

Precipitation Model Validation in 3rd Generation Aeroturbine Disc Alloys

G.B. Olson, H.-J. Jou, Jin-Won Jung, J.T. Sebastian & Abhijeet Misra
QuesTek Innovations LLC
Evanston, IL

05/12/08

Project title: Microstructure Modeling of 3rd Generation Disk Alloys

Dec'06 – Dec'09

Objectives:

1. Successful calibration and validation of databases and physics-based precipitation models in order to predict microstructure evolution in disk alloys (ME3, Alloy10, LHSR) with high degree of accuracy :
 - Intra-granular γ' precipitation
 - GB + intra-granular γ' precipitation
 - MC precipitation
 - TCP precipitation

Multi-phase precipitation
2. Support of on-going disk alloy activities at NASA GRC

Support from Rolls-Royce, AFRL

Extensive use of NIST Ni mobility database¹ in this project.

[1] C.E. Campbell, W.J. Boettinger, U.R. Kattner, *Acta Materialia*, vol. 50 (2002) pp. 775-792.

Nominal compositions (balance Ni) of four 3rd generation disc alloys studied under this program

| | | Cr | Co | Mo | W | Al | Ti | Nb | Ta | Hf | C | B | Zr |
|---------|-----|------|------|-----|-----|-----|-----|-----|-----|-----|------|-------|------|
| ME3 | wt% | 13.1 | 20.0 | 3.8 | 1.9 | 3.5 | 3.6 | 1.1 | 2.3 | - | 0.04 | 0.03 | 0.05 |
| | at% | 14.5 | 19.5 | 2.3 | 0.6 | 7.5 | 4.3 | 0.7 | 0.7 | - | 0.19 | 0.16 | 0.03 |
| LSHR | wt% | 13.0 | 21.0 | 2.7 | 4.3 | 3.5 | 3.5 | 1.5 | 1.6 | - | 0.03 | 0.03 | 0.05 |
| | at% | 14.5 | 20.7 | 1.6 | 1.4 | 7.5 | 4.2 | 0.9 | 0.5 | - | 0.15 | 0.16 | 0.03 |
| Alloy10 | wt% | 10.2 | 14.9 | 2.7 | 6.2 | 3.7 | 3.9 | 1.9 | 0.9 | - | 0.03 | 0.03 | 0.10 |
| | at% | 11.5 | 14.8 | 1.6 | 2.0 | 8.0 | 4.8 | 1.2 | 0.3 | - | 0.15 | 0.16 | 0.07 |
| RR1000 | wt% | 15.0 | 18.5 | 5.0 | - | 3.0 | 3.6 | - | 2.0 | 0.5 | 0.03 | 0.015 | 0.06 |
| | at% | 16.5 | 17.9 | 3.0 | - | 6.4 | 4.3 | - | 0.6 | 0.2 | 0.13 | 0.080 | 0.04 |

- ME3 (also called René104)
- LSHR (Low-Solvus, High-Refractory alloy developed by NASA)
- Alloy 10 (developed by Honeywell)
- RR1000 (developed by Rolls-Royce)

- ***CALPHAD fundamental database and tuning parameters***
 - Thermo-Calc® thermodynamic databases
 - ΔE : phase free energy shift in Thermo-Calc
 - DICTRA compatible mobility database
 - D_{scale} : diffusivity correction factor used in *PrecipiCalc*
 - Molar Volume: multicomponent molar volume models developed for both γ and γ' under the AIM program

- ***Material kinetic model parameters***
 - σ_{coh} : coherent surface energy
 - G_{el} : elastic coherency (misfit) energy
 - σ_{incoh} : incoherent surface energy
 - M_o : prefactor for interfacial mobility term
 - $R_{coh \rightarrow incoh}$: particle size for coherency transition

| Experiments | CALPHAD Fundamental Databases | Material Kinetic Model Parameters |
|--|-------------------------------------|--|
| Equilibrium Age + APT (literature data, QuesTek) + EDS (NASA) | Thermodynamics ΔE | |
| Diffusion Couple + Microanalysis (NASA) | Mobility D_{scale} | |
| SSDTA (OSU) + APT (QuesTek) | | σ_{coh} , G_{el} (est.) |
| Coarsening Age+SEM/TEM for γ' size and fraction (NASA) | | σ_{incoh} , M_O |
| XRD, TEM for misfit (NASA) | Molar volume | G_{el} , $R_{coh \rightarrow incoh}$ |

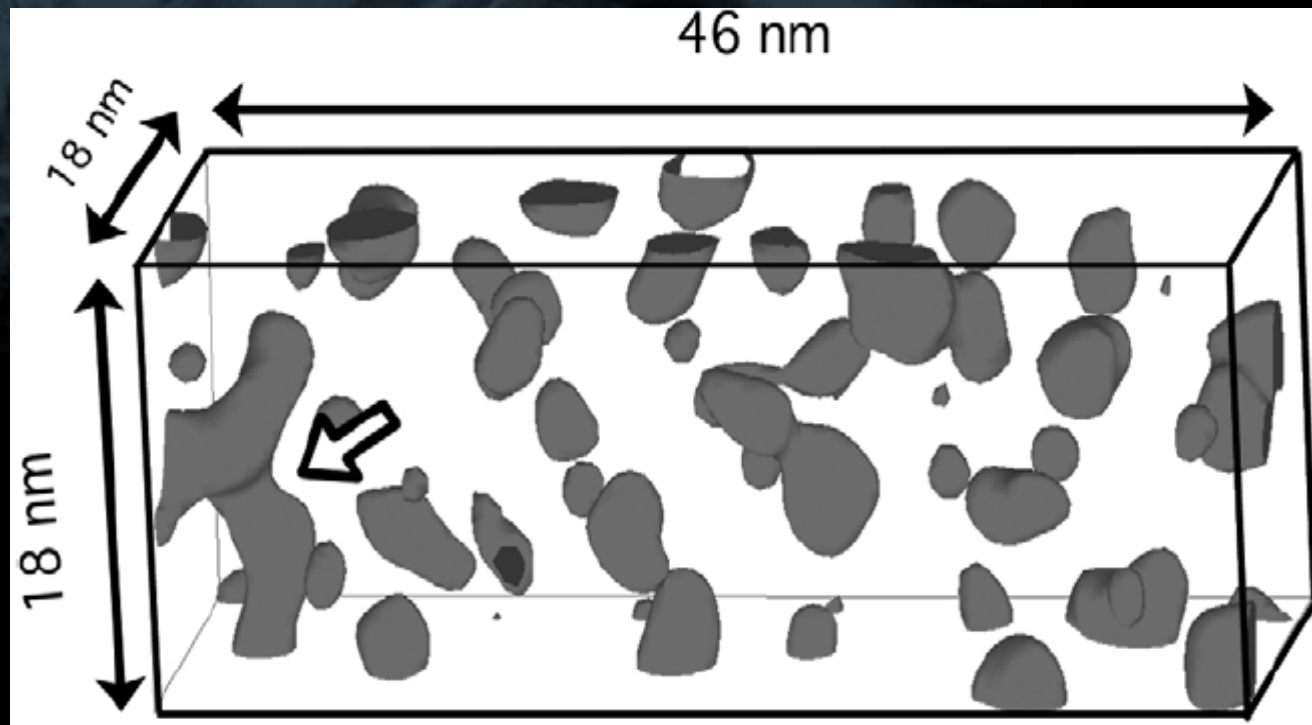
| Experiments | CALPHAD Fundamental Databases | Material Kinetic Model Parameters |
|---|-------------------------------|-------------------------------------|
| Equilibrium Age + APT (literature data, QuesTek) + EDS (NASA) | Thermodynamics ΔE | |
| Diffusion Couple + Microanalysis (NASA) | Mobility D_{scale} | |
| SSDTA (OSU) + APT (QuesTek) | | σ_{coh}, G_{el} (est.) |
| Coarsening Age+SEM/TEM for γ' size and fraction (NASA) | | σ_{incoh}, M_O |
| XRD, TEM for misfit (NASA) | Molar volume | $G_{el}, R_{coh \rightarrow incoh}$ |

Thermodynamics

calibration and validation

1. Atom Probe Tomography
 - Prior literature data
 - Current program data
2. SEM + EDS

Experimental data from: C.K. Sudbrack, R. D. Noebe, and D. N. Seidman. 2007. Compositional pathways and capillary effects during isothermal precipitation in a nondilute Ni-Al-Cr alloy. *Acta Materialia*. 55: 119-130.



APT image for Ni-5.2Al-14.2Cr (at%) after aging for 4hrs at 600°C

Overall : Ni-5.2Al-14.2Cr (at%)

| 600°C | | at% | | | | APB (J/m ²) | 600°C misfit % | % γ' fraction |
|-----------|--|------------------|--------------|--------------|--------------|----------------------------|-------------------|-------------------------|
| | | Ni | Al | Cr | RMS | | | |
| γ | Equilibrium matrix composition | APT | 81.26 | 3.13 | 15.61 | | | |
| | | 2 σ | 0.18 | 0.08 | 0.18 | 0.14 | | |
| | | Ni 5,6 | 81.40 | 3.64 | 14.96 | 0.58 | | |
| | | Ni 7 | 81.34 | 3.62 | 15.04 | 0.53 | | |
| | | TCNI1 | 81.17 | 3.93 | 14.90 | 0.76 | | |
| | Ni-NIST | 80.60 | 5.20 | 14.20 | 1.77 | | | |
| γ' | γ' equilibrium composition | APT | 76.53 | 16.69 | 6.77 | | 0.19 | -0.72 |
| | | 2 σ | 0.50 | 0.44 | 0.30 | 0.38 | 0.01 | 0.4 |
| | | Ni 5,6 | 71.98 | 16.23 | 8.80 | 1.17 | 0.19 | -0.6 |
| | | Ni 7 | 74.97 | 16.21 | 8.82 | 1.49 | 0.19 | -0.6 |
| | | TCNI1 | 75.59 | 14.55 | 9.57 | 2.49 | 0.18 | -0.8 |
| | | Ni-NIST | 75.96 | 12.25 | 11.79 | 4.74 | 0.15 | -0.9 |
| | Critical γ' - nucleus composition | APT | 72.40 | 18.30 | 9.30 | | 0.16 | -0.2 |
| | | 2 σ | 2.20 | 1.80 | 1.40 | 1.61 | 0.03 | |
| | | Ni 5,6 | 74.91 | 17.37 | 7.71 | 1.30 | 0.20 | -0.5 |
| | | Ni 7 | 74.91 | 17.40 | 7.69 | 1.30 | 0.20 | -0.5 |
| TCNI1 | | 75.36 | 16.43 | 8.21 | 1.53 | 0.20 | -0.6 | |
| | Ni-NIST | No precipitation | | | | | | |

Experimental data
from: C.K. Sudbrack,
R. D. Noebe, and D.
N. Seidman. 2007.
Acta Materialia. 55:
119-130.

Ni5, Ni6, Ni7: Saunders, N. Ni-DATA. ThermoTech Ltd., Surrey, U.K.

TCNI1: Dupin N, Ansara I, Sundman B. Calphad 2001;25:279

Ni-NIST: Kattner UR. In: Turchi PEA, Gonis A, Shull RD, editors. CALPHAD and Alloy Thermodynamics. Warrendale (PA):TMS; 2002.

Ni-10Al-8.5Cr-2Re (at%)

| 800°C | | | at% | | | | | APB (J/m ²) | 800°C misfit % | % γ' fraction |
|-----------|--------------------------------------|--------------|--------------|--------------|--------------|-------------|-------------|----------------------------|-------------------|-------------------------|
| | | | Ni | Cr | Al | Re | RMS | | | |
| γ | Equilibrium matrix composition | APT | 81.07 | 10.04 | 6.74 | 2.15 | | | | |
| | | 2 σ | 0.16 | 0.04 | 0.08 | 0.02 | 0.05 | | | |
| | | Ni 7 | 80.55 | 8.94 | 8.35 | 2.16 | 1.13 | | | |
| | | Ni-NIST | 80.22 | 8.79 | 8.87 | 2.12 | 1.42 | | | |
| γ' | Equilibrium composition | APT | 76.17 | 4.97 | 18.05 | 0.81 | | 0.19 | -0.71 | 24.8 |
| | | 2 σ | 0.26 | 0.10 | 0.18 | 0.04 | 0.12 | 0.00 | | 0.2 |
| | | Ni7 | 75.29 | 5.68 | 18.80 | 0.23 | 0.68 | 0.20 | -0.68 | 15.9 |
| | | Ni-NIST | 75.82 | 6.13 | 17.65 | 0.39 | 0.75 | | -0.77 | 7.2 |
| | composition at 80% completion | APT | 76.33 | 5.46 | 16.92 | 1.29 | | 0.17 | | 20.3 |
| | | 2 σ | 0.30 | 0.16 | 0.26 | 0.08 | 0.18 | 0.00 | | 0.2 |
| Ni7 | | 75.22 | 5.56 | 18.99 | 0.23 | 1.35 | 0.20 | | 12.8 | |

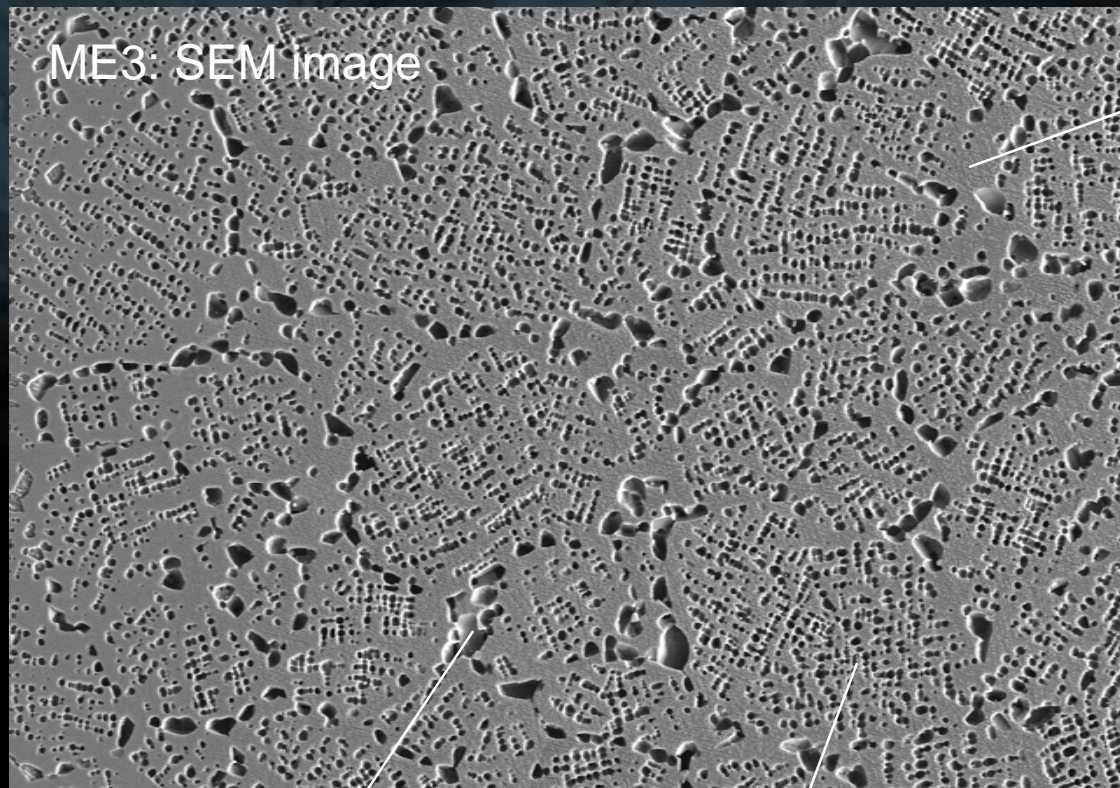
Experimental data from: K.E. Yoon, R. D. Noebe, and D. N. Seidman. 2007., *Acta Materialia*. 55: 1145-1157.

Ni-10Al-8.5Cr-2W (at%)

| 800°C | | at% | | | | | APB (J/m ²) | 800°C misfit % | % γ' fraction |
|---|------------|--------------|--------------|--------------|-------------|-------------|----------------------------|-------------------|-------------------------|
| | | Ni | Cr | Al | W | RMS | | | |
| γ equilibrium matrix composition | APT | 81.31 | 5.83 | 11.52 | 1.34 | | | | |
| | 2 σ | 0.07 | 0.04 | 0.05 | 0.02 | 0.04 | | | |
| | Ni 7 | 81.44 | 6.22 | 10.53 | 1.80 | 0.67 | | | |
| | Ni-NIST | 80.48 | 8.57 | 8.84 | 2.11 | 2.26 | | | |
| γ' equilibrium precipitate composition | APT | 76.30 | 17.00 | 3.91 | 2.80 | | 0.21 | -0.49 | 37.9 |
| | 2 σ | 0.08 | 0.07 | 0.04 | 0.03 | 0.05 | 0.00 | | 0.0 |
| | Ni7 | 75.39 | 18.00 | 4.20 | 2.42 | 0.64 | 0.22 | -0.36 | 32.1 |
| | Ni-NIST | 75.87 | 16.61 | 6.42 | 1.09 | 1.77 | | -0.61 | 18.7 |

Experimental data from: Sudbrack, C.K., D. Isheim, R. D. Noebe, N.S. Jacobson, and D. N. Seidman. 2007., *Microscopy and Microanalysis*. 10: 355-365.

ME3: 1193°C/1h / WQ + 1093°C/1000 h + WQ



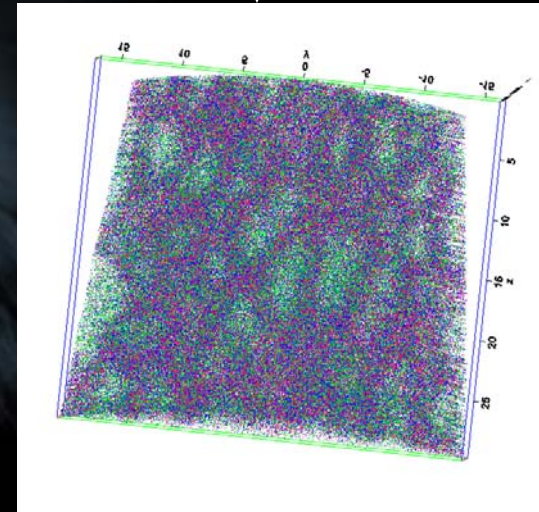
I-764ME3e 20.0kV 12.0mm x500 SE(L) 4/20/2007

60.0um

GB γ' precipitates

Intra-granular γ' precipitates

High temperature matrix
LEAP (QuesTek) at NUCAPT



Composition of high temperature matrix

EDS (NASA)

Thermodynamic database validation

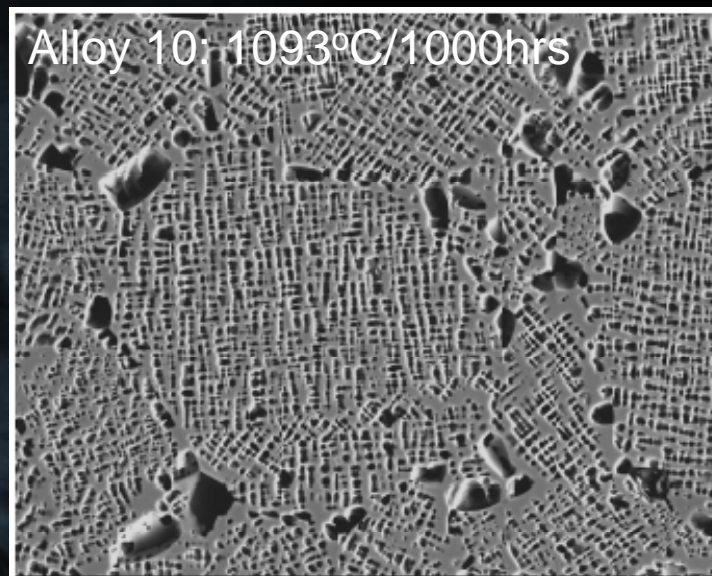
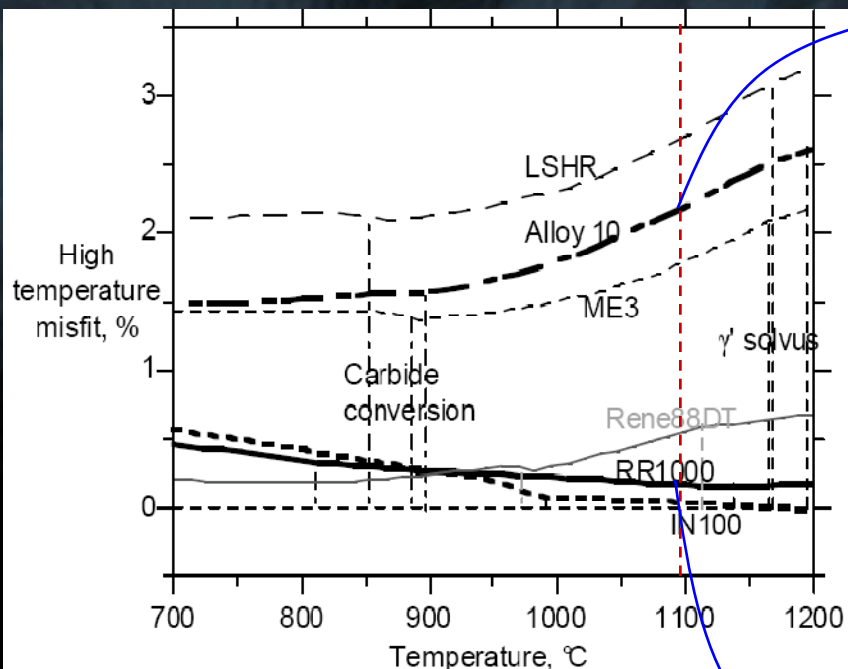
ME3 1093°C/1000hrs : APT + EDS

| | γ matrix (at 1093°C) composition, at% | | | | | | | | | | | % γ' fraction |
|-------------|--|------------|-------------|-------------|------------|------------|------------|------------|------------|-------------|-------------|----------------------|
| | Ni | Al | Cr | Co | Ti | Mo | W | Nb | Ta | C | RMS | |
| APT | 44.9 | 6.7 | 17.5 | 21.7 | 3.5 | 3.4 | 1.0 | 0.5 | 0.5 | 0.04 | | 24.8 |
| 2 σ | 0.04 | 0.02 | 0.03 | 0.03 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.002 | | 1.5 |
| EDS | 46.1 | 6.6 | 16.6 | 22.7 | 3.3 | 3.0 | 1.3* | 0.6 | - | - | | |
| Ni 5,6 | 45.7 | 5.6 | 19.7 | 22.1 | 2.4 | 3.1 | 0.7 | 0.3 | 0.3 | 0.01 | 0.93 | 30.7 |
| Ni 7 | 46.4 | 6.0 | 18.5 | 21.8 | 2.7 | 3.0 | 0.7 | 0.4 | 0.5 | 0.01 | 0.54 | 25.5 |
| Pan-Nickel | 44.3 | 5.3 | 20.3 | 23.0 | 2.4 | 2.9 | 0.8 | 0.4 | 0.5 | 0.05 | 1.19 | 32.3 |
| NIST-Ni | 44.7 | 5.1 | 19.9 | 23.8 | 2.4 | 3.2 | 0.8 | | 0.2 | | 1.44 | 29.4 |

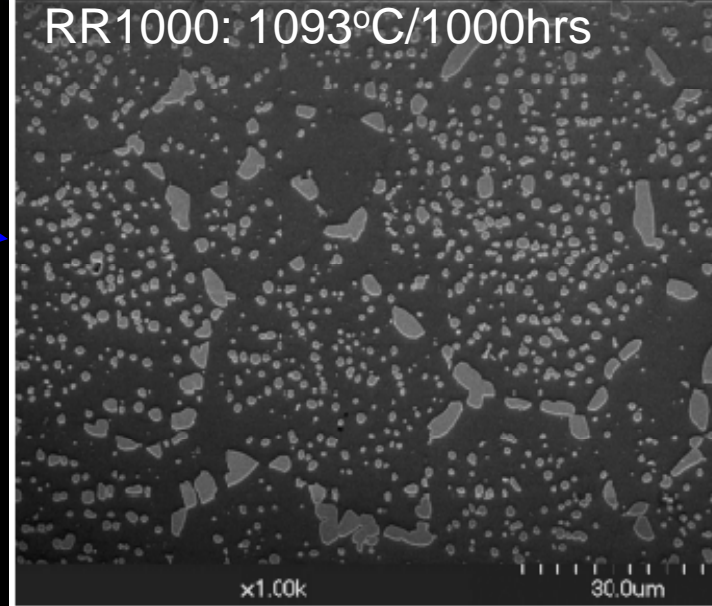
Alloy 10 1093°C/1000hrs : EDS

| | | Compositions, at% | | | | | | | | | |
|-----------|-------------|-------------------|--------------|--------------|--------------|-------------|-------------|-------------|-------------|-------------|-------------|
| | | Ni | Al | Cr | Co | Ti | Mo | W | Ta | Nb | RMS |
| γ | EDS | 53.8 | 7.0 | 13.4 | 17.5 | 3.2 | 2.3 | | 1.6 | 1.13 | |
| | Ni 5,6 | 50.8 | 5.74 | 17.60 | 17.76 | 2.61 | 2.30 | 2.54 | 0.14 | 0.50 | 1.75 |
| | Ni 7 | 51.1 | 5.97 | 16.97 | 17.72 | 2.76 | 2.21 | 2.48 | 0.20 | 0.63 | 1.49 |
| | Ni-NIST | 51.3 | 5.44 | 17.00 | 18.60 | 2.58 | 2.31 | 2.66 | 0.10 | - | 1.68 |
| γ' | EDS | 62.3 | 13.0 | 4.0 | 10.9 | 7.2 | 0.6 | | 0.9 | 1.3 | |
| | Ni 5,6 | 62.2 | 12.02 | 2.82 | 11.01 | 8.42 | 0.24 | 0.93 | 0.49 | 1.89 | 0.80 |
| | Ni 7 | 64.1 | 12.11 | 2.80 | 10.53 | 8.64 | 0.23 | 0.91 | 0.40 | 1.73 | 0.83 |
| | Ni-NIST | 66.8 | 13.5 | 1.35 | 7.54 | 9.62 | 0.13 | 0.37 | 0.68 | - | 1.93 |

Predictions of misfit model



A10-5S 20.0kV 12.0mm x1.00k SE(L) 5/2/2007 30.0um



RR1000: 1093°C/1000hrs

- *Combination of NI7 thermodynamic database and misfit model gives right ranking of relative misfit in alloys*
- *Elastic energy term to be incorporated in thermodynamic database to account for lattice misfit.*

| Experiments | CALPHAD Fundamental Databases | Material Kinetic Model Parameters |
|---|-------------------------------|-------------------------------------|
| Equilibrium Age + APT (literature data, QuesTek) + EDS (NASA) | Thermodynamics ΔE | |
| Diffusion Couple + Microanalysis (NASA) | Mobility D_{scale} | |
| SSDTA (OSU) + APT (QuesTek) | | σ_{coh}, G_{el} (est.) |
| Coarsening Age+SEM/TEM for γ' size and fraction (NASA) | | σ_{incoh}, M_O |
| XRD, TEM for misfit (NASA) | Molar volume | $G_{el}, R_{coh \rightarrow incoh}$ |

Mobility

calibration and validation

1. Diffusion Couples + Microanalysis

For NIST mobility database validation/calibration



The vacuum/inert gas hot press unit to be used to fabricate the superalloys / Ni couples

Hot Pressed at 1150 K (1610 °F)
@ 90 MPa (13.9 ksi)
(4 hrs)

Diffusion Couple "sandwiches"
stacked together

ME3 / Ni / Alloy10



Schematic of the typical diffusion couple stacking that will be used for this study



Annealed at 927°C or 1093°C for 100 or 300 hrs

$\gamma + \gamma' + MC$

$< \gamma$



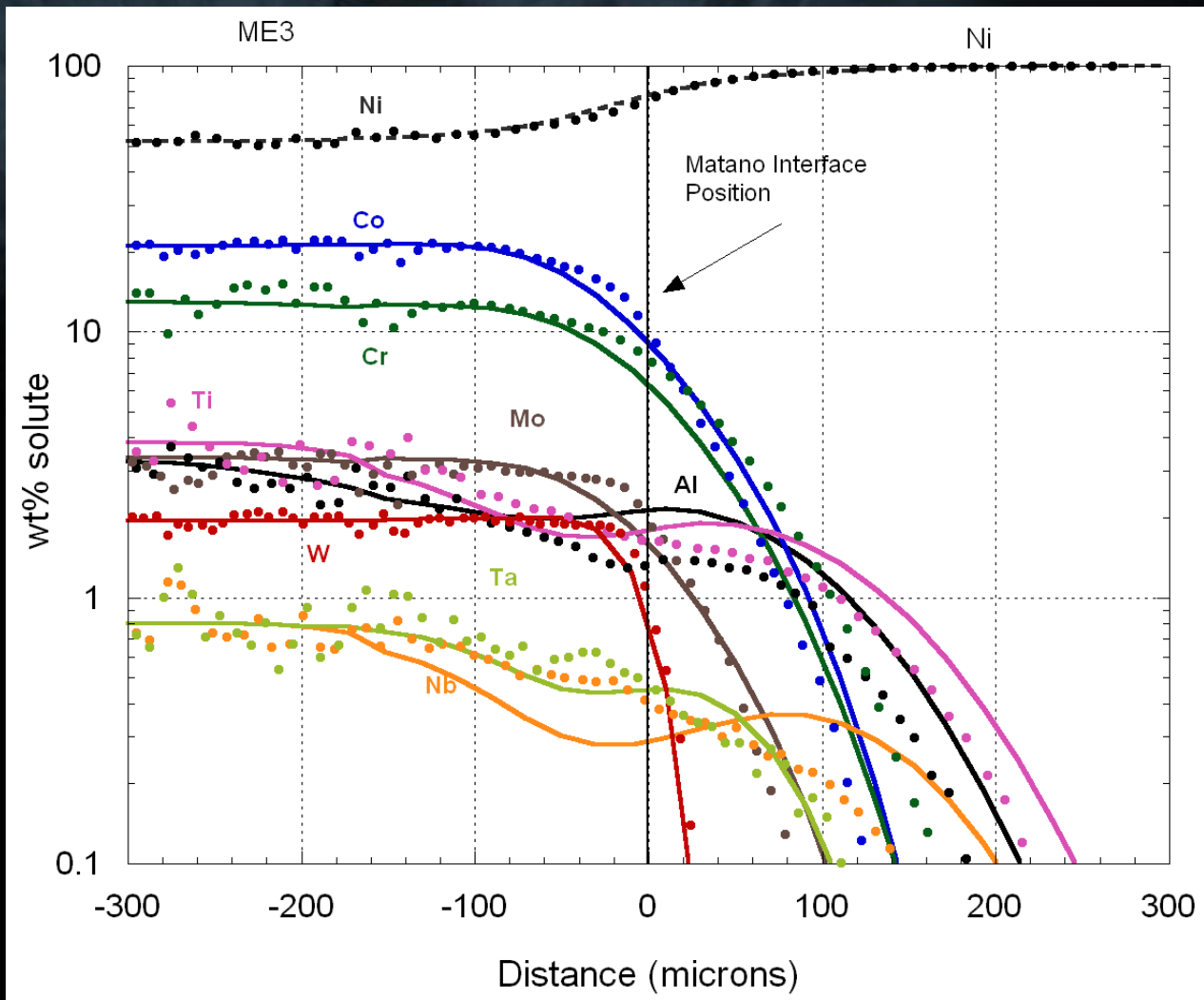
Original Interface

Matano Interface

In order to compare experimental diffusion couple results with DICTRA simulations, the average Matano interface (defined as the interface across which equal number of atoms have crossed in both directions) is equated to the zero-point grid position of the calculated profiles.

The adjoining figure shows the determined average Matano interface and its position with respect to the original interface in the diffusion couple. The Matano interface is now taken as the zero-point for comparison with calculated profiles

- Use measured compositions (average over first 50-100 μm of superalloy side)
- No diffusion through γ' ; acts only as sink or source of solute for diffusion.



Solid lines: DICTRA results
Solid circles: Measured data

- Nb, Al, and Ti diffusion is less than predicted
- Cr diffusion is more than predicted

The mobility terms in the NIST mobility database were changed slightly for Cr, Nb, and Ti for better agreement between the DICTRA simulations and the experimentally measured diffusion couples.

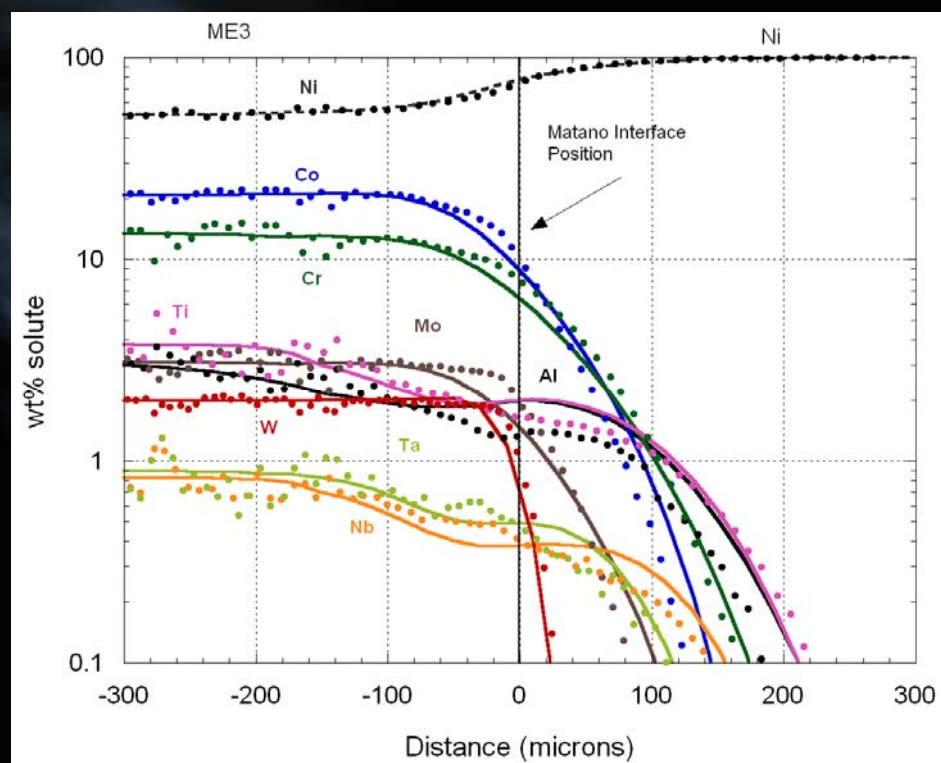
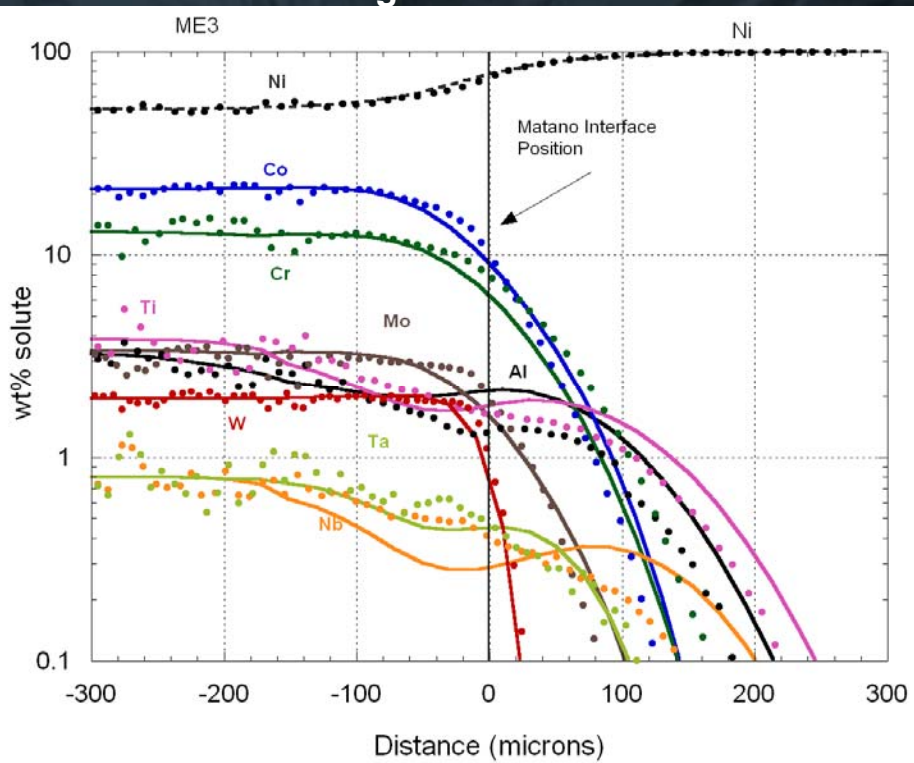
| | <u>Original Value</u> | <u>Modified Value</u> |
|--------------|--------------------------|------------------------|
| MQ(Cr in Ni) | $-287000+R*T*LN(4.3E-4)$ | $-287000+R*T*LN(6E-4)$ |
| MQ(Nb in Ni) | $-255333+R*T*LN(7.6E-5)$ | $-255333+R*T*LN(4E-5)$ |
| MQ(Ti in Ni) | $-256900+R*T*LN(8.6E-5)$ | $-256900+R*T*LN(6E-5)$ |

The comparison between the simulations using the original database and the modified database is shown in the next slides for some conditions. The agreement with experiment is much better for the simulations using the modified database.

Solid lines: DICTRA results
Solid circles: Measured data

Original database

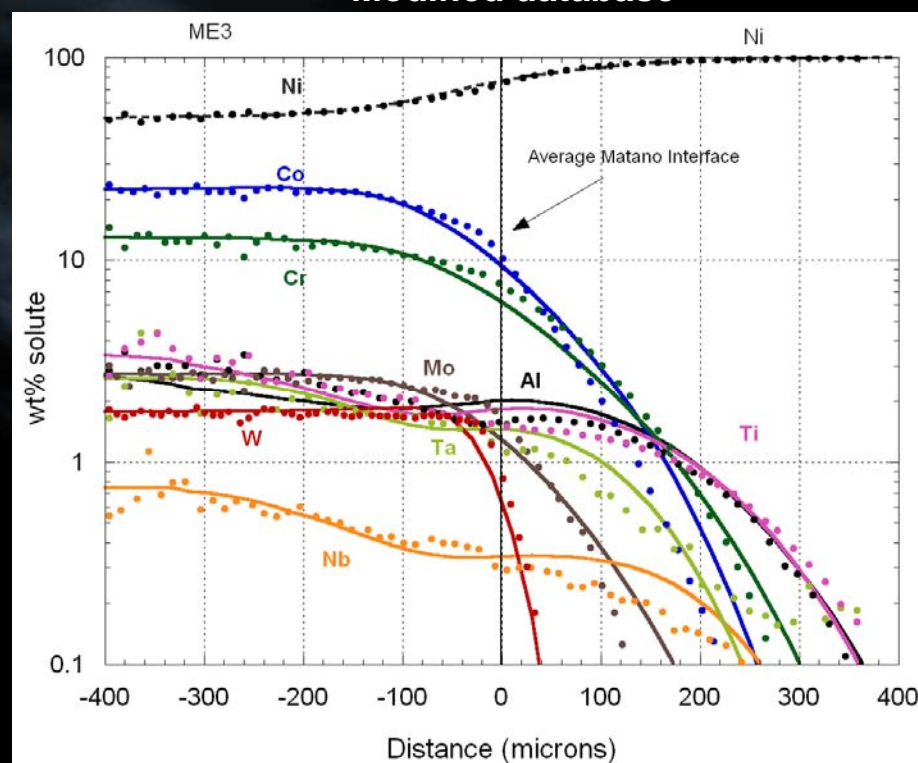
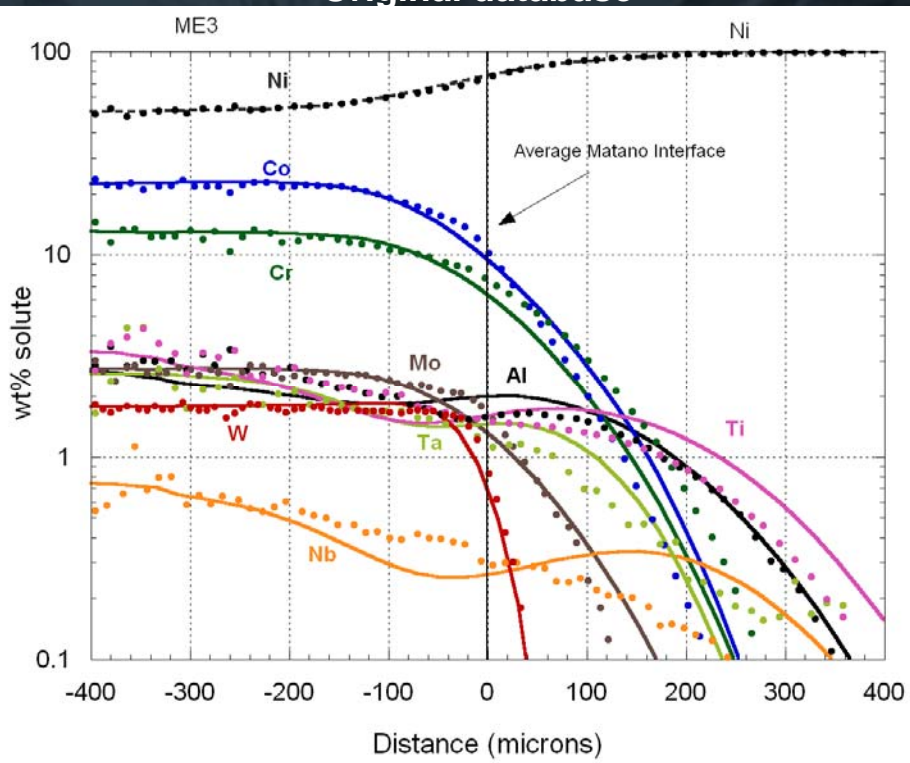
Modified database

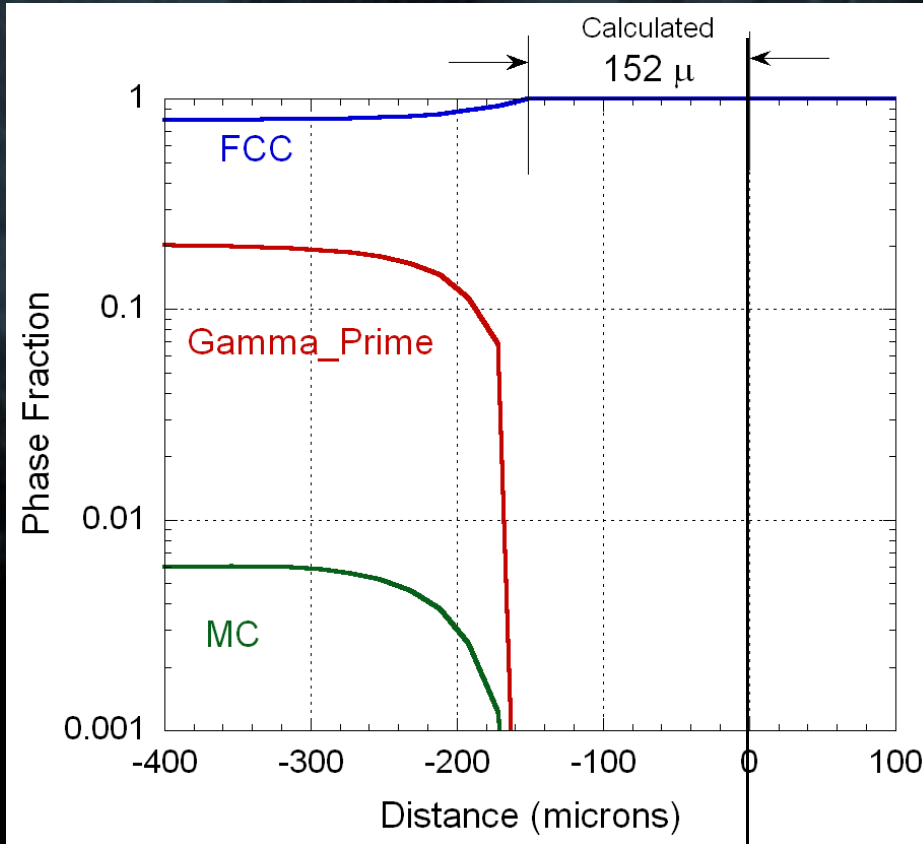


Solid lines: DICTRA results
Solid circles: Measured data

Original database

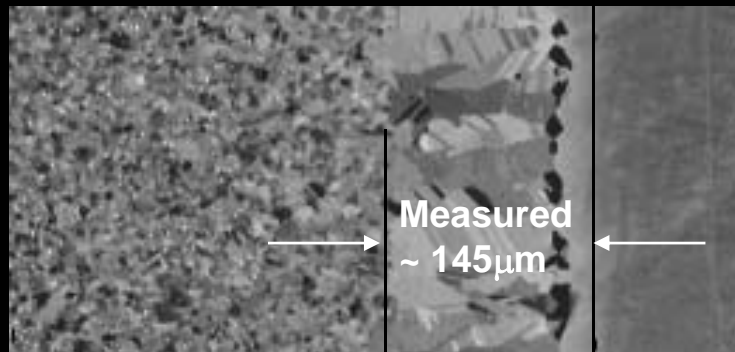
Modified database





DICTRA simulations of ME3/Ni 1093°C for 100 hrs:

- Use measured compositions
- No diffusion through γ' ; acts only as sink or source of solute for diffusion.
- Predicted phase $\gamma + \gamma' + MC / \gamma$ phase boundary is in excellent agreement with experimental measurement.



| Experiments | CALPHAD Fundamental Databases | Material Kinetic Model Parameters |
|---|-------------------------------|-------------------------------------|
| Equilibrium Age + APT (literature data, QuesTek) + EDS (NASA) | Thermodynamics ΔE | |
| Diffusion Couple + Microanalysis (NASA) | Mobility D_{scale} | |
| SSDTA (OSU) + APT (QuesTek) | | σ_{coh}, G_{el} (est.) |
| Coarsening Age+SEM/TEM for γ' size and fraction (NASA) | | σ_{incoh}, M_O |
| XRD, TEM for misfit (NASA) | Molar volume | $G_{el}, R_{coh \rightarrow incoh}$ |

Non-isothermal Precipitation

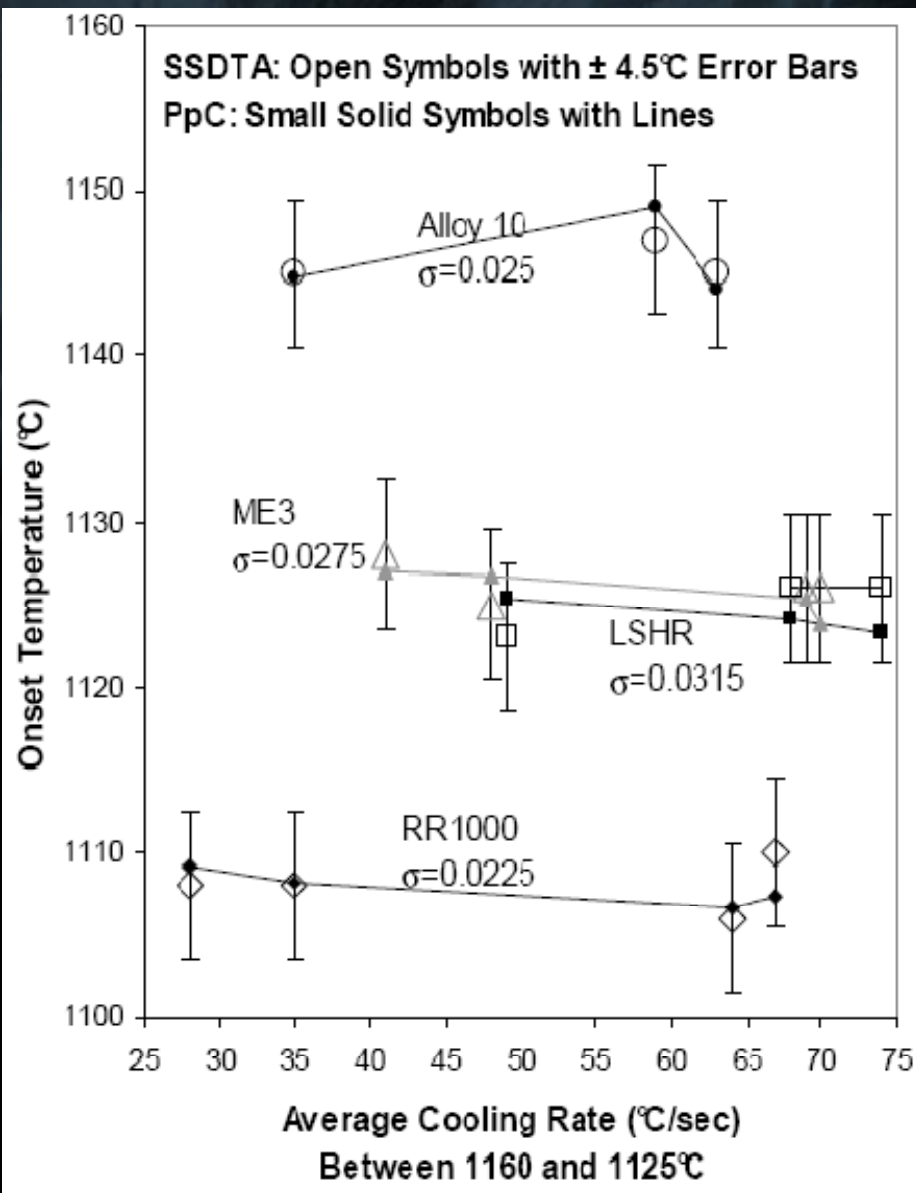
calibration and validation

1. SSDTA (onset of nucleation)
2. APT (non-isothermal microstructures)

Single Sensor Differential Thermal Analysis (SSDTA) is a novel technique developed at OSU for studying phase transformations in materials.

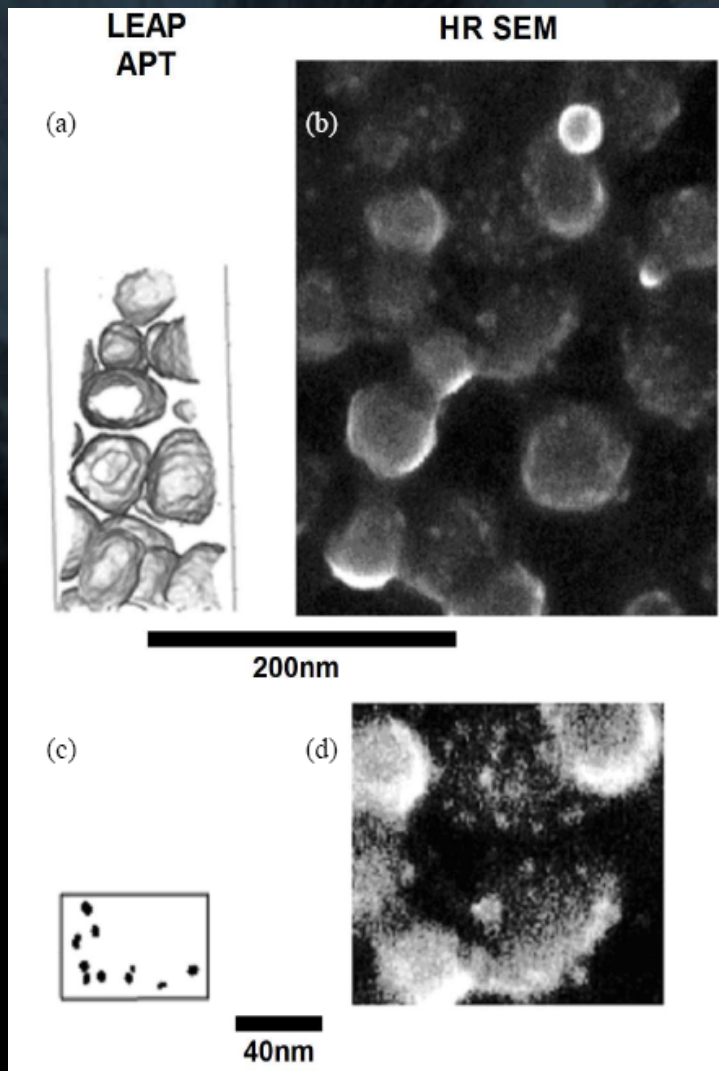
Procedure:

- Process SSDTA measured temperature profiles to obtain nucleation onset temperature (T_{onset}).
- Calculate material compositions relevant to the γ' precipitation from the matrix γ phase - remove high temperature phases (borides, carbides and undissolved γ')
- Perform PrecipiCalc simulations using NI7 and NIST mob database, with estimated surface energy.
- Compute time (or temperature) evolution of molar enthalpy.
- Compute dH/dT .
- Determine onset temperature where dH/dT changes by more than 10%.



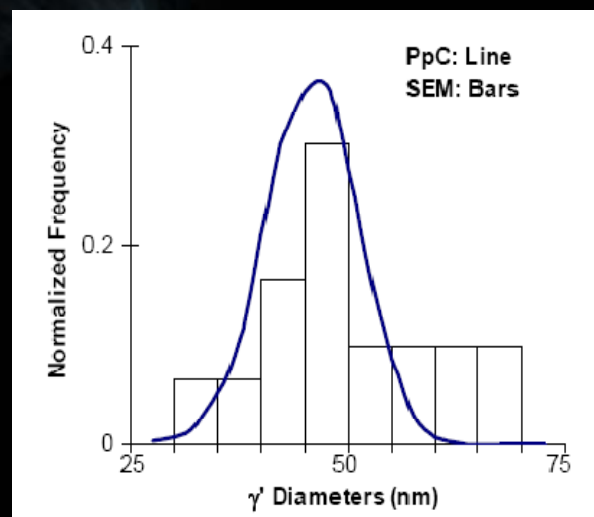
- Optimized interfacial energies for ME3, Alloy 10 and RR1000 are similar and agree with the value reported by Sudbrack et. al.¹ (~0.022-0.023 J/m²).
- LSHR has highest predicted misfit : Incorporation of coherency elastic energy G_{el} will likely reduce range of σ_{coh}

1: C.K. Sudbrack, R. D. Noebe, and D. N. Seidman. 2007. *Acta Materialia*. 55: 119-130.



γ' mean size comparison

| Alloy | LEAP APT | HR SEM | <i>PrecipiCalc</i> Predictions |
|------------|----------|---------|--------------------------------|
| ME3 -1Ar | 40-60 nm | 53.8 nm | 41 nm |
| LSHR -2Ar | - | 50.1 nm | 45.6 nm |
| RR1000-3He | 20-50 nm | 31.8 nm | 20.5 nm |

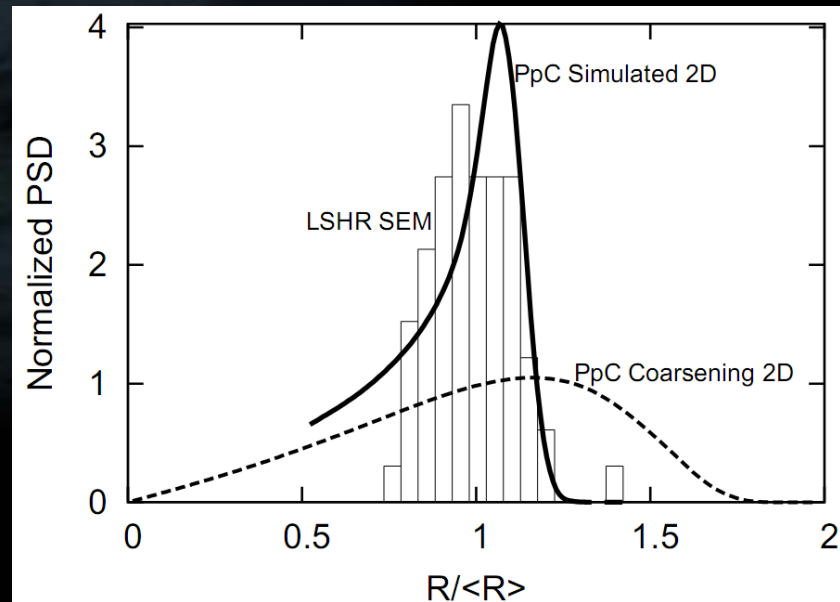


Characterization of γ' microstructure in ME3-1Ar SSDTA sample

Particle size histogram of PrecipiCalc and HR SEM in LSHR-1Ar SSDTA sample

γ' mean size comparison

| Alloy | HR SEM | <i>PrecipiCalc</i> Predictions |
|--------|--------|--------------------------------|
| ME3 | 430 nm | 348 nm |
| LSHR | 408 nm | 402 nm |
| RR1000 | 376 nm | 396 nm |



Comparison shows good agreement between experimental SEM (bars) and *PrecipiCalc* simulated (converted to 2D, solid line) and normalized particle size distributions for LSHR furnace cooled sample. 2D coarsening size distribution is shown in a dashed line

| Experiments | CALPHAD Fundamental Databases | Material Kinetic Model Parameters |
|---|-------------------------------|-------------------------------------|
| Equilibrium Age + APT (literature data, QuesTek) + EDS (NASA) | Thermodynamics ΔE | |
| Diffusion Couple + Microanalysis (NASA) | Mobility D_{scale} | |
| SSDTA (OSU) + APT (QuesTek) | | σ_{coh}, G_{el} (est.) |
| Coarsening Age+SEM/TEM for γ' size and fraction (NASA) | | σ_{incoh}, M_O |
| XRD, TEM for misfit (NASA) | Molar volume | $G_{el}, R_{coh \rightarrow incoh}$ |

Coarsening

calibration and validation

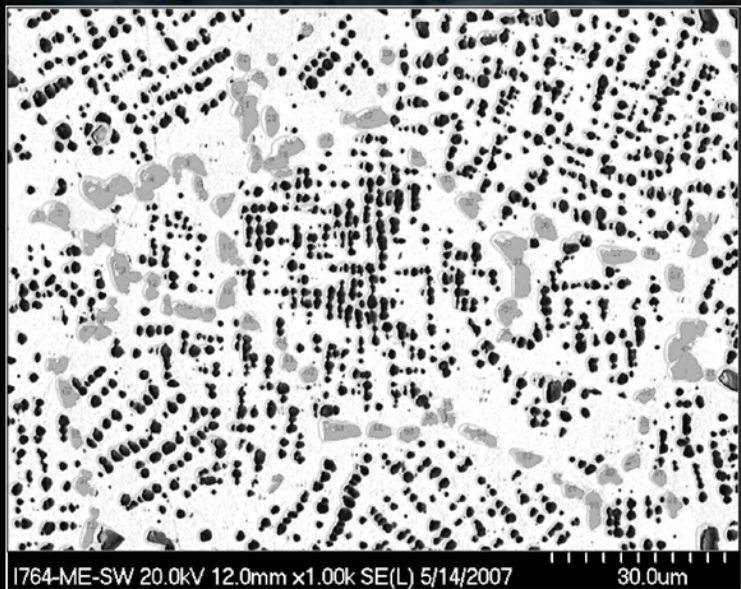
1. SEM + TEM for γ' size and fraction

ME3, LSHR and Alloy 10:

- Supersolvus treated at 1193°C for 1hr + WQ
- Aged:
 - 1093°C/20hrs and 1000hrs
 - 927°C/1000hrs
 - 760°C/1000hrs

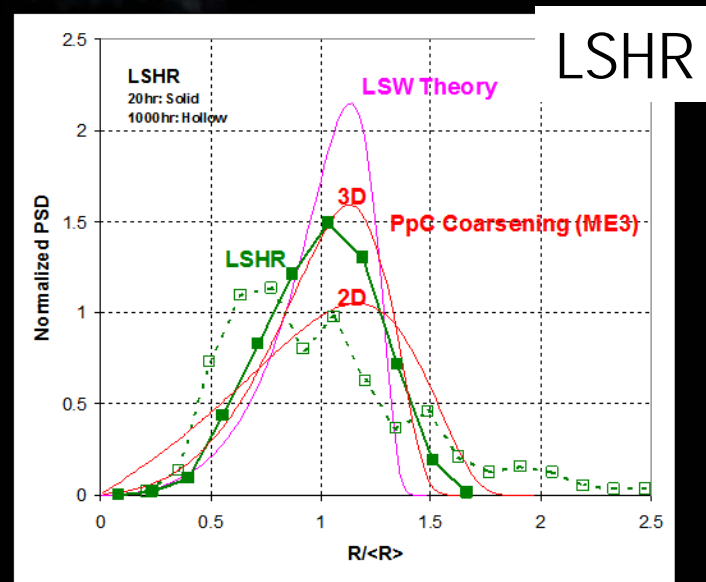
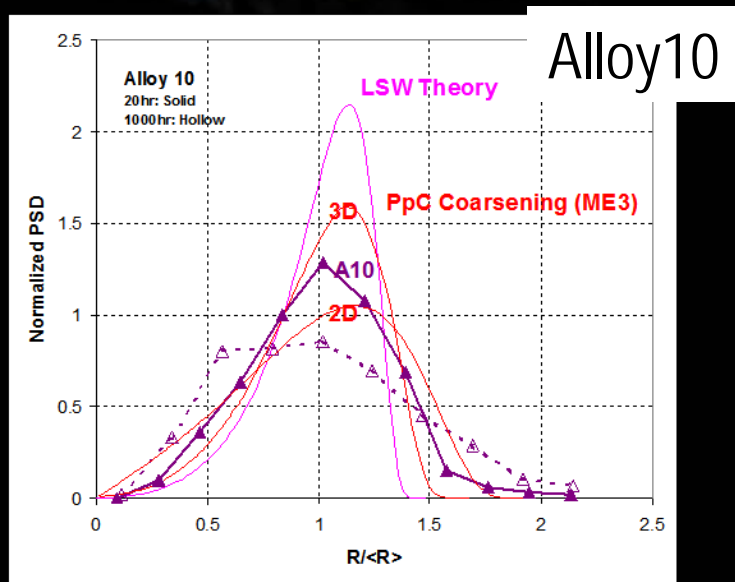
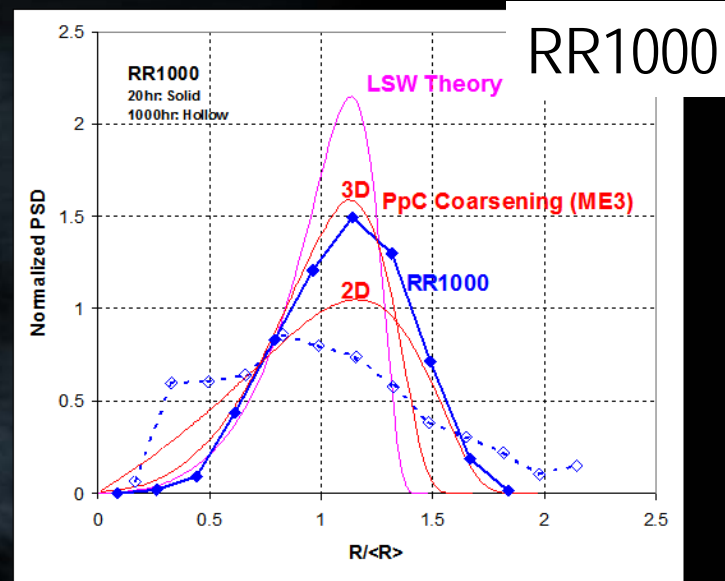
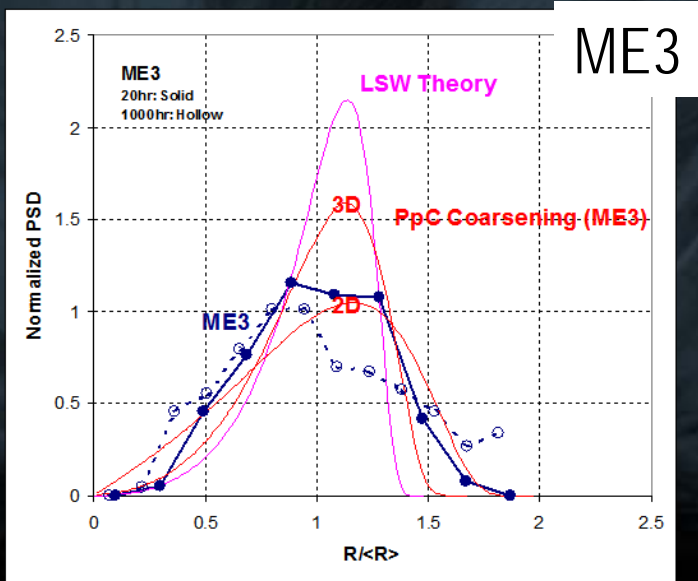
PrecipiCalc modeling of coherent intragranular γ' is ongoing

Experimental measured γ' mean equivalent diameters (μm) of isothermally aged samples.



SEM image of ME3 super-solvus + aged at 1093°C for 1000hrs. Intragranular and GB γ' are represented as black and grey.

| Aging Conditions | Exp | ME3 | | LSHR | | Alloy 10 | |
|------------------|-----|-------|-------|-------|-------|----------|-------|
| | | G | GB | G | GB | G | GB |
| Before Aging | TEM | 0.044 | - | 0.028 | - | 0.044 | - |
| 1093C-20h | SEM | 0.510 | 0.810 | 0.504 | 0.984 | 0.546 | 1.084 |
| 1093C-1000h | SEM | 1.380 | 2.840 | 1.420 | 2.996 | 0.894 | 2.618 |
| 927C-1000h | SEM | 0.584 | 0.758 | 0.598 | 0.954 | 0.670 | 1.224 |
| 760C-1000h | TEM | 0.058 | - | 0.062 | - | 0.062 | - |





- Focused experiments performed at NASA GRC for calibration of databases and precipitation models.
- Measured phase compositions show best agreement with Thermotech Ni7 thermodynamic database.
- Prediction of high misfit in high-refractory 3rd generation alloys supported by microstructural evidence: XRD for confirmation.
- Comparison of diffusion couple experiments with DICTRA predictions indicate NIST mobility database (in combination with Ni7) gives sufficient accuracy to support *PrecipiCalc* simulations.
- SSDTA measurement of critical nucleation under-cooling defines reasonable values of coherent interfacial energies.
- *PrecipiCalc* simulations of non-isothermal precipitation gives good agreement with observed particles sizes and compositions.

Accuracy of predictions validated so far indicates that available fundamental databases and precipitation models offer sufficient fidelity for effective application of AIM methodology to 3rd generation aeroturbine disc alloys



- John Gayda and Tim Gabb of NASA GRC.
- Jeff Simmons and Chris Woodward of AFRL
- David Furrer, Rob Mitchell and Mark Hardy of Rolls-Royce Corporation
- Carelyn Campbell of NIST
- Boian Alexandrov of Ohio State University
- Eugene Kang of Northwestern University
- David Siedman of Northwestern University