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

Semanti Mukhopadhyay, Kamal Kadirvel, Don McAllister 
Christopher Zenk, Michael Mills and Yunzhi Wang 
The Ohio State University 
Department of Materials Science and Engineering

Richard DiDomizio 
GE Global

Robert Hayes 
Metals Technology Inc.

University Turbine Systems Research (UTSR) 
DE-FE0031278 Program Manager Patcharin Burke
Outline

• Background
• Co-precipitation Concept
• Program overview
• Present Status:
  Alloy preparation and testing
  Creep testing status
  Deformation Mechanisms in $\gamma'/\gamma''$ alloys
• Summary
Today’s combined cycle efficiency is ~62%  
Future turbine combined cycle efficiency is ~65%  

INCREASING WHEEL TEMPERATURE  
Pressure Ratio: Higher  
Firing Temperature: Higher  
Sealing Flows: Lower  
Cooling Flows: Lower  

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

**External with heat exchanger**

Cooling circuits

**Internal**

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

**Invent a better γ” (Ni₃Nb) strengthened alloy**

Data from Special Metals Datasheet

718 Yield Strength

Yield Stress (ksi)

Temperature (°F)

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

Use an Aviation disk alloy strengthened with γ’ (Ni₃Al)

Critical Cooling Rate

Pass

Fail

Water Quench

Air Cool

External with heat exchanger

Internal

Use an Aviation disk alloy strengthened with γ’ (Ni₃Al)

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

• Leverage the coprecipitation of $\gamma'$ and $\gamma''$ to restrict $\gamma'$ 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

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
Pls:
Mike Mills
Yunzhi Wang
Bob Hayes
Rich DiDomizio

Experiments:
Semanti Mukhopadhyay
Christopher Zenk

Modeling:
Longsheng Feng
Kamalnath Kadrivel
Hariharan Sriram
Alloy 718 is favored for its high temperature strength retention and weldability.

- Widely used as a jet engine disk alloy

- $\gamma'$ and $\gamma''$-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

Structure and Composition of Composite Particles in Alloy 718

HAADF-STEM

[100] Zone

γ"

γ'

[010]

[001]

2 nm

SuperX EDS

γ" Nb rich (Ni₃Nb)

γ' Al rich (Ni₃Al)

γ Fe rich (FCC matrix)

Effect of Coprecipitation on Precipitate Coarsening

- Precipitate \( \gamma'' \) heterogeneously on all 6 interfaces of \( \gamma' \) to restrict \( \gamma' \) coarsening during slow cooling of thick section components.

Phase field model simulation showing that \( \gamma'' \) provides a barrier to diffusion of Al which is needed for \( \gamma' \) to coarsen.
Coprecipitation Alloy Screening

• Majority of alloys excluded early due to large $\gamma'$ and/or TCP phase formation
• Design of Experiments approach highlighted negative Ti effect
Strengthening Element Ratio Study

- $(Ti+Al)/Nb$ ratio increased incrementally
- $\gamma'$ size increase with addition of $\gamma'$-formers
- $\gamma''$ size stays consistent
- Precipitation sequence reverses

Systematic study provides coprecipitation chemistry limits
Coprecipitation Concept

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

Desired: form $\gamma'$ then rapidly nucleate $\gamma''$

The new alloys yield substantially finer strengthening precipitates than the slow cooled baseline structure.
Coprecipitation and Sluggish $\gamma'$ Alloys

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

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

Potential for both coprecipitation and sluggish $\gamma'$ concepts–basis for round 1 alloys in new program
“Round 1” Alloys and Heat Treatments

TEM-DF images for 718-11 and 718-27 alloys

<table>
<thead>
<tr>
<th>Alloy Name (wt%)</th>
<th>Ni</th>
<th>Cr</th>
<th>Fe</th>
<th>Al</th>
<th>Ti</th>
<th>Nb</th>
<th>Mo</th>
<th>C</th>
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<tbody>
<tr>
<td>718</td>
<td>52.5</td>
<td>19</td>
<td>18.9</td>
<td>0.5</td>
<td>0.9</td>
<td>5.13</td>
<td>3.05</td>
<td>0.02</td>
</tr>
<tr>
<td>718-011</td>
<td>52.5</td>
<td>19</td>
<td>18.9</td>
<td>1.5</td>
<td>---</td>
<td>5</td>
<td>3.05</td>
<td>0.02</td>
</tr>
<tr>
<td>718-027</td>
<td>52.9</td>
<td>18.7</td>
<td>18.9</td>
<td>1.1</td>
<td>0.95</td>
<td>4.4</td>
<td>3.05</td>
<td>0.02</td>
</tr>
</tbody>
</table>

- Solution: 982°C/3 h
- Age 1: 718°C/8 h slow: bore
- Age 2: 649°C/14 h fast: rim

- 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

Solution
1800°F / 2 hr

Stabilization
1550°F / 10 hr

Age stage 1
1325°F / 8 hr

Age stage 2
1250°F / 14 hr

Room Temp

Similar heat treatment to that used in IN718
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 1550°F and Water Quenched
Large volume fraction of γ' precipitates

Stabilized at 1570°F and Water Quenched
Large volume fraction of precipitates with an inverted contrast
Interior of grains has unidentified microstructure

Stabilized at 1600°F and Water Quenched
Breakdown of microstructure: large grains consisting of lath-like δ − η precipitates

Creep testing to commence on modified heat treat alloys
Combining a multi-phase field model with PanPrecipitation yields a quantitative simulation of coprecipitation phenomena.
Effect of Alloy Concentration on Microstructure

<table>
<thead>
<tr>
<th>Alloy</th>
<th>$c_{AI}$</th>
<th>$c_{NH}$</th>
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<tbody>
<tr>
<td>Alloy1</td>
<td>0.024</td>
<td>0.022</td>
</tr>
<tr>
<td>Alloy2</td>
<td>0.024</td>
<td>0.03</td>
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<tr>
<td>Alloy5</td>
<td>0.024</td>
<td>0.0077</td>
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<tr>
<td>Alloy6</td>
<td>0.027</td>
<td>0.017</td>
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</tbody>
</table>

- Alloy1 – Sandwich nuclei
- Alloy2 - Primarily $\gamma''$
- Alloy5 – Primarily $\gamma'$
- Alloy6 – Single sided $\gamma''$
Microstructural Evolution of Coprecipitates

T=790°C

- Powerful capability for simulating coarsening
- Comparison with experiment in progress
Deformation Mechanisms Change with Temperature

- Mechanism transitions in conventionally-processed 718 at elevated temperatures

- Mechanism changes must be incorporated into property models

Sheared $\gamma''/\gamma'/\gamma''$ composite particle after room temperature deformation

Microtwin originating in a $\gamma'/\gamma''$ composite particle after deformation at 427°C

Microtwins frequent and extend into the $\gamma$ matrix after deformation at 649°C
Generalized stacking fault energy

718 Type Alloys Ni-base superalloys

Variant 1

Variant 2

Variant 3

Perfect structure

CSF

APB

Gamma prime

Gamma double prime

CSF

APB

APB-like

ISF

SISF
Deformation pathway of $\gamma''/\gamma'/\gamma''$ precipitate

Single CA ($<110>/2$) dislocation

Frame 1

Frame 2

Frame 3

Frame 4

Frame 5

Fault in $\gamma''$ alone

Fault in $\gamma', \gamma'',$ and $\gamma$
Deformation Pathway of γ''/γ'/γ" Composite Precipitates
AC+AB dislocation
Fast-acting Yield Strength Model

\[ \tau_y = \Delta \tau_{pp} + \Delta \tau_{LS} + \Delta \tau_{HP} \]

- \( \Delta \tau_{pp} = M \sum_{i,j} W_{i,j} \Delta \tau_{i,j} \)

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

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

- \( \gamma \)’ particle shearing vs. looping population

- Volume fraction and average particle size

- Particle size distribution:

- Microstructure info

- Major inputs

- Calibrating model parameters

- Model validation

- Yield strength data

- Outputs

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