Development of a Physically Based Creep Model Incorporating Eta Phase Evolution for Nickel-Base Superalloys used in Advanced Electric Power Generation Plants

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EPRI | ELECTRIC POWER RESEARCH INSTITUTE

DOE Joint HBCU-UCR Kickoff Meeting; October 6, 2016

Outline

Application

Objective/Vision

Background

- Superalloy Microstructures
- Eta Phase
- Physically-Based Creep Constitutive Models
- Problem Statement

Team Description and Assignments

Task Descriptions

Gantt Chart

Milestones

Application

Advanced Ultra-Supercritical Steam Power Generation Plants

- Steam temperatures 700-760^{o}C
    - Far too high for steels
    - Advanced gas turbine superalloys are too expensive for large components, and are often difficult or impossible to weld
    - Creep performance becomes key driver
    - Microstructures will evolve at these temperatures

Objective/Vision

From the proposal Executive Summary:

The primary objective of this program is to develop a

physically based creep model

for Nimonic 263 that synthesizes known creep behavior based on gamma prime strengthening with a

new understanding of the effects of eta phase

on creep performance at long service times in fossil energy power plants.

Background - Superalloys

At A-USC steam temperatures, nickel-base alloys will be used extensively

- Excellent corrosion/oxidation resistance
- Good creep performance
- Superalloys with low volume fractions of gamma prime (γ') often are easy to form and weld

Background - Superalloys

Typical wrought alloys used in steam power generation plants: IN740, Nimonic 263

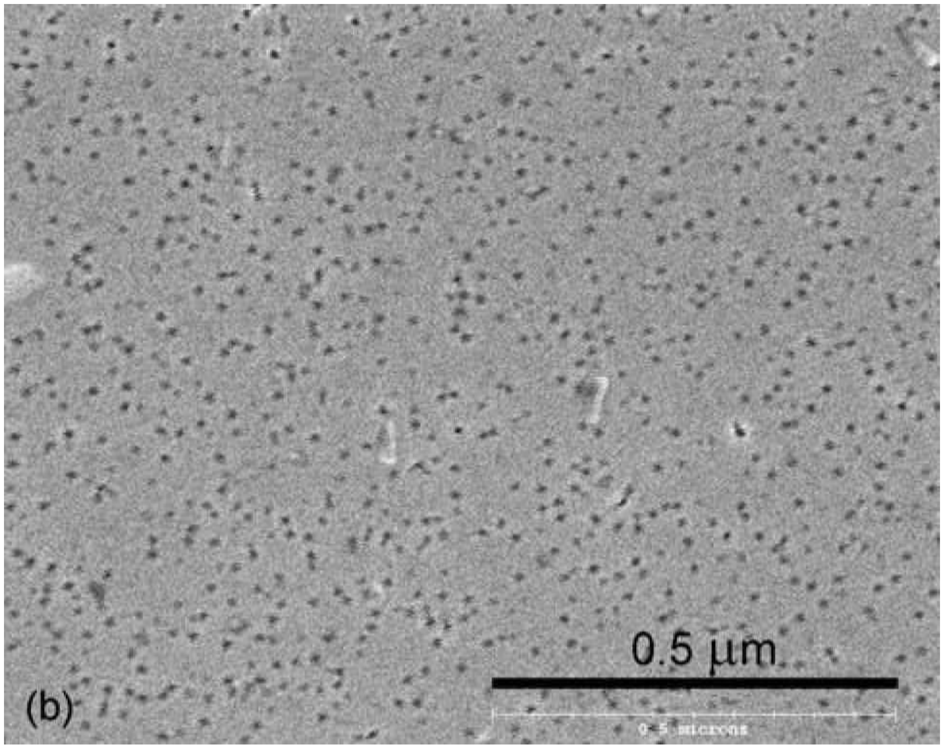
Nimonic 263 nominal composition, wt%

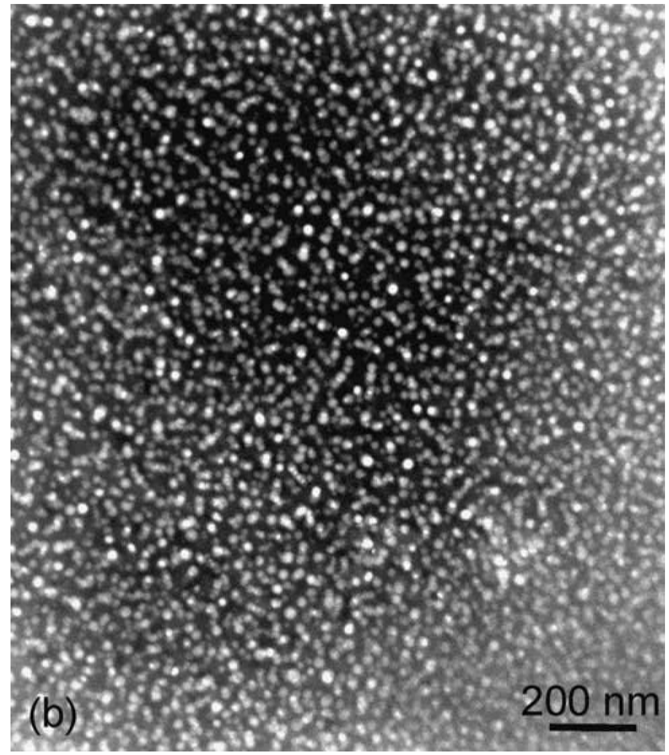
Ni	48
Co	20
Cr	20
Al	***0.6***
Ti	***2***
Fe	0.7
Mo	6
Mn	0.60
Si	0.40
C	0.06

Al and Ti are added to form strengthening $Ni_3(Al,Ti)$ γ' precipitates.

Background - Superalloys

Typical aged microstructures of Nimonic 263 (Zhao et al., 2001)





850°C – 1 hr, SEM

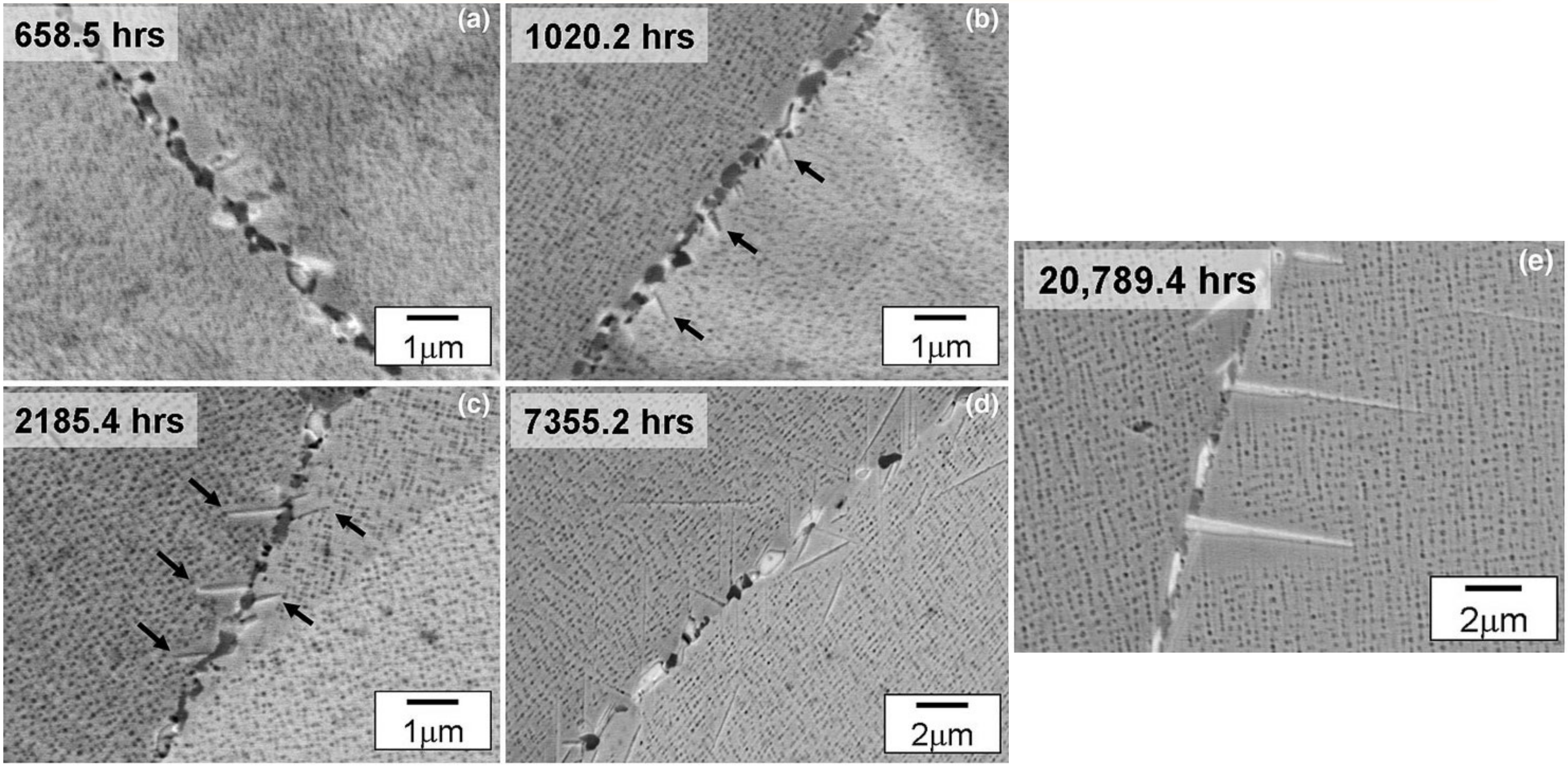
750°C, 50 hrs, TEM

Background – η phase

At long service times above 700°C, Nimonic 263 and IN740 form eta phase (η) phase at the expense of γ'.

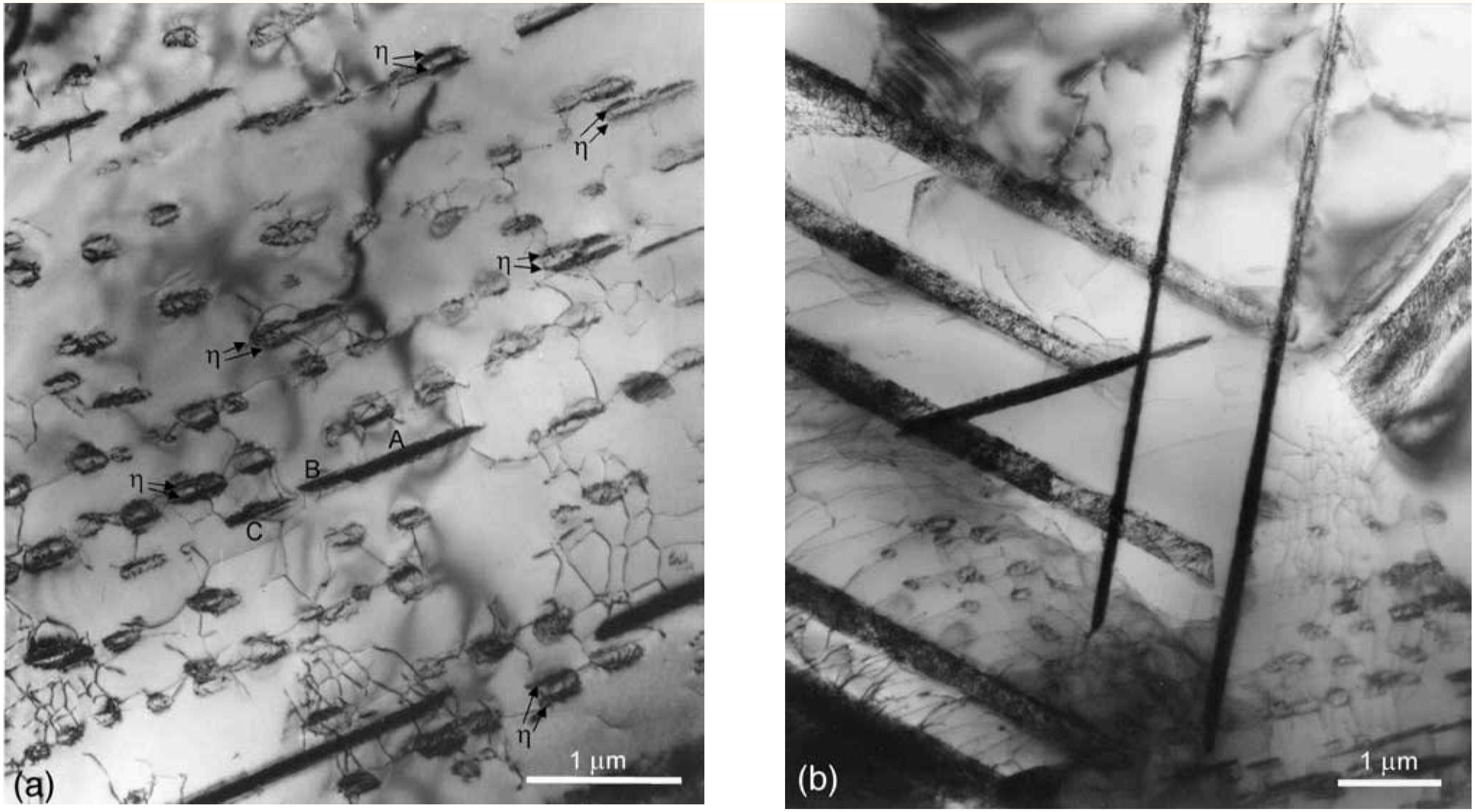
- η is based on Ni_3Ti
- η has a complex hexagonal structure
- η forms in the shape of plates or needles

Background – η phase



IN740H at 750°C Shingledecker and Pharr, 2012.

Background – η phase



Nimonic 263, 1,200 hrs at 900°C Zhao et al., 2001

Background – Physically-Based Creep Modeling

"Unified approach" to viscoplastic deformation

$$\dot{\varepsilon}_{ij} = \psi\left[\frac{s_{ij} - \Omega_{ij}}{K}\right]$$

s = deviatoric applied stress

Ω = "back stress" (tensor)

K = "drag stress" (scalar)

Ψ = model-dependent function

Background – Physically-Based Creep Modeling

"Unified approach" to viscoplastic deformation

$$\dot{\varepsilon}_{ij} = \psi\left[\frac{S_{ij} - \Omega_{ij}}{K}\right]$$

State variables Ω and K evolve to incorporate

- Strain hardening
- Dynamic recovery
- Static recovery

Background – Physically-Based Creep Modeling

“Unified approach” to viscoplastic deformation

$$\dot{\varepsilon}_{ij} = \psi \left[\frac{s_{ij} - \Omega_{ij}}{K} \right]$$

Researchers have incorporated microstructure by introducing microstructural variables into the state variable evolution equations. Microstructure can evolve as well. e.g.

- γ’ volume fraction
- γ’ size distribution
- Grain size

Background – Physically-Based Creep Modeling

Models have been developed specifically for low γ’ volume fraction superalloys by several groups. (McLean and Dyson, Manonukul et al., Oruganti, others)

One of McLean and Dyson’s flow rules is

$$\dot{\varepsilon}_c = K_1 \cdot exp\left(\frac{-Q}{kT}\right) \cdot sinh\left(\frac{K_2(\sigma - \Omega)}{kT}\right)$$

and they have incorporated γ’ coarsening in the state variable evolution equations and applied this to creep of Nimonic 90.

Problem Statement

- η phase **will form** in A-USC components in service
- There is **no agreement** in the literature about whether η phase is detrimental to creep performance
- There has been **no research** about how η phase might affect constitutive behavior (creep rates), and therefore life prediction
- η phase might also affect cavitation behavior

Team Description and Assignments

Michigan Tech Team

Department of Materials Science and Engineering

- Akhila Gorantla, PhD Student
- Walt Milligan and Paul Sanders, Professors
- Cal White, Research Professor

- Conduct research on microstructural evolution, creep deformation and damage mechanisms, effects of microstructure on constitutive behavior
- Develop physically-based creep model

Team Description and Assignments

Electric Power Research Institute

- John Shingledecker, Program Manager, Fossil Fuels and Repair Program
- EPRI support staff

- Conduct creep tests
- Provide baseline physically-based creep models and numerical tools from prior programs
- Assist Michigan Tech team in developing new physically-based creep models

Task Descriptions

Objective

Determine effects of η phase on creep performance of Nimonic 263 and develop a physically-based creep model.

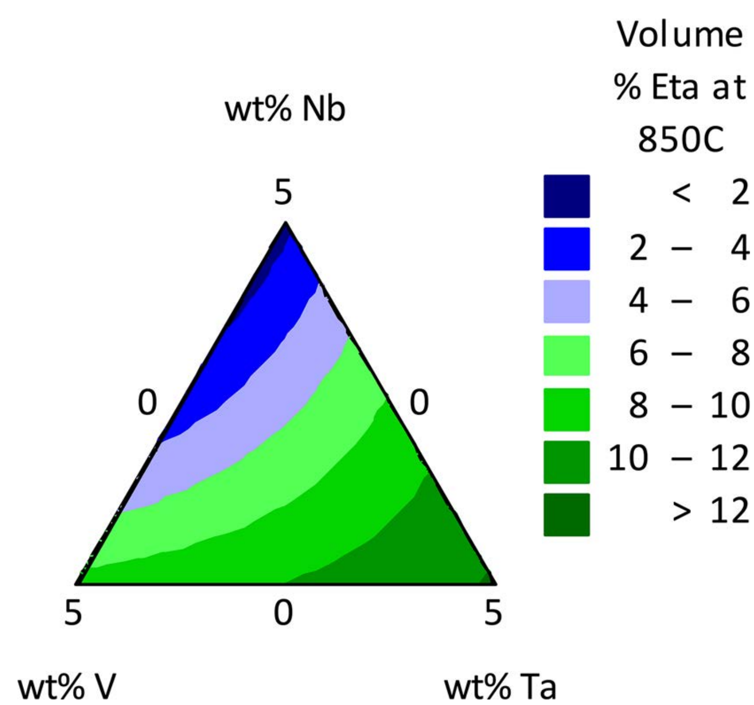
Previous Work

EPRI – Characterized creep performance of standard Nimonic 263 and implemented physically-based creep model.

Michigan Tech + EPRI – Developed a modified alloy based on Nimonic 263 that contains 100% η and no γ'. Characterized creep performance. In the process of characterizing deformation mechanisms.

η Phase Strengthened Superalloy based on N263

To study the effects of η on behavior, and to explore the possibility of actually designing an alloy strengthened by η, an alloy development program was conducted using Thermo-Calc in a DOE approach. Example:

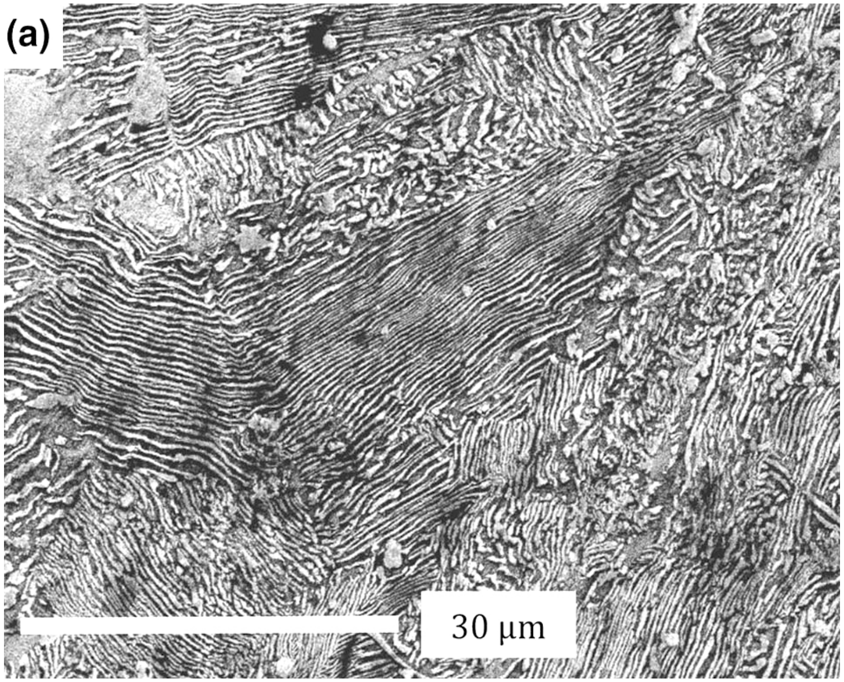


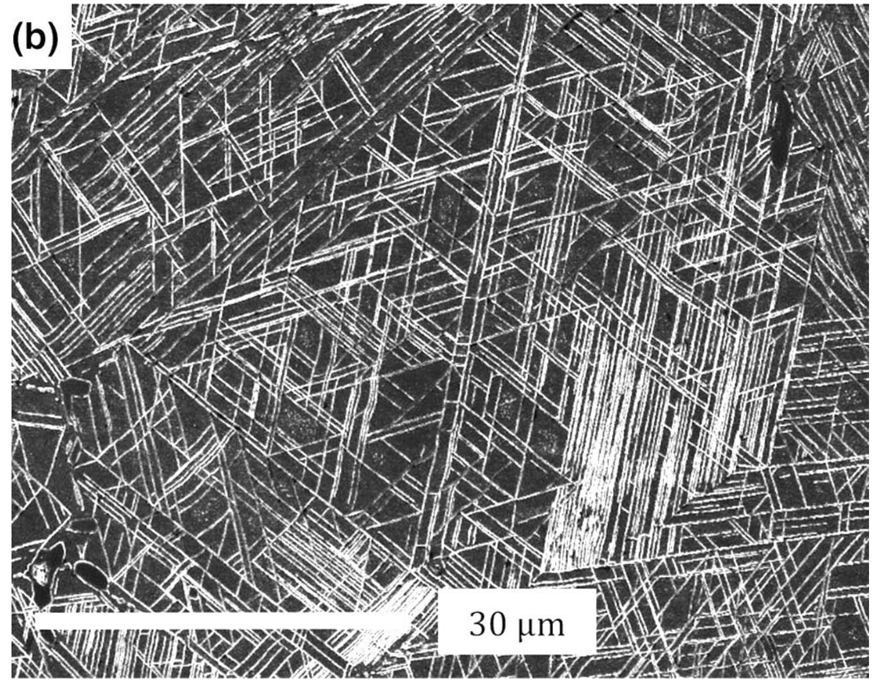
η Phase Strengthened Superalloy based on N263

Using these types of contour plots, it was possible to design and manufacture 2 different alloys that have 100% η and no γ', with a composition somewhat similar to Nimonic 263.

	Alloy 19	Alloy 20	NIMONIC 263
Ni	Bal	Bal	Bal
Co	21	21	20
Cr	18	21	20
Al	*0.13*	*0.14*	*0.6*
Fe	0.47	0.48	0.7
Mo	*0*	*0*	*6*
Mn	0.38	0.42	0.60
Si	0.19	0.19	0.40
Ti	*2.9*	*2.8*	*2*
Nb	*1.9*	*1.9*	*0*
W	*1.9*	*1.9*	*0*
Ta	*1.9*	*1.1*	*0*
V	*0*	*0.85*	*0*
C	0.07	0.07	0.06

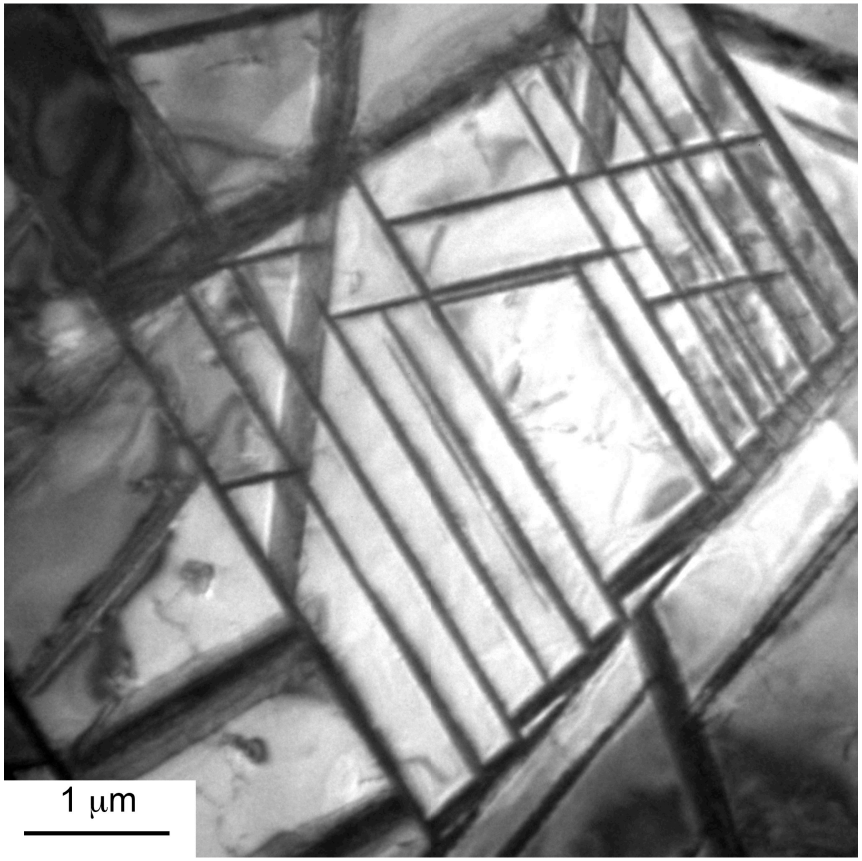
η Phase Strengthened Superalloy based on N263

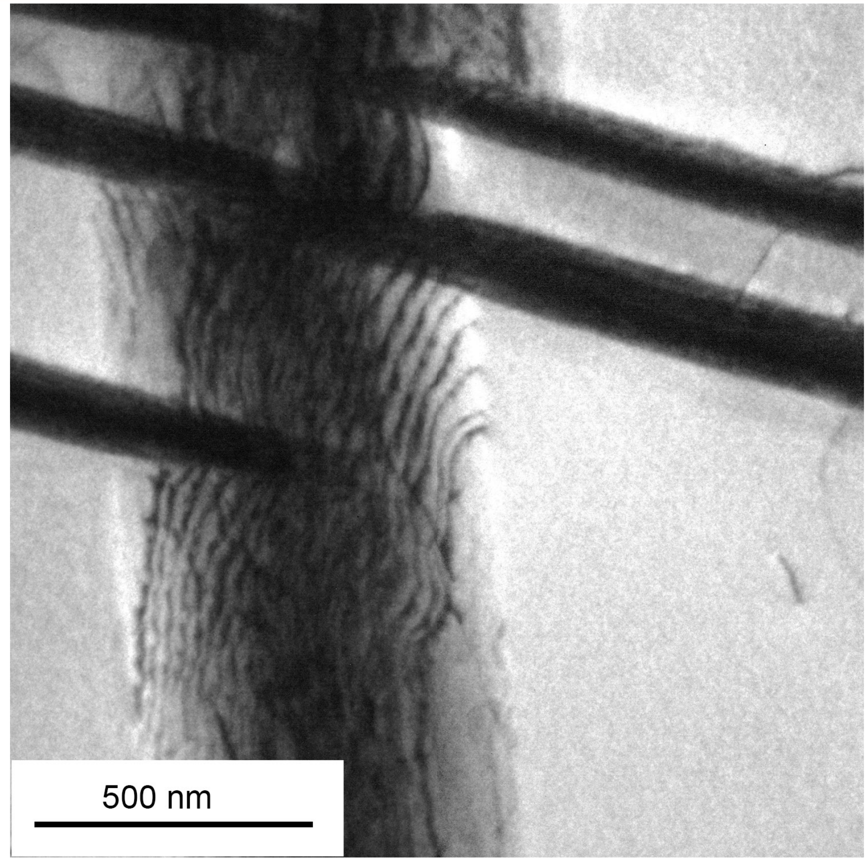




Aged at 750°C | Alloy 19 | Aged at 850°C

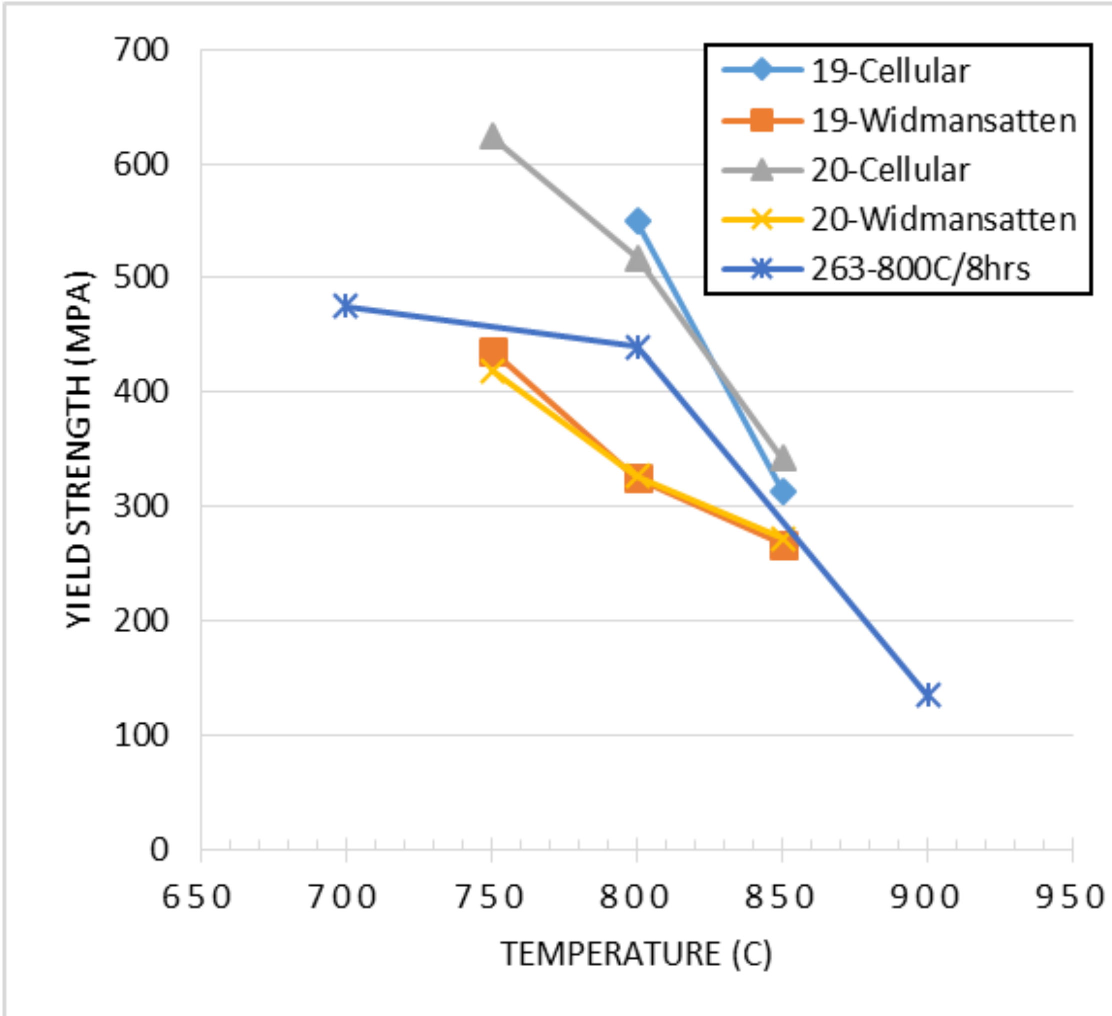
η Phase Strengthened Superalloy based on N263



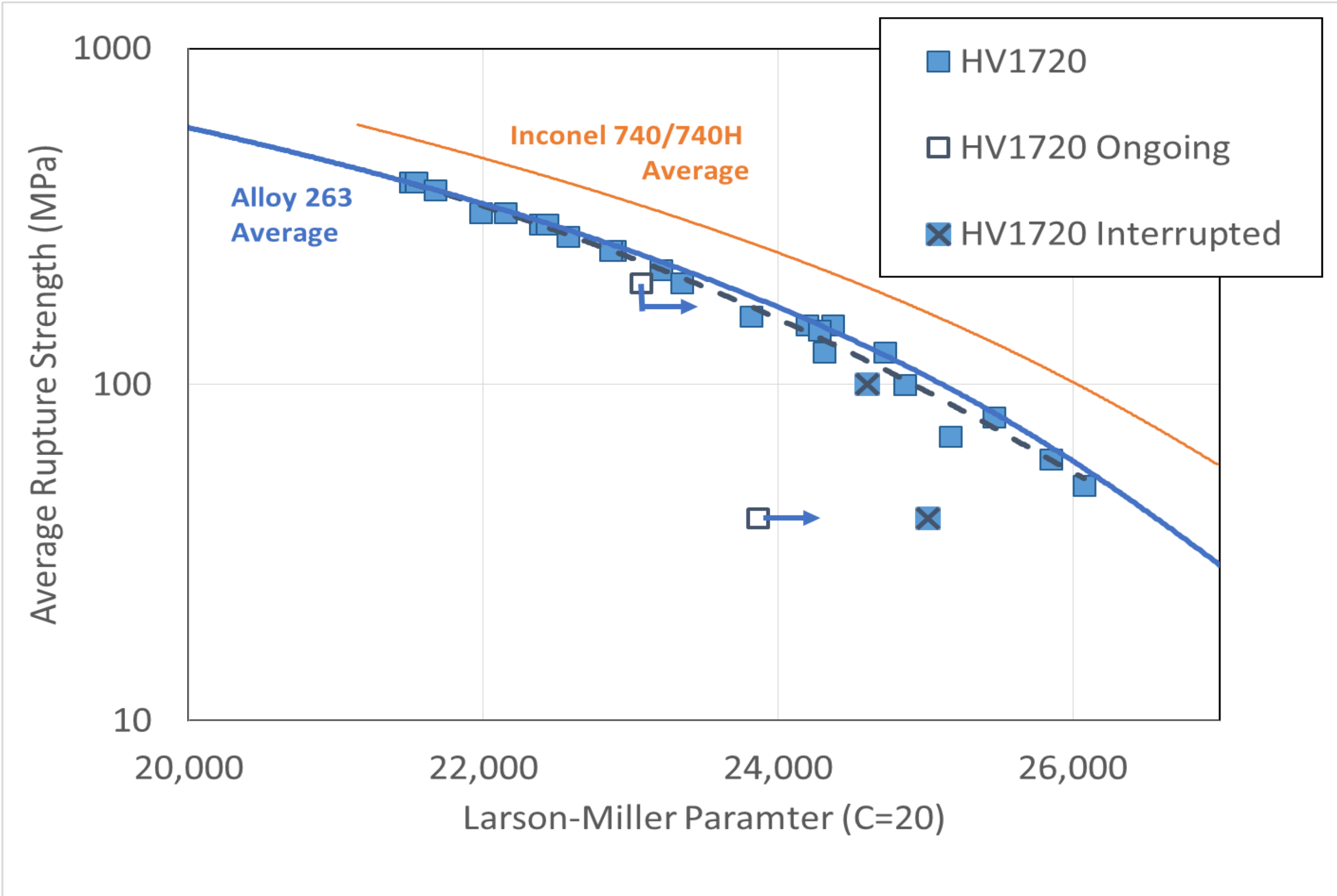


Alloy 20, TEM

η Phase Strengthened Superalloy based on N263

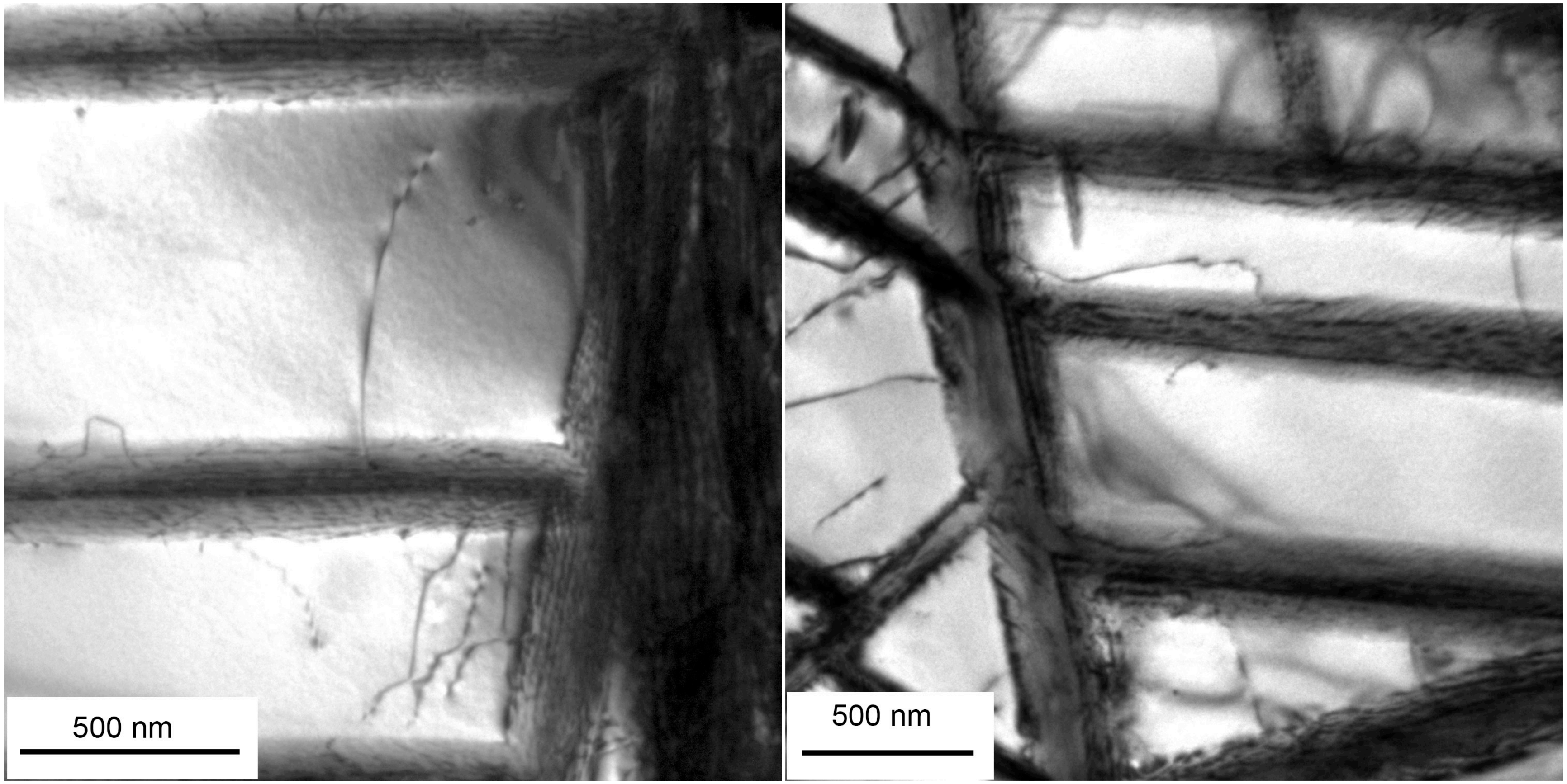


η Phase Strengthened Superalloy based on N263



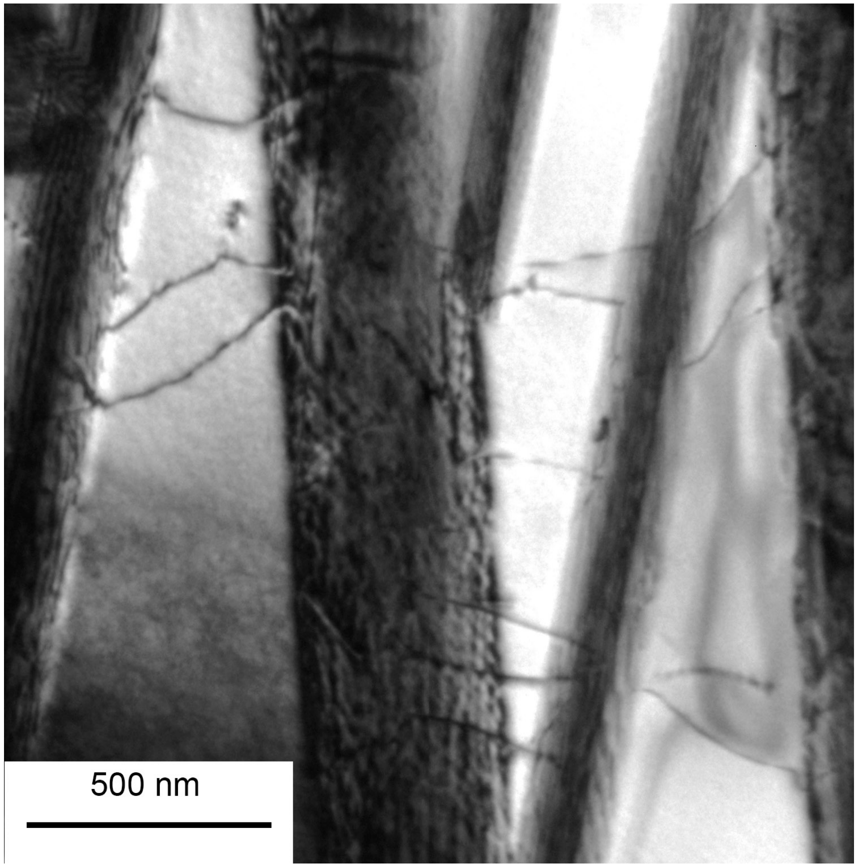
Alloy 20, Widmanstätten microstructure, creep

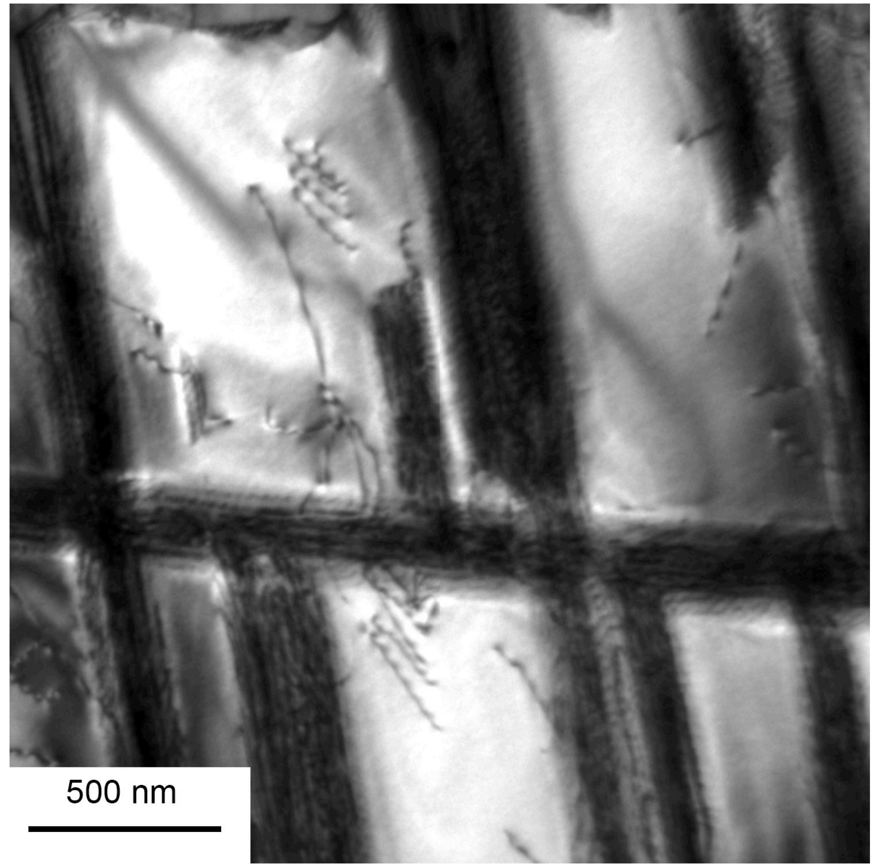
η Phase Strengthened Superalloy based on N263



Alloy 20, Widmanstätten microstructure, crept at 800^{o}C

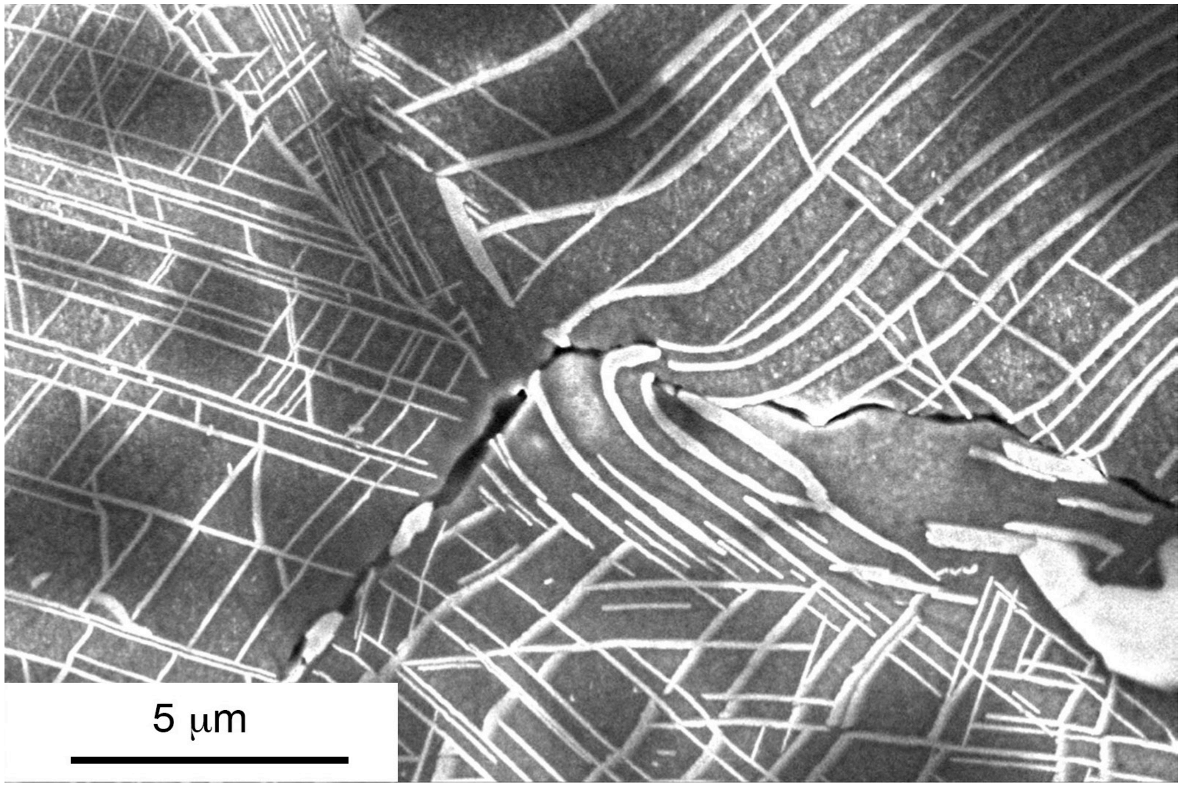
η Phase Strengthened Superalloy based on N263





Alloy 20, Widmanstätten microstructure, crept at 800°C

η Phase Strengthened Superalloy based on N263



Alloy 20, Widmanstätten microstructure, crept at 850^{o}C

The Big Picture

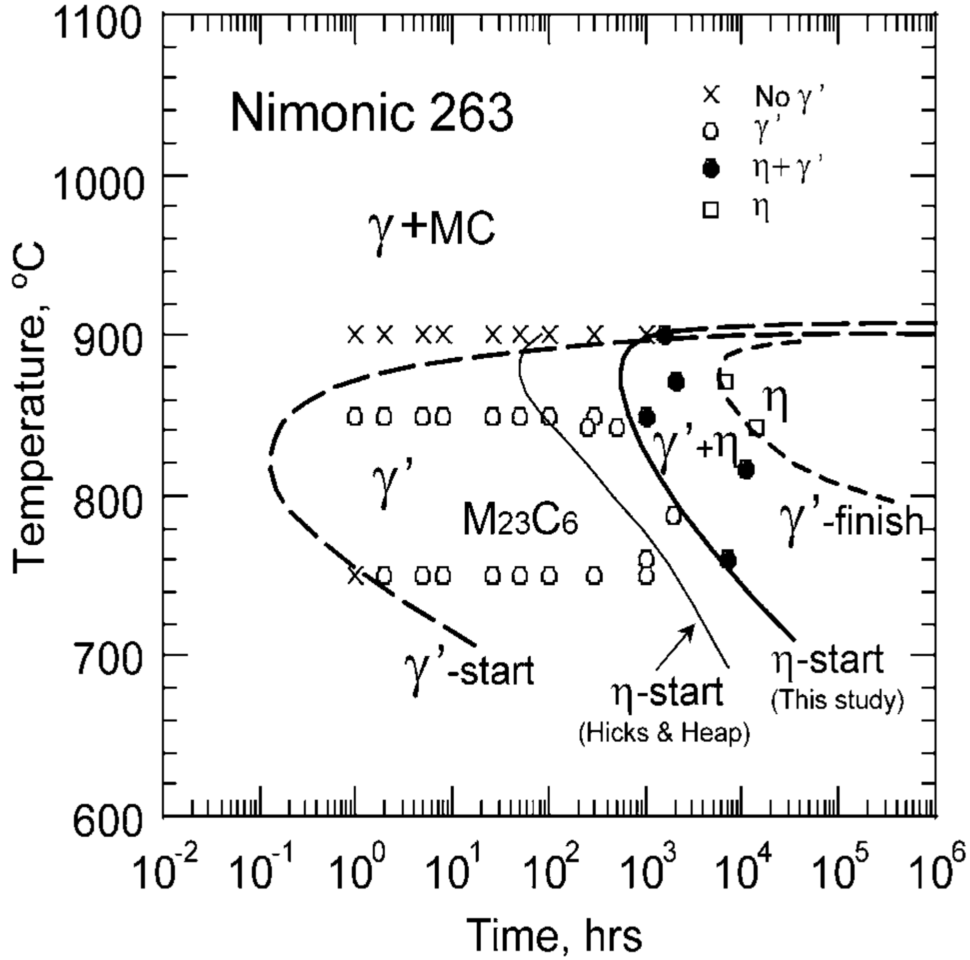
Study creep behavior varying across the microstructural spectrum from

All γ' ➔ $\gamma' + \eta$ ➔ All η

Microstructure Target	100% γ' precipitates	γ' and η precipitates	100% η precipitates
Alloy	Nimonic 263	Nimonic 263	Michigan Tech Alloy 20
Thermal processing	Commercial	**To be determined**	Heat treat to form η
Creep data available?	✔		✔
Crept specimens available?	✔		✔

First challenge is to modify Nimonic 263 so it has both $\gamma' + \eta$ at the beginning of the creep test.

TTT Curves for Nimonic 263



Zhao et al., 2001. Other research is available as well.

Planned Research – 4 Major Tasks

1. Develop heat treatments for commercial Nimonic 263 to obtain a mixture of both η and γ' phases prior to creep testing, with the γ' distribution being as close to commercial Nimonic 263 as possible.
    - Samples went into furnaces this week.

Planned Research – Major Tasks

2. Conduct creep tests on these materials at EPRI.

3. Fully characterize microstructures and deformation mechanisms during creep for all three alloys (standard Nimonic 263, Nimonic 263 heat-treated to contain $\eta + \gamma'$, and the Michigan Tech modified Nimonic 263 alloy that contains only η.)

Planned Research – Major Tasks

4. Use the knowledge gained in (2) and (3) to develop and validate a physically-based creep model that synthesizes known gamma prime creep behavior with a new understanding of the effects of η phase on creep performance.

Milestones

Milestone Description	Completion Date
1.0 Project Management and Planning	8/31/2019
1.1 Continuously revise and update milestones and timelines.	8/31/2019
1.2 Submit required reports to DOE.	8/31/2019
2.0 Develop heat treatments to form γ' and η phases in Nimonic 263 prior to creep testing	1/31/2017
2.1 Mine existing data from the literature. If insufficient, conduct simulations with Thermo-Calc and kinetics software to predict η phase formation in reasonable amounts of time for new material. Establish best route to form γ' such that γ' structure is as close to standard Nimonic 263 as possible.	11/30/2016
2.2 Validate predictions in (2.1) experimentally, and adjust as needed.	1/31/2017
Critical Decision Point. Is it possible to produce a suitable $\gamma' + \eta$ microstructure via a relatively short time (< 1,000 hour) heat treatment? If yes, continue. If not, see Section B, Risk Management, for mitigation strategies.	**1/31/2017**

Milestones

3.0 Conduct creep tests at EPRI on new Nimonic 263 that had been modified to contain both γ' and η phases.	8/31/2018
4.0 Assess microstructures as well as deformation and damage mechanisms in all three microstructural conditions (100% γ', 100% η, mixture of $\gamma' + \eta$.)	2/28/2019
4.1 Conduct optical, SEM and TEM microscopy to quantify phase transformations, precipitate size evolution, deformation mechanisms (TEM), and damage evolution.	10/31/2018
4.2 Establish effects of microstructure on deformation mechanisms in all three microstructures	1/31/2019
4.3 Use results of (4.1) and (4.2) to quantify the effects of η on creep performance of Nimonic 263.	2/28/2019

Milestones

5.0 Modify existing γ' based creep models to account explicitly for the effects of η phase as determined in (4.)	8/31/2019
5.1 Assess and integrate best damage models from the literature	2/28/2019
5.2 Adapt models to explicitly include the transformation from metastable γ' to equilibrium η and resultant changes in damage mechanisms	6/30/2019
5.3 Validate model with select creep experiments	8/31/2019

Gantt Chart

			2016		2017				2018				2019		
Task	**Start**	**End**	**Q3**	**Q4**	**Q1**	**Q2**	**Q3**	**Q4**	**Q1**	**Q2**	**Q3**	**Q4**	**Q1**	**Q2**	**Q3**
1.0 Project Mgt	9/1/16	8/31/19													
1.1 Update milestones, timelines	10/1/16	8/31/19													
1.2 Submit reports to DOE	12/1/16	8/31/19													
2.0 Develop heat treatments	9/1/16	1/31/17													
2.1 Establish best route	9/1/16	11/30/16													
2.2 Validate	11/30/16	1/31/17													
CRITICAL DECISION	**1/31/17**	**1/31/17**			**X**										
3.0 Conduct creep tests	4/31/17	8/31/18													

Gantt Chart

			2016		2017				2018				2019		
Task	**Start**	**End**	**Q3**	**Q4**	**Q1**	**Q2**	**Q3**	**Q4**	**Q1**	**Q2**	**Q3**	**Q4**	**Q1**	**Q2**	**Q3**
4.0 Assess microstructures and deformation mechanisms	1/1/17	2/28/19													
4.1 Conduct optical, SEM and TEM microscopy	1/1/17	10/31/18													
4.2 Establish deformation mechanisms	1/1/17	1/31/19													
4.3 Quantify the effects of η	1/1/18	2/28/19													
5.0 Modify existing creep models	1/1/18	8/31/19													
5.1 Assess existing models	1/1/18	2/28/19													
5.2 Adapt models for η	10/1/18	6/30/19													
5.3 Validate models	6/30/19	8/31/19													