The Effect Stacking Fault Segregation and Phase Transformations Have on Creep Strength in Ni-based Superalloys

T.M. Smith[1], B. Good[1], T. Gabb[1], B.D. Esser[2], A. Egan[2], C.M.F. Rae[3], L. Evans[1], D.W McComb[2], M.J. Mills[2]

[1]NASA Glenn Research Center, Cleveland Oh 44135 USA

[2]Center for Electron Microscopy and Analysis, The Ohio State University, Columbus Oh 43212 USA

[3] Department of Materials Science and Metallurgy, University of Cambridge, Cambridge CB2 3QZ, UK

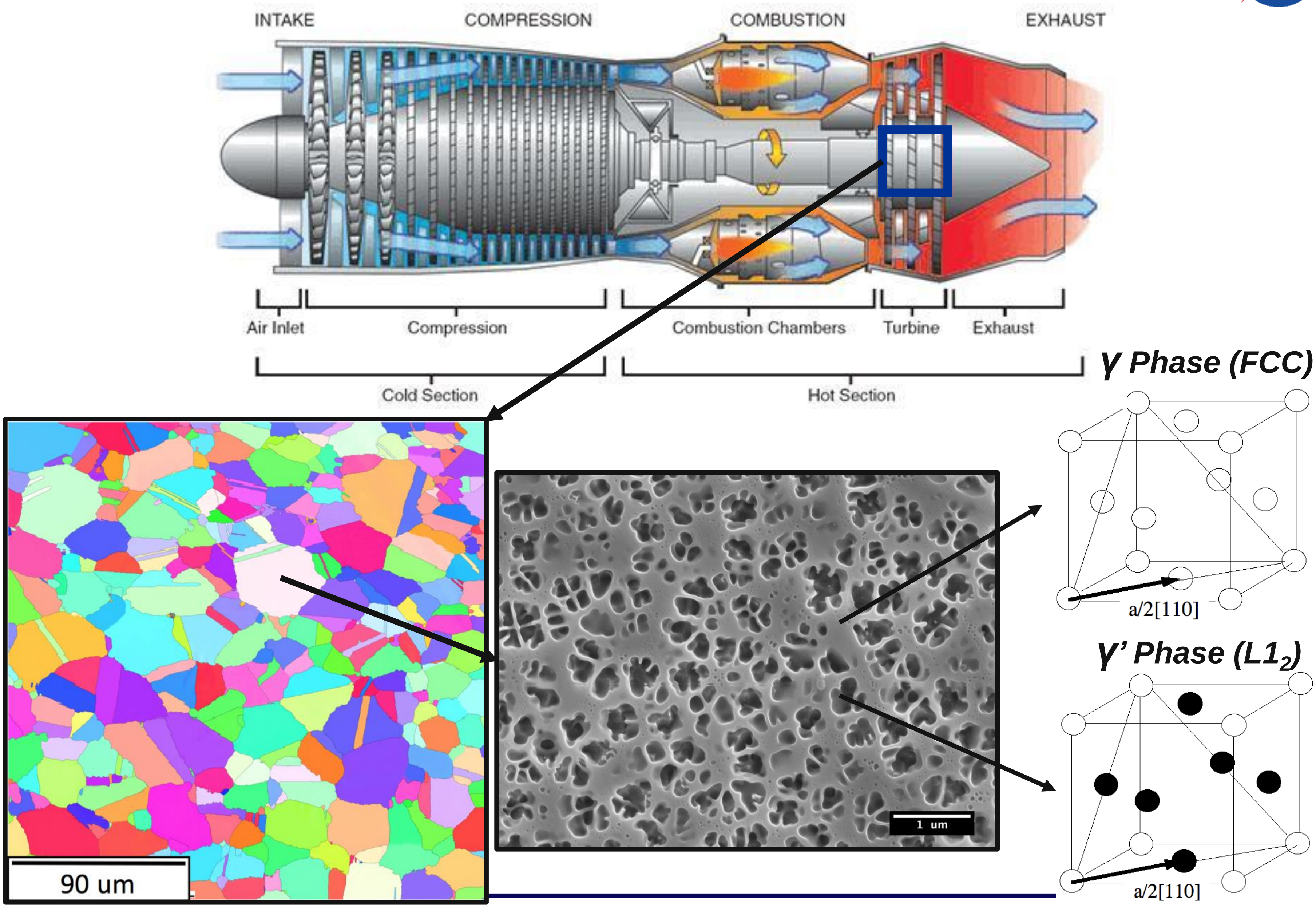
THE OHIO STATE UNIVERSITY

UNIVERSITY OF CAMBRIDGE

Support provided by NASA's Aeronautics Research Mission Directorate (ARMD) – Convergent Aeronautics Solutions Project and NASA's Advanced Air Transport Technology (AATT) Project Office (ARMD) *and NSF DMREF Program*

Center for Electron Microscopy and Analysis

Ni-Based Superalloys for Turbine Disks

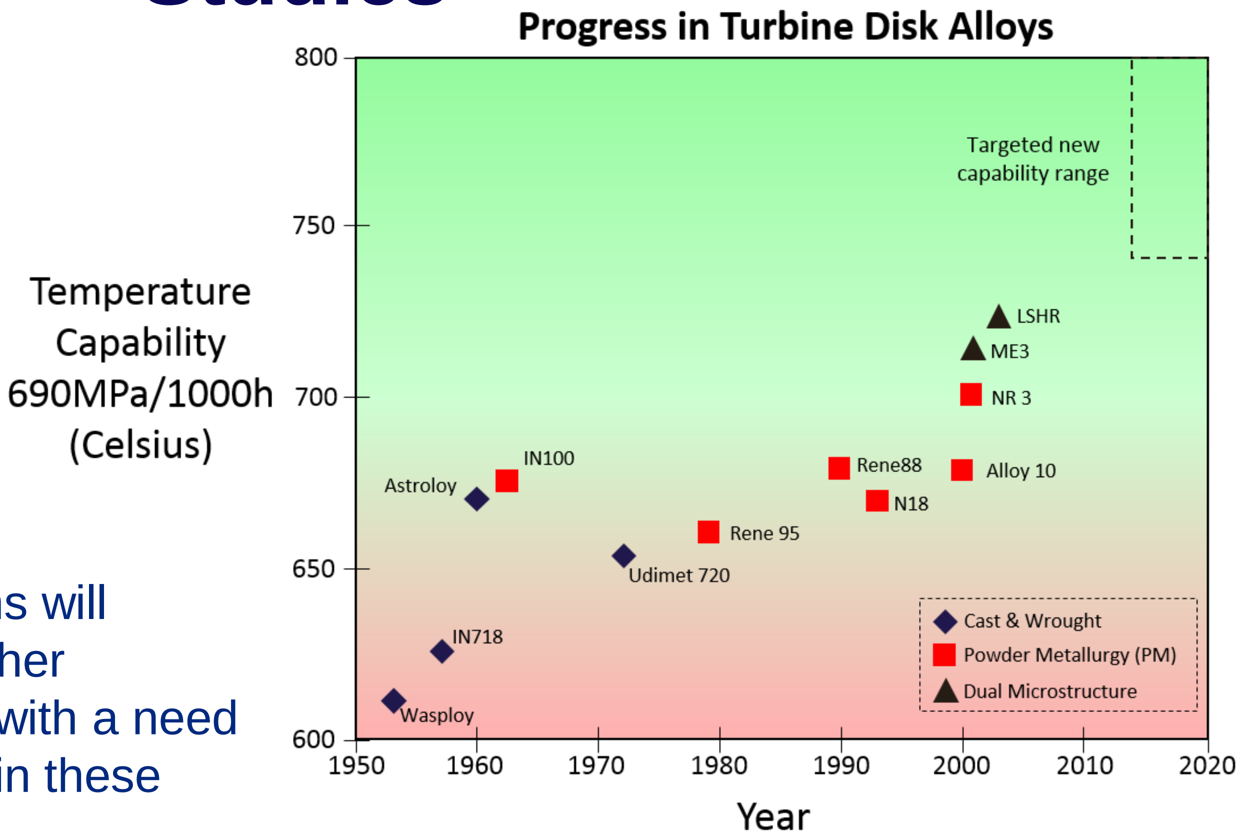


Motivation for Mechanistic Studies

- Material advancements are required to accommodate the higher compressor exit temperatures in jet turbine engines (>700°C near the rotor rim) for improved efficiency and pollution reduction.

- New deformation mechanisms will become dominant at these higher operating temperatures along with a need for improved creep properties in these disk alloys.

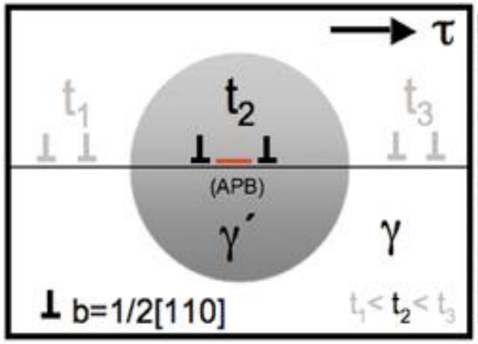
- New understanding and materials will be needed for future advancements

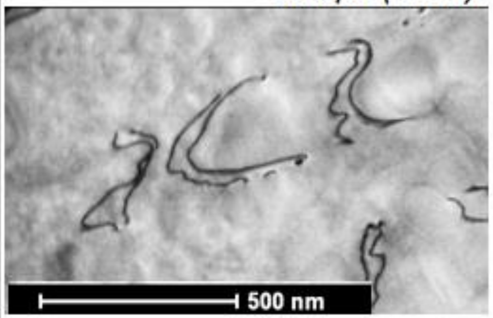


Deformation Mechanisms in Superalloys

Disk Alloys

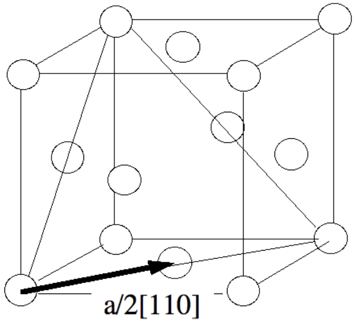
T<700° C

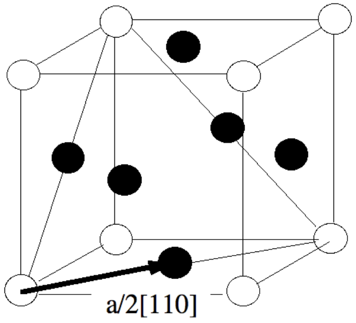




Athermal γ' shearing by 1/2<110> dislocations

γ Phase (FCC)

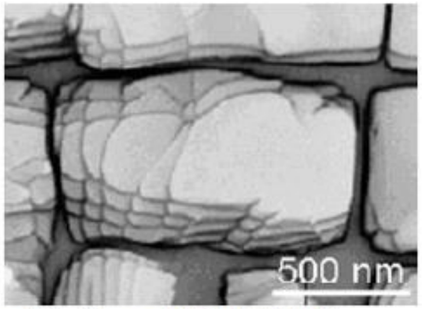




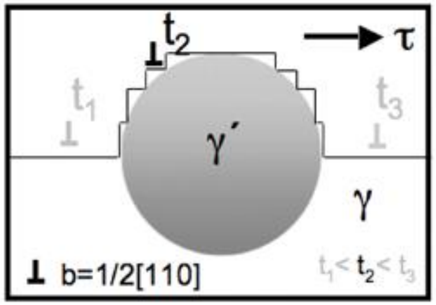
γ' Phase ($L1_2$)

Blade Alloys

T>900° C



Epishin and Link (2008)

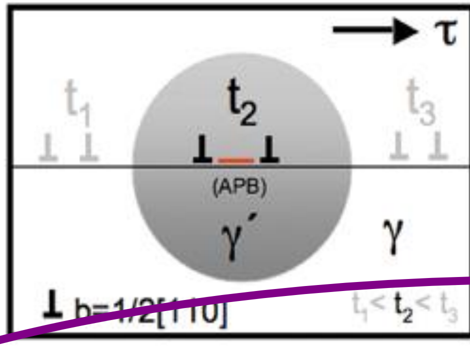


Climb By-Pass of γ′ by individual 1/2<110> dislocations

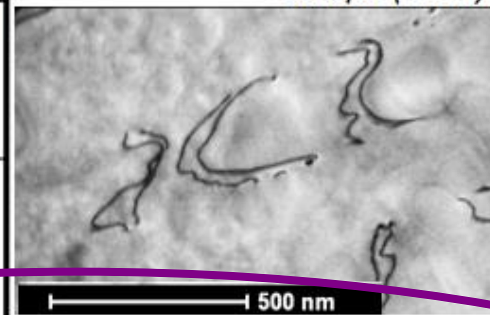
Deformation Mechanisms in Superalloys

Disk Alloys

T<700° C



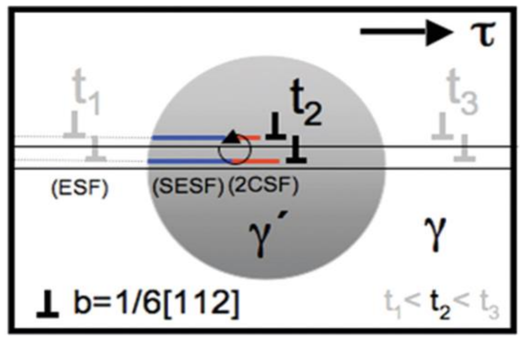
Phillips (2009)



Athermal γ' shearing by 1/2<110> dislocations

Novel mechanisms:

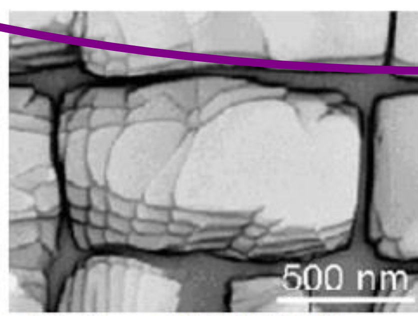
- **Stacking Fault Cutting**
- **Microtwinning**
- **Stacking Fault Ribbons**



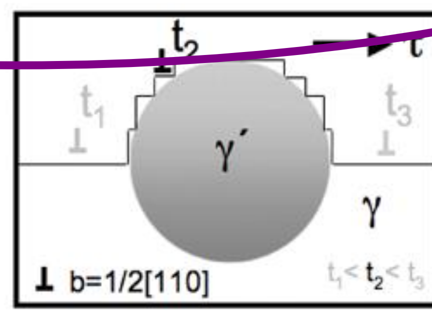
Diffusion mediated creep deformation

Blade Alloys

T>900° C

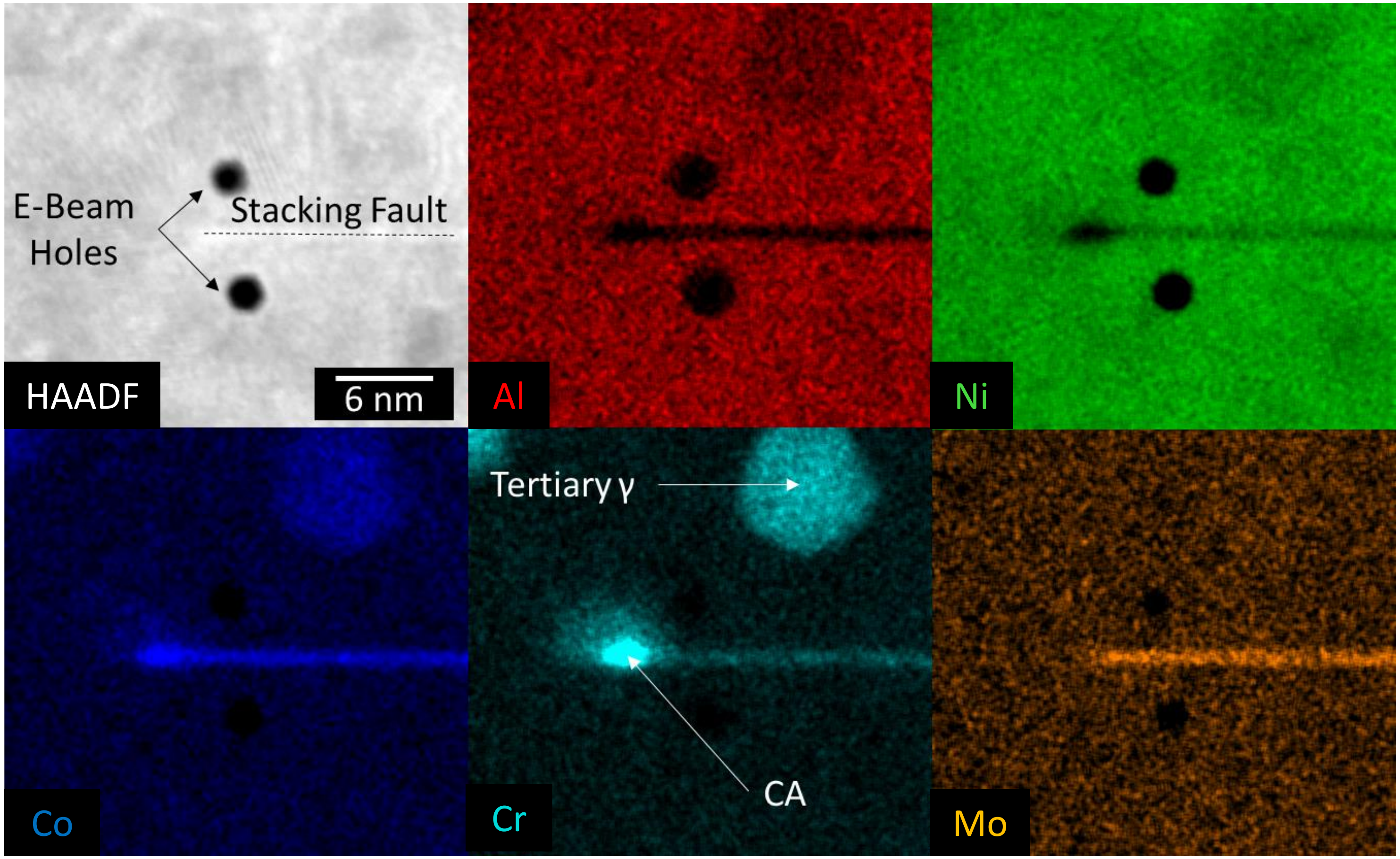


Epishin and Link (2008)



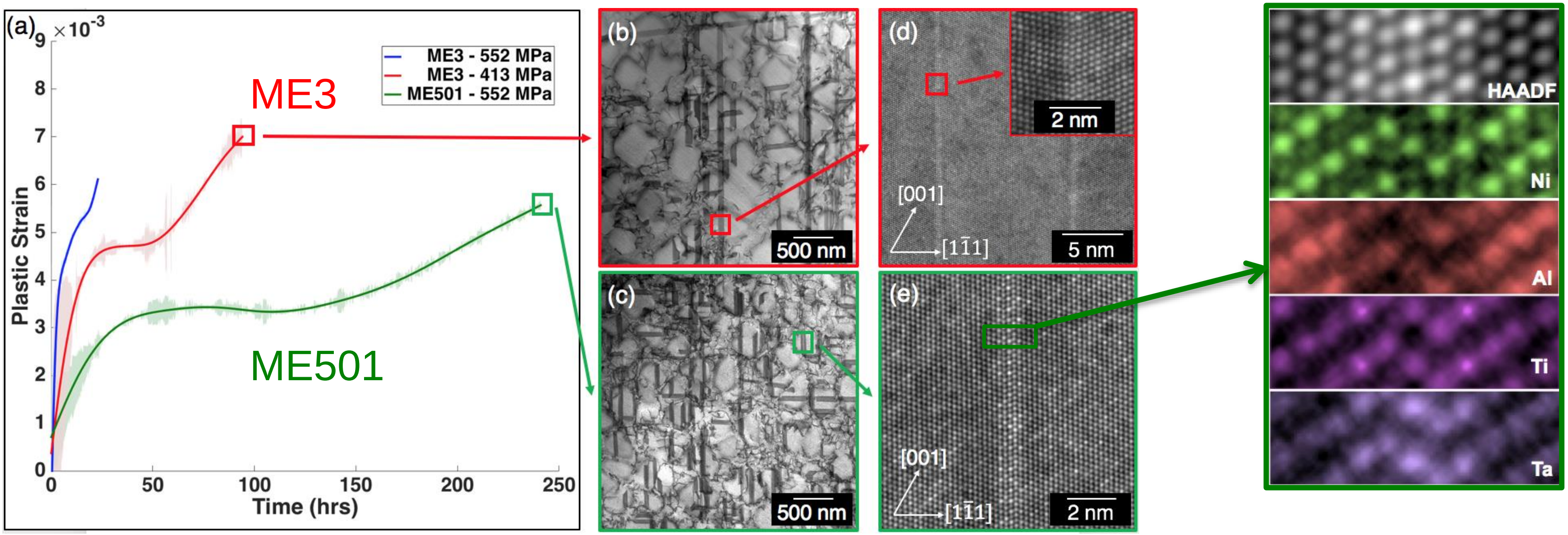
Climb By-Pass of γ′ by individual 1/2<110> dislocations

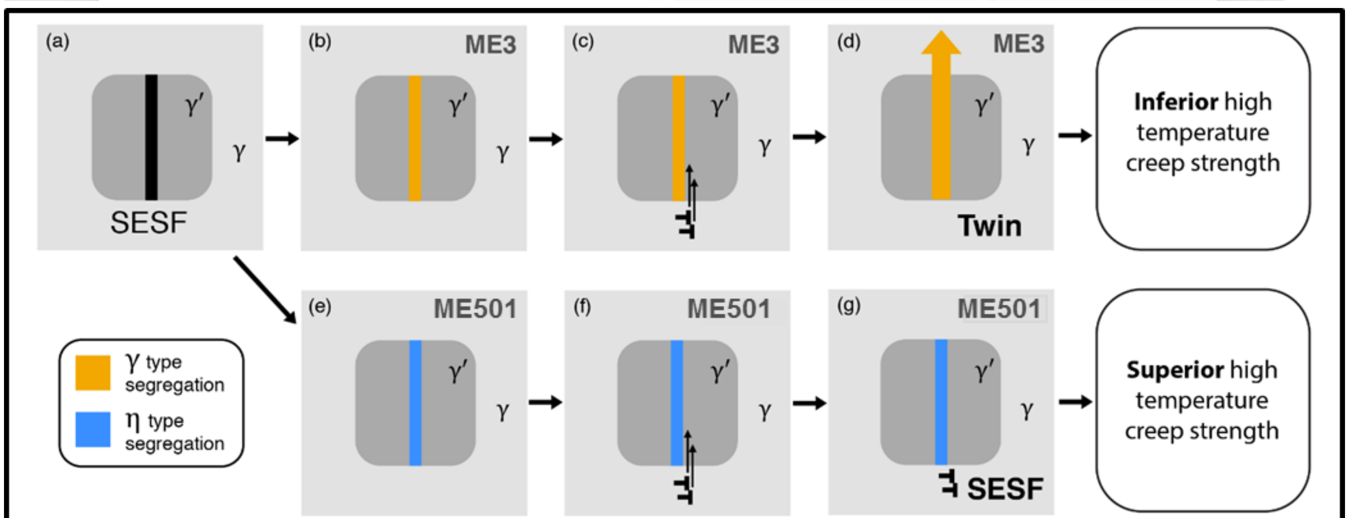
Segregation along Stacking Faults



Segregation along superlattice stacking faults has been observed in numerous Ni and Co-based superalloys.

Phase Transformation Strengthening



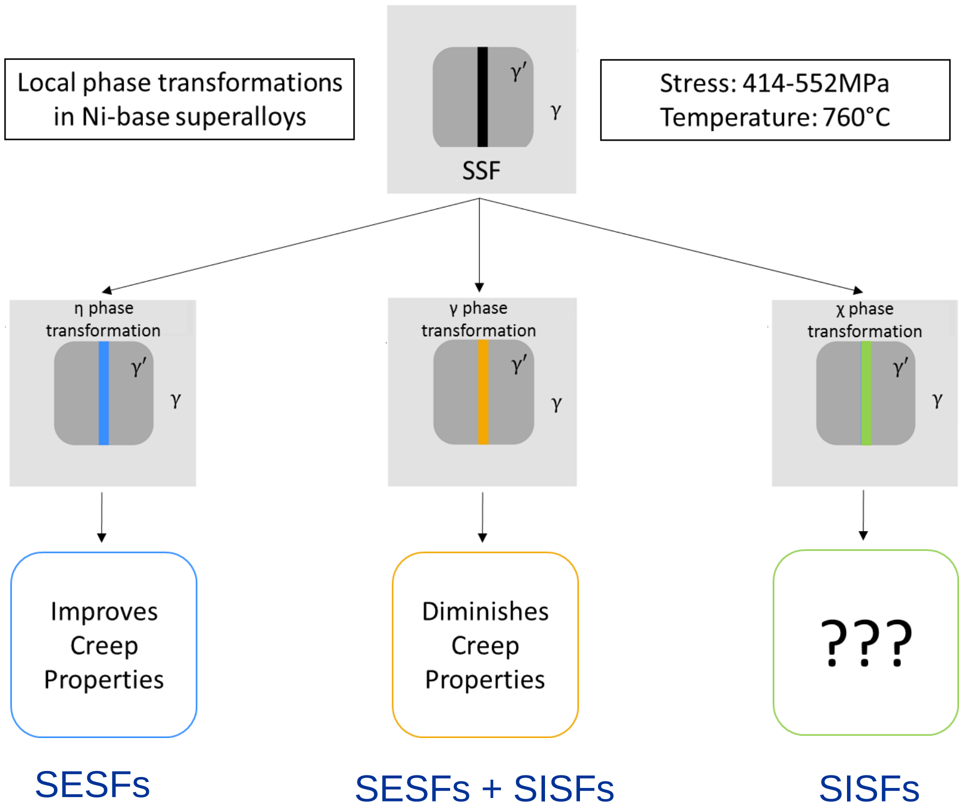


New insight into alloy effects:

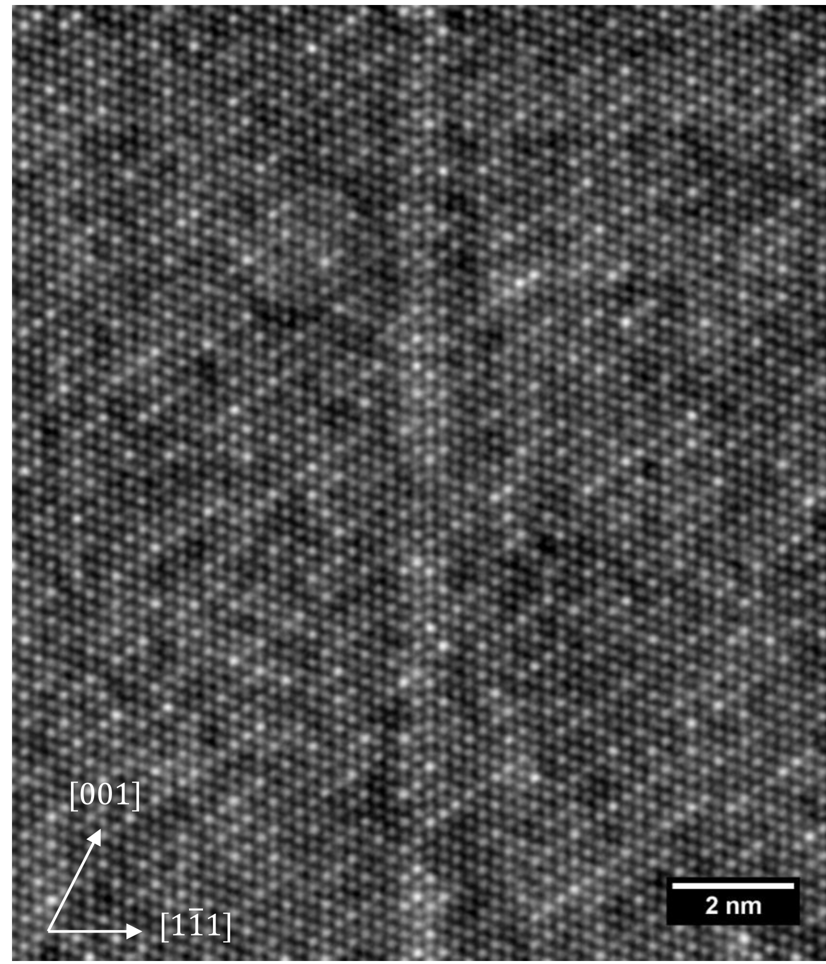
- Segregation of γ formers in ME3 promotes microtwinning
- Formation of η phase at faults in ME501 inhibits microtwinning and improves creep strength

Smith, et al. Nature Communications, 2016

Phase Transformations along SISFs



Does the observed χ (Co_3W) or γ phase transformations along SISFs have any impact on creep properties?



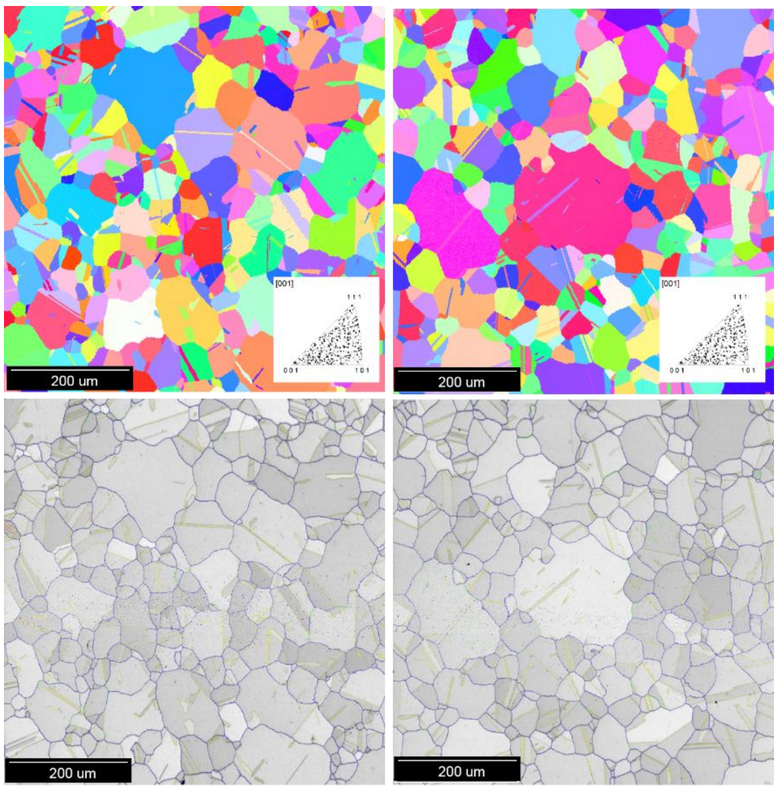
CMSX-4 (high W content)*

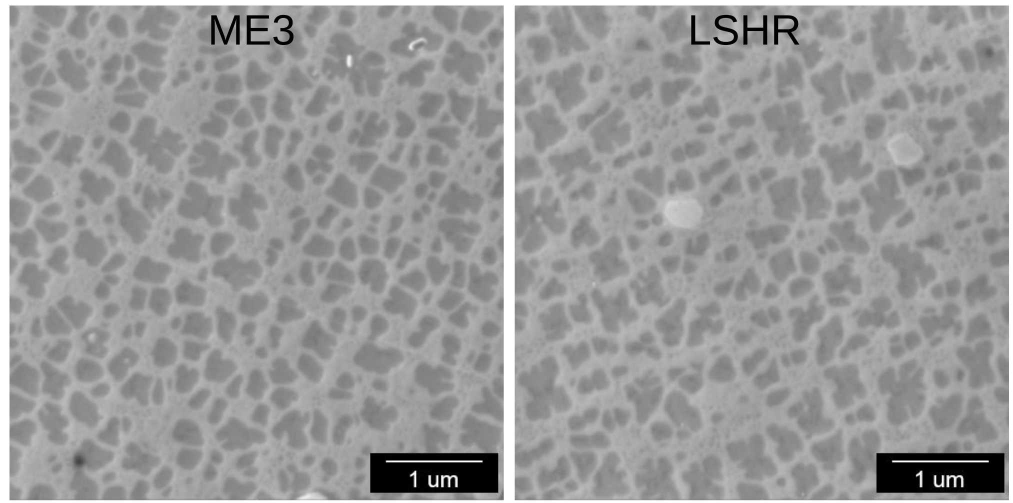
*Smith *et al.* 2018

Material Preparation

Average Alloy Composition in Weight Percent												
Alloy	Cr	Co	Al	Ti	Nb	Mo	Ta	W	Zr	B	C	Ni
LSHR	12.5	20.4	3.5	3.5	1.5	2.7	1.5	4.3	0.05	0.03	0.045	Bal
ME3	13	21	3.4	3.8	0.8	3.7	2.4	2.1	0.05	0.02	0.05	Bal

ME3 LSHR



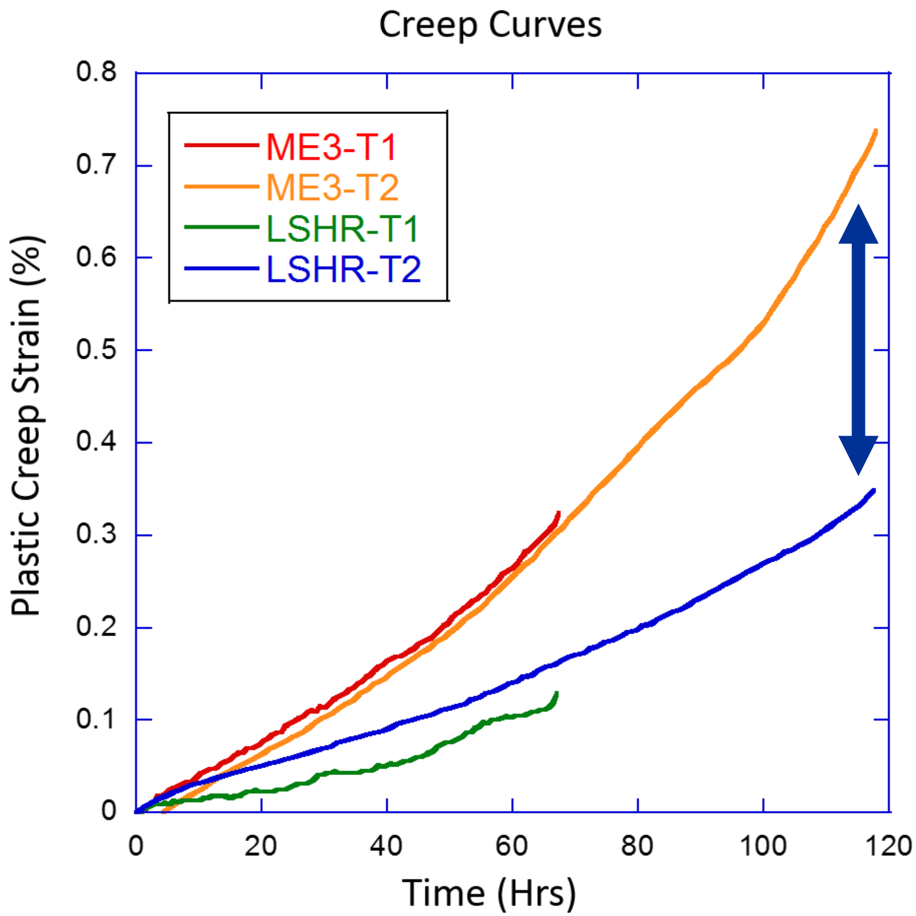


Alloy	Secondary γ' VF	Tertiary γ' VF	**Total γ' VF**	Average Secondary γ' Size	Average Tertiary γ' Size
ME3	43.97 ± .6	2.65 ± .4	**46.61 ± 1.0**	135 nm	15.4 nm
LSHR	43.52 ± 1.7	2.27 ± .1	**45.80 ± 1.8**	154 nm	15.9 nm

ME3 Average Grain Diameter = 59.2 μm
LSHR Average Grain Diameter = 59.9 μm

The two alloys are microstructurally comparable!

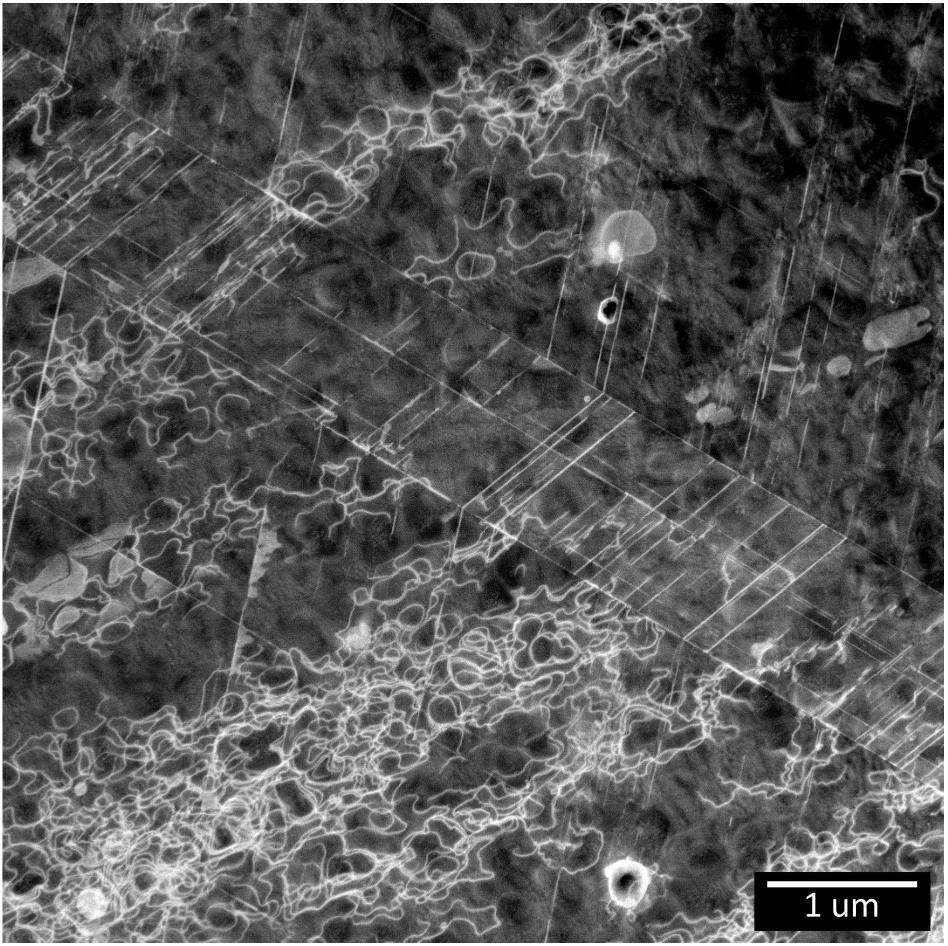
Creep Testing of ME3 and LSHR

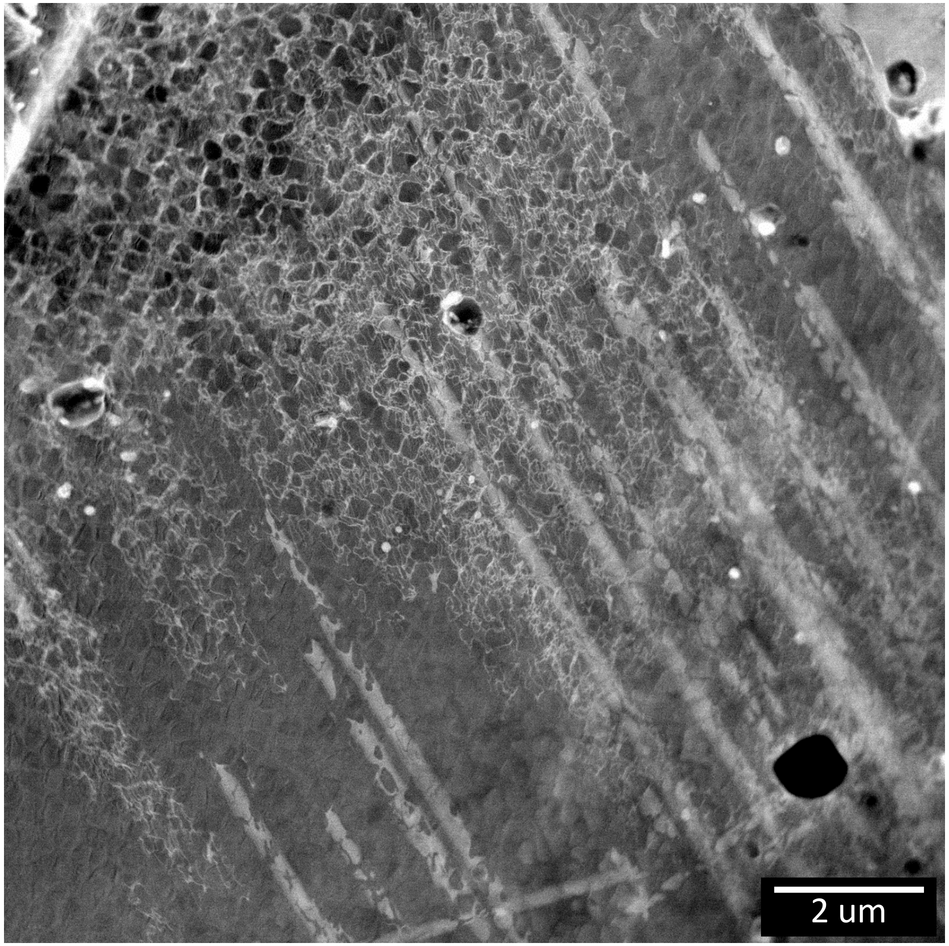


Creep tests were performed at 760°C under a stress of 552MPa

LSHR has consistently performed better in creep compared to ME3 in this temperature regime. Why?

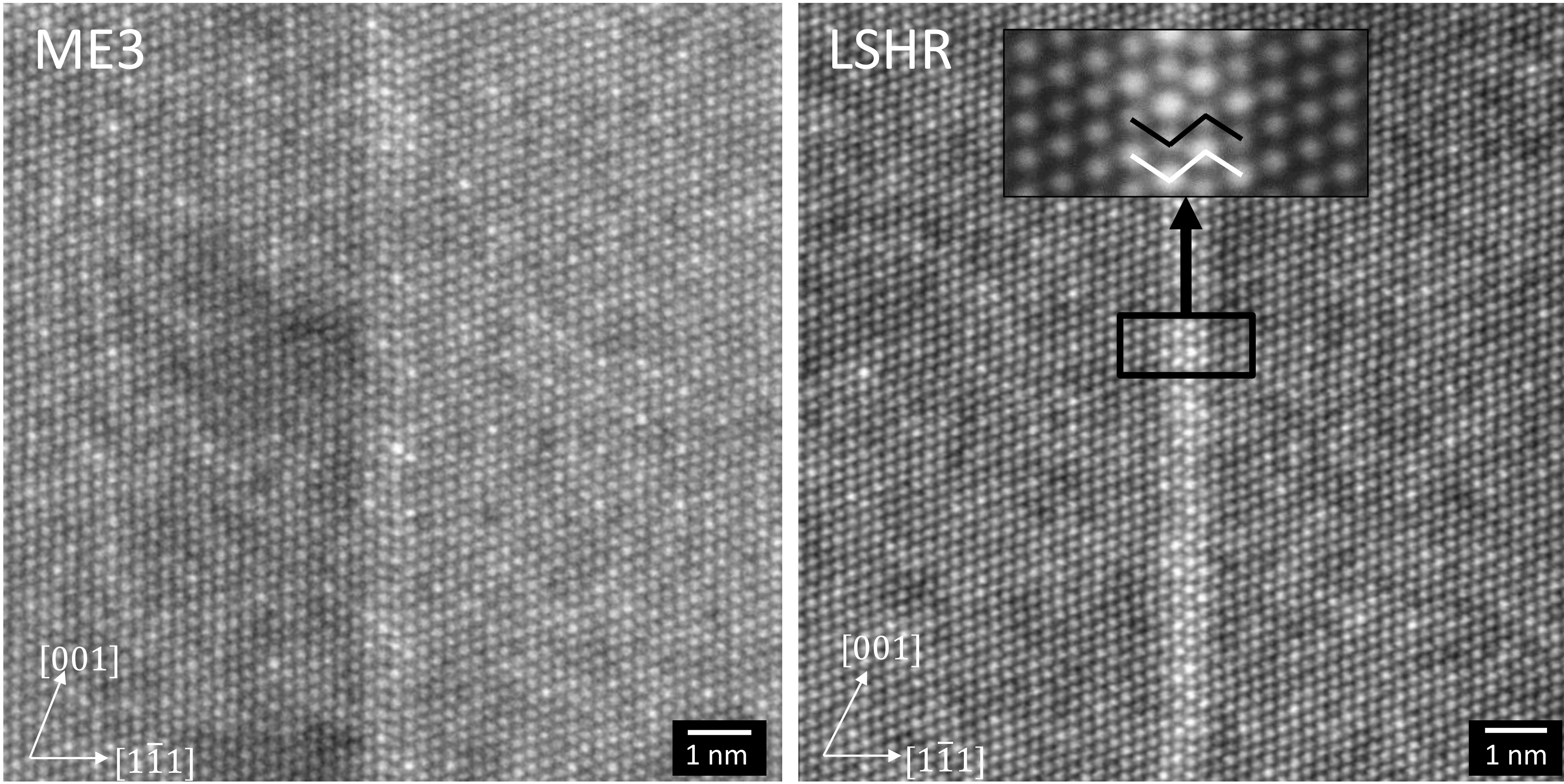
STEM Characterization





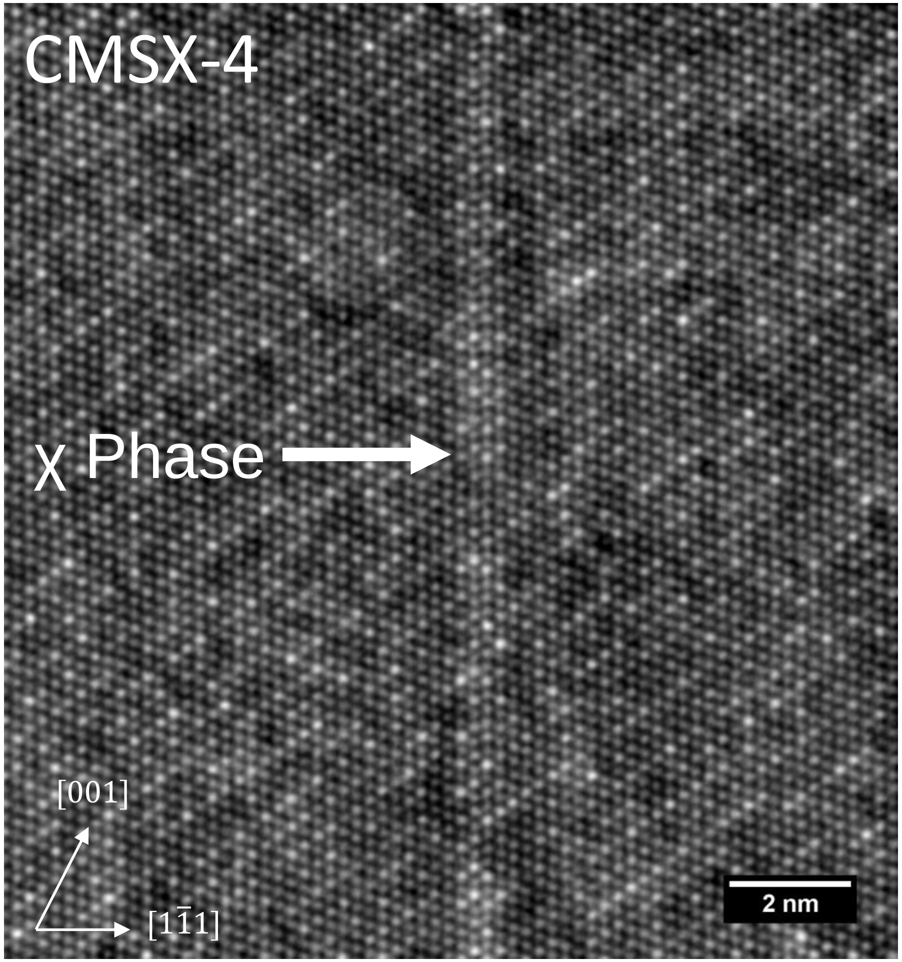
No notable differences in active deformation modes could be discerned between the two alloys.

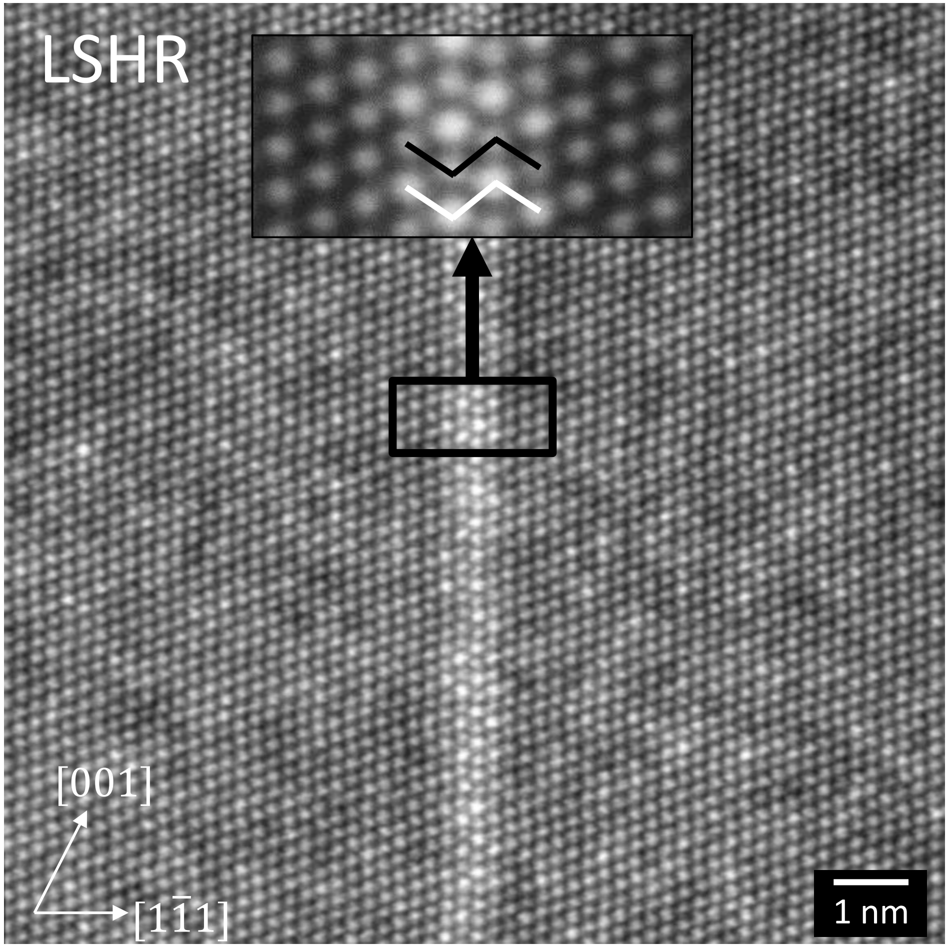
Segregation along SISFs in ME3 and LSHR



Ordered contrast exists along SISFs in LSHR but not ME3

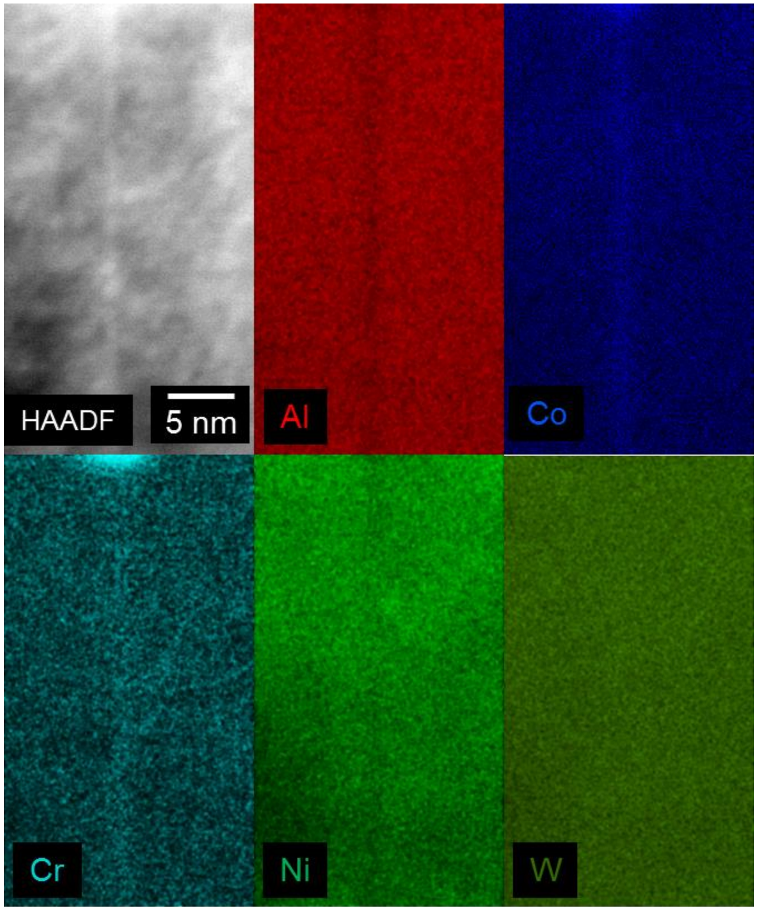
Segregation along SISFs in ME3 and LSHR

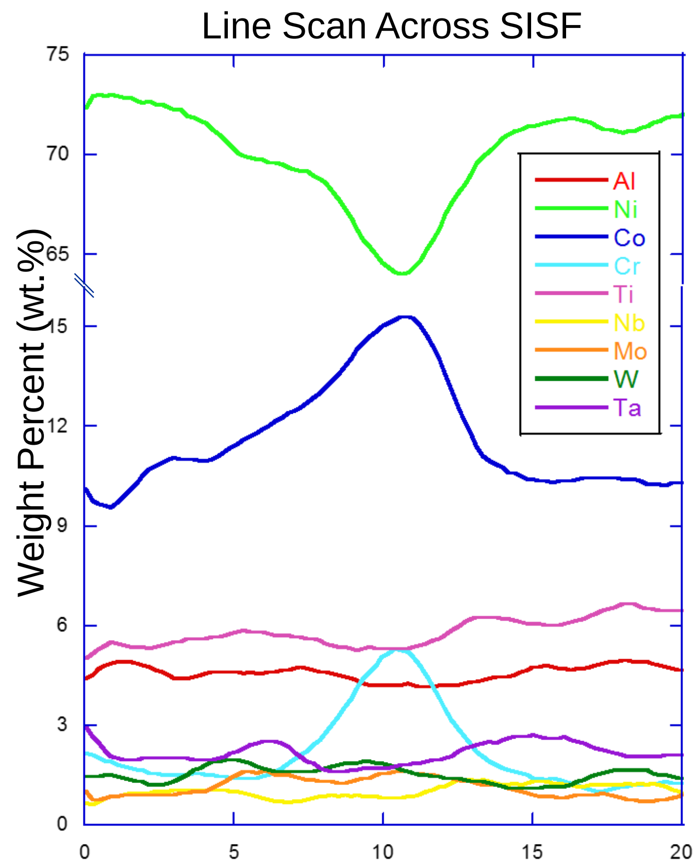




Ordered contrast exists along SISFs in LSHR but not ME3

Segregation along SISFs – ME3

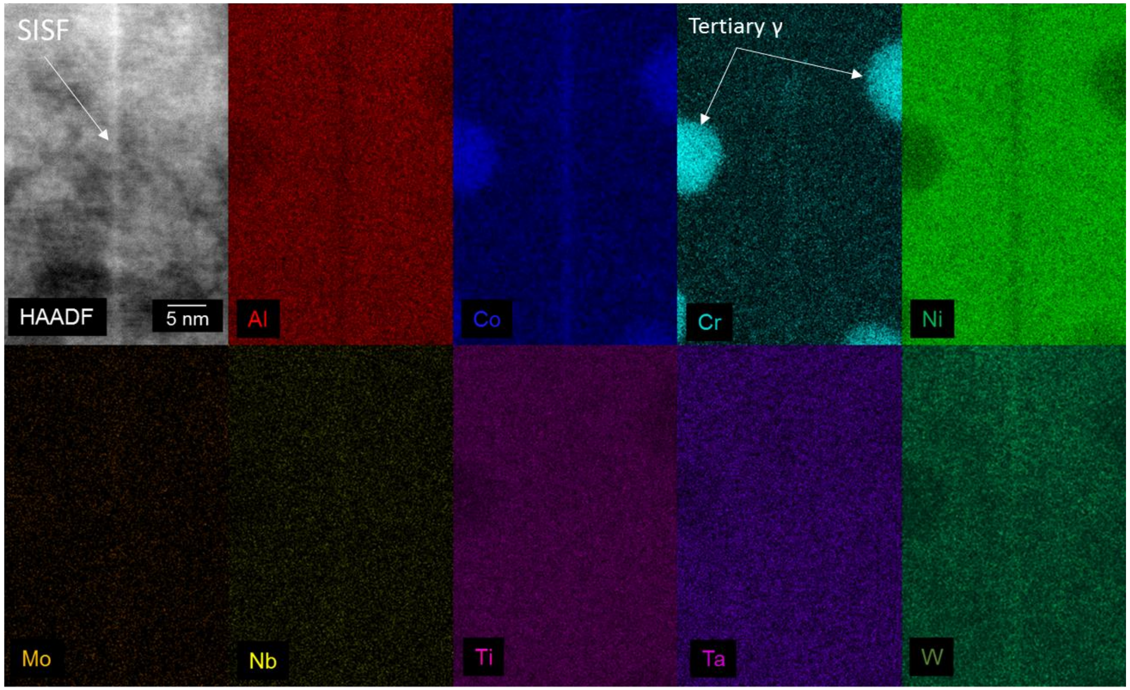


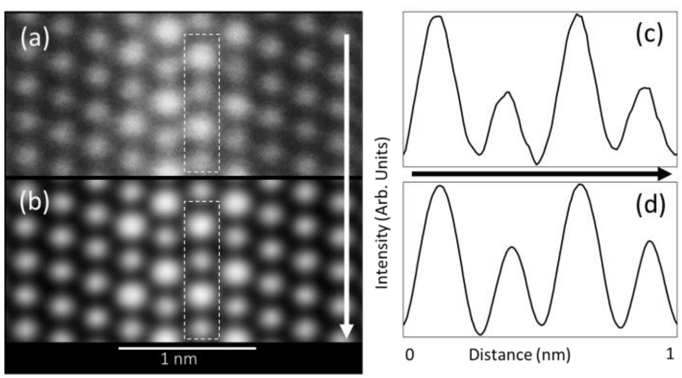


Confirmed γ phase nucleation along SISFs in ME3

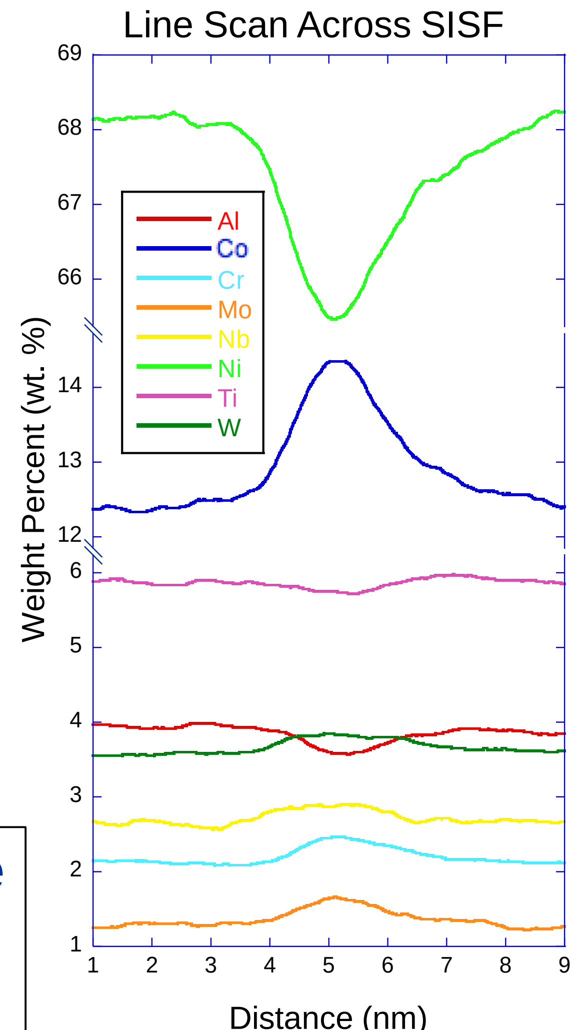
Co, Cr Segregation
Ni, Al Depletion

Segregation along SISFs - LSHR



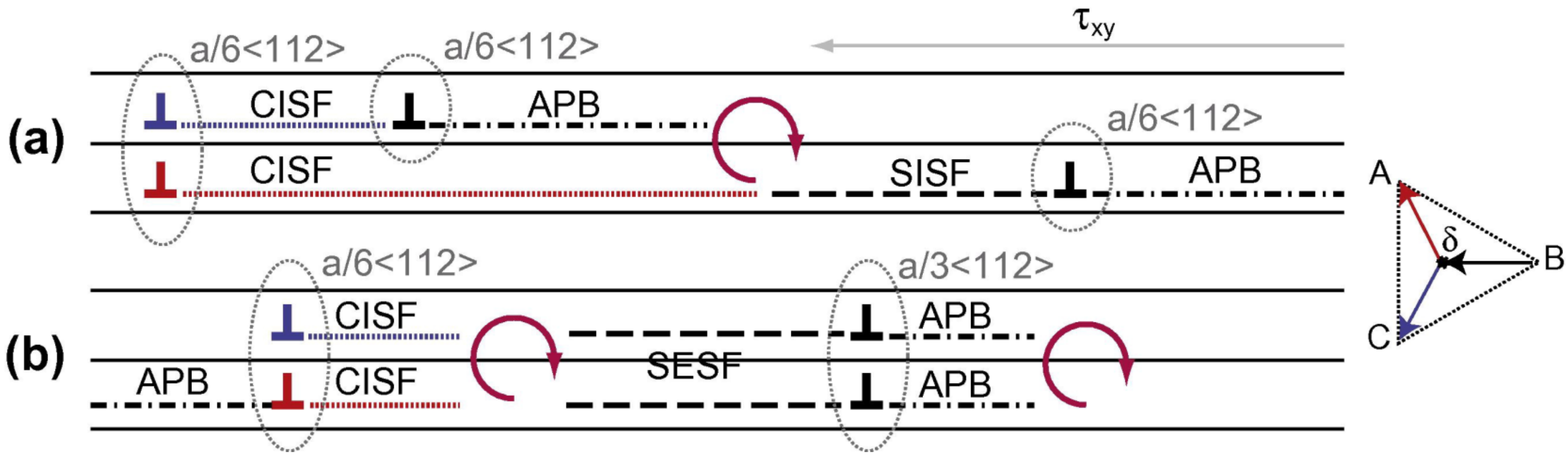


Confirmed χ phase nucleation along SISFs in LSHR



Co, W, Cr Segregation
Ni, Al Depletion

Stacking Fault Ribbon Formation



Vorontsov *et al*. Acta Materialia. 2012

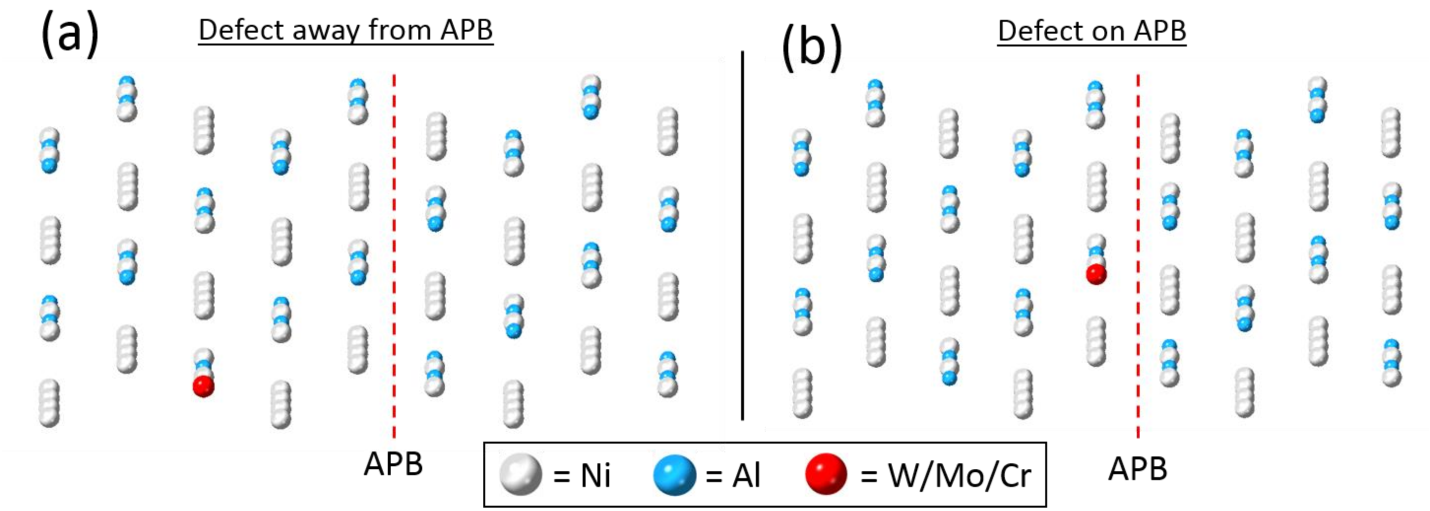
$$\frac{a}{3} < 112 > (SISF) + \frac{a}{6} < 112 > (APB) + \frac{a}{6} < 112 > (SESF) + \frac{a}{3} < 112 > = a < 112 >$$

Stacking Fault ribbons are a major source of primary creep strain in this temperature regime for single crystal superalloys

C.M.F. Rae and R.C. Reed. Acta Materialia. 2007

What effects will γ or χ phase formation along SISFs have on this shearing process?

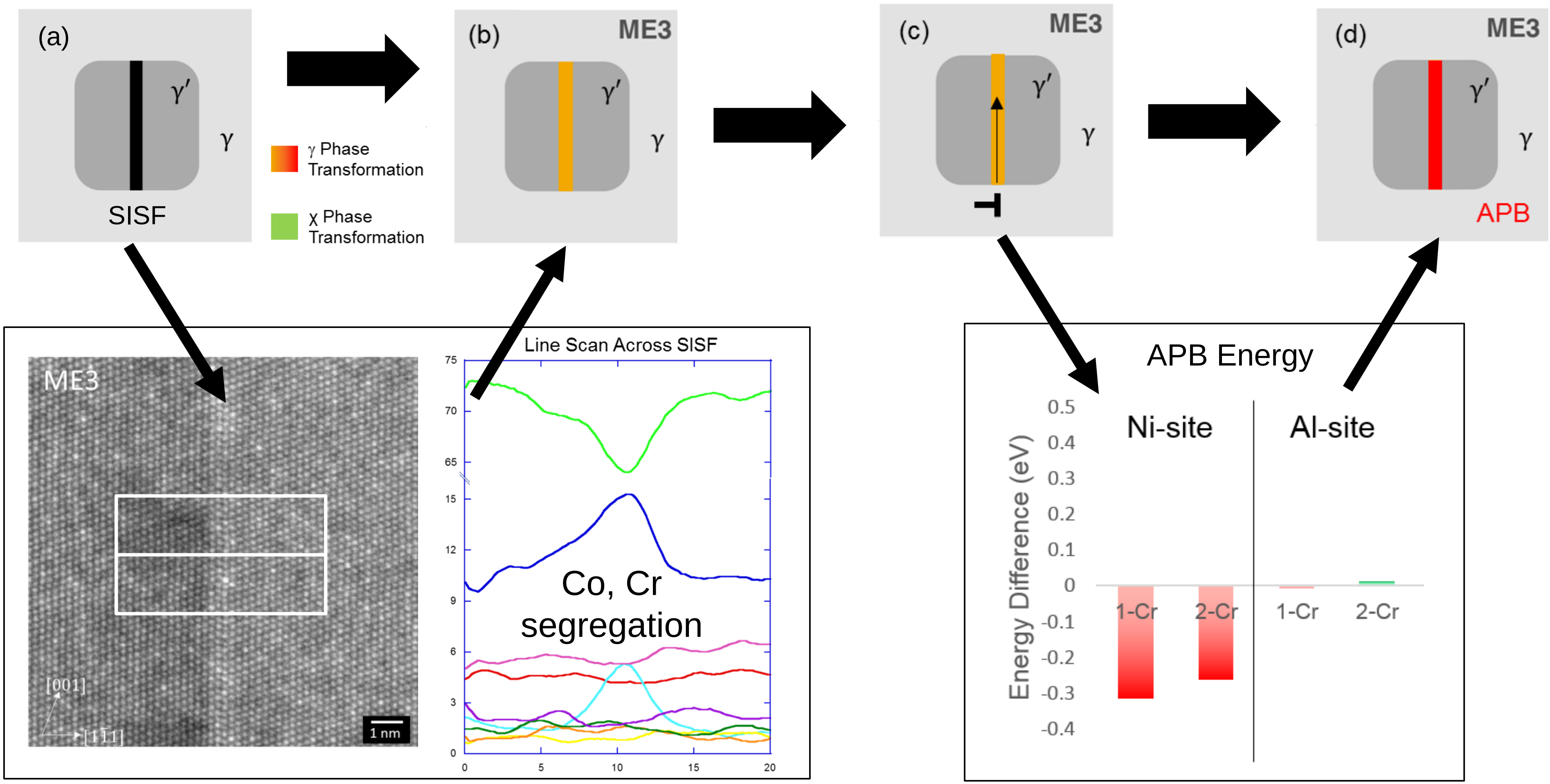
DFT Measurements



Ni_3Al γ' cells with an APB were created to explore the effect SISF segregation has on the formation of the trailing APB.

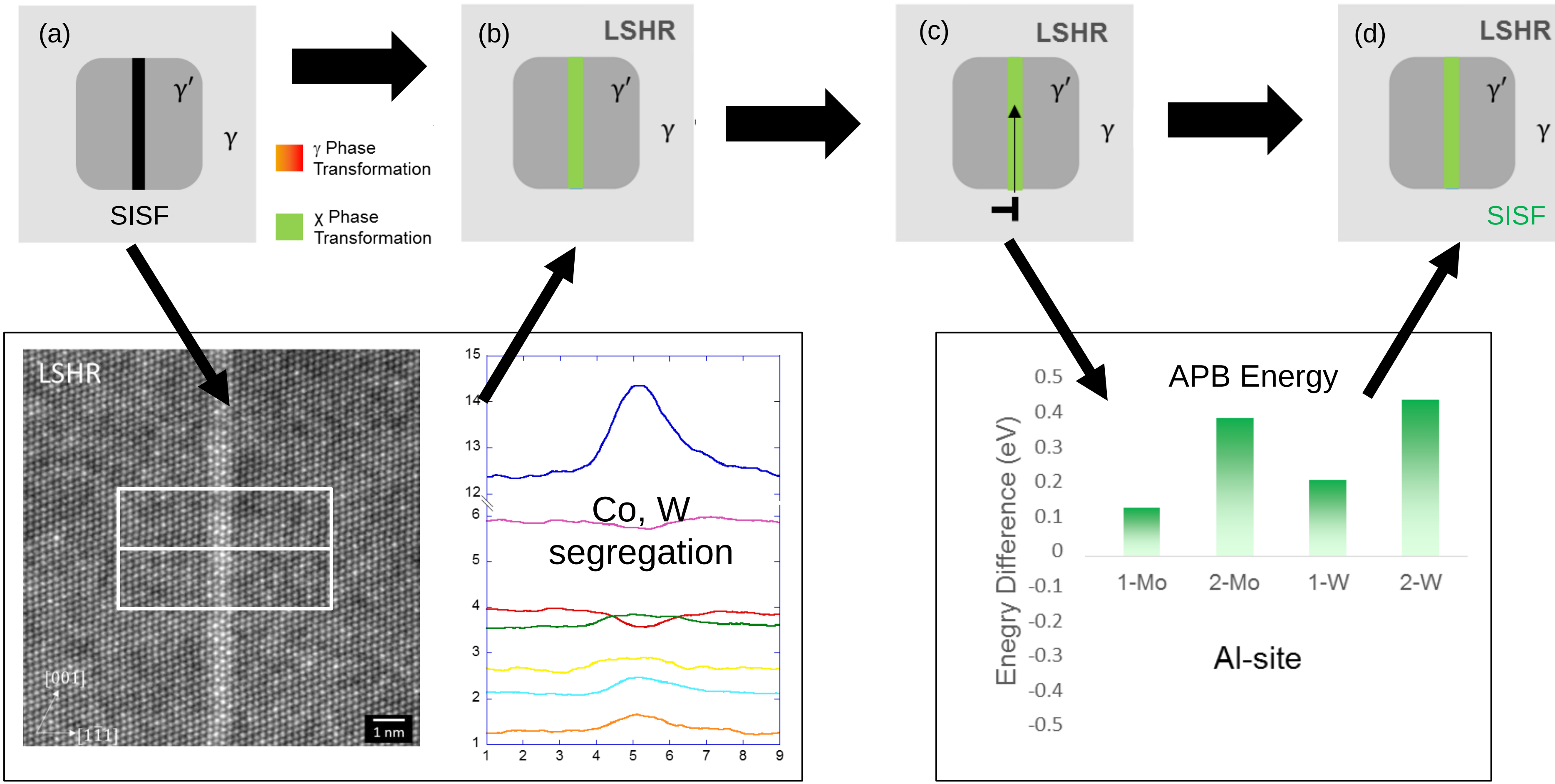
Relaxed energies were compared when a W, Mo, or Cr atom were away from the APB or on the APB.

Phase Transformation Softening – γ Phase



γ phase formation along SISF promotes stacking fault ribbon shear

Phase Transformation Strengthening – χ phase

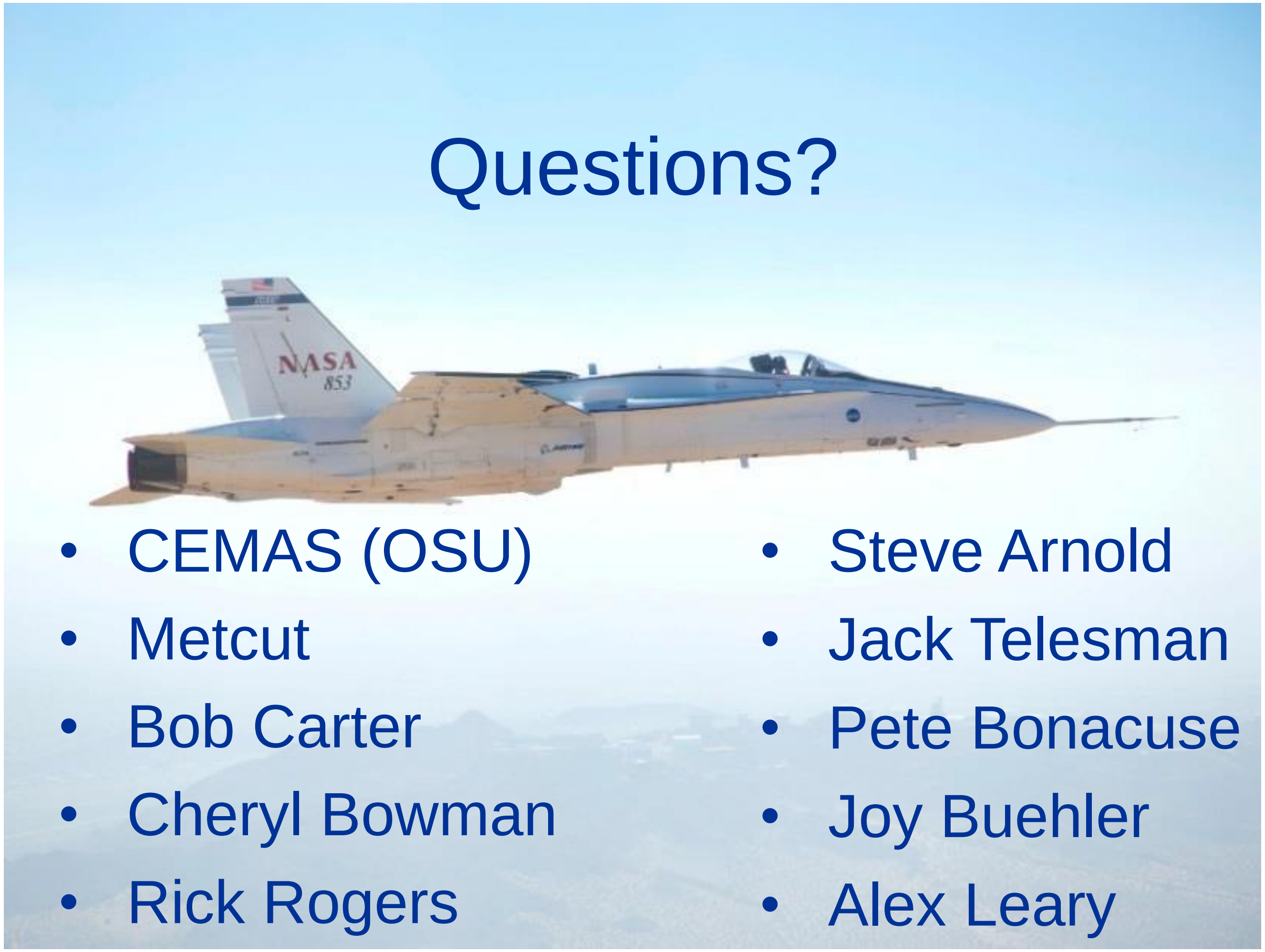


χ phase formation along SISF inhibits stacking fault ribbon shear

Conclusions

- Significant differences between ME3 and LSHR creep strain rates exist even though the microstructural differences between the two alloys are negligible.
- Slight differences in overall chemistry between the two alloys can result in notable differences in stacking fault segregation. LSHR displayed the formation of Co_3W χ phase along intrinsic stacking faults in γ′ precipitates. In contrast, ME3 displayed the formation of a Co and Cr-rich γ phase along the same fault type.
- This formation of the Co_3W phase along these intrinsic stacking faults represents a **novel phase transformation strengthening mechanism**, by inhibiting the shear of a<112> stacking fault ribbons.
- Alloy design is alive and aided by advanced characterization and modeling techniques.
- **Future work: Can the strengthening η and χ phase transformations be optimized and combined in future Ni-base disk alloy compositions?**

Acknowledgements



Questions?

- CEMAS (OSU)
- Metcut
- Bob Carter
- Cheryl Bowman
- Rick Rogers
- Steve Arnold
- Jack Telesman
- Pete Bonacuse
- Joy Buehler
- Alex Leary