Strengthening Concepts, Microstructural Control & Failure Mechanisms in Steam for Ni-Base Alloys in A-USC Boilers & Steam Turbines

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NETL Advanced USC Materials Research

- “Addressing Materials Processing Issues in Components for Advanced Power Generation” – Paul Jablonski
- “Materials Performance in USC Steam” – Gordon Holcomb
- “New High Temperature Fe-Based Alloys” – Chris Cowen
- “Materials Life Assessment in Existing Power Plants” – Jeff Hawk

NETL Advanced USC Research Team

- Paul Jablonski
  - Alloy design, melting, casting, thermo-mechanical processing, and heat treatment for microstructure & properties

- Gordon Holcomb
  - Material-environmental interactions to include fireside corrosion, oxidation, & hot corrosion

- Chris Cowen
  - Alloy design, thermo-mechanical processing, and heat treatment for microstructure & properties, and structure-property relationships

- Jeff Hawk
  - Structure-property relationships, non-traditional mechanical testing and life prediction

Worldwide Drivers for a Higher Efficiency (USC) Plant

- National energy security
- Economic & abundant coal supply
- Lower fuel costs
- Significant environmental benefits
  - *Fewer emissions of all gases per MWh*
  - *Less coal mined, transported & fired/gasified*
  - *Less solid waste for disposal*
  - *Less water used for cooling*

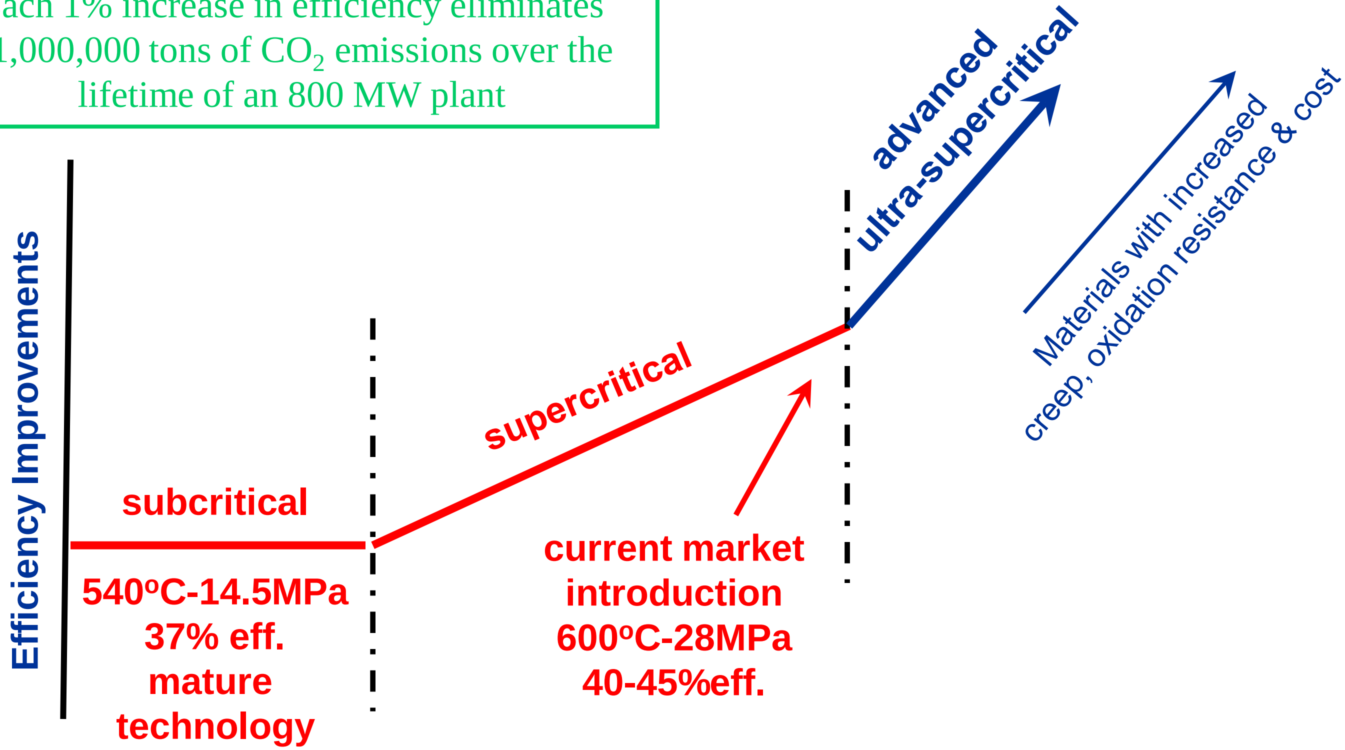
Higher efficiency is limited by materials technology!

"Materials for Advanced Ultrasupercritical (A-USC) Steam Boilers & Turbines," R. Viswanathan et al., 2nd International ECCC Conference on Creep & Fracture in High Temperature Components-Design & Life Assessment, April 21-23, 2009, Dübendorf, Switzerland (2009).

Materials Performance in USC Steam

US-DOE Advanced Power System Goal-
60% efficiency from coal generation
Steam condition: 760°C; 35 MPa

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



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

The Problem

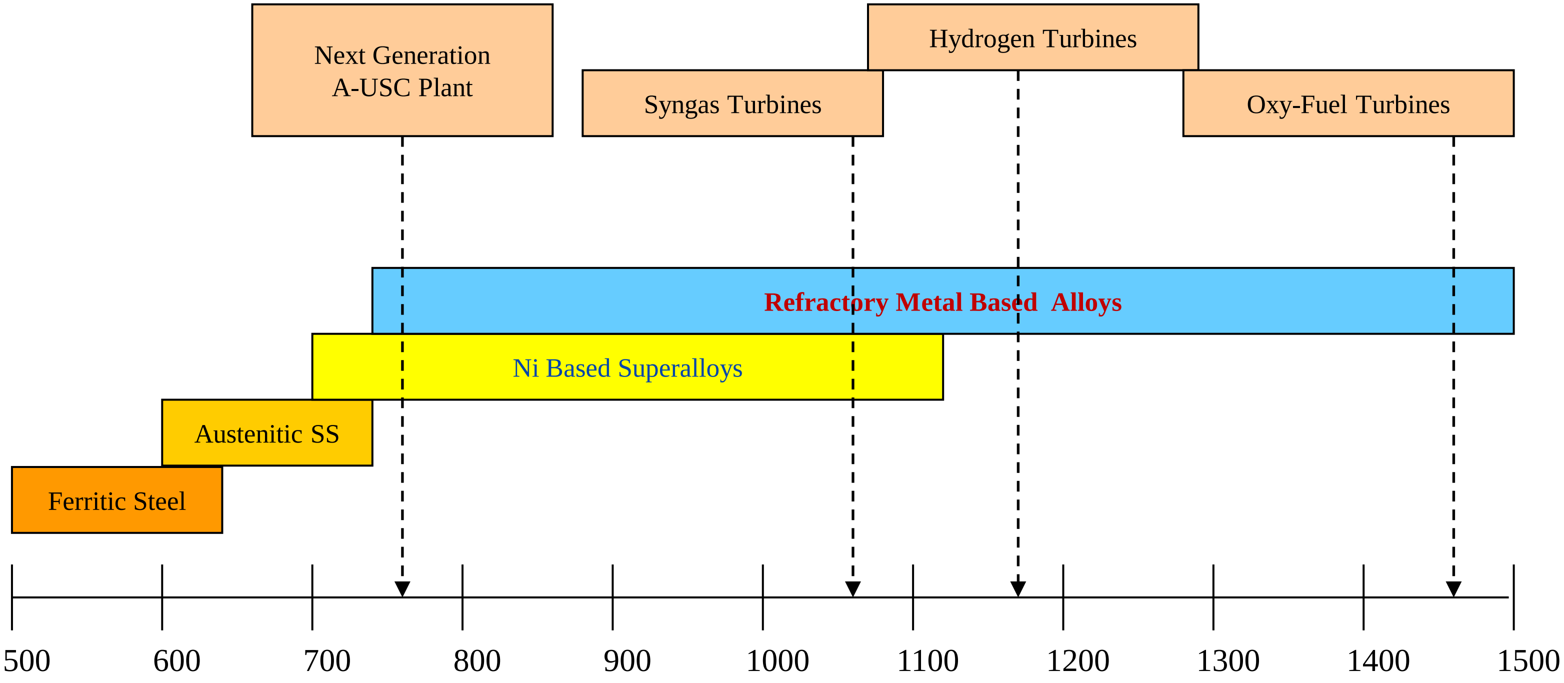
Consider the following:

- Typical power plant operating at 37% efficiency
- Apply Carbon Capture Storage (CCS) Technologies
  - Immediate plant efficiency reduction of 12% points (worst case scenario), leading to a new overall efficiency of 25%.
  - Consequently, at this new level, the power plant will produce 44% more CO_2 and consume 48% more coal to deliver the same amount of power as the original plant.

Not the best solution for reducing greenhouse gas emissions: However, by utilizing A-USC power plant technology, it is possible to raise efficiency >48%, which when combined with CCS technology can reduce the net increase in greenhouse gases relative to efficiency reductions.

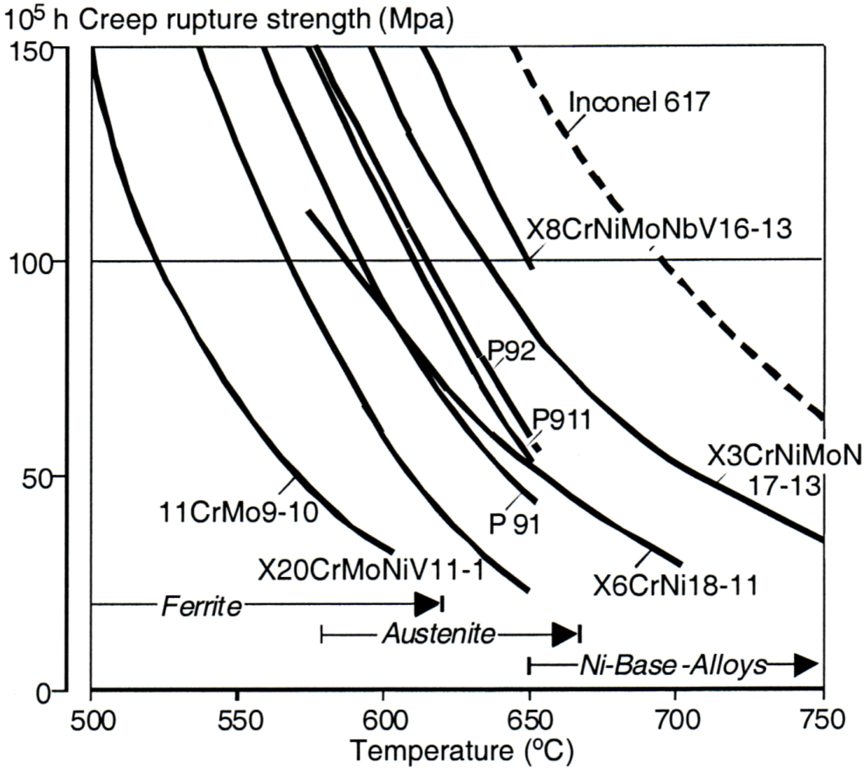
“Materials Aspects of a 700°C Power Plant,” L. Mäenpää et al., 3rd Symposium On Heat Resistant Steels and Alloys for High Efficiency USC Power Plants 2009, NIMS (2009).

New Energy Conversion Technologies & High-Temperature Structural Materials



Turbine blade substrate metal temperature (^oC) and temperature capability of structural materials.

Requirements for creep rupture strength with increasing pressure and temperature for A-USC main steam pipes.



"Creep Resistant Ferritic Steels for Power Plants," I. Von Hagen & W. Bendick, Proceedings of the International Symposium on Niobium 2001, Orlando, FL (2002), pp. 753-776.

Use of Ni-Base Alloys for A-USC Applications

Conventional Use

High Temperature
- *Jet Engine Gas Turbines*
- 900-1100°C
- Small Parts (< 10 kg)
- Oxidation Resistant

Low Temperature & Corrosion-Resistant
- *Chemical Equipment, Reactors*
- <500°C
- Large Parts
- Corrosion & Oxidation Resistant
- Weldable
- Long-term service without repair

Advanced-USC

Moderate Temperature, Large Size
- *Large pipes, turbine rotors, etc.*
- 700-800°C
- Large Parts (>5 tons)
- Corrosion & Oxidation Resistant
- Weldable
- Long-term service without repair
- Low thermal expansion

“Advanced USC Technology Development in Japan,” M. Fukuda, 3rd Symposium On Heat Resistant Steels and Alloys for High Efficiency USC Power Plants 2009, NIMS (2009).

Summary of Material Requirements for A-USC Power Plant Boilers

Properties		Material Requirements & Evaluation
High Temperature Strength	Creep	Creep strength at base metal & weldment.
	Thermal Fatigue	For large diameter & heavy wall thickness piping under non-steady thermal start-up & cool-down cycles.
	Creep Fatigue	For piping, thermal expansion at start, steady-state & stop. Creep fatigue interaction & its life assessment - plant design.
Corrosion Resistance	Hot Corrosion	Fire side corrosion for superheater tubing.
	Steam Oxidation	Scale thickness & exfoliation behavior of steam oxidation at inner surface of tubing & piping.
Weldability		Cracking such as solidification cracks, liquefaction, low ductility cracks & HAZ.
Workability		Hot bending.
Repair		Weldability of the aged tubing.
Inspection & QA		Applicability of inspection testing.
Cost Competitiveness		Materials cost & additional cost for working.

"Advances in Materials Technology for A-USC Power Plant Boilers," M. Igarashi et al., 3rd Symposium On Heat Resistant Steels and Alloys for High Efficiency USC Power Plants 2009, NIMS (2009).

Worldwide Advanced-USC ST Initiatives

European AD 700 Program to achieve Power Plant operating at approximately 700°C

Japanese “Cool Earth” initiative to achieve Power Plant operating at a range of temperatures up to 700°C

US NETL-DOE sponsored 1400°F Boiler and Steam Turbine Program to achieve a Power Plant operating at 760°C

AD700/Thermie – 700 C & 35 MPa Boiler & Steam Turbine

1. Feasibility study (1998-2004) consisting of:
    a. Process & design studies
    b. Materials development/selection, qualification & demonstration
2. Fabricability of materials & planning of next phase (2002-2006)
3. Components demonstration (2004-2009)
4. Construction of full-scale demonstration plant (2006 pre-engineering study was started)
5. 2015 target time frame for final design of a 700°C power plant

"The 700°C Steam Turbine Power Plant-Status, Development and Outlook," H. Edelmann et al., Int. J. Energy Technology and Policy, Vol. 5, No. 3, (2007) pp. 366-383.

AD700/Thermie – 700 C & 35 MPa Boiler & Steam Turbine (cont.)

Targets for boiler materials with respect to mechanical strength:

a. Martensitic alloys: 100 MPa @ 650 C for 10^5 h

b. Austenitic alloys: 100 MPa @ 700 C for 10^5 h

c. Nickel-base alloys: 100 MPa @ 750 C for 10^5 h

Targets were met for austenitic and nickel-base alloys.

“Materials for Advanced Power Engineering 2006,” R. Blum and R.W. Vanstone, Proceedings of the 8th Liege Conference, (2006) p. 41.

AD700/Thermie – 700 C & 35 MPa Boiler & Steam Turbine (cont.)

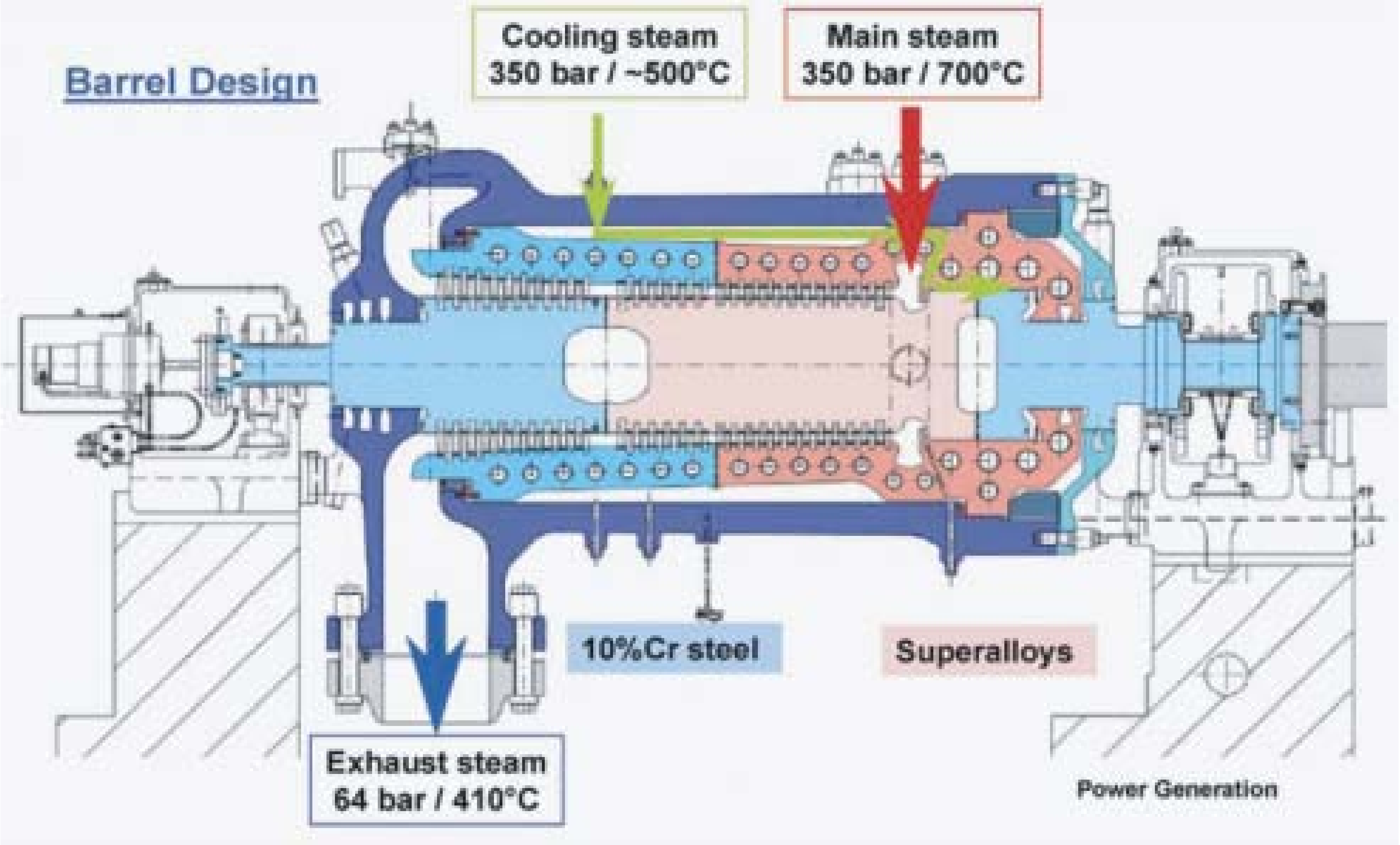
Selection of Candidate Alloys Influenced by:

1. Requirement to produce very large components
    a. Large forgings, e.g., Alloys 617, 625, 706 & 718
    b. Large castings, e.g., Alloys 617 & 625
2. Selection based on existing literature/manufacturer data for use at *100 MPa @ 750 C for* 10^5 *h*.

Nine alloys selected for preliminary investigation:

155, 230, 263, 617, 625, 706, 718, 901 and Waspaloy

"Materials for Advanced Power Engineering 2006," R. Blum & R.W. Vanstone, Proceedings of the 8th Liege Conference, (2006) p. 41.



Schematic of High Pressure (HP) Steam Turbine

"Siemens Steam Turbine Design for AD700 Power Plants," K. Wieghardt,
Power Generation 1 (2005).

AD700/Thermie – 700 C & 35 MPa Boiler & Steam Turbine (cont.)

- AD700/Thermie have <u>shown very good potential</u> for >700 C power plant technology.
- COMTES have shown utility of alloys operating at 700 C and also problems associated with their use.
- Material supply problems have been identified, mainly for very large forgings and also large nickel castings.

What next? What is needed in terms of materials and properties to go beyond 700 C?

"Materials for Advanced Power Engineering 2006," R. Blum and R.W. Vanstone, Proceedings of the 8th Liege Conference, (2006) p. 41.

'Cool Earth' Innovative Energy Technology Program: Japan

- Initiated in March 2008 to promote international cooperation and contribute to substantial global greenhouse gas emission reduction.
- Advanced Ultra Super Critical (A-USC) pressure power generation.

  Commercialize 700°C pulverized coal (PC) power system:

  - with 46% power generation efficiency by 2015
  - with 48% power generation efficiency by 2020

"Advanced USC Technology Development in Japan," M. Fukuda, 3rd Symposium On Heat Resistant Steels and Alloys for High Efficiency USC Power Plants 2009, NIMS (2009).

Possible *‘Cool Earth’* A-USC Turbine Systems

		Case 1	Case 2	Case 3
Steam Temperature				
Main	°C	600	630	700
Reheat	°C	600	700	700
Steam Pressure				
Main	MPa	25	25	25
Reheat	MPa	5	5.5	5.5
Thermal Efficiency		Base	1.03	1.047
Material (Typical)				
HPT		10Cr	10Cr	Ni
IPT		10Cr	10Cr, 25Cr	10Cr, 25Cr
Valve		10Cr	10Cr, Ni	Ni
Development Period		Done	Short	Long
Development Cost		Base	Low	High
Operability		Base	Same	Low

“Materials and Design for Advanced High Temperature Steam Turbines,” M. Fukuda et al., 3rd Symposium On Heat Resistant Steels and Alloys for High Efficiency USC Power Plants 2009, NIMS (2009).

Possible *‘Cool Earth’* A-USC Turbine Systems

		Gas Turbine	IPT
Turbine Inlet Temperature	°C	1000-1300	700
Turbine Inlet Pressure	MPa	1.5-3.5	5
Rotor Temperature	°C	400-500	400-600
Casing Temperature	°C	200-400	400-600
Blade Material Temperature	°C	600-900	650
Nozzle Material Temperature	°C	600-900	700

Case 2: A possible route to develop a hybrid A-USC steam turbine. This would improve efficiency while allowing development time for Case 3.

“Materials and Design for Advanced High Temperature Steam Turbines,” M. Fukuda et al., 3rd Symposium On Heat Resistant Steels and Alloys for High Efficiency USC Power Plants 2009, NIMS (2009).

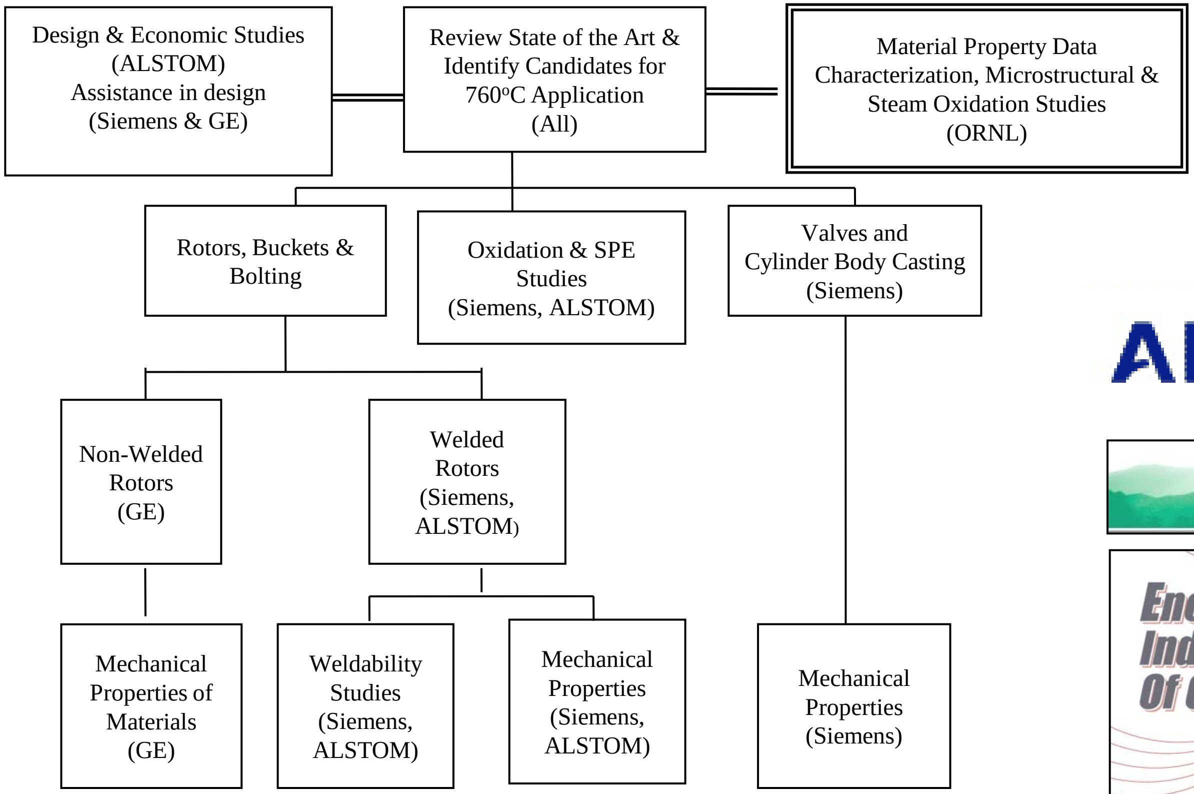
Turbine Rotor Candidate Alloys

Materials	Temperature Level	Weight	Development Target
Fenix-700	700°C	>10 ton	Ni-base material heavier than 10 tons without segregation
LTES	>700°C	30-40 ton ↑ Ni: 10 ton + Steel: 20-30 ton Welding	10 ton Ni-base material with good weldability to steel
TOS1X	>720°C		10 ton Ni-base material with good weldability to steel

"Advanced USC Technology Development in Japan," M. Fukuda, 3rd Symposium On Heat Resistant Steels and Alloys for High Efficiency USC Power Plants 2009, NIMS (2009).

NETL-DOE Sponsored A-USC Boiler & ST Program

Phase 1 ST Activities: 2006-2009



Design & Economic Studies (ALSTOM)
Assistance in design (Siemens & GE)

Review State of the Art & Identify Candidates for 760°C Application (All)

Material Property Data Characterization, Microstructural & Steam Oxidation Studies (ORNL)

Rotors, Buckets & Bolting

Oxidation & SPE Studies (Siemens, ALSTOM)

Valves and Cylinder Body Casting (Siemens)

Non-Welded Rotors (GE)

Welded Rotors (Siemens, ALSTOM)

Mechanical Properties of Materials (GE)

Weldability Studies (Siemens, ALSTOM)

Mechanical Properties (Siemens, ALSTOM)

Mechanical Properties (Siemens)

<u>Key Issues:</u>

- ➢Welded rotor materials
- ➢Non-welded rotor materials
- ➢Air casting
- ➢Erosion resistance
- ➢Oxidation resistance

NETL

ALSTOM

MAKING OHIO COAL
THE CLEAN CHOICE

OAK RIDGE NATIONAL LABORATORY

Energy Industries Of Ohio

EPRI
Electric Power Research Institute

imagination at work

SIEMENS

NETL-DOE 1400°F Boiler & Steam Turbine

- In order to increase efficiency even further, US consortium assembled to push boiler & steam turbine technology to 1400 F (760 C), and beyond. This would require precipitation strengthened nickel alloys.
- ST materials group looked at current alloys that could meet the following minimum strength requirements for a rotor disk segment:
  - > 400 MPa tensile yield strength at 760 C
  - > 100 MPa creep strength at >10^5 h at 760 C

Yield strength & creep capability are not quite good enough for AD700 rotor alloys at 760 C. The nickel alloys used at 760 C and above must be stronger and microstructurally stable (precipitate coarsening low) for times >10^5 hours.

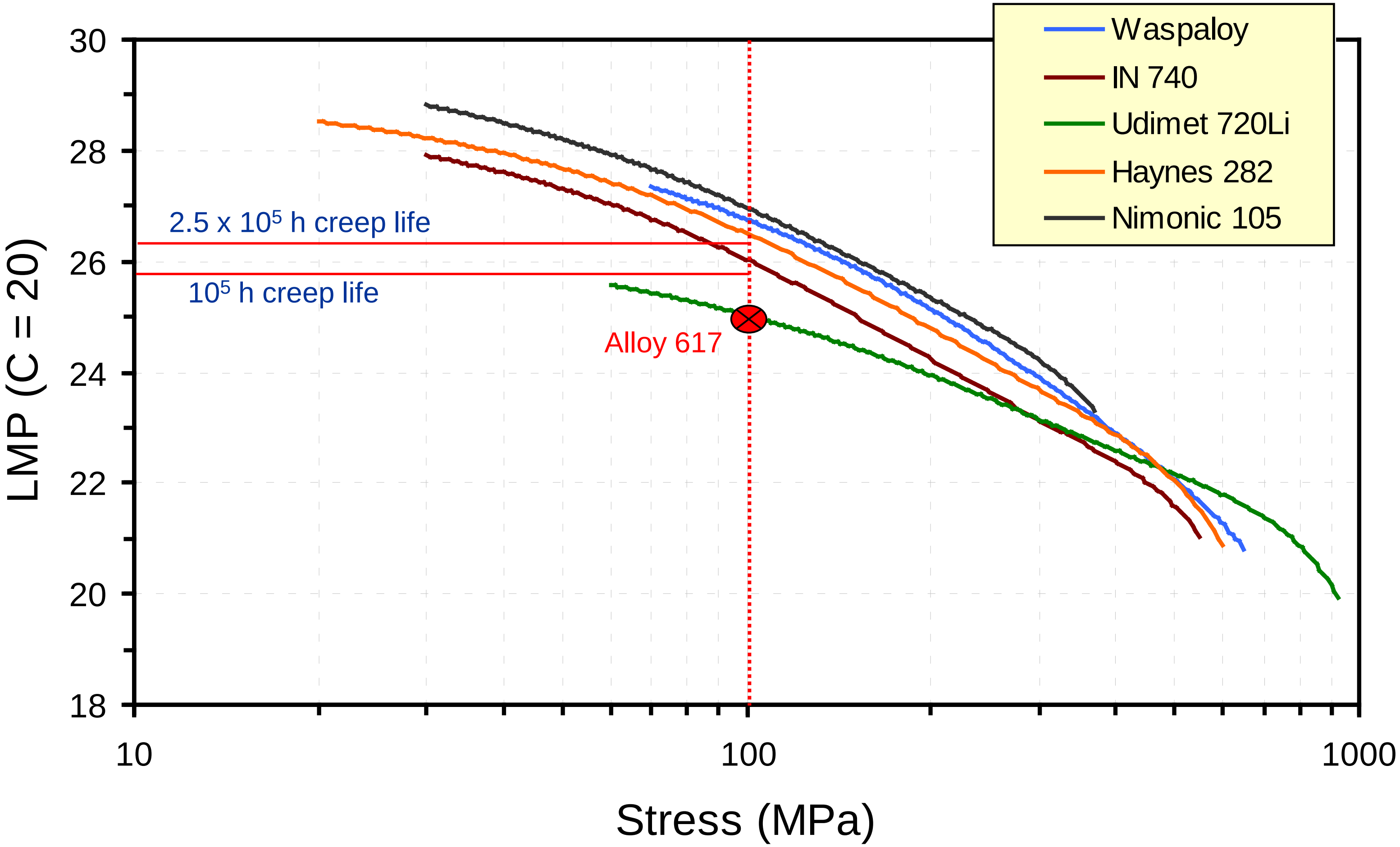
NETL-DOE 1400°F Boiler & Steam Turbine

Candidate Rotor Materials

- Nimonic®105
- Haynes®282 (H282)
- Udimet®720 (U720Li)
- Inconel®740 (IN740)
- Waspaloy

IN740 & Waspaloy were not studied due to availability of data from literature & prior studies.

NETL-DOE 1400°F Boiler & Steam Turbine



Strengthening Concepts, Microstructural Control & Failure Mechanisms in Steam for Ni-base Alloys in Advanced USC Boilers & Turbines

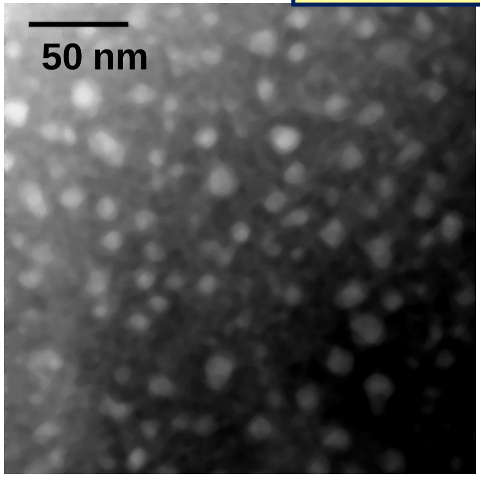
Goal A

- Optimize alloy compositions, TMP schedules and/or heat treatment conditions for Haynes 282 and Nimonic 105, and/or other relevant γ' strengthened nickel superalloys to insure, thermally stable microstructures, and to provide the best combination of tensile strength, creep resistance, and fatigue capability for large steam turbine and boiler components at temperatures ≥1400°F (760°C) in dry air and steam.

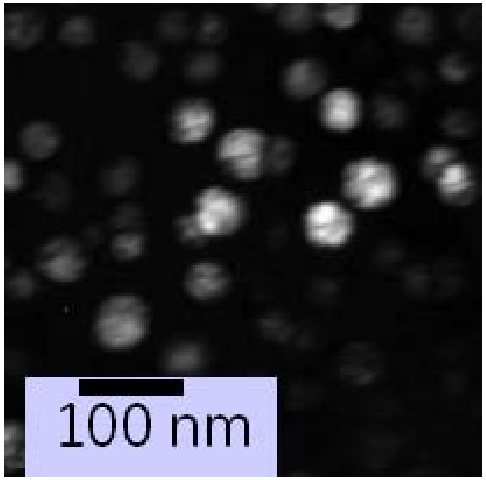
Tasks

- Characterize peak- and over-aged microstructures for Haynes 282 and Nimonic 105.
- Collate mechanical property data for creep, fatigue and creep-fatigue.

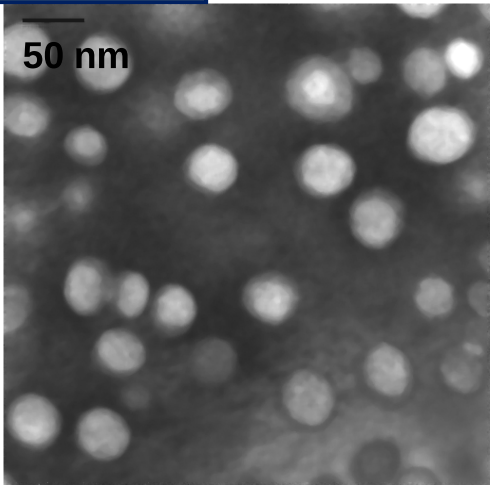
Different Heat-treatments of Haynes282



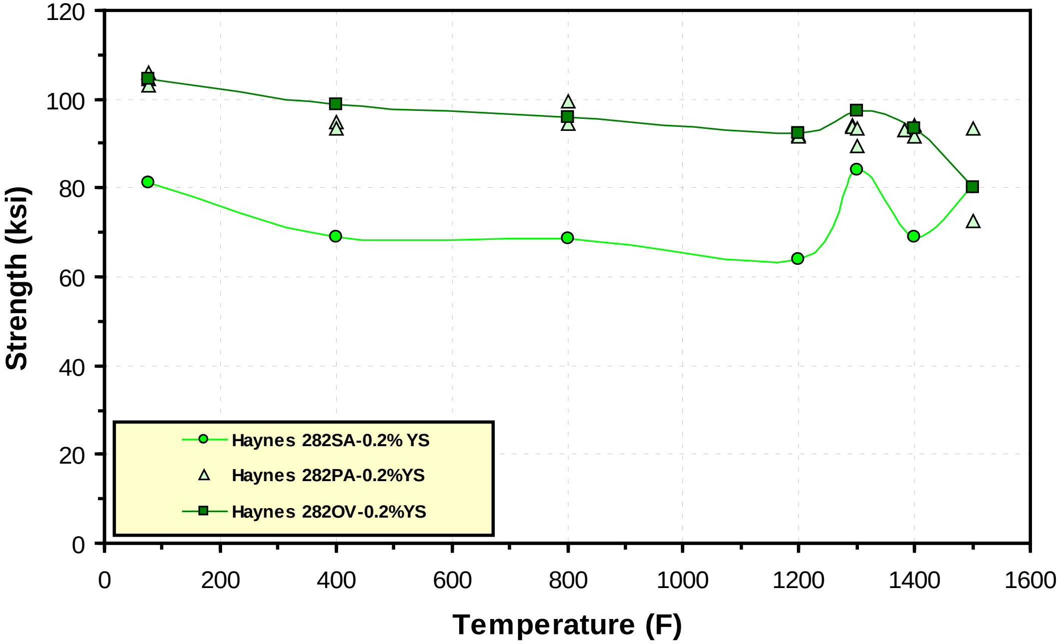
Solution Annealed



PA = SA + 8h @ 1450 F

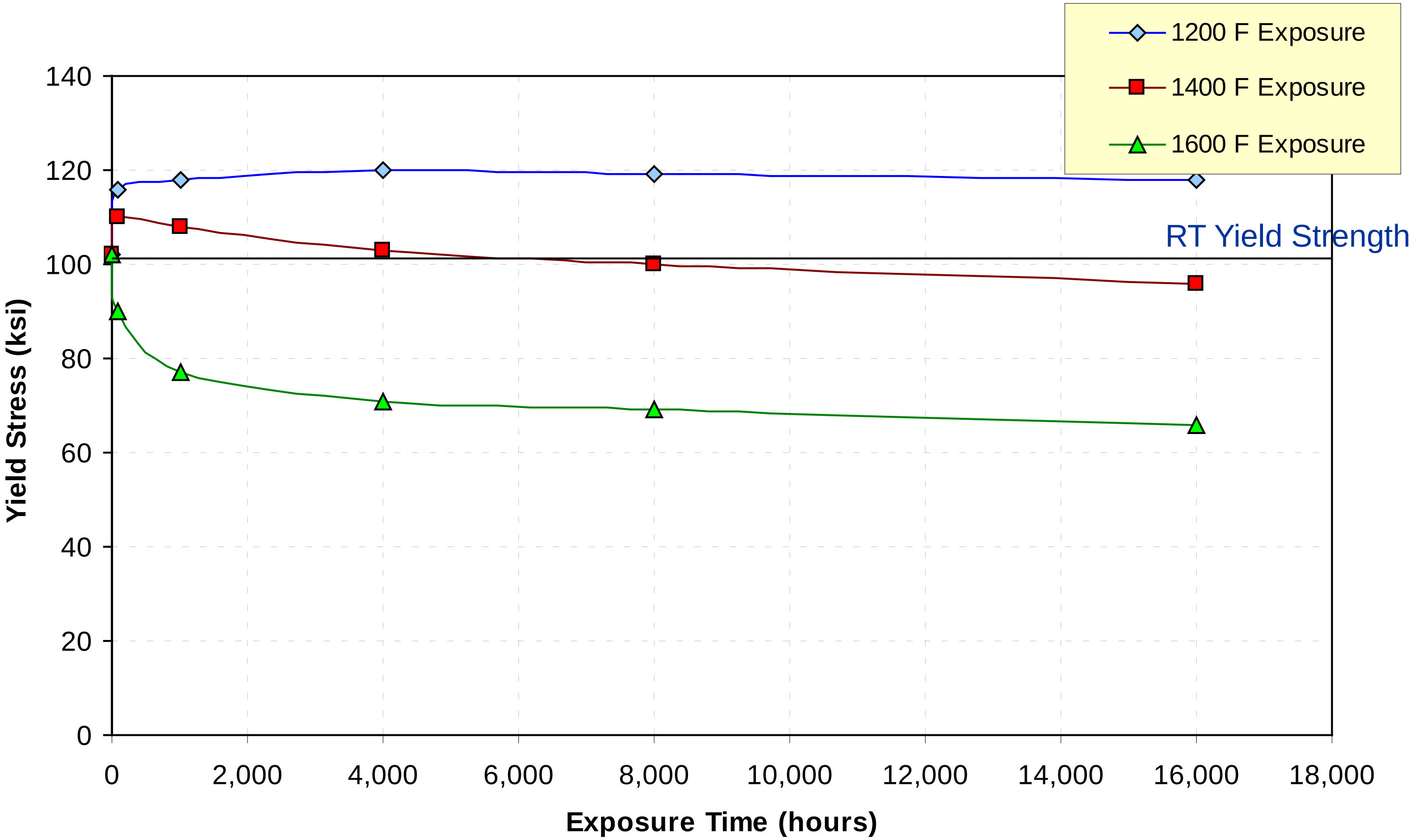


OV = PA + 250h @ 1425 F



Determine Long-Term Alloy Stability

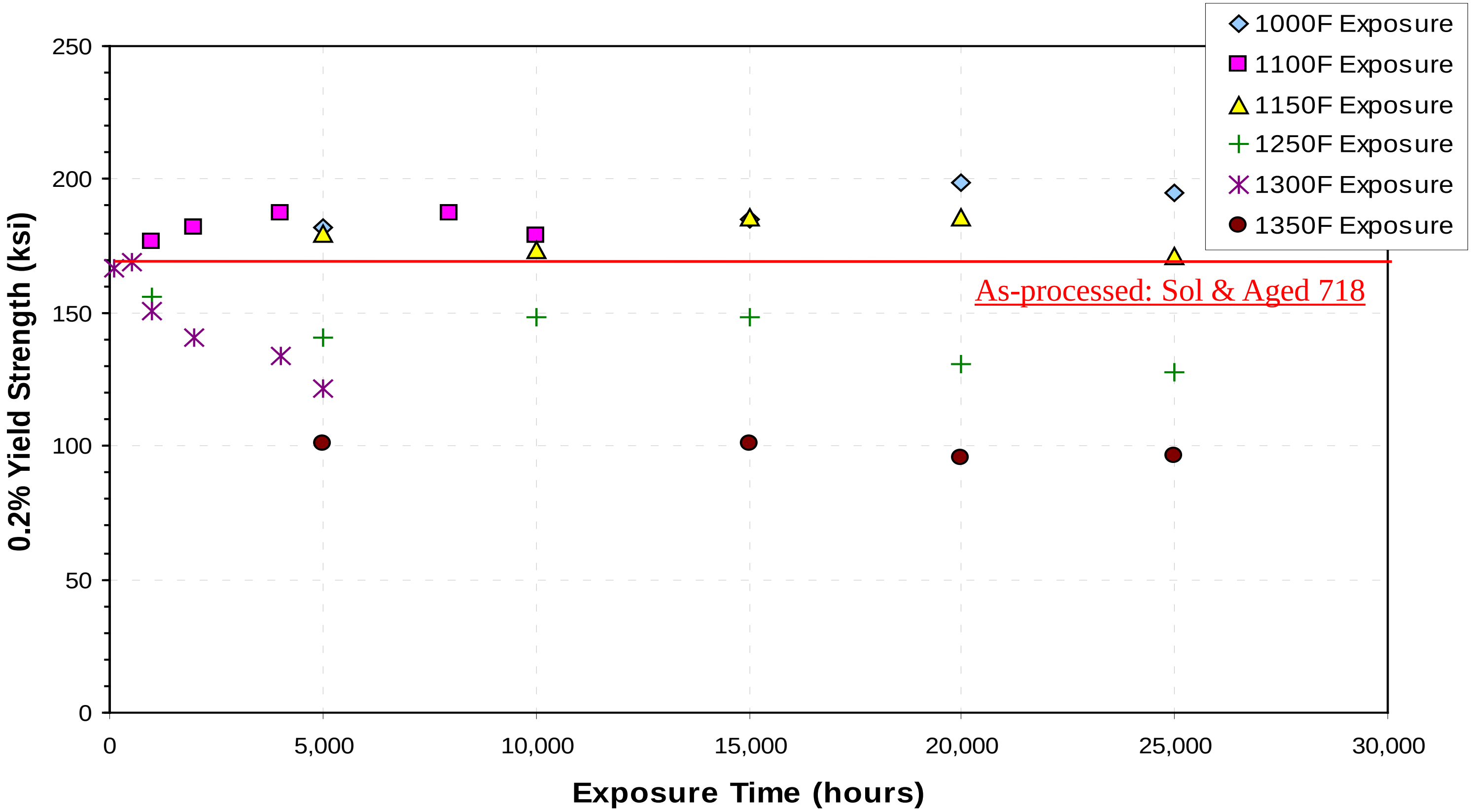
Haynes 282 – 0.2%YS at different temperatures for exposure up to 16,000 h.



For H282, the depression in 0.2% YS, for example, is shifted to higher temperatures. Longer term evaluation needed.

Long-Term Alloy Stability

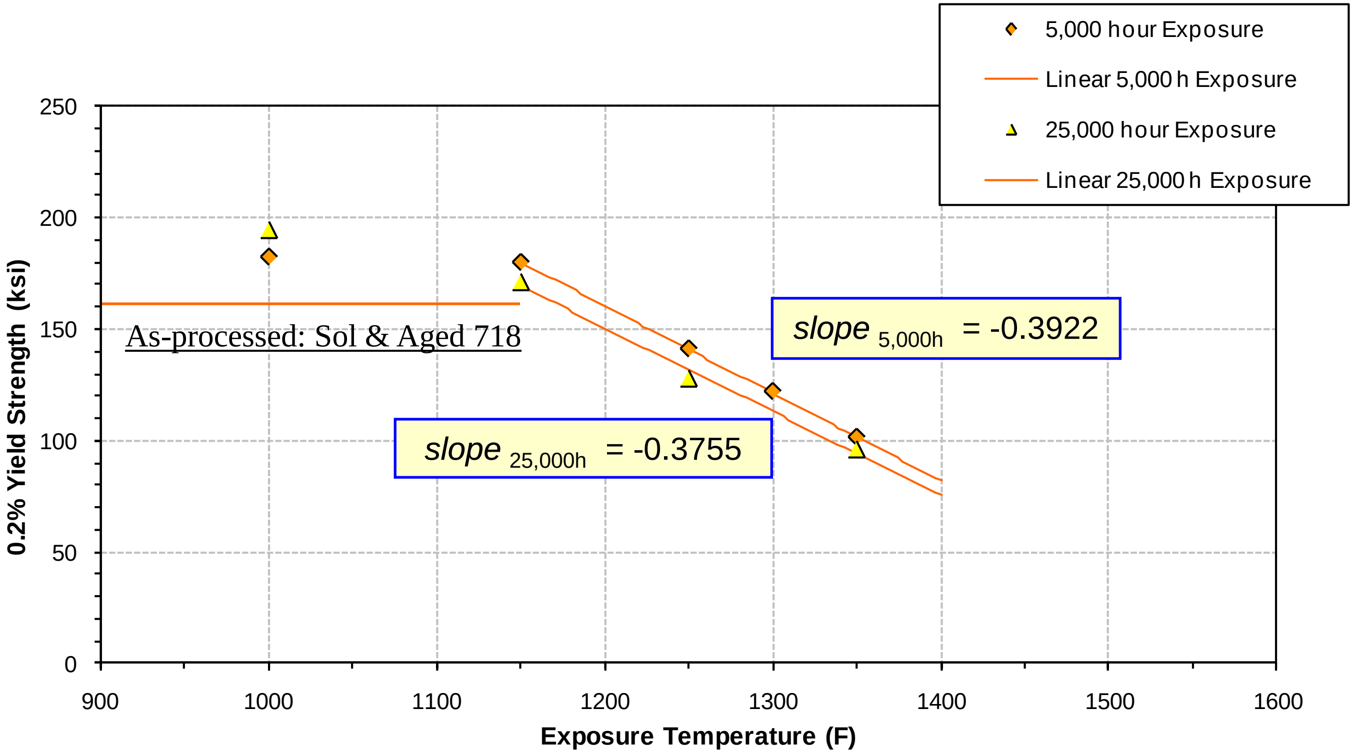
Alloy 718 – 0.2% YS behavior at different exposure temperatures as a function of time.



For example, in alloy 718 a change in exposure temperature can lead to a decrease in mechanical properties.

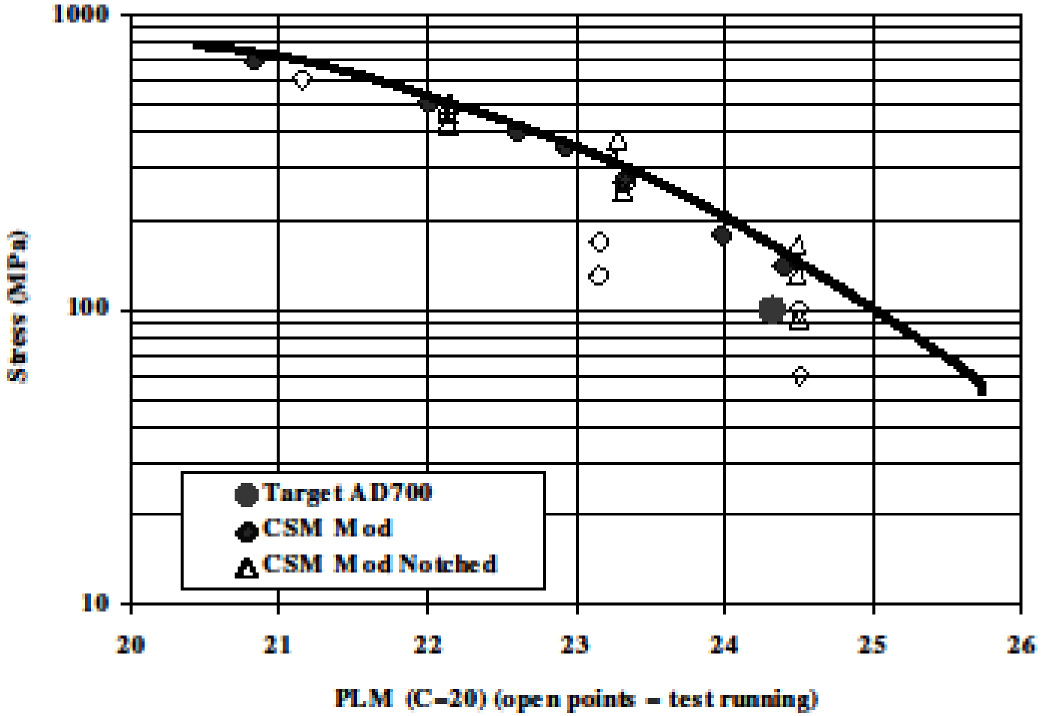
Long-Term Alloy Stability

Alloy 718 – 0.2% YS behavior at 5,000 & 25,000 h as a function of temperature.



For example, in alloy 718 a change in exposure temperature can lead to a decrease in mechanical properties.

Creep Rupture of Modified 718



As with all aircraft developed alloys, chemistry and heat treatment were designed to provide best combination of properties for short-term, high-strength use. For AD700 program, alloy 718 heat treatment was modified from normal two step age (720°C & 620°C) to one where the temperature of the aging treatments was increased by 30-40°C.

“Materials Development for Boilers and Steam Turbines Operating at 700°C,” R. Blum & R.W. Vanstone, Proceedings of the 6th International Charles Parsons Conference, (2003) p. 489-510.

Strengthening Concepts, Microstructural Control & Failure Mechanisms in Steam for Ni-base Alloys in Advanced USC Boilers & Turbines

Goal B

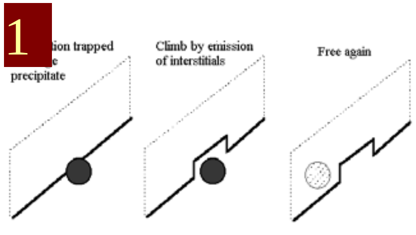
- Document the deformation mechanisms in Haynes 282 and Nimonic 105 with respect to microstructural features, and assess the long-term stability of these alloys as a function of exposure temperature and time in order to develop models that can be used to determine the life of a component.

Tasks

- Perform selected static (creep) and dynamic (fatigue and creep-fatigue) tests on Haynes 282 and Nimonic 105.
- Document deformation mechanisms in each instance.
- Relate deformation mechanism to specific stress state and chart the changes in the microstructure during testing exposure.

Deformation Mechanisms

Climb / bypass of unit 1/2<110> dislocations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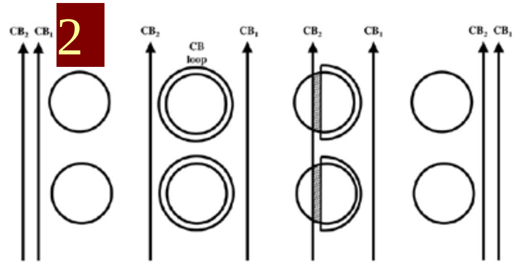
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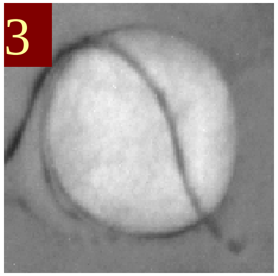
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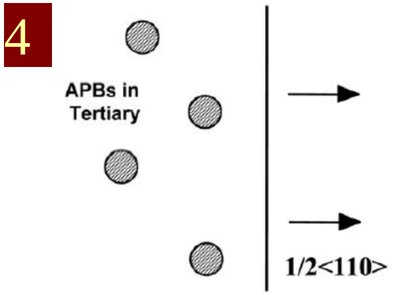
Shearing by <110> superdislocations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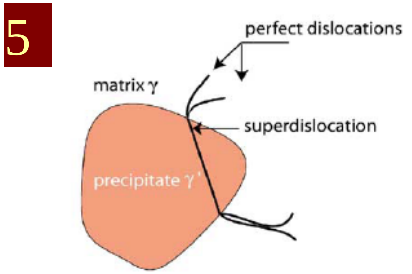
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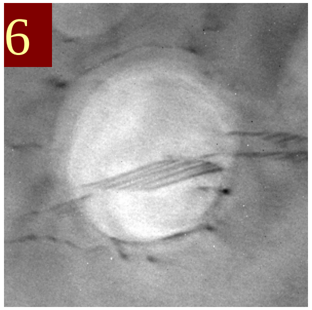
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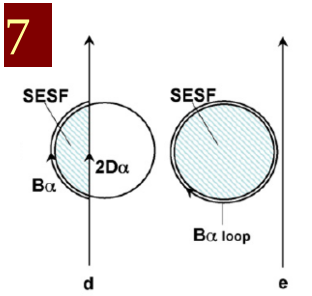
Shearing by partial dislocations (1/3<112>)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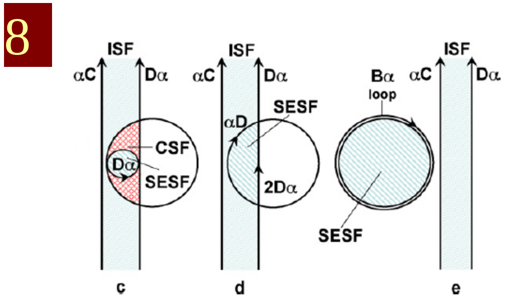
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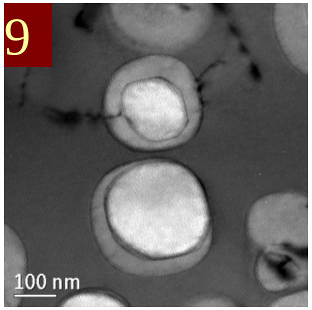
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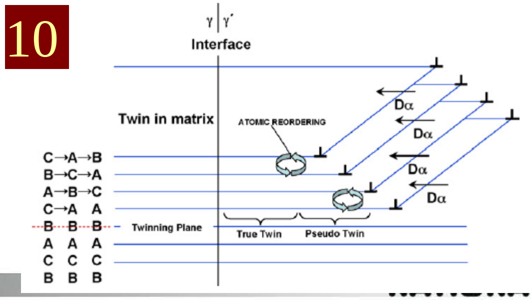
Micro-twinning (1/6<112>)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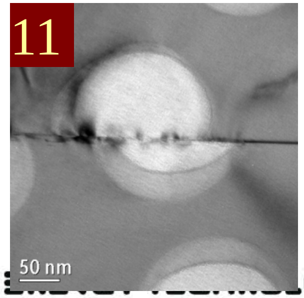
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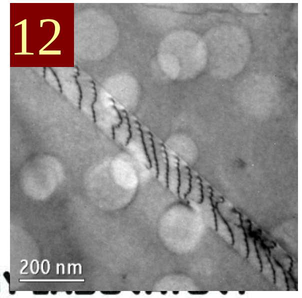
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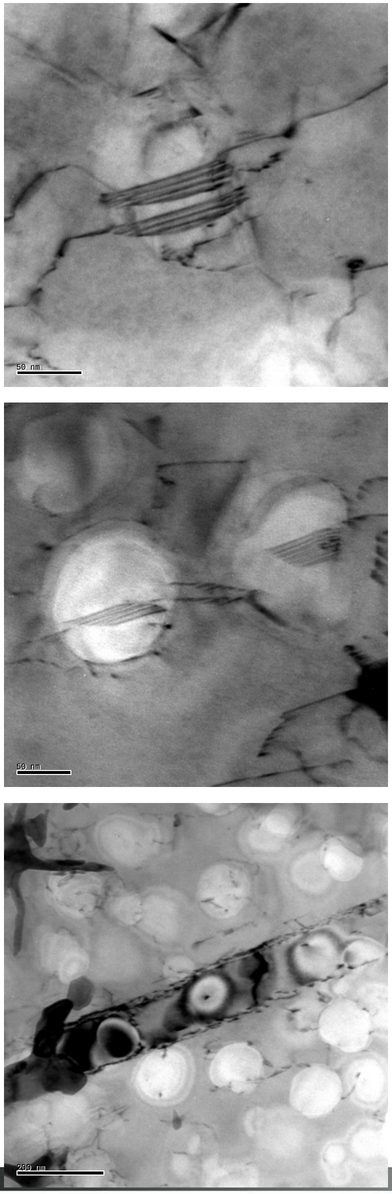
Deformation Mechanisms

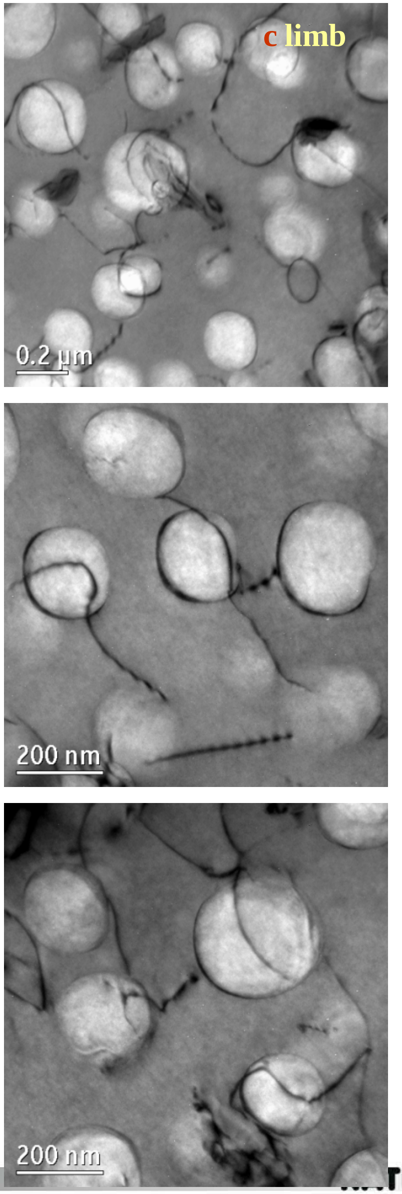
SA-1400°F-3718h d=142.5

σ = 37.5 ksi, ε = 18.78



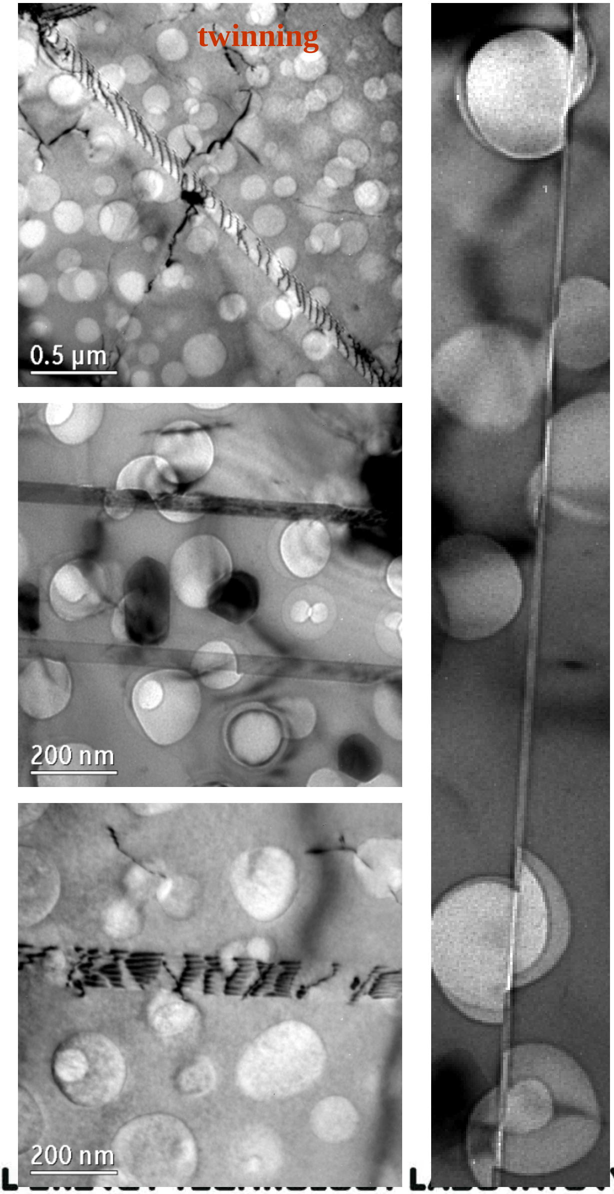
SA-1450°F-13849h, d=238.4

σ = 15 ksi, ε = 0.26

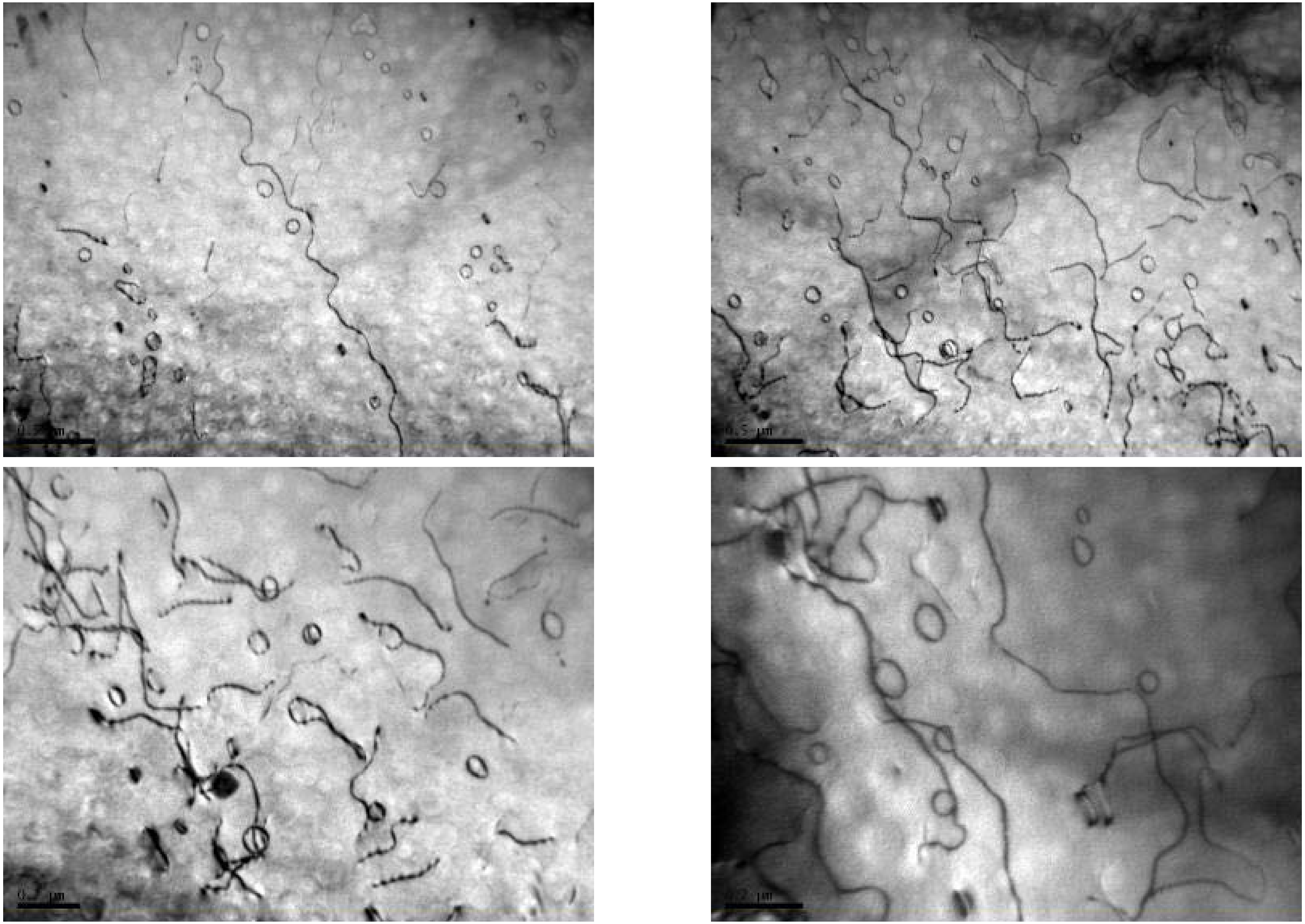


PA-1400°F-10470h, d=170.4

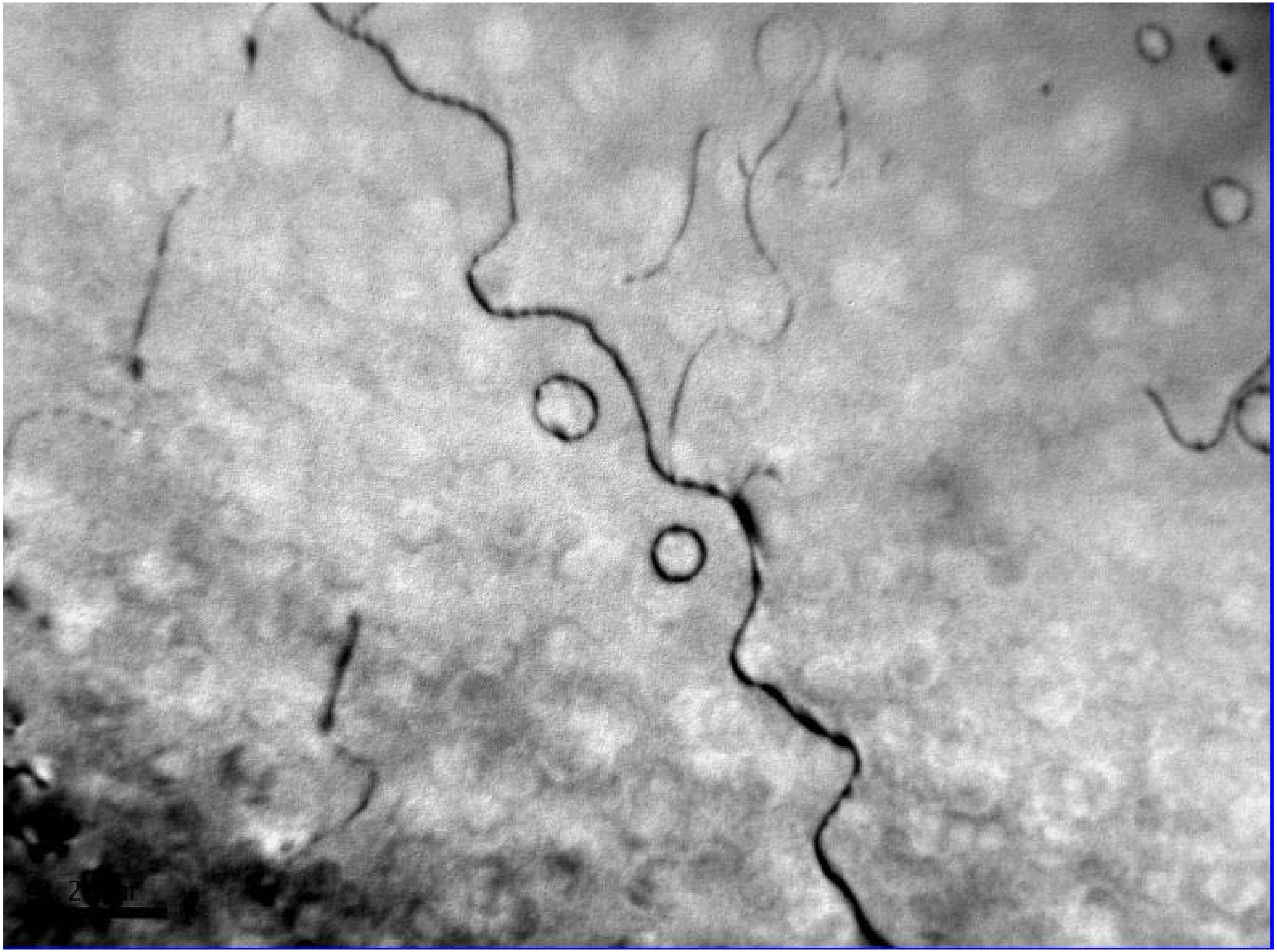
σ = 15 ksi, ε = 0.042



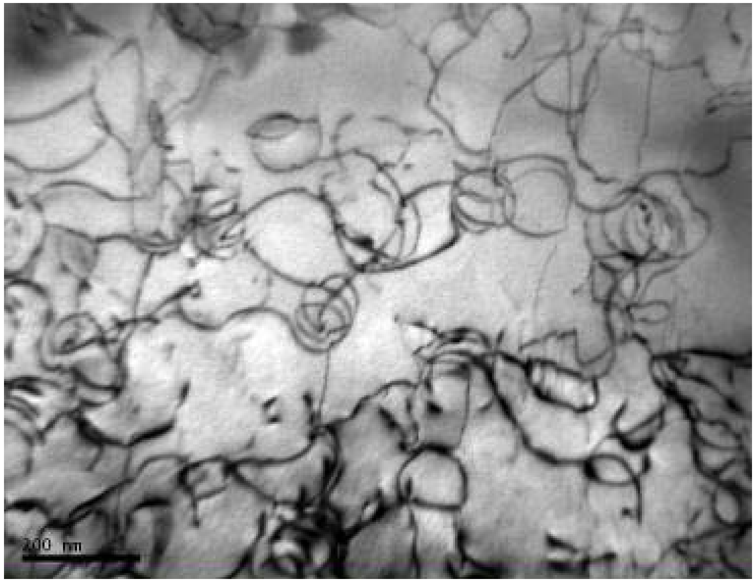
1450°F, 0.2% strain, 32.5 ksi

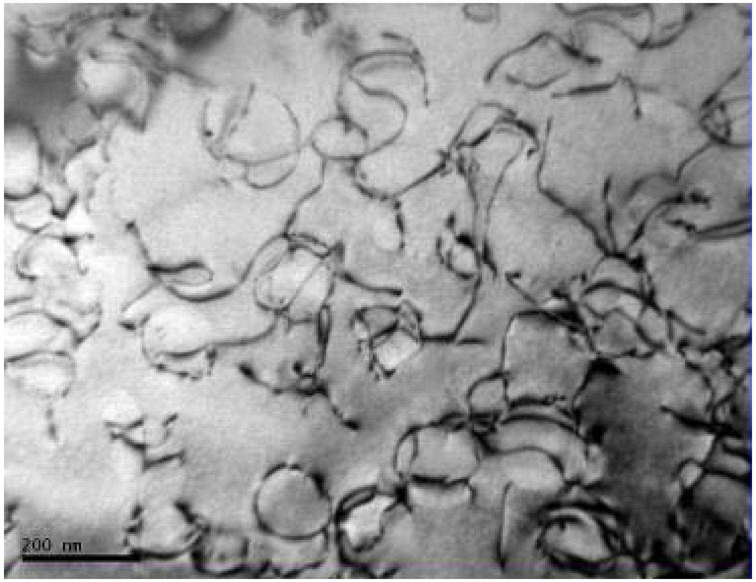


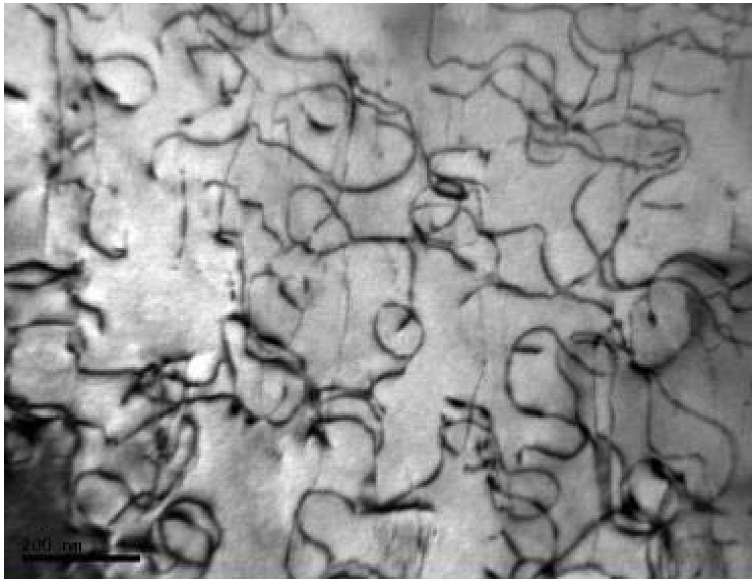
1450°F, 0.2% strain, 32.5 ksi

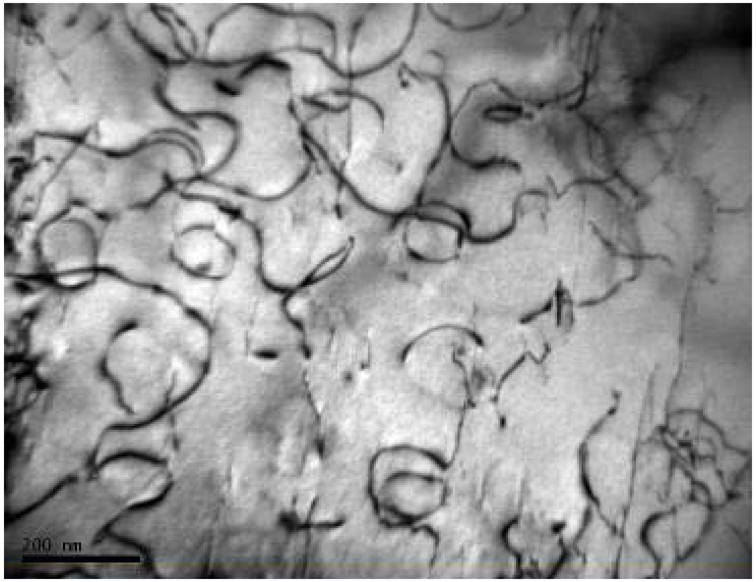


1450°F, 4% strain, 32.5 ksi

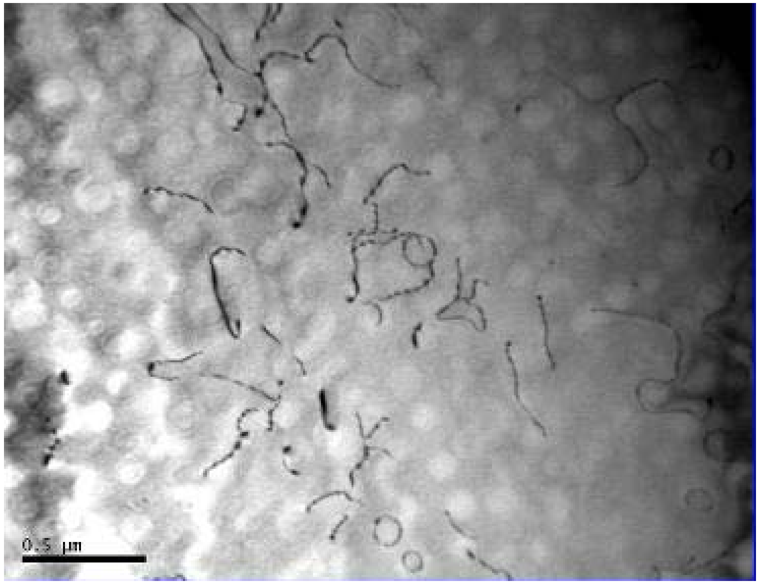


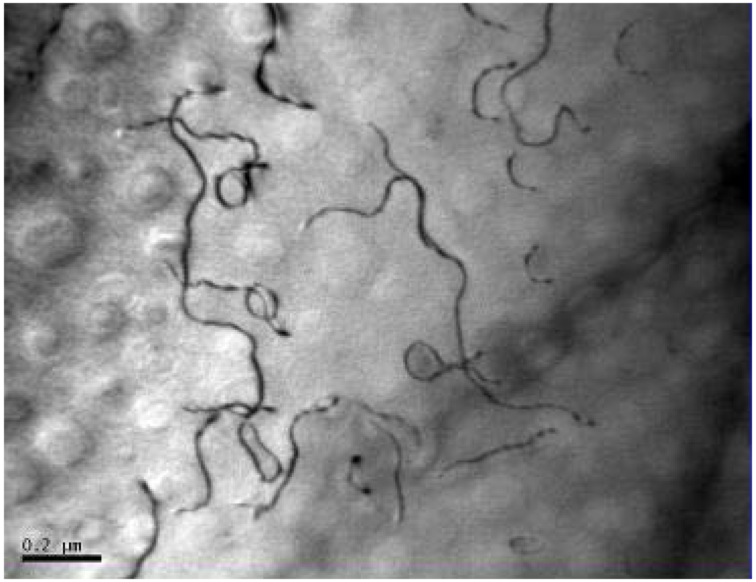


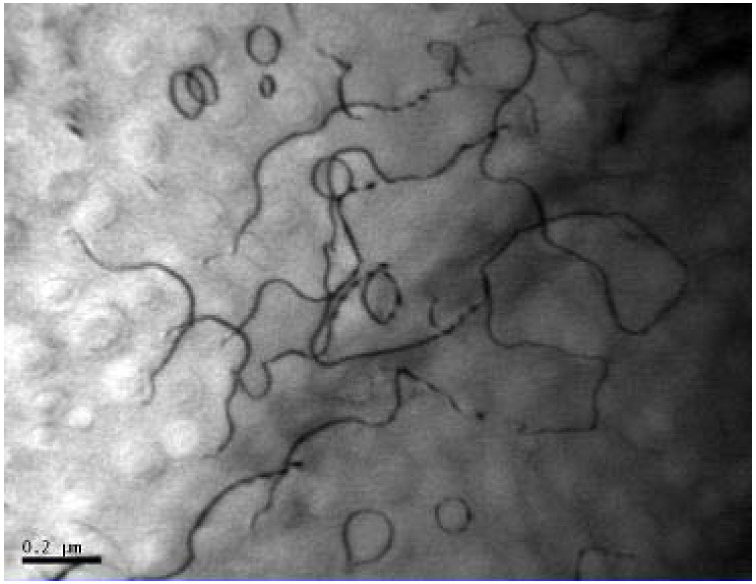


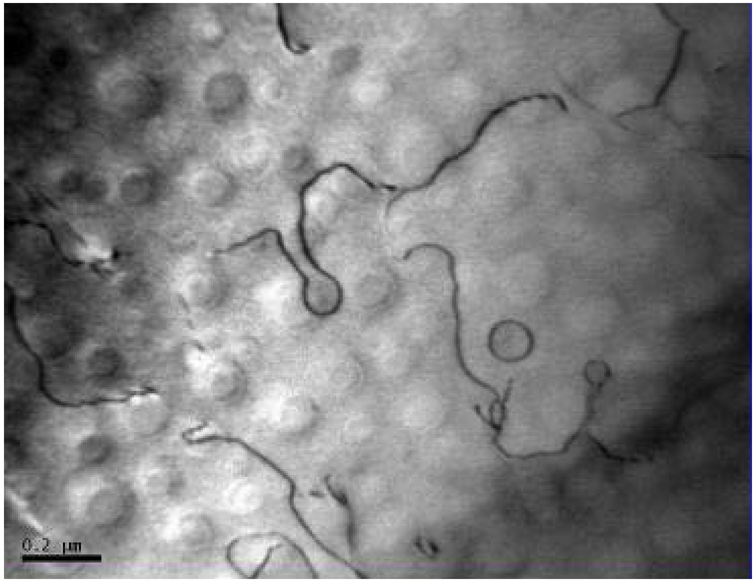


1450°F, 0.2% strain, 27.5 ksi









Summary Microstructural Observations

1. Haynes 282 is almost a classic model alloy.
2. The γ' phase has formed in the SA condition, although the precipitates are very small, and subsequent aging coarsens precipitate, but not unduly so.
3. Haynes 282 is a stable alloy in terms of phase formation and phase evolution, i.e., coarsening is <u>relatively</u> slow over time in the temperature range of interest.
4. Deformation mechanisms are also classic:
   a. At high stresses, deformation proceeds primarily via twinning/shearing process.
   b. At lower stresses, deformation proceeds primarily via classic Orowan looping and dislocation climb (cross slip).

Strengthening Concepts, Microstructural Control & Failure Mechanisms in Steam for Ni-base Alloys in Advanced USC Boilers & Turbines

Goal C

- Understand the interaction between microstructural development (e.g., alloy chemistry, TMP and heat treatment), deformation and crack growth in steam at 1400°F (760°C) to enable high performance nickel-base alloys to be developed for A-USC power plants.

Tasks

- Design high temperature, steam testing facility.
- Develop creep, fatigue and creep-fatigue testing protocols for life prediction models in dry air and steam.
- Assess literature to establish the effect of steam on creep-, fatigue-, and creep-assisted, fatigue-crack growth in solid solution and particle strengthened nickel-base superalloys.

Strengthening Concepts, Microstructural Control & Failure Mechanisms in Steam for Ni-base Alloys in Advanced USC Boilers & Turbines

Milestones

- Procure Haynes 282 & Nimonic 105 to fully implement TMP, heat treatment and mechanical testing matrices (3/31/2010).
- Characterize Haynes 282 and Nimonic 105 microstructures with respect to high temperature strengthening mechanisms with initial assessment as to high temperature strength potential (9/30/2010).
- Finalize design for environmental chamber to test in steam (9/30/2010).