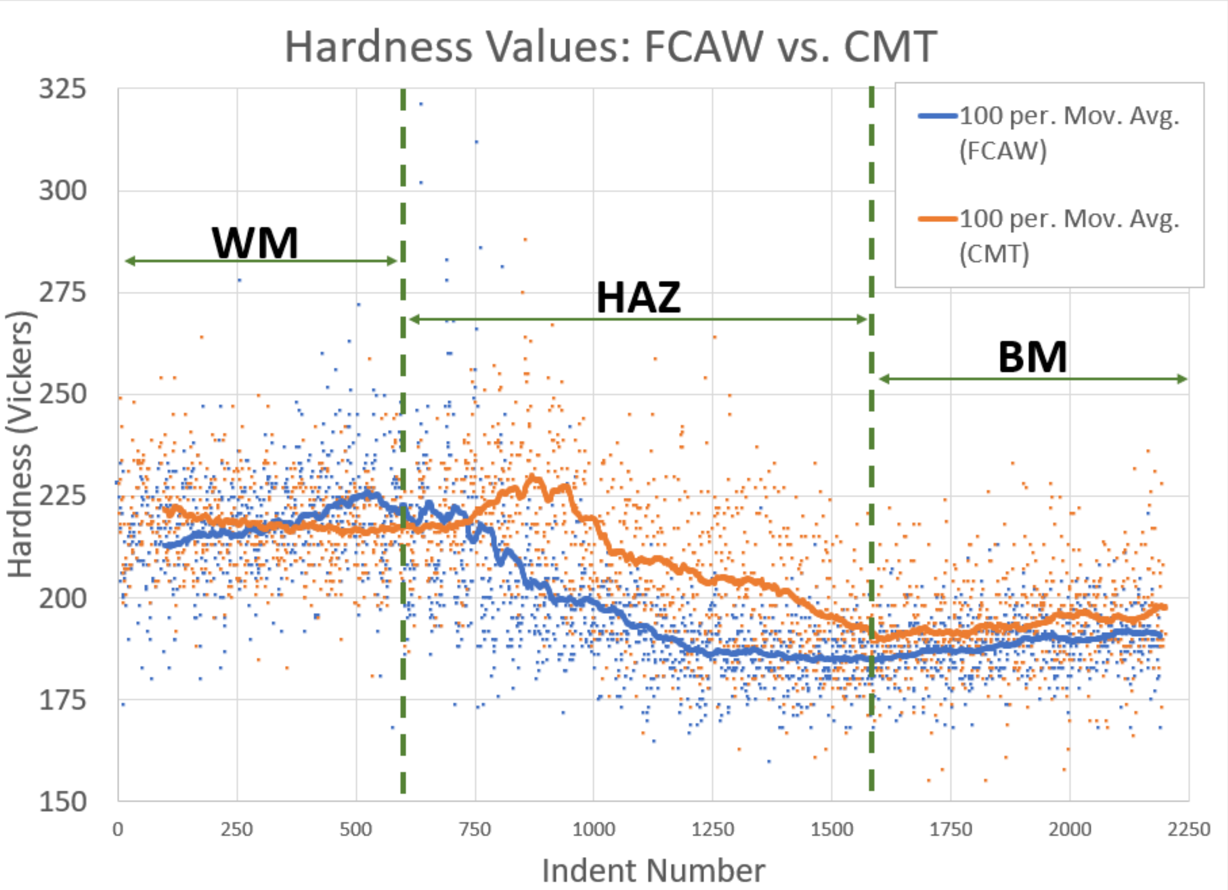


Gleeble thermal cycles for the CGHAZ Weld simulation for Grade 91 and Grade 92.

Task 4.0 - Microstructure and Hardness Characterization

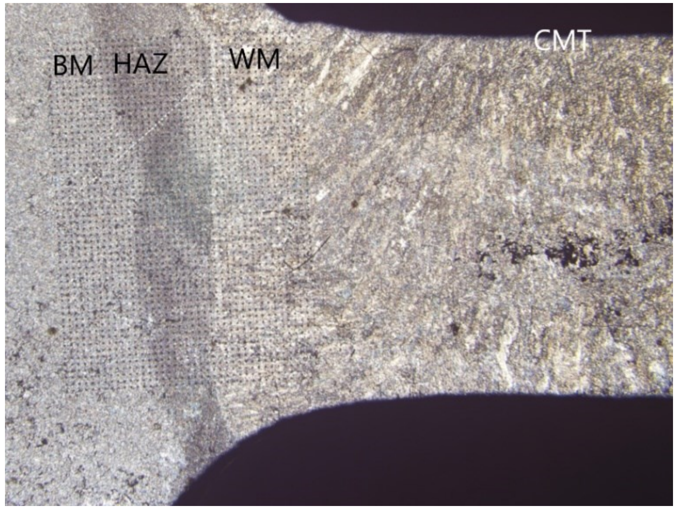


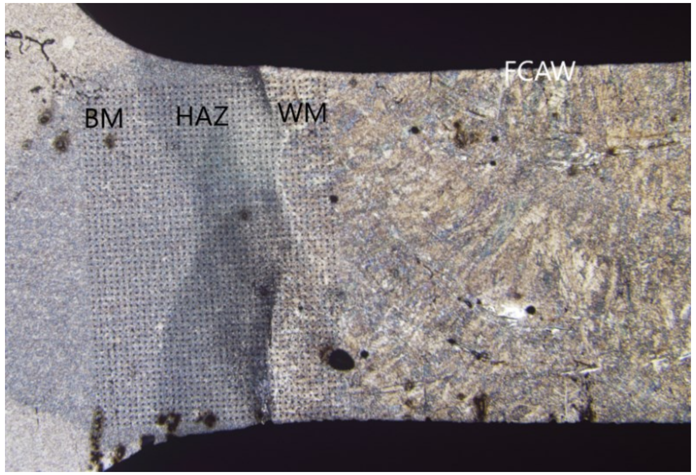
Vickers Hardness survey plot of Grade 91 samples showing the Weld Metal (WM), Heat Affected Zone (HAZ), and Base metal (BM)



Vickers Hardness survey plot of Grade 91 samples showing the Weld Metal (WM), Heat Affected Zone (HAZ), and Base metal (BM)

Gr. 91 Sample

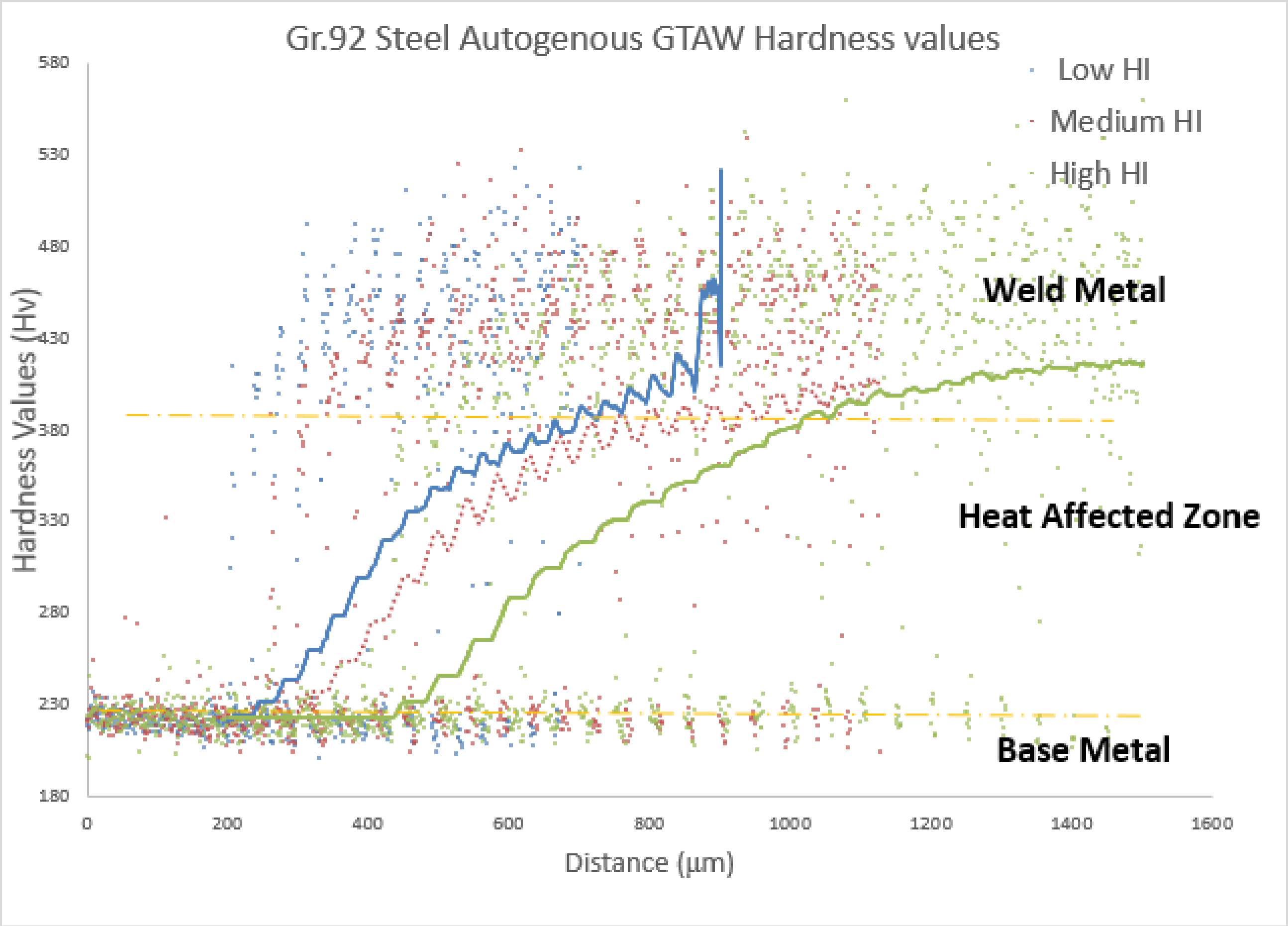




Task 4.0 - Microstructure and Hardness Characterization

Grade 92 BOP welds showing (top) Sample (bottom) cross section of sample

Gr. 92 Sample

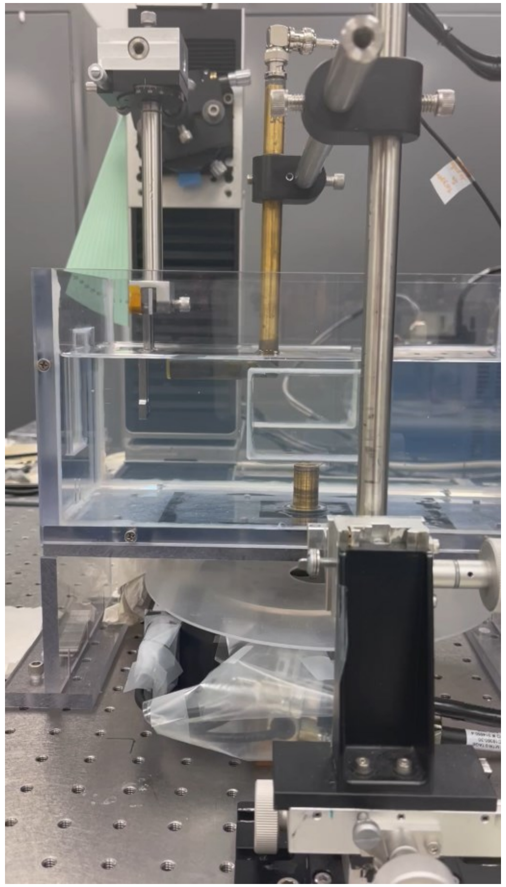


Vickers Hardness survey plot of Grade 92 BOP weld showing the Weld Metal (WM), Heat Affected Zone (HAZ), and Base metal (BM) for all three heat inputs.

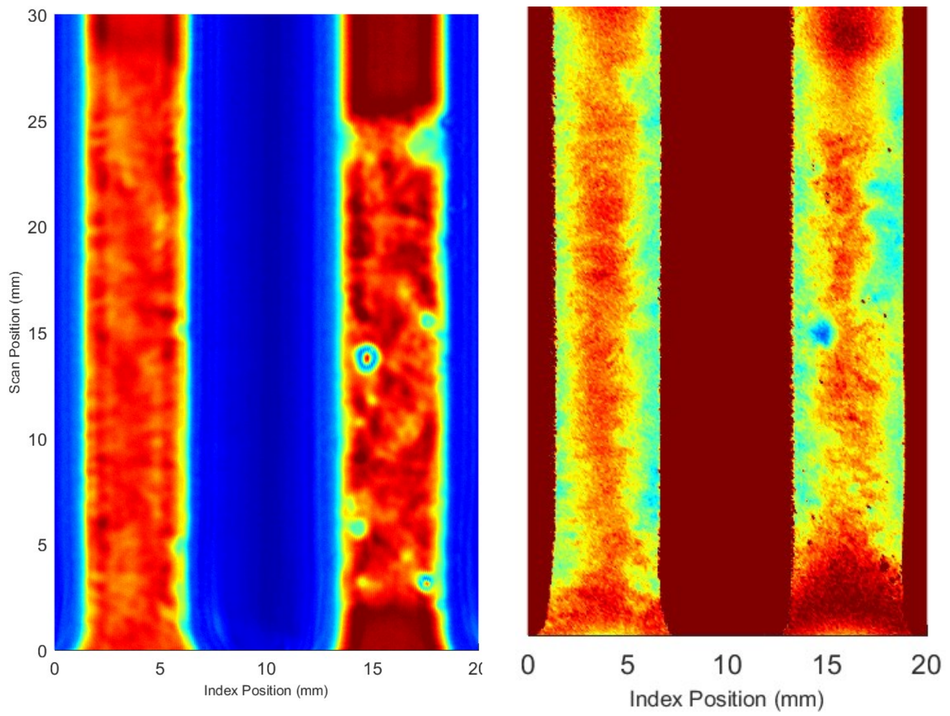
Task 5.0 - Nondestructive Evaluation

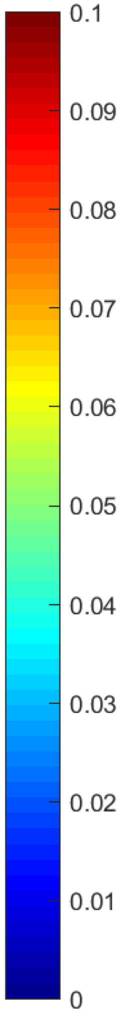
- Micro-resolution Ultrasonic testing to evaluate weld microstructures
  - Gr. 91 and Gr. 92 Steel weld microstructure
  - CMT, FCAW, and GTAW (varied heat inputs)

- Ultrasonic images correlated to weld microstructures as a characterization technique
  - Ultrasonic velocity data
  - Peak to Peak amplitude
  - Hardness measurements
  - Weld macrograph samples

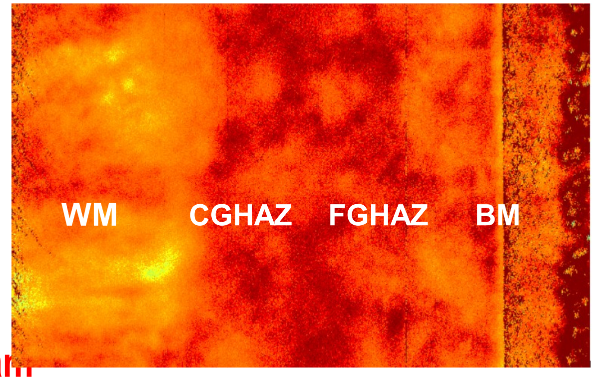


Grade 91



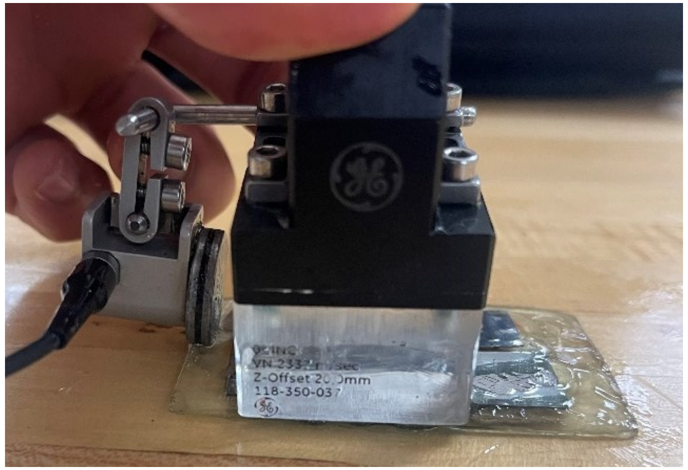


Grade 92

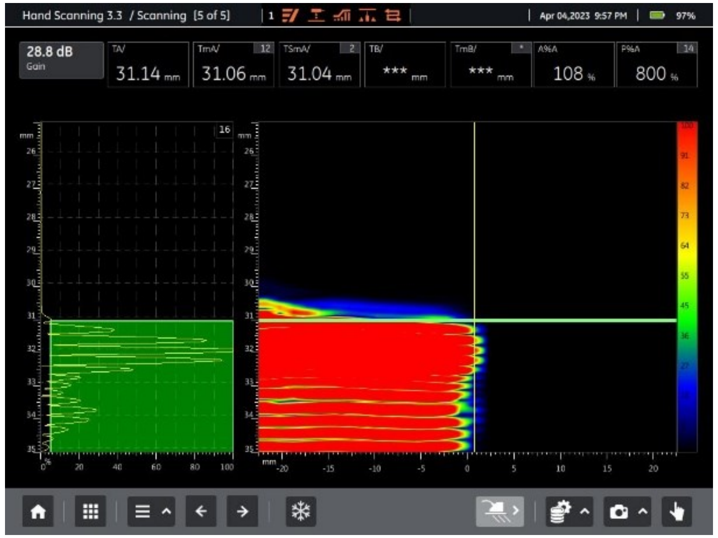


Task 5.0 - Nondestructive Evaluation

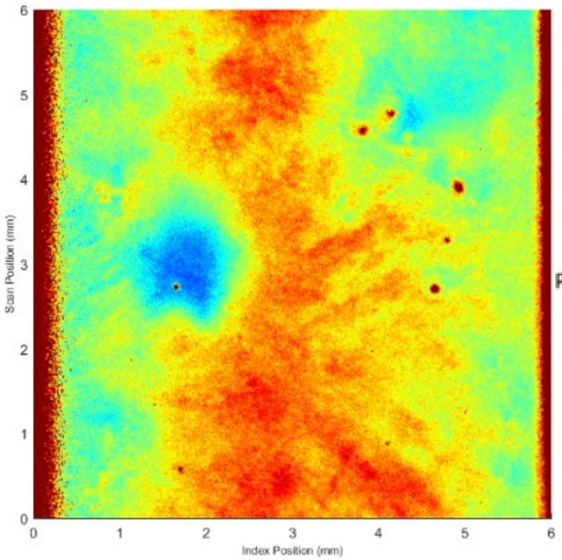
Straight beam UT



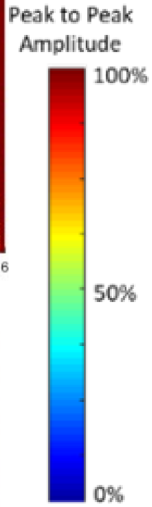
Phased array hand scan

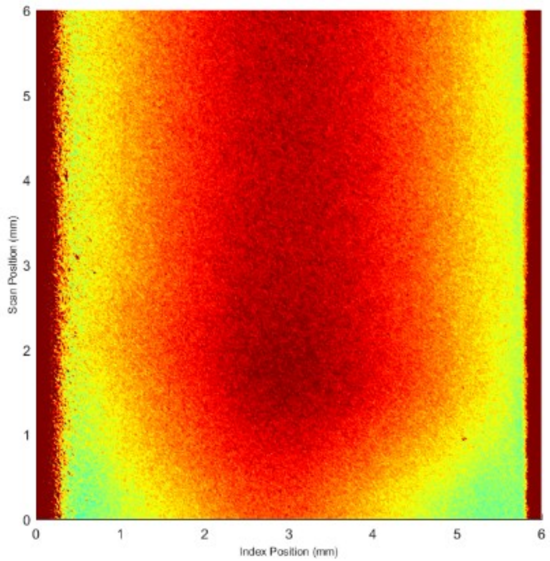


Micro-resolution ultrasonic imaging system



FCAW (weld area)



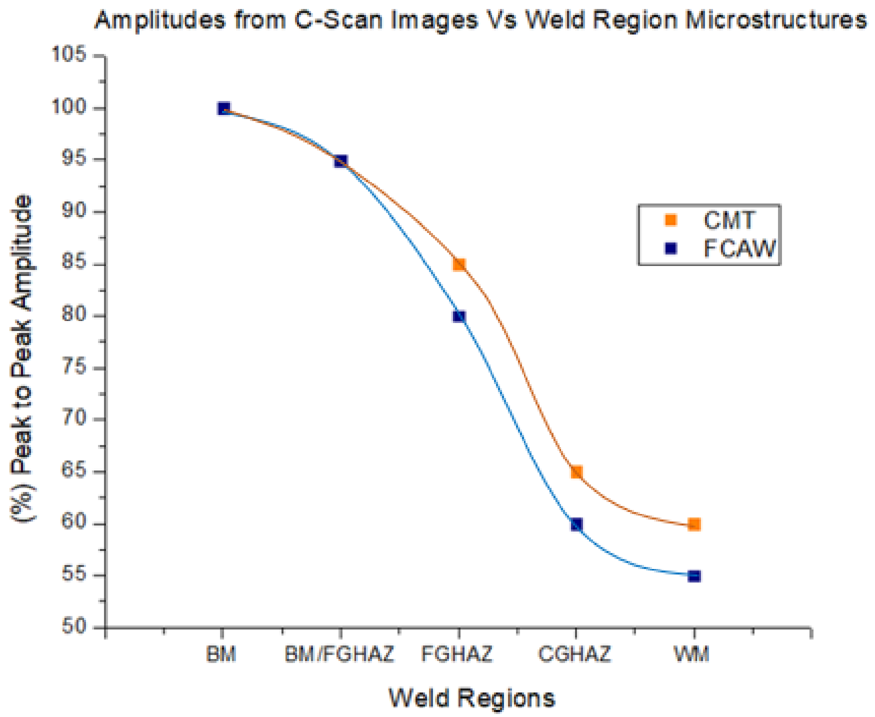


FCAW (base metal section)

Task 5.0 - Nondestructive Evaluation

Relationship between Weld Microstructures, Amplitude, and Hardness (Hv) in Grade 91

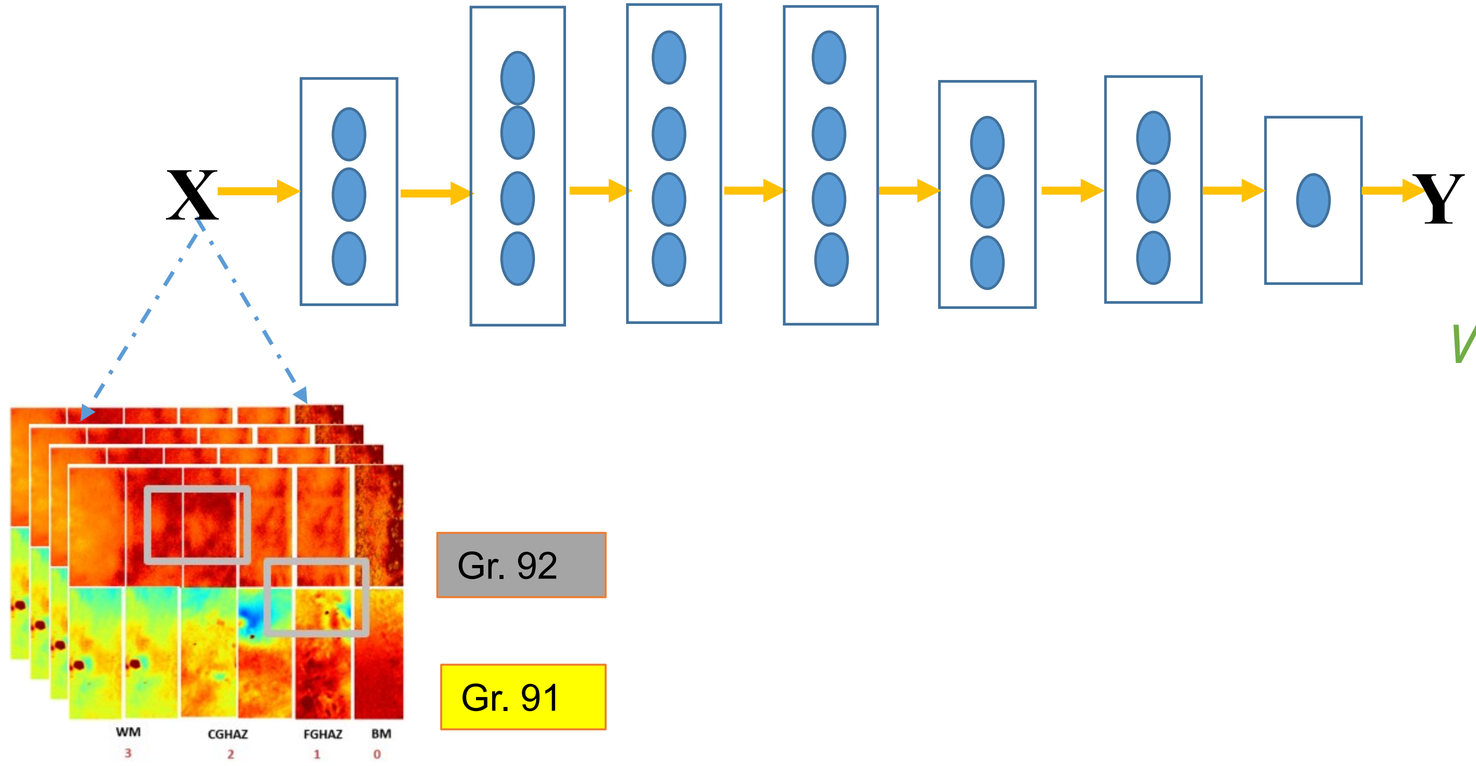
- Lower amplitude (%) signals are closely related to certain areas of the weld microstructure
- The hardness values slightly varied between the two welds based on heat input



Correlation of weld microstructure to (peak to peak) Amplitude signals ultrasonic images.

Task 5.1 - Machine Learning via CNN

- Convolutional Neural Networks (CNN) is a subtype of Neural Network for applications in image recognition
- Convolution applies a feature detector (Kernel) to the input image



Where we are **Testing Acc: 35%**

Results from current testing using, NDE images from Gr. 91 and Gr. 92 on the convolutional neural network algorithm

Where we want to be **Testing Acc: Up to 70%**

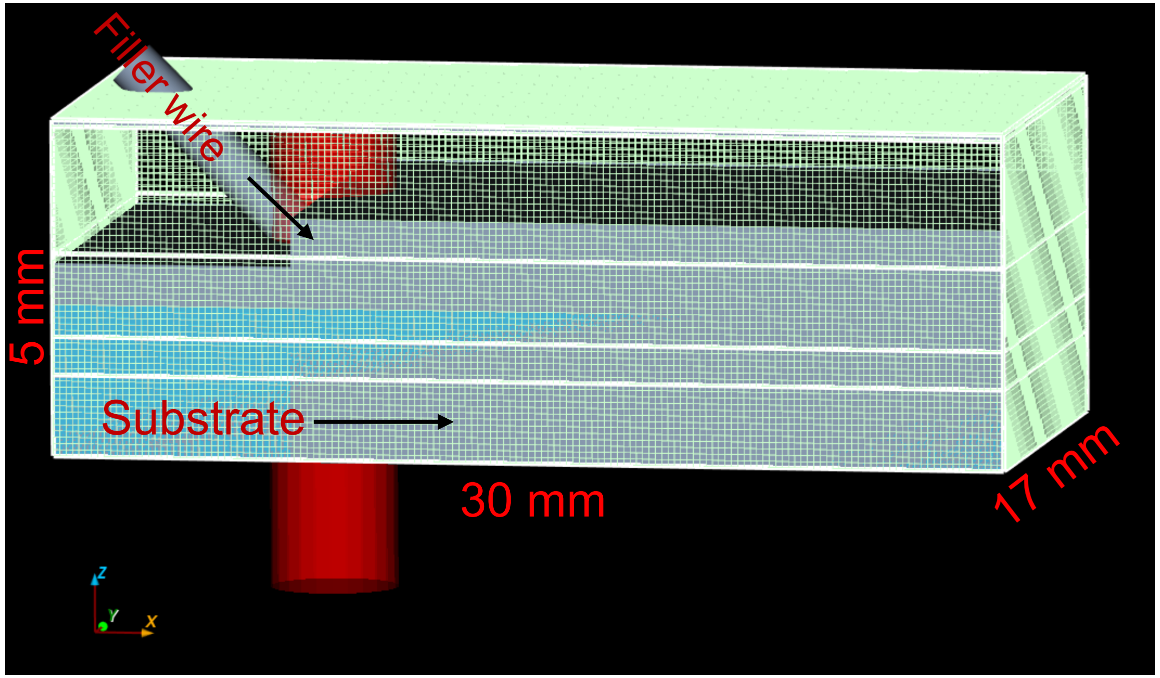
Input: **Gr.91 and Gr. 92 weld NDE C-images**

McDermott, J. "Convolutional Neural Networks-Image Classification With Keras." (2020).

Task 6 - Integrated Molten Pool and Metallurgical Modeling

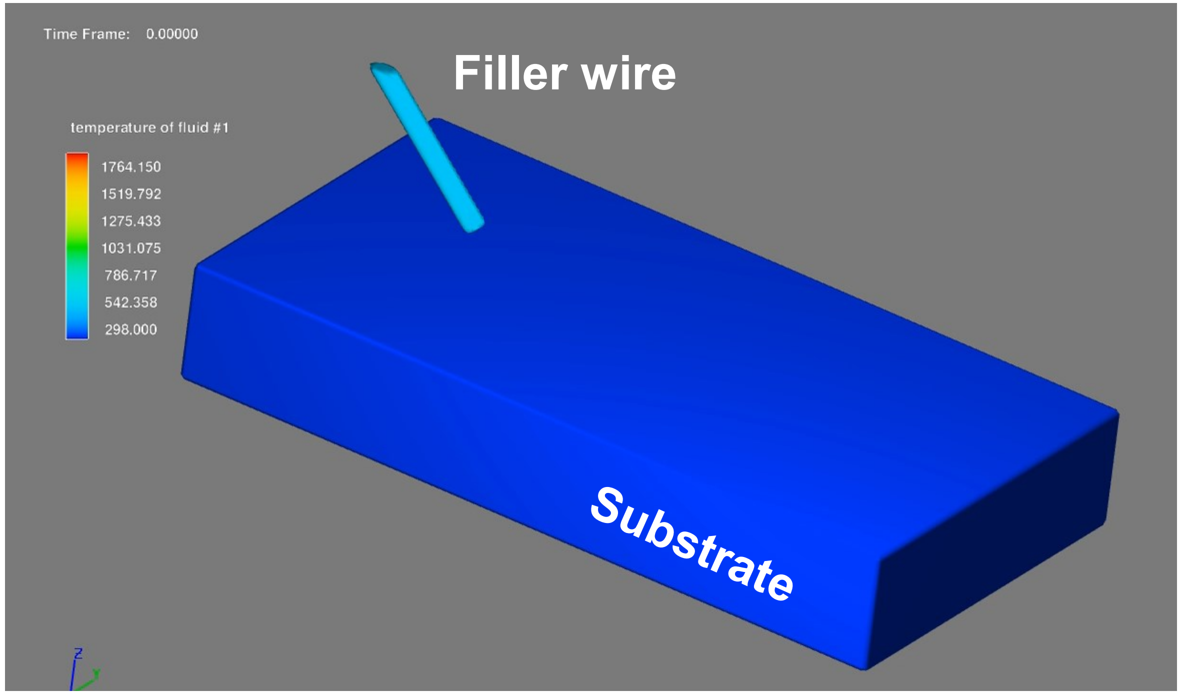
Molten pool model → *Predicted Thermal cycles* → Metallurgical model of martensite tempering

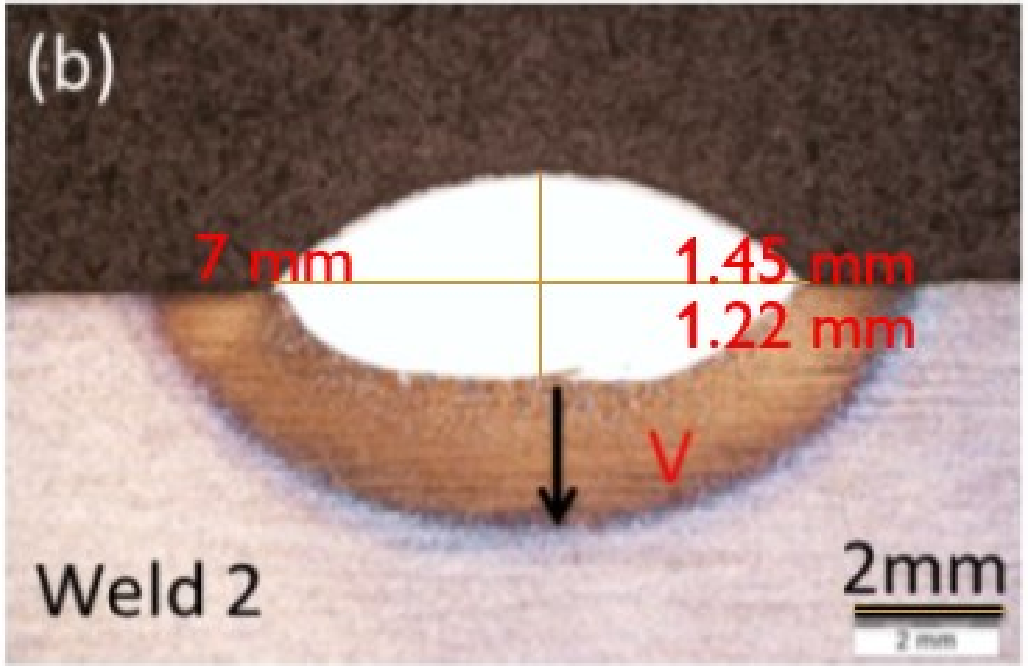
Mesh for molten pool model

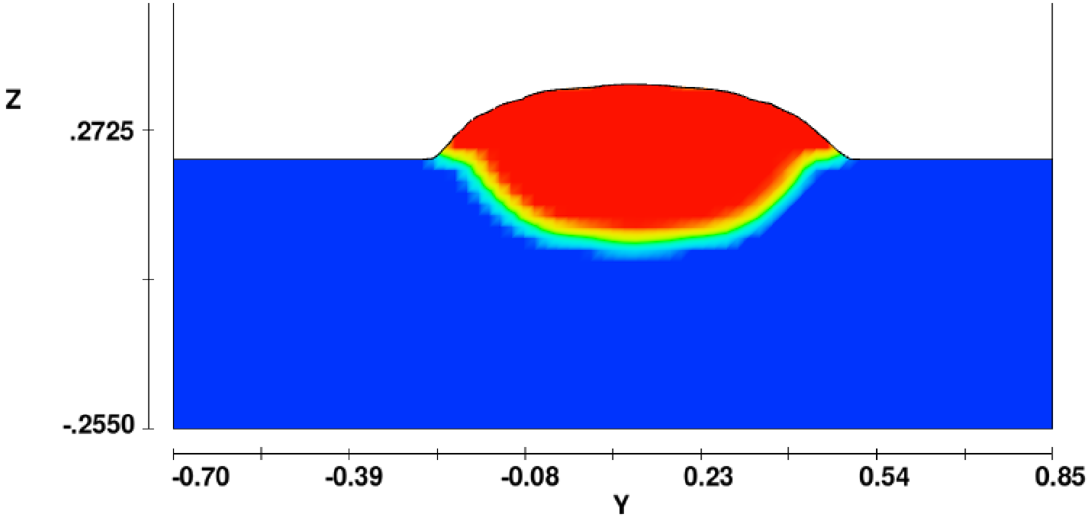


- A main limitation with the existing finite element model is that the bead shapes and sizes must be known beforehand to set up the model. Such information is not always available.
- The molten pool model predicts the bead shapes and sizes by solving mass, momentum and energy conservation equations along with Volume of Fluid (VOF) method to track molten pool free surface.
- To facilitate computational efficiency, the coordinate system is attached to the moving heat source (i.e., Eulerian frame of reference).
- For model development, experimental data of welding onto low alloy steel SA-533 is used.

Model Validation for Single Bead on Plate Weld





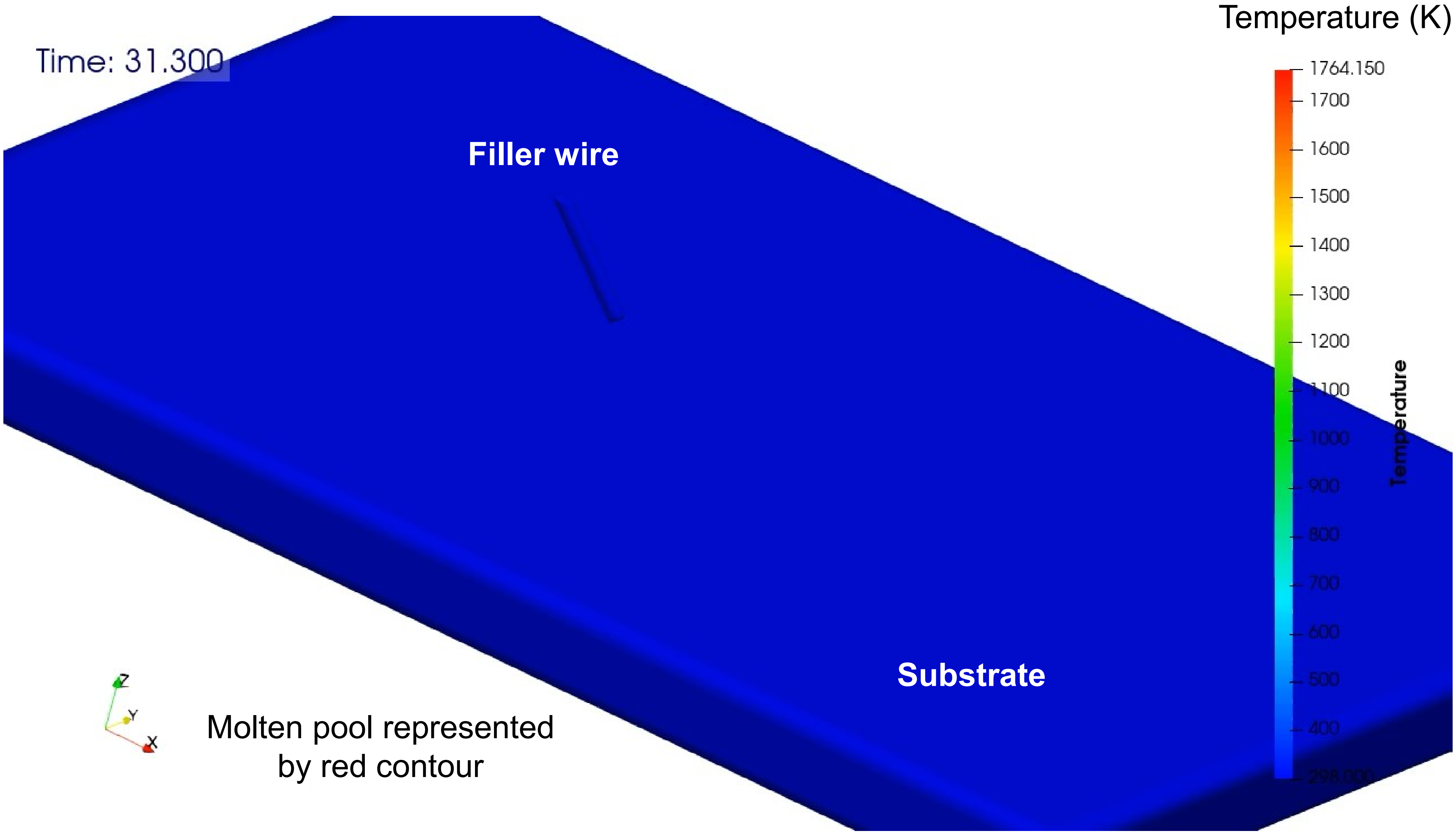


	[1]Exp. (mm)	Comp. (mm)	Error
Deposit height	1.45	1.33	8.42%
Depth	1.22	1.25	2.79%
Width	7.00	7.24	3.42%

[1]K. Zhang, M.S. Thesis, The Ohio State University, 2016

THE OHIO STATE UNIVERSITY

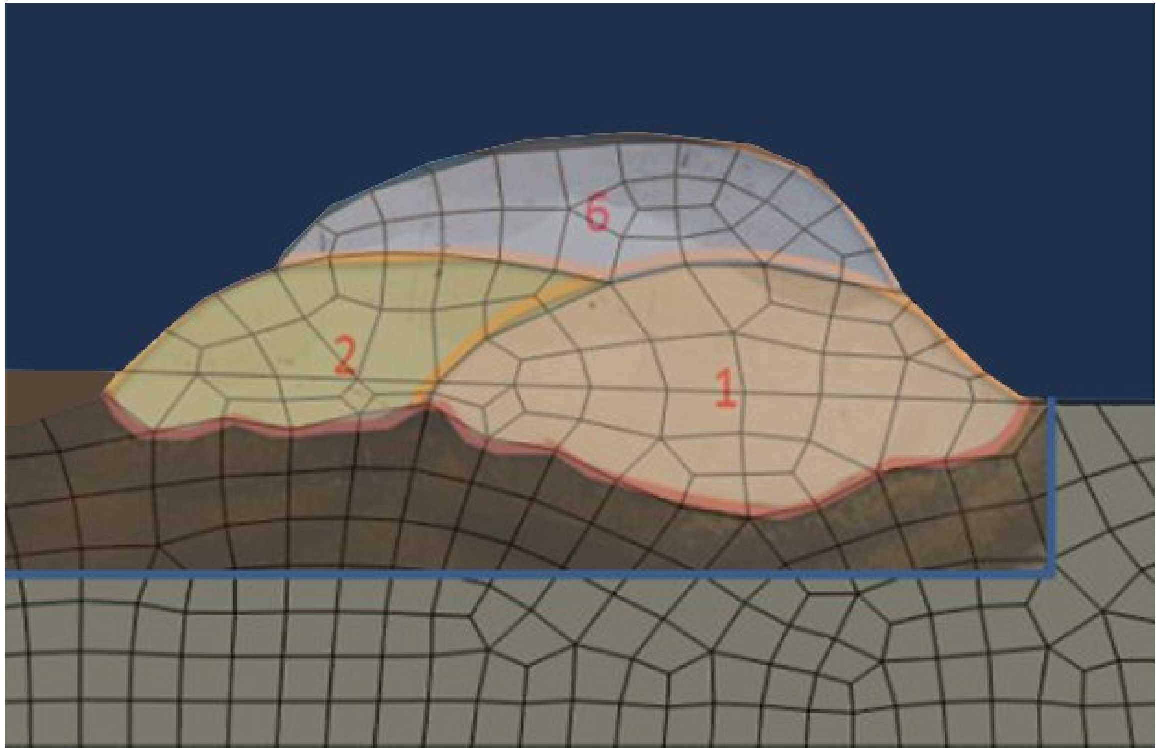
Bead Formation in Multi-Pass, Multi-Layer Weld



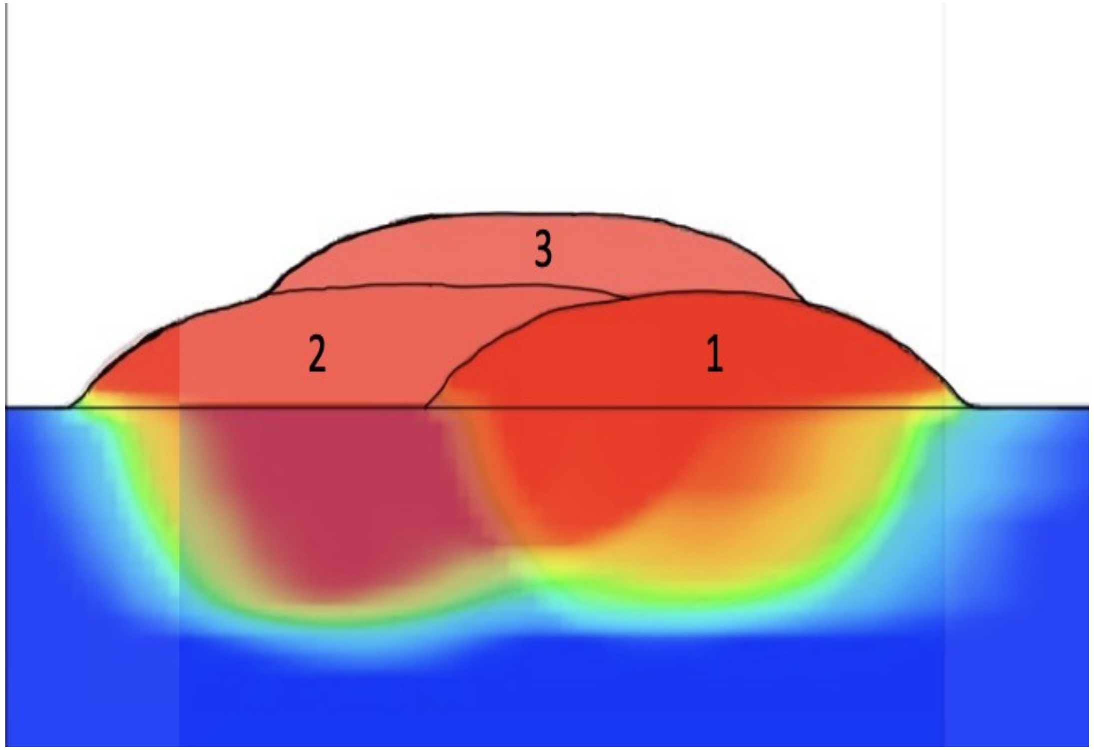
Molten pool represented by red contour

Model Validation for Three-Bead Deposit

Experimental

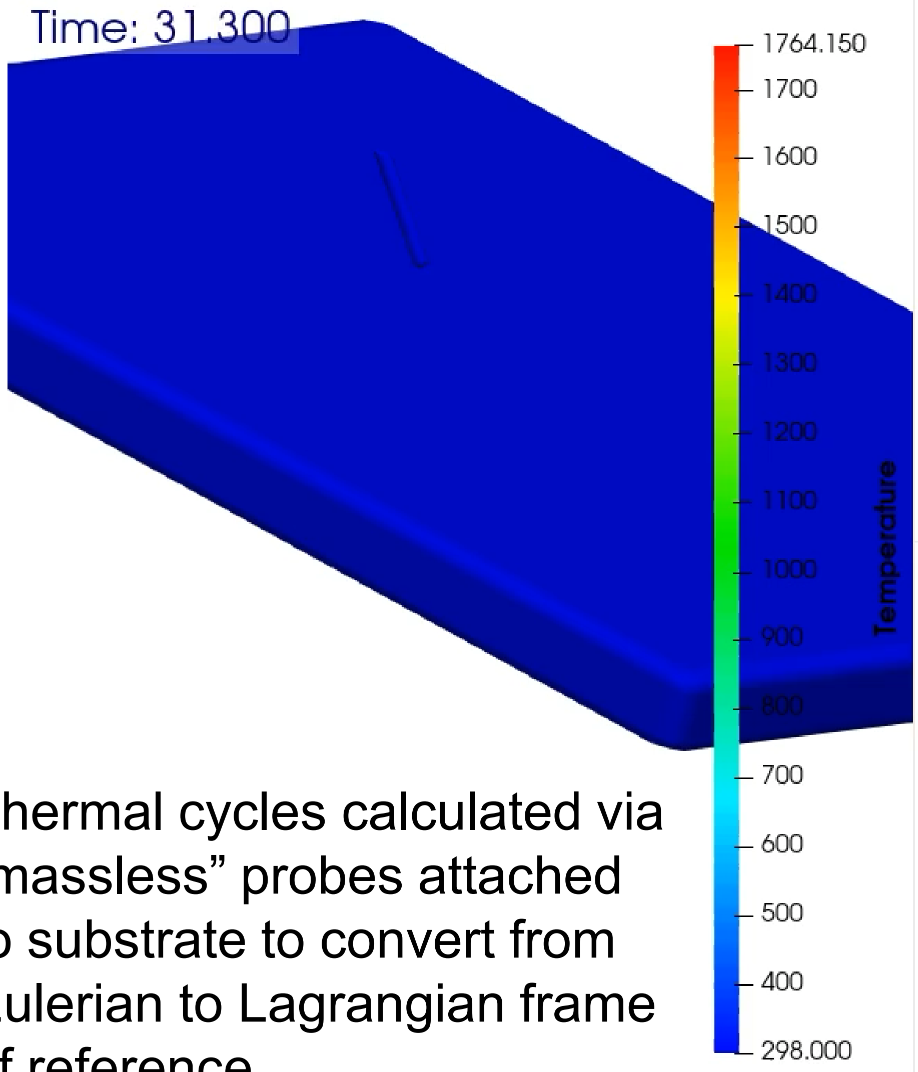


Computational

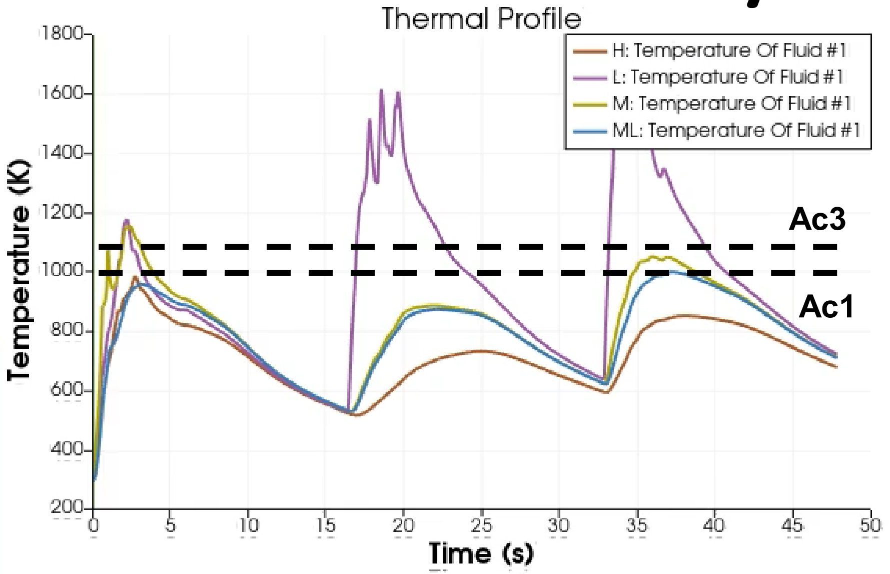


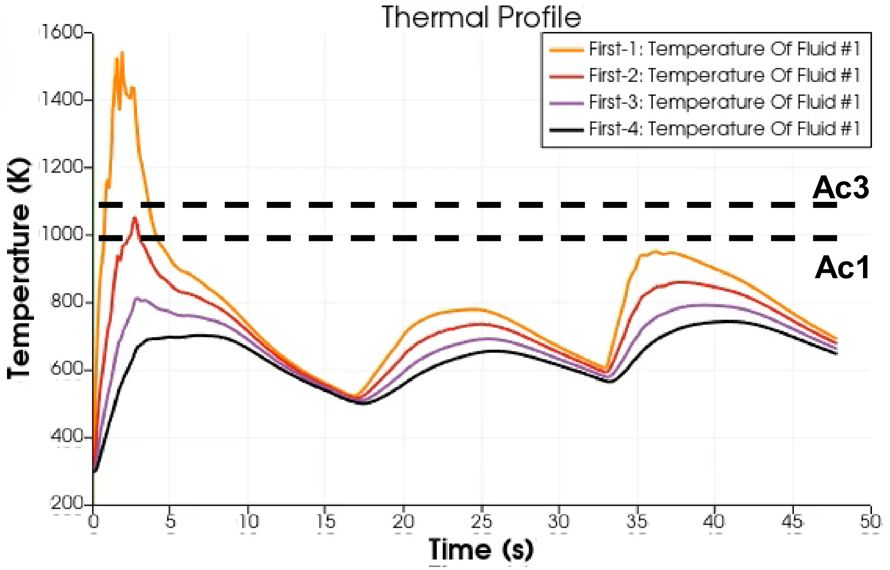
- Predicted bead shapes consistent with those observed experimentally
- As the molten pool model does not require the bead shape as an input, it can be readily used to study how welding parameters and bead placement affect the thermal profiles

Calculation of Thermal Cycles

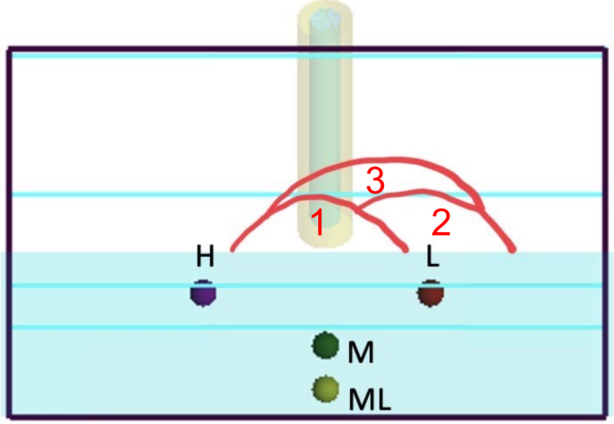


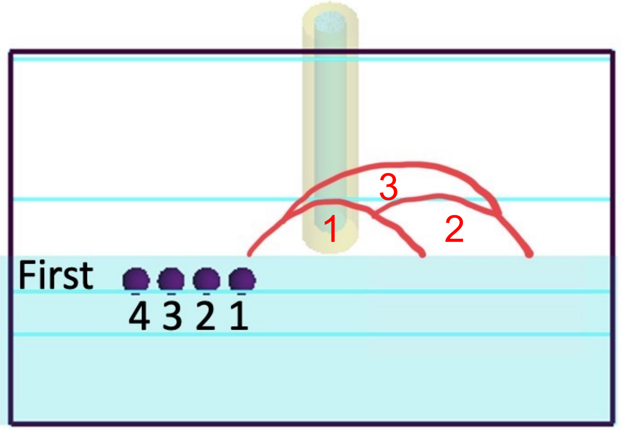
Thermal cycles calculated via "massless" probes attached to substrate to convert from Eulerian to Lagrangian frame of reference





Probe location shown on cross-section



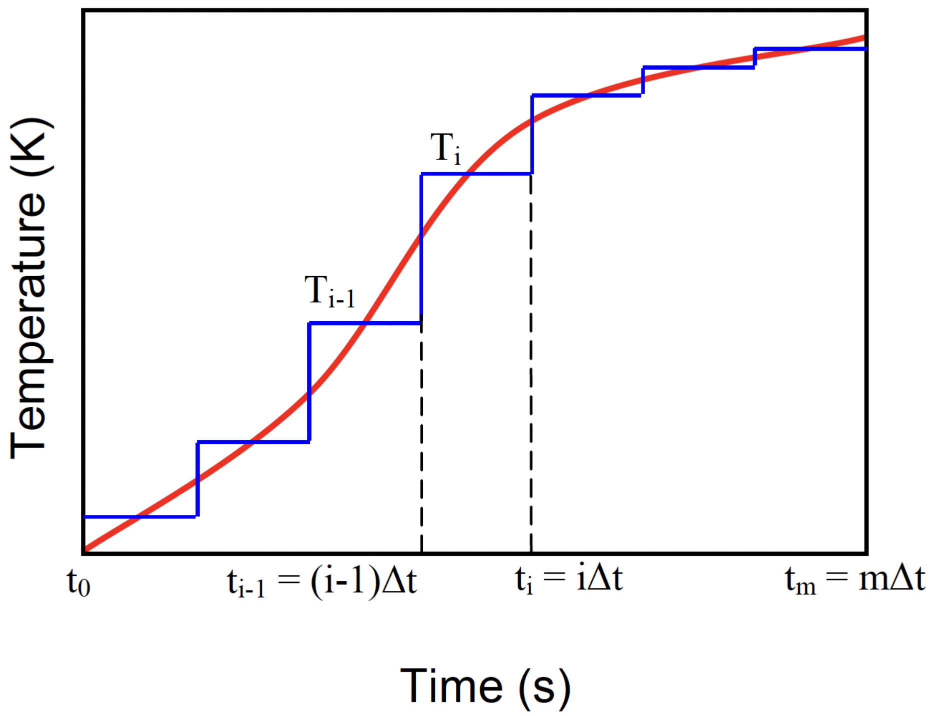


Metallurgical Model for Martensite Tempering

- Extent of tempering (ϕ) calculated by non-isothermal Johnson-Mehl-Avrami-Kolmogorov (JMAK) equation:

$$\phi_i = 1 - \exp\left\{-\{k_0 \times \exp\left(-\frac{Q}{RT_i}\right) \times (\Delta t + \tau_i)\}^n\right\} (1 \leq i \leq m)$$

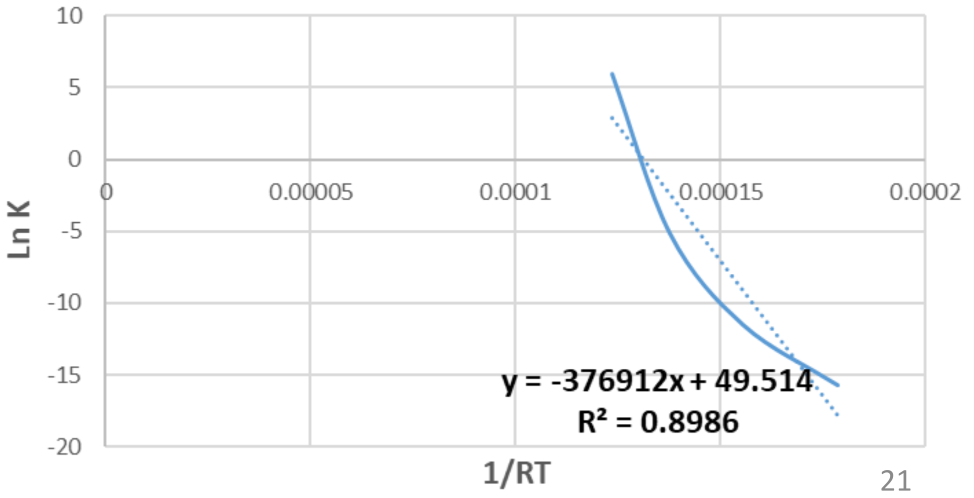
$$\tau_i = \frac{\sqrt[n]{-\ln[1 - \phi_{i-1}]}}{k_i}$$



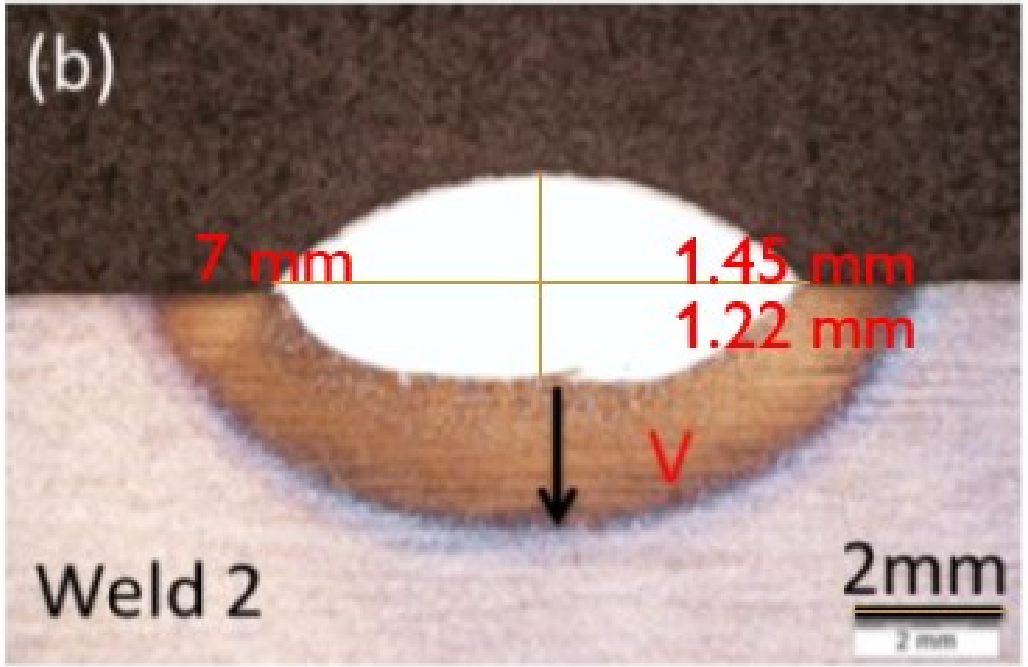
- Hardness of tempered martensite (H) calculated by

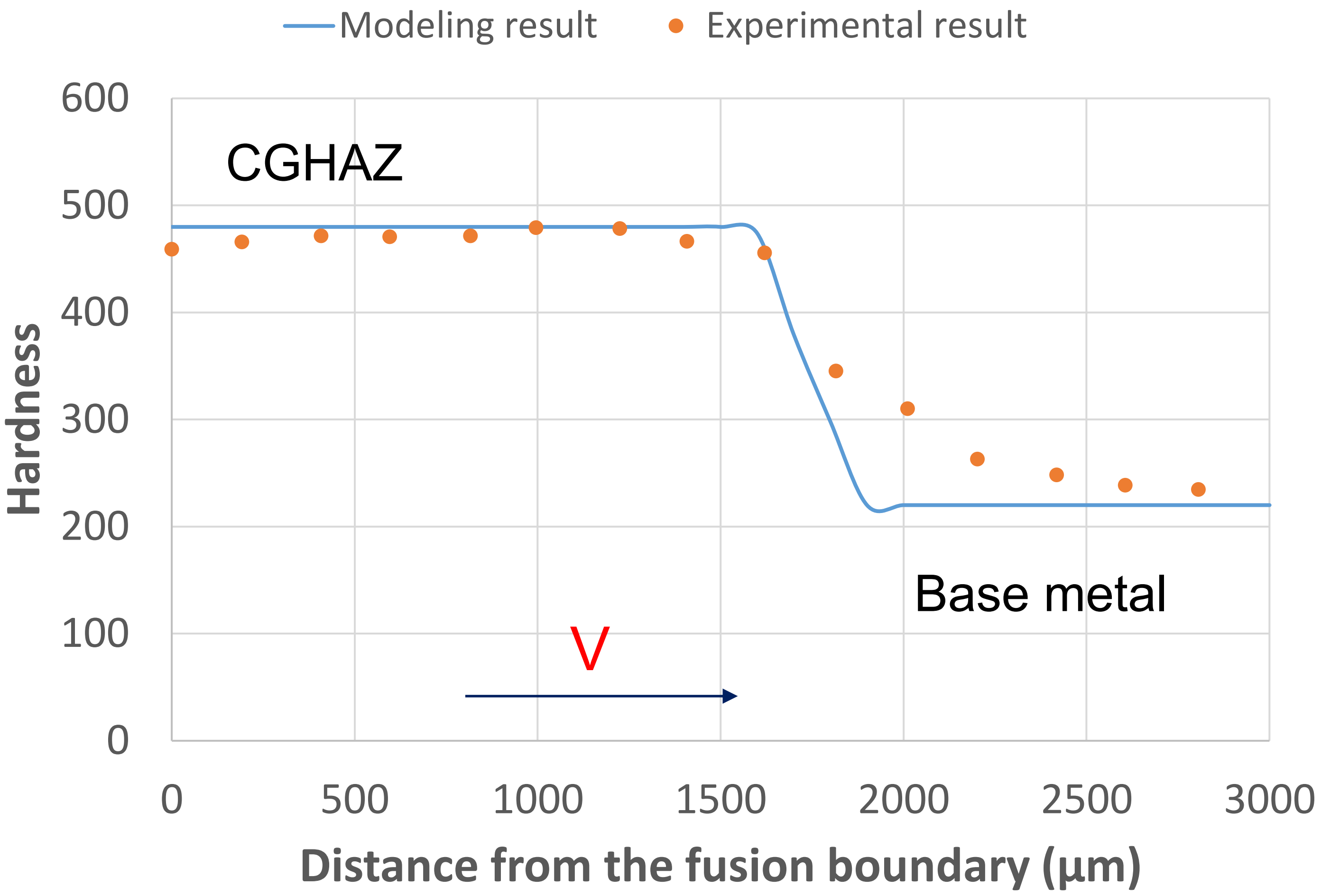
$$\phi = \frac{H_{BM} - H}{H_{BM} - H_\infty} \longrightarrow H = H_{BM} - \phi(H_{BM} - H_\infty)$$

Material parameters extracted from isothermal tempering experiments in Gleeble

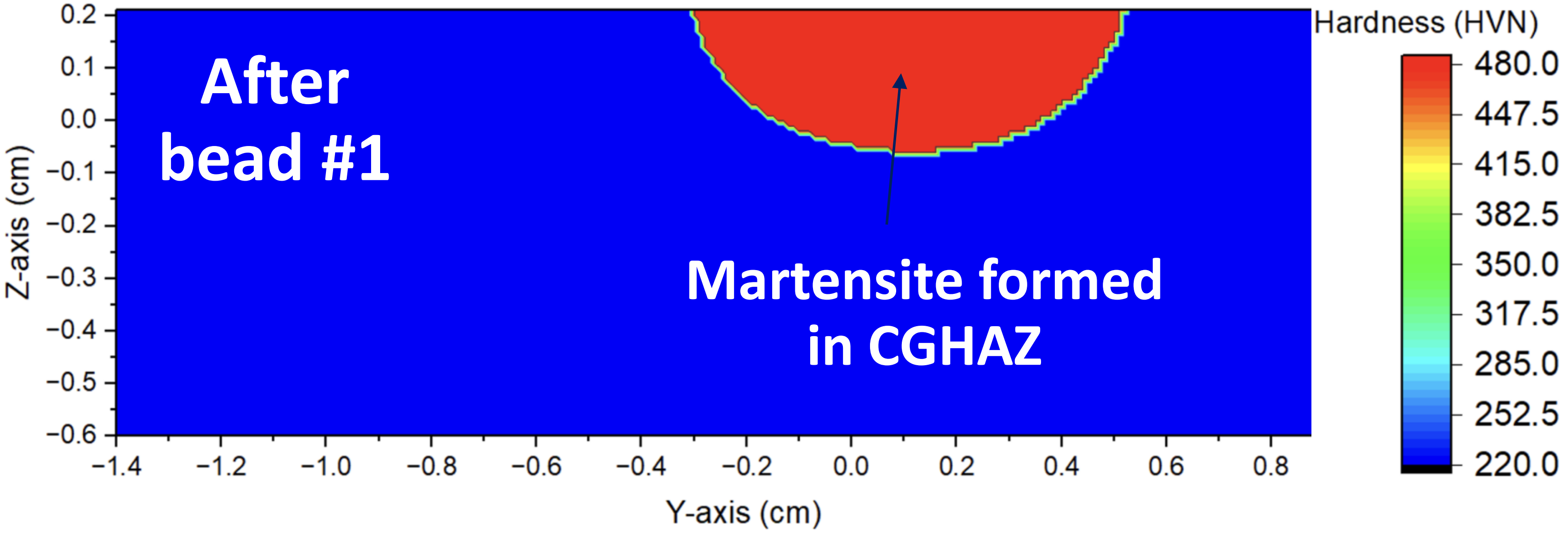


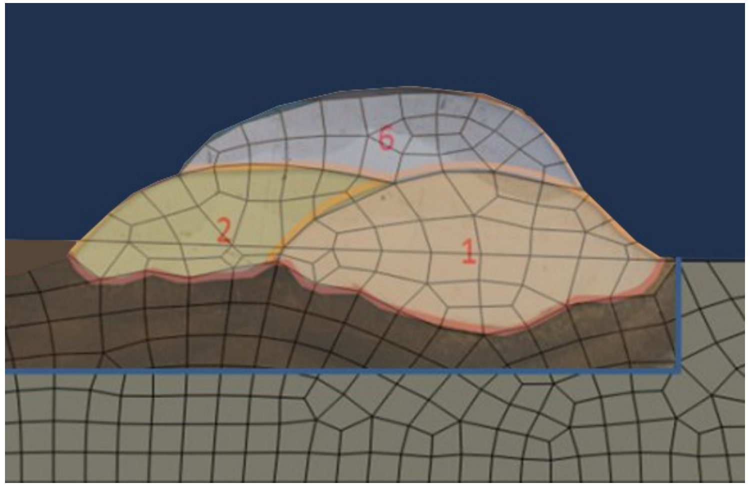
Validation of Tempering Model for Single Bead Weld

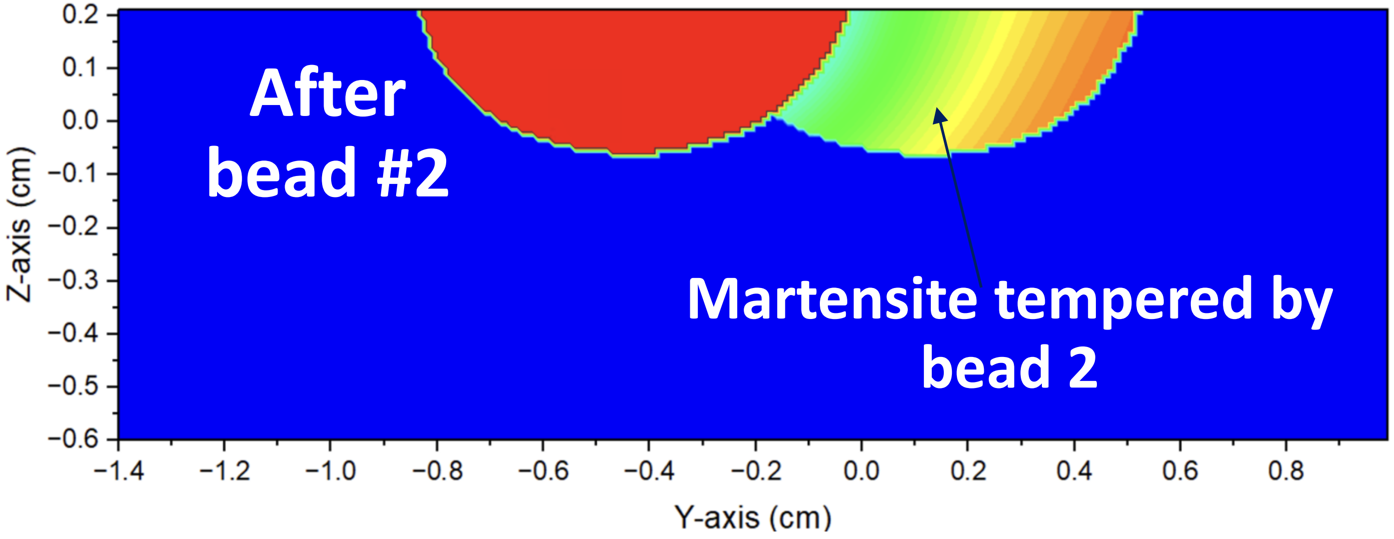


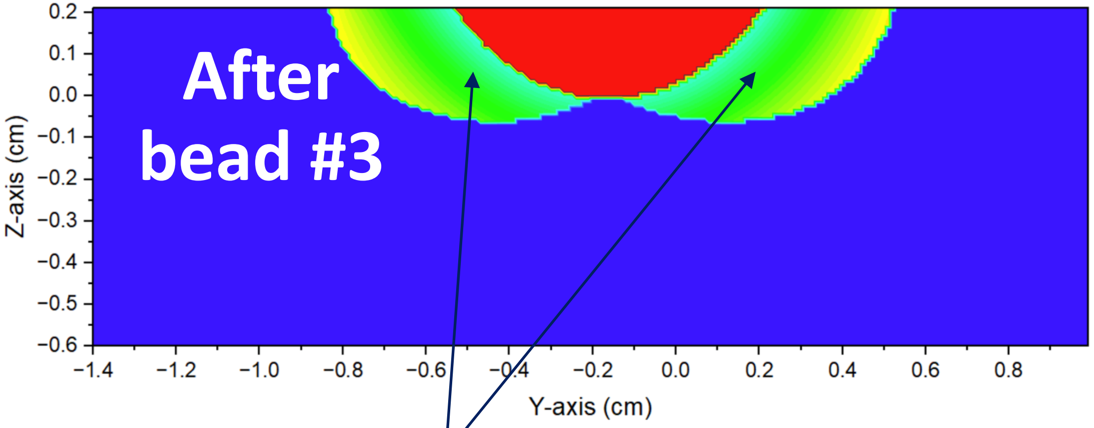


Variation of Tempering and Hardness for Three-Bead Weld



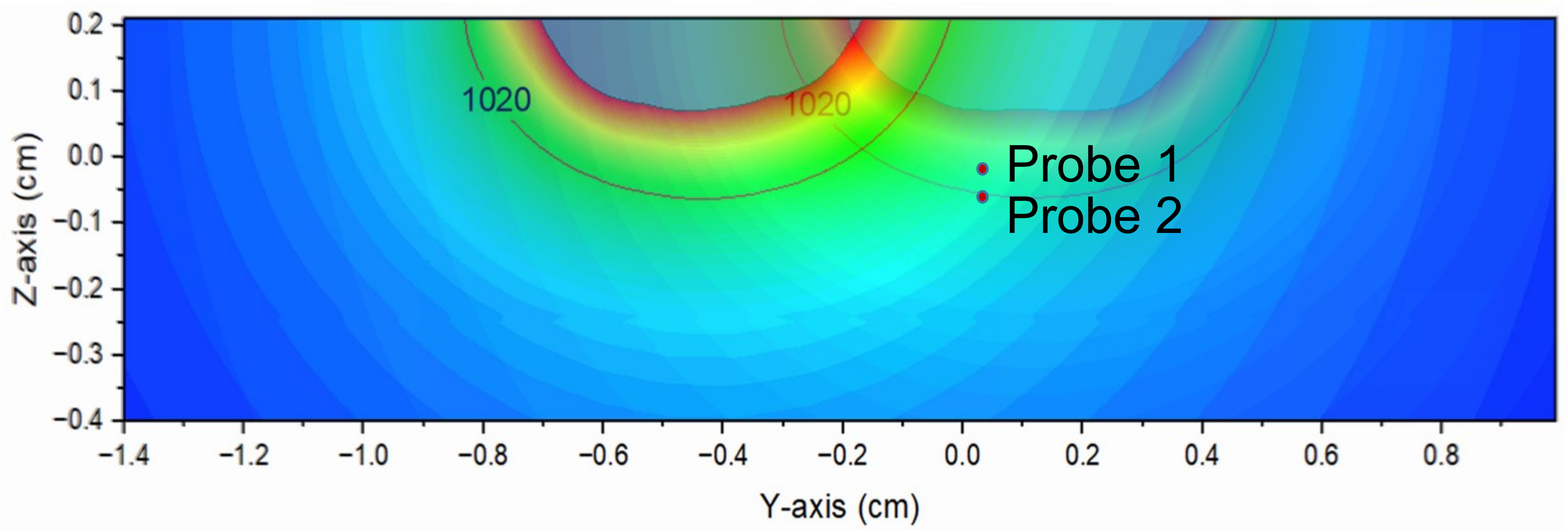






Martensite tempered by bead 3 on the second layer

Validation of Tempering for Three-Bead Weld



Location	Distance from fusion line	Measured hardness (Hv)	Calculated hardness (Hv)
Probe 1	0.7 mm	308	326
Probe 2	1.2 mm	293	305

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Summary

1. Micro-resolution ultrasonic imaging capable of detecting various weld regions such as weld metal and heat-affected zone
2. Characterization performed on CMT and FCAW samples are consistent with past characterization studies
3. GTAW bead on plate samples indicate that weld process optimization will need to be performed
4. Molten pool model capable of simulating multi-layer, multi-pass welding without knowing bead shapes and sizes beforehand
5. Extent of tempering and hardness prediction considering thermal cycles and material tempering response

Next steps

- Scan Gleeble samples using micro-resolution ultrasonic imaging to understand ultrasonic beam dynamics in the HAZ regions
- Employ GTAW-hot wire welding parameters on Grade 92 samples based on computational modeling
- Apply the integrated molten pool and metallurgical model for Grade 91 and Grade 92 welds
  - Consideration of fresh ferrite formed in the intercritical HAZ
  - Tempering parameters extracted from Gleeble isothermal tempering experiments

Publications

- A. Aryan, O. C. Onwuama, D. Bourgeois, and W. Zhang. "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." Presentation at American Welding Society Annual Professional Program, Atlanta, United States. Nov. 2022. https://doi.org/10.2172/1898594
- O. C. Onwuama, A. Aryan, J. K. Na, D. Bourgeois, and W. Zhang. "Material Characterization of Grade 91 Steel Welds using, Micro-resolution Ultrasonic Imaging System." Presentation at American Welding Society Annual Professional Program, Atlanta, United States. Nov. 2022. https://doi.org/10.2172/1898549
- O. C. Onwuama, A. Aryan, J. K. Na, D. Bourgeois, and W. Zhang. "Micro-resolution Ultrasonic Image Characterization of Grade 91 Steel Welds", Journal article submitted for peer review in April 2023.