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

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FOA 1730 University Turbine Systems Research (UTSR)

Kick-Off Telecon 27 October 2017

Outline

- Background
- Technical approach
- Project objectives
- Project structures
- Project schedules
- Project budget
- Project Management Plan and Risk Management

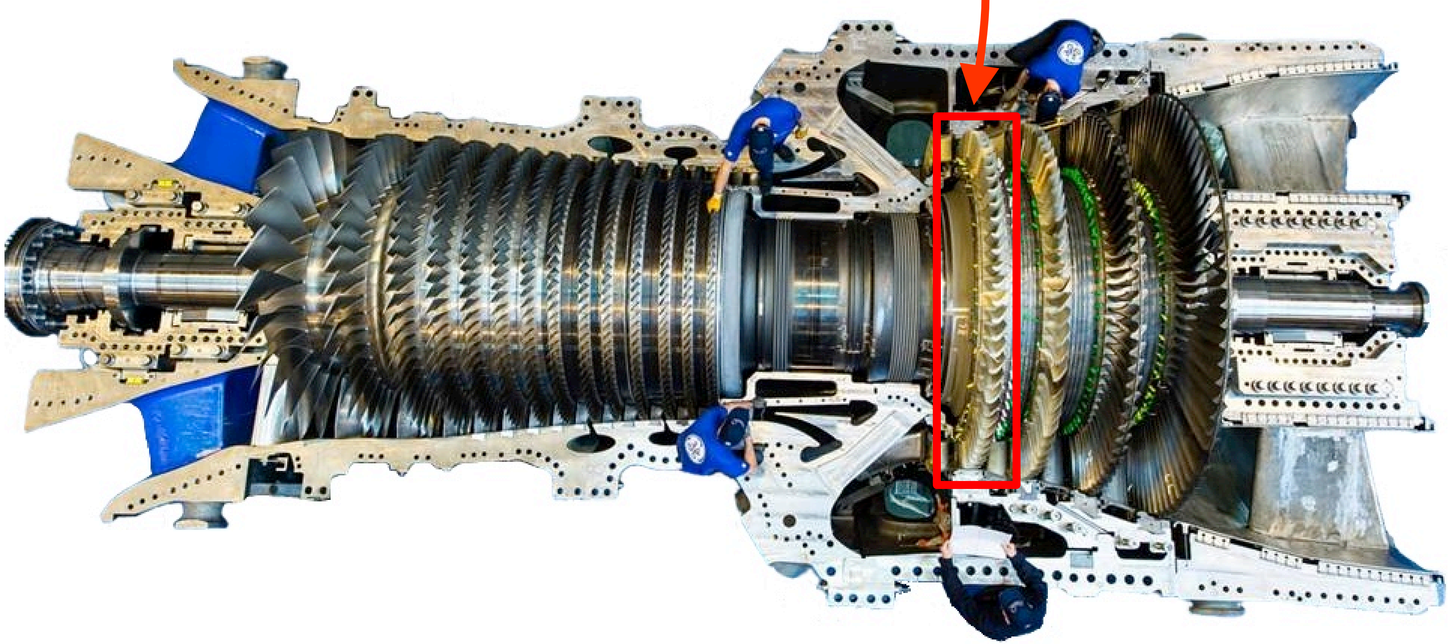
Path to Higher Efficiency Gas Turbine

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

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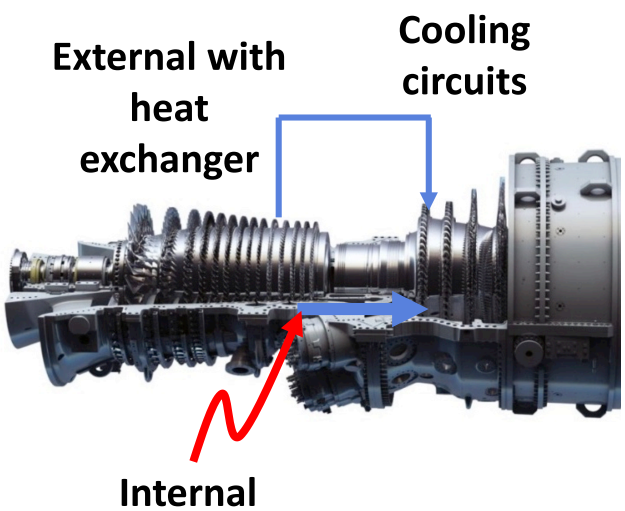
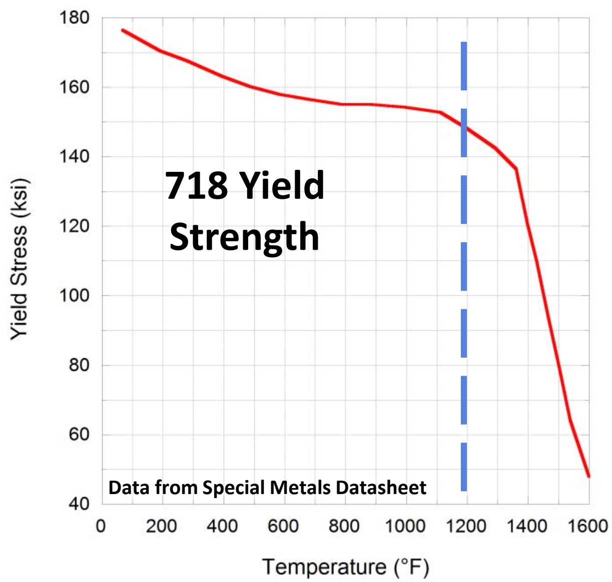
Designing a Higher Temperature Capable Wheel

Use steel and cool to lower the effective temperature



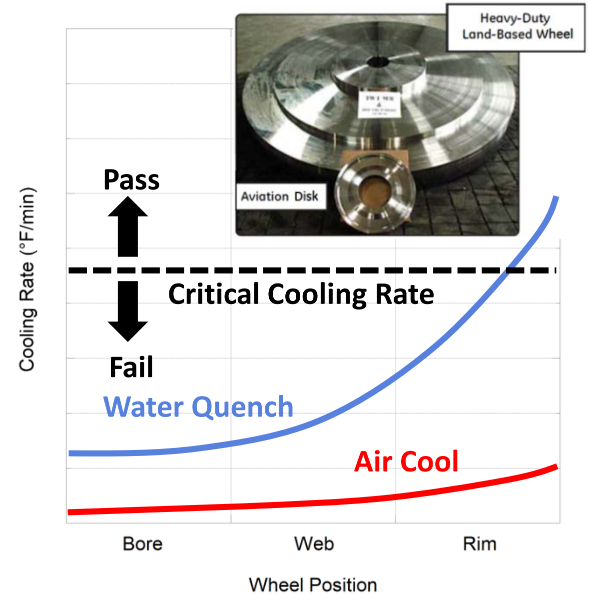
Cooling leads to reduced efficiency, increased complexity, & reliability risks.

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.

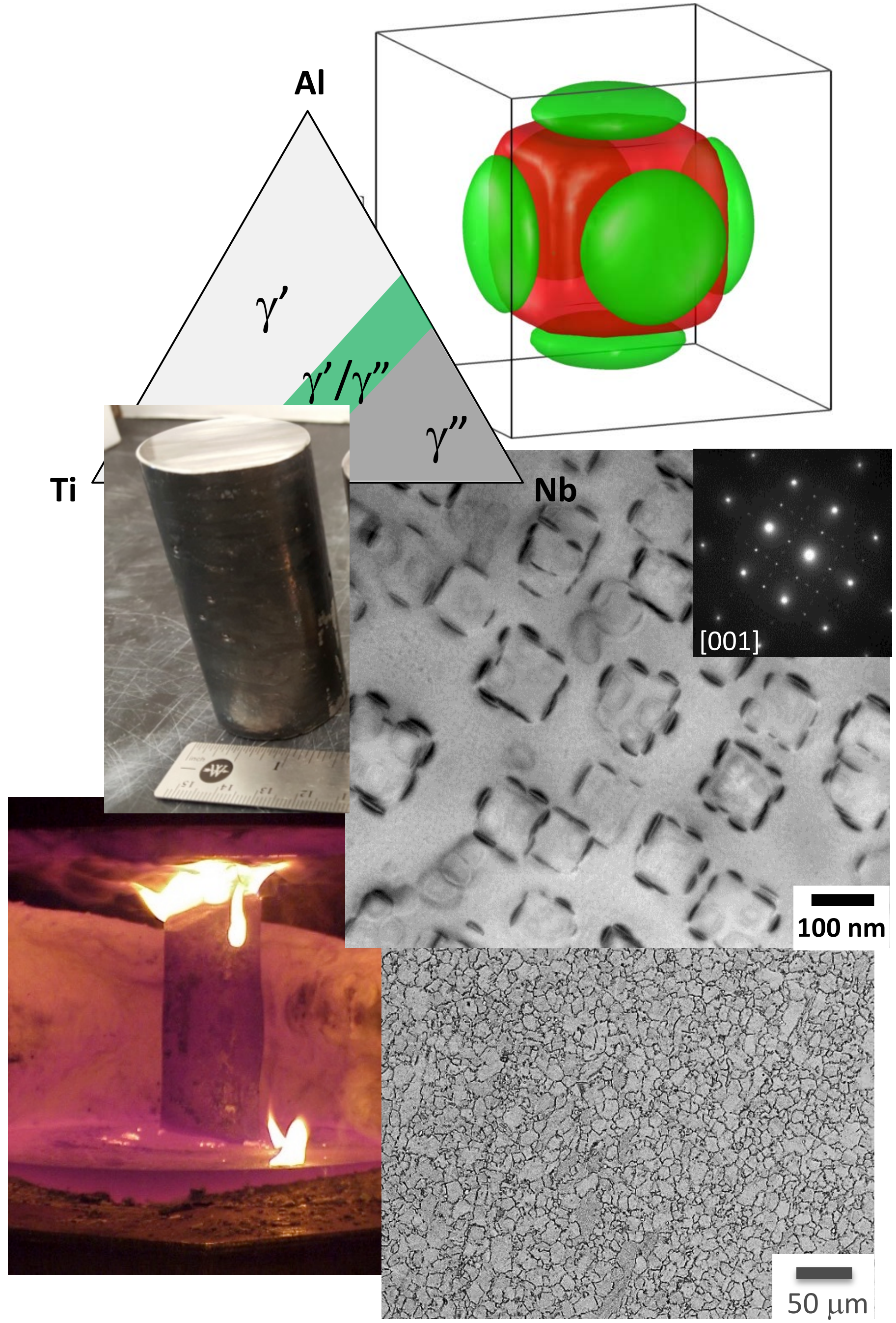
A new approach to alloy design is required to enable high temperature wheels

Coprecipitation Intro

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

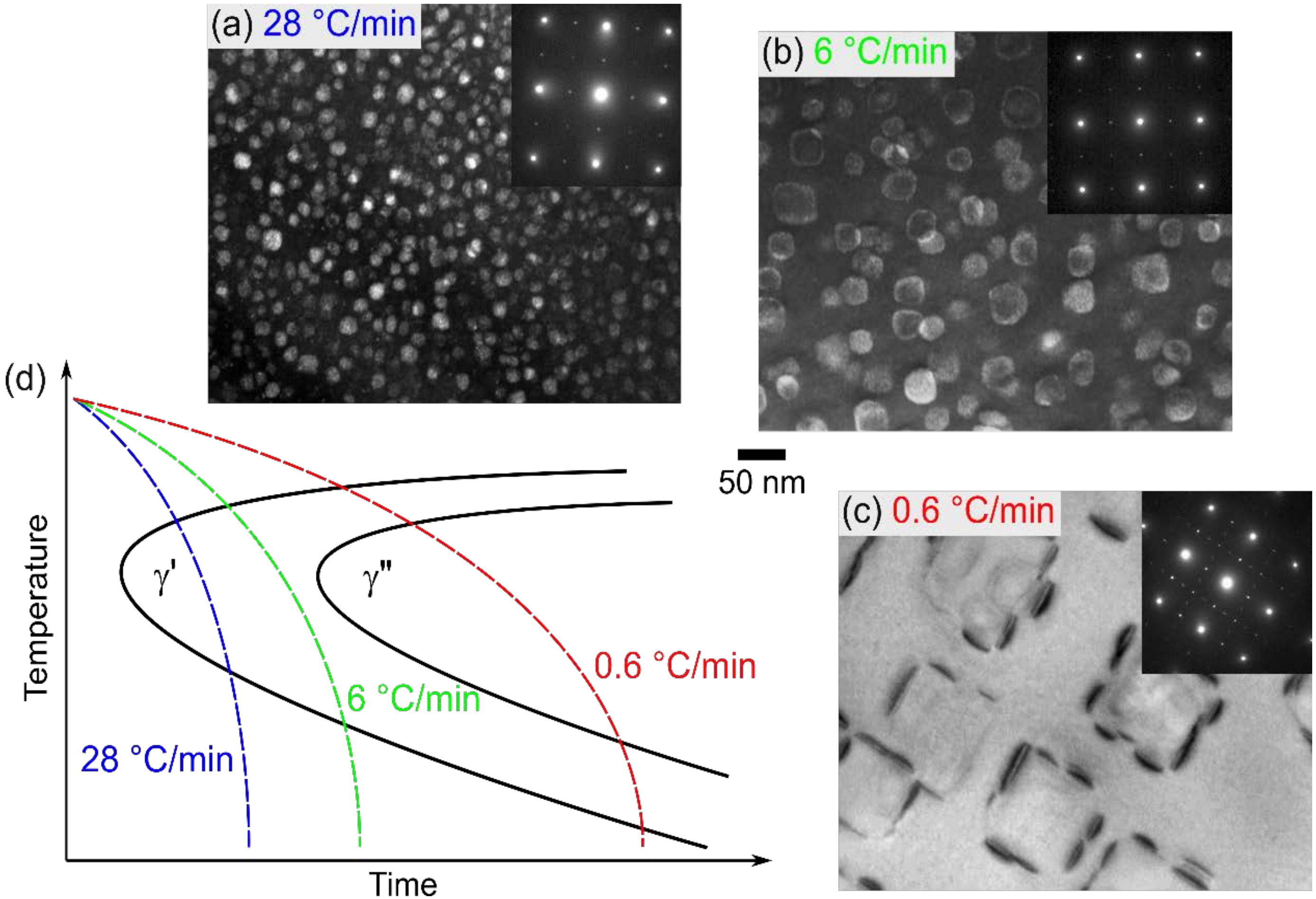
In previous NETL program (DEFE0026299):

- Proof of principle for coprecipitation concept and discovered new γ' alloy
- Developed successful sub-scale billetizing/forging procedure
- Screened tensile and hold time fatigue crack growth properties (*no creep testing or evaluation*)



Coprecipitation Concept

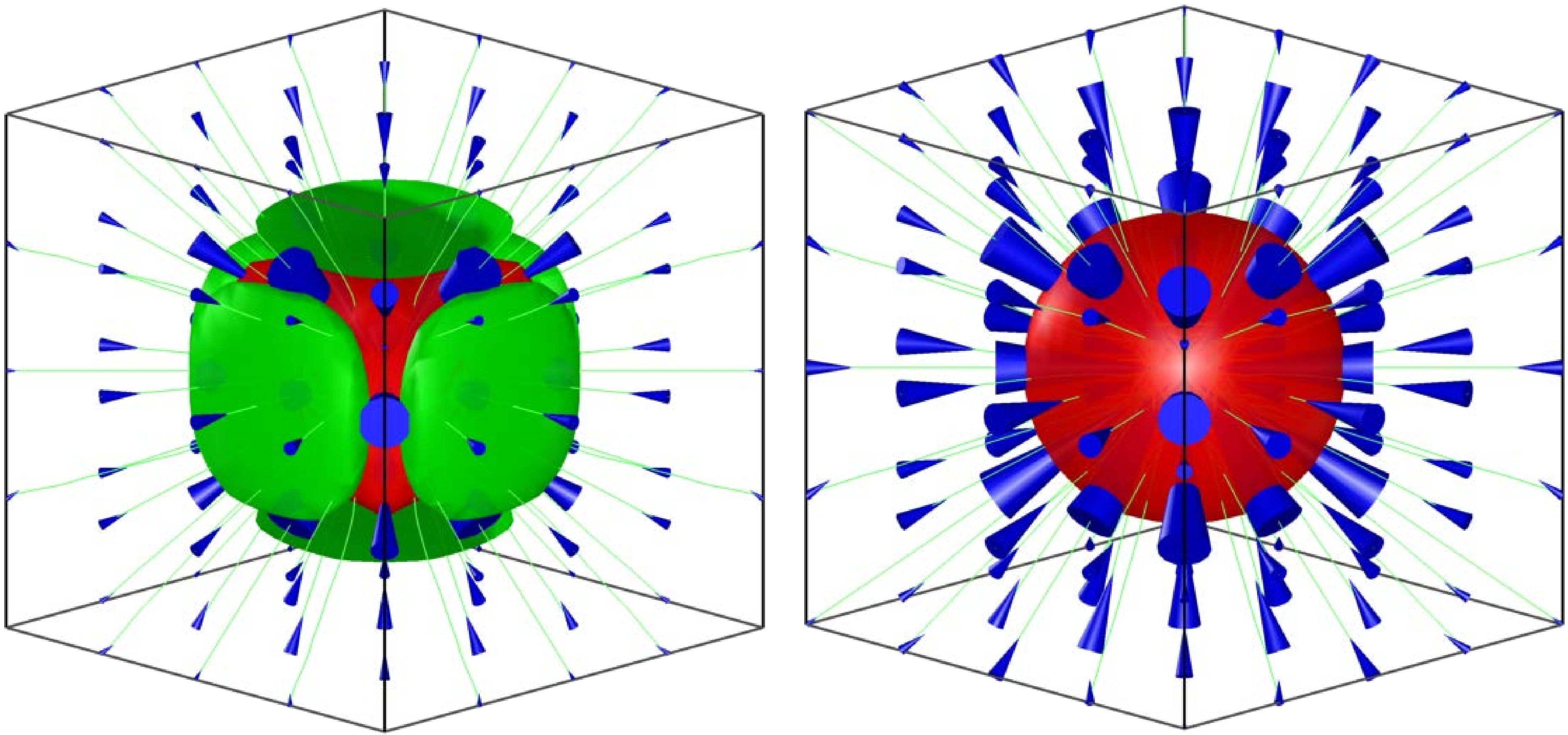
- **Leverage the coprecipitation of γ' and γ'' to restrict γ' coarsening during slow cooling of thick section components.**



Desired: form γ' then rapidly nucleate γ''

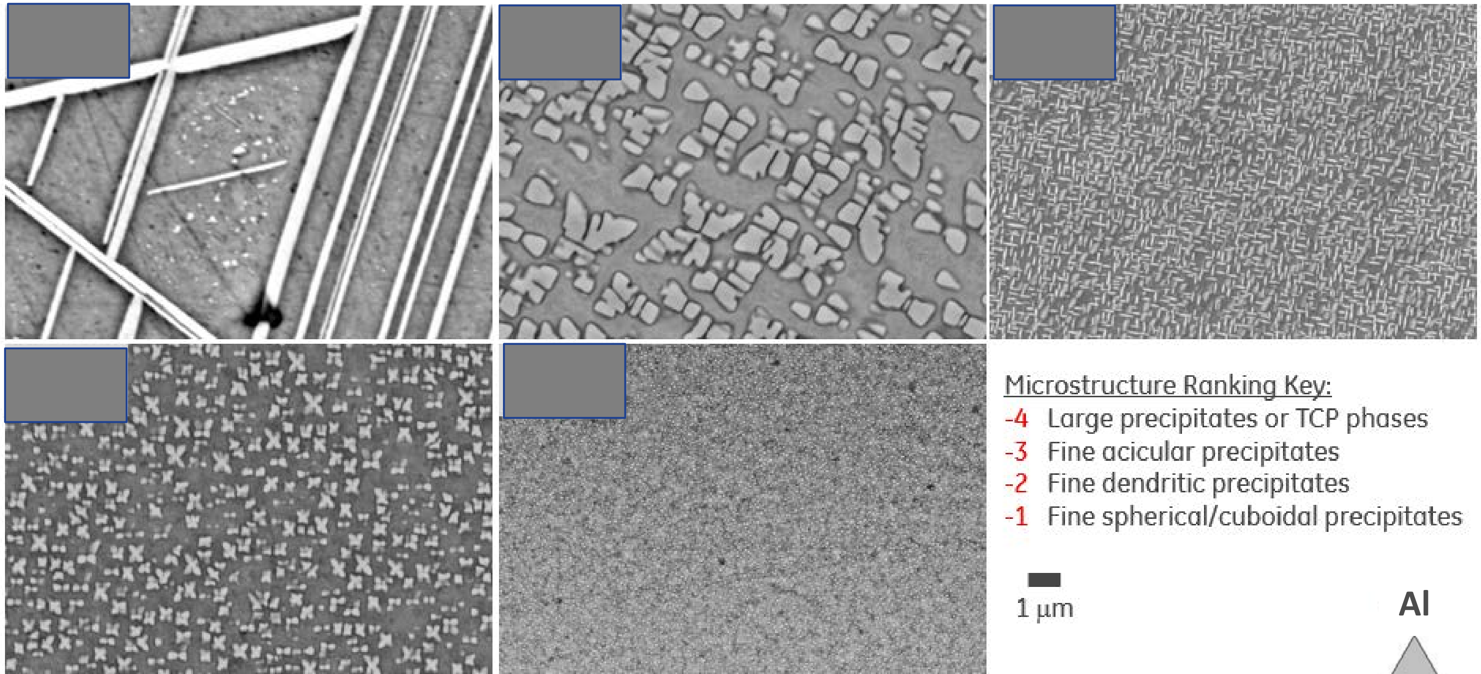
Coprecipitation Concept

- **Leverage the coprecipitation of γ’ and 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 need for γ’ to grow

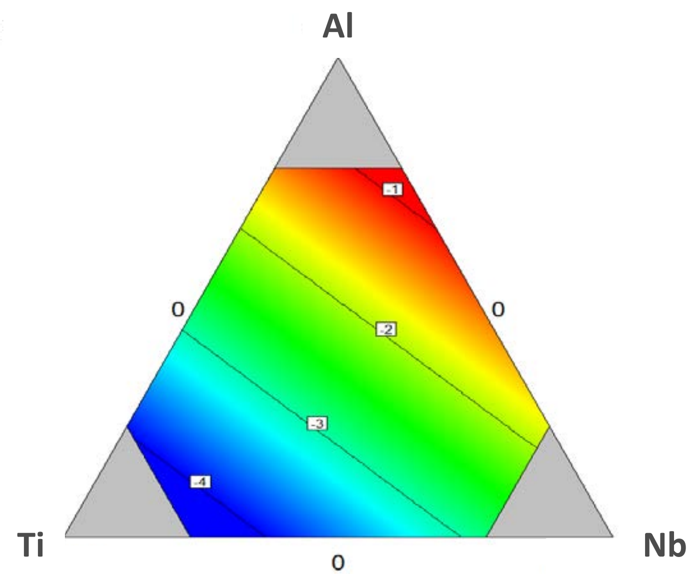
Coprecipitation Alloy Screening



Microstructure Ranking Key:
- -4 Large precipitates or TCP phases
- -3 Fine acicular precipitates
- -2 Fine dendritic precipitates
- -1 Fine spherical/cuboidal precipitates

1 μm

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

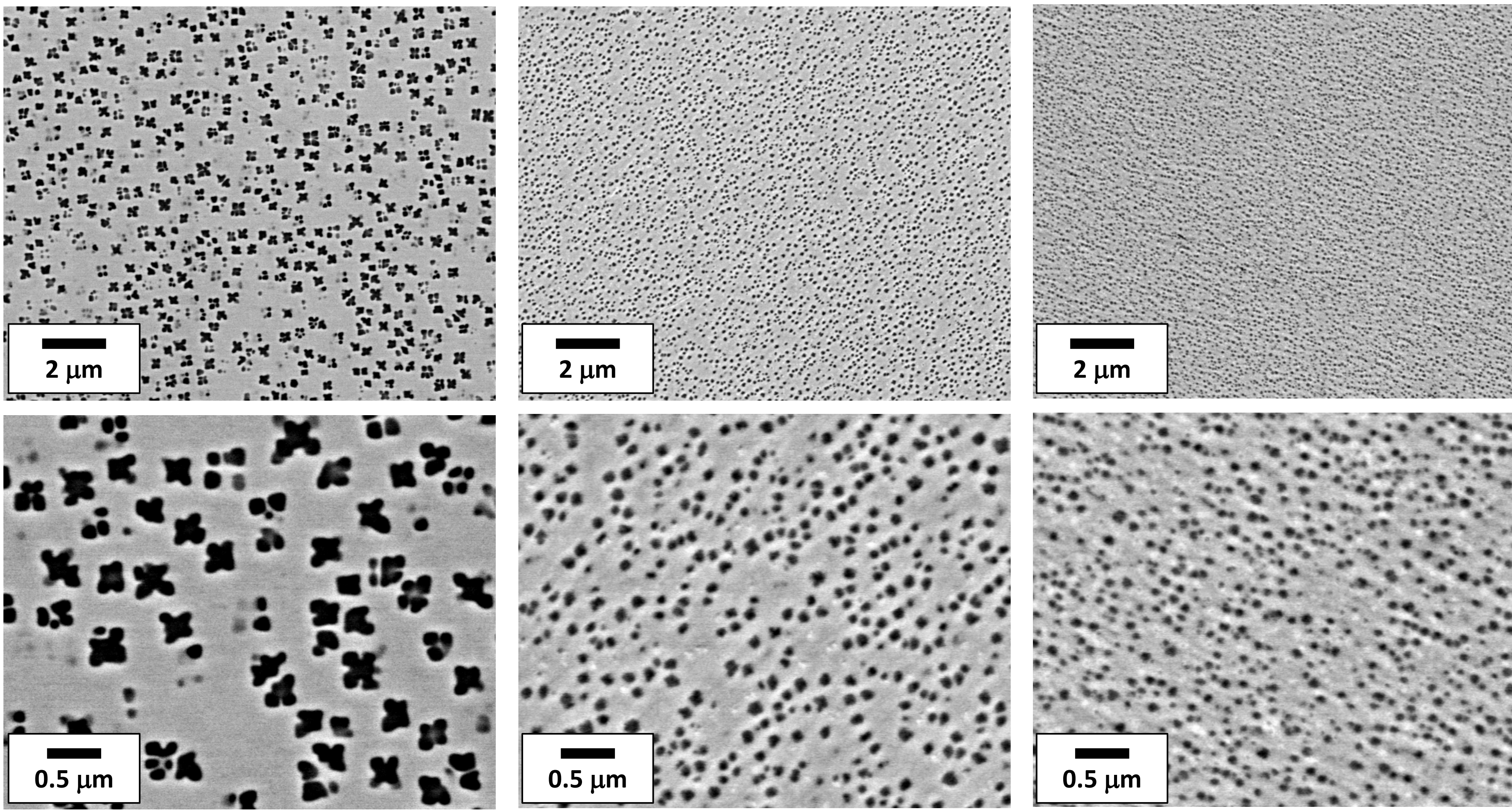


Slow Cool Precipitate Comparison

	Baseline γ' Alloy 19% Area Fraction	Coprecipitation Alloy 17±2% Area Fraction	Sluggish γ' Alloy 16±4 % Area Fraction

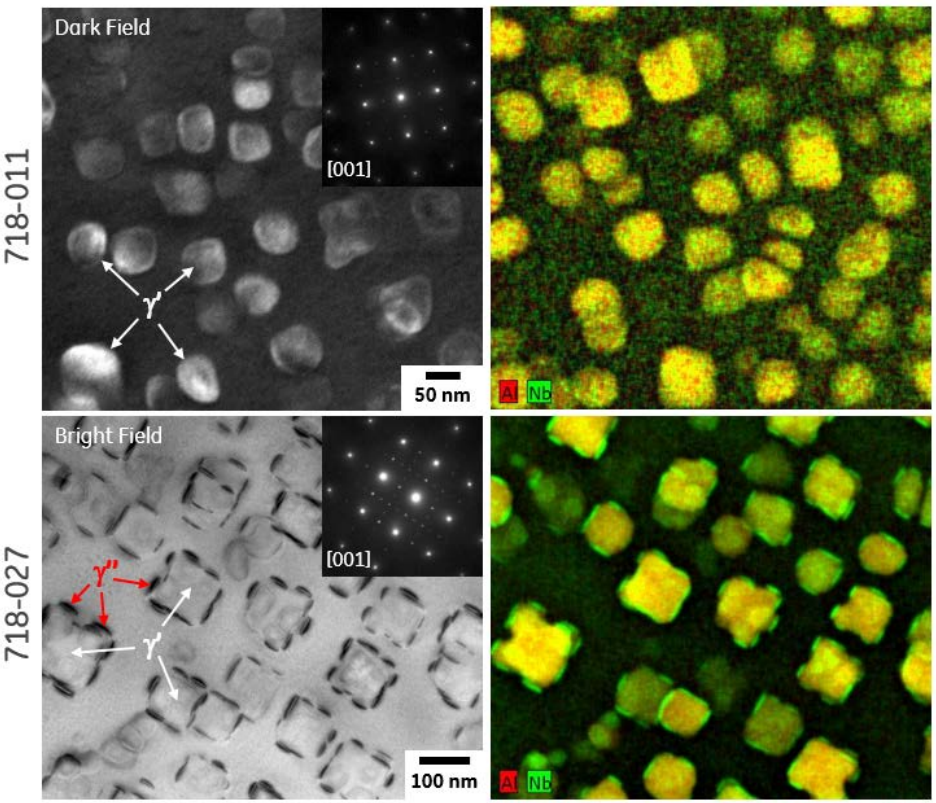
Low Magnification

High Magnification

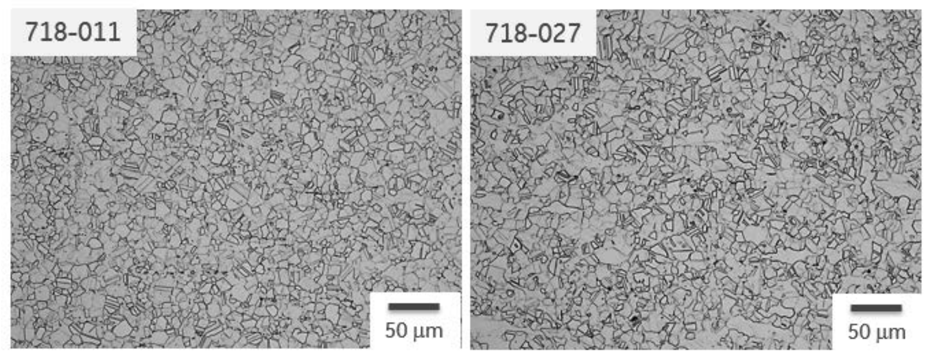


The new alloys yield substantially finer strengthening precipitates than the slow cooled baseline structure.

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

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Program Structure

Program Timeline

Mo. 1:
Program Initiation

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

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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

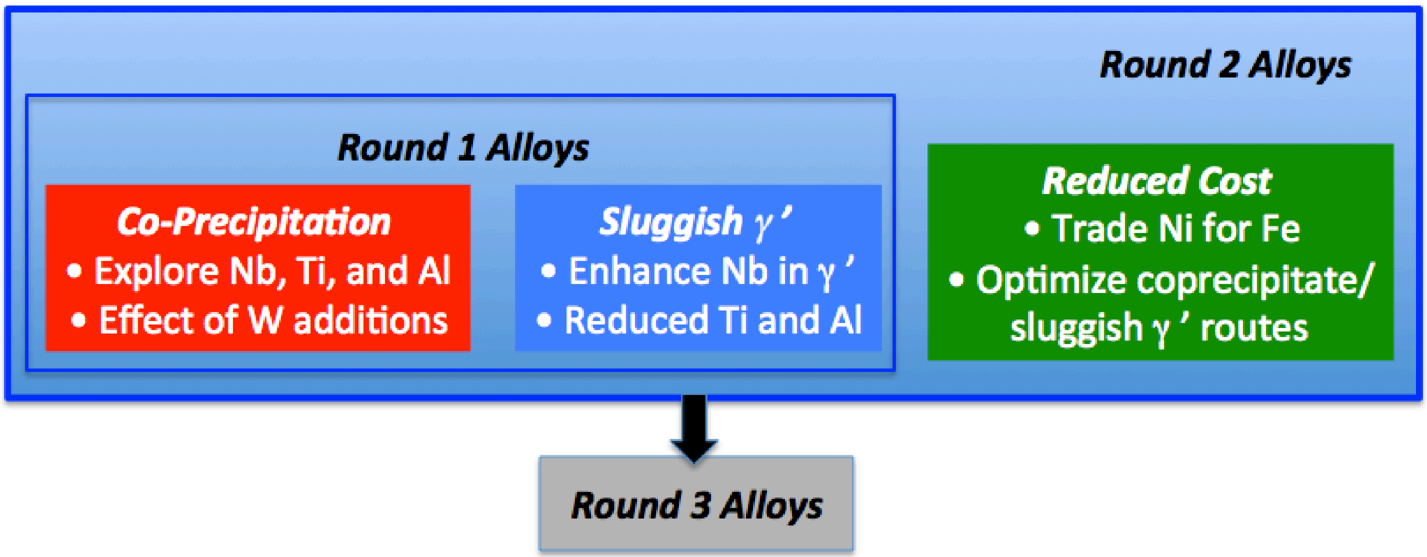
Rich DiDomizio leads alloy preparation and processing

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

Subtask 2.1 Alloy Selection and Processing



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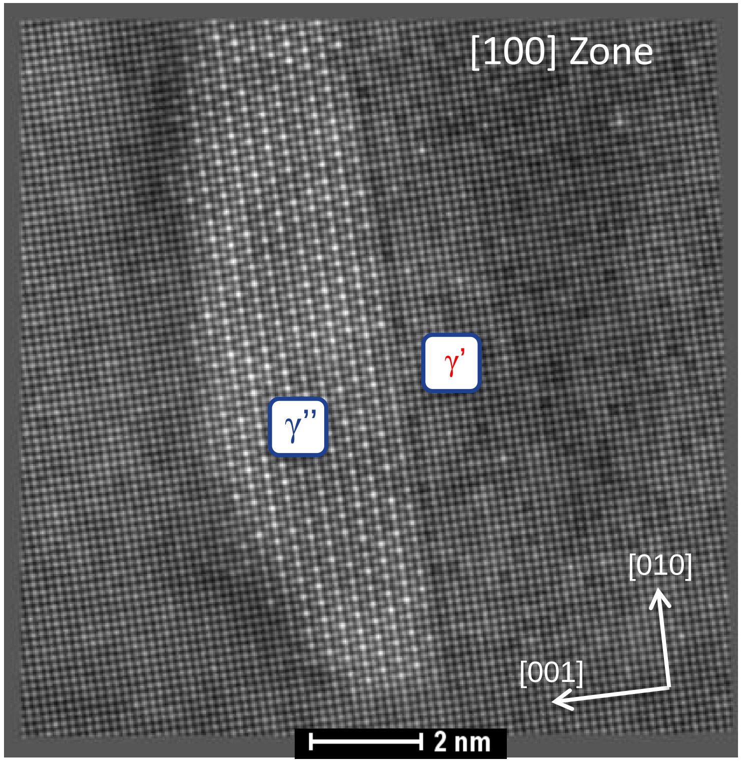
Based on the success of the previous NETL program (DEFE0026299) in inhibiting excessive coarsening of the precipitate structures upon slow cool from solvus temperatures, three rounds of alloy production and evaluation are planned in the proposed program.

Subtask 2.2 Heat Treatment and Microstructure Characterization

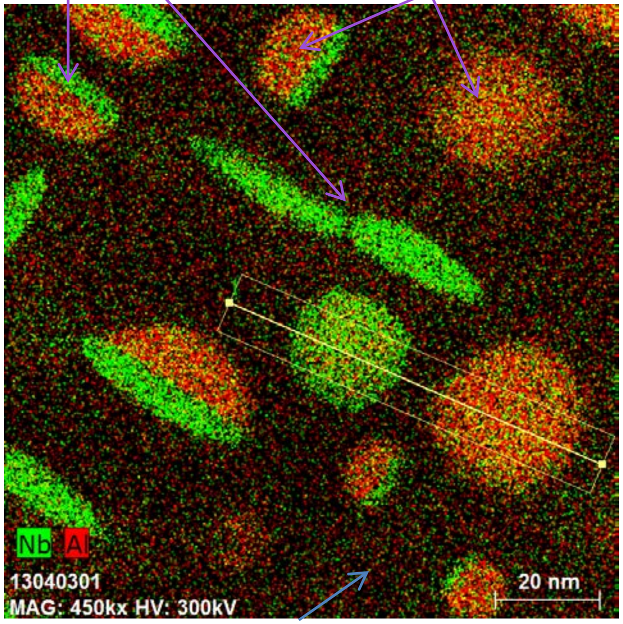
HAADF-STEM



SuperX EDS

γ'' Nb rich (Ni_3Nb)

γ' Al rich (Ni_3Al)



γ Fe rich (FCC matrix)

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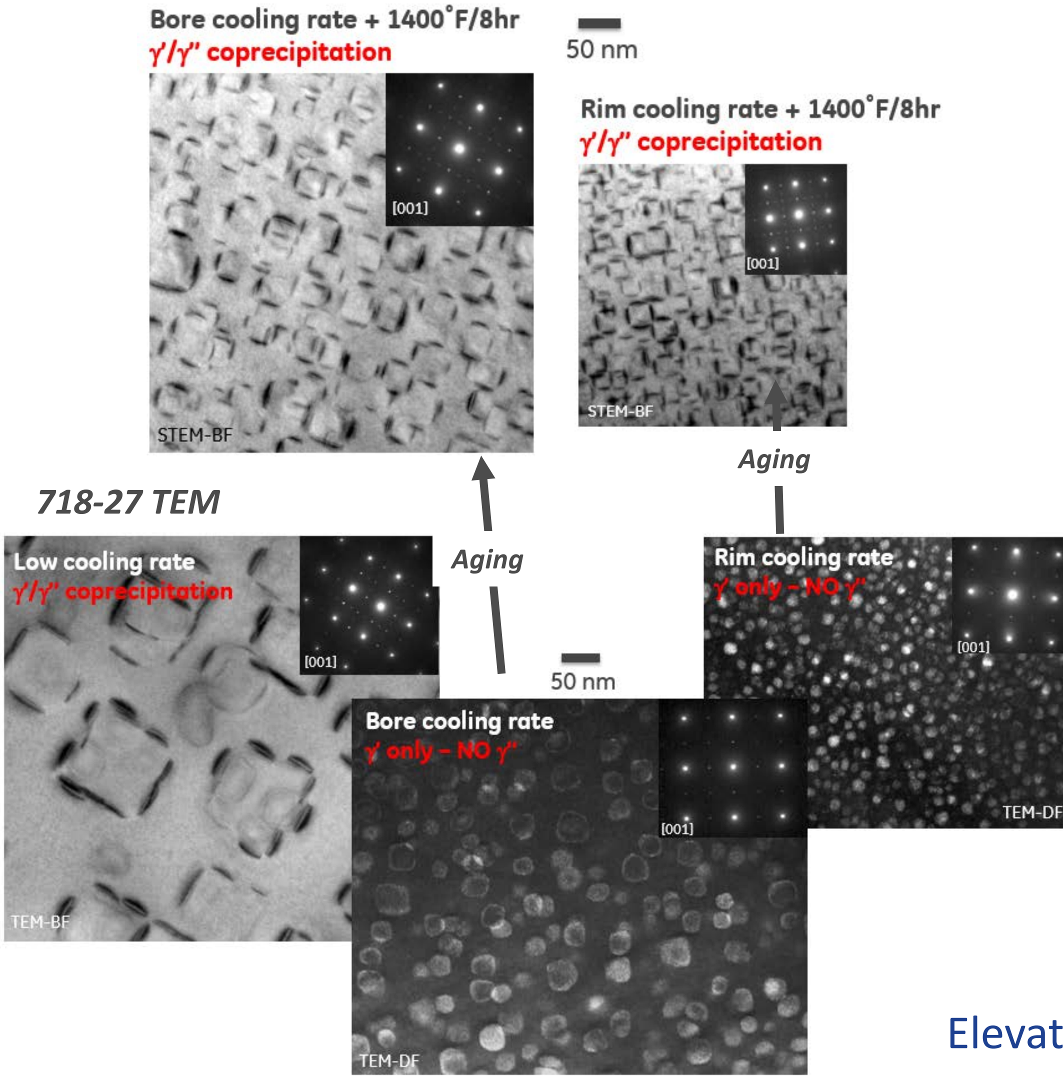
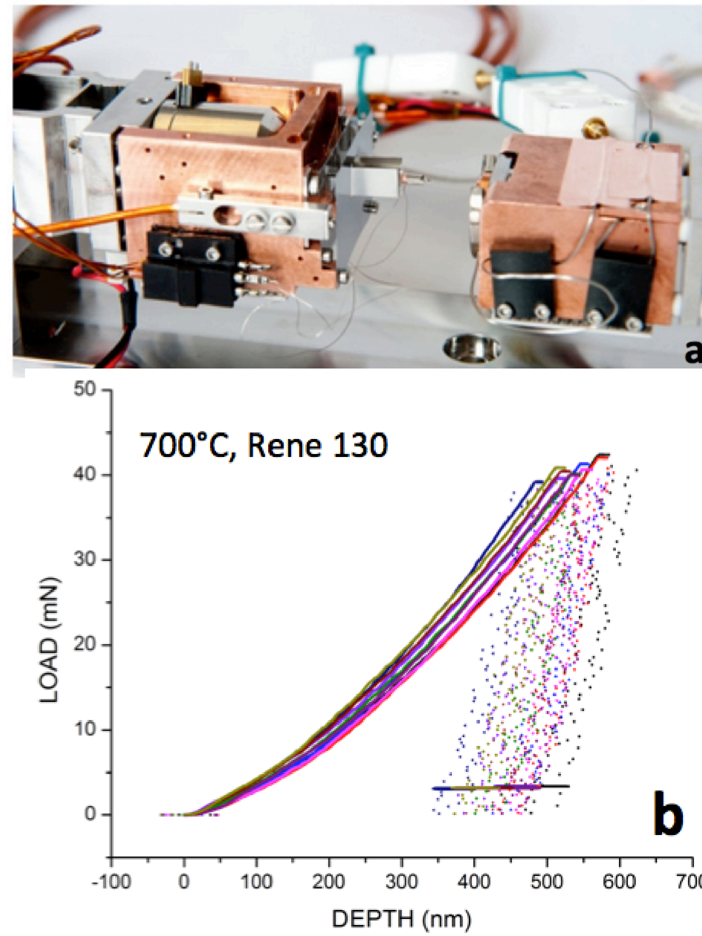
Subtask 2.3 Aging Informed by High Temperature Indentation





Elevated temperature indentation measurements will be used as accelerated probe of aging response

Subtask 2.5 High Temperature Mechanical Testing

Inputs

- Chemical free energy
- Elastic modulus
- Lattice parameter
- Diffusivity
- Interfacial energy

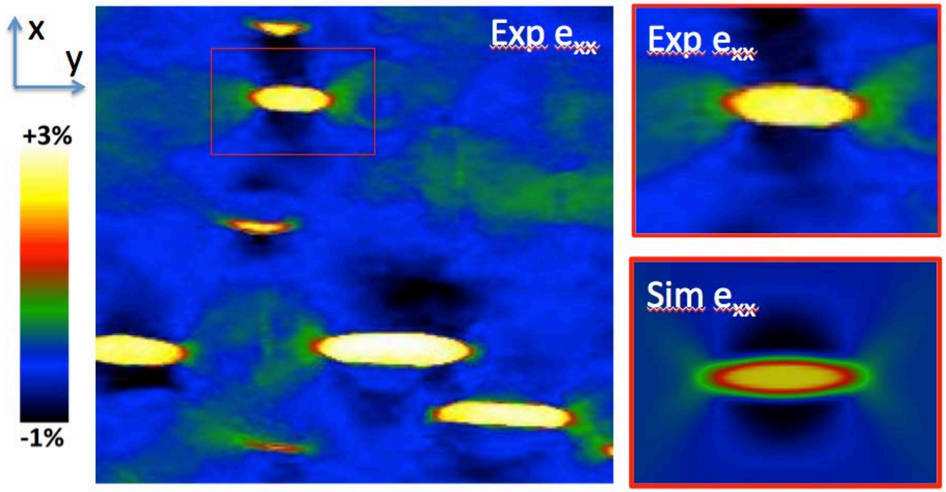
Models

- Multi-phase field model
- Isothermal and continuous cooling simulation

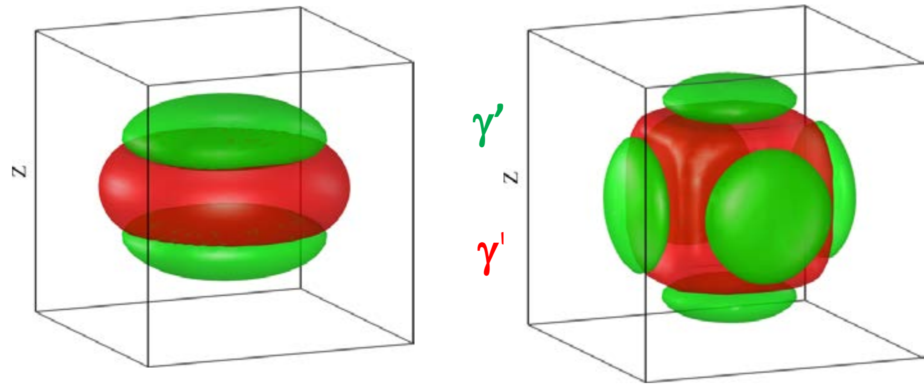
Outputs

- Compositional ranges yielding co-precipitation
- Cooling ranges leading to co-precipitation
- Co-precipitate microstructure

4D STEM Experiments at NCEM/LBL



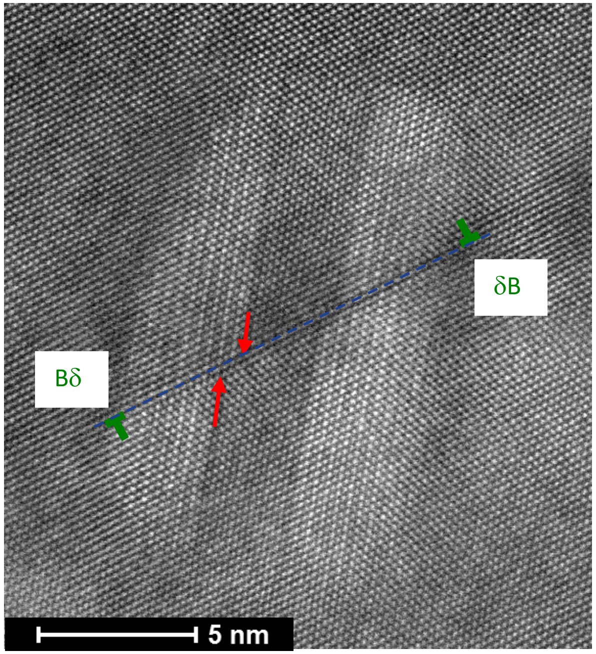
Model Output



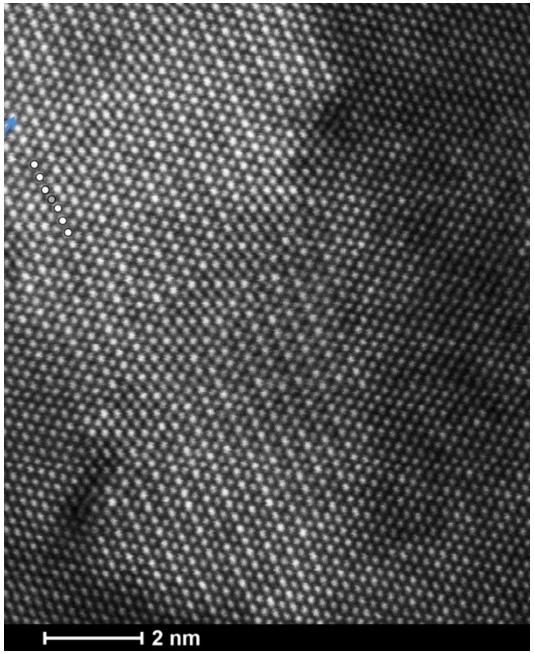
A combination of CALPHAD modeling for thermodynamic databases, PanPrecipitation simulation for CCT diagrams with detailed co-precipitation mechanisms quantified by a multi-phase field model

Subtask 3.1 Deformation Mechanism Characterization

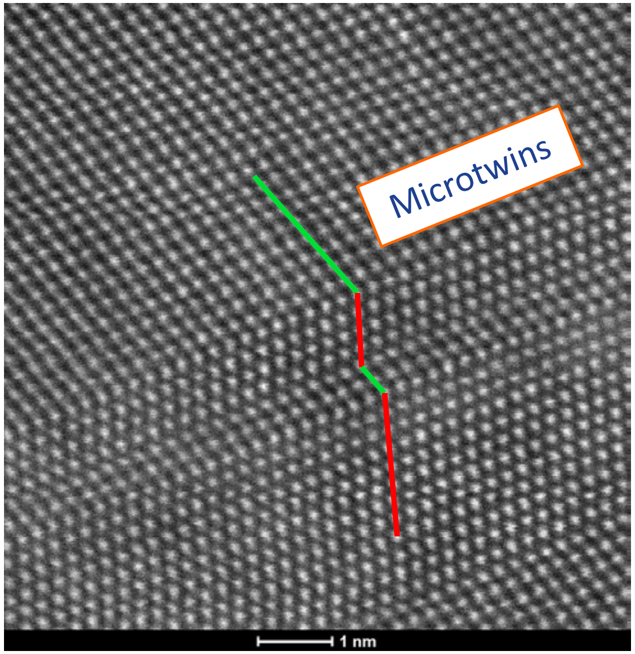
Sheared γ''/ γ'/ γ'' composite particle after room temperature deformation



Microtwin originating in a γ' / γ'' composite particle after deformation at 400°F



Microtwin extending into the γ matrix after deformation at 1200°C



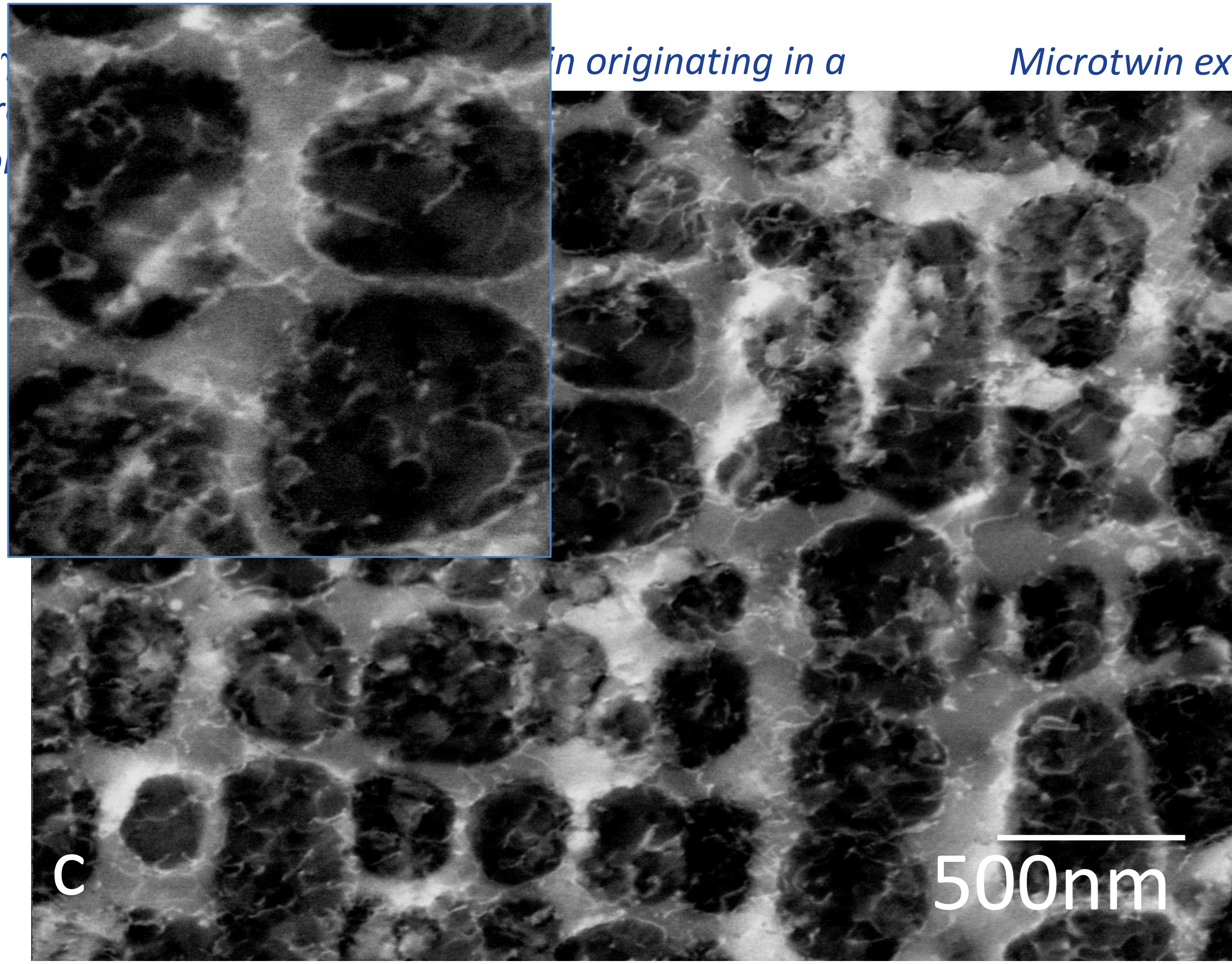
Examples of diverse mechanisms in conventionally-processed IN718 for different deformation conditions

Subtask 3.1 Deformation Mechanism Characterization

Sheared γ''/γ … particle after r… defo…

…n originating in a

Microtwin extending into … rix after … at 1200°C

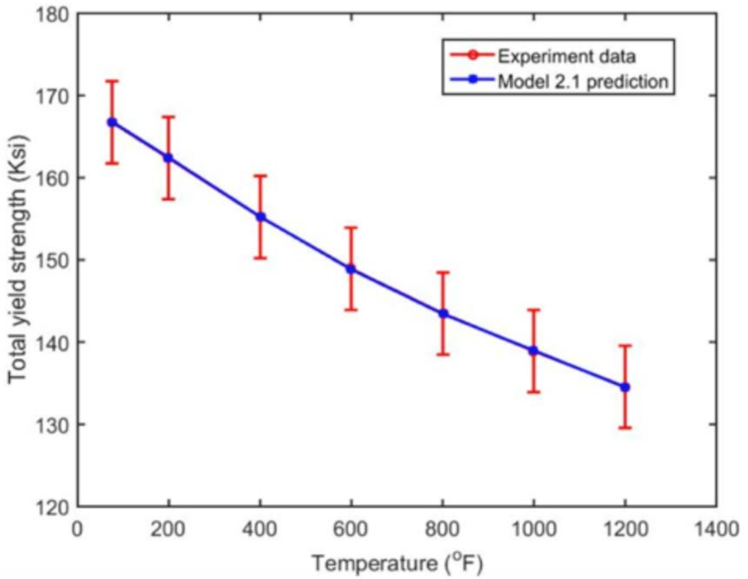


Examples of diverse mechanisms in conventionally-processed IN718 for different deformation conditions

Subtask 3.2 Yield Strength Model Development

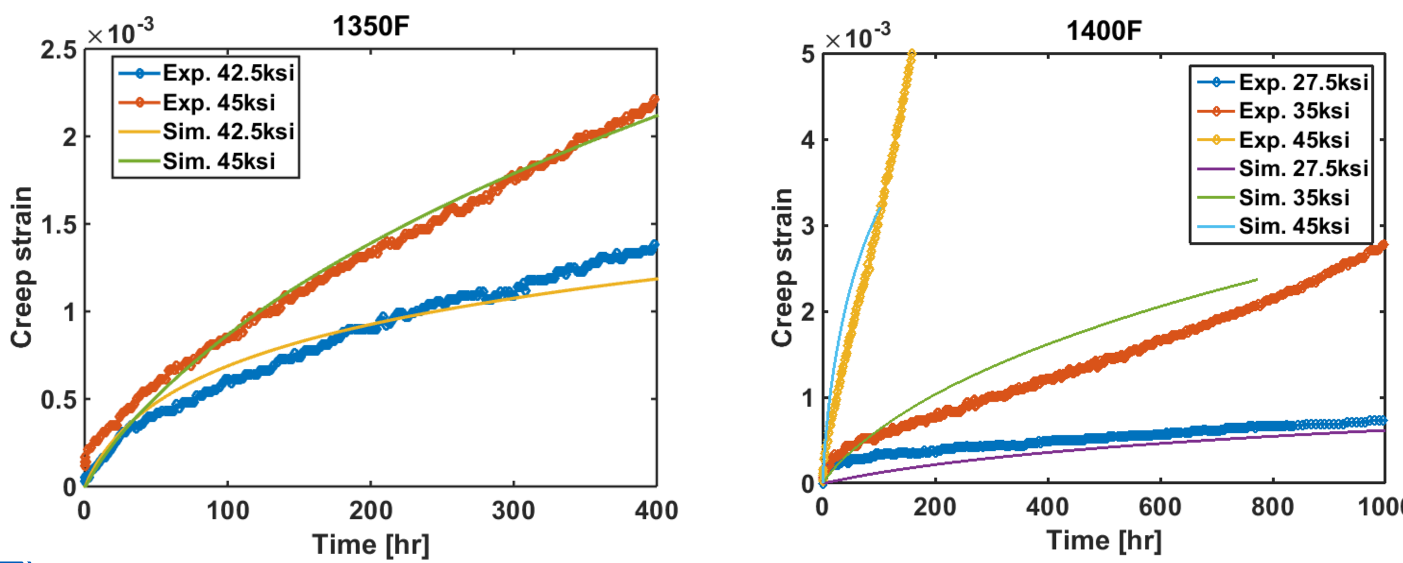
- The strengthening mechanisms in precipitate-hardened superalloys can be complex; multiple mechanisms and factors may operate to lead to the observed temperature and structure dependent strength.
- Our strength model to be developed will be based on linear superposition of multiple mechanisms revealed by detailed TEM characterization and/or phase field + ab initio modeling. Among the possible strengthening mechanisms, the model will includes (a) precipitation hardening, (b) solid- solution hardening (SSH), (c) forest dislocation hardening and (d) grain boundary strengthening (Hall-Petch relation). Such an approach has been applied to IN718 and exhibited a good agreement with the experiment

Comparison between the model prediction and the experimental measurement of the yield strength of IN718 as a function of the temperature



Subtask 3.3 Creep Model Development

- The creep model will be 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

Project Objectives

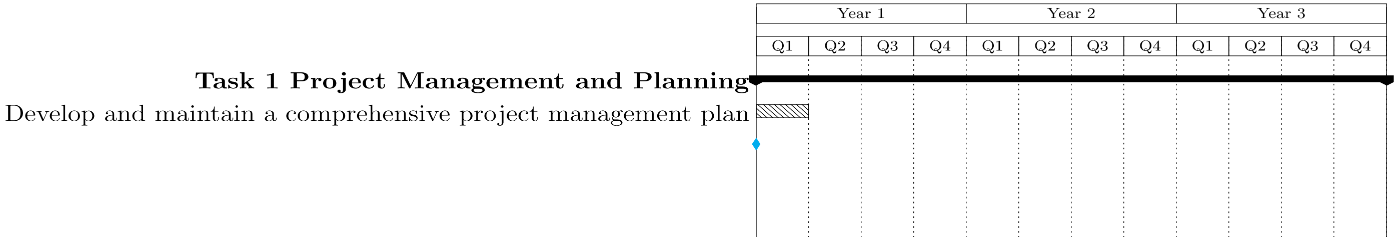
In order to increase combined cycle turbine efficiency from approximately 62% to 65% for the next-generation advanced cycle…

(1) develop a new, high performance heavy duty gas turbine wheel material:
- creep properties at 1200°F that are comparable to conventional alloy 718 operating at 1000°F.

(2) develop a multiscale modeling framework, validated for this new class of superalloys, capable of predicting microstructure evolution

(3) develop new mechanistic understanding of the yield and creep behavior of these superalloys

Project Schedule



- Program funding awarded on October 1, 2017

- Kick-Off Telecon with GE Global and Metals Technology occurred on October 4, 2017

- Face-to-face meeting will occur on December 8, 2017 at GE Global in Niskyuna, N.Y.

- Appointment of personnel at OSU:
  - Ms. Semanti Mukhopadhyay and Dr. Christopher Zenk

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Task	Decision Point	Success Criteria
2.4	Completion of aging studies for coprecipitation / sluggish γ' (Round 1) alloys	Material shows desired fine-scale precipitate structures on slow cooling and is capable of age hardening
2.5	Round 1 alloys mechanical test data complete	Understanding of how dislocations interact with precipitate structures over relevant temperature range and inform property models
2.4	Completion of aging studies including possibility of coprecipitation / sluggish γ' / high Fe (Round 2) alloys	Material shows desired fine-scale precipitate structures on slow cooling and is capable of age hardening
2.5	Round 2 alloys creep data complete	Improved creep behavior over Round 1 alloys
2.4	Completion of aging studies for Round 3 alloys	Material shows desired fine-scale precipitate structures on slow cooling and is capable of age hardening
2.5	Round 3 alloys creep data complete	Data produced aligns with creep prediction and high Fe composition is comparable in terms of properties
2.4	PanPrecipitation simulations complete	Understanding of how alloy composition and cooling rate affects the precipitation sequence
2.4	Phase field simulations complete	Understanding of how alloy composition and cooling rate affect the morphology of co-precipitates and their coarsening behavior
3	Yield strength modeling completes	Model predictions agree with experimental data
3	Creep modeling completes	Model predictions agree with experimental measurements

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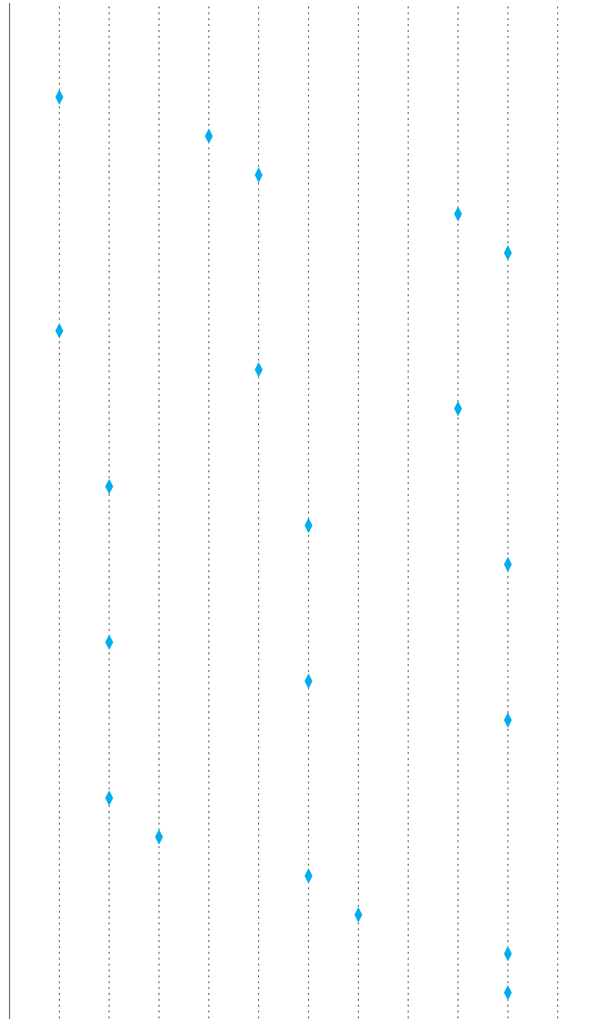

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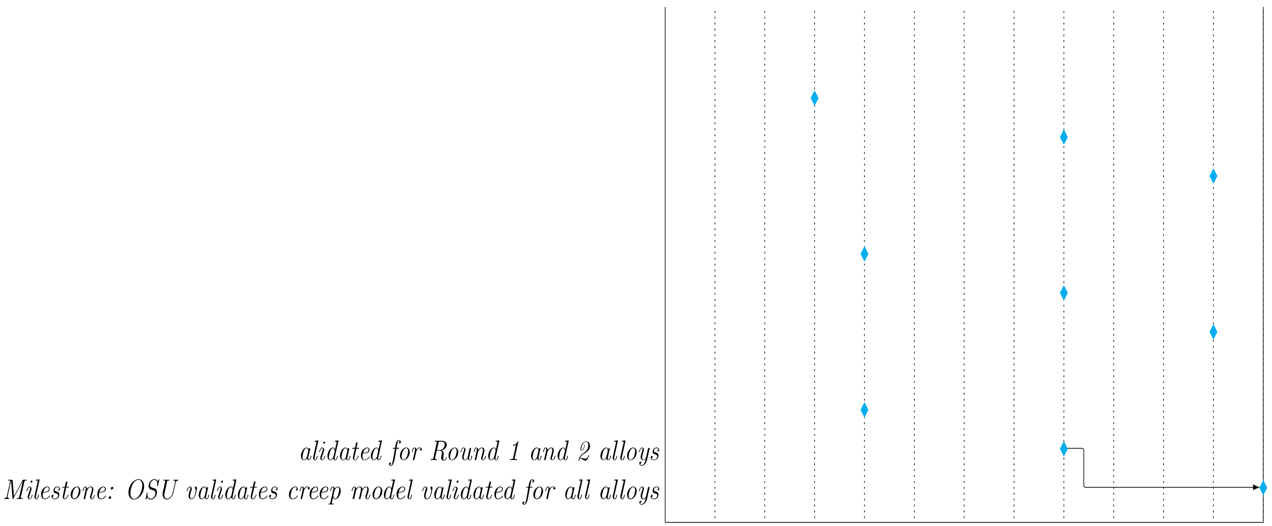

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Project Budget

Recipient Organization	Budget Period 1		Budget Period 2		Budget Period 3		Total	
	DOE Funds	Non-Federal Cost Share	DOE Funds	Non-Federal Cost Share	DOE Funds	Non-Federal Cost Share	DOE Funds	Non-Federal Cost Share
Ohio State	$194,085	78,883	$200,066	78,884	$205,850	78,884	$600,000	$236,651
Total ($)	$194,085	78,883	$200,066	78,884	$205,850	78,884	$600,000	$236,651

Cost Share:

$ 173,974 (GE Global)

$ 62,677 (MTI, Inc)

$ 236,651 (Total for 3 years)

Risk Management

Task	Risk	Impact (if not addressed)	Mitigation Plan
2.0	Changing the alloy composition results in poor forged microstructure.	Mechanical properties will be poor.	Check forged and heat treated microstructure to ensure recrystallized grains with similar grain size. Modify forging practice if needed
2.1	Unwanted secondary TCP phases form	TCP phases may result in a reduction in properties	Use ThermoCalc predictions to avoid compositions with potential TCP phase formation
3.3	Cannot achieve required creep resistance	Will require new approach to alloy design	Produce alloys with varied concentrations of strengthening phase to find required level
2.4	Pseudo ternary based phase field assessment does not make accurate prediction in higher order elemental space	Modeling will not provide useful input for material development	Extend the free energy model to a quaternary or higher-order systems
3.2	The yield strength model does not make accurate prediction for the new alloys	Modeling will not provide useful input for alloy optimization	Feed accurate microstructural and deformation mechanism information from experimental characterization into the yield strength model and reformulate the governing equation and re-calibrate the model
3.3	The creep model does not make accurate prediction for the new alloys	Modeling will not provide useful input for alloy optimization	Feed accurate microstructural evolution and creep deformation mechanism information from experimental characterization into the creep model and reformulate the governing equations and re-calibrate the model
2.4 3.2 3.3	Important model inputs such as fault energy and interfacial energy are not available for the new alloys	Modeling will not make accurate predictions of microstructural evolution and deformation	Carry out parametric study by varying systematically these parameters and comparing model predictions to experimental characterization and measurements to obtain the best estimate of the values
2.4	In Situ TEM / DSC capability is not available for first year of program	Precipitation sequences can not be validated	Utilize interrupted DSC and ex situ TEM analysis as a viable alternative

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