THE UNIVERSITY of TENNESSEE KNOXVILLE

Experimental and Computational Investigation of High-Entropy Alloys (HEAs) for Elevated-Temperature Applications (FE-0008855)

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CompuTherm FOR MATERIALS DESIGN

AMES LABORATORY U. S. Department of Energy

ILLINOIS UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN

Acknowledgements

We are very grateful to:

- Vito Cedro
- Richard Dunst
- Jessica Mullen
- Patricia Rawls
- Robert Romanosky
- Susan Maley
- Regis Conrad
- Steven Markovich
- Nicholas Anderson

Financial supports of the research from:

National Energy Technology Laboratory (NETL) (DE-FE-0008855) with Mr. V. Cedro as the program manager

Collaborators

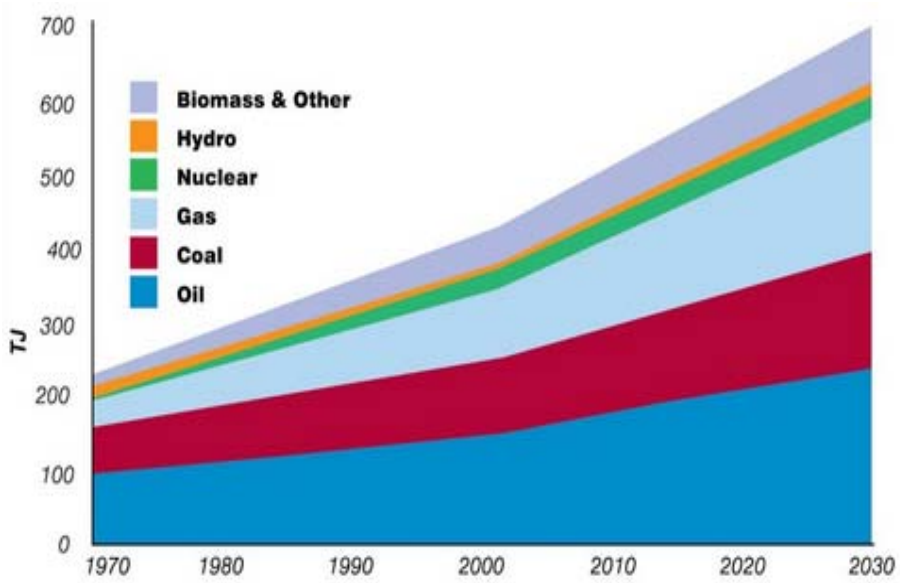
- Dr. Jonathan Poplawsky, Dr. Wei Guo, and Dr. Maikhail Feygenson, from Oak Ridge National Laboratory.
- Dr. Saurabh Kabra, Dr. Joe Kelleher, and Dr. Shuyan Zhang from the ISIS Pulsed Neutron and Muon Source at the Rutherford Appleton Laboratory, Didcot, UK.
- Group members at University of Tennessee, Knoxville

Outline of Presentation

- Background
  - ❑ High-entropy Alloys as Candidates for Fossil-energy Power Plants
- Research Plan
- Experimental Results and Discussion
  - – Microstructure
  - – Creep Behavior, Compared with Conventional Alloys
  - – In-situ Neutron-Diffraction Study of Creep Behavior
  - – Heat-treatment Effect
  - – Thermodynamic Calculations and Finite-element Modeling
- Conclusions

Background

Increase in Energy Demands and Environmental Issues



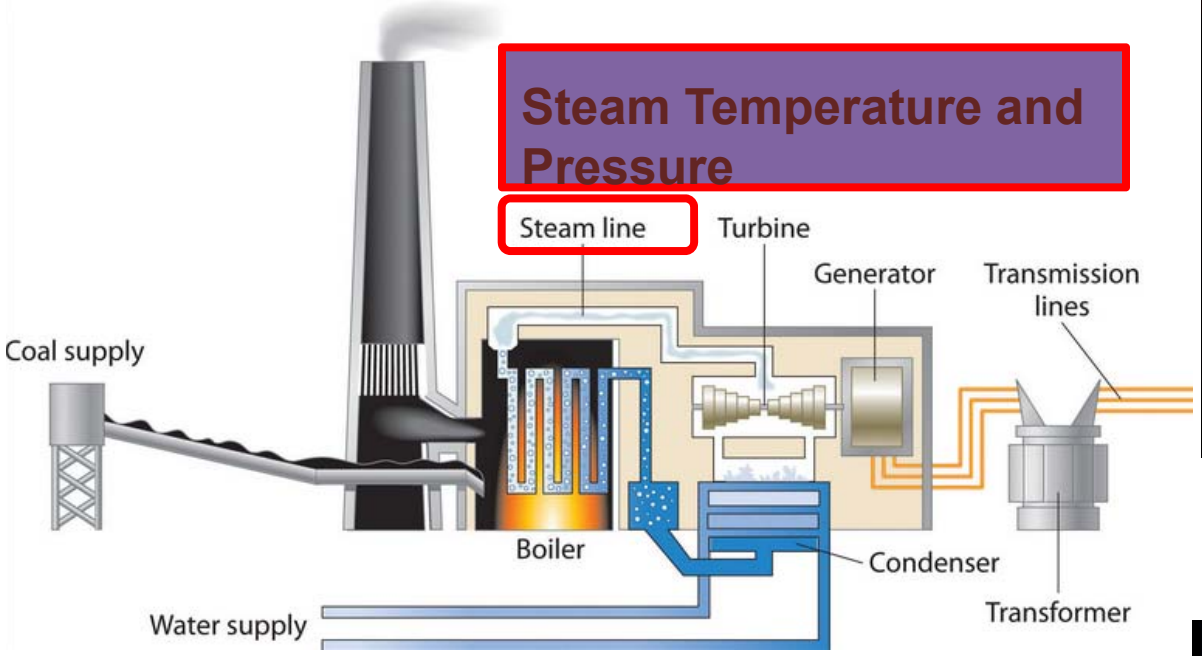
The terajoule (TJ) is equal to one trillion (10^{12}) Joules

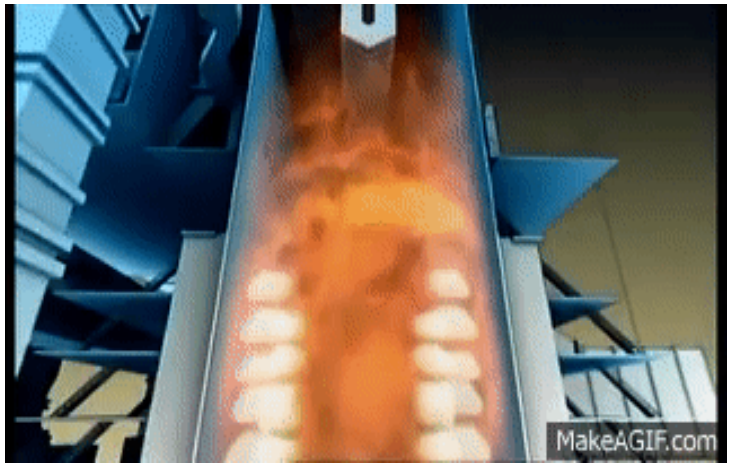
- **Fossil fuels are the most used energy source (84%) into the world, with oil accounting for 36%, coal 27%, natural gas 23% of global consumption**
- **United States Is World's Number One Fossil Fuel Subsidizer**

http://www.artinaid.com/2013/04/fossil-fuels/

http://thinkprogress.org/climate/2013/03/29/1791811/bombshell-imfstudy-united-sates-is-worlds-number-one-fossil-fuel-subsidizer/

Energy Efficiency of Power Plants

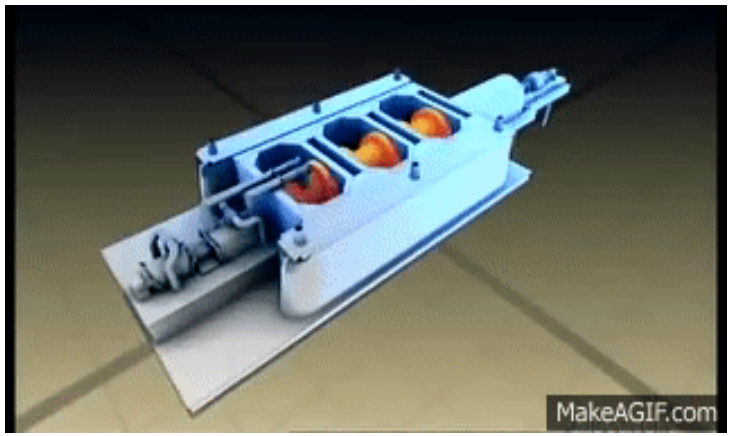




Coal powder is burned and heats the water to steam in the SS high pressure boiler tubes, which travel to the turbine

<u>Current condition</u>: 600 °C, 24 ~ 35 MPa.
<u>Expectation</u>: another 50 to 100 °C in next 20 to 30 years.

A major collaborative project in USA --- 760 °C and 35 MPa



***Coal Fired Power Plant*. Discovery Channel. N.d. *YouTube*. Web. 22 Jan. 2016. <https://www.youtube.com/watch?v=rEJKiUYjW1E>.**

Current Materials of Fossil-energy Power Plants

Material Types

- **Ferritic steels**

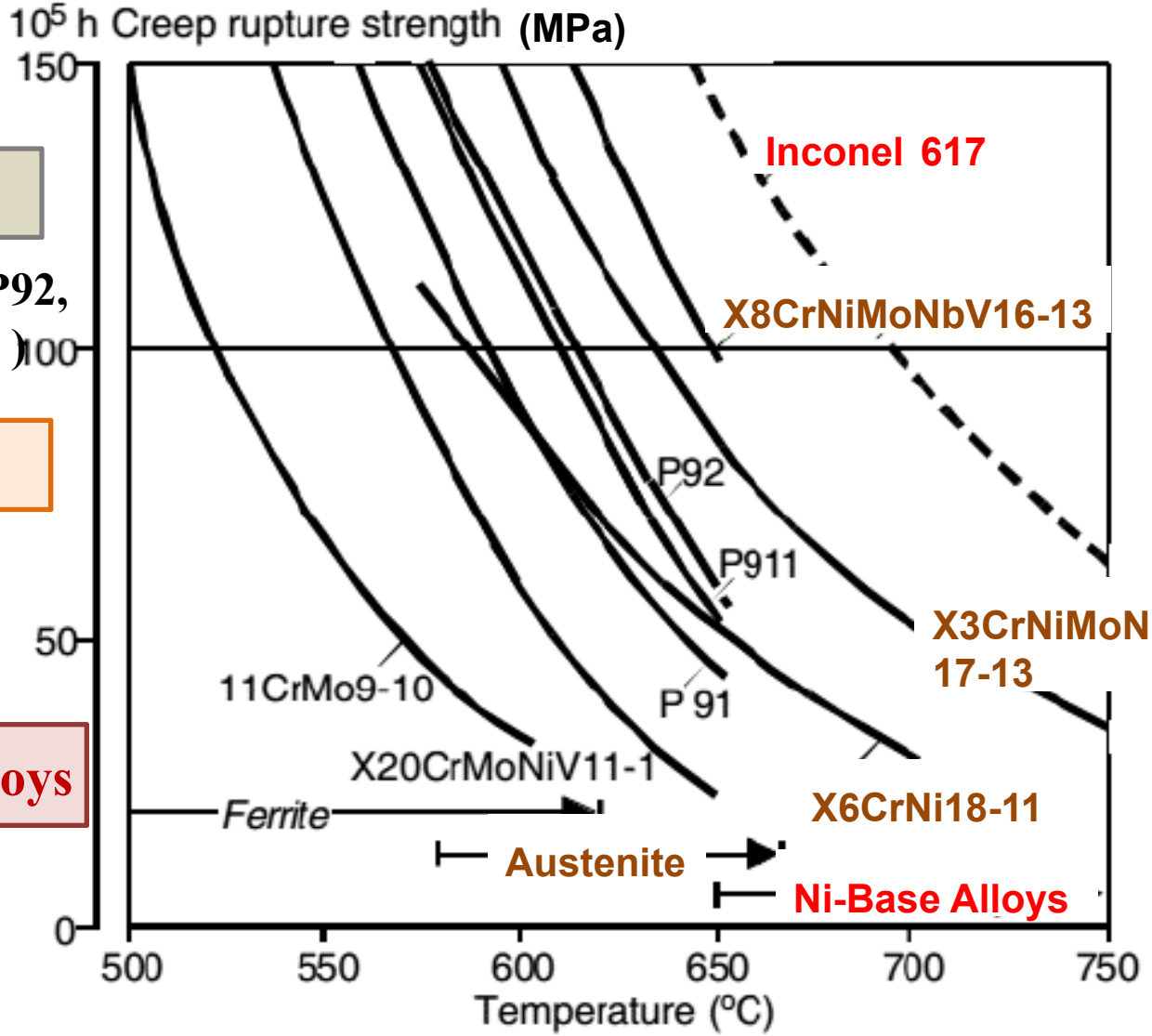
  (e.g., 11CrMo9-10, P91, P92, P911, X20CrMoNiV11-1,)

- **Austenitic steels**

  (e.g., X6CrNi18-11, X3CrNiMoN17-13, X8CrNiMoNbV16-13)

- **Nickel-based superalloys**

  (e.g., Inconel 617)



1. R.C. Reed, The Superalloys: Fundamentals and Applications. 2006, New York: Cambridge University Press.
2. I.V. Hagen and W. Bendick. Creep resistant ferritic steels for power plants. in Proceedings of the International Symposium on Niobium. 2001. Orlando, FL.
3. E. Nembach and G. Neite. Progress in Materials Science 1985; 29: 177.

High-entropy Alloys (HEAs) as New Candidates

HEAs: typically defined as **solid-solution alloys** that contain five or more principal elements in **near-equimolar ratios**, possessing a single structure rather than ordered phases, such as face-centered cubic (FCC), body-centered cubic (BCC), and hexagonal-close packed (HCP) structures.

Typical Types: (1) AlxCoCrCuFeNi; (2) CoCrFeMnNi; and (3) MoNbTaW

Characteristics:

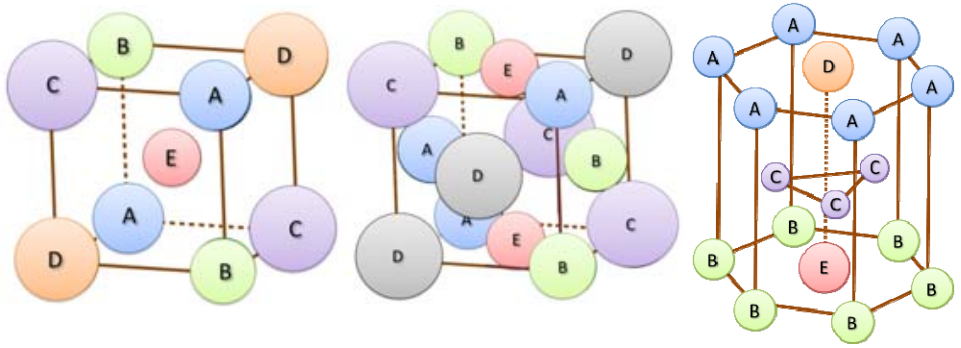
✓An identity crisis – 5 or more elements (no single element) dominates [5 atomic percent (at.%) - 35 at.%]

✓Relatively-high configurational entropy (influences stability)

✓Relatively-large lattice strains (influences strength and stability)

"Metal Buffet"

Chemically-disordered but structurally-ordered alloys



(a) BCC **(b) FCC** **(c) HCP**

1. J. W. Yeh, S. K. Chen, S. J. Lin, J. Y. Gan, T. S. Chin, T. T. Shun, C. H. Tsau, and S. Y. Chang, Advanced Engineering Materials 6, 299 (2004).
2. B. Cantor, I. T. H. Chang, P. Knight, and A. J. B. Vincent, Materials Science and Engineering A 375-377, 213 (2004).
3. Y. Zhang, T. T. Zuo, Z. Tang, M. C. Gao, K. A. Dahmen, P. K. Liaw, and Z. P. Lu, Progress in Materials Science 61, 1 (2014).
4. K. M. Youssef, A. J. Zaddach, C. Niu, D. L. Irving, and C. C. Koch. Materials Research Letters, 1-5 (2014).
5. P. D. Jablonski, J. J. Licavoli, M. C. Gao, and J. A. Hawk, JOM 67, 2278-2287 (2015).

High-entropy Alloys (HEAs)

- From the thermodynamic aspect, the Boltzmann hypothesis with the entropy of mixing ΔS_{conf}

$$\Delta S_{conf} = k_B \cdot \ln(\Omega) \xrightarrow{equimolar} \frac{R}{N_A} \ln(N)^{N_A} = R \cdot \ln(N)$$

k_B: Boltzmann's constant, Ω: Number of ways of mixing; R: Gas Constant;

N: Number of elements; N_A: Avogadro constant

- The Gibbs free energy

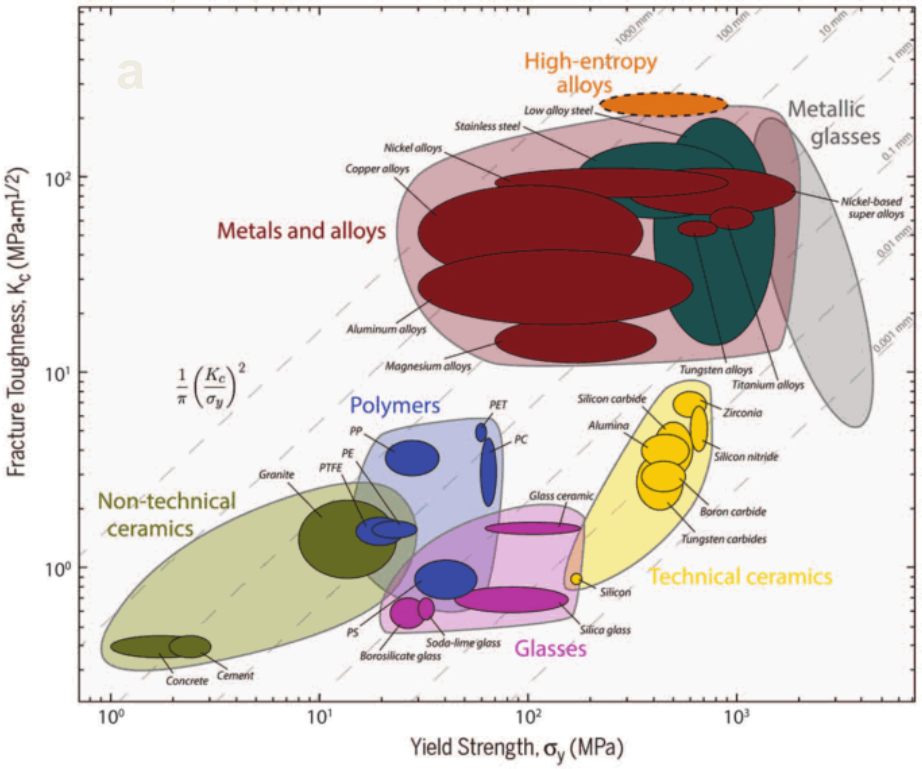
$$\Delta G_{mix} = \Delta H_{mix} - T\Delta S_{mix}$$

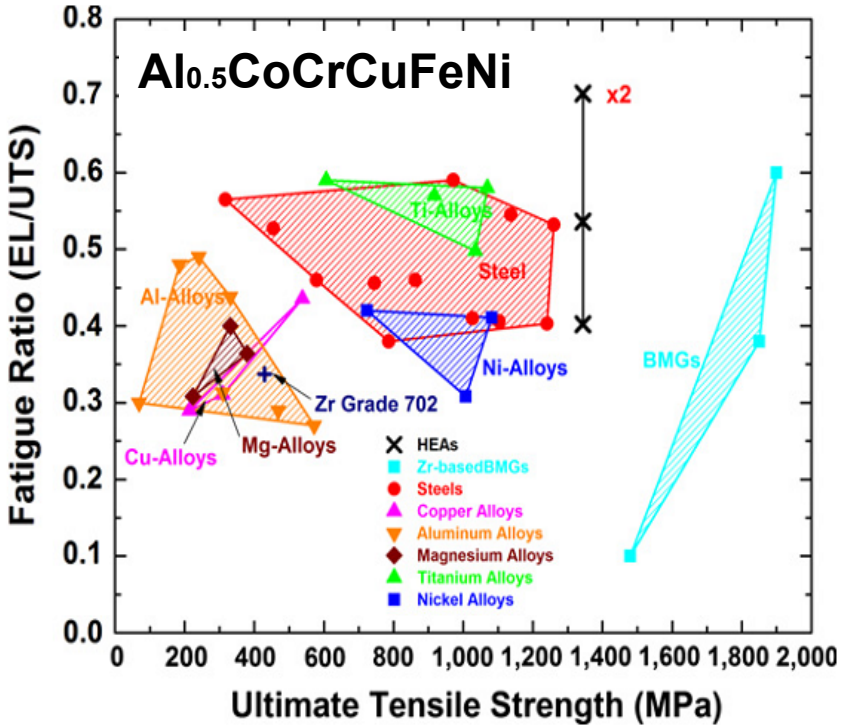
ΔHmix : Enthalpy of mixing, and T : Temperature

- ΔG_{mix} could be very small especially at high temperatures, which implies that **the multicomponent disordered solid-solution phases can be more stable than the mixing of the complex-ordered phases**, like intermetallic compounds.

1. **J. W. Yeh, S. K. Chen, S. J. Lin, J. Y. Gan, T. S. Chin, T. T. Shun, C. H. Tsau, and S. Y. Chang, Advanced Engineering Materials 6, 299 (2004).**
2. **Y. Zhang, T. T. Zuo, Z. Tang, M. C. Gao, K. A. Dahmen, P. K. Liaw, and Z. P. Lu, Progress in Materials Science 61, 1 (2014).**

Comparison with other materials





Good Fracture Toughness at 77 K of CoCrFeMnNi

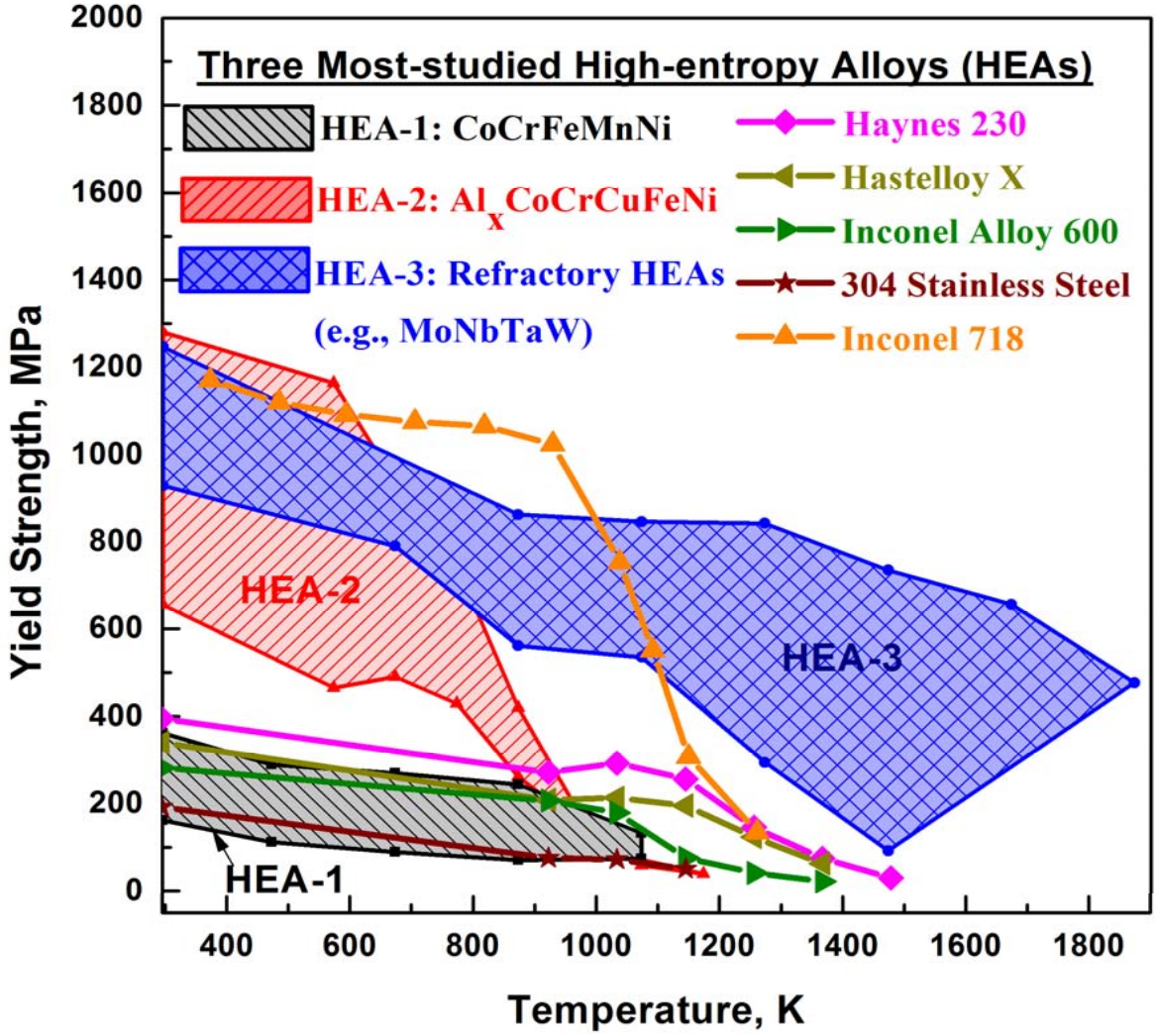
Good Fatigue Resistance of Al0.5CoCrCuFeNi

EL: Fatigue-Endurance Limit UTS: Ultimate Tensile Strength

1. B. Gludovatz, A. Hohenwarter, D. Catoor, E. H. Chang, E. P. George, and R. O. Ritchie, Science, 2014, 345(6201), pp. 1153-8.
2. M. A. Hemphill, T. Yuan, G. Y. Wang, J. W. Yeh, C. W. Tsai, A. Chuang, and P. K. Liaw, Acta Materialia 60, 5723 (2012).

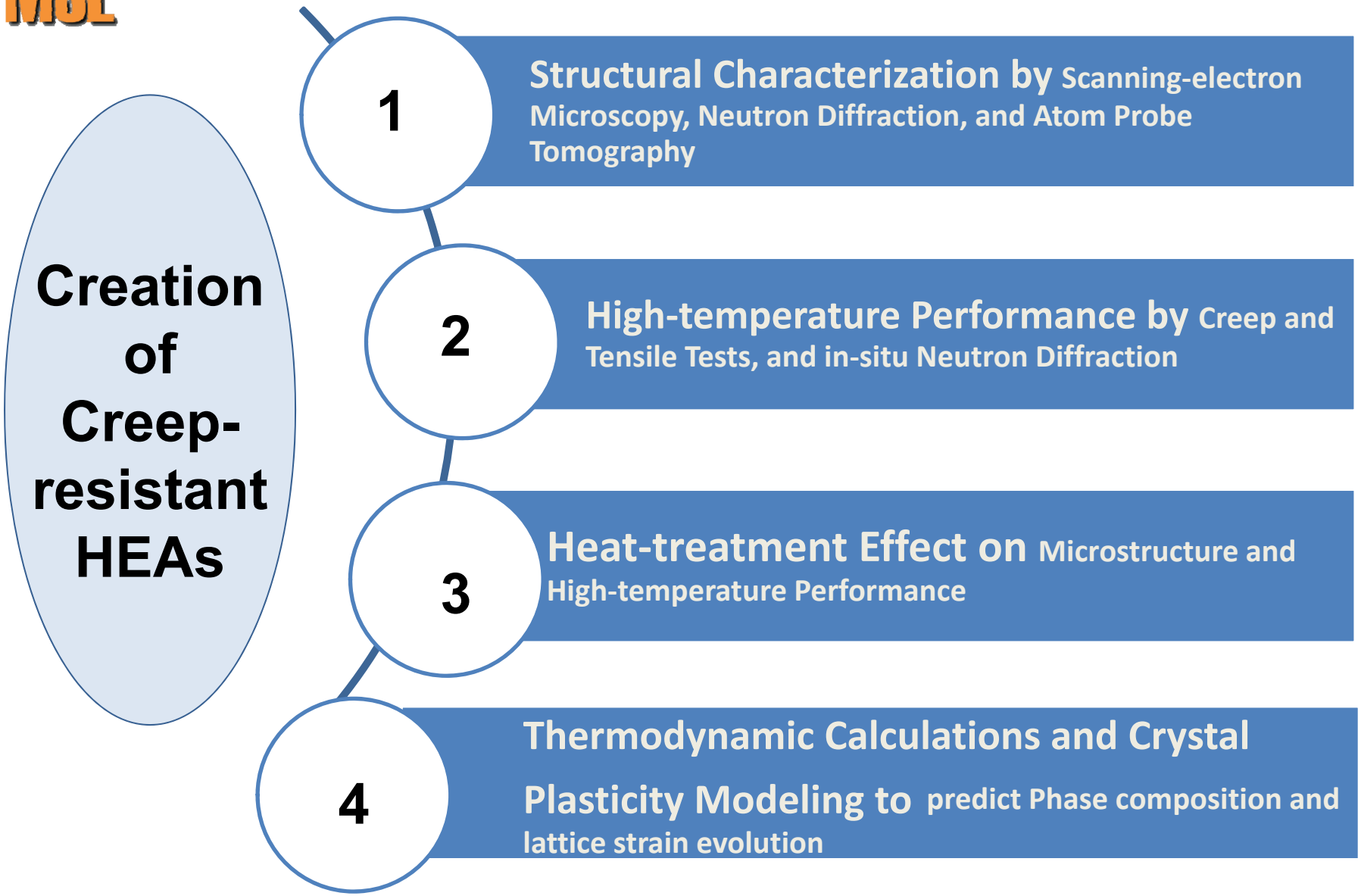
Comparison with other materials

Good High-temperature Properties



1. H. Diao, X. Xie, R. Feng, B. Chen, C. Zhang, F. Zhang, K. A. Dahmen, and P. K. Liaw, "Mechanical Behavior of Single-phase High-entropy Alloys (HEAs): An overview", in preparation.

Research Plan



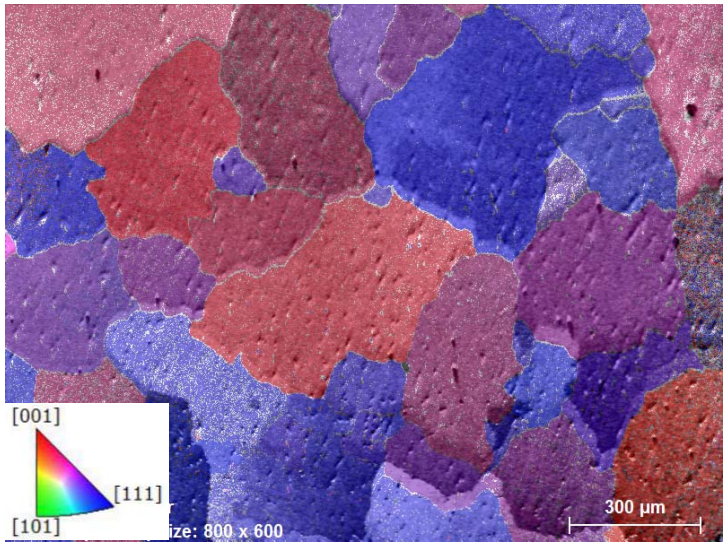
Experimental Results and Discussion

Material Processing

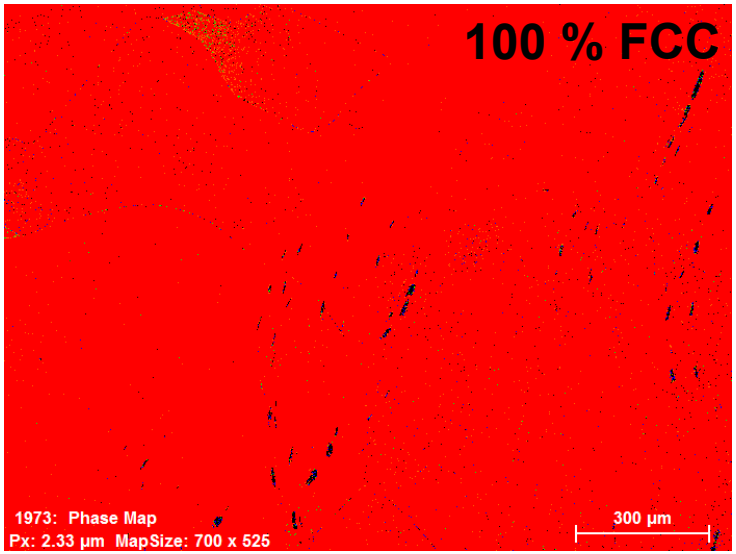
- Composition: 6.98Al-23.26Co-23.26Cr-23.26Fe-23.26Ni (atomic percentage)
- Fabrication: Sophisticated Alloys Inc.
- Condition:
  - **Single-phase Al0.3CoCrFeNi:** was fabricated by vacuum-induction melting to cast a plate of ~ 127 mm x 305 mm x 19 mm. Then the specimen has undergone the hot-isostatic-pressing (HIP) process at 1,204 C and 103 MPa for 4 hours.
  - **(FCC+B2) Al0.3CoCrFeNi:** quartz-tubed with the triple-pumped argon and undergoes the homogenization treatment at 700 C for 500 hours.

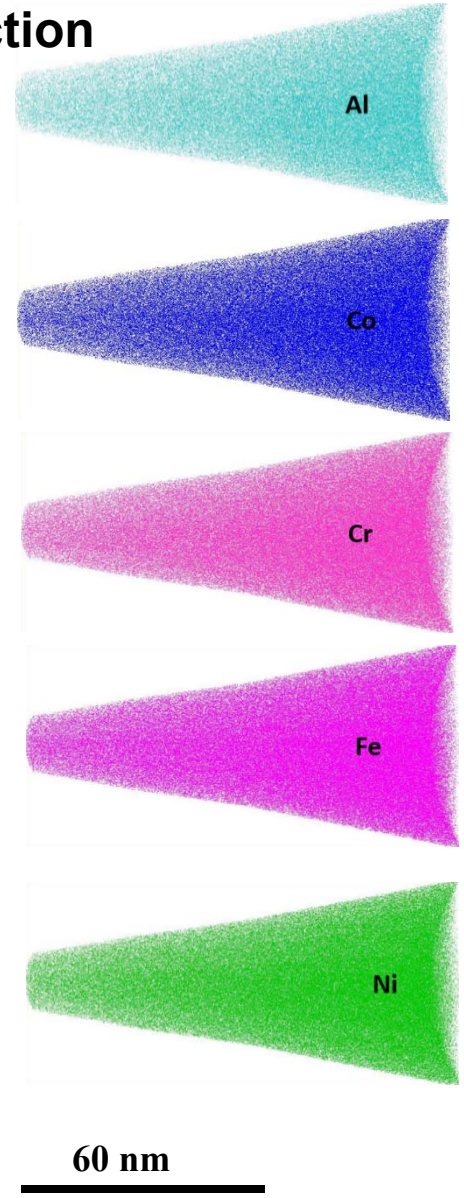
Single-phase $Al_{0.3}CoCrFeNi$

(a) Electron Backscatter Diffraction (EBSD) Characterization

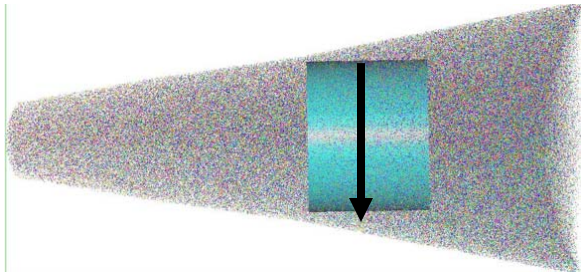


(b) Phase Map

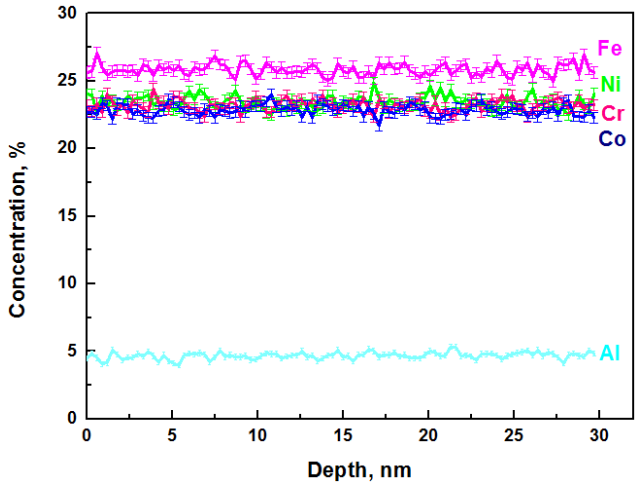




Face-centered cubic (FCC)



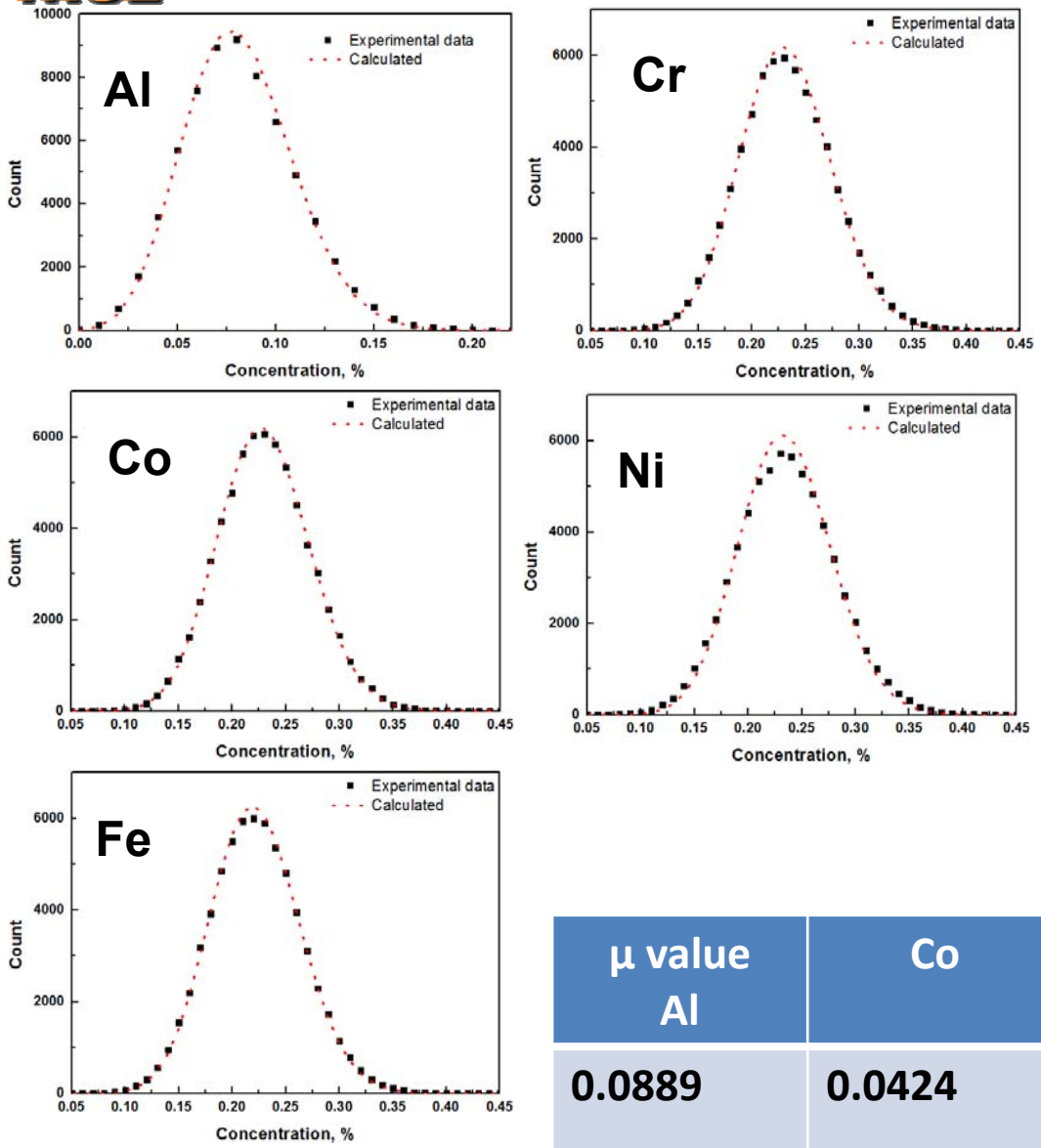
All ions



Homogeneous single-phase HEA

Grain size > 200 µm

Frequency Distribution of Atomic Clusters



Classic binomial-frequency distribution, f (n)

$$f(n) = \binom{n}{k} p^k (1-p)^{n-k}$$

where n is number of solute atoms

The normalized χ^2 statistics

$$\chi^2 = \sum_{n=0}^{N} \frac{(e(n) - f(n))^2}{f(n)}$$

e(n) is the number of blocks containing n solute atoms in the experimental data

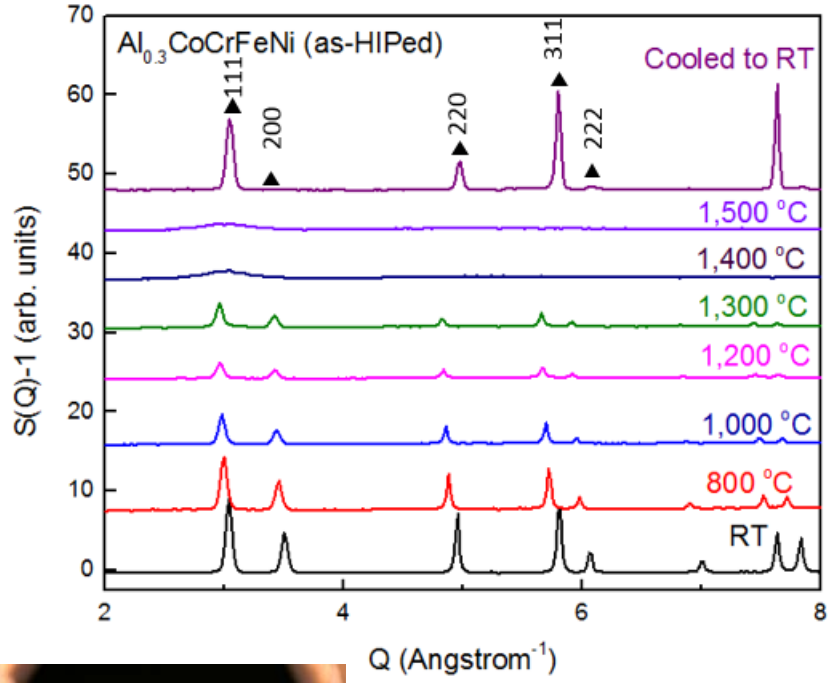
$$0 \le \mu = \sqrt{\frac{\chi^2}{N + \chi^2}} \le 1$$

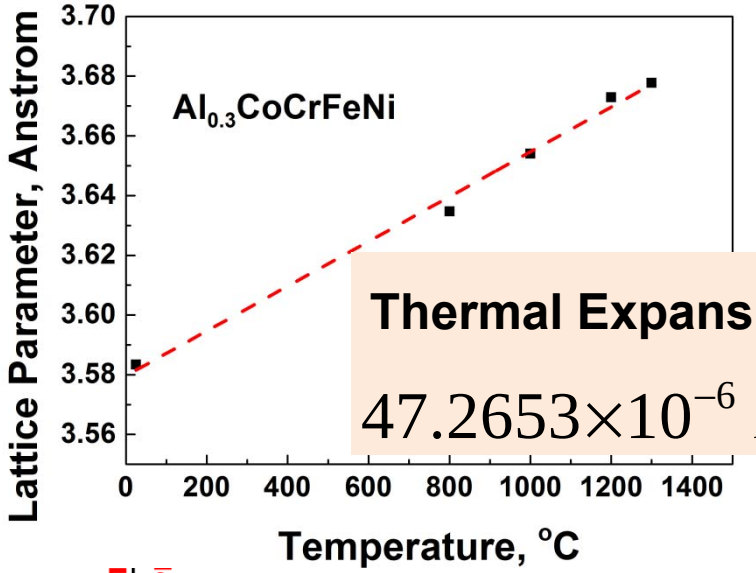
μ value Al	Co	Cr	Fe	Ni
0.0889	0.0424	0.0667	0.0561	0.1303

1. M. P. Moody, L. T. Stephenson, A. V. Ceguerra, and S. P. Ringer, Microscopy Research and Technique, Vol. 71, No. 7, pp. 542-550 (2008).

Phase Stability at High Temperatures

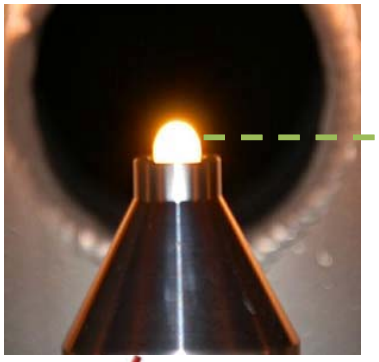
In-situ Neutron Levitation Results from the Spallation Neutron Source, ORNL



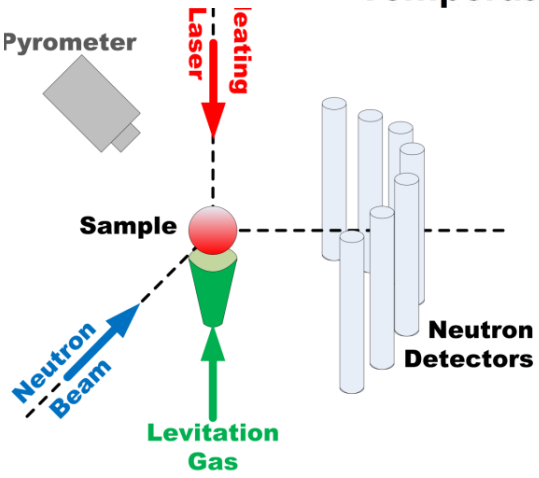


Thermal Expansion:

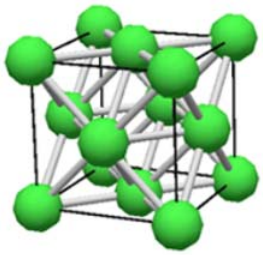
$$47.2653\times10^{-6}\ \dot{A}/K$$



Liquid metal droplet



Pure FCC phase

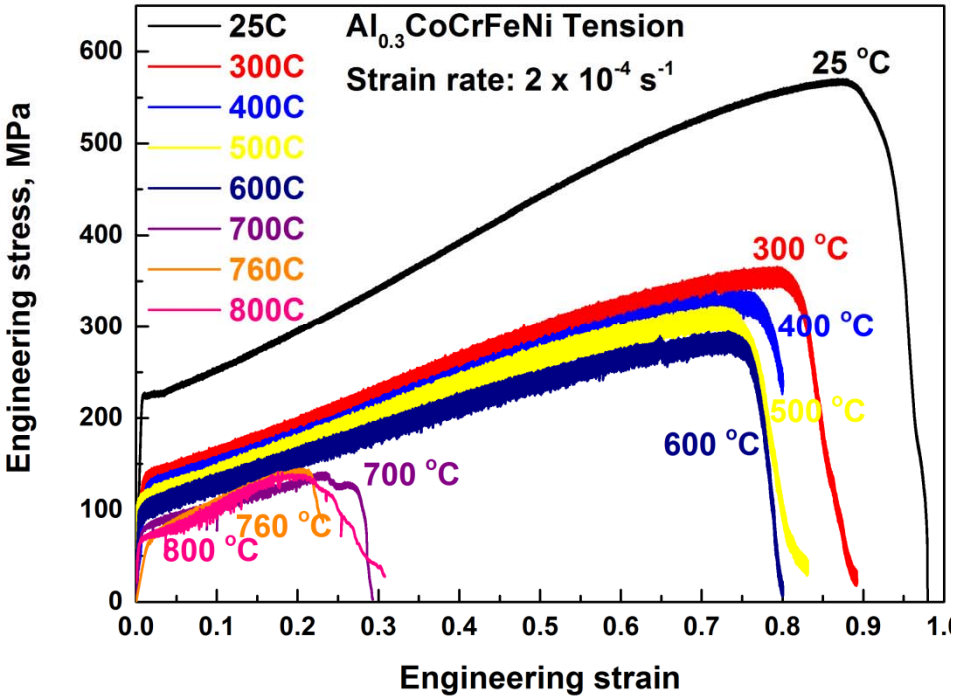


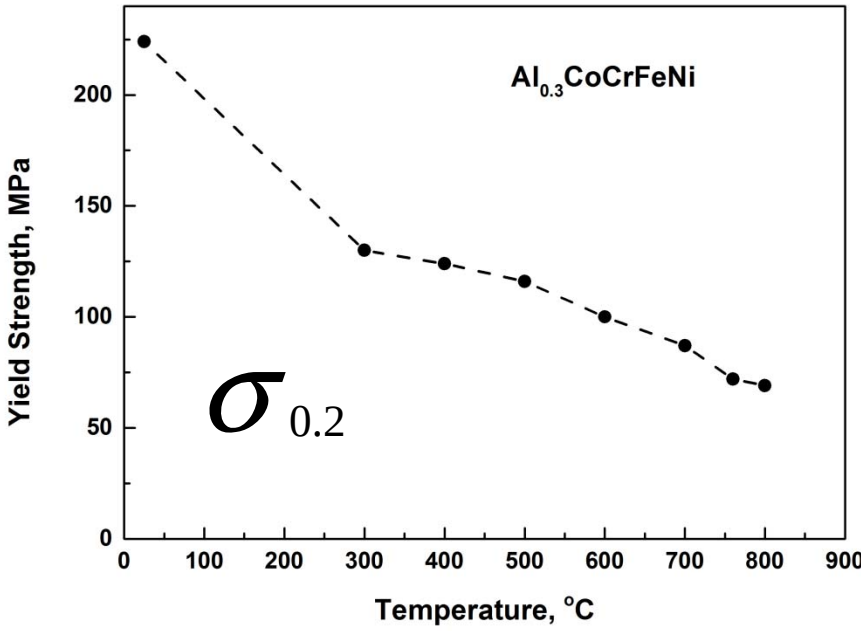
FCC_A1

The Nanoscale-Ordered Materials Diffractometer (NOMAD)

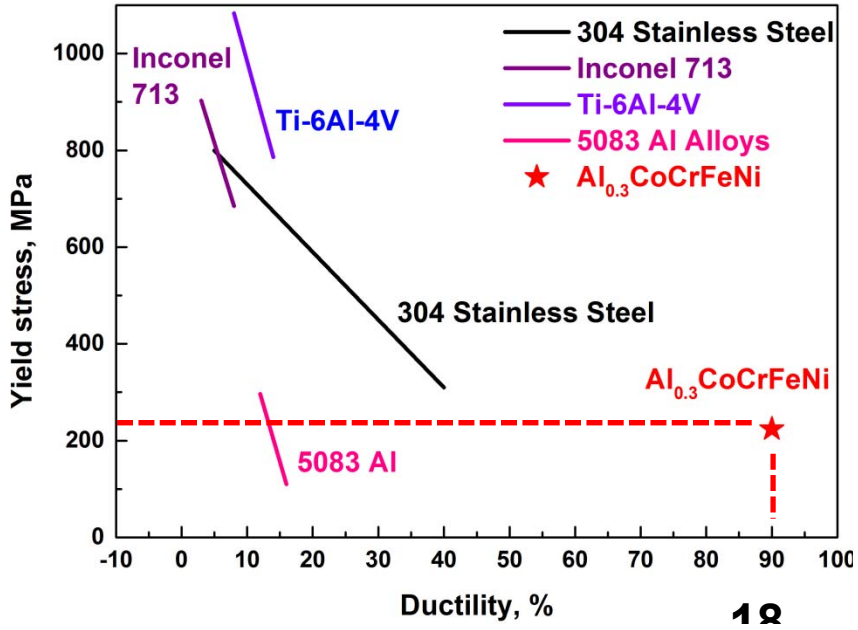
1. L. J. Santodonato, Y. Zhang, M. Feygenson, C. M. Parish, M. C. Gao, R. J. Weber, J. C. Neuefeind, Z. Tang, and P. K. Liaw, Nature Communications, Vol. 6, p. 5964 (2015).

Mechanical Behavior





The yield strength of Al0.3CoCrFeNi is comparable to Al alloys and stainless steels. However, the ductility is remarkably high.

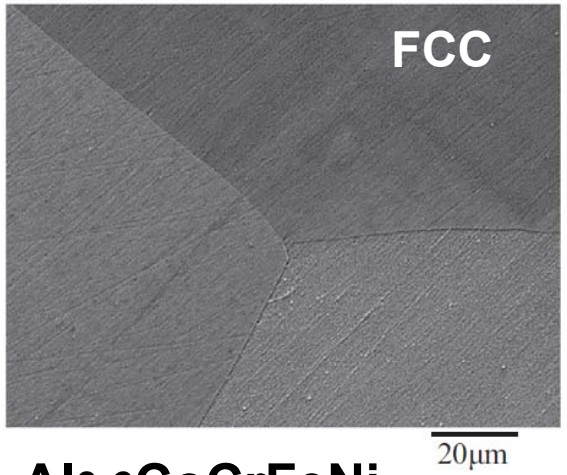


Creep Behavior of HEAs

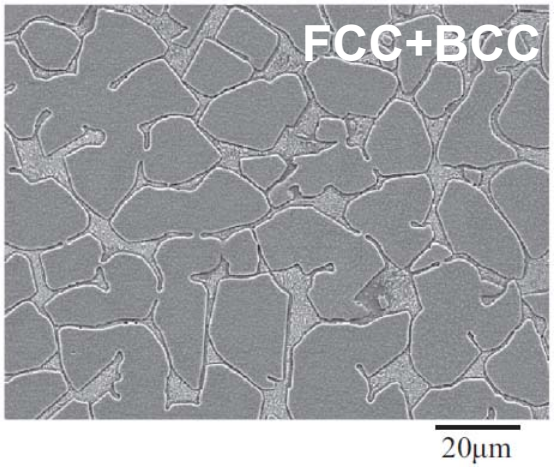
Creep Behavior of HEAs

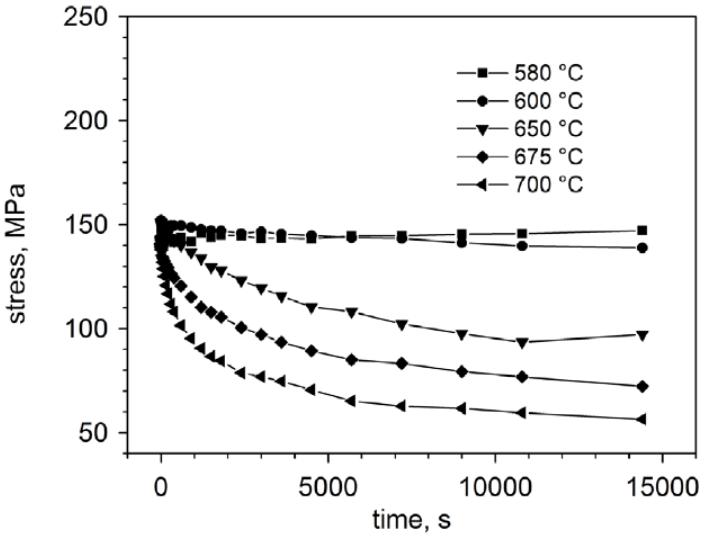
Stress Relaxation Test (SRT)

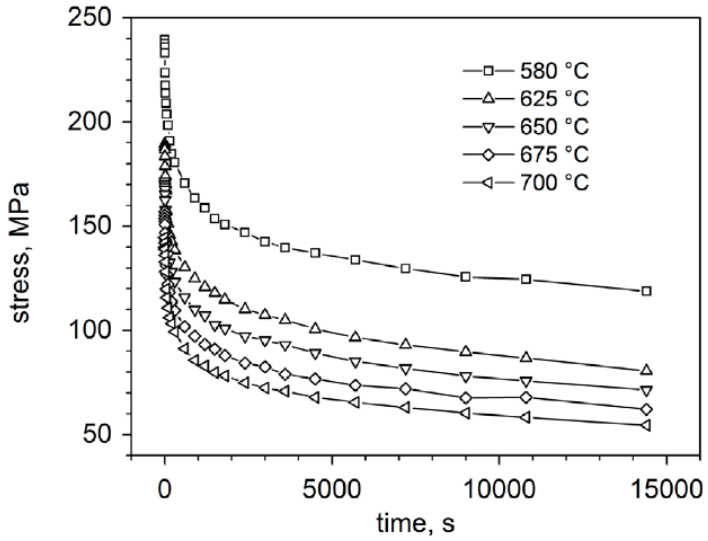
$Al_{0.15}CoCrFeNi$

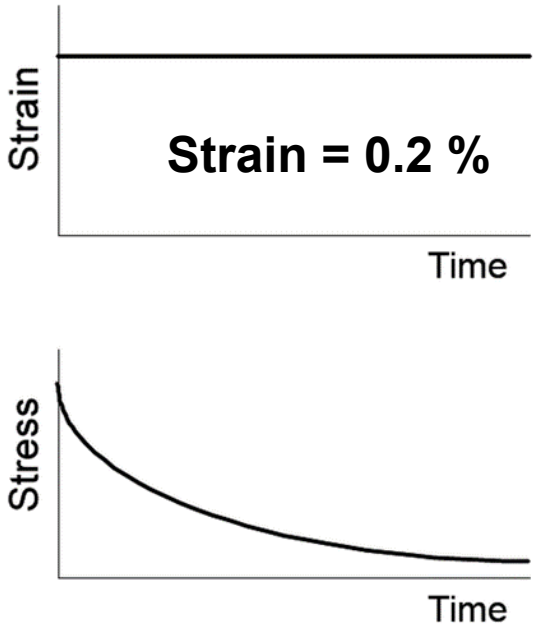


$Al_{0.6}CoCrFeNi$









1. T. Cao, J. Shang, J. Zhao, C. Cheng, R. Wang, and H. Wang, Materials Letters, Vol. 164, No., pp. 344-347 (2016).

Creep Behavior of HEAs

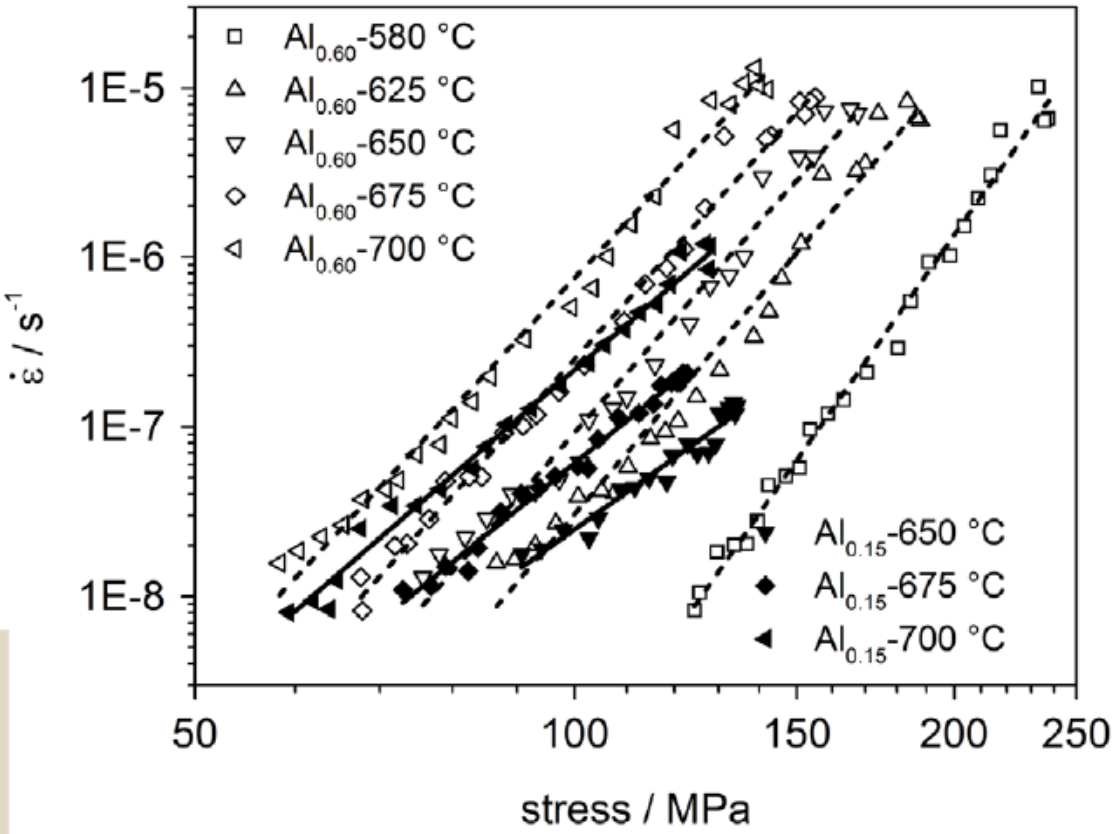
Stress Relaxation Test (SRT)

During SRT, creep rate

$$\dot{\varepsilon}_c = -\dot{\varepsilon}_e = -\frac{1}{E} \times \frac{d\sigma}{dt}$$

where $\dot{\varepsilon}_c$ is creep rate; $\dot{\varepsilon}_e$ is elastic deformation rate;

Stress; t : Test time; E : Elastic modulus.



The apparent stress exponent (n_{app}) is measured, using the Power law,

$$\dot{\varepsilon} = A\sigma^{n_{app}} \exp(-Q/RT)$$

Where $\dot{\varepsilon}$ is the steady-state strain rate, A is a constant, and σ is the applied stress

Al0.15 displays a lower creep rate than that of Al0.6 alloy under the same stress, resulting from the lower stacking fault energy.

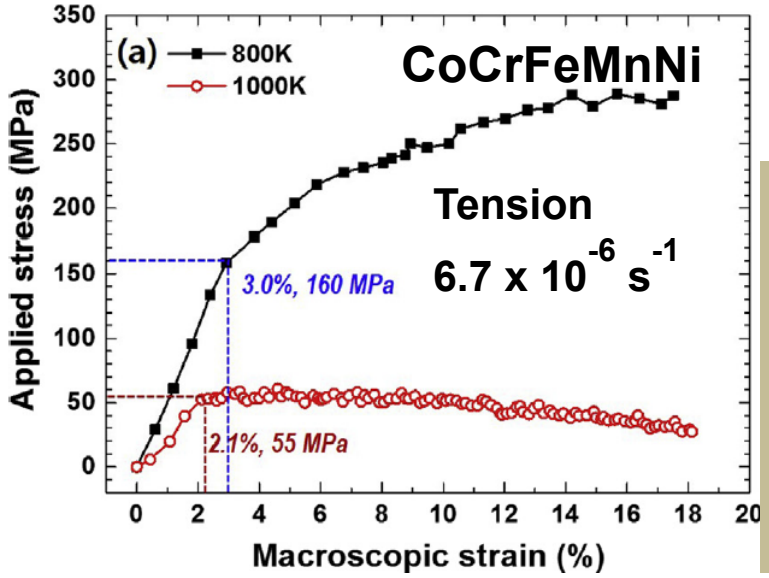
Al0.15: n = 4.98 - 6.03. Al0.60: n = 7.98 - 10.63.

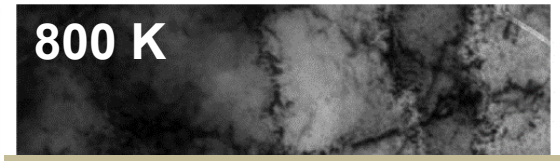
Dislocation cross-slip mechanism

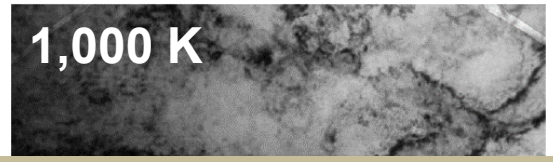
1. T. Cao, J. Shang, J. Zhao, C. Cheng, R. Wang, and H. Wang, Materials Letters, Vol. 164, No., pp. 344-347 (2016).

Creep Behavior of HEAs

Pseudo-creep deformation using in-situ neutron diffraction

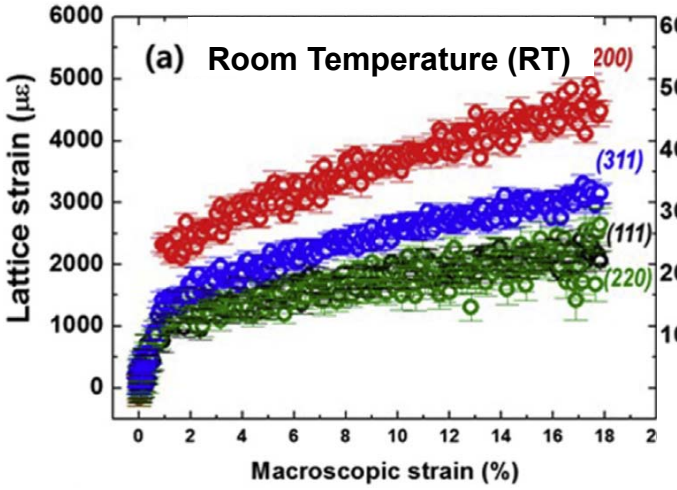


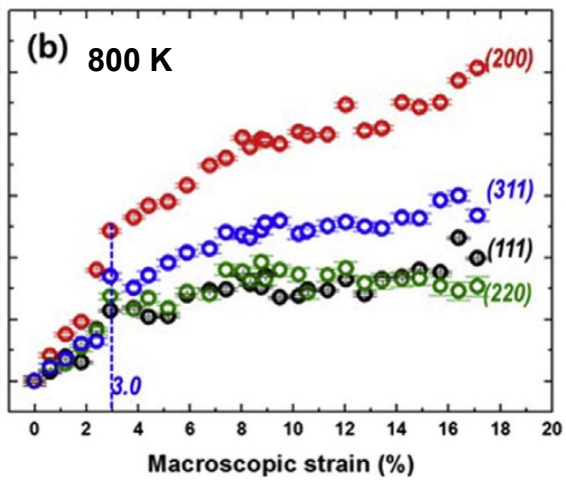


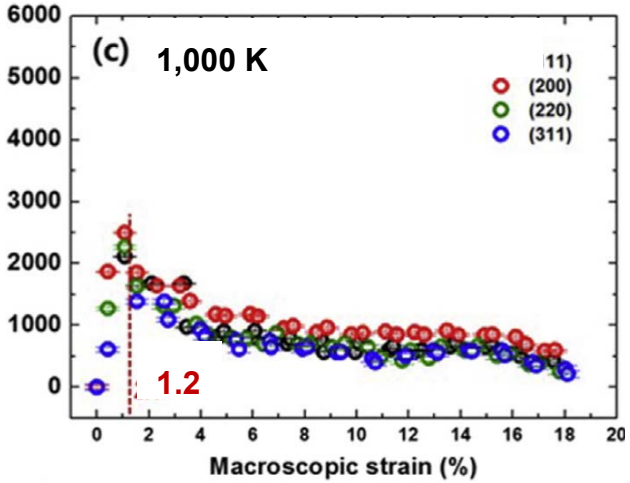


RT and 800 K, development of the dislocation substructures during plastic deformation;

1000 K, dislocation cell structure was not clearly observed, a structural relaxation.



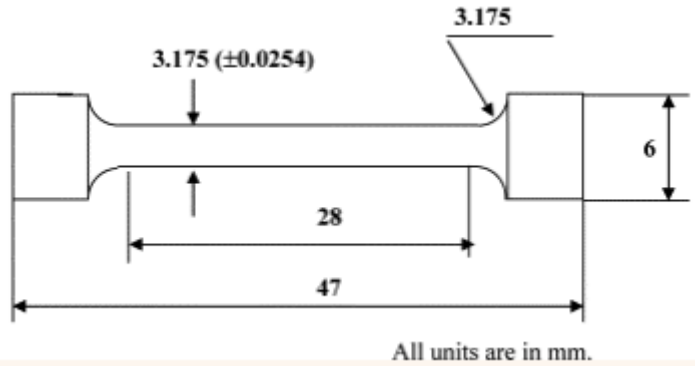


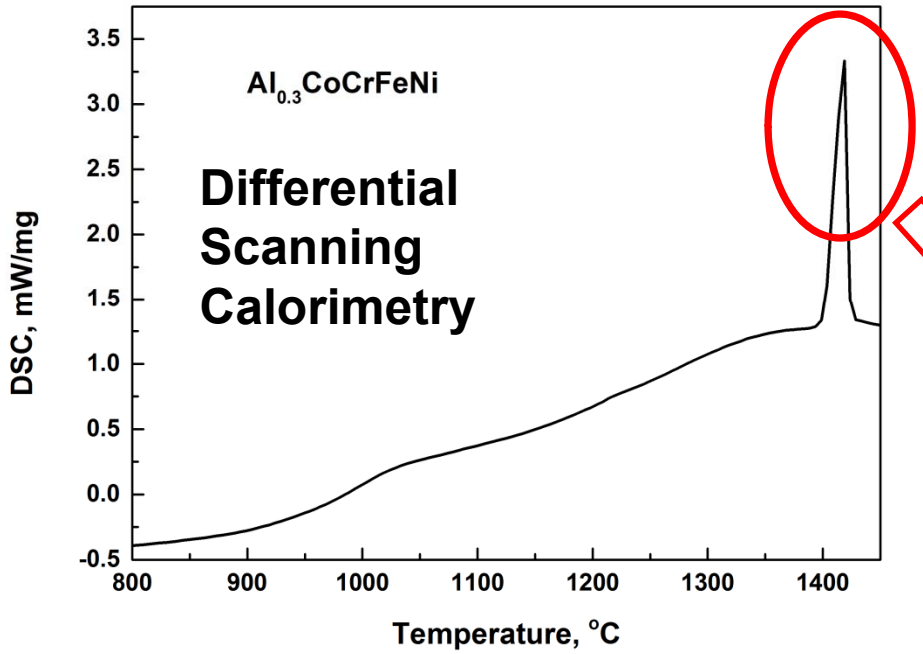


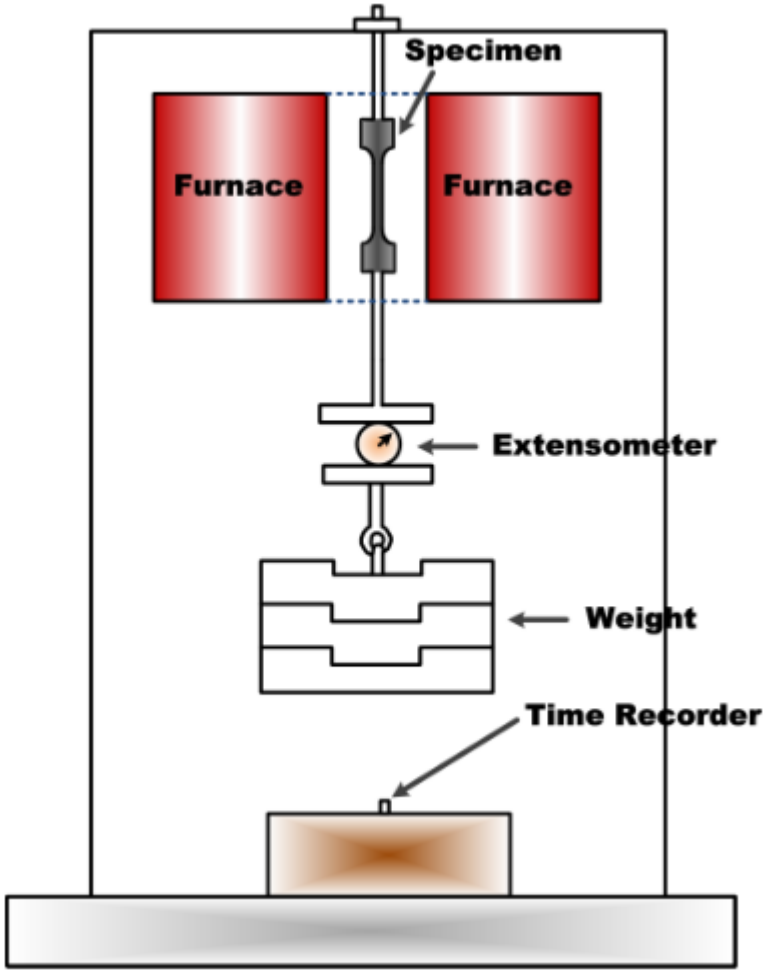
1. W. Woo, E. W. Huang, J.-W. Yeh, H. Choo, C. Lee, and S.-Y. Tu, Intermetallics, Vol. 62, No., pp. 1-6 (2015).

Study of Creep Behavi

Alloy: $Al_{0.3}CoCrFeNi$





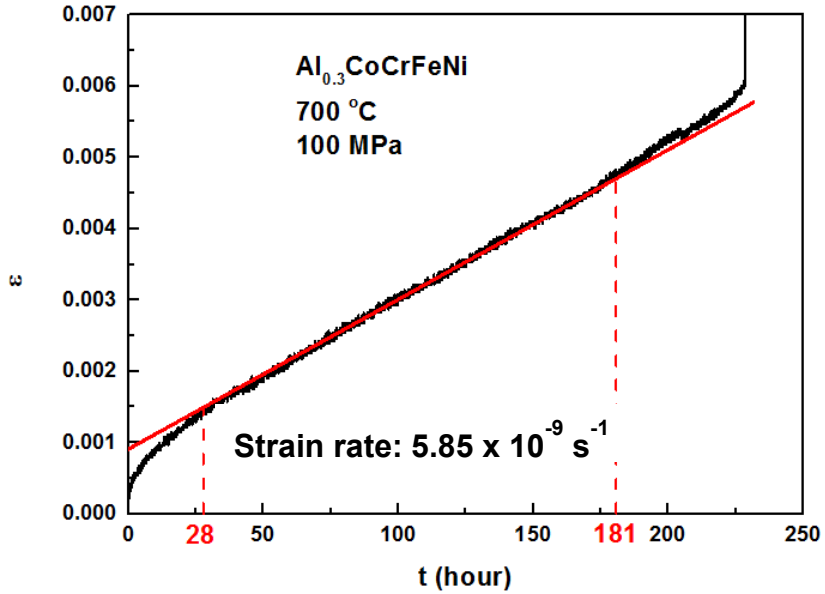


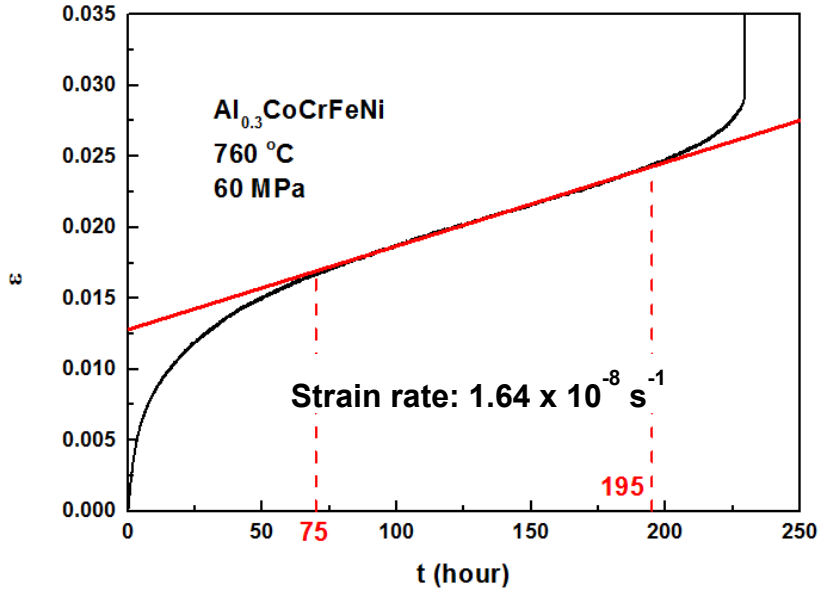
Melting Temperature : 1,401 °C

$$T \approx 0.5 \times T_m = 700^o C$$

Study of Creep Behavior

Conventional creep test at 700 - 760 °C in the stress of 40 - 120 MPa





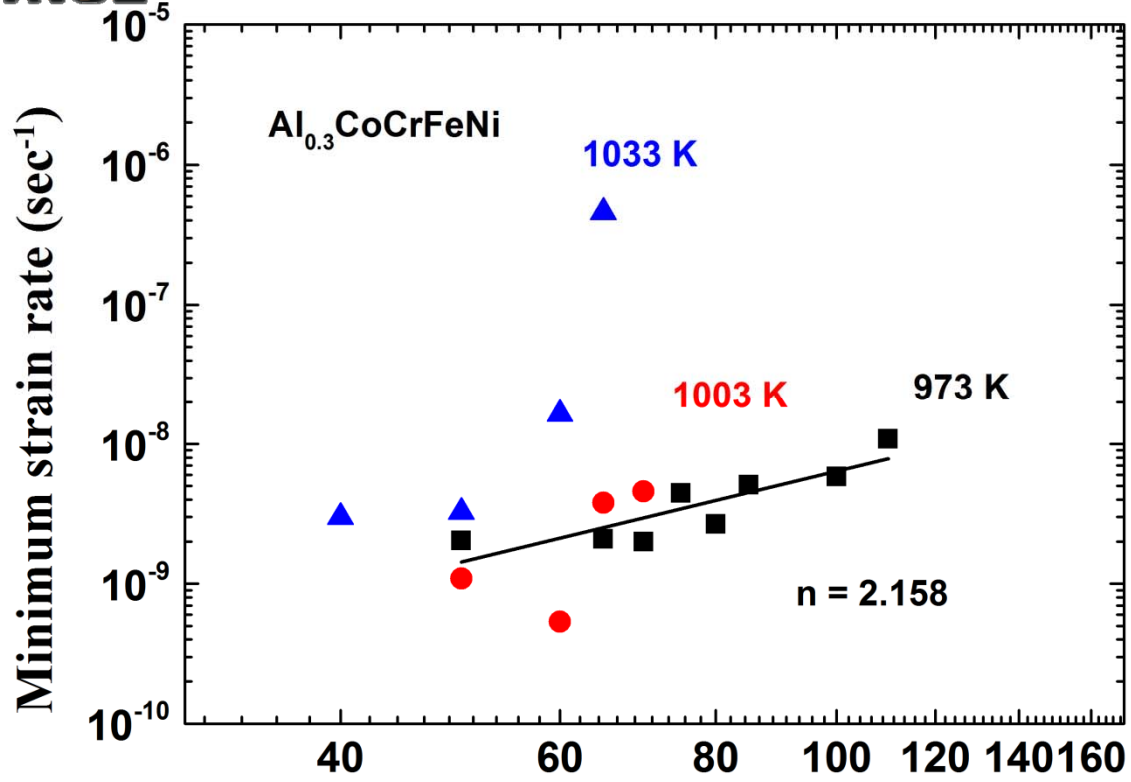
The steady-state creep-rate is calculated,

$$\dot{\varepsilon} = \frac{d\varepsilon}{dt}$$

where $\dot{\varepsilon}$ is the steady-state strain rate, ε is strain, and t is time

- ❑ **Typical three stage creep behavior is observed.**
- **Stage 1: the material experiences hardening through changes in the dislocation substructure**
- **Stage 2: hardening is balanced by dynamic recovery (e.g., dislocation annihilation)**
- **Stage 3: creep fracture**

Study of Creep Behavior



The apparent stress exponent (n_{app}) is measured, using the Power law,

$$\dot{\varepsilon} = A\sigma^{n_{app}} \exp(-Q/RT)$$

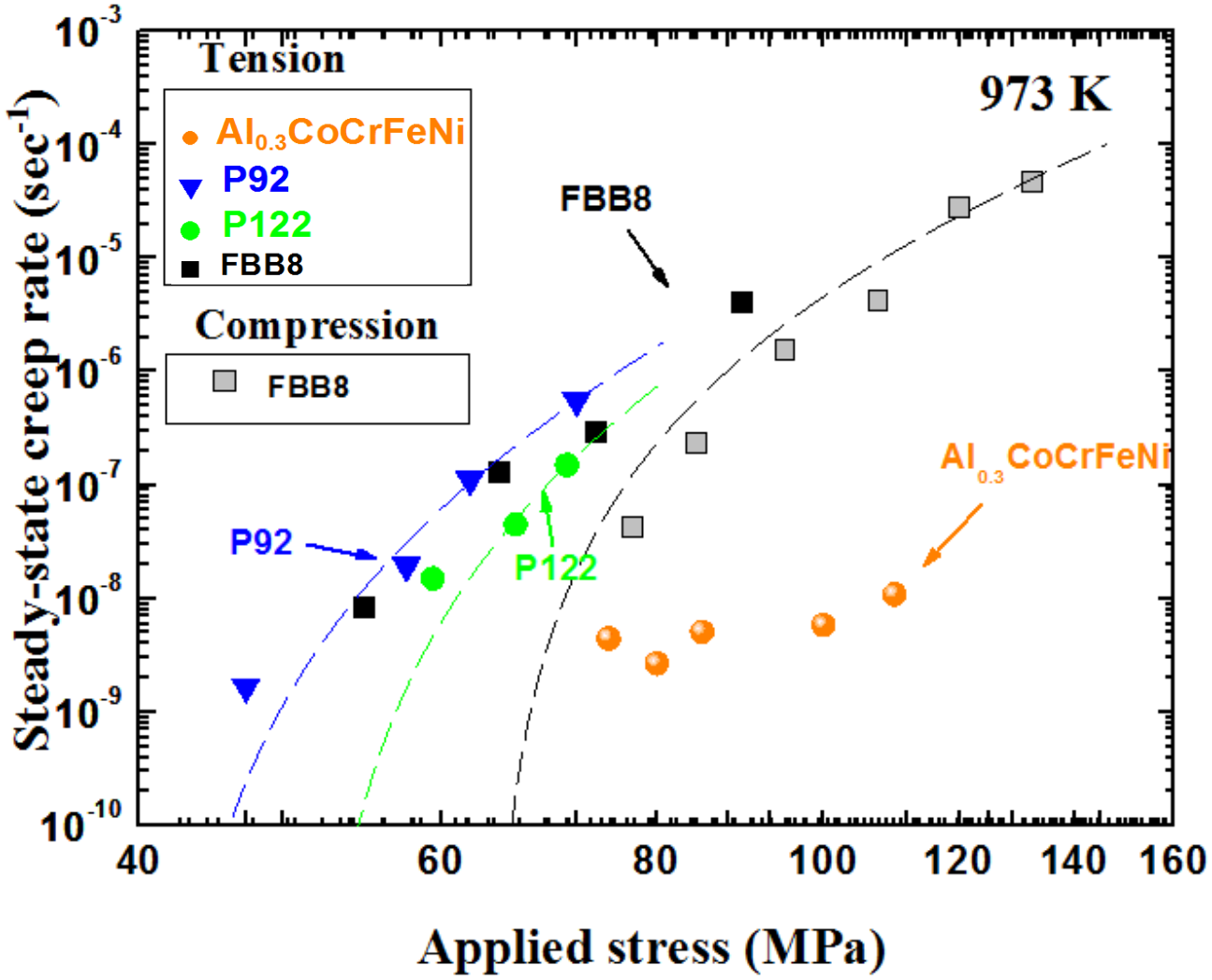
where $\dot{\varepsilon}$ is the steady-state strain rate, A is a constant, Q is activation energy, and σ is the applied stress.

Different deformation mechanisms and the associated ductility

n value	*m* value	Mechanism	expected elongation
n = 1	*m* = 1	Diffusional creep	unlimited
n = 2	*m* = 0.5	Grain-boundary sliding	300%< e <8,000%
n = 3	*m* = 0.33	Viscous dislocation glide	50%< e<300%
n = 4	*m* = 0.25	Dislocation climb	e <50%
n > 5, ...	*m* < 0.2	Particle strengthening	e <10%

- The value of n_{app} is around 2.158, which is lower than the pure metals (4 - 7).
- Creep mechanism is dislocation glide

Study of Creep Behavior



Chemical compositions:

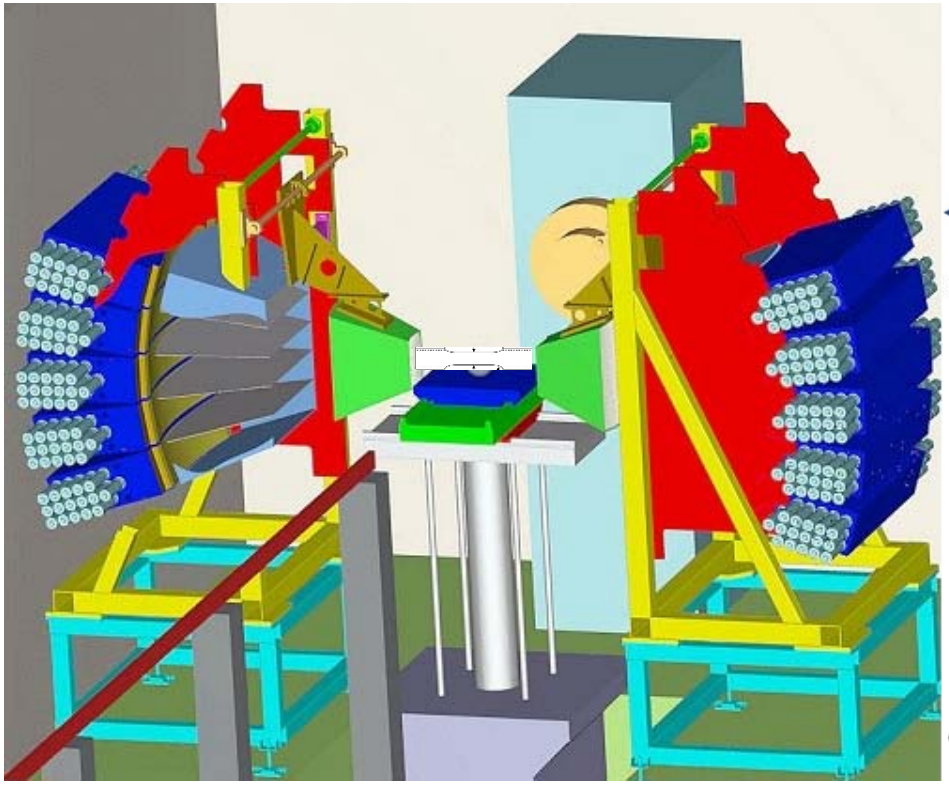
P92: Fe-9.09Cr-1.83W-0.61Mn-0.43Mo-0.23Si-0.21Ni-0.20V-0.10C-0.064Nb-0.046N-0.008P-0.003Al-0.0012B (wt. %)

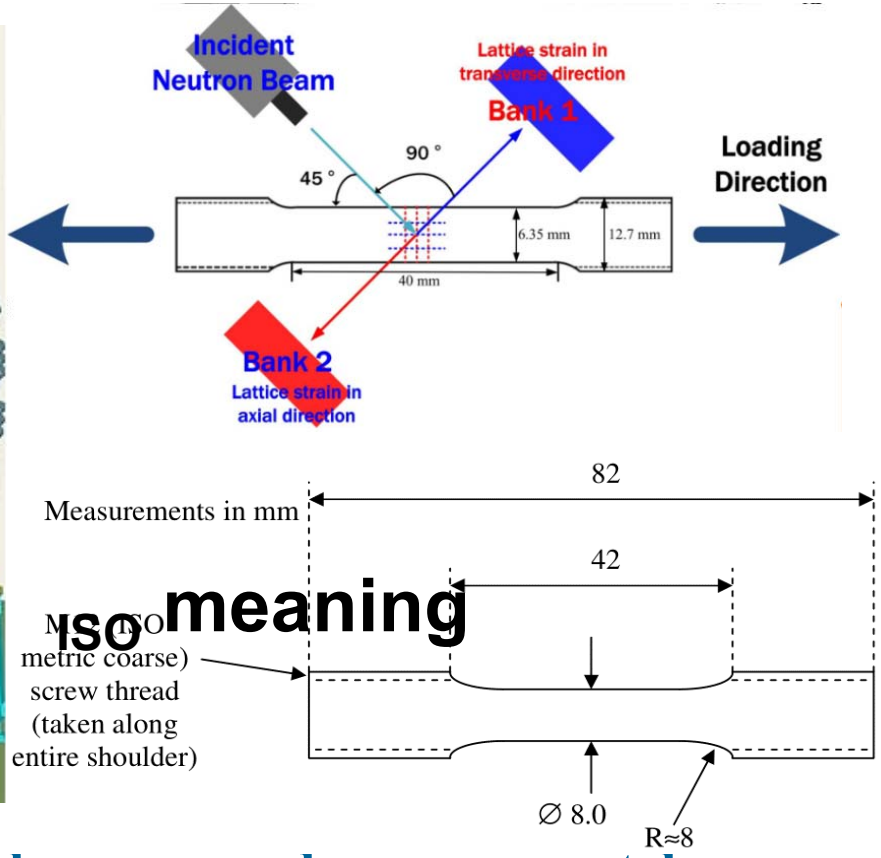
P122: Fe-10.15Cr-1.94W-0.61Mn-0.36Mo-0.27Si-0.34Ni-0.20V-0.13C-0.055Nb-0.057N-0.014P-0.017Al-0.0019B (wt. %)

FBB8: Fe-6.5Al-10Cr-10Ni-3.4Mo-0.25Zr-0.005B

The steady-state creep rate of $Al_{0.3}CoCrFeNi$ is three orders of magnitude lower than conventional ferritic steels.

In-situ Neutron-diffraction Study during Tensile Deformation



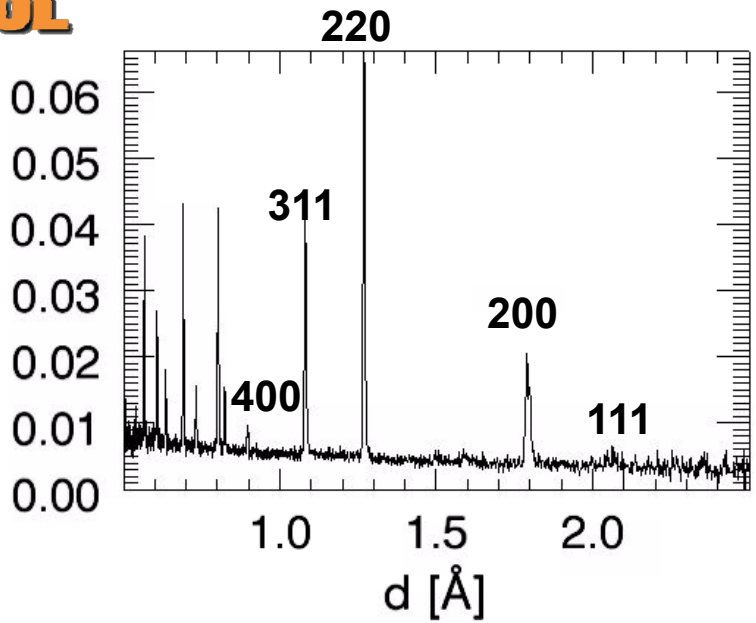


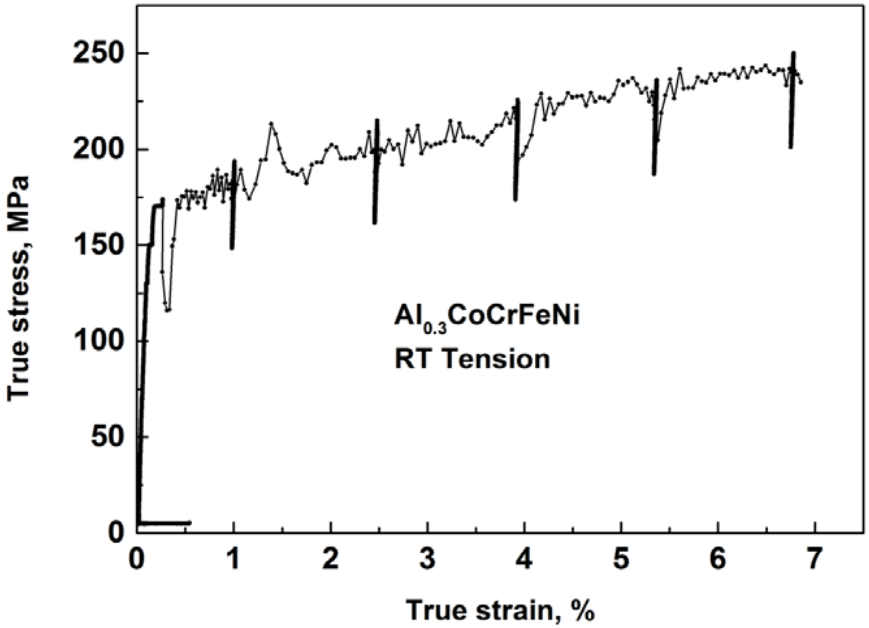
- The spacing between atom planes can be measured very accurately.
- Calculate lattice strains from change in atomic spacing due to stress.
  - Lattice strain

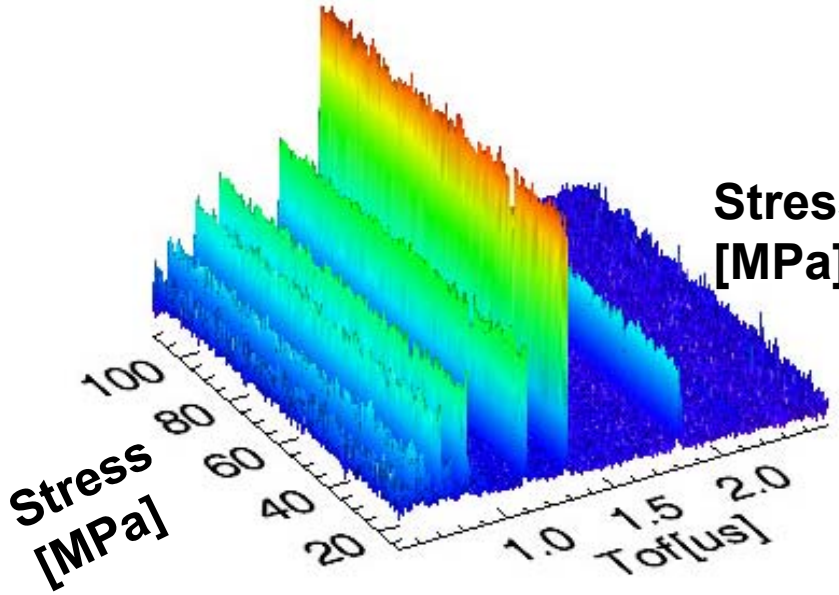
Science & Technology Facilities Council
Rutherford Appleton Laboratory, UK

1. S. Y. Lee, H. Choo, P. K. Liaw, E. C. Oliver, and A. M. Paradowska, Scripta Materialia, Vol. 60, No. 10, pp. 866-869 (2009).

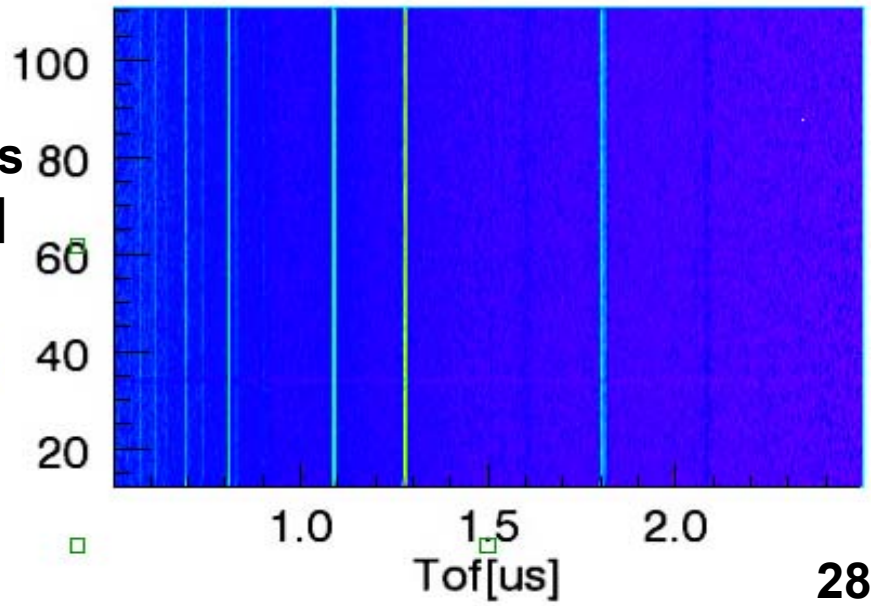
In-situ Neutron-diffraction Study during Tensile Deformation





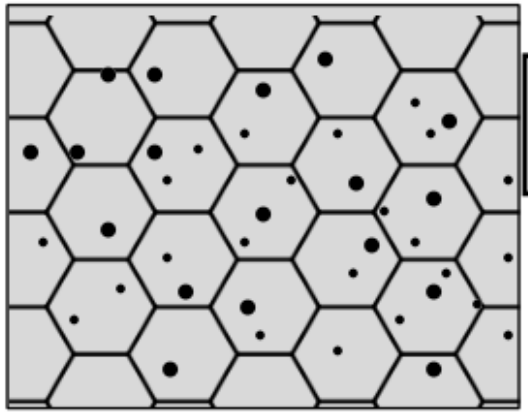


Stress [MPa]



In-situ Neutron-diffraction Study during Tensile Deformation

1. Volume-averaged phase-lattice parameter

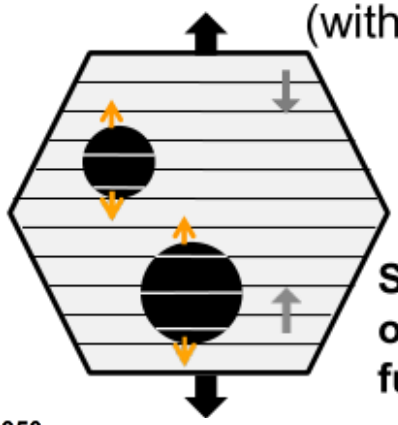


$$\varepsilon_{avg\_phase} = \frac{a - a_0}{a_0}$$

Rietveld whole-pattern fitting

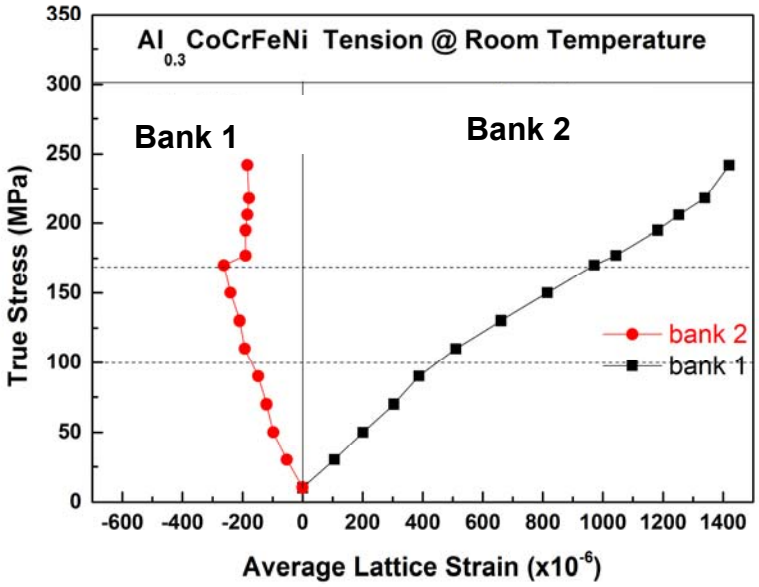
2. Local phase-plane spacing

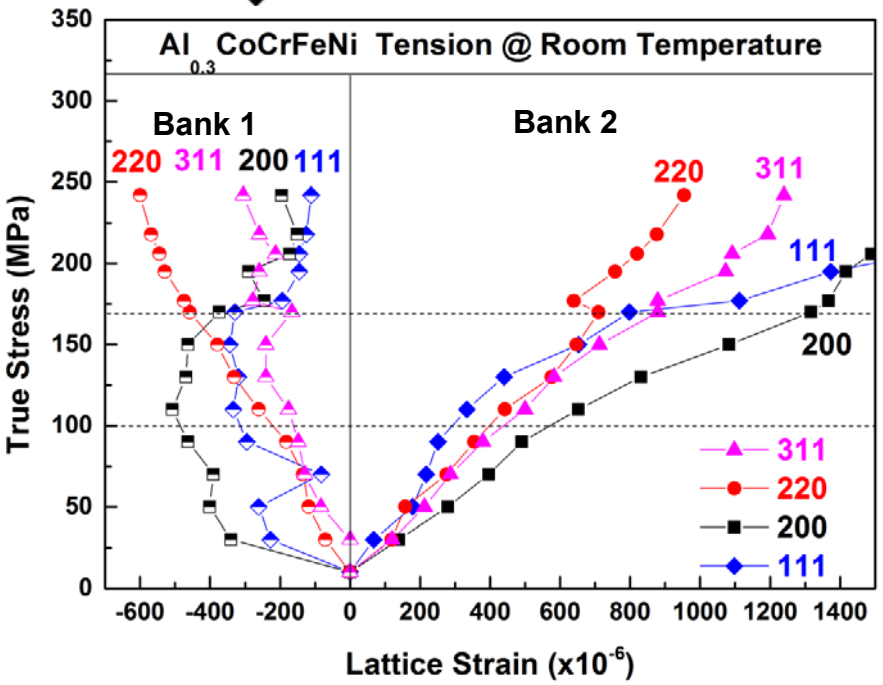
(within hkl grain family)



$$\varepsilon_{local\_\beta} = \frac{d_{hkl}^{\beta} - d_{hkl}^{\beta,0}}{d_{hkl}^{\beta,0}}$$

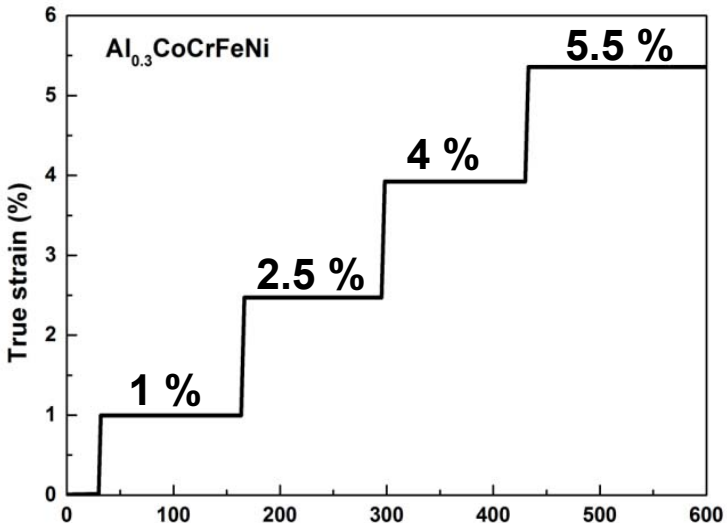
Separation of overlapping fundamental reflections

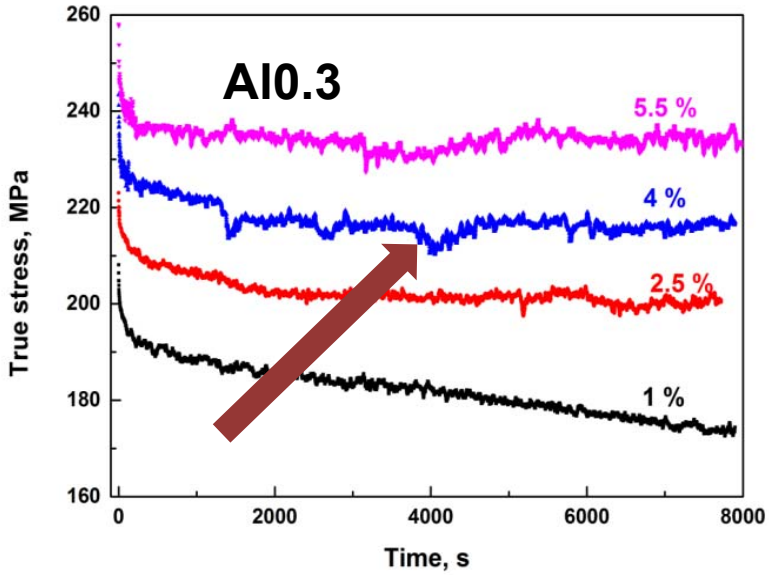


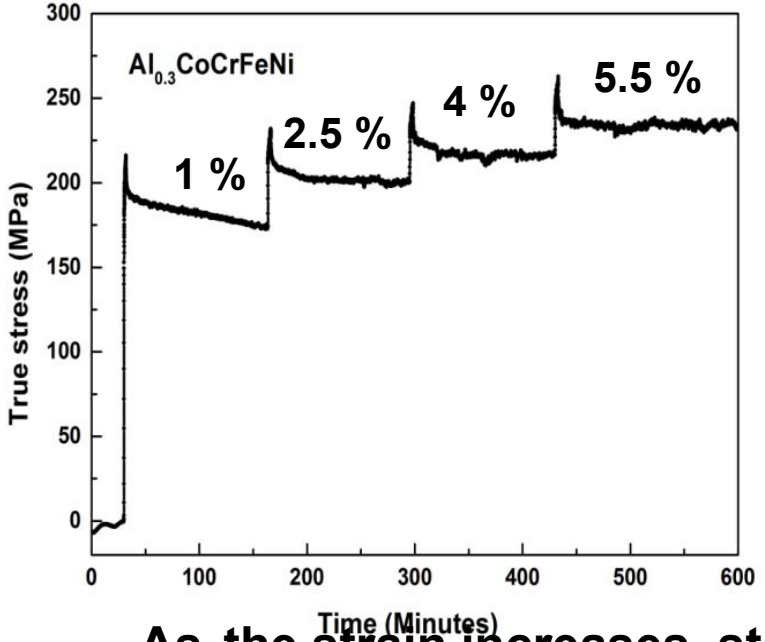


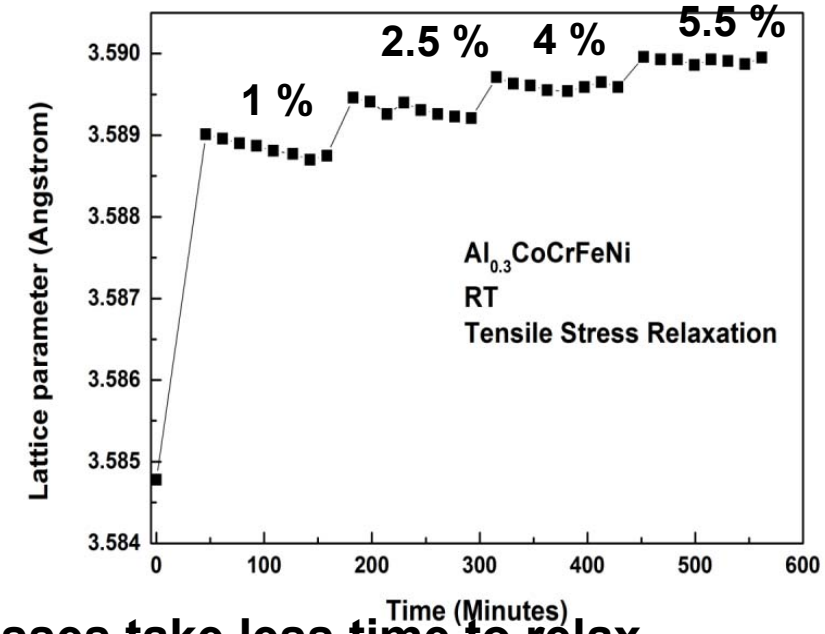
Since the yield strength is low, it is hard to obtain the anisotropic behavior of different {hkl} clearly, it is essential to further conduct stress relaxation tests.

In-situ Neutron-diffraction Study during Stress Relaxation Test



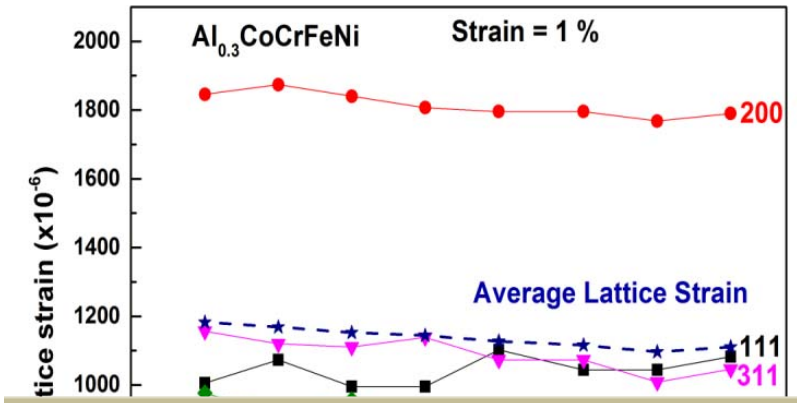


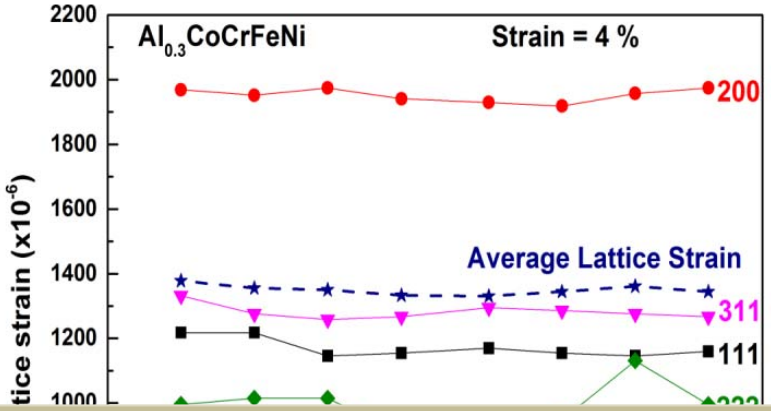




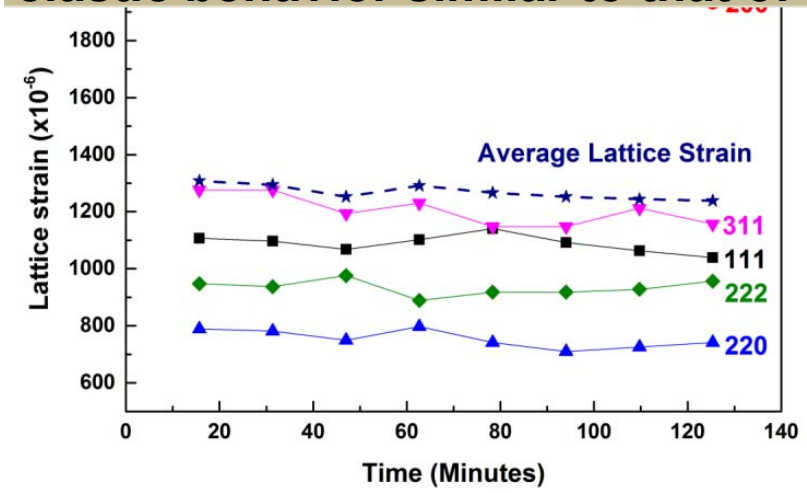
As the strain increases, stresses take less time to relax.

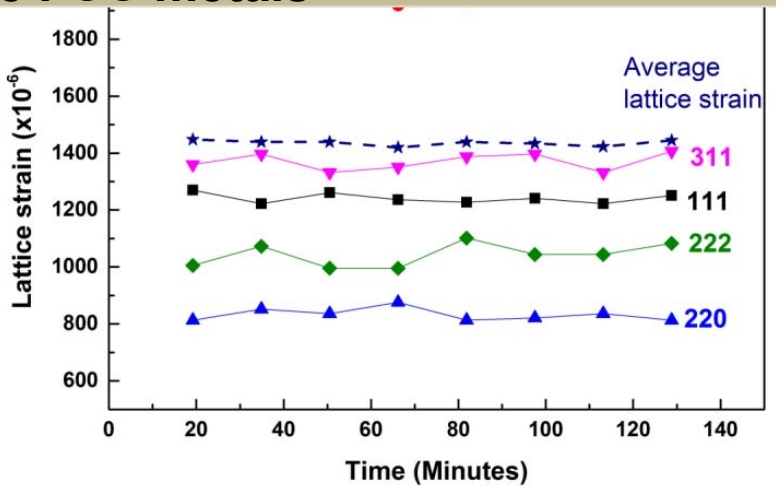
In-situ Neutron-diffraction Study during Tensile Deformation





The lattice strain change is strongly dependent on the grain orientations, indicative of strong elastic anisotropy. The {200} grains exhibit the largest elastic strain along the loading direction. The following is {311}, {111}, {222}, and {220}. This trend indicates that the current HEA exhibits the elastic behavior similar to that of simple FCC metals

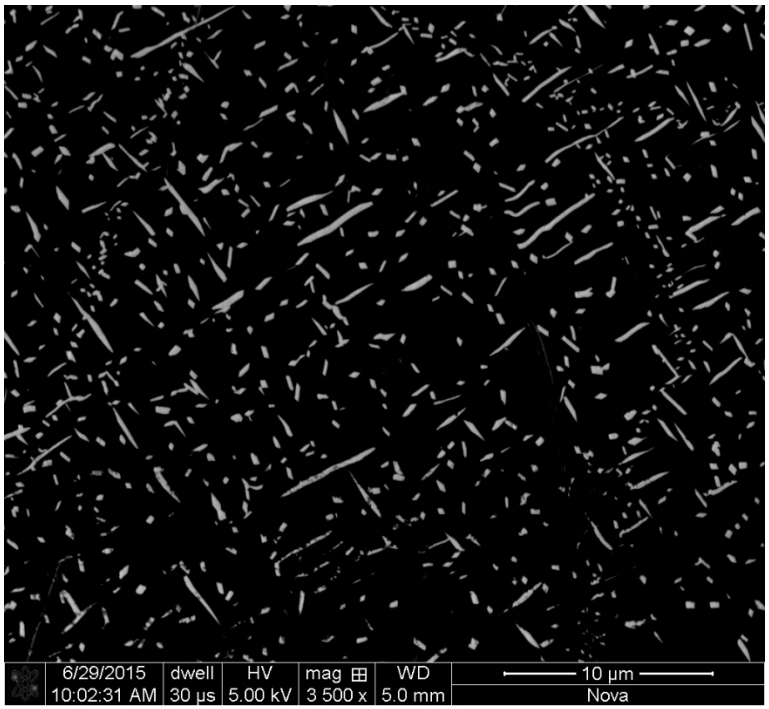


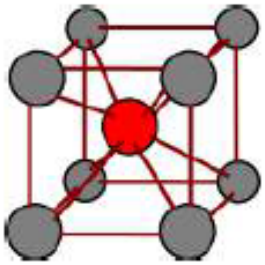


Heat-treatment Effect on Creep Behavior of HEAs

FCC + B2 $Al_{0.3}CoCrFeNi$

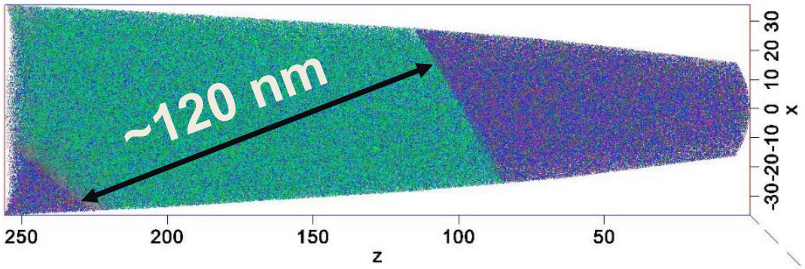
Heat-treatment effect (annealed 700 °C for 500 hours)

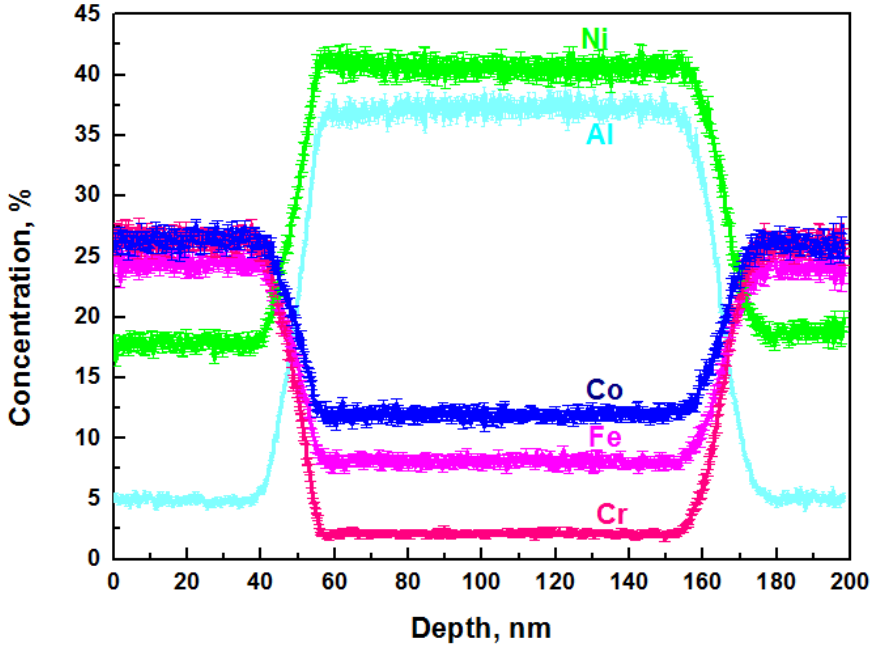




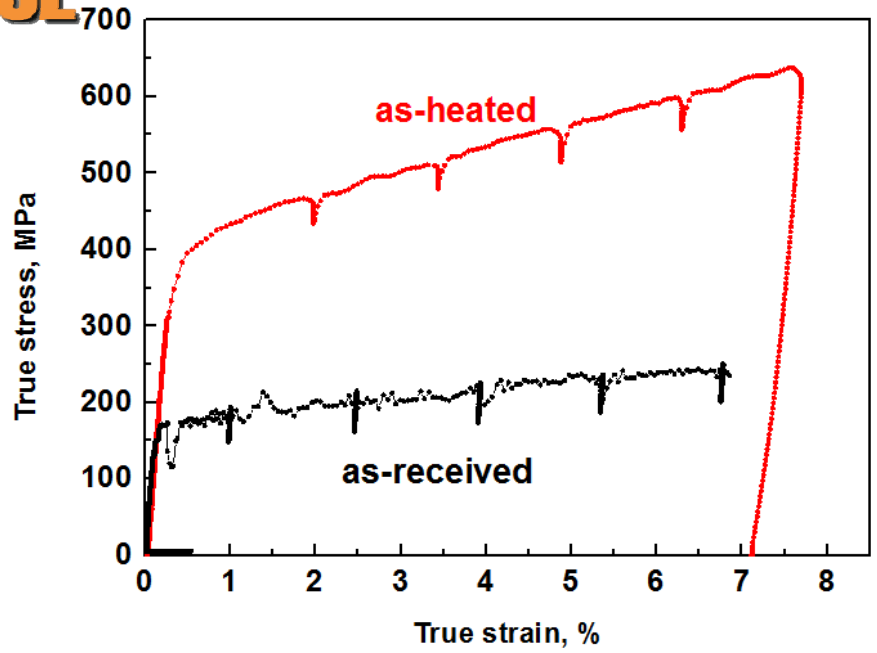
B2 structure

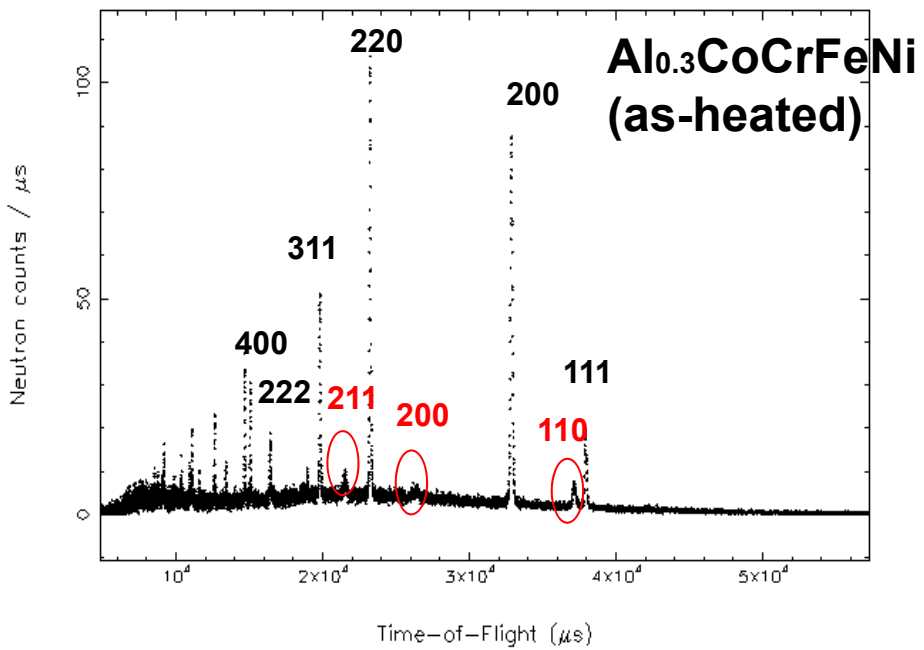
NiAl





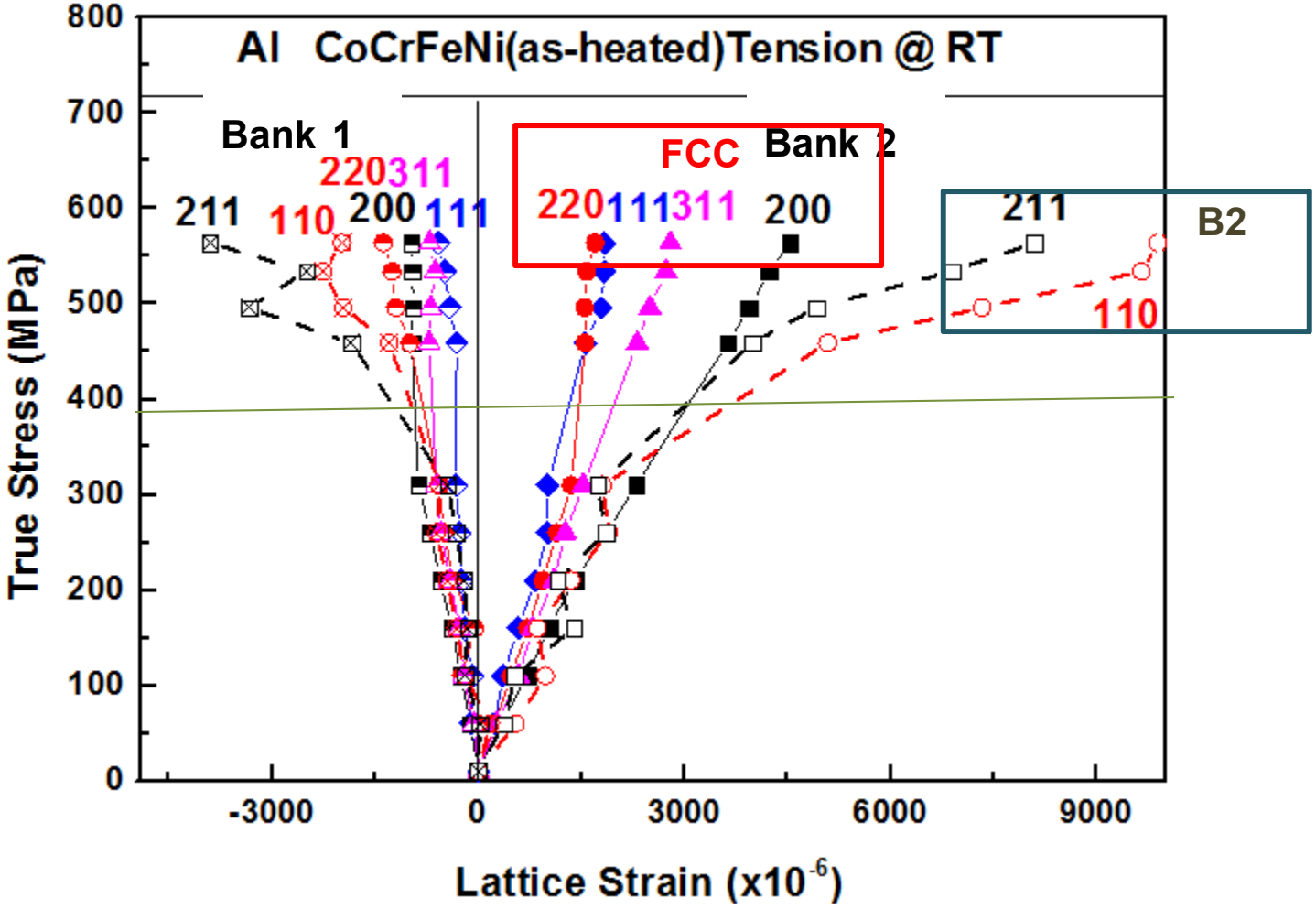
In-situ Neutron-diffraction Study during Tensile Deformation





Parameters / Phases	Lattice parameter	d_{111}	d_{110}	d_{200}	d_{220}	d_{211}	d_{311}
FCC (Angstrom)	3.58466	2.06881	-	1.79279	1.2672	-	1.08082
B2 (Angstrom)	-	-	2.0261	-	-	1.17379	-

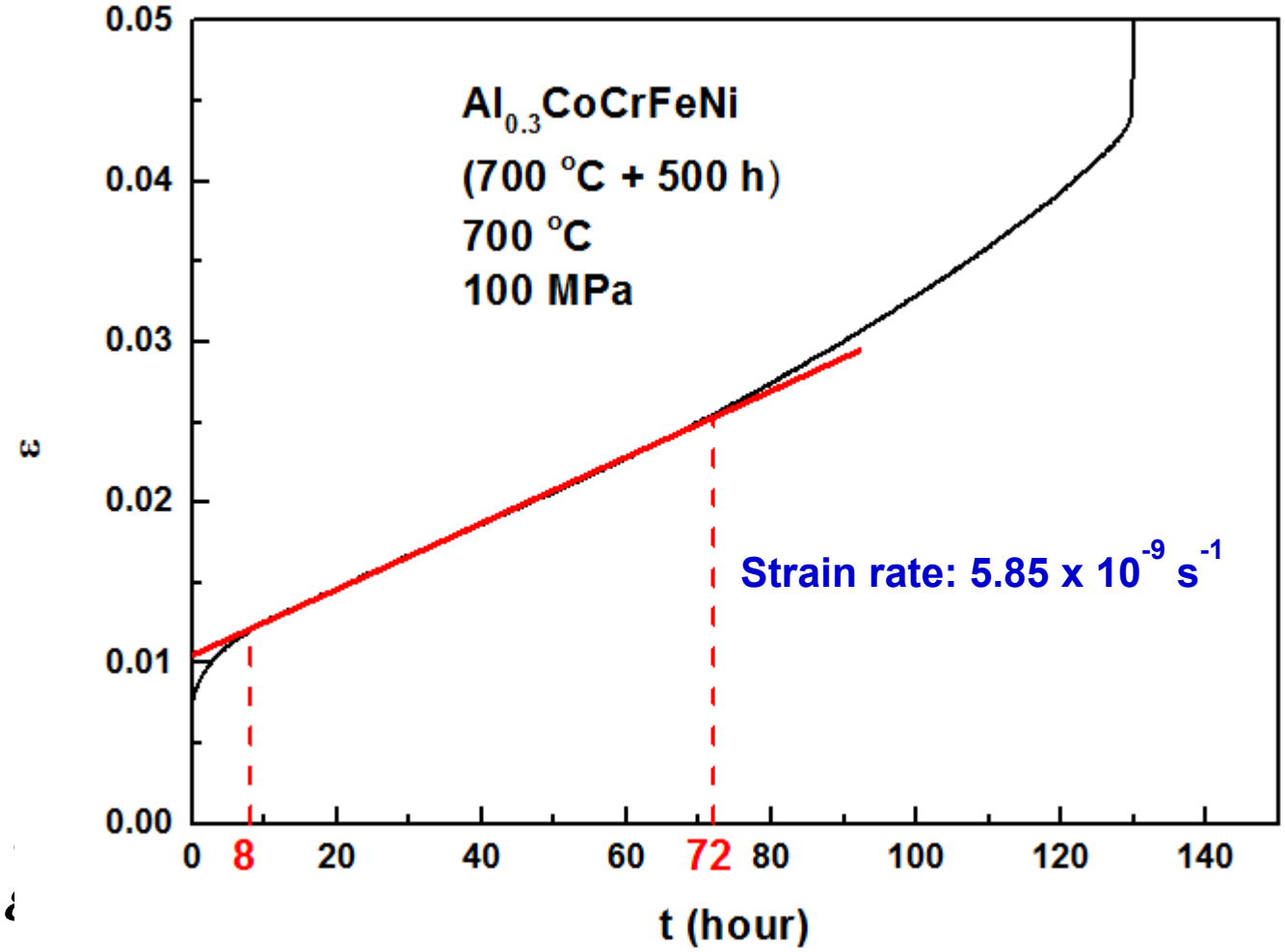
In-situ Neutron-diffraction Study during Tensile Deformation



B2 phase is the strengthening phase

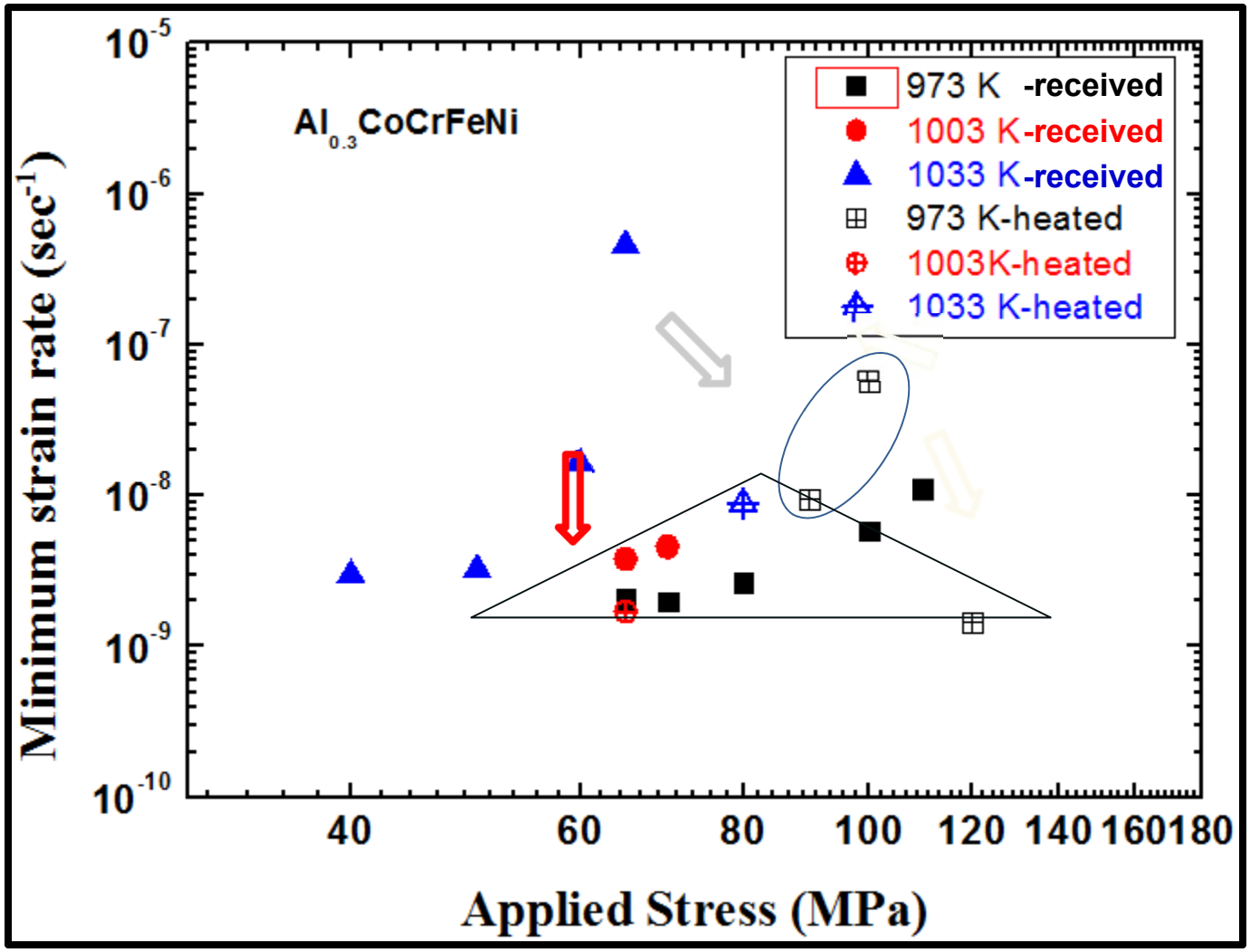
- **After yielding stresses, the slope of the B2 phase tends to become small.**
- **Load transfers from FCC to B2 phases.**

Study of Creep Behavior of HEAs after Heat Treatment



- Typical three-stage of creep behavior is observed.

Study of Creep Behavior of HEAs after Heat Treatment (Cont'd)



Thermodynamic Calculations

Thermodynamic Modeling

- The Gibbs energy of a binary solution phase can be written as:

$$G_m^{\varphi} = \sum_{i=A,B} x_i \cdot G_i^{\varphi,o} + RT \sum_{i=A,B} x_i \ln x_i + x_A \cdot x_B \sum_{v} L_v \cdot (x_A - x_B)^v$$

- The Gibbs energy of a binary intermetallic phase, described by a two-sublattice compound energy formalism, can be written as:

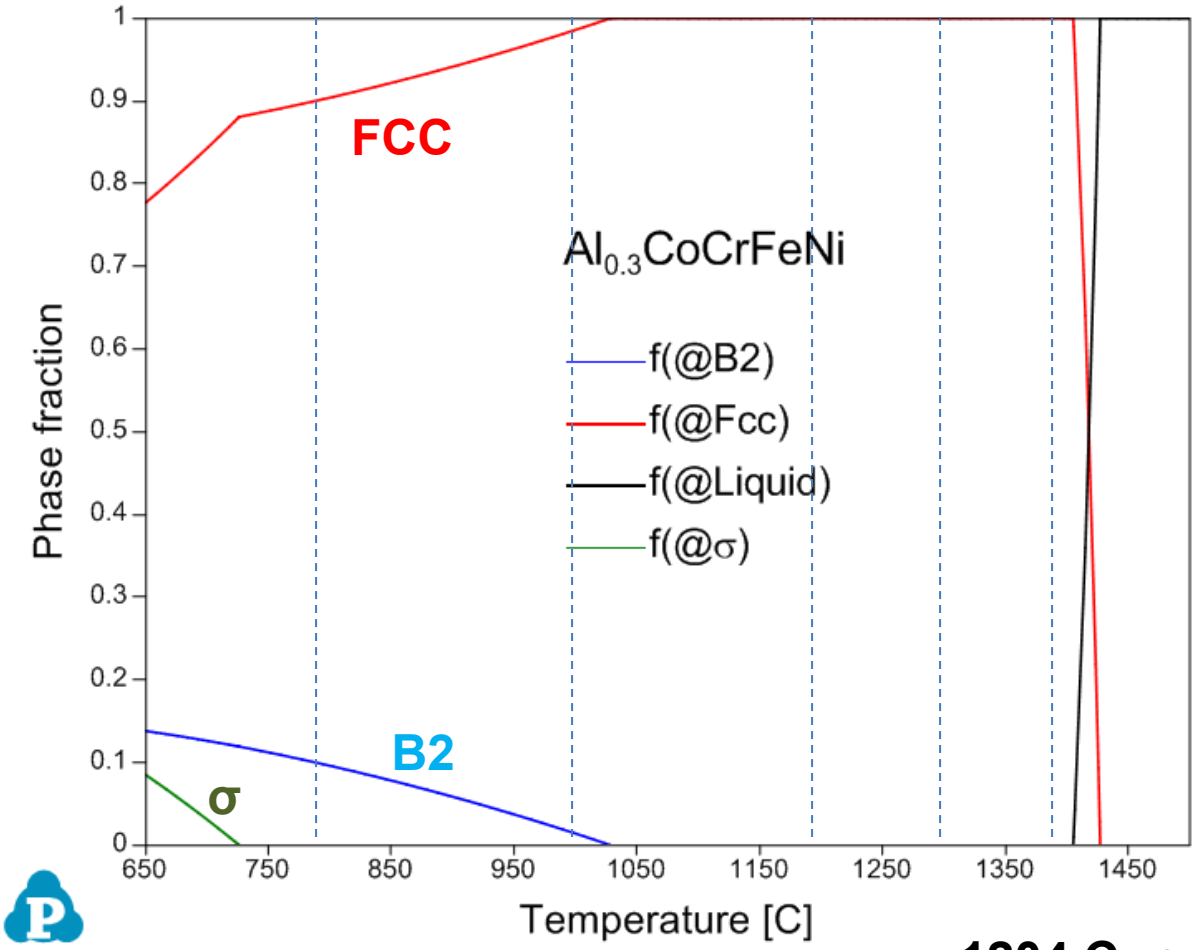
$$G_m^{\varphi} = \sum_{i=A,B} \sum_{j=A,B} y_i^I y_j^{II} G_{i:j}^{\varphi} + RT\left[\frac{p}{p+q} \sum_{i=A,B} y_i^I \ln y_i^I + \frac{q}{p+q} \sum_{i=A,B} y_i^{II} \ln y_i^{II}\right]$$
$$+ \sum_{j=A,B} y_A^I y_B^I y_j^{II} \sum_{v} (y_A^I - y_B^I)^v L_{A,B:j}^v + \sum_{i=A,B} y_i^I y_A^{II} y_B^{II} \sum_{v} (y_A^{II} - y_B^{II})^v L_{i:A,B}^v$$
$$+ y_A^I y_B^I y_A^{II} y_B^{II} L_{A,B:A,B}$$

Meaning….

- Perform thermodynamic calculations of HEAs to quantify phase compositions, phase fractions, and phase stability versus temperature and composition using the CALculation of PHAse Diagrams (CALPHAD) approach.
- Additional ternary and higher-order interaction terms may also be added to the excess Gibbs energy term.

1. C. Zhang, F. Zhang, S. Chen, and W. Cao, Jom, Vol. 64, No. 7, pp. 839-845 (2012)

Phase Transformation at High Temperatures



Experimental Results

only FCC phase found within 1 hour.

Thermodynamic Modeling Results:

800 C: 10% B2+90% FCC

1000 C: 3% B2+97 % FCC

1200 C: 100% FCC

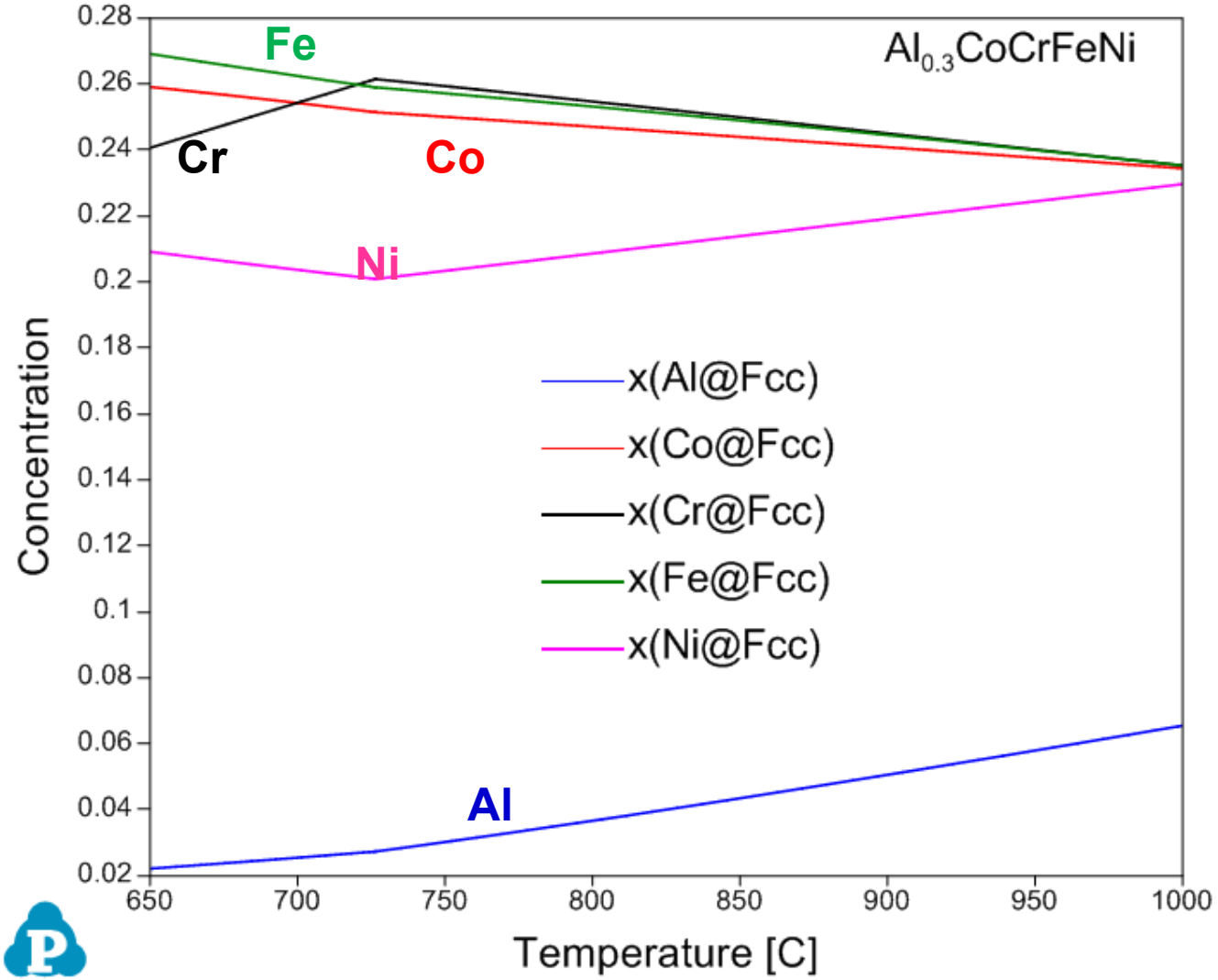
1300 C: 100% FCC

1400 C: 100% FCC

1204 C: pure FCC

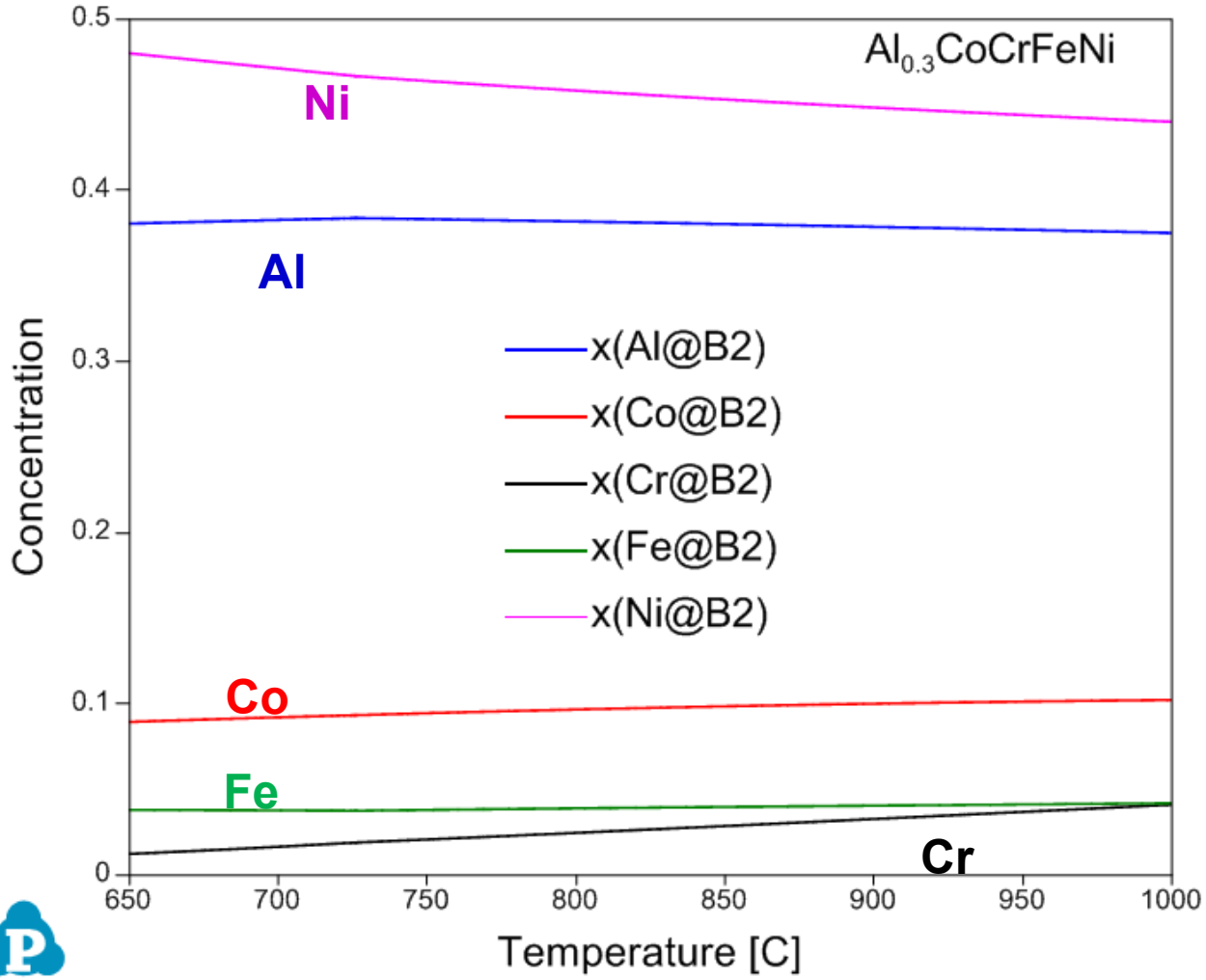
Elemental Distribution

FCC matrix



Elemental Distribution (Cont'd)

B2 phase



Thermodynamic modeling fits well

Crystal-Plasticity Finite-Element Modeling

Crystal-Plasticity Finite-Element Modeling (CPFEM)

- **Multiplicative decomposition**

$$F = F^e F^p$$

$$F_{ij} = \partial x_i / \partial X_j = F_{ik}^{\ e} F_{kj}^{\ p}$$

Tij ???

elastic $T_{ij} = C_{ijkl} E^e_{kl}$

plastic $\dot{F}^p_{ik} F^{p-1}_{kj} = \sum_{\alpha=1}^{N} \dot{\gamma}^{(\alpha)} s_i^{(a)} m_j^{(a)}$

- **Flow rule**

$$\dot{\gamma}^{\alpha} = \dot{\gamma}^{o} \left[\frac{\tau^{\alpha}}{g^{\alpha}} \right]^{N}$$

$$\tau^{\alpha} = m_i^{\alpha} F_{ij}^{e-1} J \sigma_{jk} F_{kl}^{e} s_l^{\alpha}$$

- **Hardening law**

$$\dot{g}^{\alpha} = \sum_{\beta} h_{\alpha\beta} \left| \dot{\gamma}^{\beta} \right|$$

$$h_{\alpha\beta} = h_{\alpha\alpha} \left[q + (1-q)\delta_{\alpha\beta} \right]$$

$\dot{\gamma}^0$: **characteristic strain rate**

τ^{α} : **resolved shear stress of α slip system**

g^{α} : **flow strength of α slip system**

N : **stress exponent**

$h_{\alpha\beta}$: **hardening moduli**

$h_{\alpha\alpha}$: **self-hardening moduli**

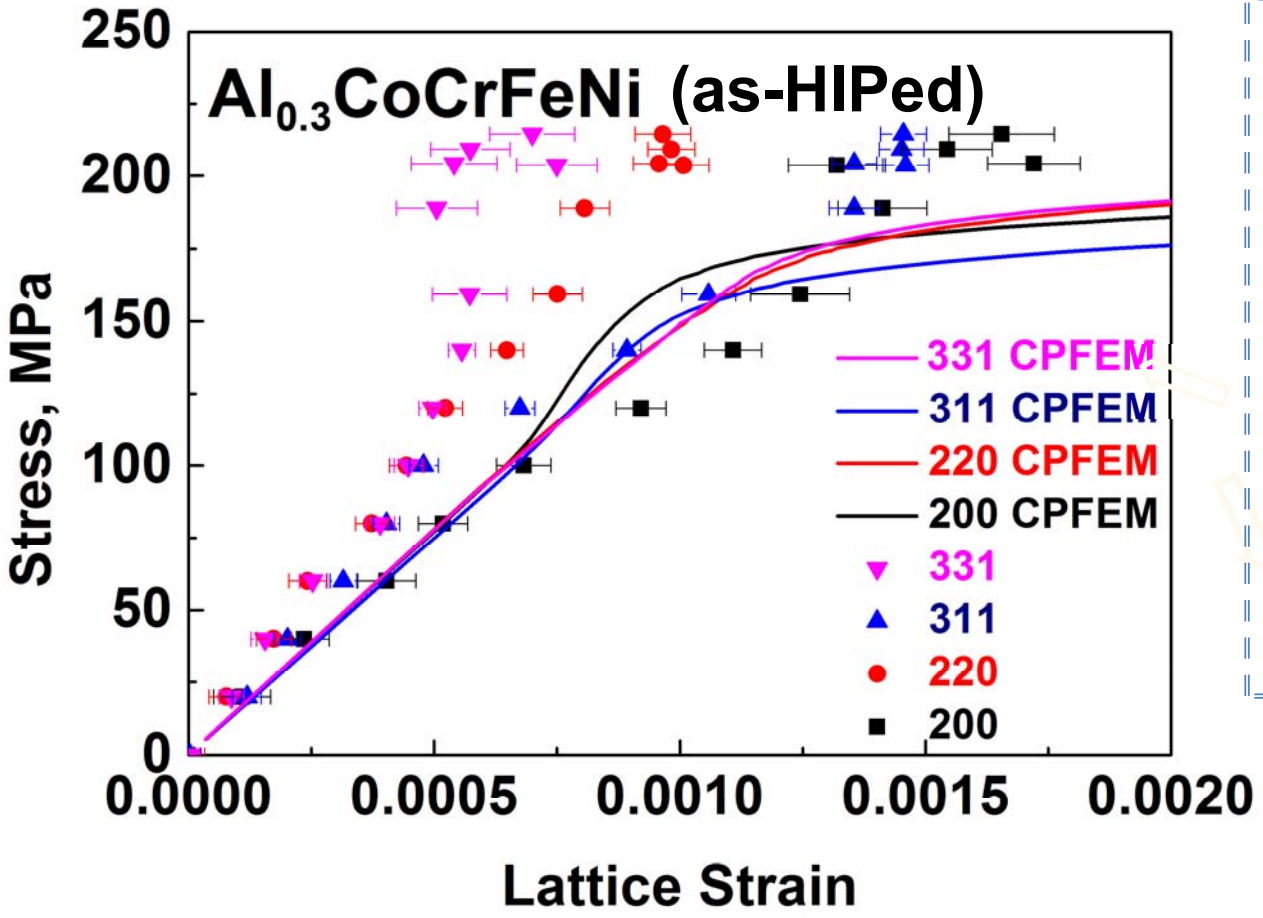
q : **latent hardening coefficient**

h_0 : **initial hardening modulus**

τ_0 : **initial slip strength**

τ_s : **saturation slip strength**

Crystal-Plasticity Finite-Element Modeling (CPFEM) (Cont'd)



The model predicts well,

- The 200 elastic strain
- Elastic-Plastic transition

More improvement needs to done in the future.

CPFEM shows qualitative agreement with neutron-diffraction results.

Conclusions

- **The single-phase $Al_{0.3}CoCrFeNi$ shows better creep properties, compared with fossil-energy high-temperature materials.**
- **The in-situ neutron facility helps characterize the average and specific lattice strain evolution during tension and stress relaxation tests.**
- **Heat-treatment introduced the strengthening B2 phase into the FCC matrix. At certain temperatures and stress levels, the creep properties are improved with heat treatment.**
- **Thermodynamic calculations predicts phase transformation and elemental distribution in both the FCC matrix and B2 phase quite well.**
- **Crystal-plasticity finite-element modeling predicts the elastic strain and elastic-plastic transition well.**

Published Papers and Presentations

Papers:

1. Guo XQ, Wu W, Wu PD, Qiao H, An K, Liaw PK. On the Swift effect and twinning in a rolled magnesium alloy under free-end torsion. Scripta Materialia 2013;69:319-22.
2. Jia HL, Muntele CI, Huang L, Li X, Li G, Zhang T, et al. A study on the surface structures and properties of Ni-free Zr-based bulk metallic glasses after Ar and Ca ion implantation. Intermetallics 2013;41:35-43.
3. Ma SG, Zhang SF, Gao MC, Liaw PK, Zhang Y. A Successful Synthesis of the CoCrFeNiAl0.3 Single-Crystal, High-Entropy Alloy by Bridgman Solidification. Jom 2013;65:1751-8.
4. Shen YF, Wang YD, Liu XP, Sun X, Peng RL, Zhang SY, et al. Deformation mechanisms of a 20Mn TWIP steel investigated by in situ neutron diffraction and TEM. Acta Materialia 2013;61:6093-106.
5. Tang Z, Gao MC, Diao HY, Yang TF, Liu JP, Zuo TT, et al. Aluminum Alloying Effects on Lattice Types, Microstructures, and Mechanical Behavior of High-Entropy Alloys Systems. Jom 2013;65:1848-58.
6. Yuan T, Wang GY, Feng QM, Liaw PK, Yokoyama Y, Inoue A. Modeling size effects on fatigue life of a zirconium-based bulk metallic glass under bending. Acta Materialia 2013;61:273-9.
7. Zhang Y, Zuo TT, Cheng YQ, Liaw PK. High-entropy Alloys with High Saturation Magnetization, Electrical Resistivity, and Malleability. Scientific reports 2013;3.
8. Antonaglia J, Xie X, Schwarz G, Wraith M, Qiao JW, Zhang Y, et al. Tuned Critical Avalanche Scaling in Bulk Metallic Glasses. Scientific reports 2014;4.
9. Antonaglia J, Xie X, Tang Z, Tsai CW, Qiao JW, Zhang Y, et al. Temperature Effects on Deformation and Serration Behavior of High-Entropy Alloys (HEAs). Jom 2014;66:2002-8.
10. Chen SY, Yang X, Dahmen KA, Liaw PK, Zhang Y. Microstructures and Crackling Noise of AlxNbTiMoV High Entropy Alloys. Entropy 2014;16:870-84.

Published Papers and Presentations

Papers (Cont'd):

11. Hong HL, Wang Q, Dong C, Liaw PK. Understanding the Cu-Zn brass alloys using a short-range-order cluster model: significance of specific compositions of industrial alloys. Scientific reports 2014;4.
12. Huang EW, Qiao JW, Winiarski B, Lee WJ, Scheel M, Chuang CP, et al. Microyielding of Core-Shell Crystal Dendrites in a Bulk-metallic-glass Matrix Composite. Scientific reports 2014;4.
13. Huang L, Fozo EM, Zhang T, Liaw PK, He W. Antimicrobial behavior of Cu-bearing Zr-based bulk metallic glasses. Materials Science & Engineering C-Materials for Biological Applications 2014;39:325-9.
14. Huang L, Zhang T, Liaw PK, He W. Macrophage responses to a Zr-based bulk metallic glass. Journal of Biomedical Materials Research Part A 2014;102:3369-78.
15. Jia HL, Liu FX, An ZN, Li WD, Wang GY, Chu JP, et al. Thin-film metallic glasses for substrate fatigue-property improvements. Thin Solid Films 2014;561:2-27.
16. Wu W, Qiao H, An K, Guo XQ, Wu PD, Liaw PK. Investigation of deformation dynamics in a wrought magnesium alloy. International Journal of Plasticity 2014;62:105-20.
17. Yu PF, Feng SD, Xu GS, Guo XL, Wang YY, Zhao W, et al. Room-temperature creep resistance of Co-based metallic glasses. Scripta Materialia 2014;90-91:45-8.
18. Zhang Y, Li M, Wang YD, Lin JP, Dahmen KA, Wang ZL, et al. Superelasticity and Serration Behavior in Small-Sized NiMnGa Alloys. Advanced Engineering Materials 2014;16:955-60.
19. Zhang Y, Lu ZP, Ma SG, Liaw PK, Tang Z, Cheng YQ, et al. Guidelines in predicting phase formation of high-entropy alloys. Mrs Communications 2014;4:57-62.
20. Zhang Y, Zuo TT, Tang Z, Gao MC, Dahmen KA, Liaw PK, et al. Microstructures and properties of high-entropy alloys. Progress in Materials Science 2014;61:1-93.

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Papers (Cont'd):

21. An ZN, Jia HL, Wu YY, Rack PD, Patchen AD, Liu YZ, et al. Solid-Solution CrCoCuFeNi High-Entropy Alloy Thin Films Synthesized by Sputter Deposition. Materials Research Letters 2015;3:203-9.
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23. Carroll R, Lee C, Tsai CW, Yeh JW, Antonaglia J, Brinkman BAW, et al. Experiments and Model for Serration Statistics in Low-Entropy, Medium-Entropy, and High-Entropy Alloys. Scientific reports 2015;5.
24. Chen C, Ren JL, Wang G, Dahmen KA, Liaw PK. Scaling behavior and complexity of plastic deformation for a bulk metallic glass at cryogenic temperatures. Physical review E, Statistical, nonlinear, and soft matter physics 2015;92.
25. Huang L, Pu C, Fisher RK, Mountain DJH, Gao YF, Liaw PK, et al. A Zr-based bulk metallic glass for future stent applications: Materials properties, finite element modeling, and in vitro human vascular cell response. Acta Biomaterialia 2015;25:356-68.
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27. Li G, Xiao DH, Yu PF, Zhang LJ, Liaw P, Li YC, et al. Equation of State of an AlCoCrCuFeNi High-Entropy Alloy. Jom 2015;67:2310-3.
28. Liu S, Gao MC, Liaw PK, Zhang Y. Microstructures and mechanical properties of AlxCrFeNiTi0.25 alloys. Journal of Alloys and Compounds 2015;619:610-5.
29. Luo J, Dahmen K, Liaw PK, Shi YF. Low-cycle fatigue of metallic glass nanowires. Acta Materialia 2015;87:225-32.

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31. Tang Z, Senkov ON, Parish CM, Zhang C, Zhang F, Santodonato LJ, et al. Tensile ductility of an AlCoCrFeNi multi-phase high-entropy alloy through hot isostatic pressing (HIP) and homogenization. Materials Science and Engineering a-Structural Materials Properties Microstructure and Processing 2015;647:229-40.
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33. Uhl JT, Pathak S, Schorlemmer D, Liu X, Swindeman R, Brinkman BAW, et al. Universal Quake Statistics: From Compressed Nanocrystals to Earthquakes. Scientific reports 2015;5.
34. Wu W, Liaw PK, An K. Unraveling cyclic deformation mechanisms of a rolled magnesium alloy using in situ neutron diffraction. Acta Materialia 2015;85:343-53.
35. Yu PF, Zhang LJ, Cheng H, Zhang H, Jing Q, Ma MZ, et al. Special Orientation Relationships of CuZr2 in the Annealed Zr64.5Cu35.5 Metallic Glass. Metall Mater Trans A 2015;46A:1855-9.
36. Zuo TT, Yang X, Liaw PK, Zhang Y. Influence of Bridgman solidification on microstructures and magnetic behaviors of a non-equiatomic FeCoNiAlSi high-entropy alloy. Intermetallics 2015;67:171-6.
37. Bian XL, Wang G, Chen HC, Yan L, Wang JG, Wang Q, et al. Manipulation of free volumes in a metallic glass through Xe-ion irradiation. Acta Materialia 2016;106:66-77.
38. Chen SH, Chan KC, Wang G, Wu FF, Xia L, Ren JL, et al. Loading-rate-independent delay of catastrophic avalanches in a bulk metallic glass. Scientific reports 2016;6.

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Papers (Cont'd):

39. Tong X, Wang G, Yi J, Ren JL, Pauly S, Gao YL, et al. Shear avalanches in plastic deformation of a metallic glass composite. International Journal of Plasticity 2016;77:141-55.
40. Yu PF, Cheng H, Zhang LJ, Zhang H, Jing Q, Ma MZ, et al. Effects of high pressure torsion on microstructures and properties of an Al0.1CoCrFeNi high-entropy alloy. Materials Science and Engineering a-Structural Materials Properties Microstructure and Processing 2016;655:283-91.
41. Yu PF, Cheng H, Zhang LJ, Zhang H, Ma MZ, Li G, et al. Nanotwin's formation and growth in an AlCoCuFeNi high-entropy alloy. Scripta Materialia 2016;114:31-4.

Published Papers and Presentations

Presentations:

2013 TMS Meeting , San Antonio, TX, USA, March 3-9, 2013

1. Automatic Fabrication of High-Entropy Alloys and Their Properties, Y. Yokoyama, X. Xie, J. Antonaglia, M. Hemphill, T. Zhi, T. Yuan, G. Wang, C. Tsai, J. Yeh, A. Chuang, K. Dahmen, P. K. Liaw (invited)
2. Extracting Materials Properties from Crackling Noise and Slip Avalanche Statistics of Slowly-Sheared Materials, K. Dahmen, X. Xie, J. Antonaglia, M. Laktionova, E. Tabachnikova, Z. Tang, J. Qiao, J. Greer, J. W. Yeh, J. Uh, P. Liaw
3. Non-Equilibrium and Equilibrium Phases in AlCoCrFeNi High-Entropy Alloys, Z. Tang, O. Senkov, C. Parish, L. Santodonato, D. Miracle, G. Wang, C. Zhang, F. Zhang, P. K. Liaw
4. Ordering Behavior in the Al(x)CoCrCuFeNi High-Entropy Alloys, L. Santodonato, Y. Zhang, M. Gao, C. Parish, M. Feygenson, Z. Tang, J. Neuefeind, R. Weber, P. K. Liaw
5. Computational Modeling of High-Entropy Alloys, M. Gao, D. Tafen, J. Hawk, Y. Wang, M. Widom, L. Santodonato, P. K. Liaw(invited)
6. Minor Phase and Defect Effects on Fatigue Behavior of Wrought Al0.5CoCrCuFeNi High-Entropy Alloys, Z. Tang, M. Hemphill, T. Yuan, G. Wang, J. Yeh, C. Tsai, P. K. Liaw
7. Phase Separation and Intermetallic Formation in "High-Entropy" Alloys, C. Parish, M. Miller, L. Santodonato, Z. Tang, P. K. Liaw.
8. Computational Thermodynamics Aided High-Entropy Alloy Design, C. Zhang, F. Zhang, S. Chen, W. Cao, J. Zhu, Z. Tang, P. K. Liaw
9. Statistical Fatigue-Life Modeling for High-Entropy Alloys, T. Yuan, M. Hemphill, Z. Tang, G. Wang, A. Chuang, C. Tsai, J. Yeh, P. K. Liaw (invited).
10. A Combinatorial Approach to the Investigation of Metal Systems that Form Both High Entropy Alloys and Bulk Metallic Glasses, B. Welk, P. K. Liaw, M. Gibson, H. Fraser

Published Papers and Presentations

Presentations (Cont'd):

- The 9th International Conference on Bulk Metallic Glass (BMG-IX) 2012, Xiamen, China
  1. Computational Thermodynamics Aided High-Entropy Alloy Design, C. Zhang, F. Zhang, S. L. Chen, W. S. Cao, Z. Tang, P. K. Liaw
- 2014 TMS Meeting, San Diego, CA, USA, February 16-20, 2014
  1. Aluminum Alloying Effects on Lattice Types, Microstructures, and Mechanical Behavior of High-entropy Alloys Systems, Z.Tang, M. Gao, H. Y. Diao, T. F. Yang, J. P. Liu, T. T. Zuo, Y. Zhang, Z. P. Lu, Y. Q. Cheng, Y. W. Zhang, K. Dahmen, P. K. Liaw, T. Egami.
  2. The Influence of Cu and Al on the Microstructure, Mechanical Properties and Deformation Mechanisms in the High Entropy Alloys CrCoNiFeCu, CrCoNiFeAl1.5 and CrCoNiFeCuAl1.5, B. Welk, B. B. Viswanathan, M. Gibson, P. K. Liaw, and H. Fraser.
  3. The Influence of Alloy Composition on the Interrelationship between Microstructure Mechanical Properties of High Entropy Alloys with BCC/B2 Phase Mixtures, B. Welk, D. Huber, J. Jensen, G. Viswanathan, R. Williams, P. K. Liaw, M. Gibson, D. Evans, and H. Fraser.
  4. The Oxidation Behavior of AlCoCrFeNi High-entropy Alloy at 1023-1323K (750-1050oC), Wu Kai, W. S. Chen, C. C. Sung, Z. Tang, and P. K. Liaw.
  5. Strain-rate Effects on the Structure Evolution of High Entropy Alloys, X. Xie, J. Antonaglia, J. P. Liu, Z. Tang, J. W. Qiao, G. Y. Wang, Y. Zhang, K. Dahmen, and P. K. Liaw.
  6. Neutron diffraction studies on creep deformation behavior in a high-entropy alloy CoCrFeMnNi under high temperature and low strain rate, W. C. Woo, E. W. Huang, J. W. Yeh, P. K. Liaw, and H. Choo.
  7. The Hot Corrosion Resistance Properties of AlxFeCoCrNi, S. Z. Yang, M. Habibi, L. Wang, S. M. Guo, Z. Tang, P. K. Liaw, L. X. Tan, C. Guo, and M. Jackson.

Published Papers and Presentations

Presentations (Cont'd):

- 2014 TMS Meeting, San Diego, CA, USA, February 16-20, 2014 (Cont'd)
  8. Environmental-temperature Effect on a Ductile High-entropy Alloy Investigated by In Situ Neutron-diffraction Measurements, E. W. Huang, C. Lee, D. J. Yu, K. An, P. K. Liaw, and J. W. Yeh.
  9. Using the Statistics of Serrations in the Stress Strain Curves to Extract Materials Properties of Slowly-sheared High Entropy Alloys, Karin Dahmen, X. Xie, J. Antonaglia, M. Laktionova, E. Tabachnikova, J. W. Qiao, J. W. Yeh, C. W. Tsai, J. Uh, and P. K. Liaw.
  10. Mechanical Behavior of an Al0.1CoCrFeNi High Entropy Alloy, M. Komarasamy, N. Kumar, Z. Tang, R. Mishra, and P. K. Liaw.
  11. Characterizing Multi-component Solid Solutions Using Order Parameters and the Bragg-Williams Approximation, L. Santodonato, and P. K. Liaw.
  12. Ultra Grain Refinement in High Entropy Alloys, N. Tsuji, I. Watanabe, N. Park, D. Terada, A. Shibata, Y. Yokoyama, P. K. Liaw.
  13. Nanostructure Evolution through High-pressure Torsion and Recrystallization in a High-entropy CrMnFeCoNi Alloy, N. Park, A. Shibata, D. Terada, Y. Yokoyama, P. K. Liaw, and N. Tsuji.
  14. Distinguished Work-hardening Capacity of a Ti-based Metallic Glass Matrix Composite upon Dynamic Loading, J. W. Qiao, H. J. Yang, Z. H. Wang, and P. K. Liaw.
- The 10th International Conference on Bulk Metallic Glass 2014, Shanghai, China, University of Science and Technology, Beijing, June 6-16, 2014
  1. Characterization of Serrated Flows in BMG and HEAs, X. Xie, S. Y. Chen, J. Auto, J. P. Liu, J. W. Qiao, P. K. Liaw (invited).
- National Institute of Materials Science, Japan, 2014
  1. Fatigue Behavior of BMG and HEAs, X. Xie, G. Y. Wang, P. K. Liaw.

Published Papers and Presentations

Presentations (Cont'd):

- University of Science and Technology, Beijing, China, June 9, 2014 (Invited)
  1. Characterization of Serrated Flows in High-Entropy Alloys and Bulk-Metallic Glasses, P. K. Liaw.
- Beihang University, Beijing, China, June 10, 2014 (Invited)
  1. Characterization of Serrated Flows in High-Entropy Alloys and Bulk-Metallic Glasses, P. K. Liaw.
- National Institute of Materials Science, Japan, June 23-24, 2014 (Keynote)
  1. Fatigue Behavior of Bulk Metallic Glasses and High Entropy Alloys, Peter K. Liaw.
- 2014 Gordon Research Conferences, Hong Kong, China, July 20-25, 2014
  1. Loading Condition Effects on the Serrated Flows in Bulk Metallic Glasses (BMGs) (poster), X. Xie, J. Antonaglia, J. W. Qiao, Y. Zhang, G. Y. Wang, K. A. Dahmen, and P. K. Liaw.
  2. Characterization of Deformation Dynamics in Bulk Metallic Glasses (BMGs) (Invited), X. Xie, J. Antonaglia, J. W. Qiao, Y. Zhang, G. Y. Wang, Y. Yokoyama, K. A. Dahmen, and P. K. Liaw.
- Central South University, Changsha, Hunan, China, July 26th, 2014 (Invited)
  1. Serration Behaviors of High Entropy Alloys and Bulk Metallic Glasses, X. Xie, J. Antonaglia, J. W. Qiao, Y. Zhang, G. Y. Wang, Y. Yokoyama, K. A. Dahmen, and P. K. Liaw.
- Dalian University of Technology, Dalian, Liaoning, China, July 28th, 2014 (Invited)
  1. Serration Behaviors of High Entropy Alloys and Bulk Metallic Glasses, X. Xie, J. Antonaglia, J. W. Qiao, Y. Zhang, G. Y. Wang, Y. Yokoyama, K. A. Dahmen, and P. K. Liaw.

Published Papers and Presentations

Presentations (Cont'd):

- University of California, Los Angeles, California, US, October 17th, 2014 (Invited)
  1. Serration Behaviors of High Entropy Alloys and Bulk Metallic Glasses, X. Xie, J. Antonaglia, J. W. Qiao, Y. Zhang, G. Y. Wang, Y. Yokoyama, K. A. Dahmen, and P. K. Liaw.
- Yale University, New Haven, Connecticut, US, October 10th, 2014 (Invited)
  Serration Behaviors of High Entropy Alloys and Bulk Metallic Glasses, X. Xie, J. Antonaglia, J. W. Qiao, Y. Zhang, G. Y. Wang, Y. Yokoyama, K. A. Dahmen, and P. K. Liaw.
- University of Cambridge, Cambridge, United Kingdom, December 8th, 2014 (Invited)
  Serration Behaviors of High Entropy Alloys and Bulk Metallic Glasses, X. Xie, J. Antonaglia, J. W. Qiao, Y. Zhang, G. Y. Wang, Y. Yokoyama, K. A. Dahmen, and P. K. Liaw.
- 2015 TMS Meeting, Orlando, FL, USA, March 15-19, 2015
  1. On the Friction Stress and Hall-Petch Coefficient of a Single Phase Face-Centered-Cubic High Entropy Alloy Al0.1FeCoNiCr (Invited), Nilesh Kumar, Mageshwari Komarasamy, Zhi Tang, Rajiv Mishra, and Peter Liaw.
  2. Strength and Deformation of Individual Phases in High-Entropy Alloys, A. Giwa, Haoyan Diao, Xie Xie, S. Y. Chen, Zhi Tang, Karin Dahmen, and Peter Liaw.
  3. Al-Co-Cr-Fe-Ni Phase Equilibria and Properties, Zhi Tang, Oleg Senkov, Chuan Zhang, Fan Zhang, Carl Lundin, and Peter Liaw.
  4. Fatigue Behavior of an Al0.1CoCrNiFe High Entropy Alloy, Bilin Chen, Xie Xie, Shuying Chen, Ke An, and Peter Liaw.
  5. Modeling Plastic Deformation and the Statistics of Serrations in the Stress versus Strain Curves of Bulk Metallic Glasses and Other Materials (Invited), Karin Dahmen, James Antonaglia, Wendelin Wright, Xiaojun Gu, Xie Xie, Michael LeBlanc, Junwei Qiao, Yong Zhang, Todd Hufnagel, Jonathan Uhl, and Peter Liaw.

Published Papers and Presentations

Presentations (Cont'd):

- **2015 TMS Meeting, Orlando, FL, USA, March 15-19, 2015 (Cont'd)**
  6. **Deformation Twinning in the High-Entropy Alloy Induced by High Pressure Torsion at Room Temperature, Gong Li, P.F. Yu, P.K. Liaw, and R.P. Liu.**
  7. **Microstructures and Mechanical Behavior of Multi-Component AlxCrCuFeMnNi High-Entropy Alloys, Haoyan Diao, Zhinan An1; Xie Xie, Gongyao Wang, Chuan Zhang, Fan Zhang, Guangfeng Zhao, Fuqian Yang, Karin Dahmen, and Peter Liaw.**
  8. **The Characterization of Serrated Plastic Flow in High Entropy Alloys, Shuying Chen, Xie Xie, James Antonaglia, Junwei Qiao, Yong Zhang, Karin Dahmen and Peter Liaw.**
  9. **Segregation and Ti-Zr-Hf-Ni-Pd-Pt High Entropy Alloy under Liquid State, Y. Yokoyama, Norbert Mattern, Akitoshi Mizuno, Gongyao Wang, and Peter Liaw.**
  10. **A Model for the Deformation Mechanisms and the Serration Statistics of High Entropy Alloys, Karin Dahmen, Bobby Carroll, Xie Xie, Shuying Chen, James Antonaglia, Braden Brinkman, Michael LeBlanc, Marina Laktionova, Elena Tabachnikova, Zhi Tang, Junwei Qiao, Jien Wei Yeh, Chi Lee, Che Wei Tsai, Jonathan Uhl, and Peter Liaw.**
  11. **Computational-Thermodynamics-Aided Development of Multiple-Principal-Component Alloys (Invited), Chuan Zhang, Fan Zhang, Shuanglin Chen, Weisheng Cao, Jun Zhu, Zhi Tang, Haoyan Diao, and Peter Liaw.**
  12. **Sputter Deposition Simulation of High Entropy Alloy via Molecular Dynamics Methodology (Invited), Yunche Wang, Chun-Yi Wu, Nai-Hua Yeh, and Peter Liaw.**

Published Papers and Presentations

Presentations (Cont'd):

2016 TMS Meeting, Nashville, TN, USA, February 14-18, 2016

1. **Deviation from High-Entropy Configurations in the Al1.3CoCrCuFeNi Alloy, Louis Santodonato, Yang Zhang, Mikhail Feygenson, Chad Parish, Michael Gao, Richard Weber, Joerg Neuefeind, Zhi Tang, and Peter Liaw.**
2. **A Bragg-Williams Model of Ordering in High-entropy Alloys, Louis Santodonato, and Peter Liaw**
3. **Exploration of High Entropy Alloys for Sustainable Energy Storages, Jingke Mo, Yunzhu Shi, Peter Liaw, Feng-Yuan Zhang.**
4. **Structure Evolution during Cooling of Al0.1CrCuFeMnNi High-entropy Alloy, Haoyan Diao, Chuan Zhang, Louis Santodonato, Mikhail Feygenson, Joerg Neuefeind, Xie Xie, Fan Zhang, and Peter Liaw.**
5. **Atomic and Electronic Basis for Viscous Flow Mediated Avalanches of Ultrastrong Refractory High Entropy Alloys, William Yi Wang, Shunli Shang, Yi Wang, Yidong Wu, Kristopher Darling, Xie Xie, Oleg Senkov, Laszlo Kecskes, Karin Dahman, Xidong Hui, Peter Liaw, and Zi-Kui Liu.**
6. **Microstructure and Mechanical Properties of YxCoCrFeNi High Entropy Alloys, Gong Li, Huan Zhang, Lijun Zhang, Pengfei Yu, Hu Cheng, Qin Jing, Mingzhen Ma, Peter Liaw, and Riping Liu**
7. **Fracture Toughness and Fatigue Crack Growth Behavior of High Entropy Alloys, Mohsen Seifi, Dongyue Li, Zhang Yong, Peter Liaw, and John Lewandowski.**
8. **Microstructures and Properties of CoFeMnNiX (X = Al, Ga, Sn) High Entropy Alloys, Ting Ting Zuo, Xiao Yang, Michael Gao, Shu Ying Chen, Peter Liaw, and Yong Zhang**

Published Papers and Presentations

Presentations (Cont'd):

- **2016 TMS Meeting, Nashville, TN, USA, February 14-18, 2016 (Cont'd)**

9. **Deviation from High-Entropy Configurations in the Al1.3CoCrCuFeNi Alloy, Louis Santodonato, Yang Zhang, Mikhail Feygenson, Chad Parish, Michael Gao, Richard Weber, Joerg Neuefeind, Zhi Tang, Peter Liaw.**
10. **A Statistical Study of the Potential-scan-rate and Al-content Dependent Metastable Pitting (Serration) Behavior of AlxFeCoCrNi High-entropy Alloys, Yunzhu Shi, Bin Yan, Xie Xie, Zhi Tang, Karin Dahmen, and Peter Liaw.**
11. **Serrated Plastic Flow in CoFeMnNi, CoCrFeMnNi, and CoCrFeNi High Entropy Systems, Joseph Licavoli, Karin Dahmen, Paul Jablonski, Michael Gao, Peter Liaw, and Jeffrey Hawk.**
12. **Microstructural Characterization and Phase Evolution of Al1.5CrFeMnTi and Al2CrFeMnTi, Rui Feng, Chanho Lee, Peiyong Chen, Michael Gao, Chuan Zhang, Fan Zhang, and Peter Liaw.**
13. **Serrated Flows in High Entropy Alloys (HEAs), Shuying Chen, Peter Liaw, Xie Xie, Karin Dahmen, Yong Zhang, and Junwei Qiao.**
14. **Deformation and Structural Modeling of a Quenched Al0.1CrCoFeNi Multi-principal Element Alloy under High Strains, Aayush Sharma, Peter Liaw, and Ganesh Balasubramanian.**
15. **A Model for the Deformation Mechanisms and the Serration Statistics of High Entropy Alloys, Karin Dahmen1; Robert Carroll, Xie Xie, Shuying Chen, Michael LeBlanc, Jien Wei Yeh, Chi Lee, Che Wei Tsai, Peter Liaw, and Jonathan Uhl.**
16. **Computational-Thermodynamics-Aided Development of Lightweight High Entropy Alloys, Chuan Zhang, Jun Zhu, Fan Zhang, Shuanglin Chen, Chuan Zhang, Rui Feng, Shuying Chen, Haoyan Diao, and Peter Liaw.**

Published Papers and Presentations

Presentations (Cont'd):

17. Computational High-Entropy Alloy Design and Phase Equilibria of an Al-Co-Cr-Fe-Ni System, Zhi Tang, Oleg Senkov, Jonathon Poplawsky, Chuan Zhang, Fan Zhang, Carl Lundin, and Peter Liaw.
18. A Novel, Single Phase, Refractory CrMoNbV High-entropy Alloy, Rui Feng, Michael Widom, Michael Gao, and Peter Liaw.

❖ Lunch Lecture, Knoxville, TN, USA, February 26, 2016 (Invited)

1. Deviation from High-Entropy Configurations in the Al1.3CoCrCuFeNi Alloy, Louis Santodonato, Yang Zhang, Mikhail Feygenson, Chad Parish, Michael Gao, Richard Weber, Joerg Neuefeind, Zhi Tang, and Peter Liaw.

❖ The Joint Institute for Neutron Sciences (JINS) Invited Lecture, Knoxville, TN, USA, March 21, 2016 (Invited)

1. Deviation from High-Entropy Configurations in the Al1.3CoCrCuFeNi Alloy, Louis Santodonato, Yang Zhang, Mikhail Feygenson, Chad Parish, Michael Gao, Richard Weber, Joerg Neuefeind, Zhi Tang, and Peter Liaw.

Thanks