Ni-Based Alloys for Advanced Ultrasupercritical Steam Boilers

P.F. Tortorelli, K.A. Unocic, H. Wang
Oak Ridge National Laboratory

J.P. Shingledecker
EPRI

Fossil Energy Crosscutting Research Program Review

April 25, 2015

Pittsburgh, Pennsylvania

U.S. DEPARTMENT OF ENERGY

OAK RIDGE National Laboratory

Acknowledgements

Bob Swindeman

John Shingledecker

Michael Santella

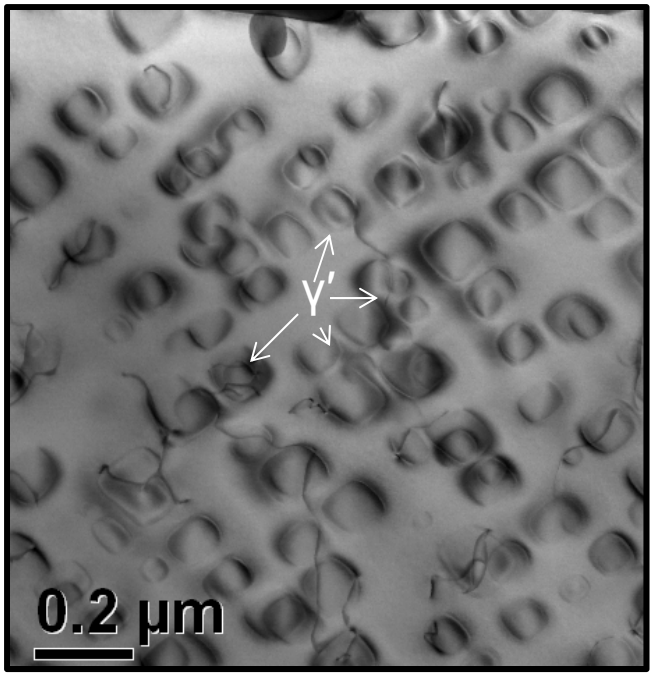
Peter Tortorelli

Ian Wright

Acknowledgments

- Jeremy Moser, creep testing
- Tom Geer and Tracie Lowe, specimen prep and microstructural analysis
- Vito Cedro, NETL, federal project manager

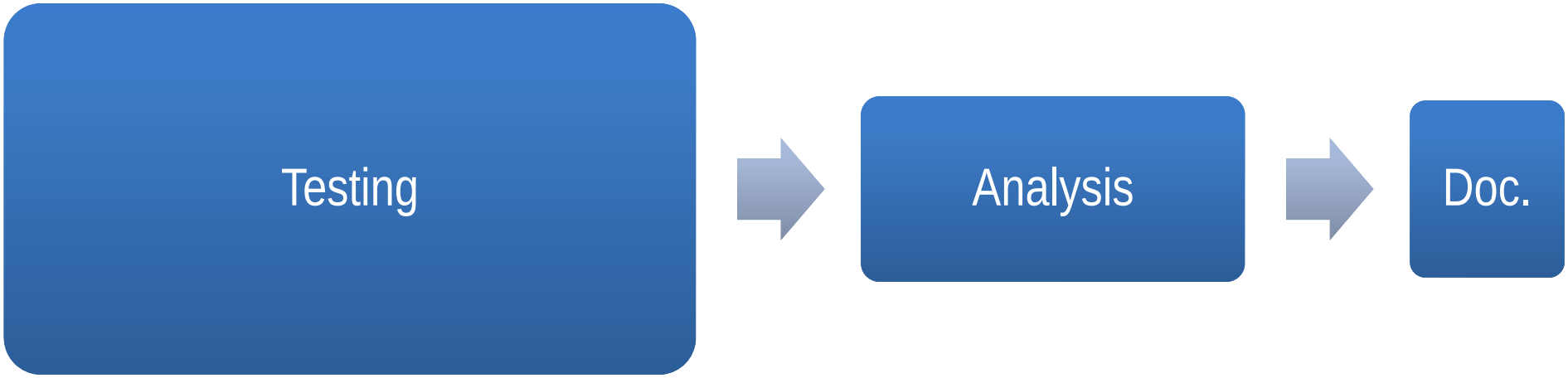
ORNL's Role in the A-USC Boiler Effort



Inconel 740

- Generate high quality creep-rupture data using accepted test methods
  - Nickel-base alloys, including code case for Inconel 740
  - Supplement minimum required data for code-approved alloys, e.g., alloy 617, Inconel 740
  - Identify fabrication & welding issues on creep strength
- Understand microstructural underpinnings of creep strength and failure
- Predict life with confidence

Nature of Work Has Changed

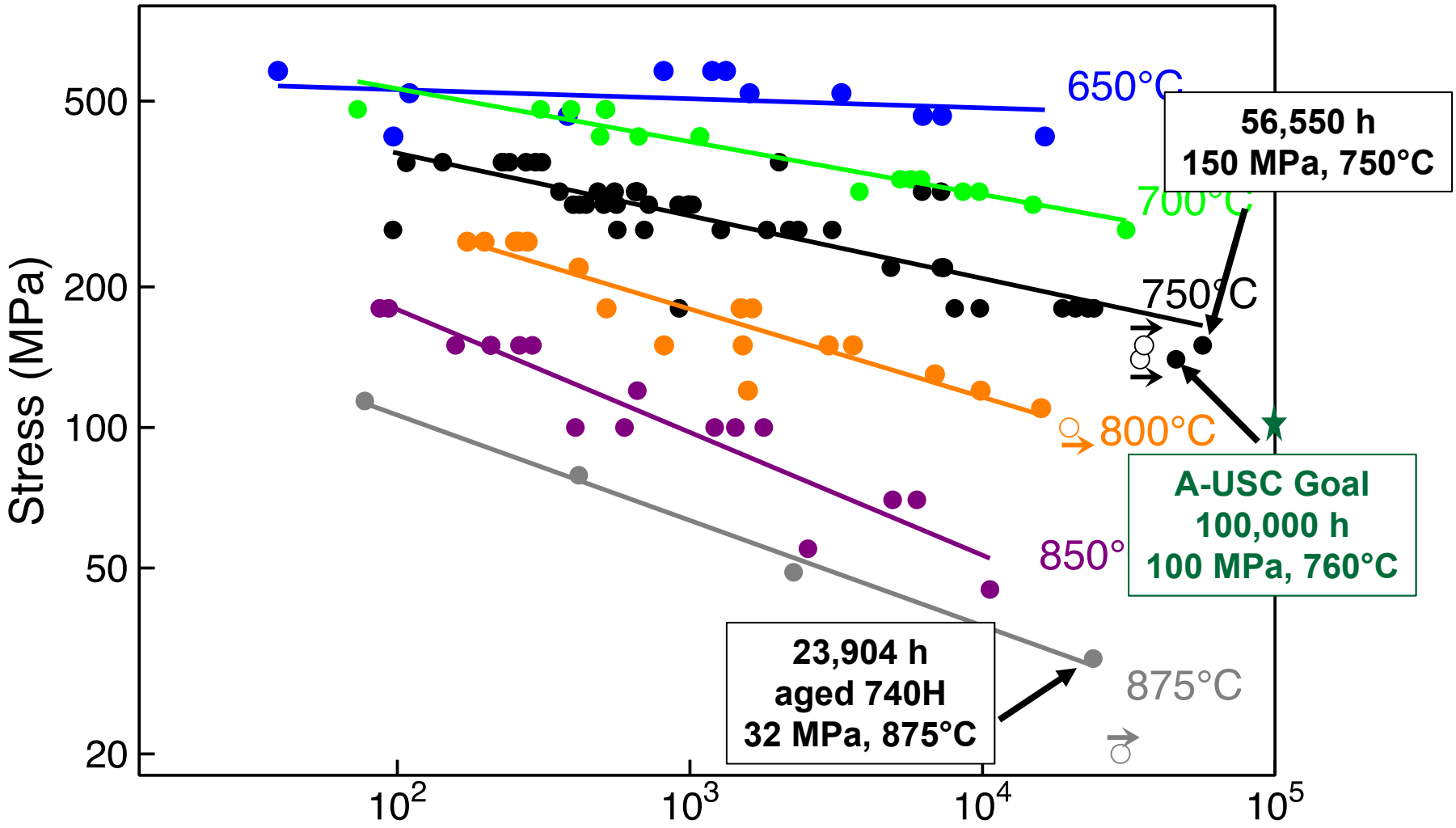


Focus of Work Has Been on Ni-Based Alloys

	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
282	Bal.	20	10	1.5	2.1	-	8.5	1.5	0.3	0.15	0.06	0.005
617	Bal.	22	11	1.2	0.4	-	8.6	0.7	0.03	0.1	0.06	0.003

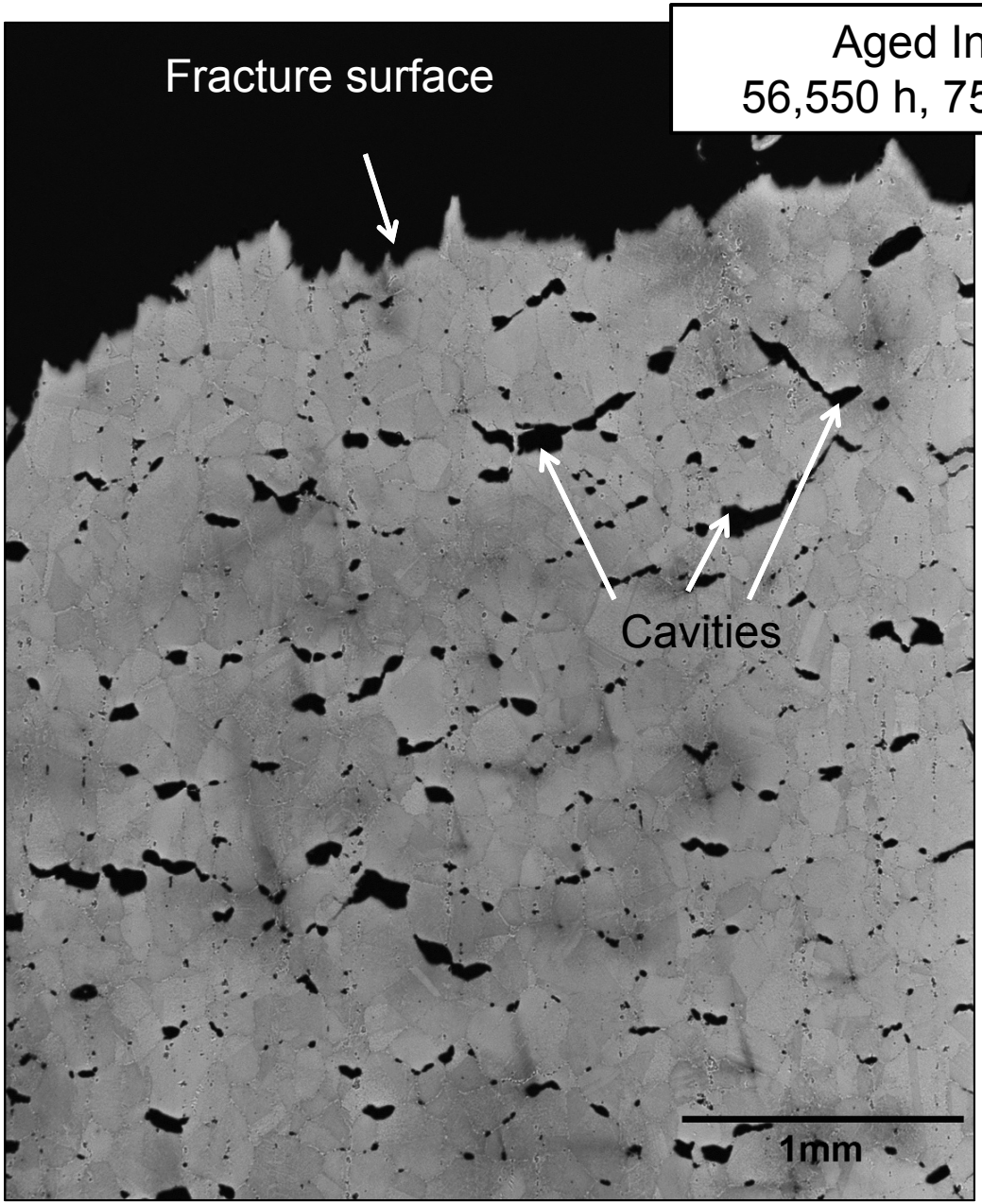
- Both Inconel 740 and Haynes 282 form γ′ (Ni_3Al, Ni_3Ti) and carbides
- Alloy 617CCA (617B) is mainly solid solution strengthened
- Only Inconel 740 forms η (Ni_3Ti), with 740H having significantly less susceptibility to its formation (several studies)
- Vol% η that forms during exposure seems to have little effect on creep rupture (Shingledecker and Pharr, Tortorelli et al.)
- Alloys have elements that promote internal oxidation (Pint et al., Wright et al.)

Long-Term Creep-Rupture Data for 740/740H Build Confidence in A-USC Boiler Use



K.A. Unocic et al., JOM 66 (2014) 2535-42.

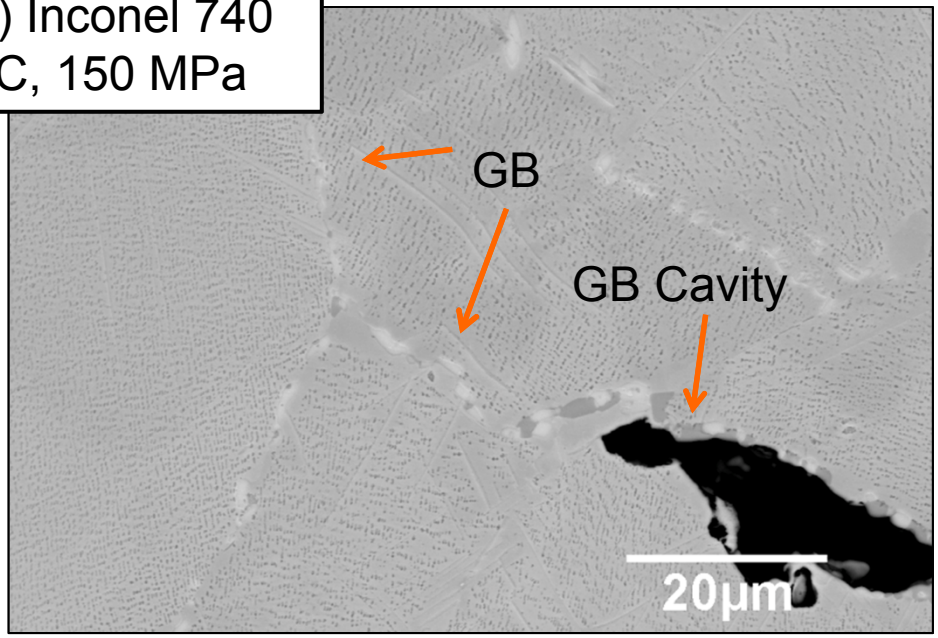
High Density of Cavities After 56,550 h



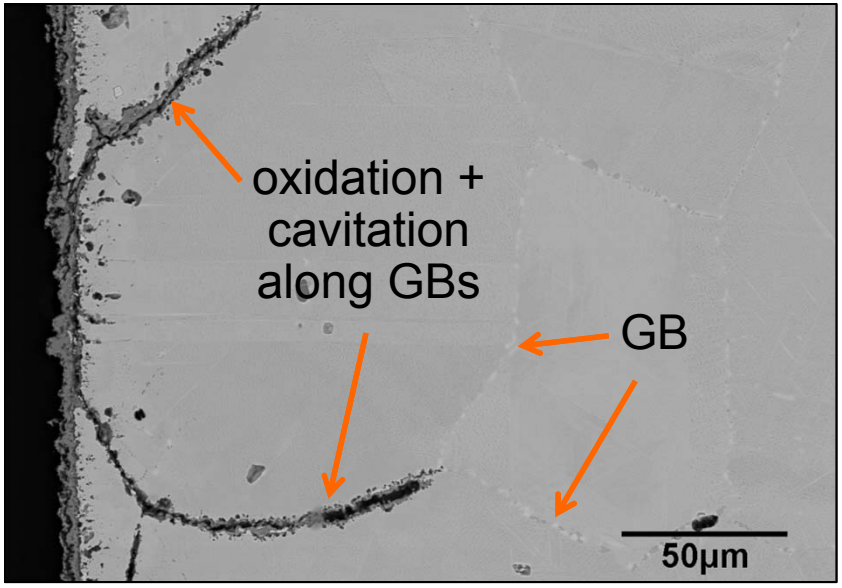
Grain Boundary Cavitation

Aged (8h/800°C) Inconel 740
56,550 h, 750°C, 150 MPa

Center

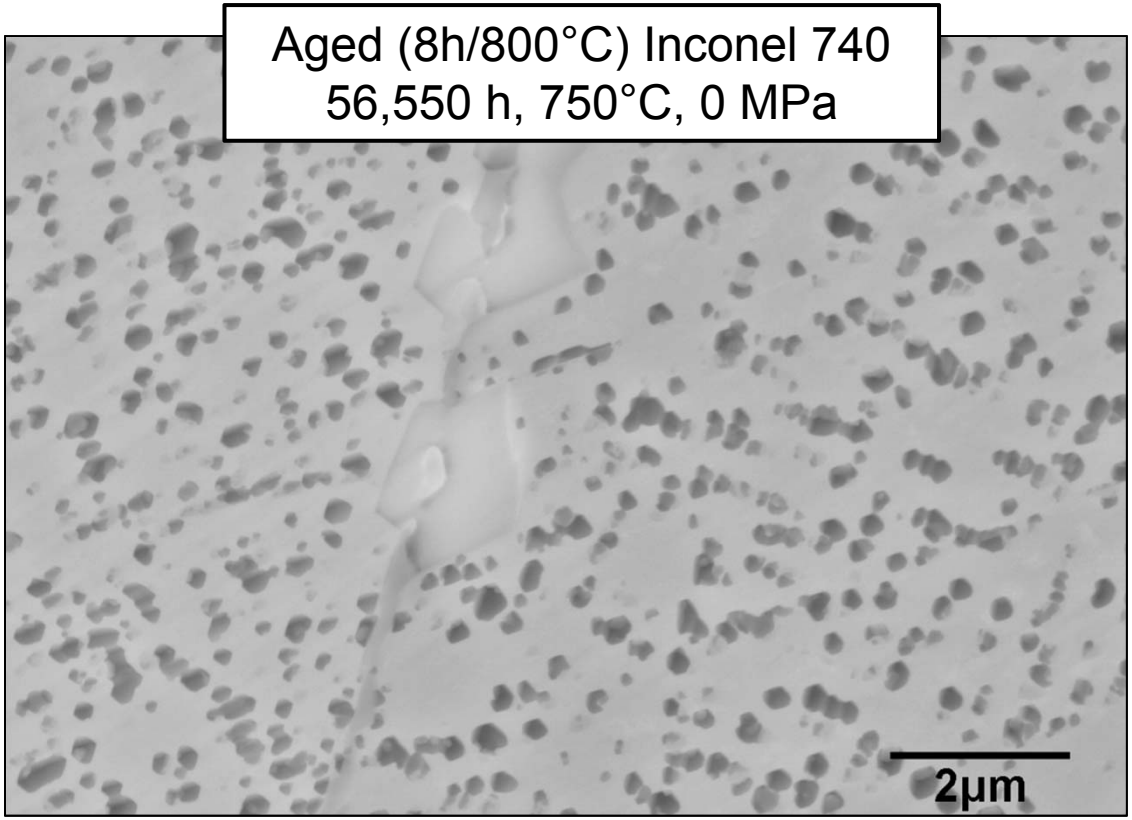


Near edge

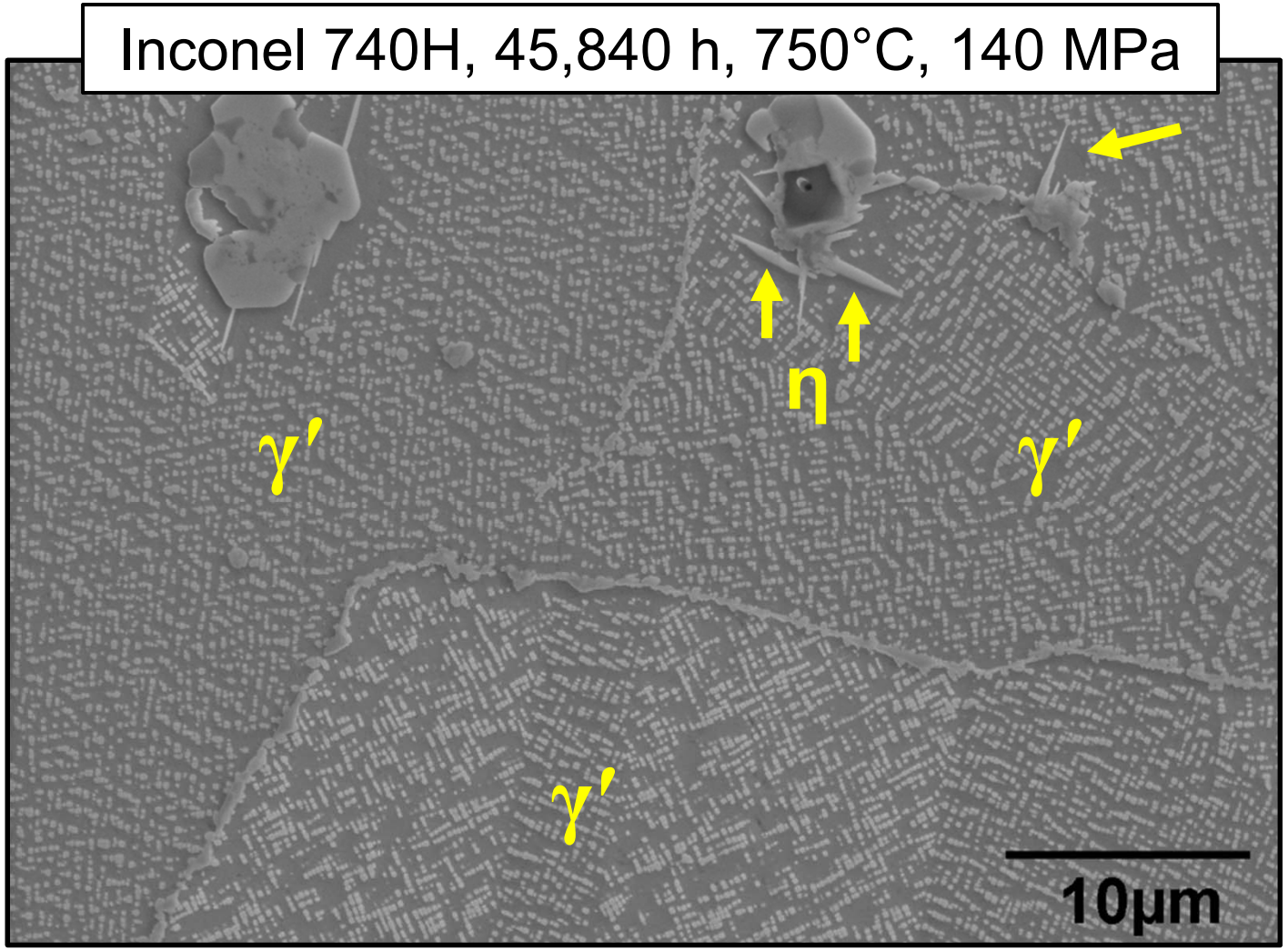


Loading direction

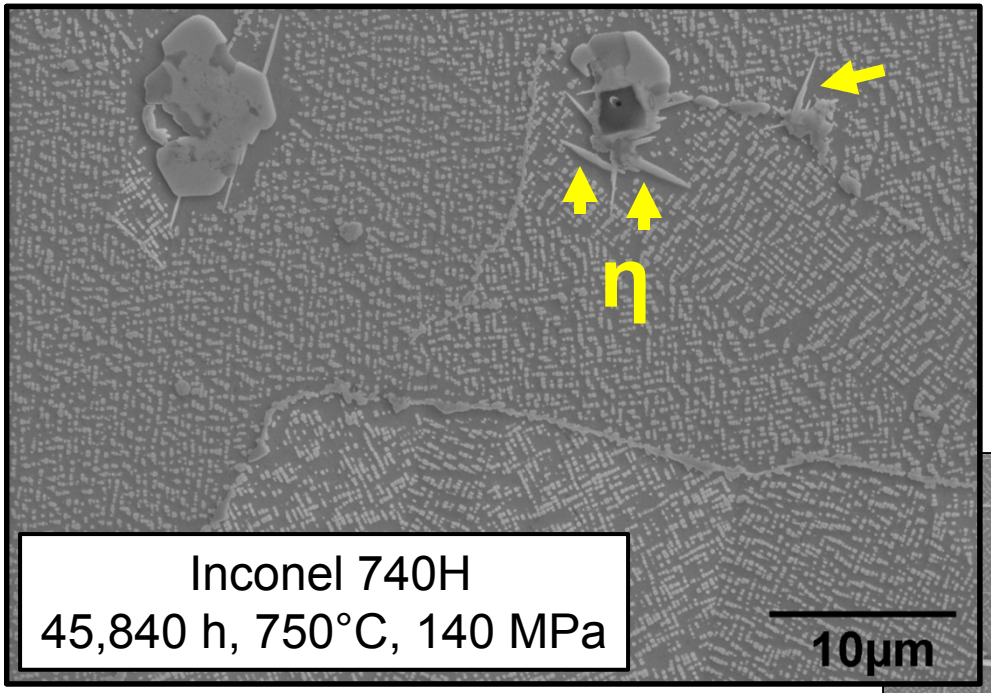
Little γ′ Depletion Noted at GBs

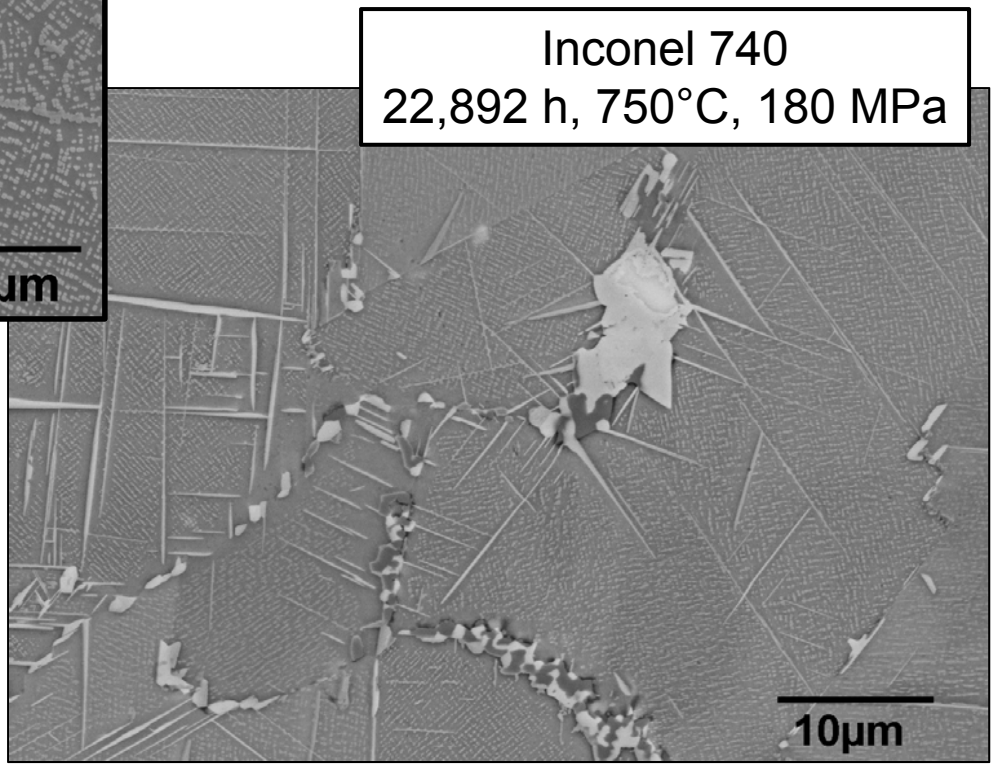


740H Long-Term Creep-Rupture Specimen Showed "Good" Microstructural Stability

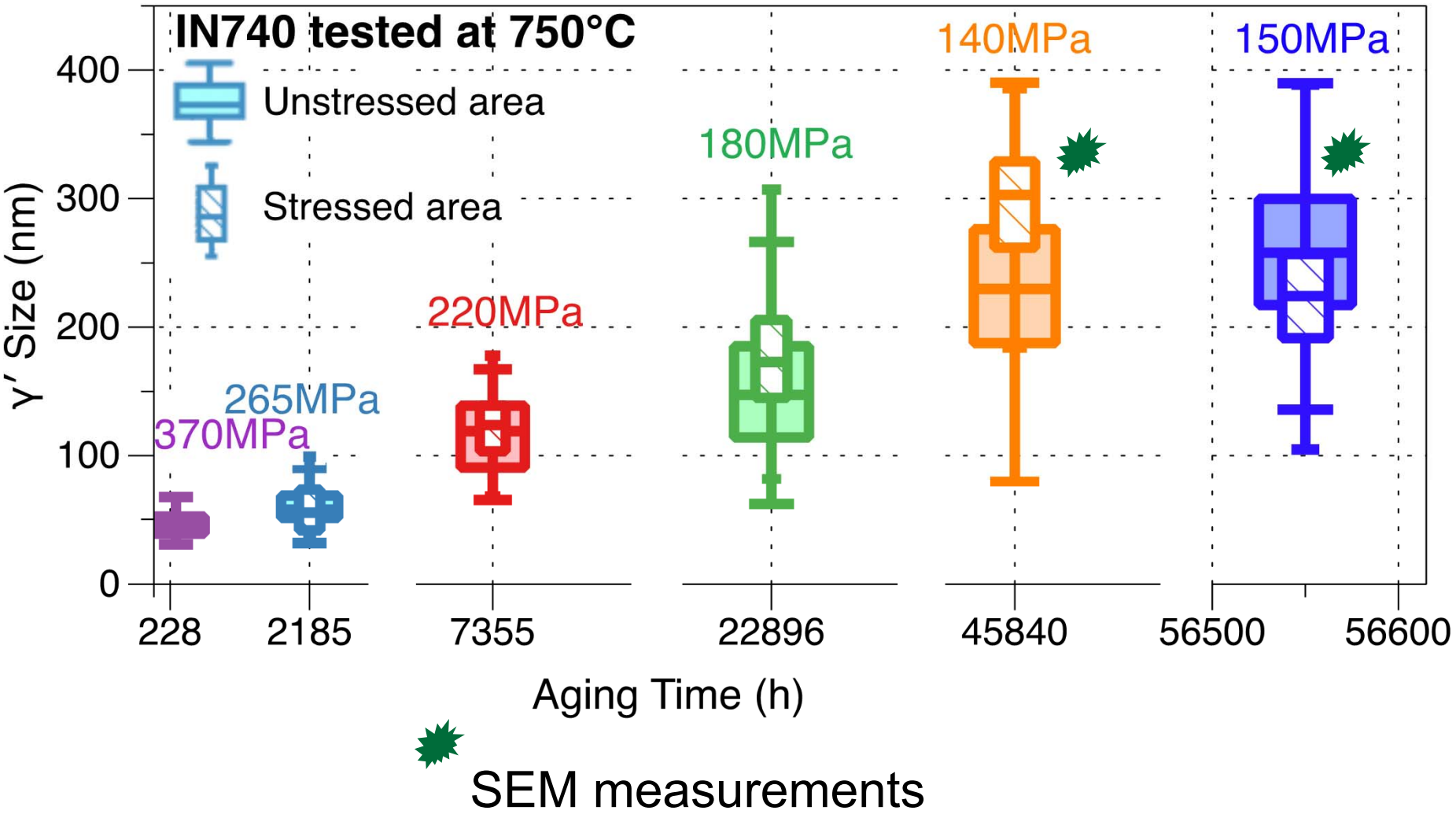


Despite ~46,000 h at 750°C under Load, Little Eta Phase Observed for Inconel 740H



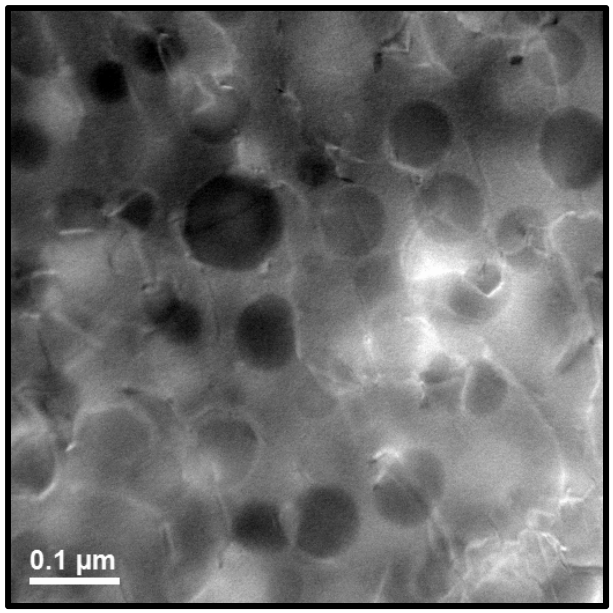


γ′ Size Measurements Show Coarsening But Little Change in Later Stages

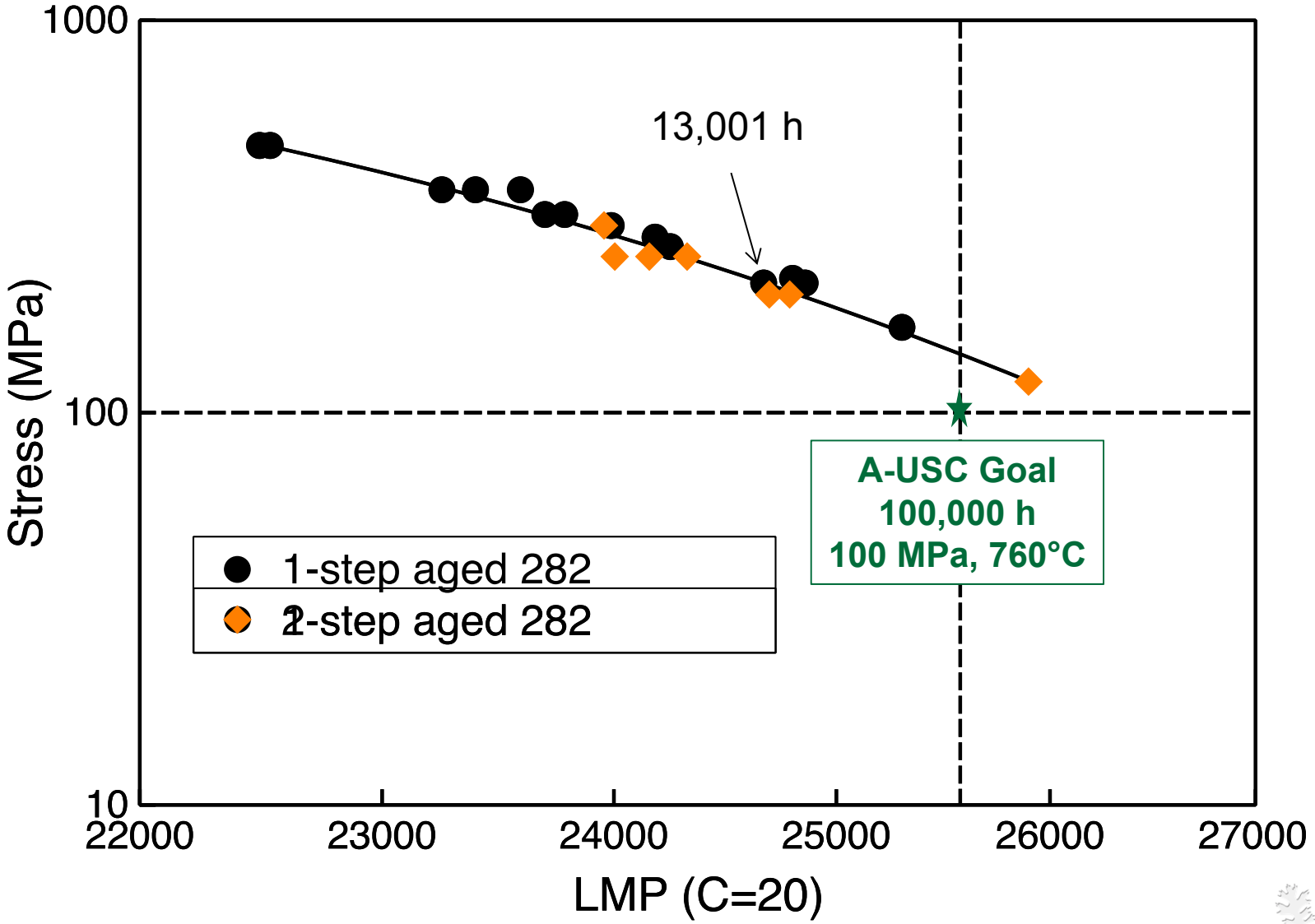


Boiler-Relevant Creep-Rupture Data for Haynes alloy 282

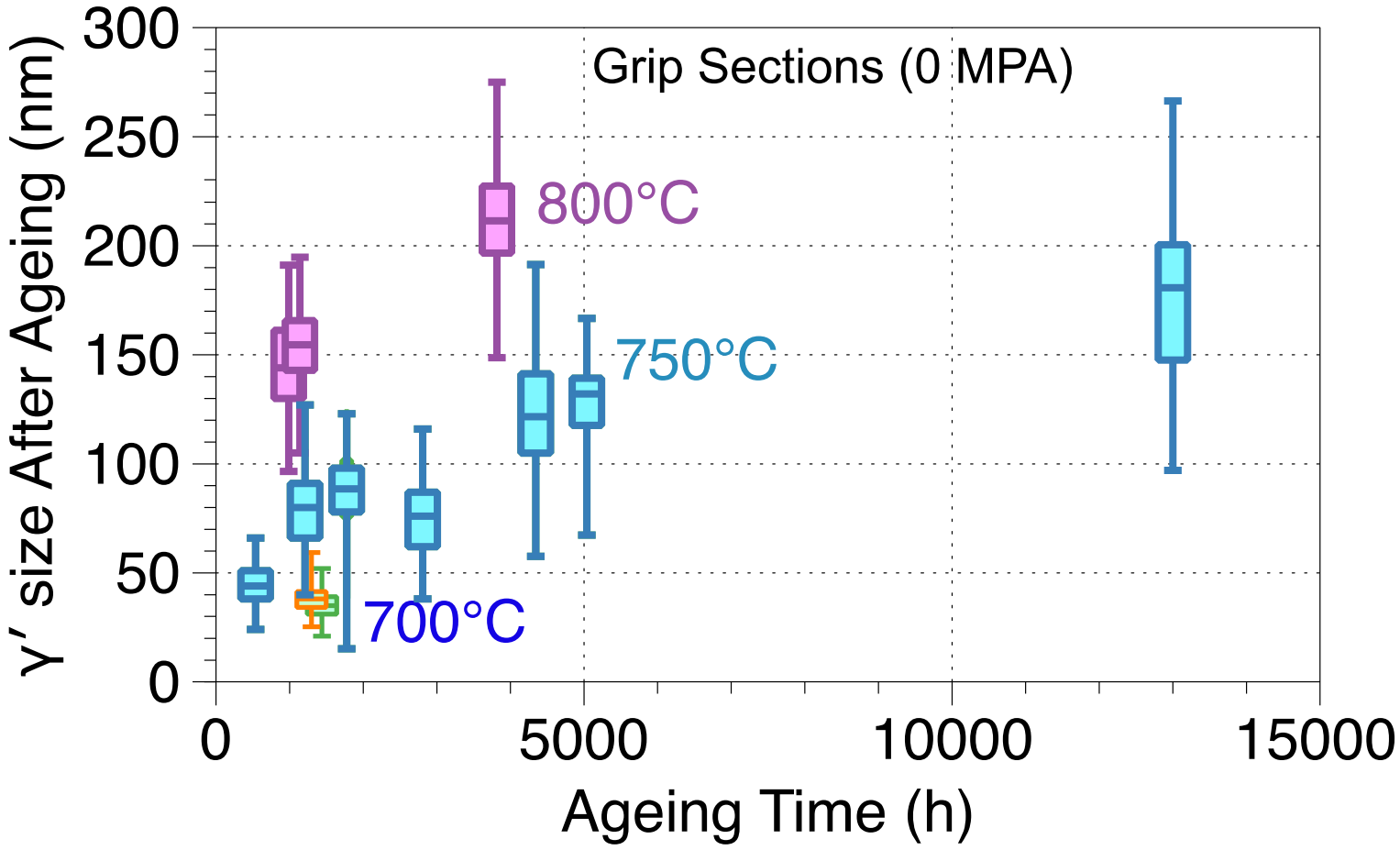
- Interest in Haynes 282 for boiler application triggered by turbines part of A-USC program
- Work to date has shown Haynes 282 may be preferred to 740
  - better creep-rupture resistance
  - minimal debits due to welding (and, possibly, cold work)
- Recommended 2-stage aging protocol (1010°C/1h+788°C/8h) deemed problematical by boiler manufacturers
- 2013: determined a one-step aging treatment (800°C/4h)
- FY15: Completed a creep-rupture test campaign for one-step aged Haynes 282
- Code case test campaign starting (different project)



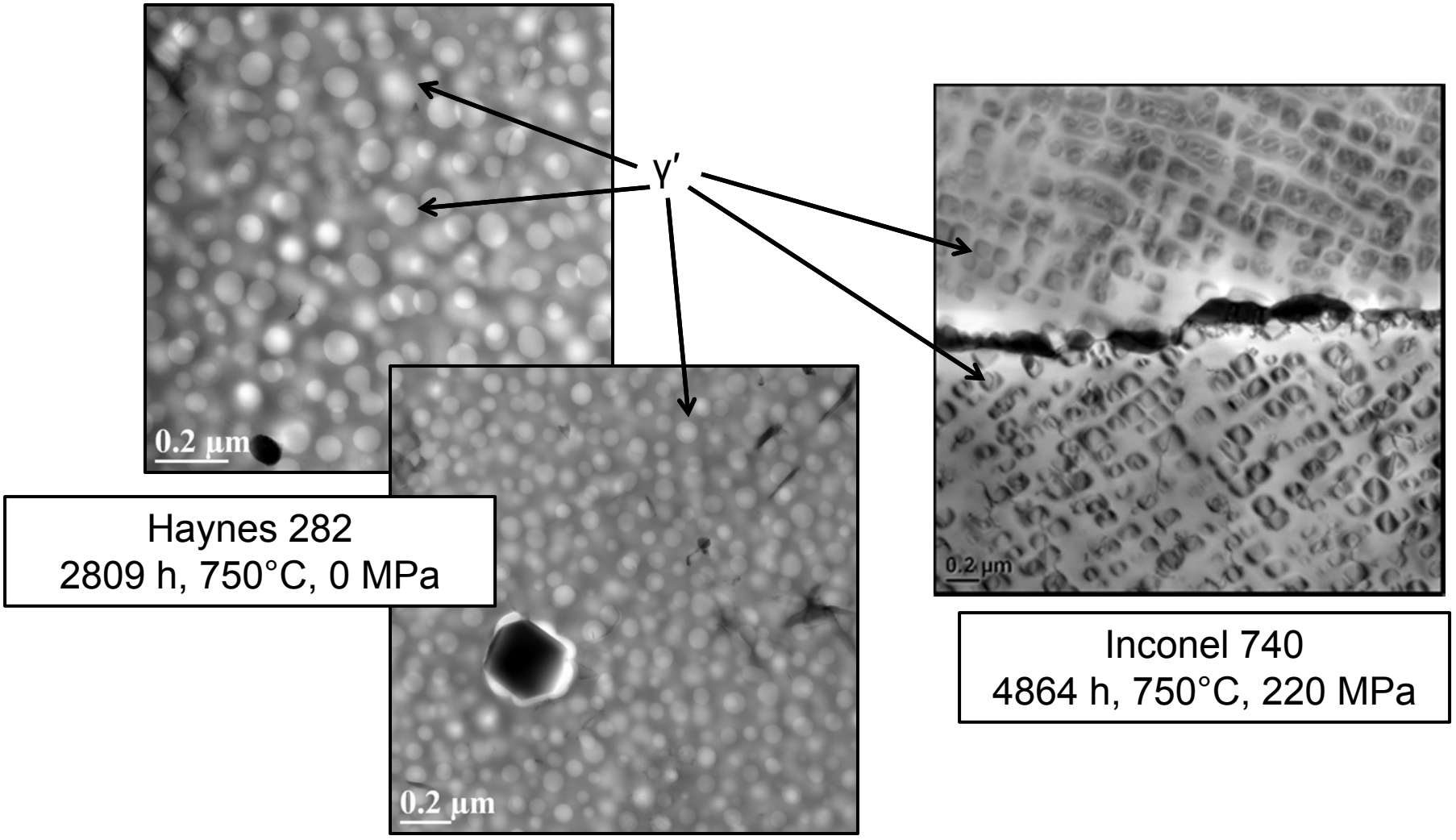
Little Difference in Creep-Rupture Lifetimes for the Two Aging Treatments



Significant γ′ Coarsening Observed for Haynes 282 Creep Specimens



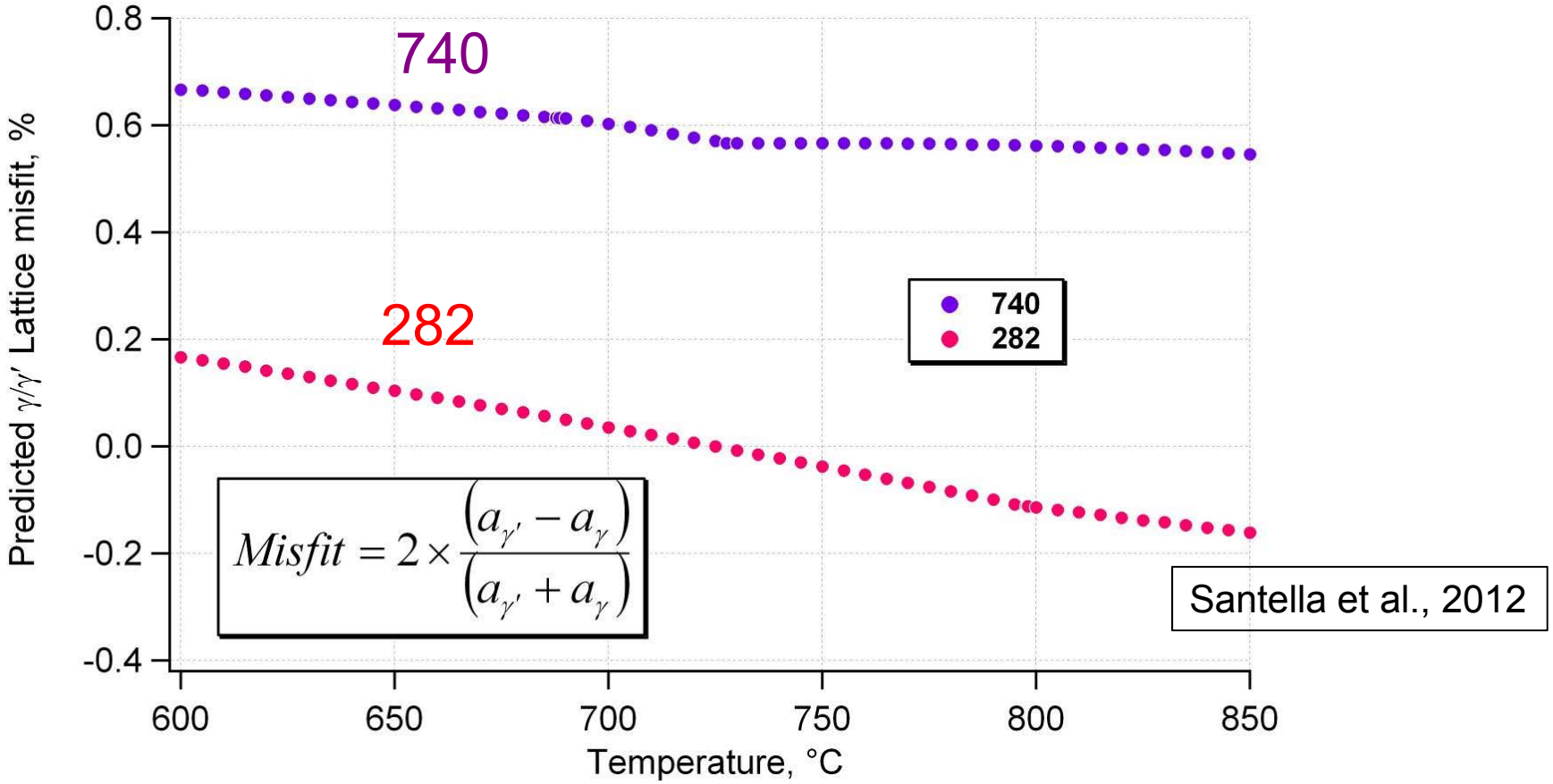
Spherical γ′ in Haynes 282 Contrasts with Cuboidal γ′ in Inconel 740



Haynes 282
2809 h, 750°C, 0 MPa

Inconel 740
4864 h, 750°C, 220 MPa

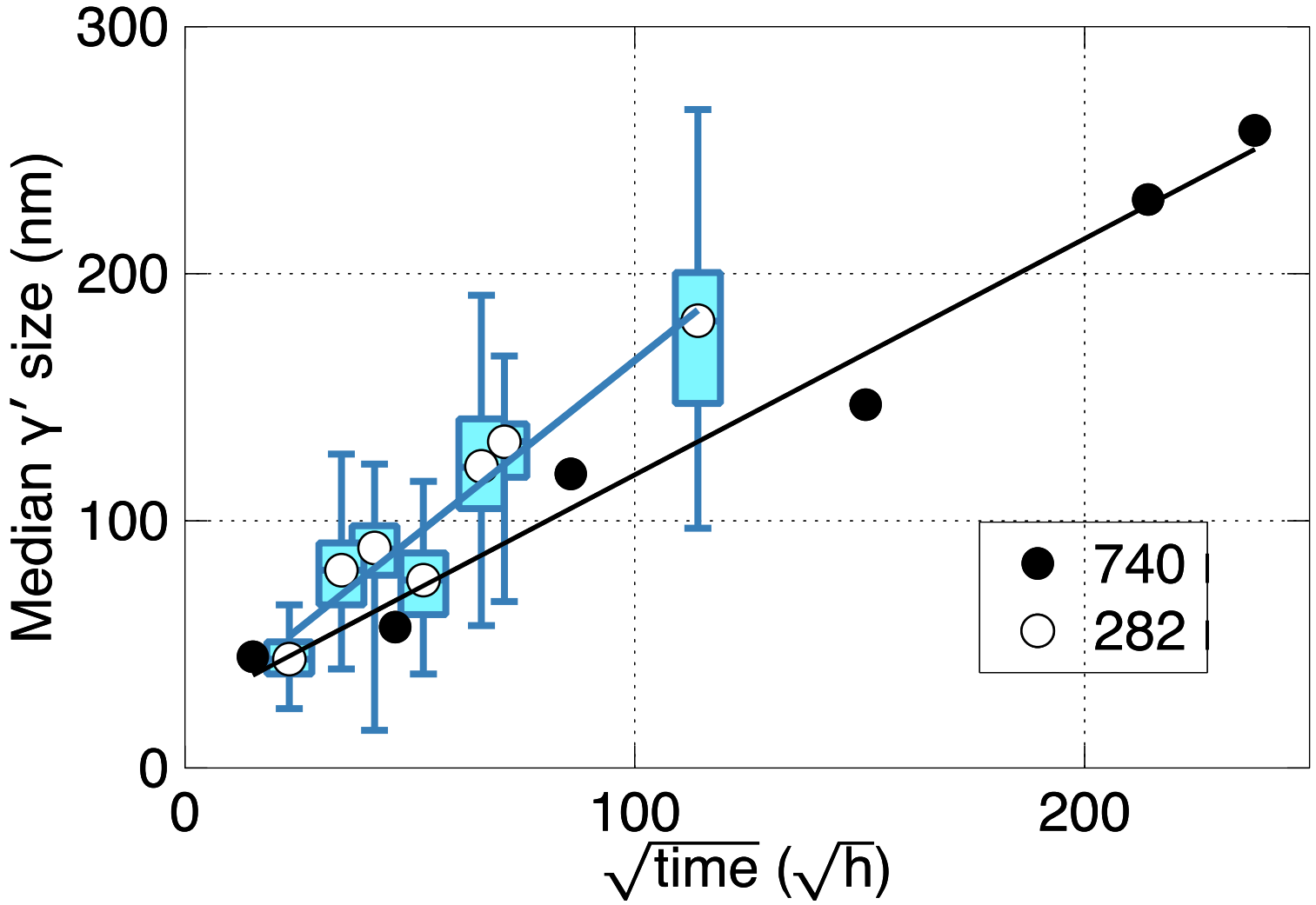
Differences in Shape Can Be Explained by Respective γ/γ′ Lattice Mismatches



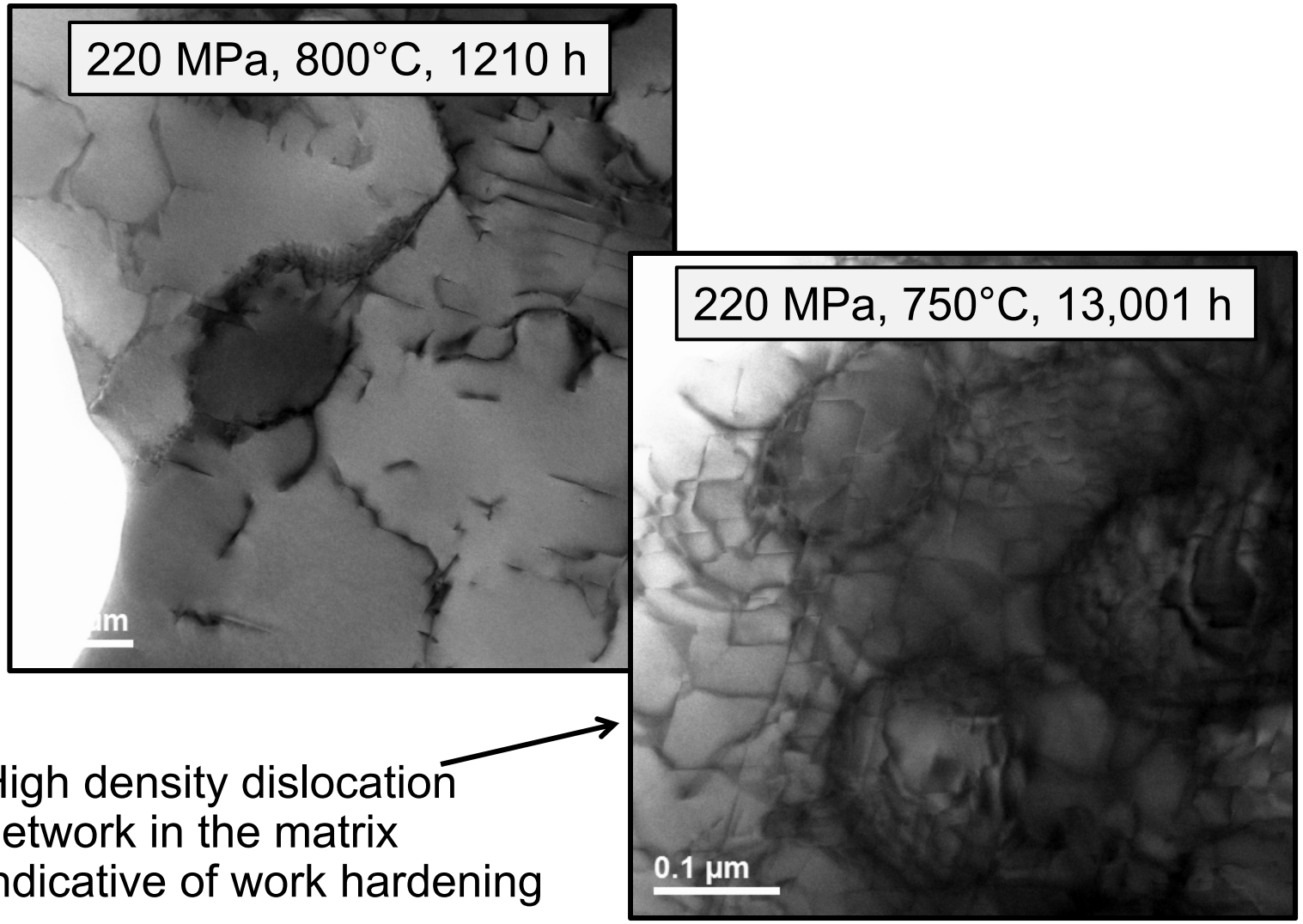
Larger misfit results in greater interfacial energy

- Cuboidal shape of precipitates
- Larger driving force for coarsening

Median 282 γ′ Size Falls Above that of 740 But within Scatter

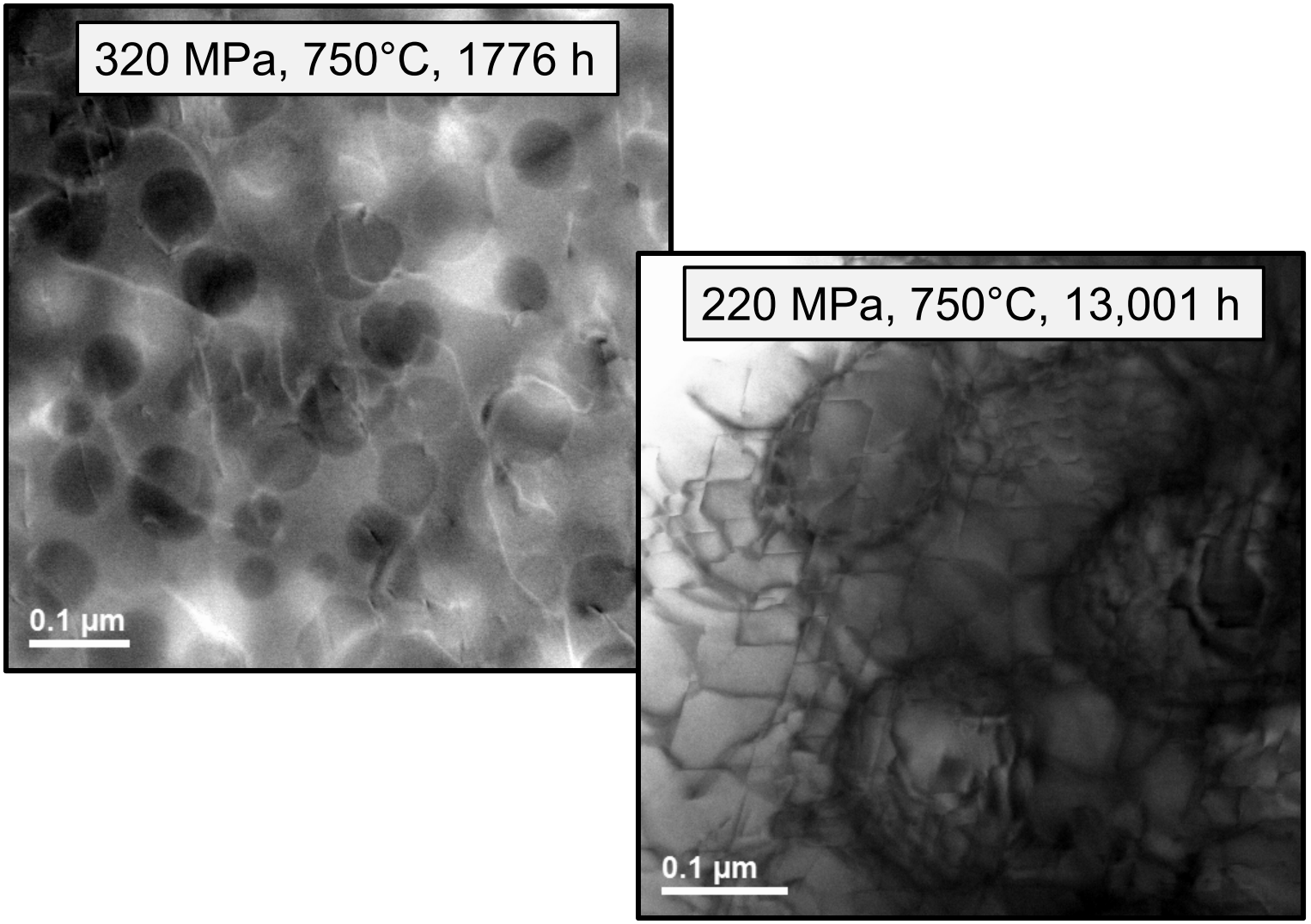


Particle Strengthening in Haynes 282

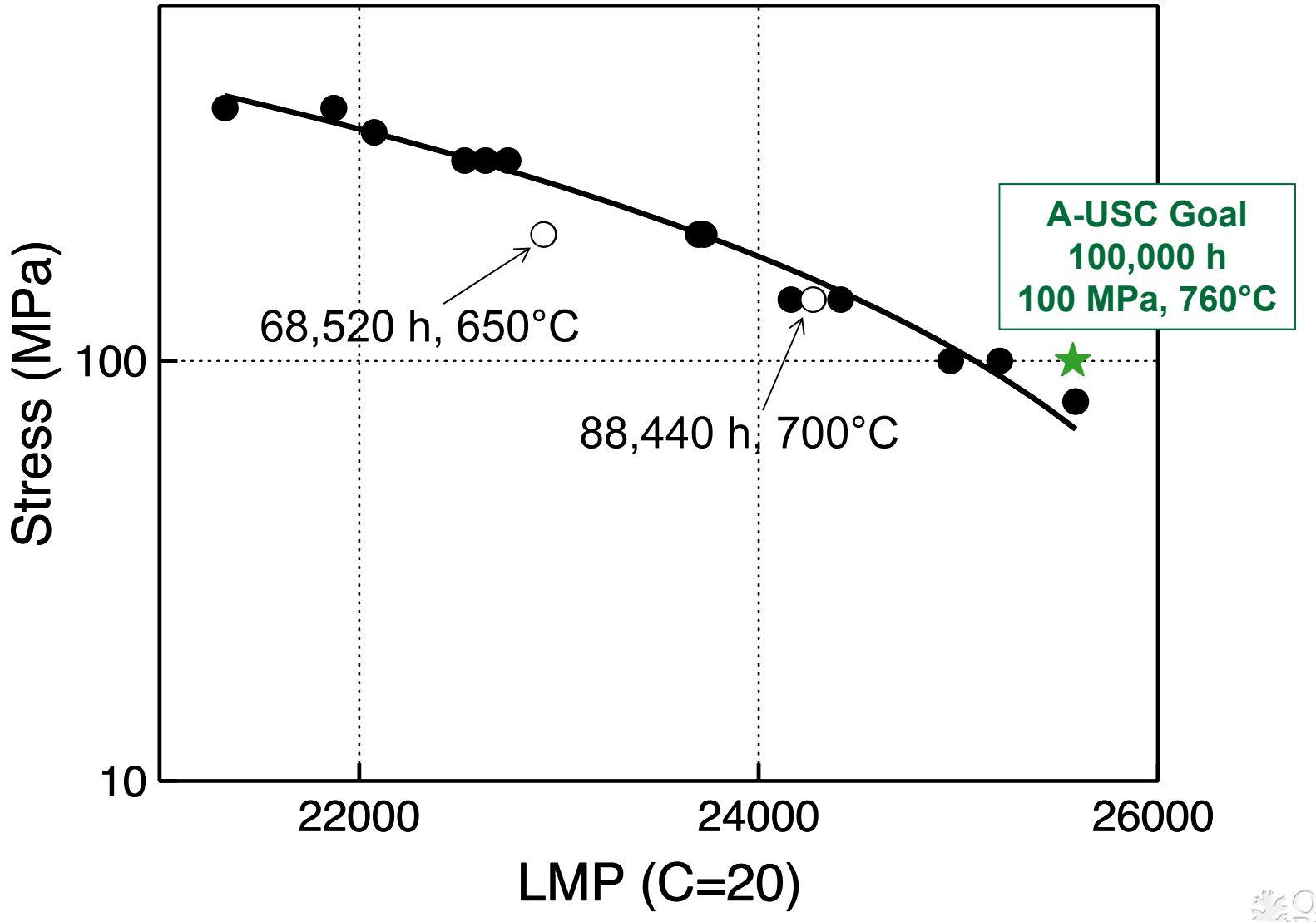


High density dislocation network in the matrix indicative of work hardening

Similar Behavior as Load Varied



Creep-Rupture Testing of Alloy 617CCA Completed Earlier in Program

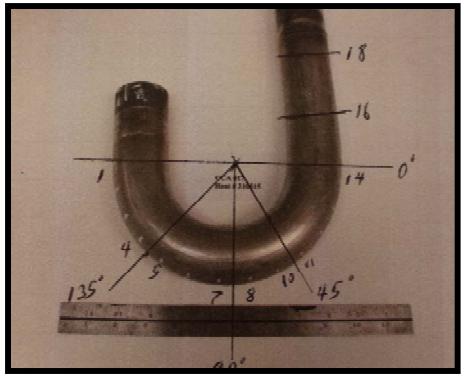


617 Bend Tests Followed Approach Used for Inconel 740

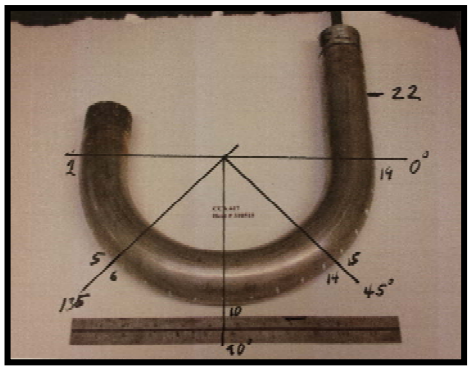
Shingledecker and Pharr, J. Mater. Eng. Perf., 2013

Cold-forming:

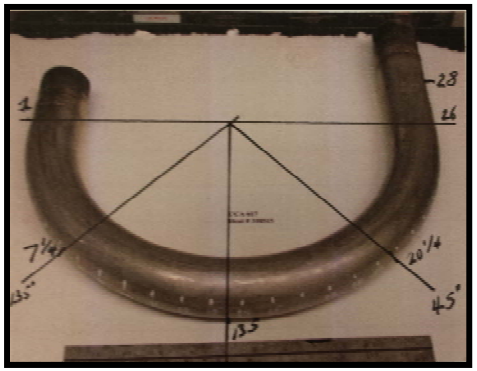
76.2 mm bend
33% OFS (outer fiber strain)



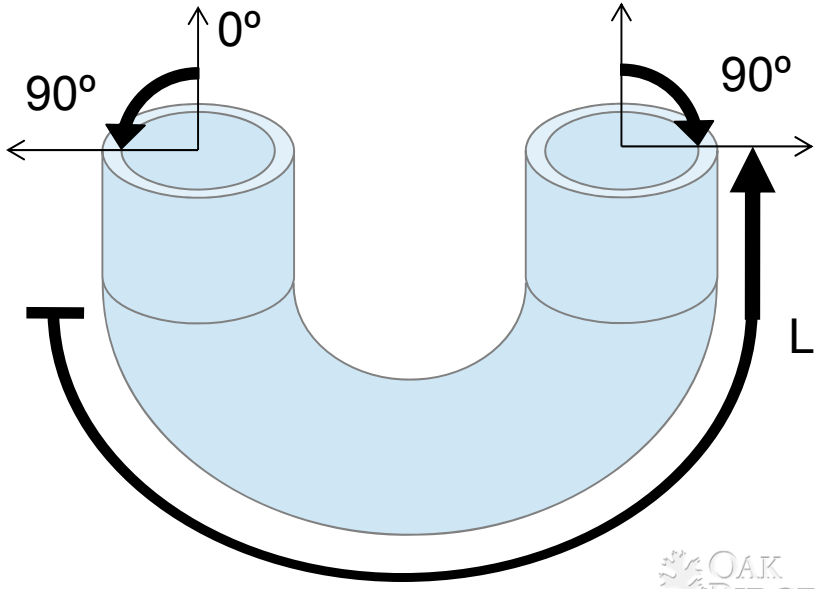
127.0 mm bend
20% OFS



171.4 mm bend
15% OFS

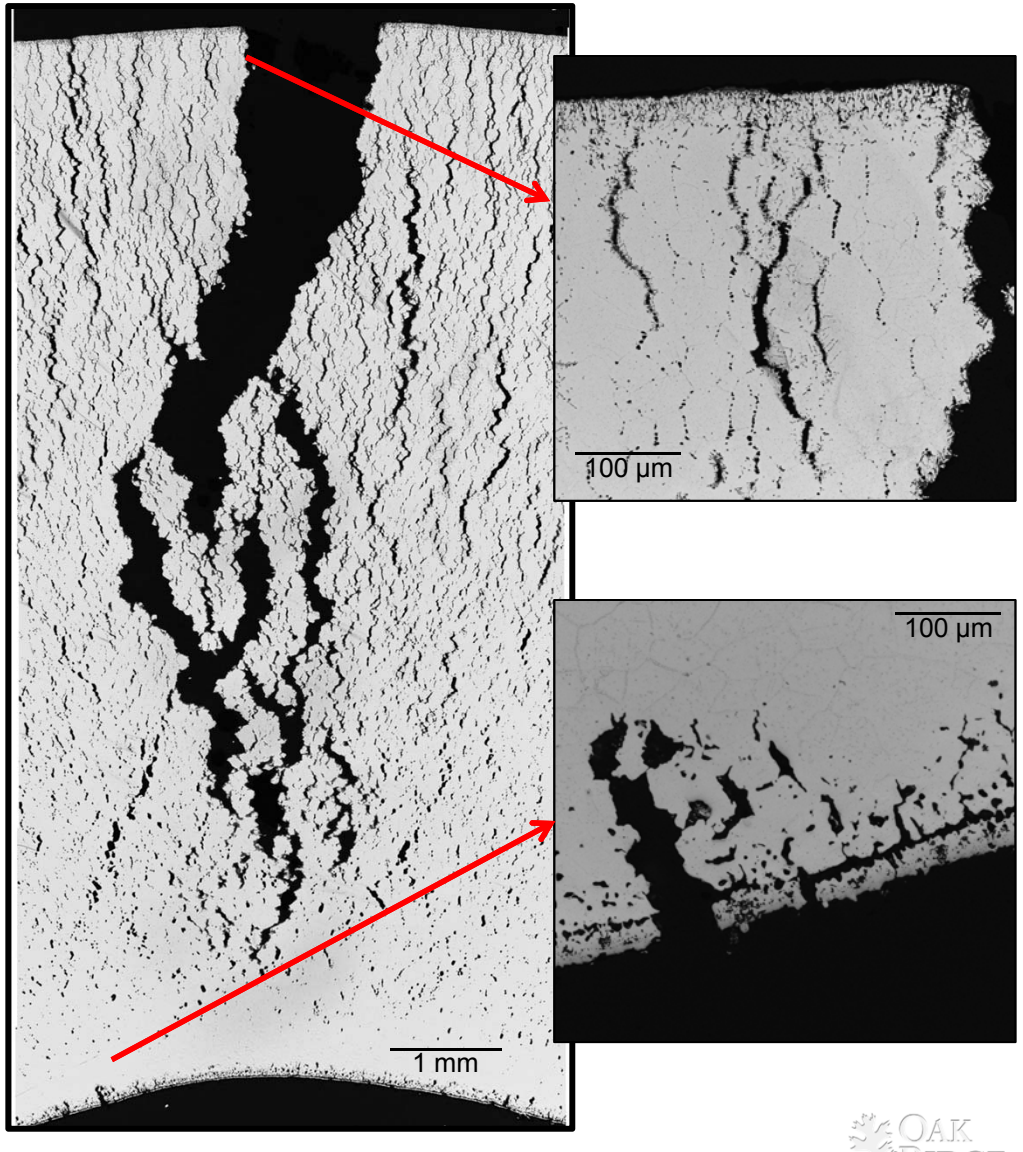


- 775° C, 38.6 MPa
- Strain Tracked by Diameter Increase With Time
- Outer Diameter measured at 0, 45, 90, 135º along tube length *L*

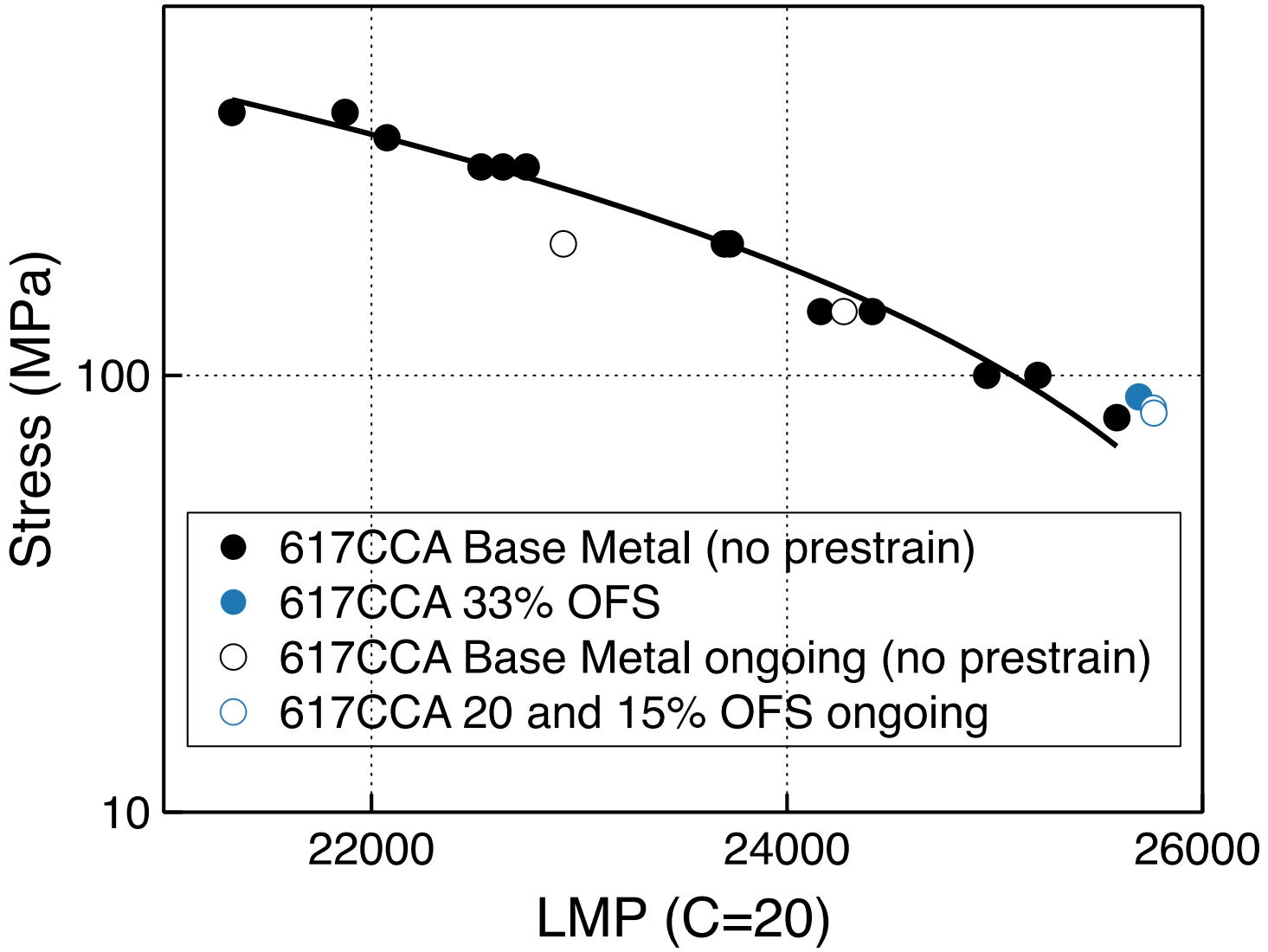


First alloy 617 Failure at ~32,800 h Recorded in Past Year

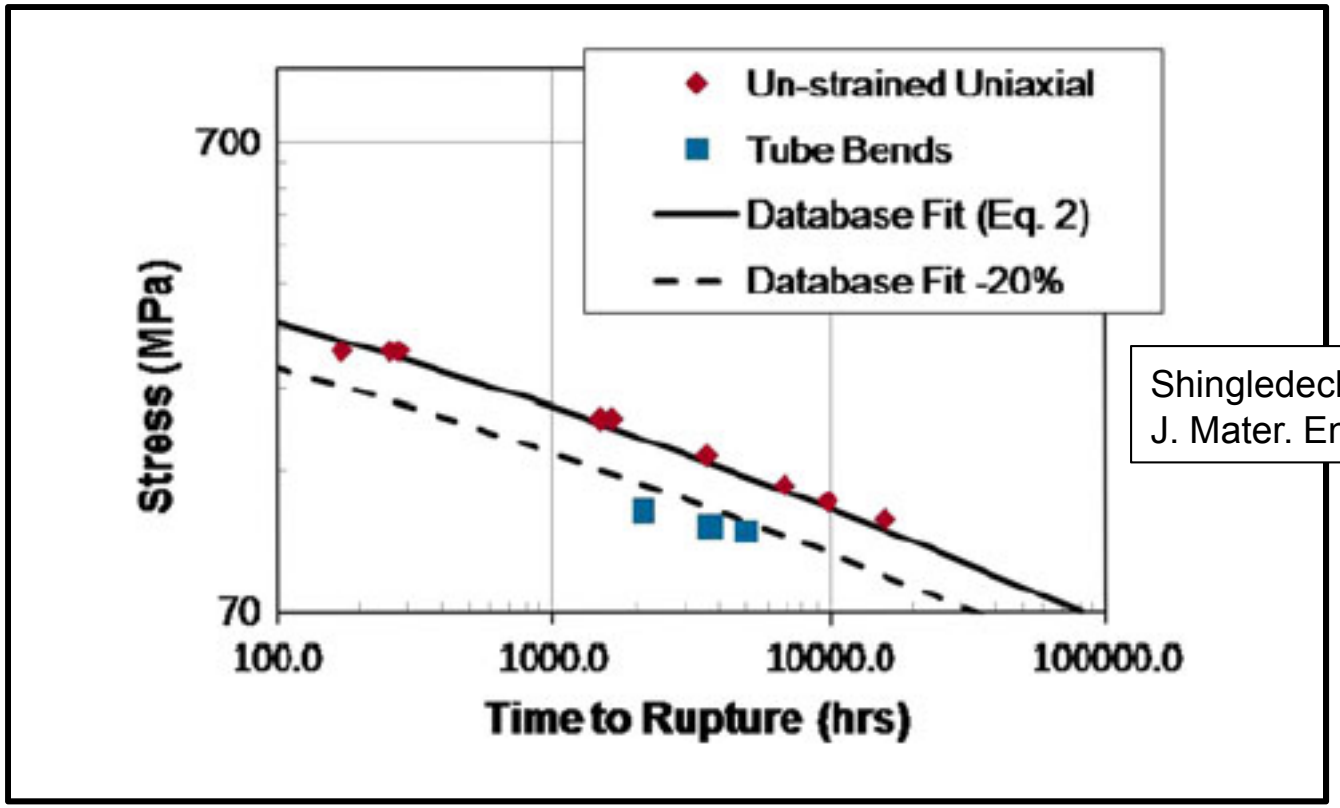
775°C, 38.6 MPa, 33% OFS



Cold Work by Tube Bending Had No Effect on Creep-Rupture Lifetime for 617CCA



In Contrast, Inconel 740 Showed a Significant Debit due to Cold Work of Tube Bends



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

Creep rupture of solid solution Ni-based alloys like 617CCA thought to be less susceptible to cold work effects than precipitation-strengthened alloys such as Inconel 740

Milestones

FY14

Prepare a summary report analyzing all results to date on creep behavior of alloy 282 (Completed)

Complete a report or paper on oxidation effects on Ni-based superalloys under creep conditions (Completed)

Complete a summary report on all alloy 617 data produced by the A-USC program with a comparison to other 617 databases. (Now May 2015)

Complete a proof-of-principle creep test of a co-extruded pipe (Now June 2015)

FY15

Complete a report or paper on the long-term high-temperature microstructural stability of Inconel 740 (Completed)

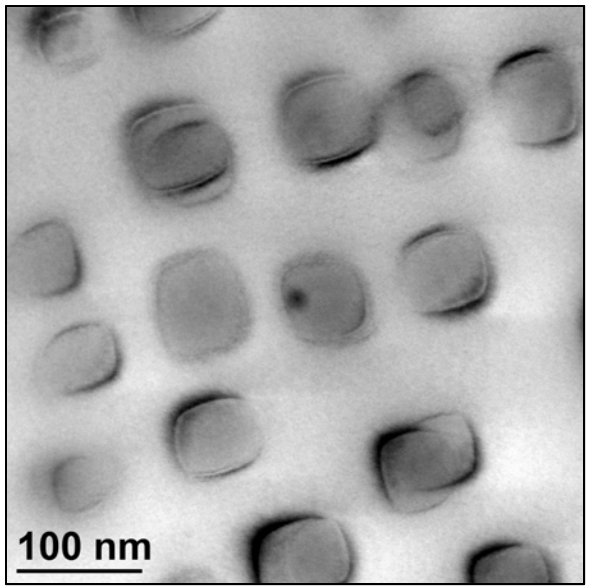
Issue final reports by alloy type on ORNL work for the A-USC boiler project (September 2015, probably December 2015)

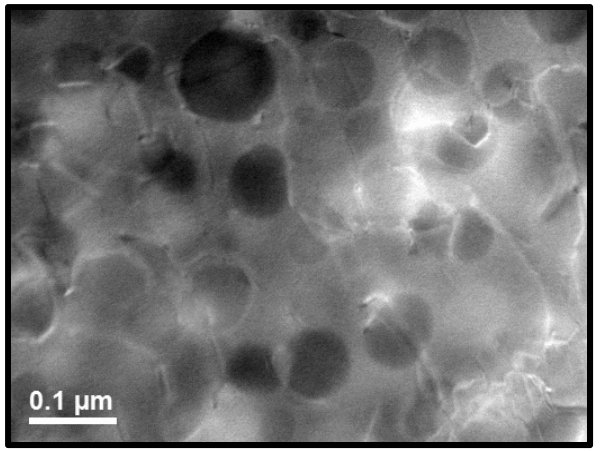
Remaining Work Before End of A-USC Boiler Consortium Project in Dec. 2015

- Completion of microstructural analyses of specimens with longest rupture times and use of such data in advanced lifetime models for Ni-based superalloys
- Increasing max temperature in Inconel 740/740H code case to 825°C
- Multiple summary reports/papers on the different alloys tested and analyzed during the course of the A-USC boiler project

Summary

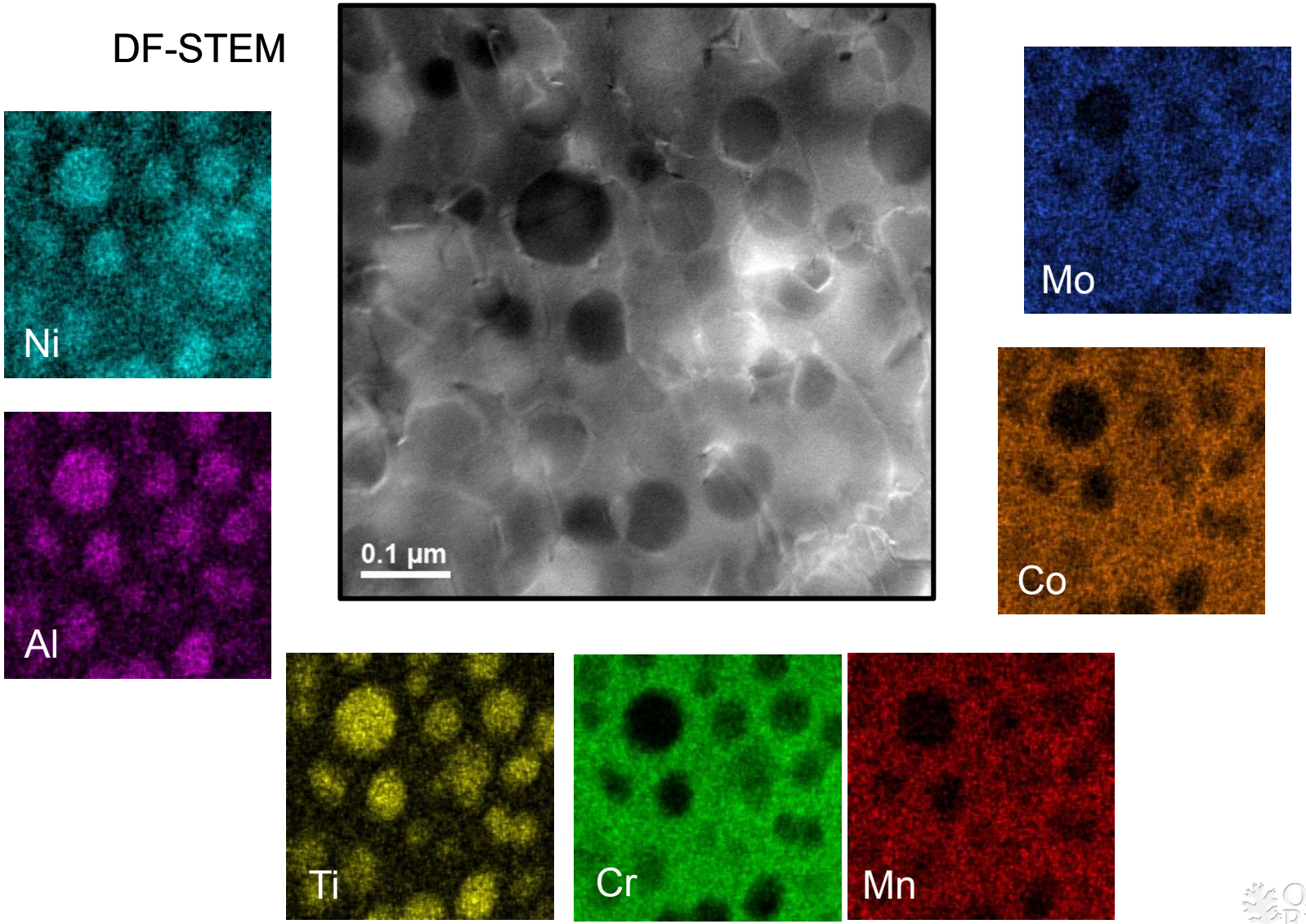
- Creep testing and microstructural analysis were used to assess thermal stability and time-dependent deformation behavior of precipitation-strengthened Inconel® alloy 740 and Haynes® 282® alloy, both alloys meet A-USC goal with single-step heat treatments
- Alloy 617CCA shows no effect of cold work on creep-rupture life
- Work is focused on remaining data and microstructural analyses and documentation in a set of final reports





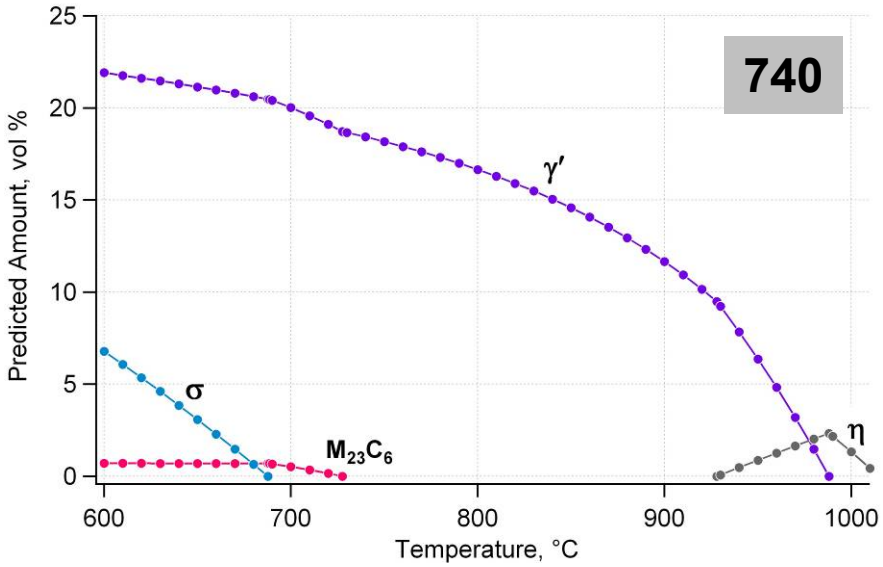
STEM Measurements Used For Aging Data

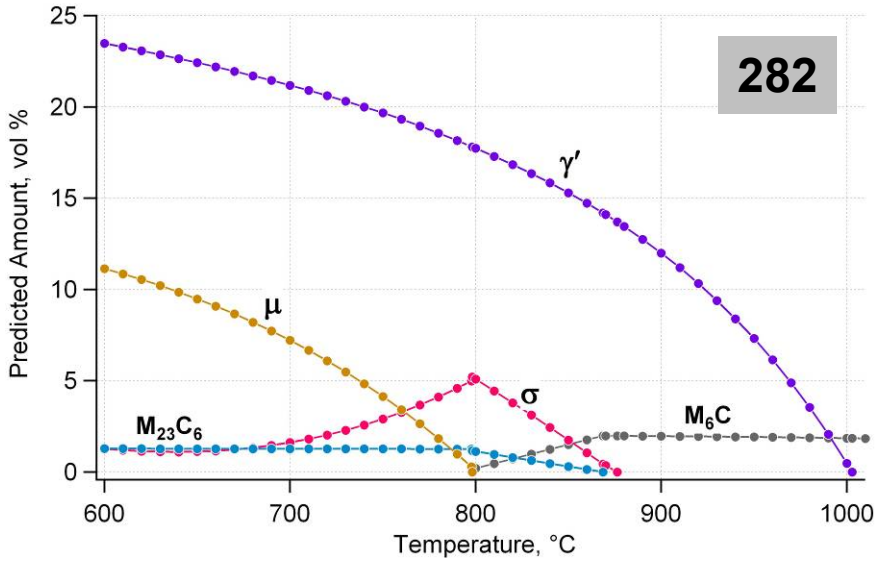
Haynes 282 – 750°C, 320MPa 1462h



γ/γ′ misfit reduces as Mo increases

	Alloy element, wt%						
Alloy	Ni	Cr	Co	Mo	Ti	Al	Nb
282	Bal.	20	10	8.5	2.1	1.5	---
740	Bal.	24	19.9	0.5	1.5	1.3	1.6





- Mo promotes formation of TCP phases, μ & σ
- TCP phases can be linked to premature creep cavitation