WRTC Temper Bead Repair Research

Temper Bead Basics, Key Research Areas, ASME Code Advancements

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NSRP Joint Welding Technology and Electrical Technologies Panel Meeting
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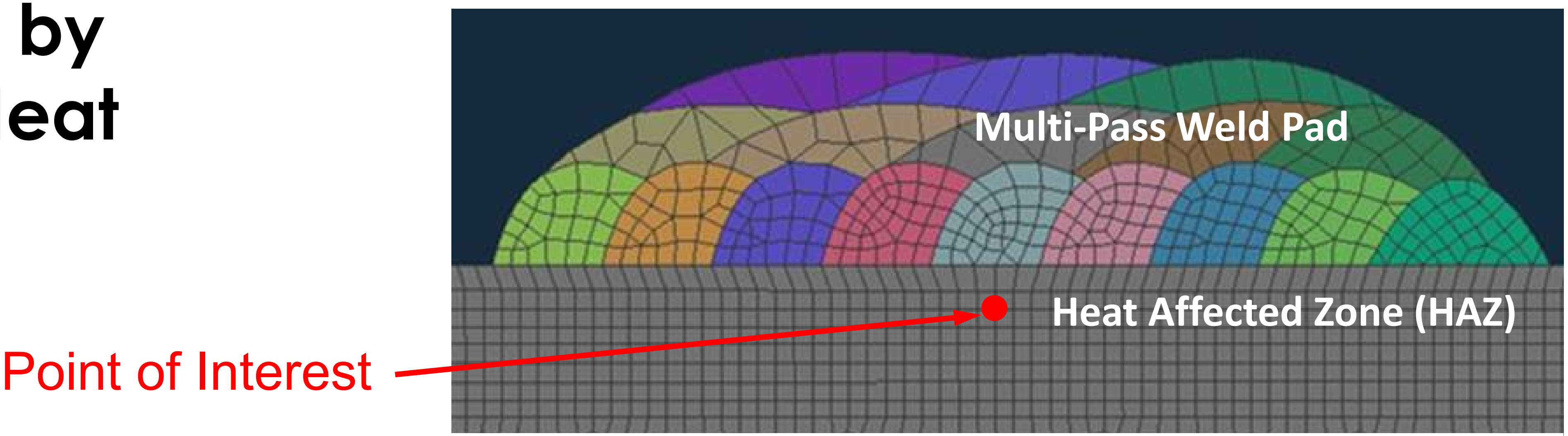
Temper Bead Welding in Nuclear Power Plants

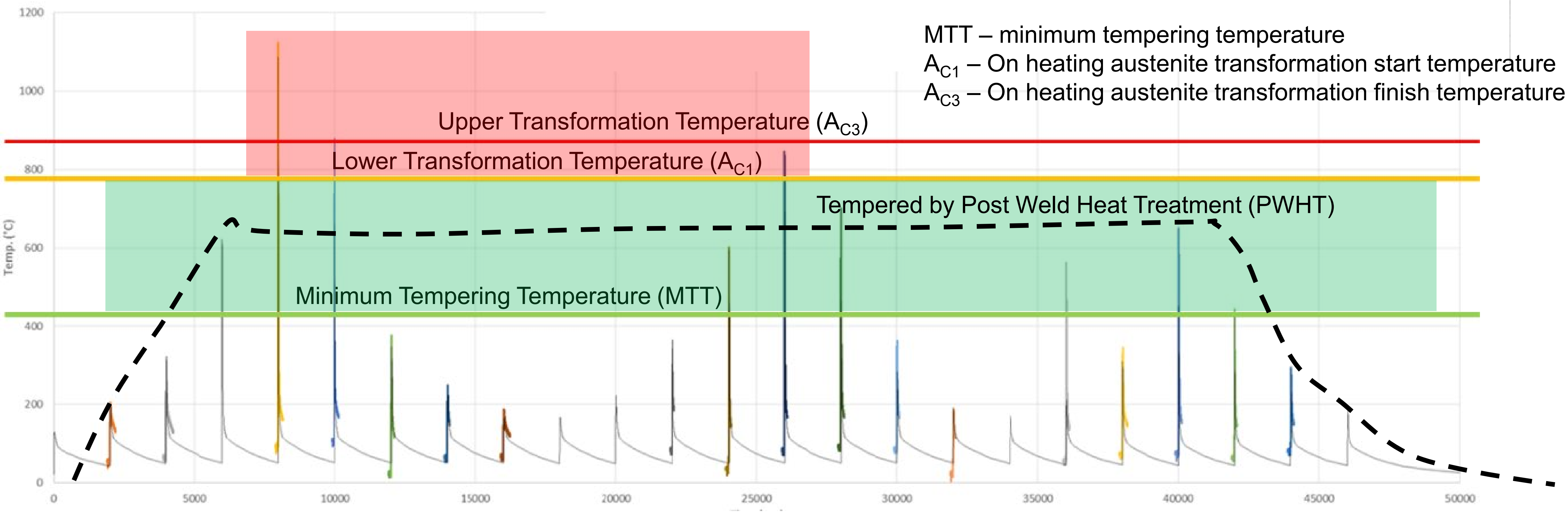
- <u>Ambient temperature temper bead welding</u> is industry recognized and is the preferred technology for making weld repairs on nuclear pressure vessels and piping when post weld heat treatment (PWHT) is not possible or impractical.
- <u>Ambient temperature</u> temper bead welding techniques are especially beneficial.
  - No preheat or post weld bakeout.
  - Temper bead welding can be done with water in the vessel or pipe (radiological shielding).
  - Ambient temperature temper bead welding has been used many times for repairs on pressurizers, steam generators, and reactor pressure vessels.

Pressurizer Relief Nozzle Weld Overlay

Reactor Vessel Instrument Nozzle Repair

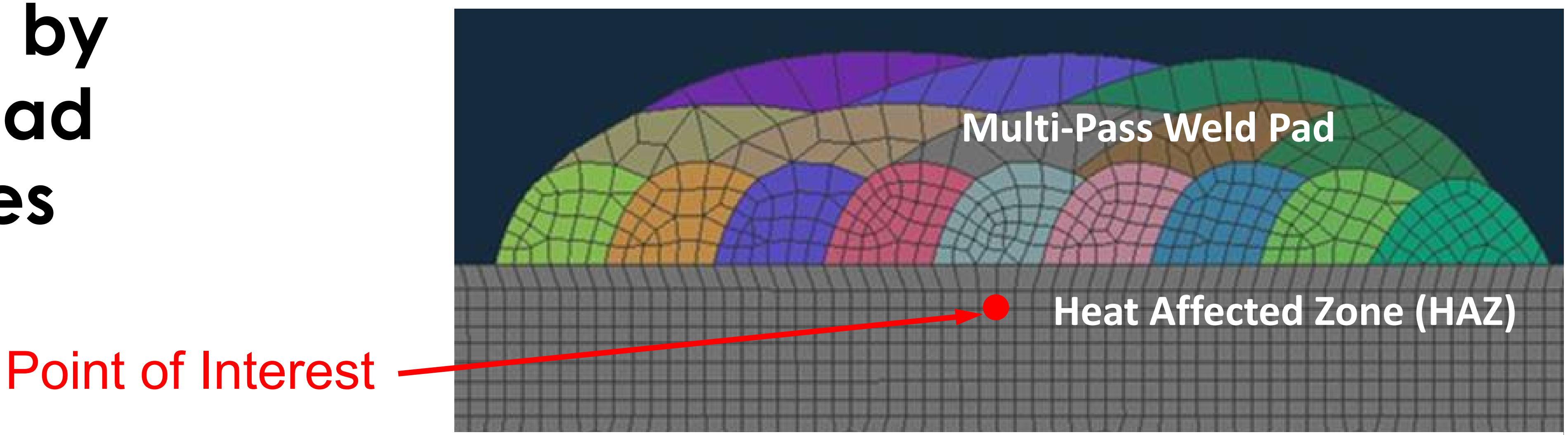
Tempering by Postweld Heat Treatment





MTT – minimum tempering temperature
A_{C1} – On heating austenite transformation start temperature
A_{C3} – On heating austenite transformation finish temperature

Tempering by Temper Bead Weld Passes



MTT – minimum tempering temperature
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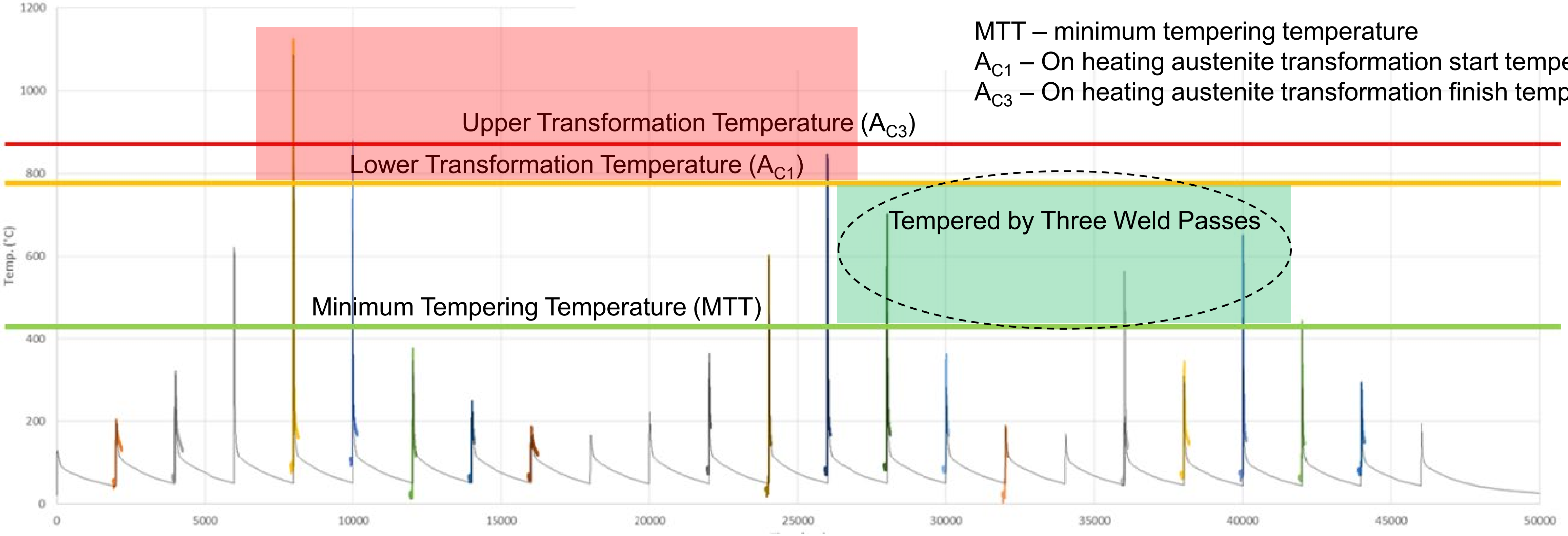
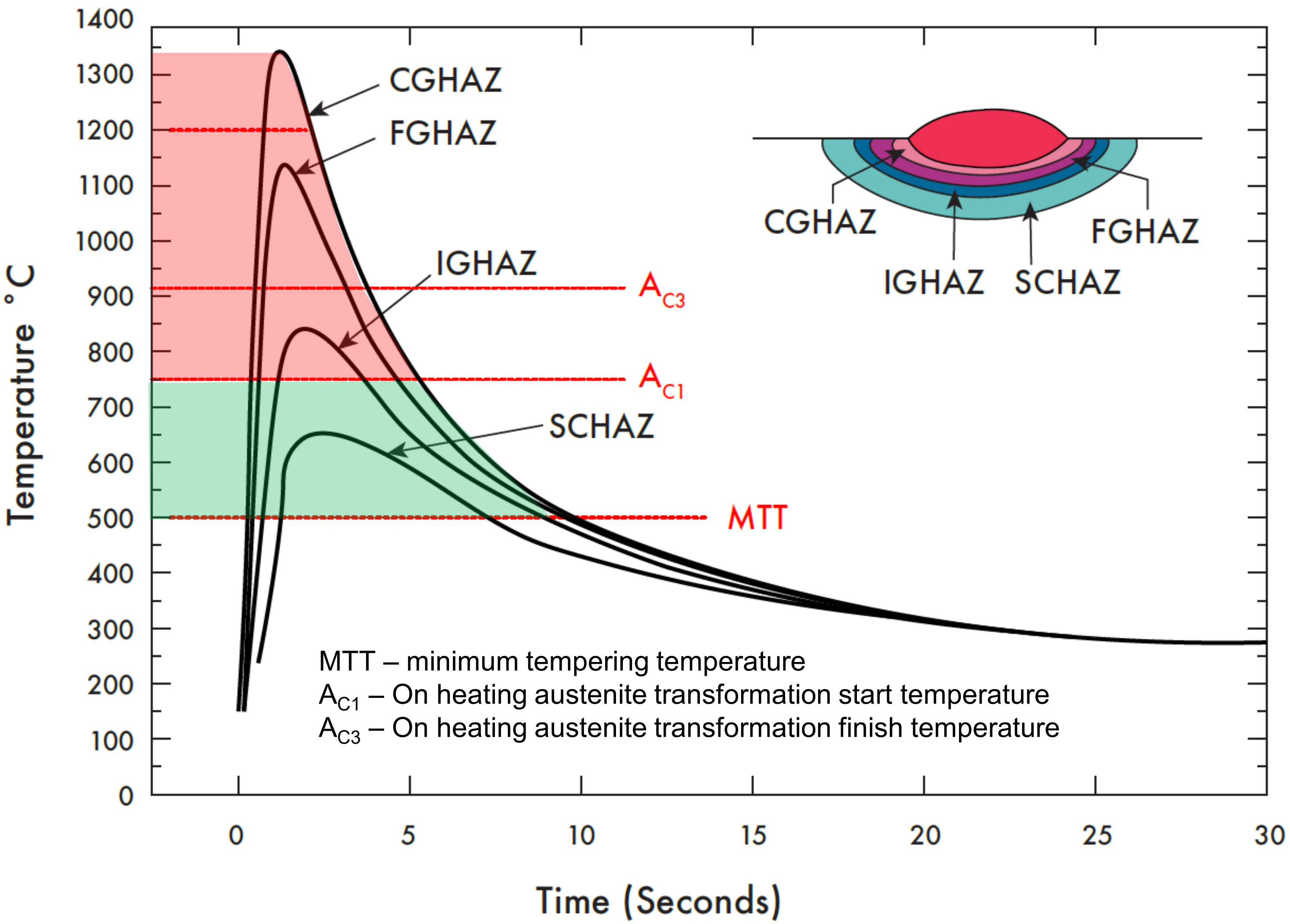


HAZ Microstructures with Various Weld Thermal Cycles

- HAZ varies depending on peak temperature during welding (distance from fusion line)
  - Coarse Grain HAZ (CGHAZ), region >1200°C with rapid grain growth
  - Fine Grain HAZ (FGHAZ), region between A_{C3} and ~1200°C
  - Intercritical HAZ (ICHAZ), partial transformation to austenite occurs, degree of transformation depends on peak temperature and duration between A_{C1} and A_{C3}
  - Subcritical HAZ (SCHAZ), region between Minimum Tempering Temperature (MTT) and A_{C1} where tempering occurs



Temper Bead Welding Advancements in the Nuclear Industry ASME Code

1977 and Beyond

Early Temper Bead Advancements – 1977 to 2001

ASME Section III to Section XI

1977

ASME Section III NB-4622.9

Manual SMAW Half Bead Technique [2, 3]

1986

Case N-432

Automatic or Machine GTAW Temper Bead Technique [1, 3]

1999

Case N-638

Ambient Temperature Machine GTAW Temper Bead Technique [1, 4]

2001

Case N-651

SMAW Temper Bead without Removing First Layer Weld Bead Crown [2, 3]

[1] Consistent layer technique

[2] Controlled deposition technique

[3] Elevated preheat and post weld hydrogen bake out required

[4] N-638 rules added as Appendix I in many repair/mitigation cases (e.g., N-740, N-847, N-766, N-, N-854, etc.)

Temper Bead Advancements – 2004 to 2020

ASME Section XI

2004

Section IX QW-290
Qualification Rules for Temper Bead Procedures

2012

Case N-829
Ambient Temperature Temper Bead for Austenitic Stainless & Nickel Alloy Cladding

2014

Case N-839
Ambient Temperature Temper Bead with Manual SMAW Process

2020

Case N-888
N-638-11 and N-839 combined into New N-888 [1]

[1] *For history and summary of changes of N-638 from revision 1 to 11 and N-888 see:*

- ✓ *Welding and Repair Technology Center: Welding and Repair Technical Issues in ASME Codes and Standards—2020.* EPRI, Palo Alto, CA: 2020. 3002018433. Chapter 2.
- ✓ *Welding and Repair Technology Center: Welding and Repair Technical Issues in ASME Codes and Standards—2014.* EPRI, Palo Alto, CA: 2014. 3002003136. Chapter 5.

Temper Bead Advancements – 2022 and Beyond

ASME Section XI

2022

N-888-1
Eliminated 48-hr Hold when Austenitic Filler Metal Is Used

In Progress

Hardness drop protocol for temper bead qualification

In Progress

Tempering Response & Modeling for Optimization of Temper Bead Techniques

In Progress

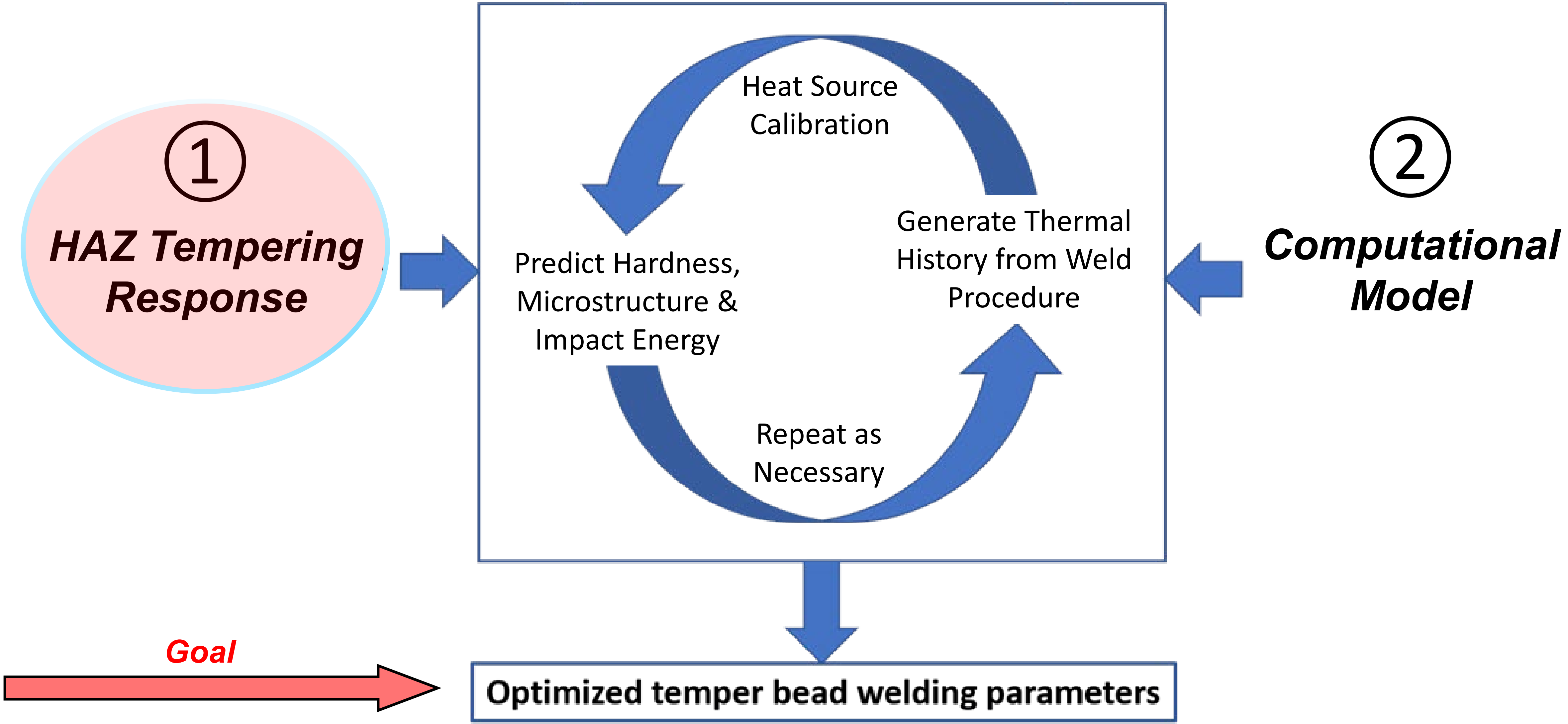
Eliminate 48-hr Hold when Ferritic Filler Metal is Used

Presentation today will focus on tempering response studies and temper bead modeling

HAZ Tempering Response Studies and Temper Bead Modeling

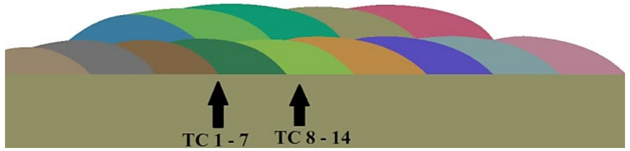
Steve McCracken and Eun Jang, EPRI

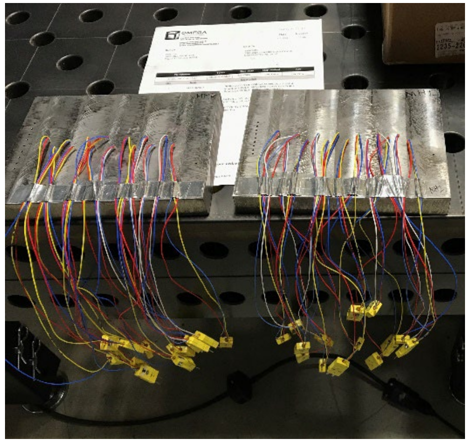
Part 1: Heat Affected Zone (HAZ) Tempering Response

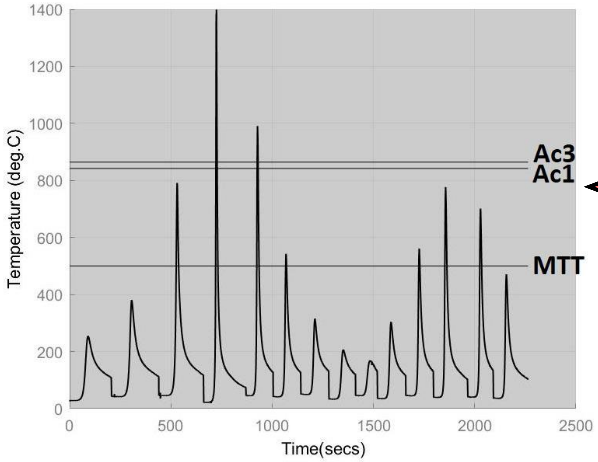


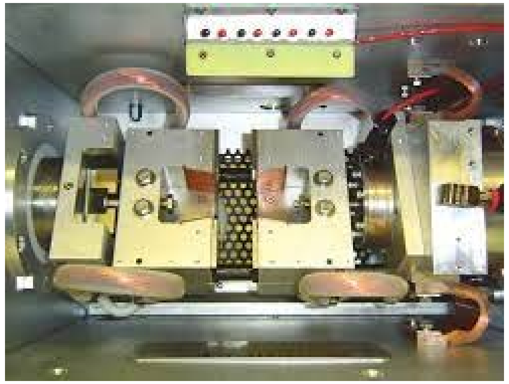
Temper Bead Experiments

- Three weld pads were made with <u>high heat input</u> (HHI), <u>medium heat input</u> (MHI) and <u>low heat input</u> (LHI)
  - Single layer pads were made first to accurately locate thermocouples
  - Each plate was instrumented with fourteen Type-K thermocouples
  - Thermal history was recorded at each thermocouple for the high, medium and low heat input weld pads
- Thermal histories were used to validate temper bead FEA models and to develop programs to simulate multi-pass weld thermal cycles in a Gleeble thermo-mechanical simulator









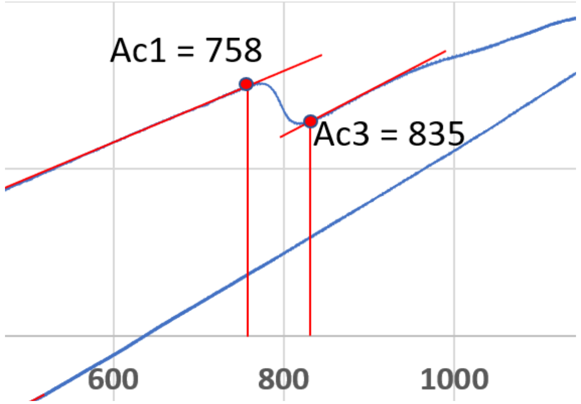
Tempering Response Experiments

- "Tempering Response" for the pad experiments was quantified using the Grange-Baughman Parameter (GBP)
- Next step was to develop Gleeble 3800 simulation programs using equivalent GBP values
- Dilatometry on the Gleeble was used to measure the upper critical A_{C1} and lower critical A_{C3} temperatures
- CGHAZ and ICHAZ microstructures were simulated in a Gleeble 3800

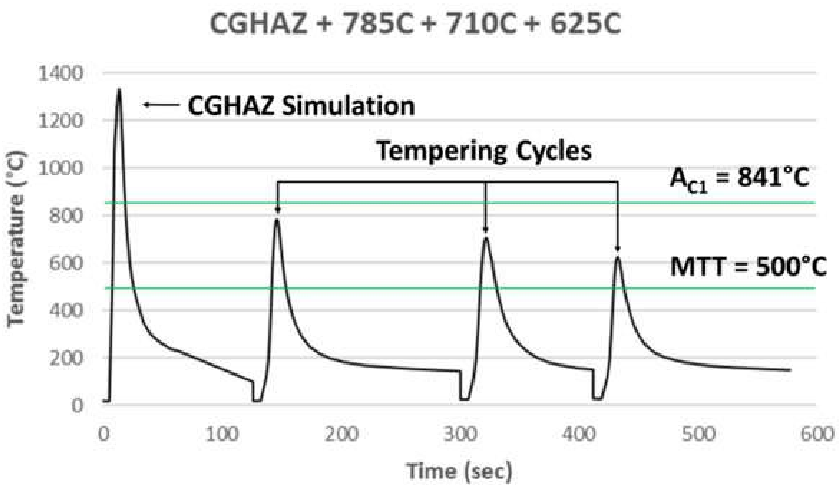
Measured Peak Temperatures During Temper Bead Pad Experiments

		Peak Temp (deg C)							
	Pass	TC1	TC2	TC3	TC4	TC5	TC6	TC7	TC8
1st Layer	1	142	171	152	175	154	202	165	198
	2	211	273	217	272	217	335	235	315
	3	370	527	343	503	338	730	385	661
	4	1390	1402	1066	1393	974	1233	1365	1125
	5	1411	1055	1449	1244	1369	995	1334	873
	6	880	438	906	517	1039	384	775	369
	7	370	262	388	289	438	246	350	242
	8	219	182	230	196	248	181	224	184
2nd Layer	9	211	312	245	326	256	395	289	356
	10	327	521	327	539	350	693	432	594
	11	820	937	910	1008	889	983	988	838
	12	1022	837	1112	945	1104	784	1053	696
	13	630	411	683	455	742	369	599	355
	14	269	192	293	218	328	186	268	183
	15	360	525	373	559	394	638	466	556

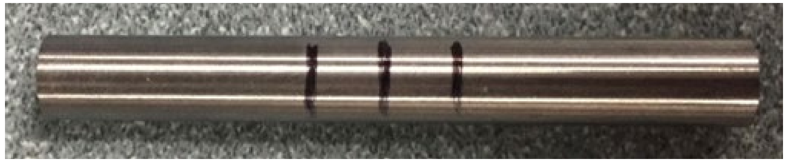
Table above is for Alloy 625 on is for SA-387 P22



Dilatometry for SA-508 W#1



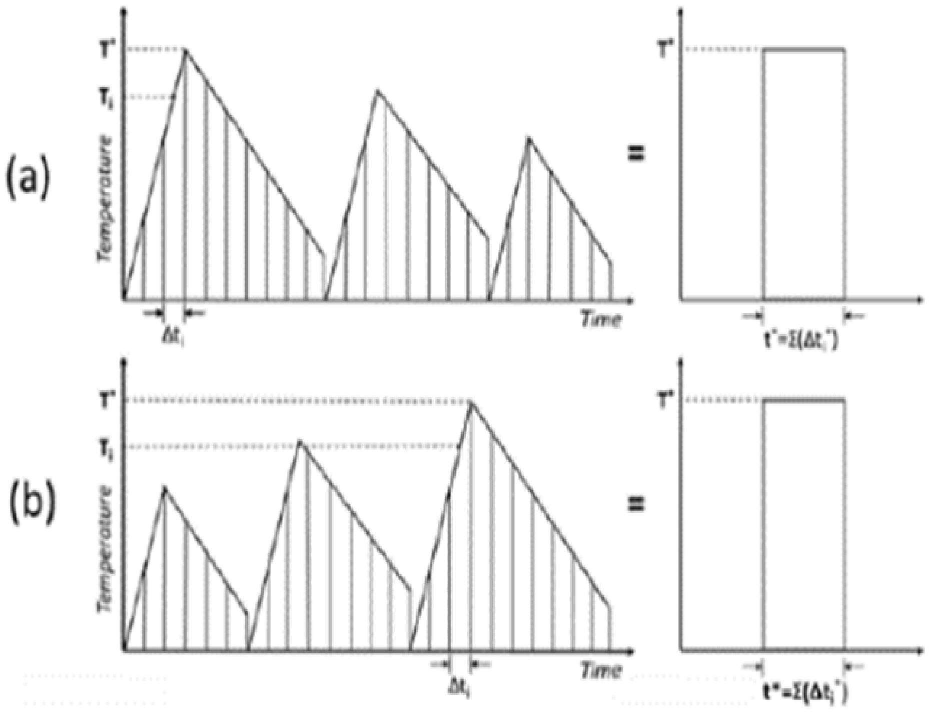
Gleeble CGHAZ with three tempering cycles



3/8" dia. by 4" long Gleeble sample

Grange-Baughman Parameter (GBP

- Grange-Baughman Parameter (GBP) is used to quantify the effective tempering response for multi-pass welding.
  - GBP accounts for the tempering effect of non-isothermal thermal cycles (welding)
  - GBP can be modified to account for the multiple and rapid reheats that occur with multi-pass welding
  - GBP can be used to relate the tempering effectiveness to the tempered hardness
- Technique may be used to quantify tempering effectiveness using actual measured thermal histories and then applied to develop Gleeble programs



Single Reheat Cycle

$$GBP = T\,(14.44 + \log(t))$$

Multiple Reheat Cycle

$$GBP_i = T_i(14.44 + \log(\Delta t_i))$$

$$GBP_i = T^*(14.44 + \log(\Delta t_i^*))$$

$$\Delta t_i^* = 10^{\left[\frac{T_i}{T^*}(14.44+\log(\Delta t_i))-14.44\right]}$$

Modified GBP technique for multi-pass welding was developed at The Ohio State University by Jeff Steward, Ph.D

Gleeble ICHAZ Tempering Simulations with GBP & Hardness

ICHAZ Simulations					
1	**2**	**3**	**4**	**GBP**	**Hardness**
-	**-**	**-**	**-**	**0**	**319**
450	-	-	-	19004	219
500	-	-	-	20807	244
510	-	-	-	21315	235
530	-	-	-	22110	222
550	-	-	-	22169	230
600	-	-	-	**23538**	**234**
625	-	-	-	24886	234
650	-	-	-	24946	223
675	-	-	-	25074	200
700	-	-	-	**26314**	**204**
725	-	-	-	**27192**	**206**
735	-	-	-	26705	195

- ICHAZ Temp = 815C
- 150 C/s Heating Rate & 50 C/s Cooling Rate

1	2	3	4	GBP	Hardness
600	**600**	-	-	**24010**	**217**
650	650	-	-	25446	209
600	700	-	-	26353	195
725	**725**	-	-	**27732**	**203**
735	735	-	-	27251	187
500	500	500	-	21469	195
600	600	700	-	26391	181
650	650	650	-	25738	195
700	**700**	**700**	-	**27148**	**207**
735	735	735	-	27571	179
550	550	550	550	23058	236
700	700	700	700	27366	211

- A_{C1} = 785C to 790C
- A_{C3} = 845C to 851C
- 73 Total Temper Bead Simulations

Gleeble CGHAZ Tempering Simulations

CGHAZ Simulations					
1	**2**	**3**	**4**	**GBP**	**Hardness**
-	**-**	**-**	**-**	**0**	**458**
500	-	-	-	**20807**	**401**
510	-	-	-	21315	395
530	-	-	-	22110	374
550	-	-	-	22169	374
600	-	-	-	**23538**	**364**
625	-	-	-	24886	336
650	-	-	-	24946	336
675	-	-	-	25074	332
700	-	-	-	**26314**	**311**
725	-	-	-	27192	312
735	-	-	-	26705	283
600	**600**	-	-	**24010**	**347**

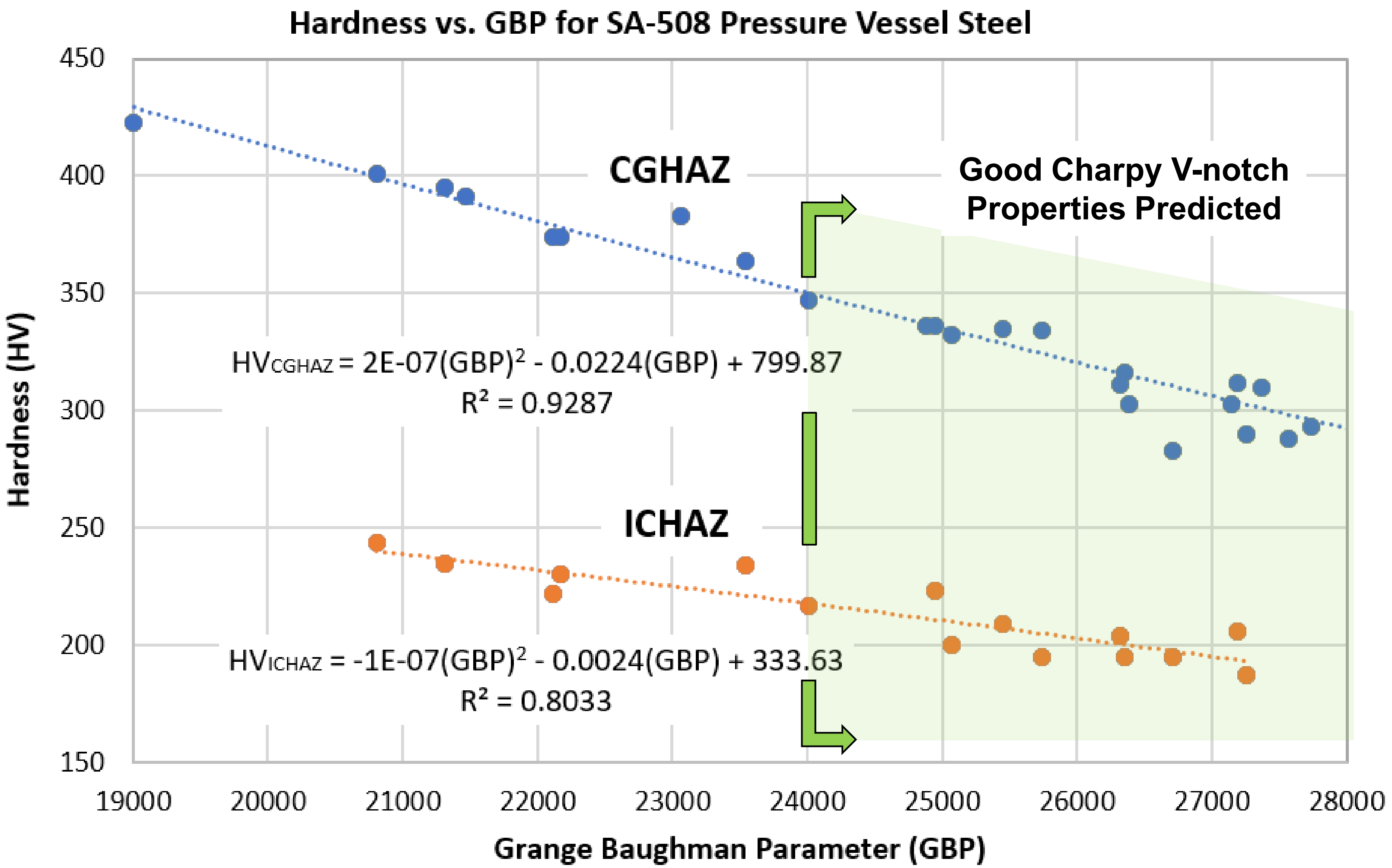
- CGHAZ Temp = 1340 C
- 150 C/s Heating Rate & 50 C/s Cooling Rate

1	2	3	4	GBP	Hardness
650	650	-	-	25446	335
600	700	-	-	26353	316
725	725	-	-	27732	293
735	735	-	-	27251	290
500	**500**	**500**	-	**21469**	**391**
600	600	700	-	26391	303
650	650	650	-	25738	334
700	700	700	-	27148	303
735	735	735	-	27571	288
550	550	550	550	23058	383
650	750	750	650	28319	315
700	**700**	**700**	**700**	**27366**	**310**

- A_{C1} = 785C to 790C
- A_{C3} = 845C to 851C
- 73 Total Gleeble Temper Bead Simulations

Hardness vs GBP Relationships – SA-508 Gr 3 Cl 2

- Vintage SA-508 Cl 2 (Ht W#1)
- GBP values represent tempering effectiveness
- GBP value increases with higher tempering efficiency
- Lower hardness expected as GBP increases
- Untempered HAZ
  - CGHAZ = 458 HV
  - ICHAZ = 319 HV
  - Unaffected BM = 190 HV
- Good Charpy V-notch properties region follows hardness drop protocol



1) Jang, E., Luo, Y.,Alexandrov, B.,McCracken, S.L., Tatman, J., Barborak, D., Quantification of the Tempering Response for Temper Bead Welding of SA-508 Low Alloy Steel, 2022 ASME Pressure Vessels and Piping Conference, Las Vegas, NV, July 17-22, PVP2022-84884.
2) Jang, E., Stewart, J., Luo, Y., Alexandrov, B., McCracken, S. L., Tempering Efficiency Evaluation for Dissimilar Weld Overlays. 2020 ASME Pressure Vessels and Piping Conference, Minneapolis, MN, July 19-24, PVP2020-21708.

Hardness Protocol for Ambient Temperature Temper Bead Procedure Qualification

- Flowchart showing peak hardness and hardness drop as indicators of appropriate level of tempered martensite in temper bead HAZ of SA-508 Gr 3 Cl 2 alloy steel.

  – Criterion 1: Peak hardness ≥ 440 HV and hardness drop ≥ 110 HV

  or

  – Criterion 2: Hardness drop ≥ 125 HV

(1) WRTC*: Alternative Hardness Test Protocol for Qualification of Temper Bead Welding: Preliminary Report*. EPRI, Palo Alto, CA: 2014. 3002003139.

(2) PVP2019-93950 – Investigation of Relationship Between Microhardness and Charpy Impact Energy for Temper Bead Welding Qualification – Part 1

(3) PVP2020-21300 – Investigation of Relationship Between Microhardness and Charpy Impact Energy for Temper Bead Welding Qualification – Part 2

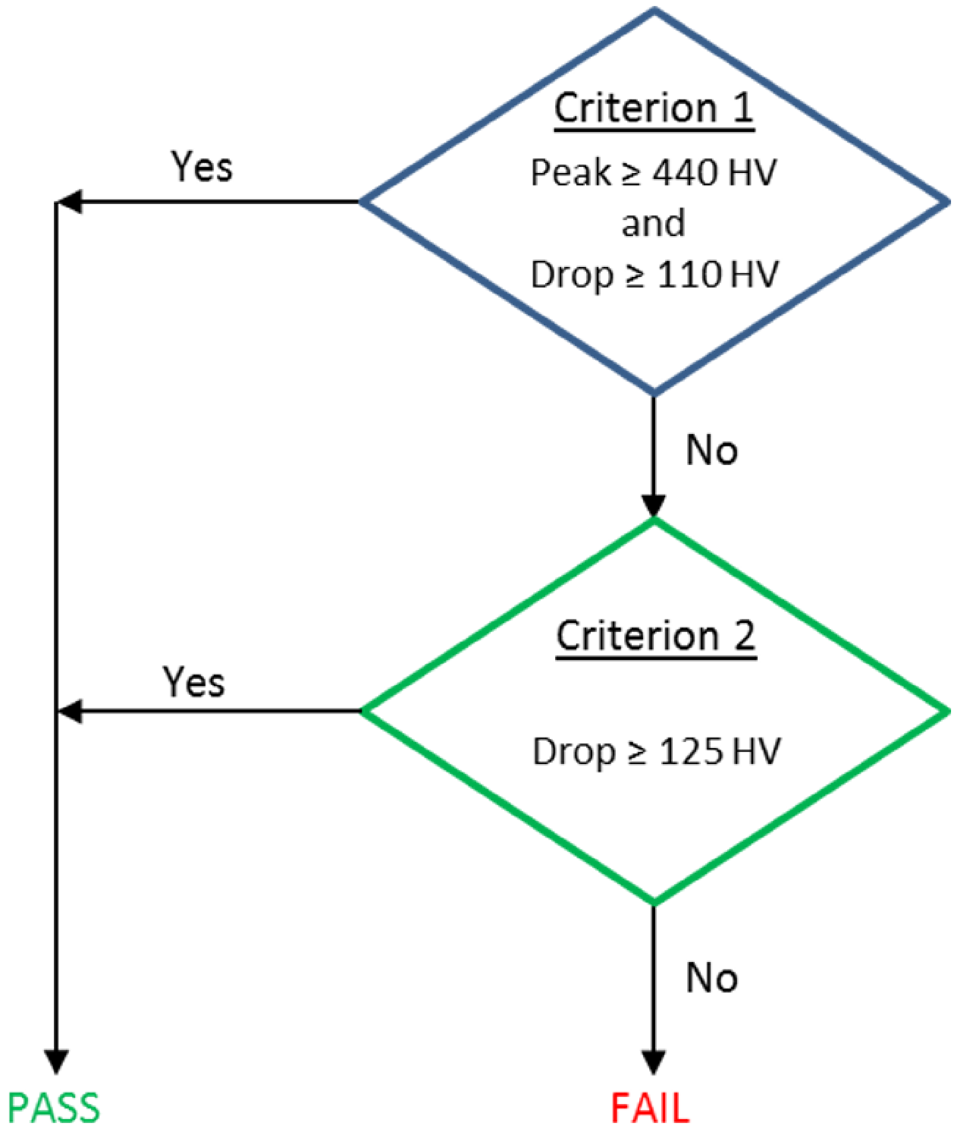
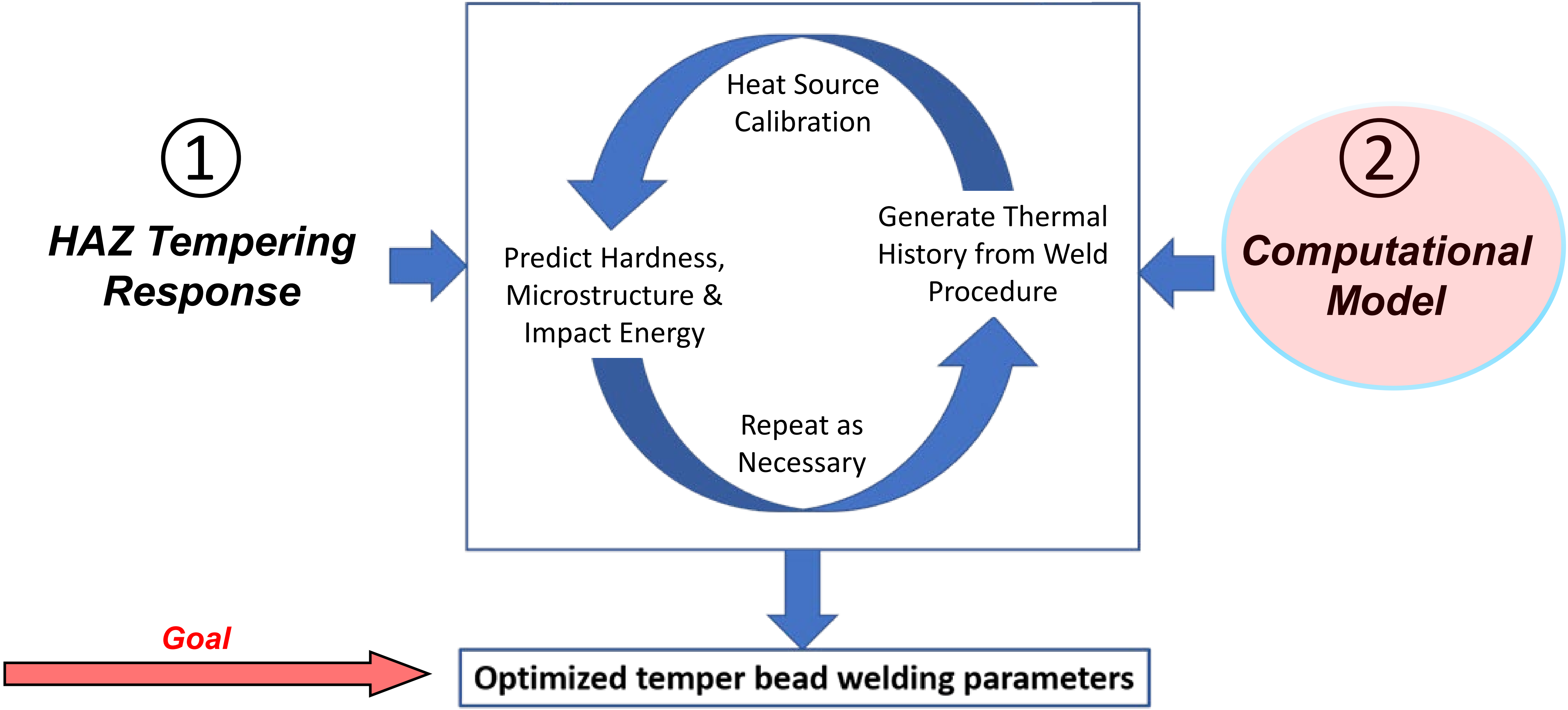


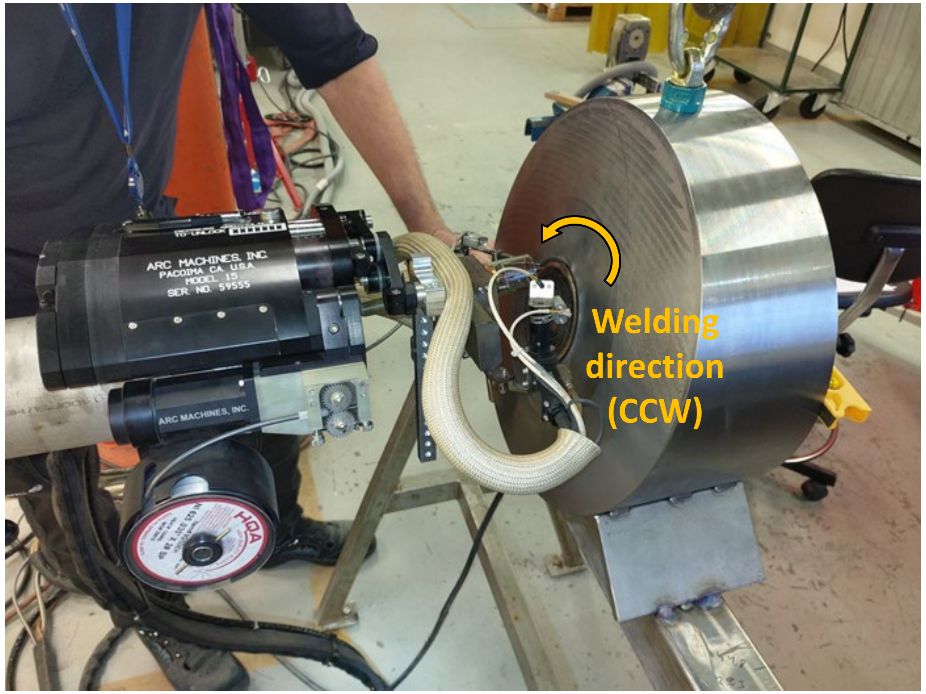
Figure from Ref. (2)

Part 2: Computational Model for Tempering Predictions

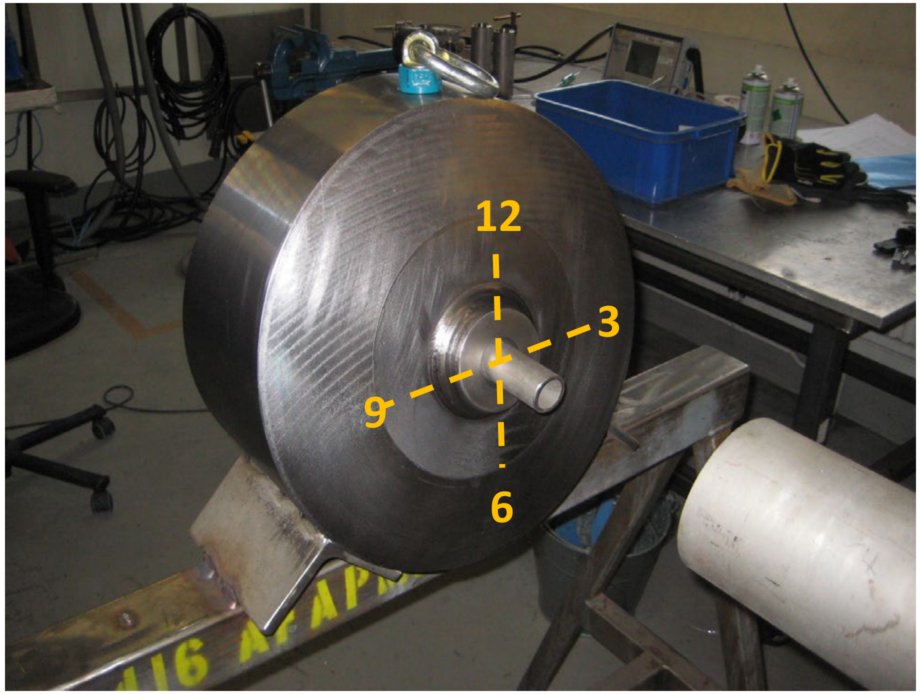


First Application Using the Tempering Response for a SA-508 Gr 3 Cl 2 Steel and the Computational Model

- The objective was to support temper bead procedure optimization by using the simulated tempering response data and newly developed computational temper bead model to predict microstructure, hardness, and tempering for the weld pad demonstration buildups.



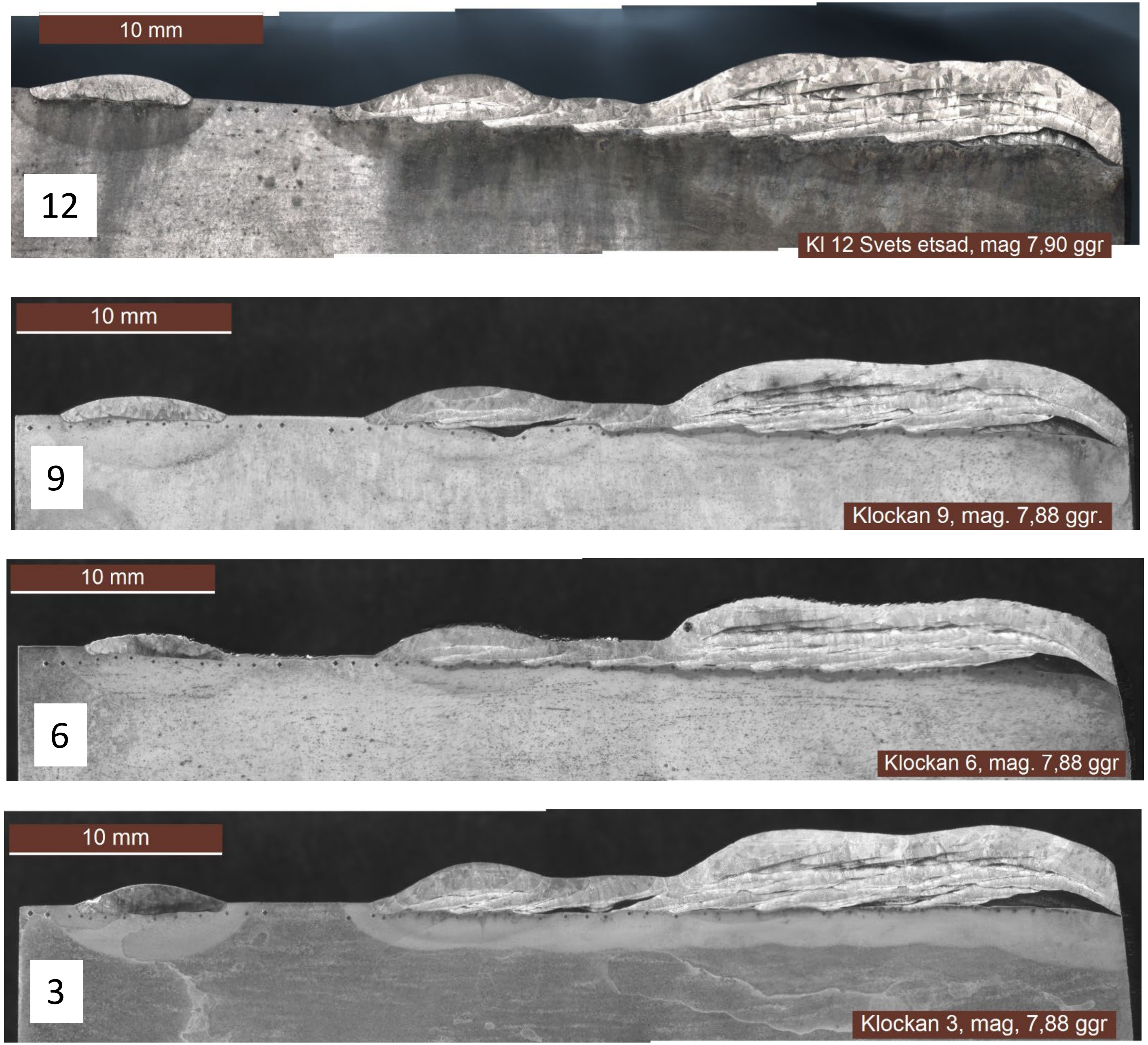
Horizontal (2G) weld pad with travel in CCW direction



Completed weld buildups using prescribed temper bead parameters

Methods

1. Etched cross sections of the weld metal buildup, (3, 6, 9, 12 o-clock)
2. Used image processing (ImageJ) to measure the weld bead geometries for 4 bead types.
   - Single bead on plate
   - Overlapping bead 1st layer
   - Single bead on 2nd (Ni-base) layer
   - Overlapping bead on 2nd (Ni-base) layer



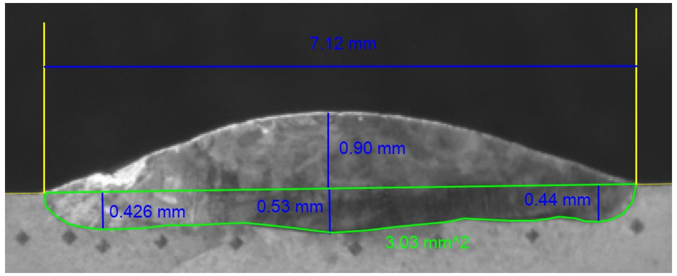
Heat Source Calibration

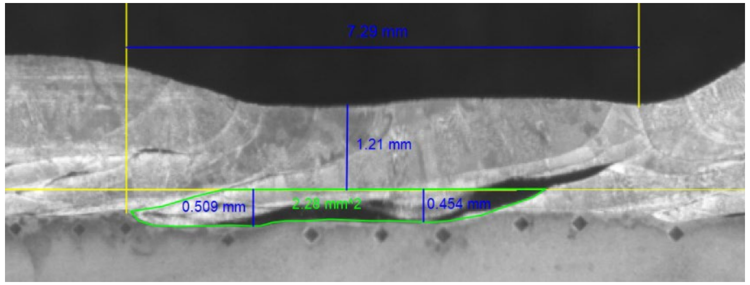
1. Sysweld software was used to simulate the temper bead welding procedure.

2. Multiple 2-D models were created to capture the various bead geometries observed in cross sections.

3. Heat source calibration was performed to match the simulated fusion zones to the cross sections.

Experimental Cross Section Profiles

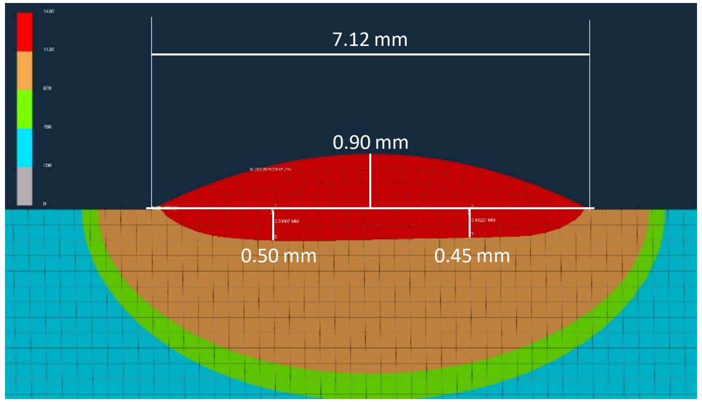


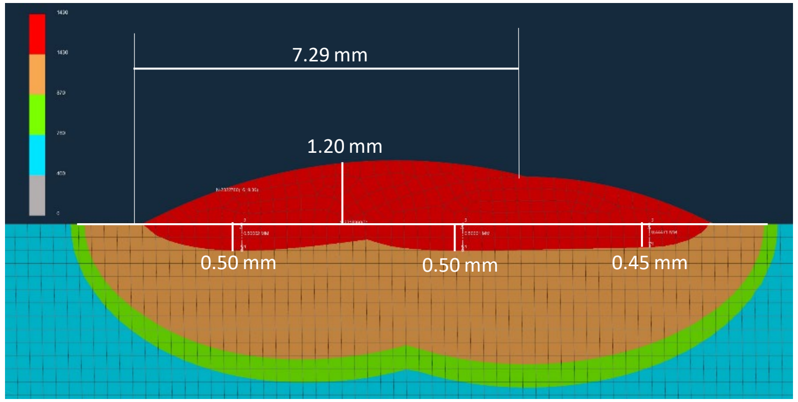


Height (mm)	0.90			
Width (mm)	7.12			
Penetration (mm)	1	2	3	Average
	0.43	0.53	0.44	0.47

Height (mm)	1.21		
Width (mm)	7.29		
Penetration (mm)	1	2	Average
	0.51	0.45	0.48

FEA Simulated Profile





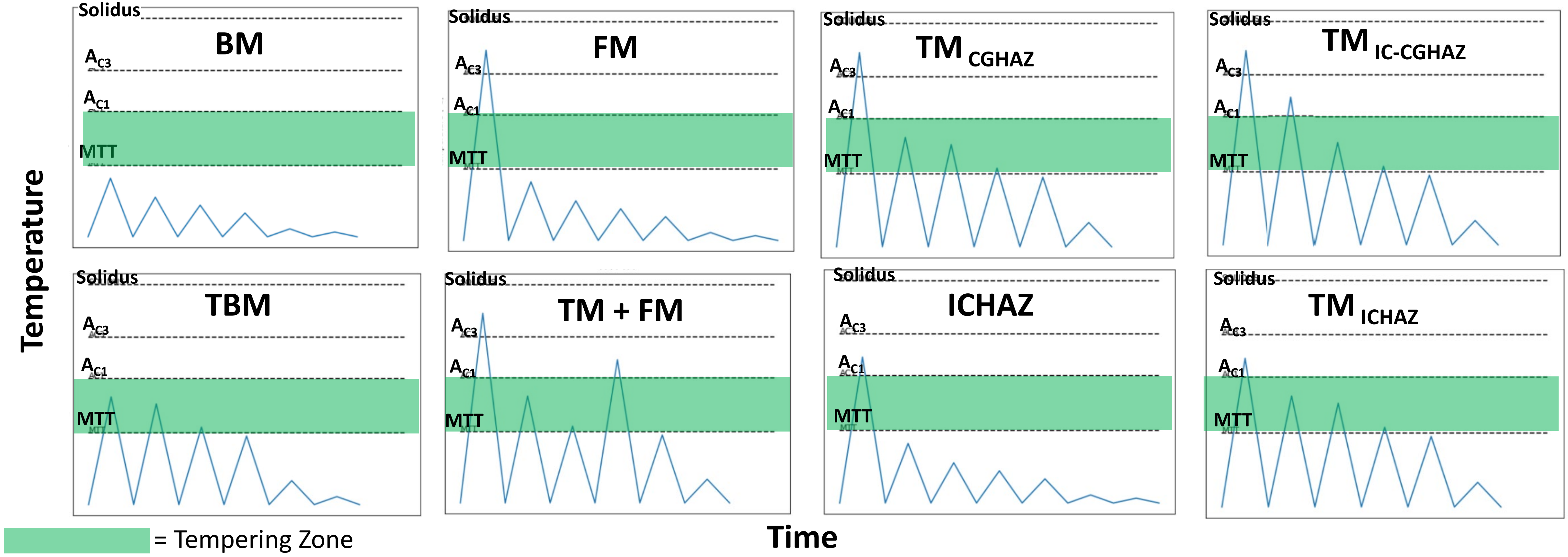
Example: 3 o'clock calibration

EPRI

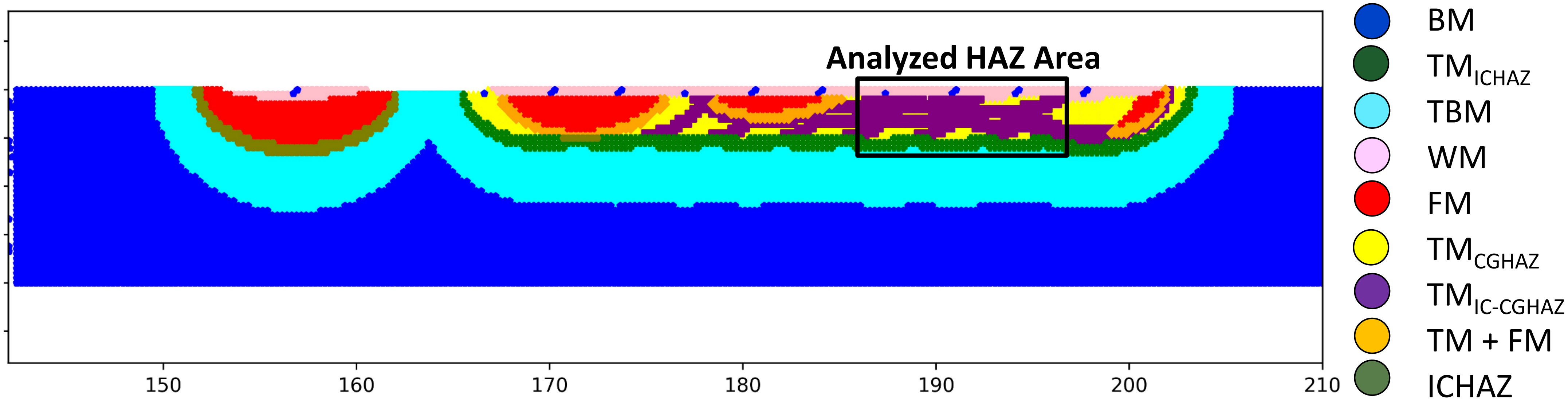
Determination of Microstructure

- Thermal histories were extracted from each node in the FEA model after the weld simulations were completed.
- Microstructure was determined from the peak temperature and sequence of thermal histories experienced during welding.
- The procedure to determine microstructure is shown below.

BM	Base Metal (Not Tempered)
TBM	Tempered Base Metal
FM	Fresh Martensite
ICHAZ	Intercritical HAZ
TM + FM	Tempered Martensite and Fresh Martensite
TM CGHAZ	Tempered Martensite in the CGHAZ
TM ICHAZ	Tempered Martensite in the ICHAZ
TM IC-CGHAZ	Tempered Martensite in the Intercritically Reheated CGHAZ

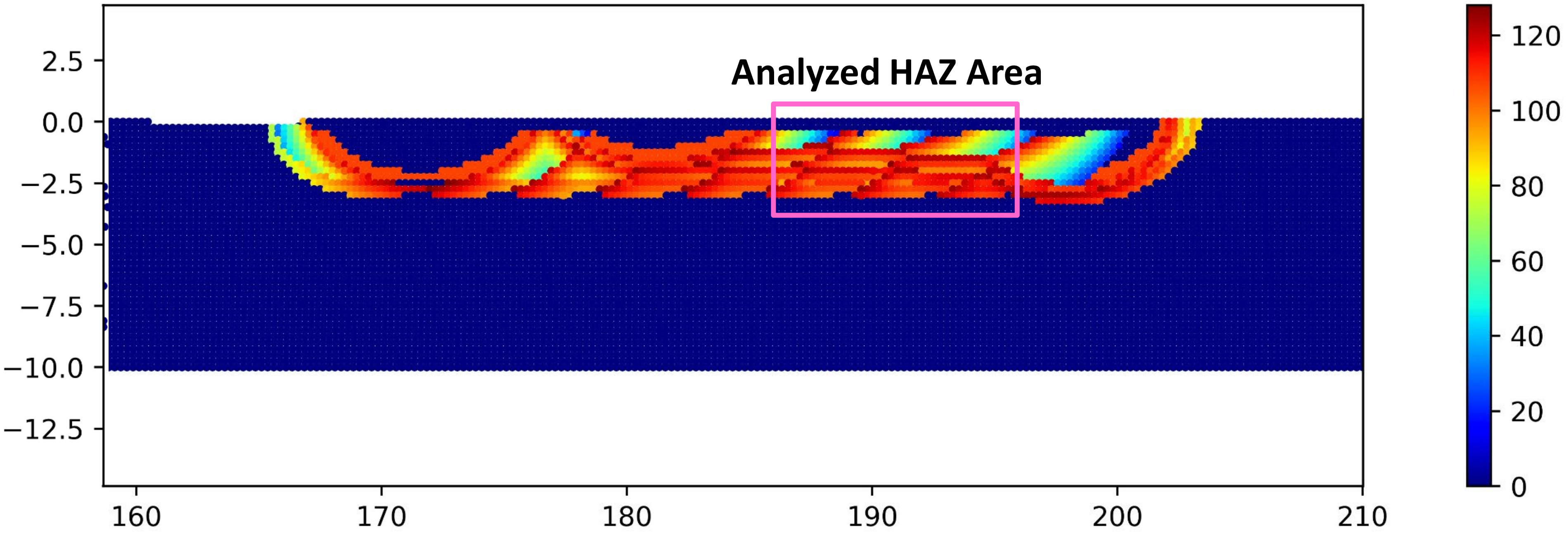


Predicted Microstructure Map – *12 and 6 o-clock (horizontal)*



- The stringer on top of the first layer (pass #20) re-austenitized the underlying HAZ and a large region of fresh martensite was observed.
- A narrow region with adequate tempering was observed between the re-austenitized regions showing tempered martensite.
- The last pass on the third layer (pass #19) also re-austenitized the HAZ causing more fresh martensite formation.
- Areas to the right (187-197 on the x-axis) showed improved tempering, indicated by the presence of tempered martensite (TM_{CGHAZ} and $TM_{IC\text{-}CGHAZ}$)

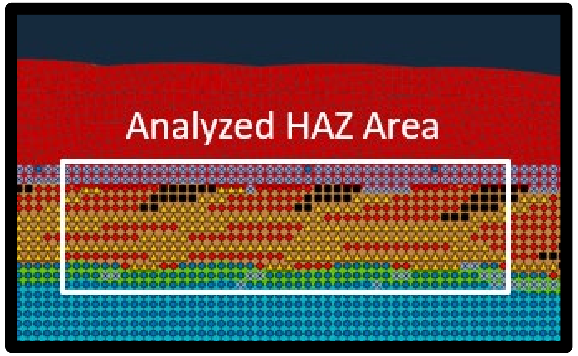
Predicted Hardness Drop – *12 and 6 o-clock (horizontal)*

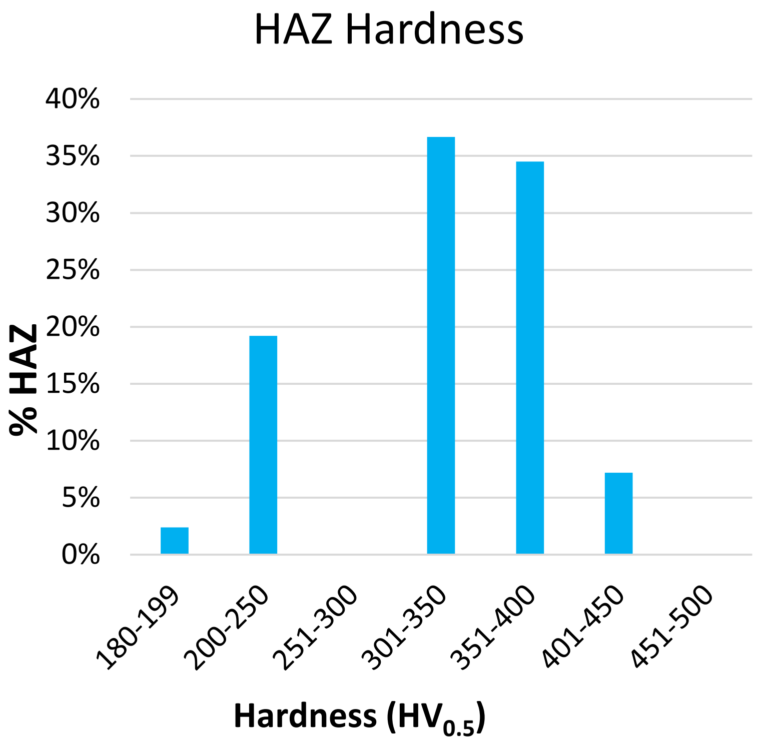


- The 12 o’clock (horizontal) position predicted large hardness drops <u>throughout the depth of the HAZ</u>
  - — Effective tempering was predicted throughout the FGHAZ and ICHAZ regions.
  - — CGHAZ was less effectively tempered
- The ICHAZ was effectively tempered with hardness drops > 100 HV
  - — Indicates sufficient heat was distributed to the bottom of the HAZ
- Stringer on the first layer (pass #20) and last pass of the 3rd layer (pass # 19) re-austenitized the HAZ and formed fresh martensite.
  - — Negligible hardness drop in these regions

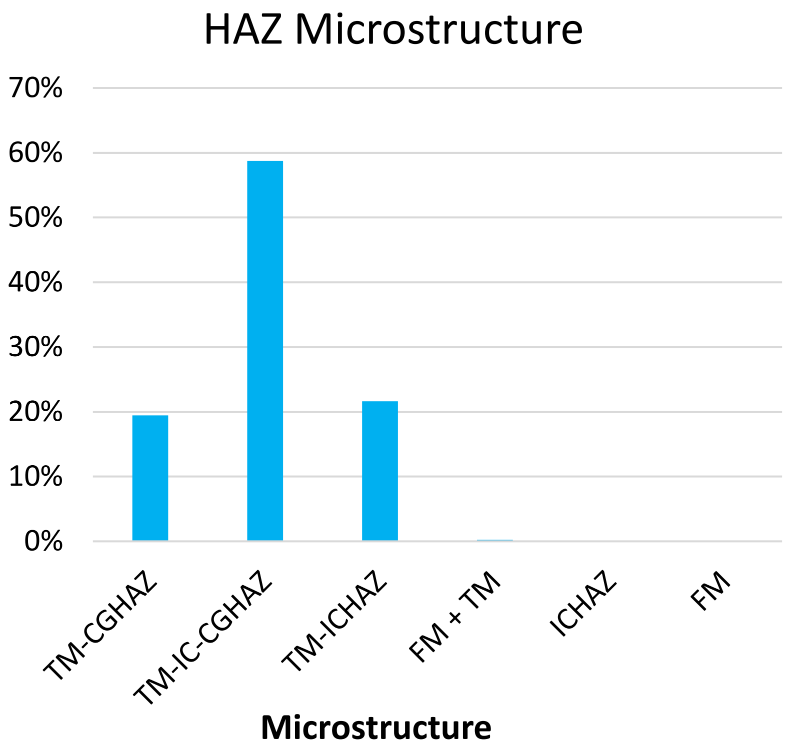
Tempering Response Plots – *12 and 6 o-clock*

The following bar charts were quantified from the HAZ region below the 3-layer weld buildup while excluding the weld toes, re-austenitized areas, and base/weld metal nodes.

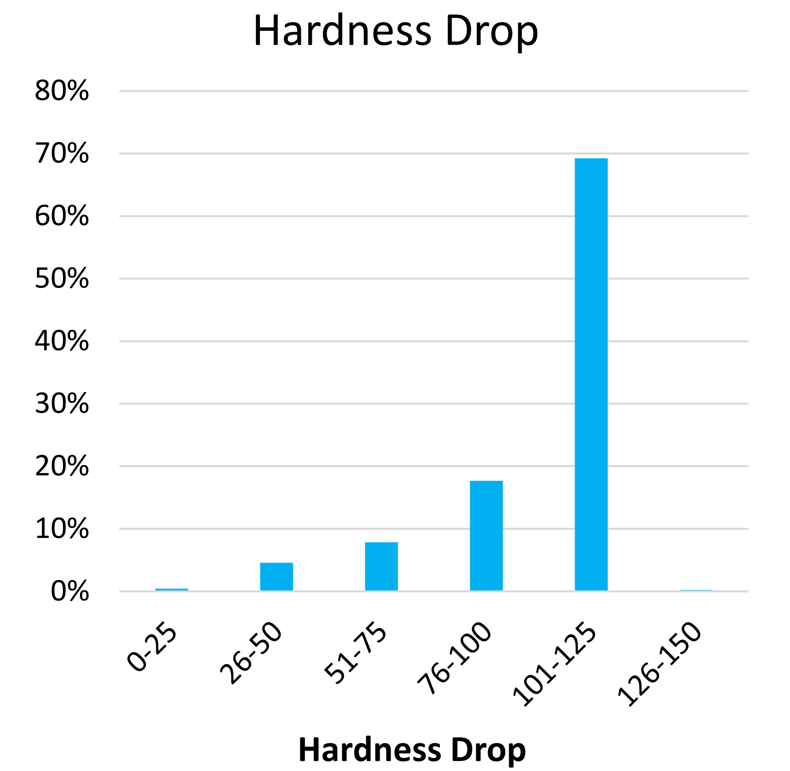




Hardness	180-199	200-250	251-300	301-350	351-400	401-450	451-500
% HAZ	2.4%	19.2%	0.0%	36.7%	34.5%	7.2%	0.0%



Microstructure	TM_{CGHAZ}	$TM_{IC-CGHAZ}$	TM_{ICHAZ}	FM + TM	ICHAZ	FM
% HAZ	19.4%	58.7%	21.6%	0.2%	0.0%	0.0%



Hardness Drop	0-25	26-50	51-75	76-100	101-125	126-150
% HAZ	0.4%	4.6%	7.9%	17.7%	69.2%	0.2%

Tempering Studies and Temper Bead Modelling References

1) Jang, E., “Tempering Kinetics and Carbide Precipitation in Low Alloy Steel Heat Affected Zones in Temper Bead Welding.” PhD Dissertation, The Ohio State University (2024).
2) Luo, Y., “Process Optimization Framework for Temper Bead Welding Procedures.” Master’s Thesis, The Ohio State University (2023).
3) Jang, E., Alexandrov, B.T., McCracken, S.L., Barborak, D. Computational Tempering Response Quantification and Tempering Efficiency Evaluation during Temper Bead Welding of Grade 22 Steel. Welding in the World (2024) – pending review
4) Jang, E., Alexandrov, B., McCracken, S.L., Barborak, D., “Tempering Procedure Effects on the Impact Toughness in Simulated Heat Affected Zone of Grade 22 Steel.” *Journal of Pressure Vessel Technology*. Aug 2024, 146(4): 041501. https://doi.org/10.1115/1.4065810.
5) Jang, E, Alexandrov, B, McCracken, SL, & Barborak, D. "Comparison of Impact Toughness Properties in Grade 22 Steel HAZ After PWHT and Temper Bead Welding." Proceedings of the ASME 2023 Pressure Vessels and Piping Conference. Atlanta, Georgia, USA. July 16–21, 2023. V001T01A008. ASME. https://doi.org/10.1115/PVP2023-106089.
6) Jang, E, Luo, Y, Alexandrov, B, McCracken, SL, Tatman, J, & Barborak, D. "Quantification of the Tempering Response for Temper Bead Welding of SA-508 Low Alloy Steel." Proceedings of the Pressure Vessels and Piping Conference. Volume 1: Codes and Standards. Las Vegas, Nevada, USA. July 17–22, 2022. V001T01A079. ASME. https://doi.org/10.1115/PVP2022-84884.
7) Jang, E, Stewart, J, Luo, Y, Qu, S, Alexandrov, B, McCracken, SL, Tatman, J, Barborak, D, & Penso, JA. "Tempering Efficiency Evaluation for Dissimilar Weld Overlays." *Proceedings of the Pressure Vessels and Piping Conference.* Volume 1: Codes and Standards. Virtual, Online. August 3, 2020. V001T01A098. ASME. *https://doi.org/10.1115/PVP2020-21708.*

Extra Slides

- Temper Bead Welding Basics
- Hardness Drop Protocol for Temper Bead Qualification
- Diffusible Hydrogen Threshold for Hydrogen Induced Cracking in Nuclear Pressure Vessel Steels
- ASME Temper Bead Code Cases – Progress and Revision Details
- Temper Bead References

Temper Bead Welding Basics

Mature Temper Bead Techniques

- **Controlled Deposition Temper Bead Technique (CDTT) – Grain Refinement**

  Goal: Resistance to Temper Embrittlement and Reheat Cracking

  – Heat input is increased in each layer by 30–80% to promote grain refinement
  – Early implementation with the SMAW process
  – Increase in heat input is typically achieved by increasing electrode diameter one sequential size (that is, 3/32 in. to 1/8 in. to 5/32 in., 2.5 mm to 3.2 mm to 4.0 mm)
  – Adjacent weld passes overlap the previously deposited bead by ~50%

- **Consistent Layer Temper Bead Technique (CLTT) – HAZ Tempering**

  Goal: Optimum HAZ Toughness

  – Heat input/power is consistent (±10%) for each layer
  – Temper bead layers penetrate the underlying layer to develop overlapping temperature profiles while preventing additional transformation (re-austenization) of the underlying HAZ
  – Utilizes controlled heat energy dissipation to develop a tempered martensitic microstructure in the first few millimeters of the HAZ [EPRI Report TR-111757]
  – Can be applied with the SMAW or GTAW process with consistent layer heat input and/or electrode diameters for each layer

Classification of Temper Bead Techniques

HAZ Grain Refinement

- Two Layer Deposition
- **Controlled Deposition**

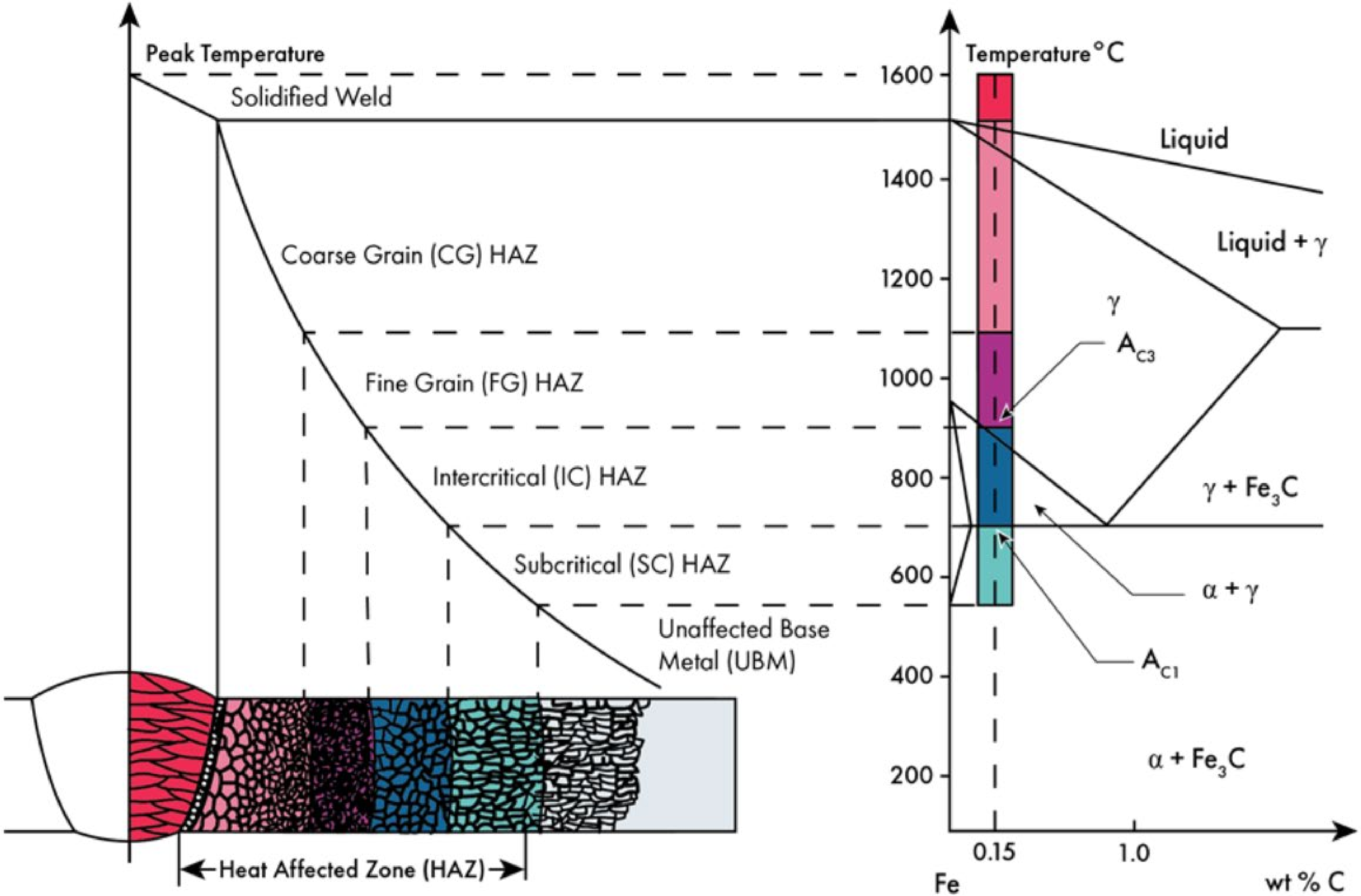
HAZ Tempering

- Half Bead Technique *(Section III NB-4622)*
- Alternative Repair Technique *(Section XI Case N-432)*
- **Consistent Layer Technique** ***(Section XI Case N-638, N-839, N-888)***

Temper bead advancements in the nuclear industry over the past two decades have been focused on the ambient temperature consistent layer technique using GTAW or SMAW

[Adapted from EPRI 3002011798]

HAZ and Fe-Fe_3C Equilibrium Phase Diagram



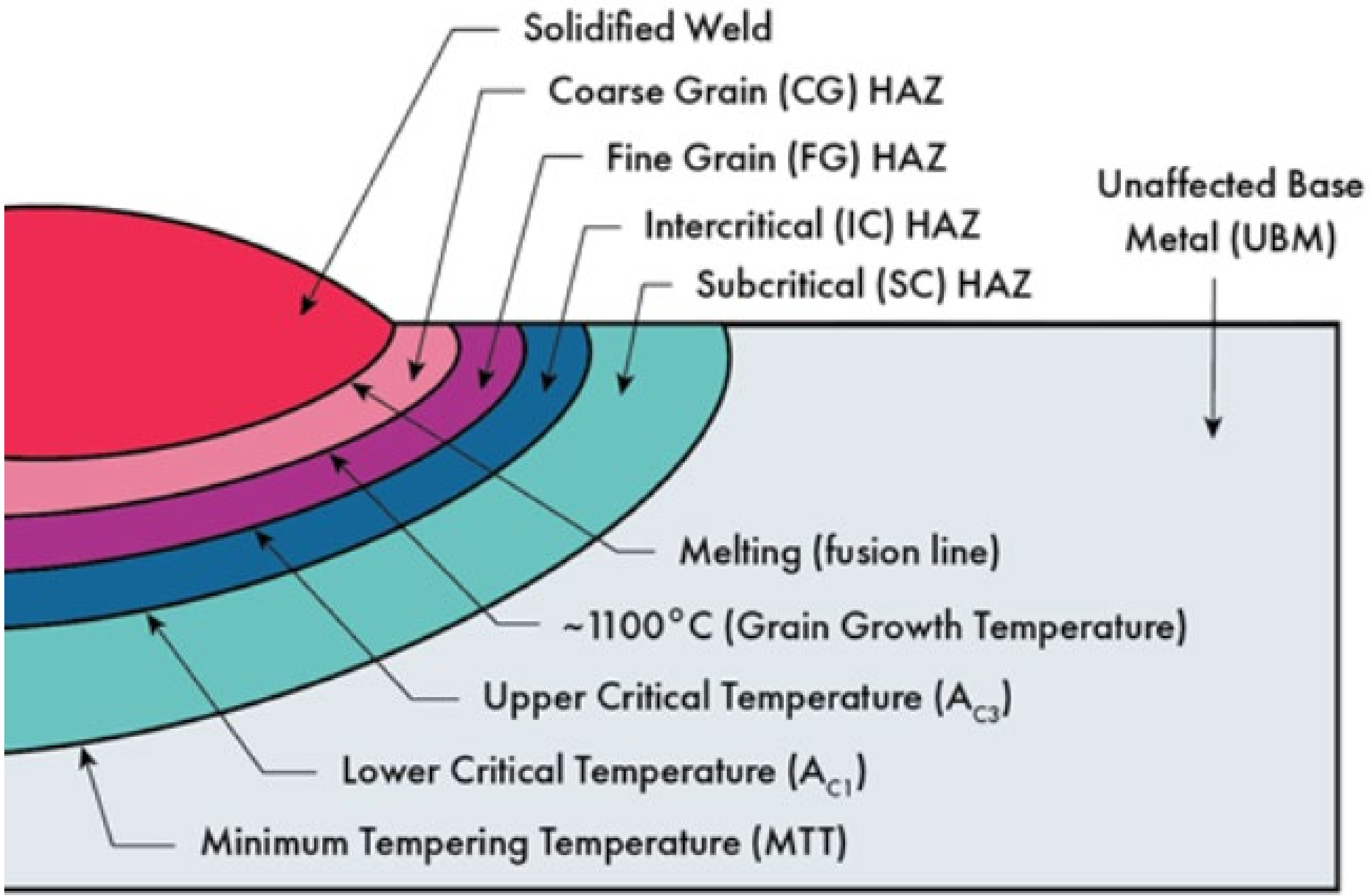
HAZ and Fe-Fe_3C Equilibrium Phase Diagram

~1100°C < CG HAZ < Melting

A_{C3} < FG HAZ < ~1100°C

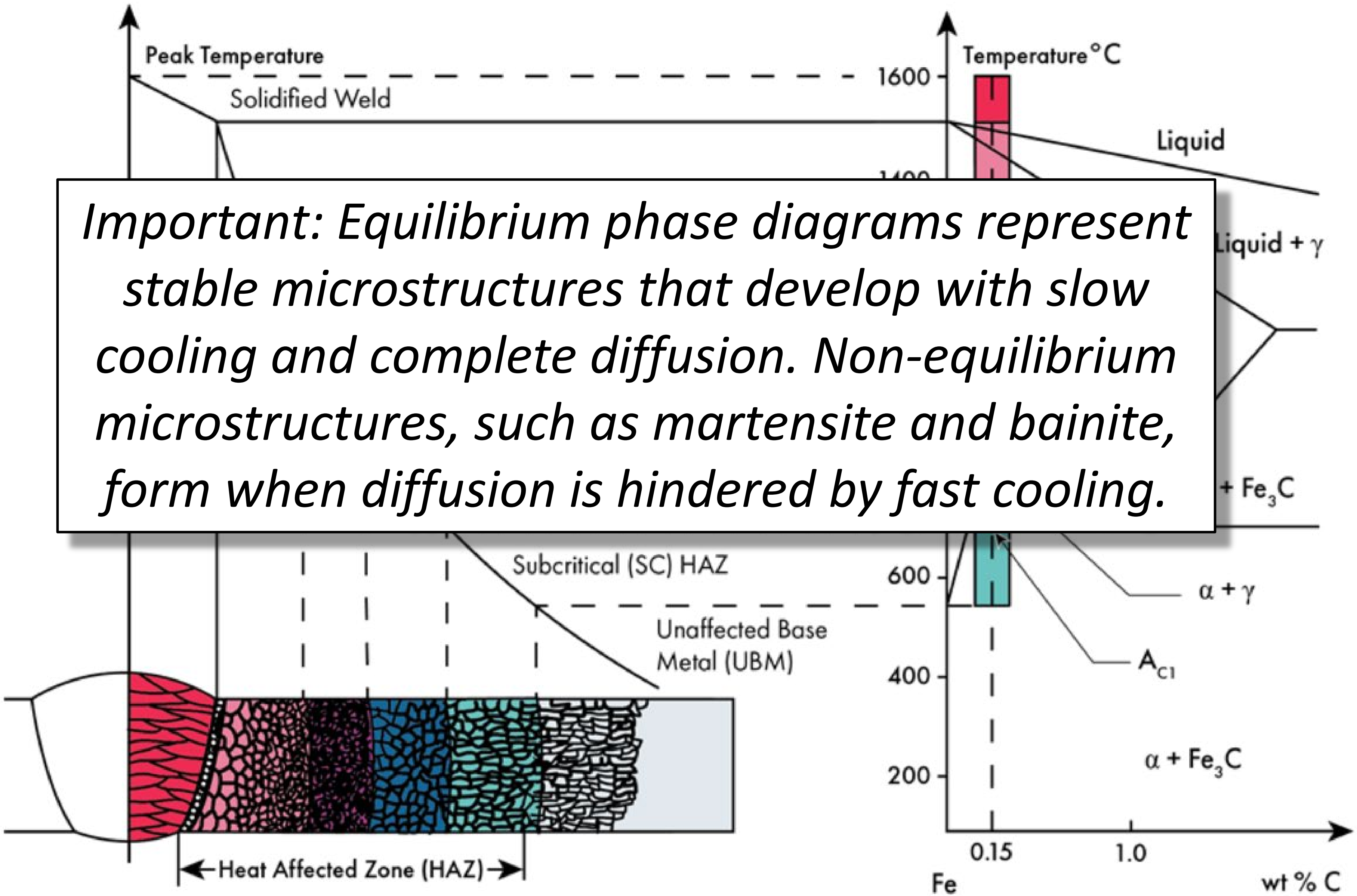
A_{C1} < IC HAZ < A_{C3}

MTT < SC HAZ < A_{C1}



EPRI

HAZ and Fe-Fe_3C Equilibrium Phase Diagram



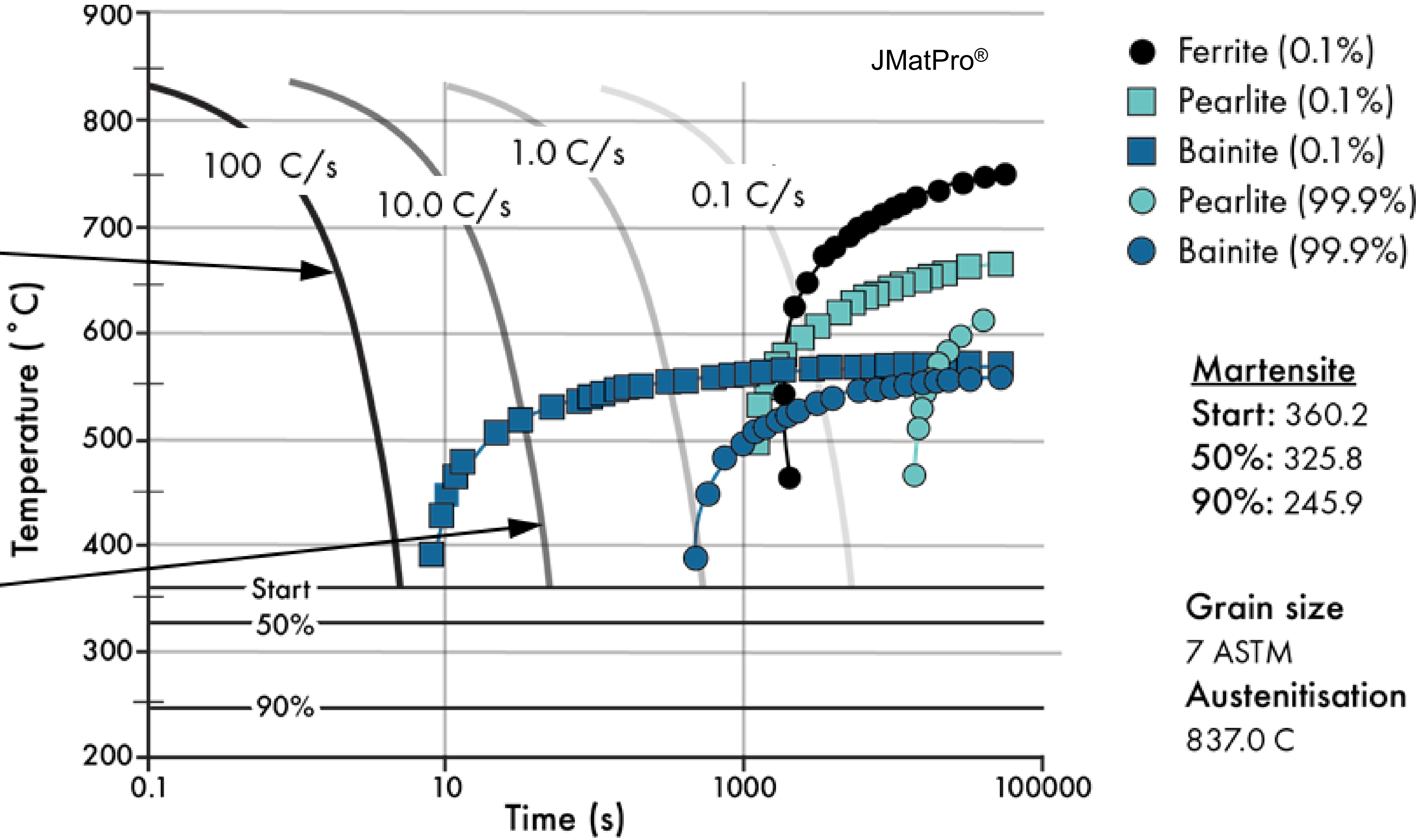
Important: Equilibrium phase diagrams represent stable microstructures that develop with slow cooling and complete diffusion. Non-equilibrium microstructures, such as martensite and bainite, form when diffusion is hindered by fast cooling.

Continuous Cooling Transformation Curve

SA-508 Composition, Quenched and Tempered Forging

Microstructure of ~100% martensite with high 100°C/s cooling rate

Mixed microstructure of martensite and upper bainite with 10°C/s cooling rate



Martensite
Start: 360.2
50%: 325.8
90%: 245.9

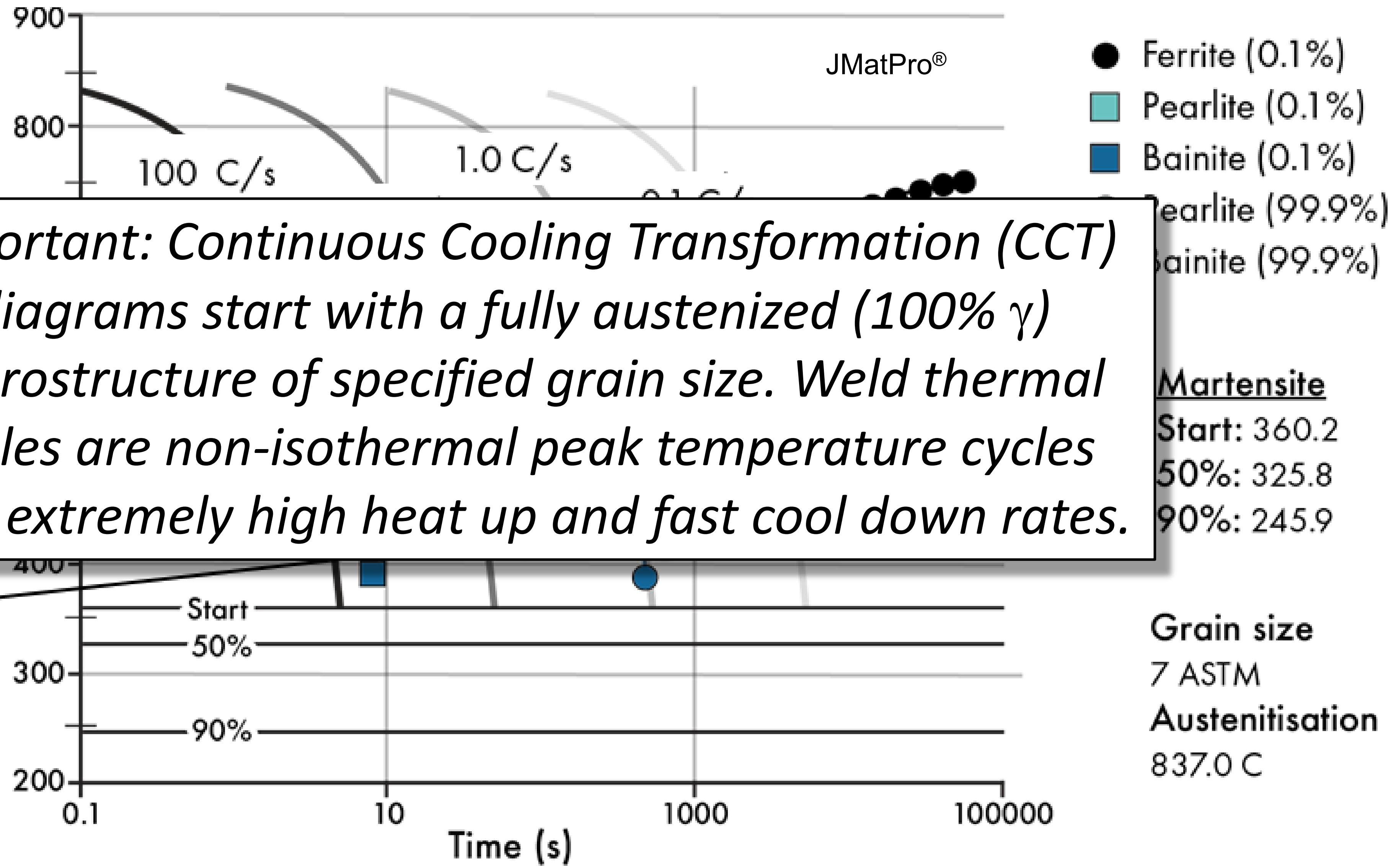
Grain size
7 ASTM
Austenitisation
837.0 C

Continuous Cooling Transformation Curve

SA-508 Composition, Quenched and Tempered Forging

Microstructure of ~100% martensite with high 100°C/s cooling rate

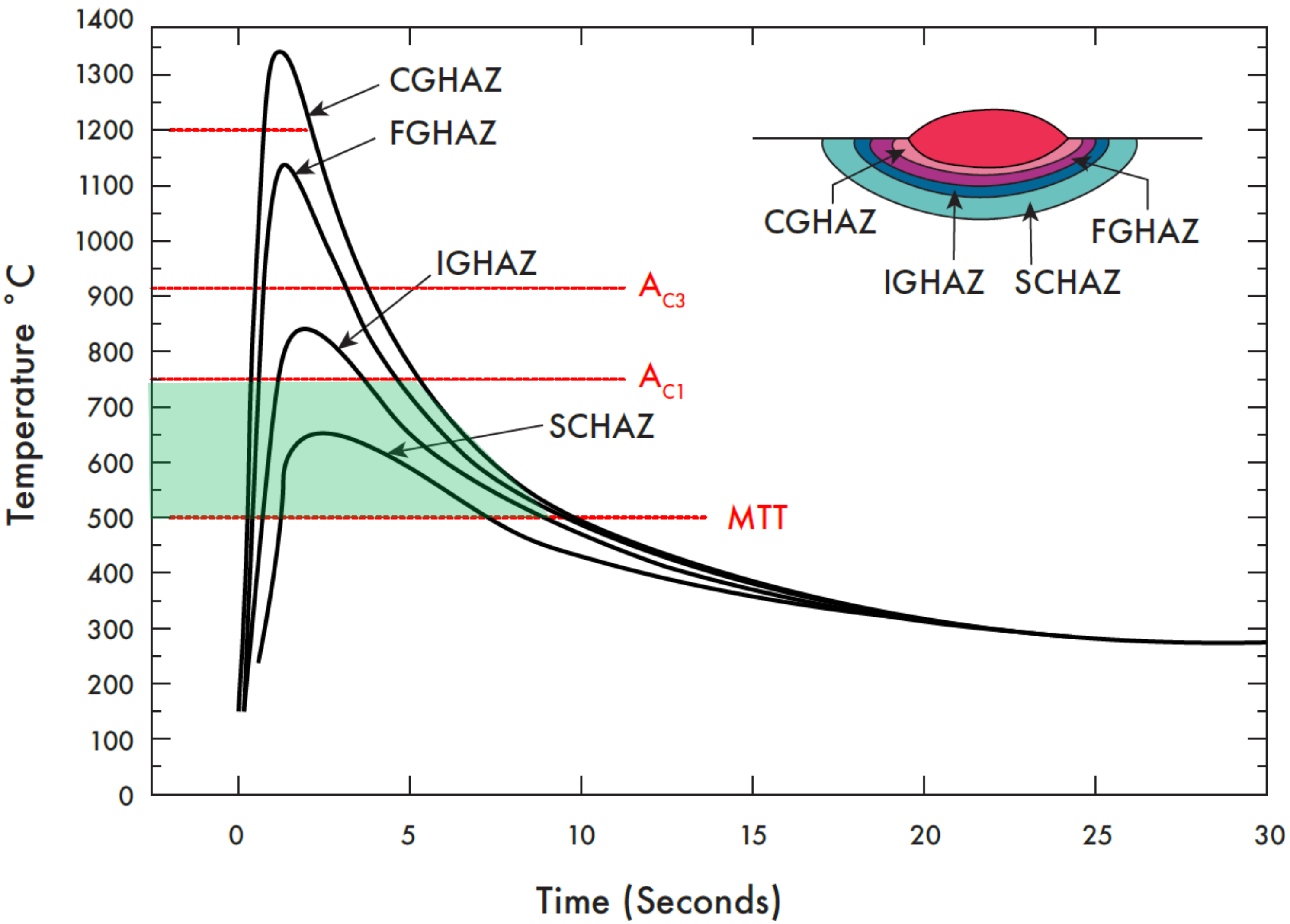
Mixed microstructure of martensite and upper bainite with 10°C/s cooling rate



Important: Continuous Cooling Transformation (CCT) diagrams start with a fully austenized (100% γ) microstructure of specified grain size. Weld thermal cycles are non-isothermal peak temperature cycles with extremely high heat up and fast cool down rates.

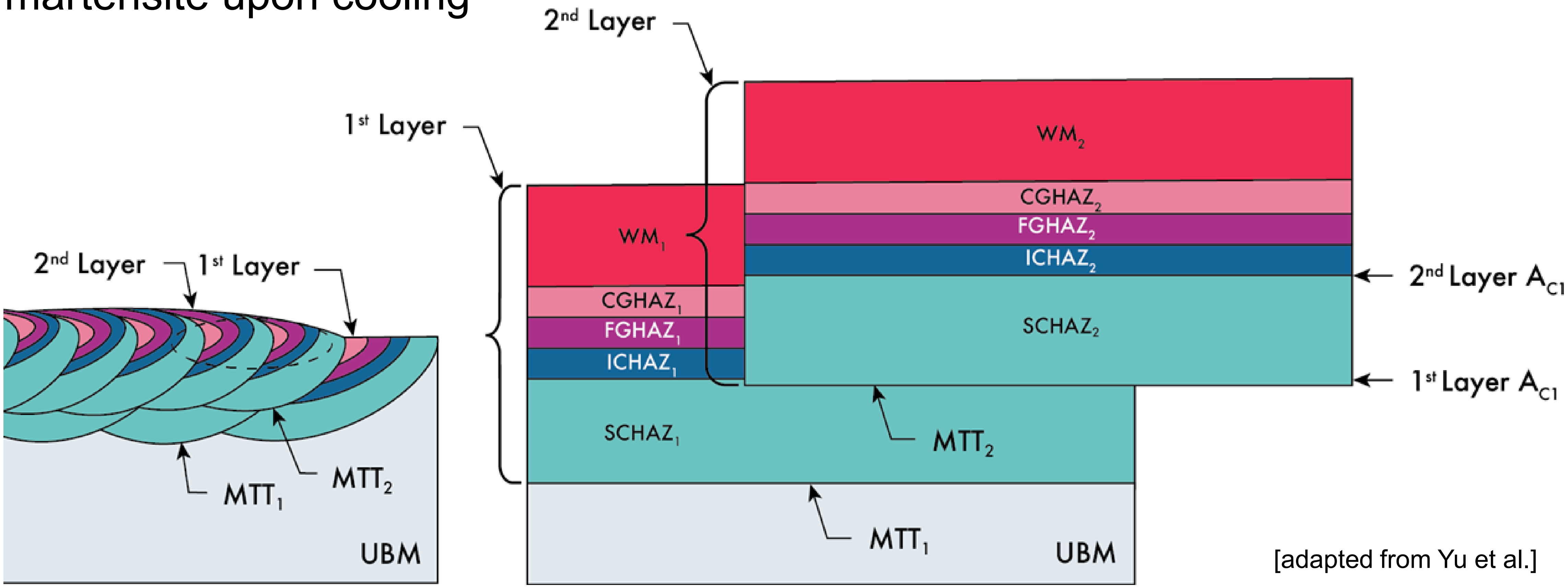
HAZ Microstructures with Various Weld Thermal Cycles

- HAZ varies depending on peak temperature during welding (distance from fusion line)
  - Coarse Grain HAZ (CGHAZ), region >1200°C with rapid grain growth
  - Fine Grain HAZ (FGHAZ), region between A_3 and ~1200°C
  - Intercritical HAZ (ICHAZ), partial transformation to austenite occurs, degree of transformation depends on peak temperature and duration between A_1 and A_3
  - Subcritical HAZ (SCHAZ), region between Minimum Tempering Temperature (MTT) and A_1 where tempering occurs



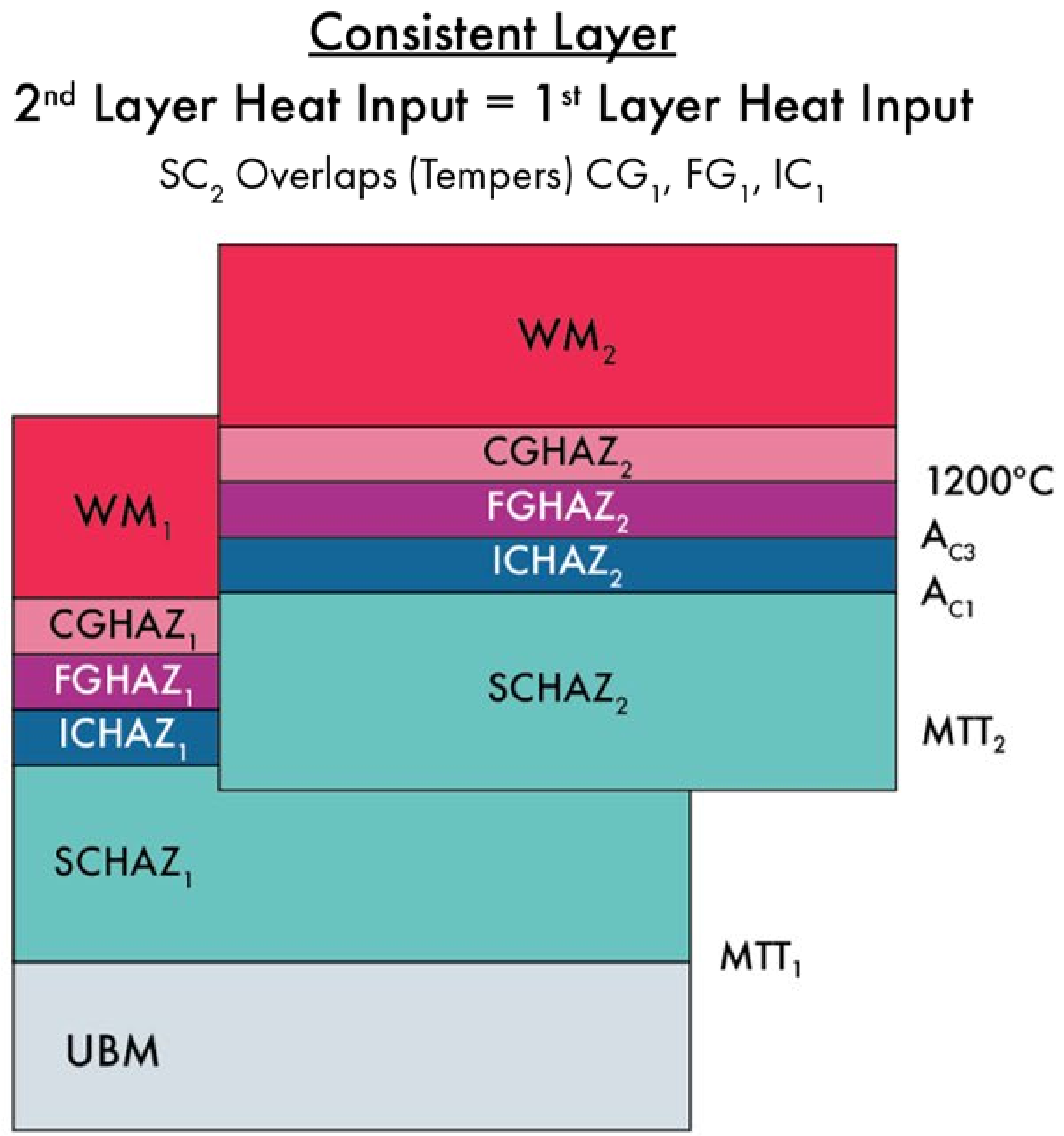
CLTT – Ideal HAZ Tempering by the 2nd Layer

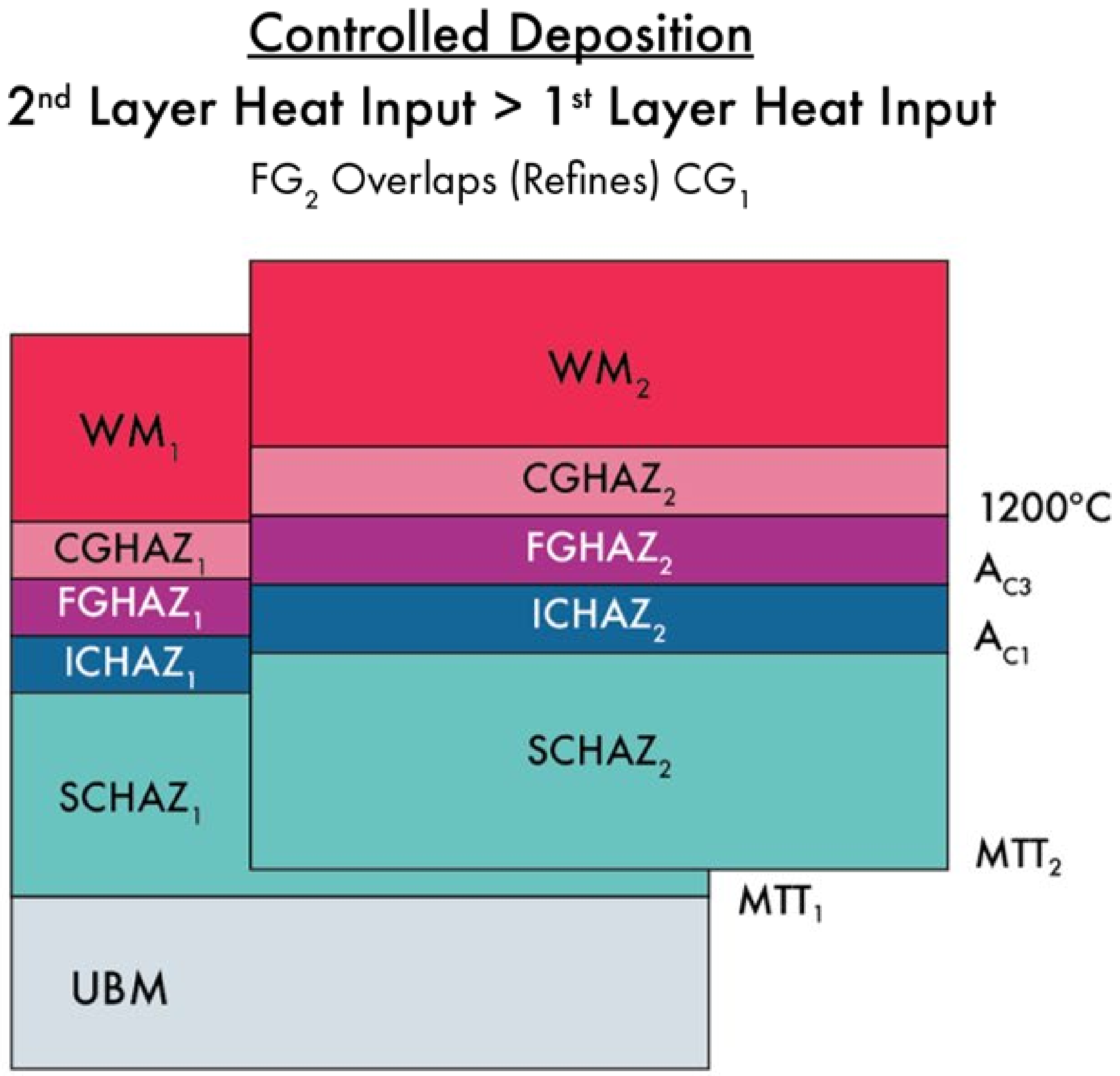
- Peak temperatures induced by subsequent passes and layers must be high enough to promote tempering without exceeding the A_{C1}
- Exceeding the A_{C1} will cause transformation to austenite, forming untempered martensite upon cooling



[adapted from Yu et al.]

Compare Consistent Layer to Controlled Deposition

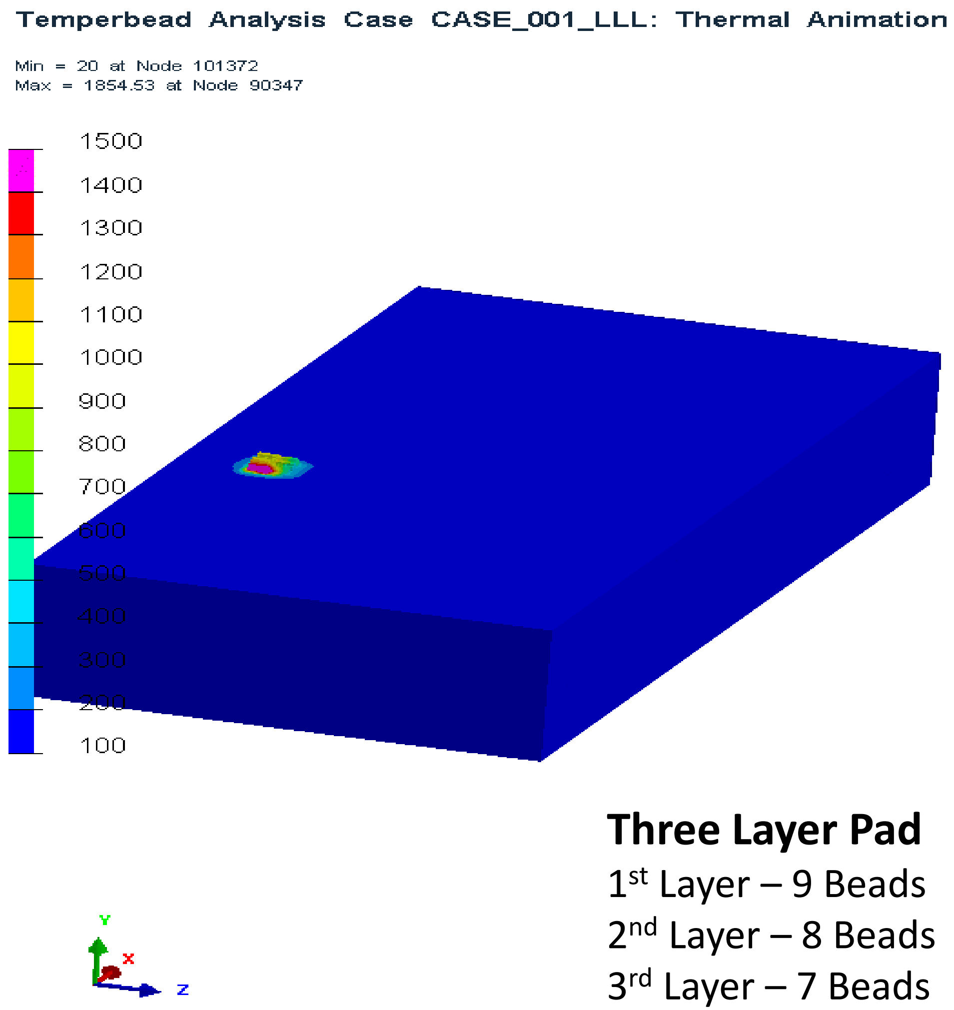


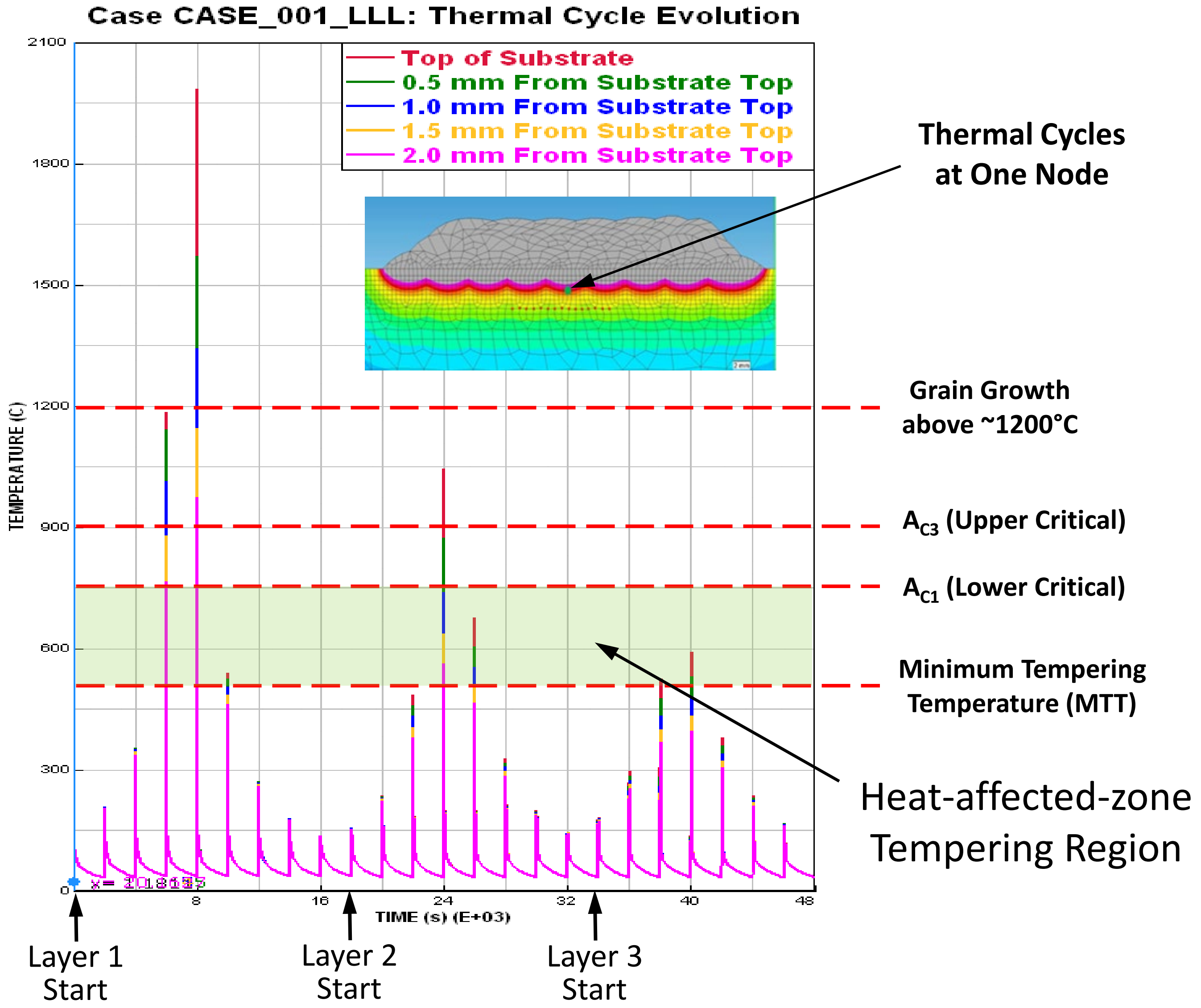


Note: Early controlled deposition used half bead and/or six layers

Tempering Response Case : CASE_001_LLL

Temper Bead Thermal Cycle Animation – Low, Low, Low Heat Input – 1st, 2nd, 3rd Layers





Three Layer Pad

1st Layer – 9 Beads

2nd Layer – 8 Beads

3rd Layer – 7 Beads

[Matt Forquer, OSU]

Consider Four Regions for Evaluating HAZ Tempering

1) **Tempered Base Metal**

   All peak temperatures between MTT and A_{C1}

2) **Tempered ICHAZ (partial martensite)**

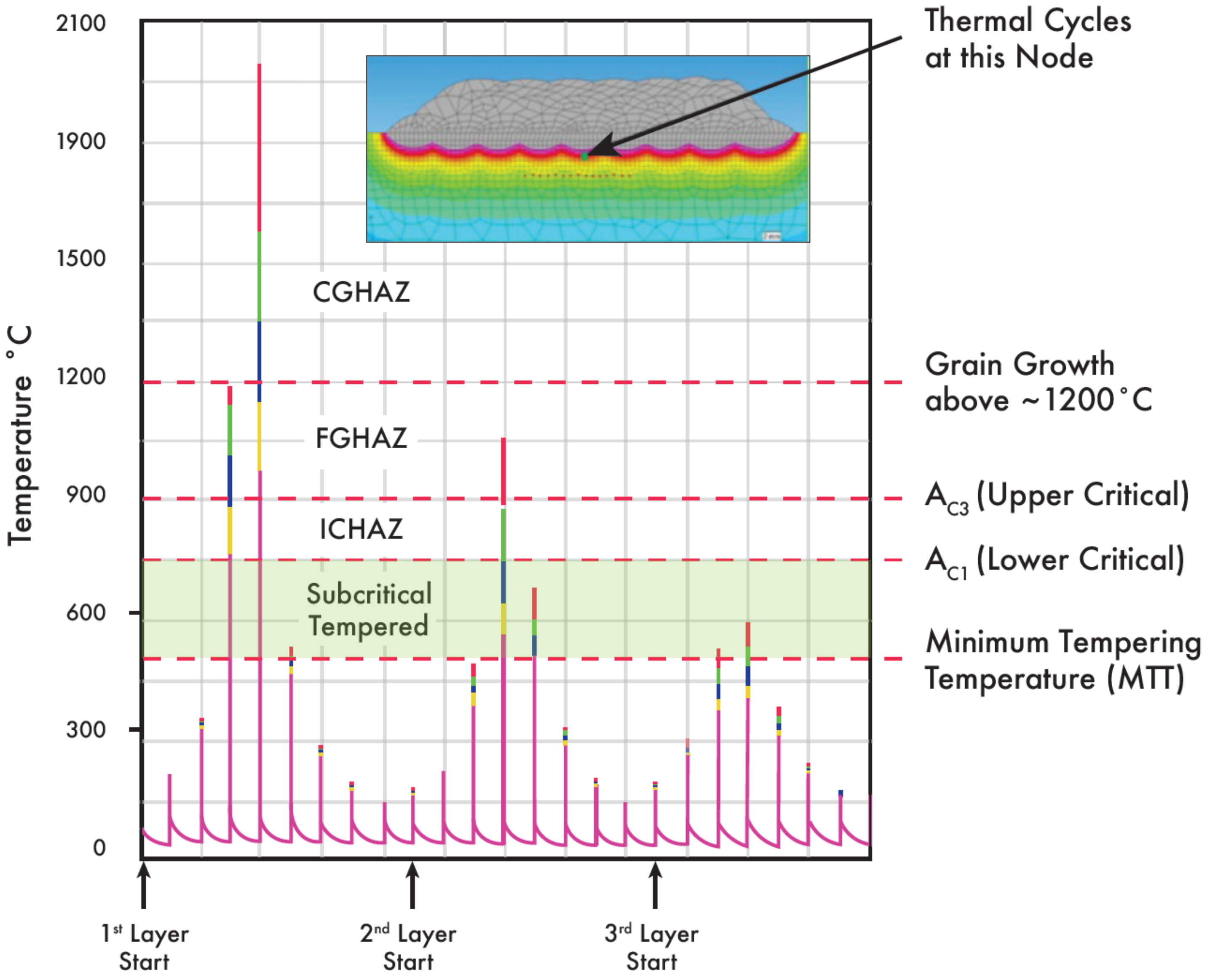
   Last peak temperature above A_{C1} is between A_{C1} and A_{C3}, with subsequent tempering cycles between MTT and A_{C1}

3) **Tempered Martensite**

   Last peak temperature above A_{C1} is above A_{C3}, with subsequent tempering cycle or cycles between MTT and A_{C1}

4) **Untempered Martensite**

   Last peak temperature is above A_{C3} with no subsequent tempering cycles

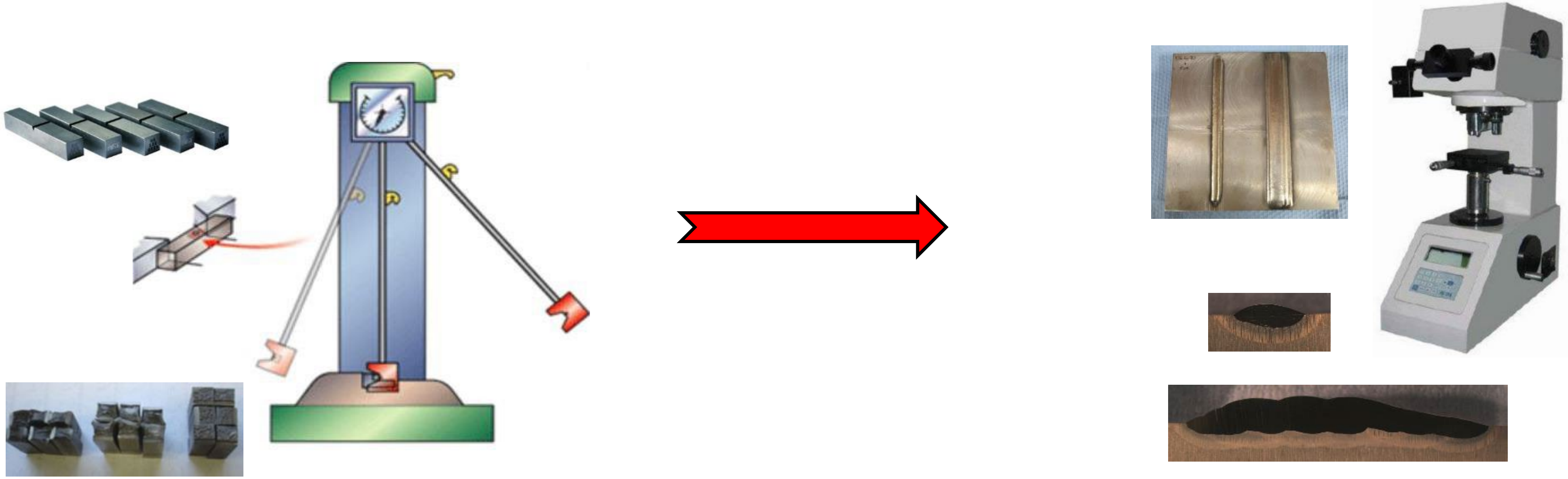


Hardness Drop Protocol for Temper Bead Qualification

Steve McCracken & Ben Sutton, EPRI
Boeing Smith & Dr. Antonio Ramirez, OSU

Motivation – Eliminate Charpy Impact Testing

- Benefits of hardness testing
  - Simple alternative to Charpy V-notch impact testing
  - Appropriate hardness test protocol is less costly and time consuming compared to Charpy V-notch testing
  - Can be used to optimize temper bead experiments in locations where Charpy samples are not possible



EPRI

Is Hardness Appropriate for Temper Bead Qualification?

- Yes – hardness is appropriate provided the hardenability of the material is properly characterized and a proper protocol is applied
- No – not appropriate if only peak hardness criterion is specified. [1]
  - Hardness alone, without knowing the microstructure or thermal history, is not adequate to verify appropriate HAZ tempering
  - Rejection by a single hardness reading (as often required in EN/ISO codes) is not reasonable
  - Use of maximum hardness criterion can potentially lead to acceptance of TB HAZ properties with poor impact properties

Proposed Temper Bead Hardness Qualification Protocol [2]

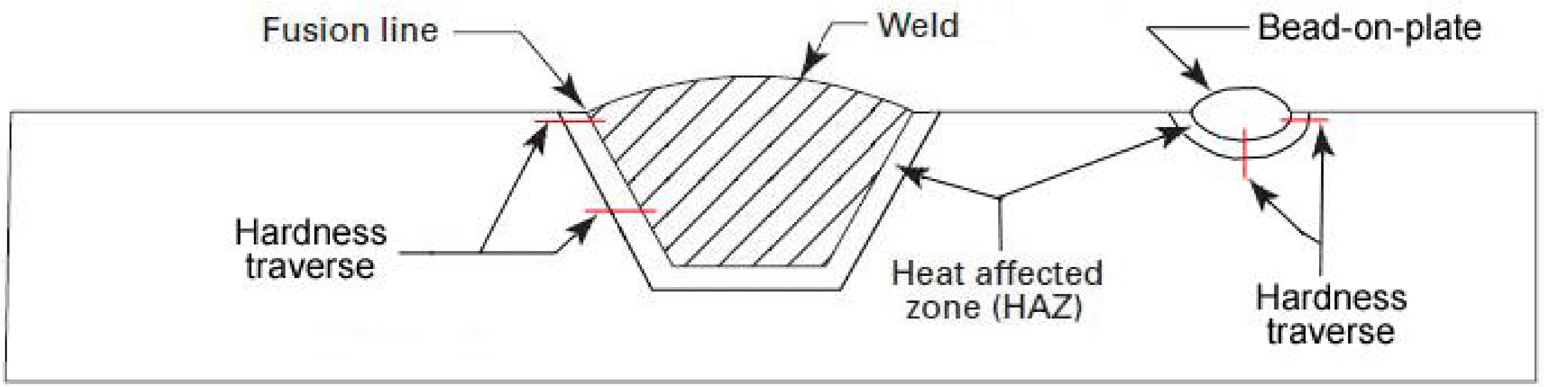
Step #1

- Make a single bead on plate and measure the HAZ hardness
- HAZ hardness should be close to calculated hardness *(example: Maynier's equation)*

$$HV_M = 127+949C+27Si+11Mn+8Ni+16Cr+21Log_{10}(V)$$ [3] Note: V=C°/hr

Step #2

- Make a temper bead pad or groove weld and measure the HAZ hardness
- Temper bead procedure is qualified with appropriate drop in hardness between untempered single bead HAZ and tempered weld HAZ

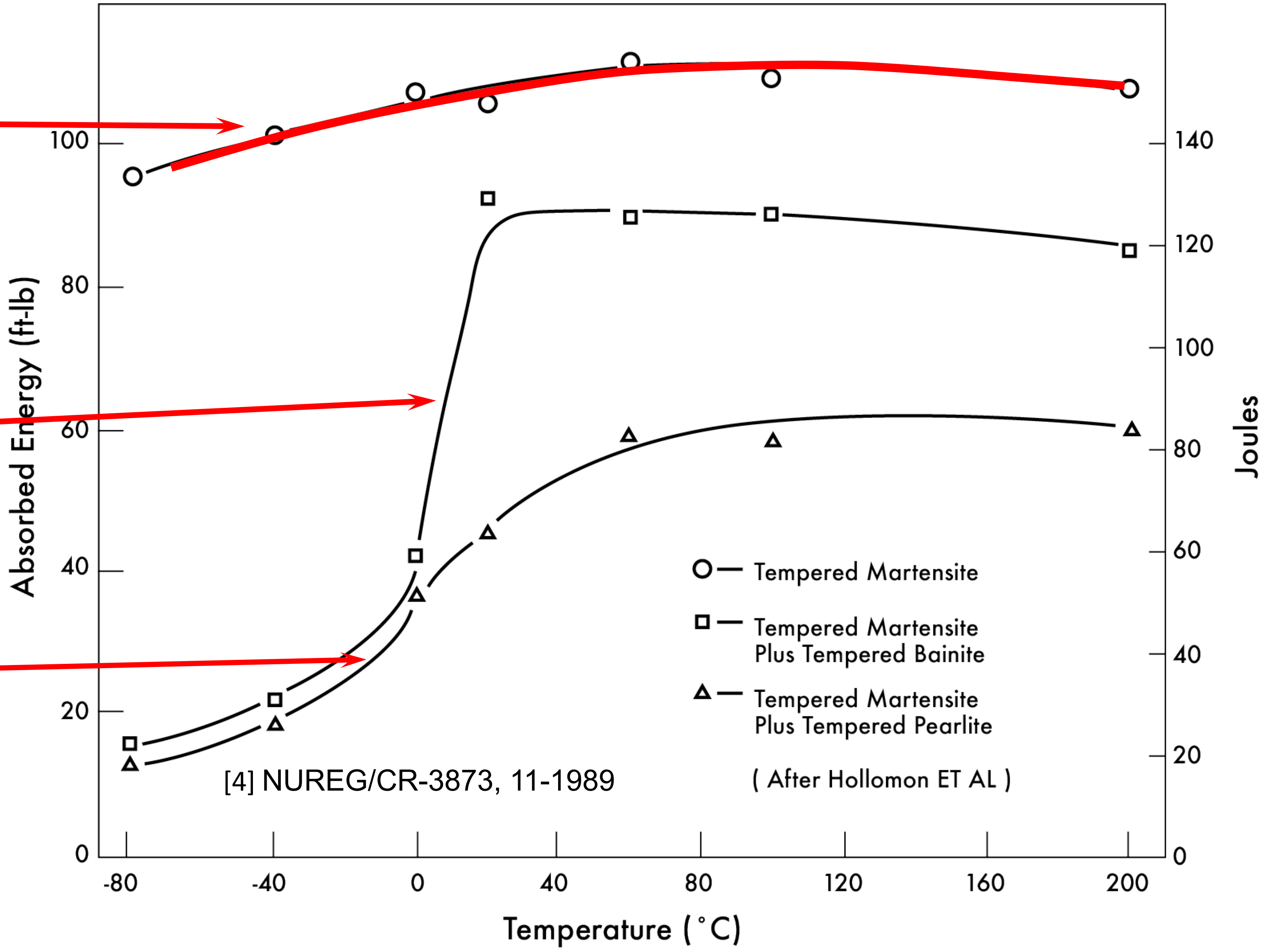


Example of possible hardness procedure qualification test coupon

Figure from Ref. [2]

Tempered Martensite Has Superior Impact Energy

- **<u>Tempered martensite</u>** has superior impact energy from high to low temperatures
- **<u>Tempered martensite plus tempered bainite</u>** shows sharp temperature transition curve
- **<u>Tempered martensite plus tempered pearlite</u>** has poorest impact energy



HAZ Hardness, Impact Energy & Microstructure

Two Step Hardness Protocol

- Tempered martensite (TM) exhibits the highest HAZ Charpy impact energy
- Bainite (B), Tempered Bainite (TB) and TTM HAZ microstructures are all in the 200 to 300 HV10 range
- Two step hardness demonstrates a TM microstructure

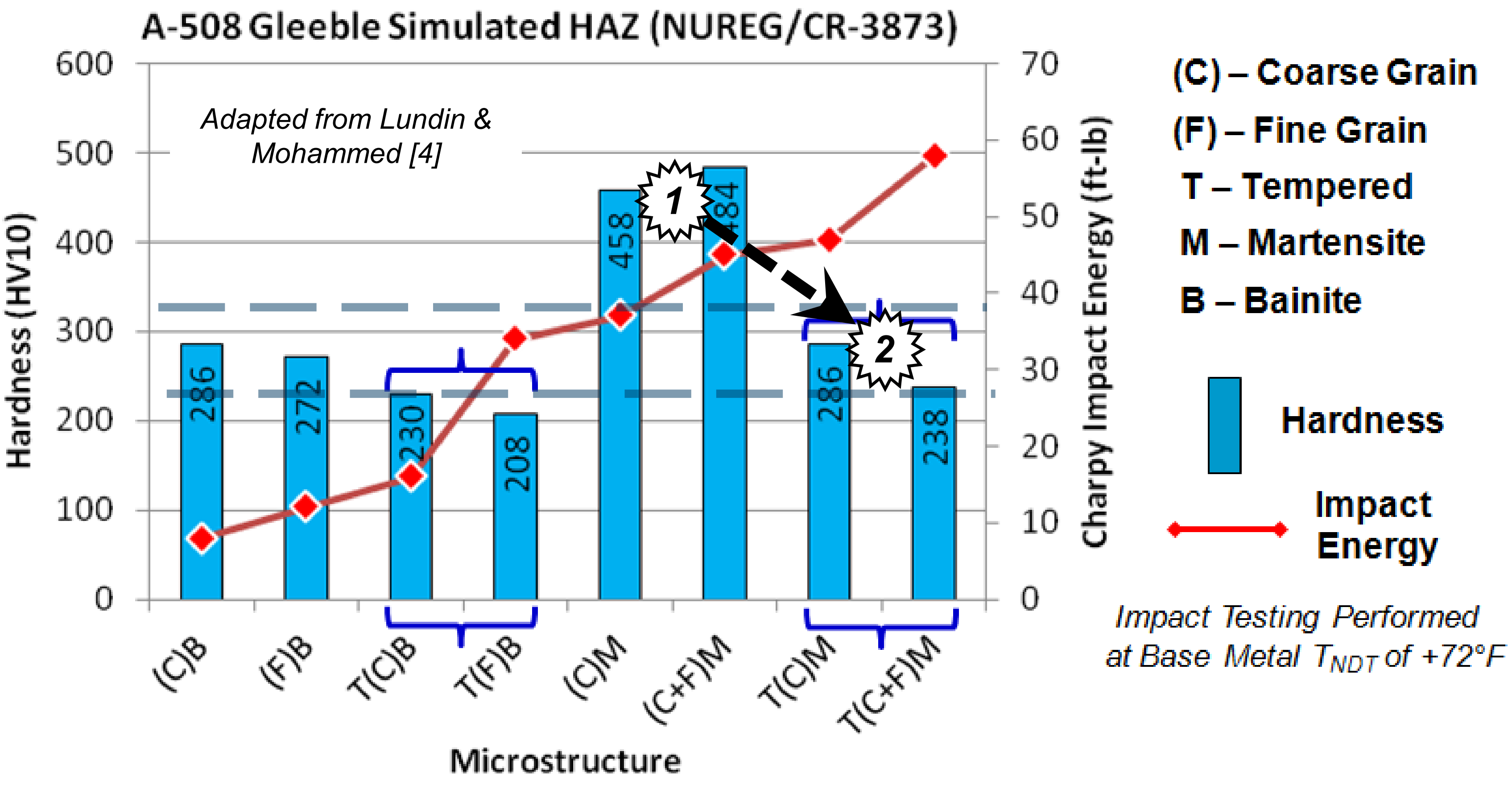


Figure from Ref. [2]

SA-508 Simulated Temper Bead HAZ Experiments

- SA-508 simulated temper bead HAZ samples made with Gleeble® thermal mechanical simulator
  - Cooling rate used to develop HAZ microstructures with varying martensite (M) and bainite (B) phase fractions
    - Samples austenized at 969°C for 5 min
    - Controlled cooling between 800° to 500°C
- Phase fractions verified with quantitative metallography
- Tempered with Gleeble® for 1 second at 635°C
- Hardness drop between untempered and tempered determined for each martensite / bainite microstructure

Cooling Rate	M%	B%	Std. Dev	Untempered Hardness (HV 0.5)	Hardness after 1s tempering at 635°C (HV 0.5)	Hardness Drop (HV 0.5)
5 C/s	19	81	9	305 ± 2	276 ± 1	29 ± 2
8 C/s	28	72	17	353 ± 2	302 ± 1	51 ± 2
10 C/s	60	40	17	386 ± 3	307 ± 2	80 ± 3
15 C/s	84	16	5	432 ± 2	329 ± 1	103 ± 2
20 C/s	77	23	12	419 ± 2	325 ± 1	94 ± 2
30 C/s	93	7	4	455 ± 1	330 ± 1	126 ± 1
40 C/s	91	9	4	441 ± 2	329 ± 1	112 ± 2
55 C/s	99	1	1	462 ± 1	342 ± 1	120 ± 1
SA-508 BM	NA	NA	NA	207 ± 8	NA	NA

Hardness drop values for Gleeble® simulated SA-508 HAZ samples with varying martensite/bainite microstructures [5]

Martensite Percentage and Hardness Drop Relationship

- Linear relationship for percentage of martensite in untempered microstructure and hardness drop after temper bead welding

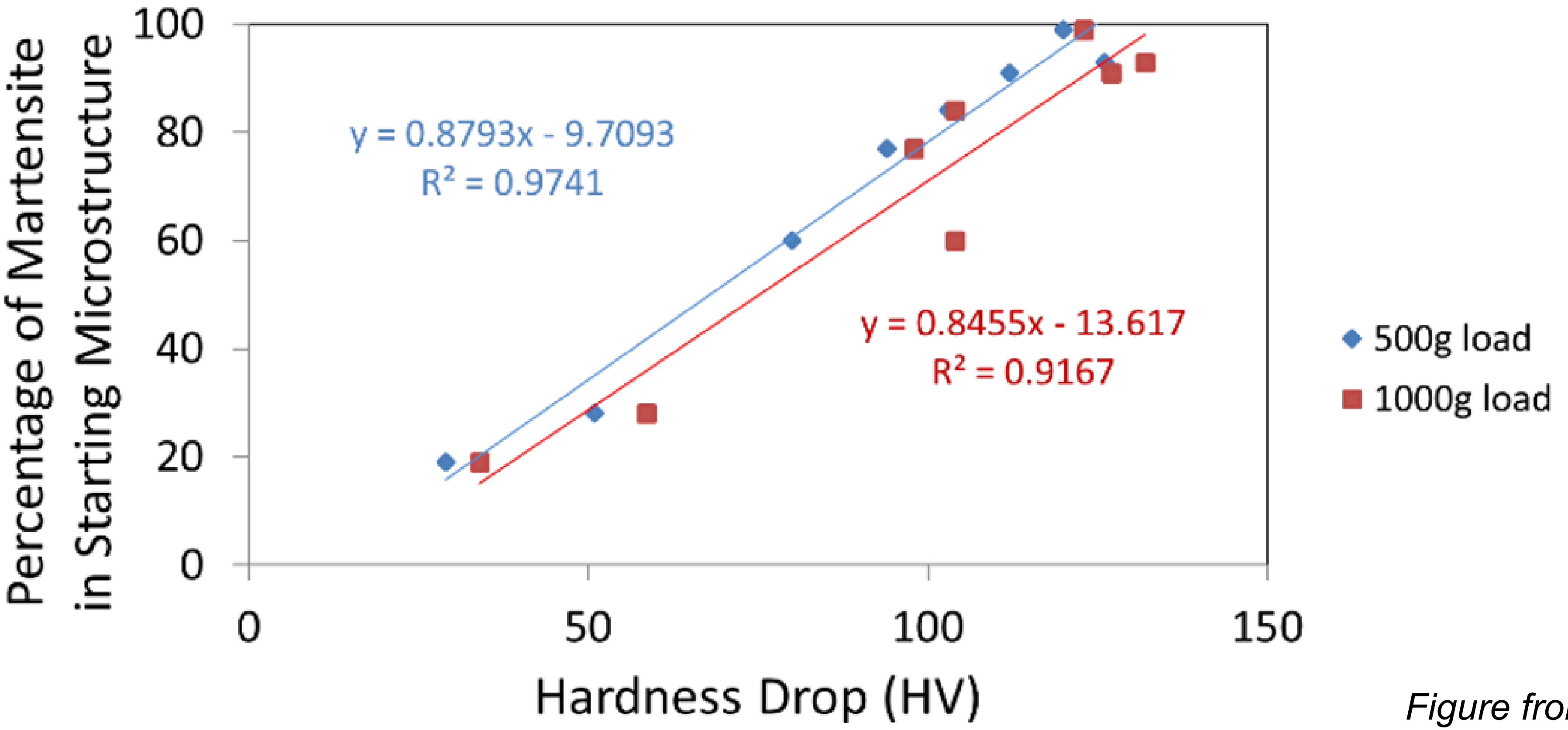


Figure from Ref. [6]

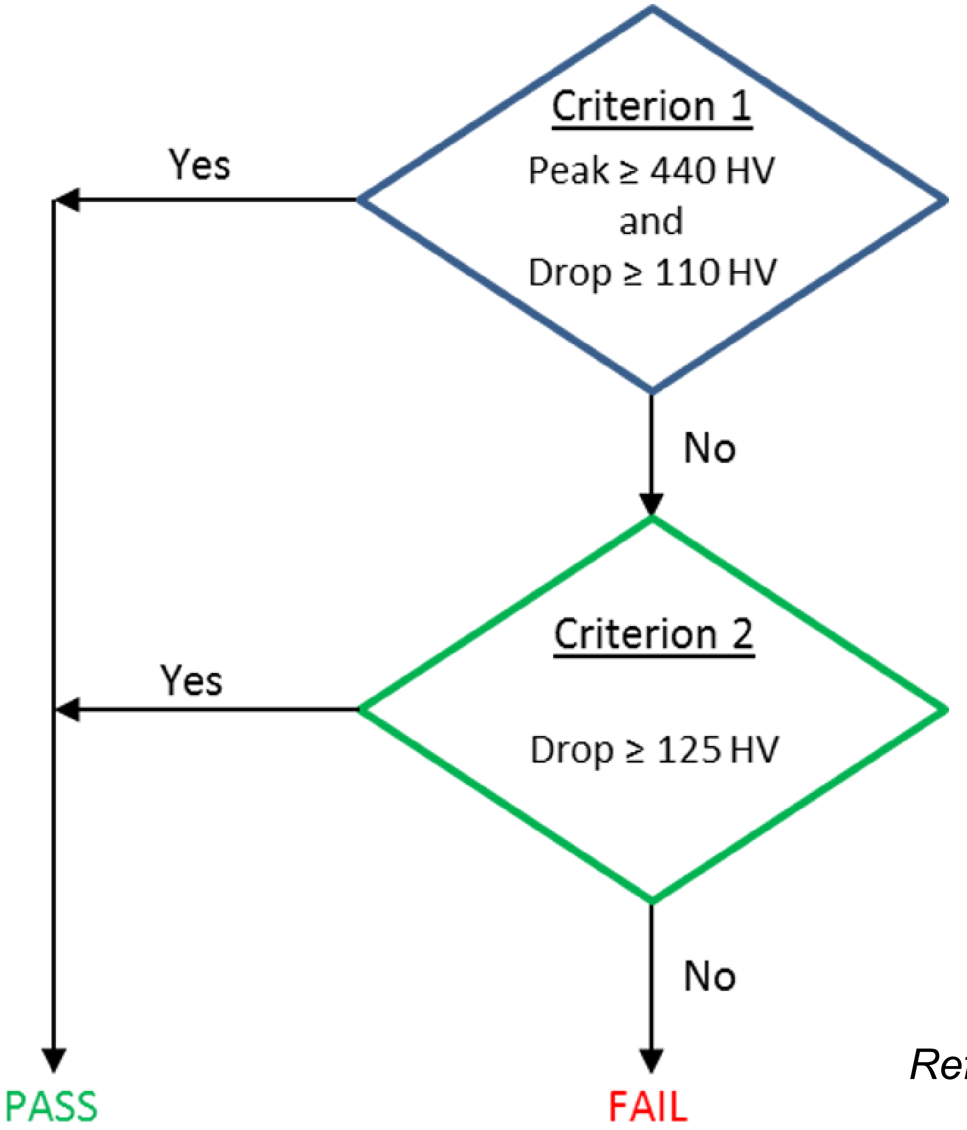
Hardness Drop Acceptance Criterion

- Flowchart showing peak hardness and hardness drop as indicators of appropriate level of tempered martensite in temper bead HAZ

  – Criterion 1: Peak hardness ≥ 440 HV and hardness drop ≥ 110 HV

  or

  – Criterion 2: Hardness drop ≥ 125 HV



Ref. [6]

Temper Bead and Hardness Protocol References

1) McCracken, SL, Smith, RE, & Barborak, D. "Validity of Hardness Criteria to Demonstrate Acceptable Temper Bead HAZ Impact Properties for Nuclear Power Applications." Proceedings of the ASME 2013 Pressure Vessels and Piping Conference. Volume 6B: Materials and Fabrication. Paris, France. July 14–18, 2013. V06BT06A006. ASME. https://doi.org/10.1115/PVP2013-97793.
2) McCracken, SL, & Sutton, B.J. "Qualification of Temper Bead Welding by an Alternative Hardness Testing Approach." Proceedings of the ASME 2015 Pressure Vessels and Piping Conference. Volume 6B: Materials and Fabrication. Boston, Massachusetts, USA. July 19–23, 2015. V06BT06A007. ASME. https://doi.org/10.1115/PVP2015-45663.
3) P. Maynier, B. Jungmann, J. Dollet, Creusot-Loire System for the prediction of the mechanical properties of low alloy steel products, Hardenability Concepts with Applications to Steel, The Metallurgical Society of AIME (1978) 518-545.
4) Lundin, C.D. And Mohammed, S., "Effect of Welding Conditions on Transformation and Properties of Heat-Affected Zones in LWR Vessel Steels," NUREG/CR-3873, November 1989.
5) Smith, B, Ramirez, AJ, McCracken, SL, & Tate, S. "Investigation of Relationship Between Microhardness and Charpy Impact Energy for Temper Bead Welding Qualification: Part 1." Proceedings of the Pressure Vessels and Piping Conference. Volume 1: Codes and Standards. San Antonio, Texas, USA. July 14–19, 2019. V001T01A096. ASME. https://doi.org/10.1115/PVP2019-93950.
6) Smith, B, Ramirez, AJ, McCracken, SL, & Tate, S. "Investigation of Relationship Between Microhardness and Charpy Impact Energy for Temper Bead Welding Qualification: Part 2." Proceedings of the Pressure Vessels and Piping Conference. Volume 1: Codes and Standards. Virtual, Online. August 3, 2020. V001T01A096. ASME. https://doi.org/10.1115/PVP2020-21300.
7) Smith, B. "The Correlation of Hardness to Toughness and the Superior Impact Properties of Martensite in Pressure Vessel Steels Applied to Temper Bead Qualification" PhD Dissertation, Ohio State University, 2021.

Diffusible Hydrogen Threshold for Hydrogen Induced Cracking in Nuclear Pressure Vessel Steels

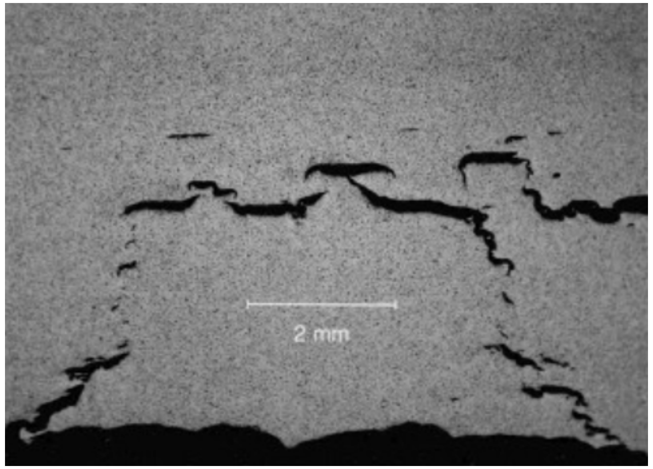
Steve McCracken, Stephen Tate, EPRI
Dr. Abbas Mohammadi, Joshua Velasquez, Fernando Romero, William Siefert, Dr. Boian Alexandrov, OSU

Motivation – Eliminate 48-hour NDE Hold in Case N-888

ASME Case N-888, Ambient Temperature Temper Bead Machine GTAW and SMAW

- 48-hour hold before NDE for detecting Hydrogen Induced Cracking (HIC)
- Large body of OE with no occurrence of HIC when austenitic weld metal is used
  - 48-hour hold requirement eliminated for austenitic weld metal
- Very little OE when ferritic weld metal used
  - Technical basis is needed to support elimination of the 48-hour hold and post weld hydrogen bakeout requirement in Case N-888

Ambient Temperature Temper Bead Weld Metal Buildup for Alloy 690 Instrument Nozzle Repair



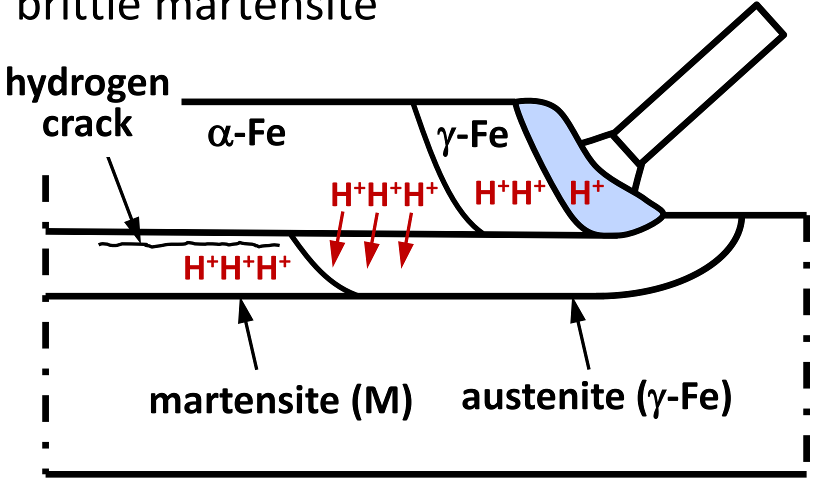
Example of Hydrogen Induced Crack in High Carbon Steel

Using Austenitic Weld Metal to Prevent HIC

- Hydrogen (H^+) has high solubility and low diffusivity in austenite (γ) relative to other phases and acts as a trap for hydrogen to prevent HIC (Park, 2002)

Ferritic Electrodes

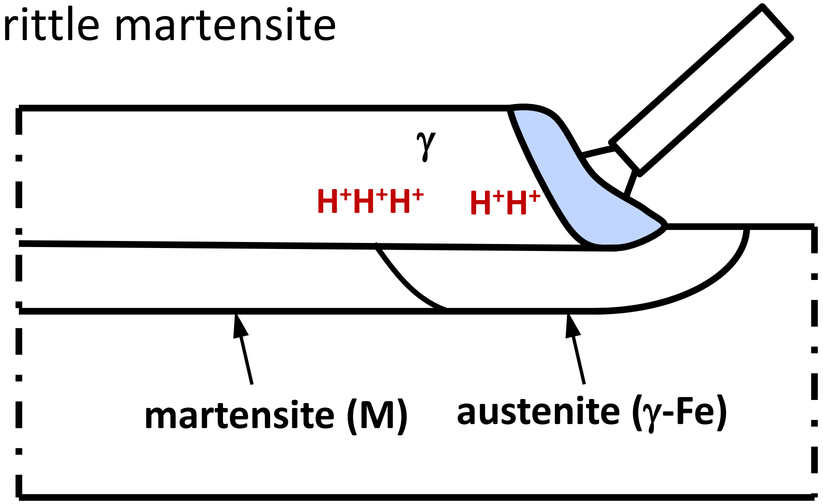
- H^+ is absorbed in the molten weld puddle
- As the solidified weld metal transforms from austenite (γ-Fe) to ferrite (α-Fe) the H^+ is rejected and diffuses into the HAZ
- When the HAZ transforms from austenite (γ-Fe) to martensite (M) the H^+ becomes trapped in the brittle martensite



Hydrogen (H^+) movement with ferritic electrode

Austenitic Electrodes

- H^+ is absorbed in the molten weld puddle
- There is no solid state transformation in the solidified weld metal so the H^+ stays in the austenitic (γ) weld metal
- There is no diffusion of potential H^+ into the brittle martensite

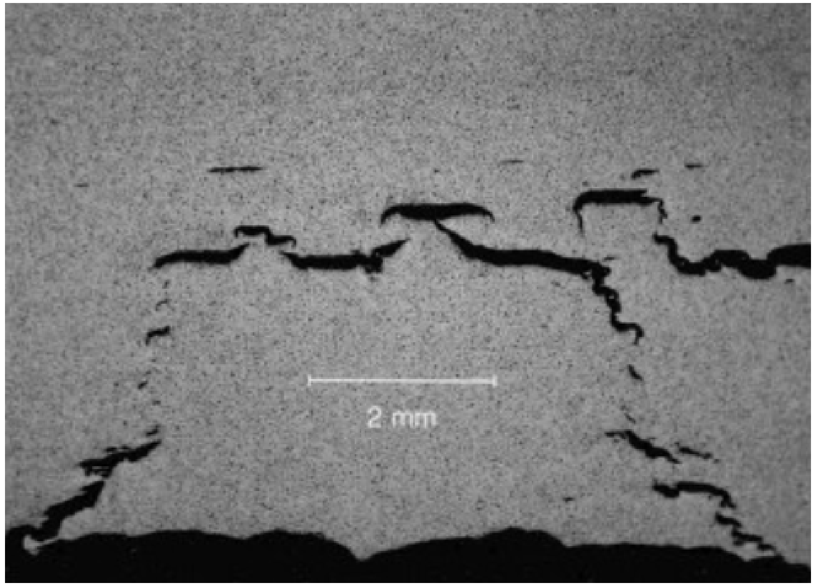


Hydrogen (H^+) movement with austenitic electrode

Schematics adapted from [Lippold 2015] and [Granjon, 1971]

Objective – Determine Diffusible Hydrogen Threshold for HIC in Nuclear Pressure Vessel Steels

- Case N-888 specifies low hydrogen process controls
  - Requires ≤ 4ml / 100g diffusible hydrogen ($H_{diffusible}$) for temper bead welding process
  - Requires stringent storage controls for welding consumables
- Determine $H_{diffusible}$ threshold for HIC in SA-508 P-No. 3 Group 3 low alloy steel
  - Low hydrogen process controls per Case N-888 are adequate if $H_{diffusible}$ threshold for HIC in SA-508 low alloy steel is ≤ 4ml / 100g



Example of Hydrogen Induced Crack Susceptible High Carbon Steel

Delayed Hydrogen Cracking Test (DHCT)

Test for Ranking Resistance to Hydrogen Cracking

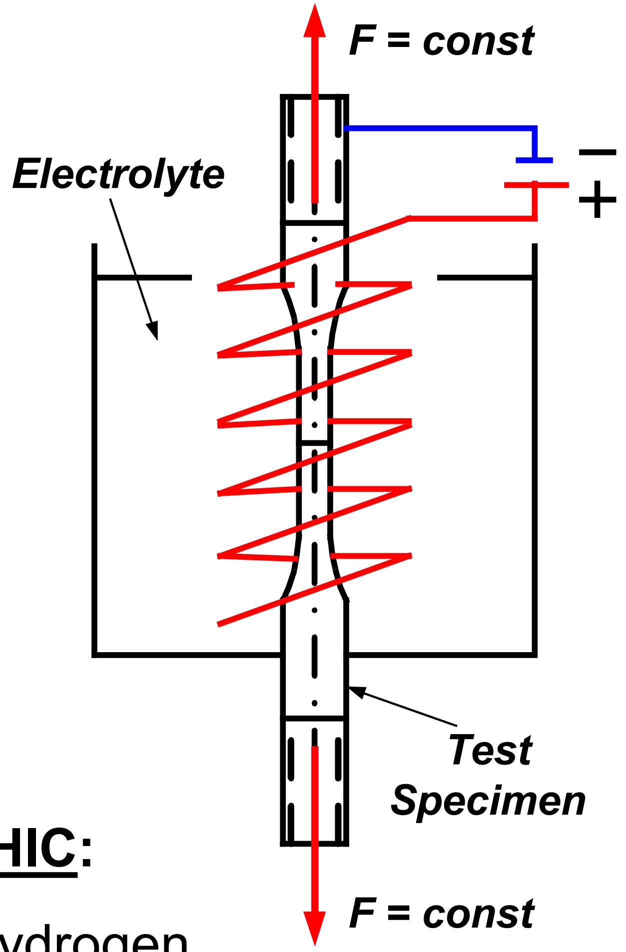
Test sample without notch, flat gauge section

Constant tensile load (slightly below YS)

- 90% YS of SA-508 base (59.94 ksi / 413 MPa)

Electrolytic charging with hydrogen (accelerated charging)

- 0.1 N H_2SO4 + 0.1 g/l Na_2S_2O3, pH 1.2,
- Current Density = 1, 8, 10, 100 mA/cm^2
- **~ 23 ml/100g** @ 100 mA/cm^2
- Expected diffusible hydrogen with low hydrogen controls **< 4 ml/100g**



Test output:

- *Time to Failure*
- *Apparent Threshold Stress*
- *Sustained Mechanical Energy*
- *Sustained Displacement*

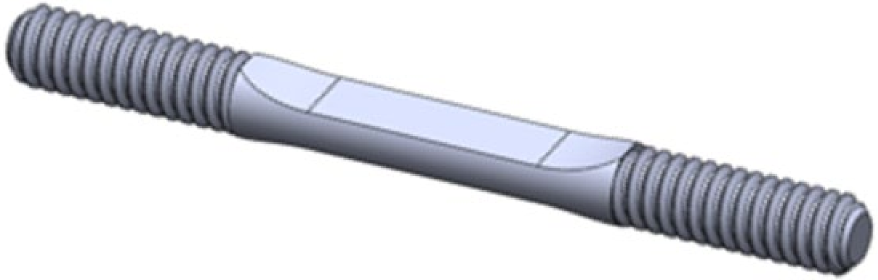
Criterion for Resistance to HIC:

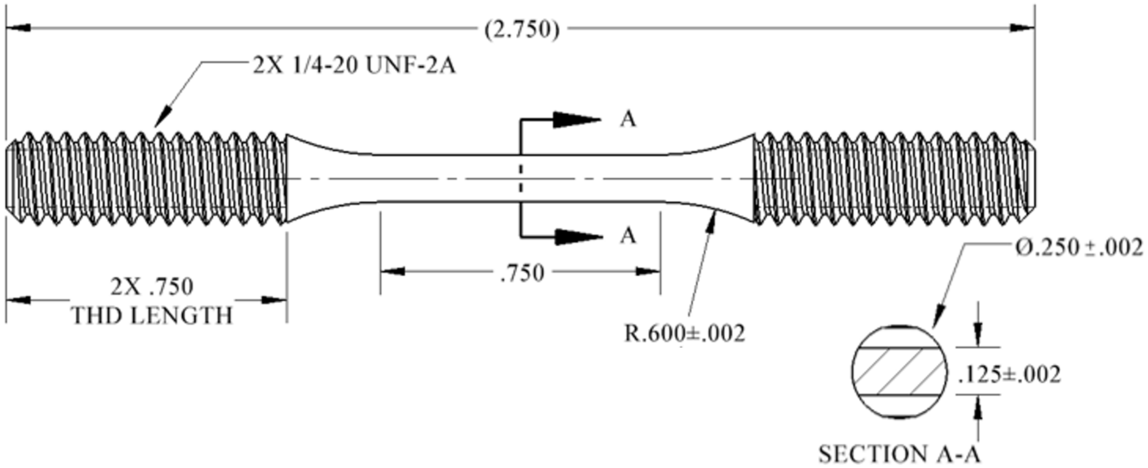
No DHCT failure for 2 x time for hydrogen saturation at load of 90% base metal YS

Criterion for Ranking HIC susceptibility:

DHCT time to failure at load of 90% base metal YS

Sample Design & Test Duration





- EDM sample machining; manual polishing of the gauge section
- 4 mm of the simulated HAZ (gauge section center) exposed to hydrogen charging
- Rest of the sample coated with electrically insulating, corrosion resistant compound

Diffusion Equation: $t = \mathrm{k}\frac{l^2}{D}$

- Time for Hydrogen Saturation: t = (half gauge thickness)^2 / D_H = 70 hours
- Half gauge thickness = 1.5875 mm; D_H = 1x10^{-7} cm^2/s for low alloy steel HAZ
- DHCT Test Time: 2 x hydrogen saturation = 140 hours (5.8 days)
- Selected Test Duration: 168 hours (7 days)

HAZ Gleeble Simulations [1]

Gleeble™ 3800 thermomechanical simulations of CGHAZ microstructures:

- Material is ASME SA-508 Class 2 (older vintage heat)
- As welded (AW) coarse-grained heat affected zone (CGHAZ)
- AW + PWHT
- AW + single temper bead weld (TBW) reheats at 675°C, 700°C, 725°C, 735°C

Condition	Temperature (°C)	Hold Time	Average Heating Rate	Average Cooling Rate	Hardness, $HV_{0.5}$	Microstructure
Base Metal	-	-	-	-	175 ± 4	base metal
AW CGHAZ	1340	-	156.0°C/s	94.3°C/s	425 ± 17	fresh M
PWHT CGHAZ	635	1 hr	200.0°C/hr	200.0°C/hr	197 ± 7	tempered M
TBW@ 675°C	675	1 s	38.0°C/s	27.8°C/s	313 ± 9	tempered M at increasing percentages
TBW@ 700°C	700	1 s	36.7°C/s	30.3°C/s	298 ± 9	
TBW@ 725°C	725	1 s	23.4°C/s	10.4°C/s	298 ± 11	
TBW@ 735°C	735	1 s	26.5°C/s	14.3°C/s	278 ± 15	tempered M and ferrite at PAGBs

M = Martensite   PAGBs = Prior Austenite Grain Boundaries

Delayed Hydrogen Crack Test (DHCT) [1]

CGHAZ Condition	DHCT Result (90% Base Metal YS) / Test Time (hr)							HIC Resistance Ranking*
	1 mA/cm²	8 mA/cm²	10 mA/cm²				100 mA/cm²	
	Test 7	Test 6	Test 1	Test 2	Test 3	Test 4	Test 5	
AW	F / 0.9	-	F < 40	F / 0.8	F / 0.9	-	F / 1.4	1
PWHT	-	NF/321	NF/168	F / 90	NF/261	NF/168	NF/335	3
TBW675	-	CF/246	NF/692	F / 0.9	F / 6.2	NF/282	F / 188	1
TBW700	-	NF/316	NF/184	NF/168	NF/310	-	NF/330	3
TBW725	NF/308	-	NF/691	NF/334	NF/168	-	NF/306	3
TBW735	-	F / 118	NF/312	NF/168	NF/260	-	CF/682	2

F = Failure, NF = No Failure, CF = Corrosion Failure

* Resistance to HIC ranked as: 1 – Susceptible, 2 – Slightly Susceptible, 3 – Resistant
10 mA/cm^2 current density was used for susceptibility ranking

Note: ~23ml/100g diffusible hydrogen with 100 mA/cm^2 charging

Conclusions and Future

- **HIC susceptibility of simulated SA-508 steel CGHAZ tested with the DHCT**
  - Constant tensile load at **90% base metal YS**
  - Accelerated hydrogen charging, **~23 ml/100g** diffusible hydrogen (**worst case scenario**)
- **Tentative criterion for HAC susceptibility**
  - No failure in DHCT for > 2 x hydrogen saturation time at 90% base metal YS
    - Highly Resistant to HIC: CGHAZ TBW@700C and TBW@725C and TBW@735 (278-289 $HV_{0.5}$)
    - Resistant to HIC: PWHT CGHAZ (197 $HV_{0.5}$)
    - Slightly Susceptible to HIC: CGHAZ TBW@675C (313 $HV_{0.5}$)
    - Susceptible to HIC: AW CGHAZ (425 $HV_{0.5}$)
- **Future work**
  - AW CGHAZ and TBW@675: DHCT at **4 ml/100g** diffusible hydrogen
  - Determine **critical hydrogen content** for HIC in all CGHAZ temper conditions

Hydrogen Induced Cracking and Temper Bead References

1) F. Romero, W. Siefert, S.L. McCracken, B. Alexandrov, Effect of Reheated CGHAZ Microstructure on Hydrogen-induced Cracking Susceptibility in SA-508 Steel. *10th International Conference on Advances in Materials, Manufacturing & Repair for Power Plants*, EPRI 2024, 2024-10.

2) Mohammadi, A, McCracken, SL, & Alexandrov, BT. "Effect of Postweld Heat Treatment and Temper Bead Welding on the Hydrogen Induced Cracking Susceptibility in the Heat Affected Zone of SA-508 Pressure Vessel Steel." *Proceedings of the ASME 2023 Pressure Vessels and Piping Conference*. Atlanta, Georgia, USA. July 16–21, 2023. V001T01A007. ASME. https://doi.org/10.1115/PVP2023-106079.

3) McCracken, SL, & Patel, A. "Elimination of the 48-Hour Hold for Ambient Temperature Temper Bead Welding with Austenitic Weld Metal." *Proceedings of the ASME 2023 Pressure Vessels and Piping Conference*. Atlanta, Georgia, USA. July 16–21, 2023. V001T01A071. ASME. https://doi.org/10.1115/PVP2023-107489.

4) Velasquez, JD, Alexandrov, BT, & McCracken, SL. "Hydrogen Induced Cracking Susceptibility in the Heat Affected Zone of SA-508 Pressure Vessel Steel." Proceedings of the Pressure Vessels and Piping Conference. Volume 4B: Materials and Fabrication. Las Vegas, Nevada, USA. July 17–22, 2022. V04BT06A008. ASME. https://doi.org/10.1115/PVP2022-84781.

ASME Temper Bead Code Cases

Progress and Revisions

Stepwise Temper Bead Progress and Advancements pg 1

N-432	1986	Automatic or Machine GTAW Temper Bead Technique. *Requires elevated preheat and post weld hydrogen bake out, and a minimum of six layers.*
N-606	1999	Ambient Temperature GTAW for BWR Control Rod Drive Housing/Stub Tube Repairs. *Reduces the number of layers from six to a minimum of three layers, reduced preheat to 10°C (50°F), eliminated post weld hydrogen bakeout.*
N-638	1999	Ambient Temperature Machine GTAW Temper Bead Technique. *Reduces the number of layers from six to a minimum of three layers, reduced preheat to 10°C (50°F), eliminated post weld hydrogen bakeout.*
N-432-1	2001	Automatic or Machine GTAW Temper Bead Technique. *Reduces the number of layers from six to a minimum of three layers. Elevated preheat and post weld hydrogen bake out still required.*
N-651	2001	SMAW Temper Bead without Removing First Layer Weld Bead Crown. N-651 is a CDTT. *Requires elevated preheat and post weld hydrogen bake out. Removal of grinding was an improvement in reducing time and potentially radiological dose.*

Stepwise Temper Bead Progress and Advancements pg 2

N-638-1	2003	Permits fluid to remain in the system to reduce radiological exposure even when the component could be drained.
N-638-2	2005	Limits repair on SA-302 Grade B materials unless the material has been modified to include 0.4% to 1.0% nickel, quenching and tempering, and application of a fine grain practice. Clarifies Charpy V-notch lateral expansion values of the HAZ is compared to unaffected base metal, and alternatives if HAZ values are less than unaffected base metal if all other requirements are met. Adds heat input limitation of 45,000 J/in for first three layers and allowing alternate means for interpass temperature measurements. Adds provisions for performing VT-1 visual examination when surface examination is impractical.
N-638-3	2006	Increases maximum area of individual weld from 65,000 mm^2 (100 in^2) to 325,000 mm^2 (500 in^2) and clarified that area limitation is based on the finished surface of the ferritic material.

Stepwise Temper Bead Progress and Advancements pg 3

N-638-4	2006	Clarifies that for ferritic weld materials NDE cannot begin until the weld has been at ambient temperature for 48 hours. When austenitic filler metals are used the NDE can begin after the three tempering layers have been in place for 48 hours. *Final NDE allowed to start 48 hours after the completion of the third layer compared to previous revisions which required the weld to be completed and then wait 48 hours.*
N-762	2007	Permits qualification of temper bead welding procedures to ASME Section IX QW-290 with added requirements for repair and replacement application in the nuclear industry per ASME Section XI. CLTT or CDTT. *Provisions of Case N-762 were added later to ASME Section XI IWA-4600.*
N-638-5	2009	Permits through-wall repairs to circumferential welds.
N-638-6	2011	Directs users to ASME Section IX QW-290 temper bead welding for welding qualifications. It clarified that previous qualifications to N-638 could be used with the provision of N-638-6. *Revision clarifies what is meant by "impractical" for taking direct interpass temperature measurements.*

Stepwise Temper Bead Progress and Advancements pg 4

N-829	2012	New case for ambient temperature temper bead for repair of austenitic stainless steel and nickel base cladding.
N-638-7	2013	Removes requirement for simulated PWHT of the procedure qualification coupon prior to temper bead welding. Provides alternative impact test rules for qualifying the temper bead procedure.
N-839	2014	New code case for ambient temperature SMAW temper bead technique. N-638-7 as the template while including process specific requirements for SMAW.
N-638-8	2014	Clarifies peening used for distortion or peening used for residual stress control which can be used on the final weld layer. Clarifies what is meant by "impractical" for conducting surface examinations. Includes NRC condition of including demonstration of UT using representative samples that contain construction type flaws.
N-638-9	2016	Includes minor wording changes to clarify that impact testing is required for procedure qualification regardless of the construction code requirements.

Stepwise Temper Bead Progress and Advancements pg 5

N-638-10	2019	Re-inserted missing sentence that was removed inadvertently from N-638-5 regarding the use of same P-Number and Group Number base material for the qualification test specimen. Deleted reference to interpass essential variable QW-406.8 which was deleted in QW-290 in 2017 Edition. Clarifies impact property temperature adjustment rules by permitting use of NB-4335.2 adjust temperature and lateral expansion methods to 2001 Edition with the 2002 Addenda or later.
N-638-11	2019	Added neutron fluence and helium threshold requirements when welding on irradiated materials in the reactor vessel beltline region. Addressed NRC condition in RG1.147 requiring UT demonstration on samples with representative construction type flaws. Permits UT per Section V low rigor.
N-888	2020	Combines N-638-11 for machine GTAW and N-839 for manual SMAW.
N-888-1	2022	Removes the 48-hour hold prior to performing examination of the temper bead layers when austenitic weld metal is used. Clarifies the simulated PWHT and UT qualification requirements.

Stepwise Temper Bead Progress and Advancements pg 6

N-888-2	2023	Revised to expand maximum ferritic surface area to be temper bead welded to from 500 in.^{2} (325,000 mm^2) to 1,000 in.^{2} (650,000 mm^2) for weld overlays or weld metal build-ups.
N-888-3	2023	Provision added to permit used of Section XI preservice acceptance standards in lieu of Construction Code Standards (ASME Section III) acceptance criteria when performing UT examinations.
N-888-4	2024	Revised to permit progressive PT examination of partial penetration groove welds in lieu of volumetric examination provided: 1) Temper bead repair uses austenitic stainless-steel or nickel-base filler metal, and 2) Volumetric examination will not provide meaningful results to weld configuration or access restrictions.
N-888-5	(1)	Revised to permit non-temper bead welding procedures after deposition of at least 3/16" (5 mm) austenitic metal deposited following the temper bead requirements of Case N-888.

(1) As of August 2024 this N-888-4 revision is still being considered by the BPV-XI committees.

Temper Bead References

Key WRTC Temper Bead Reports

1. *Welding and Repair Technology Center: Shielded Metal Arc Temper Bead Welding.* EPRI, Palo Alto, CA: 2015. 3002005536.
2. *Welding and Repair Technology Center: Alternative Hardness Test Protocol for Qualification of Temper Bead Welding: Preliminary Report.* EPRI, Palo Alto, CA: 2014. 3002003139.
3. *Welding Repair and Technology Center: Evaluation of Hardness Requirements for Temper Bead Welding – Preliminary Review.* EPRI, Palo Alto, CA: 2013. 3002000602.
4. *Welding and Repair Technology Center: Alternative Rules for Temperbead Qualification.* EPRI, Palo Alto, CA: 2012. 1025168.
5. *Welding and Repair Technology Center: Temperbead Welding Guidance*. EPRI, Palo Alto, CA: 2011. 1022879.
6. *Ambient Temperature Preheat for Machine GTAW Temperbead Applications*. EPRI, Palo Alto, CA: 1998. GC-111050.
7. *Temperbead Welding Repair of Low Alloy Pressure Vessel Steels: Guidelines*. EPRI, Palo Alto, CA: 1994. TR-103354.

More Temper Bead References

1. McCracken, SL, Smith, RE, & Barborak, D. "Validity of Hardness Criteria to Demonstrate Acceptable Temper Bead HAZ Impact Properties for Nuclear Power Applications." *Proceedings of the ASME 2013 Pressure Vessels and Piping Conference*. Volume 6B: Materials and Fabrication. Paris, France. July 14–18, 2013. V06BT06A006. ASME. https://doi.org/10.1115/PVP2013-97793.
2. McCracken, SL, & Smith, RE. "Alternative Approach for Qualification of Temperbead Welding in the Nuclear Industry." *Proceedings of the ASME 2012 Pressure Vessels and Piping Conference*. Volume 1: Codes and Standards. Toronto, Ontario, Canada. July 15–19, 2012. pp. 469-478. ASME. https://doi.org/10.1115/PVP2012-78571.
3. Stewart, J., and Alexandrov, B., 2021. "Quantification of the Hardness Response in the Heat-Affected Zone of Low Alloy Steels Subjected to Temper Bead Welding," *Journal of Manufacturing Processes*, 66, pp. 325–340.
4. W.J. Sperko, Exploring Temper Bead Welding, *Welding Journal* 84(7): 37 to 40.
5. Lundin, C.D. And Mohammed, S., "Effect of Welding Conditions on Transformation and Properties of Heat-Affected Zones in LWR Vessel Steels," *NUREG/CR-3873*, November 1989.

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