Development of High Performance Ni-base Alloys for Gas Turbine Wheels Using a Co-precipitation Approach

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Outline

- Background
- Co-precipitation Concept
- Program overview
- Present Status:

  Alloy preparation and testing

  Creep testing status

  Deformation Mechanisms in γ'/γ'' alloys
- Summary

THE OHIO STATE UNIVERSITY

Path to Higher Efficiency Gas Turbine

Today's combined cycle efficiency is ~62%

Pressure Ratio: Higher

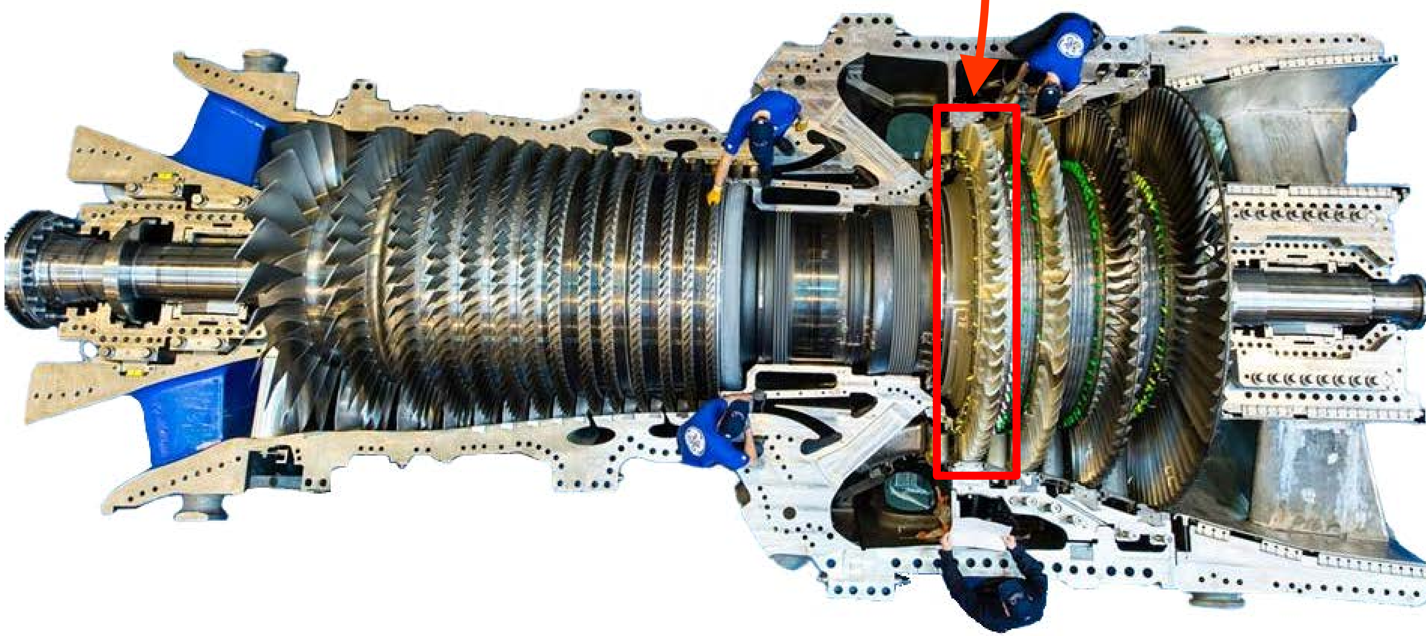
Firing Temperature: Higher

Sealing Flows: Lower

Cooling Flows: Lower

INCREASING WHEEL TEMPERATURE

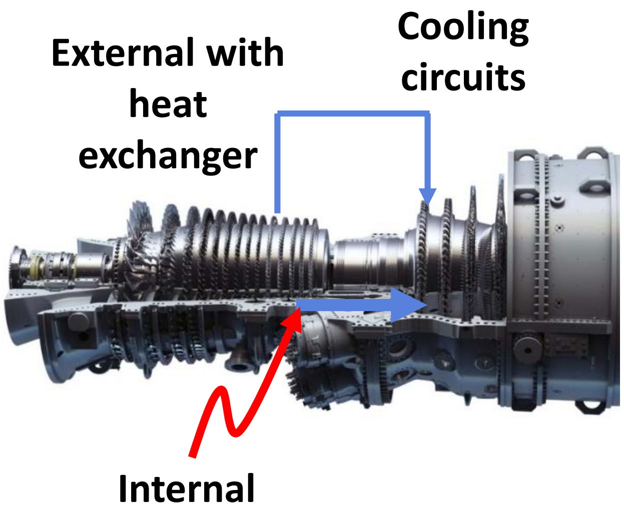
Future turbine combined cycle efficiency is ~65%



Next generation heavy duty gas turbine wheels must operate at higher temperatures to enable combined cycle efficiency improvements

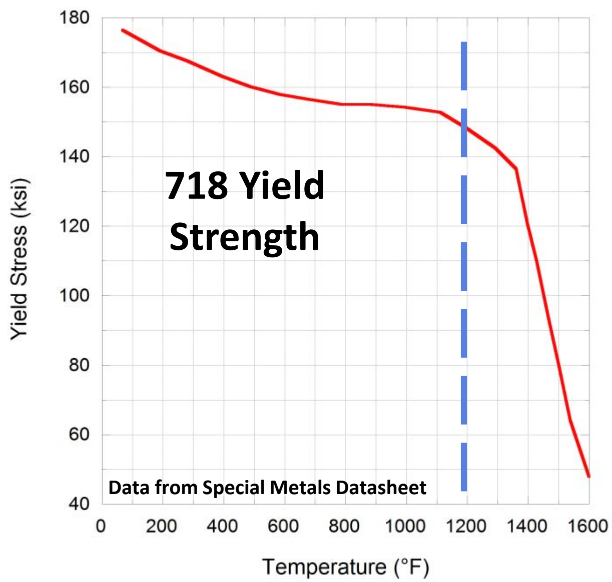
Designing a Higher Temperature Capable Wheel

Use steel and cool to lower the effective temperature



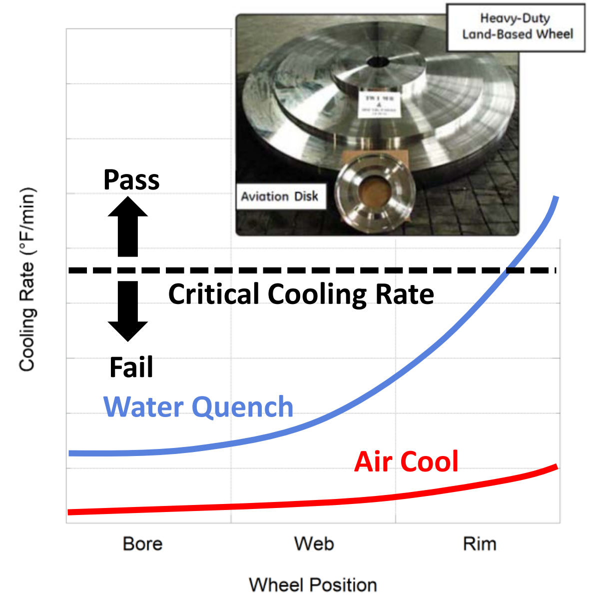
Cooling leads to reduced efficiency, increased complexity, & reliability risks.

Invent a better γ'' (Ni_3Nb) strengthened alloy



γ'' strengthening phase is unstable at temperatures >1200°F.

Use an Aviation disk alloy strengthened with γ' (Ni_3Al)



Precipitation kinetics result in severe over aging of γ', yielding poor properties.

A new approach to alloy design is required to enable high temperature wheels

Coprecipitation Concept

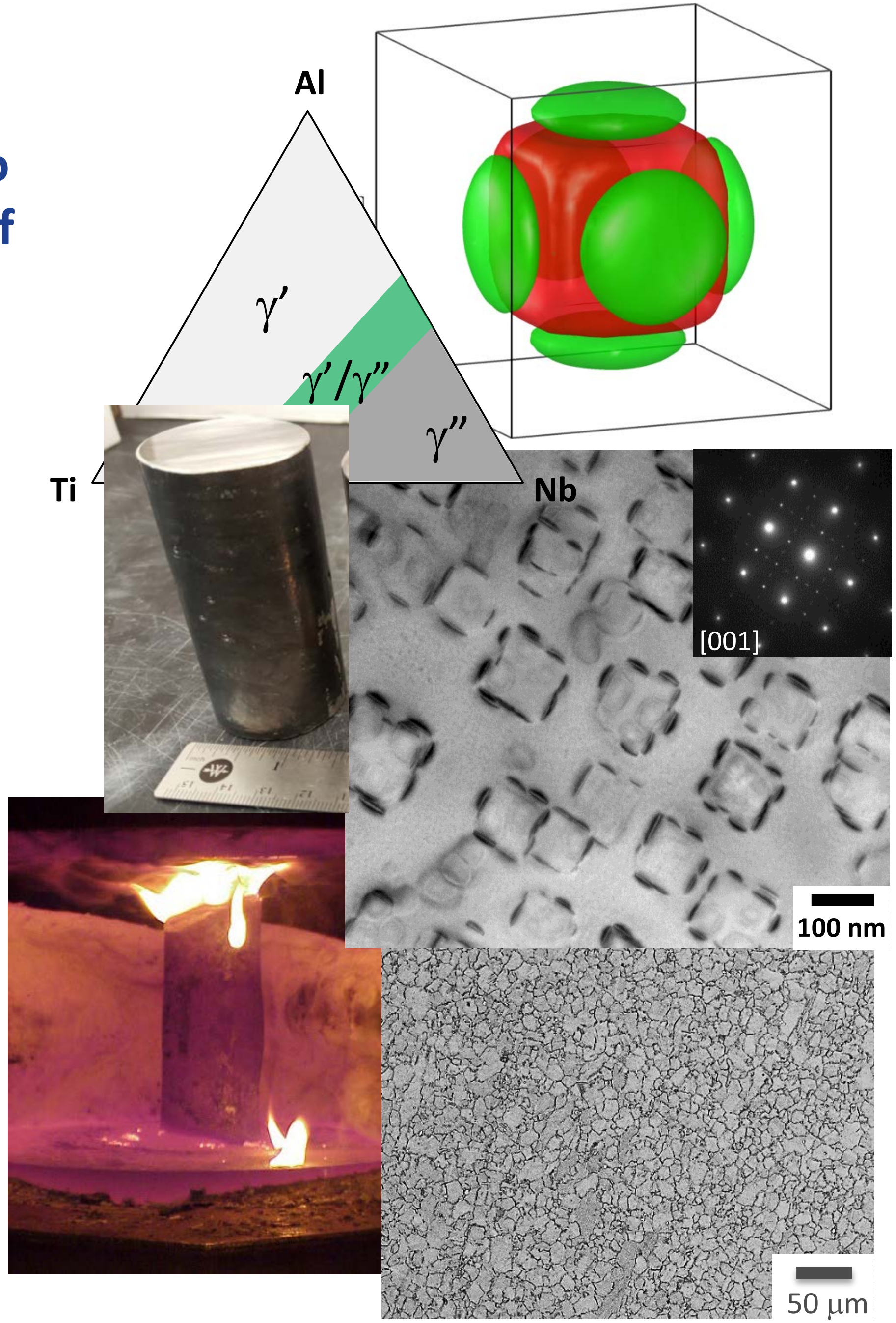
- **Leverage the coprecipitation of γ' and γ'' to restrict γ' coarsening during slow cooling of thick section components.**

- **Desire "compact" coprecipitate structure first identified by *Cozar and Pineau (1973)***

In previous NETL program (DEFE0026299):

- **Developed successful sub-scale billetizing/forging procedure**

- **Screened tensile and hold time fatigue crack growth properties (*no creep testing or evaluation*)**



Program Structure

Program Timeline

Mo. 1:
Program Initiation

Mos. 2-8:
Round 1 Alloys (2)

Mos. 9-20:
Round 2 Alloys (4)

Mos. 21-32:
Round 3 Alloys (2)

Mos. 33-34:
Program Wrap-Up

Mo. 35-36:
Documentation

1.0 Project Management [OSU]

2.0 Alloy Processing and Evaluation

- **2.1 Alloy Selection and Processing [GRC]**
- **2.2 Heat Treatment and Microstructure Characterization [GRC]**
- **2.3 Aging Informed by High Temperature Indentation [OSU]**
- **2.4 Phase Field Modeling and Characterization of Coprecipitation [OSU]**
- **2.5 Mechanical Testing [OSU/Metals Tech]**

3.0 Property Model Development

- **3.1 Deformation Mechanism Characterization [OSU]**
- **3.2 Yield Strength Model [OSU]**
- **3.3 Creep Model [OSU]**

The Ohio State University

Professor ***Michael Mills*** (PI) overall program coordination and lead on mechanical testing and deformation microstructure characterization

Professor ***Yunzhi Wang*** (co-PI) will lead the modeling efforts

GE Global Research

Rich DiDomizio leads alloy preparation and processing

Reza Shargi-Moshtaghin will perform TEM microstructure characterization of as-processed alloys

Metals Technology, Inc

Robert Hayes will perform the creep testing as cost-share to the project

Personnel

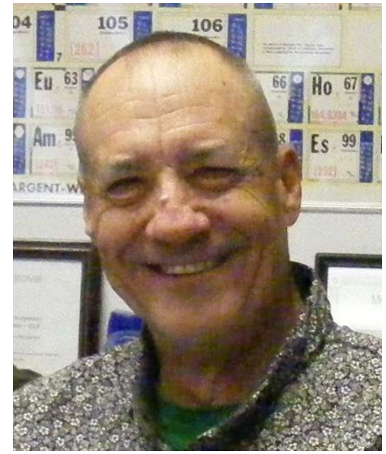
<u>PIs</u>:

Mike Mills

Yunzhi Wang

Bob Hayes

Rich DiDomizio



<u>Experiments</u>:

Semanti Mukhopadhyay

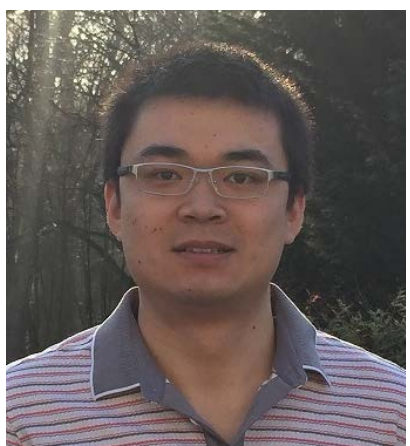
Christopher Zenk

<u>Modeling</u>:

Longsheng Feng

Kamalnath Kadrivel

Hariharan Sriram



Strengthening Phases in IN 718 Variant Alloys

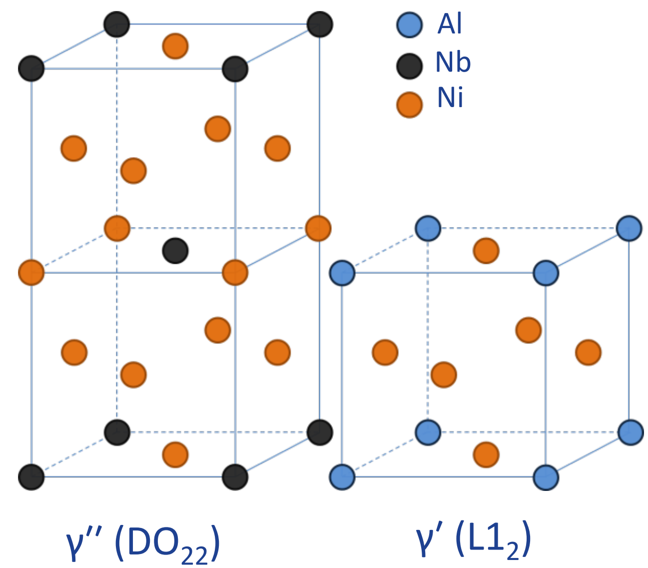
Ni	Fe	Cr	Nb	Al	Ti	Mo
53.1	18.6	18.4	5.29	0.55	1.02	3.05

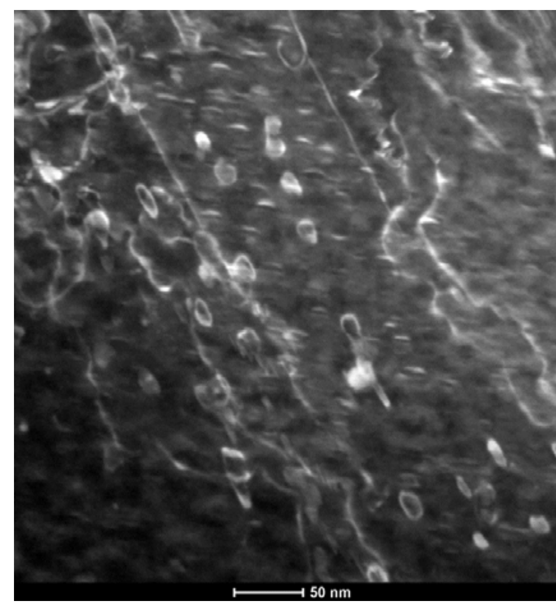
- Alloy 718 is favored for its high temperature strength retention and weldability

- Widely used as a jet engine disk alloy

- γ' and γ''-strengthened Ni-base superalloy (Nb-rich, $D0_{22}$)

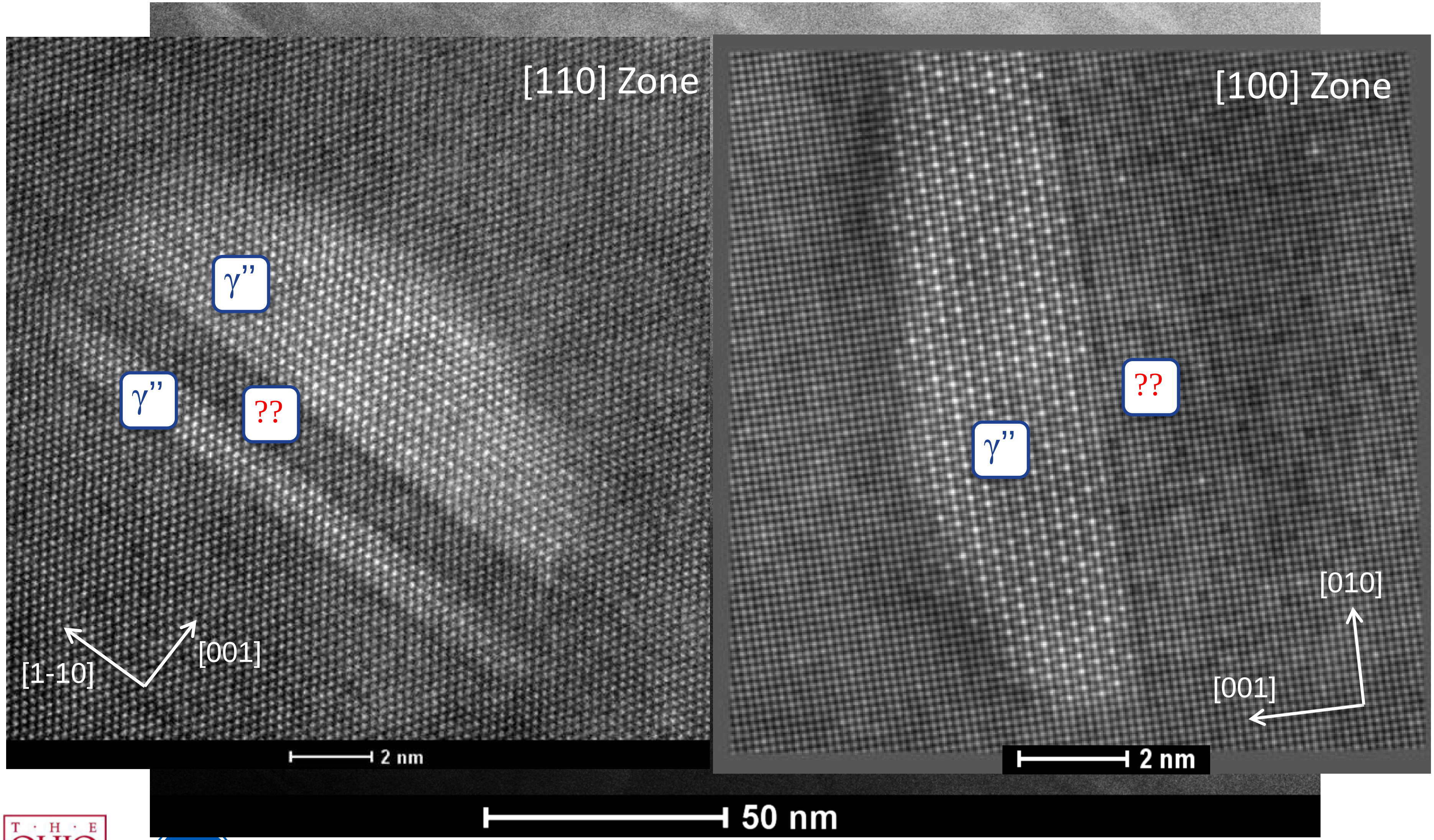
- Scant analysis of precipitate structures or deformation mechanisms for commercial heat treatments





Composite “Sandwich” Precipitates

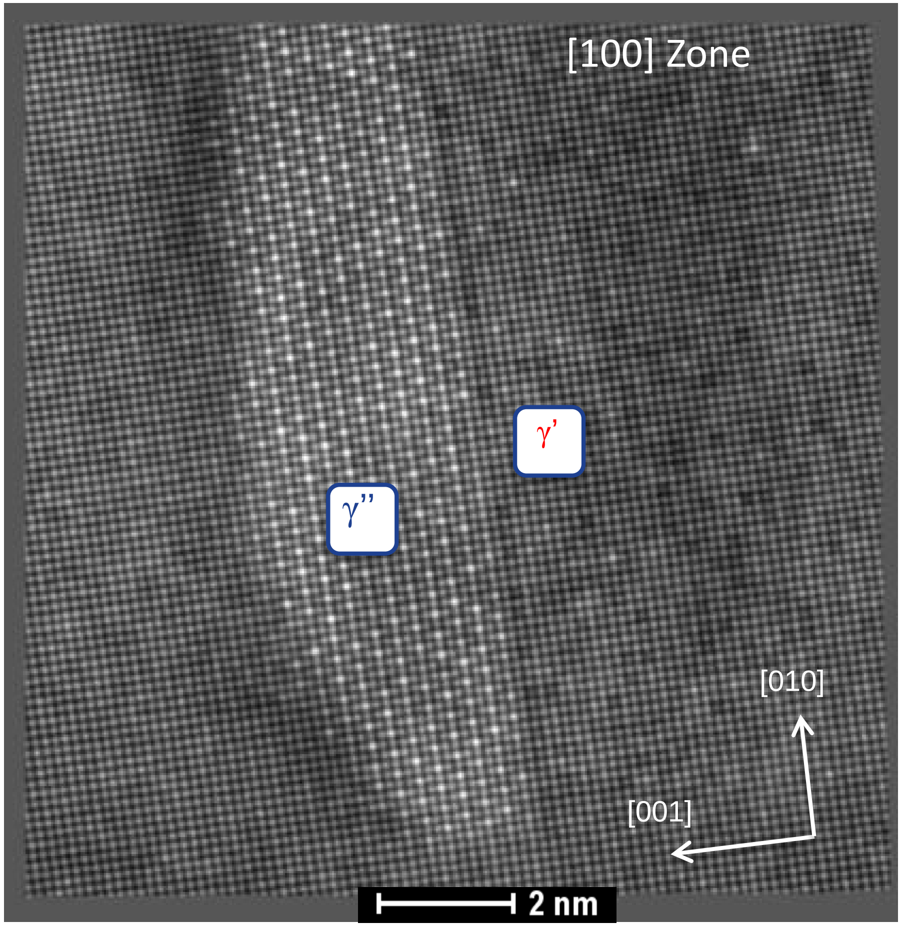
HAADF Imaging



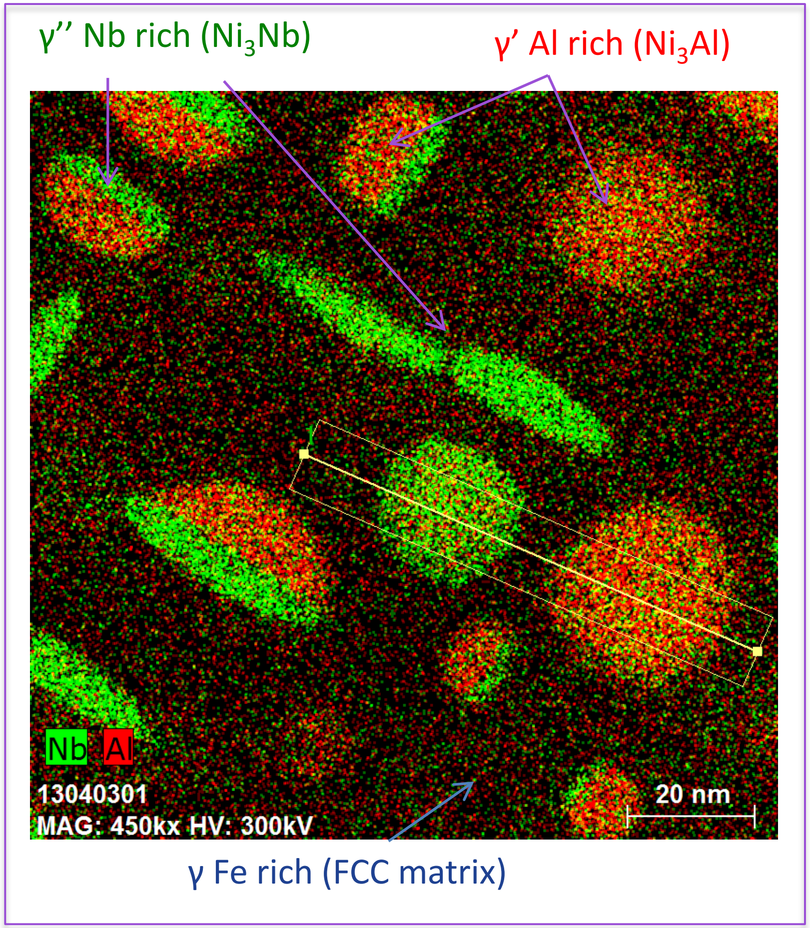
D. McAllister, et al, Superalloy 718 and Derivatives (2018)

Structure and Composition of Composite Particles in Alloy 718

HAADF-STEM



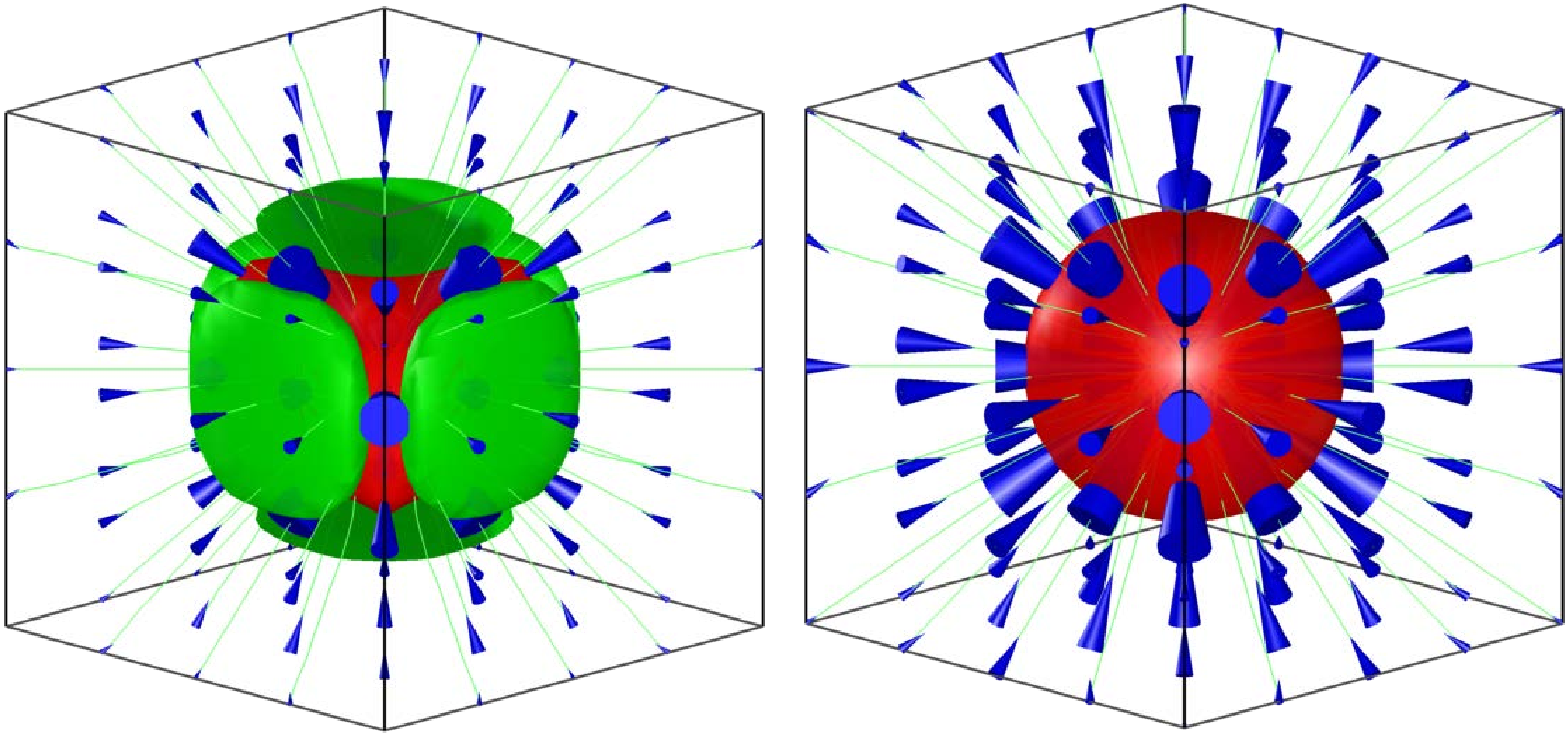
SuperX EDS



D. McAllister, et al, Superalloy 718 and Derivatives (2018)

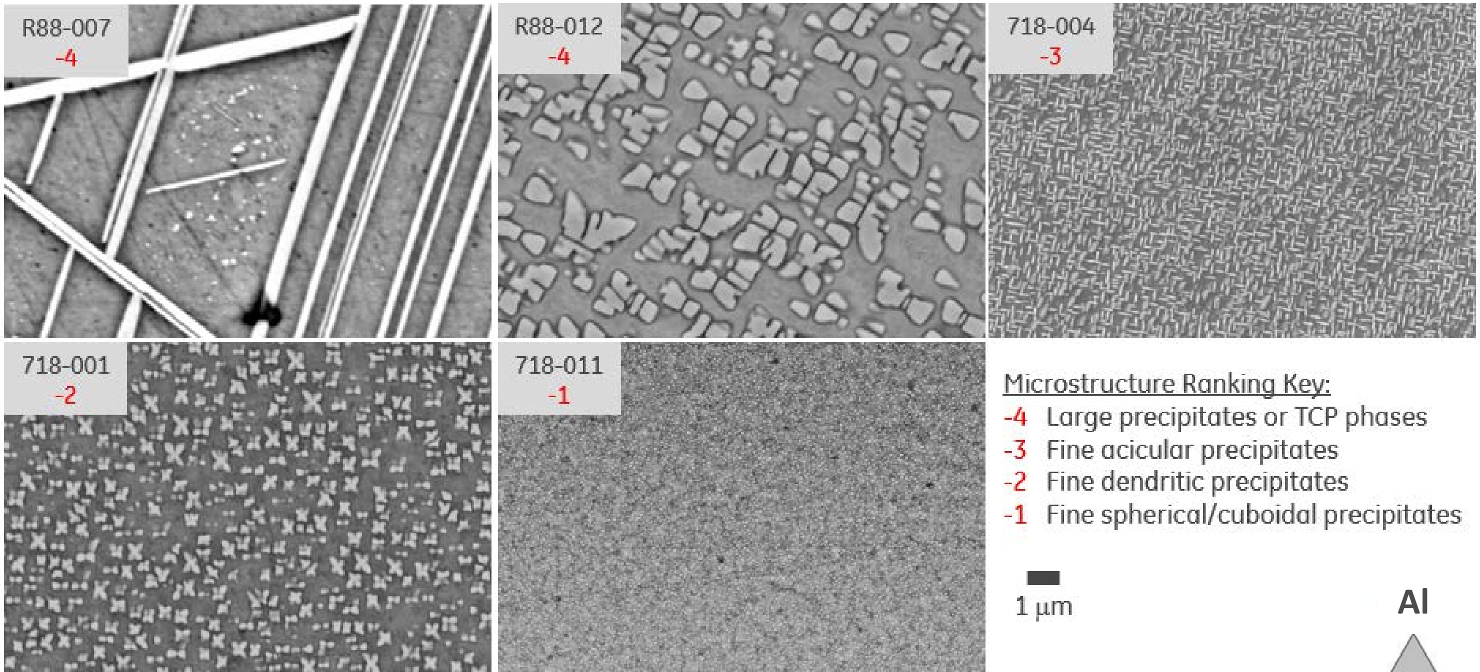
Effect of Coprecipitation on Precipitate Coarsening

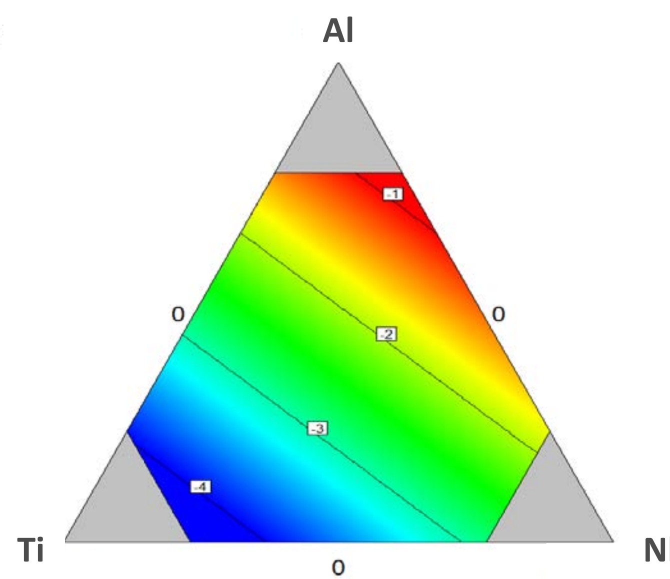
- Precipitate γ'' heterogeneously on all 6 interfaces of γ' to restrict γ' coarsening during slow cooling of thick section components



Phase field model simulation showing that γ'' provides a barrier to diffusion of Al which is needed for γ' to coarsen

Coprecipitation Alloy Screening

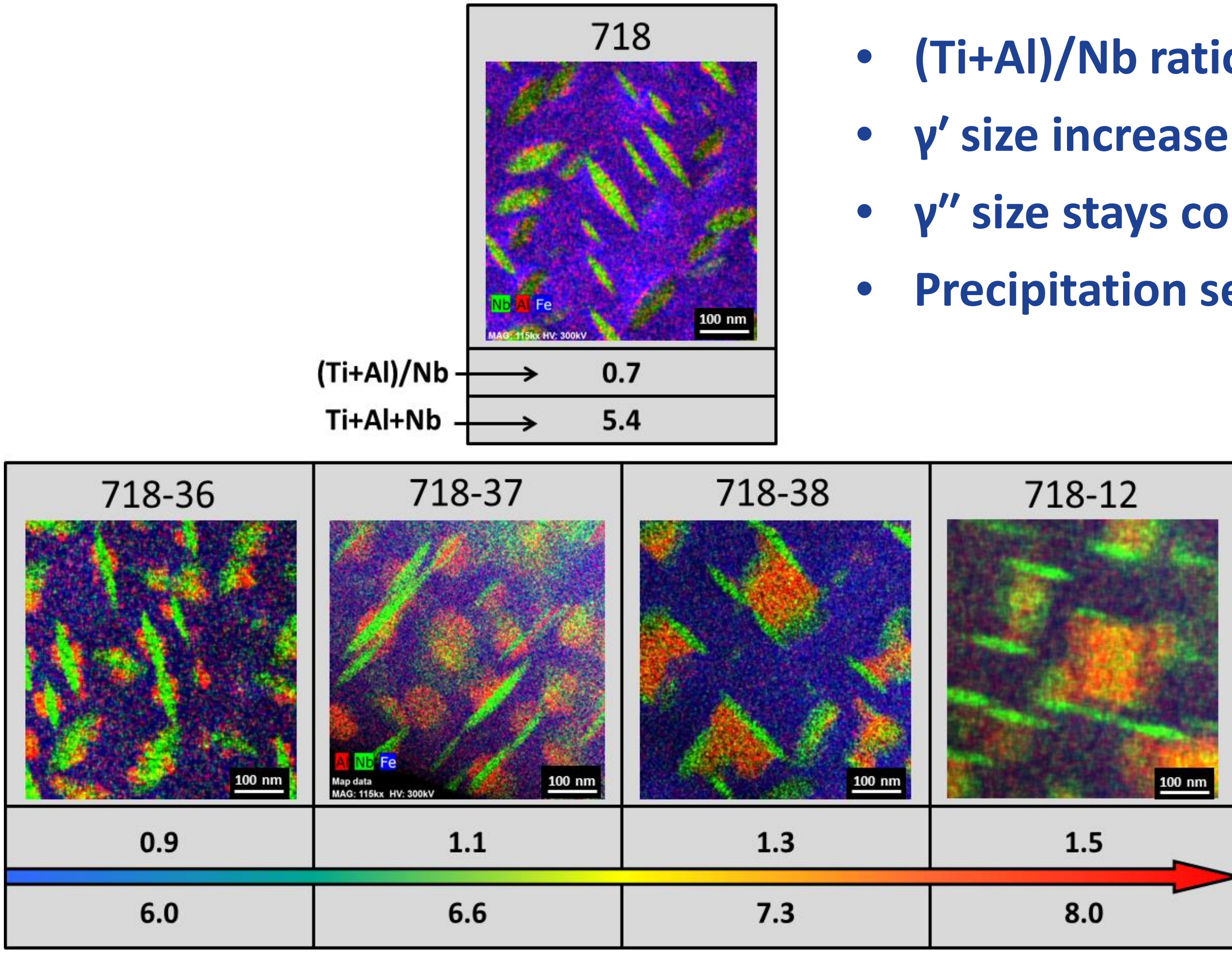




- **Majority of alloys excluded early due to large γ’ and/or TCP phase formation**
- **Design of Experiments approach highlighted negative Ti effect**

Strengthening Element Ratio Study

- (Ti+Al)/Nb ratio increased incrementally
- γ′ size increase with addition of γ′-formers
- γ″ size stays consistent
- Precipitation sequence reverses

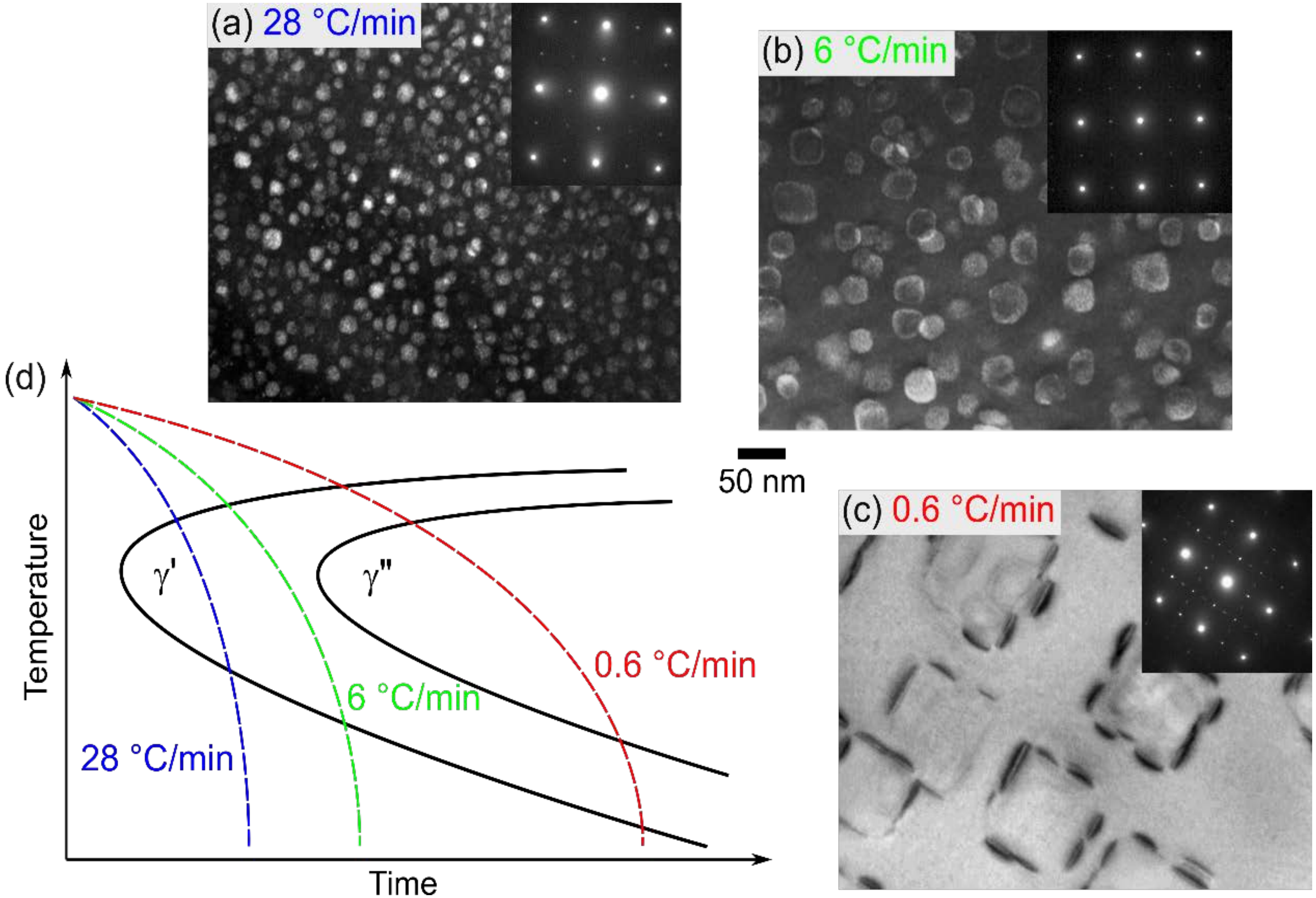


(Ti-Al)/Nb	First to Nucleate
0.9	γ″
1.1	(nearly simultaneous)
1.3	γ′
1.5	γ′

Systematic study provides coprecipitation chemistry limits

Coprecipitation Concept

- Leverage the coprecipitation of γ’ and γ’’ to restrict γ’ coarsening during slow cooling of thick section components.



Desired: form γ’ then rapidly nucleate γ’’

A. Detor, et al, Metall. Mater. Trans. (2017)

Slow Cool Precipitate Comparison

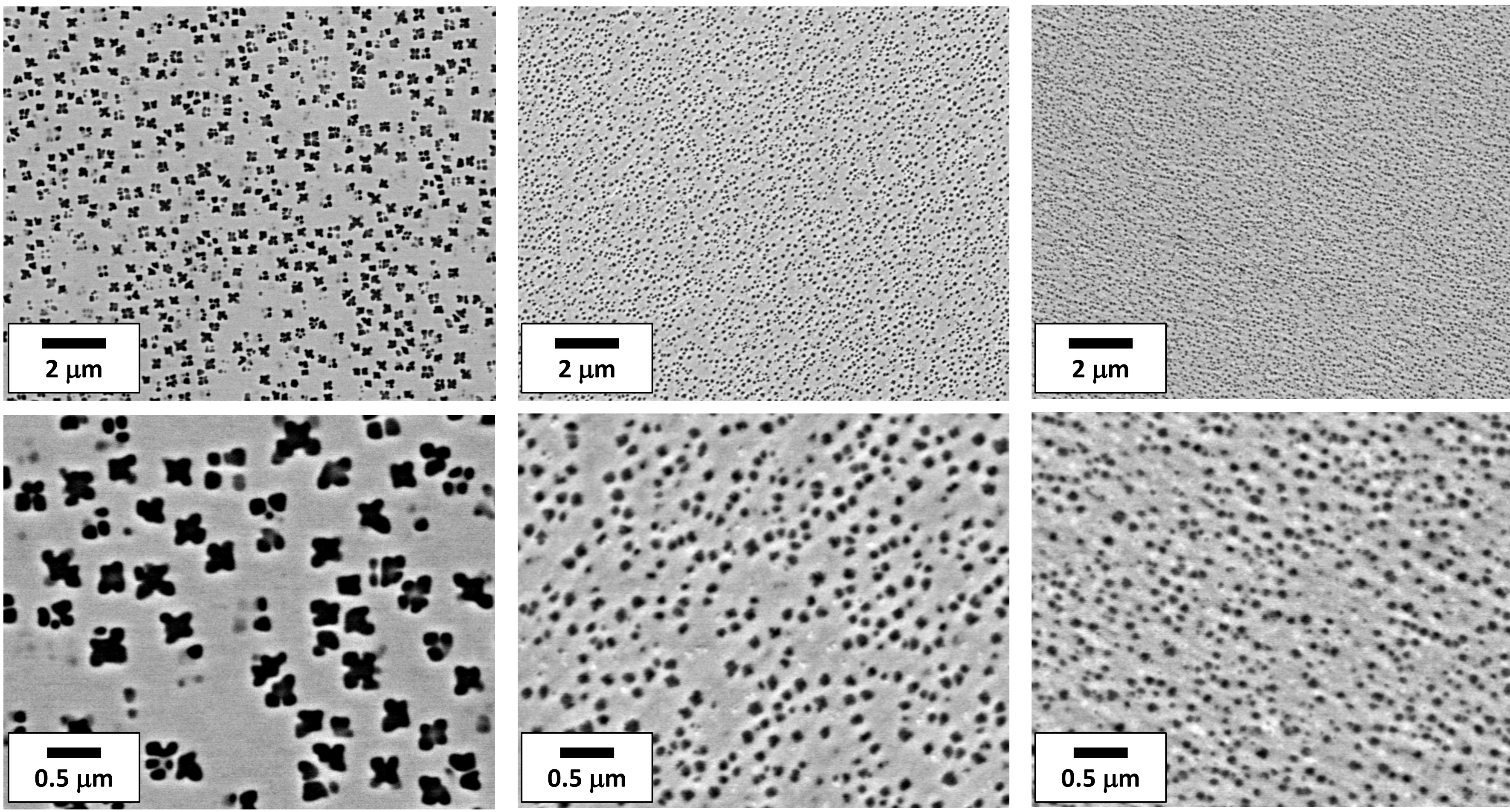
Baseline γ' Alloy
19% Area Fraction

Coprecipitation Alloy
17±2% Area Fraction

Sluggish γ' Alloy
16±4 % Area Fraction

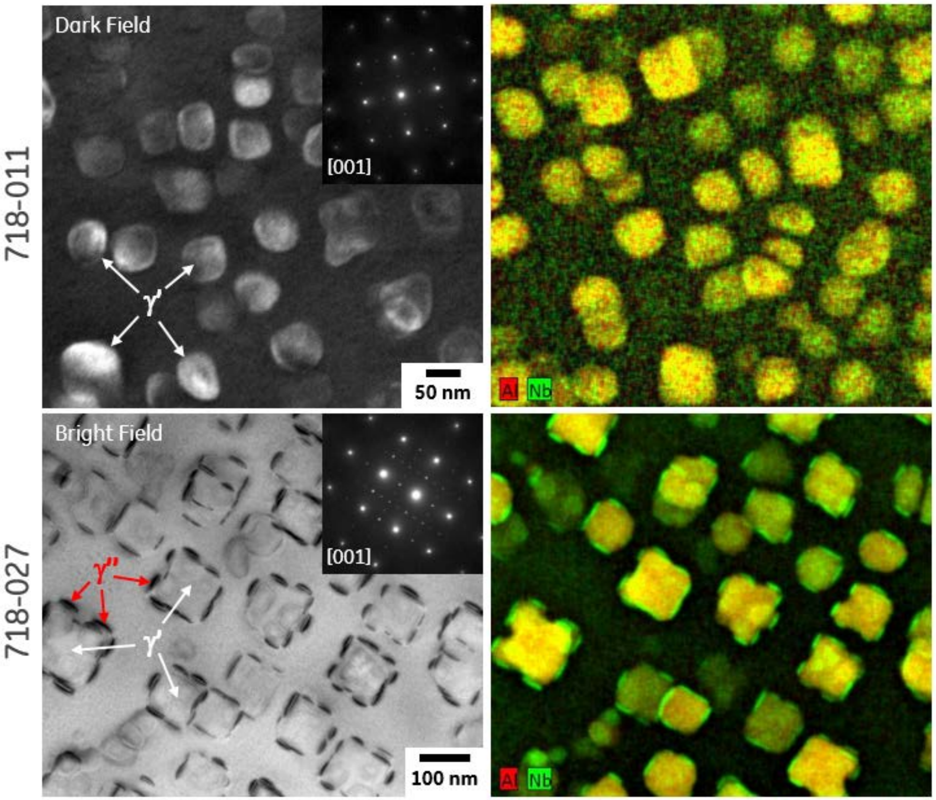
Low Magnification

High Magnification

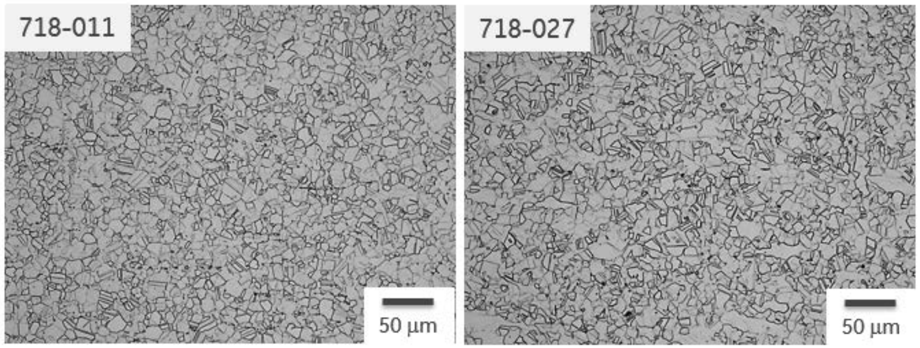


The new alloys yield substantially finer strengthening precipitates than the slow cooled baseline structure.

Coprecipitation and Sluggish γ’ Alloys



- Fine strengthening phases following conservative slow cool from homogenization
- 718-011: Al+Nb rich γ’ phase only
- 718-027: compact γ’/γ” coprecipitates
- Concepts demonstrated in other alloy bases

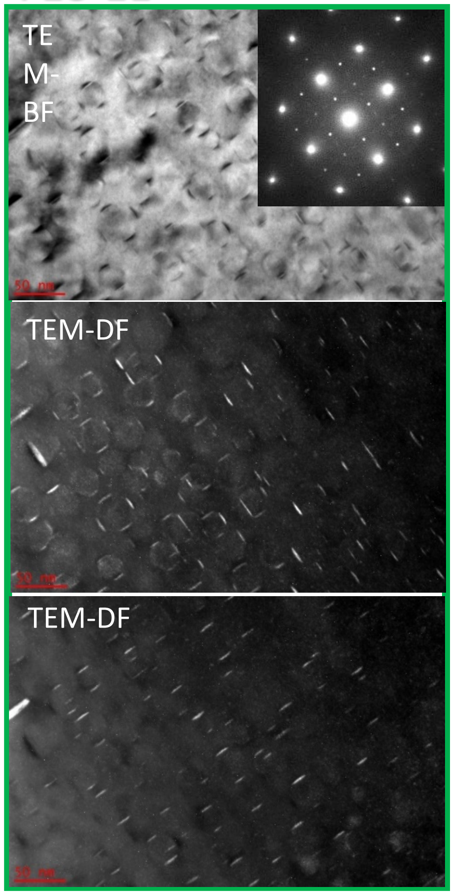


- Both alloys successfully billetized to produce fine, equiaxed grained structure

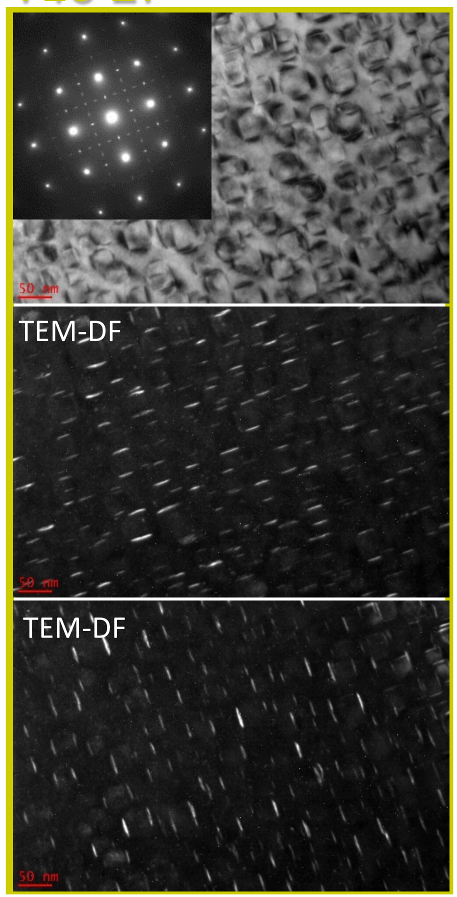
Potential for both coprecipiation and sluggish γ’ concepts–basis for round 1 alloys in new program

"Round 1" Alloys and Heat Treatments

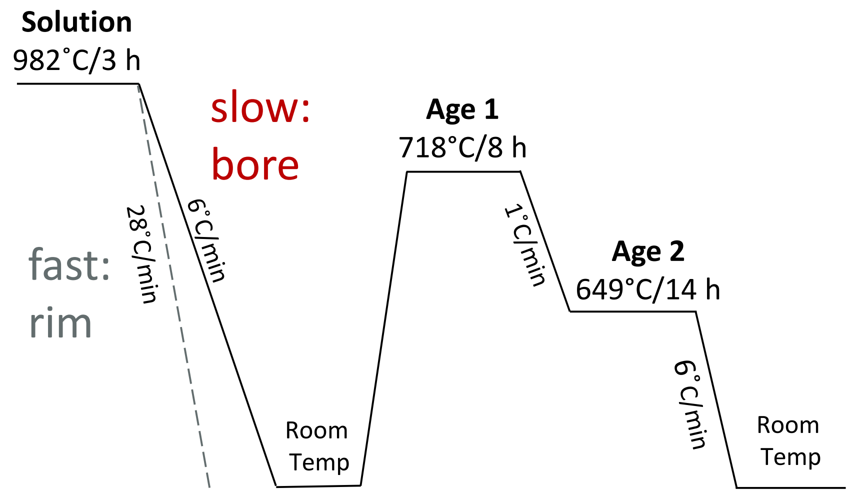
718-11



718-27

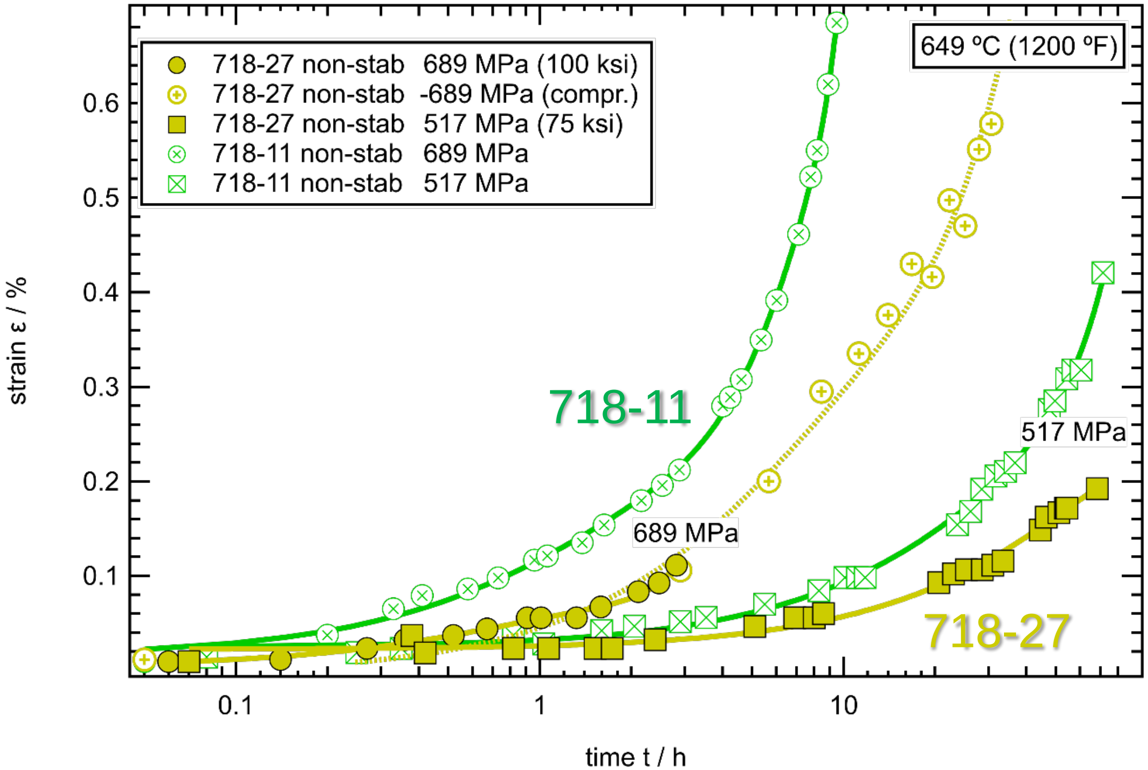


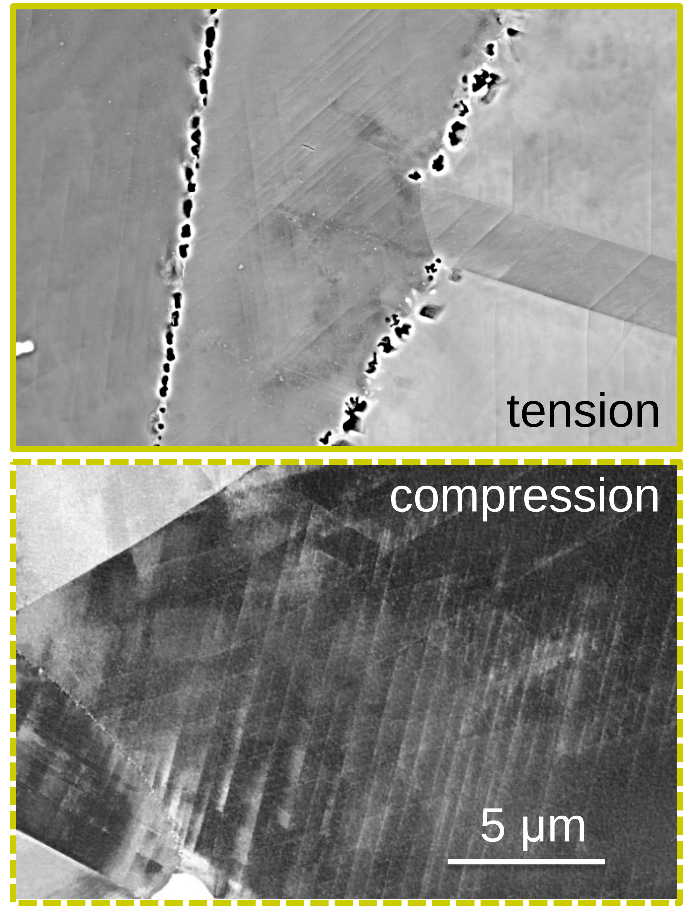
Alloy Name (wt%)	Ni	Cr	Fe	Al	Ti	Nb	Mo	C
718	52.5	19	18.9	0.5	0.9	5.13	3.05	0.02
718-011	52.5	19	18.9	1.5	---	5	3.05	0.02
718-027	52.9	18.7	18.9	1.1	0.95	4.4	3.05	0.02



- Applying double aging heat treatment forms γ′–γ″ co-precipitates in 718-27

Creep Properties at 649 °C (1200 °F)

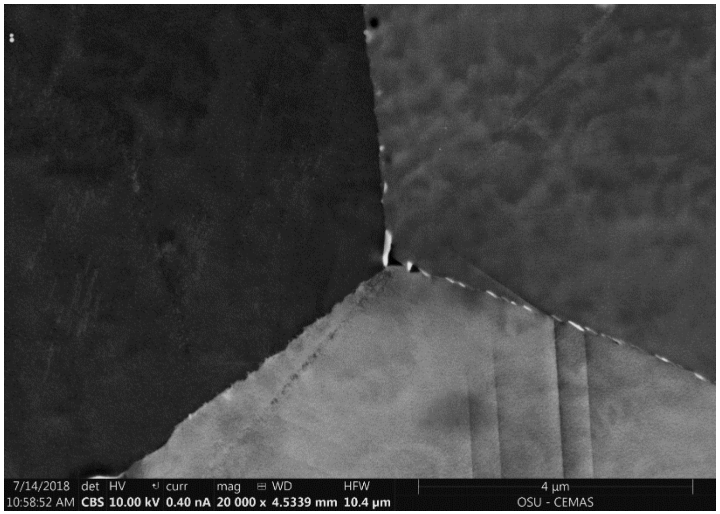




718-27: same rate in tension and compression

Premature Failure in IN718-27 After Two-step Aging

Creep at 649°C and 689 MPa:
Rupture occurs after 0.11% strain accumulated in less than **3 hours**

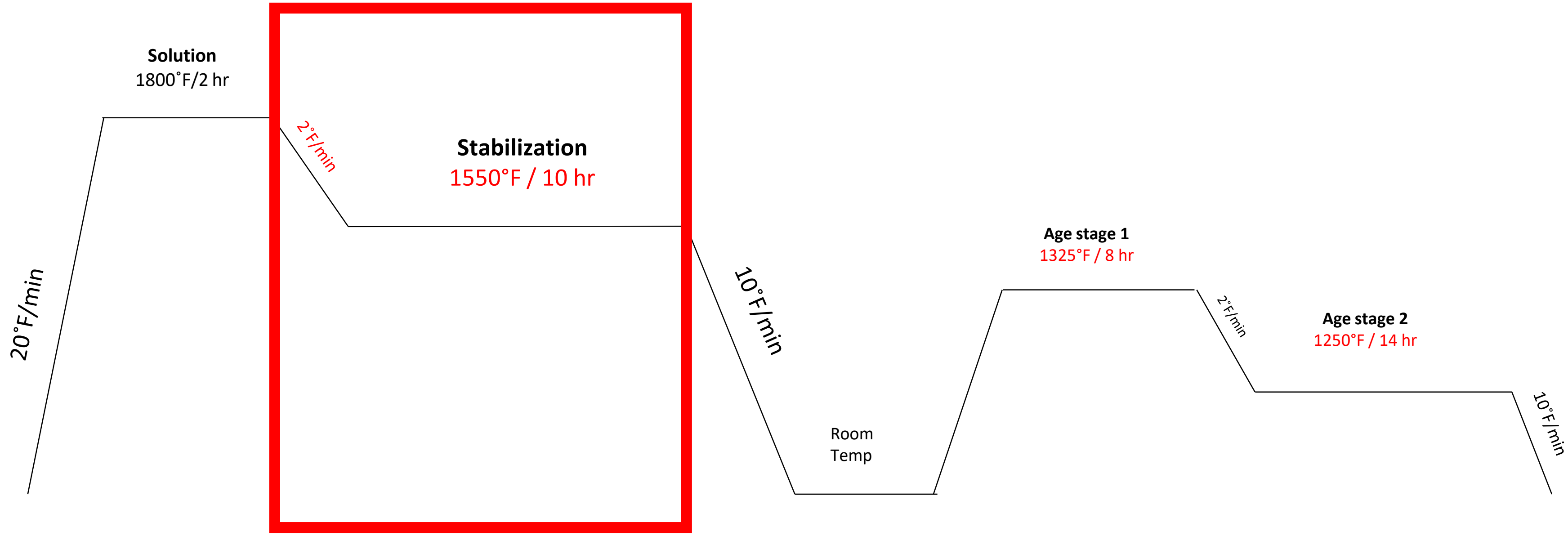


Intense grain boundary cracking, and coalescence of these cracks/voids leads to failure

SEM micrographs taken in the concentric ring configuration of the BSE detector in beam deceleration mode: Strongly diffracting grains were chosen for the images for ECCI

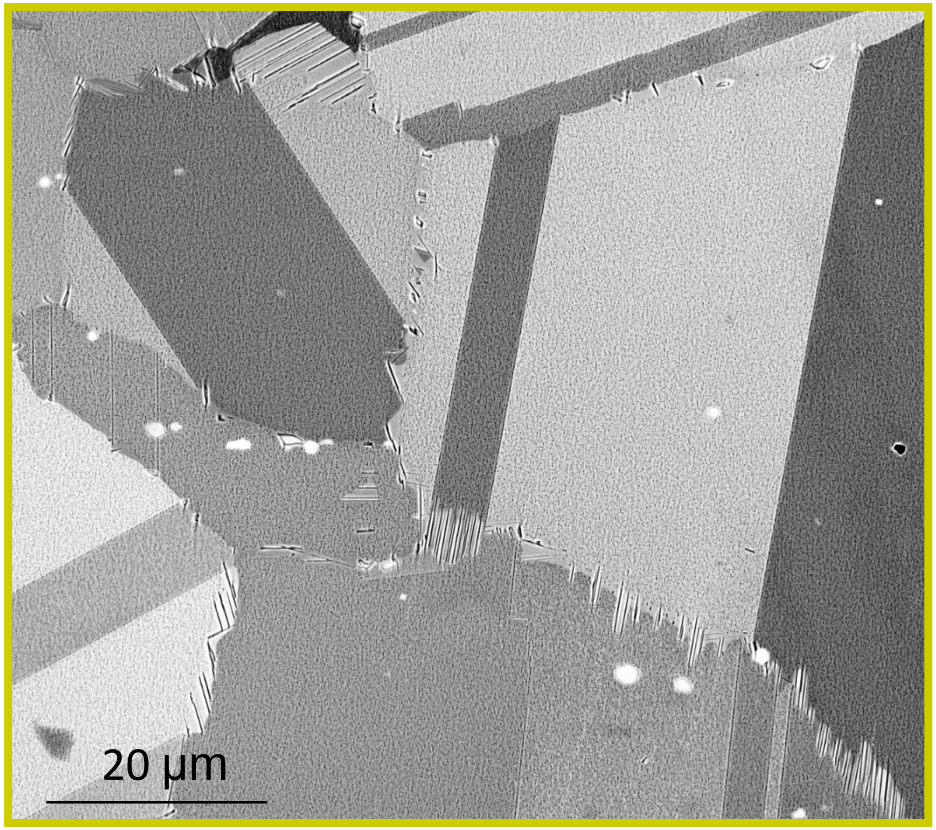
Grain boundaries must be stabilized prior to aging

Stabilization Heat Treatment

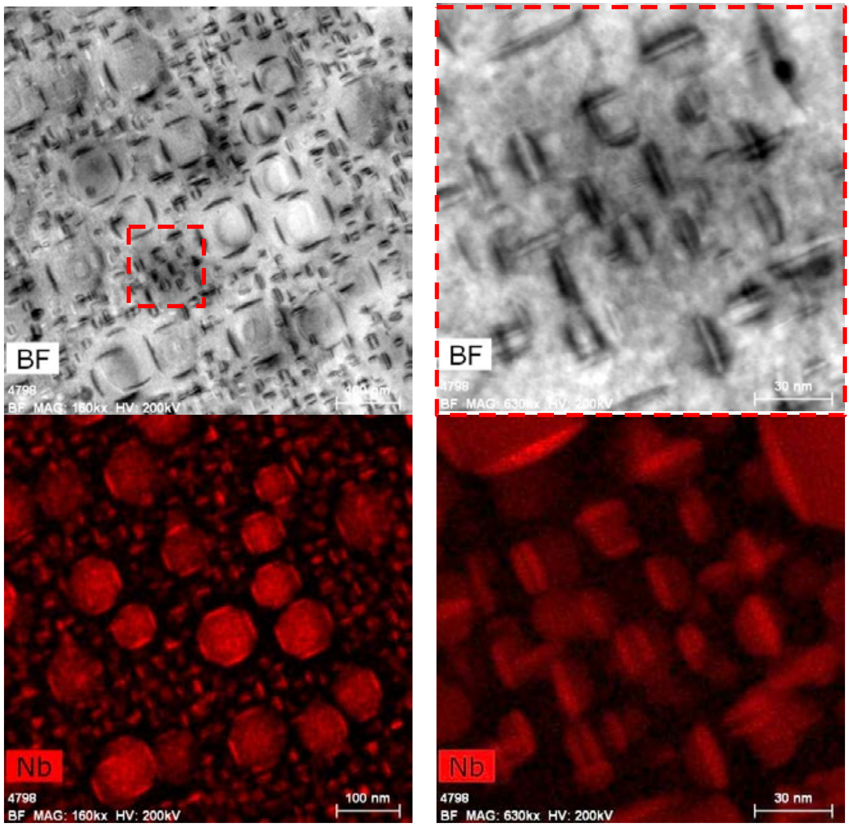


Similar heat treatment to that used in IN718

Stabilization Heat Treatment

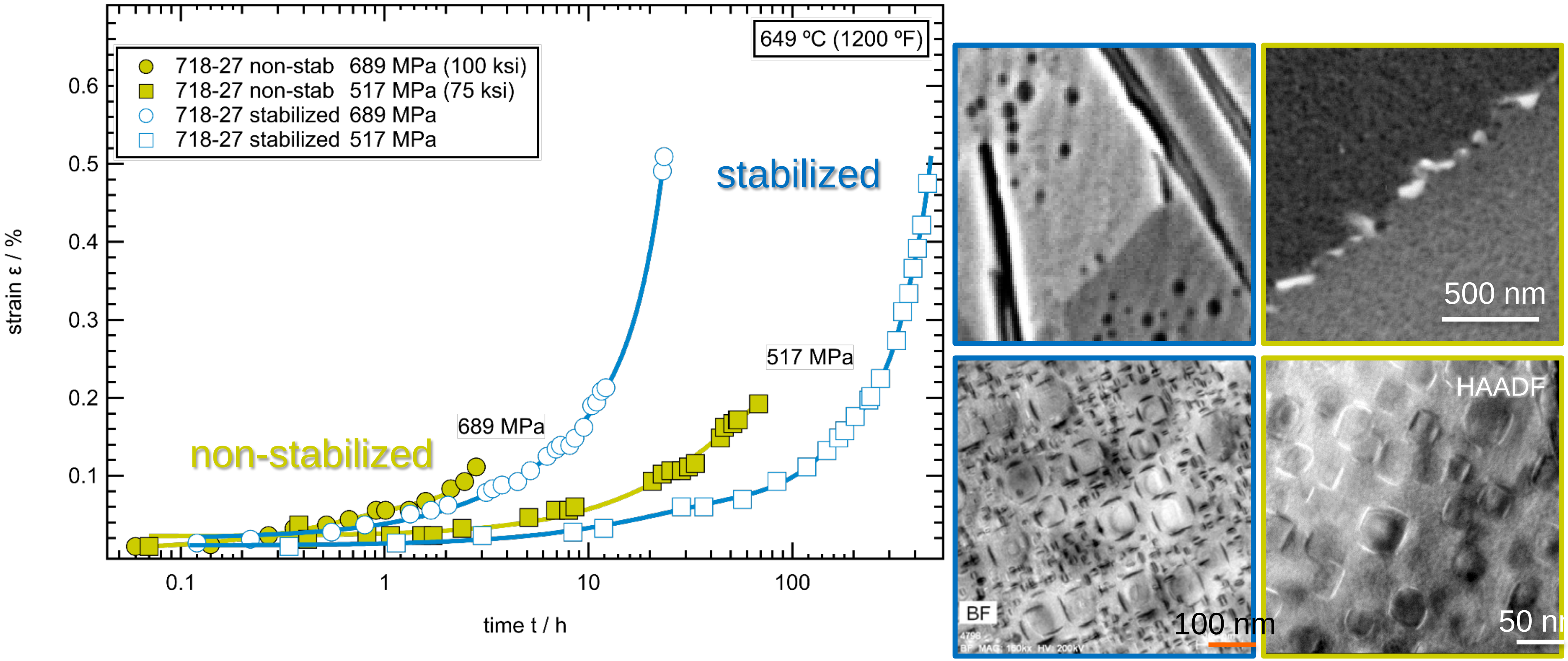


718-27



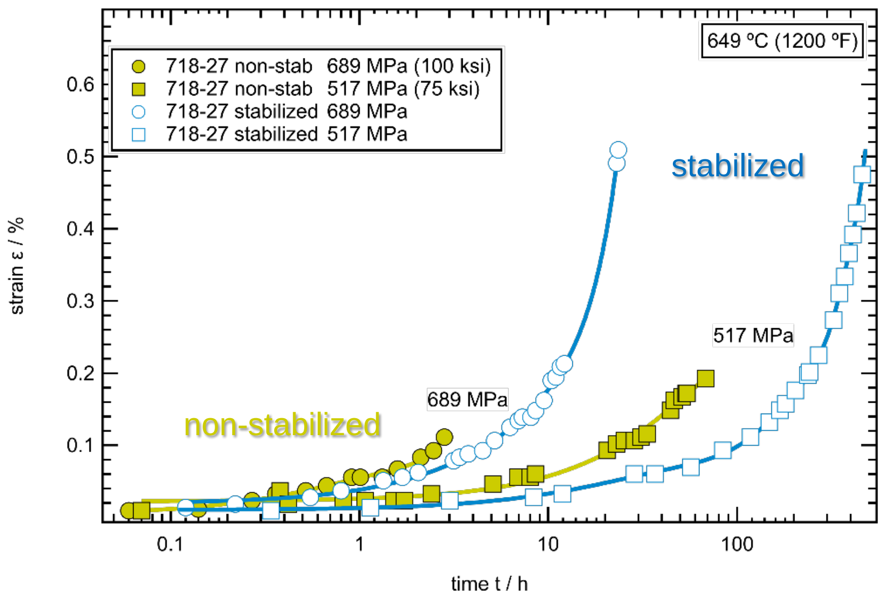
For IN718-11 stabilization step not useful since it is devoid of needed grain boundary precipitates

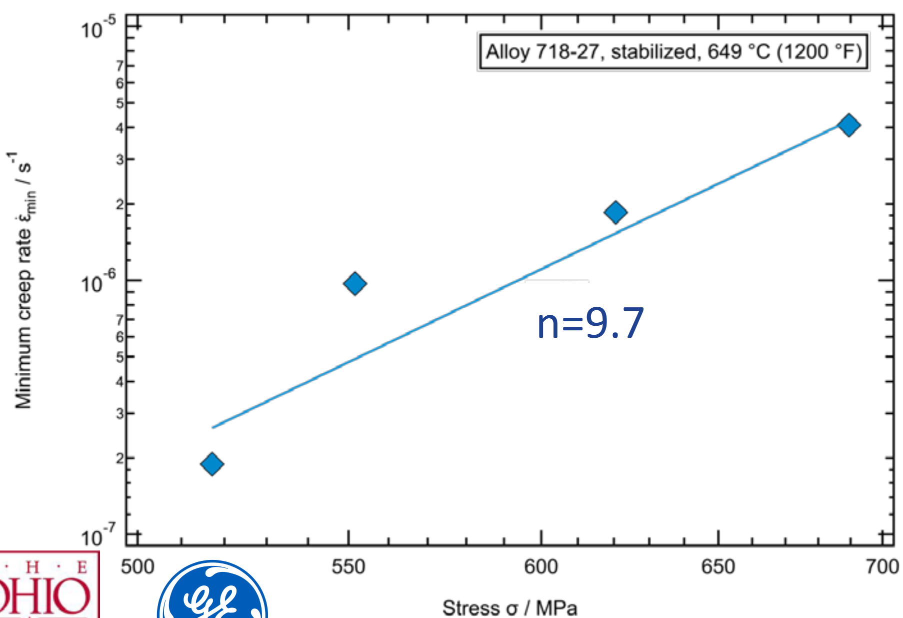
Creep Properties at 649 °C (1200 °F)

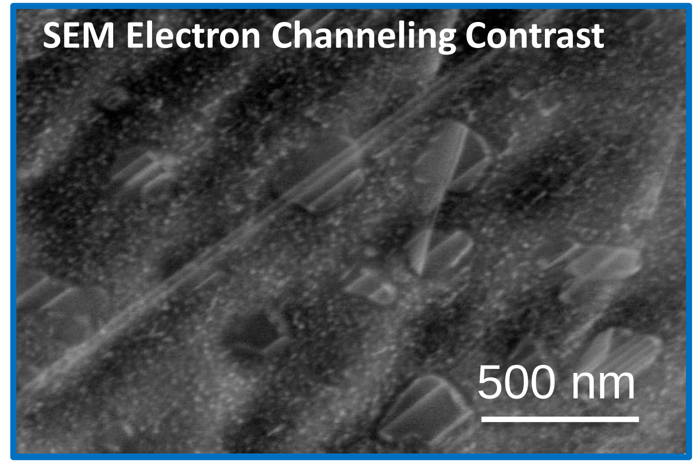


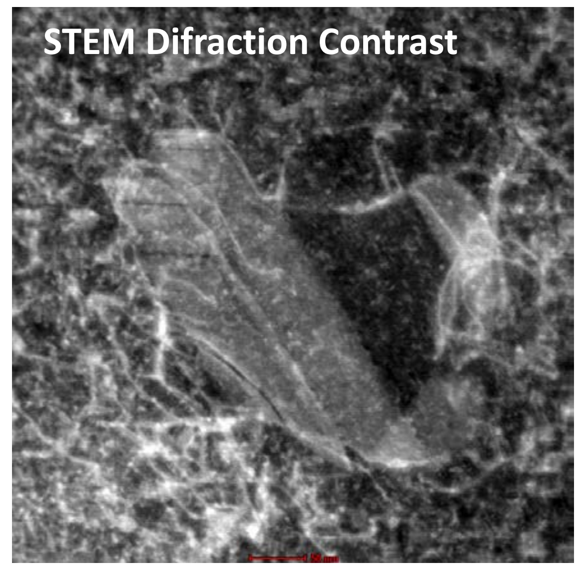
718-27: Stabilization HT significantly improves ductility and lowers creep rate

Creep Properties at 649 °C (1200 °F)



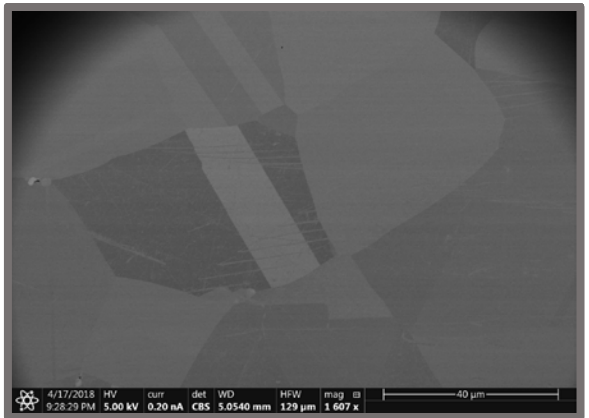


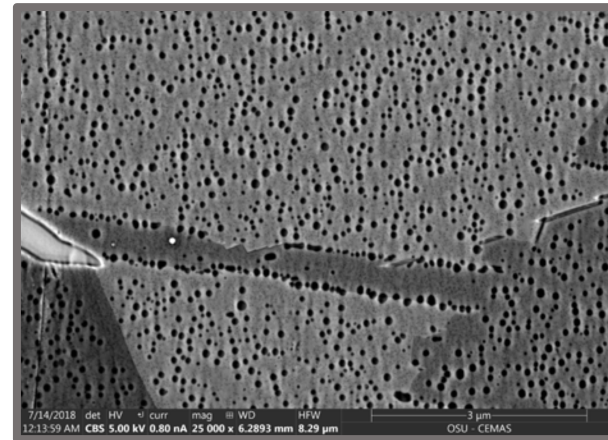


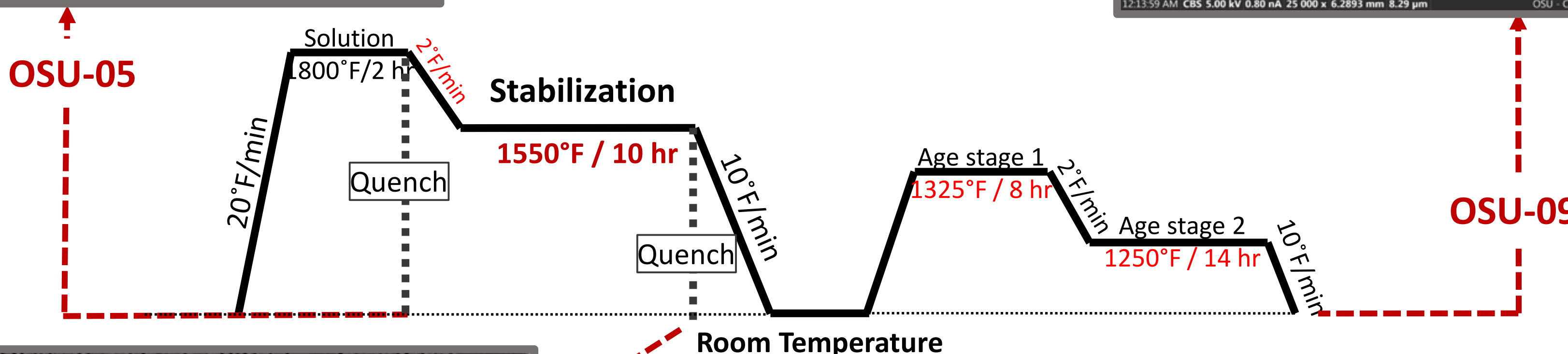


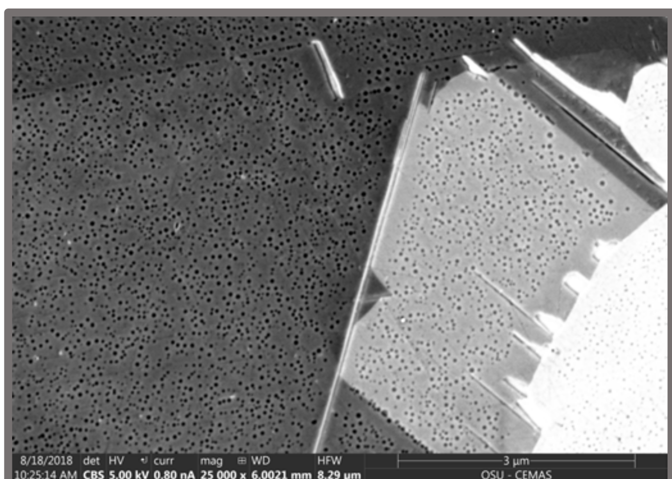
Planar faulting and dislocation interaction with precipitates

Stabilizing Heat Treatment – Plan forward







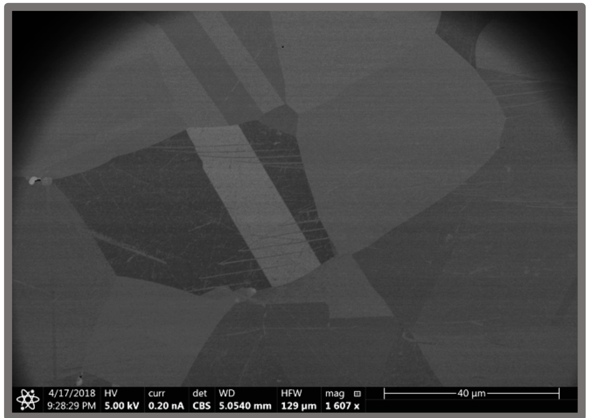


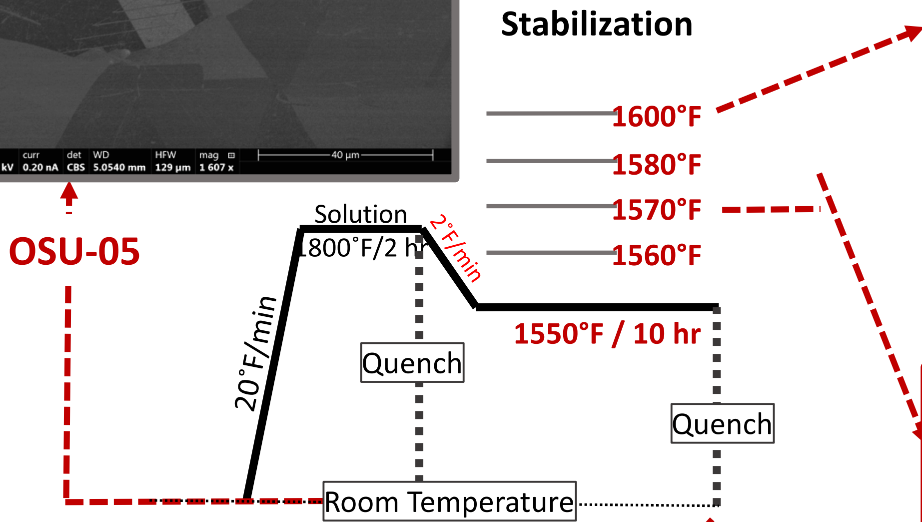
After stabilization:

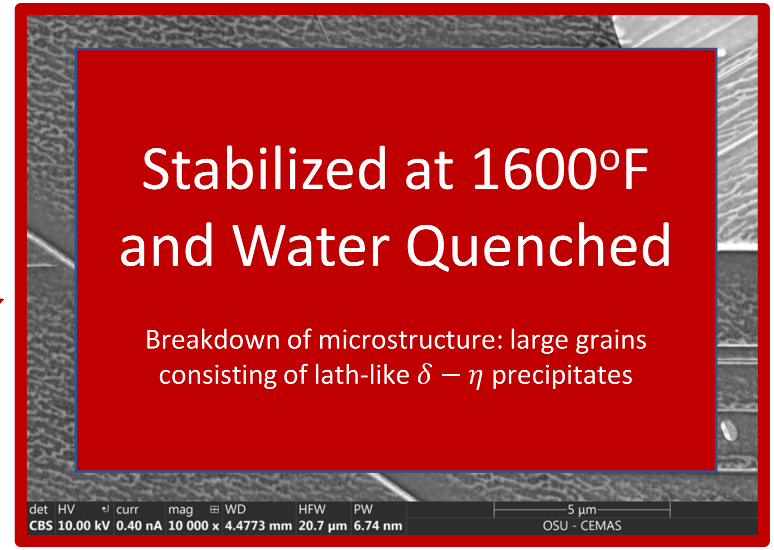
- Grain boundary precipitates (eta and delta phases) develop

- Strengthening phases (γ' and γ'') should be in solution – ***not the case***!

Modified Stabilizing Temperature

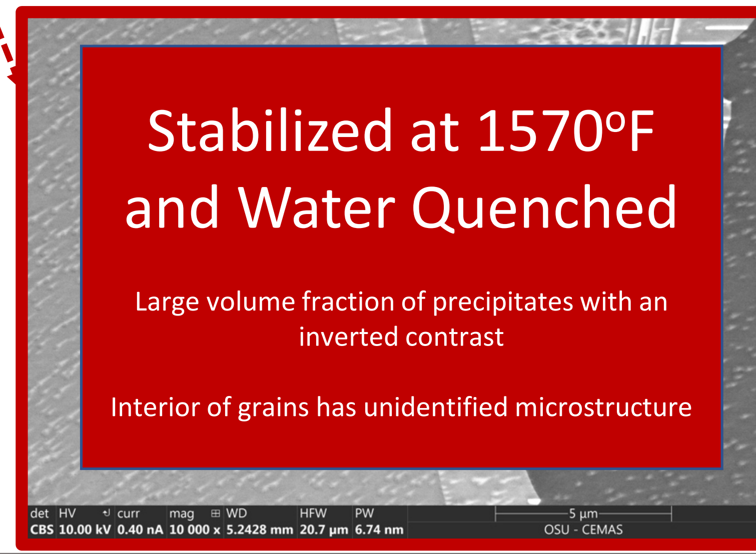






Stabilized at 1600ºF and Water Quenched

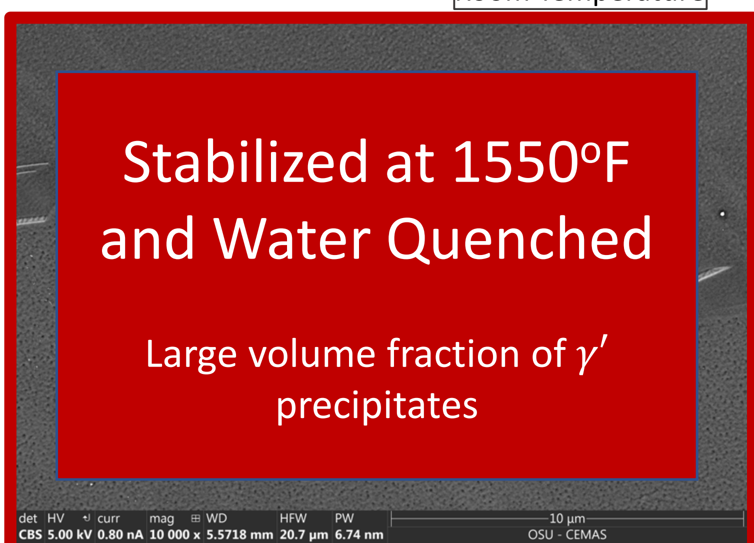
Breakdown of microstructure: large grains consisting of lath-like $\delta - \eta$ precipitates



Stabilized at 1570ºF and Water Quenched

Large volume fraction of precipitates with an inverted contrast

Interior of grains has unidentified microstructure



Stabilized at 1550ºF and Water Quenched

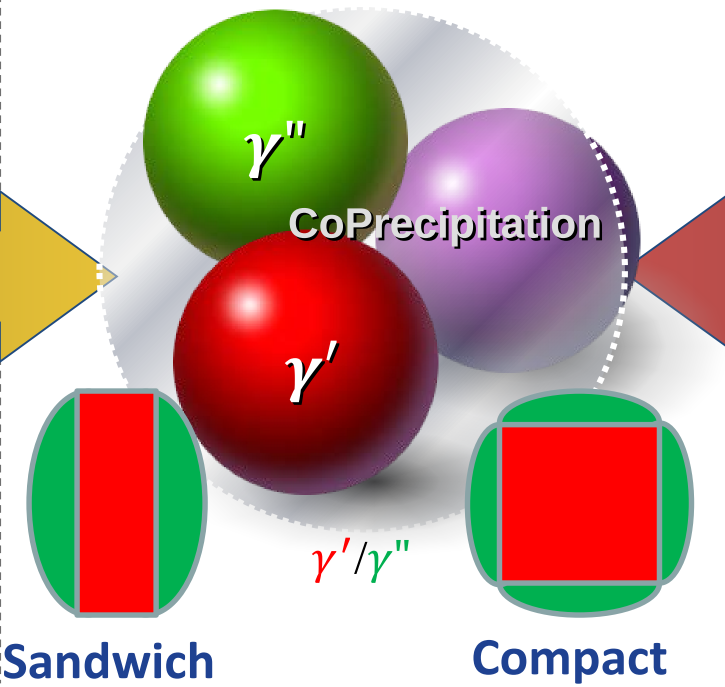
Large volume fraction of γ' precipitates

Creep testing to commence on modified heat treat alloys

Coprecipitation Model Overview

Multi-Phase Field

- **Equilibrium Shapes**
  - Sandwich $\gamma''/\gamma'/\gamma''$
  - Compact
- **Isothermal Growth**
  - Kinetics
  - Diffusion Mechanisms
- **Co-precipitation on continuous cooling**



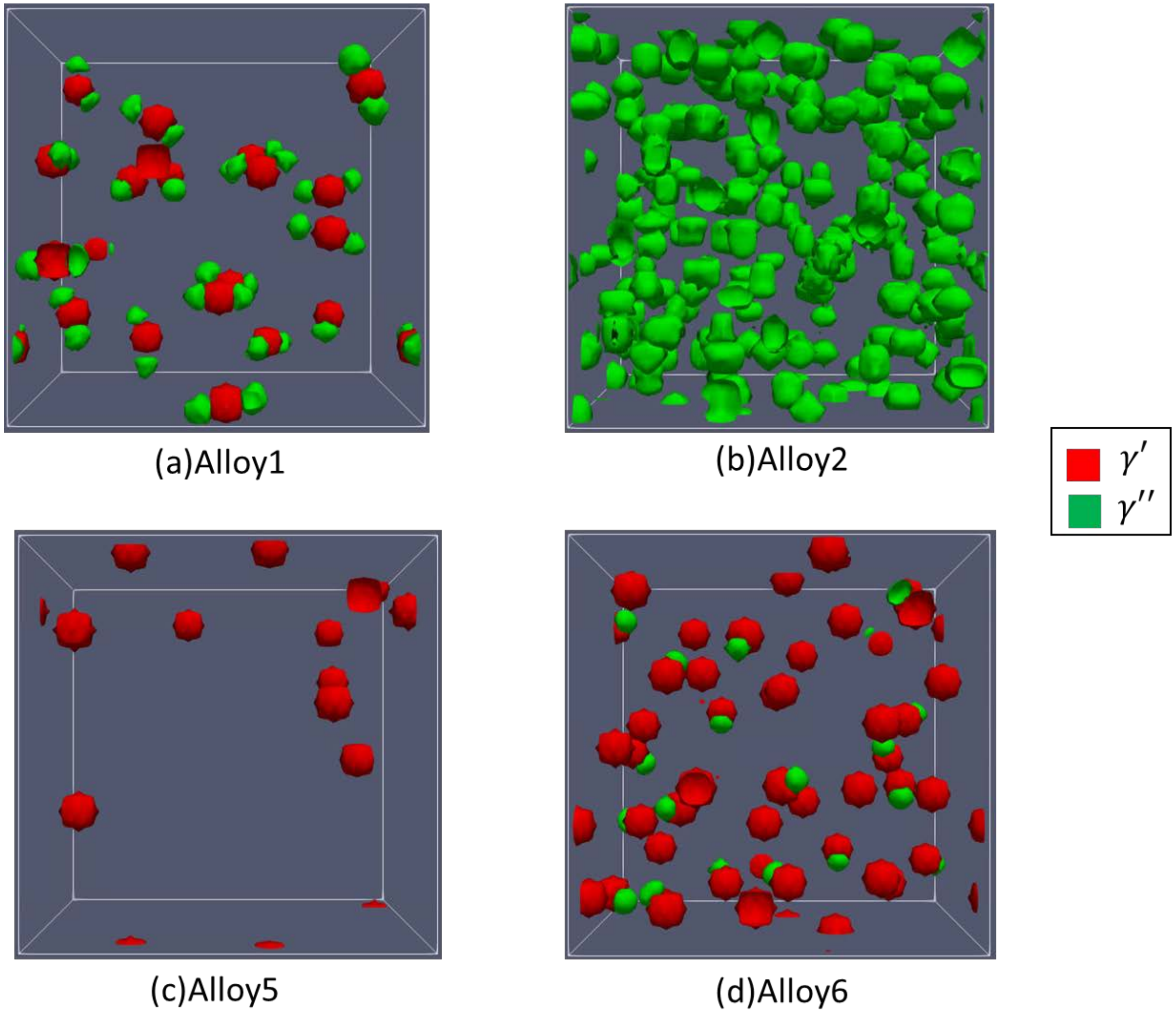
PanPrecipitation

- **Slow cool kinetics**
  - Nucleation rates
  - Phase Fractions
  - Average particle size

Combining a multi-phase field model with PanPrecipitation yields a quantitative simulation of coprecipitation phenomena

Effect of Alloy Concentration on Microstructure

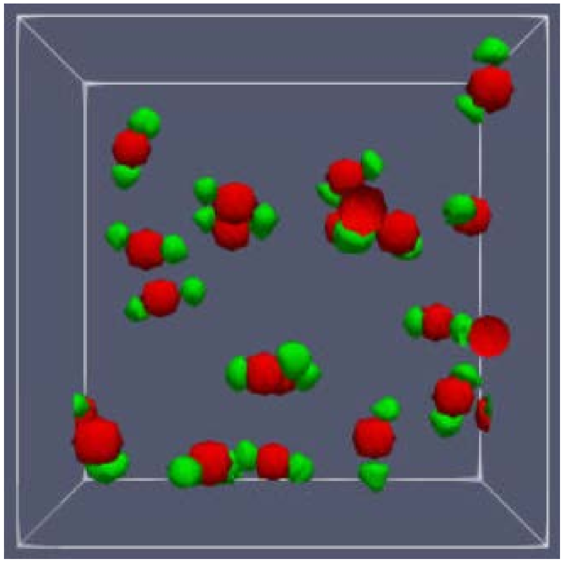
Alloy	c_{Al}	c_{Nb}
Alloy1	0.024	0.022
Alloy2	0.024	0.03
Alloy5	0.024	0.0077
Alloy6	0.027	0.017



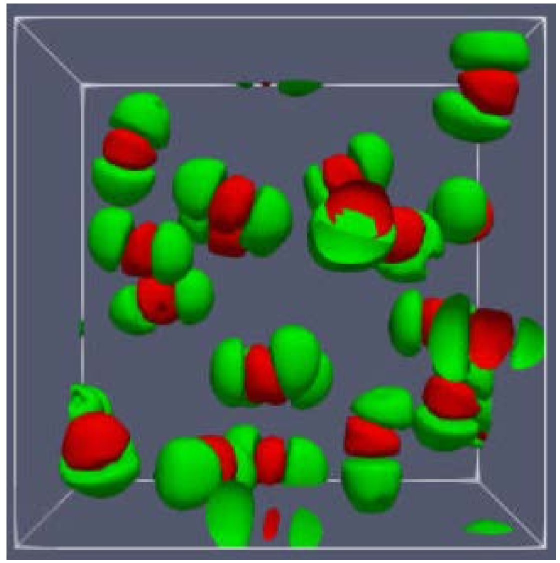
- Alloy1 – Sandwich nuclei
- Alloy2 - Primarily γ’’
- Alloy5 – Primarily γ’
- Alloy6 – Single sided γ’’

Microstructural Evolution of Coprecipitates

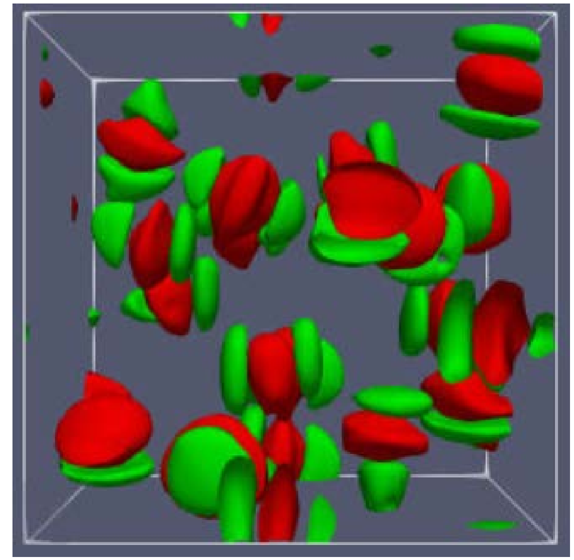
T=790°C



a)t=0sec



b)t=2.25sec

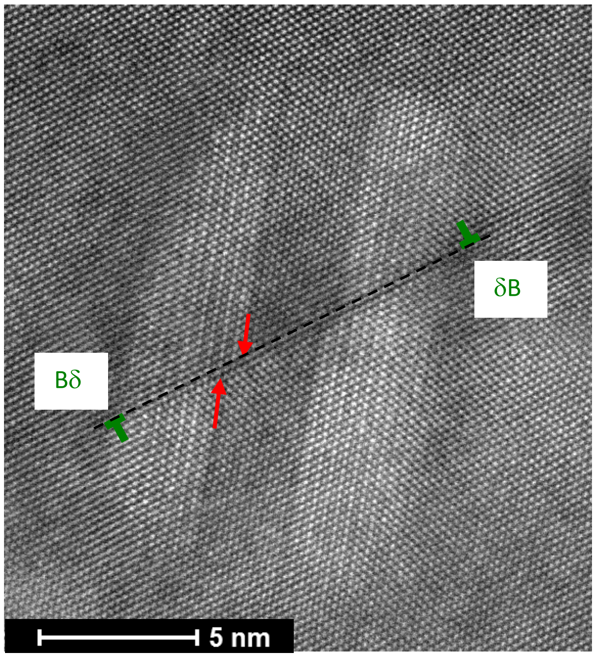


c)t=15sec

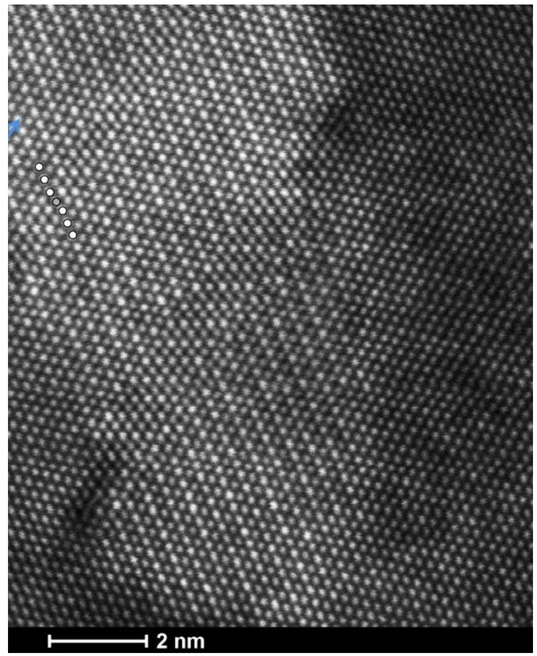
- Powerful capability for simulating coarsening
- Comparison with experiment in progress

Deformation Mechanisms Change with Temperature

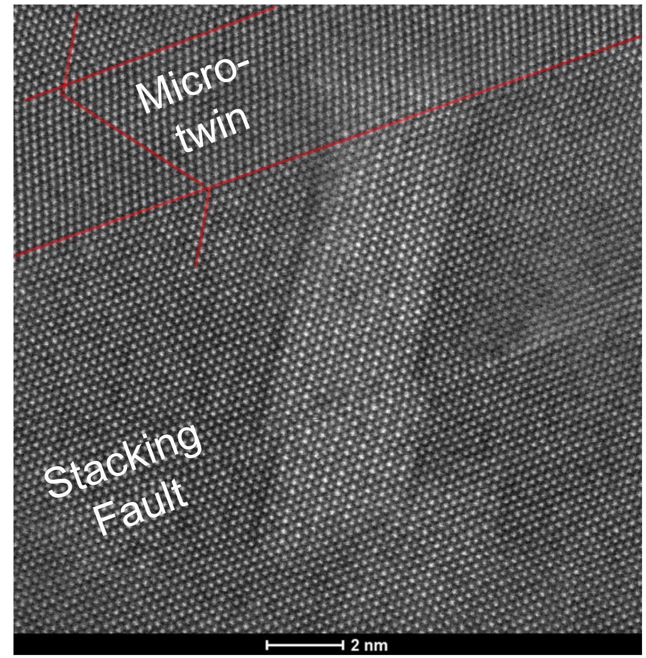
Sheared γ''/ γ'/ γ'' composite particle after room temperature deformation



Microtwin originating in a γ' / γ'' composite particle after deformation at 427°C



Microtwins frequent and extend into the γ matrix after deformation at 649°C

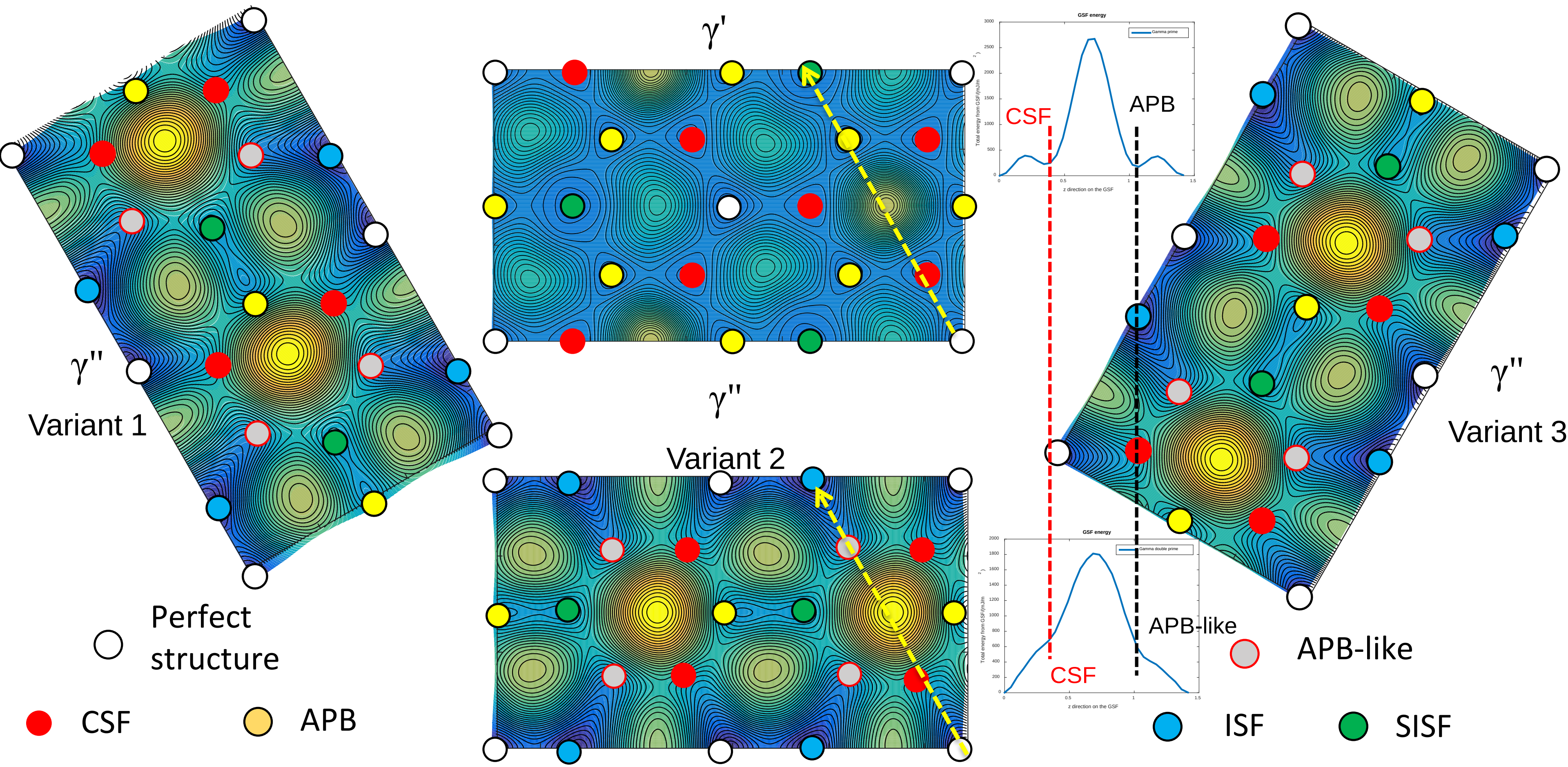


- Mechanism transitions in conventionally-processed 718 at elevated temperatures

- Mechanism changes must be incorporated into property models

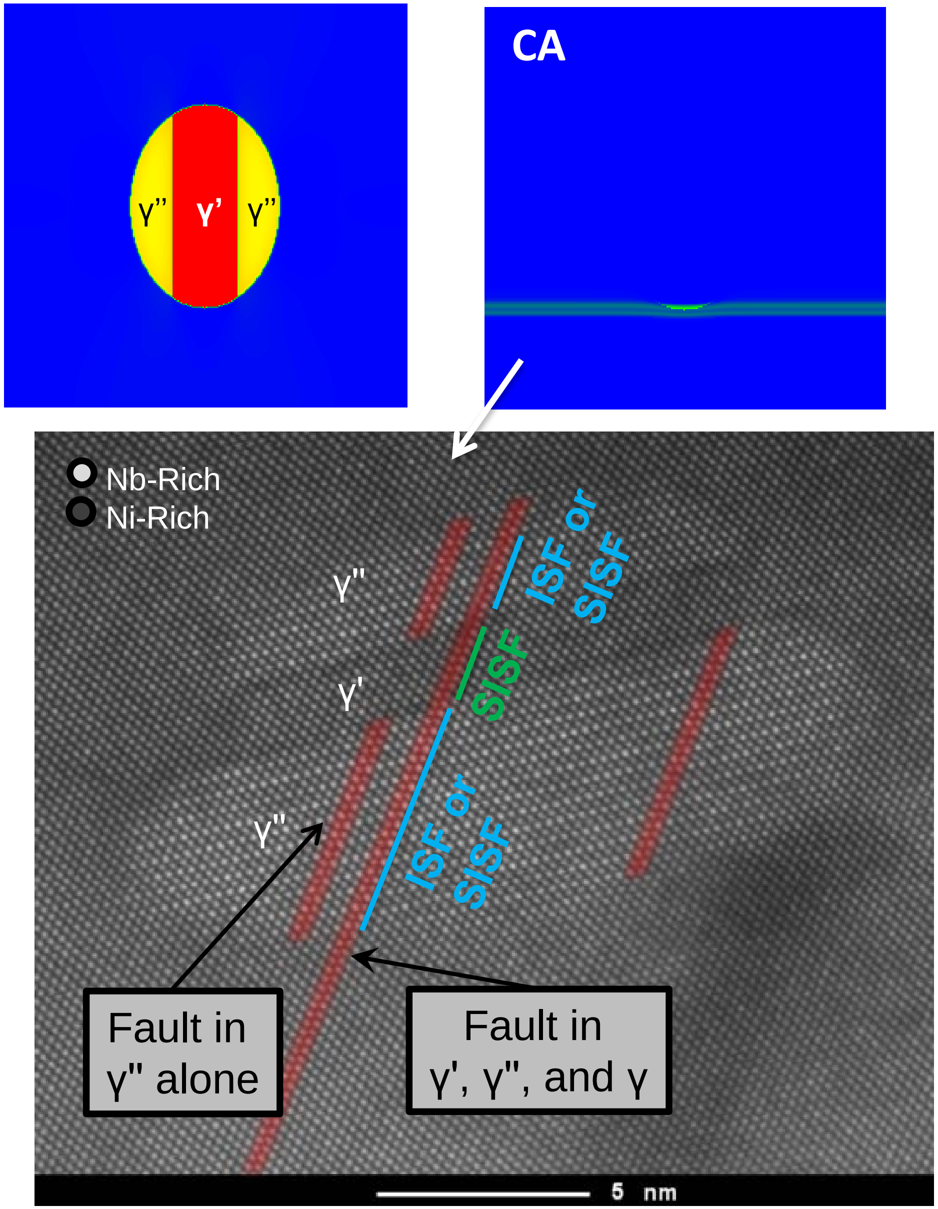
Generalized stacking fault energy

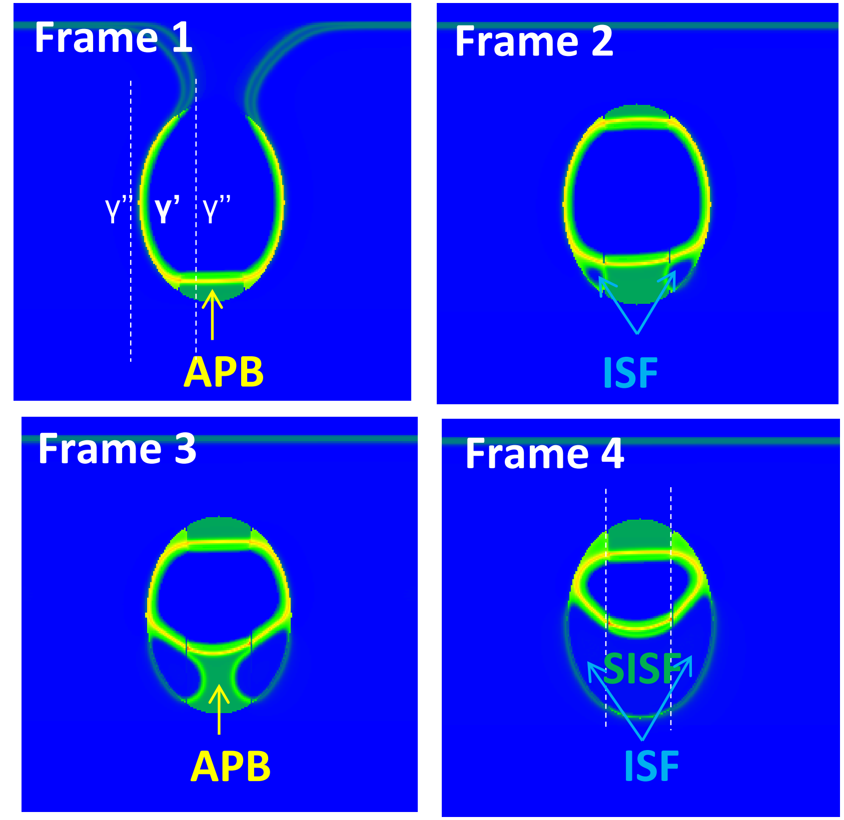
718 Type Alloys Ni-base superalloys

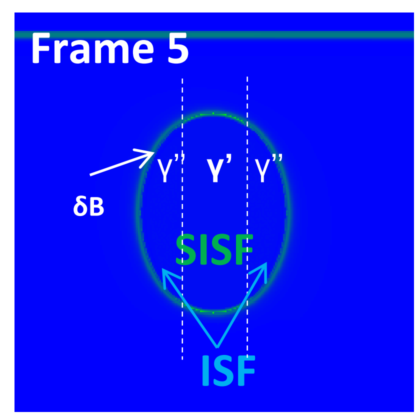


Deformation pathway of γ”/γ’/γ” precipitate

Single CA (<110>/2) dislocation

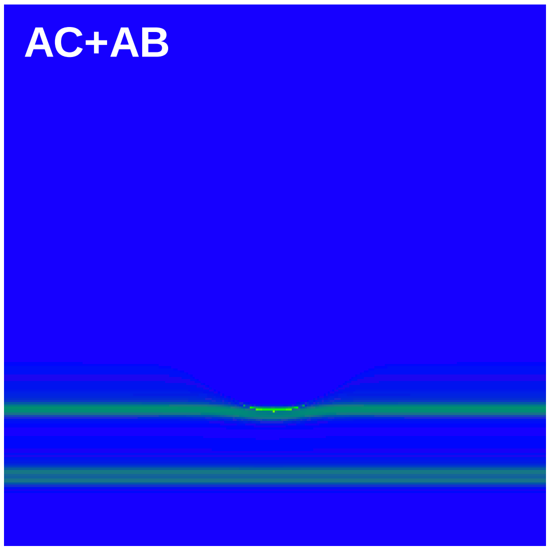


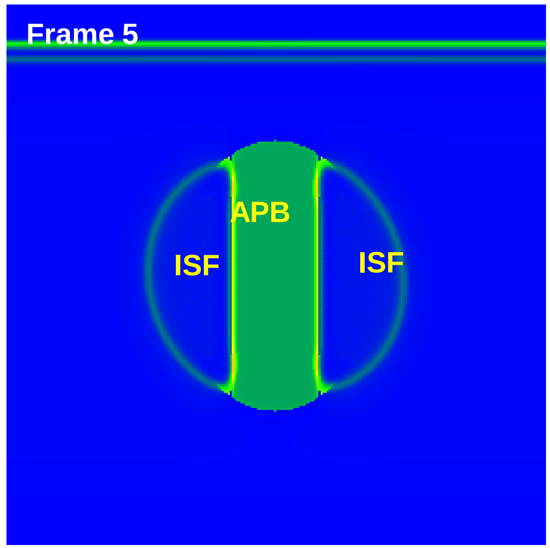


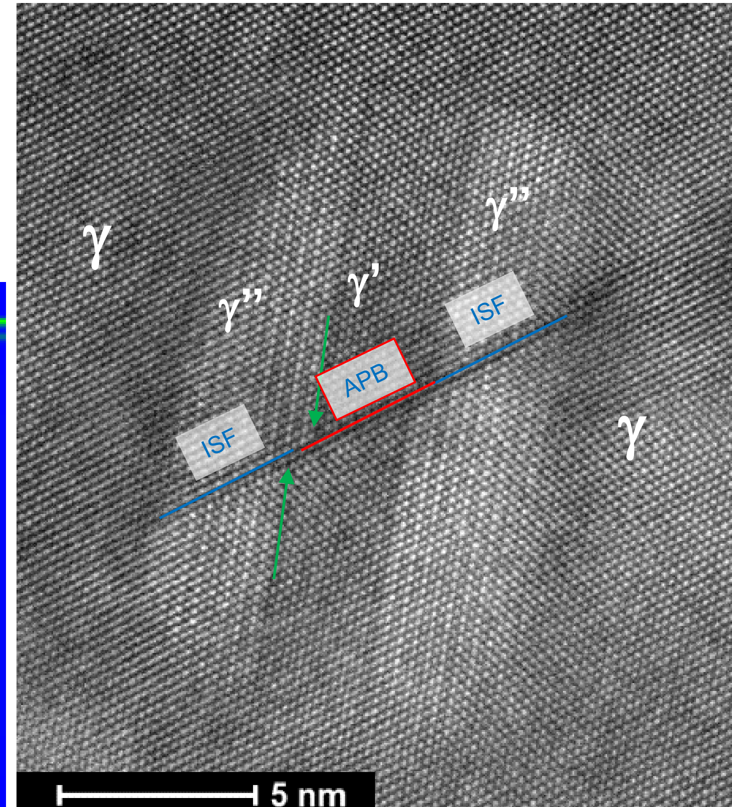


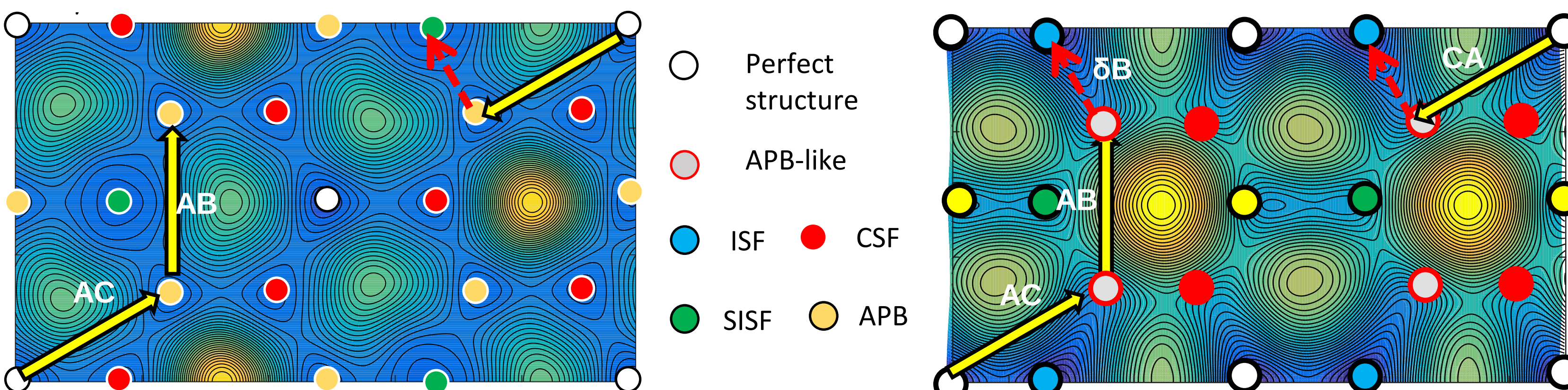
Deformation Pathway of γ”/γ’/γ” Composite Precipitates

AC+AB dislocation



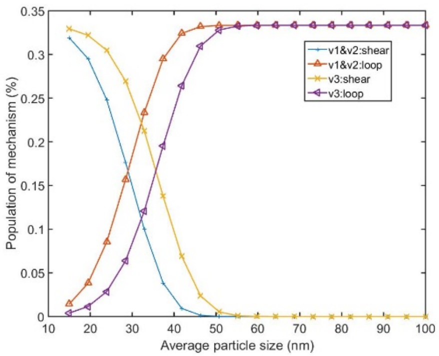






Fast-acting Yield Strength Model

- γ'' particle shearing vs. looping population

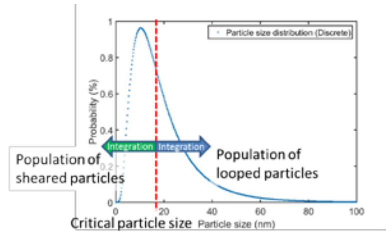


Mechanisms

CompuTherm FOR MATERIALS DESIGN

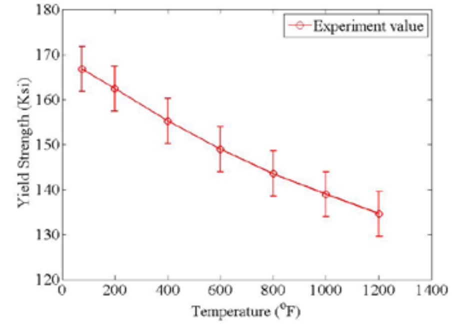
- Volume fraction and average particle size

- Particle size distribution:



Microstructure info

- Experimental measurement



Yield strength data

Major inputs

Calibrating model parameters

Model Validation

$$\tau_y = \Delta\tau_{pp} + \Delta\tau_{LS} + \Delta\tau_{HP}$$

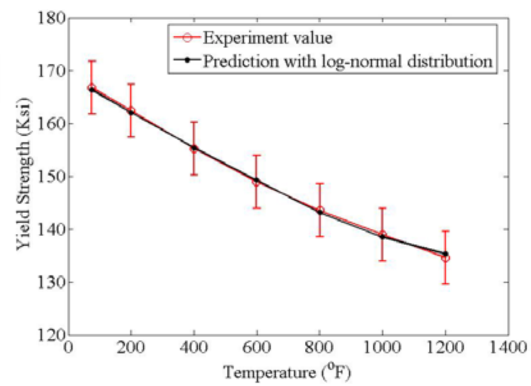
$$\Delta\tau_{pp} = M \sum_{i,j} W_{i,j} \Delta\tau_{i,j}$$

Precipitate hardening related with <112>-type (CA+BA) dislocation

Probability of each mechanism
j: shearing (1) or looping (2)
i: i-th variant

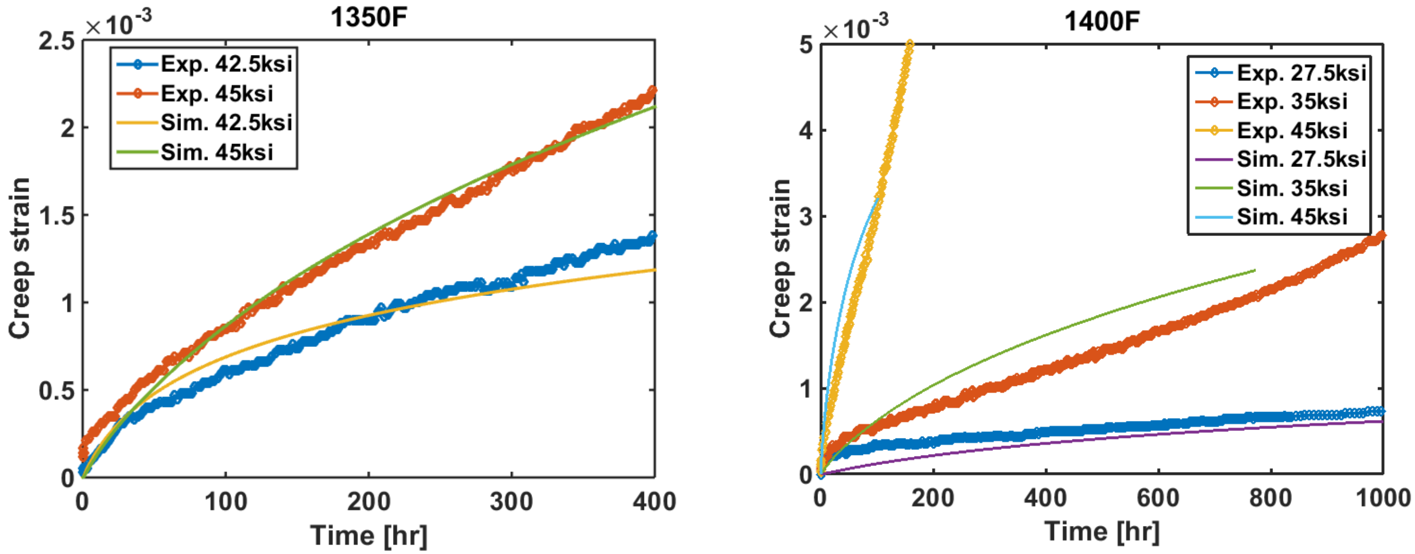
Outputs

Prediction of yield strength



Creep Model Development

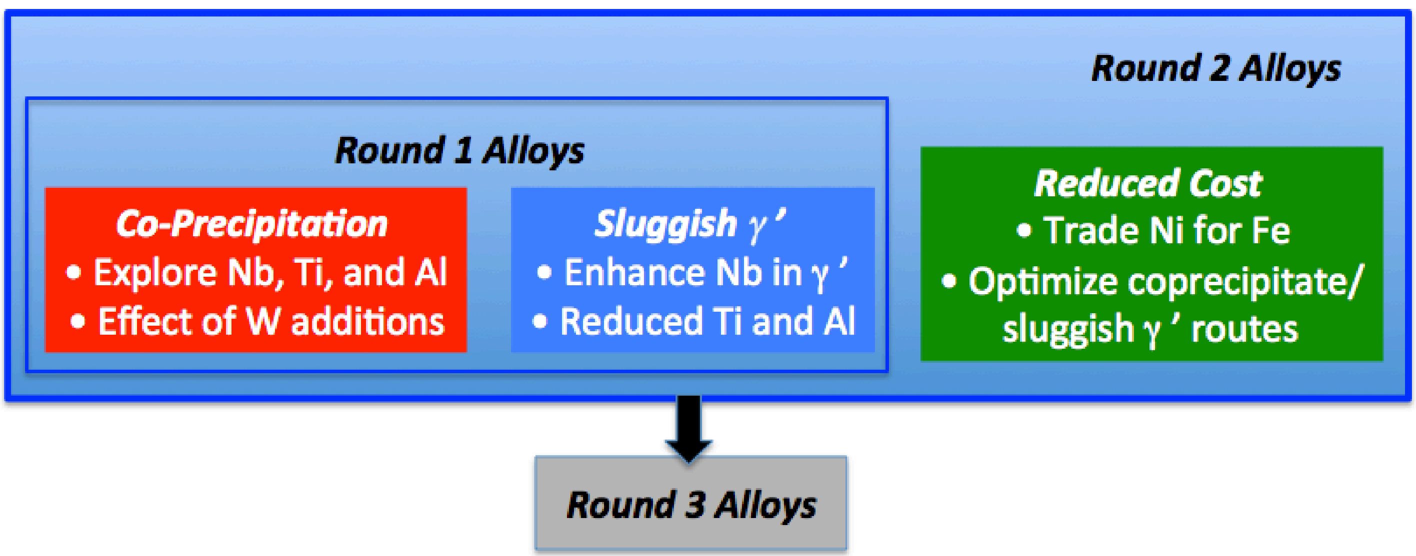
- Creep model being built on a current NETL project DEFE0027776,"ICME for Creep of Ni-Base Superalloys in Advanced Ultra-Supercritical Steam Turbines".
- The modeling framework is based on a dislocation density based crystal plasticity model developed in a previous NETL project (DEFE0024027), which captures the dislocation-precipitate interactions and is able to predict long-term creep behavior of nickel-base superalloys in full-field manner.
- The interplay between plastic deformation and the evolution of precipitate structure, which has been found critical in determining the creep strain, will be captured by integrating the creep model with the microstructural evolution model.



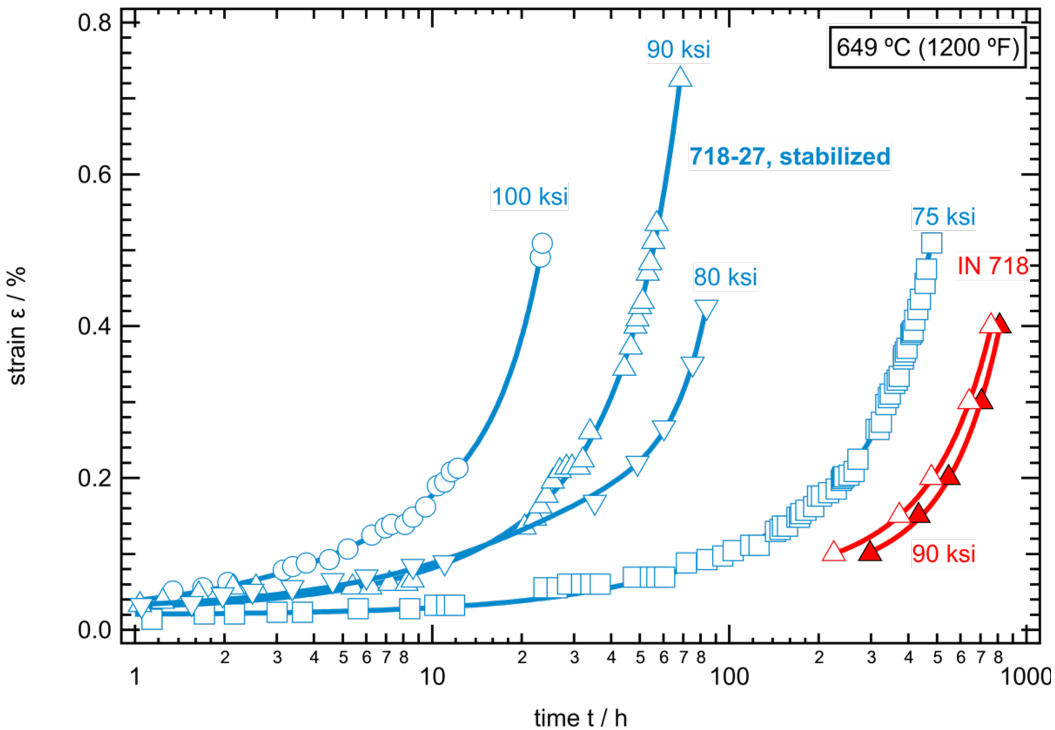
Comparison between the model prediction and the experimental creep curves of Haynes 282 at two different temperatures

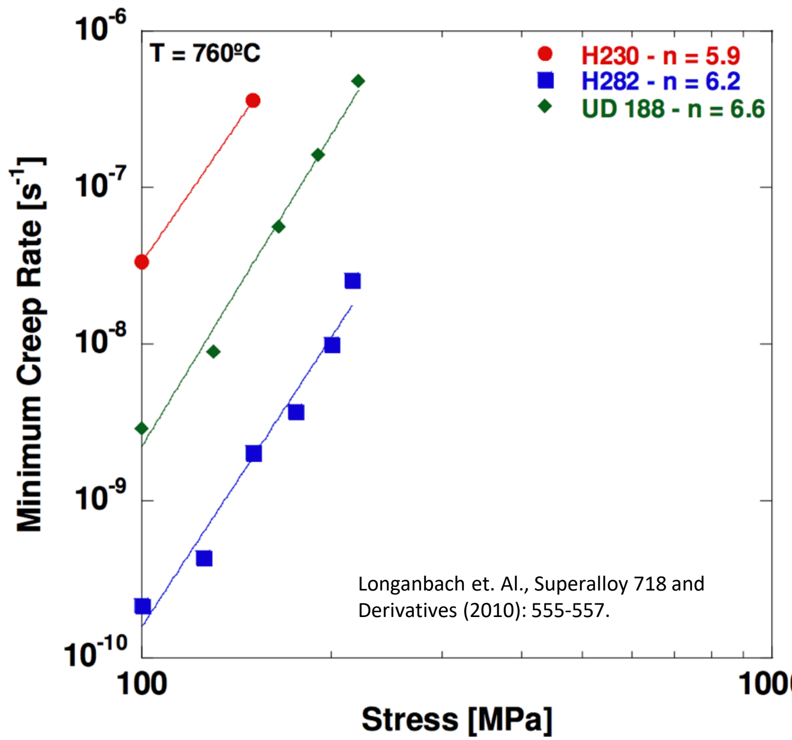
Progress in Year 1

- Round 1 alloys defined and produced by GE GRC
- Creep testing at OSU and Metals Technology Inc.
- With microstructure characterization feedback, several generations of heat treatments have improved creep performance
- Phase field model developed for co-precipitation
- Deformation mechanism analysis in progress for developing improved creep and strength models



Creep Properties at 649 °C (1200 °F)





- Conventionally heat treated Haynes 282 ruptures at 1% strain at 1200°F (649°C) at 80 ksi (550 MPa) in 1000 hours
- Stress exponent for Haynes 282 at 760°C is 6.2
- Stress exponent for stabilized IN718-27 at 649°C is 9.7