Development of a Physically-Based Creep Model Incorporating ETA Phase Evolution for Nickel-Base Superalloys

Ninad Mohale – Student Researcher, Michigan Tech, nrmohale@mtu.edu

PI: Walter Milligan, Michigan Tech, milligan@mtu.edu

Co-PI's: John Shingledecker, EPRI; Cal White and Paul Sanders, Michigan Tech

2019 Annual Review Meeting for Crosscutting Research; 04/11/2019

DE-FE-0027822: Performance period 8/15/2016 – 3/31/2019

Michigan Technological University 1885

EPRI | ELECTRIC POWER RESEARCH INSTITUTE

U.S. DEPARTMENT OF ENERGY | NETL NATIONAL ENERGY TECHNOLOGY LABORATORY

Project Objectives

The primary objective of this program is to develop a

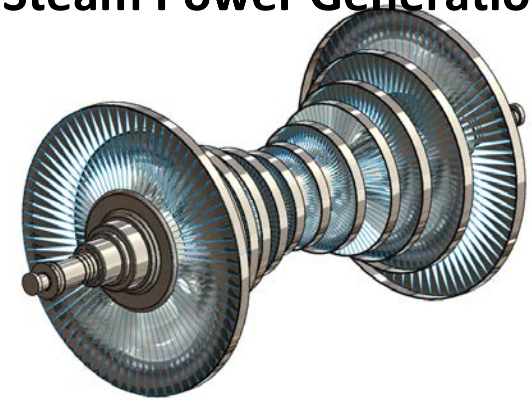
physically based creep model

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

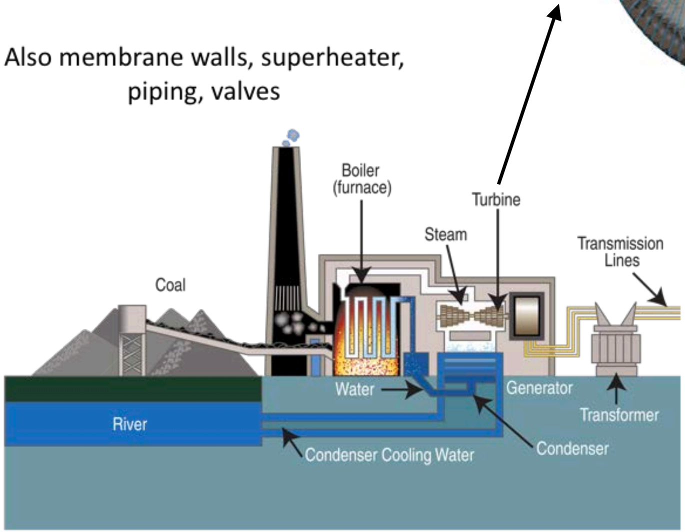
new understanding of the effects of eta phase

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

A-USC Steam Power Generation Plants



Also membrane walls, superheater, piping, valves



Steam temperature	750°C	(~1400°F)
Steam Pressure	35MPa	(5000 psi)

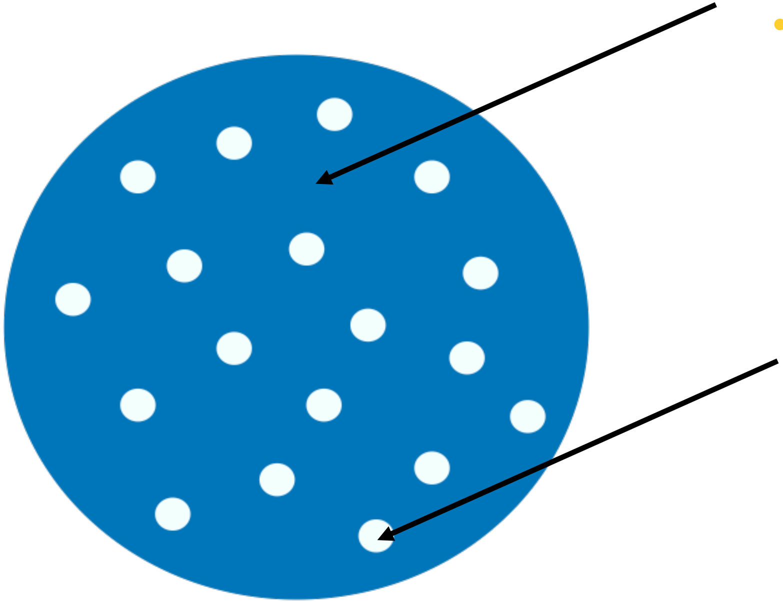
High Temperature
Corrosive Environments
Long Service Life (>15 years)

One candidate material is Nimonic 263

- Nickel Superalloy
- Easy to form and weld
- Excellent corrosion/oxidation resistance
- Good creep performance
- Strengthening mechanisms
    - Precipitate strengthening
    - Solid solution strengthening
- Other common materials include Haynes 282 and Inconel 740

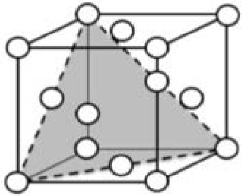
Ni	48
Co	20
Cr	20
Mo	6
Ti	**2**
Al	**0.60**
Fe	0.70
Mn	0.60
Si	0.40
C	0.06

N263 - Typical microstructure



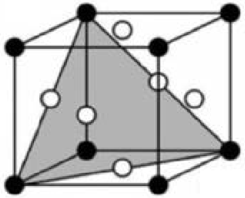
γ matrix (fcc)

- Solid solution strengthened phase

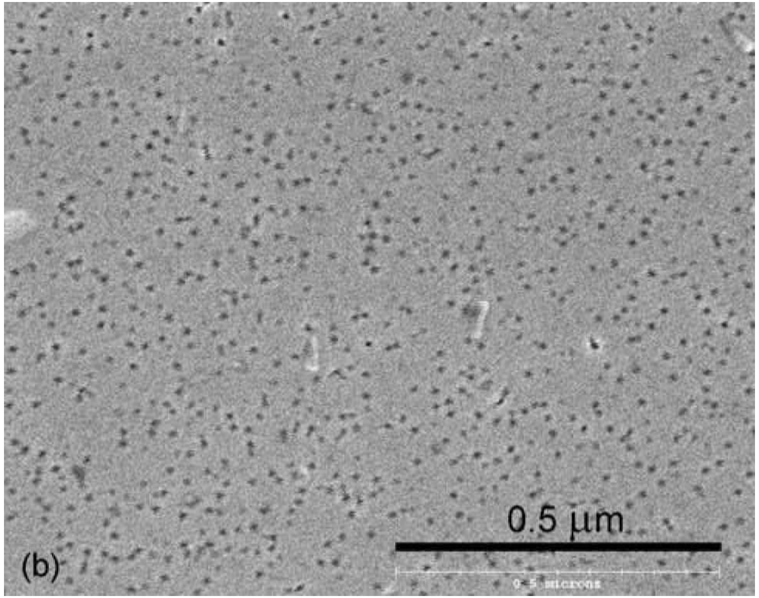


γ' particles ($L1_2$)

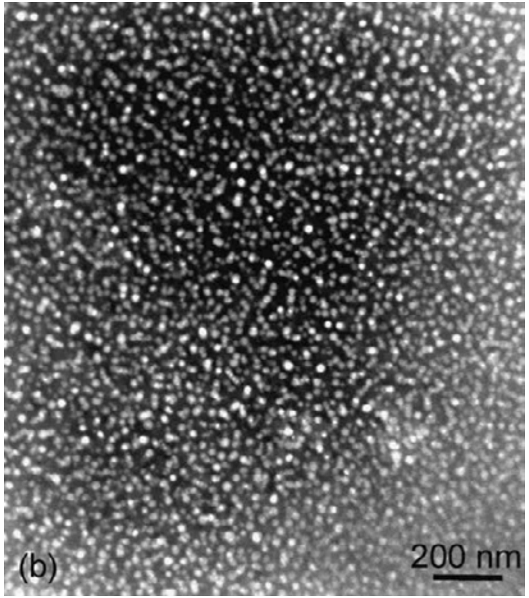
- $Ni_3(Ti,Al)$
- Coherent with γ matrix
- Precipitate strengthening phase



N263 - Typical microstructure



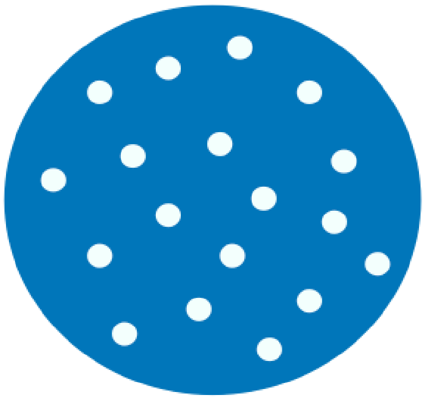
850°C 1 hour - SEM



750°C 50 hour - TEM

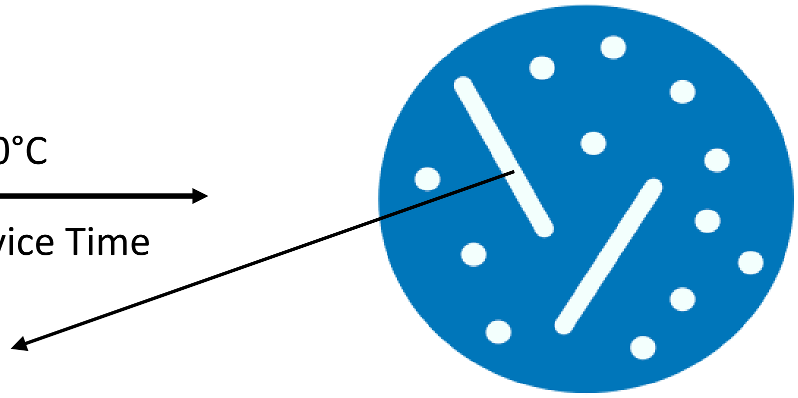
Zhao 2001

γ’ is metastable, converts to η with time.



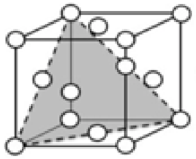
T > 700°C

Long Service Time

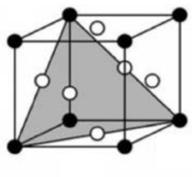


η phase (DO_{24})

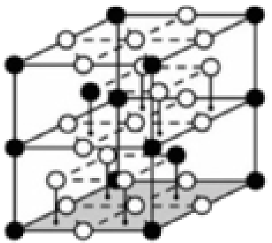
- Ni_3Ti
- Forms at the expense of γ’
- Not completely coherent with γ matrix
- Slow kinetics of formation



γ matrix

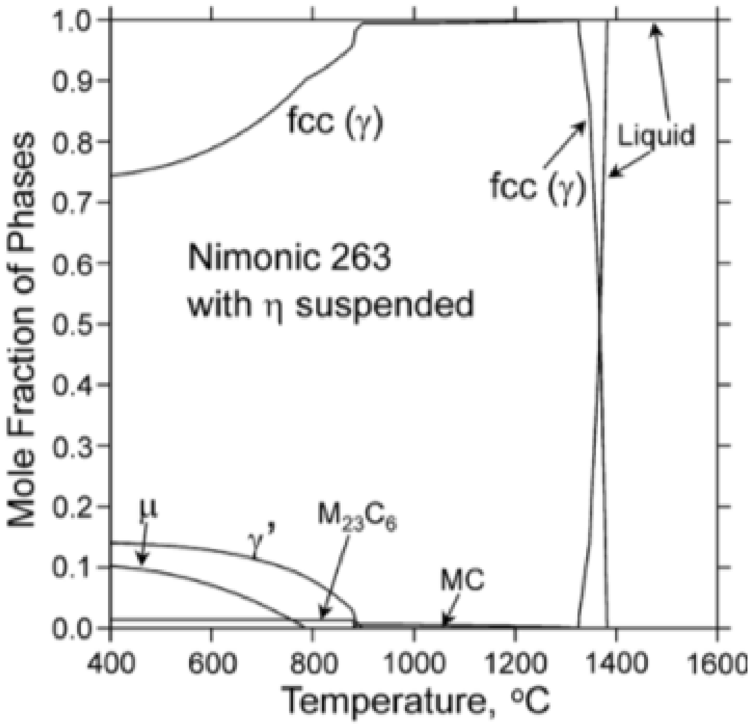


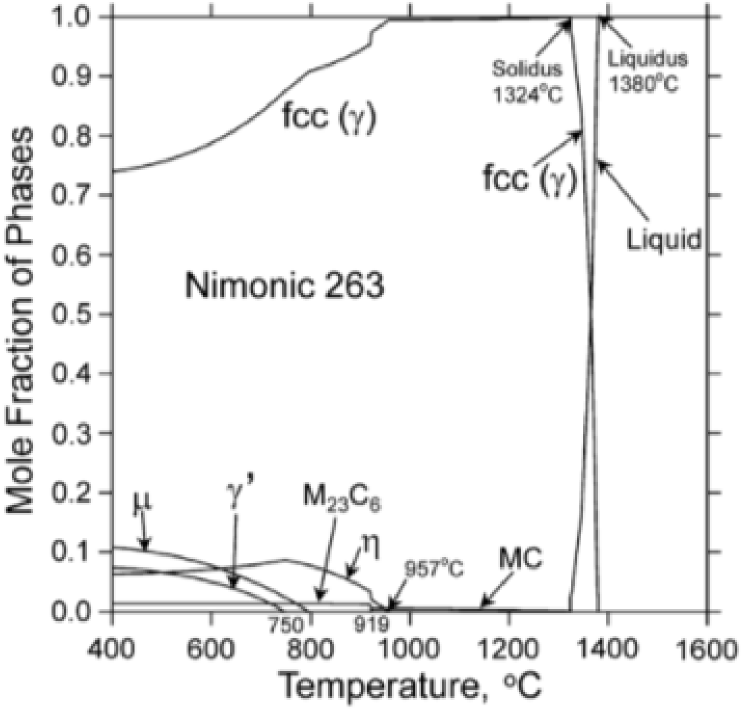
γ’ particles



η particles

η has slow kinetics of formation.

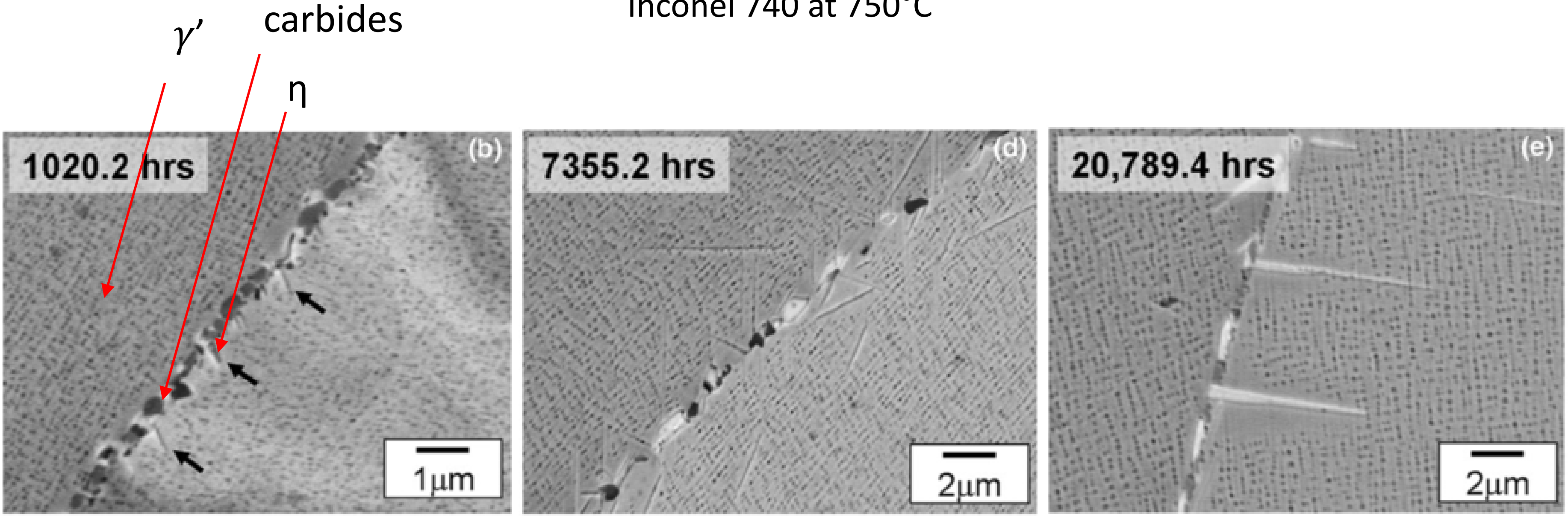




Often 'Turned off' in Thermocalc simulations for initial conditions

η forms DURING creep tests.

Inconel 740 at 750°C



Start of η Phase at Grain Boundary

η Phase Evolution

η phase formed DURING test

Shingledecker, 2012

There are conflicting reports in the literature about effects of η on creep properties.

Nimonic 263 [Zhang 2002]	800 °C	700 hrs	Reduces creep ductility; cavity nucleation and microcracking; avoid near grain boundary
Nimonic 263 [Zhao 2002]	816 - 840 °C	1100-1400 hrs	Claim detrimental to strength and ductility
Inconel 740 [Zhao 2003]	750 - 850°C	1000 hrs	Presence at grain boundaries reduced impact toughness
Inconel 740 [Evans 2004]	816 °C	2500 hrs	Reduce γ' strengthening/limit grain boundary ductility
Inconel 740 [Shingledecker 2012]	750 °C	2000-20000 hrs	Not detrimental to creep; formation kinetics faster under stress
Inconel 740 [Shingledecker 2013]	750 - 850°C	1000-20000 hrs	Reduced creep rupture ductility above 7 vol% eta
Inconel 740 [Unocic 2014]	750 °C	2000-23000 hrs	Not detrimental to creep

Problem statement

- η phase **will form** in A-USC components in service
- There is **no agreement** in the literature about whether | 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

We aim to study the effects of η on creep properties of Nimonic 263

- Study creep deformation and failure mechanisms varying across the microstructural spectrum

15% γ'

Material 1
γ' only

Standard N263
Contains γ' only,
prior to creep test

7% γ'
6% η

Material 2
γ' + η

Standard N263
Heat treated prior to
creep test to contain
γ' and η

15% η

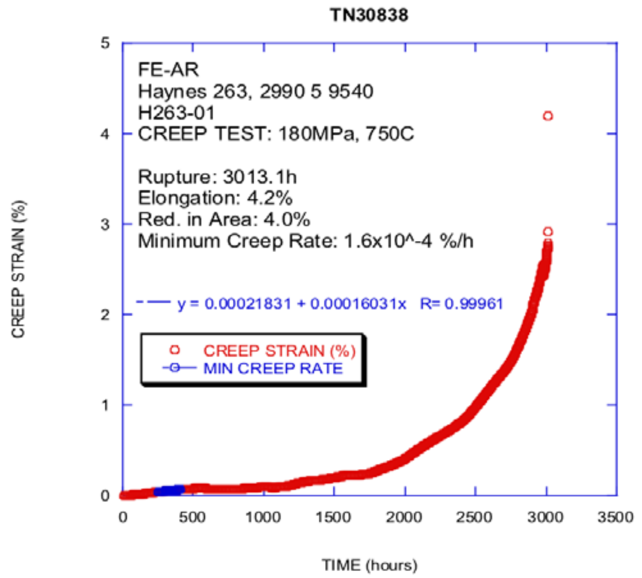
Material 3
η only

Modified Michigan Tech
alloy that contains η only,
prior to creep test

Michigan Technological University | EPRI Electric Power Research Institute | U.S. Department of Energy | National Energy Technology Laboratory

Material 1 – γ' only

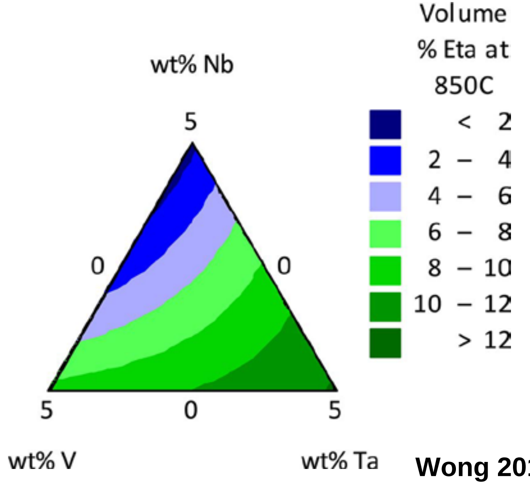
- Standard Commercial Nimonic 263
- Widely studied
- Creep data available from an earlier research carried out by EPRI
- Crept specimens from EPRI available for deformation studies



Michigan Technological University
EPRI ELECTRIC POWER RESEARCH INSTITUTE
U.S. DEPARTMENT OF ENERGY
NETL NATIONAL ENERGY TECHNOLOGY LABORATORY

Material 3 – η only

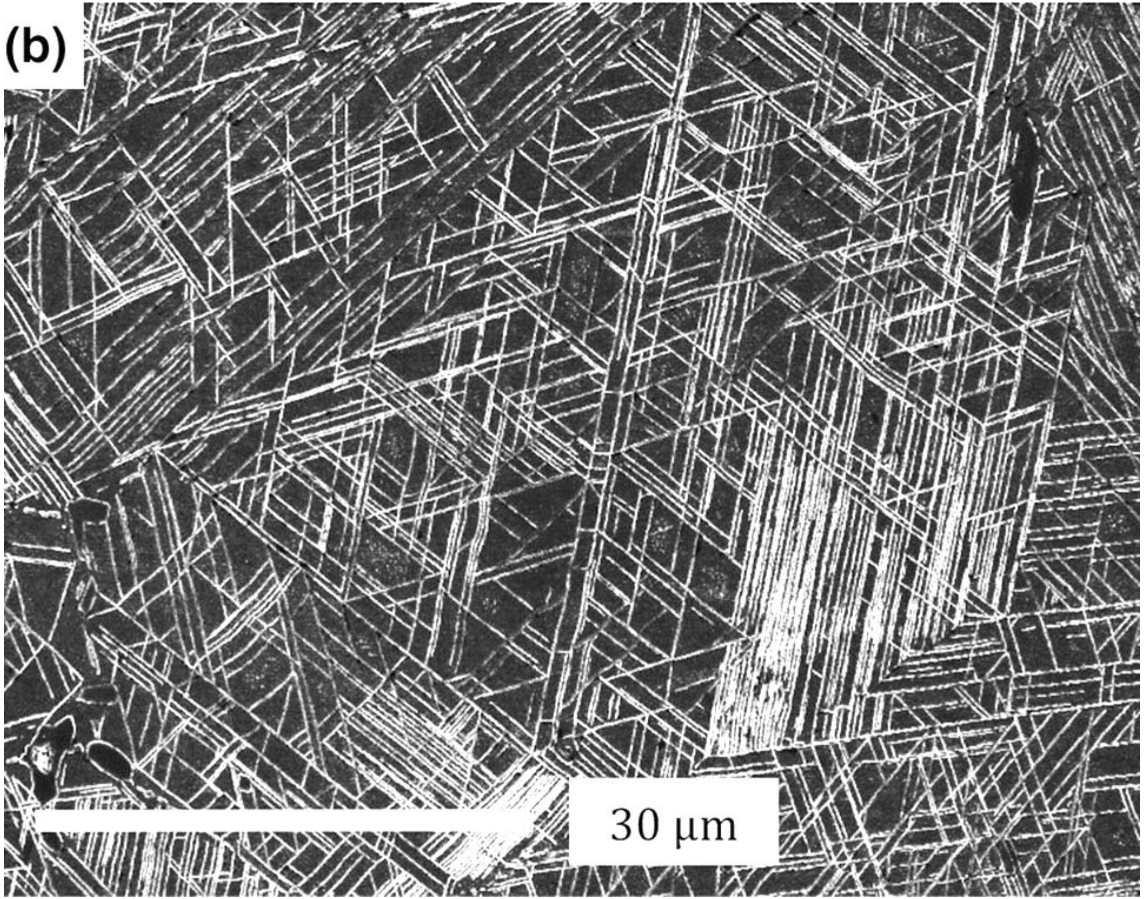
- Earlier Michigan Tech research - Goal to create Nimonic 263 with all η and no γ'
- DOE Approach using Thermo-Calc



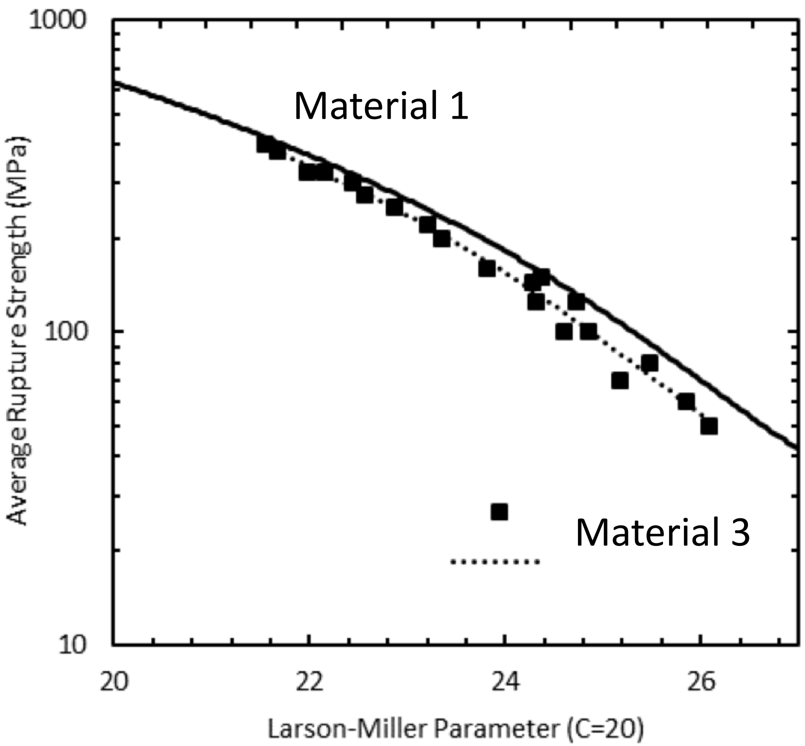
Wong 2015

Alloy Element	Ni	Cr	Co	Ti	W	Nb	Ta	V	Fe	Mn	Al	C	Mo
Nimonic 263	Bal	19.8	19.9	2.10	0.16	0.01	0	0.01	0.40	0.39	0.47	0.06	5.93
Alloy 20	Bal	20.8	20.7	2.75	1.94	1.92	1.09	0.85	0.48	0.42	0.14	0.07	0.01

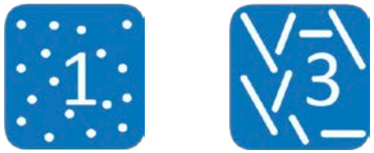
Material 3 aged at 850°C



Material 3 – Creep Performance

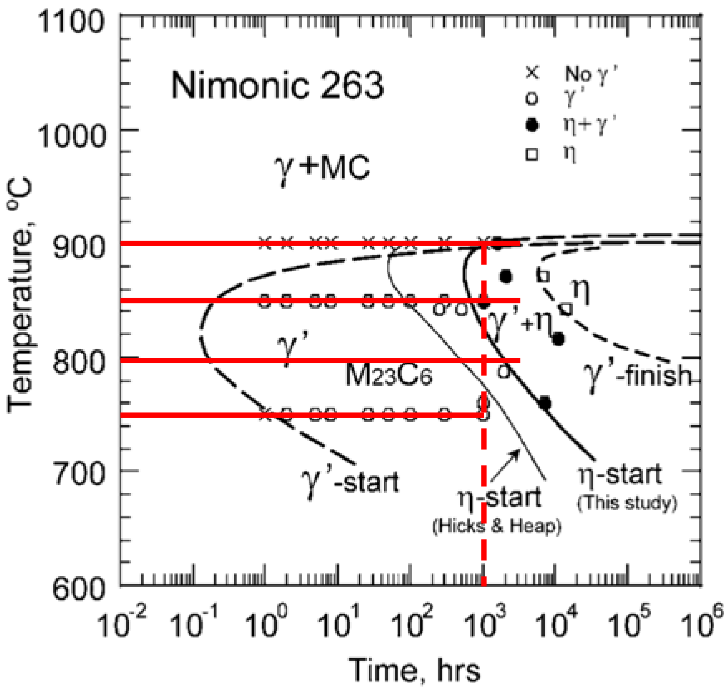


Creep tests were carried out from 700°C to 850°C



Material 2 – γ' + η

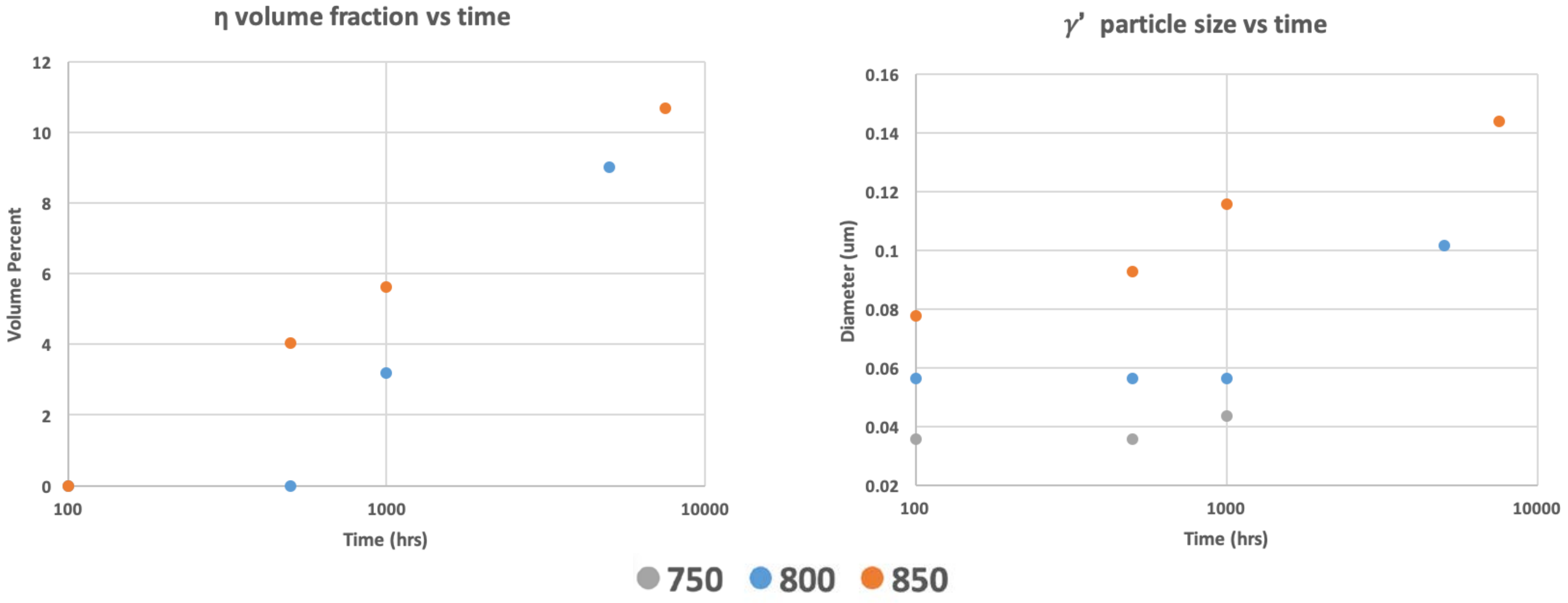
- Performed simulations in ThermoCalc with η phase 'on' and 'off' to work around sluggish η phase formation
- Conducted Literature review for experimental findings of phase formations to supplement ThermoCalc
- Samples were heat treated at 750°C, 800°C, 850°C, 900°C for 100hr, 500hr, 1000hr, 5000hr



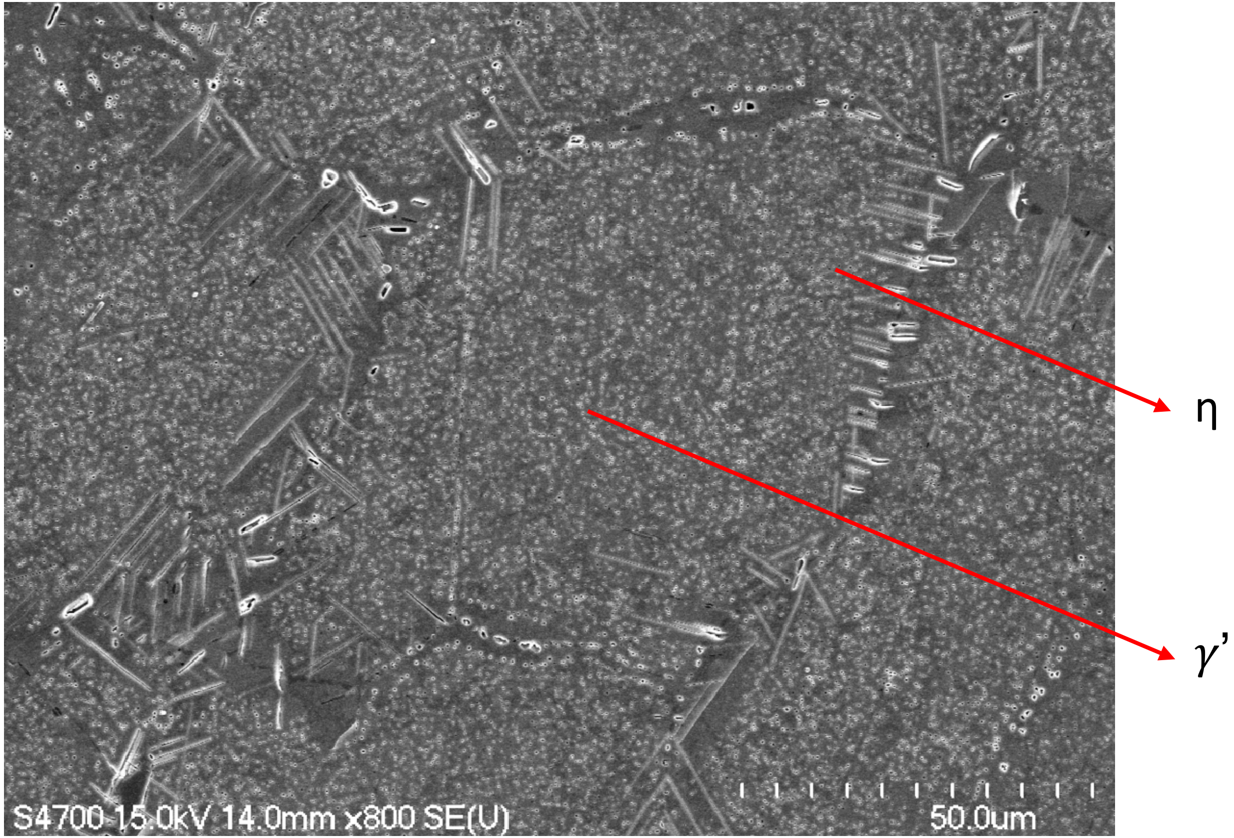
η volume fraction and γ' particle size vs time

750 °C – Very little η develops in these times

900°C – Near solvus temperature, most γ' and η has dissolved



We chose 850°C 1000H heat treatment for Material 2



Creep tests

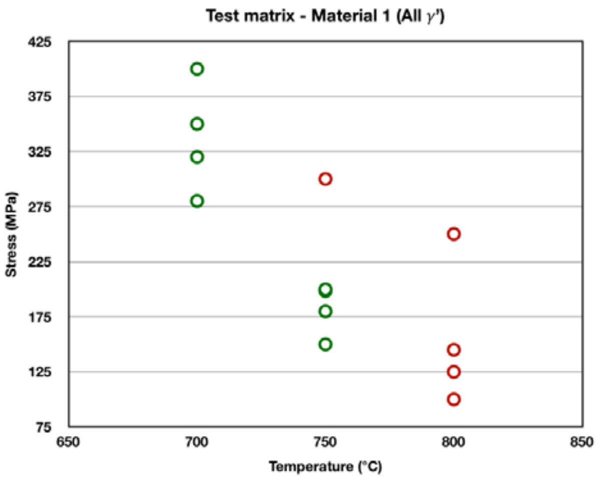
Characterization

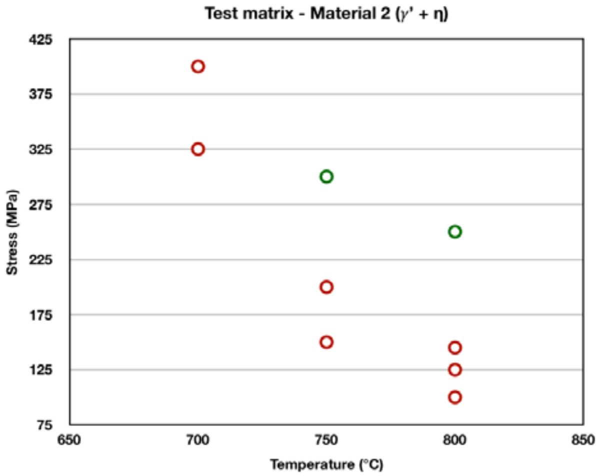
Modelling

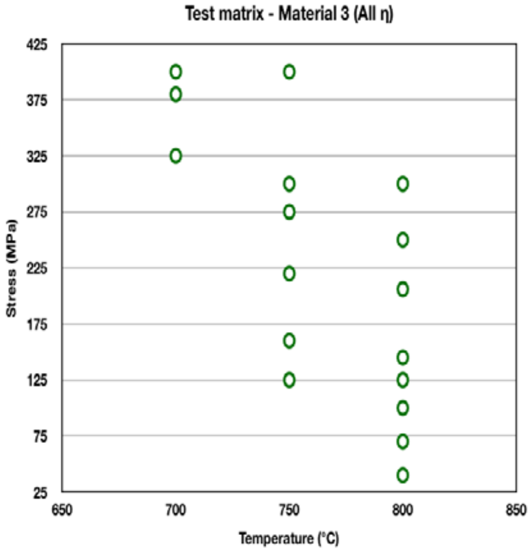
Creep test matrix

Creep tests

Completed   Scheduled

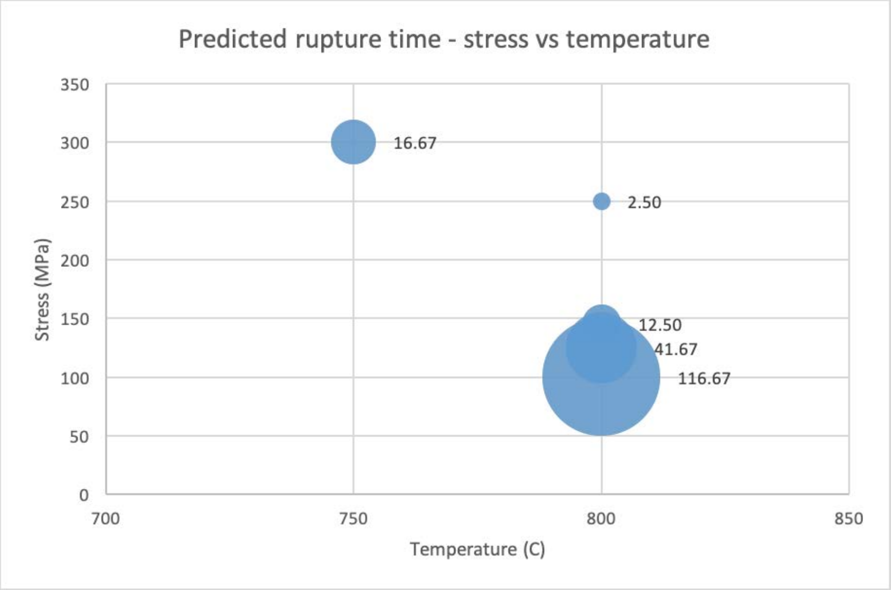


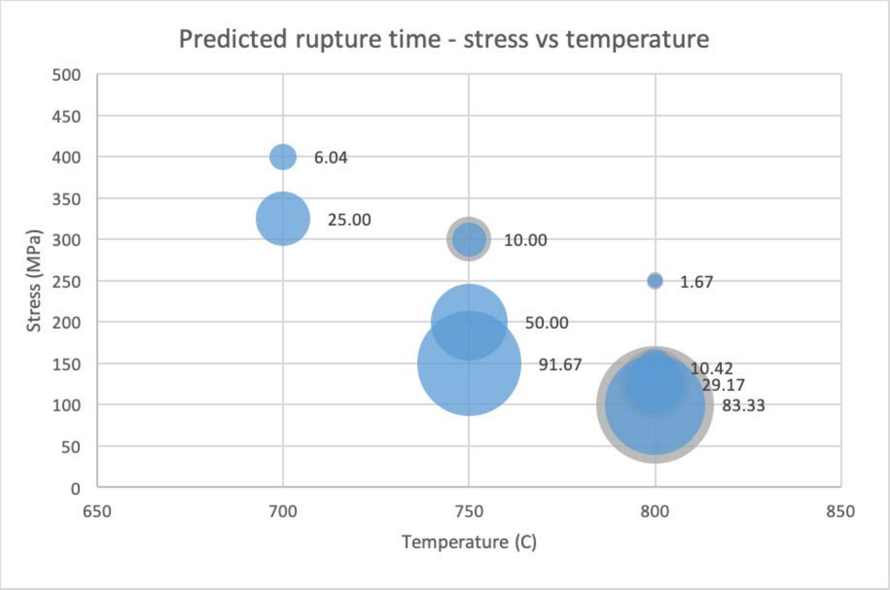




Michigan Technological University   EPRI ELECTRIC POWER RESEARCH INSTITUTE   U.S. DEPARTMENT OF ENERGY   NETL NATIONAL ENERGY TECHNOLOGY LABORATORY

Predicted rupture time (days)

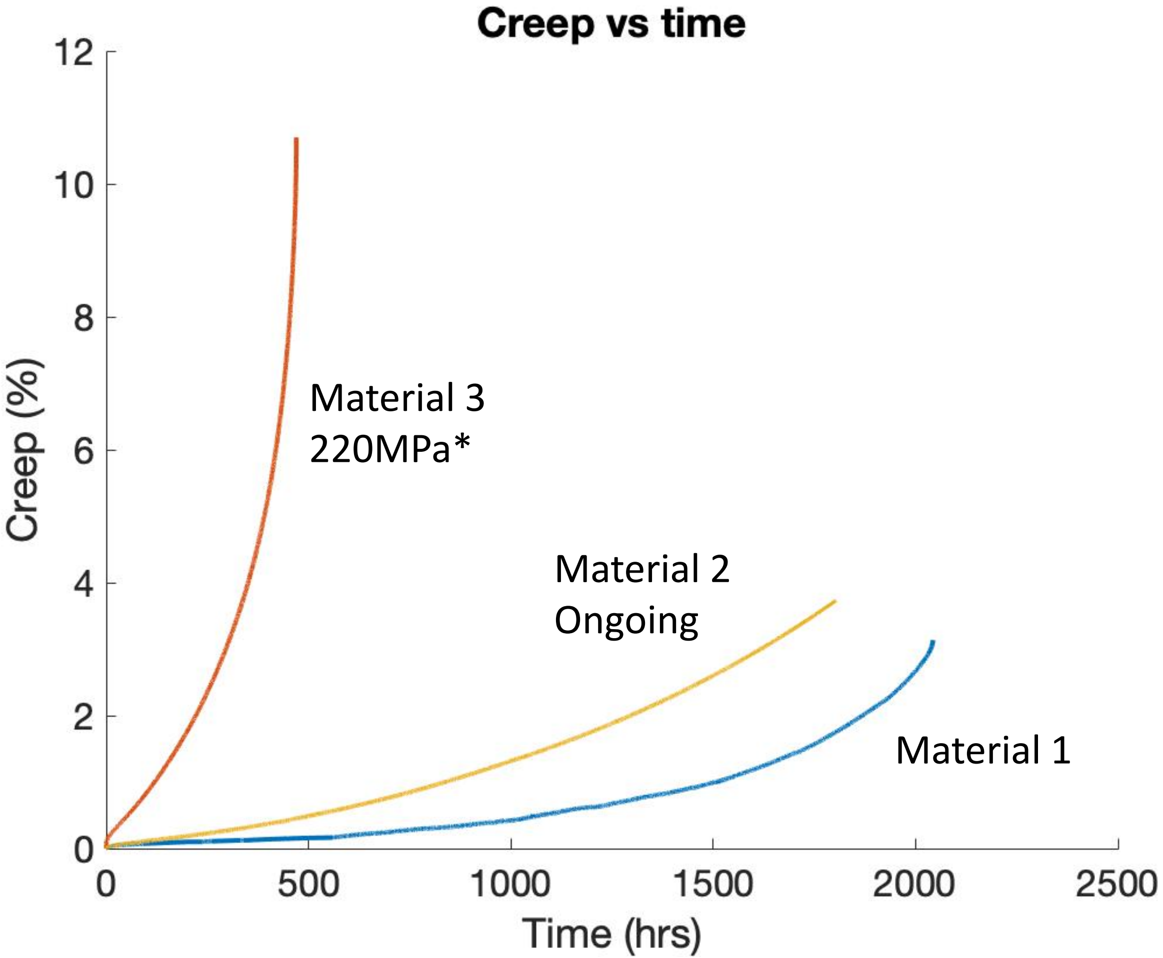




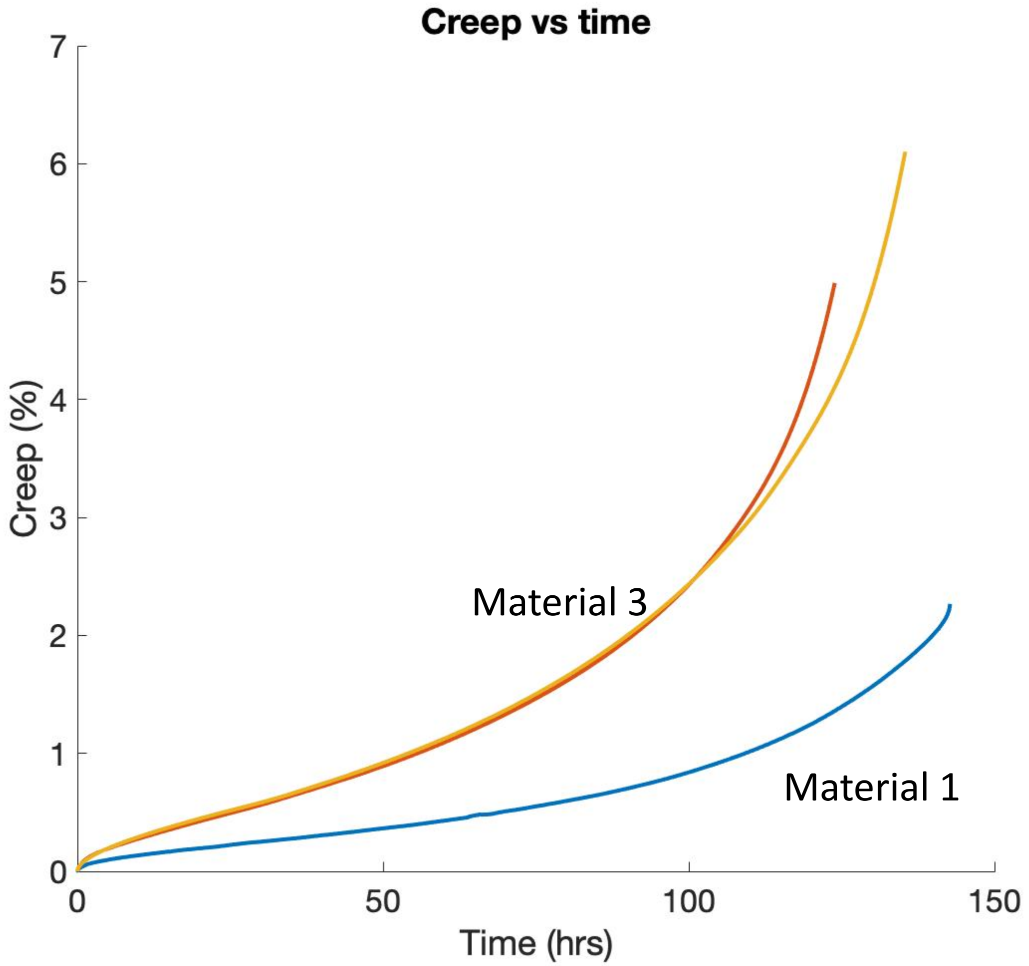
~500 days of creep tests planned
~170 days considering 3 frames
Should be done by October

Considering stress change creep tests

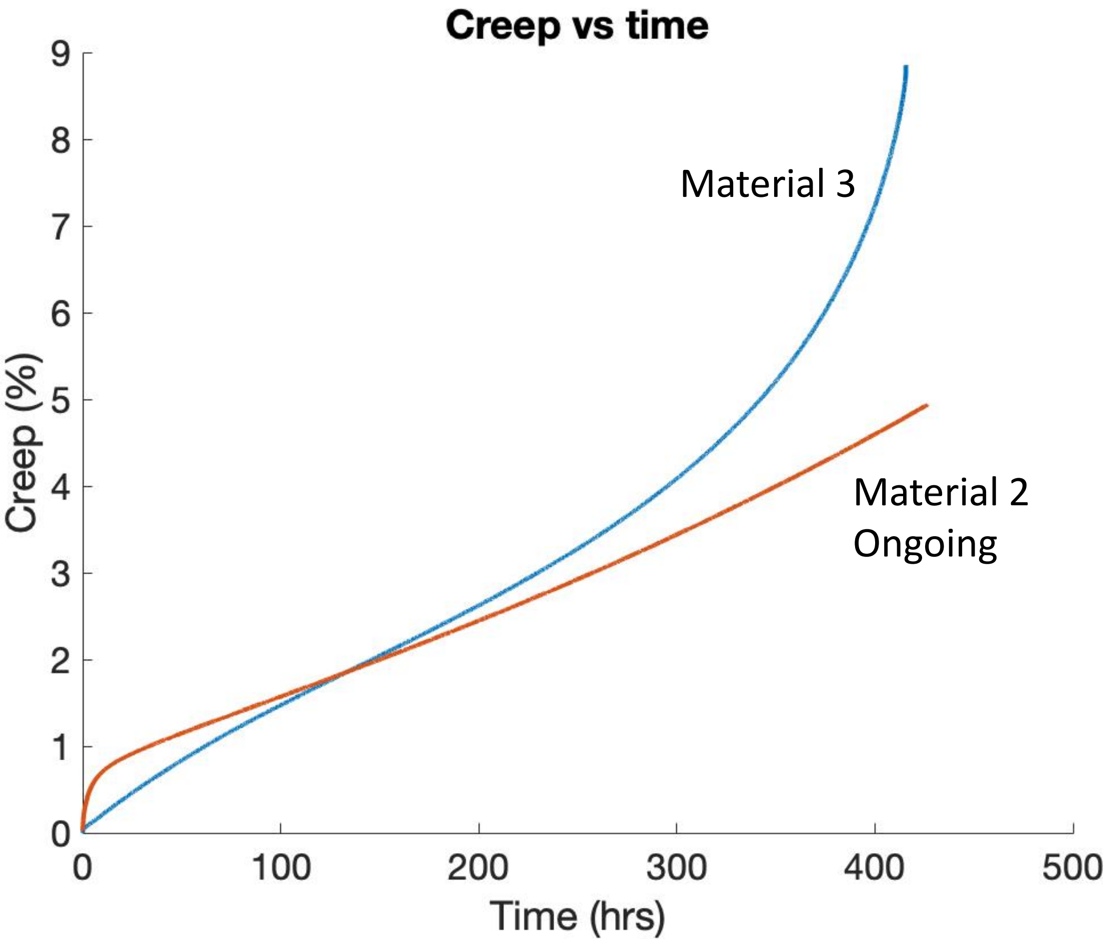
Creep tests at
700C 200MPa



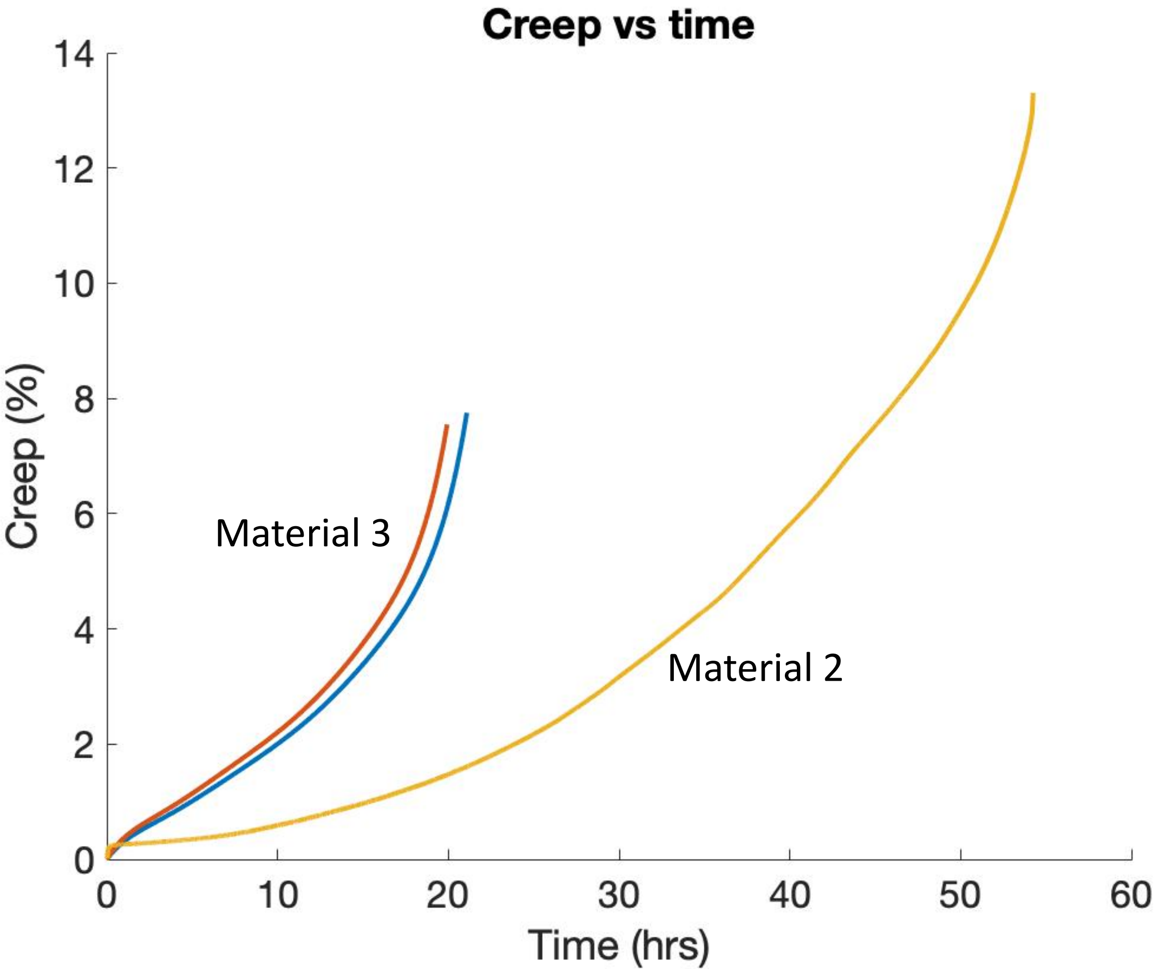
Creep tests at
700C 400MPa



Creep tests at
800C 145MPa



Creep tests at
800C 250MPa



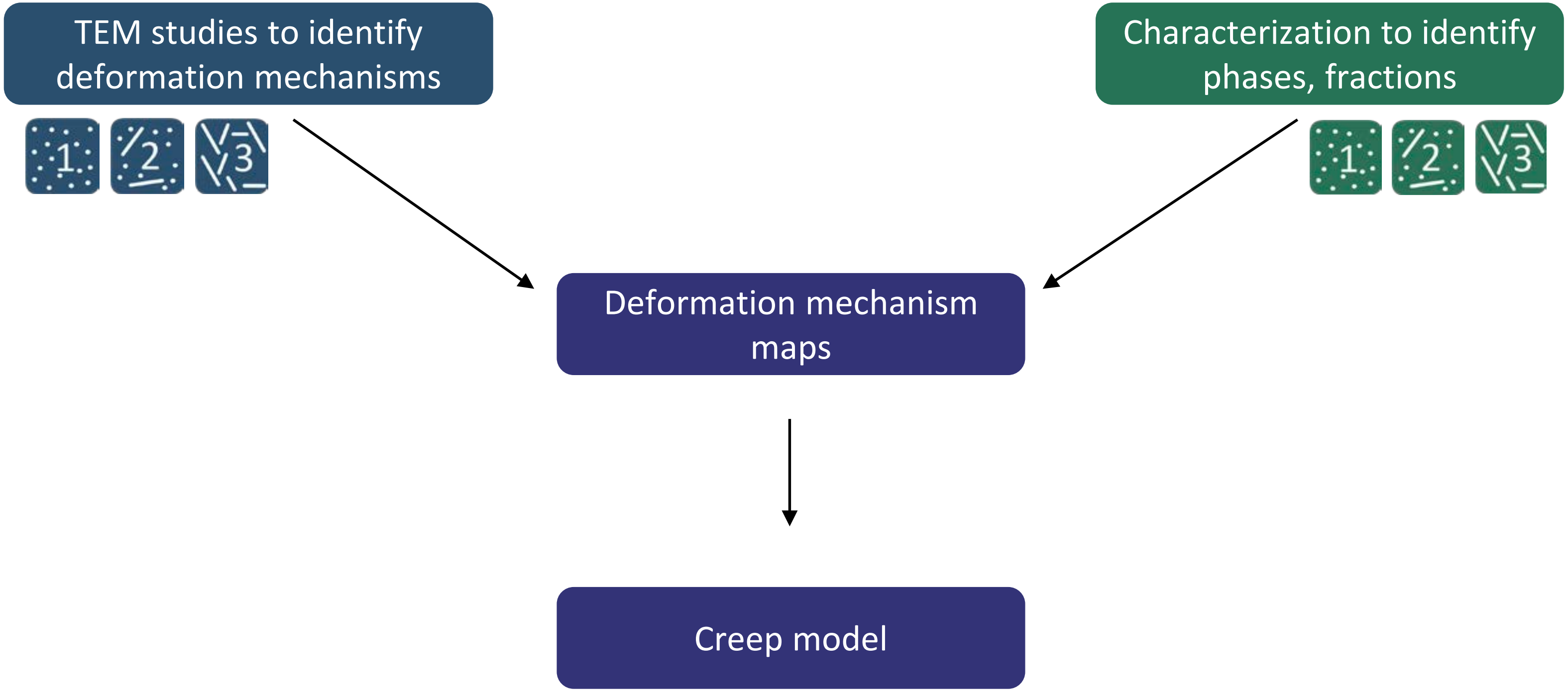
Creep tests - preliminary summary

- Creep properties (first glance) – 

> 

> 

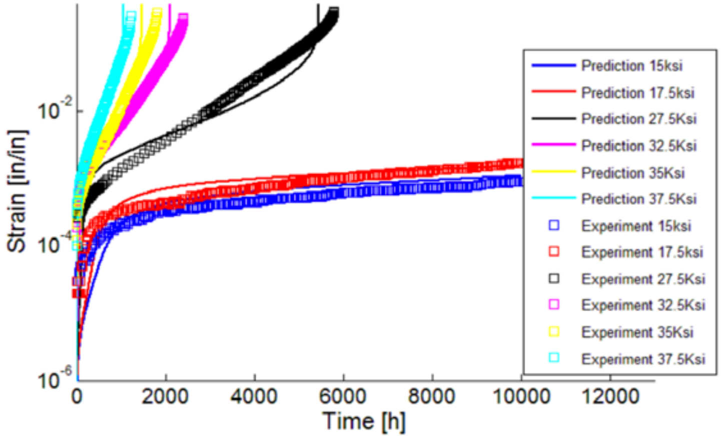
- Potential reasons:
  - Presence of η, and/or
  - Coarsened γ’, and/or
  - Reduced γ’ volume fraction
- Requires further experimentation and modelling


TEM studies to identify deformation mechanisms
Characterization to identify phases, fractions
Deformation mechanism maps
Creep model

Choosing a baseline creep model for γ' strengthened Nickel superalloys

Modelling

- Substantial prior research has been conducted by many investigators to develop physically-informed creep models for these types of alloys. (Dyson et al., many others)
- DOE-sponsored research by Shen Chen and his team at GE Global Research resulted in an outstanding model that worked very well for Haynes 282
  - DE-FE0005859 and DE-FE0024027



Shen Chen 2014

Creep model

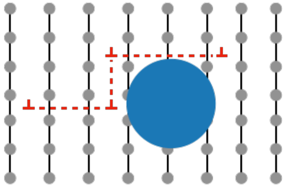
- Chen Shen's code based on Dyson model used at starting point
- His material - Haynes 282 with γ' (no η)
- The model includes microstructural parameters such as γ' size and volume fraction, APB energy, γ' coarsening in service, diffusional parameters, etc.
- The output of the code is plot of creep strain vs time for given input temperature, stresses, variables and precipitate coarsening data over time. ***Includes cavitation and failure.***

$$\varepsilon_{creep} = \varepsilon_{dislocation} + \varepsilon_{diffusion}$$

$$\varepsilon_{dislocation} = \varepsilon_{climb} + \varepsilon_{shearing}$$

$$\sigma_{shear} = \frac{\gamma_{APB}}{2b}\left[\left(\frac{12\gamma_{APB} f r}{\pi G b^2}\right)^{\frac{1}{2}} - f\right]$$

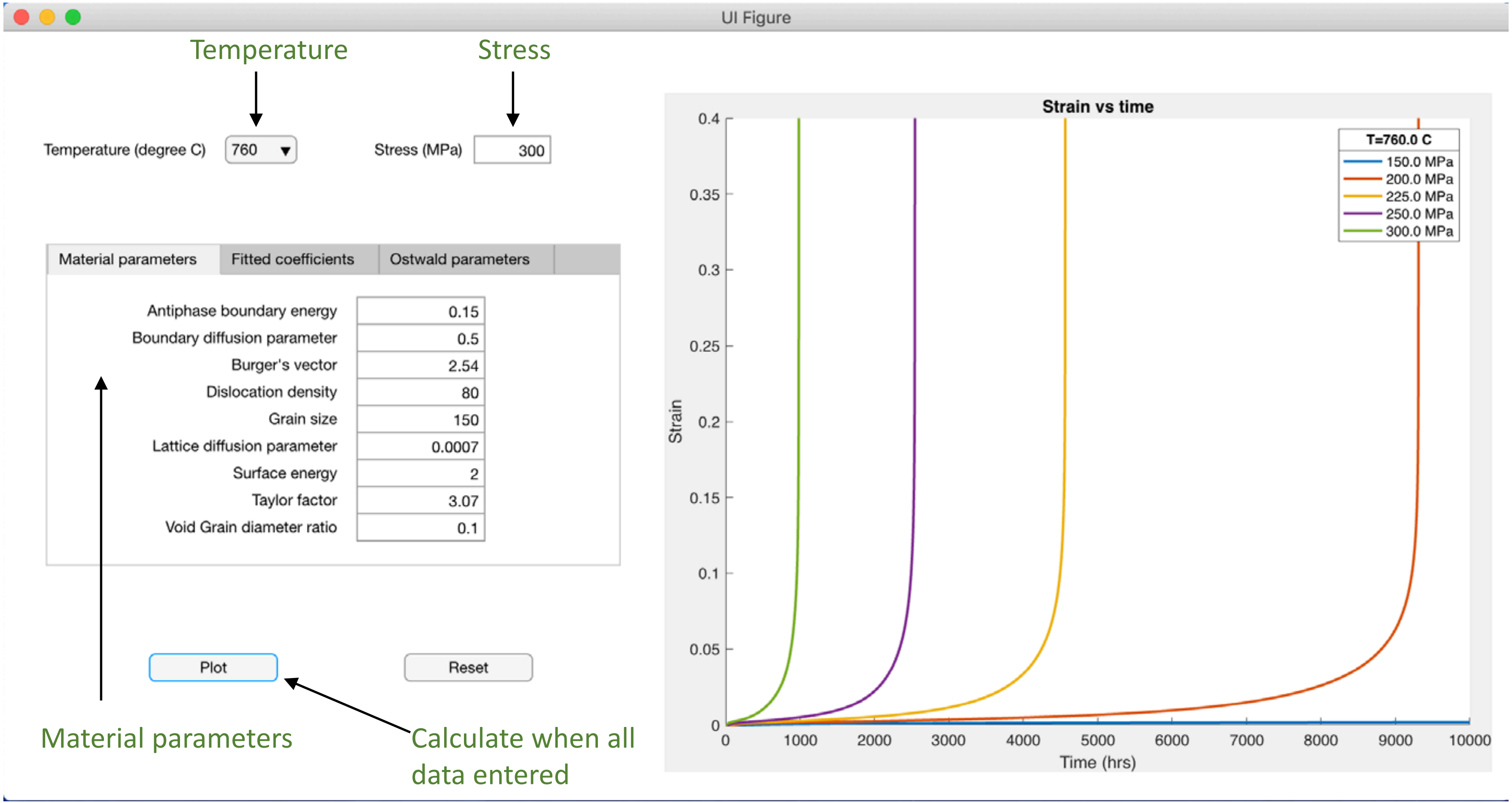
$$\sigma_{climb} = \frac{2f}{1+2f}\,\sigma_{eff}\left[1 - \exp\left(-\frac{1+2f}{2(1-f)} E \frac{\varepsilon^{disloc}}{\sigma_{eff}}\right)\right]$$



$$\dot{\varepsilon}^{disloc} = \begin{cases} \rho A f (1-f)\left(\sqrt{\frac{\pi}{4f}} - 1\right)\sinh\left(C\,\frac{\sigma_{eff} - \sigma_B - \sigma_0}{M k T}\, b^2 \lambda\right) & if\ \sigma_{eff} - \sigma_B - \sigma_0 > 0 \\ 0\ otherwise & \end{cases}$$

Code development

Chen Shen's model		Our model
Material parameters hard-coded in MATLAB model	→	Implemented a Graphical User Interface (GUI) that allows the user to change important variables
Precipitate coarsening handled by a look-up table and interpolation	→	Changed code to allow input of an LSW precipitate coarsening model


UI Figure
Temperature
Stress
Temperature (degree C)
760
Stress (MPa)
300
Material parameters
Fitted coefficients
Ostwald parameters
Antiphase boundary energy 0.15
Boundary diffusion parameter 0.5
Burger's vector 2.54
Dislocation density 80
Grain size 150
Lattice diffusion parameter 0.0007
Surface energy 2
Taylor factor 3.07
Void Grain diameter ratio 0.1
Plot
Reset
Material parameters
Calculate when all data entered
Strain vs time
Strain
Time (hrs)
T=760.0 C
150.0 MPa
200.0 MPa
225.0 MPa
250.0 MPa
300.0 MPa

Summary

- Aim - To quantify effects of η phase on Creep properties of Nimonic 263
- Compare three microstructures, (all γ') - (γ' + η) - (all η)
- Creep tests indicate increased strain rates from 

Summary

- Study deformation and damage mechanisms using TEM
- Create Deformation Mechanism Maps for three microstructures
- Modify existing creep model to incorporate η phase effects

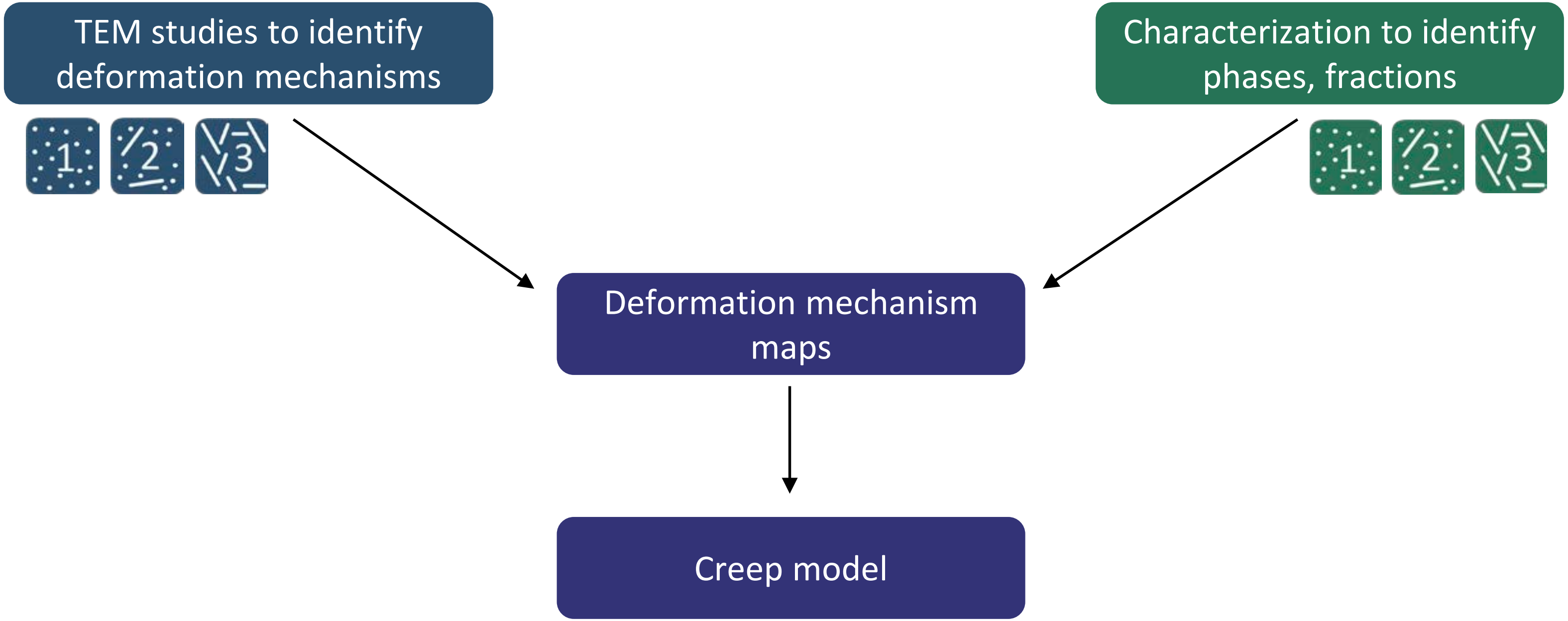
Milestones

Milestone Title/Description	Planned Completion Date	Actual Completion Date
2.0 Develop heat treatments to form γ' and η phases in Nimonic 263 prior to creep testing	1/31/2017	3/1/2018
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	3/1/2018
2.2 Validate predictions in (2.1) experimentally, and adjust as needed.	1/31/2017	6/15/2018
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	12/22/2017
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	25%

Milestones

Milestone Title/Description	Planned Completion Date	Actual Completion Date
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	25%
4.1 Conduct optical, SEM and TEM microscopy to quantify phase transformations, precipitate size evolution, deformation mechanisms (TEM), and damage evolution.	10/31/2018	30%
4.2 Establish effects of microstructure on deformation mechanisms in all three microstructures	1/31/2019	0%
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	0%
5.0 Modify existing γ' based creep models to account explicitly for the effects of η phase as determined in (4.)	8/31/2019	35%
5.1 Assess and integrate best damage models from the literature	2/28/2019	60%
5.2 Adapt models to explicitly include the transformation from metastable γ' to equilibrium η and resultant changes in damage mechanisms	6/30/2019	0%
5.3 Validate model with select creep experiments	8/31/2019	0%

Questions?



Michigan Technological University

EPRI ELECTRIC POWER RESEARCH INSTITUTE

U.S. DEPARTMENT OF ENERGY

NETL NATIONAL ENERGY TECHNOLOGY LABORATORY