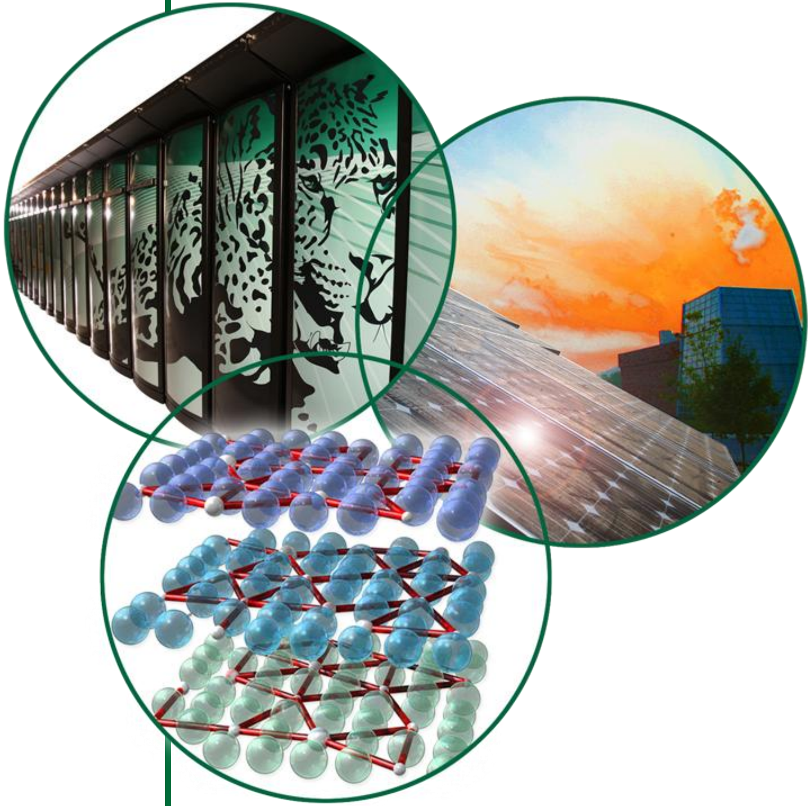
Improving the Performance of Creep-Strength-Enhanced Ferritic (CSEF) Steels



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OAK RIDGE NATIONAL LABORATORY
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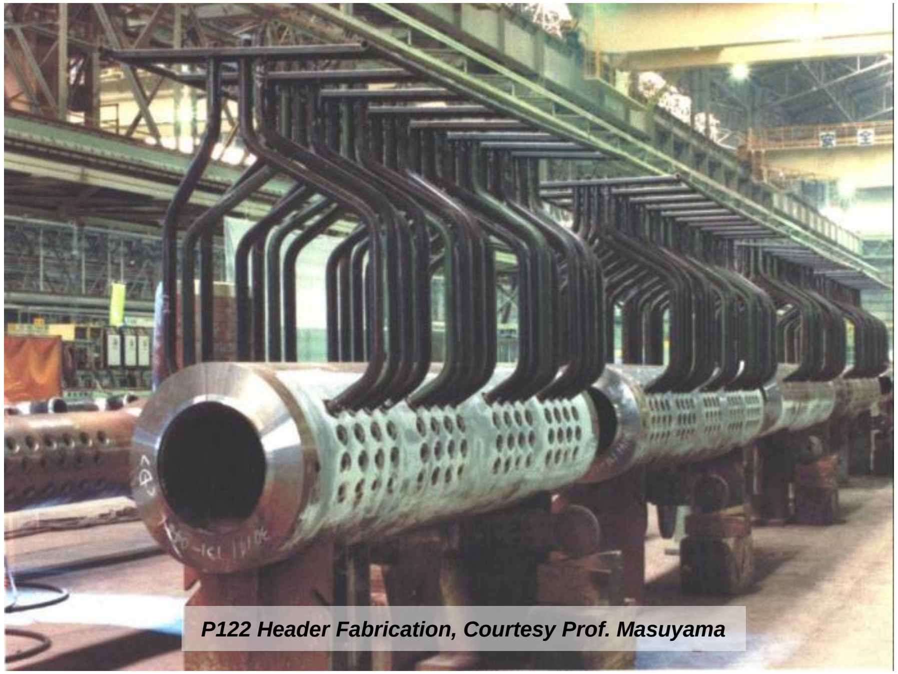
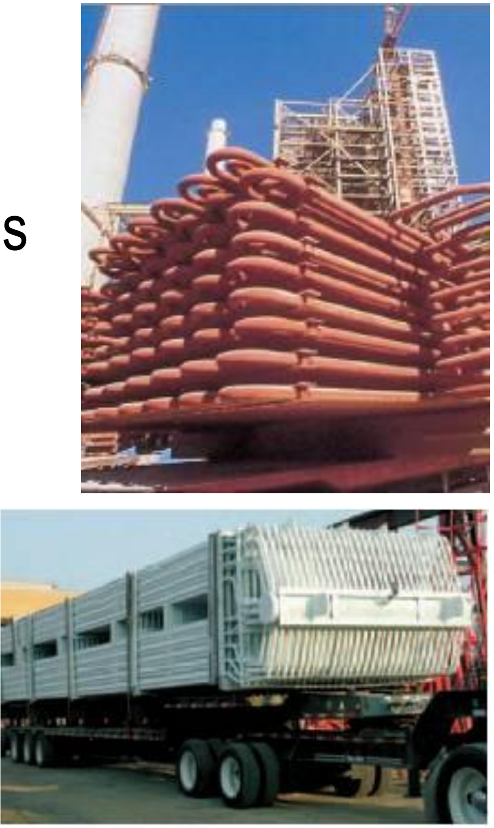
- Dr. Pete Tortorelli, ORNL
- Allan Frederick, Jeff McNabb, and Jeremy Moser, ORNL for technical support
- Dr. Fujio Abe, NIMS, Japan
- Informal collaborations continue with ASME, boiler manufacturers, and EPRI

Estimated CSEF needs for construction of a High-Efficiency Boiler

- Headers & piping
  - P91/P92 – 1,000,000 lbs
- Boiler tubing
  - T23, T91, T92 Alloy Grades – 2,600,000 lbs



P122 Header Fabrication, Courtesy Prof. Masuyama

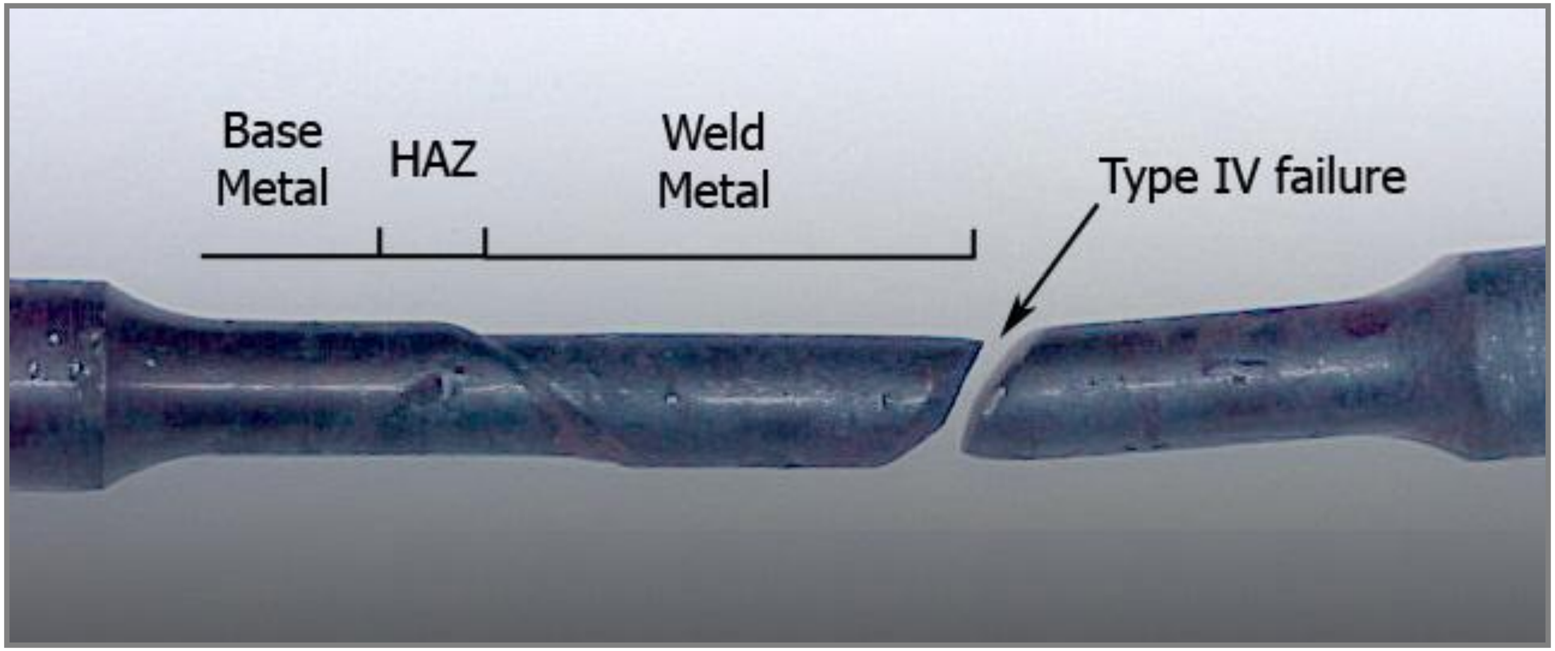


Images courtesy of The Babcock & Wilcox Company, www.babcock.com

Purpose is to build fundamental understanding needed to maximize performance of CSEF steels

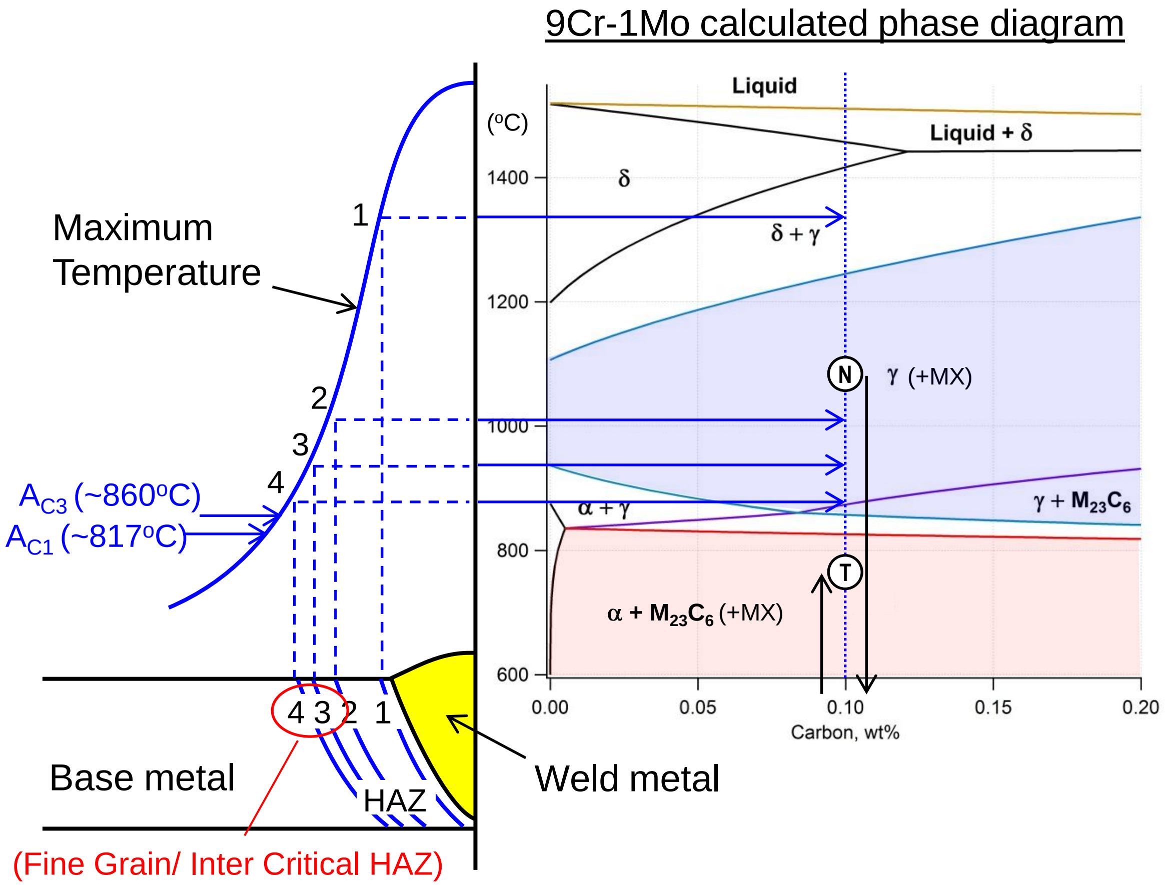
- Activities combine basic & applied R&D with strong power industry interactions
- Specific goals include:
  - Improving the structural performance of (9-12)Cr-Mo steels
  - Provide science-based guidelines for maximizing safe operating temperatures
  - Understand the fundamental causes of current temperature limitations
    - Causes of Type IV failures
    - Possible ways of minimizing/eliminating Type IV failures

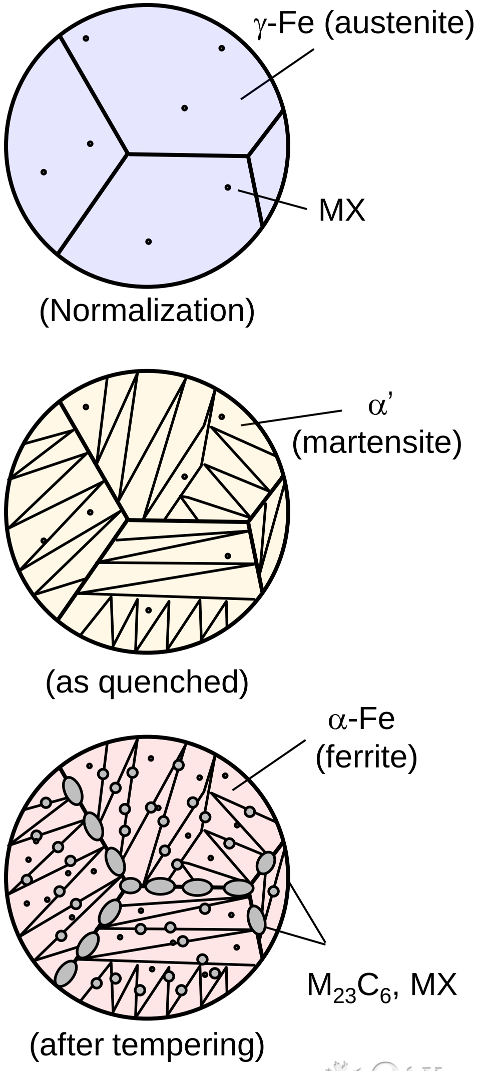
Long-time weldment properties may not meet projections from short-time data



- Type IV failure is due to weakened microstructures in HAZs
- Weld Strength Factors (WSF = $\sigma_{weld} / \sigma_{base\ metal}$) for CSFE steels can be as low as 0.5 at ~600°C.
- Unpredictable behavior that causes unplanned outages, concerns about reliability & safety, more aggressive inspection procedures

Type IV failures depend on gradients of microstructures/properties in weld HAZs

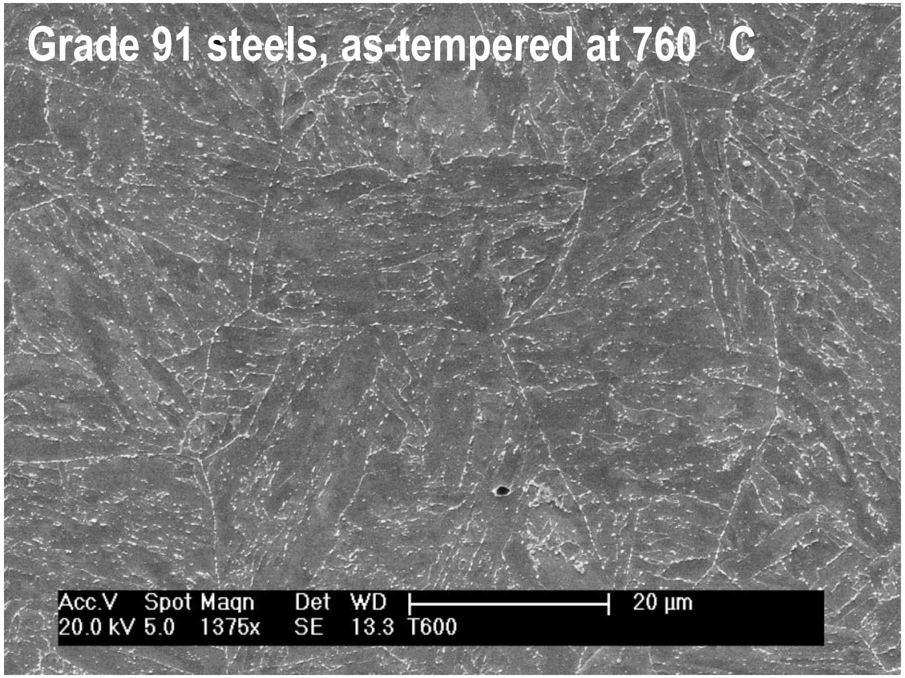

9Cr-1Mo calculated phase diagram



- Post Weld Heat Treatment (PWHT) is applied to temper HAZ/ weld metal.
- Type IV failures take place at FG/ICHAZ, even after PWHT.

Approach to improved CSEF steels relies on two strategies

1. **Modified heat treatments:**
   - Could be effective with <u>existing alloys</u>
   - Implementation could be straightforward
     - ASME Code approval required
2. **Modified alloys:**
   - <u>Newly developed alloys</u> appear more resistant to Type IV behavior
   - Limited experience with welding
     - Behavior is not understood



Grade 91 steels, as-tempered at 760 C

- Martensitic matrix with $M_{23}C_6$ and MX
- Prior austenite grain size is from 15 to 30 microns

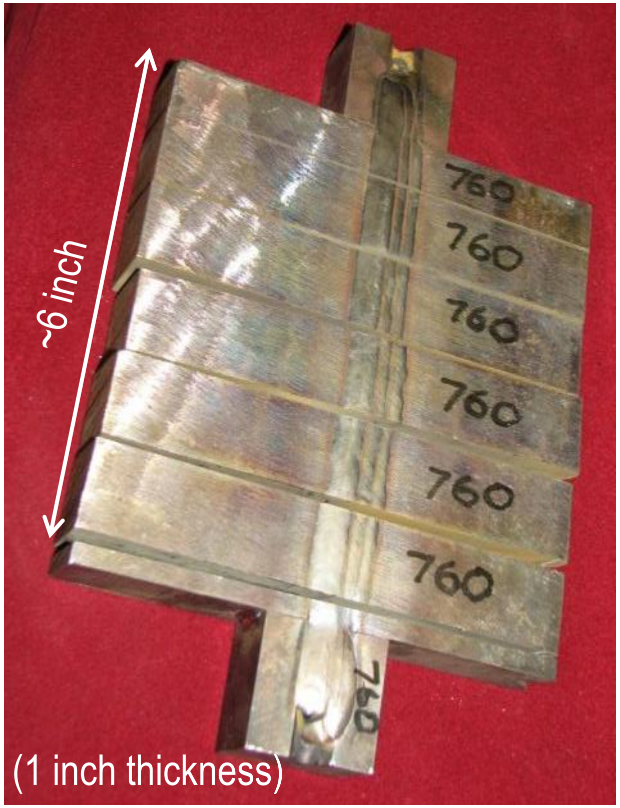
Contents of this presentation

1. **Modified heat treatments (Gr 91):**
   - Characterization/creep test results of PWHT samples (ORNL/OSU)
   - *In-situ* diffraction study of HAZ simulated samples (OSU)
2. **Modified alloys (Gr 92):**
   - Creep test results of Experimental 9Cr steel (ORNL/NIMS)

Table: Chemical composition of the alloy studies

(wt%)	Fe	C	Mn	Si	**Cr**	**W**	**Mo**	Ni	Co	V	Nb	**N**	**B**
Gr 91	Bal.	0.08	0.27	0.11	**8.61**	**-**	**0.89**	0.09	-	0.21	0.07	**0.06**	**<0.001**
Gr 92	Bal.	0.09	0.47	0.16	**8.72**	**1.87**	**0.45**	-	-	0.21	0.06	**0.05**	**0.002**
N130B	Bal.	0.08	0.49	0.30	**8.97**	**2.87**	**-**	-	2.91	0.18	0.05	**0.002**	**0.013**

Modified temper-PWHT concept is being comprehensively revaluated (FY10~)



Sample Preparation Sequence

Pre-weld Temper (1.5h), ^{o}C
800
760
700
650
600

(in ASME: 730-800^{o}C)

Weld with 9Cr filler →

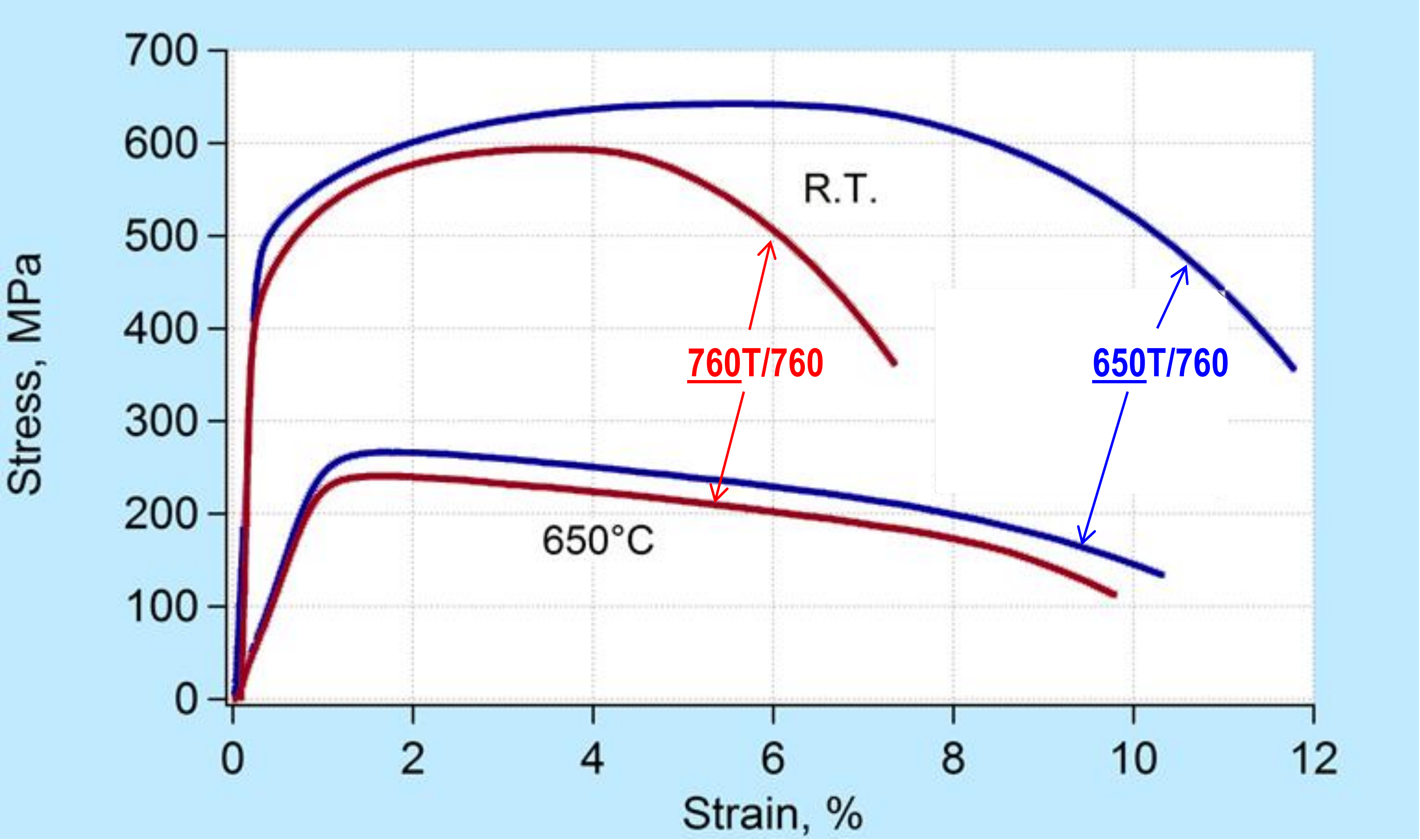
PWHT (4h), ^{o}C
800
760
700

(in ASME: 730-775^{o}C)

Sample IDs are described such as 650T/760 or 760T/760

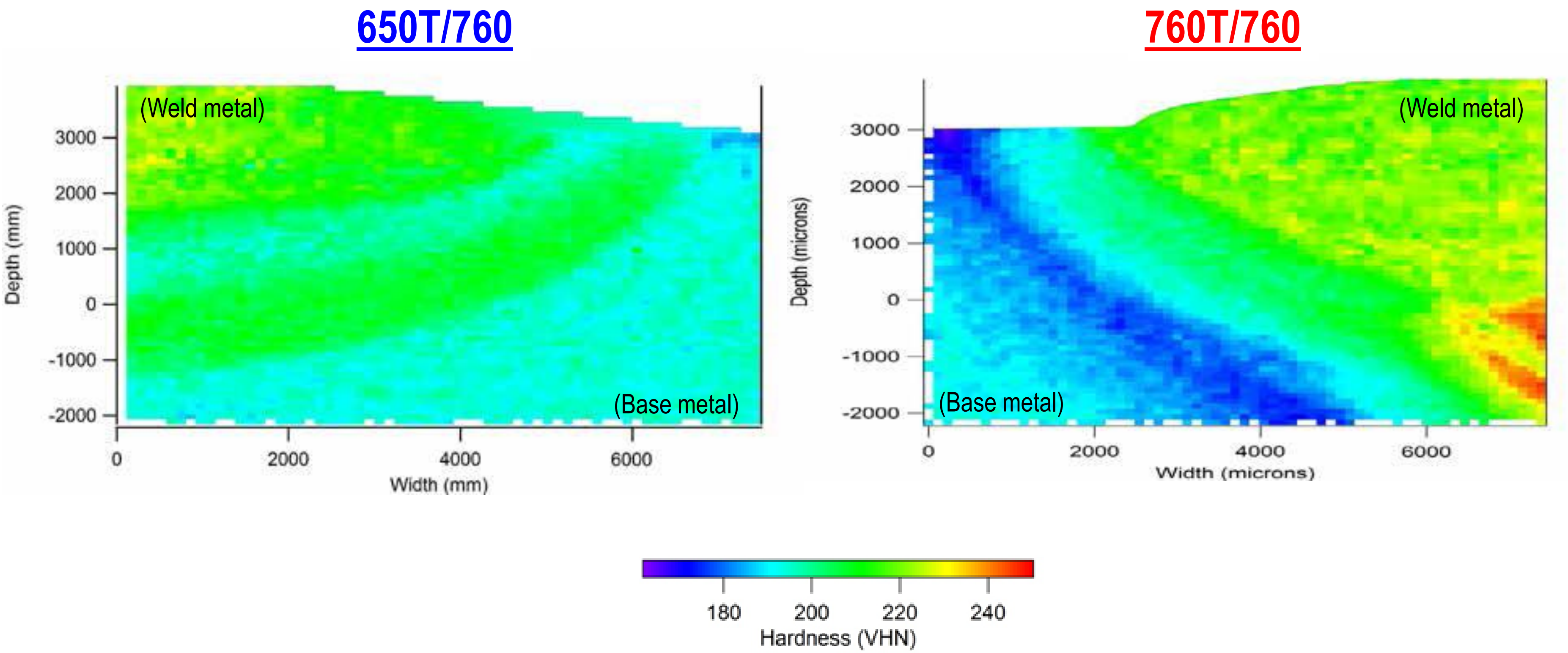
- ✓ Mechanical property screening (tensile, hardness, and creep testing)
- ✓ Metallography

Improved Tensile Properties for Lower Pre-weld Tempering Temperature



- 650T/760 showed higher strength and better ductility than 760T/760

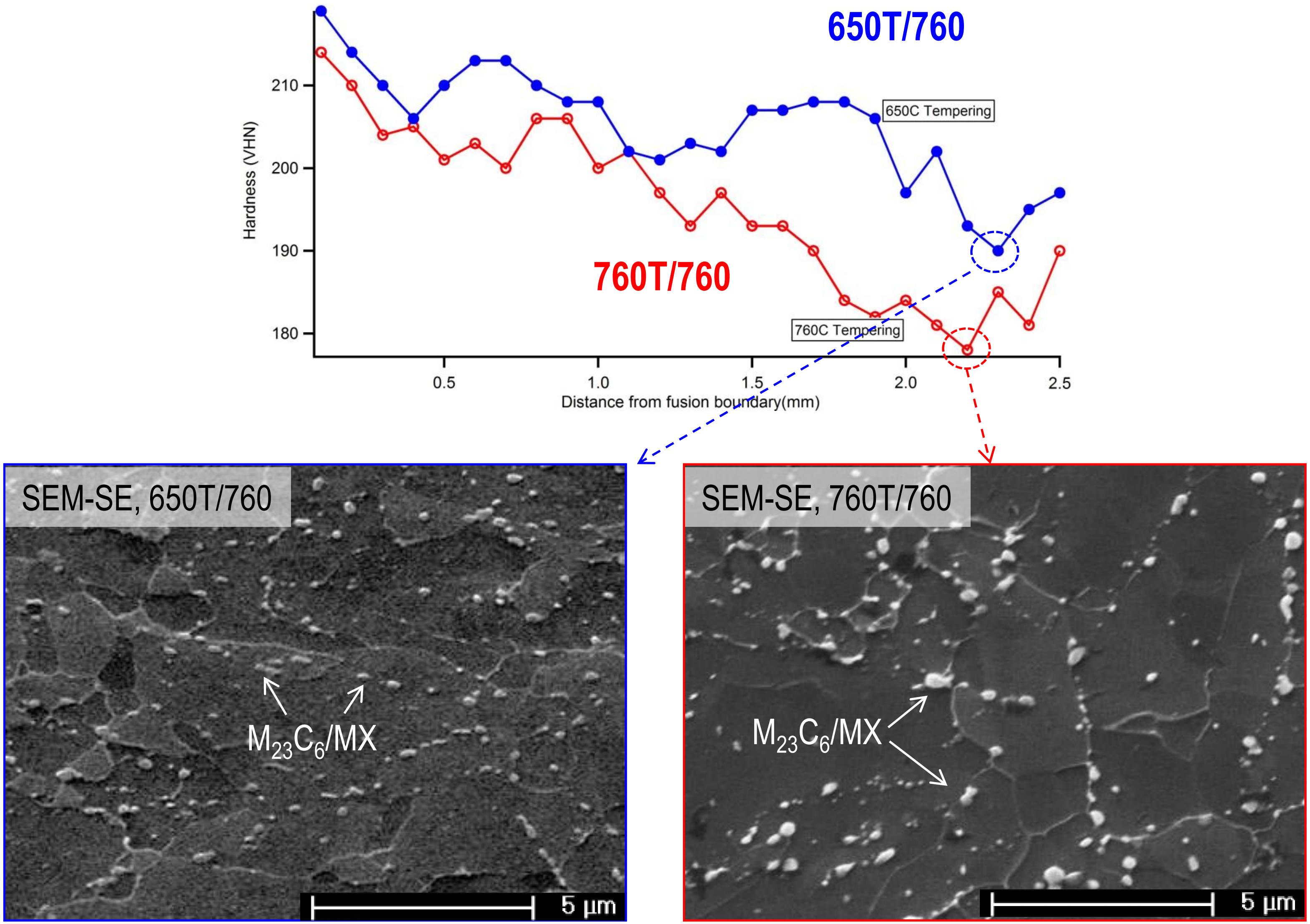
Different Hardness Distribution in HAZ after PWHT


650T/760

760T/760

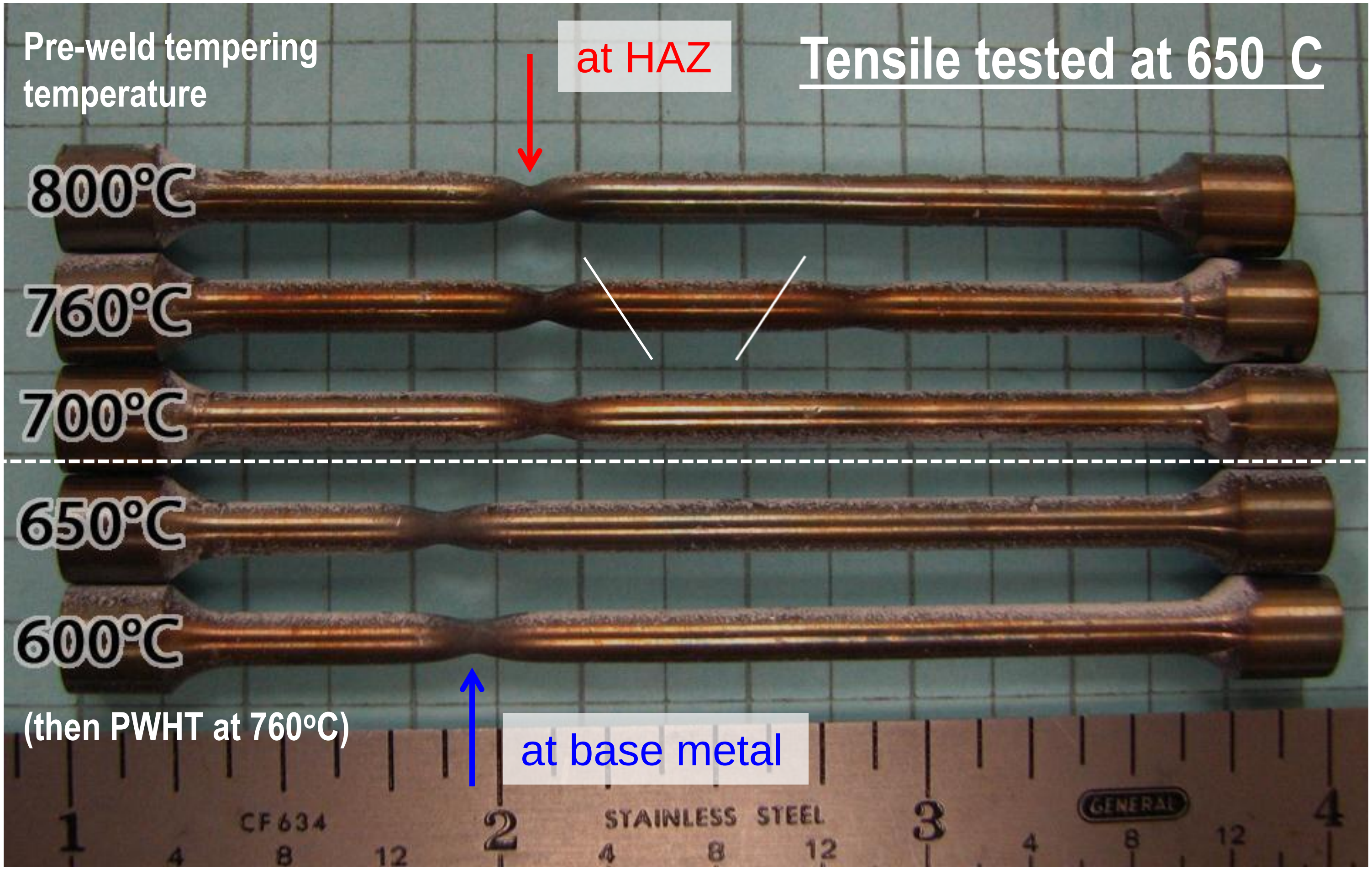
- Distinct soft zone and wide hardness range in 760T/760 specimen

Coarsening of Carbides Trigger Softening



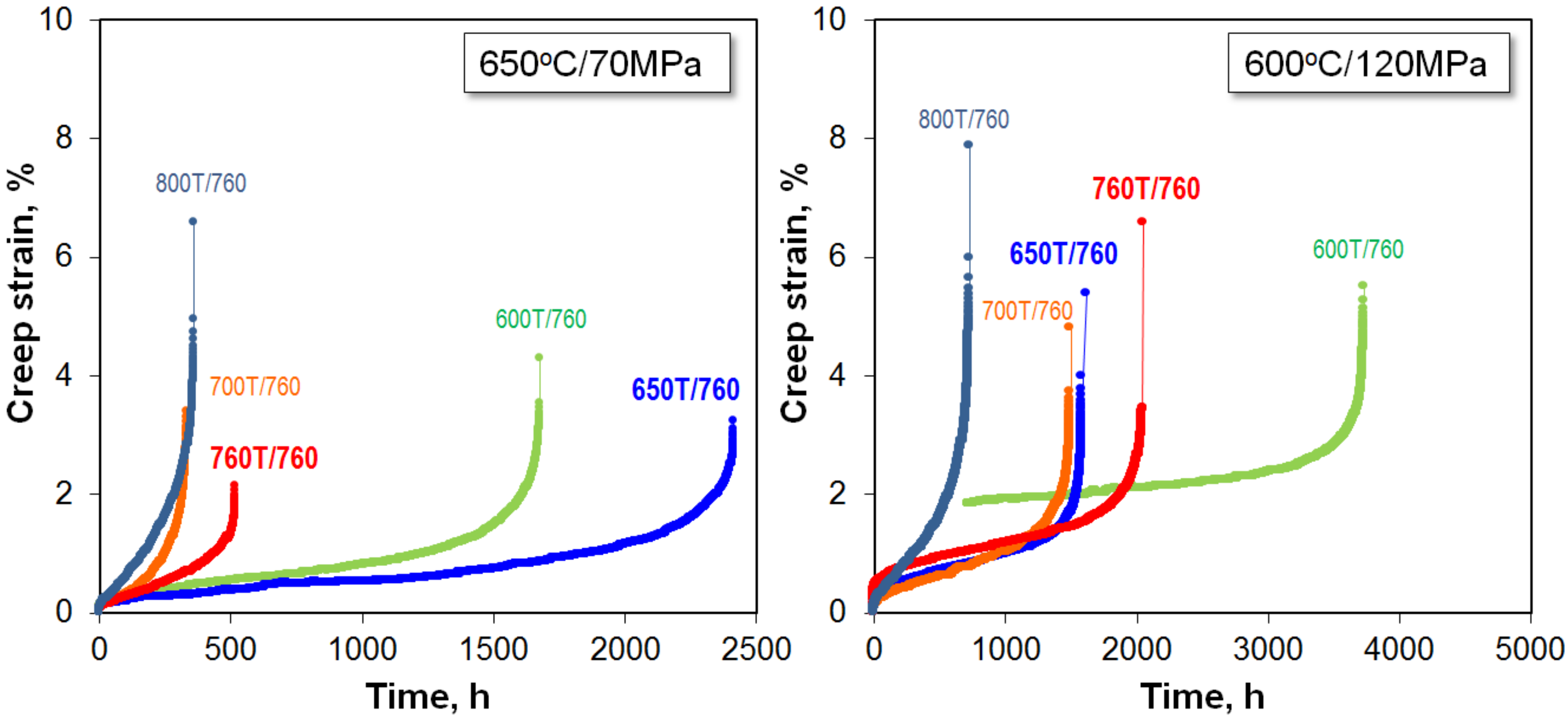
- Coarser $M_{23}C_6$/MX were observed in 760T/760.

Lower tempering temperature shifted fracture locations to base metal



- Fracture behavior transition between 700/650°C

Creep-rupture lives also showed transition

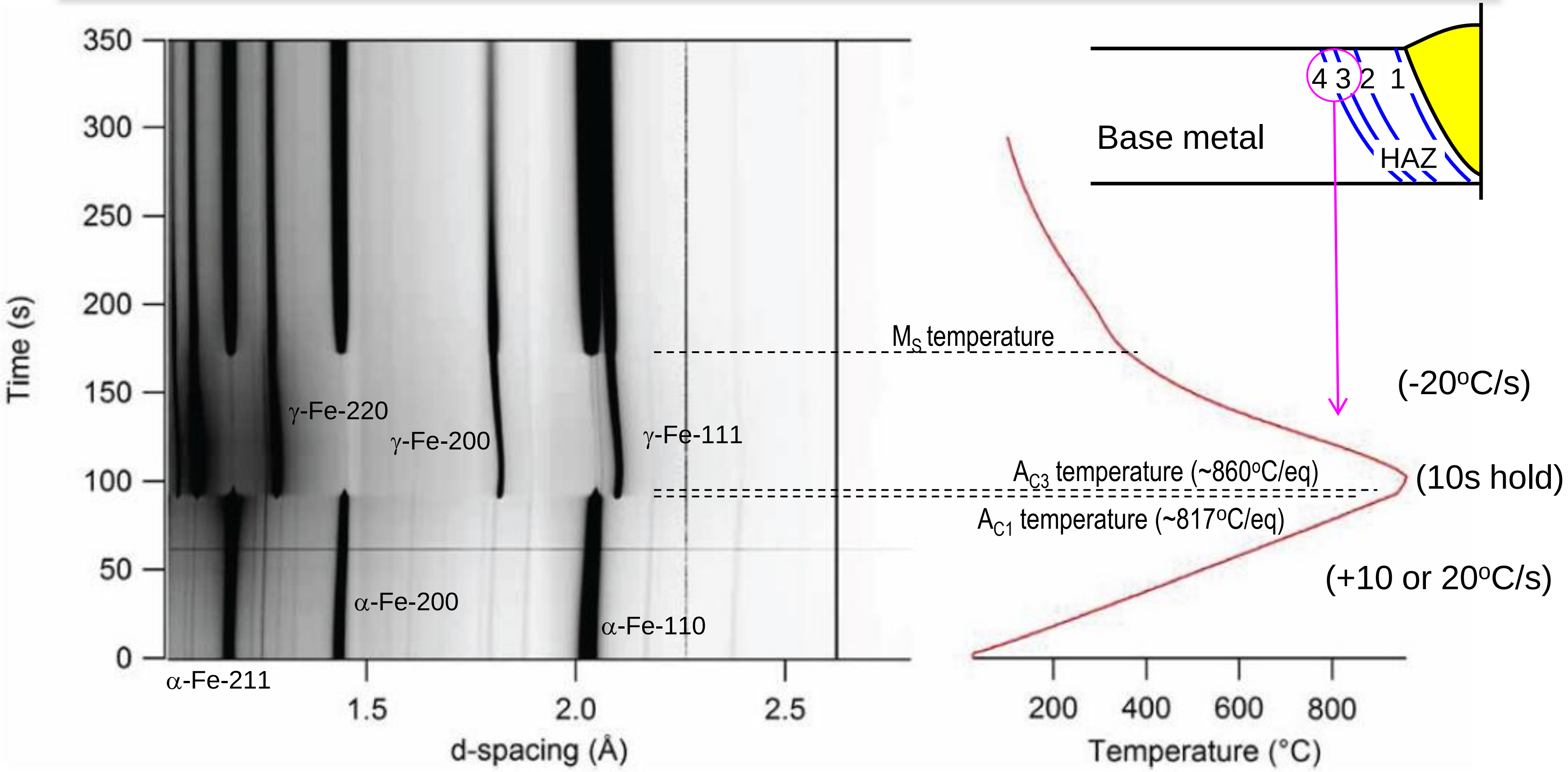


- At 650°C/70MPa: Rupture life for “650T/760” ≃ **5X life** for “760T/760”
- At 600°C/120MPa: need further considerations

In-situ diffraction study of HAZ simulated samples (OSU)

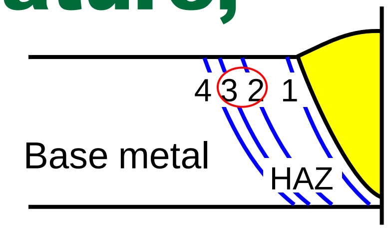
Motivation:	To understand the mechanism of tempering temperature dependence of softening after PWHT.
Output:	Dissolution, Nucleation, and Growth of $M_{23}C_6$ during heating and cooling process explain the variety of microstructure (and properties).

Synchrotron diffraction experiments can capture the transformation dynamics

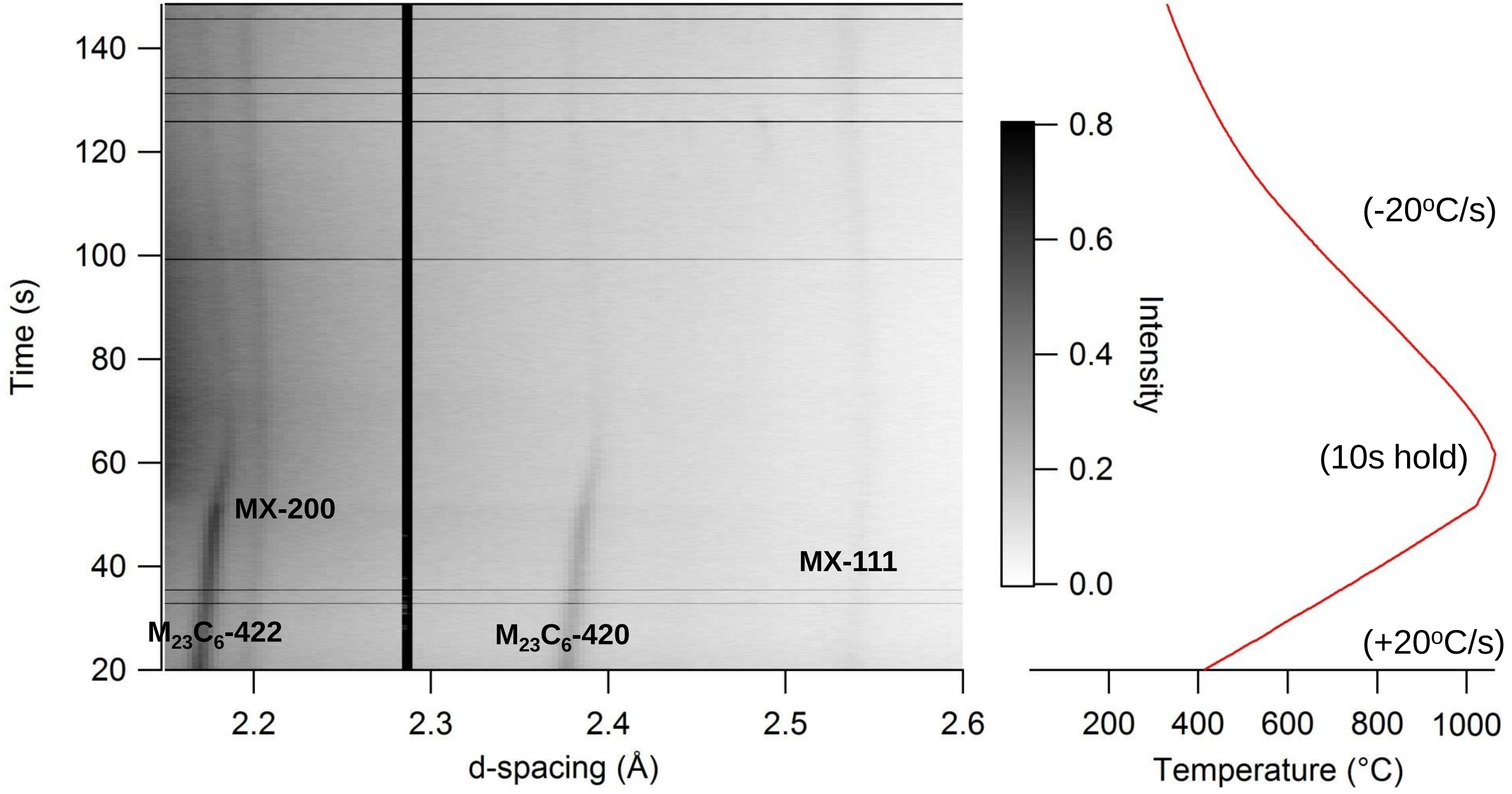


- **Tested two different tempered samples (at 650 and 760°C), at SP8, Japan (by X. Yu and S. Babu, OSU)**
- **Much higher time resolution than conventional XRD**

$M_{23}C_6$ dissolved above A_{C3} temperature, but MX remained after cooling

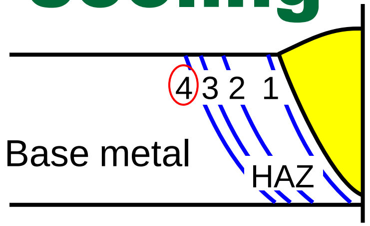


(Tempered at 760°C, Peak temperature = 1050°C)

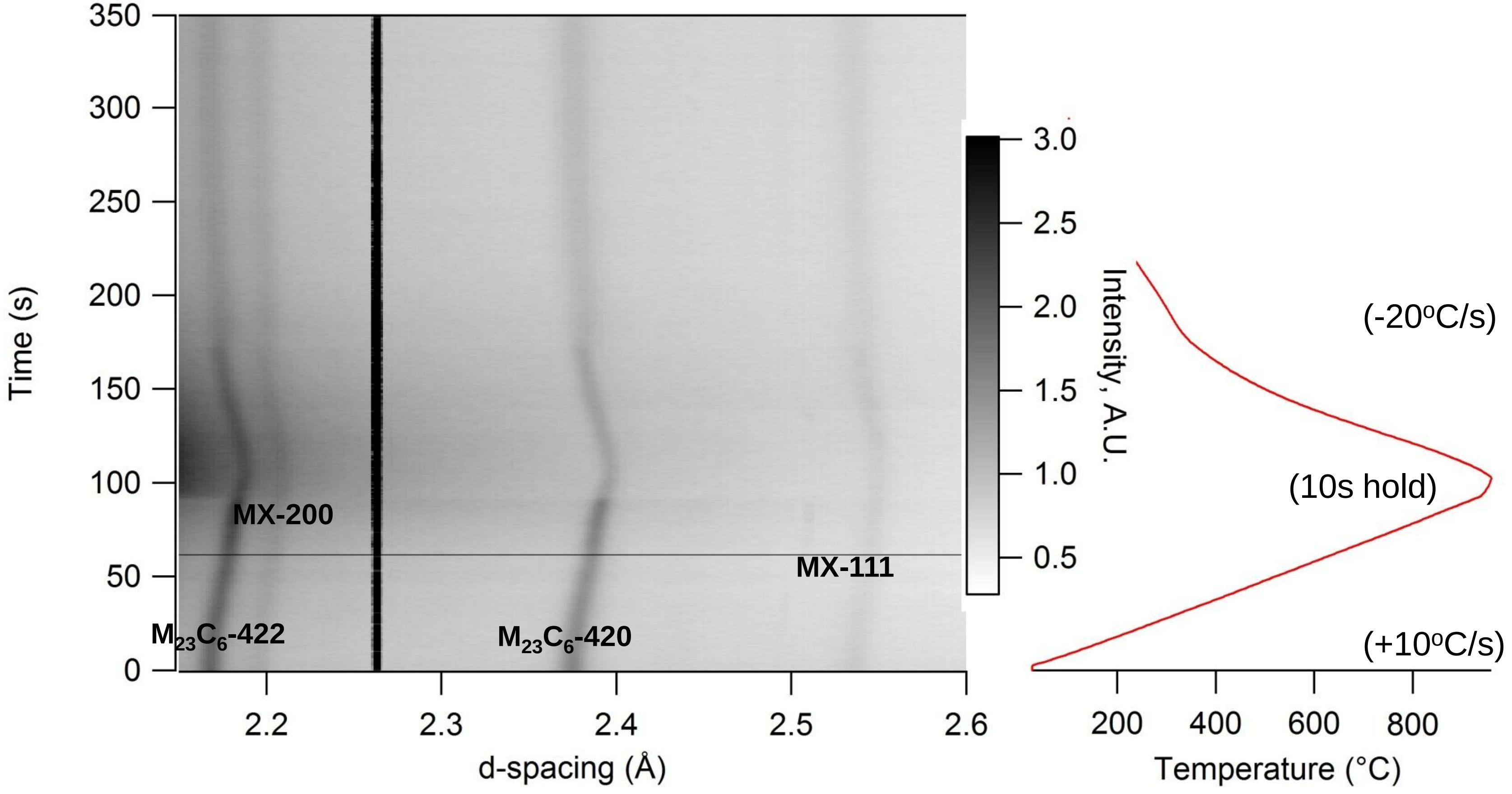


- Contrast of $M_{23}C_6$ after peak temperature is very weak.

Both $M_{23}C_6$ and MX remained after cooling

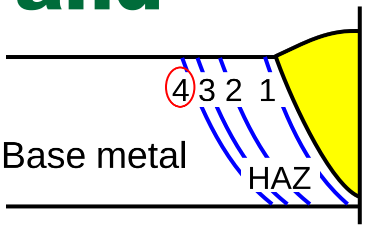


(Tempered at 760°C, Peak temperature = 950°C)

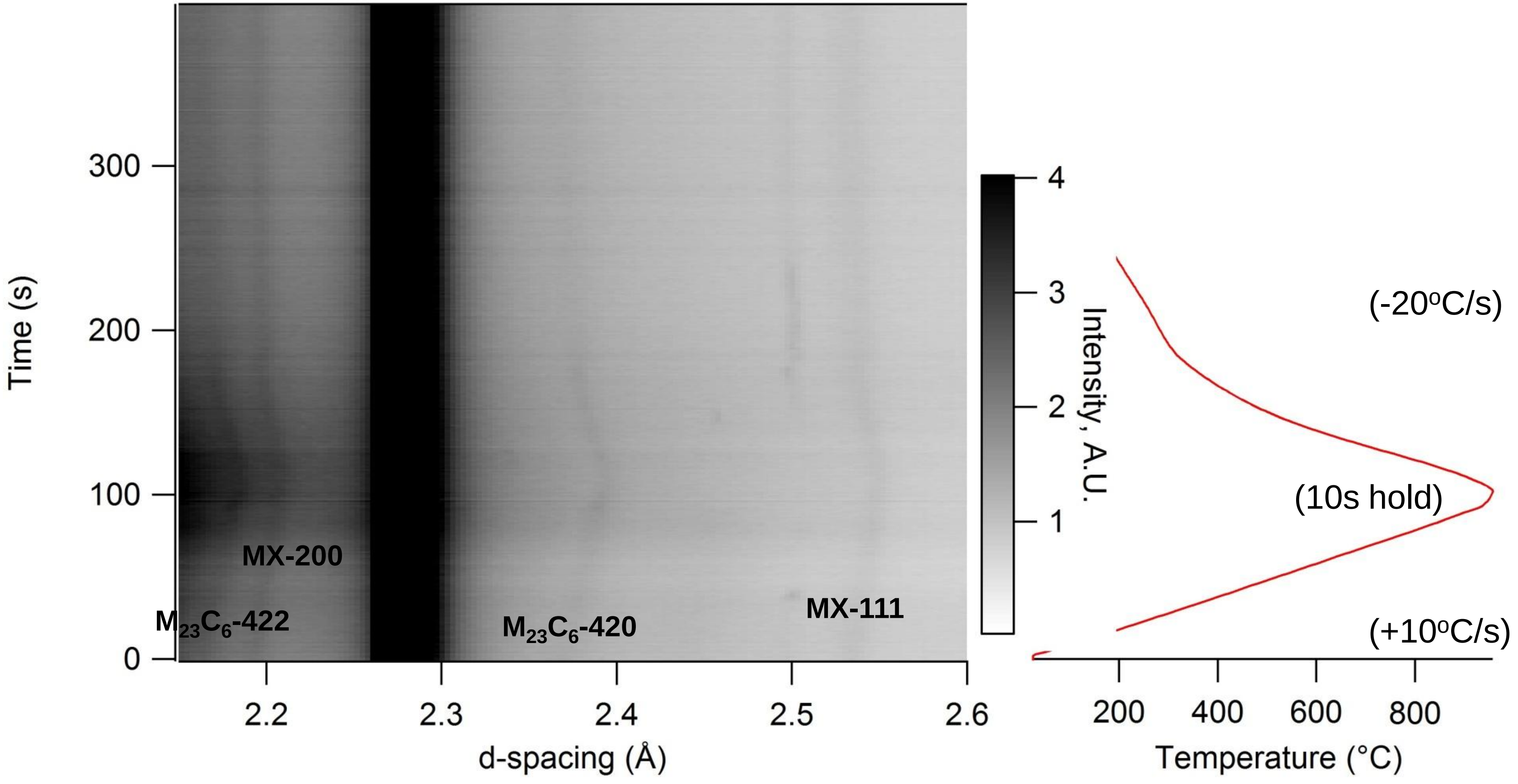


- Lower peak temperature formed residual $M_{23}C_6$.

No obvious $M_{23}C_6$ observed before and after testing

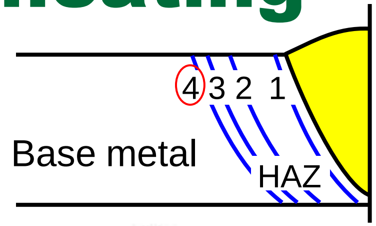


(Tempered at 650°C, Peak temperature = 950°C)

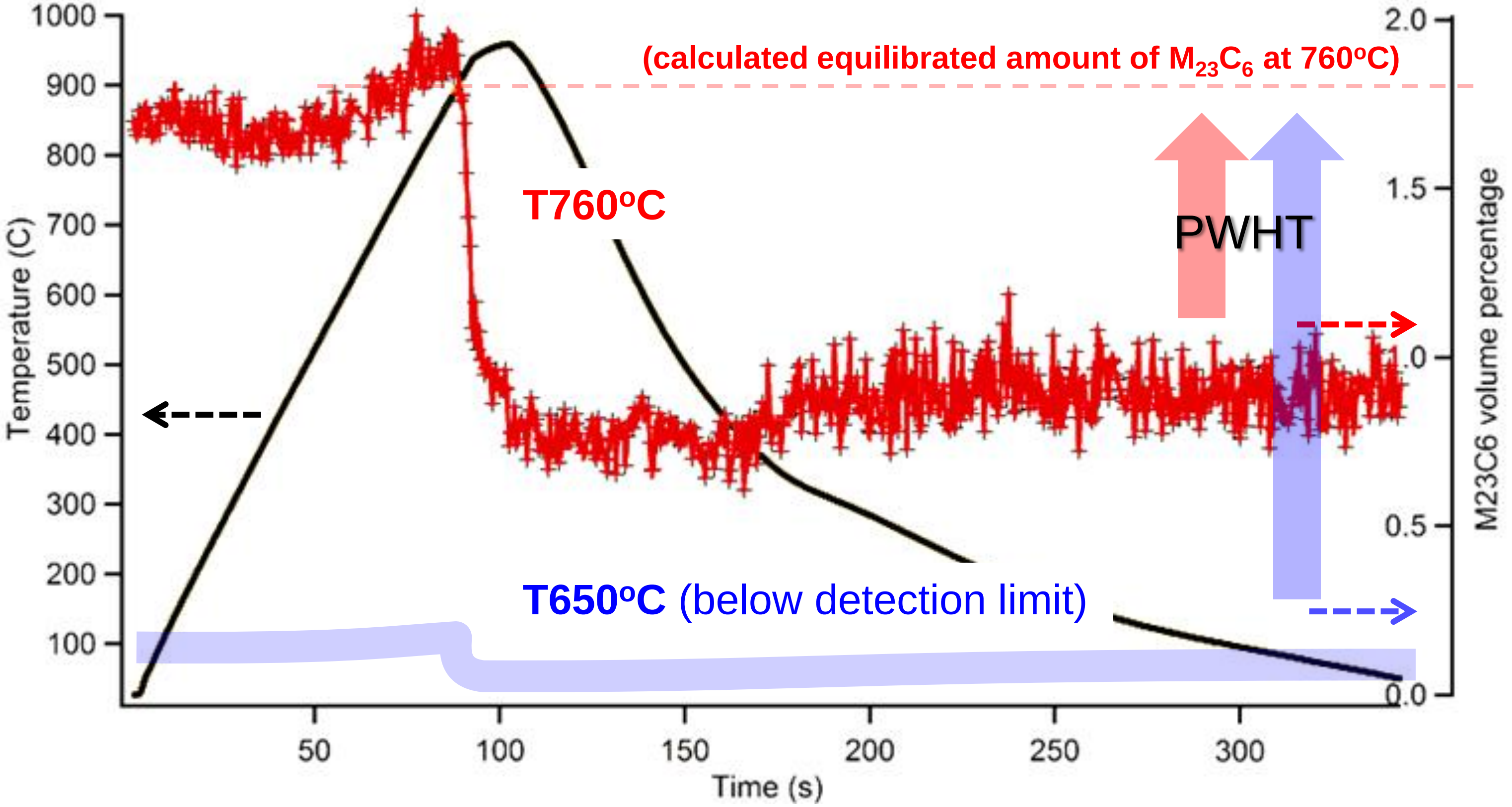


- The amount of $M_{23}C_6$ is lower than the detection limit.

Residual $M_{23}C_6$ due to insufficient heating



(Tempered at 760°C, Peak temperature = 950°C)



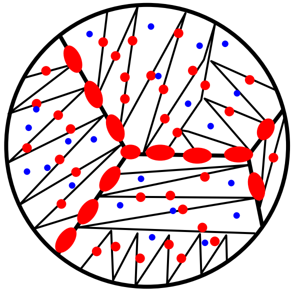
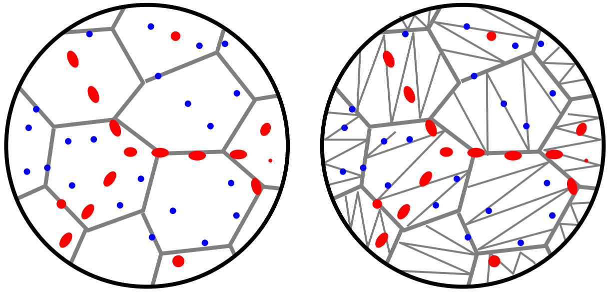
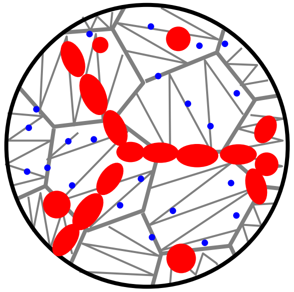
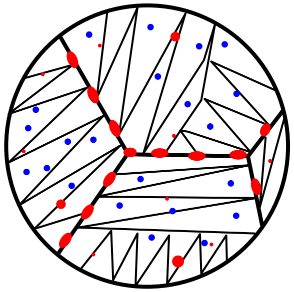
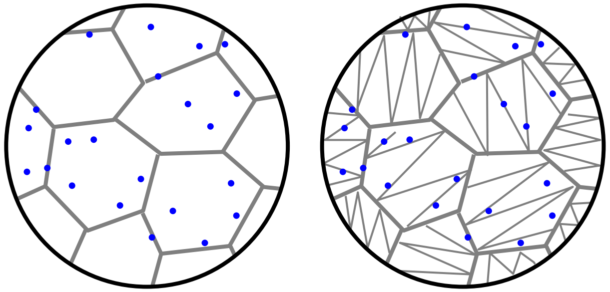
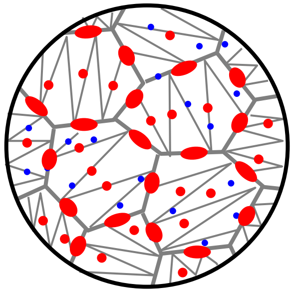
The $M_{23}C_6$ formation mode during PWHT at 760°C:

in T760°C: coarsening of residual $M_{23}C_6$

in T650°C: nucleation and growth (fine precipitate)

Low temperature pre-weld tempering can minimize the formation of coarse $M_{23}C_6$

Table: Microstructure evolution at fine grain heat affected zone

	Pre-weld temper	Weld (at FGHAZ)	PWHT
High temperature pre-weld tempering (e.g. 760T/760)		 (during welding) → (after cooling)	
Low temperature pre-weld tempering (e.g. 650T/760)		 (during welding) → (after cooling)	

● : $M_{23}C_6$ ● : MX

Creep test of Experimental 9Cr steel (ORNL/NIMS)

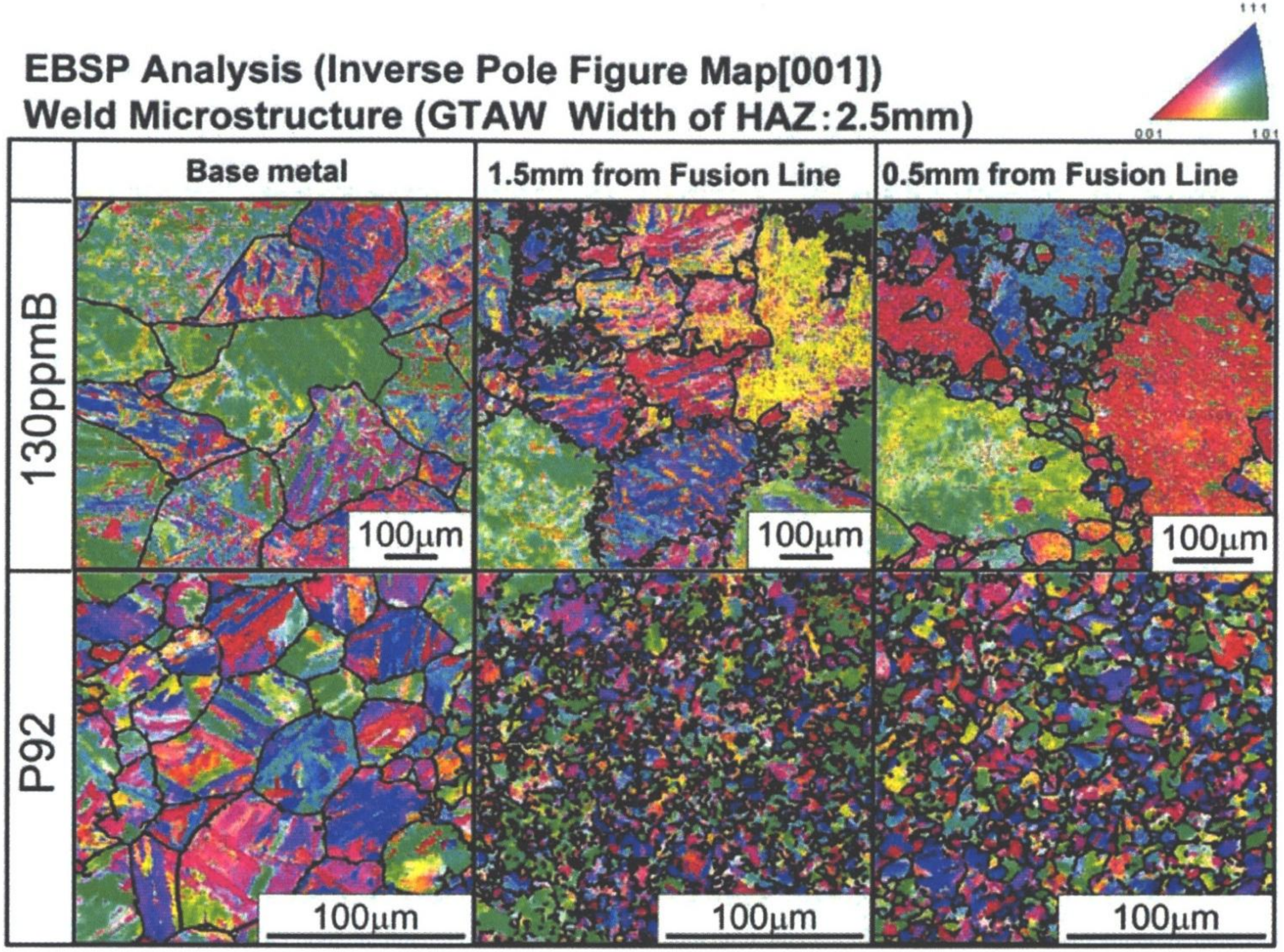
Table: Chemical composition of the alloy studies

(wt%)	Fe	C	Mn	Si	Cr	W	Mo	Ni	Co	V	Nb	**N**	**B**
N130B	Bal.	0.08	0.49	0.30	8.97	2.87	-	-	2.91	0.18	0.05	**0.002**	**0.013**
Gr 92	Bal.	0.09	0.47	0.16	8.72	1.87	0.45	-	-	0.21	0.06	**0.05**	**0.002**

Improved HAZ behavior in modified 9Cr steel

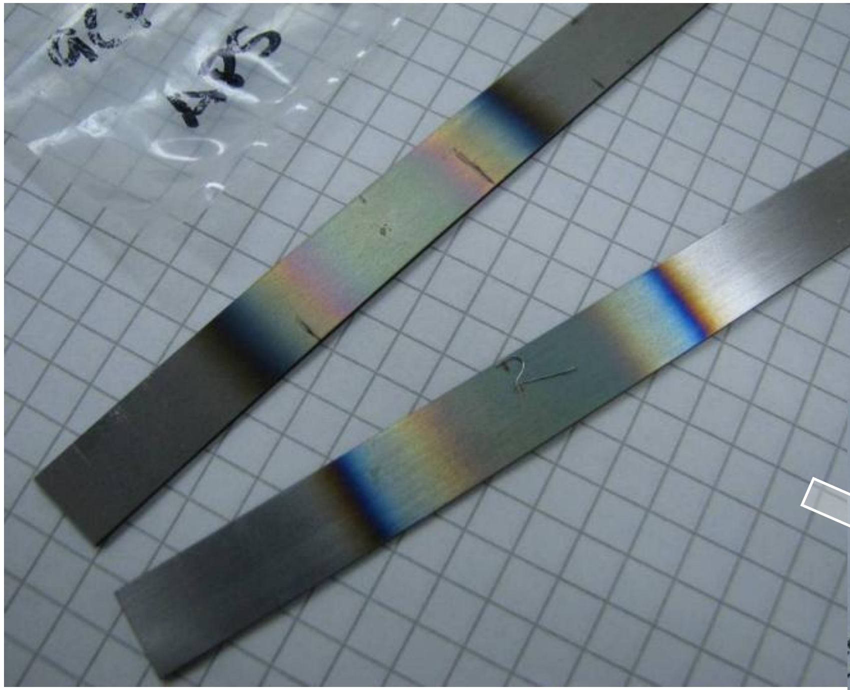
N130B (NIMS)

P92 (reference)

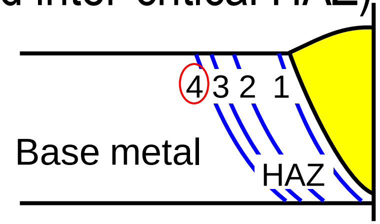


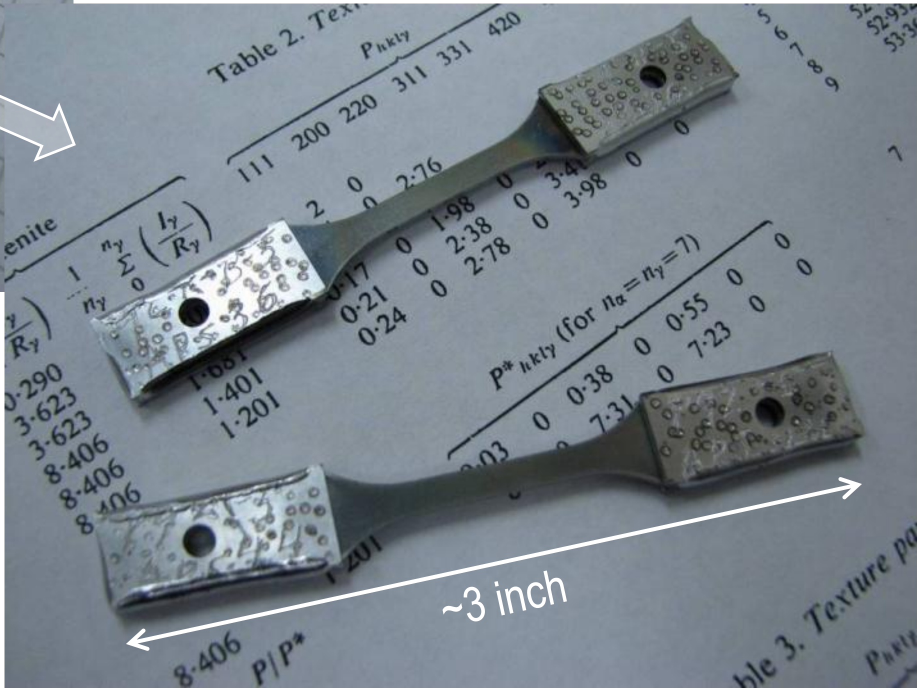
- The B addition resulted in sluggish austenitization (from diffraction study at APS, ORNL).
- No fine grain formation was due to stabilization of $M_{23}C_6$ (NIMS).

Specimens simulated HAZ (P92/N130B)



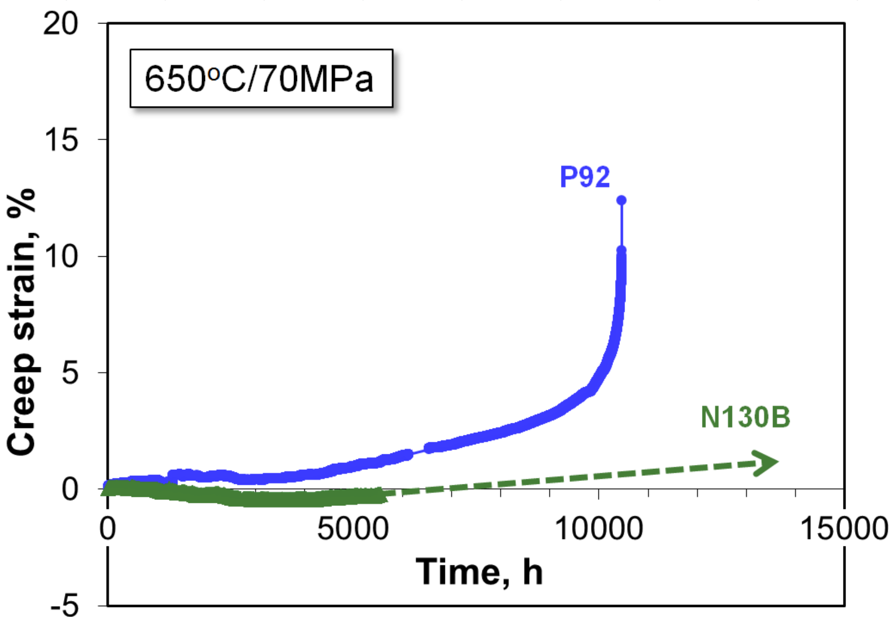
- Specimens with T_{peak} = 900 C (simulated inter-critical HAZ)





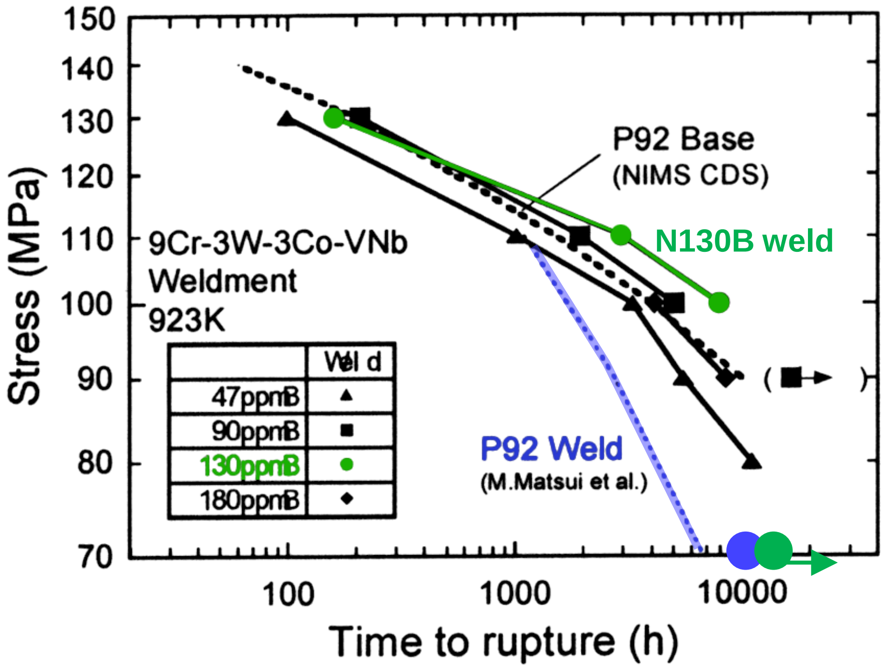
Improved creep properties in N130B

Creep curves of HAZ simulated specimens



P92: ~10500h
N130B: >14,000h (still running)

Creep-rupture lives of weldments



- Microstructure characterization is required for better understanding.

Summary

1. **Modified heat treatments (Gr 91):**
   - Lower pre-weld tempering temperature can improve mechanical properties
     (Better tensile strength/ductility, 5x longer rupture life at 650°C/70MPa)
   - Control of $M_{23}C_6$ dissolution/precipitation is the key to improve the mechanical properties of weld 9Cr steels
2. **Modified alloys:**
   - Eliminating FGHAZ has a potential to avoid type IV failure
     (Improved creep properties of the N and B modified steel)

Future plan:

- Complete characterization of creep-rupture specimens
- Propose new processing route/ alloy compositions based on the current results
  - *Higher strength, better oxidation resistance, and type IV failure resistance*

FY11 Milestones & Status:

- Complete tensile testing of 'best' plates
  - Status: Met
- Initiate long-term creep-tests of welded joints
  - Status: Met
- Evaluate aged microstructures and issue a technical paper/report on current state of studies
  - Status: Delayed until FY12 (scheduled July 31, 2012).
- Evaluate initial creep-test results, determine progress
  - Status: Met

FY12 Milestones & Status:

- Characterize cross-weld specimens of 9Cr steel weldments subjected to non-standard heat treatments
  - Status: Met
- Evaluate creep-test results of synchrotron diffraction specimens
  - Planned May 31, 2012
- Produce a publication on initial results of microstructure characterization of creep specimens from modified heat treatment study (in collaboration with OSU)
  - Planned July 31, 2012
- Initiate production of experimental heats of new, advanced creep strength enhanced ferritic steels with resistance to type IV cracking
  - Planned September 30, 2012