A New Superalloy Enabling Heavy Duty Gas Turbine Wheels for Improved Combined Cycle Efficiency

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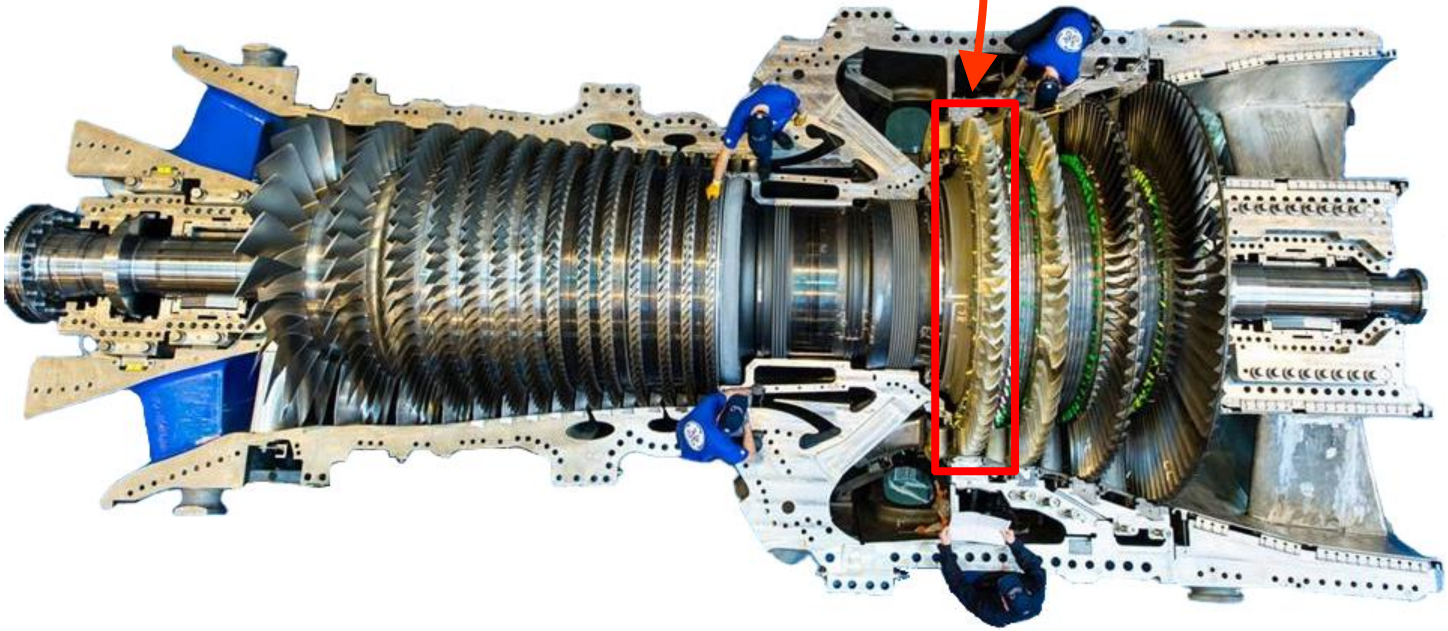
Path to Higher Efficiency Gas Turbine

Today's combined cycle efficiency is ~62%

Pressure Ratio: Higher
Firing Temperature: Higher
Sealing Flows: Lower
Cooling Flows: Lower

INCREASING WHEEL TEMPERATURE

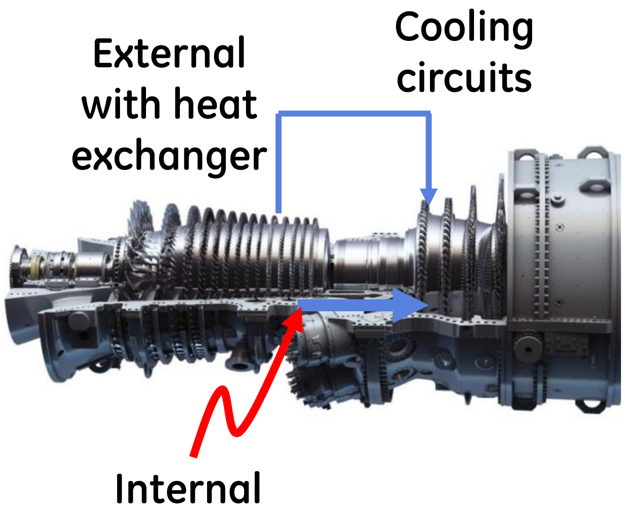
Future turbine combined cycle efficiency is ~65%



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

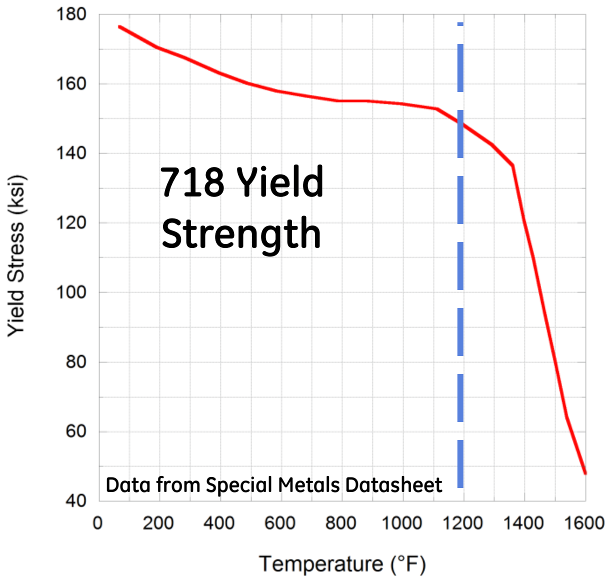
Designing a Higher Temperature Capable Wheel

Use steel and cool to lower the effective temperature



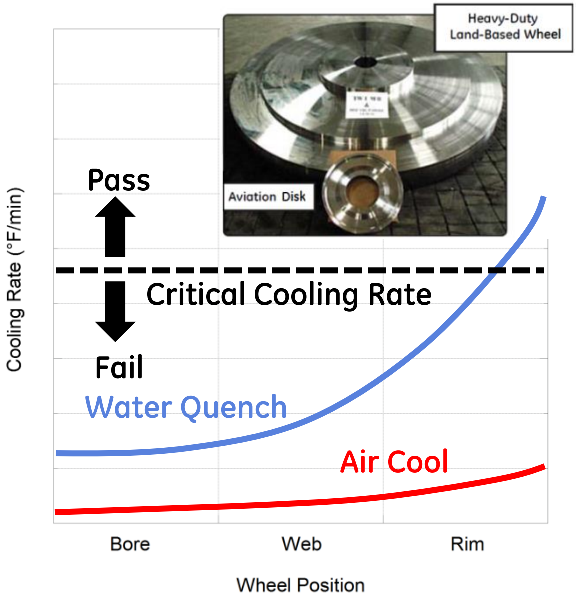
Cooling leads to reduced efficiency, increased complexity, & reliability risks.

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)

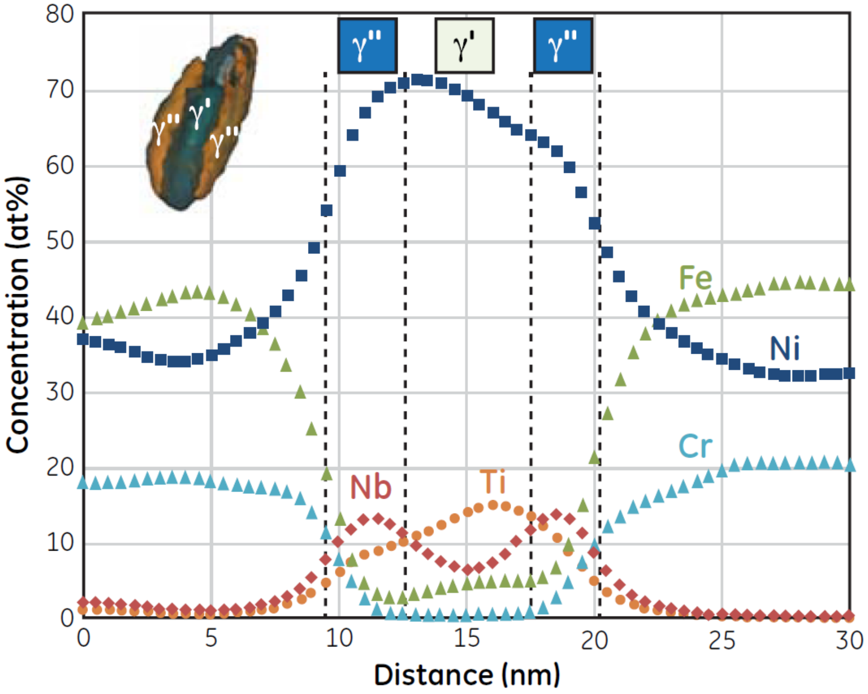


Precipitation kinetics result in severe over aging of γ', yielding poor properties.

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

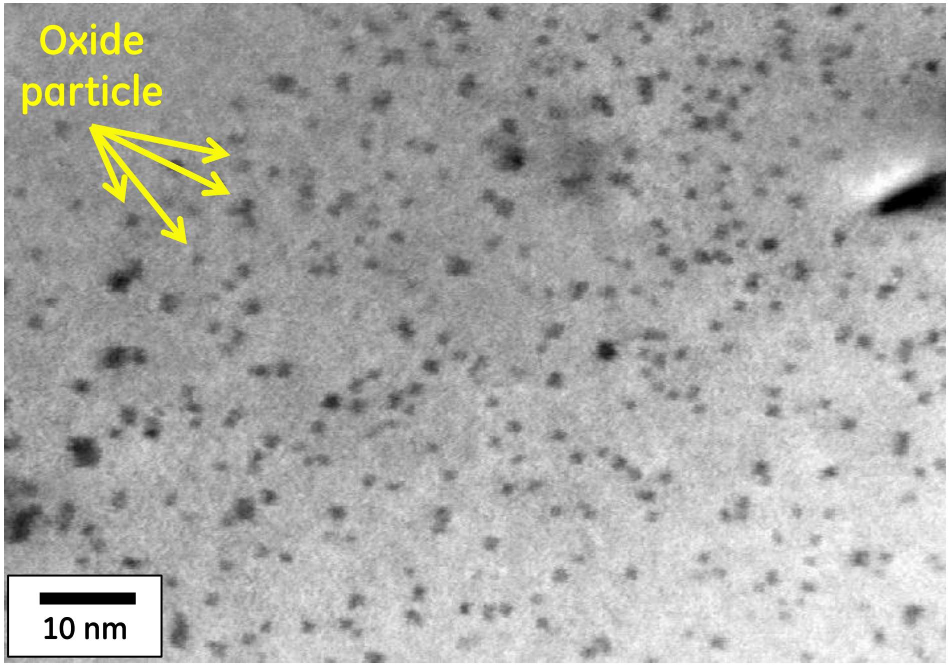
Advanced Wheel Concepts

Coprecipitation



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

Oxide Dispersion Strengthening



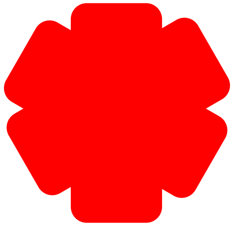
Extend the oxide strengthening concept of nanostructured ferritic alloys to Ni-based alloys.

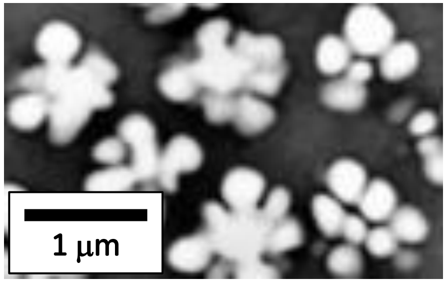
Two fundamentally different approaches being pursued during Phase 1.

Coprecipitation Overview

Current Strengthening Phase Precipitation

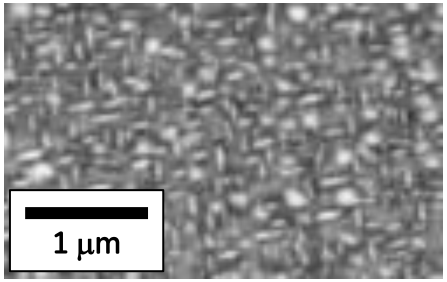
Slow
Cooled
γ' (Ni_3Al)





Overaged/Ineffective

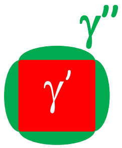
Slow
Cooled
γ'' (Ni_3Nb)



Temperature Limited

Desired Coprecipitation

Slow
Cooled
γ'/γ''



Precipitation of γ'' limits the coarsening/overaging of γ' enabling γ' to act as an effective strengthening phase in slow cooled parts

- γ' believed to nucleate first, enrichment in Nb at γ'/γ interface promotes γ'' nucleation
- Subsequent coarsening limited by diffusion of Al, Ti through Nb-rich γ''

Cozar, Pineau, Met Trans, 4, 47-59 (1973)

γ'' phase intended only to prevent γ' over-aging upon slow cooling.

Coprecipitation Model

Inputs

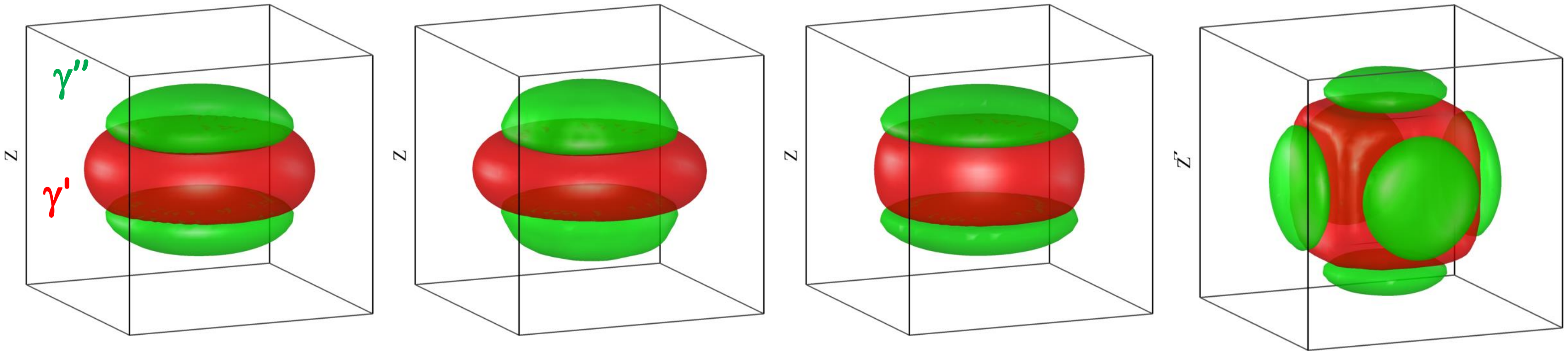
- Chemical free energy
- Elastic modulus
- Lattice parameter
- Diffusivity
- Interfacial energy

Models

1) Isothermal multi-phase field model
2) Continuous cooling simulation

Outputs

1) Prediction of compositional ranges that yield coprecipitation
2) Slow cooled microstructure prediction

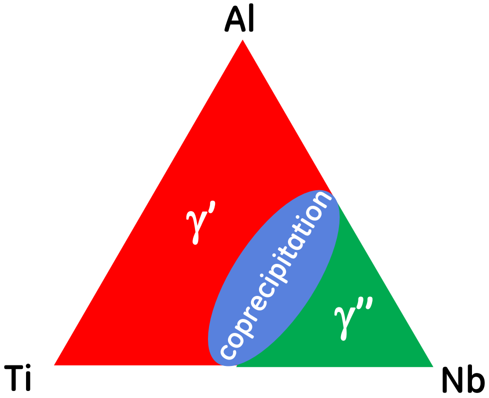


A parametric study of interfacial energies (γ/γ', γ/γ'', γ'/γ'') shows how their variation leads to different coprecipitation shapes.

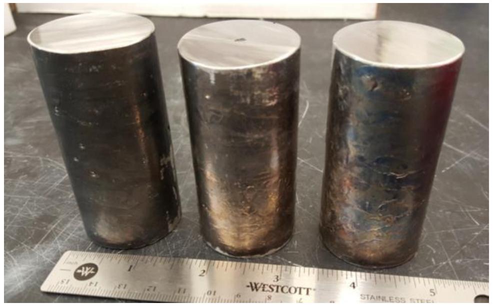
The phase field model allows coprecipitation parametric studies to be successfully completed.

Coprecipitation Experimental Approach

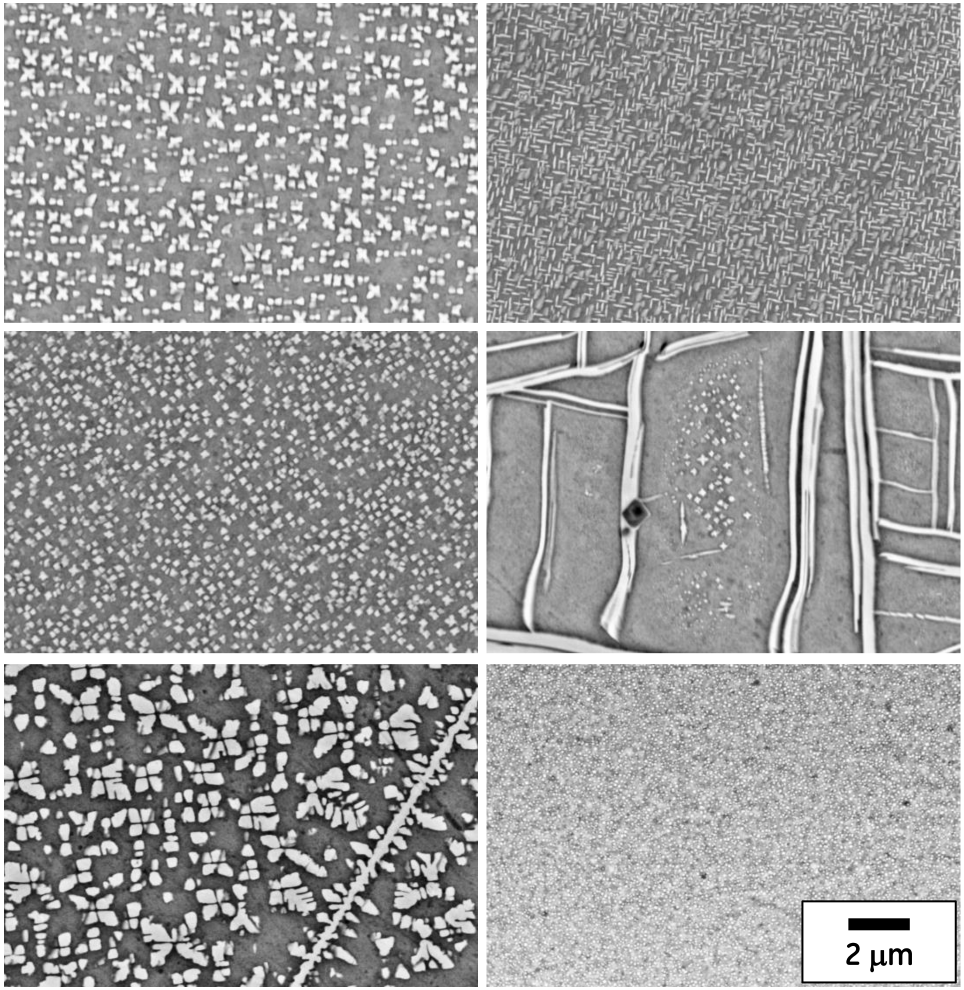
- Choose base alloys to vary chemistry



- Vacuum induction melt & homogenize

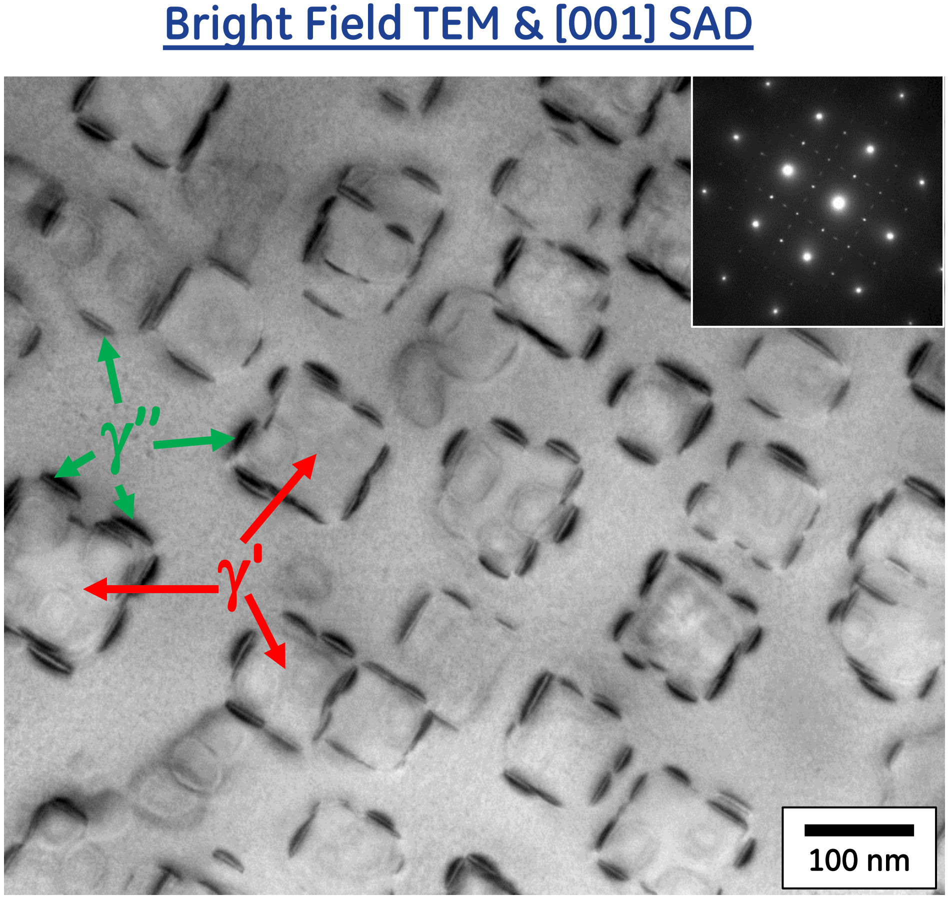


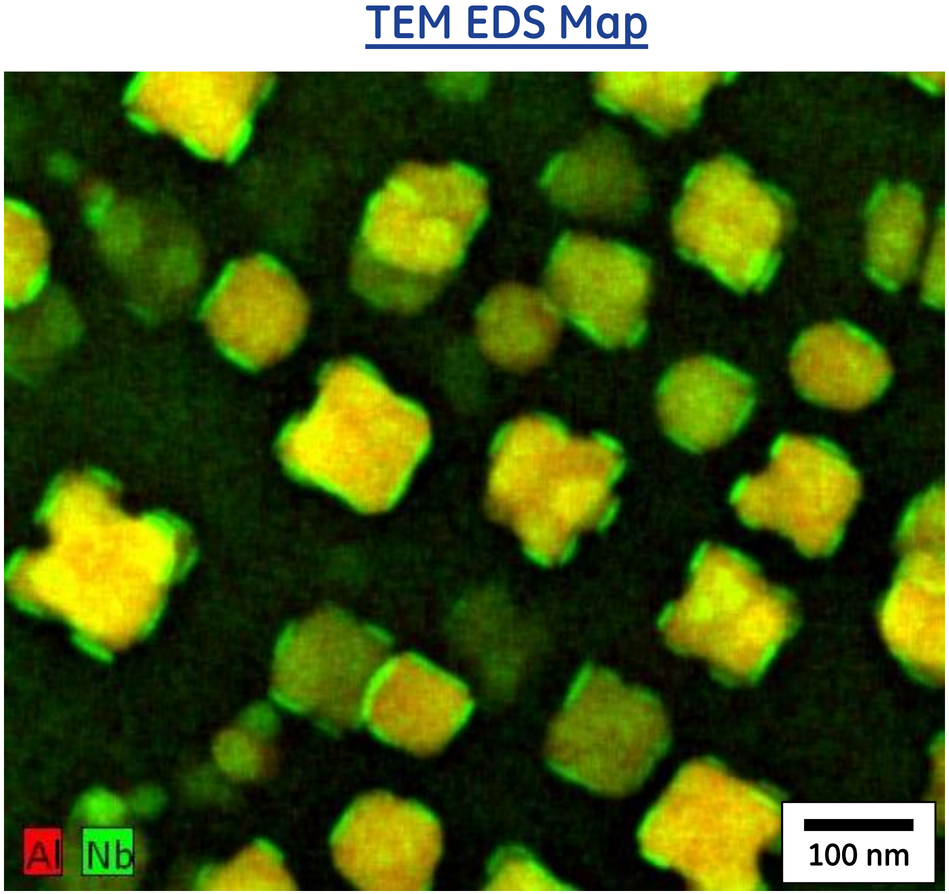
- Slow cool from homogenization & examine precipitate structure



Process allows for rapid alloy chemistry screening for desired space showing fine precipitates without deleterious TCP phases.

Slow Cool Coprecipitation Results

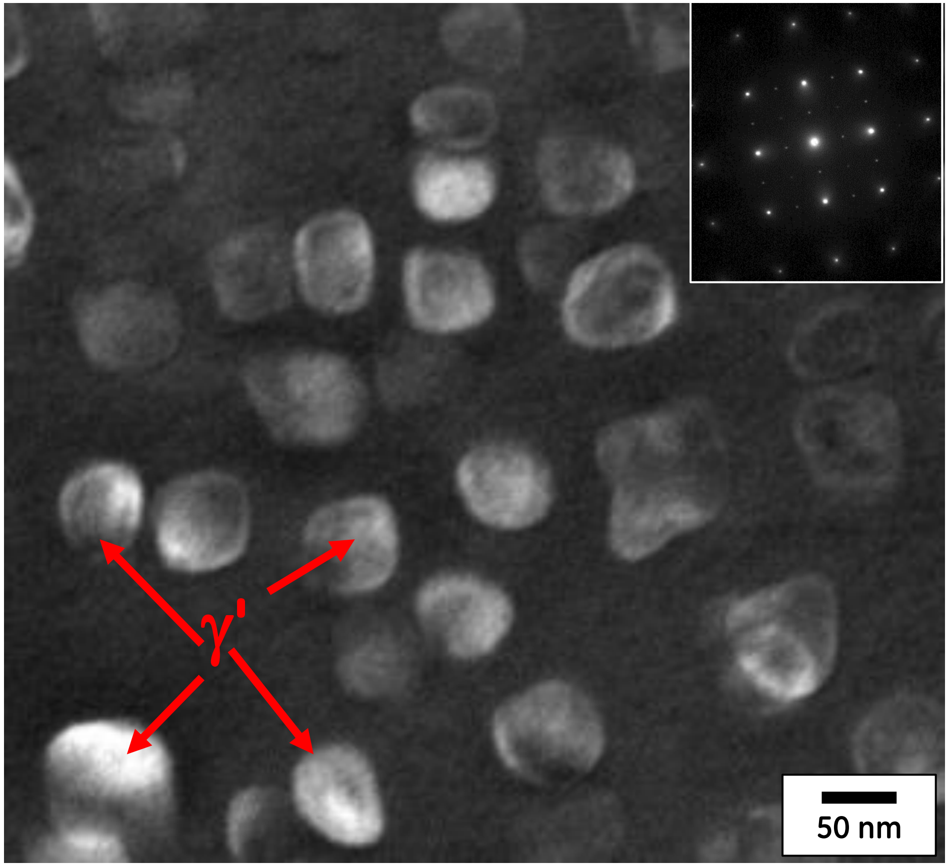




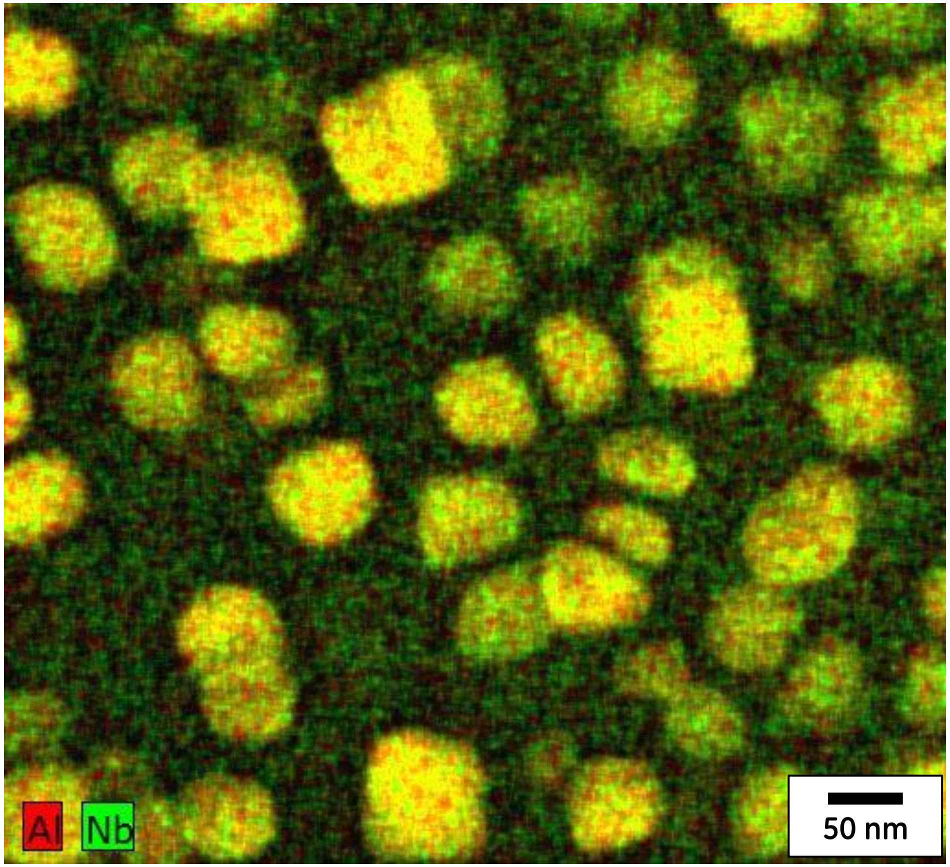
γ'' precipitation on γ' precipitates have successfully led to a fine γ' size following a slow cool from homogenization.

Slow Cool Sluggish γ' Precipitation Results

Dark Field TEM & [001] SAD

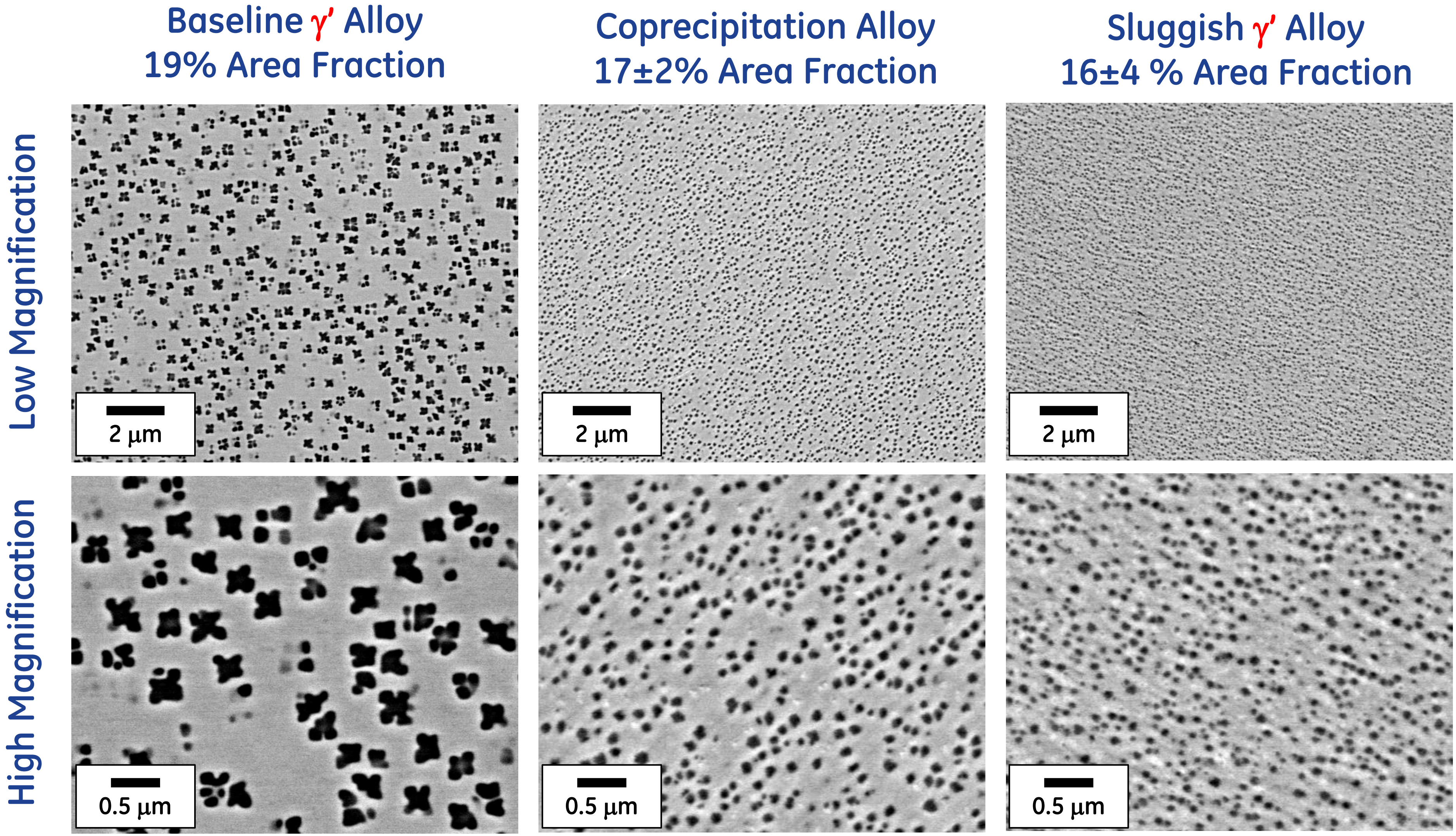


TEM EDS Map



This composition surprisingly yields very fine γ' precipitates despite the slow cooling rate imposed (no coprecipitation seen).

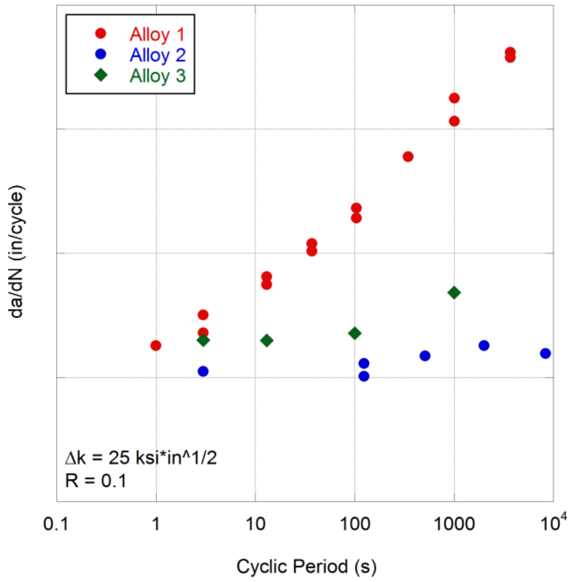
Slow Cool Precipitate Comparison

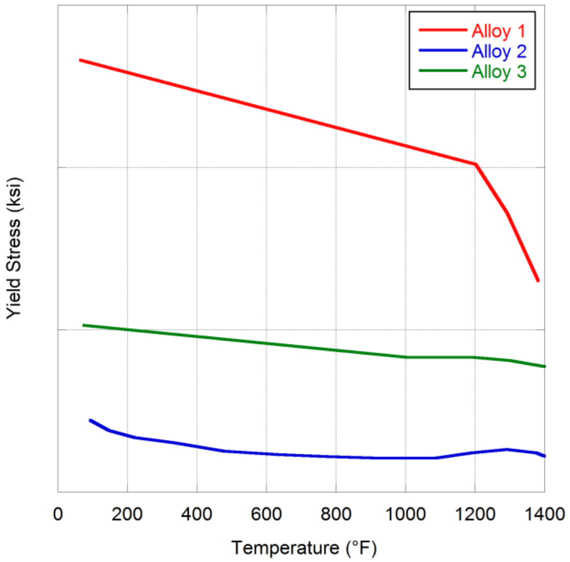


The new alloys yield substantially finer strengthening precipitates than the slow cooled baseline structure.

Oxide Dispersion Strengthening Overview & Approach

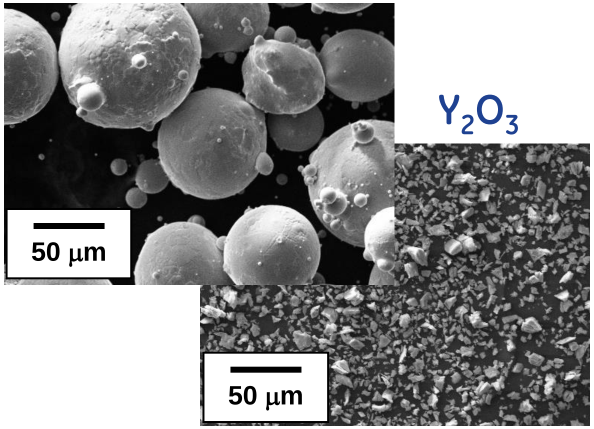
Hold time fatigue crack growth data



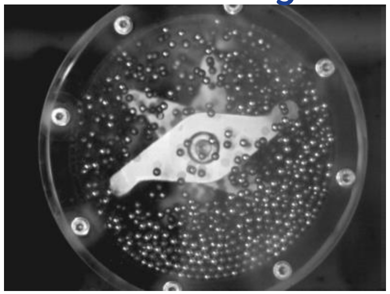


Tensile data

Ni Alloy Powder



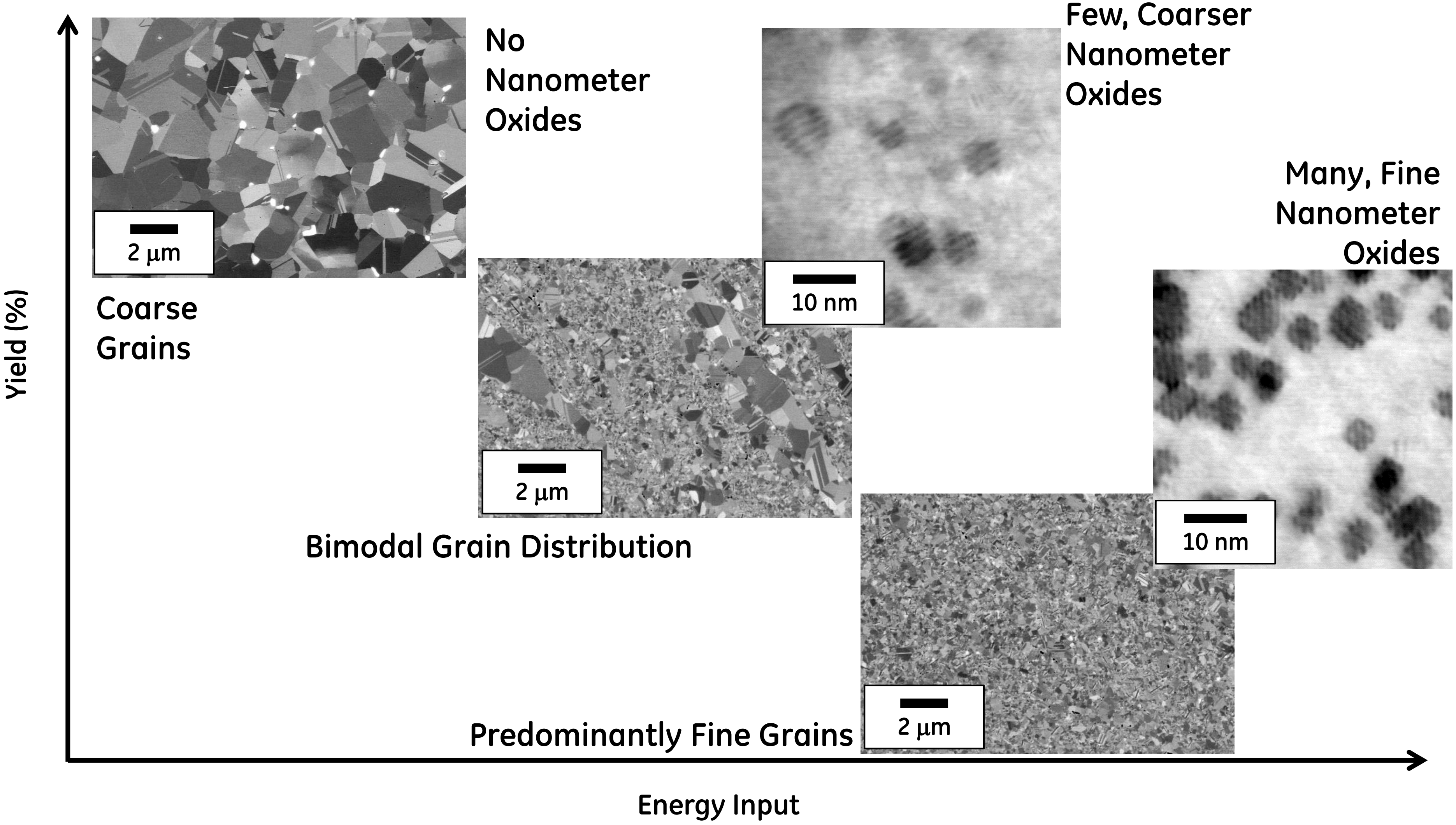
High energy ball milling



HIP + Forge

Use oxides to strengthen existing alloys without debiting the desired hold time fatigue crack growth resistance.

ODS Process Development



Coarse Grains

No Nanometer Oxides

Bimodal Grain Distribution

Few, Coarser Nanometer Oxides

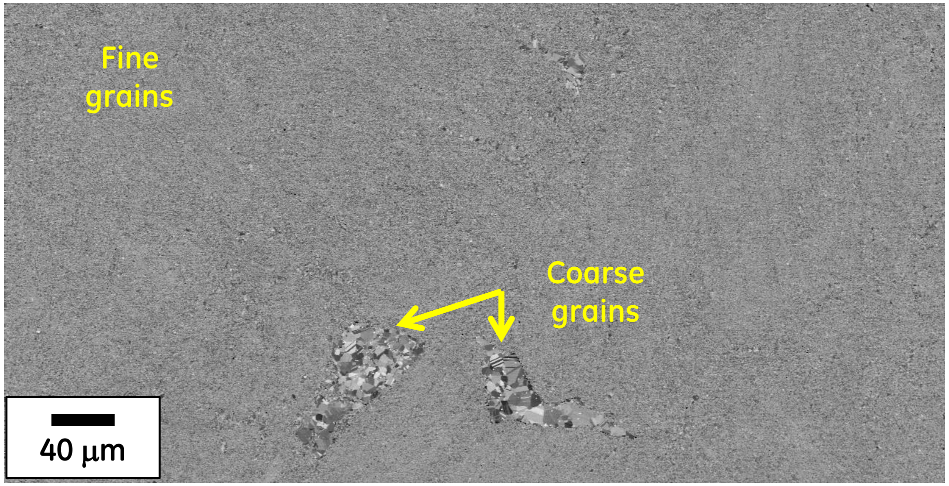
Predominantly Fine Grains

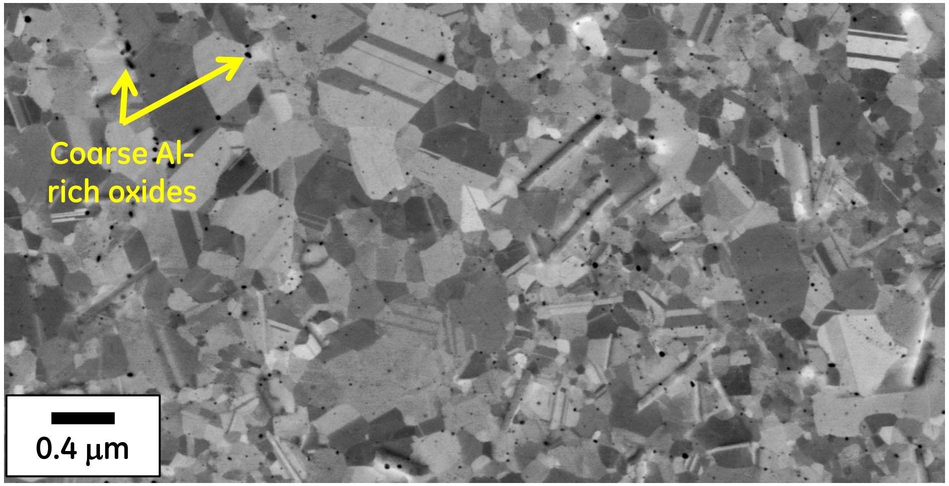
Many, Fine Nanometer Oxides

Current selected process gives up high yield to increase mill energetics to drive grain refinement and homogeneous oxide precipitation.

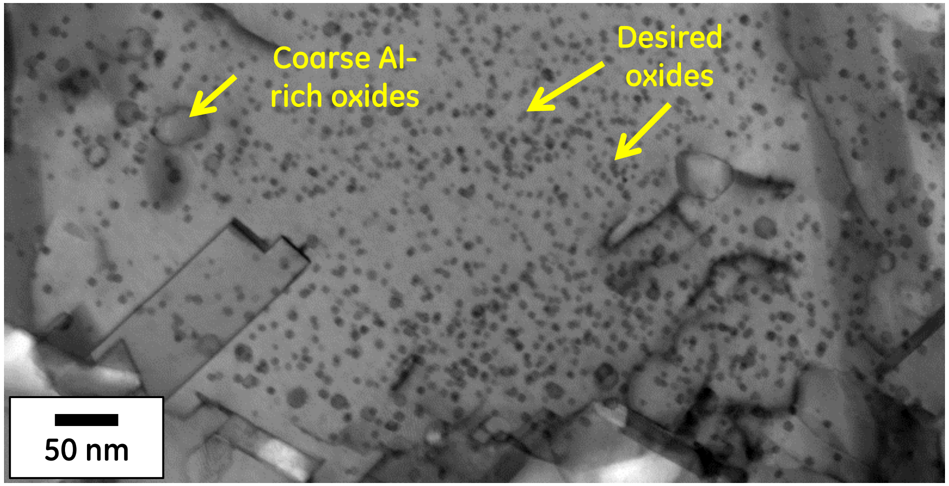
ODS Alloy 2 As-HIP Results Summary

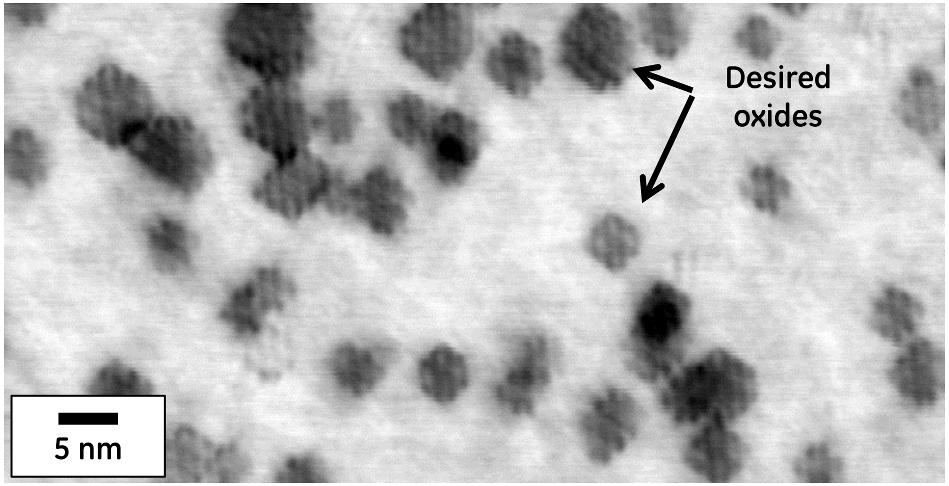
SEM





TEM

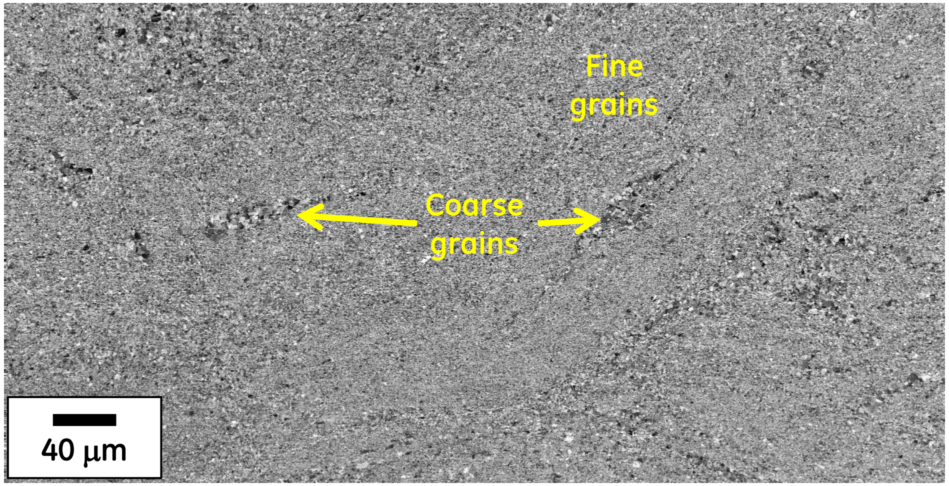


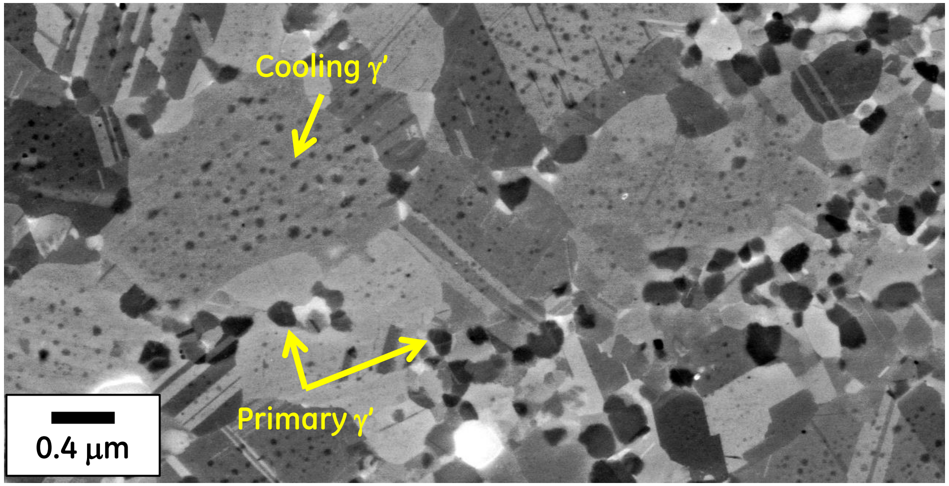


Initial results show dense oxide precipitation that can be controlled by chemistry and mill energy.

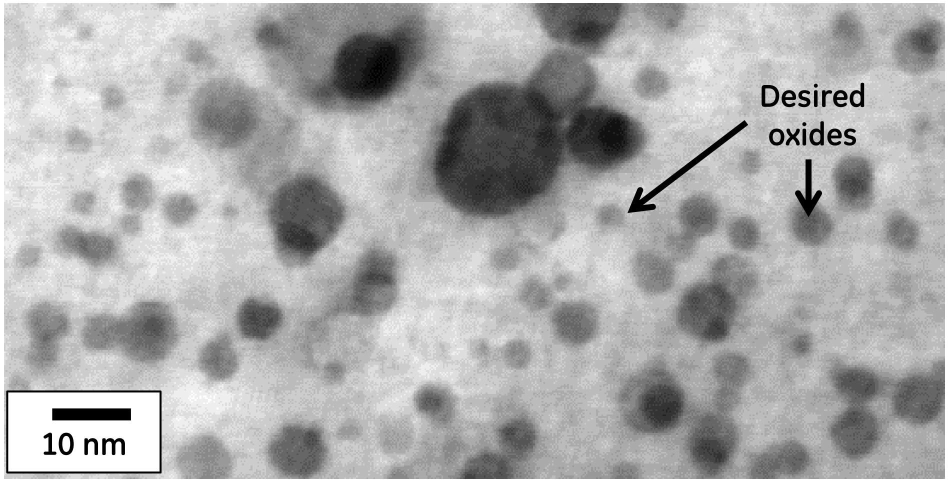
ODS Alloy 3 As-HIP Results Summary

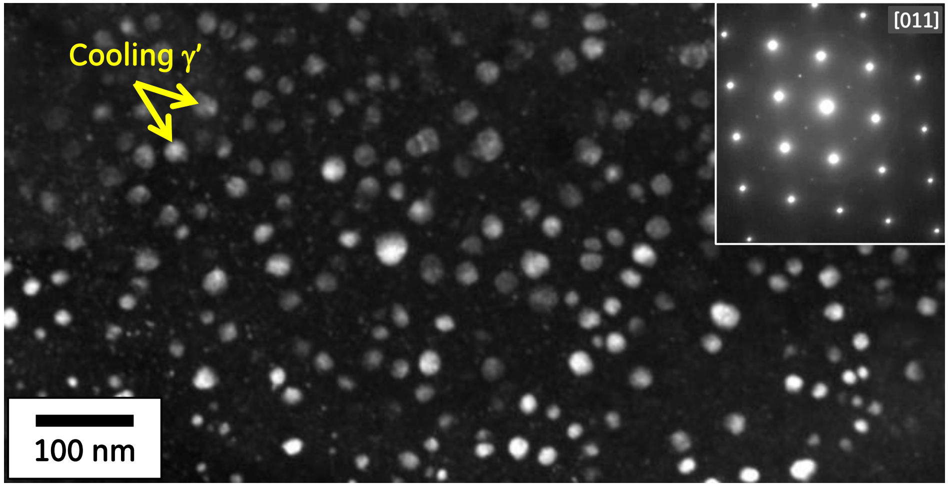
SEM





TEM





Initial results show dense oxide precipitation coexists with γ' precipitation.

Conclusions & Next Steps

- Experimental results for coprecipitation & ODS support the technical feasibility of each concept
- Established a 3D phase-field model with γ'/γ'' co-precipitation
- Thermo-mechanical processing is critical to achieving a viable broken down microstructure suitable for mechanical testing
- Hold time fatigue crack growth and tensile tests will be used to screen the effectiveness of each alloy