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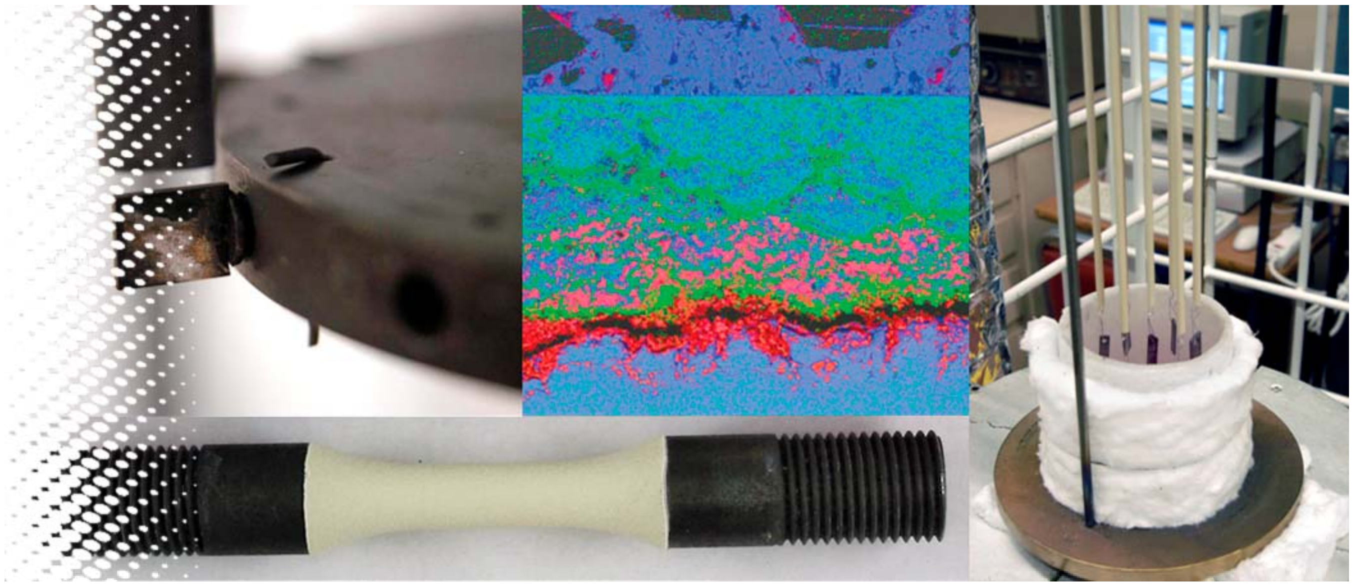

Cast Alloys for Advanced Ultra Supercritical Steam Turbines

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U.S. DEPARTMENT OF ENERGY

Surface Stability of Materials in High-Temperature Aggressive Environments, Vail, CO, May 16-20, 2010

Outline

Introduction

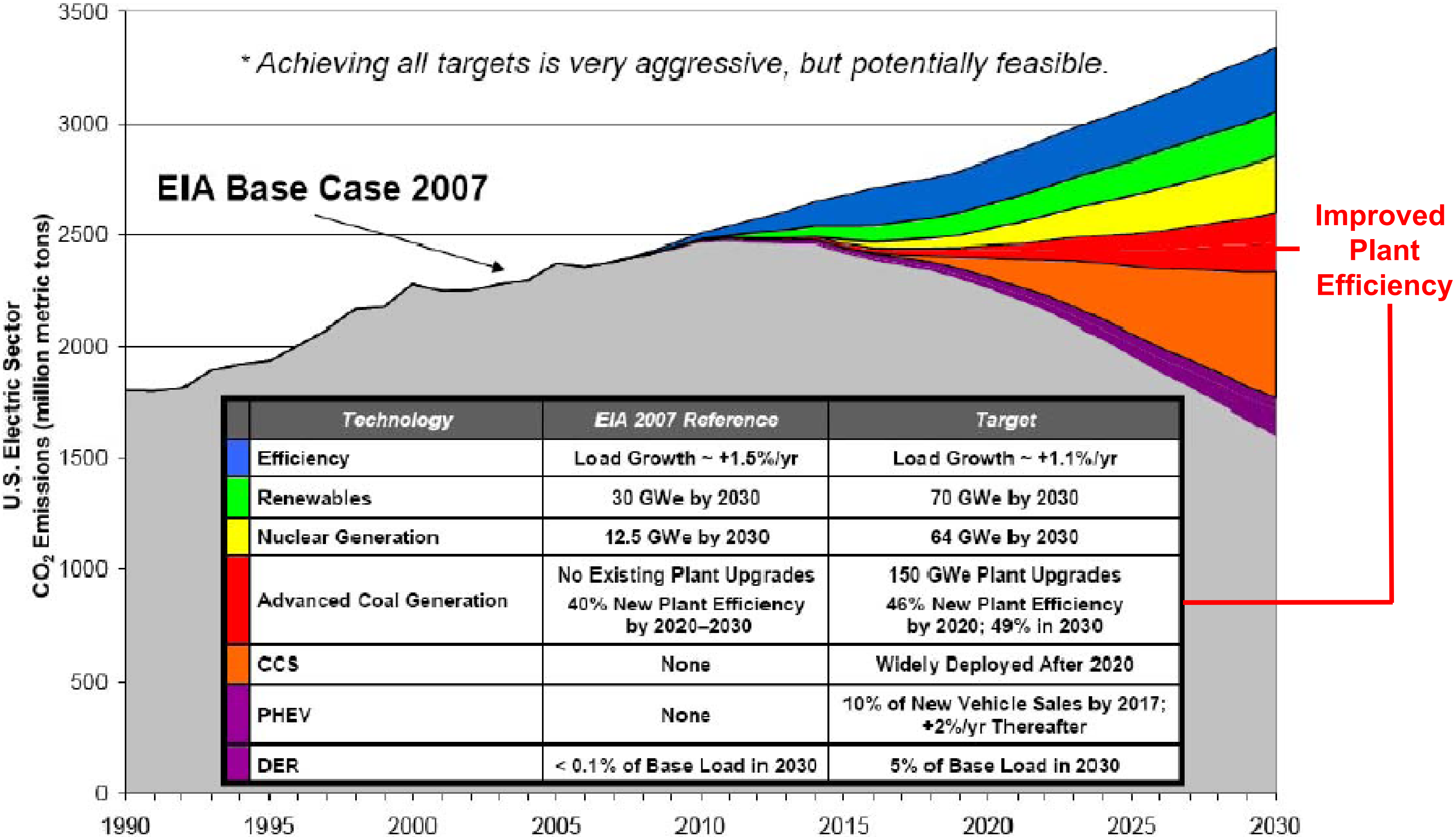
- Ultra Supercritical Steam Turbines
- Research Aims

Results

- Casting and Homogenization
- Oxidation Behavior

Summary

Impact of Advanced Coal Generation on CO_2 Emissions



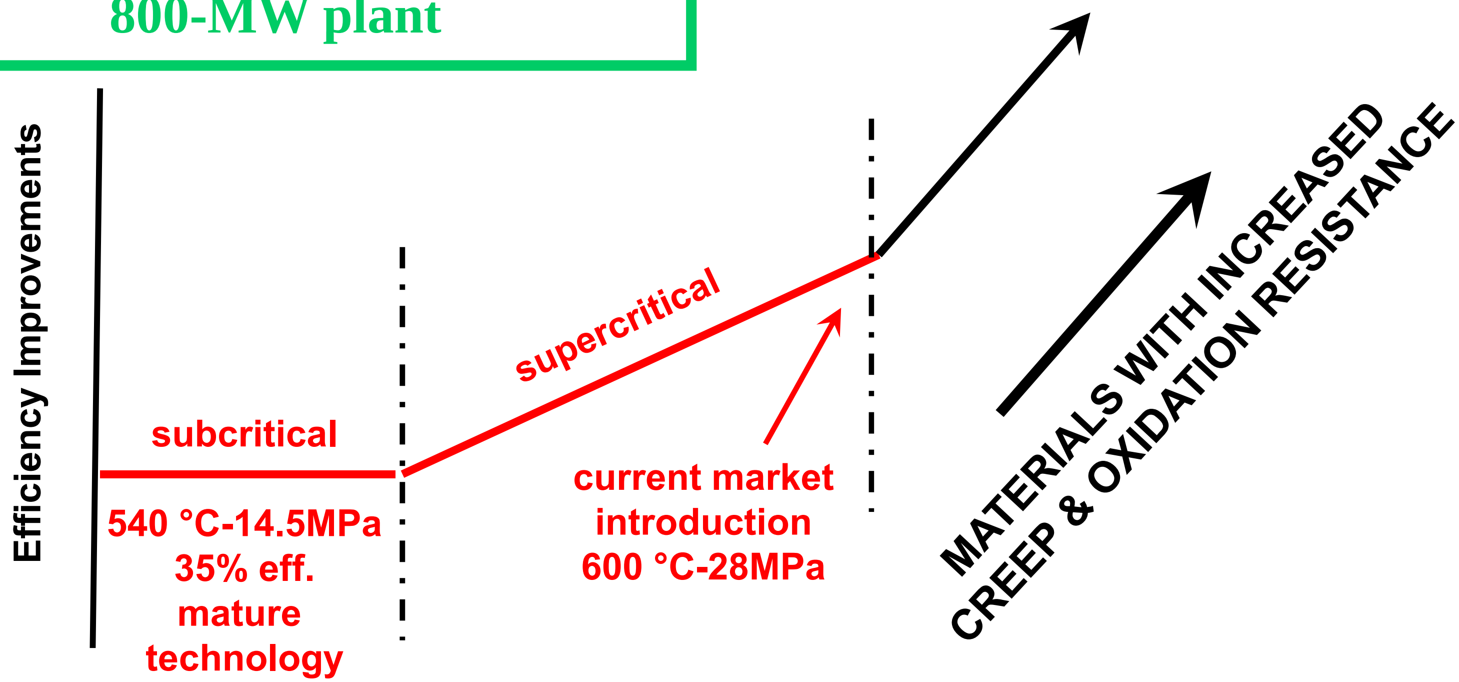
Technology	EIA 2007 Reference	Target
Efficiency	Load Growth ~ +1.5%/yr	Load Growth ~ +1.1%/yr
Renewables	30 GWe by 2030	70 GWe by 2030
Nuclear Generation	12.5 GWe by 2030	64 GWe by 2030
Advanced Coal Generation	No Existing Plant Upgrades 40% New Plant Efficiency by 2020–2030	150 GWe Plant Upgrades 46% New Plant Efficiency by 2020; 49% in 2030
CCS	None	Widely Deployed After 2020
PHEV	None	10% of New Vehicle Sales by 2017; +2%/yr Thereafter
DER	< 0.1% of Base Load in 2030	5% of Base Load in 2030

EPRI, 2007

Increasing Efficiency

Each 1% increase in efficiency eliminates ~1,000,000 tons of CO_2 emissions over the lifetime of an 800-MW plant

US-DOE Advanced Power Systems:
46%-48% efficiency from coal generation
Steam condition: 760 °C - 35MPa
~ 5ksi



Subcritical: < 22 MPa
Supercritical (SC): > 22.1 MPa, 538 to 565 °C
Ultra Supercritical (USC): 565 to ~675 °C (advanced ferritic & austenitic steels required)
Advanced Ultra Supercritical (A-USC): > ~675 °C (nickel-base superalloys required)

Adapted from: Viswanathan, et al , 2005 and Swanekamp, 2002

Technological Issues

There is an immediate and continuing need for increased power production.

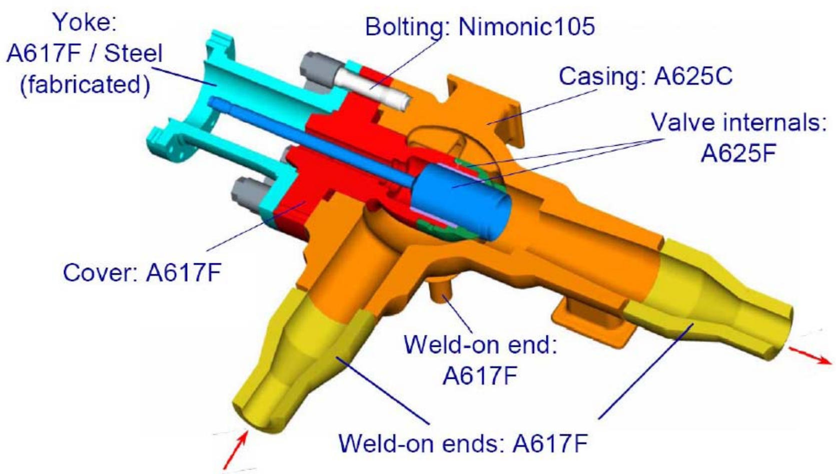
Increases in Temperature and Pressure increase efficiency and decrease CO_2 production along with other pollutants.

Higher Temperature and Pressure place greater demands upon the Materials.

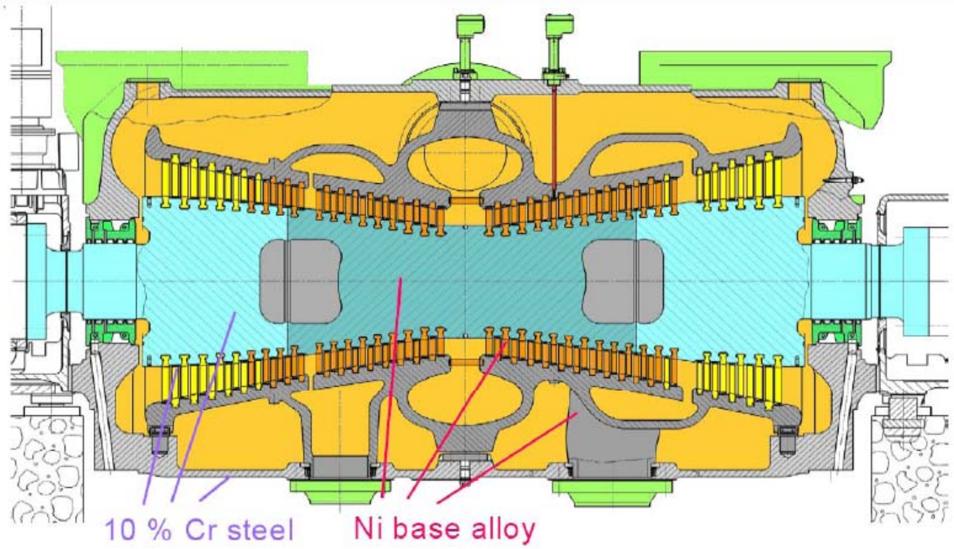
Large castings are required for some components—many technical issues.

Example Components

- **Castings**
  - 1-15 tons
  - Up to 100 mm in thickness



Valve Bodies



Turbine Casing

Courtesy Alstom

Challenges for A-USC Castings

Traditionally wrought alloys are being considered due to proven weldability in thick sections

- Large pour weights (1-15T)
- Thick section components
- Slow cooling rates
- Segregation prone alloys

Our approach is to examine a suite of traditionally wrought Ni-based superalloys cast under conditions designed to emulate the full sized casting

- A computationally optimized homogenization heat treatment was developed to improve the performance of these materials

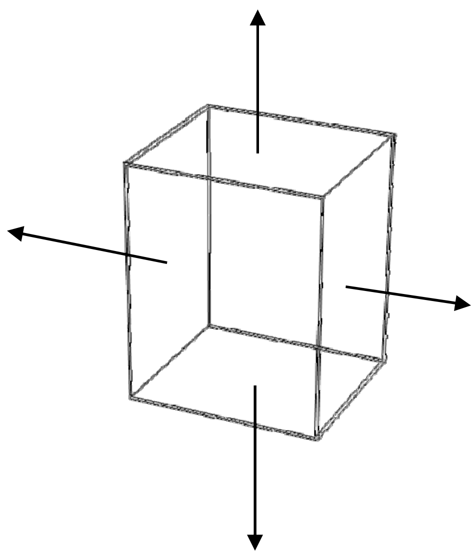
Steam oxidation resistance

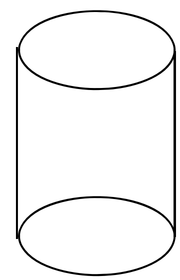
- Compare the steam oxidation behavior of cast versions of candidate Ni-based superalloys with their wrought counterparts

Alloys Under Consideration

Solid Solution	Age Hardenable
H230	N105
IN617	H263
IN625	H282
	IN740

Our Model Casting Geometry

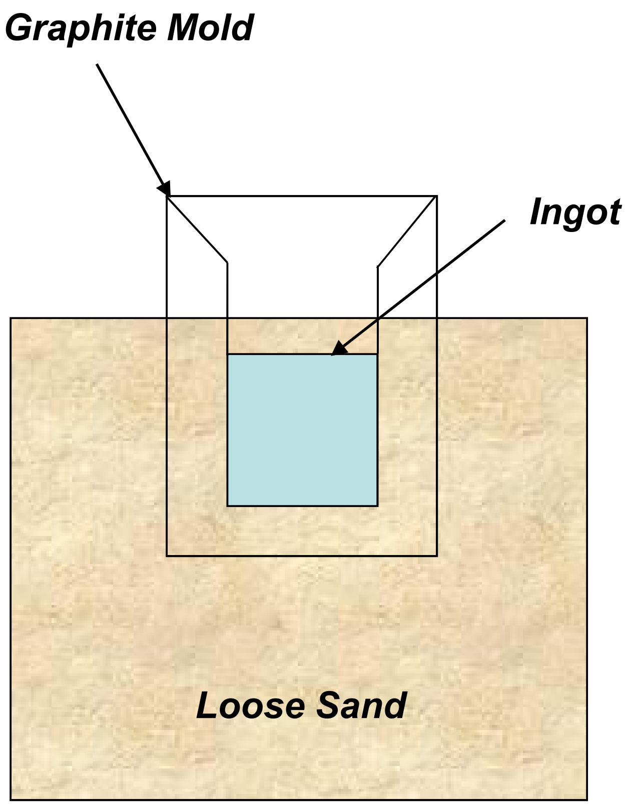




The actual component is nominally 4in thick and "infinite" in the other directions.

Our casting is nominally 4in in diameter and 4-5in tall.

“Enhanced” Slow Cooling

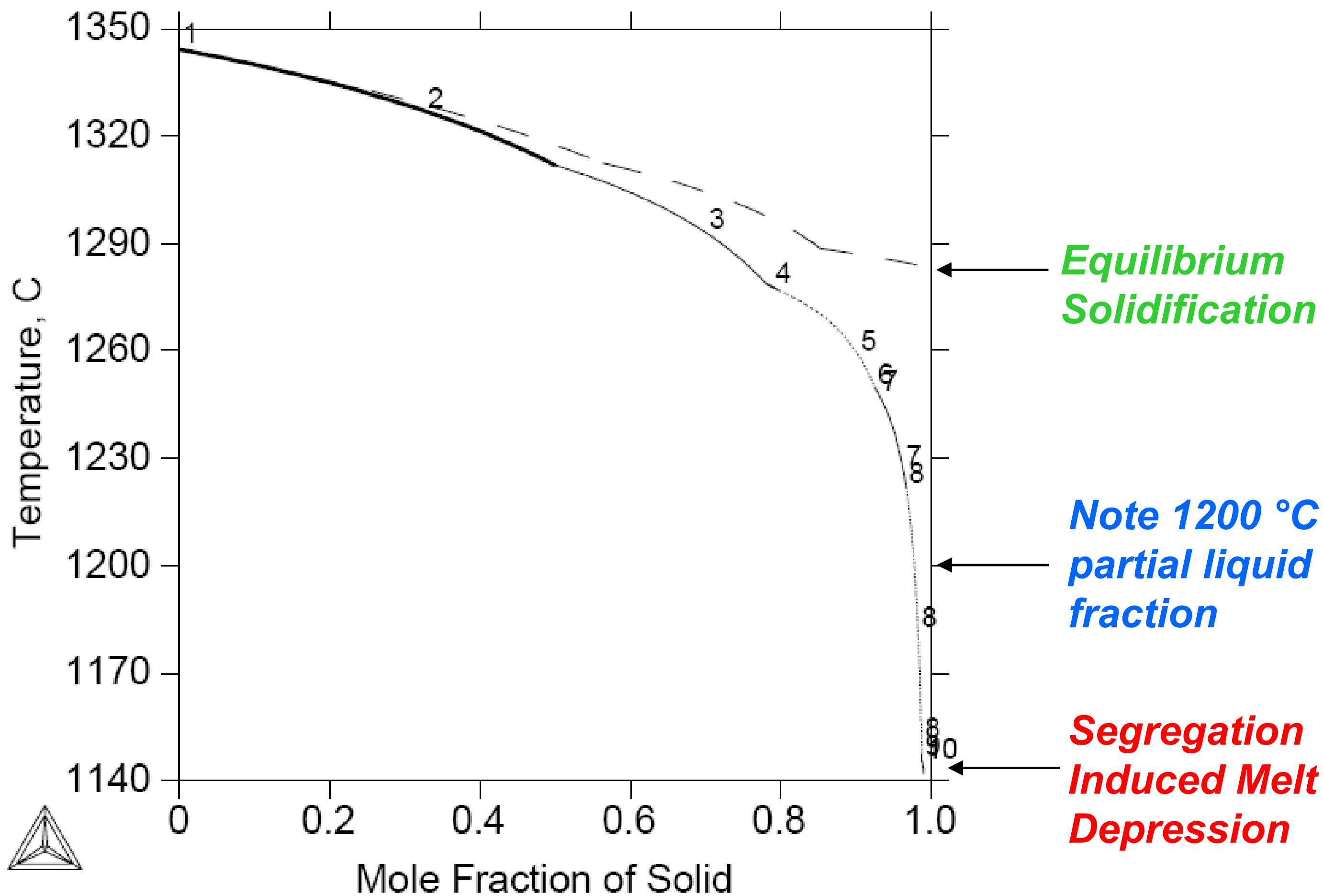


- Casting layout shown schematically in cross section on the left
- A permanent graphite mold was used. This mold was surrounded by loose sand such that the top of the casting was below the sand line
- This attempts to emulate the “semi-infinite” plate model of the turbine casing

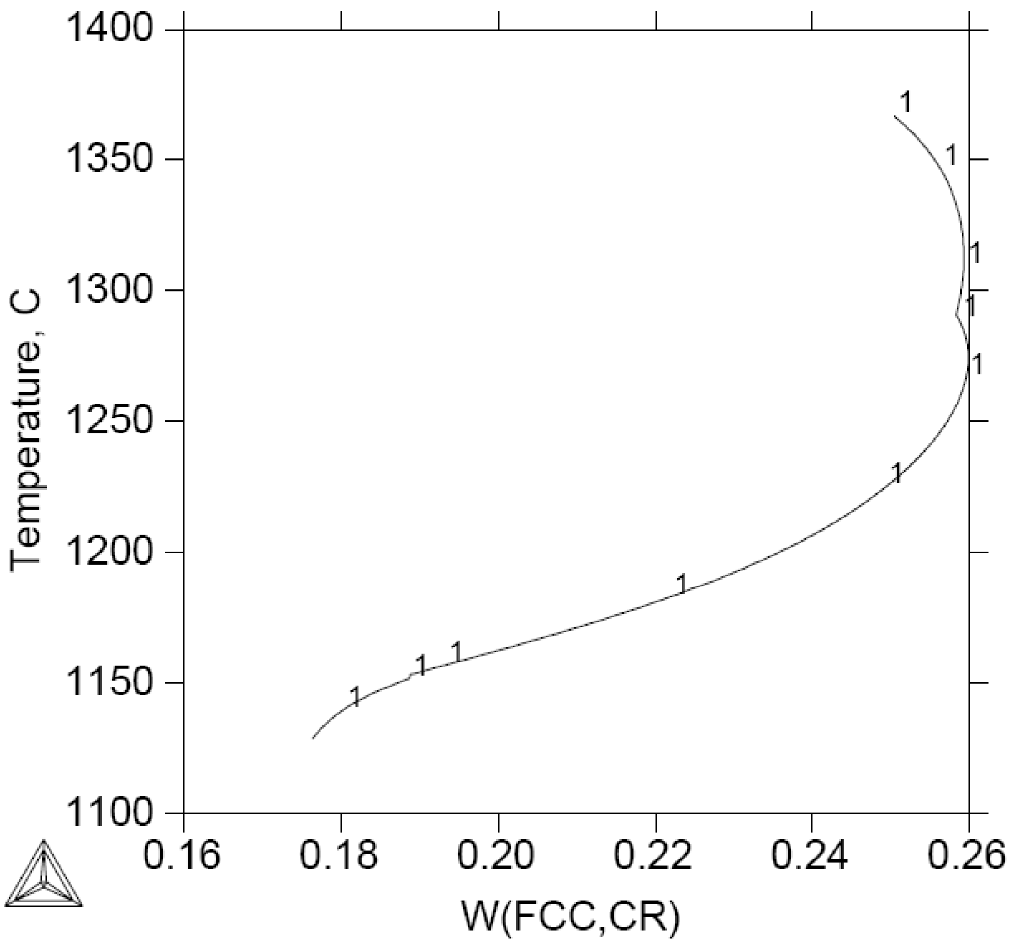
First Ingot Chemistries

	C	Cr	Mo	Co	Al	Ti	Nb	Mn	Si	B	W	
Nimonic 105	**0.15**	**14.85**	**5.00**	**20.00**	**4.70**	**1.10**		**0.50**	**0.50**	**0.05**		***Aims***
	0.16	***14.61***	***5.02***	***20.04***	***4.43***	***1.10***		***0.51***	***0.51***	***0.05***		***Results***
Haynes 230	**0.120**	**22.00**	**2.00**		**0.35**			**0.70**	**0.50**		**14.00**	
	0.12	***21.59***	***2.01***		***0.37***			***0.69***	***0.50***		***13.91***	
Haynes 263	**0.070**	**20.00**	**5.80**	**20.00**	**0.35**	**2.10**		**0.50**	**0.35**			
	0.07	***19.68***	***5.74***	***19.89***	***0.40***	***2.04***		***0.50***	***0.34***			
Haynes 282	**0.070**	**19.50**	**8.50**	**10.00**	**1.50**	**2.10**		**0.25**	**0.15**	**0.005**		
	0.07	***19.22***	***8.48***	***9.84***	***1.44***	***2.08***		***0.24***	***0.15***	***0.01***		
IN617	**0.120**	**22.00**	**9.00**	**12.50**	**1.10**	**0.30**		**0.50**	**0.50**			
	0.12	***21.73***	***8.96***	***12.35***	***1.04***	***0.31***		***0.50***	***0.49***			
IN625	**0.070**	**21.00**	**9.00**		**0.10**	**0.10**	**3.60**	**0.50**	**0.35**			
	0.07	***20.71***	***8.92***		***0.15***	***0.089***	***3.58***	***0.49***	***0.34***			
IN740	**0.030**	**25.00**	**0.50**	**20.00**	**1.30**	**1.50**	**1.50**	**0.30**	**0.30**	**Fe:**	**0.70**	
	0.04	***24.71***	***0.50***	***20.03***	***1.24***	***1.48***	***1.50***	***0.30***	***0.31***		***0.57***	

N105—Solidification



Weight Fraction Cr in FCC Phase—IN740

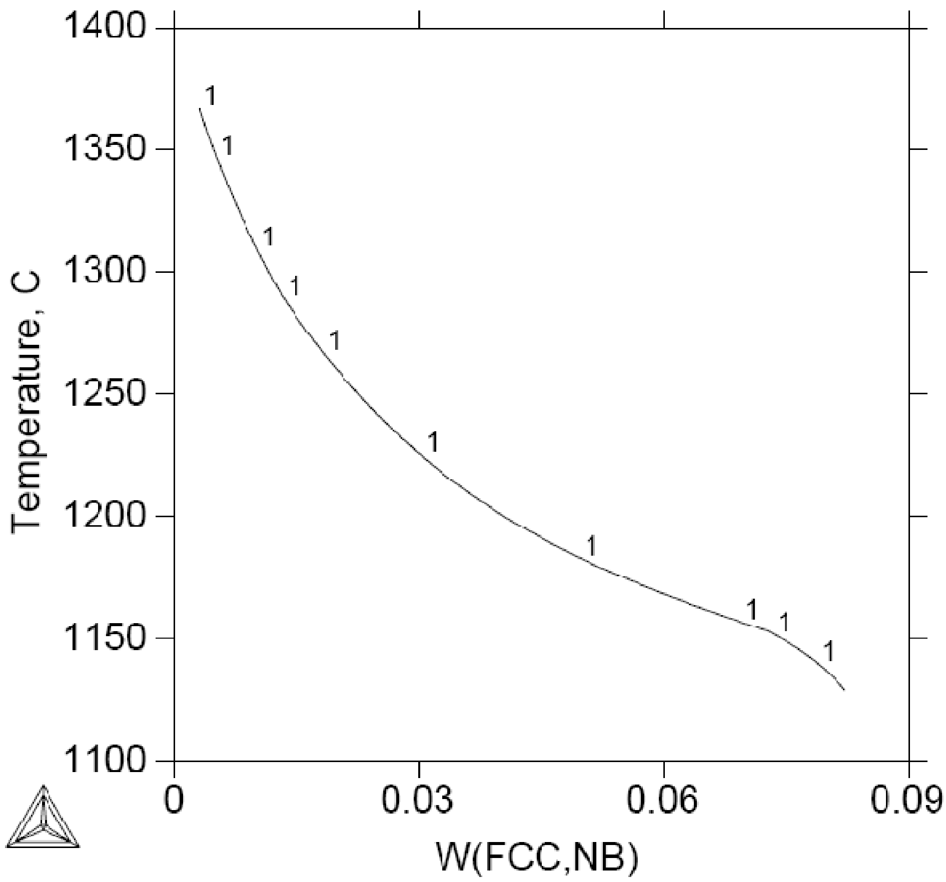


The weight fraction of Cr in the FCC phase changes with temperature in IN740.

This is on a Scheil calculation basis.

The irregularity in the curve occurs at a second phase formation temperature.

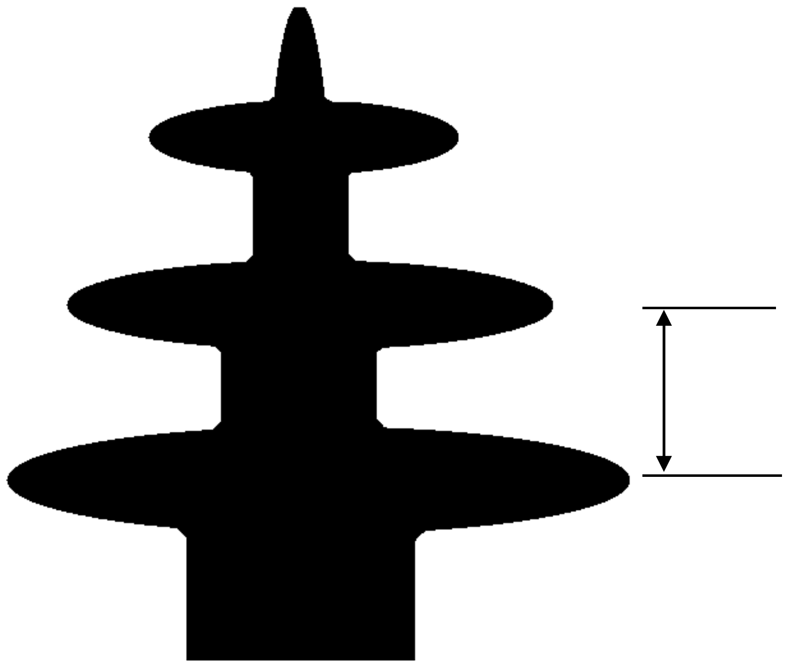
Weight Fraction Nb in FCC Phase—IN740



The weight fraction of Nb changes in the FCC phase with temperature in IN740.

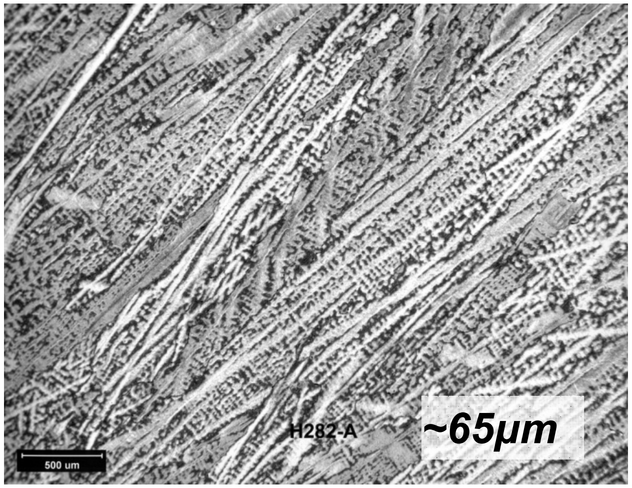
This is on a Scheil calculation basis.

Critical Microstructural Features

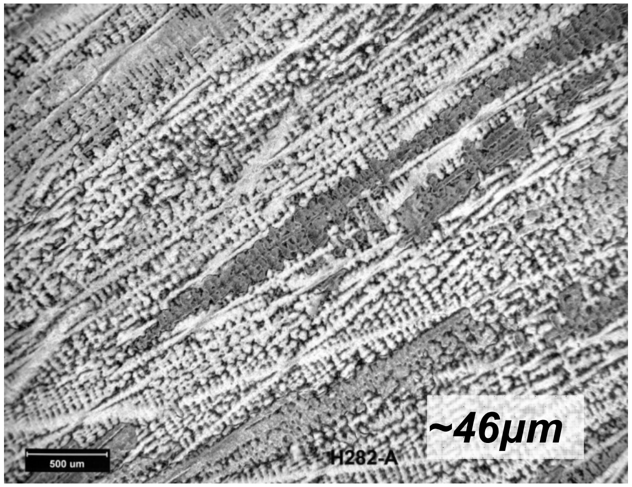


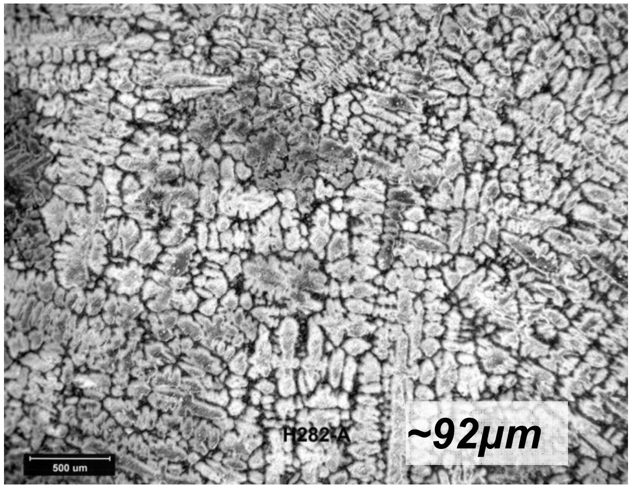
- *A very useful measurement is the secondary dendrite arm spacing (sdas)*
- *Solidification modelers use sdas to estimate the local cooling (solidification) rate*
- *We used sdas as a characteristic diffusion distance to base homogenization heat treatments: d=0.5x(sdas)*

H282 Secondary Dendrite Arm Spacing

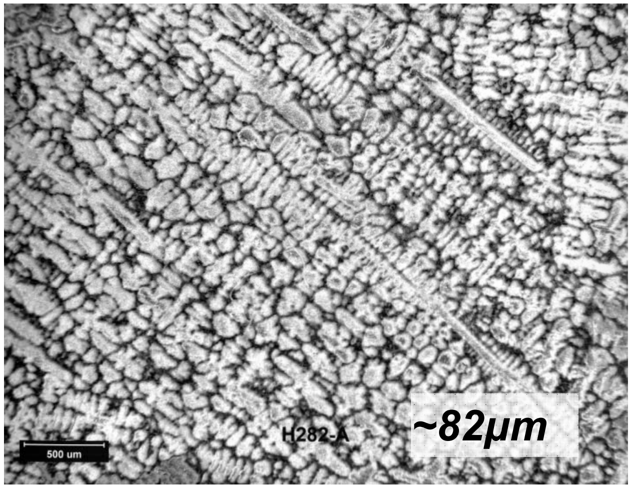


Columnar zone



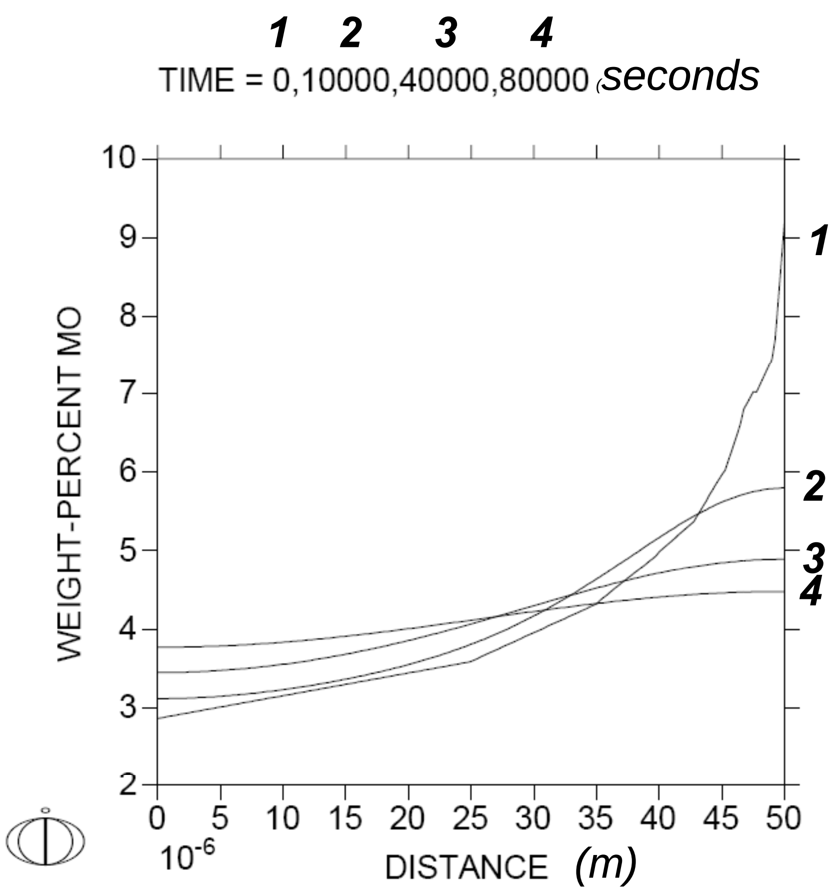


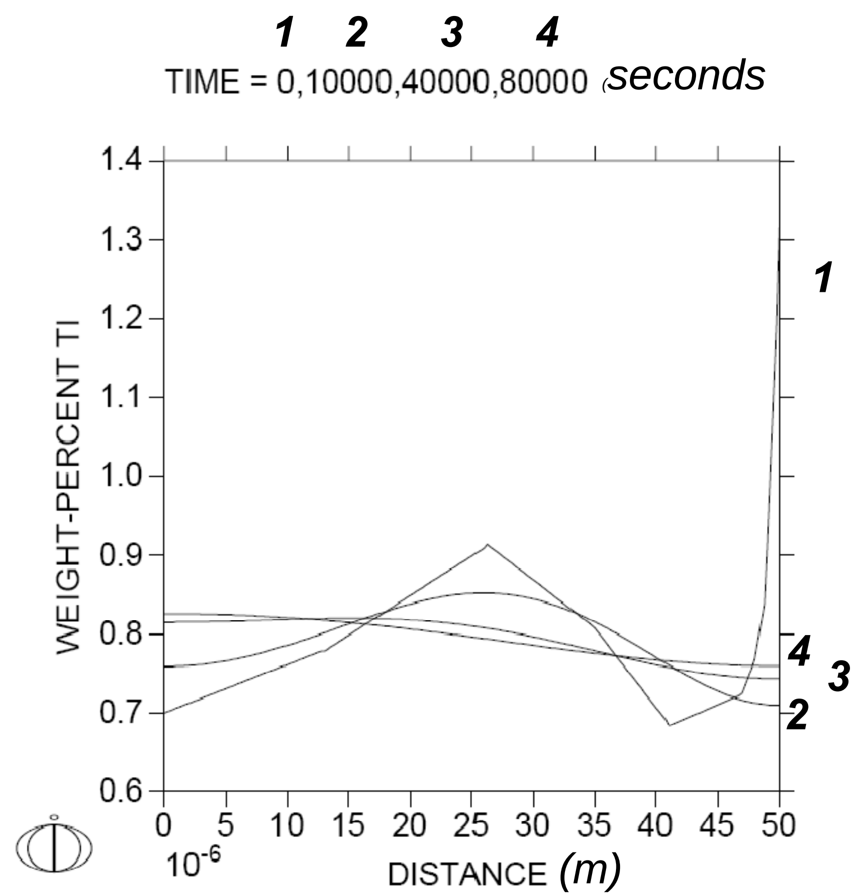
Equiaxed zone



N105—1100 °C Heat Treatment

Since the largest measured sdas<100μm; we used 50μm as the characteristic diffusion distance





Neither Mo or Ti are fully homogenized even after 22.4h at 1100 °C with this basic heat treatment

Section Summary: As-Cast Profiles

The refractory elements W, Mo, and Nb do not homogenize after ~22h/1100 °C

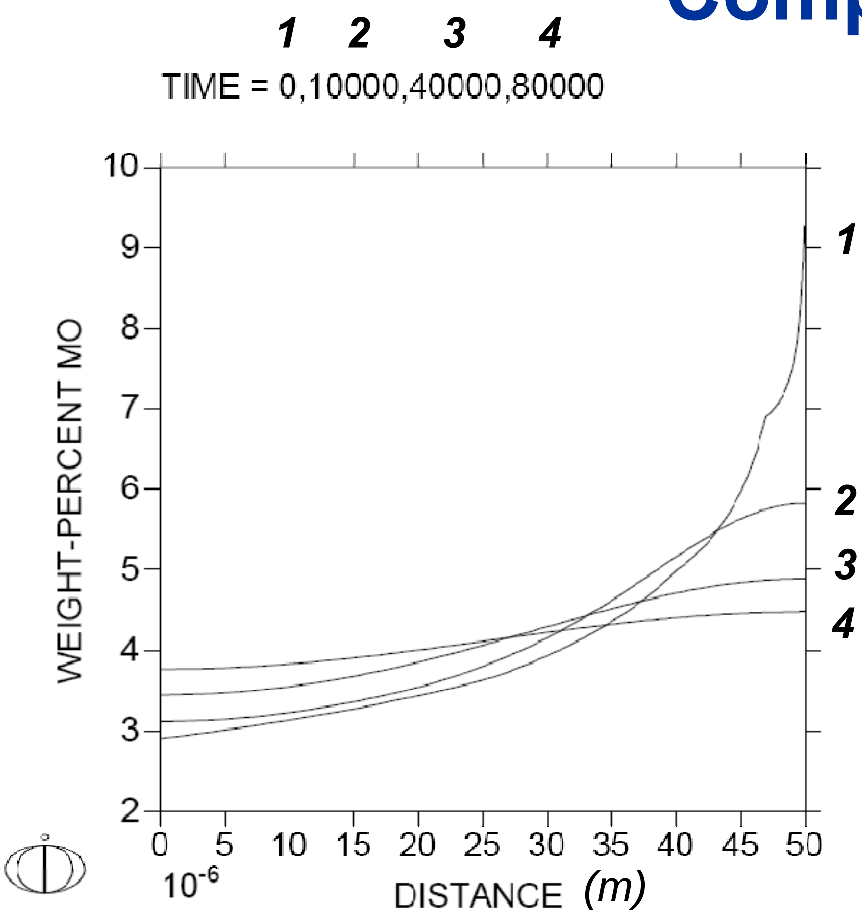
Significant segregation of the second phase strengthening elements Al, Nb and Ti were observed in many alloys…to the point that ½ to ⅔ of the casting would be considered "lean"

In some cases, Cr poor regions are predicted

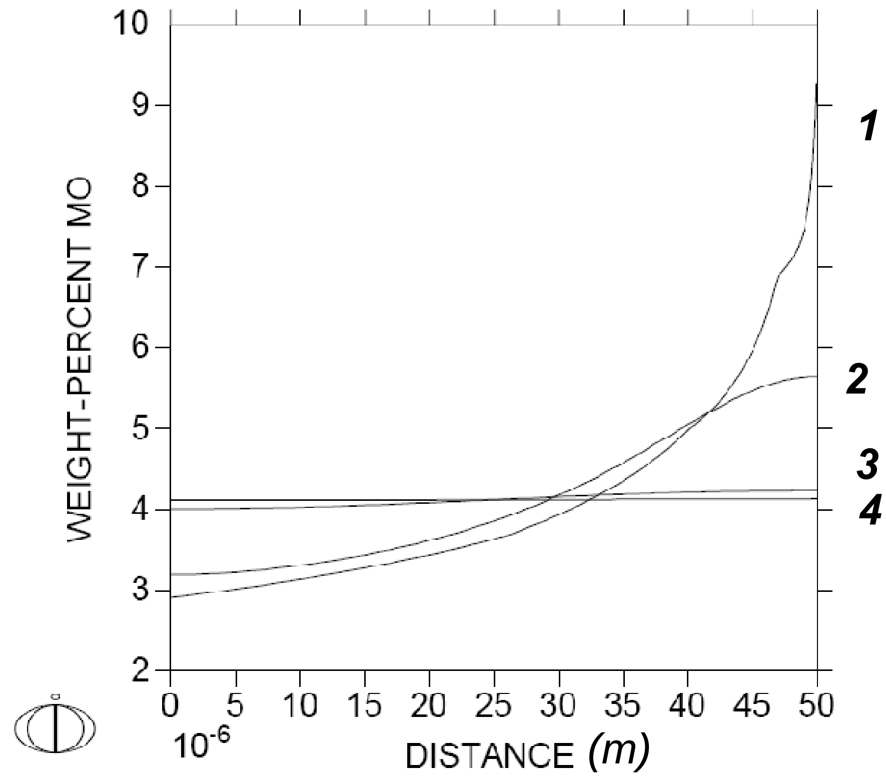
Significant Co segregation was observed in some alloys

Significant partitioning of Mn and Si to the interdendritic region was predicted. This result suggests that a turn down in the levels of these elements may be beneficial (e.g., for welding)

N105—Homogenization Heat Treatment Comparison



Isothermal at 1100 °C



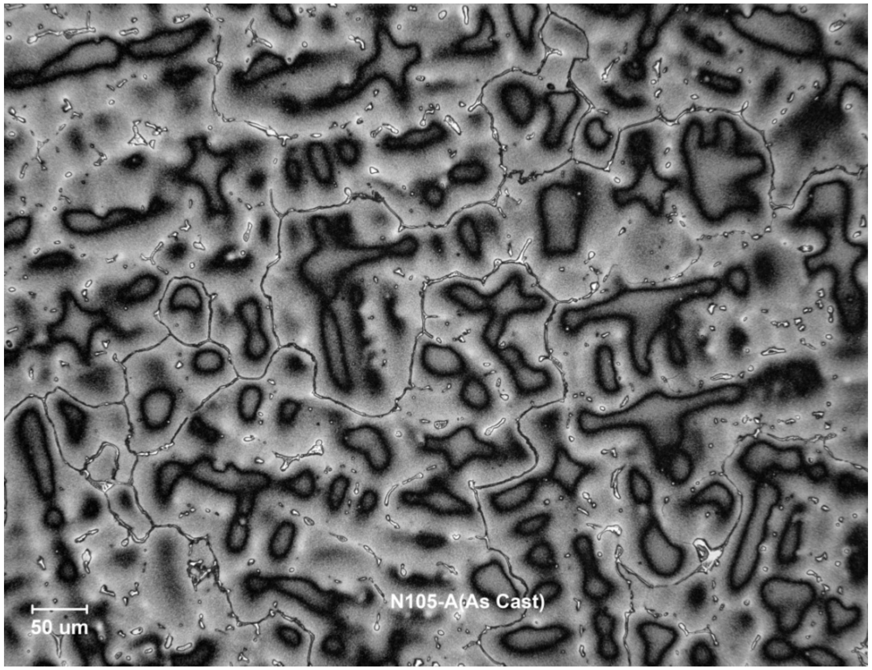
1100 °C/10,000s+1200 °C/remaining time

Patent Pending

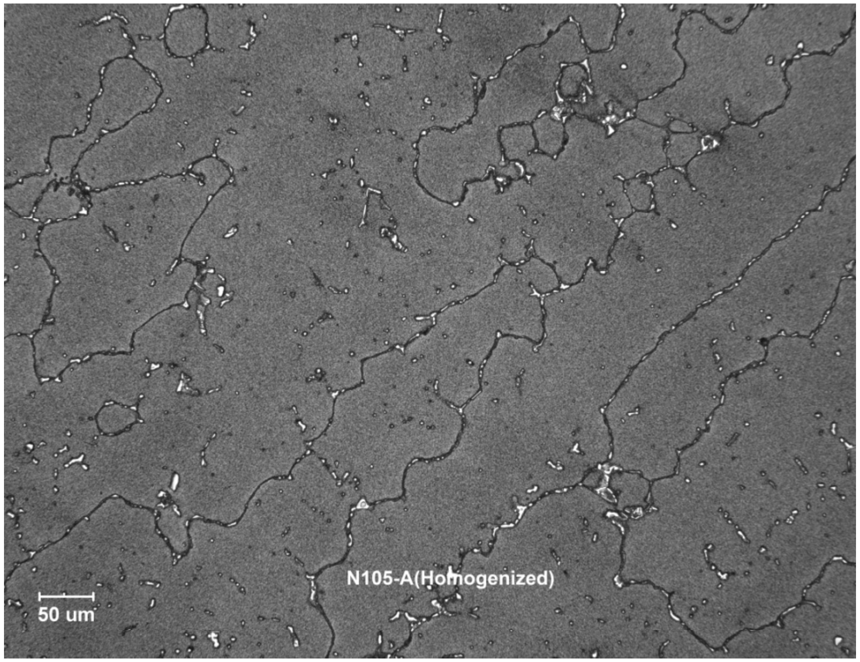
Metall. Trans. B, ***40B****, (2009) 182.*

Nimonic 105

Qualitative Confirmation of the Effectiveness of the Homogenization Heat Treatment

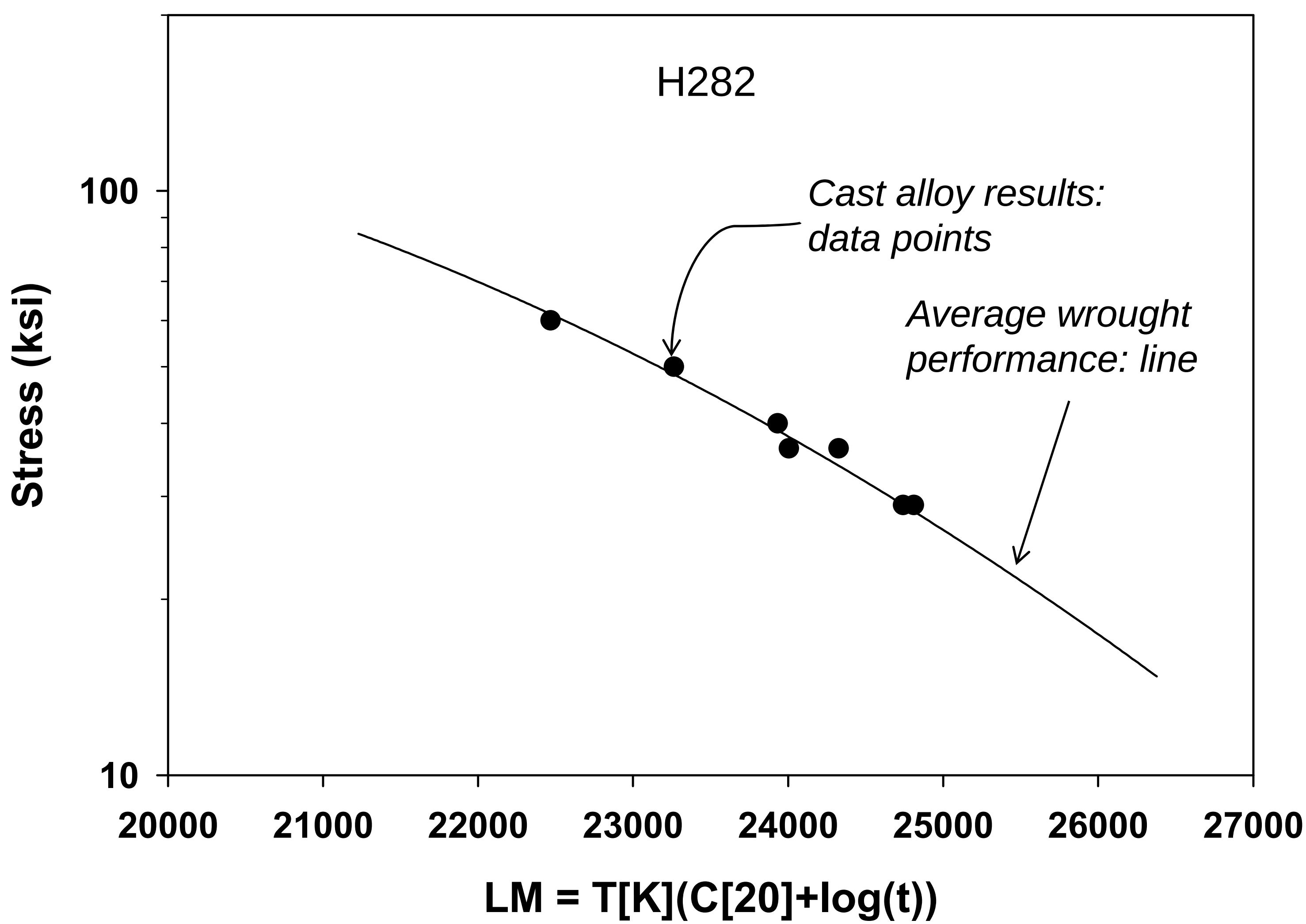


As-Cast

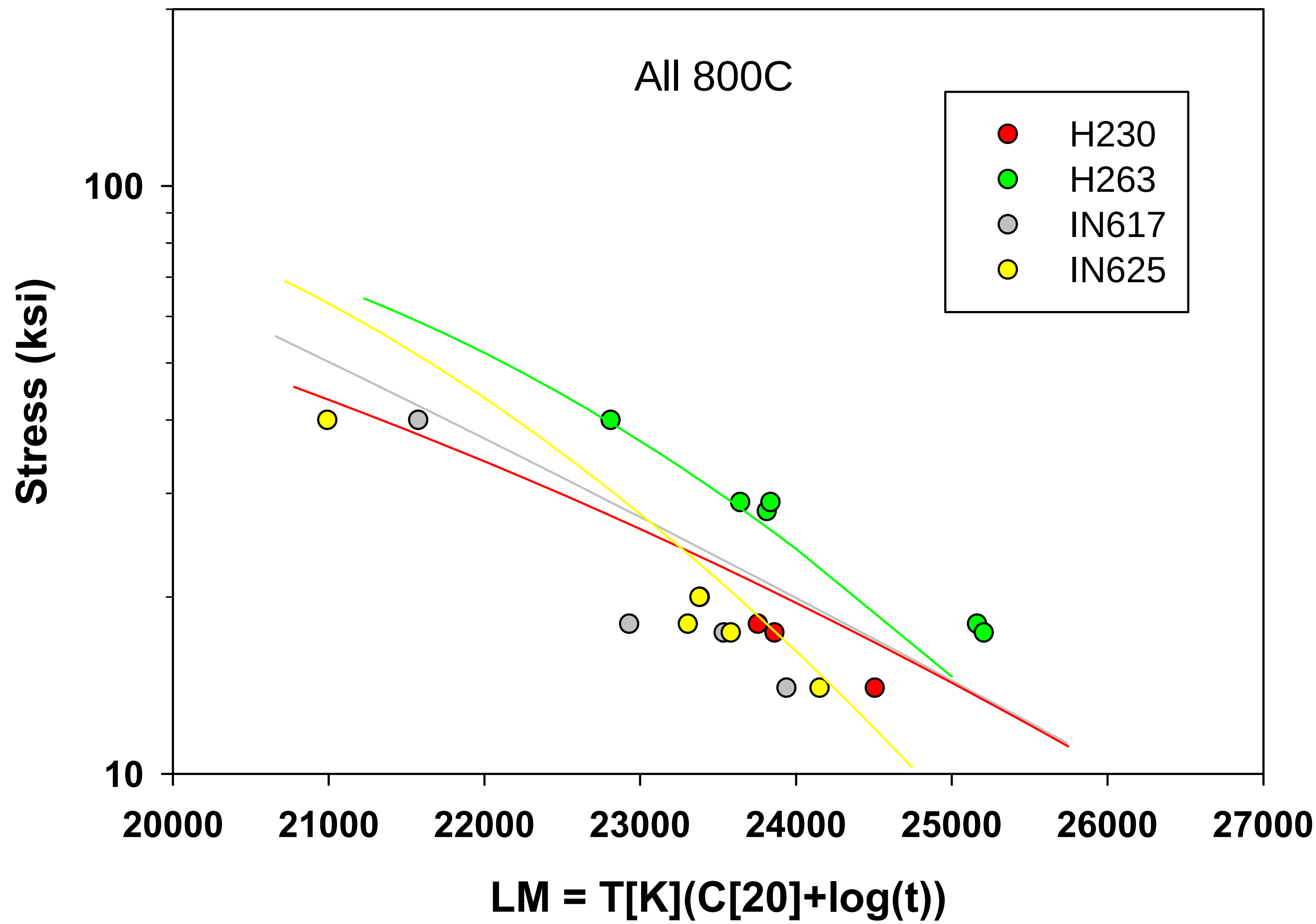


Homogenized

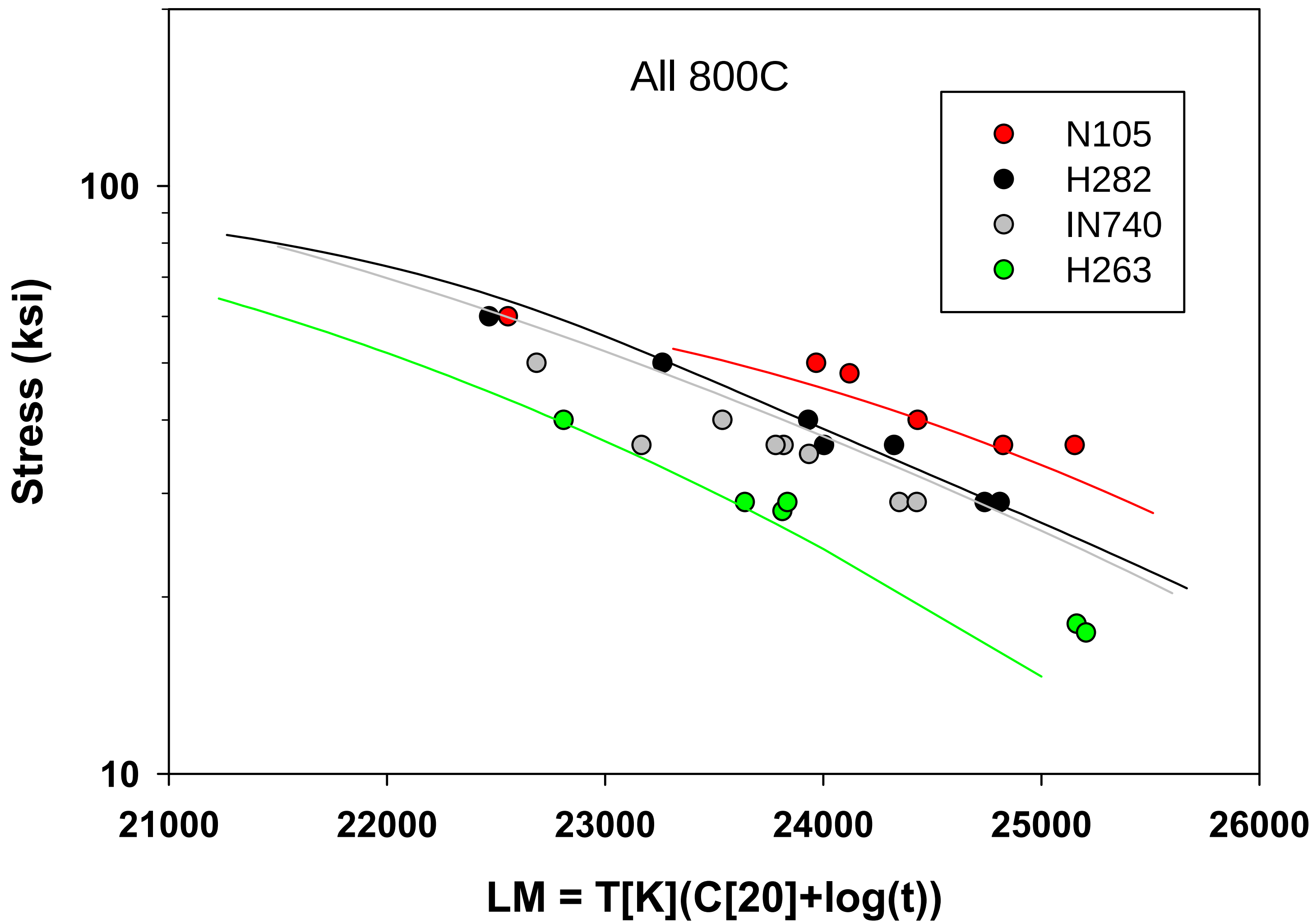
800 °C Creep Results



Solid Solution Alloys



Gamma Prime Formers



Alloys Under Consideration for Steam Oxidation Resistance

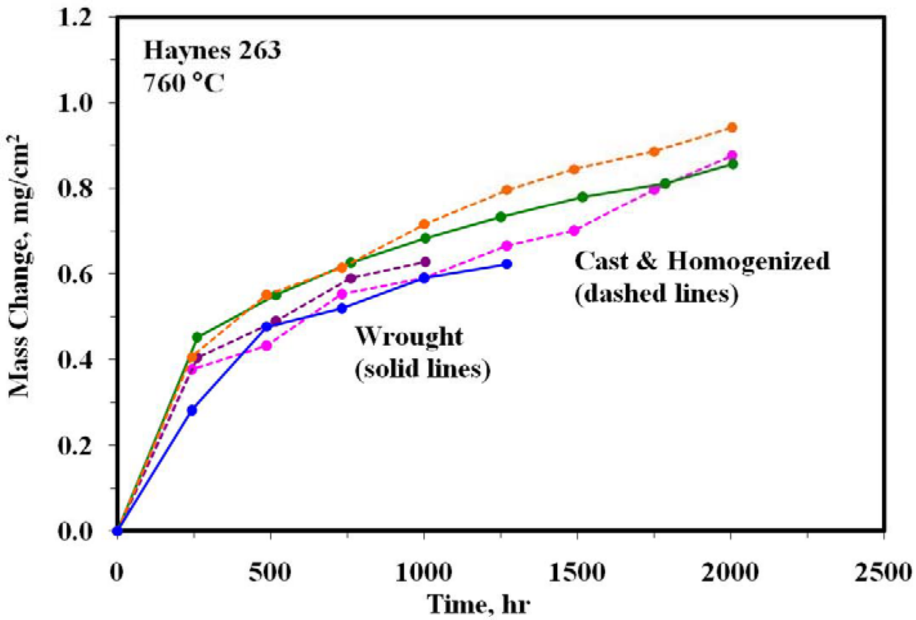
Solid Solution	Age Hardenable
H230	N105
IN617	H263
IN625	H282
	IN740

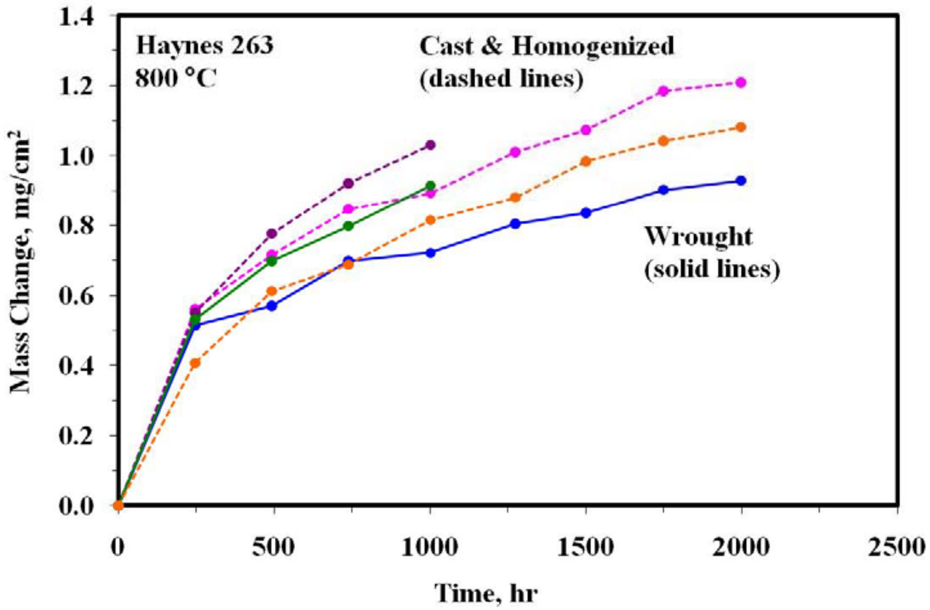
Isothermal tests in deaerated steam

760 and 800 °C

250 hour cycles for 1000 and 2000 total hours

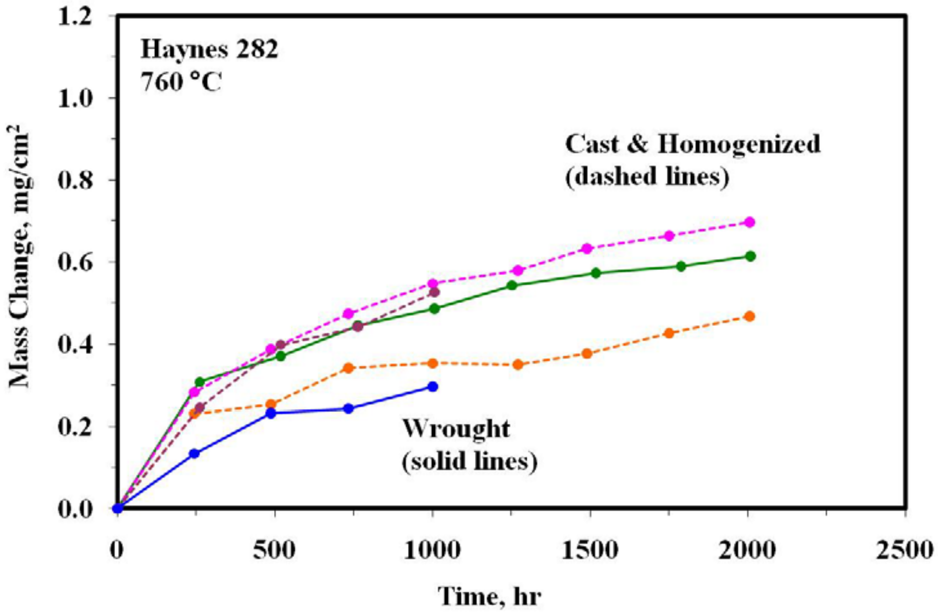
Oxidation Results H263

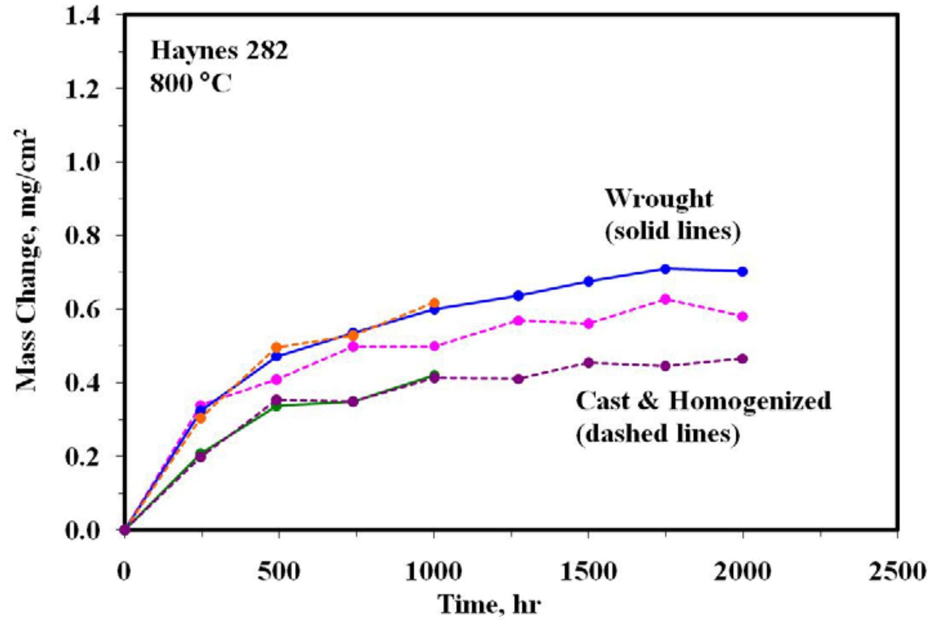




No significant differences between cast & homogenized and wrought

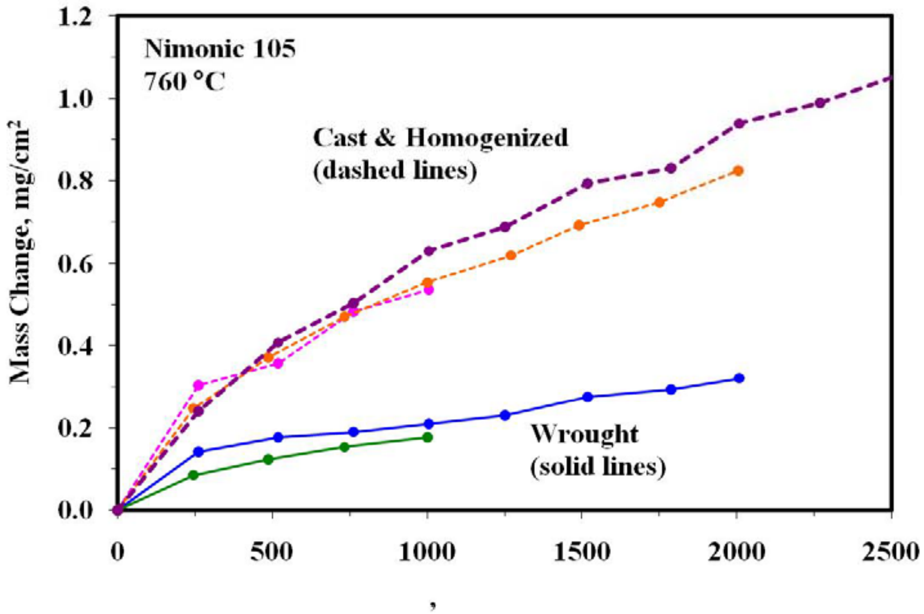
Oxidation Results H282

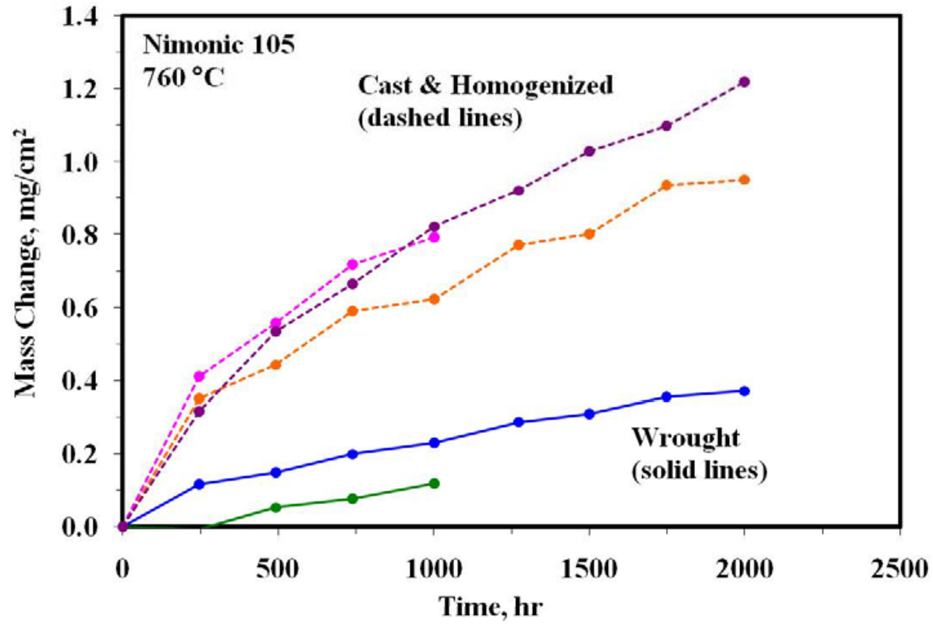




No significant differences between cast & homogenized and wrought

Oxidation Results N105





Significant differences between cast & homogenized and wrought

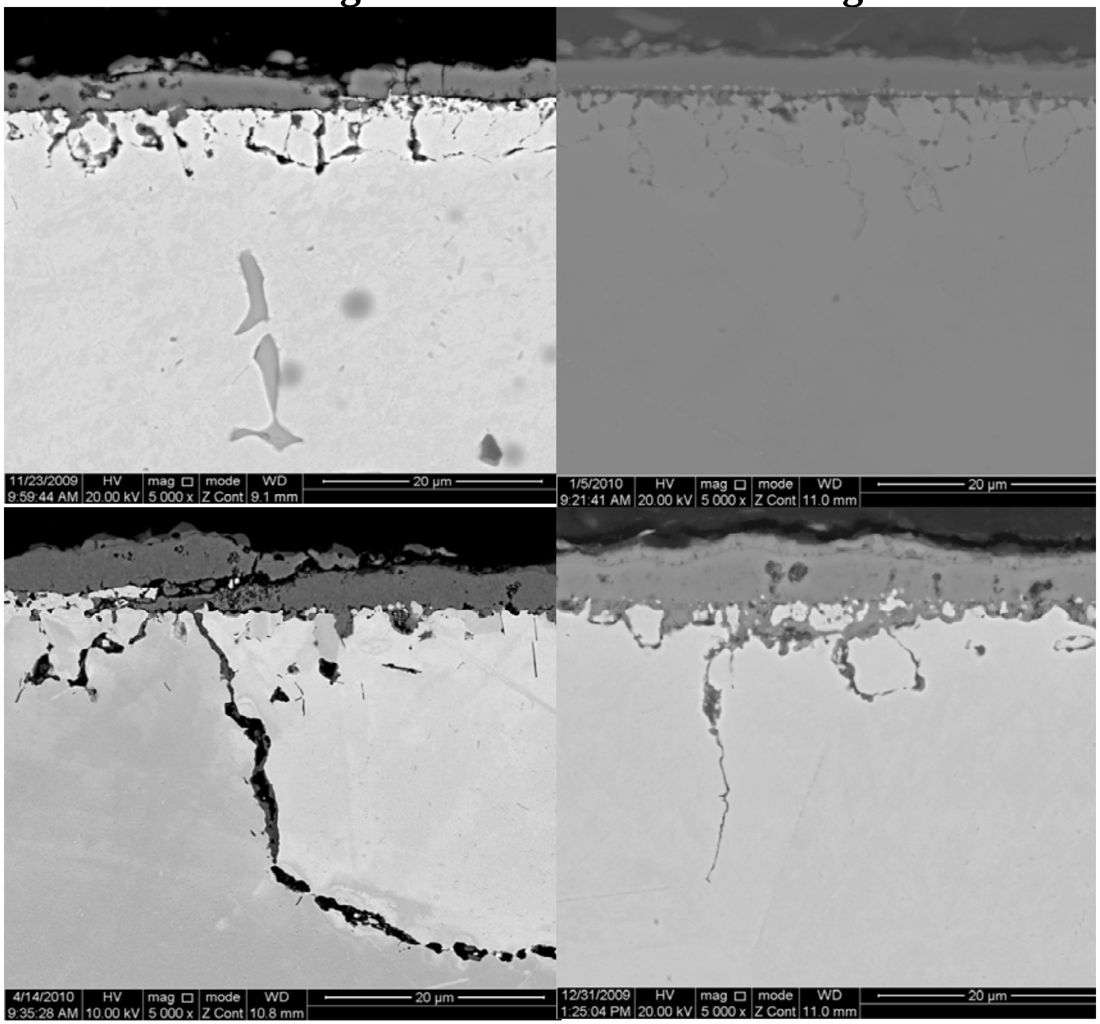
Wrought versions show much less mass gain with time

Exposure in Steam for 1000 hr—H263

Cast and Homogenized | Wrought

760 °C

800 °C



External chromia scales

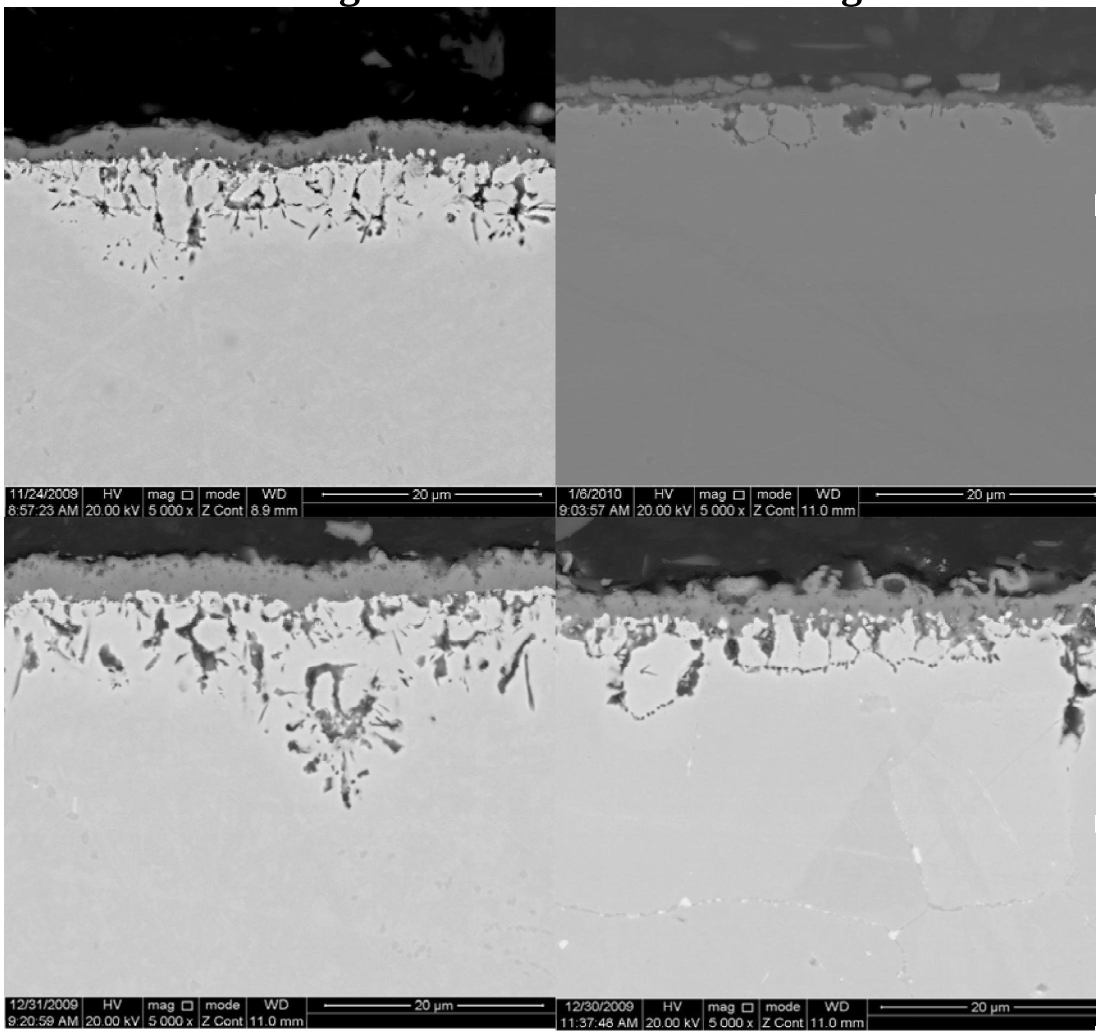
Internal oxidation of Ti and Al was more pronounced in the C&H alloys

Exposure in Steam for 1000 hr—H282

Cast and Homogenized | Wrought

760 °C

800 °C



Over much the same as in H263

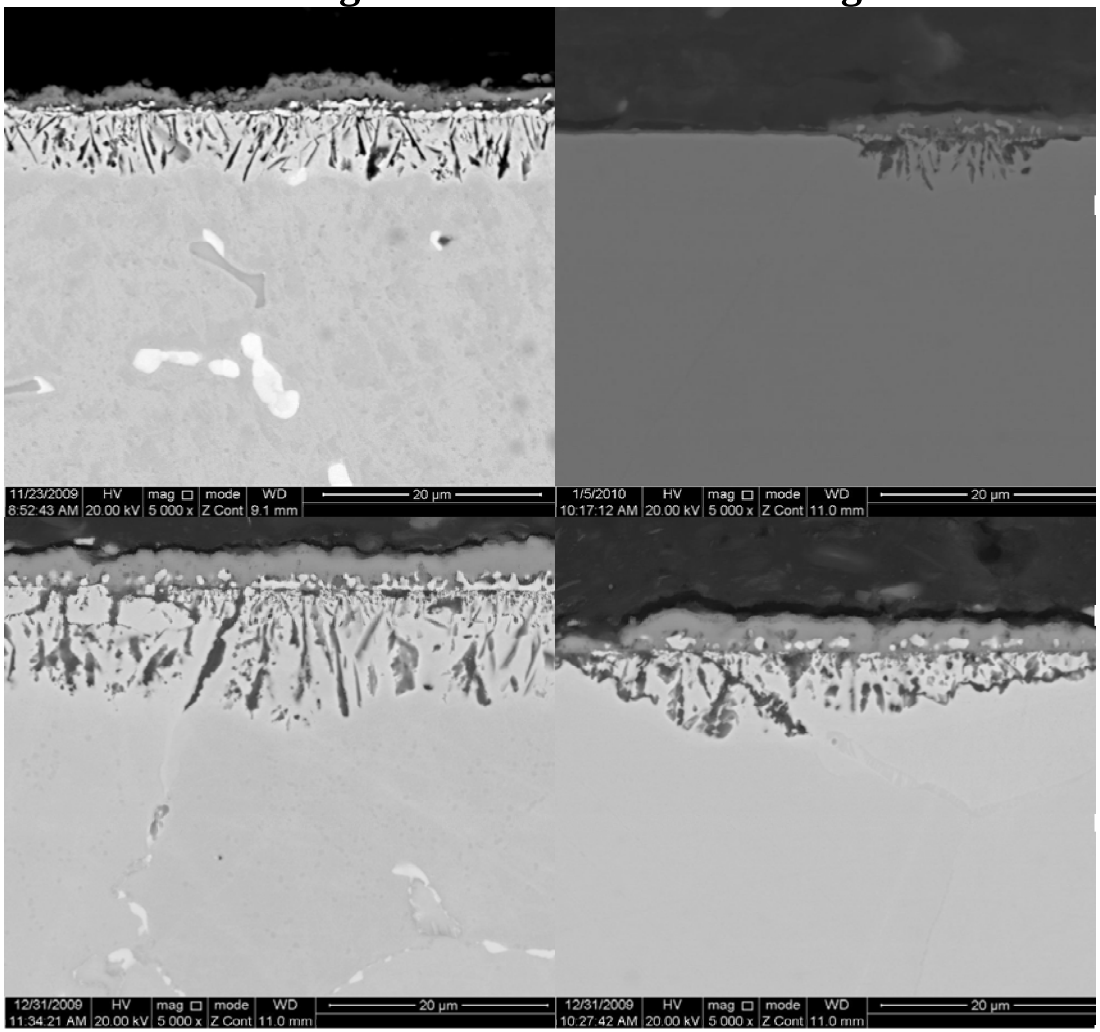
External chromia scales

Internal oxidation of Ti and Al was more pronounced in the C&H alloys

Exposure in Steam for 1000 hr—N105

Cast and Homogenized | **Wrought**

760 °C / **800 °C**



Two types of structures were found

- *One with a chromia external scale and internal oxidation of Al and Ti*
- *One with a very thin alumina external scale—found on sections of the wrought alloys at both temperatures*

Alumina scales are much more protective

Scaling Behavior

External Scale and Internal Oxidation Behavior, 760 °C

Alloy		T hr	External Scale Thickness µm	External Scale std %	Internal Oxidation Thickness µm	Internal Oxidation std %	Internal Oxidation Maximum µm
Haynes 263	Cast	1000	2.81 + 0.63	22%	4.70 + 4.08	87%	28.20
		2000	3.34 ± 0.97	29%	9.79 ± 5.35	55%	42.62
	Wrought	1000	2.79 ± 0.37	13%	7.11 ± 3.49	49%	16.44
		2000	4.36 ± 0.64	15%	5.18 ± 2.68	52%	23.94
Haynes 282	Cast	1000	2.54 ± 0.43	17%	6.92 ± 3.73	54%	34.22
		2000	4.53 ± 1.36	30%	6.26 ± 4.73	76%	38.00
	Wrought	1000	1.13 ± 0.35	30%	1.81 ± 1.07	59%	10.21
		2000	3.00 ± 0.55	18%	5.09 ± 2.20	43%	25.13
Nimonic 105	Cast	1000	1.52 ± 0.50	33%	5.95 ± 0.69	12%	9.90
		2000	2.86 ± 0.81	28%	10.09 ± 1.90	19%	17.58
	Wrought	1000	0.39 ± 0.47	119%	0.60 ± 1.22	201%	9.25
		2000	0.98 ± 0.86	89%	2.46 ± 2.75	112%	14.86

H263 & H282—External scaling similar between C&H and Wrought
H263 & H282—Internal scaling more pronounced in C&H
N105 Wrought clearly shows partial alumina coverage
Alumina coverage shrinking with time as shown by scaling kinetics

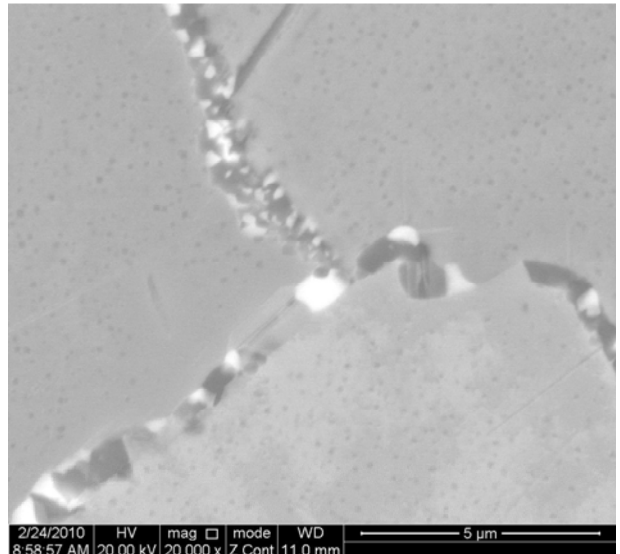
Microstructure after 1000 hr at 800 °C—H263

Light precipitates are Mo-rich carbides

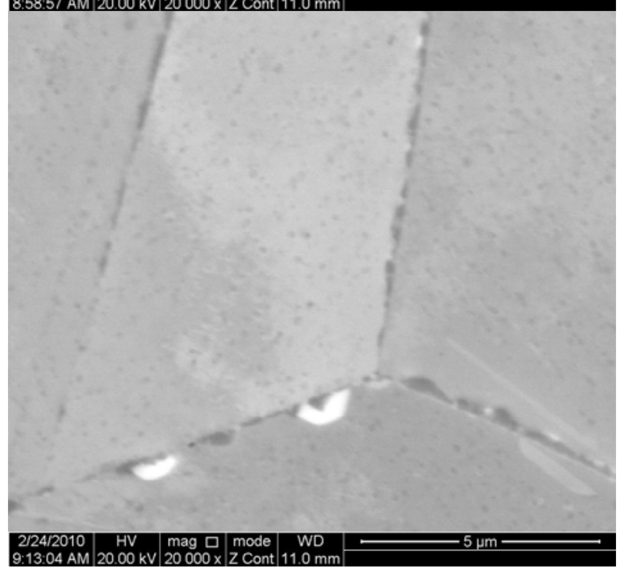
Dark precipitates are Cr-rich carbides

More gb precipitate coverage in C&H alloy

Cast and Homogenized



Wrought



Microstructure after 1000 hr at 800 °C—H282

Light precipitates are Mo-rich carbides

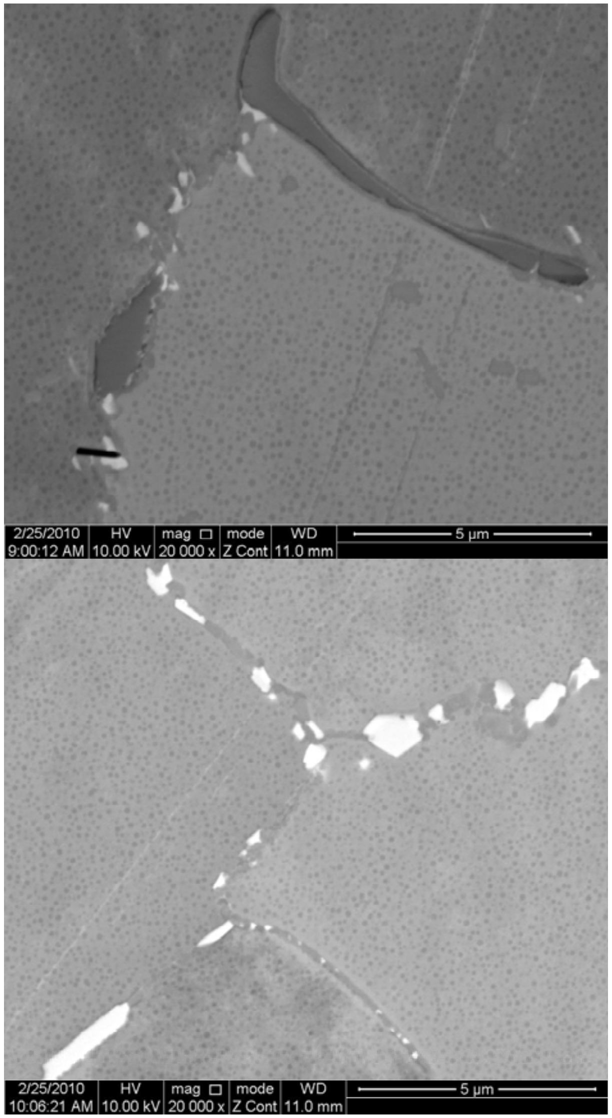
Large dark precipitates are Ti-rich carbides

Smaller dark precipitates are Cr-rich carbides

More gb precipitate coverage in C&H alloy

Cast and Homogenized

Wrought



Microstructure after 1000 hr at 800 °C—N105

Light precipitates are Mo-rich carbides

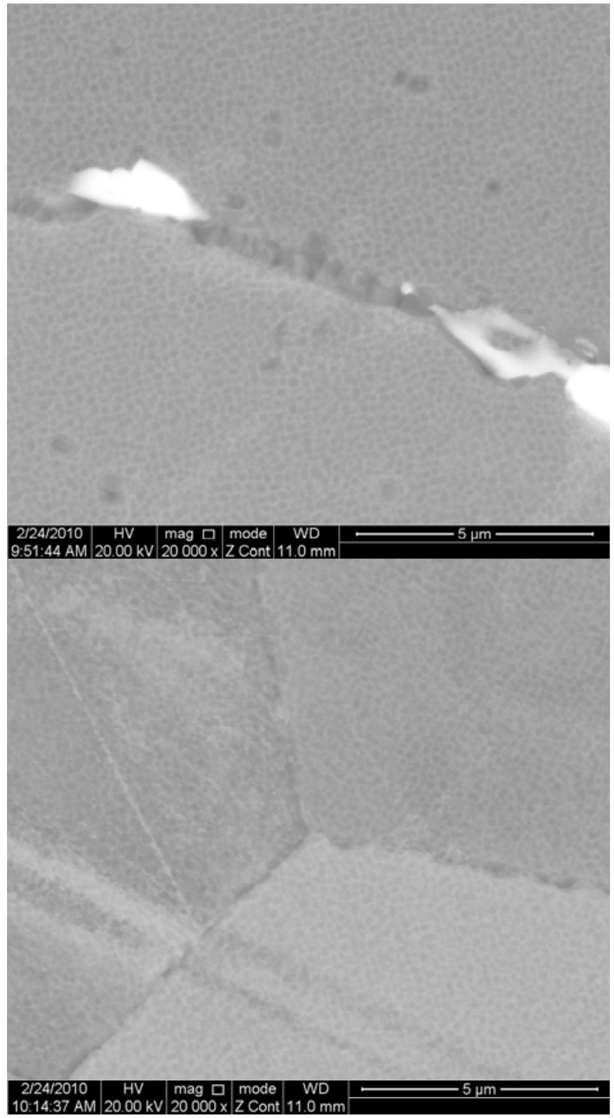
Dark precipitates are Ti and Cr-rich carbides in C&H alloy

Dark precipitates are Cr-rich carbides in wrought alloy

More gb precipitate coverage in C&H alloy

Cast and Homogenized

Wrought



Summary I

The development of high creep strength and steam oxidation resistant cast alloys for use in A-USC steam turbines is required to meet the need of some of the large components that comprise the turbine

A computationally optimized homogenization heat treatment was developed to improve the performance of these materials

Haynes 263, Haynes 282, and Nimonic 105, were selected based on good cast-alloy creep resistance for further examination in terms of steam oxidation resistance

Summary II

Haynes 263 and Haynes 282

- External chromia scale (both the C&H alloys and the wrought alloys)
- Internal oxidation of Al and Ti (both the C&H alloys and the wrought alloys)
- The overall mass gain and parabolic kinetics were similar
- The depth of internal oxidation was greater in the C&H alloys
- More Mo-rich and Cr-rich carbides were found along the grain boundaries of the C&H alloys
- Ti-rich carbides were found along grain boundaries of the C&H Haynes 282 alloys

Nimonic 105

- Wrought alloys exhibited lower oxidation kinetics than the C&H alloys
- Some of the surface of the wrought alloys was covered by a very protective alumina scale
- Where alumina was not present, a chromia scale was present with internal oxidation of Al and Ti
- The fraction of the surface protected by the alumina scale decreased with time
- C&H grain boundaries contained Mo-rich carbides, Ti-rich carbides, and Cr-rich carbides
- Only Cr-rich carbides on the wrought Nimonic 105 grain boundaries