Ni-Based Alloys for Advanced Ultrasupercritical Steam Boilers

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EPRI

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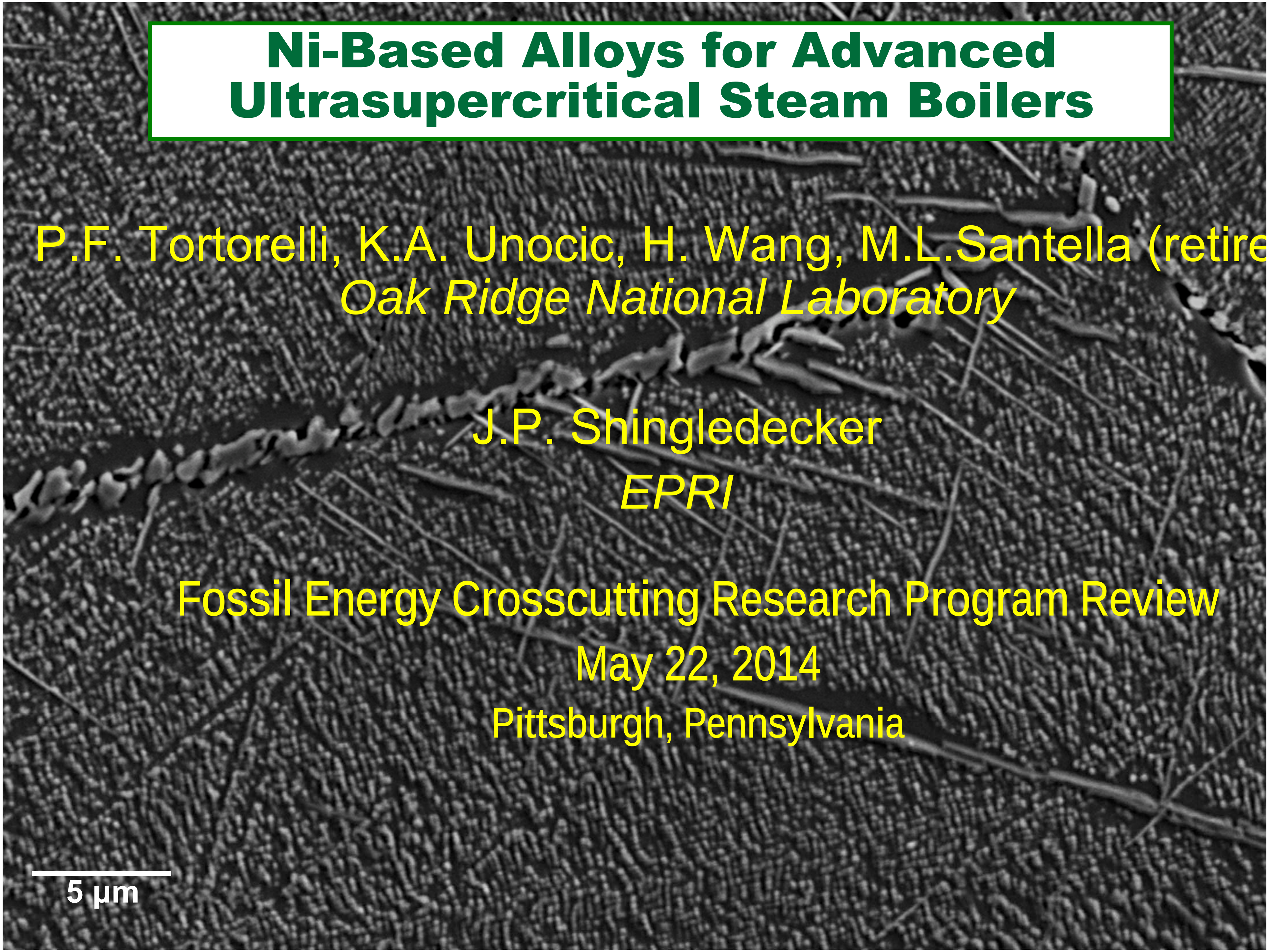
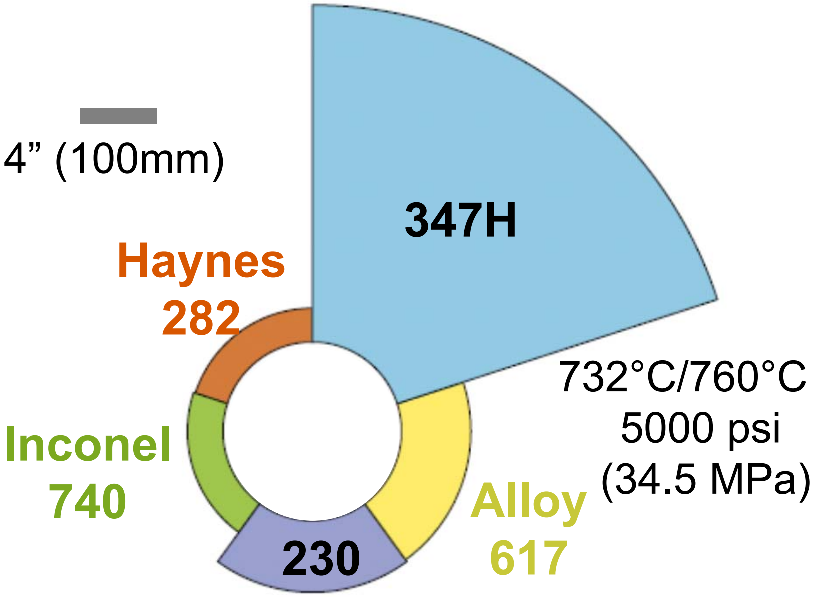


Acknowledgments

- Jeremy Moser, creep testing
- Tracie Lowe, specimen prep and microstructural analysis
- Donovan Leonard, microprobe analysis
- Vito Cedro, NETL, federal project manager

Work Motivated by Need for Ni-based Alloys in Advanced Ultrasupercritical Steam Boilers



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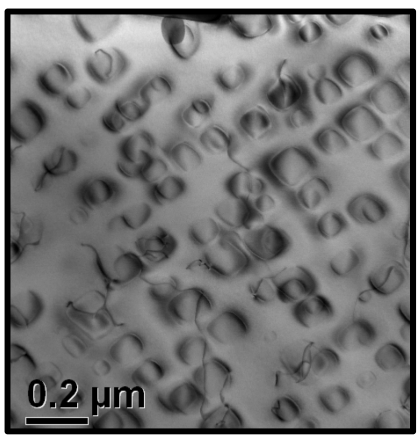

Inconel 740

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

ORNL Work Is Part of the U.S. A-USC Program
(U.S. Dept. Of Energy, Ohio Economic Develop. Corp.)

MAKING OHIO COAL
THE CLEAN CHOICE

Energy Industries Of Ohio

EPRI ELECTRIC POWER RESEARCH INSTITUTE

ALSTOM

B&W

NETL

GE imagination at work

FOSTER WHEELER

RILEYPower
A Babcock Power Inc. Company

U.S. DEPARTMENT OF ENERGY

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ORNL's role:

- Generate high quality creep-rupture data using accepted test methods
  - Inconel 740, Haynes 282
  - 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

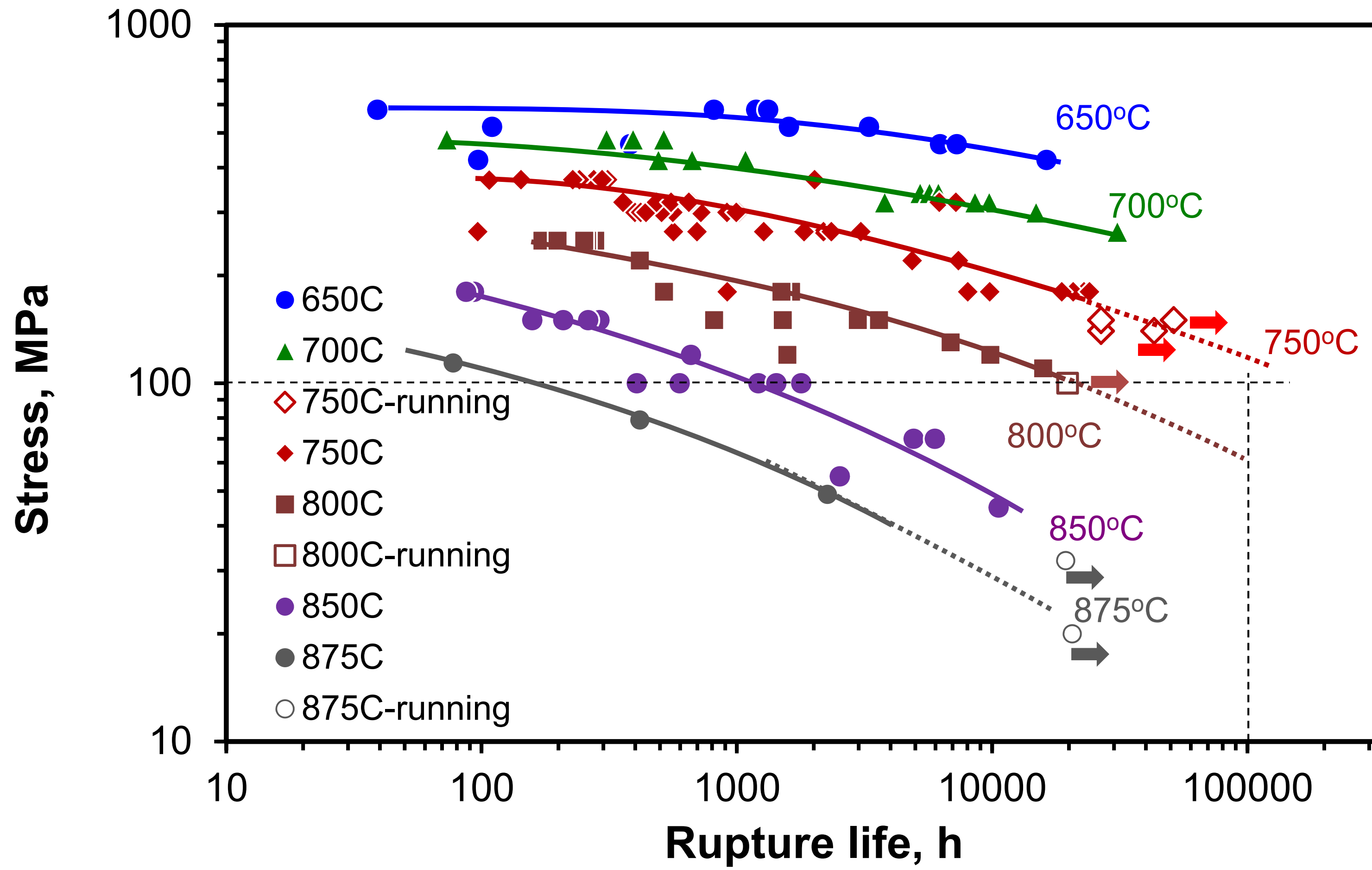
Focus of Recent Work Has Been on Inconel 740/740H and Haynes 282

	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

- Both Inconel 740 and Haynes 282 form γ′ (Ni_3Al, Ni_3Ti) and carbides
- Only Inconel 740 forms η (Nb_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.)
- Both alloys types have elements that promote internal oxidation (Pint et al., Wright et al.)

Creep-Rupture Results

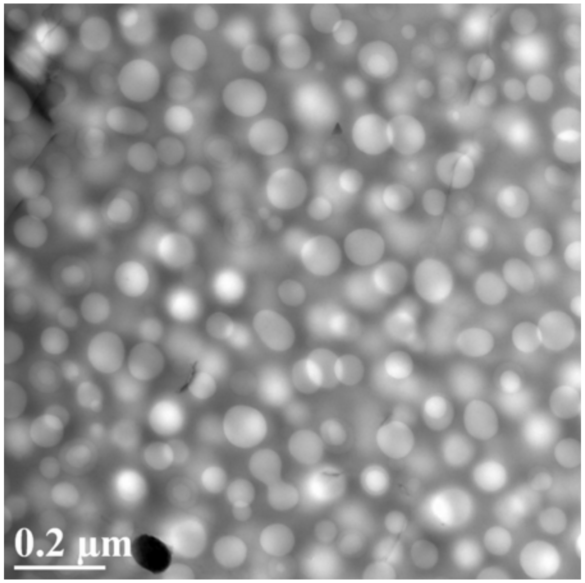
Long-Term Creep-Rupture Data for 740/740H Build Confidence in A-USC Boiler Use



Generating Similar Data for Haynes 282

In Process of Developing Qualified 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
  - longer creep-rupture lifetimes
  - minimal debits due to welding and cold work
- Recommended 2-stage aging protocol (1010°C/1h+788°C/8h) deemed problematical by boiler manufacturers
- Last year: determined a one-step aging treatment (800°C/4h)
- This year: first dataset for one-step aged Haynes 282



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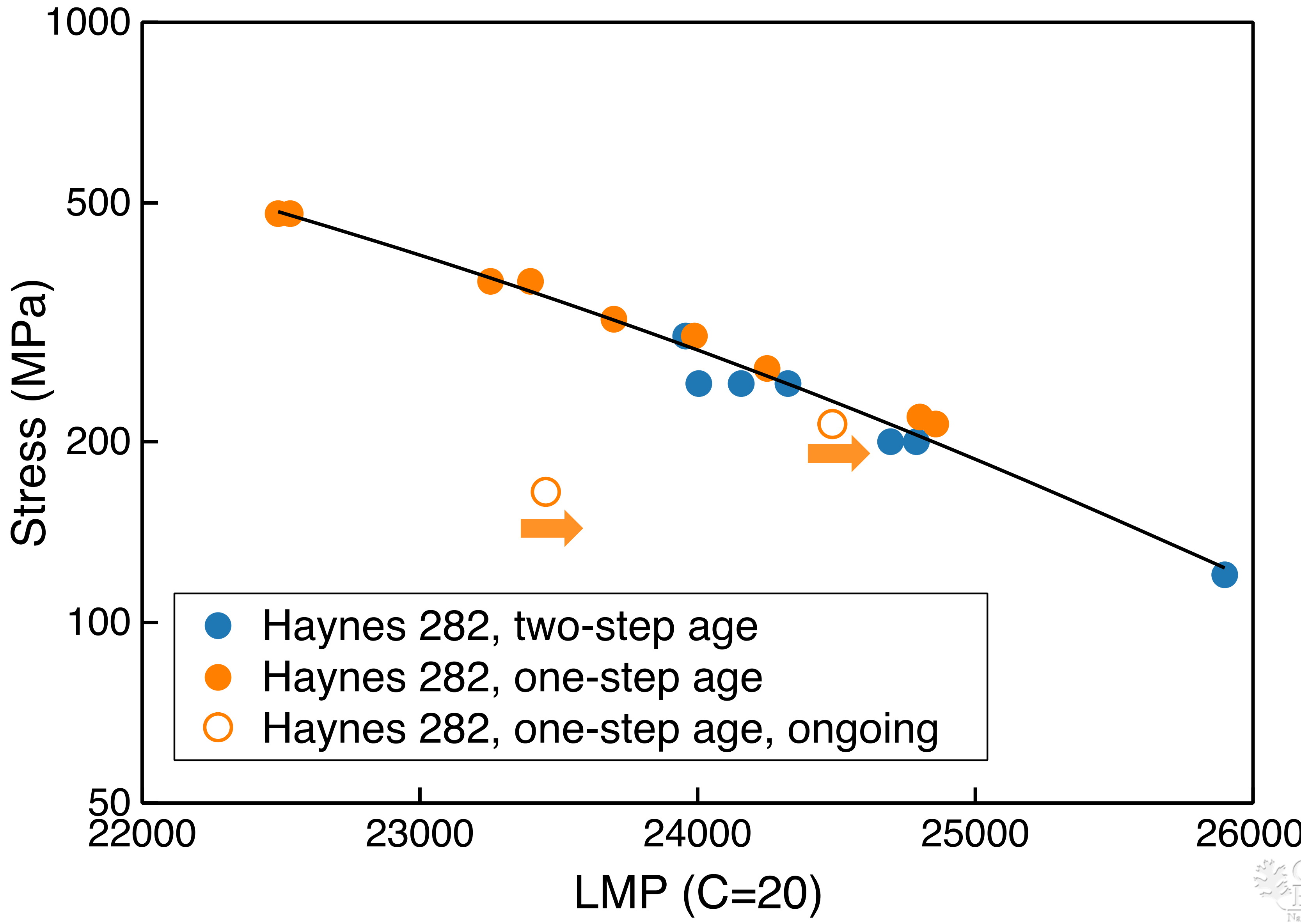
Little Difference between 1-step and 2-step Aged Haynes 282 Creep-Rupture Data



Microstructural Stability over Long Times with Particular Attention to γ′

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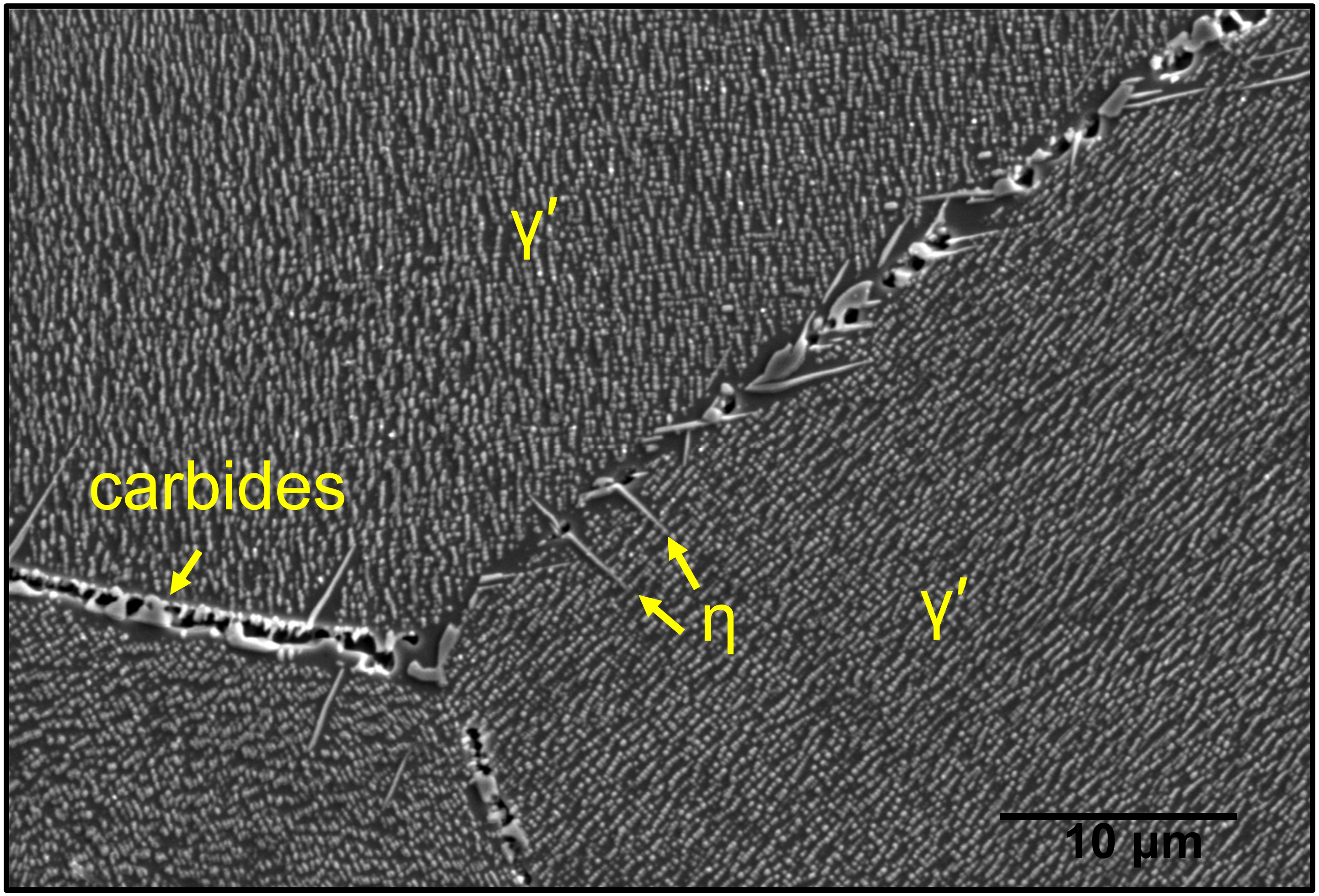
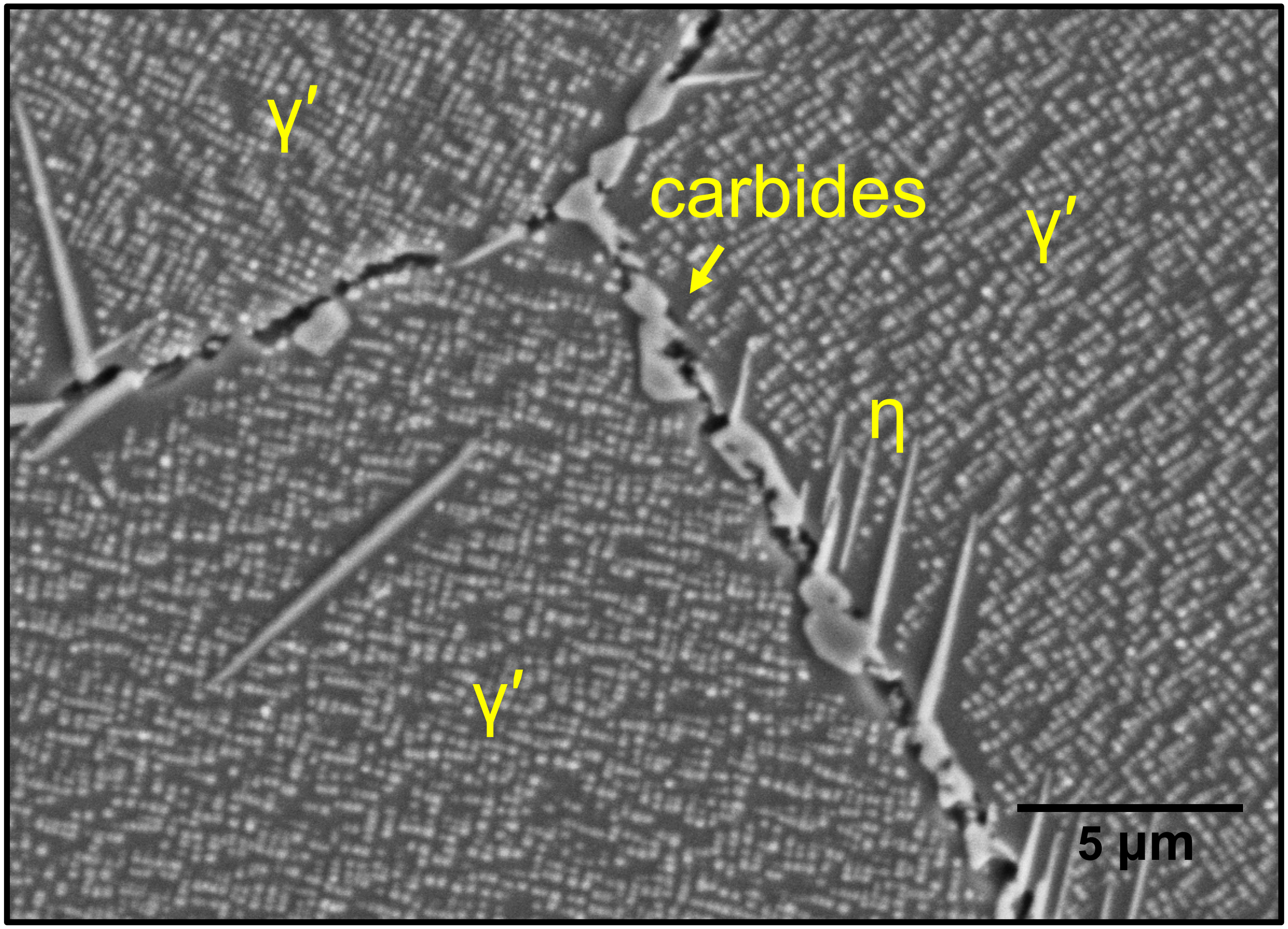
Inconel 740: Little Evidence of γ′ Depletion at 750°C after Extended Testing

Inconel 740, 20,789 h, 750°C, 180 MPa



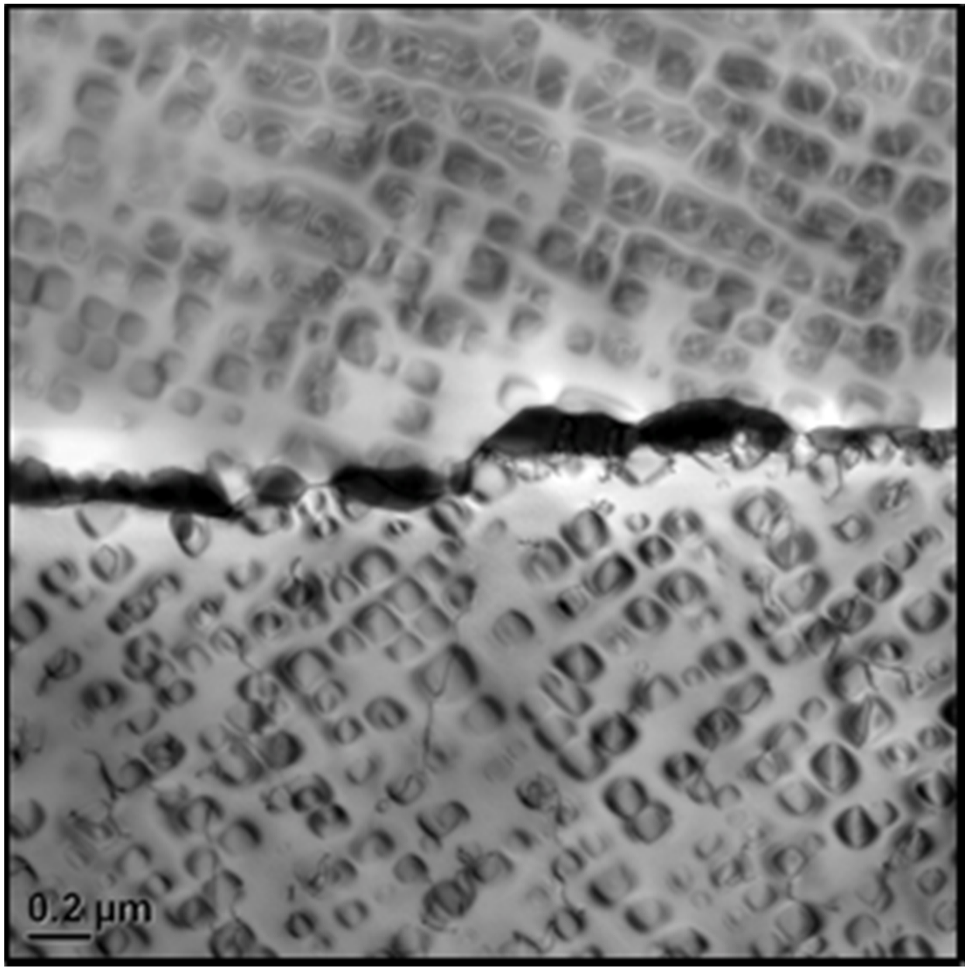
Little Evidence of γ′ Depletion Near Grain Boundaries in Bulk at 750°C

Inconel 740, 20,789 h, 750°C, 180 MPa



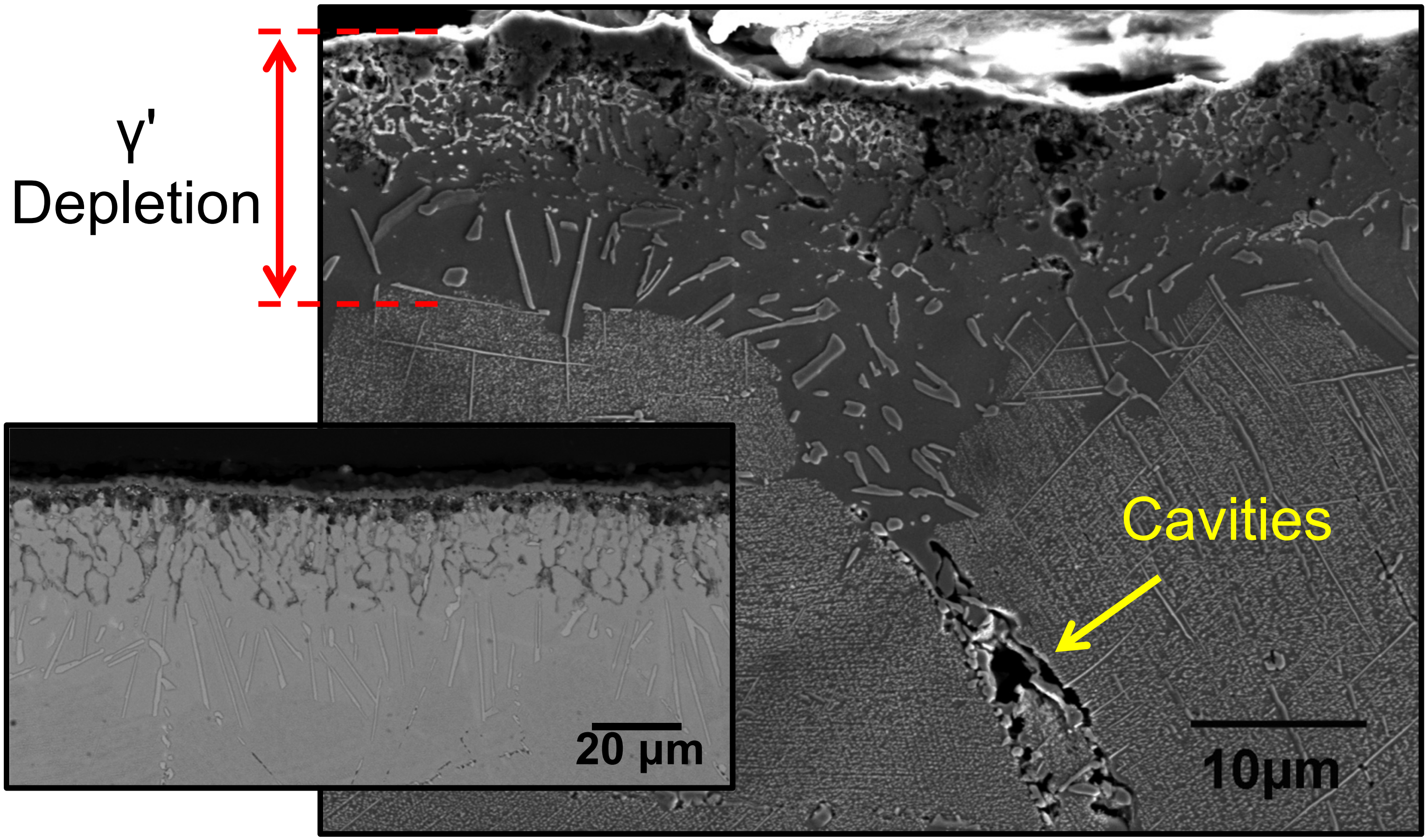
Little Evidence of γ′ Depletion Near Grain Boundaries in Bulk at 750°C

Inconel 740, <u>4864 h</u>, 750°C, <u>220 MPa</u>

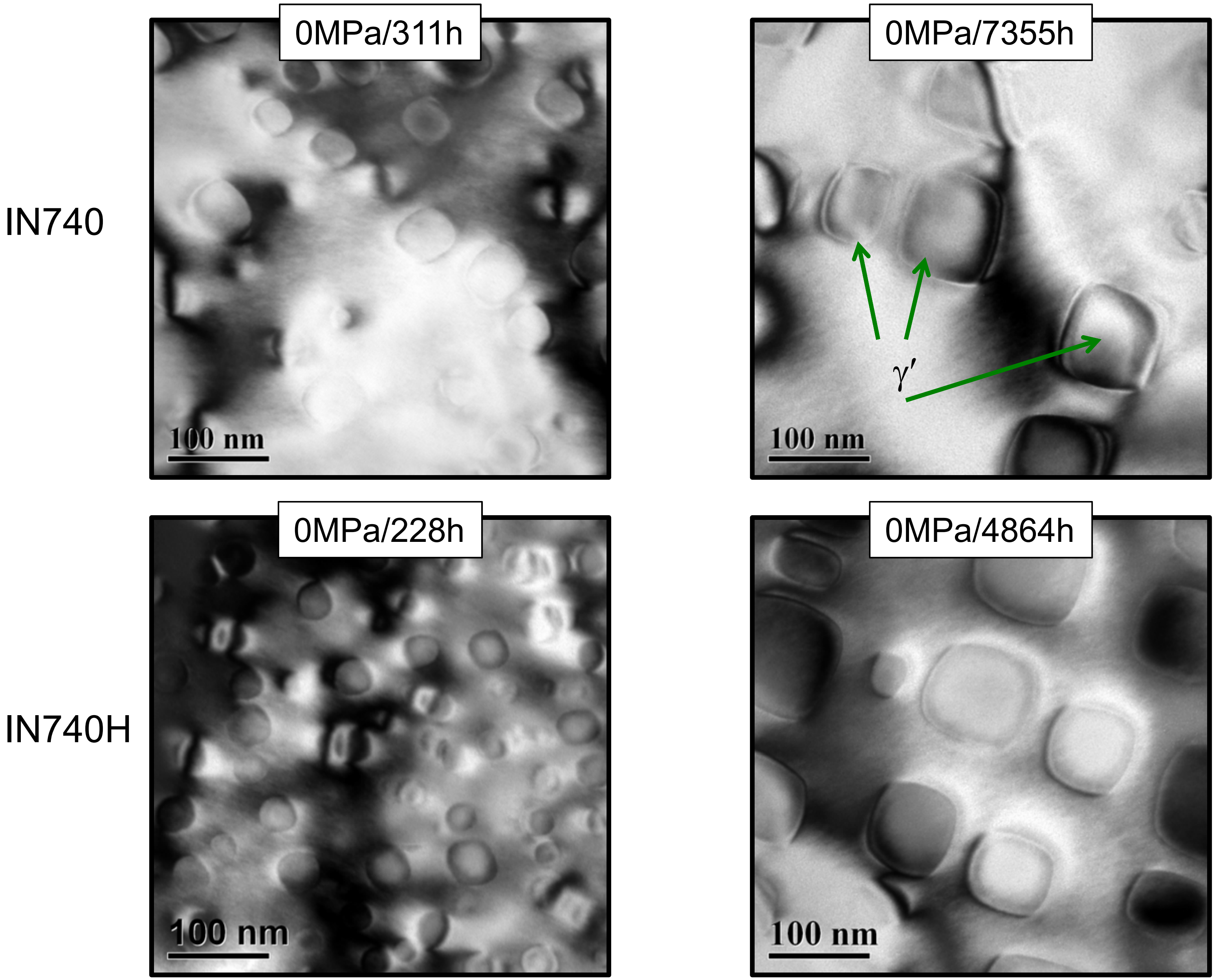


γ′ Depletion Observed Near Surfaces in Contact With Test Environment

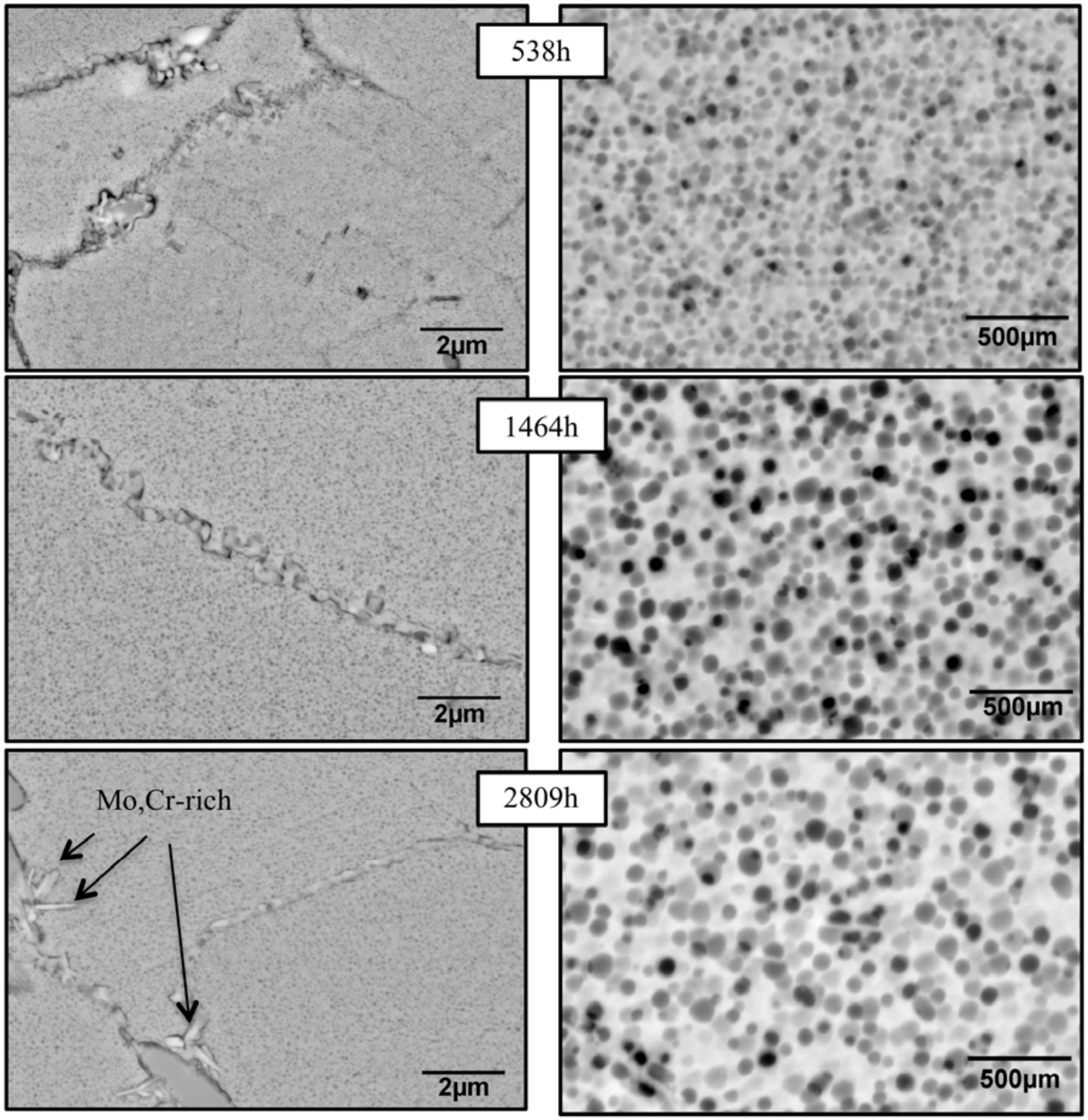
20,879 h, 180 MPa, 750°C



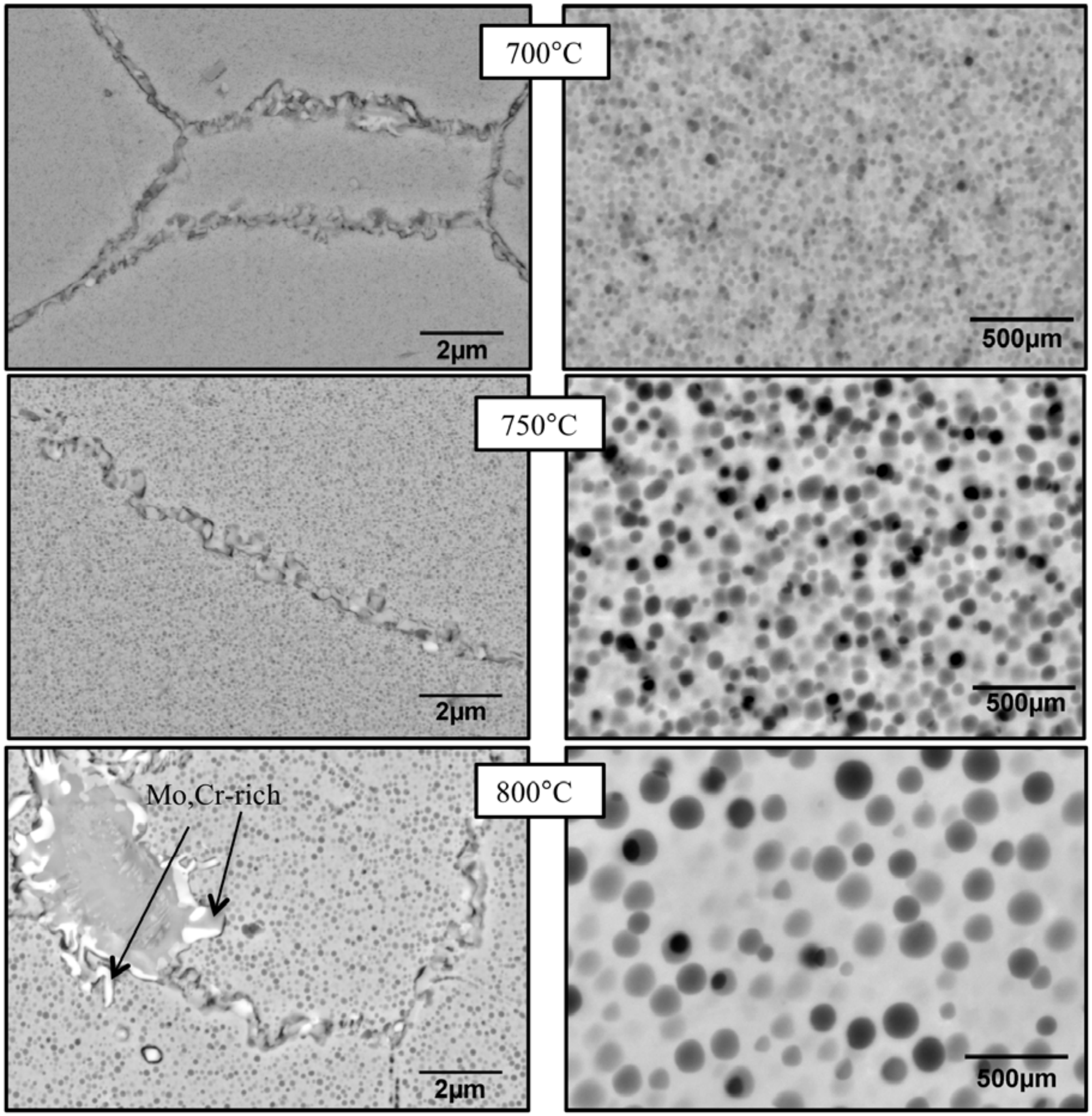
Modest (2-3X) Coarsening of γ′ in Inconel 740 with No Change in Shape



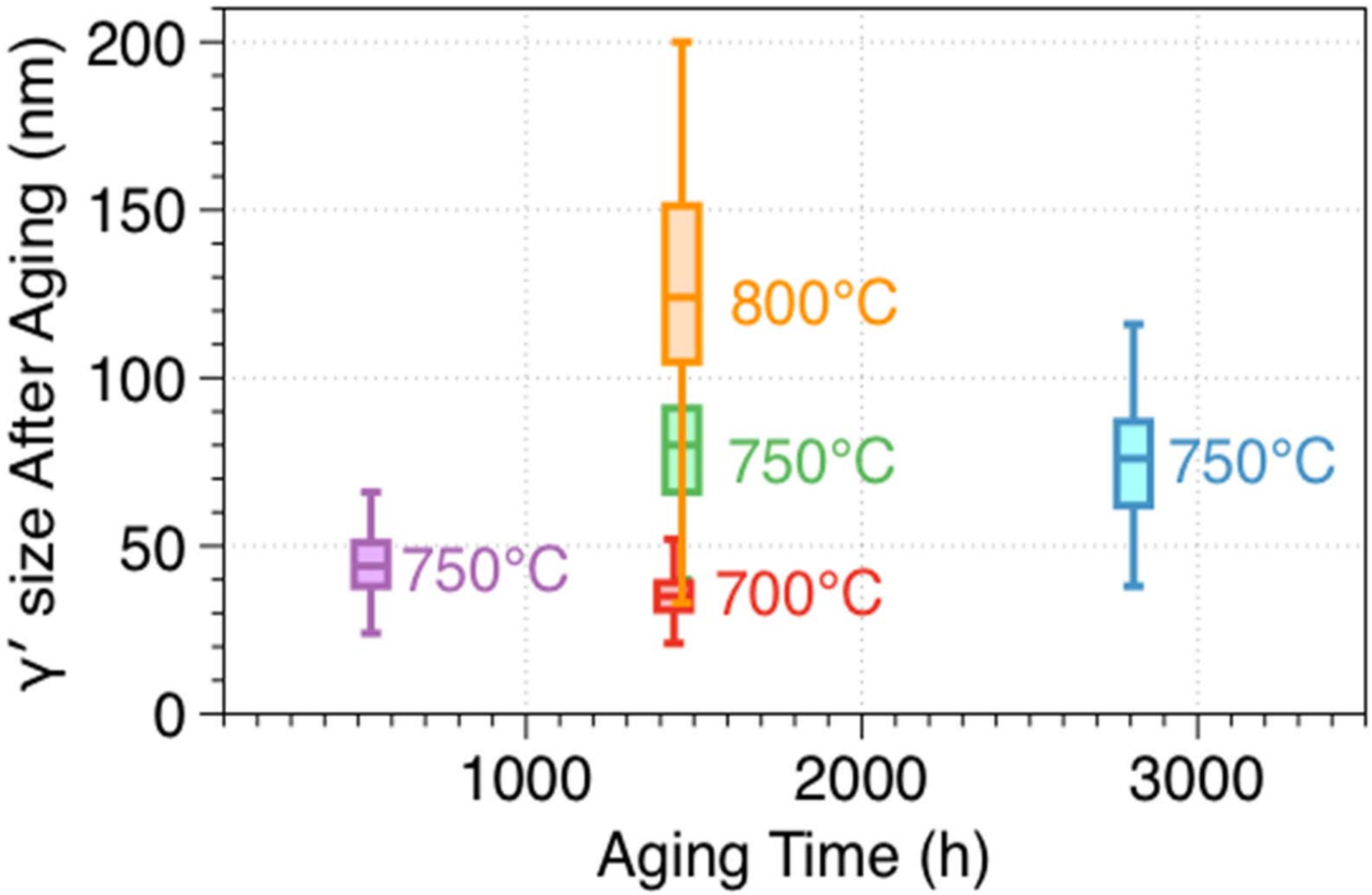
Also Observed Some Coarsening of γ′ in Haynes 282 with Time



...and Temperature (Greater Effect)



Coarsening Kinetics of γ′ in Haynes 282



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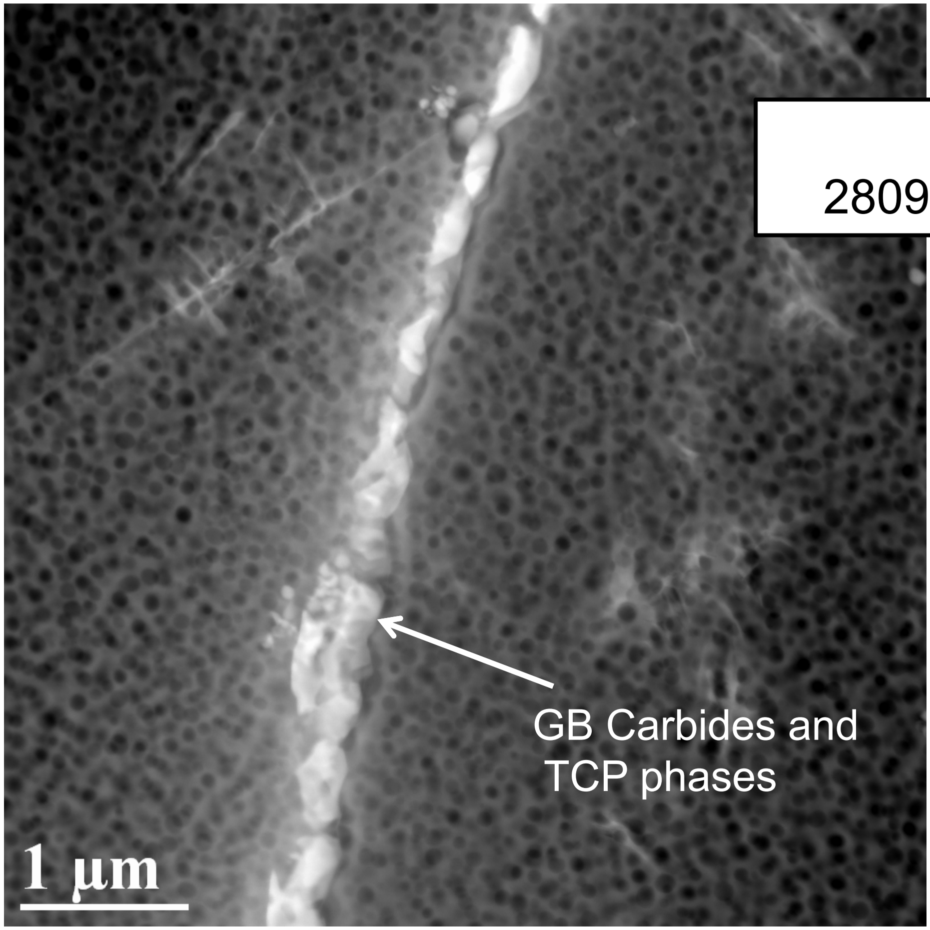
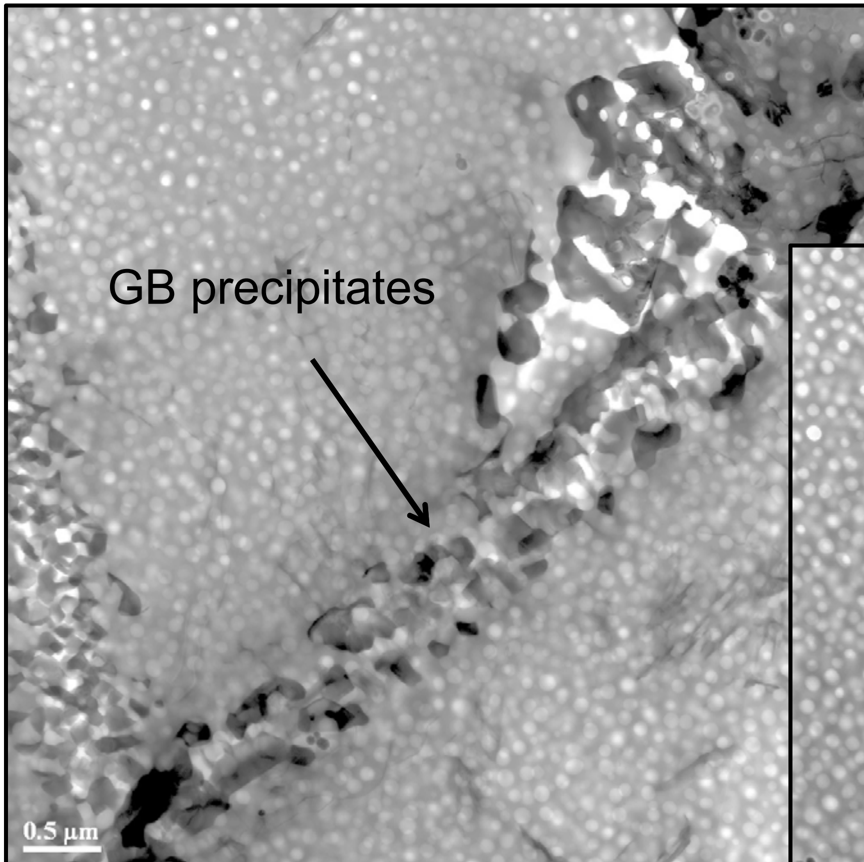
No Evidence of γ′ Depletion in Bulk of Haynes 282 Specimen

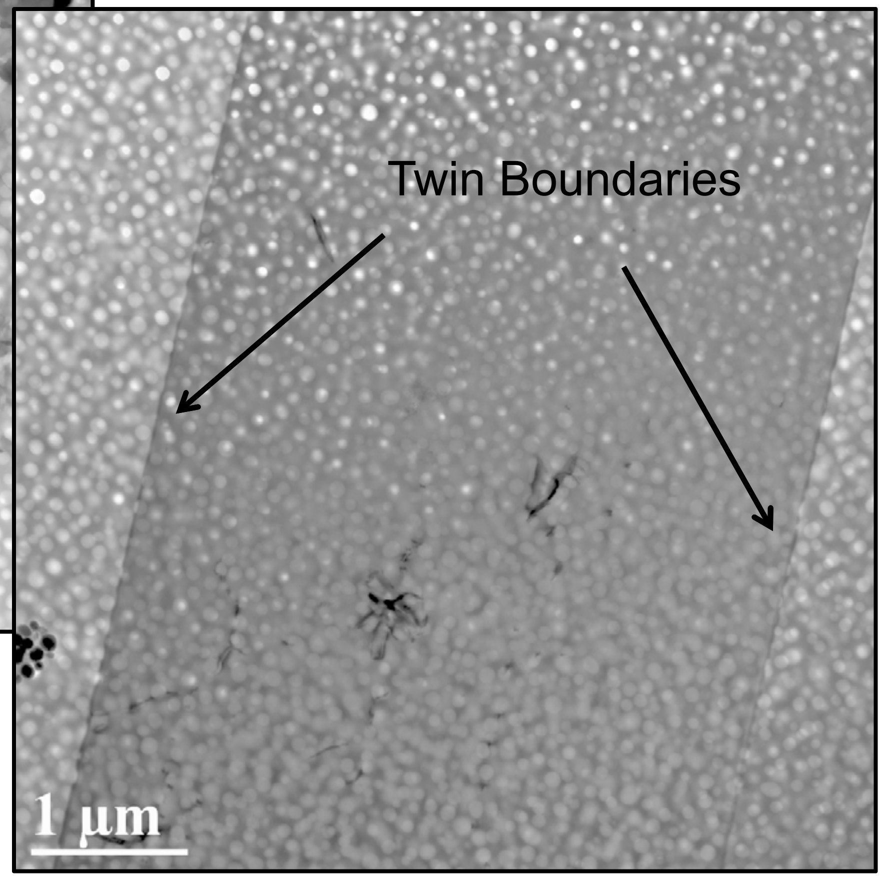
Haynes 282
2809 h, 750°C, 0 MPa



Dark field image

No Evidence of γ′ Depletion in Bulk of Haynes 282 Specimen

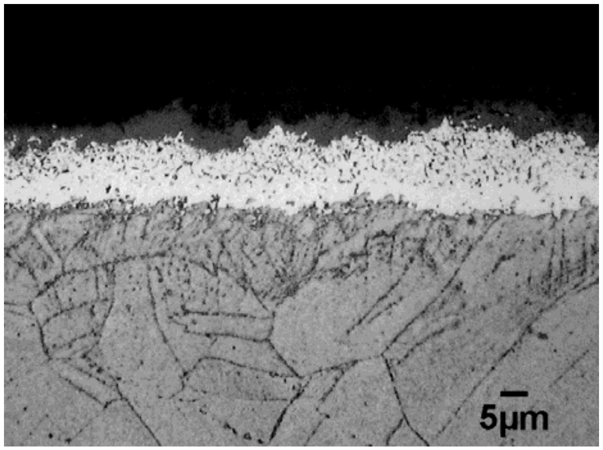




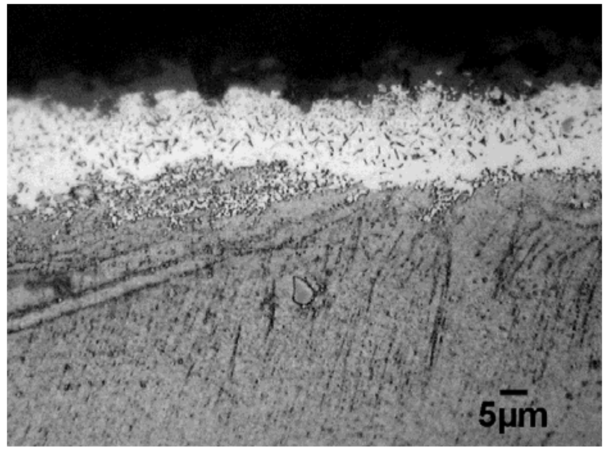
Haynes 282
2809 h, 750°C, 0 MPa

As with Inconel 740, γ′ Depletion Was Observed Near Surfaces in Contact with Test Environment

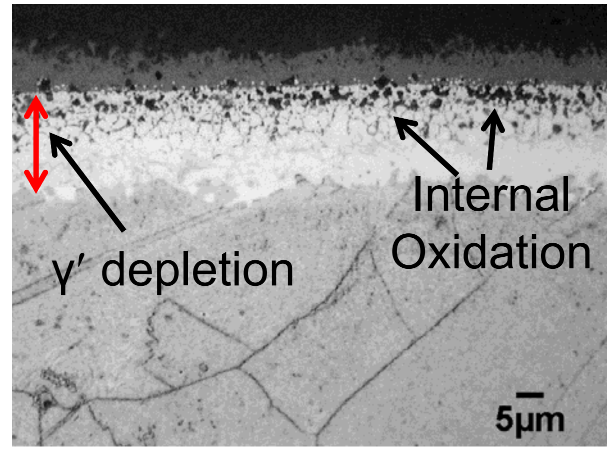
538h/0MPa



1464h/0MPa

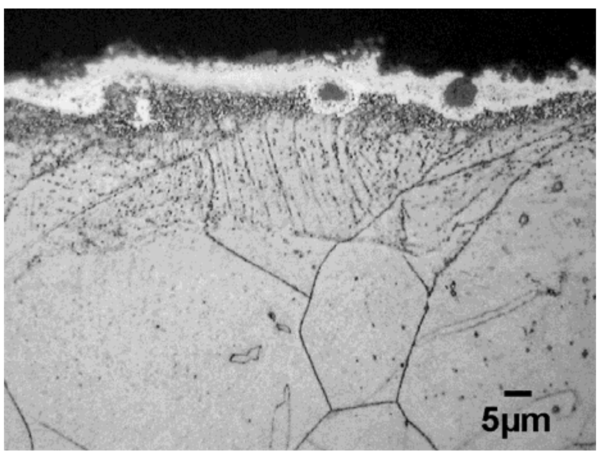


2809h/0MPa

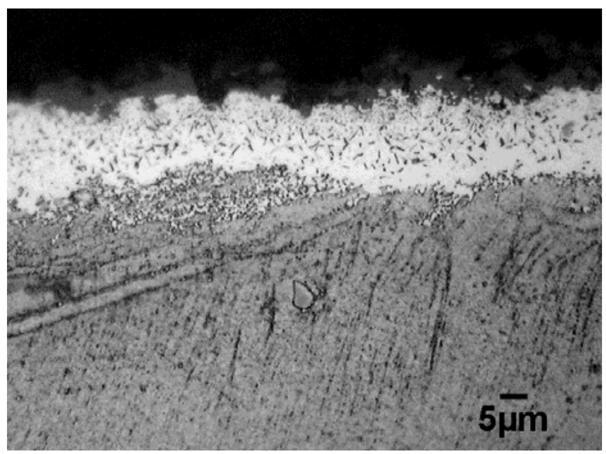


Increasing Exposure Time

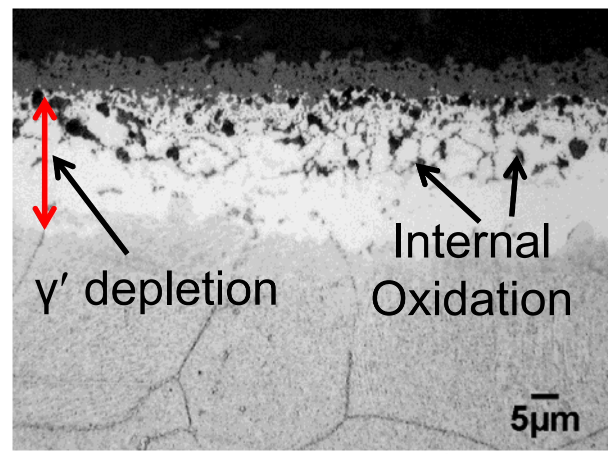
1440h/700°C



1464h/750°C

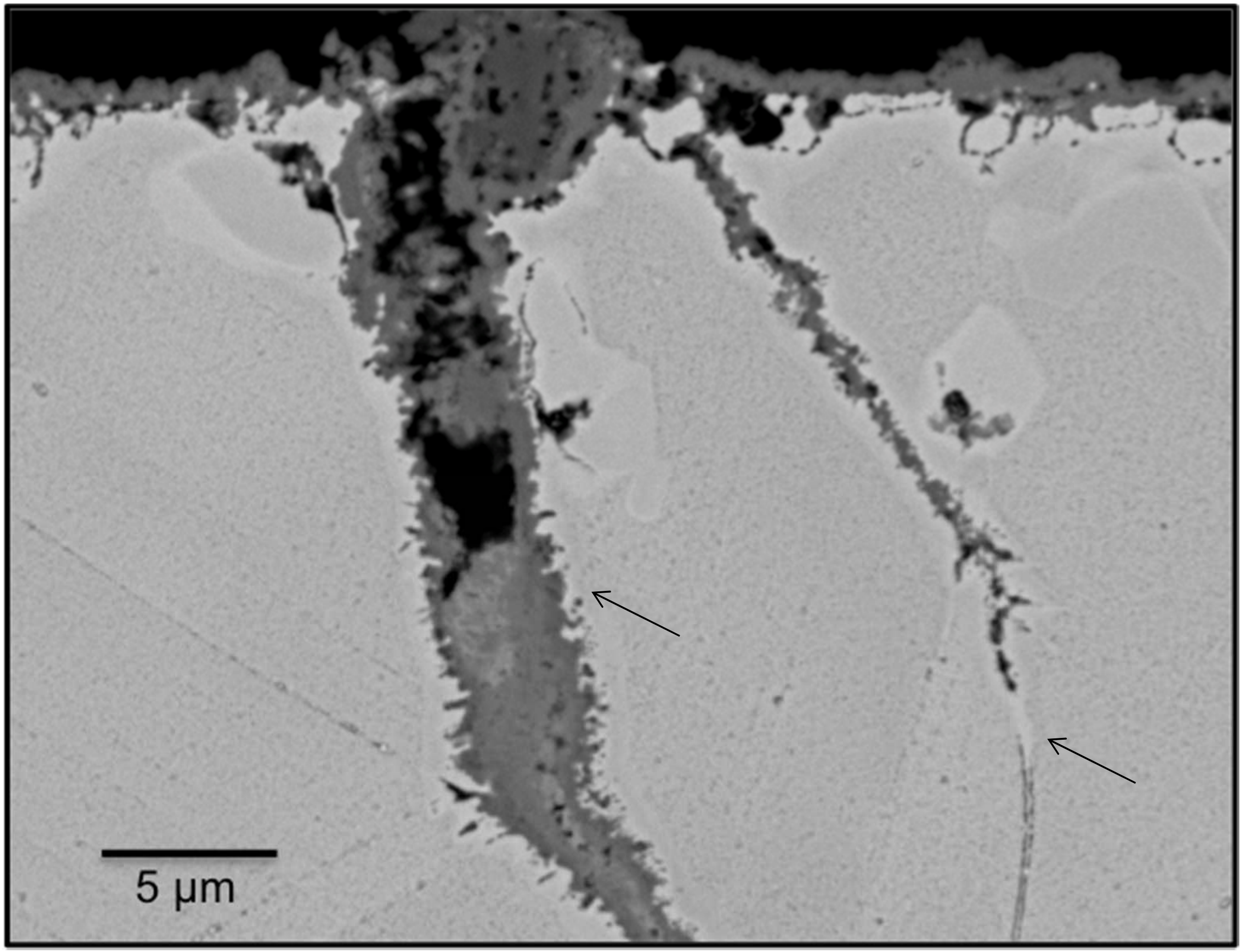


1464h/**800**°C



Increasing Temperature

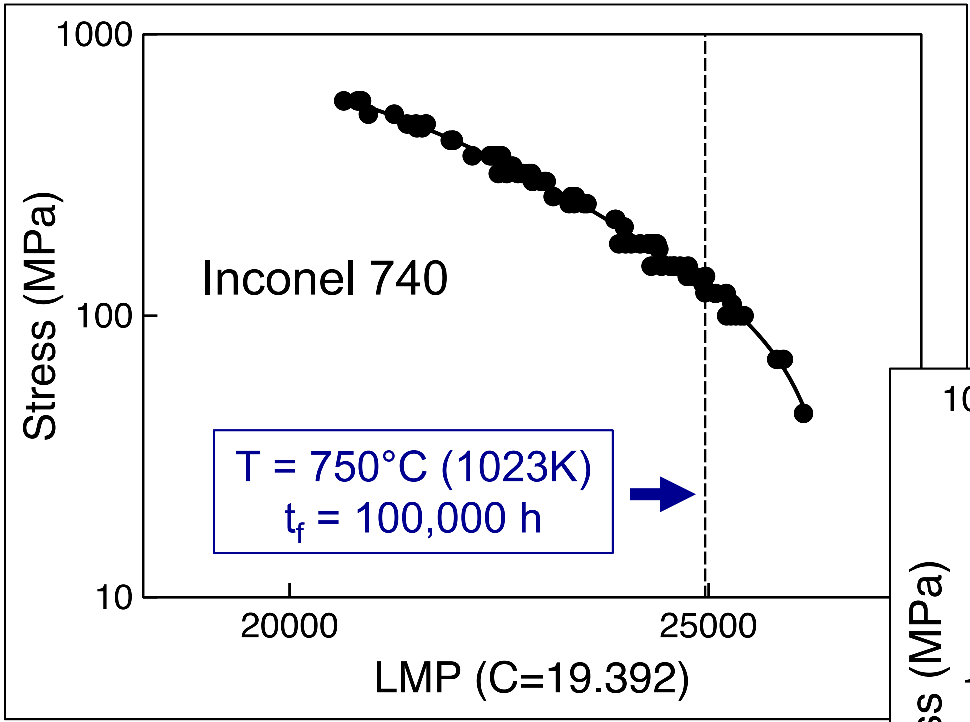
γ′ Depletion Along and Below Internal Penetrations



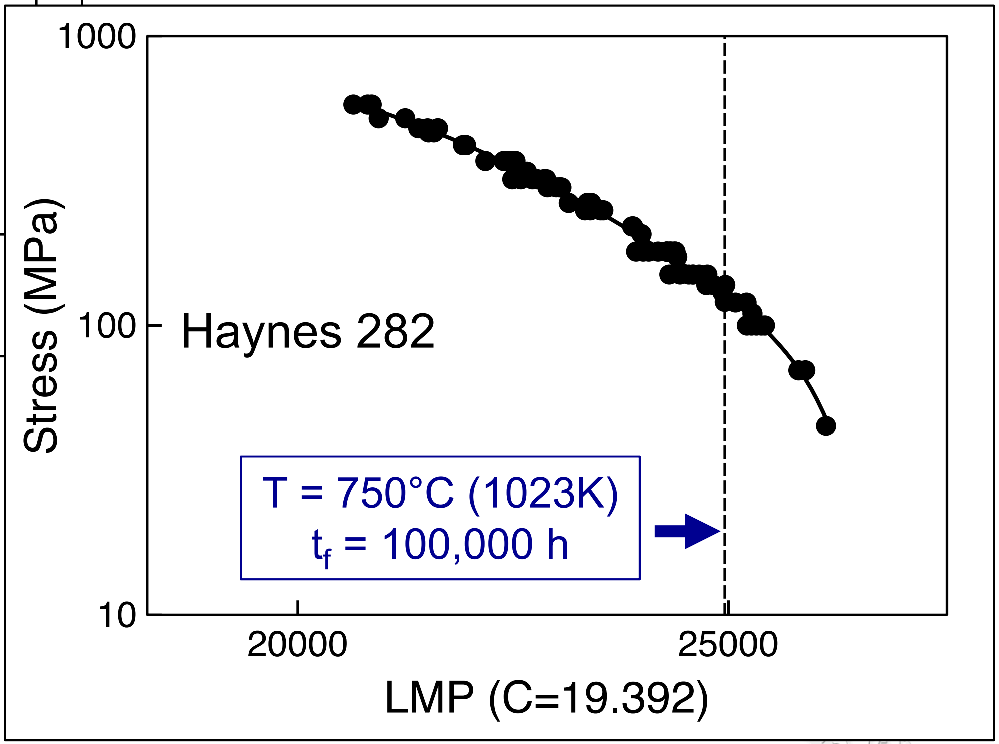
Aged Haynes 282, 538 h, 350 MPa, 750°C

Lifetime Prediction

Extrapolation of Larson-Miller Plots for 100,000 h Life: Haynes 282 > Inconel 740



$$LMP = T\,(\log t_f + C)$$



Extrapolation of Larson-Miller Plots for 100,000 h Life: Haynes 282 > Inconel 740

Temperature (°C)	σ for 100,000 h Rupture Life ($\sigma_{100,000\ h}$) (MPa)	
	Inconel 740	Haynes 282
650	336	–
700	214	248
750	127	138
800	54	70

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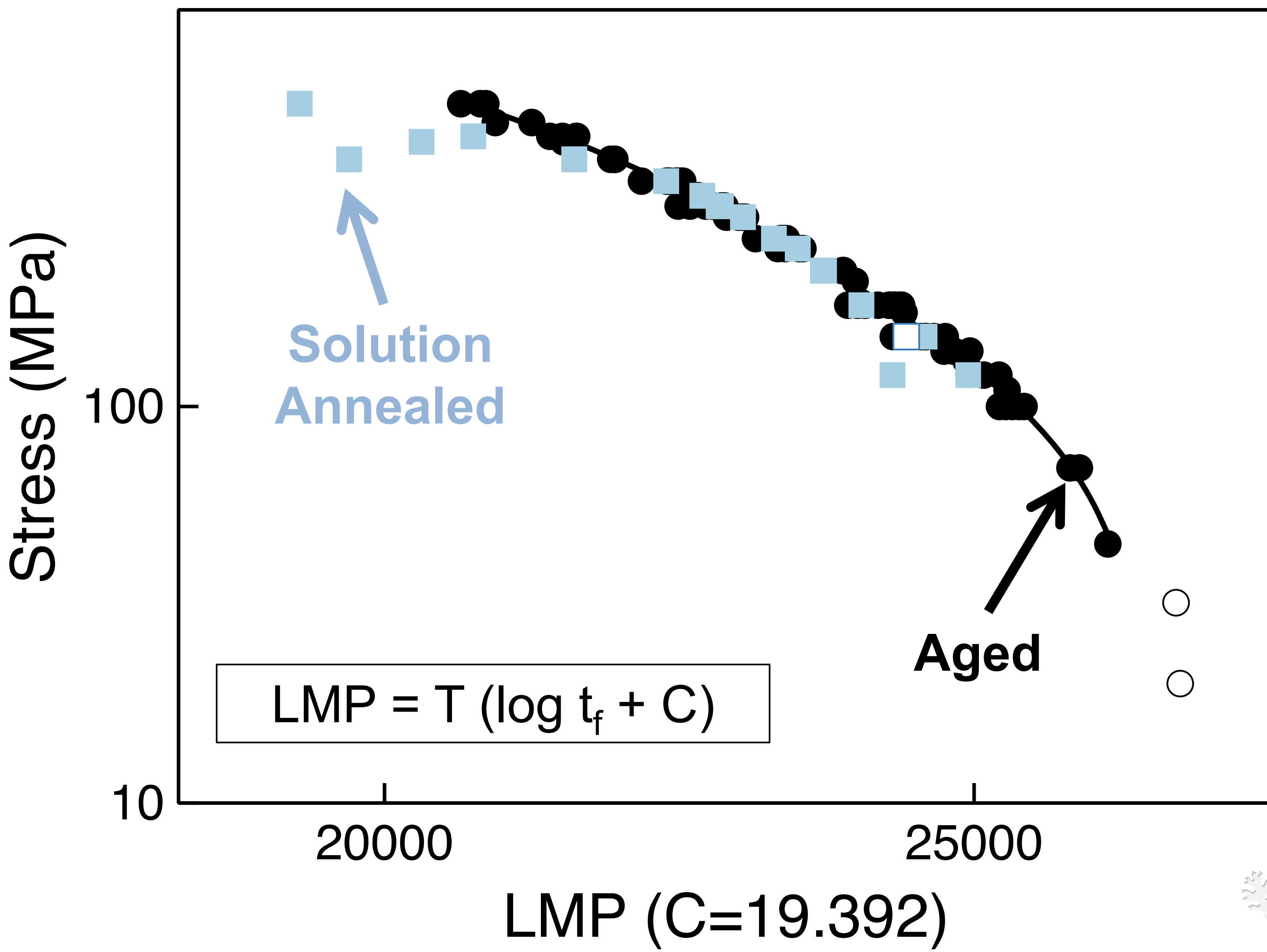
We Have Also Examined Wilshire Approach

- Evans (*Mater. Metall. Trans.*, 2013): improvements in life prediction methods for traditional boiler steels need to be extended to Inconel 740 and Haynes 282; suggested Wilshire et al. as a possible approach
- Based on accepted power law description, Wilshire et al. (*Int'l. Mater. Rev.*, 2008) proposed:

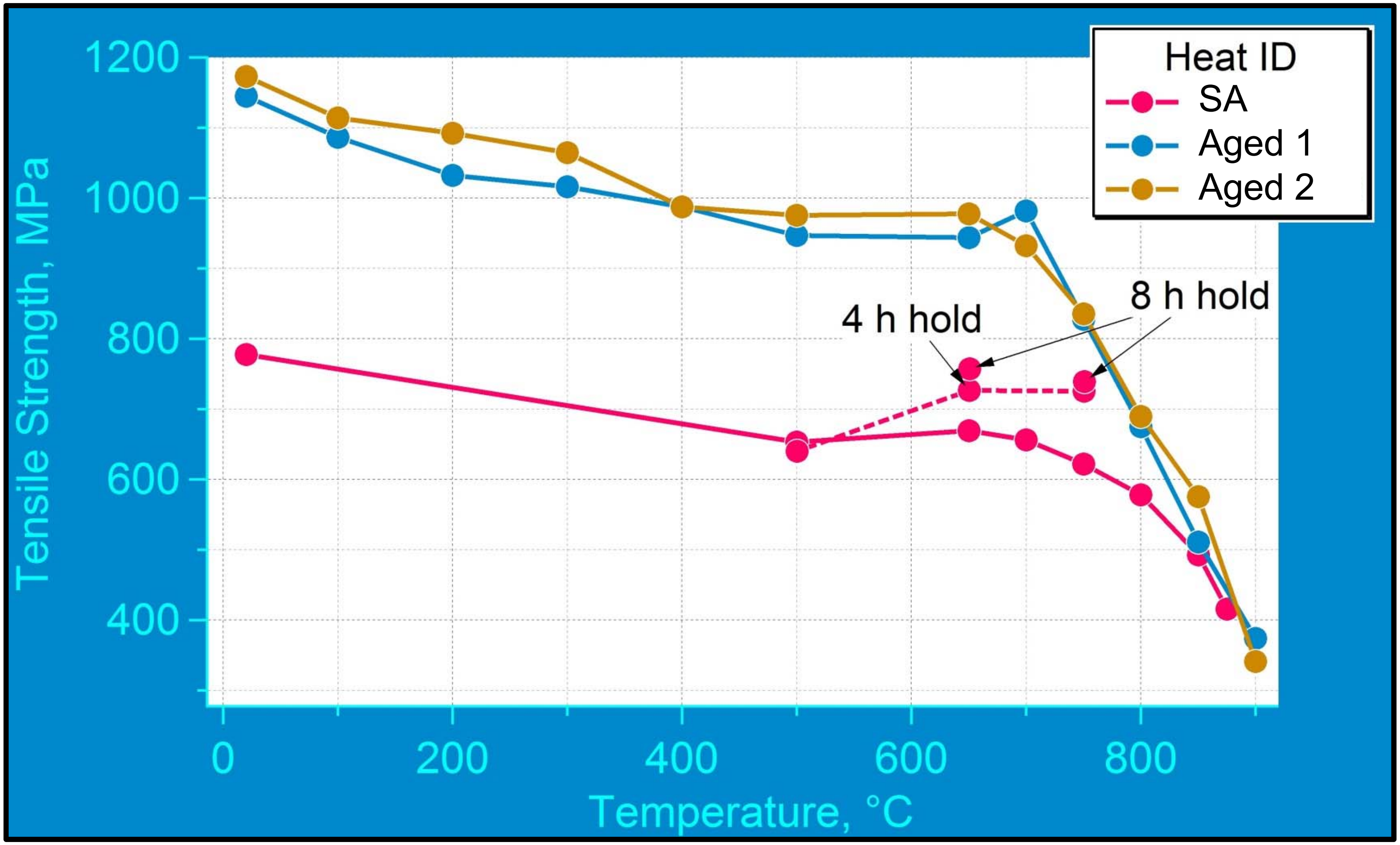
$$\sigma = \sigma_{TS} \exp\{-k_1[t_f \exp(-Q_c^* / RT)]^u\}$$

  - $t_f \to 0$, as $\sigma \to \sigma_{TS}$; $t_f \to \infty$, as $\sigma \to 0$
  - special case of more a general cumulative probability distribution function
  - Need to measure σ_{TS} and then determine k_1 & u
- ***Our creep results show that rupture time doesn't necessarily scale with σ_{TS}***

Except at Highest Stresses, Lifetimes Similar for Solution Annealed (SA) and Aged 740/740H



… Despite Tensile Strength (σ_{TS}) of SA 740 Being Significantly Less Than That of Aged



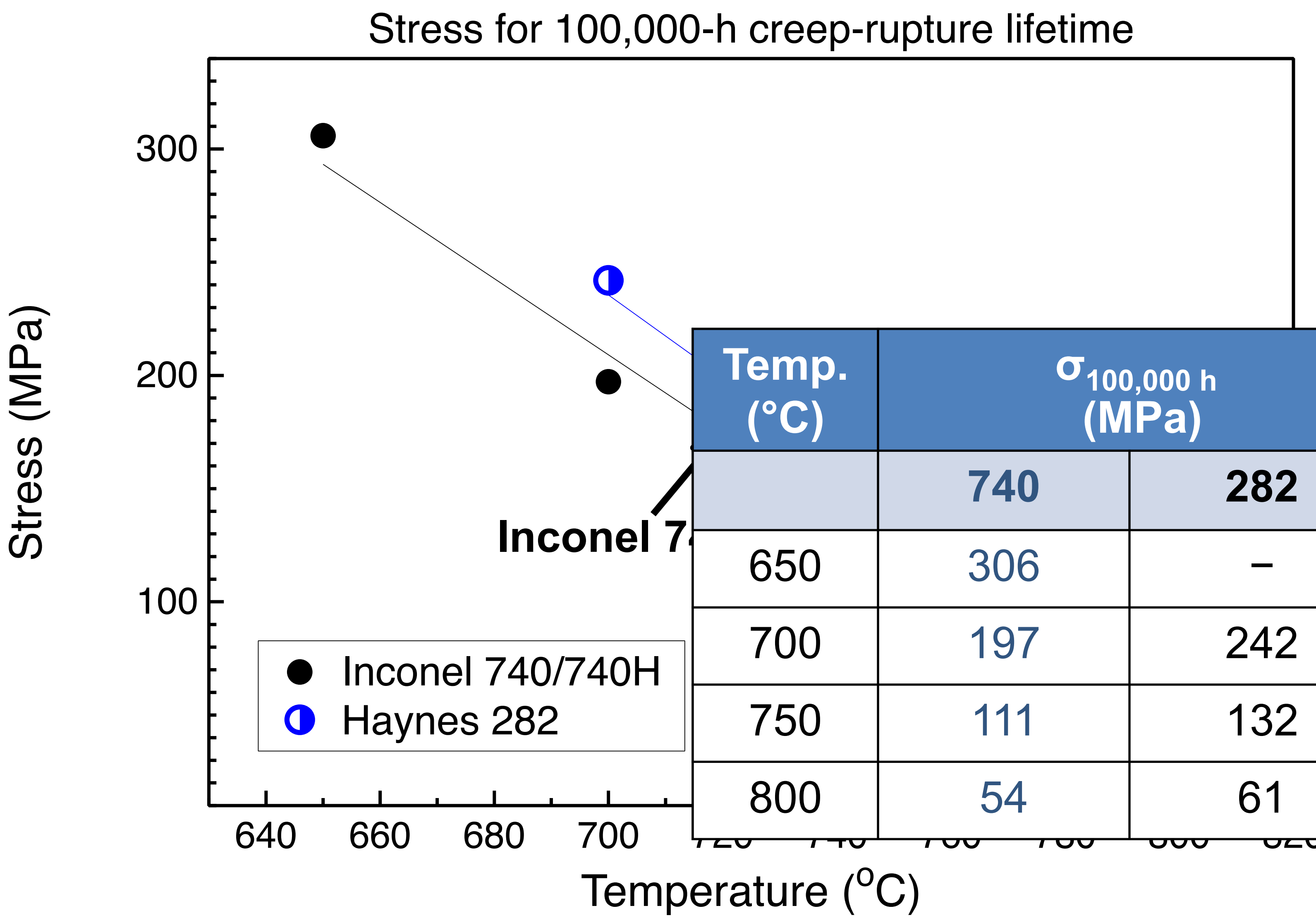
We Have Also Explored Wilshire Approach

- Evans (*Mater. Metall. Trans.*, 2013): improvements in life prediction approaches for traditional boiler steels need to be extended to Inconel 740 and Haynes 282
- Based on accepted power law description, Wilshire et al. (*Int'l. Mater. Rev*., 2008) proposed:

$$\sigma = \sigma_{TS} \exp\{-k_1[t_f \exp(-Q_c^* / RT)]^u\}$$

  - $t_f \to 0$, as $\sigma \to \sigma_{TS}$; $t_f \to \infty$, as $\sigma \to 0$
  - Has the form of a Weibull distribution function, special case of more a general cumulative probability distribution function
  - Need to measure σ_{TS} and then determine k_1 & u
- ***Our creep results show that rupture time doesn't necessarily scale with*** $\boldsymbol{\sigma_{TS}}$
- Examined predicted lifetimes for <u>aged</u> Inconel 740 and Haynes 282

Wilshire Analysis Also Predicted Better Creep Rupture Lifetimes for Haynes 282



Temp. (°C)	$\sigma_{100,000\ h}$ (MPa)	
	740	**282**
650	306	–
700	197	242
750	111	132
800	54	61

Wilshire Analysis (W) More Conservative Than Simple LMP Extrapolation (LM) In Most Cases

Temp. (°C)	σ for 100,000 h Rupture Life ($\sigma_{100,000\ h}$) (MPa)			
	Inconel 740		Haynes 282	
	W	LM	W	LM
650	306	336	–	–
700	197	214	242	248
750	111	127	132	138
800	54	54	61	70

- Neither methodology accounts for microstructural effects
- Will be exploring life prediction approaches that do

Milestones

<u>FY13</u>

Compare weld strength reduction for alloy 282 to that for Inconel 740/740H and report results to the A-USC Steering Committee ✔

Complete report analyzing all results to date on creep behavior of Inconel 740/740H ✔

Complete a study of the effect of heat treatment on the creep-rupture life of wrought alloy 282 ✔

<u>FY14</u>

Complete a summary report on all alloy 617B data produced by the A-USC program with a comparison to other 617 databases. (July 2014)

Complete a proof-of-principle creep test of a co-extruded pipe (August 2014)

Prepare a summary report analyzing all results to date on creep behavior of alloy 282. (September 2014)

Complete a report or paper on oxidation effects on Ni-based superalloys under creep conditions (September 2014)

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

- Sufficient creep-rupture and microstructural data to verify effectiveness of one-step aging treatment for Haynes 282 developed on project
- Completion of microstructural analyses of specimens with longest rupture times and use of such data in advanced lifetime models for Ni-based superalloys
- 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
- Simple Larson-Miller estimates and a modified power-law model (Wilshire) were used to predict stress levels needed for creep lifetimes of 10^5 h at various temperatures
- Except for very high stresses, little difference in creep-rupture times measured to date for solution annealed vs. aged specimens – inconsistent with Wilshire model assumption of dependence of creep-rupture life on σ_{TS}
- Data indicate greater creep-rupture resistance for Haynes 282 than Inconel 740, but both precipitation-strengthened alloys exhibit good thermal stability for A-USC boiler application and should meet the A-USC goal of 100,000 h at 750°C