Alloys for Advanced Ultrasupercritical (A-USC) Steam Boilers

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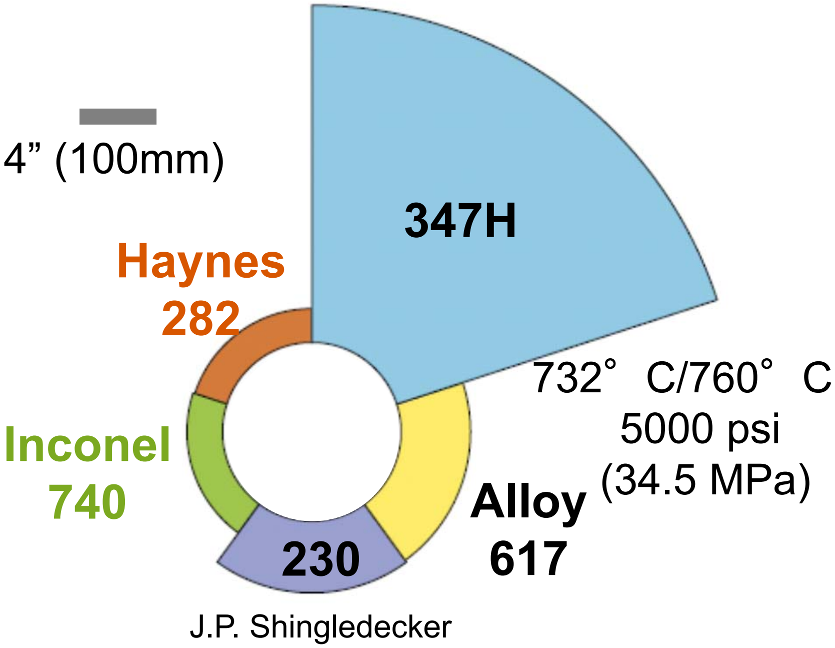
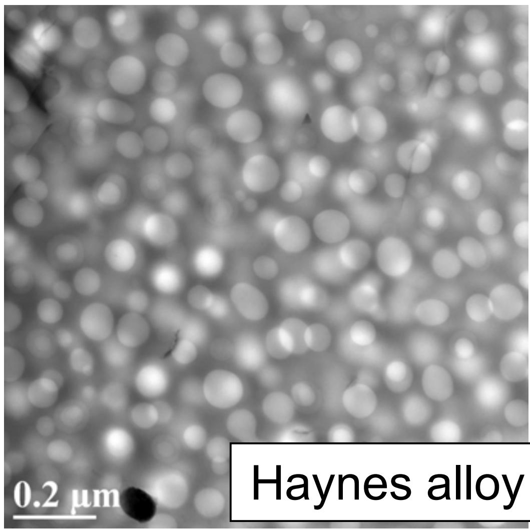
OAK RIDGE National Laboratory

Acknowledgments

- Jeremy Moser, Brian Sparks, Ralph Martin, ORNL: mechanical testing
- Tom Geer, Tracie Lowe, Hu Longmire, ORNL: specimen prep and microstructural analysis
- Bob Swindeman, Ian Wright, ORNL: starting it all
- Vito Cedro, NETL, federal project manager
  (Pat Rawls, Udaya Rao)
- A-USC Consortium

Work Motivated by Need for New Boiler Alloys for A-USC Steam Conditions

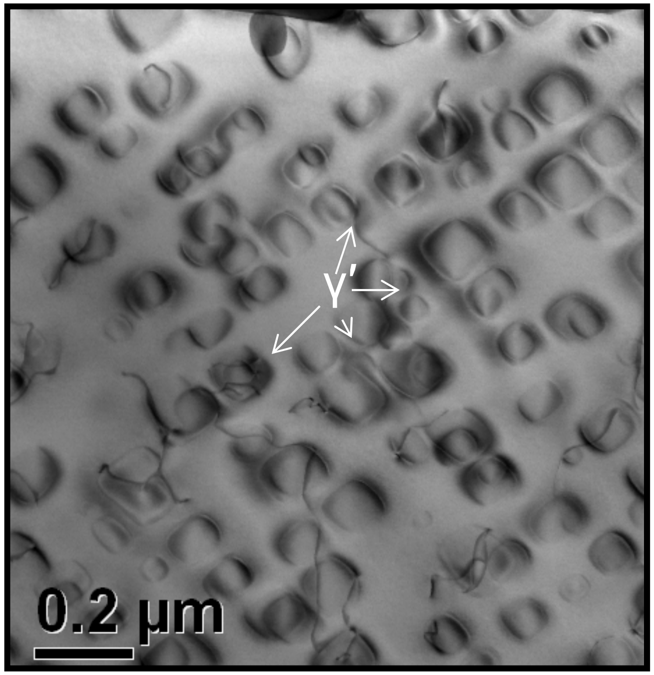




Haynes alloy 282

- U.S. <u>advanced</u> ultrasupercritical (A-USC) steam
  - 760° C
  - >3500 psi (24 MPa)
- A-USC boliers require precipitation-strengthened nickel-based alloys for hottest parts of boiler (superheater, reheater)
- Until A-USC boiler project, little attention to this need for nickel-based alloys
- Long-term data needed for code development and confidence in life prediction

ORNL's Role in the A-USC Boiler Effort



Inconel 740

- Produce high quality creep-rupture data using accepted test methods
  - Nickel-base alloys, including code case for Inconel 740 (with ongoing code case project for Haynes 282)
  - Supplement minimum required data for code-approved alloys,
  - Identify fabrication & welding issues on creep strength
  - Compare alloys
- Understand microstructural underpinnings of creep strength and failure
- Predict life with confidence

Work Included Six Advanced Boiler Alloys

Alloy	Nominal Composition (wt%)
304H	Fe-18Cr-8Ni
347H	Fe-18Cr-10Ni-Nb
Super 304H	Fe-18Cr-10Ni-Nb-N-Cu
NF 709	Fe-20Cr-25Ni-Mo-Nb-N-B
HR3C	Fe-25Cr-20Ni-Nb-N
Sanicro 25	Fe-22Cr-25Ni-Nb-N-Cu
HR6(7)W	Fe-23Cr-45Ni-6(7)W-Nb-Ti
230	Ni-22Cr-14W-2Mo
617	Ni-22Cr-9Mo-10Co
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740(H)	Ni-25Cr-20Co-Al-Ti-Nb
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Highest creep strength of code-approved austenitic stainless steels at time project started

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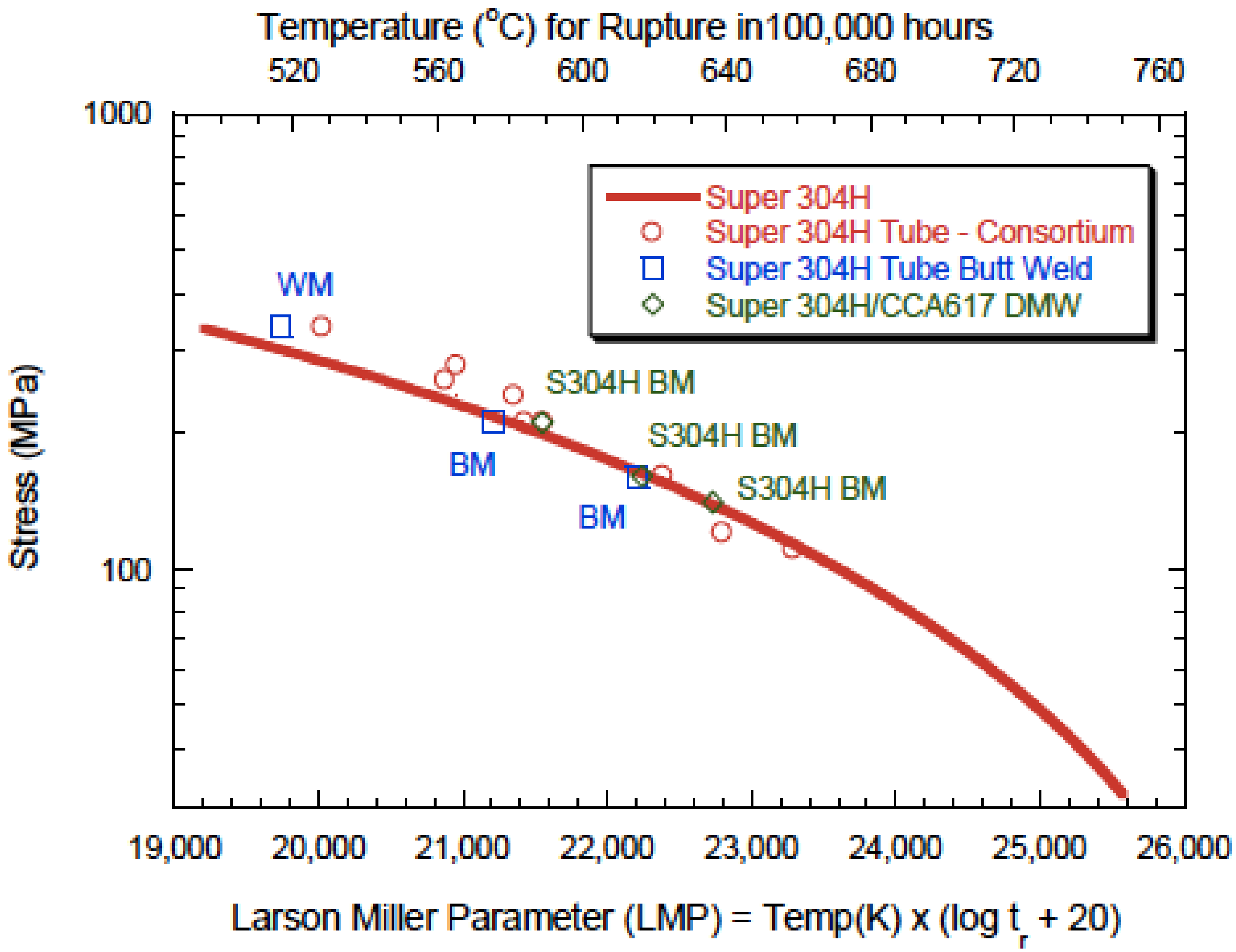
Super 304H – Project Data Out to 50,000 h with No Surprises

- Strengthened by carbides and nano-sized Cu precipitates
- No weld strength reduction factor observed



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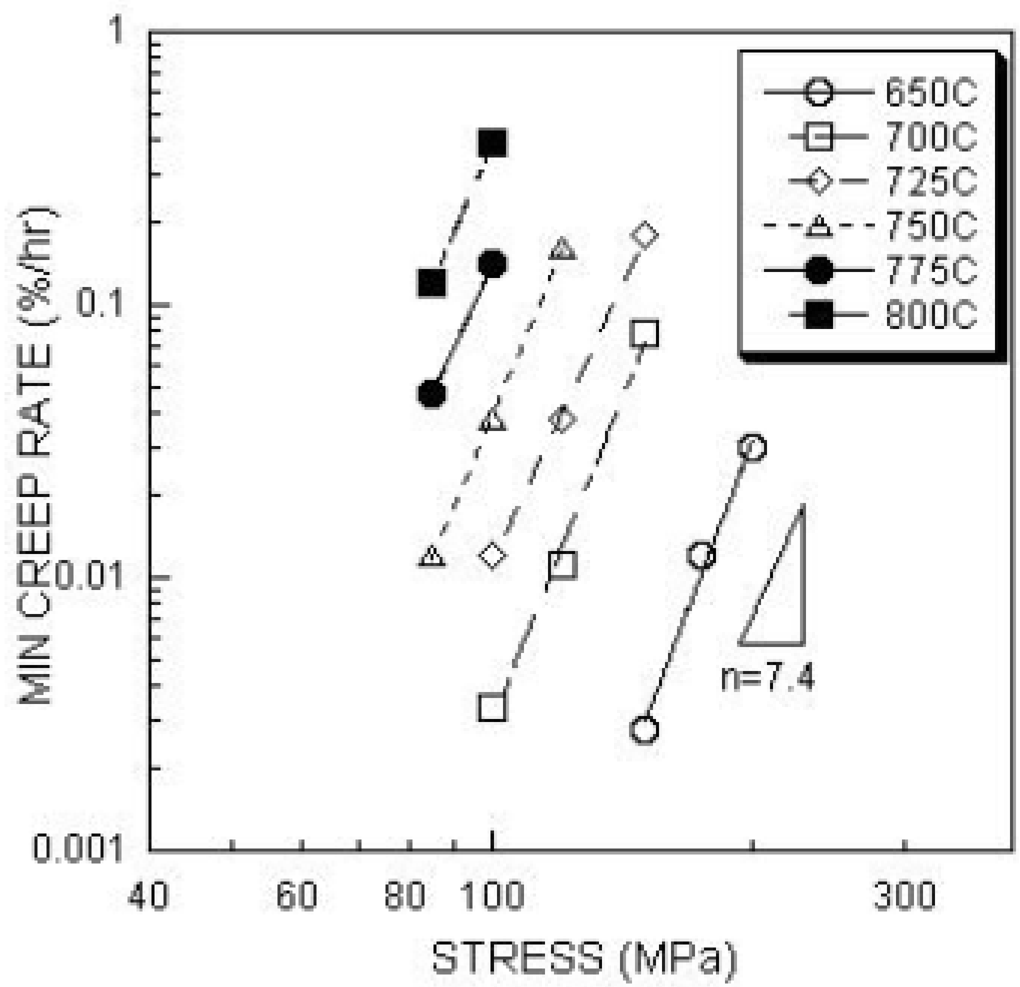
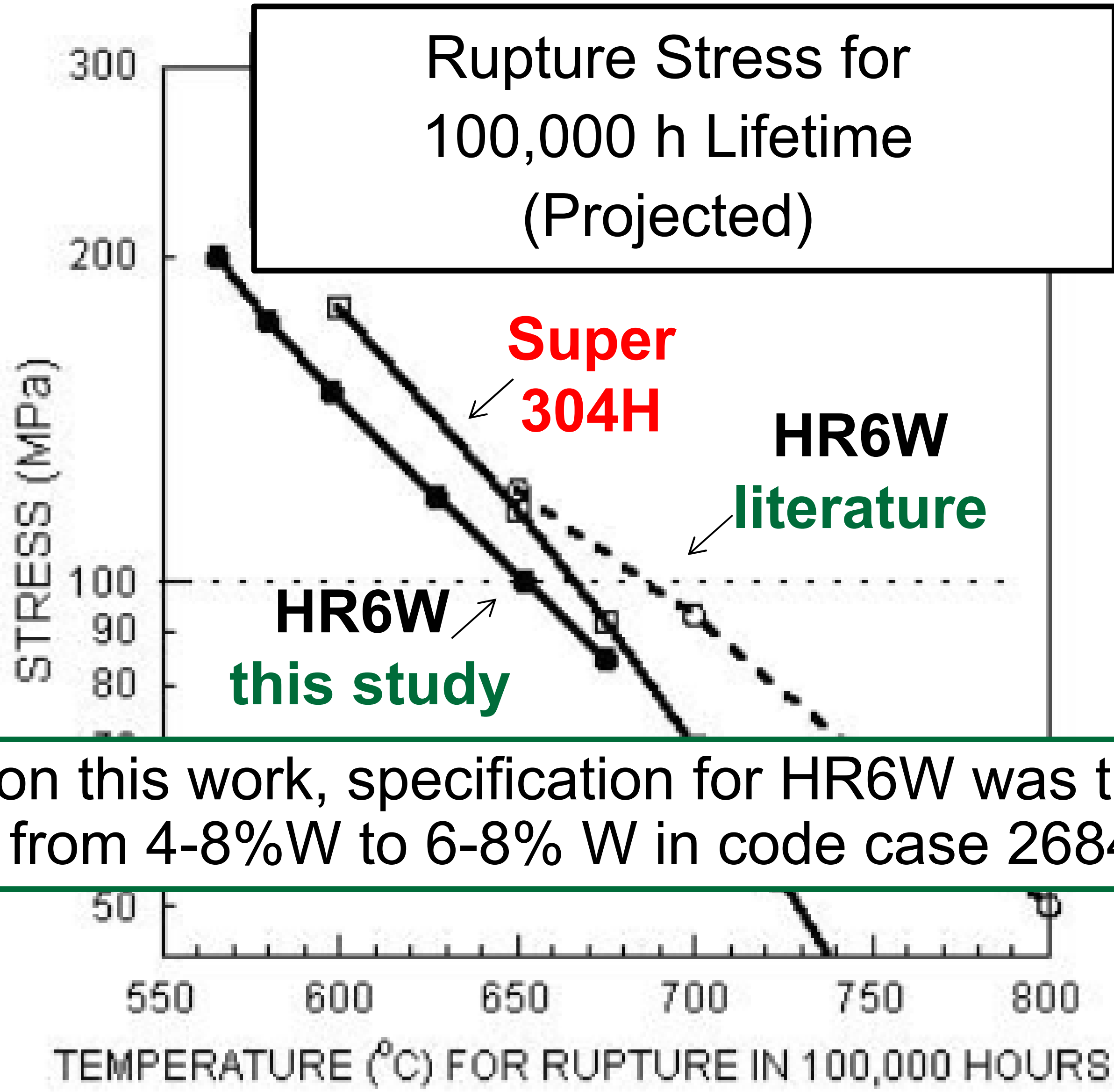
Investigate alloy with "lower" Ni content to span the gap between stainless steels and Ni-based alloys

HR6W Was Well Behaved in Creep

- Consistent mechanism across test temperature range
- Mapped fracture modes with intergranular predominant at lower stresses, longer times
- Good ductility in all fracture modes
- One heat tested (borderline 6%W)

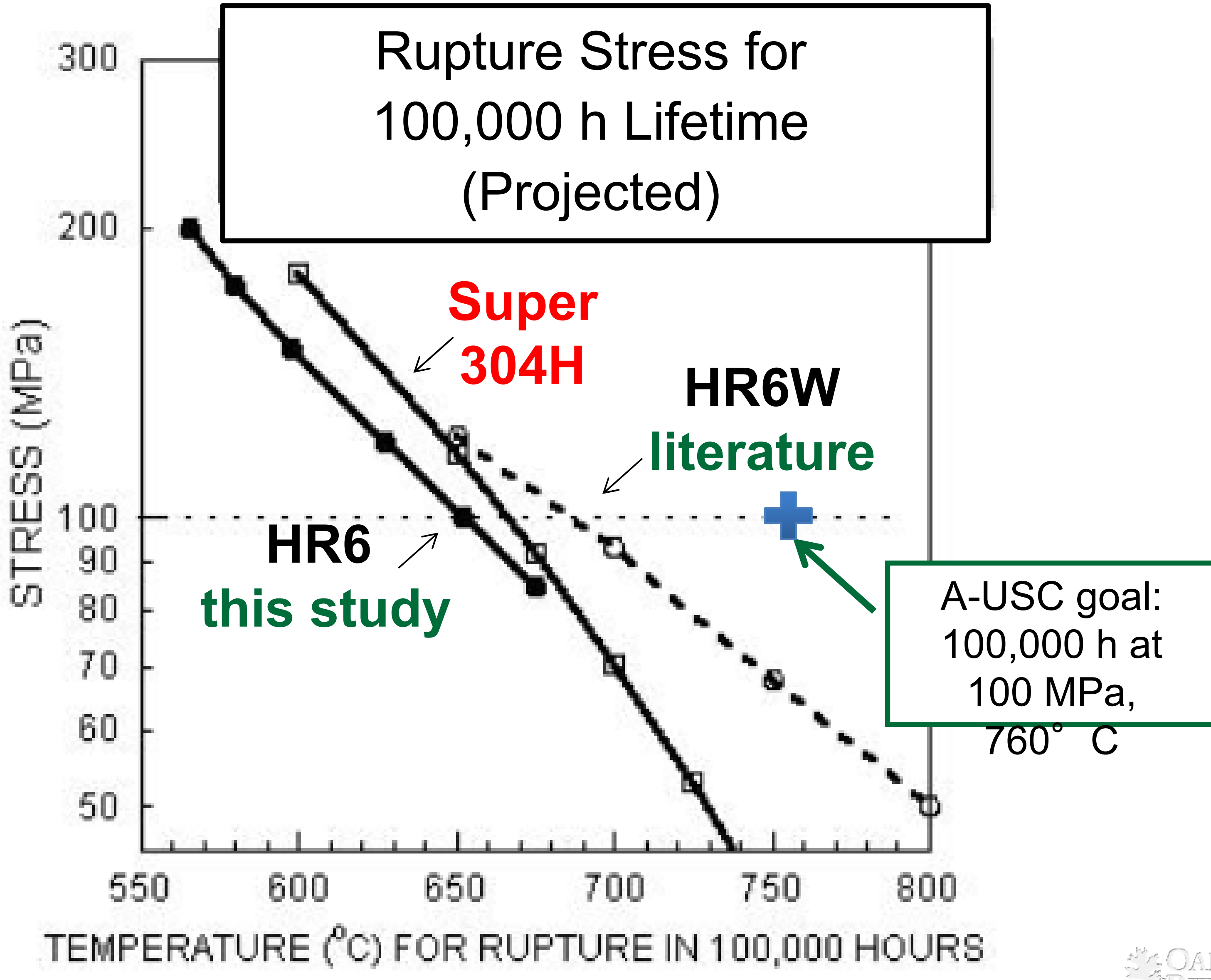


Creep-Rupture Strength of This HR6W Heat Was Not Better than Best Stainless Steel



Based on this work, specification for HR6W was tightened from 4-8%W to 6-8% W in code case 2684

These Two Alloys Not Suitable for Highest T, P of A-USC Boilers



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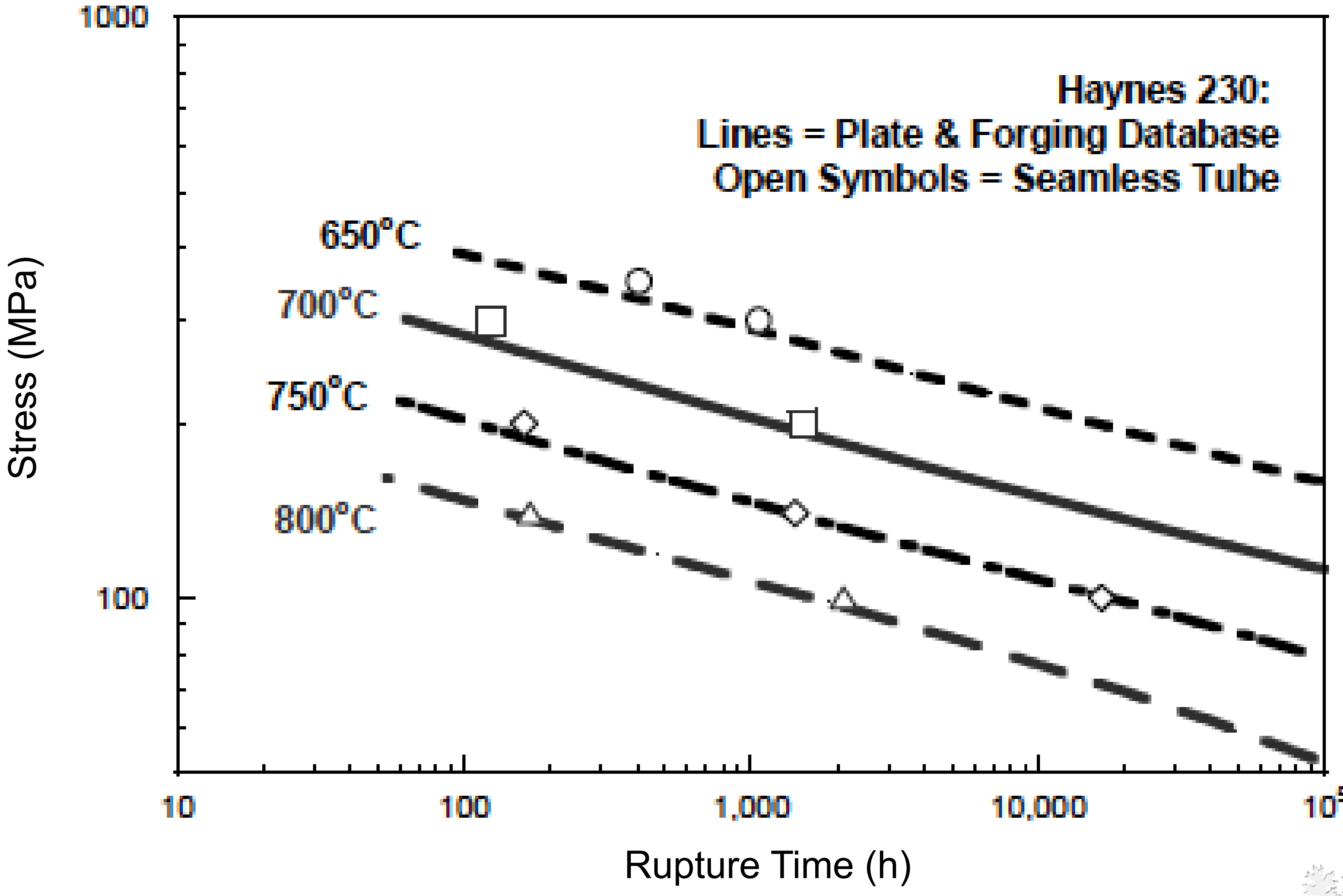
Haynes 230 Showed Stable Microstrucutre and Good Creep Behavior



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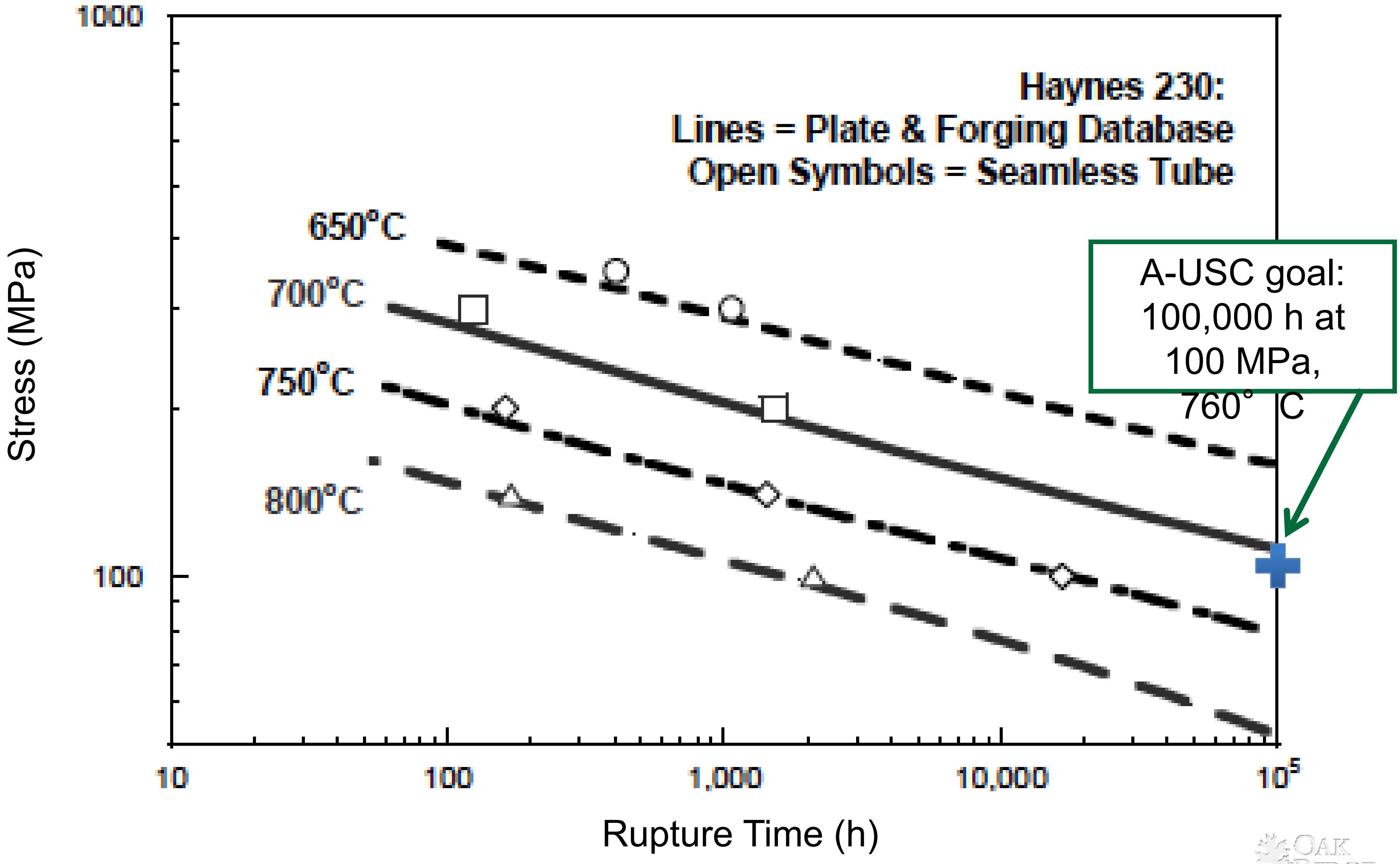
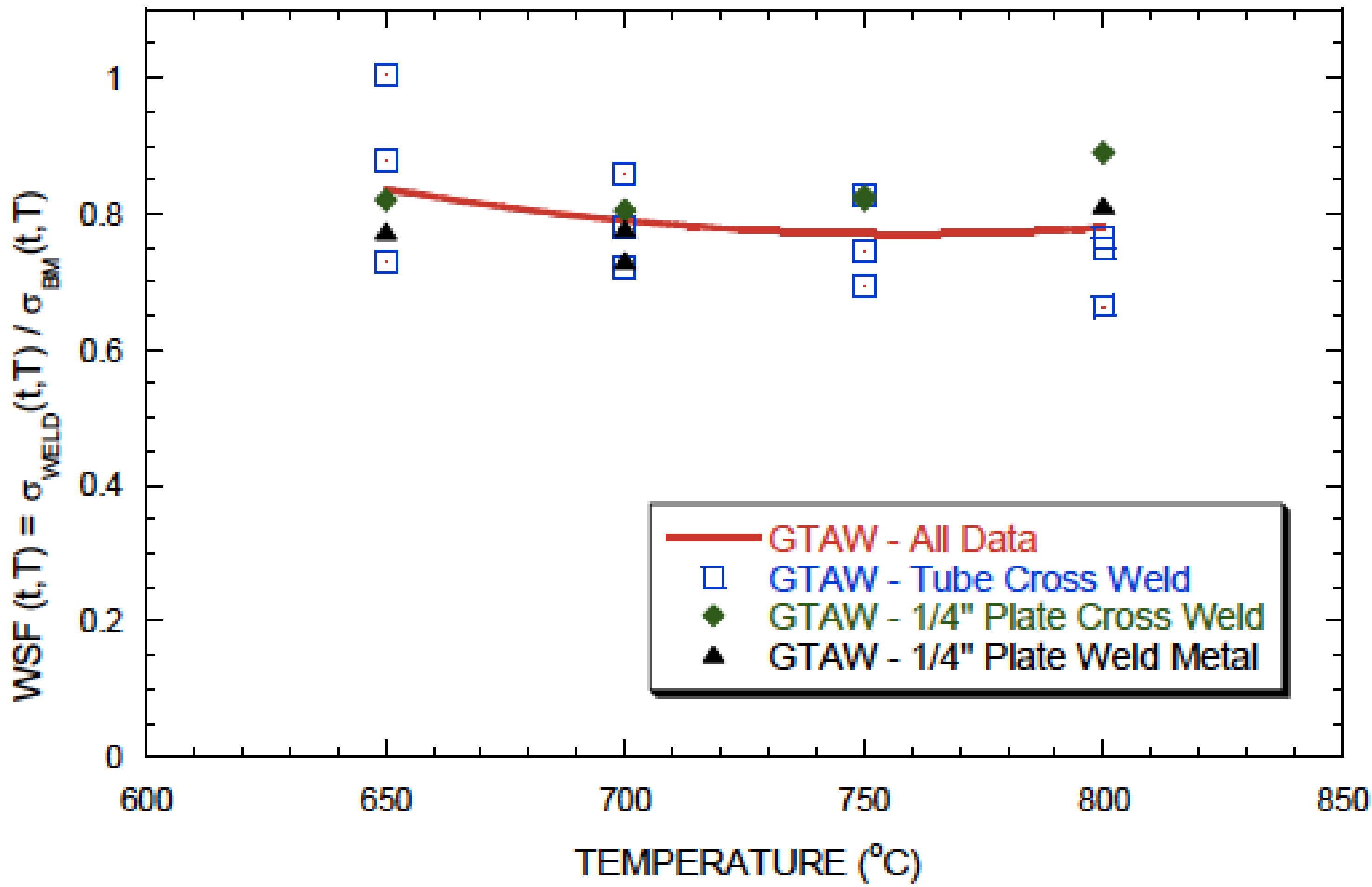
Haynes 230 Showed Stable Microstructure and Good Creep Behavior

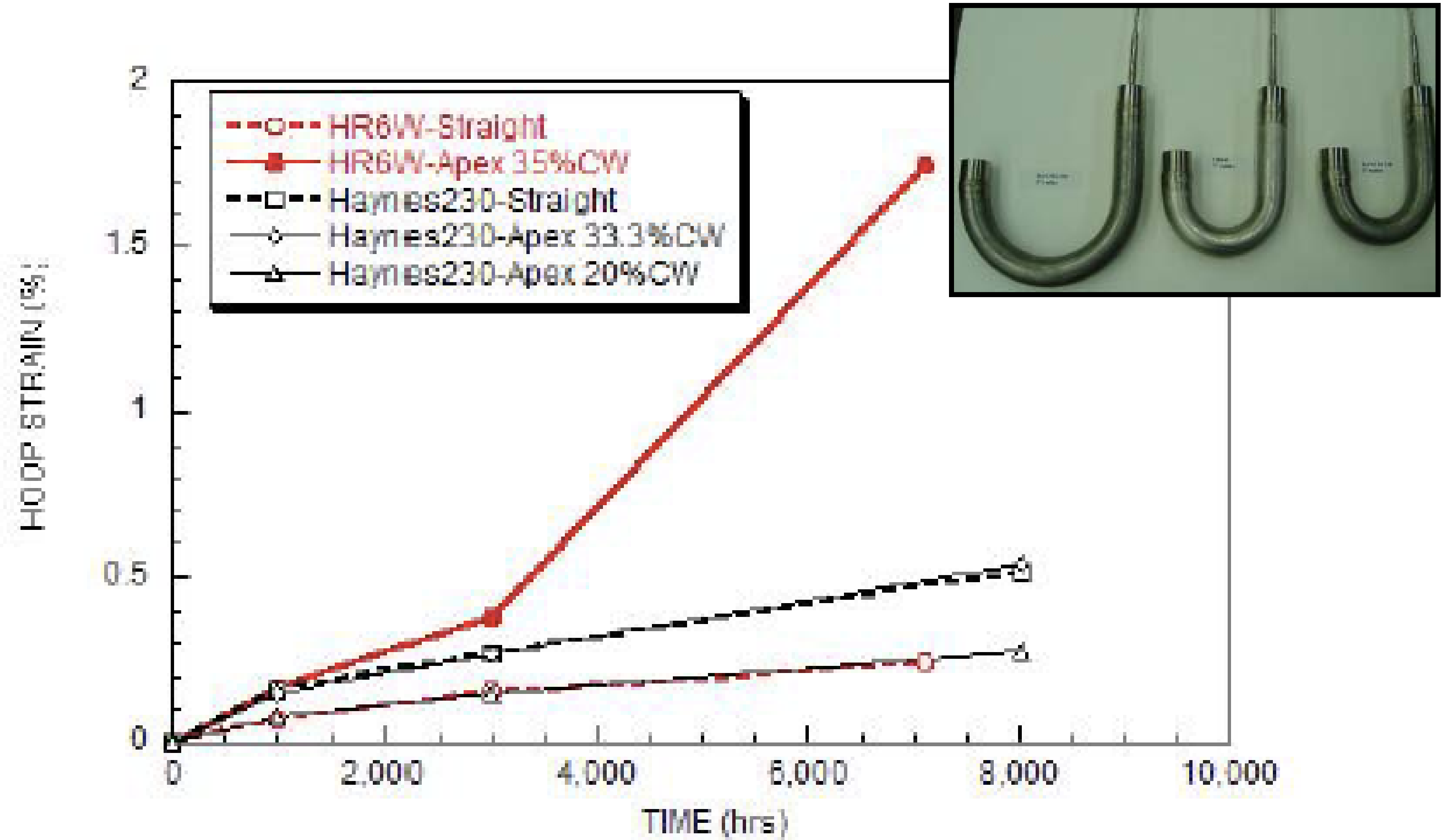


Haynes 230 Weldments Showed Weld Strength Reduction Factor of 0.8



Rules drafted and now part of code case

In Contrast to HR6W, Moderate Cold Work (Bends) Had Little Effect on Creep Resistance



Factored into code cases

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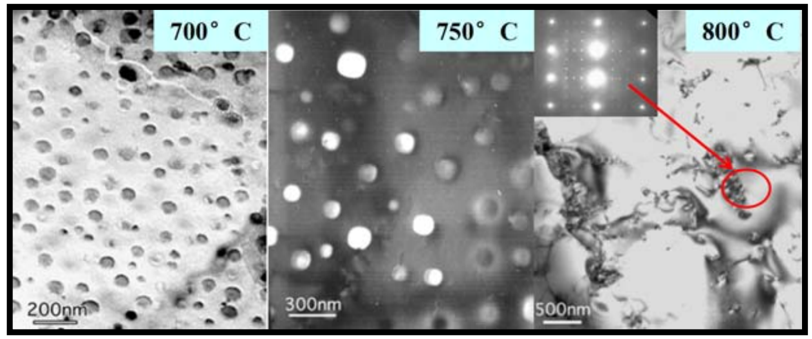
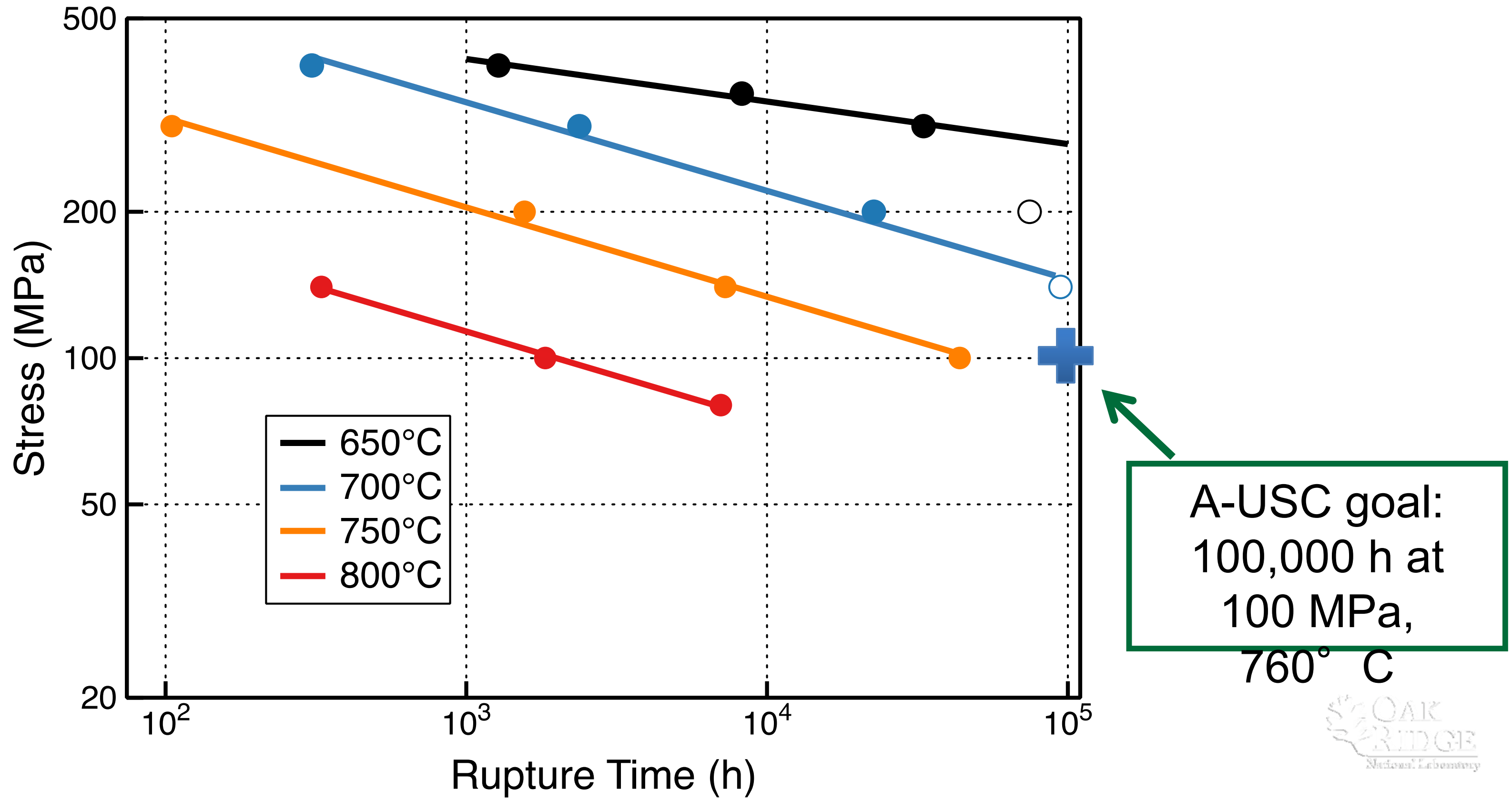
CCA617

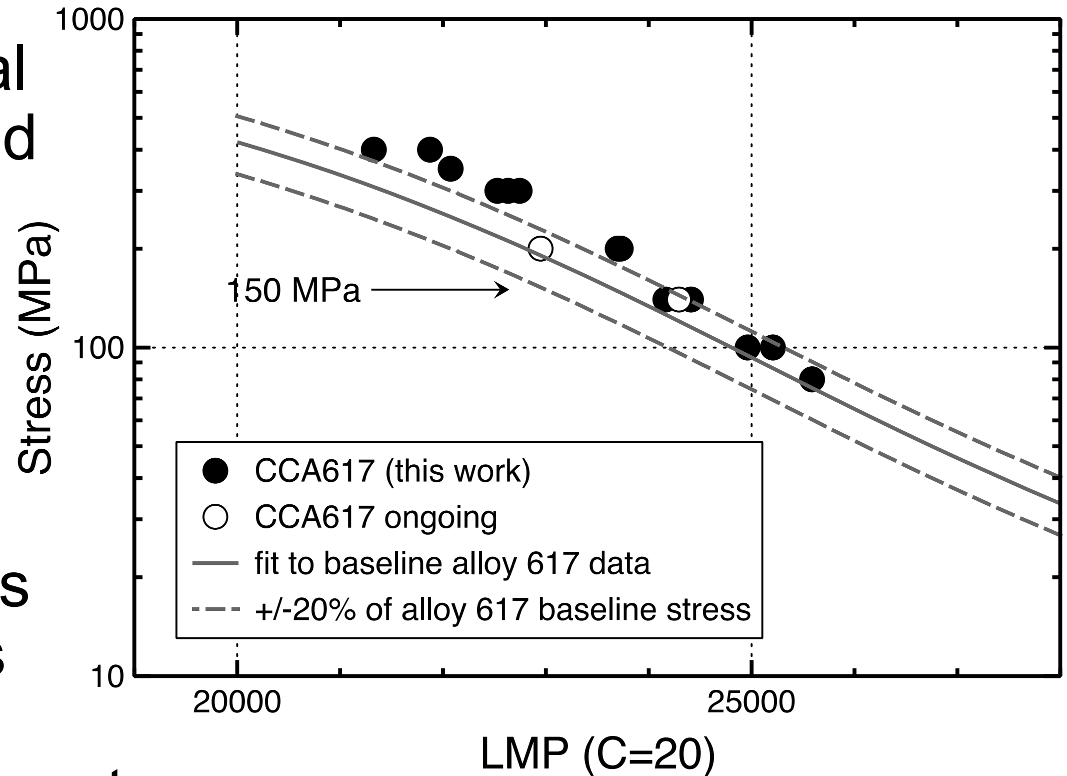
- “Solid solution strengthened” Ni-based alloy, but has some γ′
- Rapid, stable precipitation of limited amount of γ′ up to 750° C



- Long-term creep testing to greater than 90,000 hours



Other Important CCA617 Findings



- Refined controlled chemical composition of CCA617 had significantly better creep-rupture strength than conventional alloy 617 at ~150 MPa and above
- Creep rupture of weldments depended on weld process
  - gas tungsten arc and shielded metal arc weldments had better creep-rupture lives than submerged arc welded specimens
  - assessment of WSF's for CCA617 vs. 617
- No effect of cold work (tube bending) on creep-rupture
- Thermal shock testing reproduced damage predictions using straightforward creep and fatigue models

Other CCA617 Findings

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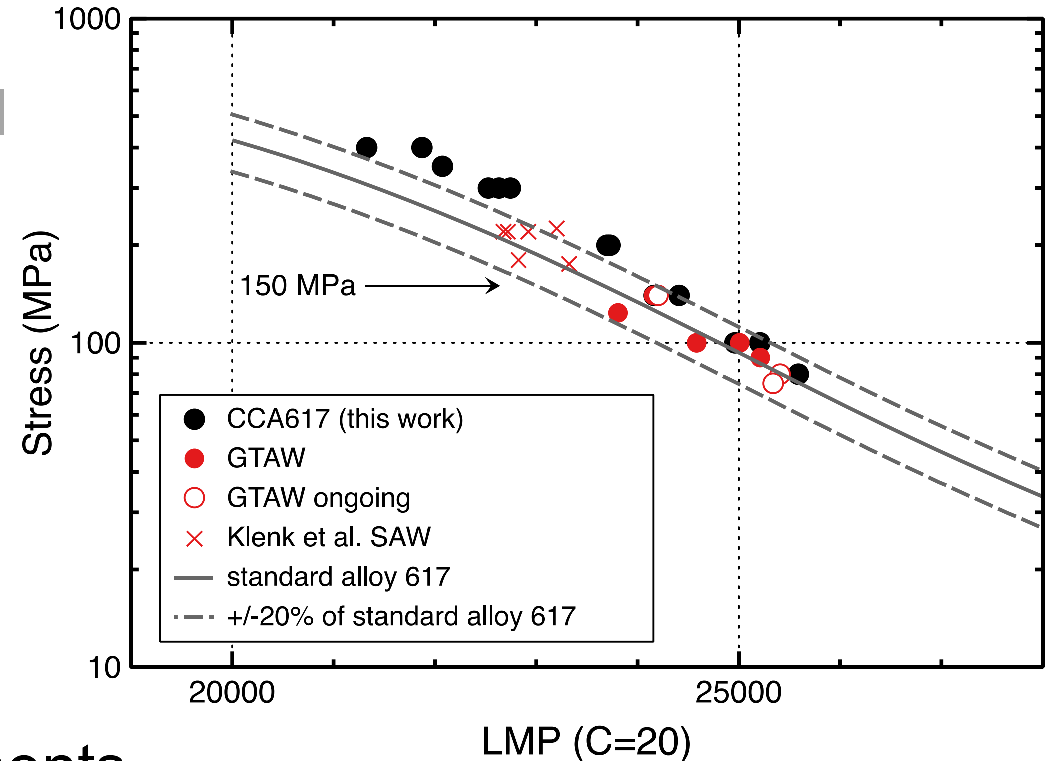

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Other CCA617 Findings

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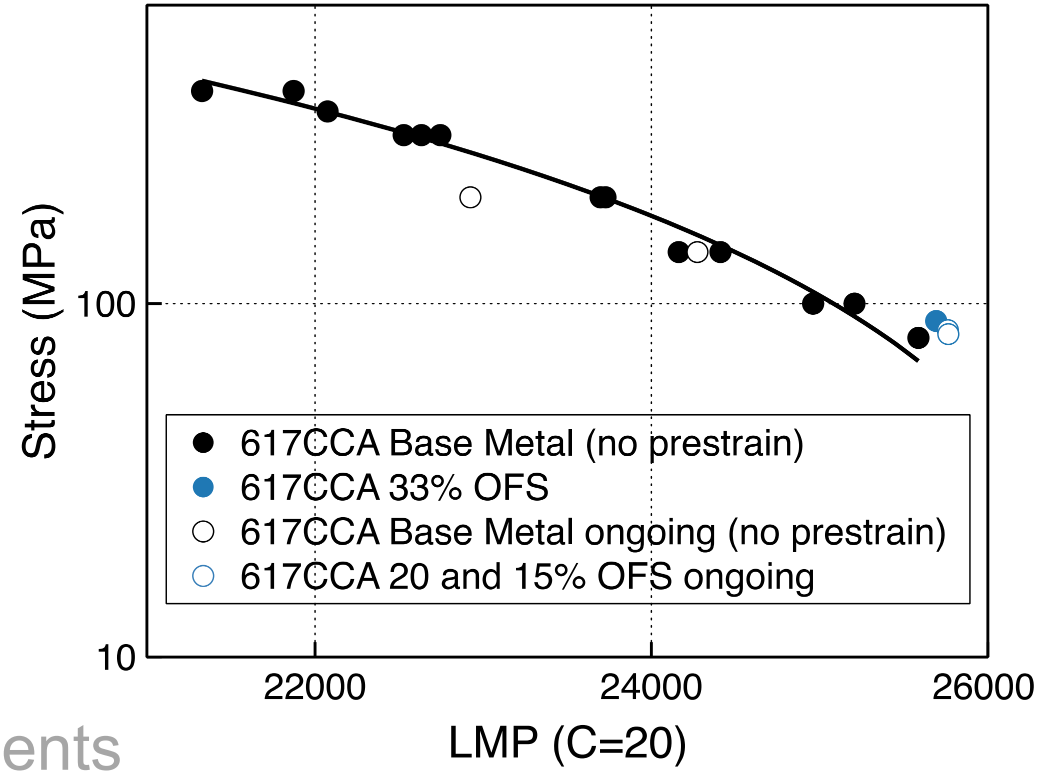

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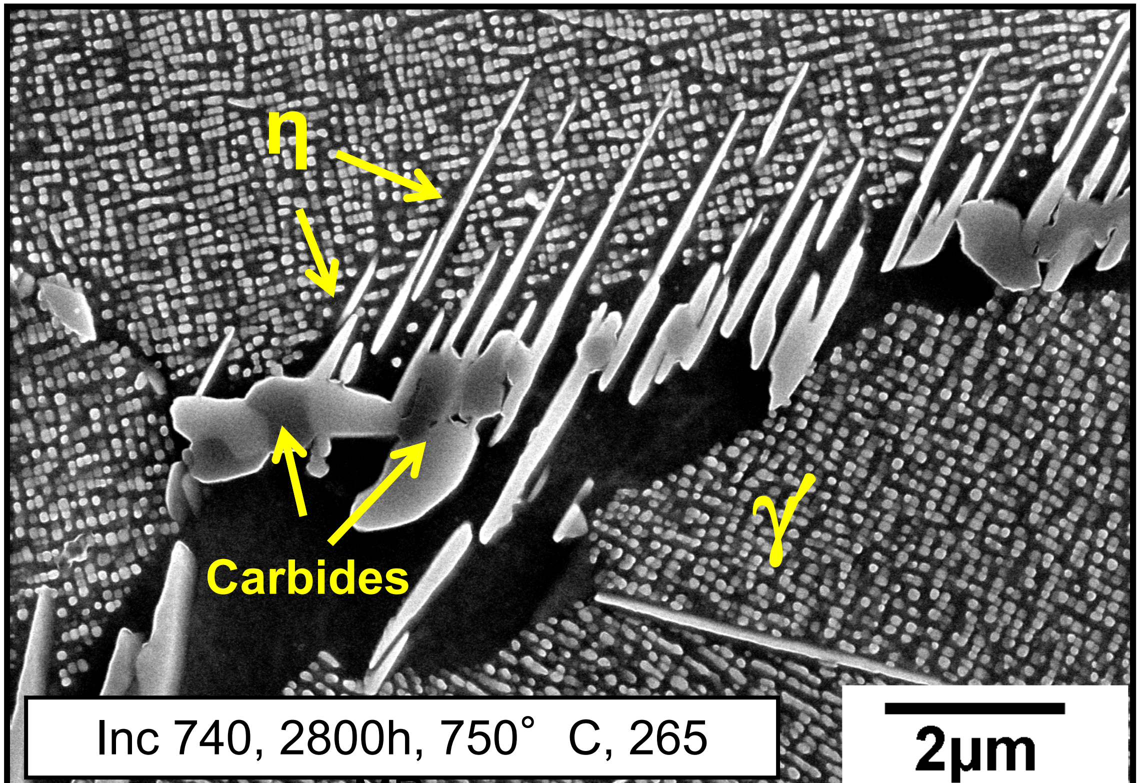
Inconel 740/740H

Nominal Compositions of Inconel 740 and 740H (wt%)

	Ni	Cr	Co	Al	Ti	Nb	Mo	Fe	Mn	Si	C	B
740	Bal	25	20	0.9	1.8	2.0	0.5	0.7	0.3	0.5	0.03	-
740H	Bal	25	20	1.4	1.4	1.5	0.5	1.0	-	0.2	0.03	0.001

- H refinement of 740 composition to improve fabricability
  (Baker and Gollihue, 6th EPRI Conf. on Advances in Materials Technology for Fossil Power Plants, 2011)
- Higher Al for improved γ' stabililty
- Lower Ti, Nb for decreased susceptibility to η phase
- Lower Si to avoid any G phase

740 Base Metal Microstructure Is Sufficiently Stable to Meet A-USC Creep-Rupture Goals

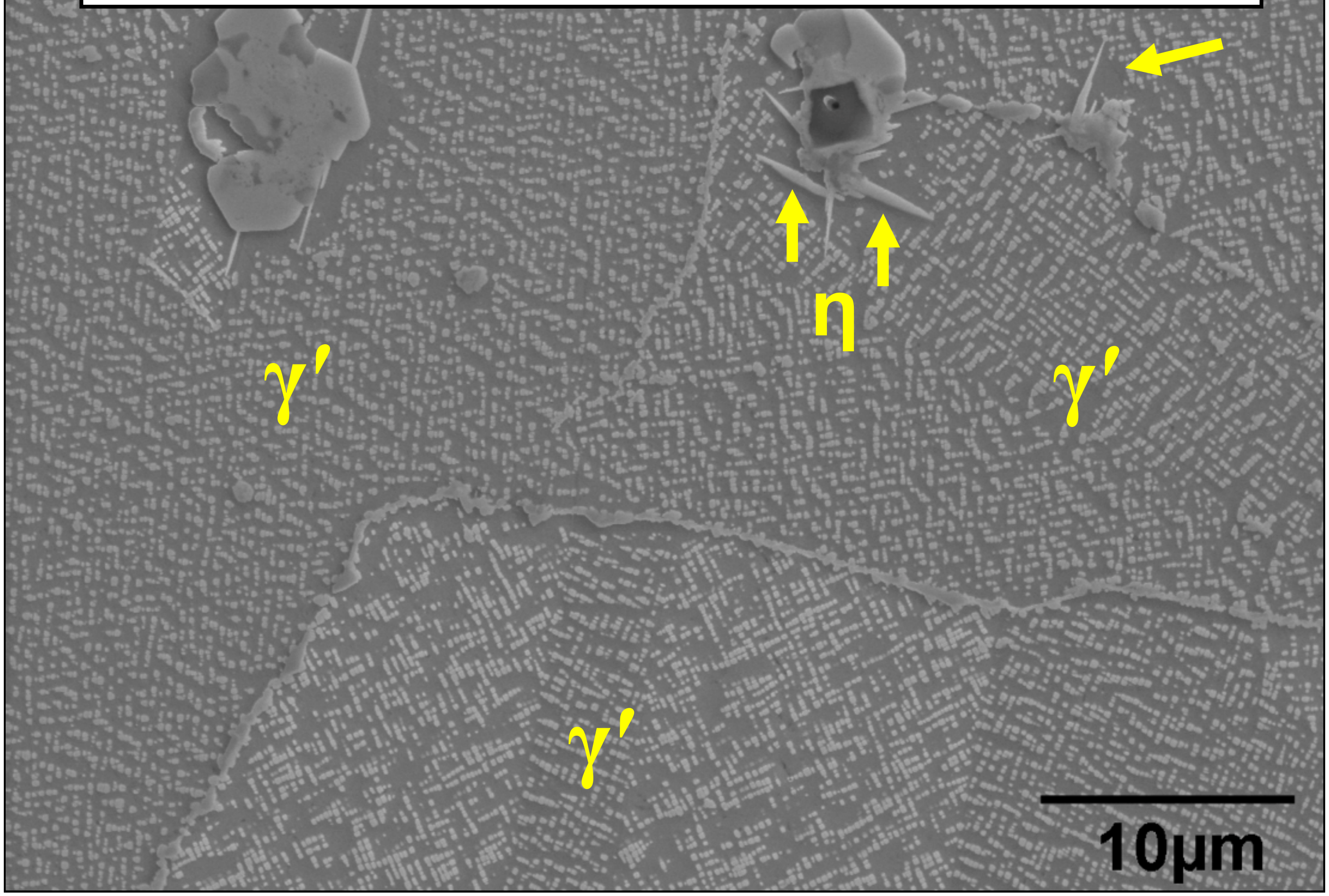


- Size and shape of the γ'
- Disposition of carbides
- η (Nb_3Ti) formation and growth

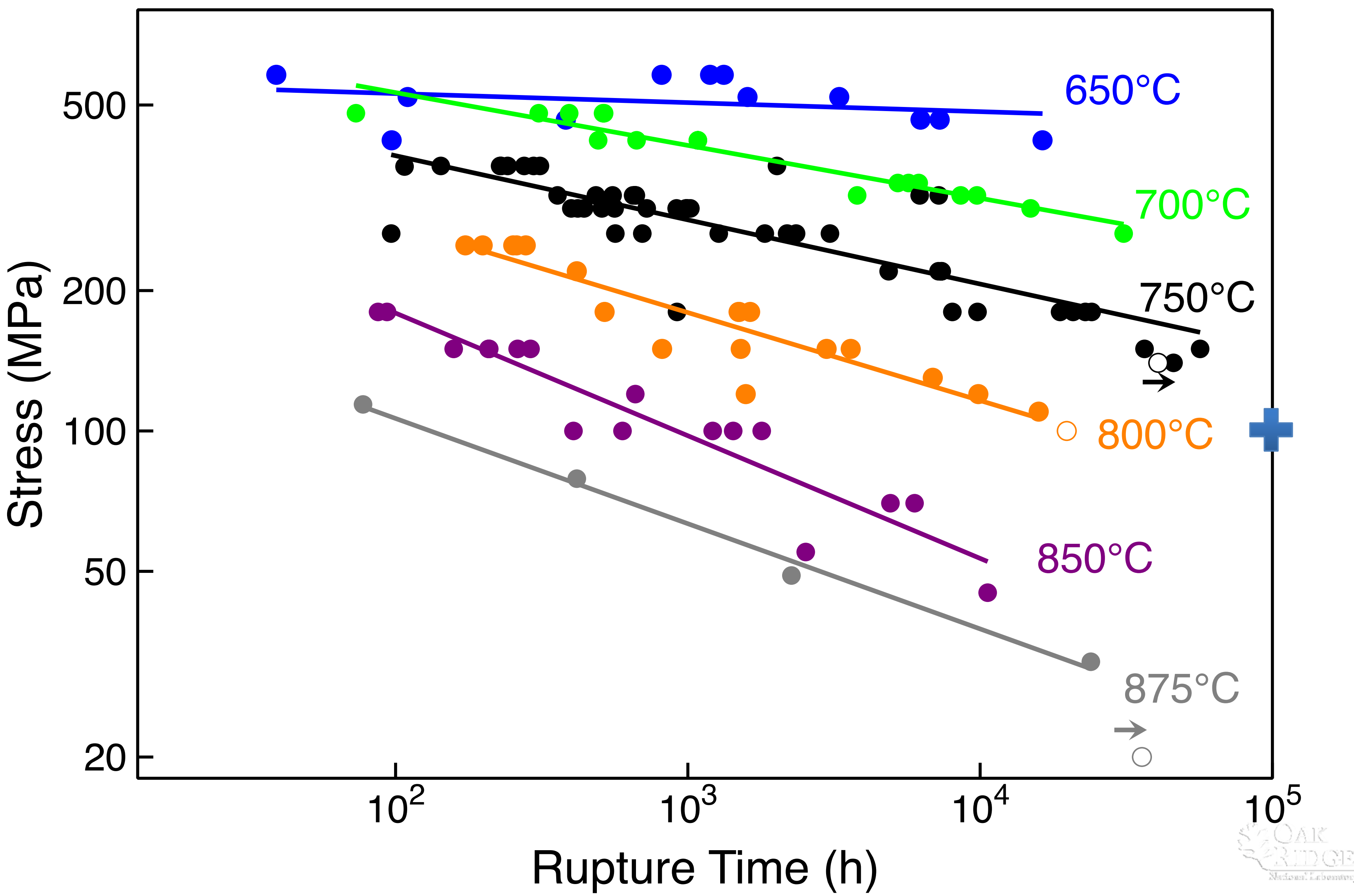
- Needed to understand long-term stability under stress as part of validation of lifetime prediction approaches
- Showed that 740H modification does indeed eliminate η phase, but its presence in 740 has minimal effect on creep-rupture life

Little Evidence of γ′ Depletion at 750° C after Extended Testing

Inconel 740H, 45,840 h, 750° C, 140 MPa



Extensive Creep-Rupture Results for Inconel 740/740H Showed A-USC Target Exceeded



And Provided Database for Successful ASME Code Case (2702) for Inconel 740/740H

EPRI | ELECTRIC POWER RESEARCH INSTITUTE

U.S. DEPARTMENT OF ENERGY

Energy Industries Of Ohio

Ohio | Coal Development Office

Inconel® Alloy 740 Code Case Approval is Major Step for Advanced Ultrasupercritical Power Plants

A consortium funded by the U.S. Department of Energy (DOE) Office of Fossil Energy and the Ohio Coal Development Office (OCDO) has successfully gained American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code (B&PVC) approval for use of Inconel® Alloy 740 in Fossil Steam Boilers. This is a major step by the U.S. Department of Energy in the development of high-temperature materials needed for Advanced Ultrasupercritical (A-USC) steam cycles. These materials enable steam temperatures up to 760° C (1400° F), which can dramatically improve efficiency and reduce emission of all effluents (including carbon dioxide [CO_2]) by about 30% over the current U.S. coal-fired power generating fleet.

The long-term research necessary to gain approval was conducted by the U.S. DOE/OCDO A-USC Steam Boiler Consortium made up of the U.S. Boiler Manufacturers (ALSTOM Power, Babcock & Wilcox, Babcock Power, and Foster Wheeler) led by the Energy Industries of Ohio (EIO), the Electric Power Research Institute (EPRI), and the National Energy Technology Laboratory (NETL), with support from Oak Ridge National Laboratory (ORNL). The program has recorded a number of major accomplishments, and ASME B&PV Code approval of Inconel® Alloy 740 is one of the most critical steps needed before an A-USC demonstration power plant can be constructed.

The U.S. DOE/OCDO A-USC Consortium

In 2001, the U.S. DOE challenged the U.S. boiler and steam turbine suppliers to develop a pre-competitive R&D program which would lead to higher-efficiency coal-fired power plants with reduced emissions. The goal of the program is to develop materials technologies necessary to build and operate an A-USC boiler with steam temperatures up to 760°C (1400°F). Studies show the cost for reducing CO_2 by moving from conventional supercritical to A-USC designs is far lower than that of any other CO_2 capture and storage systems. Higher-efficiency generation also requires less coal, less cooling water, smaller environmental control systems, and less coal mined and transported.

The major barrier to realizing A-USC technology is the materials which could withstand the higher steam temperatures and pressures. The boiler team developed a comprehensive program with research primarily focused on a group of nickel-based alloys, including research into

Hot extrusion of an Inconel® Alloy 740 (ASME Code Case 2702) Pipe at Wyman-Gordon (PCC Energy), Houston, Texas. The 10,000-plus-pound ingot was cast by Special Metals Corporation, Huntington, West Virginia. Inconel® Alloy 740 is the prime candidate alloy for advanced ultrasupercritical steam boilers. (Photo courtesy of Wyman-Gordon)

"The approval of Code Case 2702 will help enable future power steam boilers to operate with very high efficiencies, beyond today's technology, significantly reducing CO_2 emissions from coal-fired power plants."

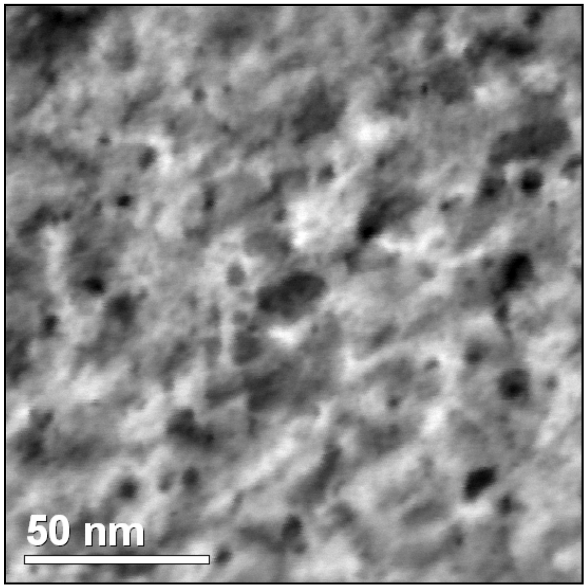
~ John Shingledecker, EPRI Senior Project Manager and A-USC Steam Boiler and Turbine Consortia Technical Lead

Oak Ridge National Laboratory

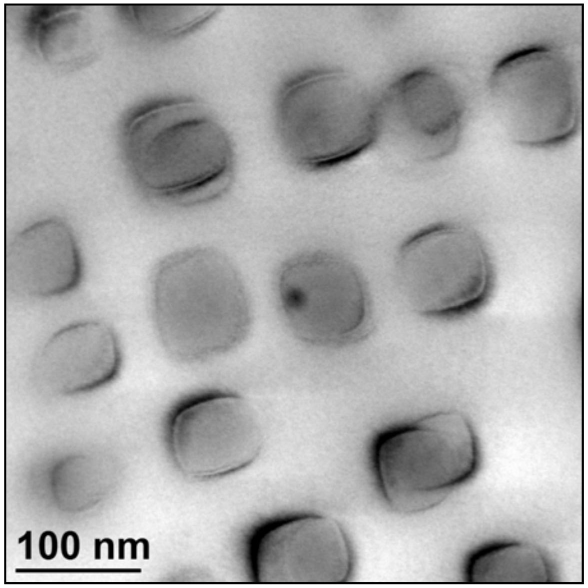
Transmission Electron Microscopy (TEM) Part of Study of Microstructural Stability

- Measure γ′ coarsening kinetics
- Evaluate strenthening mechanisms (not discussed here)

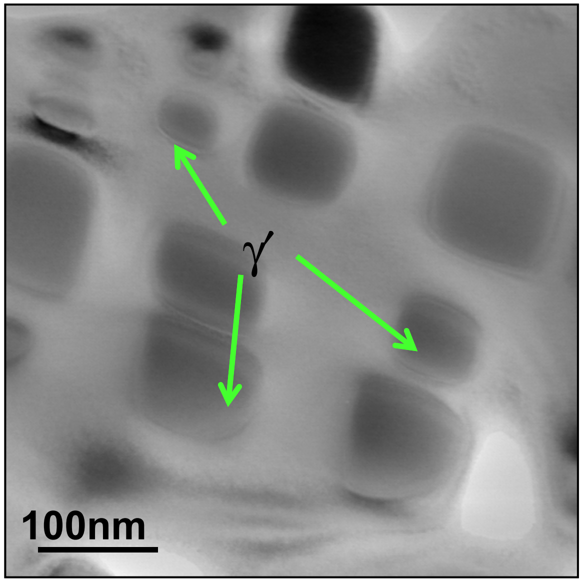
0h/0MPa



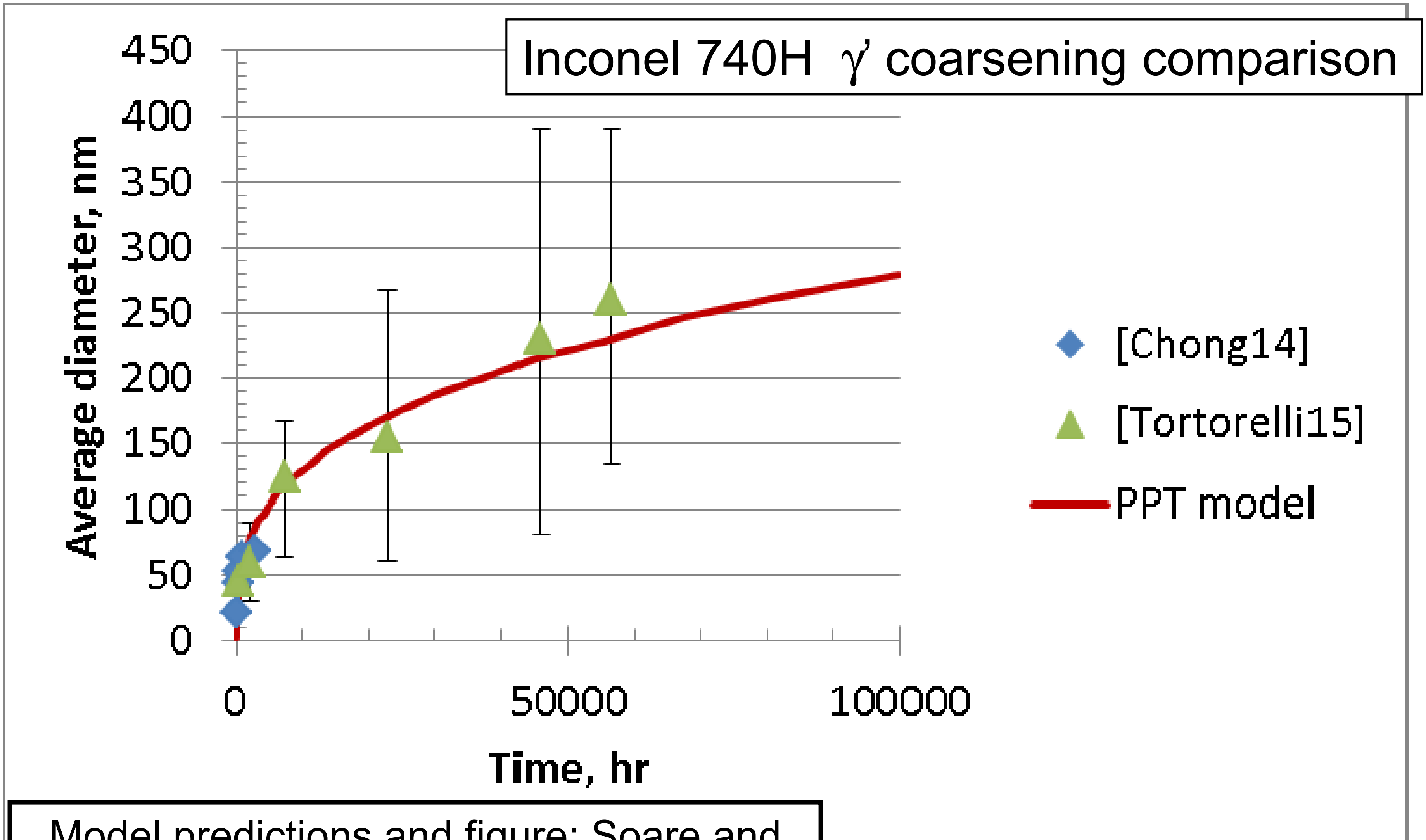
2185h/0MPa



22,896h/0MPa

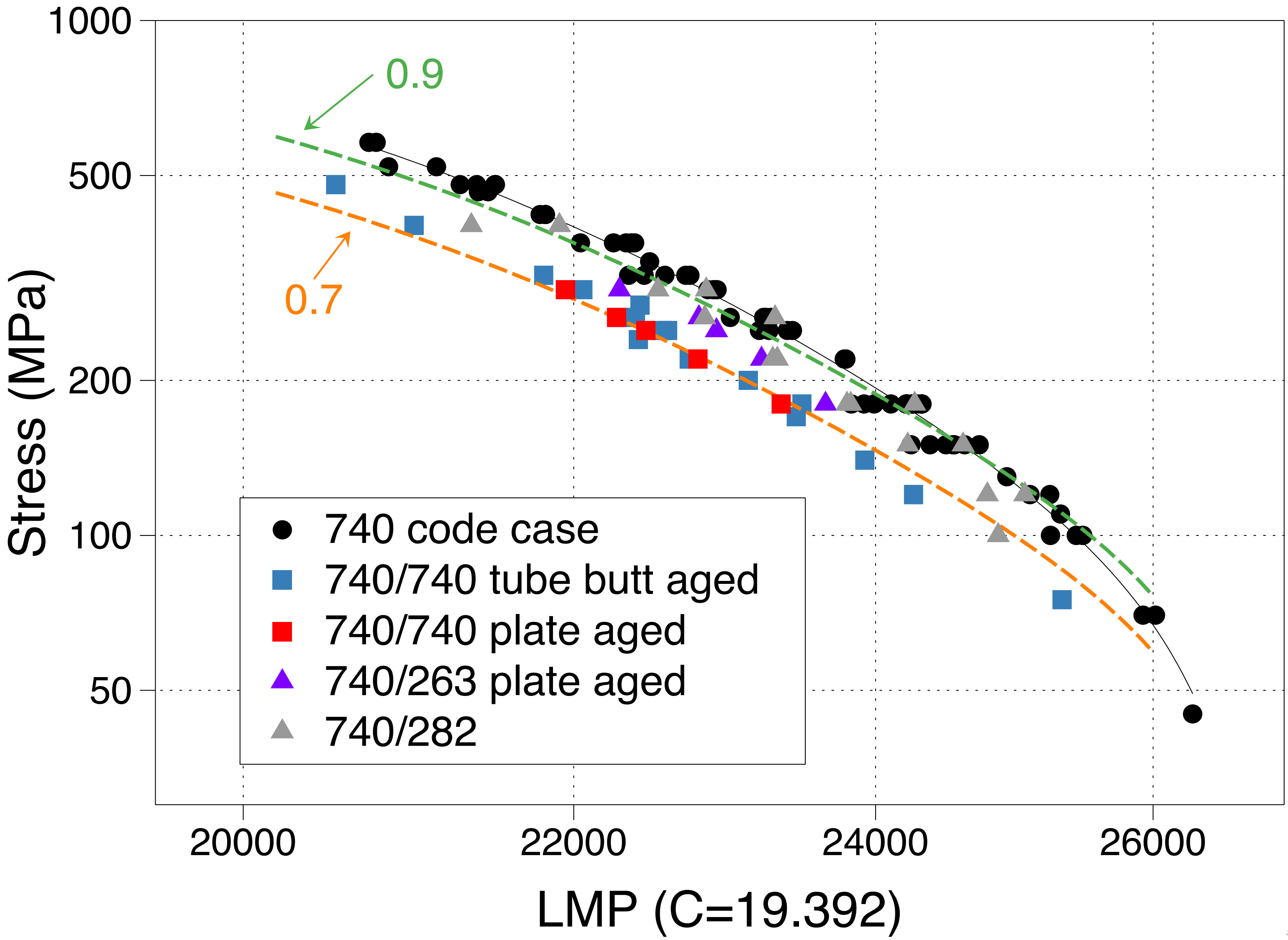


A-USC Data Confirmed Predicted γ′ Coarsening by Soare and Shen

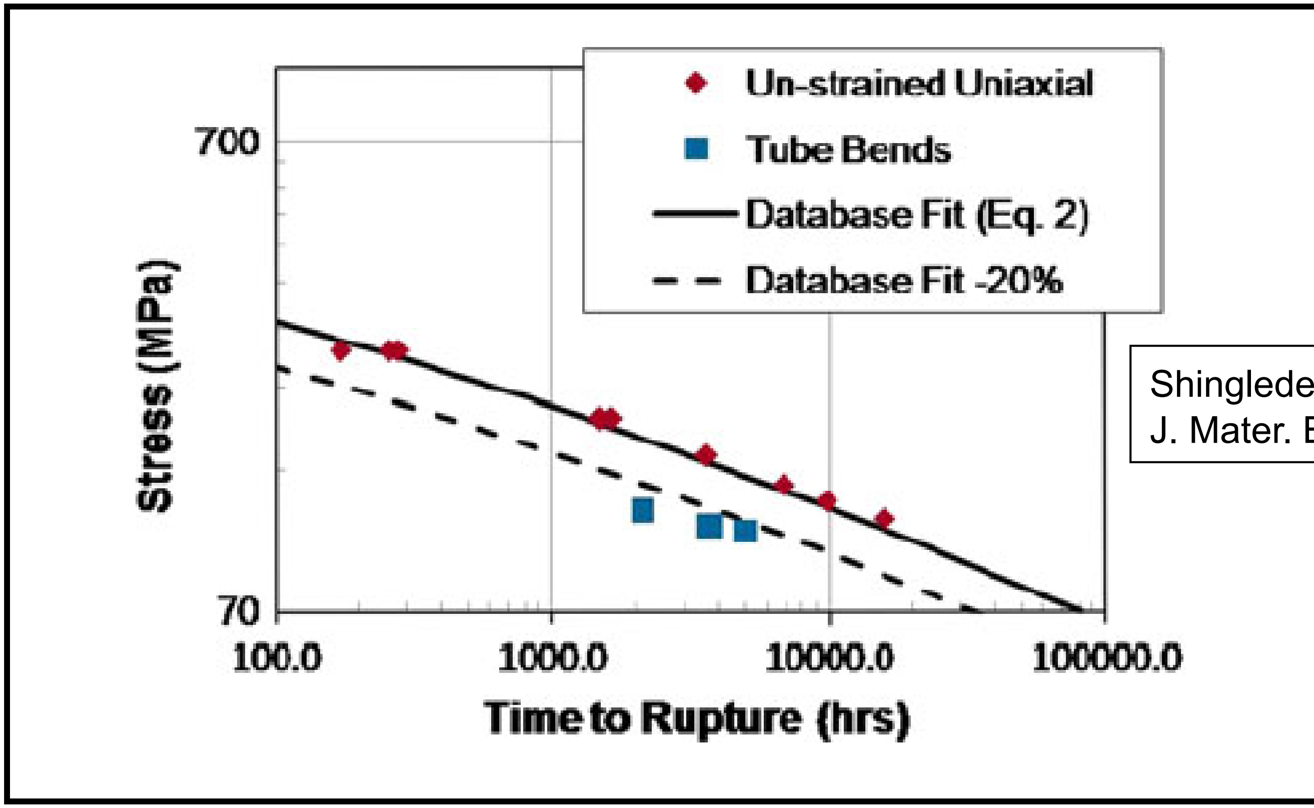


Model predictions and figure: Soare and Shen, GE Global Research

Alternative Filler Metals Improved Creep-Rupture Strength of Inconel 740 Weldments



Unlike 230 and CCA617, 740 Had a Significant Creep Debit Due to Cold Work of Tube Bends



Shingledecker and Pharr, J. Mater. Eng. Perf., 2013

Creep rupture of solid-solution Ni-based alloys thought to be less susceptible to cold work effects than precipitation-strengthened alloys such as Inconel 740

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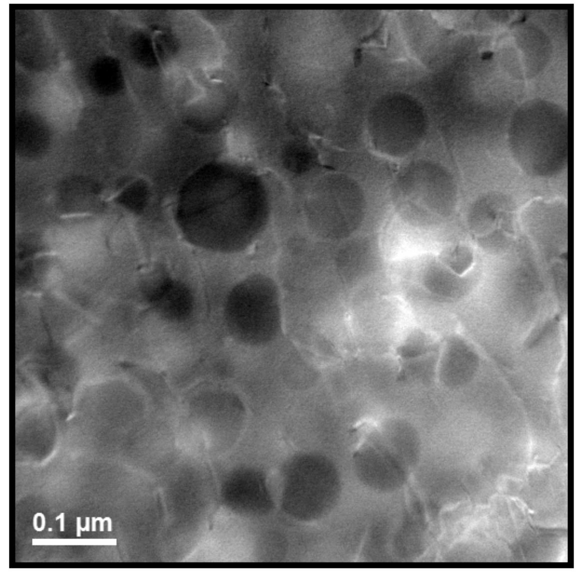
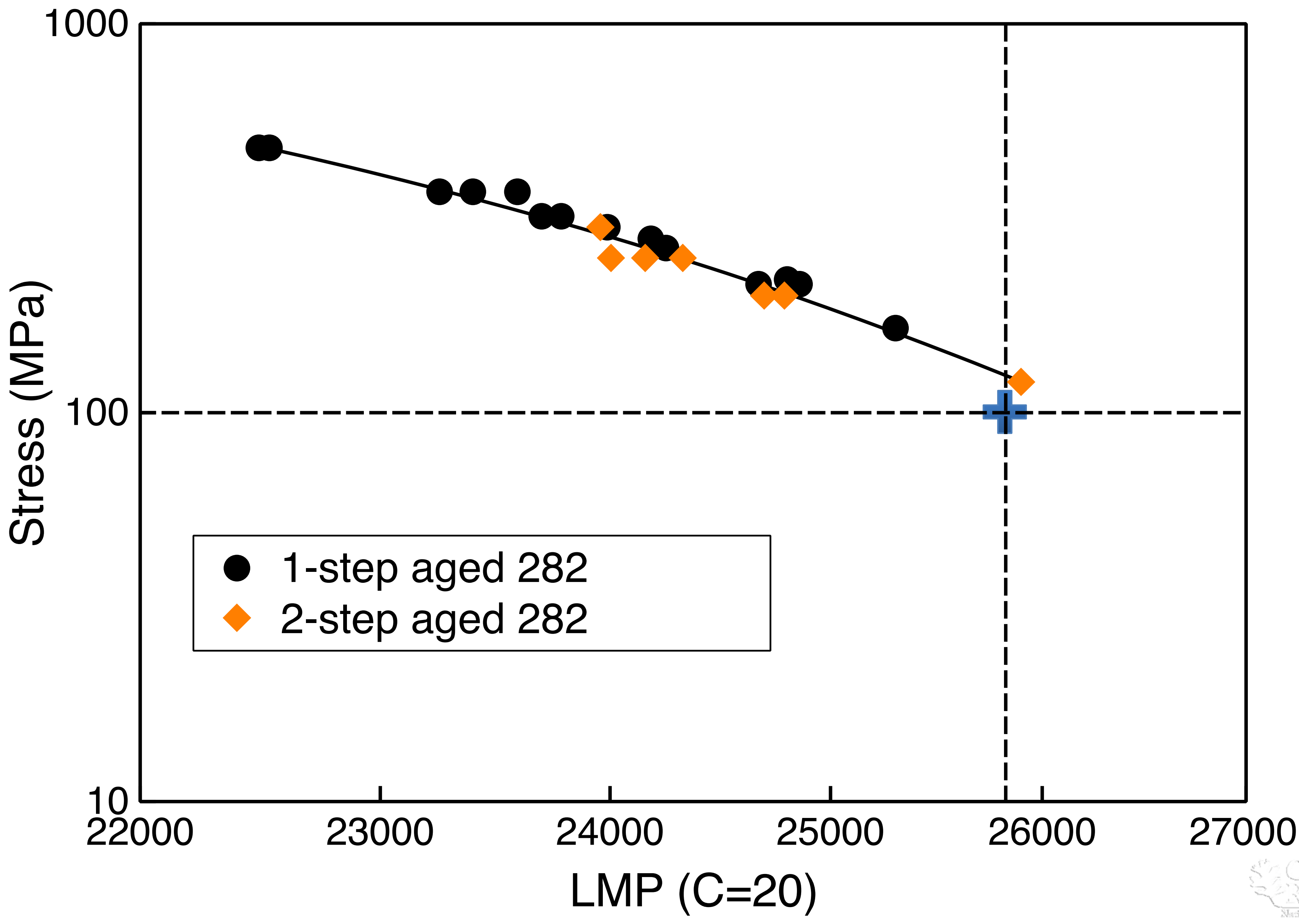
Boiler-Relevant Creep-Rupture Data for Haynes alloy 282 Was Generated

- For Haynes 282, work showed
  - better creep-rupture resistance than Inconel 740/740H
  - minimal debit in creep-rupture strength due to welding
- Recommended 2-stage aging protocol (1010° C/1h+788° C/8h) deemed problematical by boiler manufacturers
- 2013: determined a one-step aging treatment (800° C/4h)
- 2015: Completed a creep-rupture test campaign for one-step aged Haynes 282

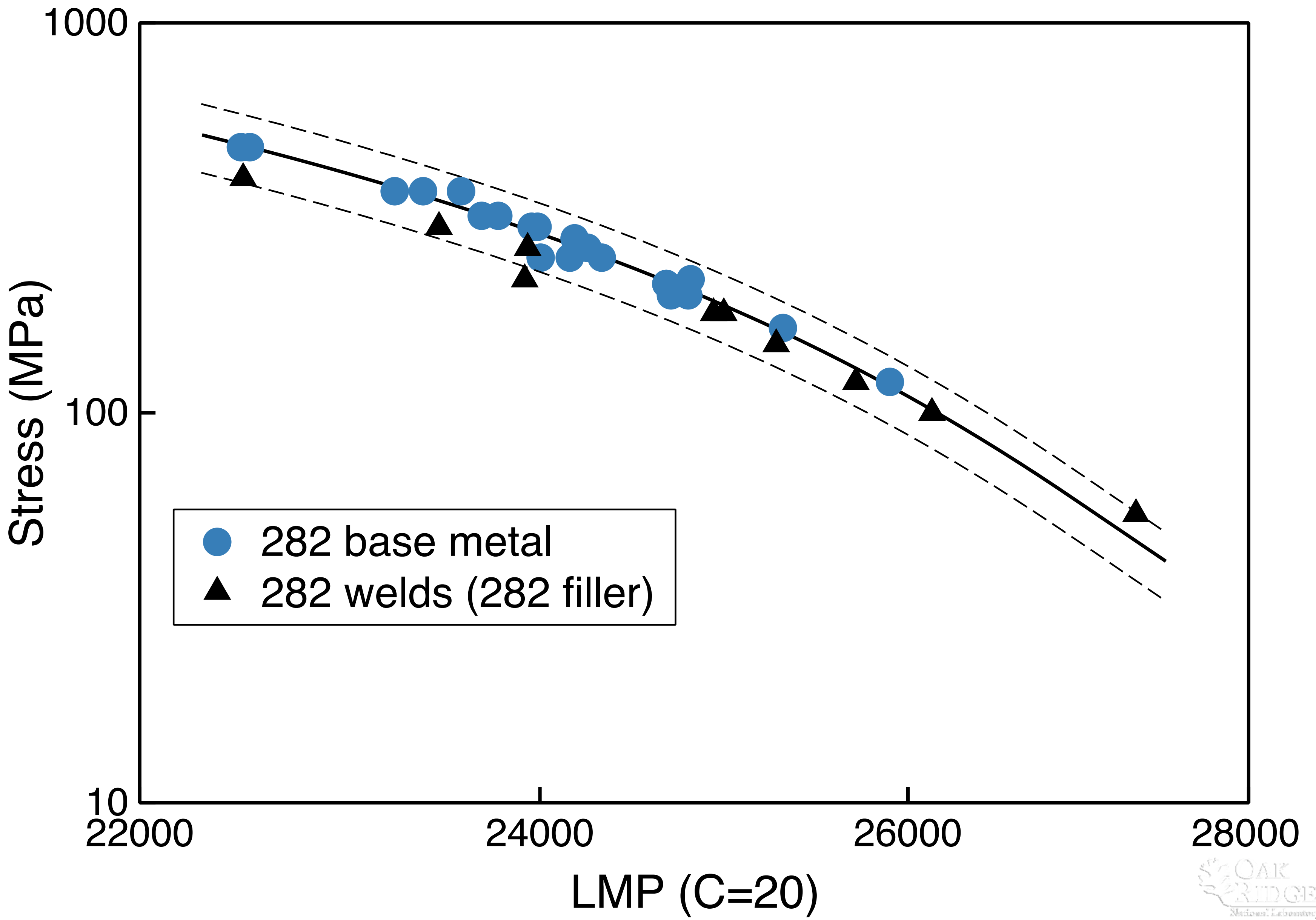


- Code case test campaign for wrought 282 starting (different project)

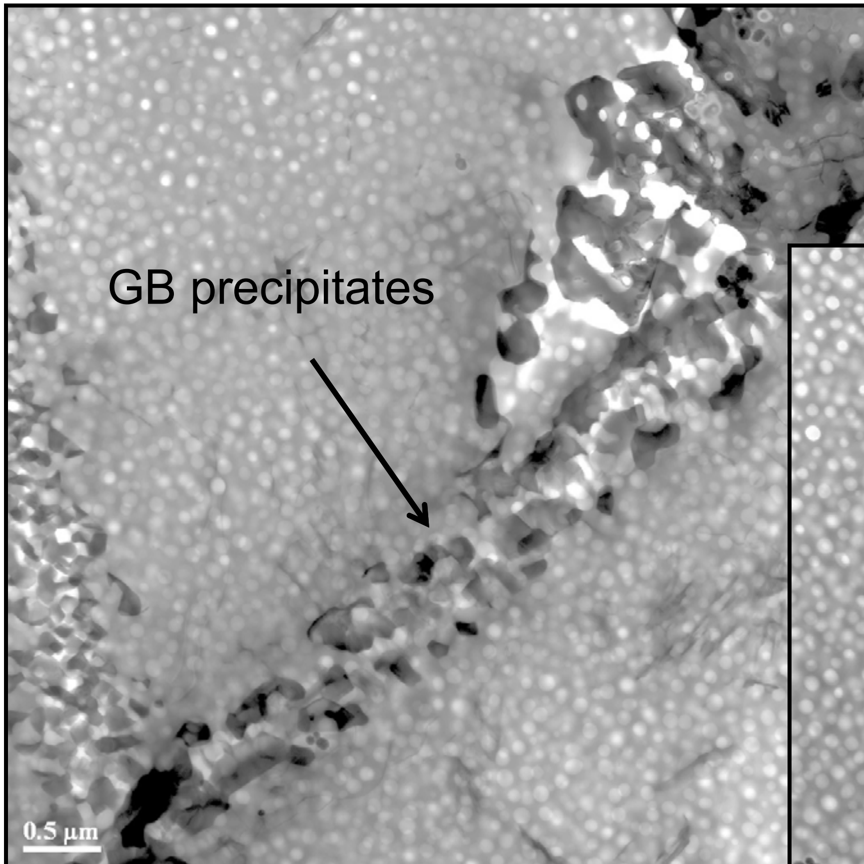
Little Difference in Creep-Rupture Lifetimes for the Two Aging Treatments

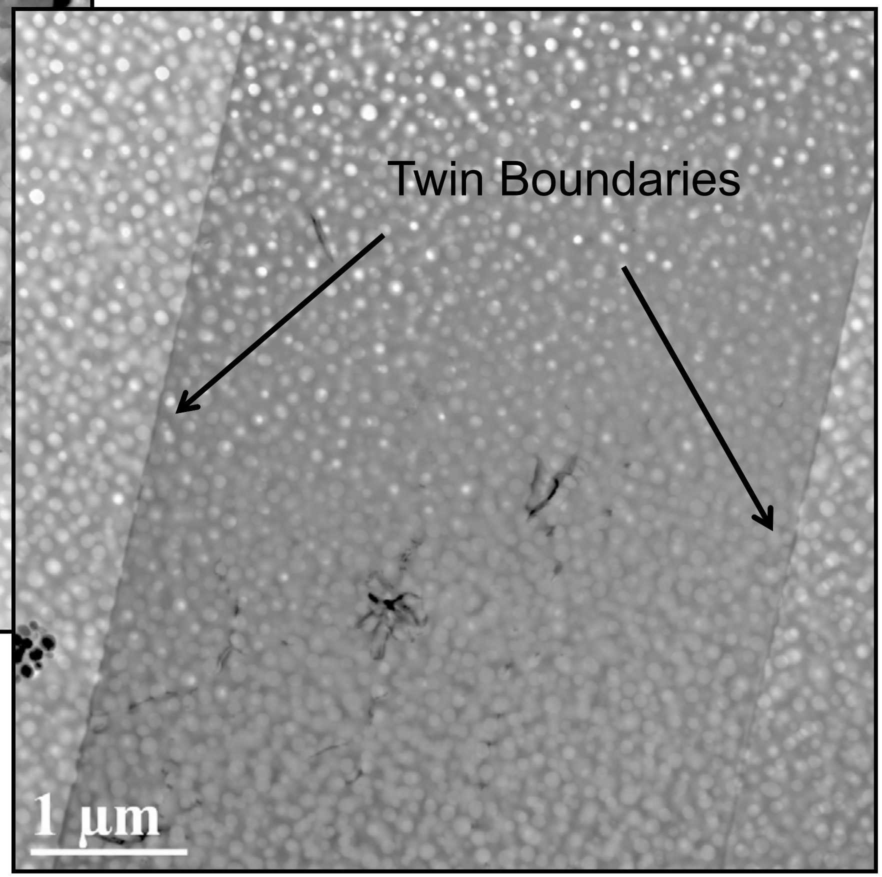


Haynes 282 Cross Weld Specimen with 282 Filler Metal Show Minimal, If Any, WSRF



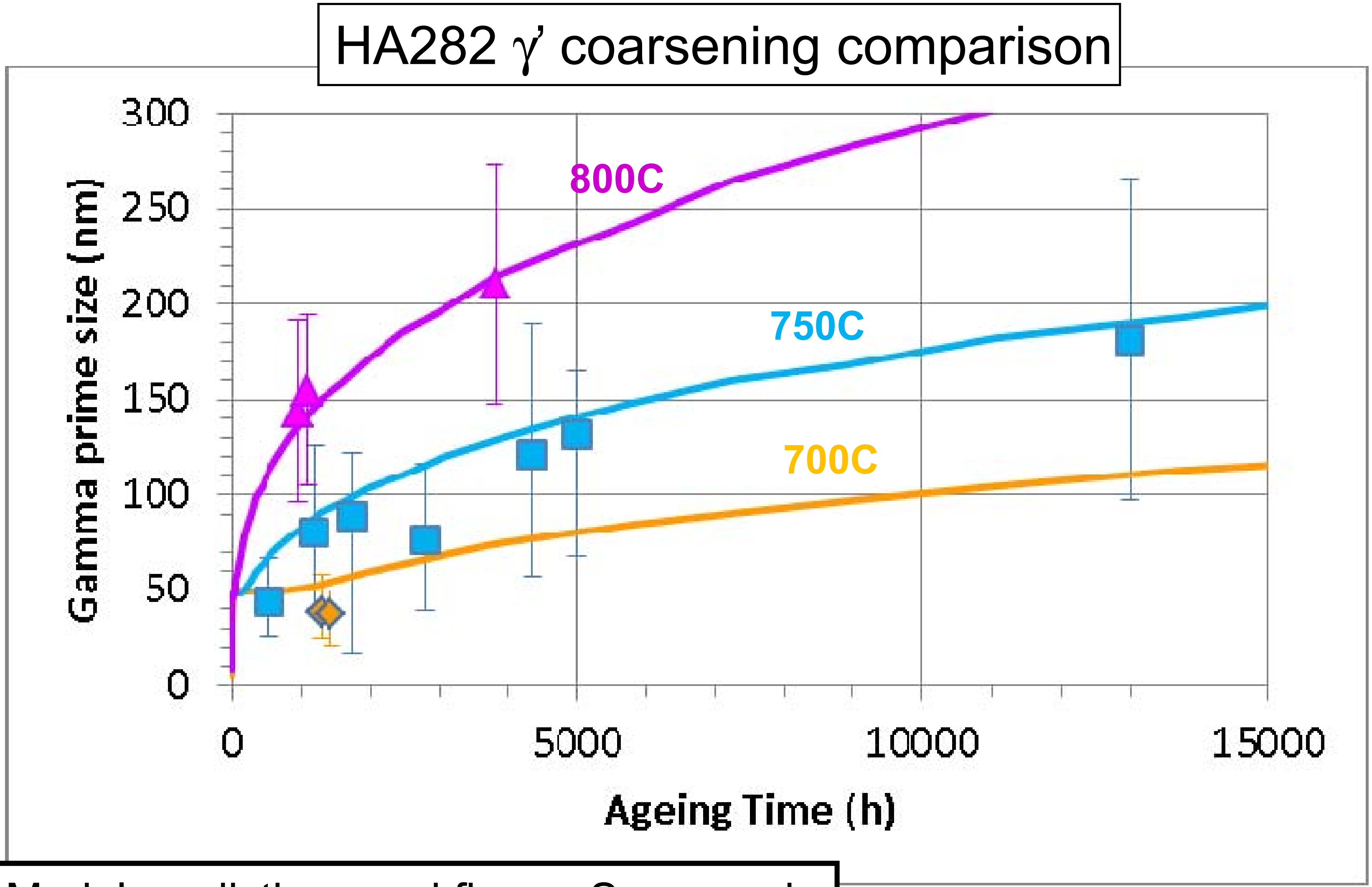
No Evidence of γ′ Depletion in Bulk of Haynes 282 Specimen, Even at High Mag





Haynes 282
2809 h, 750° C, 0 MPa

TEM Data Showed Good Agreement with Predictions of GE Precipitation Model



Model predictions and figure: Soare and Shen, GE Global Research

Summary: A-USC Boiler Mechanical Behavior

- Alloys with requisite mechanical properties for 760° C and up to 35 MPa internal pressure do exist
- Long-term creep-rupture testing (20,000 to ~95,000 h) has been critical to assessing material stability and providing the basis for confidence in using these materials
- Databases have led to improvements in the code (ex: cold work rules, WSRFs)
- Code Case 2702 for Inconel 740/740H approved by ASME
- Novel testing approaches were developed (tube bend, thermal shock, large specimen creep, notches)
- Data developed to support both component design by rule and design by analysis
- Research led to consideration of 282 for boilers and to actions (outside of consortium) by material manufacturers (740H piping, HR6W reformulation, 282 code case)