Project Number: DE-FE-0011194
Research Area:
Topic B: High Performance Materials for Long-Term Fossil Energy Applications

SERRATION BEHAVIOR OF HIGH-ENTROPY ALLOYS (HEAs)

Project: FE0011194

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Acknowledgements

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Outline of presentation

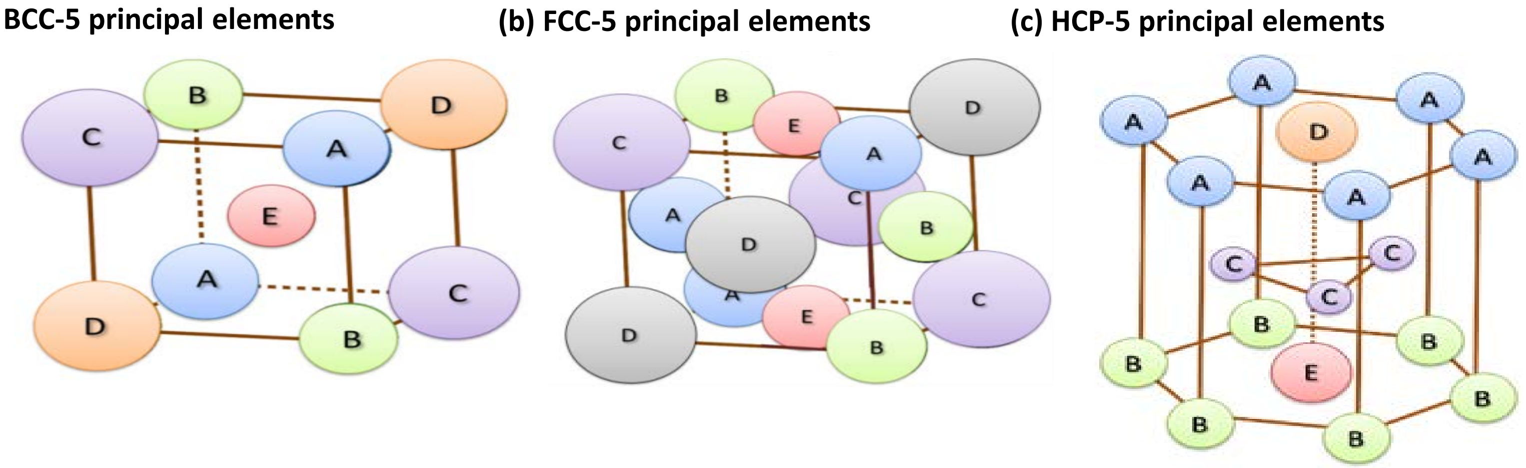
- **Introduction of high entropy alloys (HEAs) and serration behavior**
- **Compression and tension experiments and characterization of serration behavior**
- **Theoretical modeling, comparison to experiments on macroscopic and microscopic scales, and methods to circumvent experimental resolution issues.**
- **Summary**

High Entropy Alloys (HEAs)

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 body-centered cubic (BCC) structures, face-centered cubic (FCC), and/or hexagonal-closed packed (HCP) structures

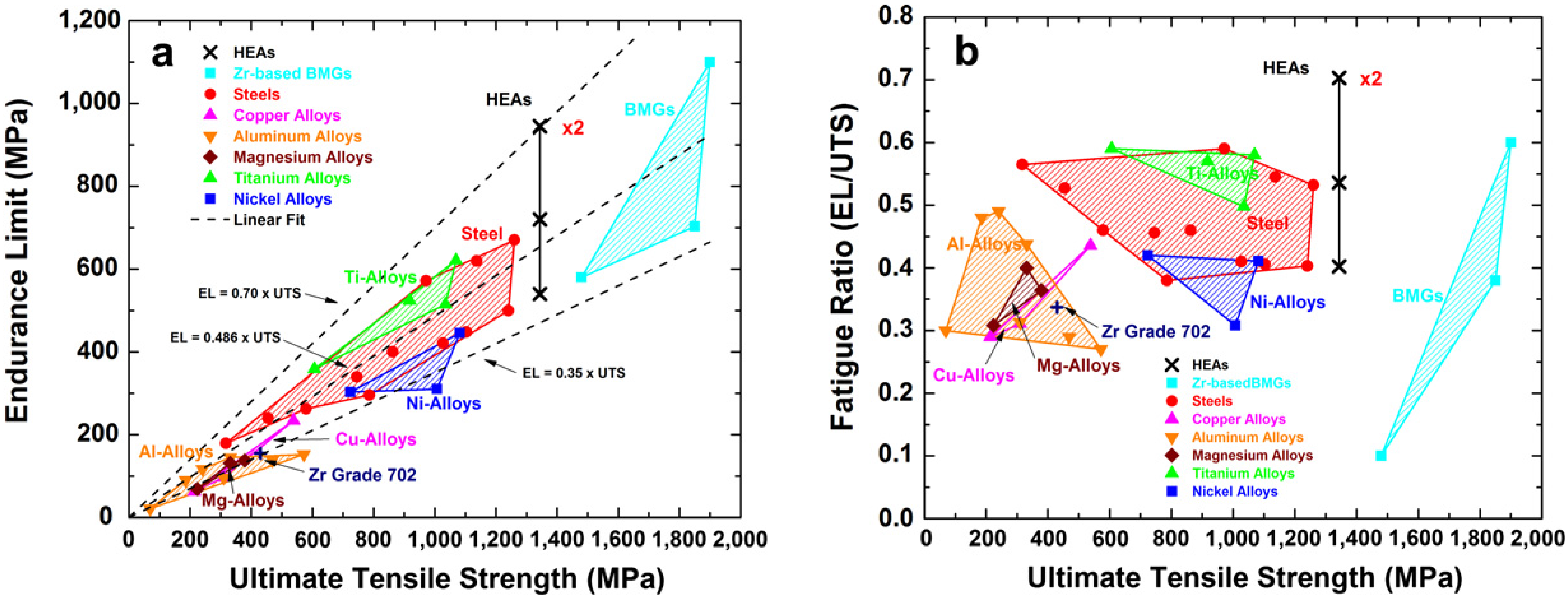
Advantages of HEAs:

- ❖ Great high-temperature properties and ductility
- ❖ Strong fatigue and fracture resistance
- ❖ Balanced mechanical and magnetic behavior
- ❖ High wear resistance
- ❖ Elevated-temperature softening resistance



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, Adv. Eng. Mater. 6, 299 (2004).
2. B. Cantor, I. T. H. Chang, P. Knight, A. J. B. Vincent, Mater. Sci. Eng. 375: 213-218., (2004).
3. Y. Zhang, T. T. Zuo, Z. Tang, M. C. Gao, K. A. Dahmen, P. K. Liaw, and Z. P. Lu, Prog. Mater. Sci. 61, 1 (2014).
4. L.J. Santodonato, Y. Zhang, M. Feygenson, C.M. Parish, M.C. Gao, R.J. Weber, J.C. Neuefeind, Z. Tang, P.K. Liaw. Nat. Commun. 6:5964 (2015).
5. P. D. Jablonski, J. J. Licavoli, M. C. Gao, and J. A. Hawk, JOM 67, 2278-2287 (2015)
6. M. Gao and D. Alman, "Searching for Next Single-Phase High-Entropy Alloy Compositions", Entropy, 2013, 15(10), pp. 4504-4519.

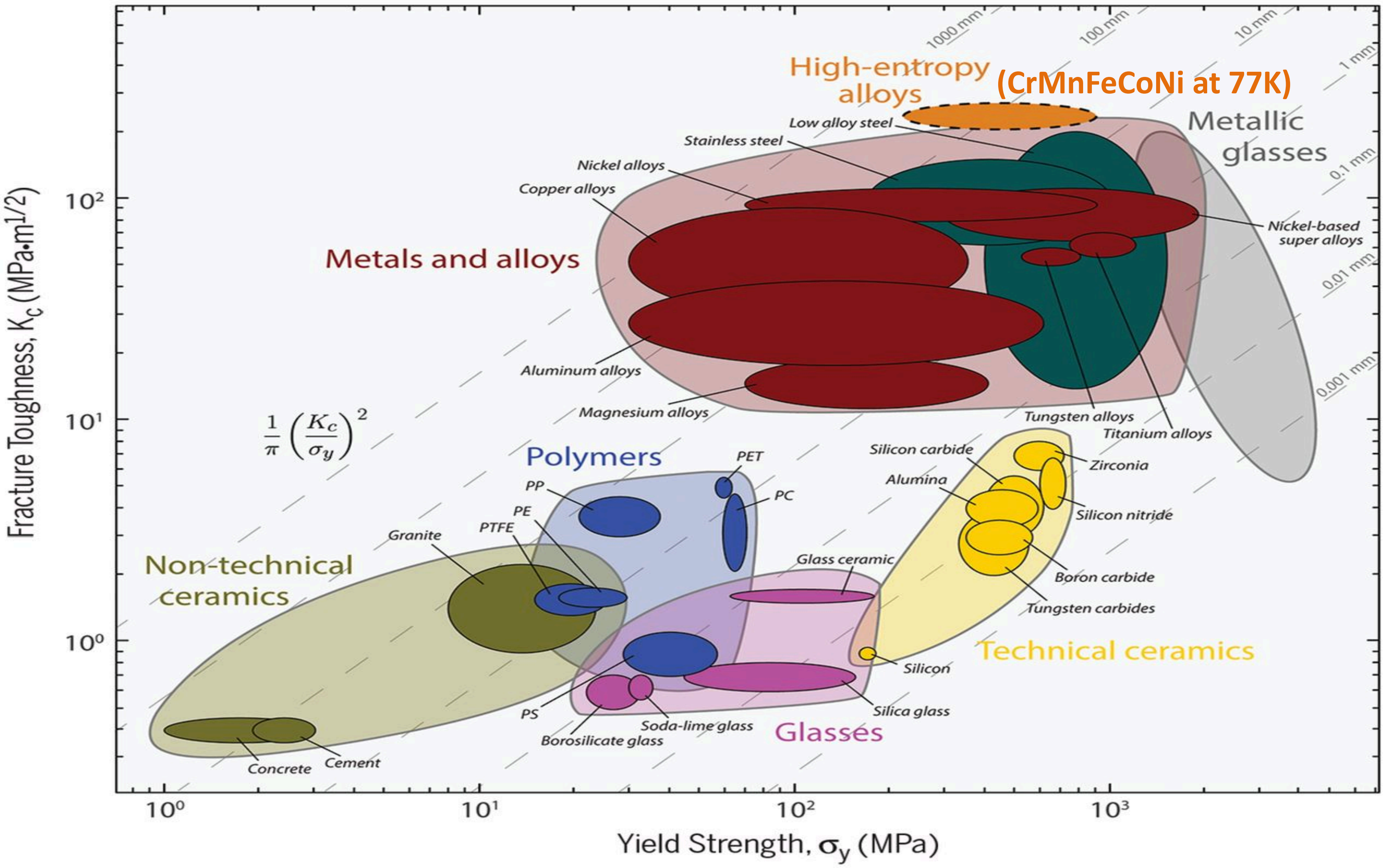
Comparison of fatigue properties with other alloys



EL: Endurance limit; UTS: Ultimate tensile strength

1. Tang Z, Yuan T, Tsai C-W, Yeh J-W, Lundin CD, Liaw PK. Fatigue behavior of a wrought Al0.5CoCrCuFeNi two-phase high-entropy alloy. Acta Materialia 2015; 99:247-258.

Comparison with Other Materials (Cont'd)

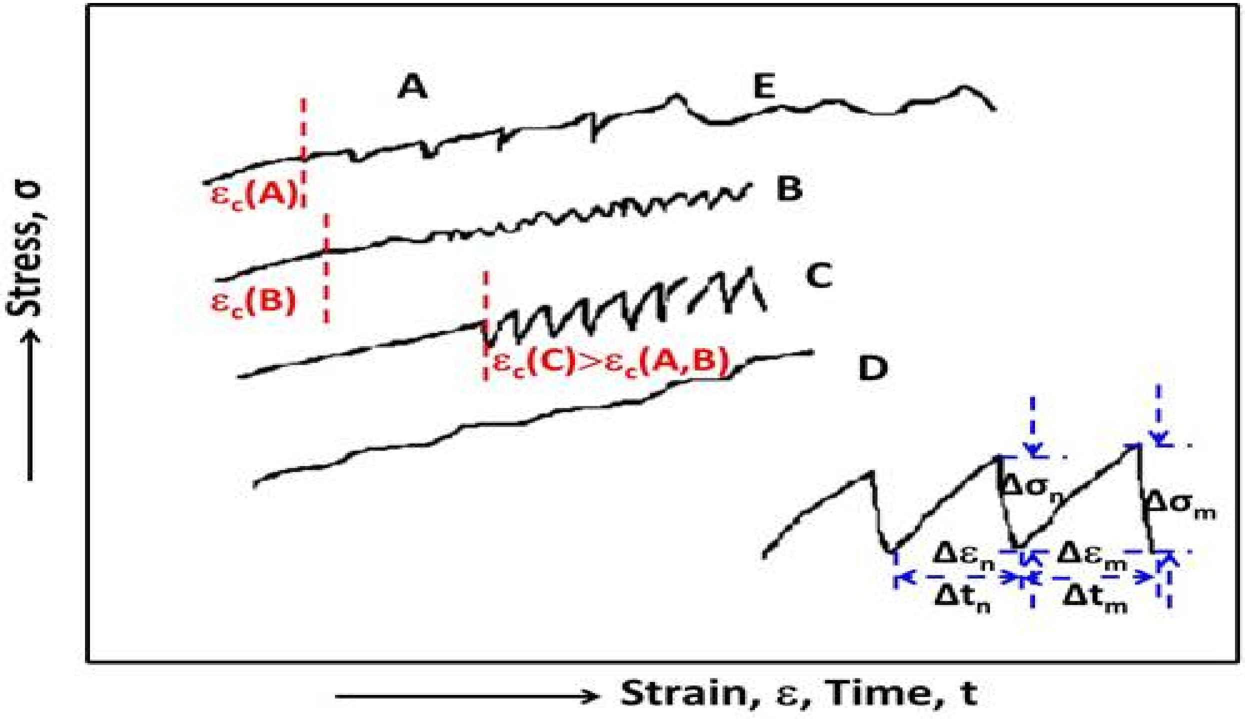


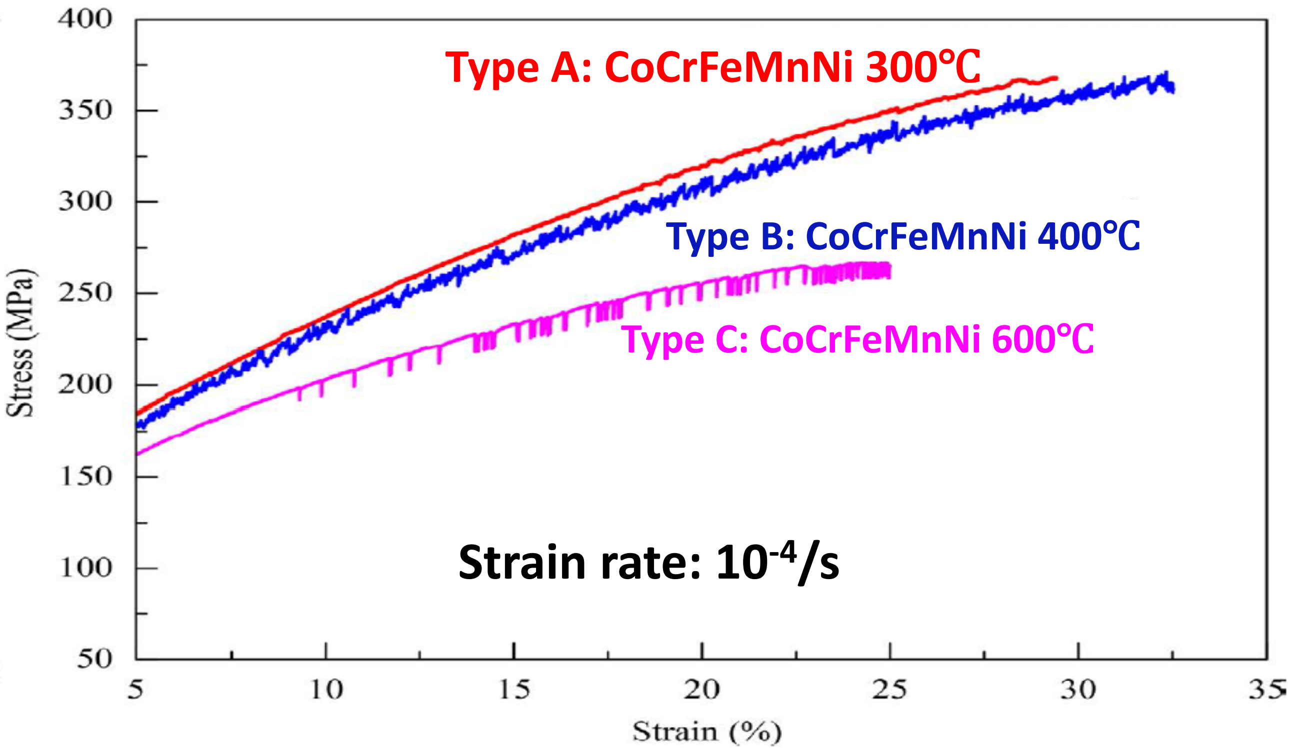
Fracture Toughness vs. Yield Strength Comparison of HEAs, Conventional Alloys, and Bulk Metallic Glasses (BMGs)

1. **B. Gludovatz, A. Hohenwarter, D. Catoor, E. H. Chang, E. P. George, and R. O. Ritchie, Science, 2014, 345(6201), pp. 1153-1158.**

Serration behavior

- Serration behavior, inhomogeneous deformation, appears in certain temperature and strain rate regimes in solid-solution alloys,
- They are also called Portevin-Le Chatelier (PLC) effect, serrated flow, and jerky flow, corresponding to sharp, small-scale jumps in stress-strain curves

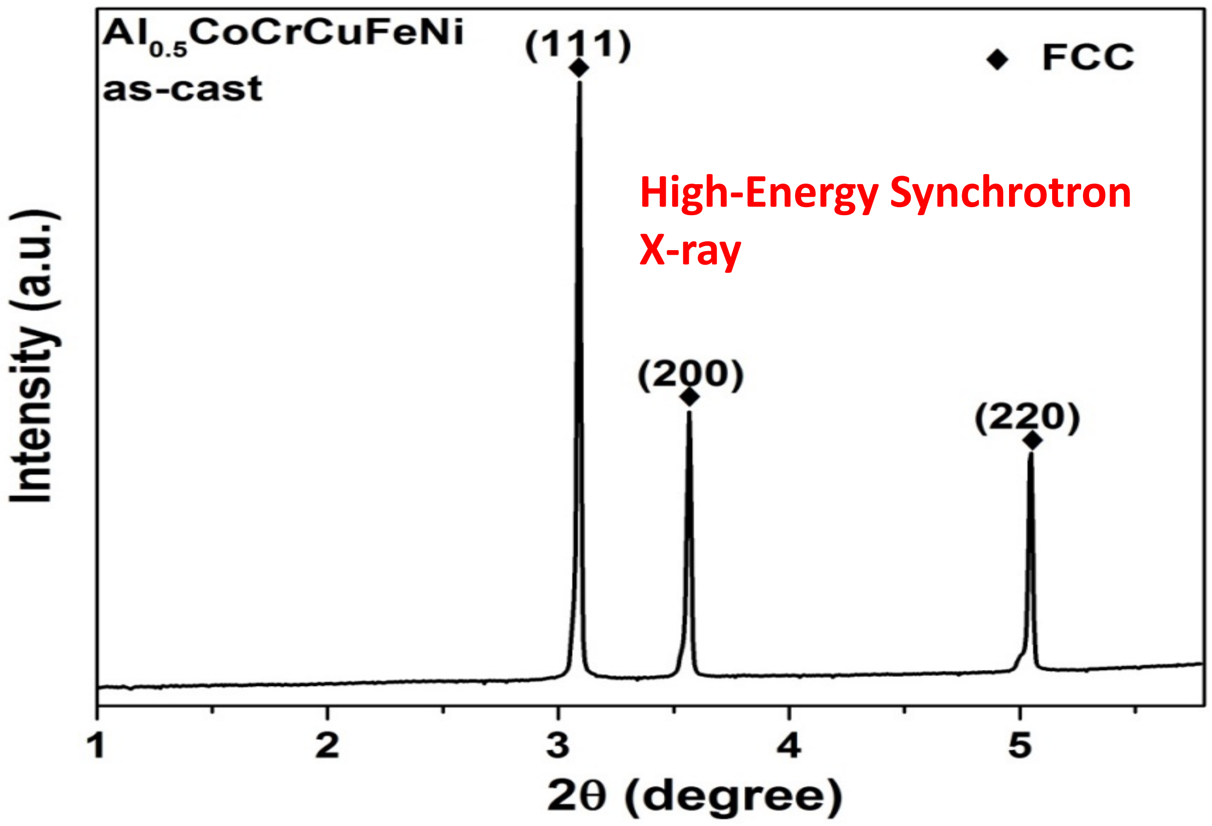


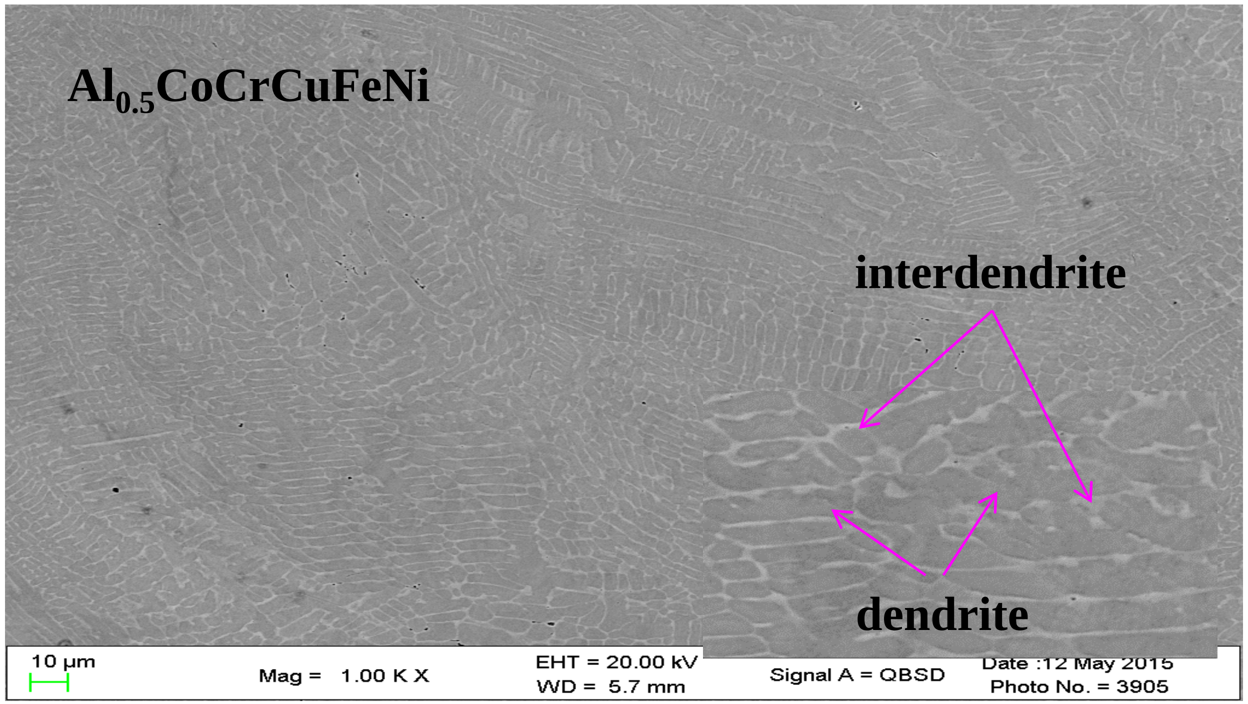


1. P. Rodriguez, "Serrated plastic flow", Bull. Mater. Sci., 1984, 6(4), pp. 653-663.
2. R. Carroll, C. Lee, C. W. Tsai, J. W. Yeh, J. Antonaglia, B. A. Brinkman, M. LeBlanc, X. Xie, S. Y. Chen, P. K. Liaw and K. A. Dahmen, Scientific Reports, 2015, 5, p. 16997.

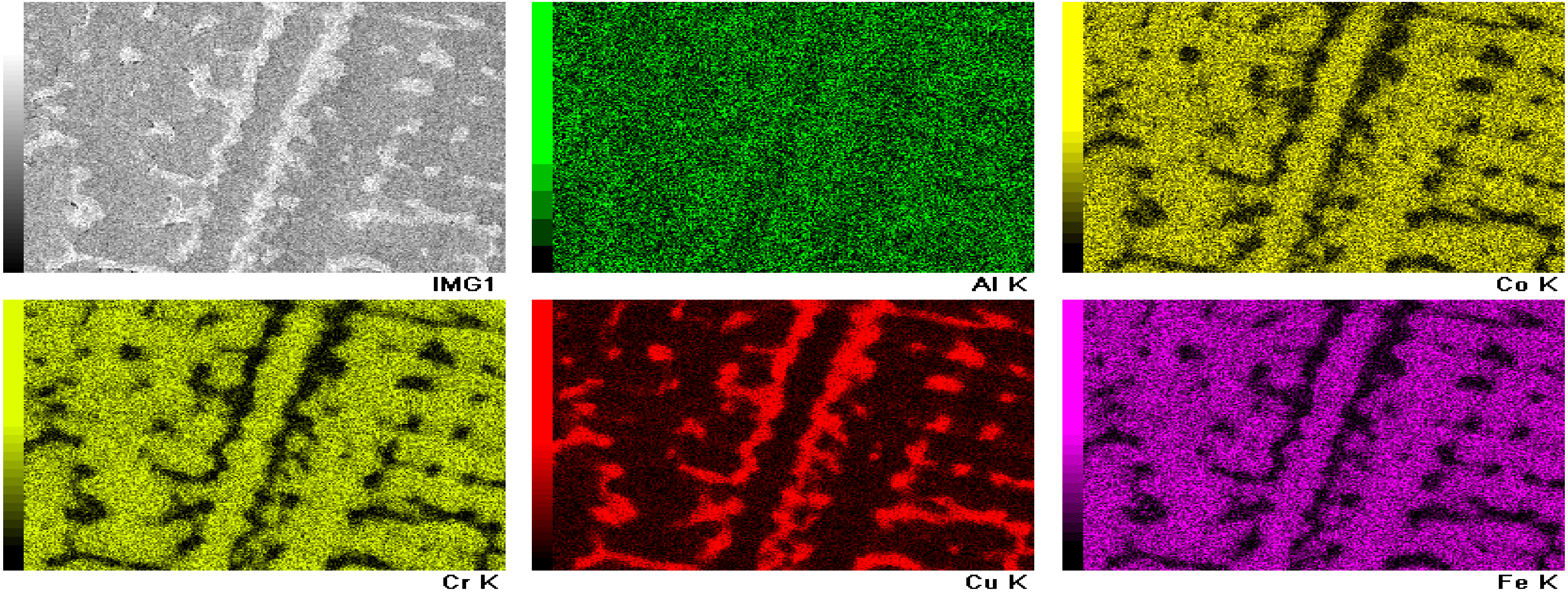
Microstructure at room temperature

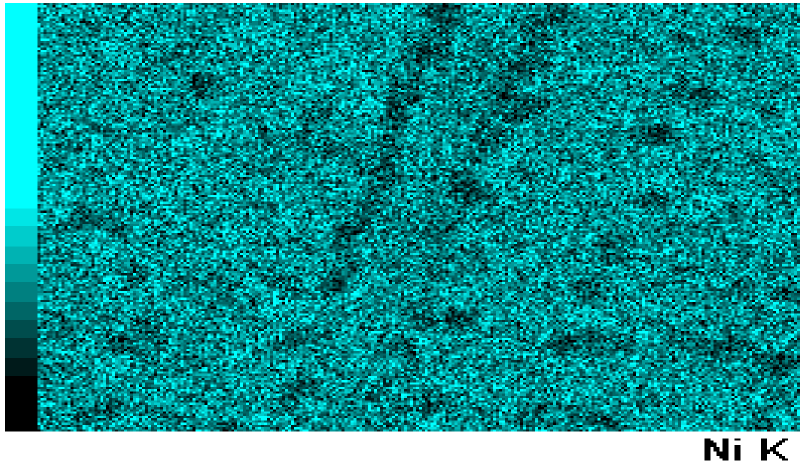
Advanced Photon Source, Argone national laboratory





- **The bright contrast on the scanning electron microscope (SEM) image shows the dendrite and interdendrite structures**
- **The peaks in the synchrotron diffraction patterns appears as a single FCC phase**

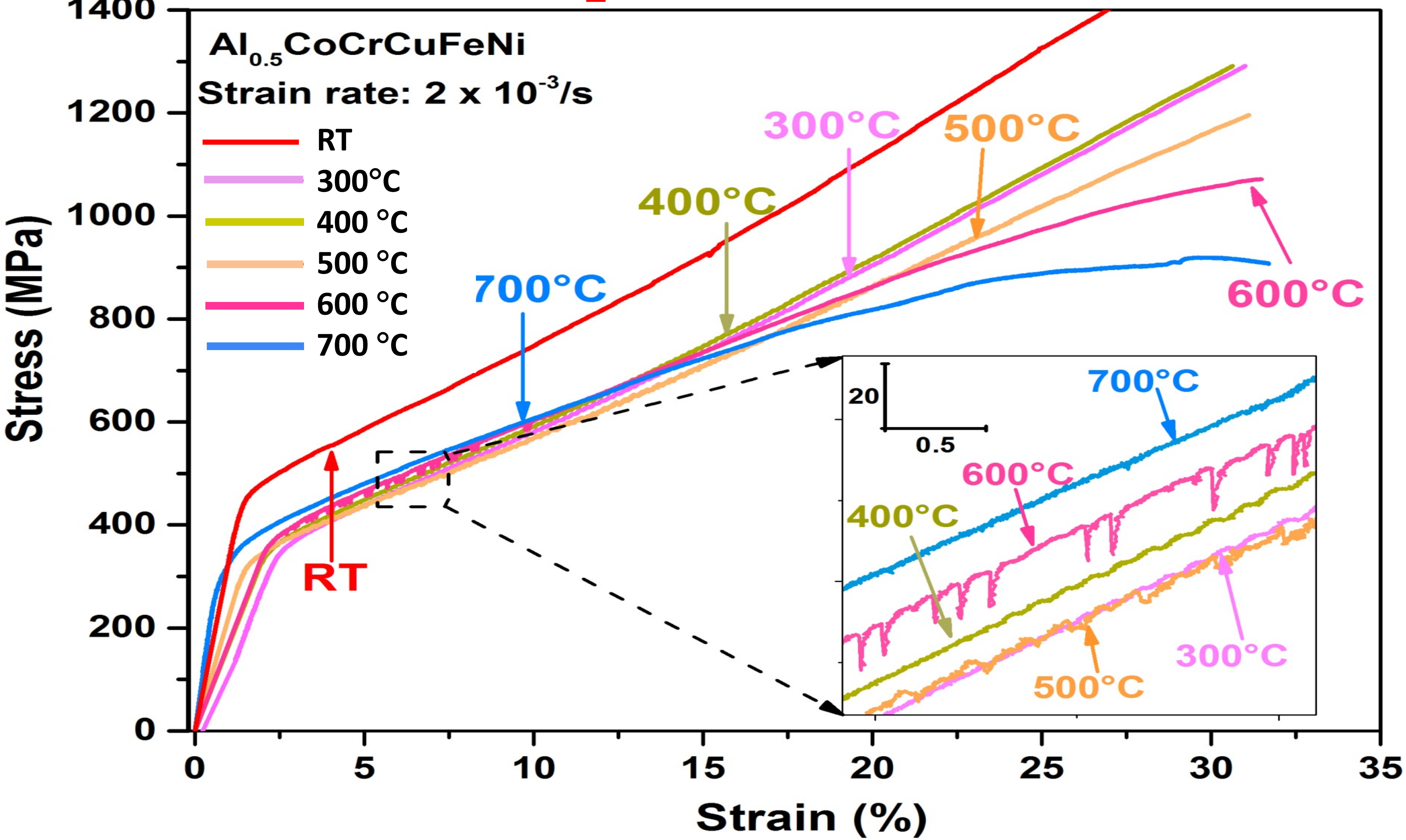




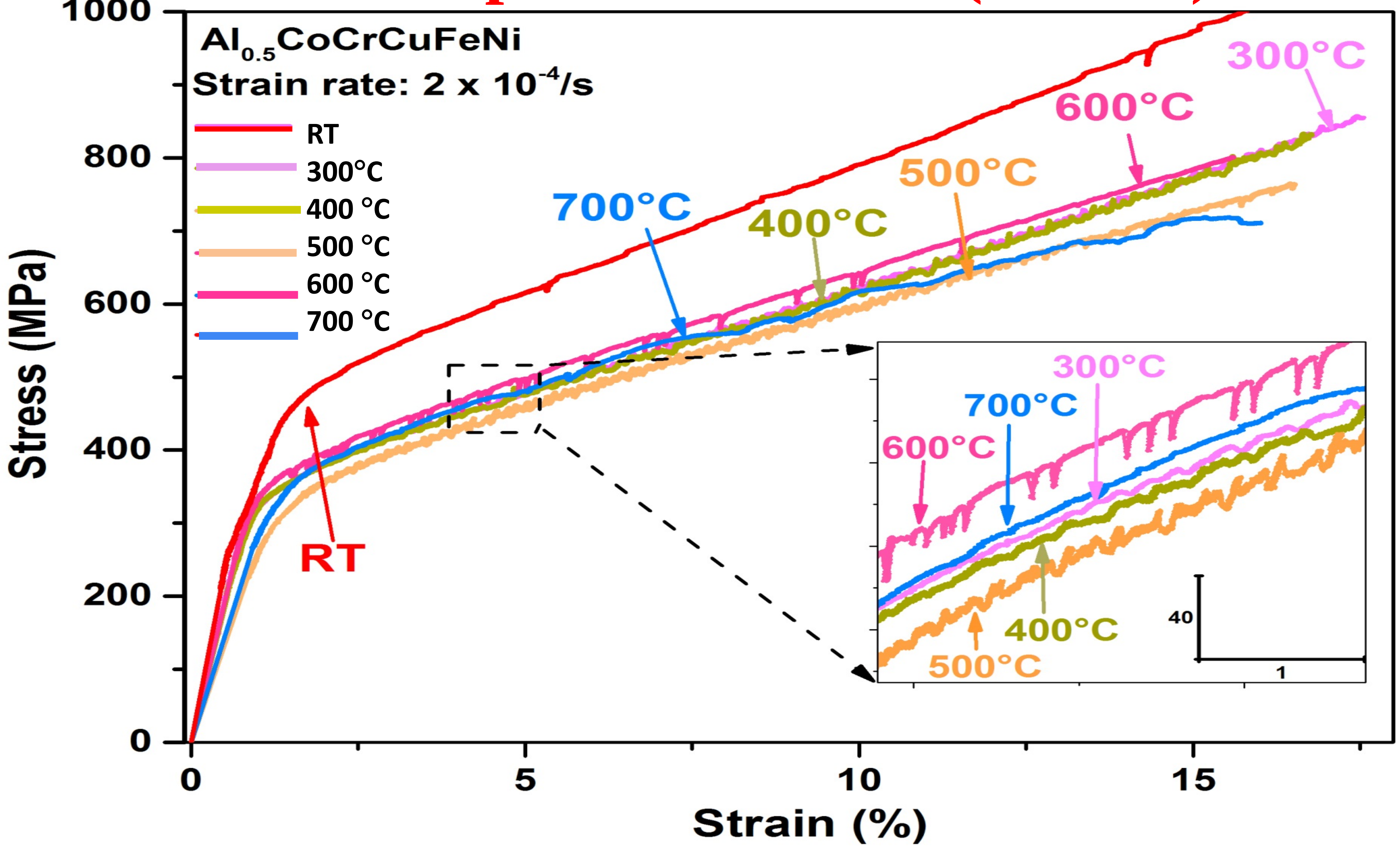
- Energy-dispersive x-ray spectroscopy (EDS) mappings show that the interdendrite is exclusively rich in Cu, consistent with previous investigation.

1. **Tsai C-W, Chen Y-L, Tsai M-H, Yeh J-W, Shun T-T, Chen S-K. Deformation and annealing behaviors of high-entropy alloy Al0.5CoCrCuFeNi. Journal of Alloys and Compounds 2009; 486:427-435.**

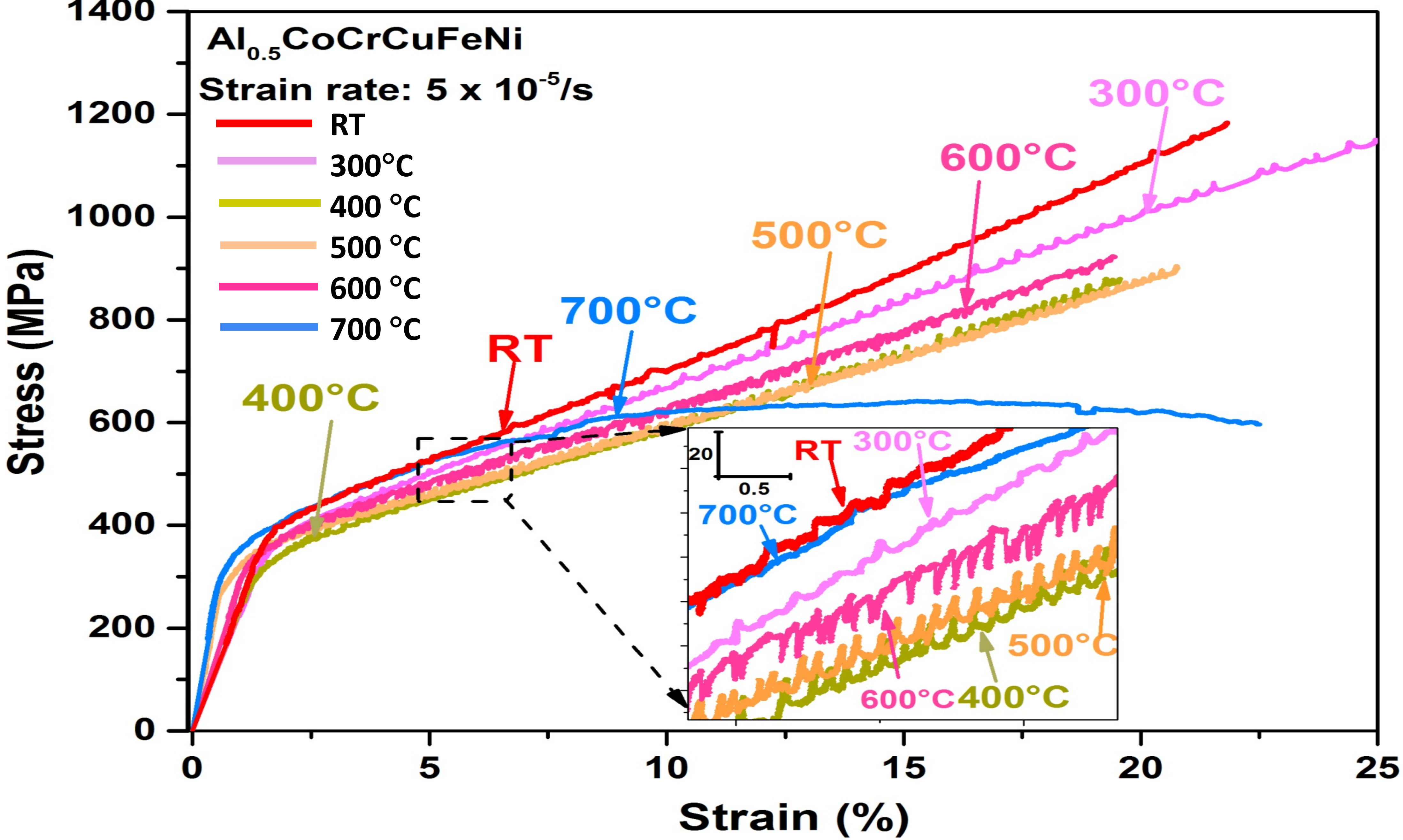
Compression results

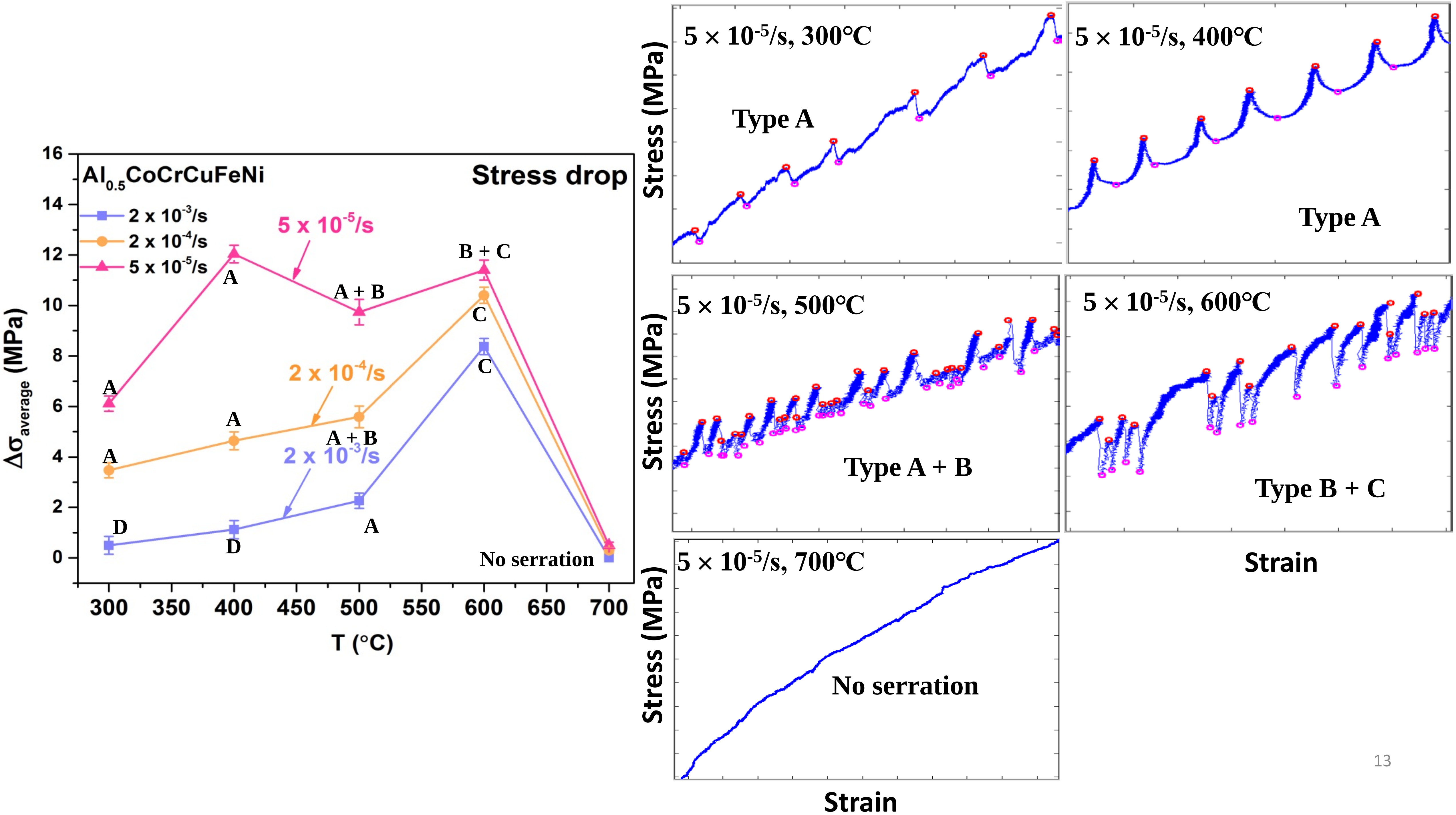


Compression results (Cont'd)

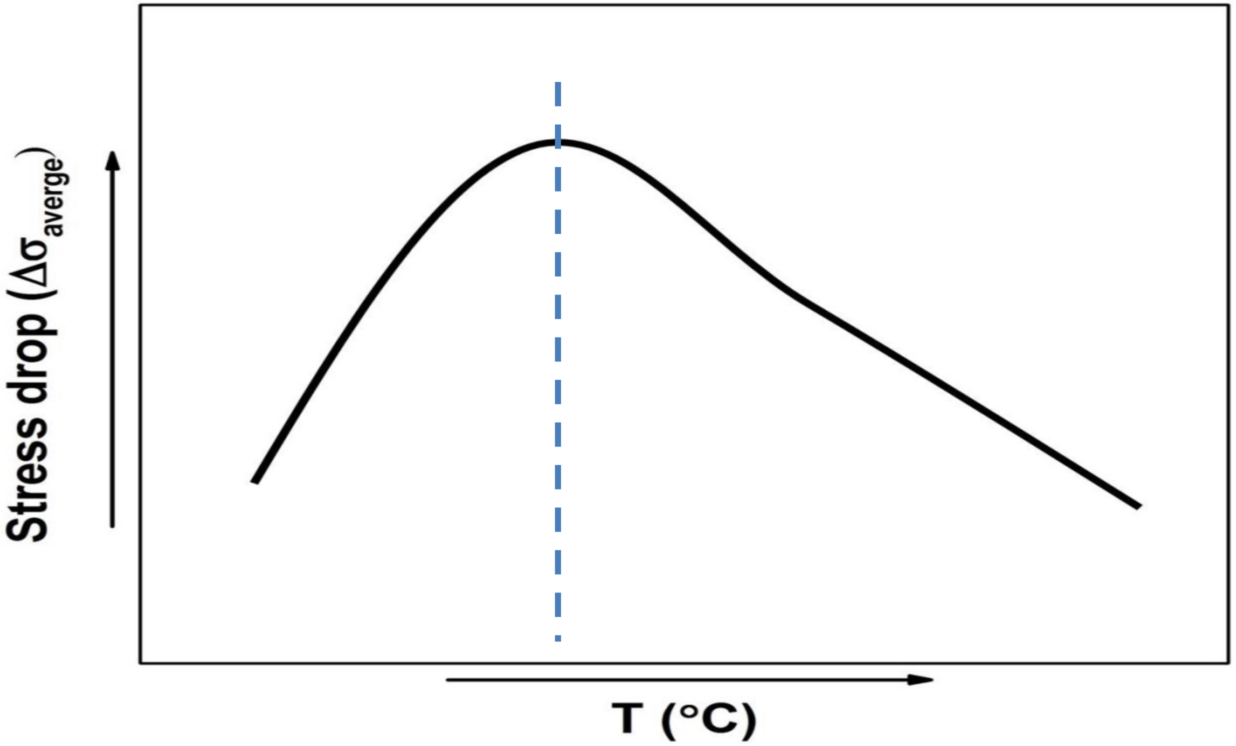


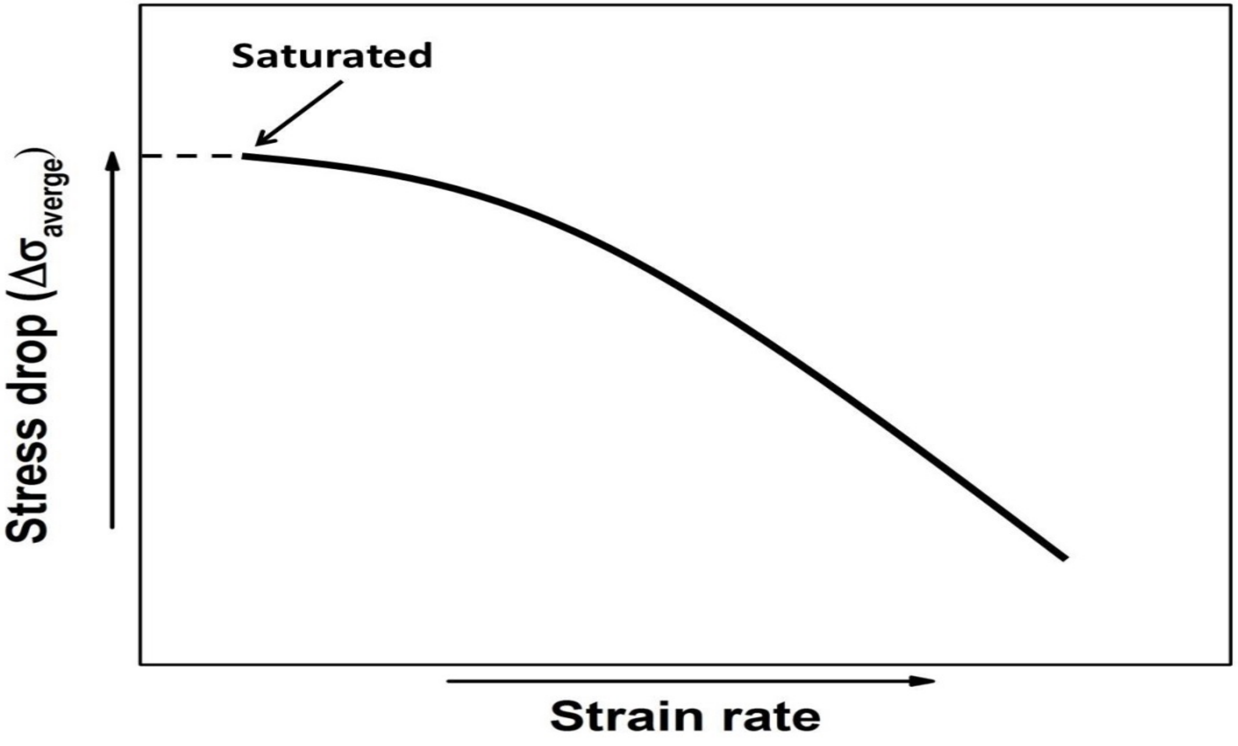
Compression results (Cont'd)




Al0.5CoCrCuFeNi
Stress drop
2 x 10-3/s
2 x 10-4/s
5 x 10-5/s
Δσaverage (MPa)
T (°C)
No serration
5 × 10-5/s, 300°C
Type A
5 × 10-5/s, 400°C
Type A
5 × 10-5/s, 500°C
Type A + B
5 × 10-5/s, 600°C
Type B + C
5 × 10-5/s, 700°C
No serration
Stress (MPa)
Strain

Characterization of serration behavior (Cont’d)





- **High or low temperature cannot stimulate the serrated flow. Only a certain temperature range (300 - 600 °C in our study) can be helpful**

- **Low strain rate is easier for solutes to catch the moving dislocations, resulting in higher stress drop**

Review: Our Simple Analytic Model of Plasticity

(Dahmen, Ben-Zion, Uhl, PRL 2009, Nature Phys. 2011, Carroll, *et al*. Scientific Reports 2015)

One Tuning Parameter:

- Weakening ε
- Applied to Crystals, Bulk Metallic Glasses, HEAs

Two Experimentally Relevant Loading Conditions:

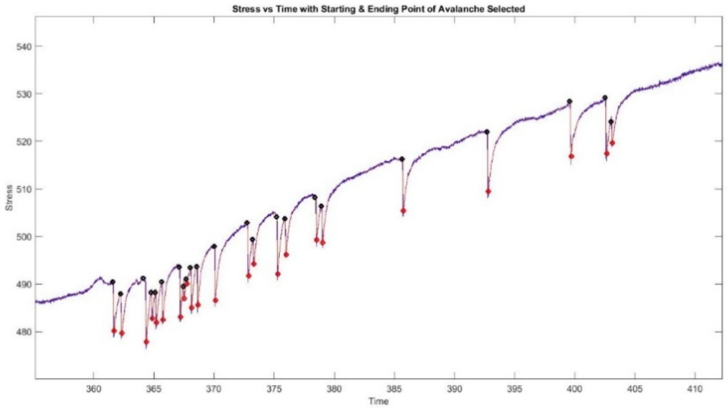
- Linearly increasing strain loading condition
- Linearly increasing stress loading condition

EXACT Predictions in 3 Dimensions (no fitting)

- Histograms of slip-sizes, durations, power spectra, …
- Brittle (ε > 0), ductile (ε = 0) & hardening materials (ε < 0)

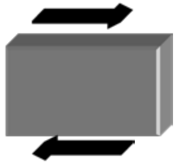
Predictions agree with first experiments,
Many predictions for future experiments…

Stress vs. Time
(Chen & Liaw)



Strain-rate v

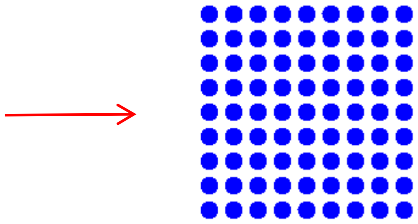
Stress F

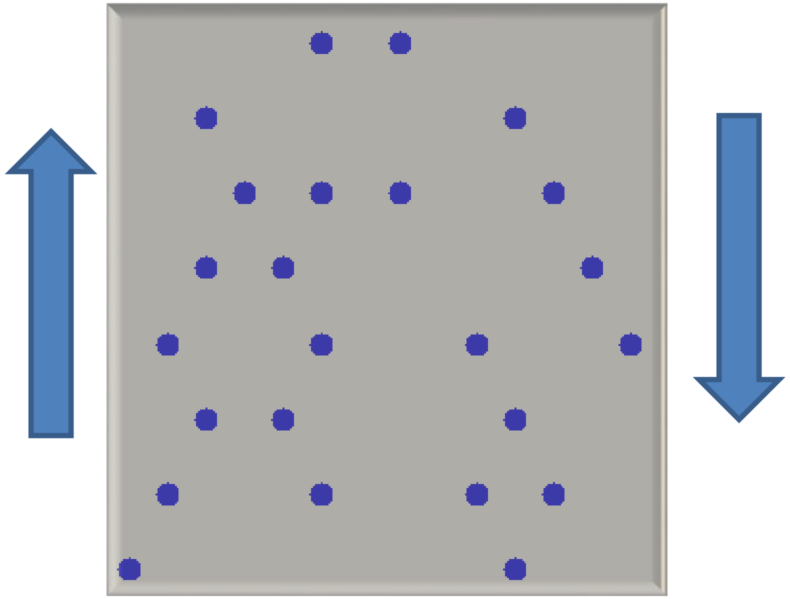


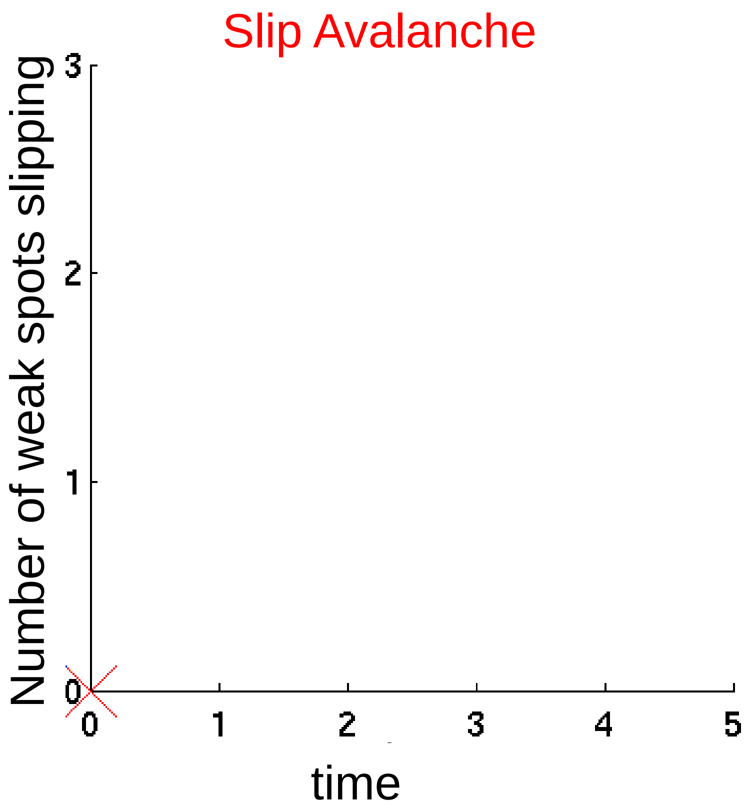
Main Idea of the simple (mean field) model:

Shear material:

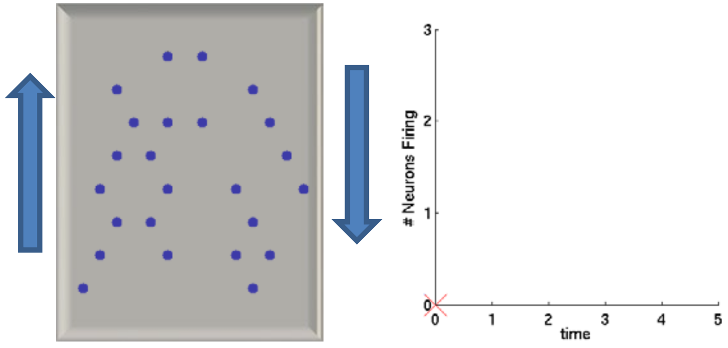
1. Weak spot slips and weakens
   triggers other weak spots to slip in a Slip Avalanche,
   weak spots reheal
2. Repeat

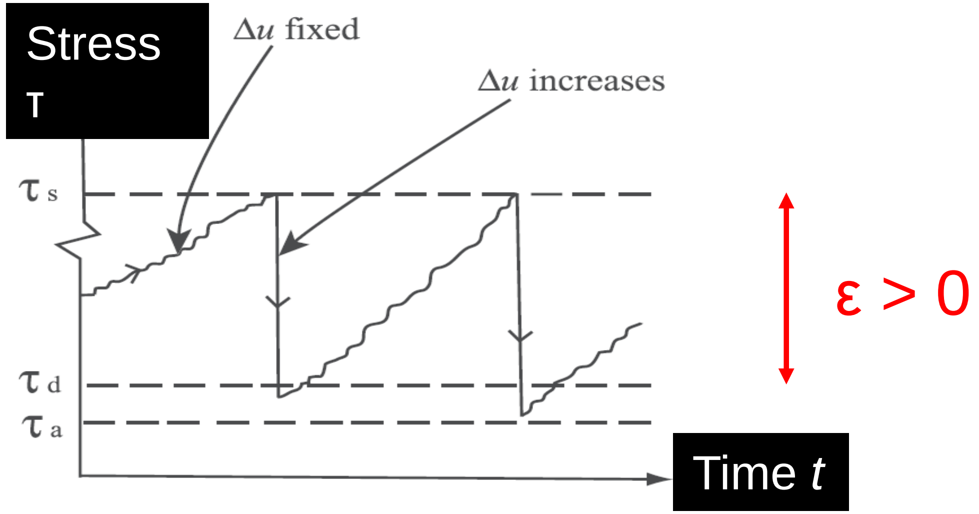






Interpretation through the model:





$$\varepsilon = (\tau_s - \tau_d)/\tau_s = \text{dynamic weakening}$$

weakening (ε > 0)

during failure avalanche:

failed regions get weakened by O(ε)

reheal to old strength after avalanche

Model predictions agree with initial experimental results on the slip statistics at different temperatures and strain rates. (Work in progress).

Coarse Grained Model for Slip Evolution in Heterogeneous Medium:

$$\eta\, \partial u(\mathbf{r},t)/\partial t \;=\; F + \sigma_{int}(\mathbf{r},t) - f_R[u,\ \mathbf{r},\ \text{history}]$$

Slip velocity ~ stress + interaction + Pinning due to heterogeneities

interaction:

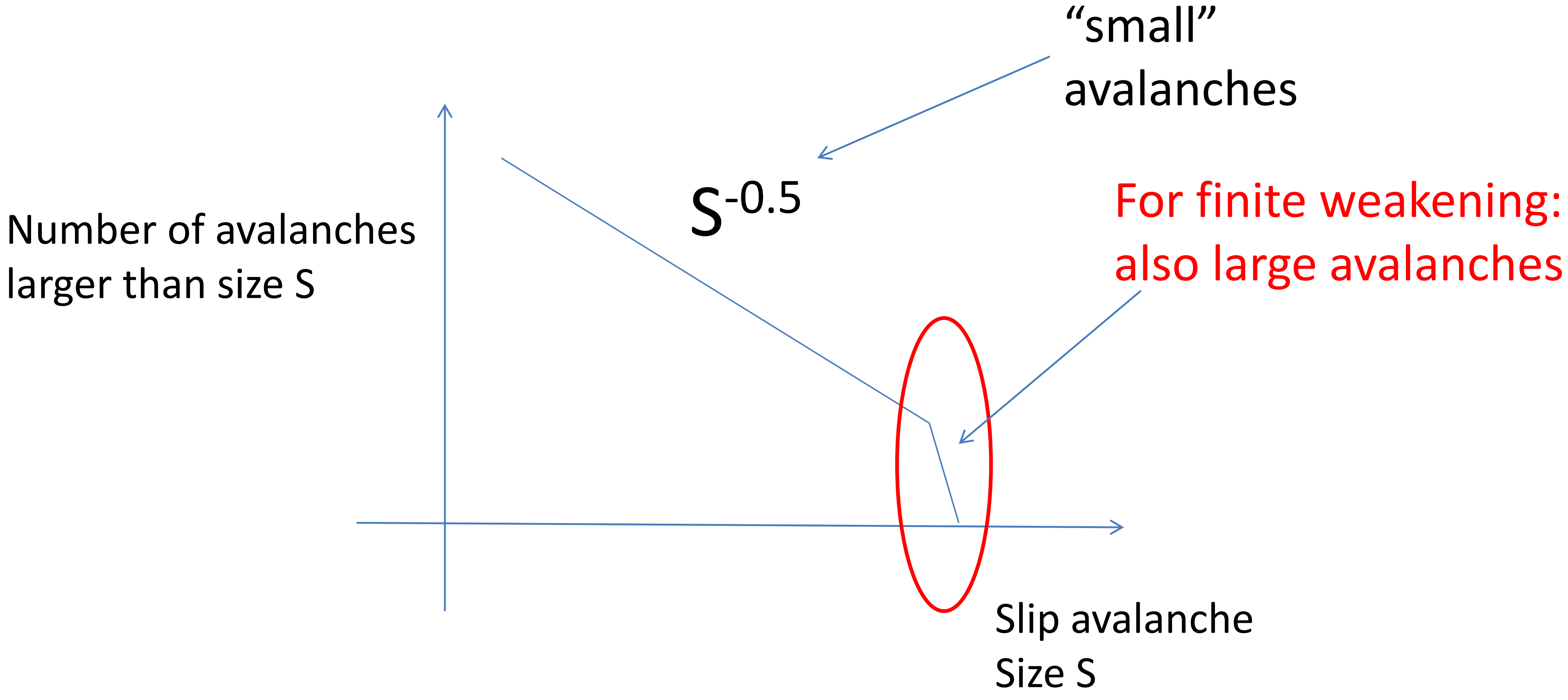
$$\sigma_{int}(\mathbf{r},t) \;=\; \int_{-\infty}^{t} dt' \int d^d r'\ J(\mathbf{r}-\mathbf{r}',\, t-t') \times [u(\mathbf{r}',t') - u(\mathbf{r},t)]$$

Renormalization Group:

Interaction sufficiently long range

→ **Analytic MEAN FIELD THEORY GIVES EXACT RESULTS FOR PHYSICAL DIMENSION !**

For zero weakening model: many predictions, for example power law scaling behavior of avalanche size distributions



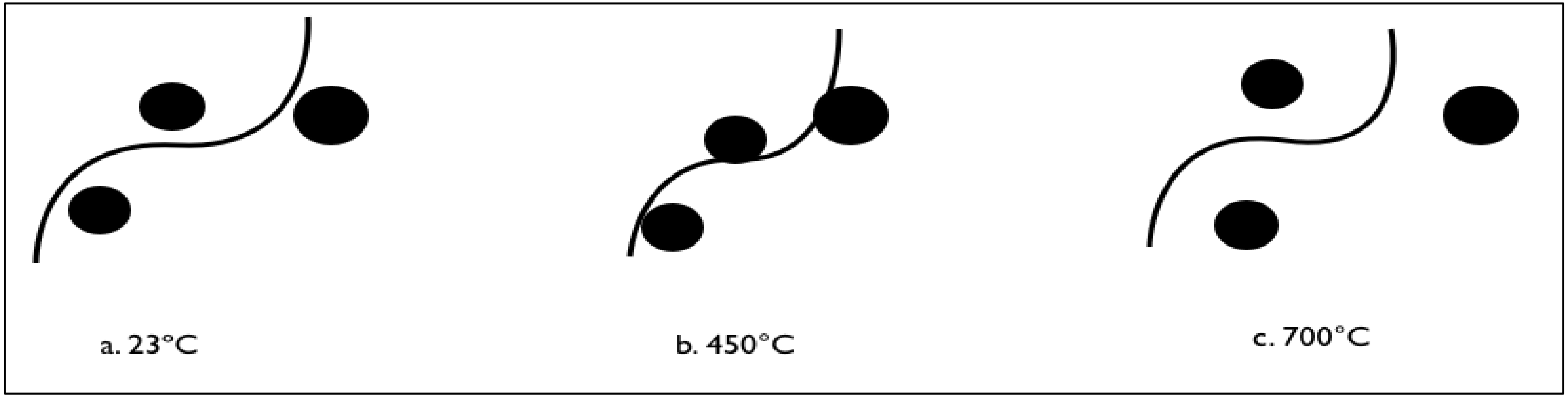
For High Entropy Alloys (Dynamic Strain Aging):

Serrations in *temperature widow*: for 300°C < Temperature < 600 °C

Model: Weakening ε depends on Temperature & Strain-Rate

In this range, **higher temperature** means faster (stronger) pinning of dislocation => **greater "weakening"** when dislocations break loose

Weakening ε ~ Dislocation-Pinning-Rate (T)/Strain-Rate



Robert Carroll, Chi Lee, Che-Wei Tsai, Jien-Wei Yeh, James Antonaglia, Braden Brinkman, Michael LeBlanc, Xie Xie, Shuying Chen, Peter K. Liaw, and Karin A. Dahmen, Experiments and Model for Serration Statistics in Low-Entropy, Medium-Entropy, and High-Entropy Alloys, Scientific Reports 5, 16997 (2015), and S.Y. Chen et al. preprint in preparation (2017)

1. Testing the model against predictions for macroscopic samples of different materials under tension and compression

(experiments: P. Liaw, S.Y. Chen, J.W. Yeh,
data analysis and theory: Shu Li, B. Carrol, K.A. Dahmen)

Experiments on different materials agree with model predictions:

higher temperature ⇒ higher weakening ⟹ materials transitions from A to B to C PLC bands

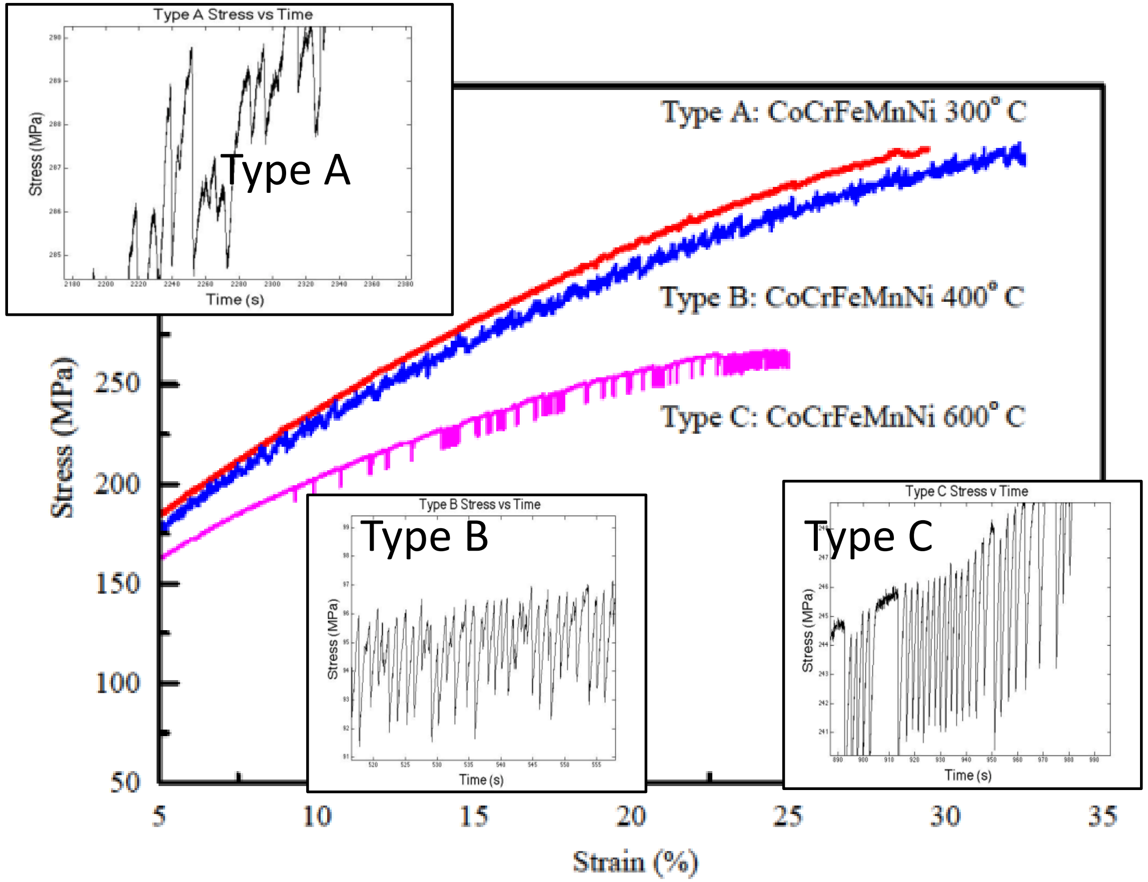
$Al_{0.5}CoCrCuFeNi$ (compression)

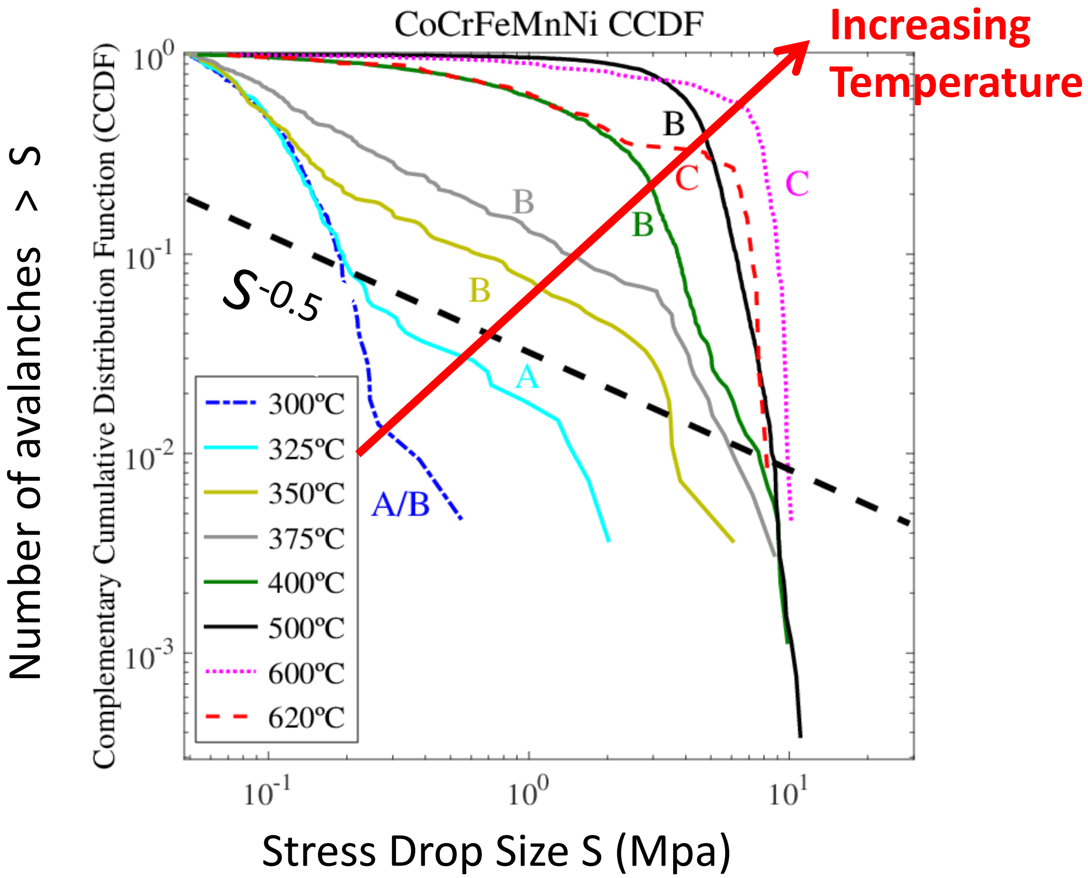
Strain Rate (/s)	Temperature (℃)	Serration Behavior	PLC- Band Type
2E-3	400	Yes	A or D
	500	Yes	A
2E-4	400	Yes	A
	500	Yes	A/B
	600	Yes	C
	700	None	
5E-5	400	Yes	A
	500	Yes	A/B
	600	Yes	B/C

CoCrFeMnNi (tension)

Strain-rate	Temperature (°C)	Serration Behavior	PLC-Band Type
1×10^{-2}/s	300	None	None
	400	Yes	A
	500	Yes	A
	600	Yes	A
1×10^{-3}/s	300	Yes	A
	400	Yes	A
	500	Yes	B
	600	Yes	B
1×10^{-4}/s	300	Yes	A
	400	Yes	B
	500	Yes	B
	600	Yes	C

Slip size distributions for High Entropy Alloys agree with Mean Field Model Predictions: Higher temperature means higher "weakening" parameter ε





Tension: Robert Carroll, Chi Lee, Che-Wei Tsai, Jien-Wei Yeh, James Antonaglia, Braden Brinkman, Michael LeBlanc, Xie Xie, Shuying Chen, Peter K. Liaw, and Karin A. Dahmen, Experiments and Model for Serration Statistics in Low-Entropy, Medium-Entropy, and High-Entropy Alloys, Scientific Reports 5, 16997 (2015), and **similar under compression,** see S.Y. Chen et al. preprint in preparation (2017)

Comparison of model predictions to **nanopillar compression experiments**

Model agrees with HEA **Nano-Pillar Compression**

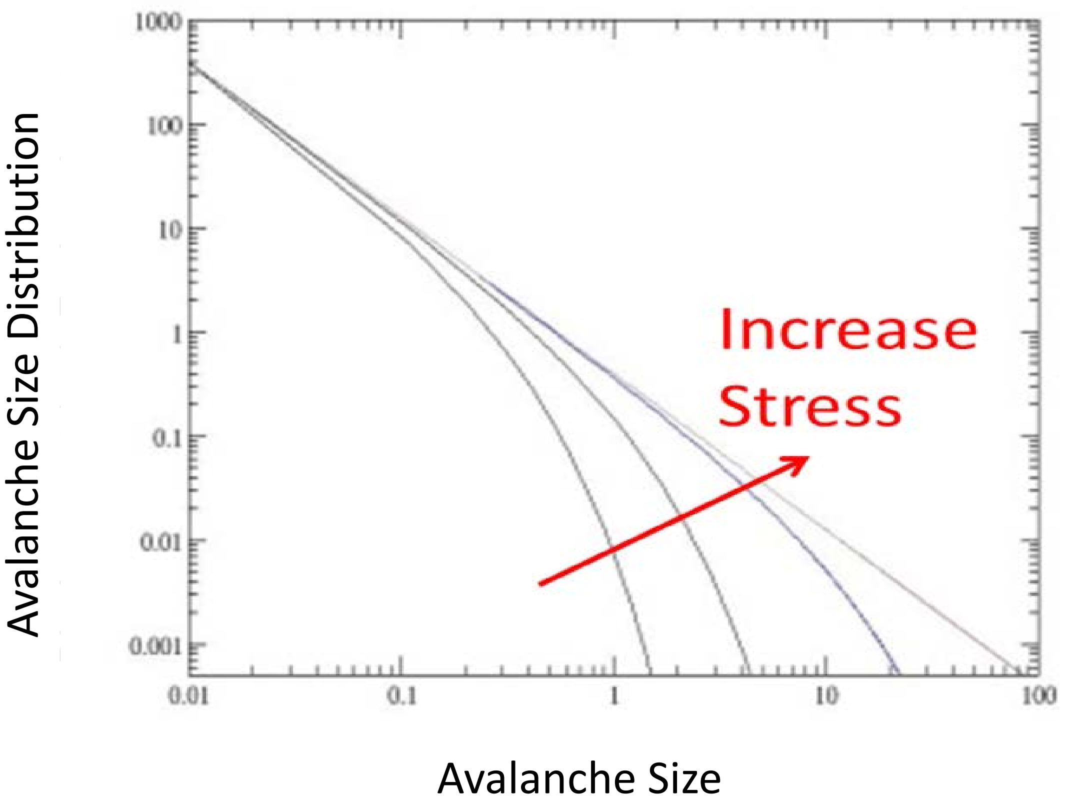
Yang Hu, Shu Li, Wei Guo, Peter Liaw, KD, and Jian-Min Zuo, submitted (2016)

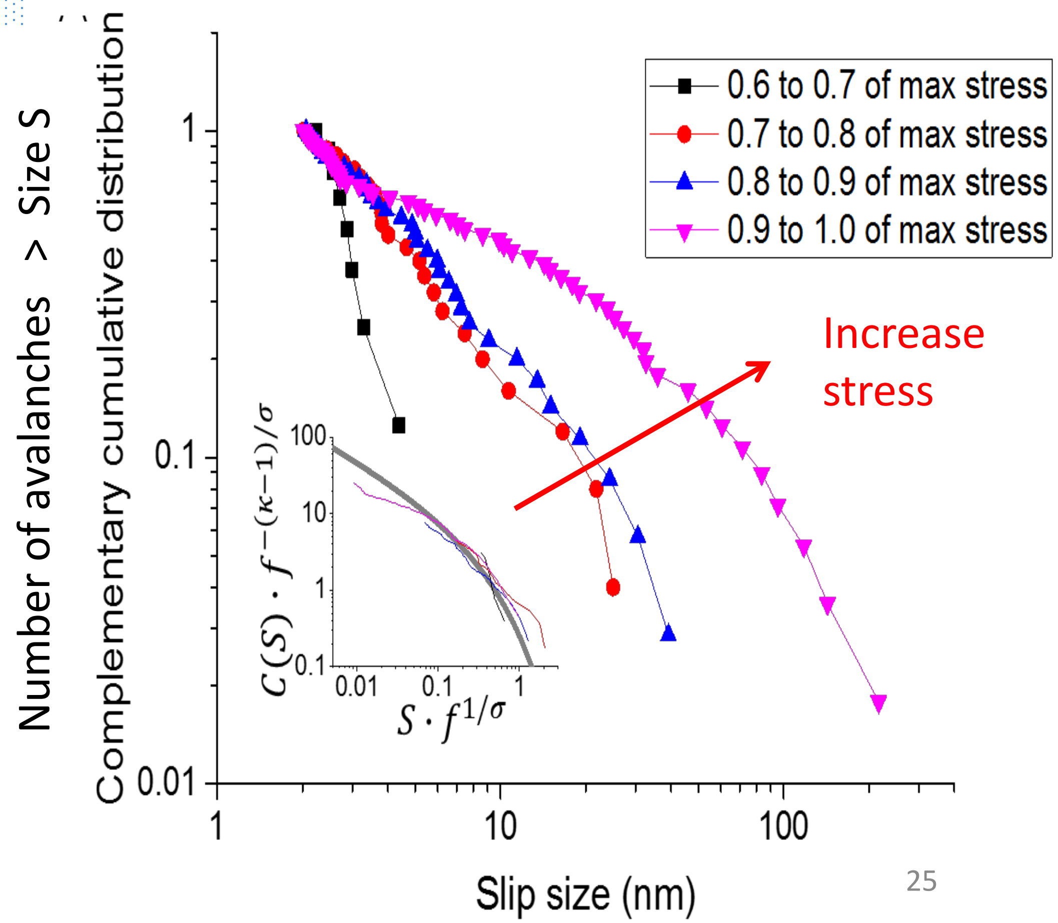
($Al_{0.1}CoCrFeNi$)

Model prediction:

$D(S) \sim 1/s^{\kappa}\,\mathcal{D}(s\,(F-F_c)^{1/\sigma})$ with $\kappa = 1.5$ and $\sigma = 2$

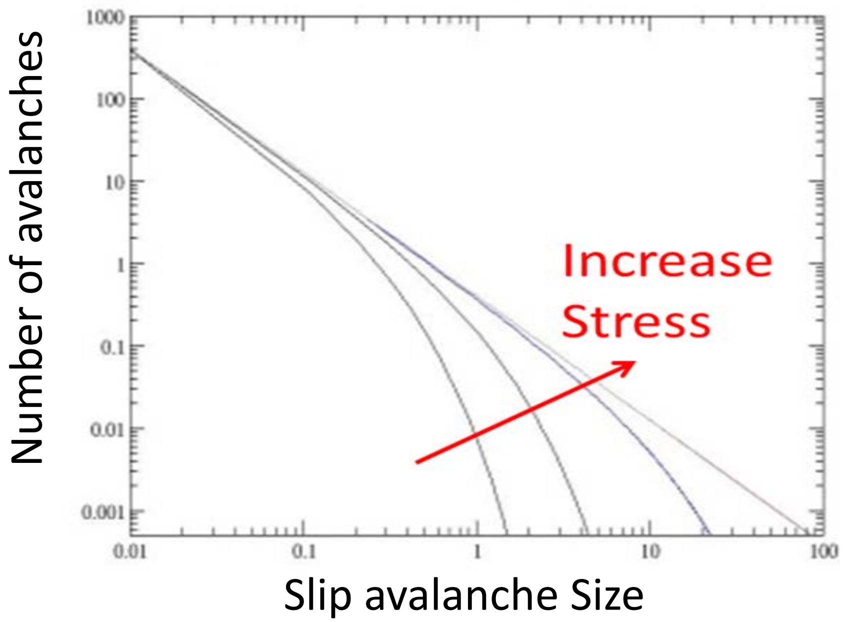
(a)

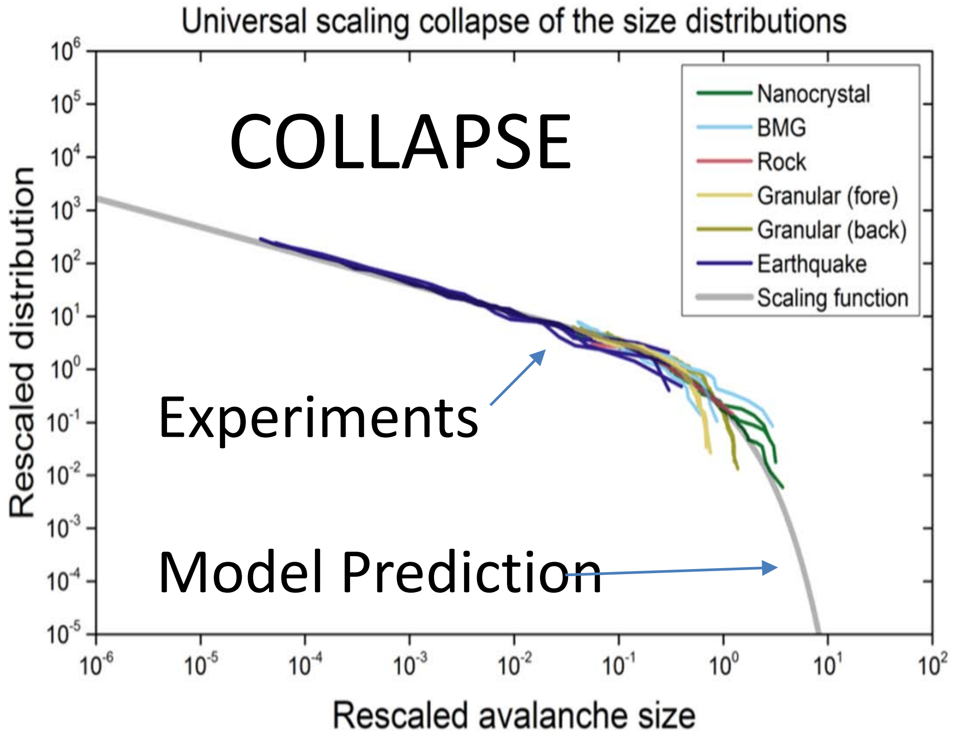




Experiments spanning 12 decades in size agree with HEA experiments on macroscopic samples and nm samples and with mean field model predictions:

Mean Field Model Prediction: Experiments on 5 Systems agree:

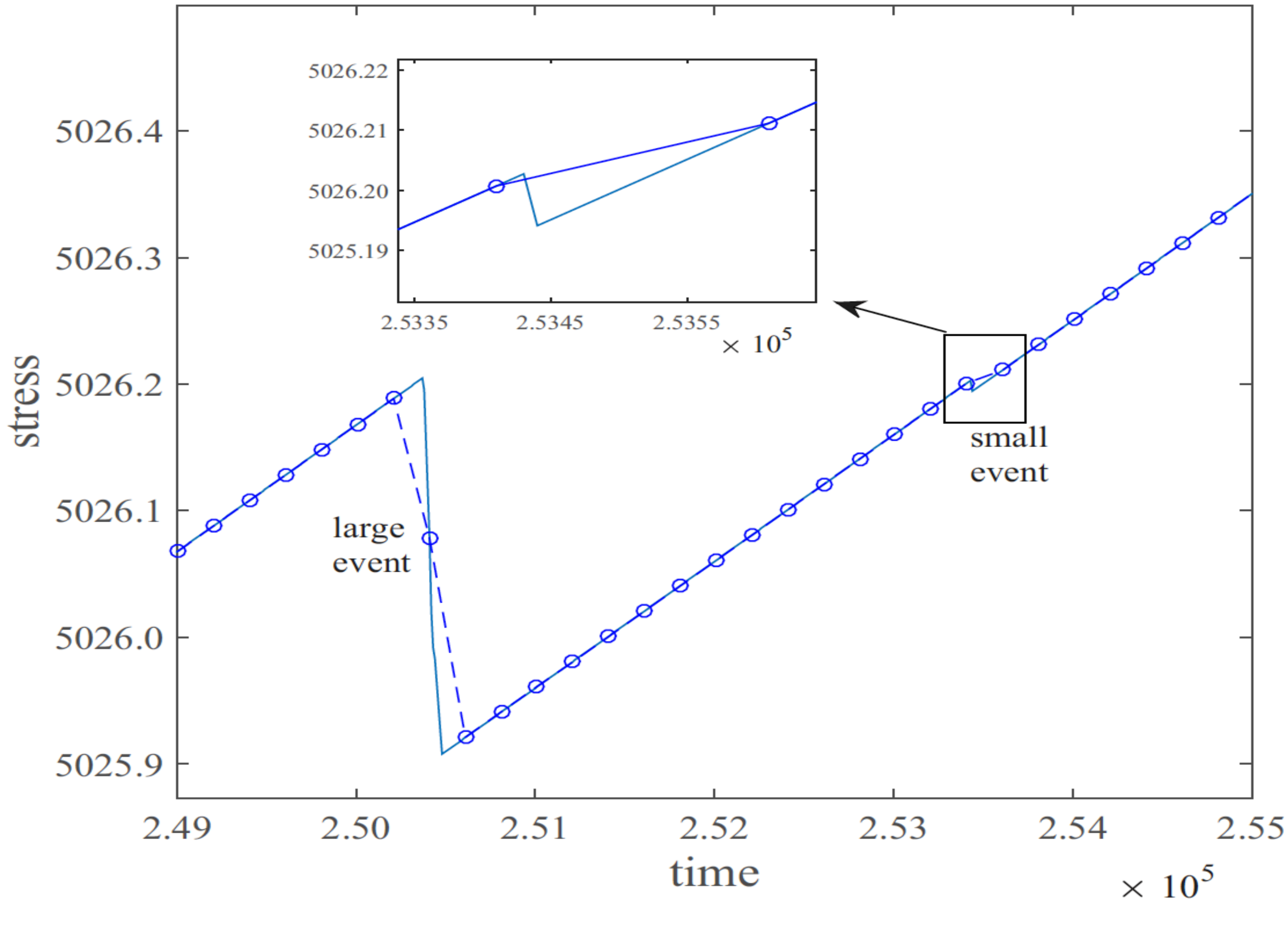




Jonathan T. Uhl, Shivesh Pathak, Danijel Schorlemmer, Xin Liu, Ryan Swindeman, Braden A.W. Brinkman, Michael LeBlanc, Georgios Tsekenis, Nir Friedman, Robert Behringer, Dmitry Denisov, Peter Schall, Xiaojun Gu, Wendelin J. Wright, Todd Hufnagel, Andrew Jennings, Julia R. Greer, P.K. Liaw, Thorsten Becker, Georg Dresen, and KD (Scientific Reports, 2015)

How to avoid effects of low time resolution:

(Physical Review E **94**, 052135 (2016))



Conclusion on Experiments and Mean Field Model:

1. Fit-free model predictions for the statistics of slips (noise) in the stress strain curves agree with experimental data on:

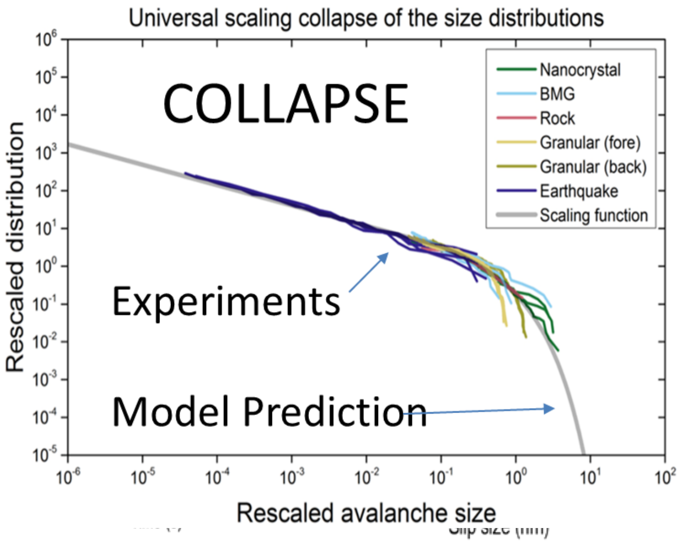
- High Entropy Alloys (**macro** and **nano** scale):

Dependence on temperature, strain rate, stress.

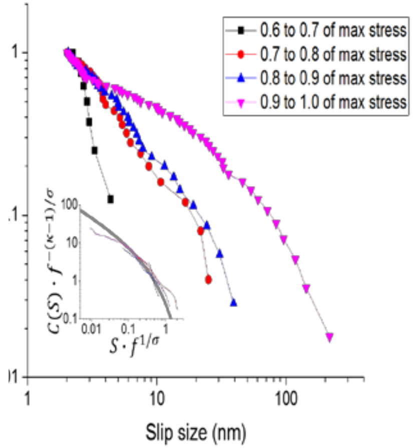
- Largest serrations seen within

300°C < Temperature < 600 °C

- Larger serrations for slower strain rates

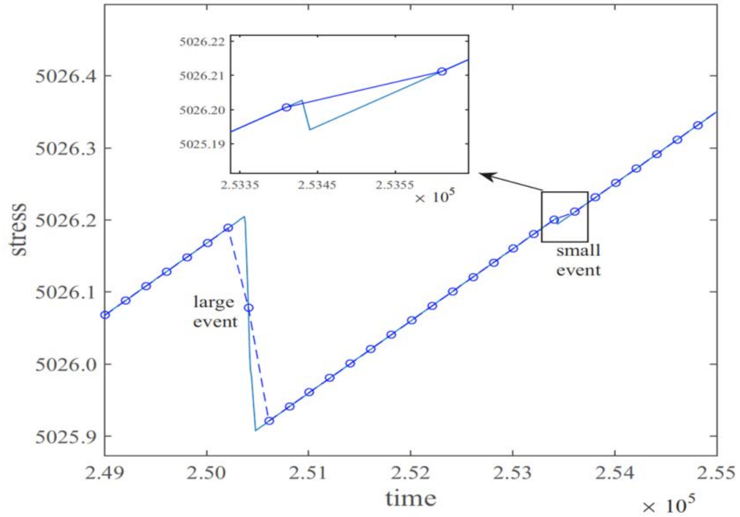


nm scale HEAs:



2. Stress dependence in nm scale HEAs

Agrees with previous results spanning 12 decades in length: Nano-crystals, Bulk Metallic Glasses, Granular Materials , Rocks, Earthquakes



3. New general method to avoid low time resolution effects

MS&T Symposium:

COLLECTIVE PHENOMENA IN MATERIALS (3)

To be held at the 2018 Materials Science and Technology (MS&T) Conference,
October 14-18, 2018, Columbus OH

ABSTRACT DEADLINE: *March 15, 2018*

www.matscitech.org

Papers will be published in Metallurgical and Materials Transactions.

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University of Illinois at Urbana Champaign

P. K. Liaw and Dr. G. Y. Wang
The University of Tennessee, Knoxville

Publications

1. M.-R. Chen, S.-J. Lin, J.-W. Yeh, S.-K. Chen, Y.-S. Huang, and C.-P. Tu, "Microstructure and Properties of Al0.5CoCrCuFeNiTix (x = 0–2.0) High-Entropy Alloys", Materials Transactions, 2006, 47(5), pp. 1395-1401.
2. J. Antonaglia, X. Xie, G. Schwarz, M. Wraith, J. Qiao, Y. Zhang, P. K. Liaw, J. T. Uhl, and K. A. Dahmen, "Tuned Critical Avalanche Scaling in Bulk Metallic Glasses", Scientific Reports, 2014, 4, p. 4382.
3. S. Y. Chen, X. Yang, K. Dahmen, P. Liaw, and Y. Zhang, "Microstructures and Crackling Noise of AlxNbTiMoV High Entropy Alloys", Entropy, 2014, 16(2), pp. 870-884.
4. H. L. Hong, Q. Wang, C. Dong, and P. K. Liaw, "Understanding the Cu-Zn Brass Alloys Using a Short-range-order Cluster Model: Significance of Specific Compositions of Industrial Alloys", Scientific Reports, 2014, 4, p. 7065.
5. E. W. Huang, J. Qiao, B. Winiarski, W. J. Lee, M. Scheel, C. P. Chuang, P. K. Liaw, Y. C. Lo, Y. Zhang, and M. Di Michiel, "Microyielding of Core-Shell Crystal Dendrites in a Bulk-Metallic-Glass Matrix Composite", Scientific Reports, 2014, 4, p. 4394.

Publications (Cont'd)

6. L. Huang, E. M. Fozo, T. Zhang, P. K. Liaw, and W. He, "Antimicrobial Behavior of Cu-bearing Zr-based Bulk Metallic Glasses", Materials Science and Engineering: C Materials for Biological Applications., 2014, 39, pp. 325-9.
7. H. Jia, F. Liu, Z. An, W. Li, G. Wang, J. P. Chu, J. S. C. Jang, Y. Gao, and P. K. Liaw, "Thin-Film Metallic Glasses for Substrate Fatigue-Property Improvements", Thin Solid Films, 2014, 561, pp. 2-27.
8. Z. Tang, L. Huang, W. He, and P. K. Liaw, "Alloying and Processing Effects on the Aqueous Corrosion Behavior of High-Entropy Alloys", Entropy, 2014, 16(2), pp. 895-911.
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1. Micro-segregation and Metastable Phase Stability of Cast Ti-Zr-Hf-Ni-Pd-Pt High Entropy Alloys, Y. Yokoyama, S. Itoh, Y. Murakami, I. Narita, G. Wang, and P. K. Liaw.
2. Modeling Plastic Deformation and the Statistics of Serrations in the Stress Versus Strain Curves of Bulk Metallic Glasses, K. Dahmen, J. Antonaglia, X. Xie, J. W. Qiao, Y Zhang, J. Uh, and P. K. Liaw.
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6. Ultra Grain Refinement in High Entropy Alloys: N. Tsuji, I. Watanabe, N. Park, D. Terada, A. Shibata, Y. Yokoyama, P. K. Liaw.

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7. 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.
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10. 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.
11. Characterizing Multi-component Solid Solutions Using Order Parameters and the Bragg-Williams Approximation, L. Santodonato, and P. K. Liaw.
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13. 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.
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17. University of Science and Technology, Beijing, China, June 9, 2014 (Invited) Characterization of Serrated Flows in High-Entropy Alloys and Bulk-Metallic Glasses, P. K. Liaw.

18. Beihang University, Beijing, China, June 10, 2014 (Invited) Characterization of Serrated Flows in High-Entropy Alloys and Bulk-Metallic Glasses, P. K. Liaw.

19. Workshop on Deformation, Damage and Life Prediction of Structural Materials, National Institute of Materials Science, Japan, June 23-24, 2014 (Keynote) Fatigue Behavior of Bulk Metallic Glasses and High Entropy Alloys, Peter K. Liaw.

20. 2014 Gordon Research Conferences, Hong Kong, China, July 20-25, 2014 (poster) Loading Condition Effects on the Serrated Flows in Bulk Metallic Glasses (BMGs), X. Xie, J. Antonaglia, J. W. Qiao, Y. Zhang, G. Y. Wang, K. A. Dahmen, and P. K. Liaw.

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22. Central South University, Changsha, Hunan, China, July 26th, 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.

2014

Presentations (Cont'd)

23. Dalian University of Technology, Dalian, Liaoning, China, July 28th, 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.

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25. 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.

26. 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

27. Mechanical Response of Zr-based BMG after Mechanical Rejuvenation by High-Pressure Torsion, Koichi Tsuchiya; Fanqiang Meng; Yoshihiko Yokoyama; Karin Dahmen; Peter Liaw.

28. Strength and Deformation of Individual Phases in High-Entropy Alloys, A. Giwa; Haoyan Diao; Xie Xie; Shuying Chen; Zhi Tang; Karin Dahmen; Peter Liaw; Julia Greer.

29. Temperature Evolution in Bulk Metallic Glasses Under Different Loading Conditions, Xie Xie; Junwei Qiao; Gongyao Wang; Yoshihiko Yokoyama; Karin Dahmen; Peter Liaw.

30. Xe Ion Irradiation Induced Surface Homogeneity in a Metallic Glass, Xilei Bian; Gang Wang; K.C. Chan; H.C. Chen; Long Yan; Na Zheng; A. A. Teresiak; Yulai Gao; Qijie Zhai; Norbert Mattern; Jurgen Eckert; P.K. Liaw; Karin Dahmen.

31. Modeling Plastic Deformation and the Statistics of Serrations in the Stress versus Strain Curves of Bulk Metallic Glasses and Other Materials, Karin Dahmen; James Antonaglia; Wendelin Wright; Xiaojun Gu; Xie Xie; Michael LeBlanc; Junwei Qiao; Yong Zhang; Todd Hufnagel; Jonathan Uhl; Peter Liaw.

2015 TMS Meeting Orlando, FL, USA, March 15-19, 2015

32. On the Friction Stress and Hall-Petch Coefficient of a Single Phase Face-Centered-Cubic High Entropy Alloy, Al0.1FeCoNiCr, Nilesh Kumar, Mageshwari Komarasamy, Zhi Tang, Rajiv Mishra, and Peter Liaw.

33. Al-Co-Cr-Fe-Ni Phase Equilibria and Properties, Zhi Tang, Oleg Senkov, Chuan Zhang, Fan Zhang, Carl Lundin, and Peter Liaw.

34. Fatigue Behavior of an Al0.1CoCrNiFe High Entropy Alloy, Bilin Chen, Xie Xie, Shuying Chen, Ke An, and Peter Liaw.

35. Flow and Fracture Behavior of a High Entropy Alloy, Yong Zhang, Peter Liaw, and John Lewandowski.

36. Deformation Twinning in the High-Entropy Alloy Induced by High Pressure Torsion at Room Temperature, Gong Li1, P. F. Yu, P. K. Liaw, and R. P. Liu.

37. 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.

38. Computational-Thermodynamics-Aided Development of Multiple-Principal-Component Alloys, Chuan Zhang, Fan Zhang, Shuanglin Chen, Weisheng Cao, Jun Zhu, Zhi Tan, Haoyan Diao, and Peter Liaw.

2015 TMS Meeting (Cont'd)

39. Sputter Deposition Simulation of High Entropy Alloy via Molecular Dynamics Methodology, Yunche Wang, Chun-Yi Wu, Nai-Hua Yeh, and Peter Liaw.

40. Microstructures and Mechanical Behavior of Multi-Component AlxCrCuFeMnNi High-Entropy Alloys, Haoyan Diao; Zhinan An; Xie Xie; Gongyao Wang; Chuan Zhang; Fan Zhang; Guangfeng Zhao; Fuqian Yang; Karin Dahmen; Peter Liaw.

41. The Characterization of Serrated Plastic Flow in High Entropy Alloys, Shuying Chen; Xie Xie; James Antonaglia; Junwei Qiao; Yong Zhang; Karin Dahmen; Peter Liaw.

42. 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 Brinkman1; Michael LeBlanc; Marina Laktionova; Elena Tabachnikova; Zhi Tang; Junwei Qiao; Jien Wei Yeh5; Chi Lee; Che Wei Tsai; Jonathan Uhl; Peter Liaw.

2015 MS&T Meeting

43. Modeling Plastic Deformation and Avalanches in Bulk Metallic Glasses and Other Materials, Karin Dahmen; James Antonaglia; Michael LeBlanc; XJ Gu; Wendelin Wright; Xie Xie; Robert Maass; Todd Hufnagel; Junwei Qiao; Peter K. Liaw; Yong Zhang; Susan Lehman; Don Jacobs; Jonathan Uhl.

44. The Serrated Flows in High Entropy Alloys, Shuying Chen; Xie Xie; James Antonaglia; Junwei Qiao; Yong Zhang; Karin Dahmen; Peter Liaw.

45. The Study of the Serrated Flow in Bulk Metallic Glasses, Xie Xie; Abid Khan; Junwei Qiao; Yong Zhang; Gongyao Wang; Karin Dahmen; Peter Liaw.

46. Serration Behavior and Pop-in Phenomena in AlxCrCuFeMnNi High Entropy Alloys, Haoyan Diao; Xie Xie; Shuying Chen; Fuqian Yang; Karin Dahmen; Peter Liaw.

2015 MS&T Meeting (Cont'd)

47. Small and Large Serrations During Uniaxial Compression of a Bulk Metallic Glass: Wendelin Wright; Xiaojun Gu; Steven Robare; Kate VanNess; Todd Hufnagel; Jonathan Uhl; James Antonaglia; Yun Liu; Xin Liu; Michael LeBlanc; Karin Dahmen; Xing Tong; Gang Wang; Jun Yi; Simon Pauly; K.A. Dahmen; P.K. Liaw; Jurgen Eckert.

48. Investigation of Shear-Band Dynamics by Nanoindentation and Thermography for Bulk Metallic Glasses, Xie Xie; Shu Li; Guangfeng Zhao; Peizhen Li; Shuying Chen; Fuqian Yang; Karin Dahmen; Peter Liaw.

49. Effects of Cohesion On Avalanche Statistics for a Slowly-Driven Conical Bead Pile: Susan Lehman; Nathan Johnson; Catherine Tieman; Elliot Wainwright; Donald Jacobs; Karin Dahmen; Michael LeBlanc.

2015 MS&T Meeting (Cont'd)

50. Ferritic Superalloys with Superior Creep Resistance Reinforced by Novel Hierarchical NiAl/Ni2 TiAl Precipitates: Gian Song; Zhiqian Sun; Lin Li; Xiandong Xu; Michael Rawlings; Christian Liebscher; Bjørn Clausen; Jonathan Poplawsky; Donovan Leonard; Shenyan Huang; Zhenke Teng; Chain Liu; Mark Asta; Yanfei Gao; David Dunand; Gautam Ghosh; Mingwei Chen; Morris; Peter Liaw.

51. Duplex Precipitates and Their Effects on the Room-temperature Fracture Behavior of a NiAl-strengthened Ferritic Alloy: Zhiqian Sun; Gian Song; Jan Ilavsky ; Peter Liaw Grain Boundary on the Nanoindentation Creep Behavior of Al0.3CoCrFeNi High-entropy Allay: Gong Li; Lijun Zhang ; Pengfei Yu ; P.K. Liaw.

52. Effects of Ion and Neutron Irradiation on the Serration Behavior and Mechanical Properties of Zr52.5Cu17.9Ni14.6Al10Ti5 (BAM-11) Bulk Metallic Glass: Jamieson Brechtl; Xie Xie; Peter Liaw; Steven Zinkle.

2016 TMS Meeting

53. Effect of Composition on Mechanical Rejuvenation by HPT Deformation in Zr-Cu-Al-Ni Metallic Glass, Koichi Tsuchiya; Jiang Qiang; SeiichiroII; Shinji Kohara; Koji Ohara; Osami Sakata; Karin Dahmen; Peter Liaw.

54. Temperature Dependent slip Avalanche Statistics in Bulk Metallic Glasses – Experiments and Model, Corey Fyock; Peter Thurnheer; Robert Maass; Michael LeBlanc; Peter Liaw; Jonathan Uh; Joerg Loeffler; Karin Dahmen.

55. Nanoindentation for Bulk Metallic Glasses, Xie Xie; Guangfeng Zhao; Peizhen Li; Shuying Chen; Fuqian Yang; Karin Dahmen; Peter Liaw.

56. A Statistical Study of the Potential-scan-rate and Al-content Dependent Metastable Pitting (Serration) Behavior of AlxFeCoCrNi High-entropy Alloys, Yunzhu Shi; Bin Yang; Xie Xie; Zhi Tang; Karin Dahmen; Peter Liaw.

2016 TMS Meeting (Cont'd)

57. Serrated Plastic Flow in CoFeMnNi, CoCrFeMnNi, and CoCrFeNi High Entropy Systems: Joseph Licavoli; Karin Dahmen; Paul Jablonski; Michael Gao; Peter Liaw; Jeffrey Hawk.

58. Serrated Flows in High Entropy Alloys (HEAs), Shuying Chen; Peter Liaw; Xie Xie; Karin Dahmen; Yong Zhang; Junwei Qiao.

59. A Model for the Deformation Mechanisms and the Serration Statistics of High Entropy Alloys, Karin Dahmen; Robert Carroll; Xie Xie; Shuying Chen; Michael LeBlanc; Jien Wei Yeh; Chi Lee; Che Wei Tsai; Peter Liaw; Jonathan Uhl.

60. Exploring the Structure-composition Design Space in Multi-component Alloy Systems Using Nature Inspired Optimization Algorithms: Aayush Sharma; Rahul Singh; Peter Liaw; Ganesh Balasubramanian.

61. Time-dependent Mechanical Properties of Metallic Glass via Molecular Dynamics Simulations: Yunche Wang; Nai-Hua Yeh; Peter Liaw.

62. Deformation and Structural Modeling of a Quenched Al0.1CrCoFeNi Multi-principal Element Alloy under High Strains: Aayush Sharma; Peter Liaw; Ganesh Balasubramanian.

2016 TMS Meeting (Cont'd)

63. Microstructural Evolution of Single Ni2TiAl or Hierarchical NiAl/Ni2TiAl Precipitates in Fe-Ni-Al-Cr-Ti Ferritic Alloys during Thermal Treatment: Gian Song; Yanfei Gao; Zhiqian Sun; Jonathan Poplawsky; Peter Liaw.

64. Deviation from High-Entropy Configurations in the Al1.3CoCrCuFeNi Alloy: Louis Santodonato1; Yang Zhang; Mikhail Feygenson; Chad Parish; Michael Gao; Richard Weber; Joerg Neuefeind; Zhi Tang; Peter Liaw.

65. A Bragg-Williams Model of Ordering in High-entropy Alloys: Louis Santodonato; Peter Liaw.

66. Nano-sized Precipitate Stability and Its Controlling Factors in a NiAlstrengthened Ferritic Alloy: Zhiqian Sun; Gian Song; Jan Ilavsky; Gautam Ghosh; Peter Liaw.

67. Exploration of High Entropy Alloys for Sustainable Energy Storages: Jingke Mo; Yunzhu Shi; Peter Liaw; Feng-Yuan Zhang.

68. Structure Evolution during Cooling of Al0.1CrCuFeMnNi High entropy Alloy: Haoyan Diao; Chuan Zhang; Louis Santodonato; Mikhail Feygenson; Joerg Neuefeind3; Xie Xie; Fan Zhang; Peter Liaw.

2016 TMS Meeting (Cont'd)

69. Investigation of Simulated Local Atomic Structure above and below the Melting Temperature of a Metallic Glass: Cang Fan; C.T. Liu; Jingfeng Zhao; P.K. Liaw.

70. Intergranular Strain Evolution near Fatigue Crack Tips in Polycrystalline Materials: Yanfei Gao; Rozaliya Barabash; Peter Liaw.

71. Insights into ß-Relaxation-Mediated Performance of Metallic Glasses: An Integrated Density-Functional-Theory and Electron-Work-Function Study: William Yi Wang; Shunli Shang; Kristopher Darling; Yi Wang; Laszlo Kecskes; Peter Liaw; Xidong Hui; Zi-Kui Liu.

72. Atomic and Electronic Basis for Viscous Flow Mediated Avalanches of Ultrastrong Refractory High Entropy Alloys: William Yi Wang; ShunliShang; Yi Wang; Yidong Wu; Kristopher Darling; Xie Xie; Oleg Senkov; Laszlo Kecskes; Karin Dahman; Xidong Hui; Peter Liaw; Zi-Kui Liu.

73. Microstructure and Mechanical Properties of YxCoCrFeNi High Entropy Alloys: Gong Li; Huan Zhang; Lijun Zhang; Pengfei Yu; HuCheng; Qin Jing; Mingzhen Ma; P. K Liaw; Riping Liu.

74. Microstructures and Properties of CoFeMnNiX (X = Al, Ga, Sn) High Entropy Alloys: Ting Ting Zuo; Xiao Yang; Michael Gao; Shu Ying Chen; Peter Liaw; Yong Zhang.

2016 TMS Meeting (Cont'd)

75. Microstructural Characterization and Phase Evolution of Al1.5CrFeMnTi and Al2CrFeMnTi: Rui Feng; Chanho Lee; Peiyong Chen; Michael Gao; Chuan Zhang; Fan Zhang; Peter Liaw.

76. 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; Peter Liaw.

77. A Novel, Single Phase, Refractory CrMoNbV High-entropy Alloy: Rui Feng; Michael Widom; Michael Gao; Peter Liaw.

78. Microstructural Characterization and Mechanical Experiments of Light-weight AlxCrFeMn High-Entropy Alloys: Peiyong Chen; Chanho Lee; Rui Feng; Michael Gao; Fan Zhang; Chuan Zhang; Peter Liaw.

79. Microstructural Characterization in AlxCrFeMnTix advanced Light Weight High-Entropy Alloys: Chanho Lee; Peiyong Chen; Rui Feng; Michael Gao; Fan Zhang; Chuan Zhang; Peter Liaw.

80. Microstructural Characterization of a Ni2HfAl-Precipitate- Strengthened Ferritic Alloy: Shao-Yu Wang; Gian Song; Peter K. Liaw.

81. ICMT Seminar, From nanocrystals to earthquakes, solid materials share similar (universal) failure characteristics, University of Illinois at Urbana Champaign, Karin Dahmen

82.. Workshop of the National Academies of Sciences Engineering, and Medicine: Workshop on Emerging and timely capabilities and research objectives: High Entropy Materials, Ultra-strong Molecules and Nanoelectronics, Universal Slip Statistics in theory and experiments, DC, Karin Dahmen and Peter Liaw

83. 2016 Conference on avalanches, plasticity and nonlinear response in nonequilibrium solids, Universal Slip Statistics in theory and experiments, Kyoto, Japan, Karin Dahmen

84. Colloquium, Universal slip statistics: from nanocrystals to earthquakes, Cornell University, Karin Dahmen

85. SIAM Meeting on Mathematical Aspect of Materials Science (MS16); Session AA: Modeling Mechanical Response in Disordered and Structurally Complex Materials Systems , Universal Slip Statistics: from Nanocrystals to Bulk Metallic Glasses , Sheraton Philadelphia Society Hill Hotel, Karin Dahmen

86. Symposium on Deformation of disodered Materials, Universal Slip Statistics, Shanghai, China, Karin Dahmen and Peter Liaw

87. JpGU Meeting, Session on New frontiers in earthquake statistics, physics-based earthquake forecasting, and earthquake model testing, Universal Slip Statistics: from Nanocrystals to Bulk Metallic Glasses, Tokyo, Japan, Karin Dahmen and Peter Liaw

88. BMG XII, Universal Slip Statistics: from Nanocrystals to Bulk Metallic Glasses, St Louis, Karin Dahmen and Peter Liaw

89. Gordon conference on Thin Film & Small Scale Mechanical Behavior, Universal Slip Statistics: from Nanocrystals to Bulk Metallic Glasses, Bates College, Karin Dahmen

90. Hysteresis, Avalanches and Interfaces in Solid Phase Transformations Conference, Universal Slip Statistics: from Nanocrystals to Bulk Metallic Glasses, Oxford, UK, Karin Dahmen

91. Annual MRS meeting, Universal Slip Statistics: from Nanocrystals to Bulk Metallic Glasses, Boston Karin Dahmen and Peter Liaw

92. Symposium on High Entropy Alloys, Universal Slip Statistics: from Nanocrystals to High Entropy Alloys, Taipei, Taiwan, Karin Dahmen and Peter Liaw

93. Keynote talk at a Symposium on plastic deformation of solid materials (presented by collaborators), Universal Slip Statistics: from Nanocrystals to Granular Materials, Mexico , Karin Dahmen.

94. Conference on Avalanches, Universal Slip Statistics: from Nanocrystals to Bulk Metallic Glasses, Barcelona, Spain, Karin Dahmen and Peter Liaw

95. International Workshop on scale bridging of Materials Science, Universal Slip Statistics, Tokyo, Japan, Karin Dahmen and Peter Liaw

96. Colloquium, Universal Slip Statistics, University of Calgary. Karin Dahmen

97. DOE Crosscutting Review Meeting, Serrations in High Entropy Alloys, Pittsburgh. Karin Dahmen and Peter Liaw

98. Plasticity Workshop, Statistics of Deformation Responses, Texas A&M University. Karin Dahmen

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

100. International Workshop on Advanced Material, Yangzhou, China, March 29, 2016 (Invited), Deviation from High-Entropy Configurations in the Al1.3CoCrCuFeNi Alloy, Peter Liaw.

101. Neutron Imaging: Application to Materials Science Workshop, Oak Ridge, TN, USA, May 25, 2016, High Entropy Alloys, Peter Liaw.

102. QuestTek Inovation LLC, Evanston, IL, July 25, 2016 (Invited), Deviation from High-Entropy Configurations in the Al1.3CoCrCuFeNi Alloy, Peter Liaw.

103. Osaka University, Osaka, Japan, July 29, 2016 (Invited),from High-Entropy Configurations in the Al1.3CoCrCuFeNi Alloy, Peter Liaw.

104. Osaka University, Osaka, Japan, July 29, 2016 (Invited), Serration Behavior of Bulk Metallic Glasses and High Entropy Alloys, Peter Liaw.

105. Kyoto University, Kyoto, Japan, August 1, 2016 (Invited), Serration Behavior of Bulk Metallic Glasses and High Entropy Alloys, Peter Liaw.

106. Pacific Rim International Conference on Advanced Materials and Processing (PRICM9), Kyoto, Japan, August 3, 2016 (Invited), 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.

107. Pacific Rim International Conference on Advanced Materials and Processing (PRICM9), Kyoto, Japan, August 3, 2016 (Invited), Characterization of Shear-Band Dynamics by Thermography for Bulk Metallic Glasses: Xie Xie, Junwei Qiao, Yenfei Gao, K. Dahmen, and P. Liaw

International Conference on High-entropy Materials (ICHEM), Hsinchu, Taiwan, November 6, 2016

108. Deviations from High-Entropy Configurations in the AlxCoCrCuFeNi Alloys, P. K. Liaw

109. Experimental and Computational Investigation of High-entropy Alloys for Elevated-Temperature Applications, H. Y. Diao, W. Guo, J. D. Poplawsky, D. Ma, and P. K. Liaw

110. Dynamic response of Al0.3CoCrFeNi high-entropy alloy: Remarkable resistance to shear localization, M. A. Meyers, H. Y. Diao, and P. K. Liaw

111. A Cuboidal B2 Nanoprecipitation Enhanced Body-Centered-Cubic Alloy Al0.7CoCrFe2Ni with Prominent Tensile Properties, C. Dong, and P. K. Liaw

112. The Role of the CALPHAD Approach in the Design of High Entropy Alloys, F. Zhang, H. Y. Diao, and P. K. Liaw

Materials Research Society (MRS), Boston, MA, USA, November 27, 2016

113. Deviations from High-Entropy Configurations in the AlxCoCrCuFeNi Alloys: Louis Santodonato, Yang Zhang, Mikhail Feygenson, Chad Parish, Michael Gao, Richard Weber, Joerg Neuefeind, Zhi Tang, James Morris, and P.K. Liaw

114. Spatiotemporal Collective Dynamics of Dislocations in High-Entropy Alloy Nanopillars, Yang Hu, Li Shu, Wei Guo, P.K. Liaw, Karin Dahmen, and Jian-Min Zuo

115. Experiments and Model for Serration Statistics in Low-Entropy, Medium-Entropy, and High-Entropy Alloys, Karin Dahmen, Robert Carroll, Jien-Wei Yeh, P.K. Liaw, Xie Xie, Michael LeBlanc, Shuying Chen, and Che-Wei

116. Fracture and Fatigue Resistant Al0.3CoCrFeNi High Entropy Alloy, Mohsen Seifi, Yunzhu Shi, P.K. Liaw, Mingwei Chen, and John Lewandowski

117. Experimental and Computational Investigation of High Entropy Alloys for Elevated-Temperature Applications, P.K. Liaw, Haoyan Diao, Chuan Zhang, Dong Ma, Joe Kelleher, Karin Dahmen, Saurabh Kabra, and Fan Zhang

118. Fracture and Fatigue Resistance of High Entropy Alloys, John Lewandowski, Mohsen Seifi, Yunzhu Shi, Mingwei Chen, and Peter K. Liaw

2016 MS&T Meeting

119. Atomic and Electronic Basis for the Serration Behavior of Ultrastrong BCC Refractory High Entropy Alloys: William Yi Wang; Jinshan Li1 ; Shun-Li Shang; Yi Wang; Kristopher Darling; Xie Xie; Oleg Senkov; Laszlo Kecskes; Xidong Hui; Karin Dahmen; Peter Liaw; Zi-Kui Liu

120. Heat-treatment Effect on the Serrated Flows in AlxCoCrFeNi (x = 0.1, 0.3, 0.5, and 0.7) High-entropy Alloys (HEAs): Haoyan Diao; Chih-Hsiang Kuo; James Brechtl; Steven Zinkle; Karin Dahmen; Peter Liaw

121. The Study of Serrated Plastic Flow in Refractory High Entropy Alloys: Shuying Chen; Chien-Chang Juan; Jien-Wei Yeh; Karin Dahmen; Peter Liaw.

122. An In-situ TEM Observation on the Stability of Al0.3CoCrFeNi High Entropy Alloys under High Temperature Oxidation Environments: Elaf Anber; Wayne Harlow; Haoyan Diao; Peter Liaw; Mitra Taheri

123. Multiscale Entropy Analysis on the Serrated Flow of Unirradiated and Irradiated Alloy Systems Undergoing Mechanical Testing at Different Strain Rates and Temperatures: Jamieson Brechtl; Xie Xie; Shuying Chen; Haoyan Diao; Yunzhu Shi; Peter Liaw; Steven Zinkle

2016 MS&T Meeting(Cont’d)

124. Microstructure Stability of Mo/W/Ti/Zr/Nb/Ta-alloyed 310S Austenite Stainless Steels Designed by a Cluster Model: Qing Wang; Donghui Wen; Wen Lu; Guoqing Chen; Chuang Dong; Peter K. Liaw

2017 TMS Meeting

125. Formation and Properties of Biodegradable Mg-Zn-Ca-Sr Bulk Metallic Glasses for Biomedical Applications, Shujie Pang; Haifei Li; Ying Liu; Peter K. Liaw; Tao Zhang .

126. Shear-Coupled Grain Growth and Texture Development in a Nanocrystalline Ni-Fe Alloy during Cold Rolling, Li Li; Tamas Ungar; L Toth; Z Skrotzki; Y Ren; Zs Fogarassy; X.T. Zhou; Peter Liaw

127. A Highly Fracture and Fatigue Resistant Al0.3CoCrFeNi High Entropy Alloy, Mohsen Seifi1; Yunzhu Shi; Peter Liaw; Mingwei Chen; John Lewandowski

128. Design of Light-weight High-Entropy Alloys, Rui Feng; Michael C. Gao; Chanho Lee; Michael Mathes; Tingting Zuo; Shuying Chen; Jeffrey A. Hawk; Yong Zhang; Peter K. Liaw

129. The Design of Creep-resistant High Entropy Alloys for Elevated-temperature Applications, Haoyan Diao; Chuan Zhang; Fan Zhang; Karin Dahmen; Peter Liaw

130. The Creep-resistant High Entropy Alloys (HEAs), Haoyan Diao; Dong Ma; Wei Guo; Jonathan Poplawsky; Chuan Zhang; Fan Zhang; Karin Dahmen; Peter Liaw

2017 TMS Meeting (Cont'd)

131. Deviations from High-Entropy Configurations in the AlxCoCrCuFeNi Alloys, Louis Santodonato; Yang Zhang; Mikhail Feygenson; Chad Parish1; Michael Gao4; Richard Weber; Joerg Neuefeind; Zhi Tang; James Morris; Peter Liaw.

132. The Study of Fatigue Behavior in Refractory High Entropy Alloys, Shuying Chen; Chien-Chang Juan; Jien-Wei Yeh; Karin Dahmen; Peter Liaw.

133. Strength and Deformation of Far-from-Equilibrium Metallic Systems at the Nano-scale: High-Entropy Alloys and Metallic Glasses, Julia Greer; Rachel Liontas; Adenike Giwa; H. Diao; Peter Liaw.

134. Weldability and Welding Solidification of an HEA Alloy, Joshua Burgess; Carl L undin; Zhi Tang; Peter Liaw; GE Power

135. Pre-osteoblastic Cell Responses to High-entropy Alloys, Jinbo Dou; Haoyan Diao; Yunzhu Shi; Peter K. Liaw; Shanfeng Wang.

136. Bringing High-entropy Alloys Close to High-temperature Applications: Single Crystal Growth, Microstructure Characterization, and Mechanical Tests, Qingfeng Xing; Haoyan Diao; Deborah Schlagel; Trevor Riedemann; Peter Liaw; Thomas Lograsso

2017 TMS Meeting (Cont'd)

137. Irradiation Responses of High-entropy Alloys at Elevated Temperatures, Songqin Xia; Michael Gao; Tengfei Yang; Peter Liaw; Yong Zhang

138. Strong Grain-size Effect on Deformation Twinning of an Al0.1CoCrFeNi High entropy Alloy, Shiwei Wu; G. Wang; J. Yi; Q. J. Zhai; P. K. Liaw

139. Study on the Microstructure and Mechanical Behavior of the New Type SA508-IV Reactor Pressure Vessel (RPV) Steel by Different Methods, Xue Bai; Sujun Wu; Peter K. Liaw; Lin Shao

140. Modeling Slips in Solids and Comparison to Experiments, Karin Dahmen; Michael LeBlanc; Peter Liaw; Robert Maass; Jonathan Uhl; Wendelin Wright; Xie Xie;

141. In Situ TEM Investigation of the Thermal, Mechanical, and Corrosion Stability of High Entropy Alloys, Mitra Taheri; Elaf Anber; Daniel Scotto-D'Antuono; Wayne Harlow; Haoyan Diao; Peter Liaw

142. On the Proper Determination of Power Law Exponents for Slip Statistics Using Experimental Data from Bulk Metallic Glasses, Wendelin Wright; Michael LeBlanc; Aya Nawano; Xiaojun Gu; J.T. Uhl; Karin Dahmen

2017 TMS Meeting (Cont'd)

143. Nanoscale Phase Separation in Al0.5CoCrFeNiCu High Entropy Alloys, as Studied by Atom Probe Tomography, Keith Kniplin1; Joshue Tharpe; Peter Liaw

144. Small Angle Neutron Scattering Study of HEA Microstructure Evolution with Temperature and Applied Magnetic Field, Louis Santodonato; Lisa DeBeer-Schmitt; Kenneth Littrell1; Peter Liaw

145. Composition, Temperature, and Crystal Size Effects on the Mechanical Response of AlCoCrFeNi High Entropy Alloy, Gi-Dong Sim; Quan Jiao; Peter K. Liaw; Rajiv Mishra; Jaafar El-Awady

146. An In Situ TEM Observation on Thermal Stability of High Entropy Alloys, Elaf Anber; Dan Scotto D'Antuono; Andrew Lang; Haoyan Diao; Peter Liaw; Mitra Taheri

147. Elastic Properties of High entropy Alloys from First-principles, Wei Chen; Haoyan Diao; Peter Liaw.

148. Predicting Structural and Chemical Properties of Mo-based Refractory High entropy Alloys, Aayush Sharma; Prashant Singh; D. D. Johnson; Peter Liaw; Ganesh Balasubramanian

149. Alloy Design of Creep-resistant High Entropy Alloys for Elevated-Temperature Applications, Peter Liaw; Haoyan Diao; Chuan Zhang; Fan Zhang; Karin Dahmen

2017 TMS Meeting (Cont'd)

150. A Computational Investigation on Diffusion in High-entropy Alloys, Chuan Zhang; Fan Zhang; Shuanglin Chen; Weisheng Cao; Jun Zhu; Haoyan Diao; Peter Liaw

151. Modeling Slips in Slowly Deformed High Entropy Alloys and Comparison to Experiments, Karin Dahmen; XJ Gu; Li Shu; Aya Nawano; Shuying Chen; Peter Liaw; J.T. Uhl; Wendelin Wright; Jien-Wei Yeh

152. The Serrations of TiZrTM1TM2 (TM=Hf, Mo, Ta, V and W) High Entropy Alloys: An Integrated First-principles Calculation and Finite-elements Method Study, William Yi Wang; FengBo Han; Yi Dong Wu; Deye Lin; Bin Tang; Jun Wang; Shun-Li Shang; Yi Wang; HongChao Kou; Xi-Dong Hui; Karin Dahmen; Peter Liaw; JinShan Li; Zi-Kui Liu

153. Understanding and Designing High-entropy Alloys using a Cluster-plus-Glue-Atom Model, Qing Wang; Xiaona Li; Chuang Dong; Peter K. Liaw

154. A Multifaceted Approach to Analyze the Serration Behavior in High Entropy Alloys and Other Material Systems, Jamieson Brechtl; Xie Xie; Shuying Chen; Haoyan Diao; Yunzhu Shi; Tengfei Yang; Bilin Chen; Karin Dahmen; Peter Liaw; Steven Zinkle

2017 TMS Meeting (Cont'd)

155. Fatigue Behavior of High-entropy Alloys, Peiyong Chen; Bilin Chen; Michael Hemphill; Zhi Tang; Tao Yuan; Gongyao Wang; Che-Wei Tsai; Andrew Chuang; Carl D Lundin; Jien-Wei Yeh; Mohsen Seifi; Dongyue Li; John J Lewandowski; Karin A Dahmen; Peter K Liaw

156. Aluminum Diffusion in High Entropy Alloys, K. Michael Mathes; Thanh Tran; Peter Liaw.

157. Dynamic Behavior and Grain Refinement of AlxCoCrFeNi High-entropy Alloy, Zezhou Li; Shiteng Zhao; Haoyan Diao; Shima Sabbaghianra; Terence G. Langdon; Peter K. Liaw; Marc A. Meyers

158. Stress State, Strain Rate and Temperature Sensitivity of Alx(CrCoFeNi)1-x High Entropy Alloys (HEAs), Omar Rodriguez; Paul Allison; Haoyan Diao; Peter Liaw; Neng Wang; Lin Li

159. Effect of Size on the Intermittent Deformation Behavior of Metallic Glass Particles: So Yeon Kim; Jinwoo Kim; Koji Nakayama; Karin Dahmen; Eun Soo Park

Thank you for your attention!

Conclusion on Experiments and Mean Field Model:

1. **Fit-free model predictions for the statistics of slips (noise) in the stress strain curves agree with experimental data on:**

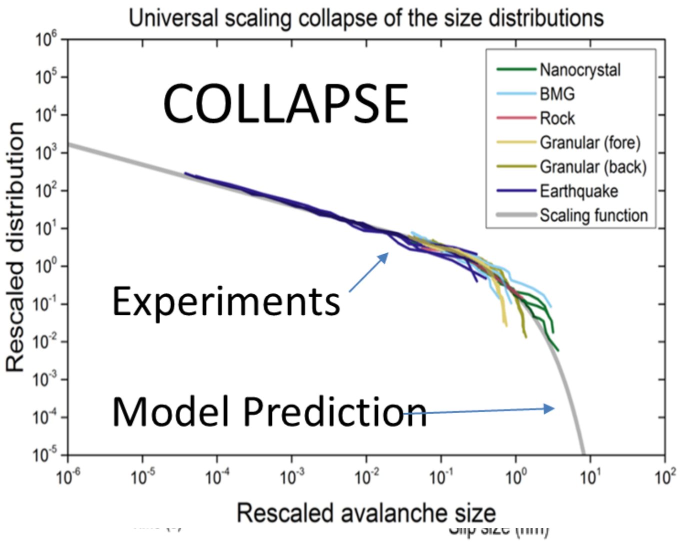
- High Entropy Alloys (**macro** and **nano** scale):

Dependence on temperature, strain rate, stress.

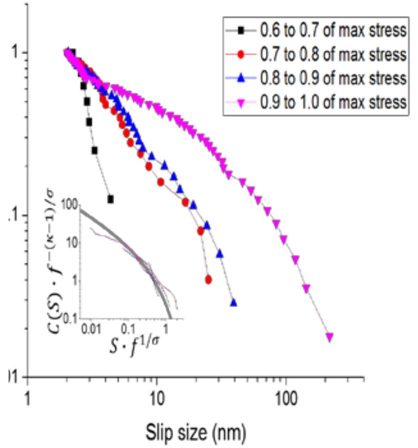
- Largest serrations seen within

300°C < Temperature < 600 °C

- Larger serrations for slower strain rates

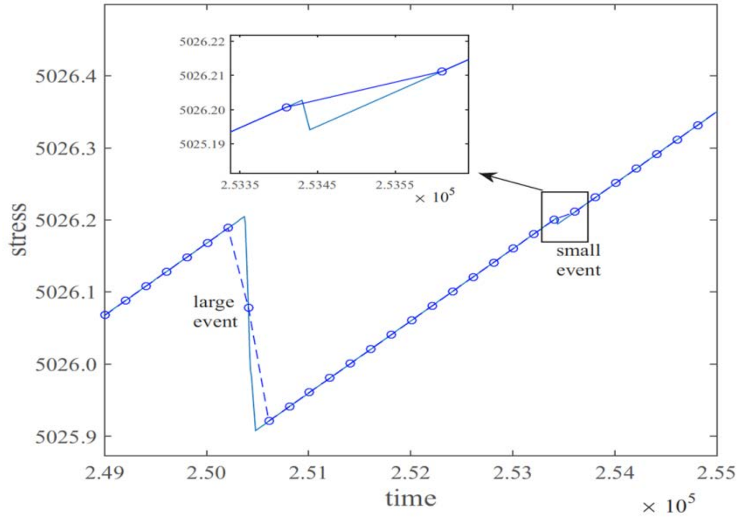


nm scale HEAs:



2. **Stress dependence in nm scale HEAs**

Agrees with previous results spanning 12 decades in length:
Nano-crystals, Bulk Metallic Glasses, Granular Materials , Rocks, Earthquakes



3. **New general method to avoid low time resolution effects**

Summary

- **For $Al_{0.5}CoCrCuFeNi$ HEA:**
  - **The serration behavior is observed in the compression experiments conducted in the temperature range of RT - 700 °C, with strain rates of 2×10^{-3}/s, 2×10^{-4}/s, and 5×10^{-5}/s;**
  - **On one hand, the stress-drop amplitudes increase with increasing temperature and reach the maximum value, then, decrease to a minimum value. On the other hand, the stress-drop magnitude decreases with increasing the strain rate.**

	RT	300°C	400°C	500°C	600°C	700°C
2×10^{-3}/s	None	D	D	A	C	None
2×10^{-4}/s	None	A	A	A + B	C	None
5×10^{-5}/s	A	A	A	A + B	B + C	None

Backup Slides

Slip Avalanches in High Entropy Alloys and other Materials

Graduate Students:
Michael LeBlanc, Braden Brinkman, Tyler Earnest
Nir Friedman,
Georgios Tsekenis , Will McFaul, Mo Sheikh, Patrick Coleman, **Shu Li**

Undergrad Students:
Robert Carroll, Jim Antonaglia, Aya Nawano, Gregory Schwarz, Abid Khan, Xin Liu, Shivesh Pathak, Shu Li, Corey Fyock, James Beadsworth, Jordan Sickle, John Weber, Shuyue Zhang

Outside Theory Collab.:

Simple Plasiticity Model:
K.Dahmen, Y. Ben-Zion, J.T. Uhl

Earthquakes:
D.S. Fisher, S.Ramanathan, KD

Magnets: J.P. Sethna , KD

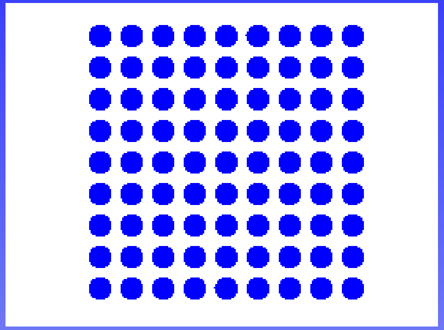
Experiments:

Nanocrystals/HEAs
J. Greer, A. Jennings, R. Maass (Caltech, UIUC), **Jimmy Zuo, Yang Hu**, **Jien-Wie Yeh, P. Liaw, Shuying Chen, Haolin Diao, Joseph Licavoli**

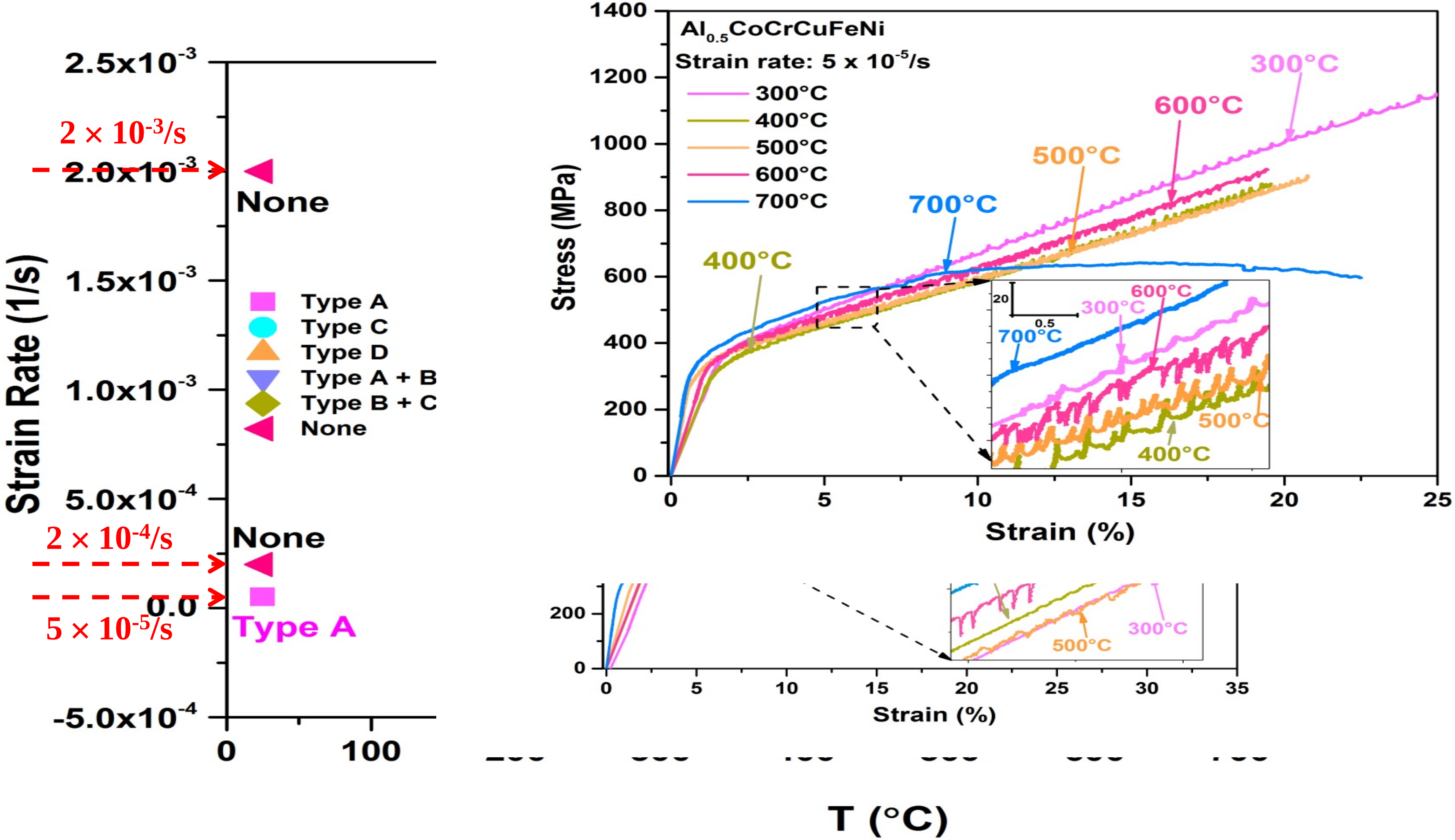
Amorphous Materials:
J. Greer, T. Hufnagel**, P. Liaw**, Y. Li, R. Maass, J. Qiao, E. Salje, K. Tsuchiya, W. Wright, X. Xie Y. Zhong,

Granular Materials: B. Behringer, B. Hartley, K. Daniels, M Schroeter,
P. Schall, D. Denisov

Rocks: D. Schorlemmer, T. Becker, G. Dresen (Berlin)

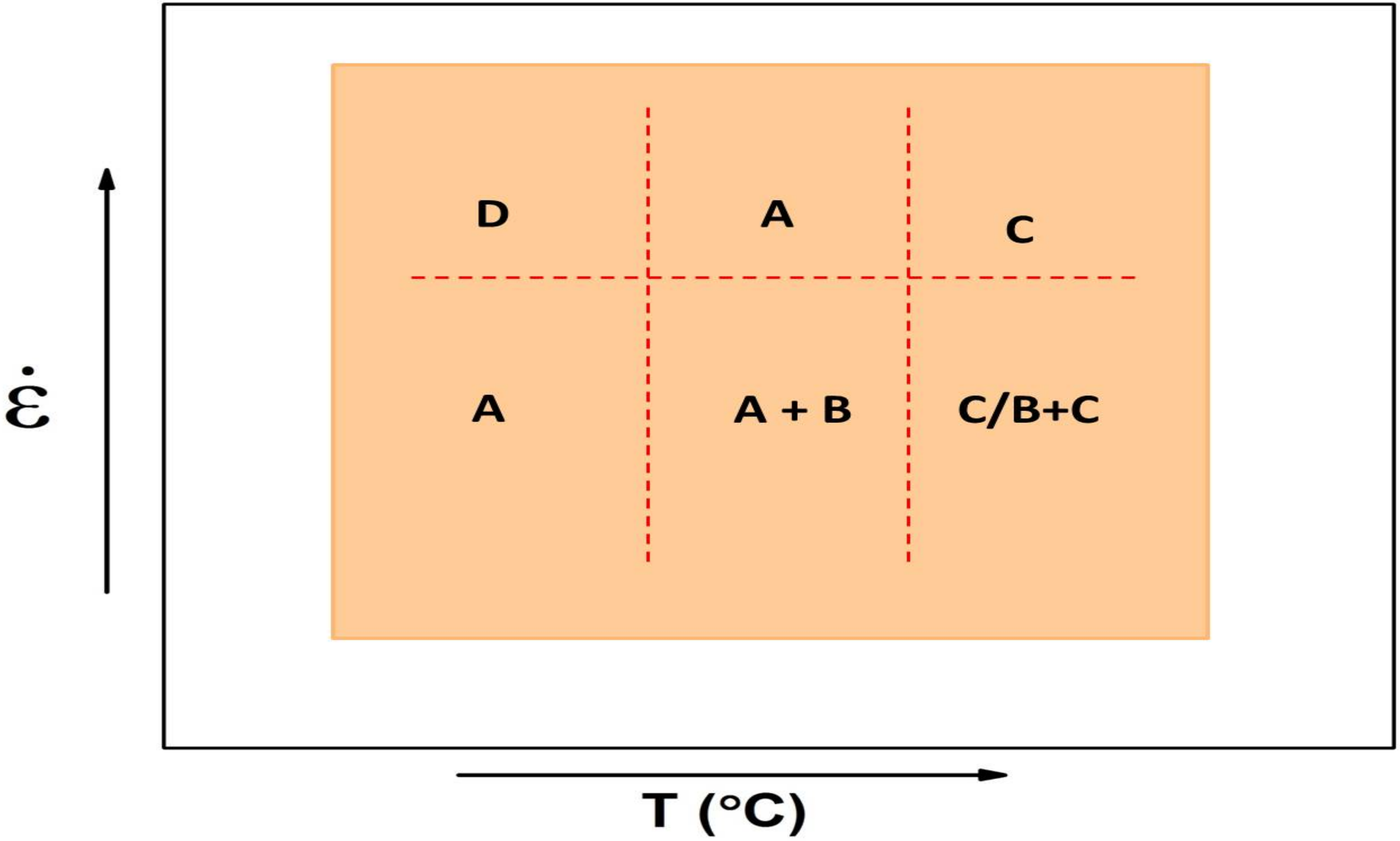


Characterization of serration behavior (Cont’d)



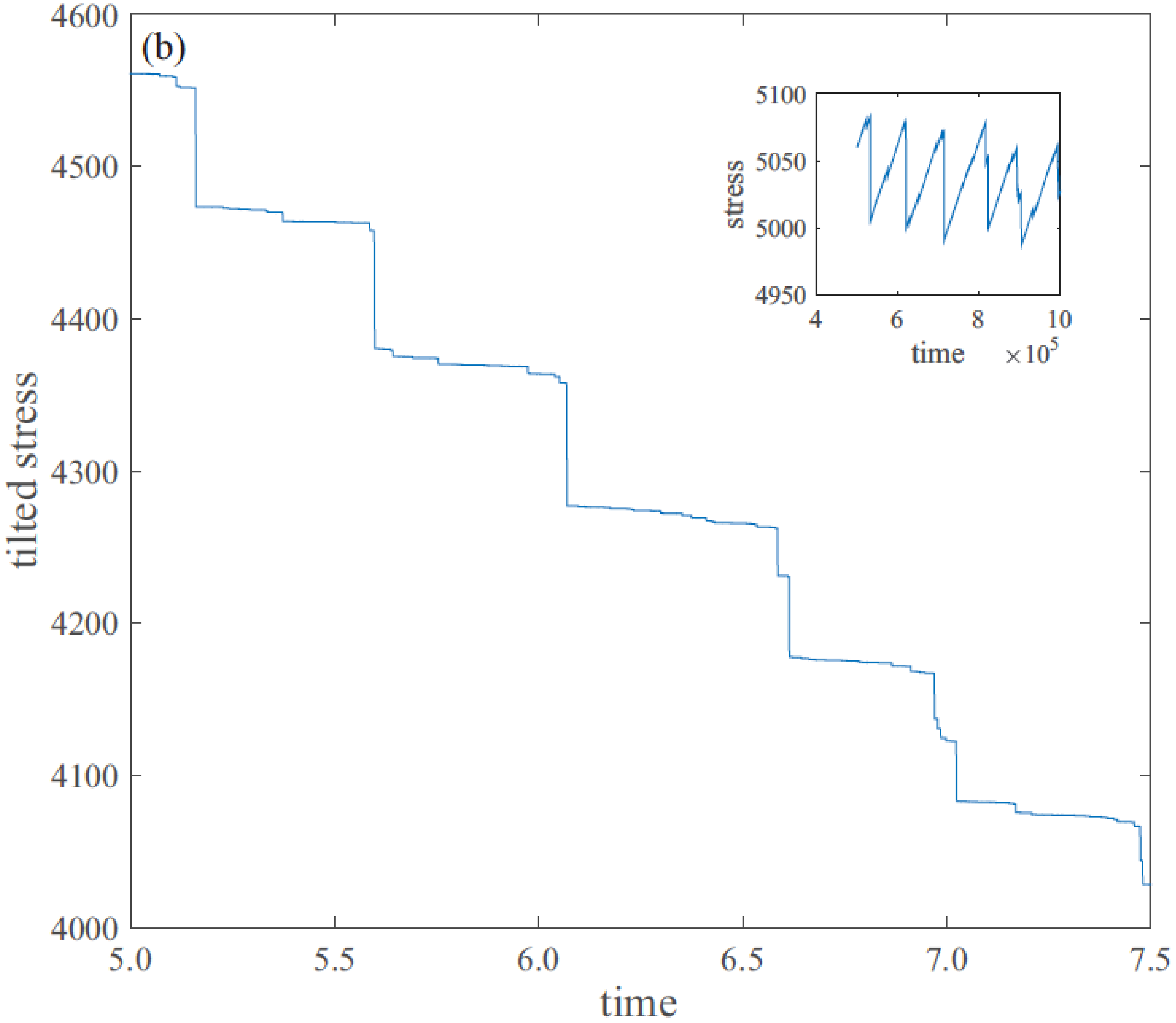
- At high temperatures or low strain rates, type C serrations tend to occur, while at low temperatures or high strain rates, type A serrations tend to appear, which could be ascribed to the different mechanism of interaction between solutes and moving dislocations

Characterization of serration behavior (Cont’d)



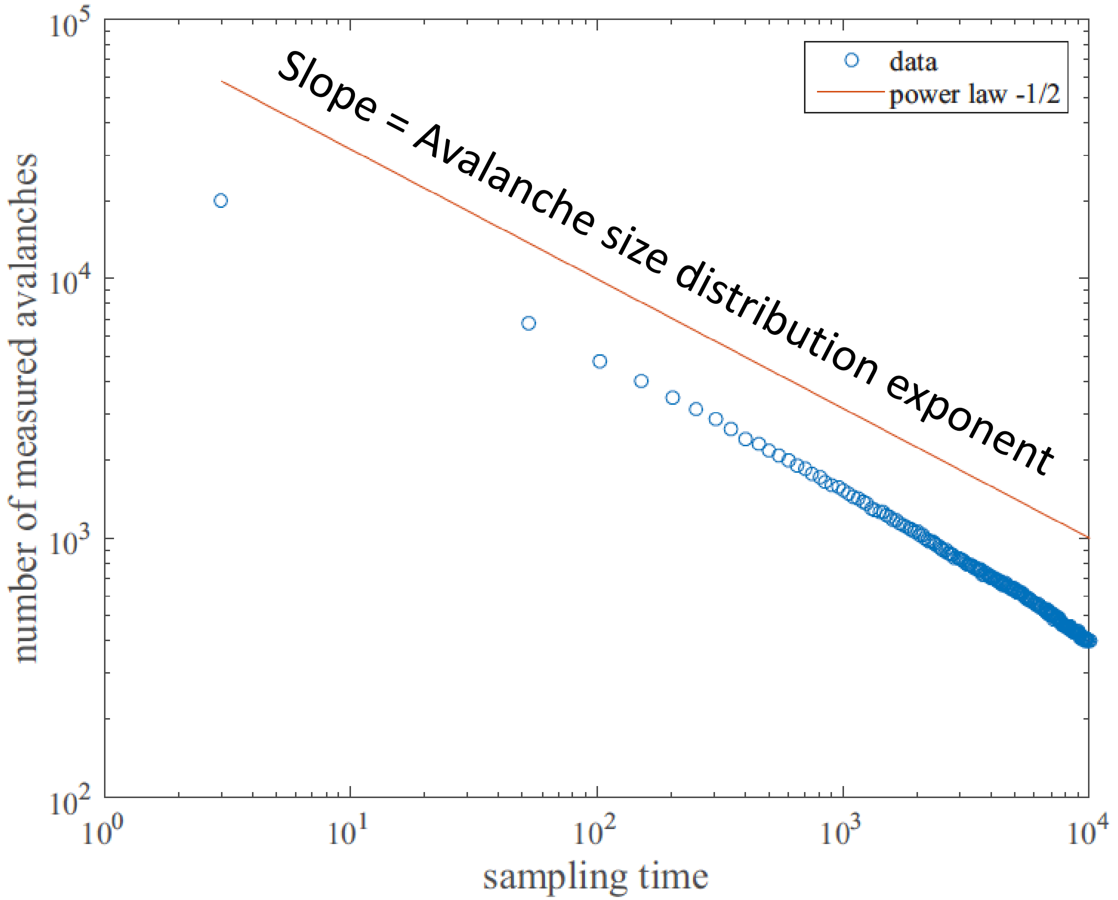
Solution: Subtracting out the elastic response

(Physical Review E **94**, 052135 (2016))

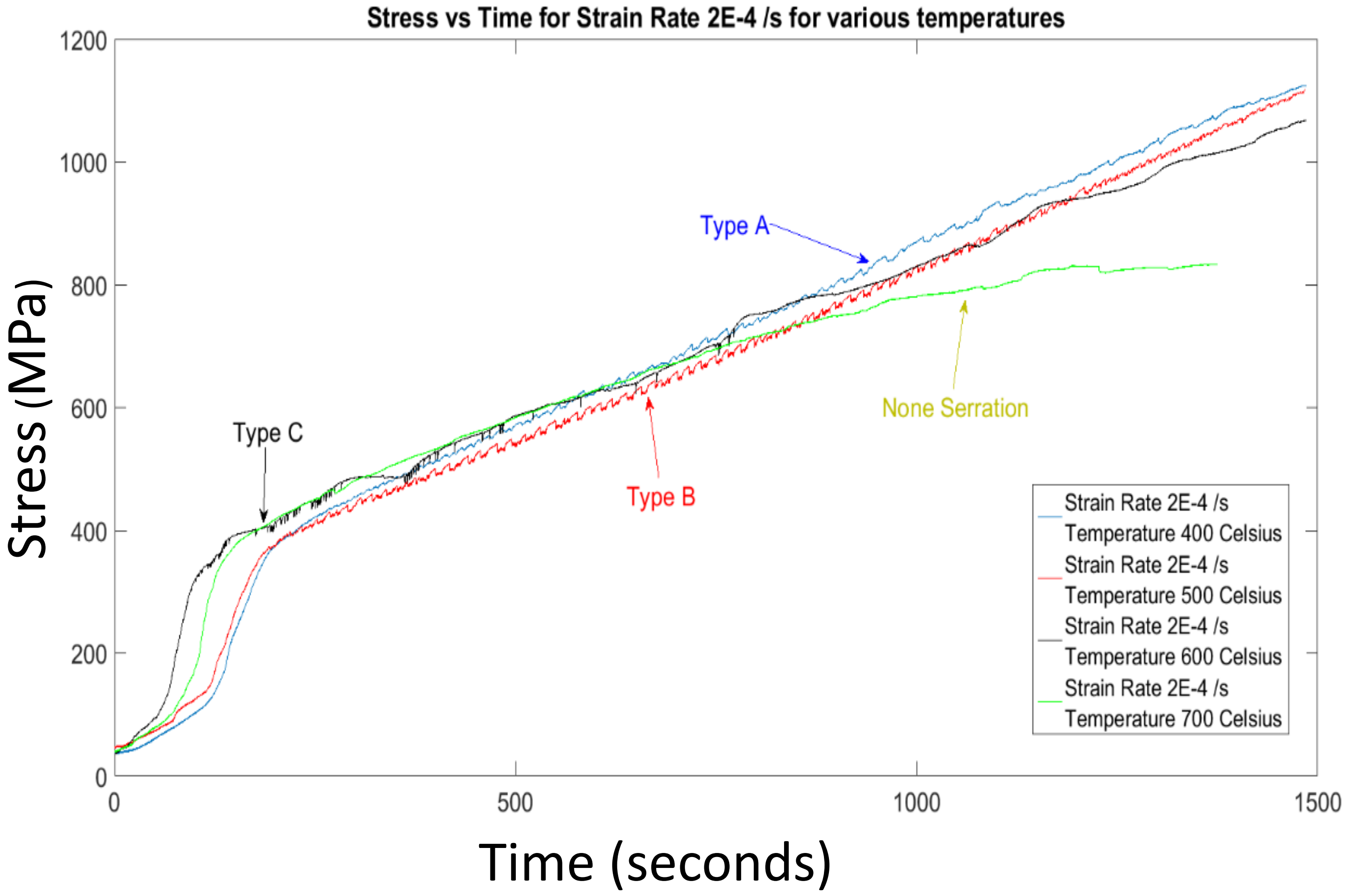


Assessing if the time resolution is sufficient: plot the number of avalanches versus time between data points

(Physical Review E **94**, 052135 (2016))



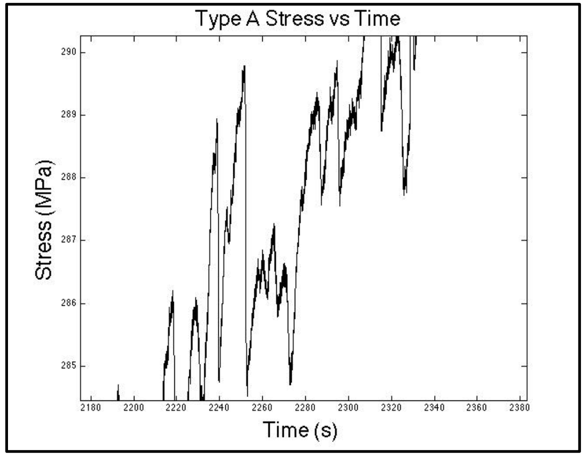
Modeling slip avalanches (the noise) in stress – strain curves of High Entropy Alloys on macroscopic and microscopic scales



Experiments by S.Y. Chen and P. Liaw. Data analysis and theory: Shu Li and K. Dahmen, preprint 2017.

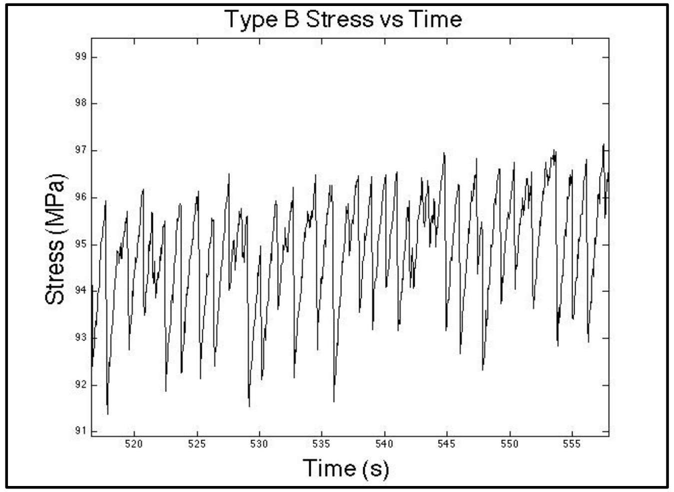
Stress versus time curves

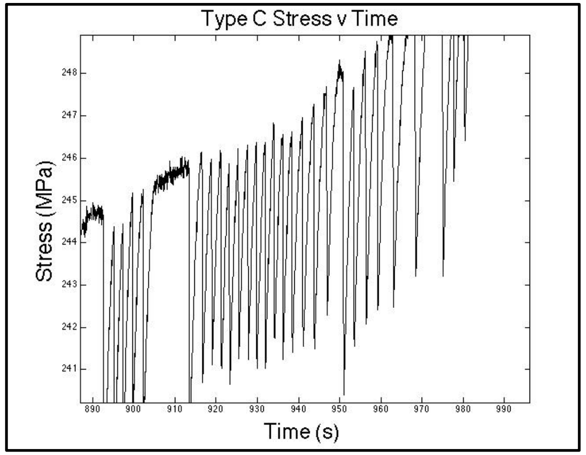
Chi Lee, Che-Wei Tsai, Jien Wie Yeh, Peter Liaw, Bobby Carroll, Michael LeBlanc, Braden Brinkman, Jonathan T. Uhl, Karin Dahmen



TYPE A: CoCrFeMnNi at 375°C at 10^{-4}/s strain rate – Exhibits power law slip size distributions with the mean field exponent κ=1.5!

Type B example from CoCrFeNi at 10^{-4}/s strain rate.



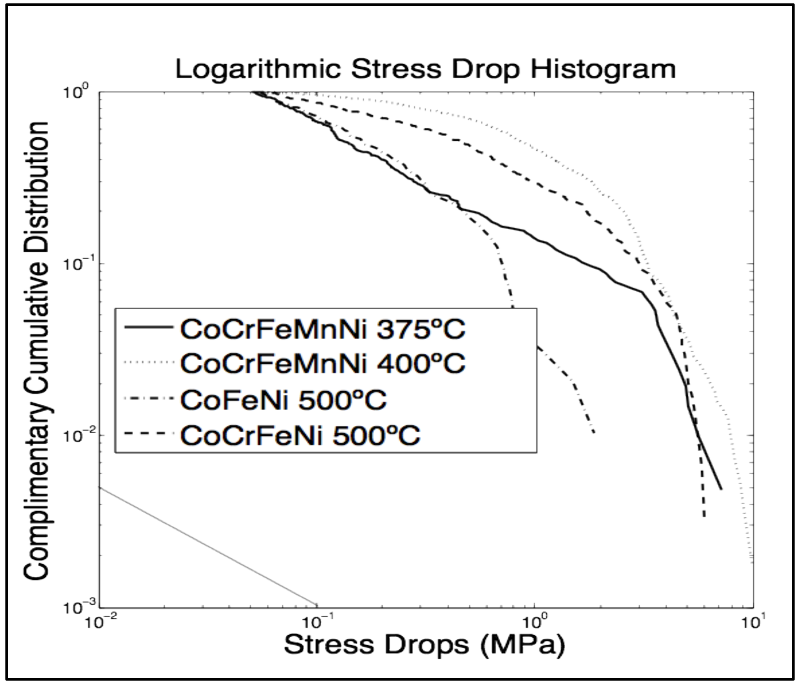


Type C example from CoCrFeNi 600°C at 10^{-4}/s strain rate.

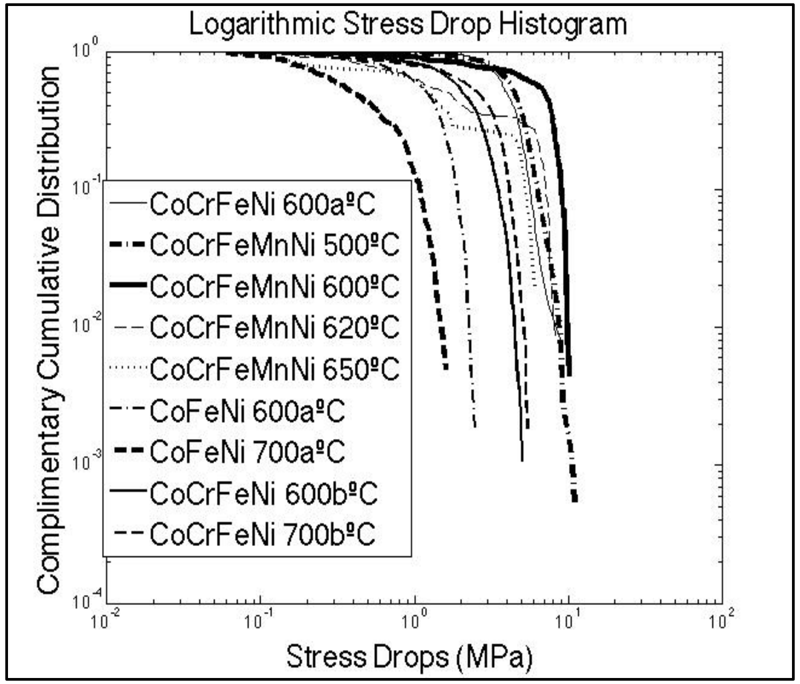
Slip Size Distributions for different materials and temperatures

Chi Lee, Che-Wei Tsai, Jien Wie Yeh, Peter Liaw,
Bobby Carroll, Michael LeBlanc, Braden Brinkman, Jonathan T. Uhl, Karin Dahmen

Type A or close to Type A



Types B and C

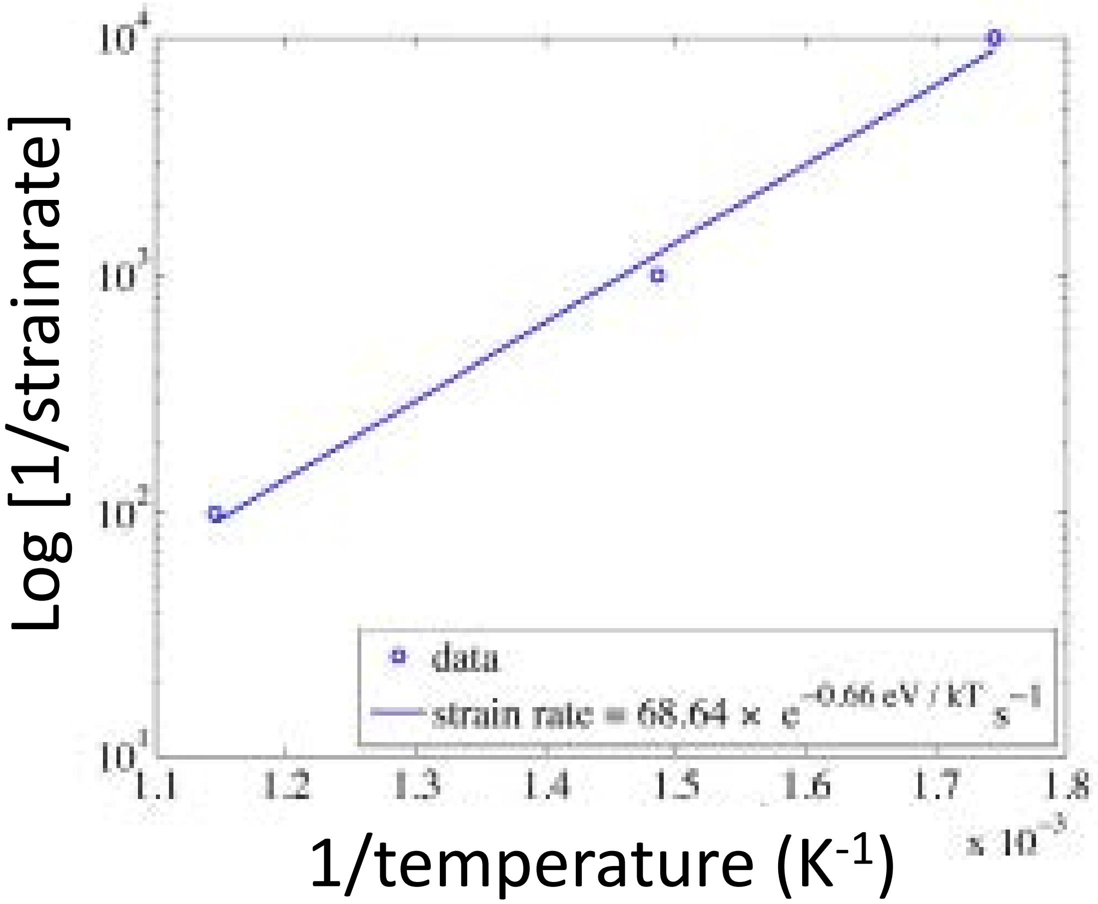


Weakening ε ~ Dislocation-Pinning-Rate(T)/Strain-Rate

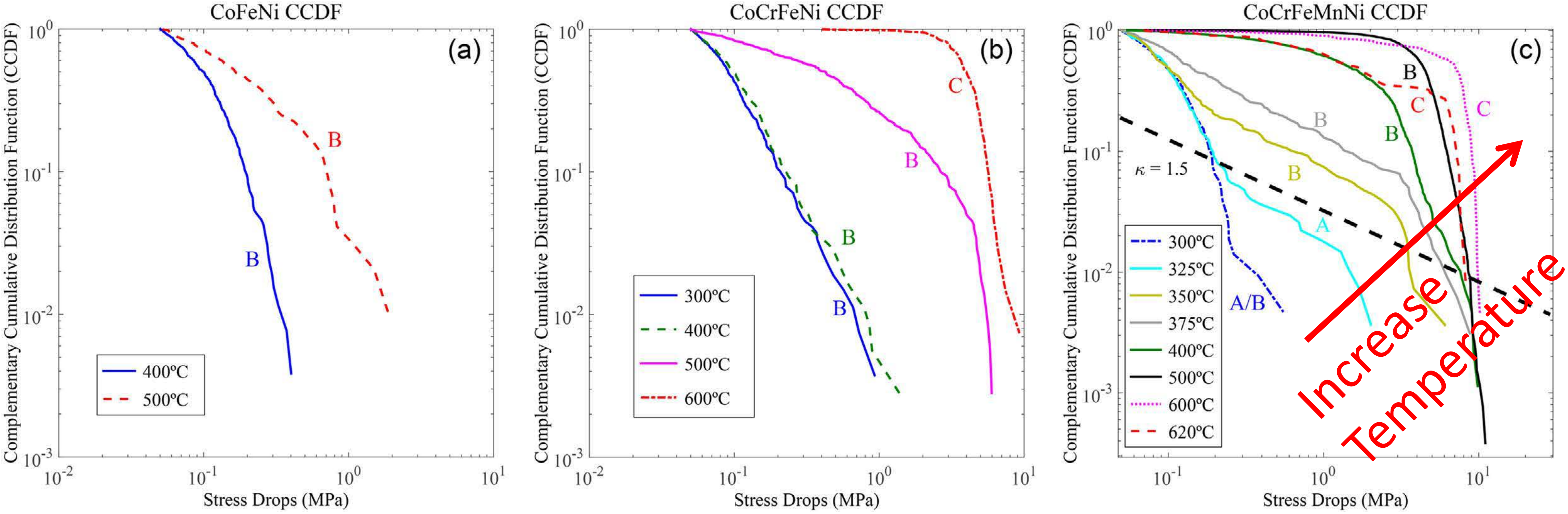
=> Expect Identical Slip Statistics for

Dislocation-Pinning Rate ~ exp[-Energybarrier/(k*Temperature)] ~ Strain-Rate

Strain-rate	Temperature (°C)	Serration Behavior	PLC-Band Type
1×10^{-2}/s	300	None	None
	400	Yes	A
	500	Yes	A
	600	Yes	A
1×10^{-3}/s	300	Yes	A
	400	Yes	A
	500	Yes	B
	600	Yes	B
1×10^{-4}/s	300	Yes	A
	400	Yes	B
	500	Yes	B
	600	Yes	C



Serration statistics for different compositions:
Less components implies slower pinning rate (Jien-Wie Yeh)
=> Less components means smaller weakening ε



Many predictions from the simple mean field model for crackling noise statistics, time series properties, etc.

Description	Name	Exponent (i.e. slope)	MFT model prediction
Avalanche size distribution	D(S,F)	κ	3/2
Cutoff of avalanche size distribution	D(S,F)	1/σ	2
Distribution of max stress drop rates	$D(V_{max})$	μ	2
Distribution of square of max stress drop rates	$D(V_{max}^2)$		3/2
Avalanche duration distribution	D(T,F)	1+(κ-1)/συz	2
Cutoff of avalanche duration distribution	D(T,F)	υz	1
Distribution of avalanche energies	D(E,F)	1+(κ-1)/(2-συz)	4/3
Cutoff of distribution of avalanche energies	D(E,F)	(2-συz)/σ	3
Average avalanche size versus duration	<S>	1/συz	2
Average avalanche duration versus size	<T>	συz	1/2
Average energy versus size	<E>	2-συz	3/2
Stress drop rate profiles at fixed duration	<V(t)|T>	1/συz-1	1
Power Spectra of stress drop rates	P(ω)	1/συz	2
Strain Rate versus stress, …. etc	dγ/dt	β	1

KD, Ben-Zion, Uhl, PRL 2009, Nature Phys. 2011, Tsekenis, Uhl, Goldenfeld, KD, EPL 2013, PRL 2012, LeBlanc, Angheluta, Goldenfeld, KD PRE 2013, James Antonaglia, Wendelin J. Wright, Xiaojun Gu, Rachel R. Byer, Todd C. Hufnagel, Michael LeBlanc, Jonathan T. Uhl, and Karin A. Dahmen, PRL 2014, J. Antonaglia, X.Xie, M. Wraith, J.Qiao, Y. Zhang, P.K. Liaw, J.T. Uhl, and K.A. Dahmen, Nature Scientific Reports 4, 4382 (2014).