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

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Bernd Kuhn, Michal Talik
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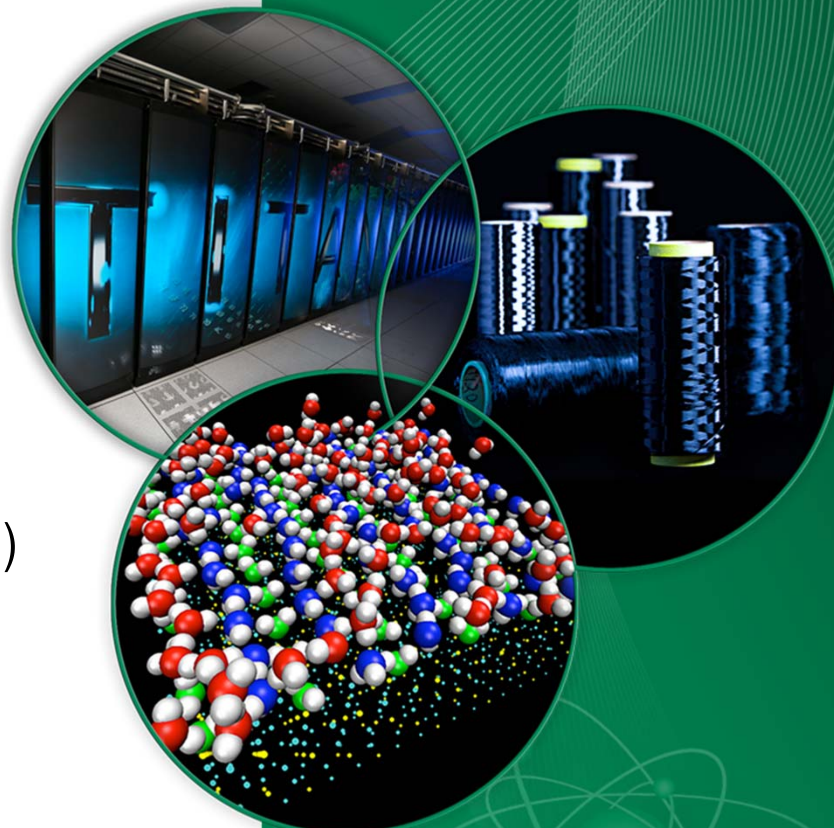

Acknowledgments:
Drs. Mike Santella, Pete Tortorelli, Bruce Pint, Ian Wright, and Vito Cedro
The Crosscutting Research Program, Office of Fossil Energy, U.S. Department of Energy

May 19 – 23, 2014 NETL Crosscutting Research Review Meeting, Pittsburgh, PA

U.S. DEPARTMENT OF ENERGY

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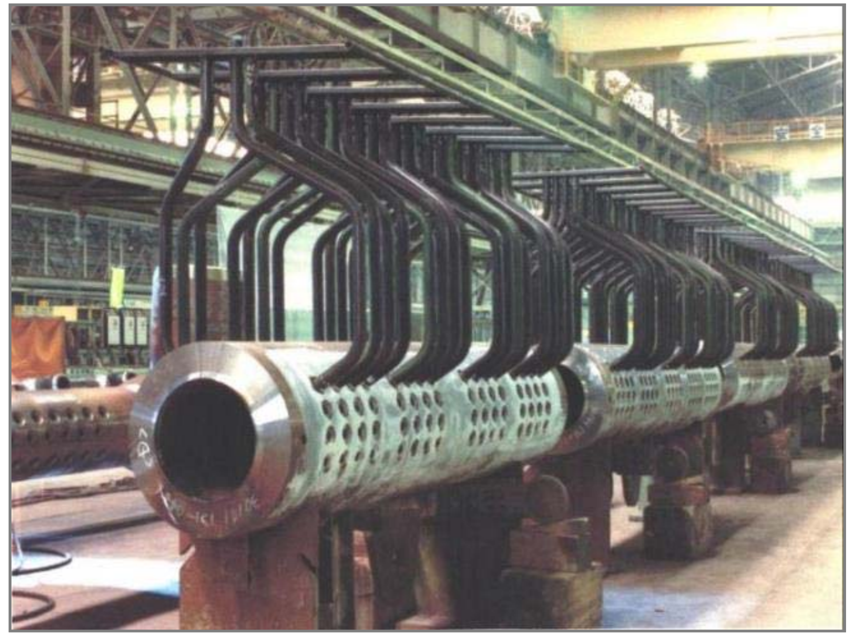
Outline of this talk

- Motivation of this project
- Efforts in FY13-FY14
  1. Optimization of heat treatments
  2. New alloy development
- Milestone status in FY13/FY14
- Summary / Future Work



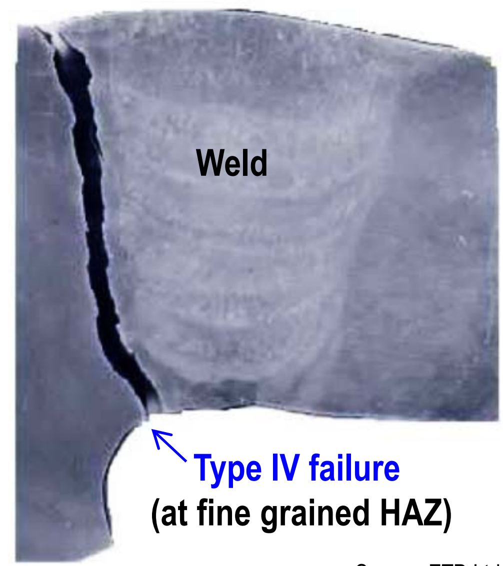
CSEF Steel Header Fabrication, Courtesy Prof. Masuyama

Why "Improvement" of CSEF required?

- **Majority of structural components for High-Efficiency Boilers (T23, T/P91, T/P92)**
- **Life of weldments shorter than Base Metal**
  - Type IV failure shortens the material life, caused by weakened microstructure at the heat affected zone (HAZ)

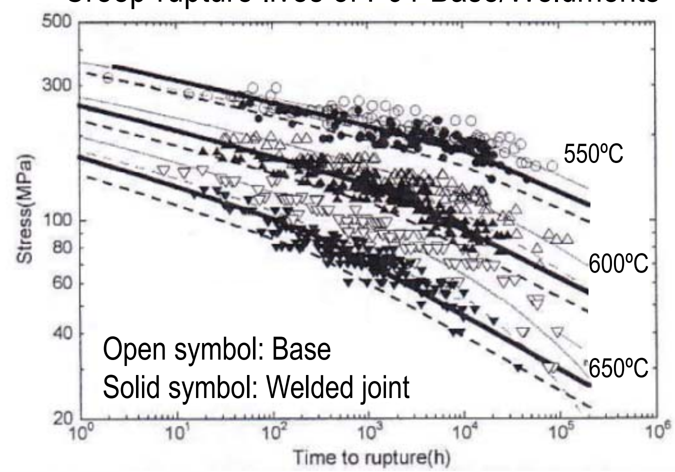
⇩

- **Type IV failure of traditional F-M steel weldments is unavoidable**
  - To minimize: Optimization of heat treatment
  - To eliminate: New alloy development



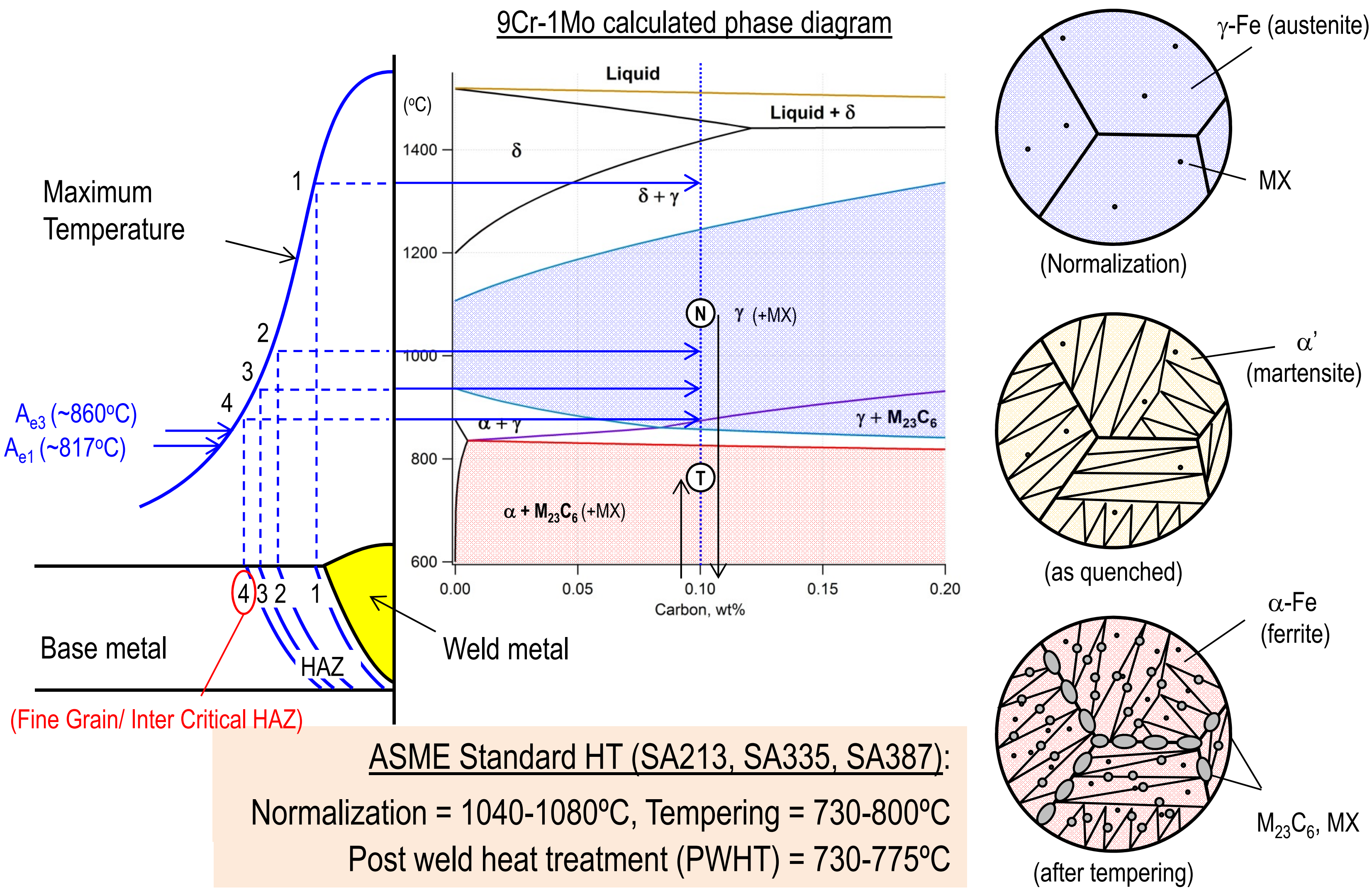
Source: ETD Ltd.

Creep-rupture lives of P91 Base/Weldments



Source: Yaguchi et al., ASME 2012 PVP

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



ASME Standard HT (SA213, SA335, SA387):

Normalization = 1040-1080°C, Tempering = 730-800°C

Post weld heat treatment (PWHT) = 730-775°C

Minimize/Eliminate Type IV failure in CSEF steel weldments

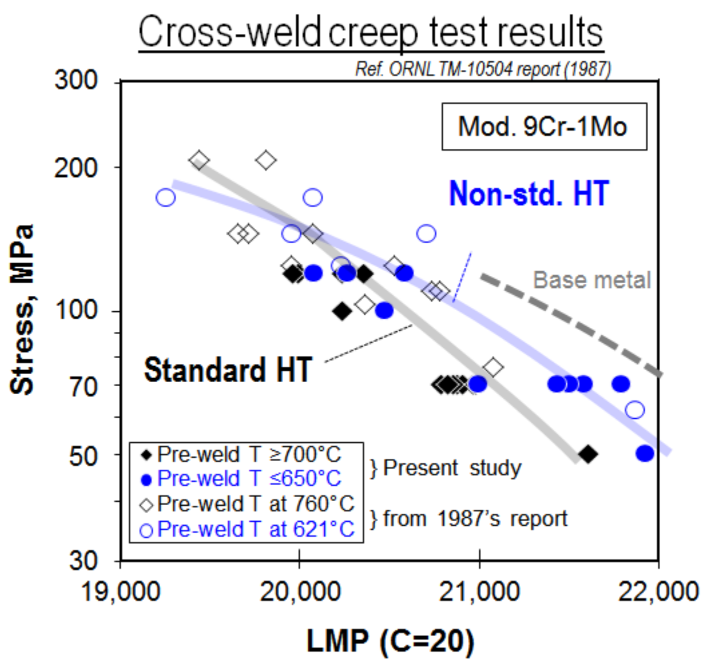
1. **Optimization of heat-treatment: Grade 91 steel**
   – Target existing CSEF steels (feasible, inexpensive)
   – Based on cumulative efforts of scientific understanding + breakthrough concepts

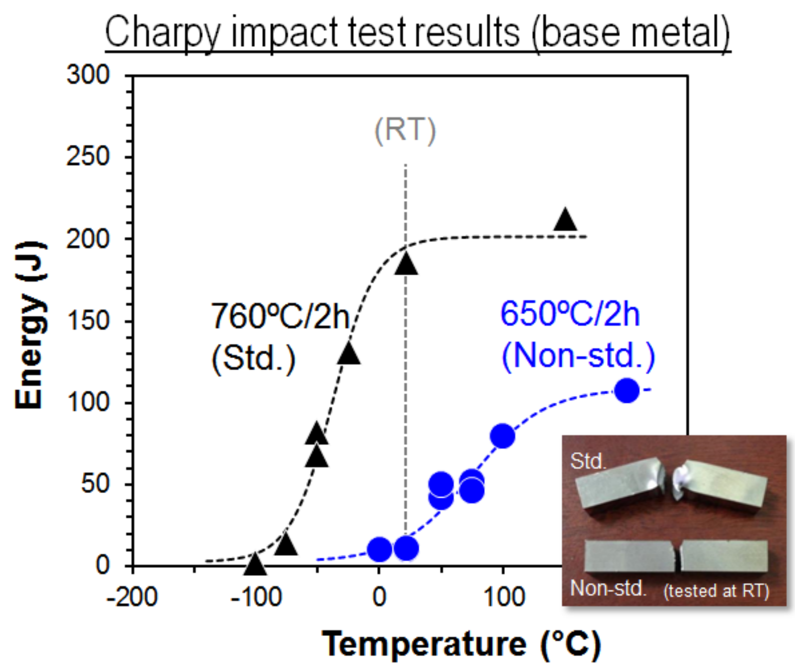
2. **New alloy development: High Cr ferritic steel**
   – Target new ferritic alloys (essentially free from Type IV failure)
   – Theoretically no upper temperature limit due to no transformation

Achievement in "Optimization of HT"

FY13:

- Non-standard heat treatment (lower temperature pre-weld tempering) improved cross-weld properties after PWHT compared to standard heat-treated specimens.
- Non-standard heat treated base metal showed poor RT toughness, which could be due to supersaturated carbon in the "half-tempered" matrix.

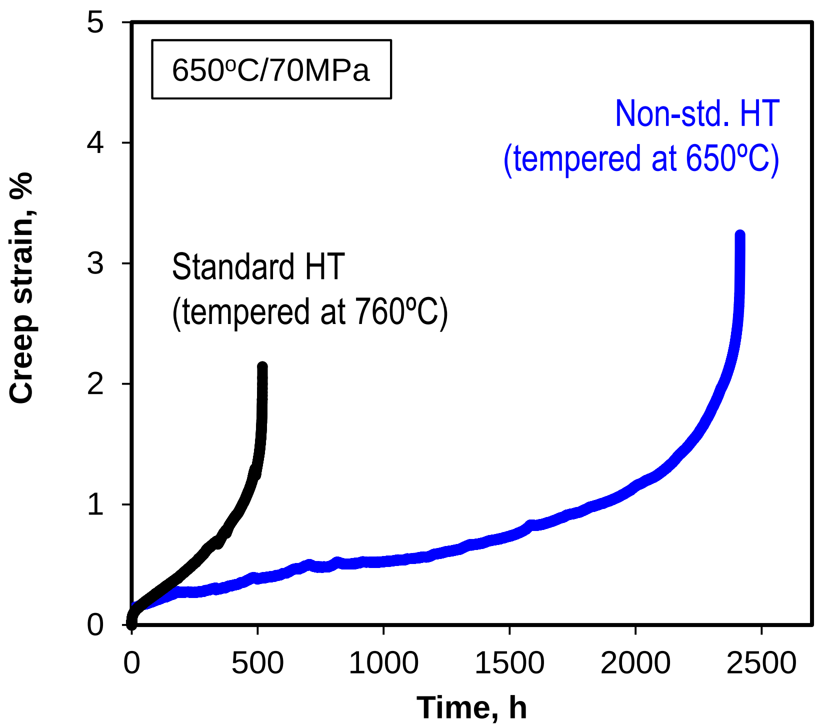




Y. Yamamoto et al., Proc. 7th Intl. conf. Adv. Mater. Tech. for Fossil Power Plants, 2014
Y. Yamamoto et al., Proc. ASME Symp. Elev.Temp. Appl. of Mater. for Fossil, Nuclear, and Petrochemical Industries, 2014

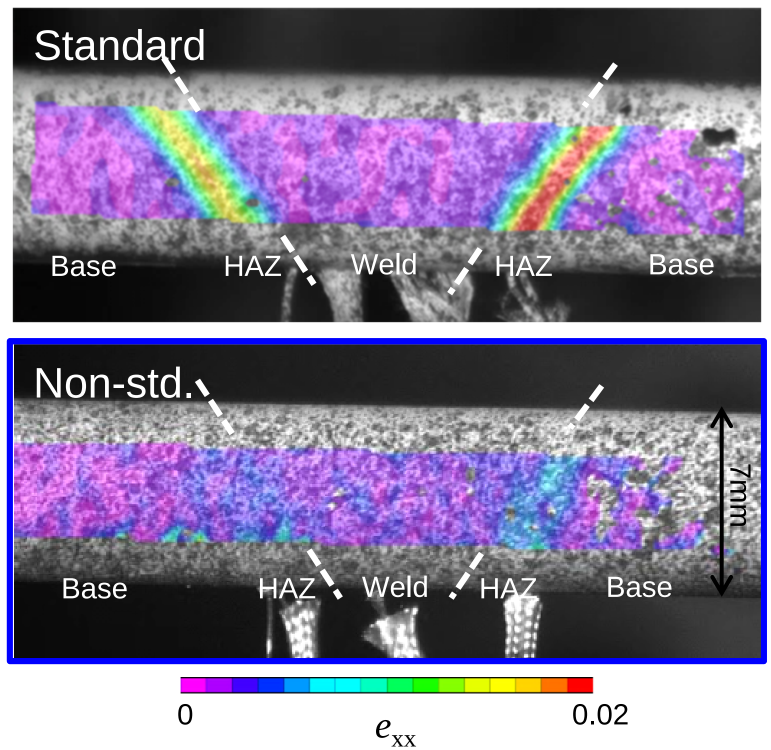
Non-standard heat treatment improved creep-resistance at FGHAZ

<u>Creep-rupture curves of cross-weld Gr 91</u>



- Improved cross-weld creep resistance

<u>*In-situ* creep strain measurement*,**</u>



- Creep deformation concentrated at HAZ

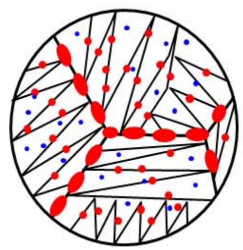
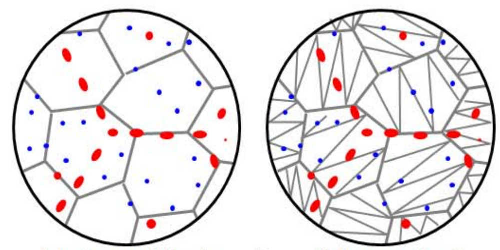
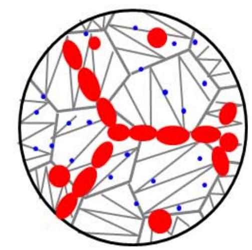
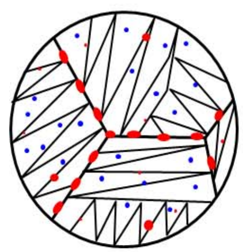
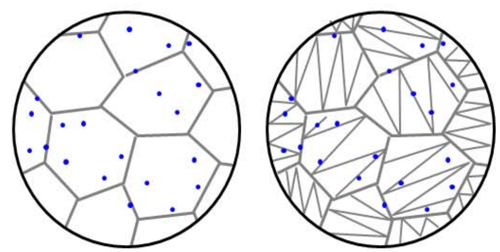
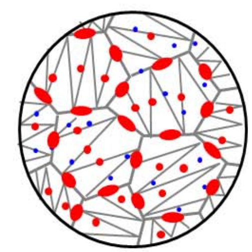
*measured by digital image correlation technique

**tested at 650C/70MPa <u>for 90h</u>

X. Yu et al., Proc. 7th Intl. conf. Adv. Mater. Tech. for Fossil Power Plants, 2014

Low temperature pre-weld tempering led complete dissolution/ re-precipitation of $M_{23}C_6$ after PWHT

Table: Microstructure evolution at fine grain heat affected zone

	Pre-weld temper	Weld (at FGHAZ)	PWHT
Standard HT (tempered at 760ºC)		 (during welding) → (after cooling)	
Non-std. HT (tempered at 650ºC)		 (during welding) → (after cooling)	

●: $M_{23}C_6$ •: MX

- Dispersion of <u>fine strengthening carbides</u> ($M_{23}C_6$) at FGHAZ is the key to improve creep properties

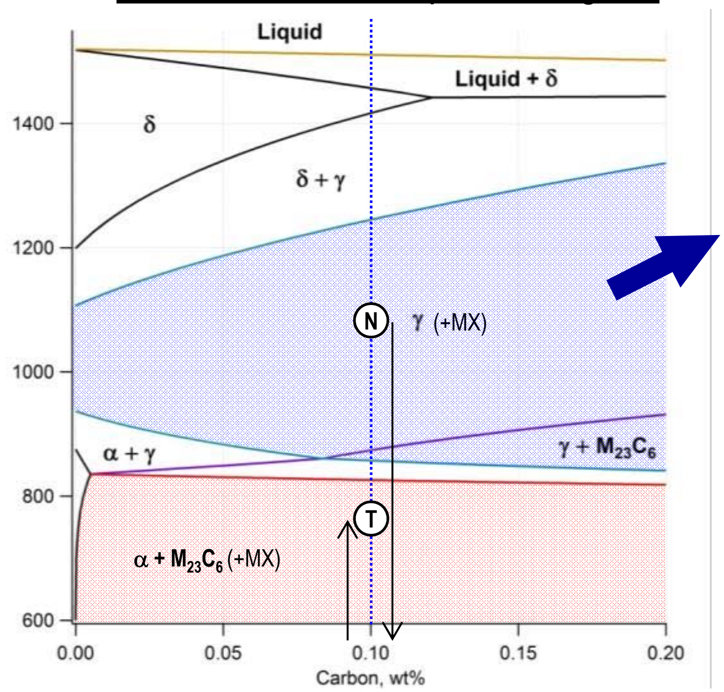
X. Yu et al., Acta Materialia, vol. 61 (2013) p. 2194-2206.

Achievement in "Optimization of HT" (cont.)

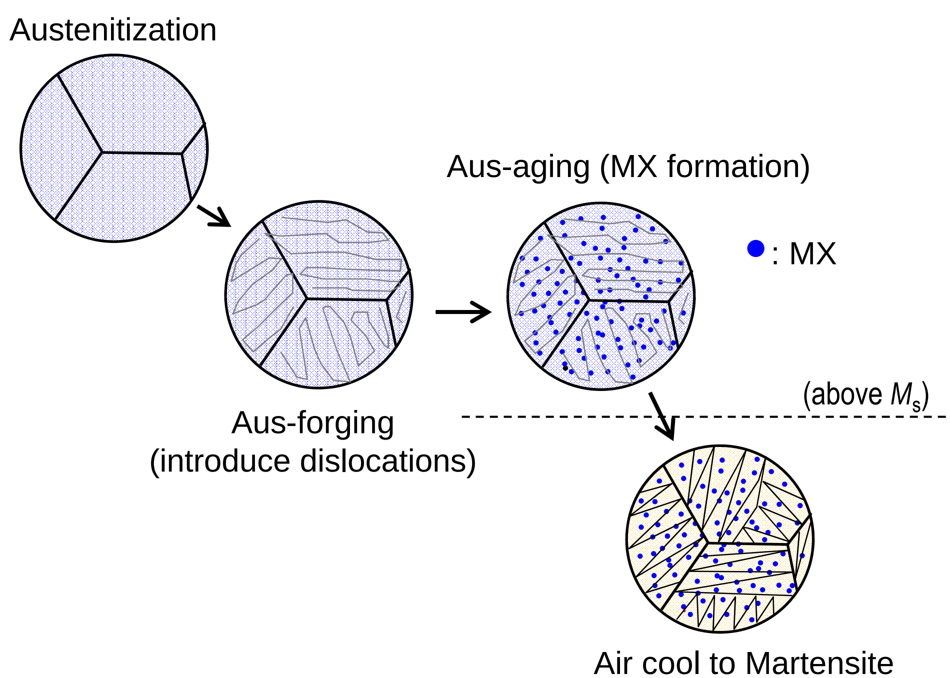
FY14:

- Applied aus-forging and aus-aging (thermo-mechanical treatment or TMT*) to promote stable MX formation prior to welding which successfully improved cross-weld creep properties with sufficient RT toughness of the base metal

9Cr-1Mo calculated phase diagram



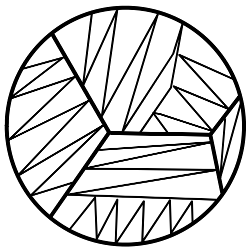
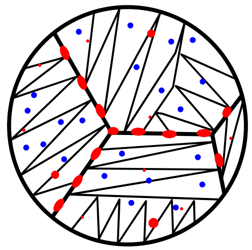
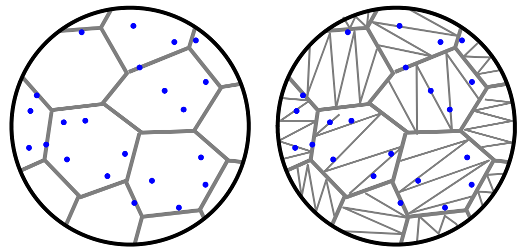
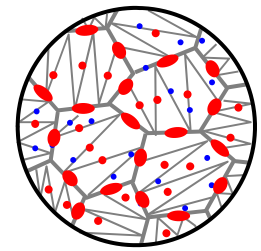
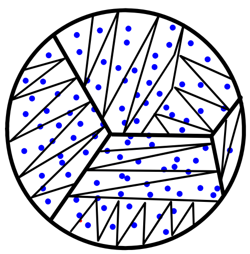
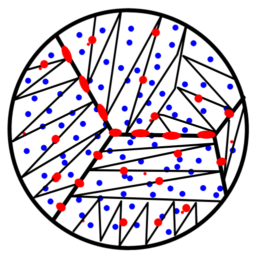
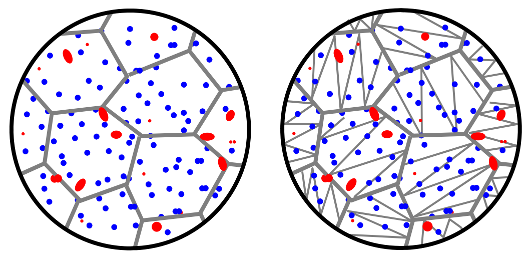
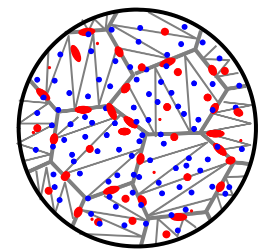
TMT process



*Ron Klueh et al., Scripta Materialia (2005), J. Nuclear Materials (2007)

Expected microstructure evolution of TMT 9Cr steel before/after weldment

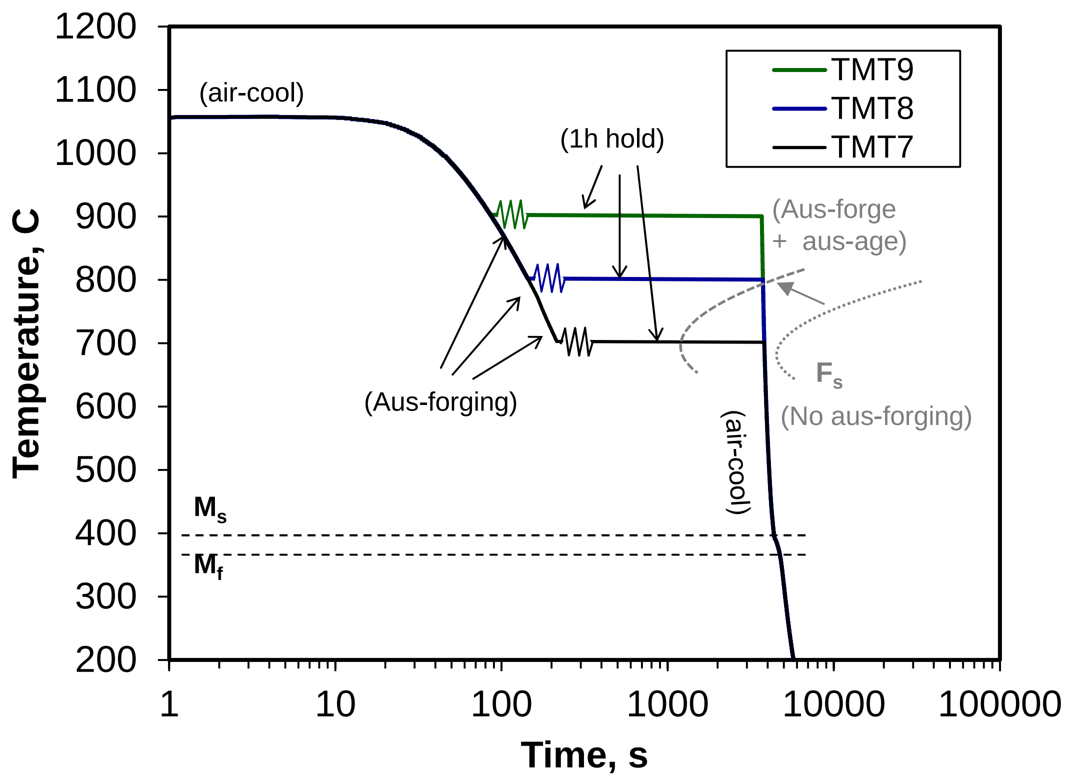
Table: Microstructure evolution at fine grain heat affected zone

	As normalized or As TMT	Pre-weld temper	Weld (at FGHAZ)	PWHT
Non-std. HT		 (at 650C)	 (during welding) ➡ (after cooling)	
TMT (+ std. temper)		 (at 760C)	 (during welding) ➡ (after cooling)	

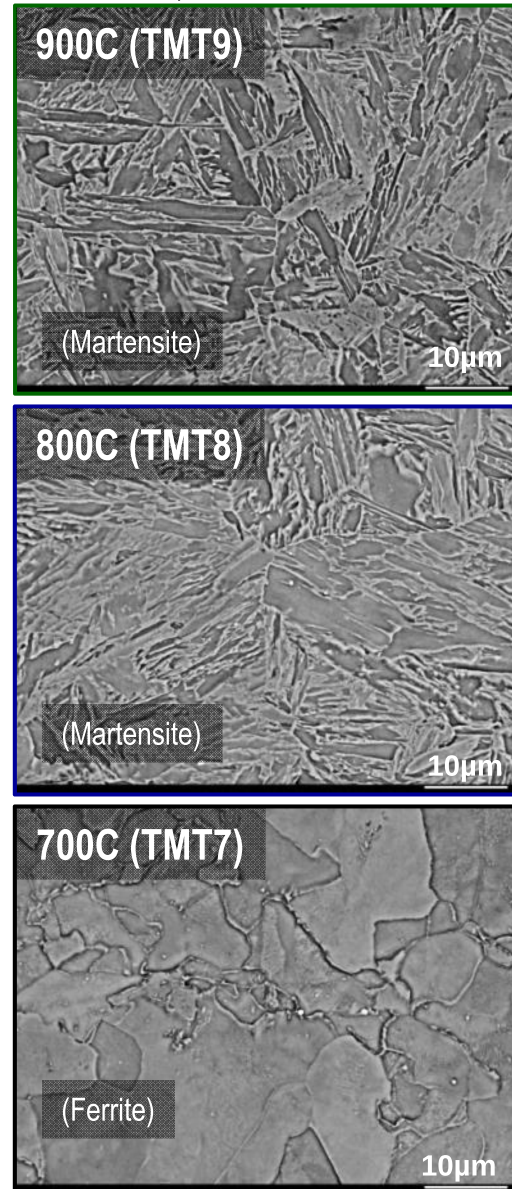
● : MX ⬬ : $M_{23}C_6$

- MX at FGHAZ is stable and insensitive to heating/cooling process during welding

Expected microstructure obtained above 800C

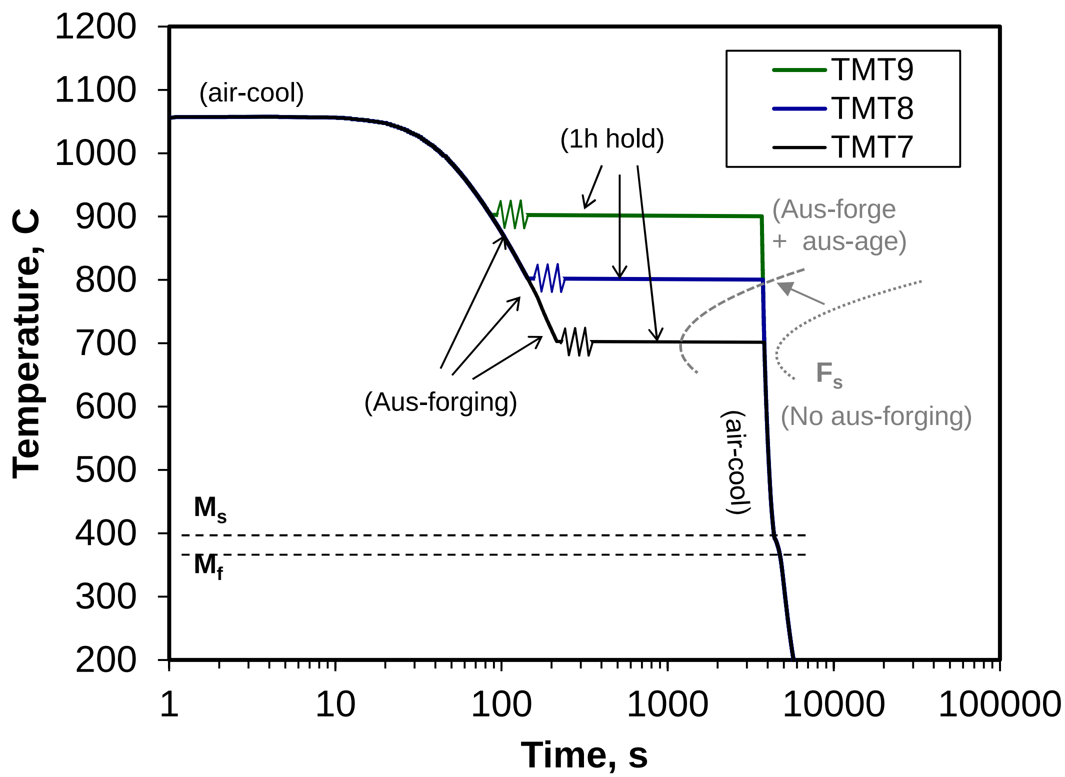


SEM-BSE, as TMT (*7% aus-forged)



- TMT at 800 and 900°C resulted in formation of the martensitic microstructure

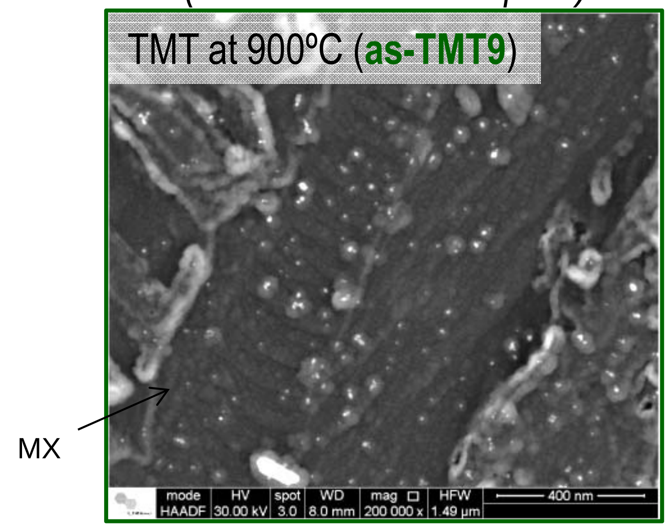
Expected microstructure obtained above 800C

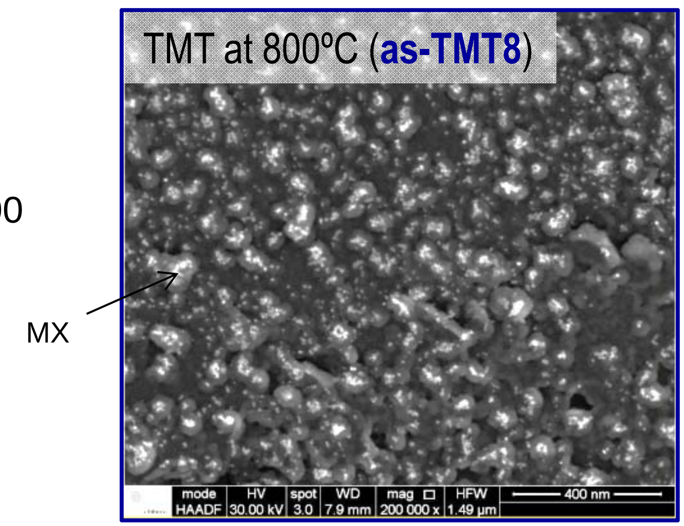


- TMT at 800 and 900°C resulted in formation of the martensitic microstructure

STEM-HAADF images

(carbon extraction replica)

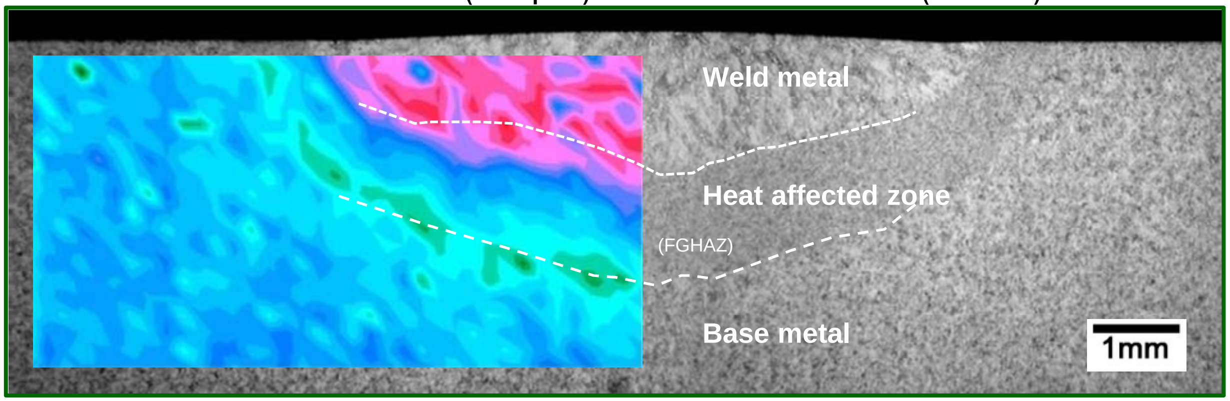




Dense MX increased Hv even at FGHAZ

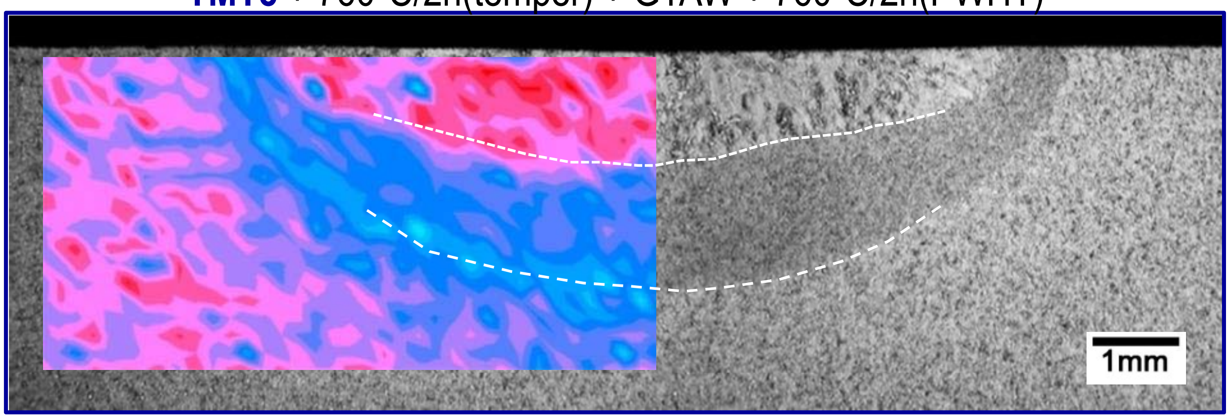
Hardness map

TMT9 + 760ºC/2h(temper) + GTAW + 760ºC/2h(PWHT)



- Distinct soft zone formed similar to standard heat treated sample (HTT)

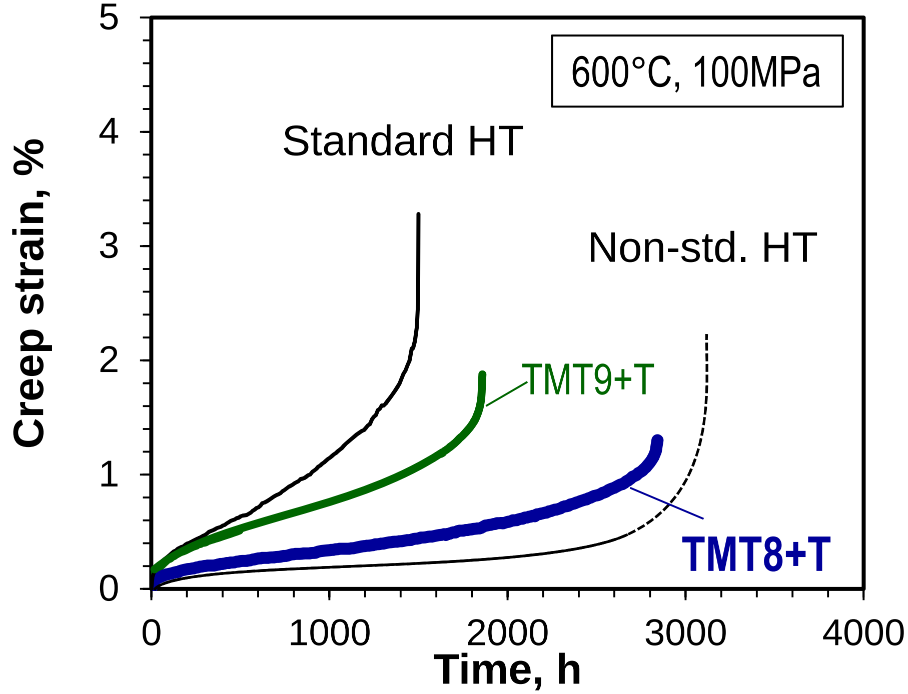
TMT8 + 760ºC/2h(temper) + GTAW + 760ºC/2h(PWHT)



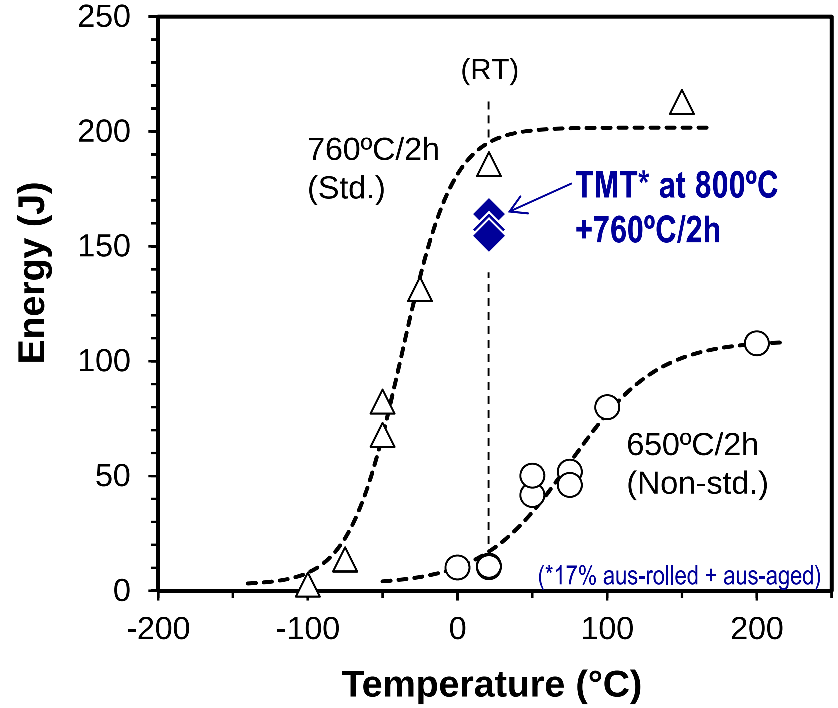
- Whole area showed higher Hv, even at FGHAZ

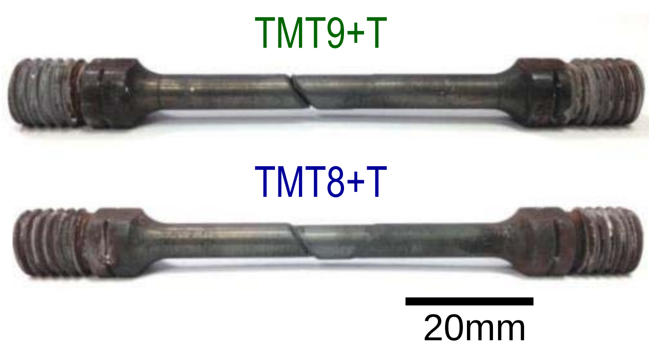
Improved properties in TMT8+T

Creep-rupture curves (Cross-weld)



Charpy impact test results (Base metal)

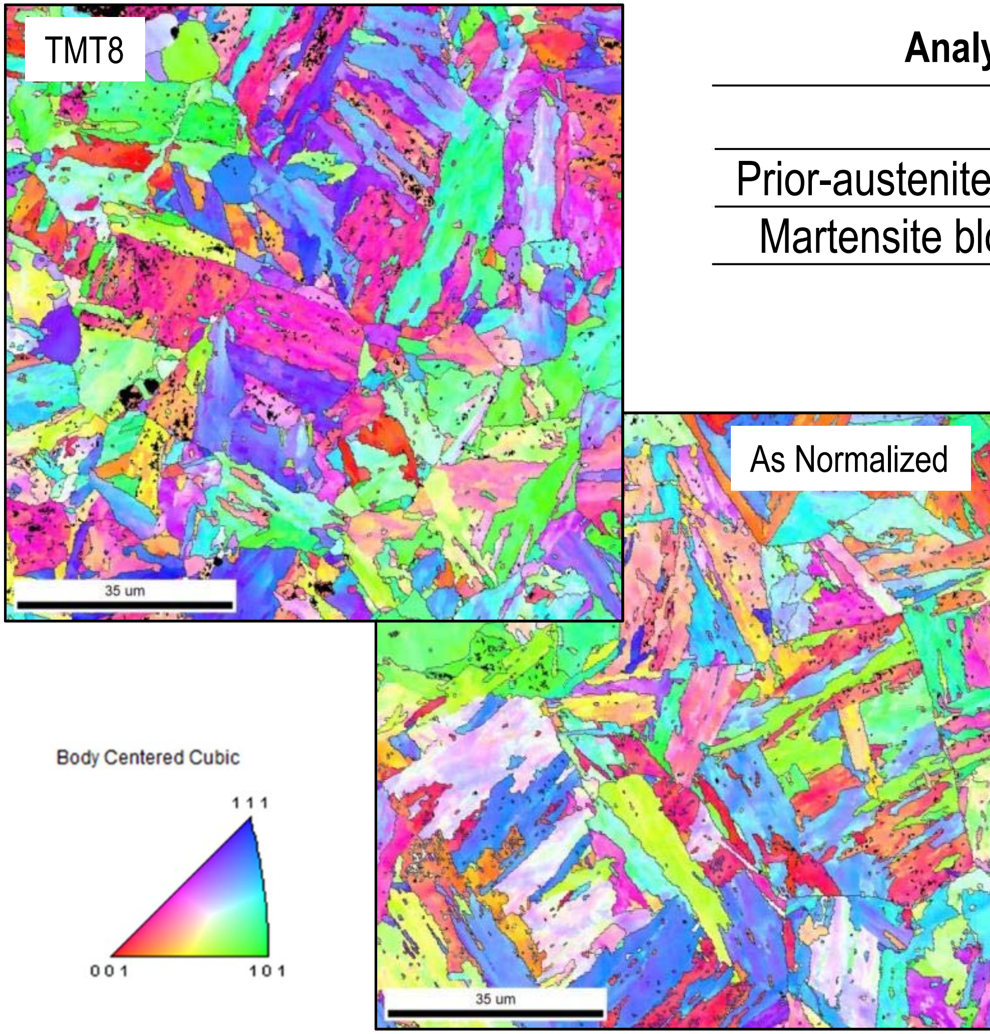




- Maintain creep property improvement after GTAW + PWHT
- Decent RT toughness comparable to standard HT sample

Characterization efforts in progress

OIM IPF color map (SEM-EBSD)



Analyzed microstructure factors* (unit: µm)

	TMT800	As-normalized
Prior-austenite grain size	29	40
Martensite block width	5.0	4.6

*obtained from the images shown in this slide.

- No significant difference in prior austenite grain size / martensite block width
- Need detailed characterization of MX (size, distribution, etc.)

Achievement in “New Alloy Development”

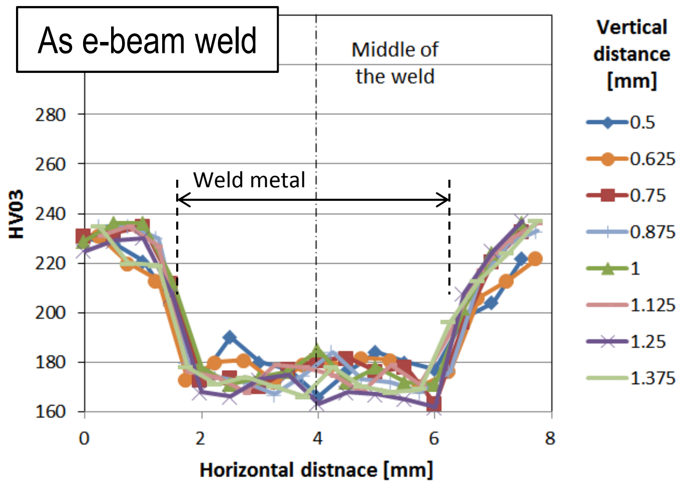
- Collaboration with Forschungszentrum Jülich GmbH, Germany were initiated in FY13
- Objective: Develop alloy compositions (parent and weld filler metals) optimized for the weldments of a new high-Cr ferritic steel strengthened by intermetallic phases, “HiperFer” (based on Crofer 22H®)
  – *Led by Dr. Bernd Kuhn, Forschungszentrum Jülich (FZJ), Germany with ORNL support*
  – *Identify and qualify suitable welding processes, and evaluate the properties of both the base / cross-weld specimens.*
- FZJ student worked at ORNL in a collaborative effort.
  – *Initiated microstructure characterization of trial e-beam weld HiperFer steels.*

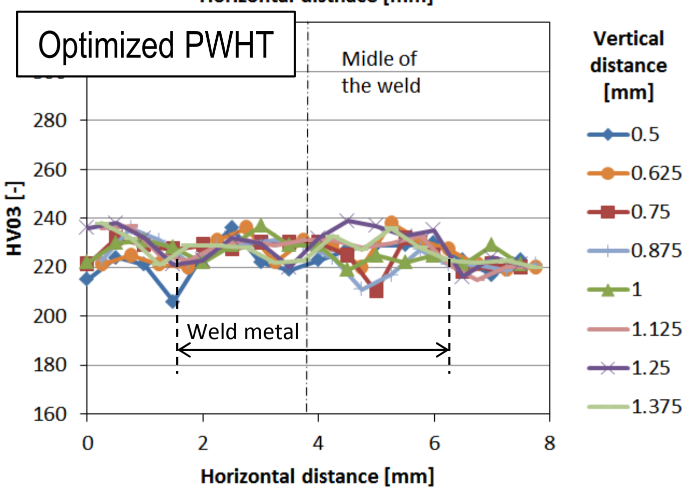
Table: Target composition ranges

	Fe	Cr	W	Nb	Si	Mn	C	N
wt%	Bal.	17 - 23	1 - 7	0.3 - 1	≤ 0.25	≤ 0.5	< 0.01	< 0.015

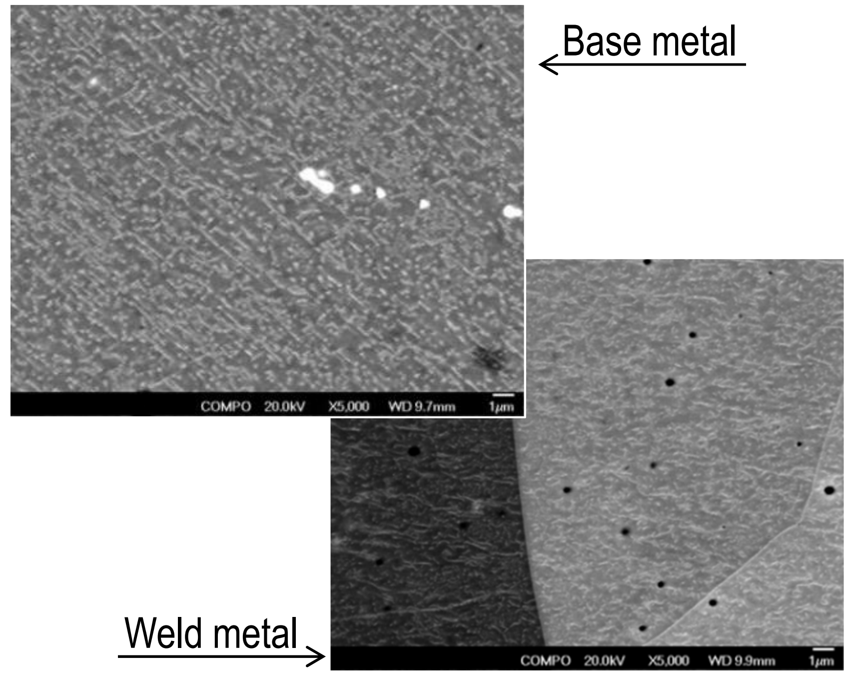
Optimization of pre-/post- e-beam weld heat-treatment in progress

Hardness profiles across e-beam weld metal





SEM-BSE images after optimized PWHT



- Selected HiperFer used for e-beam weld study
- Optimized pre- and post-weld HT successfully eliminated inhomogeneity of second-phase dispersion (and Hv profile as well).

FY13 Milestones & Status

- Characterize multi-pass welded Grade 91 steel (December 2012).
  - Status: Met
- Rank initial oxidation results of Al-containing 9Cr steel (March 2013).
  - Status: Met
- Complete short-time stress-rupture tests (June 2013).
  - Status: Met
- Complete correlation of microstructure with creep strength for synchrotron diffraction specimens (September 2013).
  - Extended to the end of FY16 since the creep-rupture tests are still in progress and more than 20,000h of additional testing will be required to be completed

FY14 Milestones & Status

- Complete optimization of TMT on Grade 91 steel (March 2014)
  - Status: Met
- Assess mechanical properties of TMT Grade 91 steel (September 2014)
  - Status: Met

Three proceedings papers have been published:

Y. Yamamoto, M.L. Santella, X. Yu, S.S. Babu, "*Effect of Non-Standard Heat Treatments on Creep Performance of Creep-Strength Enhanced Ferritic (CSEF) Steel Weldments*," in *Proceedings of the 7th International Conference on Advances in Materials Technology for Fossil Power Plants* (Oct. 22-25, 2013, Waikoloa, HI), eds. D. Gandy and J. Shingledecker, ASM International, Materials Park, OH (2014), pp. 1016-1024.

X. Yu, Z. Feng, Y. Yamamoto, "*In-Situ Full Field Creep Deformation Study of Creep Resistant Materials Welds*," in *Proceedings of the 7th International Conference on Advances in Materials Technology for Fossil Power Plants* (Oct. 22-25, 2013, Waikoloa, HI), eds. D. Gandy and J. Shingledecker, ASM International, Materials Park, OH (2014), pp. 1432-1440.

Y. Yamamoto, X. Yu, S.S. Babu, "*Improvement of Creep Performance of Creep Strength Enhanced Ferritic (CSEF) Steel Weldments through Non-Standard Heat Treatments*," S2-1 ETS 2014-1009, in *Proceedings of the ASME Symposium on Elevated Temperature Application of Materials for Fossil, Nuclear, and Petrochemical Industries* (March 25-27, 2014, Seattle, WA), ASME (2014).

Summary

Optimization of HT:

– New TMT approaches: *Aus-forging & aus-aging evaluation*

- *Successfully improved cross-weld creep properties with decent room temperature toughness of the base metal*
- *Feedback from Non-standard HT study supported the idea of the strengthening mechanism*

New Alloy Development :

– Weldment development of a new high-Cr ferritic steel, under a collaboration with Forschungszentrum Jülich (FZJ) GmbH, Germany.

- *FZJ student worked at ORNL in a collaborative effort*
- *Optimization of Pre-/Post- E-beam Weld Heat-Treatment in Progress*

Future Work in FY14

FY14:

Wrap up the study of the 9Cr steel weldments on September 2014

- *Microstructure characterization will be performed to investigate the microstructure-property relationship*
- *Several creep-rupture tests (selected TMT base metals and weldments) will be continued*

Materials/HT Used in This Study

Table: Chemical composition of the alloy studies (Grade 91, #30176)

wt%	C	Mn	Si	Cr	Mo	Ni	V	Nb	N	B
Base	0.08	0.27	0.11	8.61	0.89	0.09	0.21	0.07	0.06	<0.001
Filler	0.08	0.41	0.31	8.62	0.92	0.15	0.24	0.08	0.04	<0.001

*From computational thermodynamics: A_{e1}=~**820**°C, A_{e3}= ~**860**°C

Table. Temperature range of standard HT (ASME SA213, SA335, SA387) and current study

HT	Standard	Current Study
Normalize	1040-1080°C	1050°C
Temper	730-800°C	600, 650, 700, 760, or 800°C
PWHT	730-775°C**	760 or 800°C

** ~790°C, if 1 ≤ (Mn + Ni) < 1.5; ~800°C, if (Mn + Ni) < 1.