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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Outline

- **Introduction of high entropy alloys (HEAs) and serration behavior**
- **Objective**
- **Experimental results of serration behavior**
- **Modeling of serration statistics**
- **Conclusions**
- **Papers and presentations**

Acknowledgements

We are very grateful to

(1) Jessica Mullen

(2) Steven R. Markovich

(3) Patricia Rawls

(4) Vito Cedro

(5) Richard Dunst

(6) Susan Maley

(7) Robert Romanosky

(8) Regis Conrad

(9) National Energy Technology Laboratory (NETL)

for sponsoring this project

Objectives

- **To provide the fundamental understanding of the serration behavior for low entropy alloys (LEAs), medium entropy alloys (MEAs), and high-entropy alloys (HEAs) through**

    - ❖**Mechanical experiments**
    - ❖**Slip-avalanche modeling**
    - ❖**Theoretical analysis**
    - ❖**Comparing model predictions to experimental results**

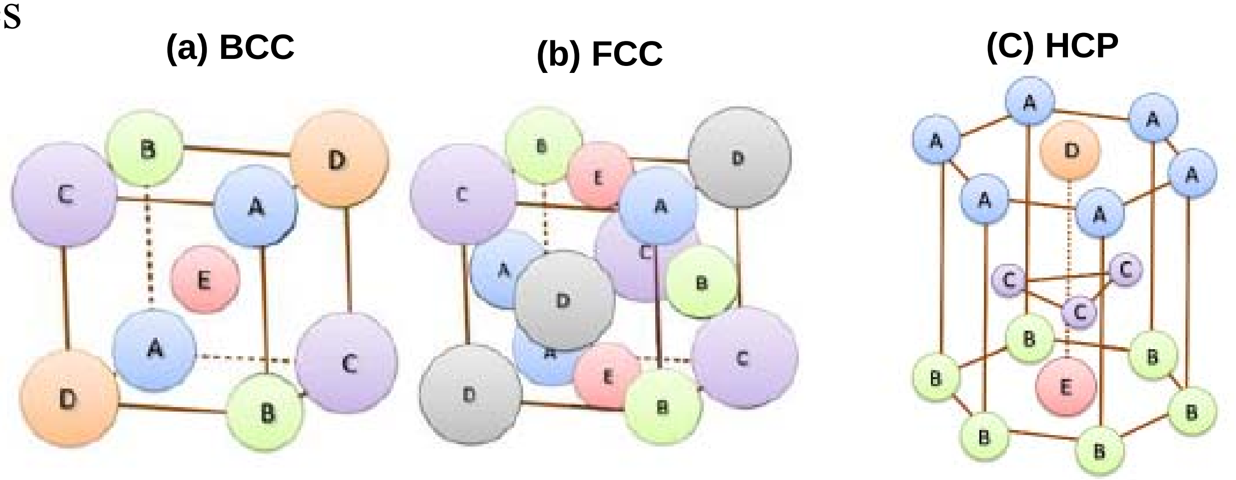
- **To develop and test serration-based models to predict the mechanical performance and creep behavior for long-term fossil-energy applications of HEAs**

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

Advantages of HEAs:

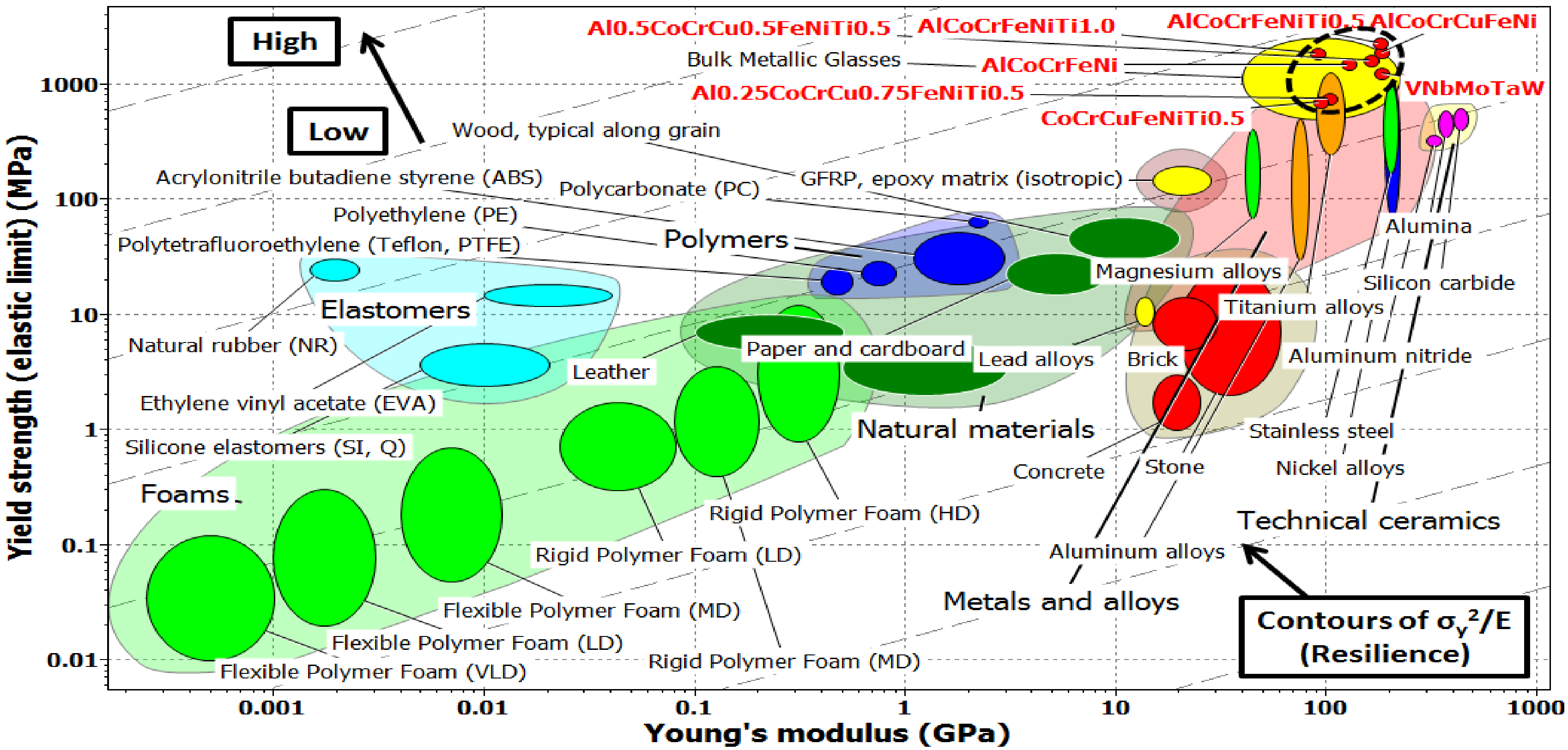
- ❖ **Great high-temperature properties and ductility**
- ❖ **Strong fatigue resistance**
- ❖ **Balanced mechanical and magnetic behavior**
- ❖ **High wear and fracture resistance**
- ❖ **Elevated-temperature softening resistance**



BCC: Body-Centered Cubic
FCC: Face-Centered Cubic
HCP: Hexagonal-Closed-Packed

*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)
*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).
*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).
*K. M. Youssef, A. J. Zaddach, C. Niu, D. L. Irving, and C. C. Koch, Materials Research Letters, 2014, pp. 1-5.
*B. Gludovatz, A. Hohenwarter, D. Catoor, E. H. Chang, E. P. George, and R. O. Ritchie,, Science, 2014, 345(6201), pp. 1153-8.

Comparison with Other Materials



❖ An Ashby map showing the range of yield strength (σ_y) versus Young's modulus for HEAs and other materials

***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).**

Low high entropy alloys (LEAs), Medium high entropy alloy (MEAs), and High entropy alloys (HEAs) could be defined by:

$$\Delta S_{mix} = -R\sum_{i=1}^{n} c_i \ln(c_i) \xrightarrow{equimolar\ (c_i=1/n)} -R\ln\frac{1}{n} = R\ln n$$

ΔS_{mix}: mixing entropy

c_i: atomic percentage of ith element

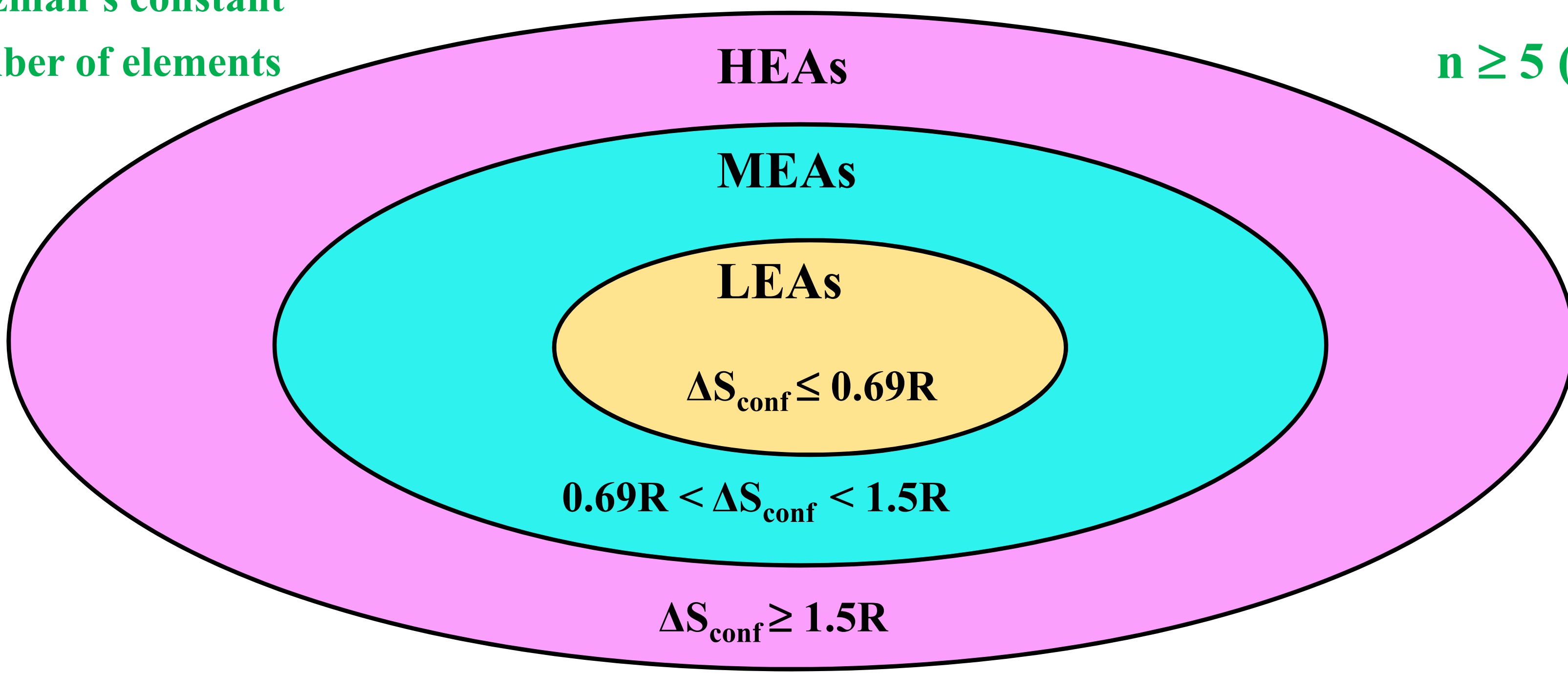
R: Bolzman's constant

n: number of elements

n = 1, 2 (LEAs);

n = 3, 4 (MEAs);

n $\geq$ 5 (HEAs)



R. Carroll, C. Lee, C. W. Tsai, J. W. Yeh, J. Antonaglia, B. A. Brinkman, M. LeBlanc, X. Xie, S. Chen, P. K. Liaw and K. A. Dahmen, Scientific Reports, 2015, 5, p. 16997.

Experimental procedures and results

Experimental procedure:

Five alloys, from low entropy to high entropy, were studied as below:

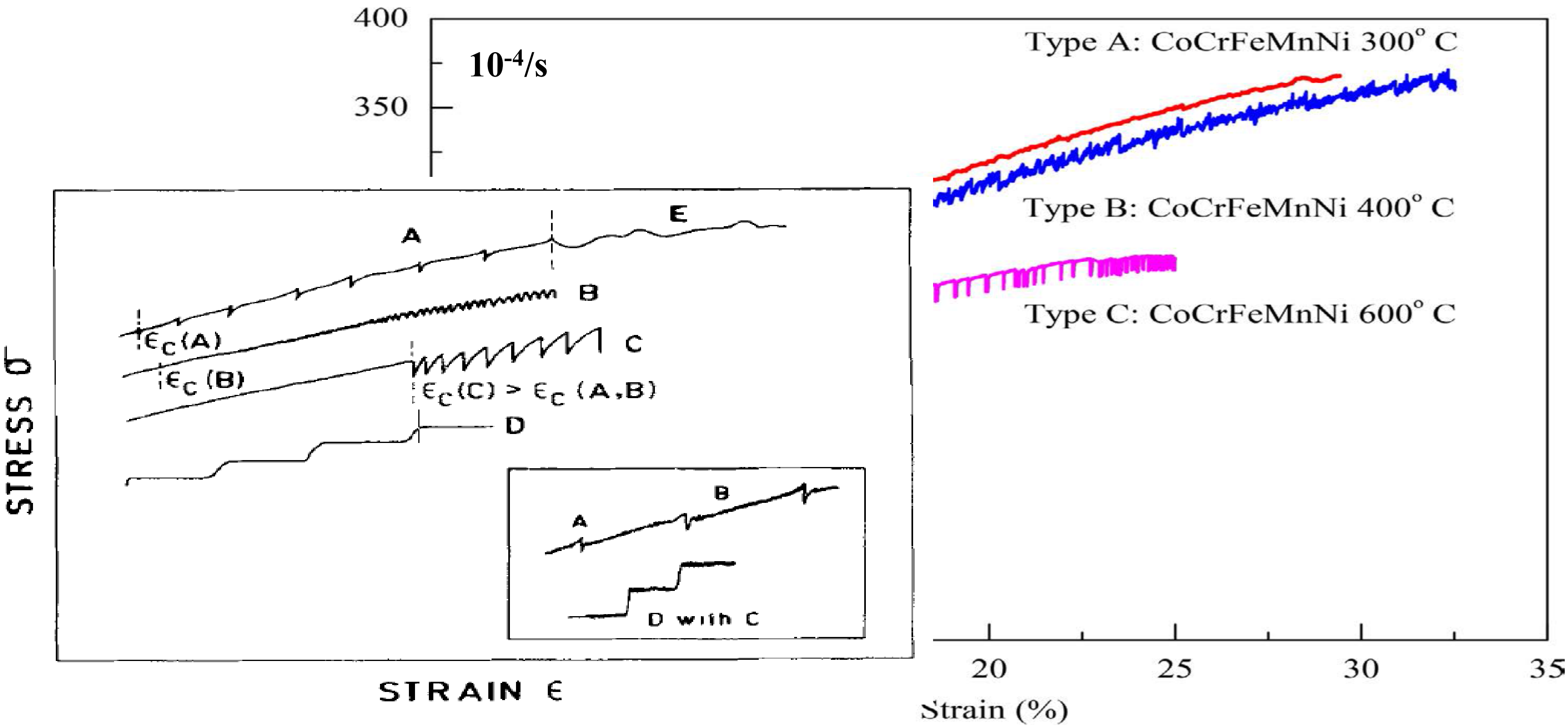
Number of elements	Ni	CoNi	CoFeNi	CoCrFeNi	CoCrFeMnNi
LEAs	√	√			
MEAs			√	√	
HEAs					√

Experimental procedures:

Five alloys, from low entropy to high entropy, were studied:

- **Method: Arc-melting + cold rolling (reduction: 65%) + homogenization treatment at 1,100 ℃ for 6 hours**
- **Tensile test strain rates: 10^{-5}/s to 10^{-2}/s**
- **Tensile test temperatures: 275 to 700 ℃**
- **Plate samples: 10 x 43 x 1 mm**

Tensile experiments



P. Rodriguez, "Serrated plastic flow", Bull. Mater. Sci., 1984, 6(4), pp. 653-663.

R. Carroll, C. Lee, C. W. Tsai, J. W. Yeh, J. Antonaglia, B. A. Brinkman, M. LeBlanc, X. Xie, S. Chen, P. K. Liaw and K. A. Dahmen, Scientific Reports, 2015, 5, p. 16997.

Serration types of LEAs at 10^{-4}/s

Alloy	Temperature (℃)	Serration behavior	Serration Type
Ni	300	None	None
	400	None	None
	500	None	None
	600	None	None
	700	None	None
CoNi	300	None	None
	400	None	None
	500	None	None
	600	None	None
	700	None	None

R. Carroll, C. Lee, C. W. Tsai, J. W. Yeh, J. Antonaglia, B. A. Brinkman, M. LeBlanc, X. Xie, S. Chen, P. K. Liaw and K. A. Dahmen, Scientific Reports, 2015, 5, p. 16997.

Serration types of MEAs at 10^{-4}/s

Alloy	Temperature (℃)	Serration behavior	Serration Type
CoFeNi	300	None	None
	400	Yes	B
	500	Yes	B
	600	None	None
	700	None	None
CoCeFeNi	300	Yes	B
	400	Yes	B
	500	Yes	B
	600	Yes	C
	700	None	None

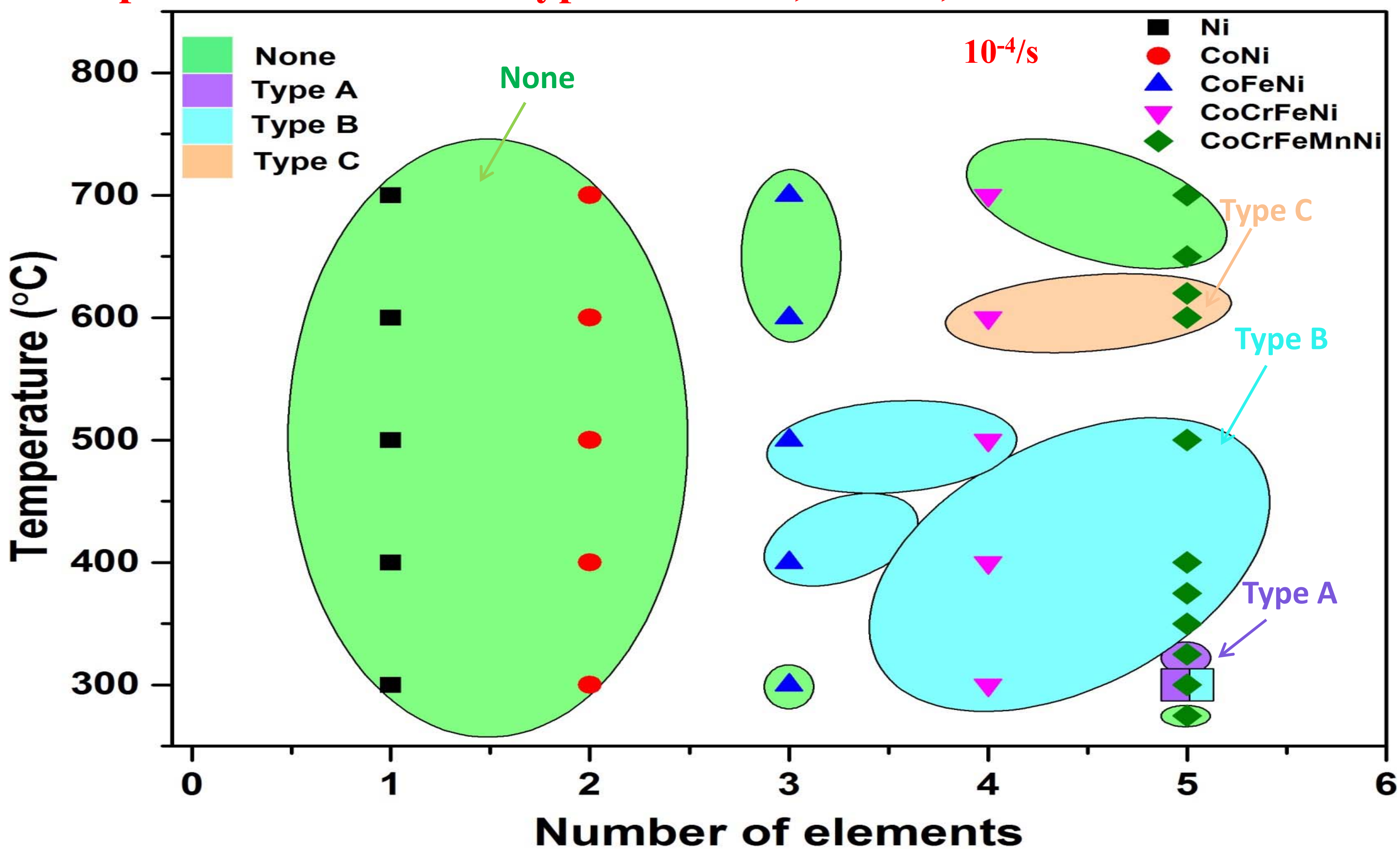
R. Carroll, C. Lee, C. W. Tsai, J. W. Yeh, J. Antonaglia, B. A. Brinkman, M. LeBlanc, X. Xie, S. Chen, P. K. Liaw and K. A. Dahmen, Scientific Reports, 2015, 5, p. 16997.

Serration types of HEAs at 10^{-4}/s

Alloy	Temperature (℃)	Serration behavior	Serration Type
CoCeFeMnNi	275	None	None
	300	Yes	A/B
	325	Yes	A
	350	Yes	B
	375	Yes	B
	400	Yes	B
	500	Yes	B
	600	Yes	C
	620	Yes	C
	650	None	None
	700	None	None

R. Carroll, C. Lee, C. W. Tsai, J. W. Yeh, J. Antonaglia, B. A. Brinkman, M. LeBlanc, X. Xie, S. Chen, P. K. Liaw and K. A. Dahmen, Scientific Reports, 2015, 5, p. 16997.

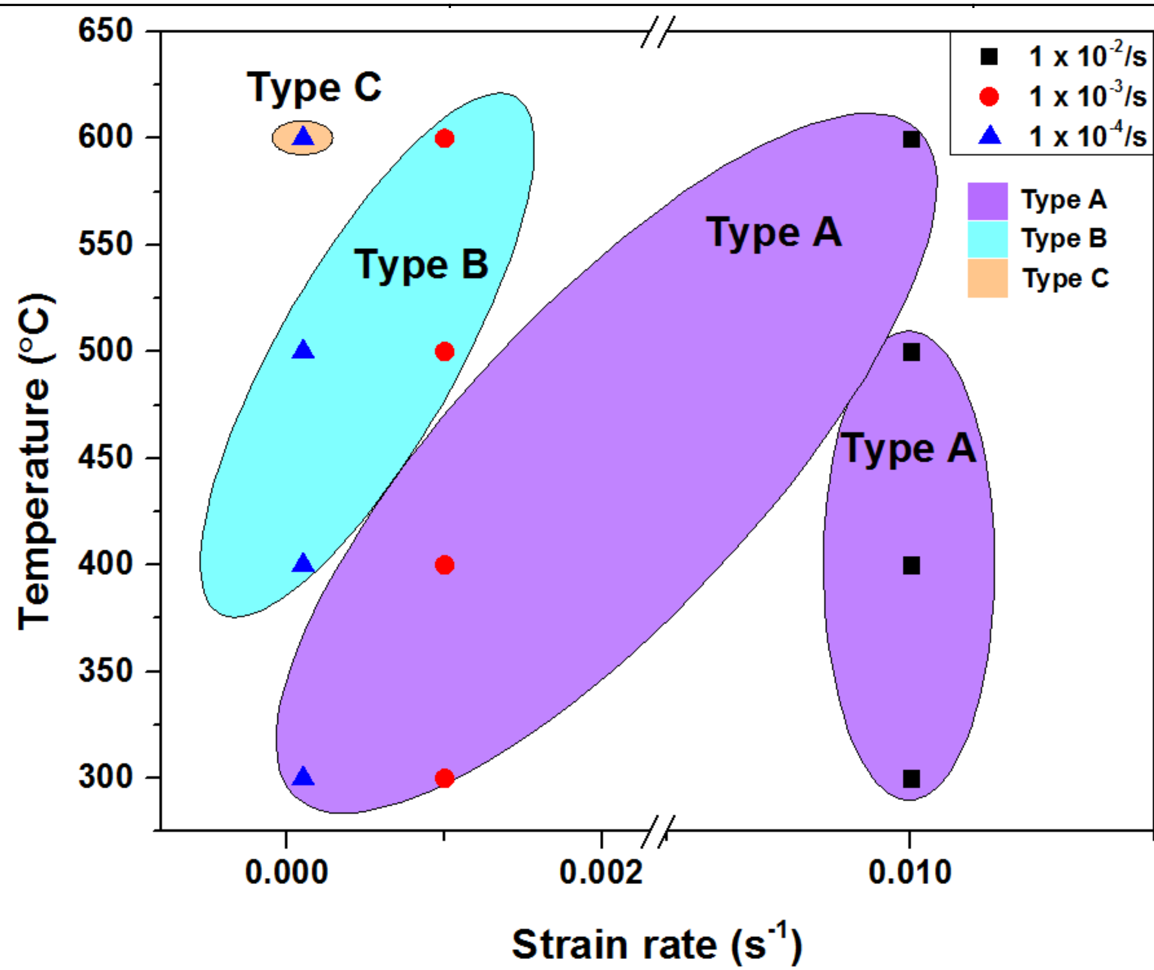
Comparison of Serration types of LEAs, MEAs, and HEAs



R. Carroll, C. Lee, C. W. Tsai, J. W. Yeh, J. Antonaglia, B. A. Brinkman, M. LeBlanc, X. Xie, S. Chen, P. K. Liaw and K. A. Dahmen, Scientific Reports, 2015, 5, p. 16997.

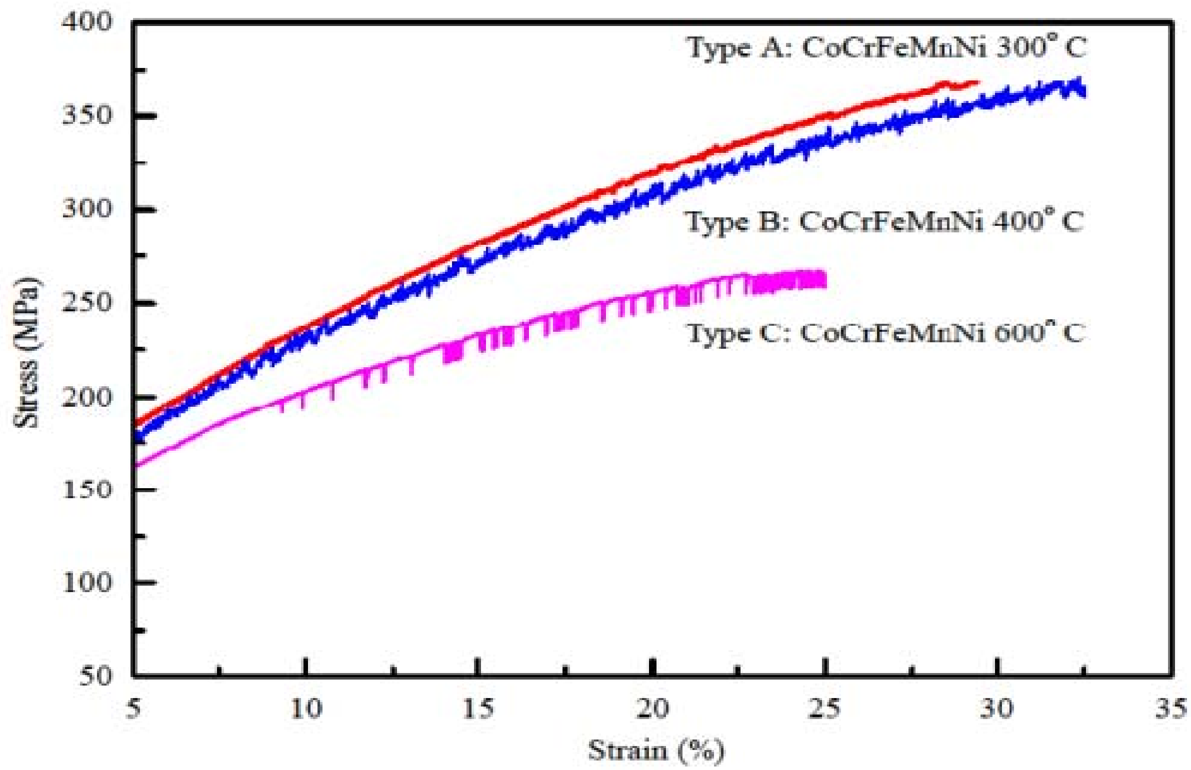
CoCrFeMnNi alloy tested with various strain rates

Strain-rate		ration Type
1×10^{-2}/s		None
		A
		A
		A
1×10^{-3}/s		A
		A
		B
		B
1×10^{-4}/s		A
		B
		B
		C



R. Carroll, C. Lee, C. W. Tsai, J. W. Yeh, J. Antonaglia, B. A. Brinkman, M. LeBlanc, X. Xie, S. Chen, P. K. Liaw and K. A. Dahmen, Scientific Reports, 2015, 5, p. 16997.

Modeling slip avalanches (the noise) in stress – strain curves of High Entropy Alloys

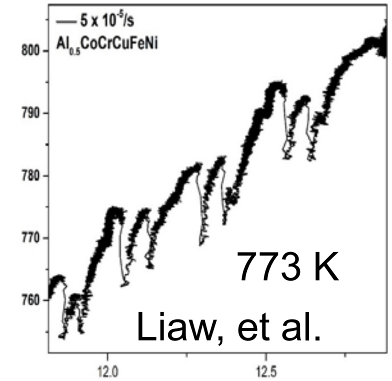


Experiments by Jien Wie Yeh et al.: High Entropy Alloy under tension, Related data: P. Liaw, O. Senkov, D. Miracle, et al.

Our Simple Analytic Model of Plasticity

(Dahmen, Ben-Zion, Uhl, PRL 2009, Nature Physics 2011)

Stress vs. Strain

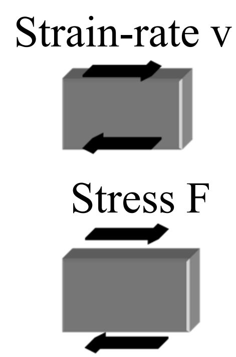


One Tuning Parameter:

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

Two Experimentally Relevant Loading Conditions:

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



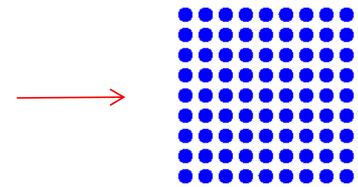
EXACT Predictions in 2 and 3 Dimensions (no fitting)

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

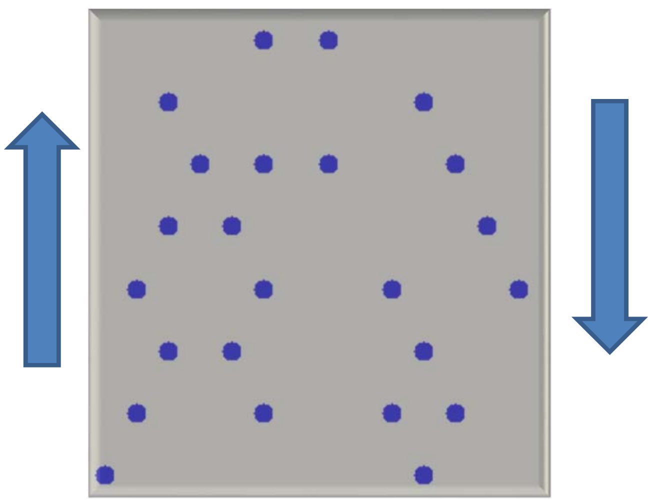
Predictions agree with first experiments,
Many predictions for future experiments…

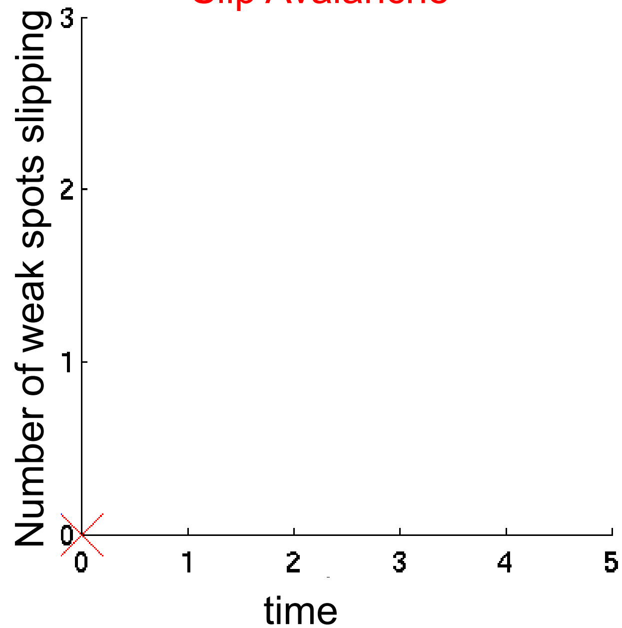
Main Idea of the simple (mean-field) model:

Shear material:

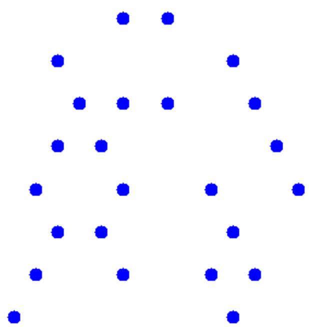


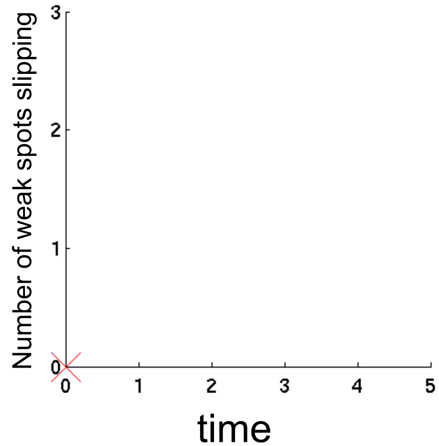
1. Weak spot slips and weakens
   triggers other weak spots to slip in a Slip Avalanche,
   weak spots reheal
2. Repeat

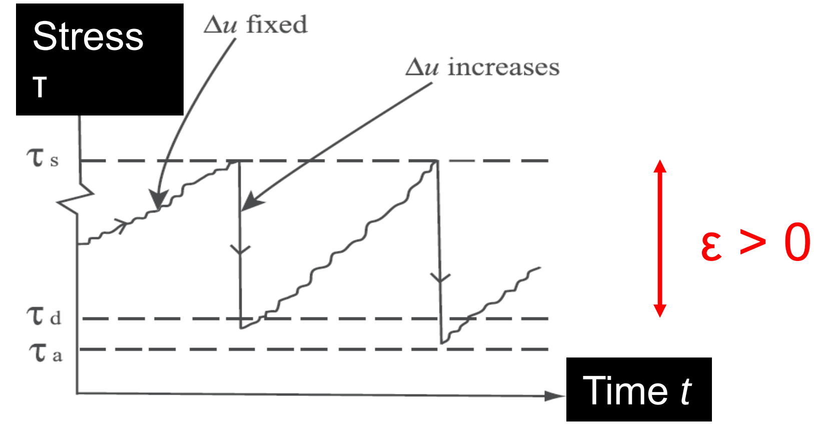




Interpretation through the model:







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

weakening (ε > 0)

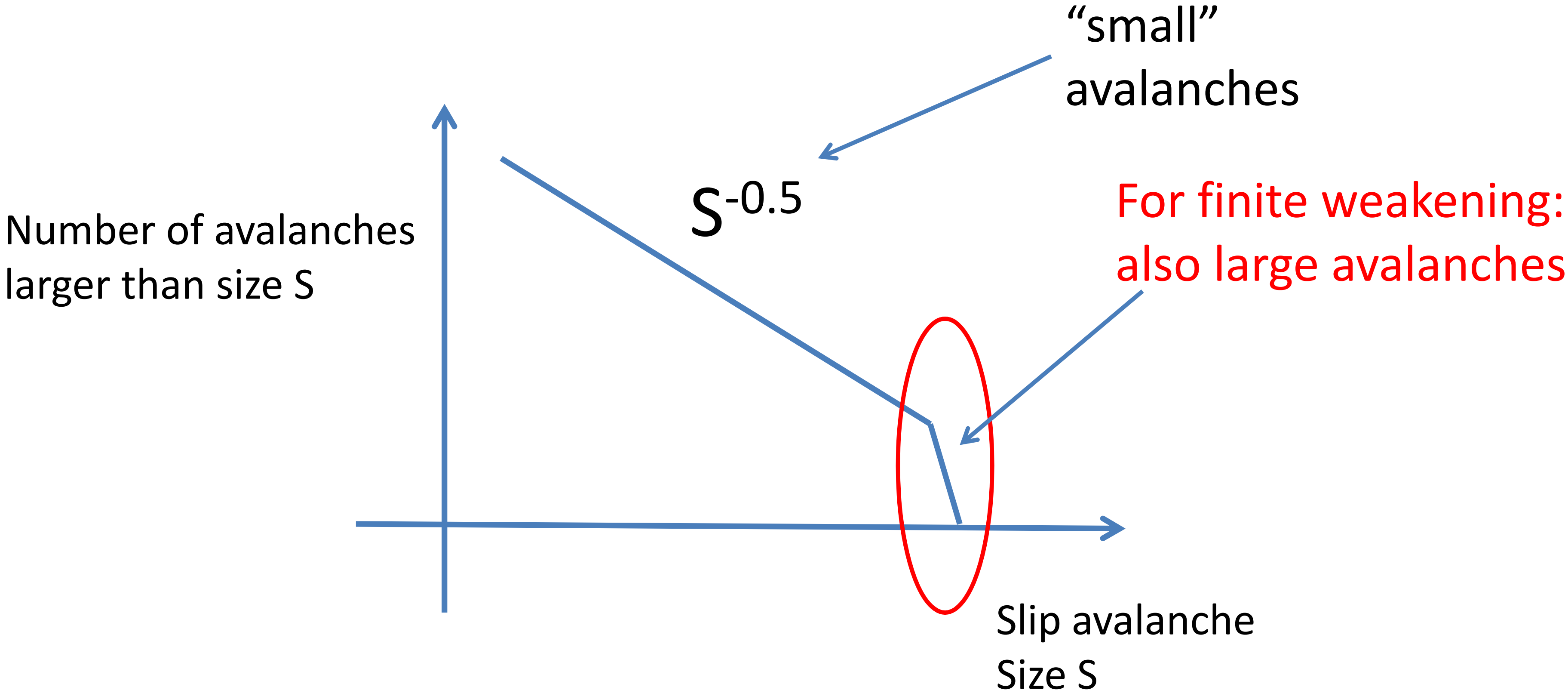
during failure avalanche:

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).

For zero weakening model predicts power law scaling behavior of avalanche size distributions



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 for PDF and ½ for CCDF
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).

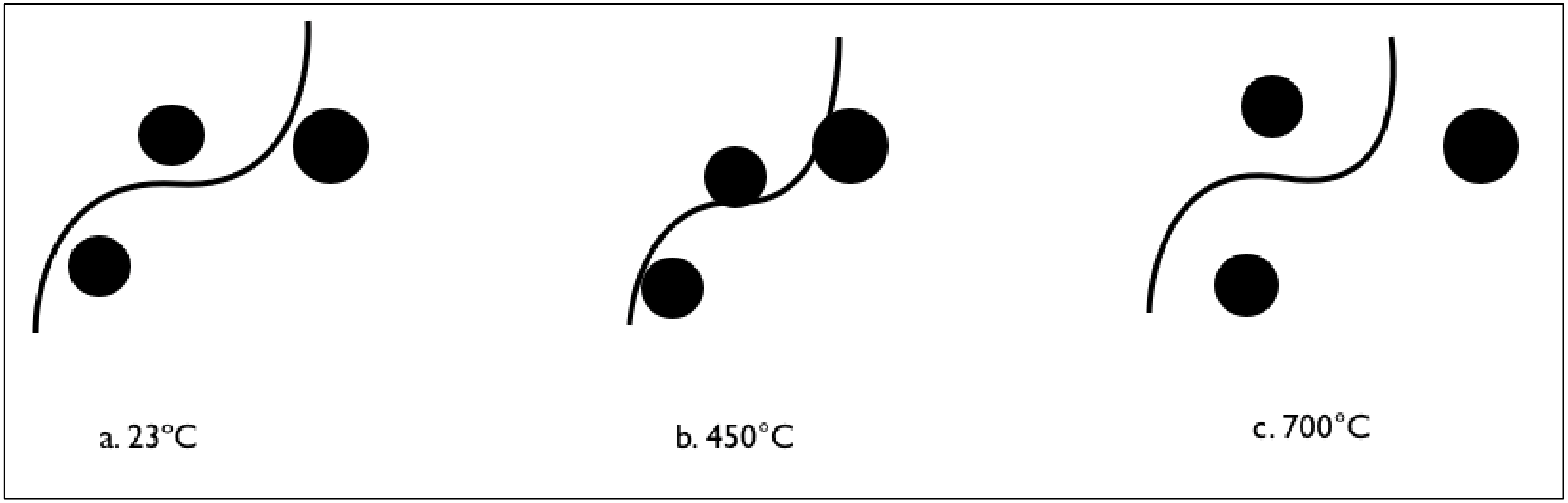
For High Entropy Alloys (Dynamic Strain Aging):

Weakening ε depends on Temperature T and Strain-Rate

Observe Serrations for 300°C < Temperature < 600 °C

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

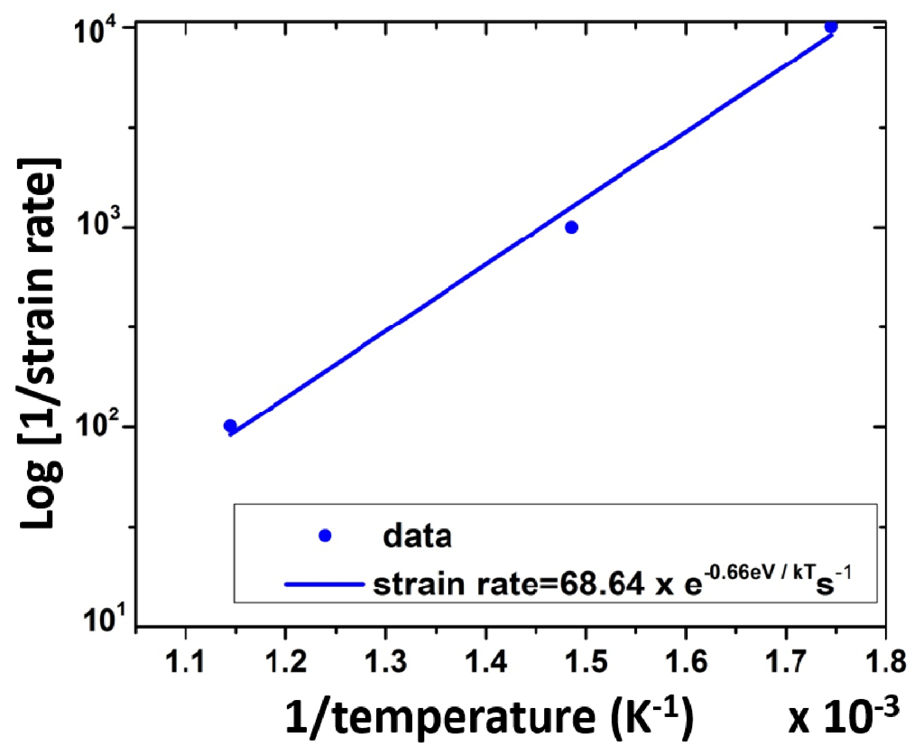


Weakening ε ~ Dislocation-Pinning-Rate(T)/Strain-Rate

=> Expect Identical Slip Statistics for

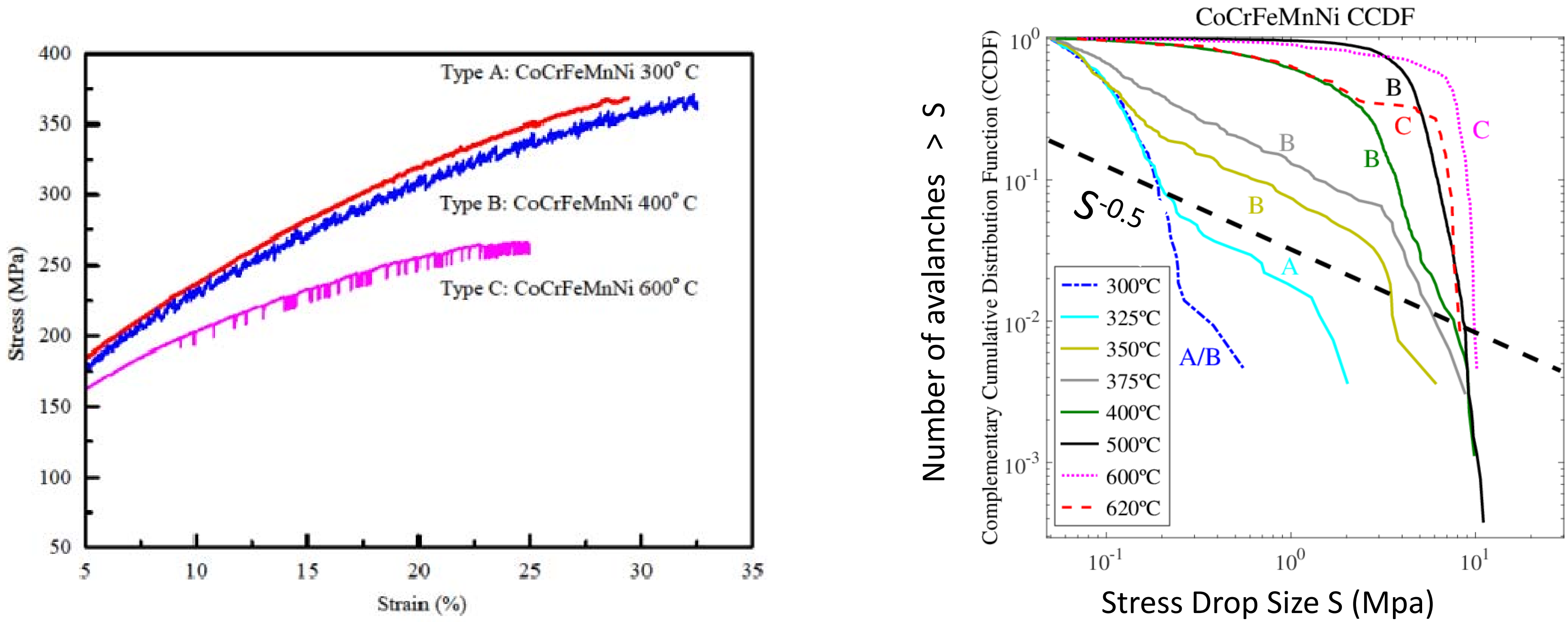
Dislocation-Pinning Rate ~ exp[-Energybarrier/(k*Temperature)] ~ Strain-Rate

Strain-rate	Temperature (℃)	Serration behavior	Serration 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



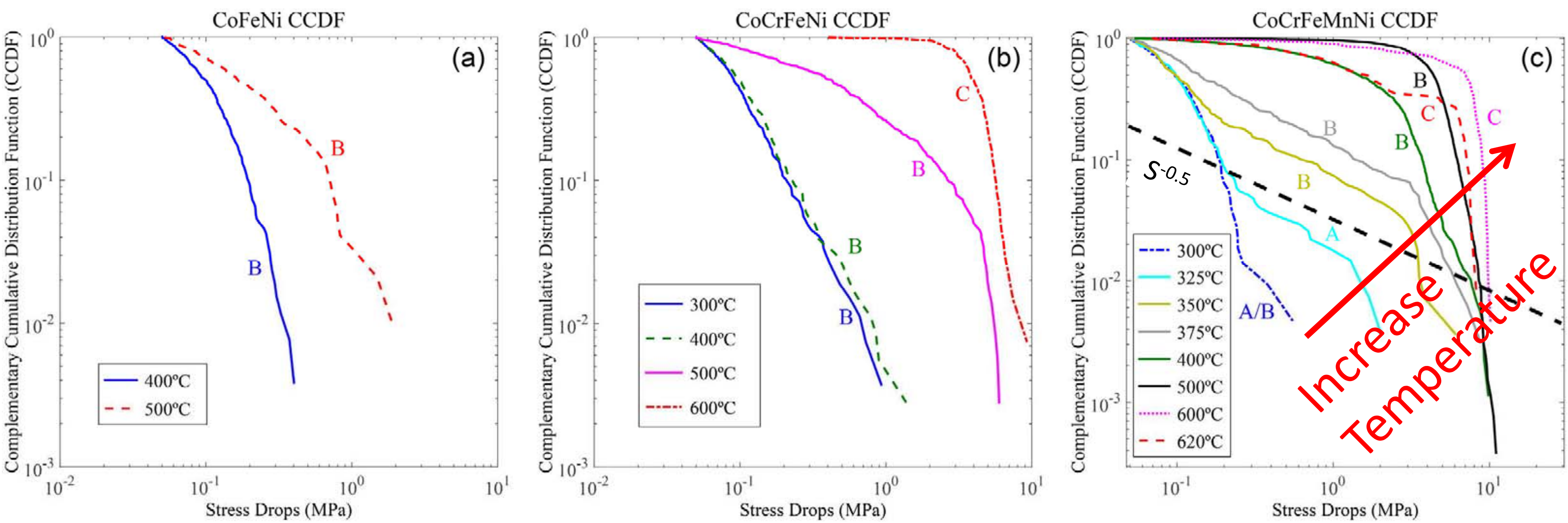
For fixed (slow) strainrate:

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

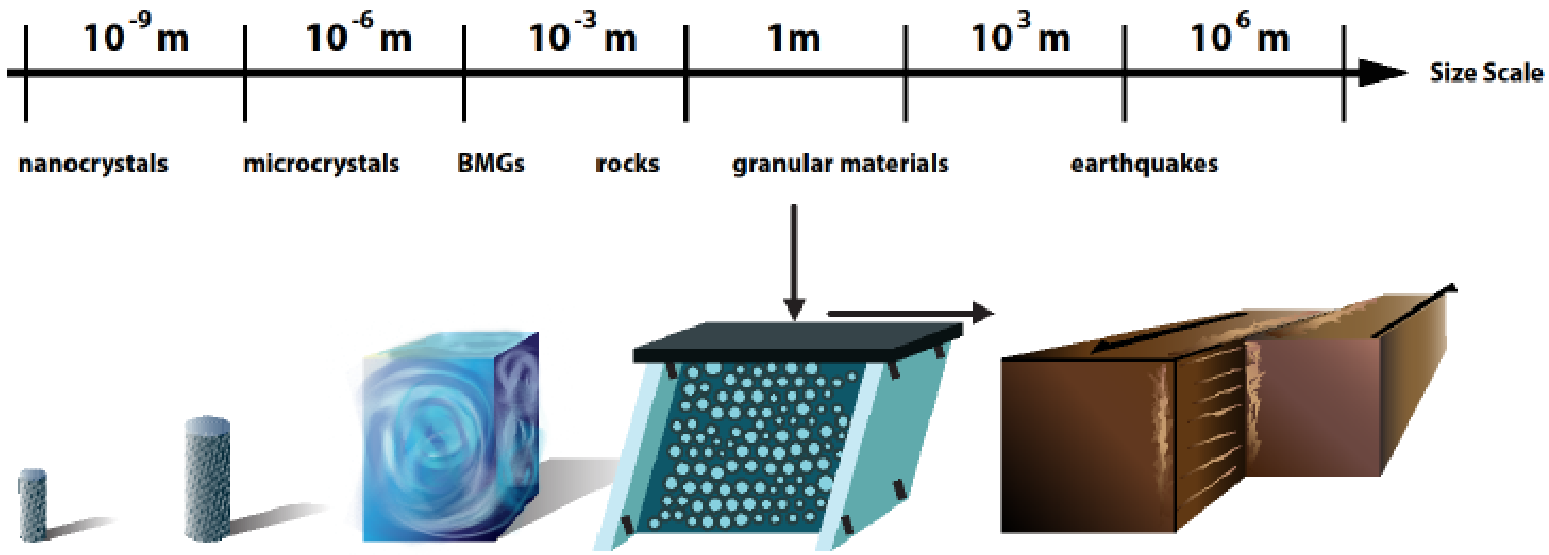


Robert Carroll, Chi Lee, Che-Wei Tsai, Jien-Wei Yeh, James Antonaglia, Braden Brinkman, Michael LeBlanc, Xie Xie, Shuying Chen, Peter K. Liaw, and Karin A. Dahmen, Scientific Reports 5, 16997 (2015).

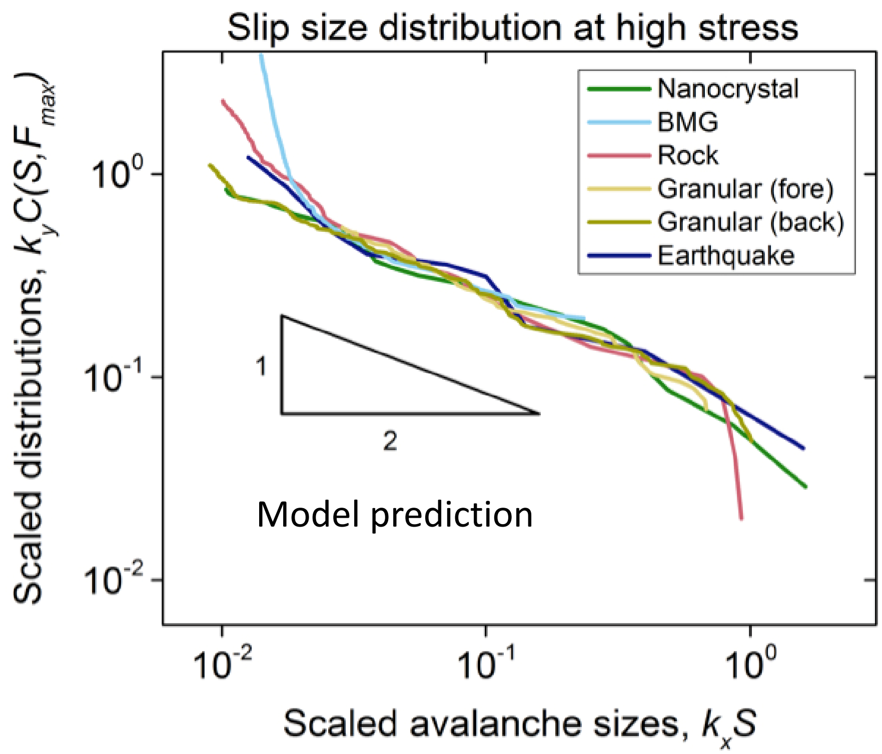
Serration statistics for different compositions:
Less components implies slower pinning rate (Jien-Wie Yeh)
=> Less components means smaller weakening ε



Comparing Model Predictions to Experiments Spanning 12 Decades in Length Scale



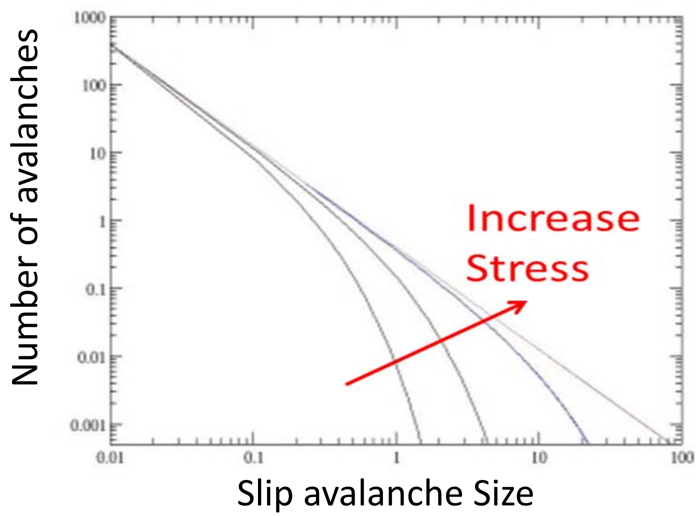
Experiments agree with mean field model predictions: for **exponents** and **scaling functions**



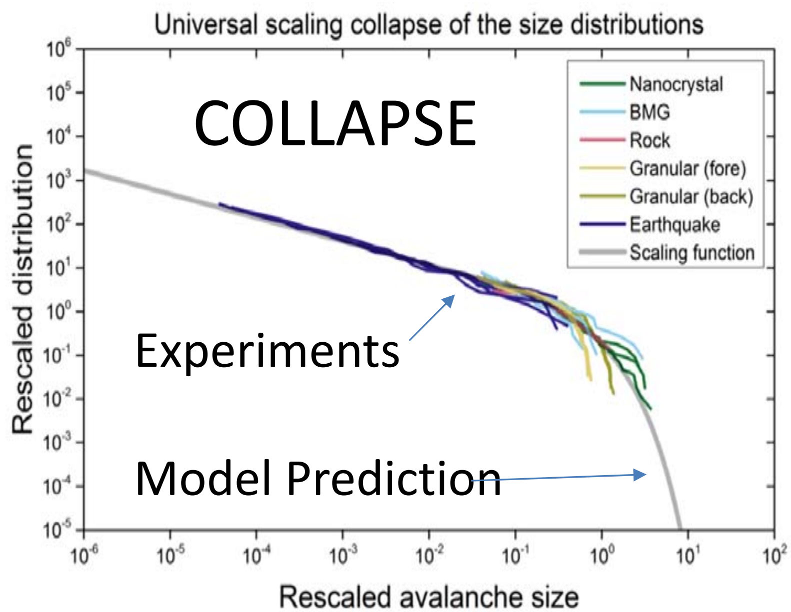
Jonathan T. Uhl, Shivesh Pathak, Danijel Schorlemmer, Xin Liu, Ryan Swindeman, Braden A.W. Brinkman, Michael LeBlanc, Georgios Tsekenis, Nir Friedman, Robert Behringer, Dmitry Denisov, Peter Schall, Xiaojun Gu, Wendelin J. Wright, Todd Hufnagel, Andrew Jennings, Julia R. Greer, P.K. Liaw, Thorsten Becker,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

Experiments agree with mean field model predictions: for **exponents** and **scaling functions**

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)

MS&T Symposium:

COLLECTIVE PHENOMENA IN MATERIALS (3)

To be held at the 2015 Materials Science and Technology (M S&T) Conference,
October 23-27, 2016, Salt Lake City, UT

ABSTRACT DEADLINE: *March 31st, 2016*

www.matscitech.org

Papers will be published in Metallurgical and Materials Transactions.

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

Conclusions for High Entropy Alloys

- **For LEAs (Ni and CoNi), MEAs (CoFeNi and CoCrFeNi), and HEA (CoCrFeMnNi) with a single FCC structure, large serration phenomena are only found in MEAs and HEA, which is in remarkable agreement with the predictions of a simple MFT model.**
- **The MFT theory thereby provides the first quantitative explanation for the observed serration statistics and their dependence on temperature, strain rate, and composition of LEAs, MEAs, and HEAs.**
- **The results of this study can be used for (1) materials evaluation and (2) alloys design with prescribed serration properties in desired temperature and strain-rate ranges.**

Dissemination of results:

- **33 Papers published in Scientific Journals (Nature Communications, Scientific Reports,….).**
- **More than 79 Presentations at national and international Conferences, Workshops, Universities, and National Labs.**

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.
9. T. T. Z. Yong Zhang, Zhi Tang, Michael C. Gaoc, Karin A. Dahmen, and Z. P. L. Peter K. Liaw, "Microstructures and Properties of High-Entropy", Progress in Materials Science, 2014, 61, pp. 93, p. 1.
10. P. F. Yu, S. D. Feng, G. S. Xu, X. L. Guo, Y. Y. Wang, W. Zhao, L. Qi, G. Li, P. K. Liaw, and R. P. Liu, "Room-Temperature Creep Resistance of Co-Based Metallic Glasses", Scripta Materialia, 2014, 90-91, pp. 45-48.
11. Y. Zhang, M. Li, Y. D. Wang, J. P. Lin, K. A. Dahmen, Z. L. Wang, and P. K. Liaw, "Superelasticity and Serration Behavior in Small-Sized NiMnGa Alloys", Advanced Engineering Materials, 2014, 16(8), pp. 955-960.

Publications (Cont'd)

12. Y. Zhang, Z. P. Lu, S. G. Ma, P. K. Liaw, Z. Tang, Y. Q. Cheng, and M. C. Gao, "Guidelines in Predicting Phase Formation of High-Entropy Alloys", MRS Communications, 2014, 4(2), pp. 57-62.
13. 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, "Deviation from High-Entropy Configurations in the Atomic Distributions of a Multi-Principal-Element Alloy", Nature Communication, 2015, 6, p. 5964.
14. Y. F. Cao, X. Xie, J. Antonaglia, B. Winiarski, G. Wang, Y. C. Shin, P. J. Withers, K. A. Dahmen, and P. K. Liaw, "Laser Shock Peening on Zr-based Bulk Metallic Glass and Its Effect on Plasticity: Experiment and Modeling", Scientific Reports, 2015, 5, p. 10789.
15. R. Carroll, C. Lee, C. W. Tsai, J. W. Yeh, J. Antonaglia, B. A. W. Brinkman, M. LeBlanc, X. Xie, S. Y. Chen, P. K. Liaw, and K. A. Dahmen, "Experiments and Model for Serration Statistics in Low-Entropy, Medium-Entropy, and High-Entropy Alloys", Scientific Reports, 2015, 5, p. 16997.

Publications (Cont'd)

16. C. Chen, J. L. Ren, G. Wang, K. A. Dahmen, and P. K. Liaw, "Scaling Behavior and Complexity of Plastic Deformation for a Bulk Metallic Glass at Cryogenic Temperatures", Physical review E, 2015, 92(1), p. 012113.
17. S. Y. Chen, X. Xie, B. L. Chen, J. W. Qiao, Y. Zhang, Y. Ren, K. A. Dahmen, and P. K. Liaw, "Effects of Temperature on Serrated Flows of Al0.5CoCrCuFeNi High-Entropy Alloy", JOM, 2015, 67(10), pp. 2314-2320.
18. H. Y. Diao, L. J. Santodonato, Z. Tang, T. Egami, and P. K. Liaw, "Local Structures of High-Entropy Alloys (HEAs) on Atomic Scales: An Overview", JOM, 2015, 67(10), pp. 2321-2325.
19. L. Huang, C. Pu, R. K. Fisher, D. J. H. Mountain, Y. F. Gao, P. K. Liaw, W. Zhang, and W. He, "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, pp. 356-368.

Publications (Cont'd)

20. G. Li, D. H. Xiao, P. F. Yu, L. J. Zhang, P. K. Liaw, Y. C. Li, and R. P. Liu, "Equation of State of an AlCoCrCuFeNi High-Entropy Alloy", JOM, 2015, 67(10), pp. 2310-2313.
21. S. Liu, M. C. Gao, P. K. Liaw, and Y. Zhang, "Microstructures and Mechanical Properties of AlxCrFeNiTi0.25 Alloys", Journal of Alloys and Compounds, 2015, 619, pp. 610-615.
22. M. Seifi, D. Y. Li, Z. Yong, P. K. Liaw, and J. J. Lewandowski, "Fracture Toughness and Fatigue Crack Growth Behavior of As-Cast High-Entropy Alloys", JOM, 2015, 67(10), pp. 2288-2295.
23. G. Song, Z. Q. Sun, L. Li, X. D. Xu, M. Rawlings, C. H. Liebscher, B. Clausen, J. Poplawsky, D. N. Leonard, S. Y. Huang, Z. K. Teng, C. T. Liu, M. D. Asta, Y. F. Gao, D. C. Dunand, G. Ghosh, M. W. Chen, M. E. Fine, and P. K. Liaw, "Ferritic Alloys with Extreme Creep Resistance via Coherent Hierarchical Precipitates", Scientific Reports, 2015, 5, p. 16327.

Publications (Cont'd)

24. **Z. Q. Sun, G. Song, J. Ilavsky, G. Ghosh, and P. K. Liaw, "Nano-sized Precipitate Stability and Its Controlling Factors in a NiAl-strengthened Ferritic Alloy", Scientific Reports, 2015, 5, p. 16081.**
25. **Z. Tang, O. N. Senkov, C. M. Parish, C. Zhang, F. Zhang, L. J. Santodonato, G. Y. Wang, G. F. Zhao, F. Q. Yang, and P. K. Liaw, "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, pp. 229-240.**
26. **J. T. Uhl, S. Pathak, D. Schorlemmer, X. Liu, R. Swindeman, B. A. W. Brinkman, M. LeBlanc, G. Tsekenis, N. Friedman, R. Behringer, D. Denisov, P. Schall, X. J. Gu, W. J. Wright, T. Hufnagel, A. Jennings, J. R. Greer, P. K. Liaw, T. Becker, G. Dresen, and K. A. Dahmen, "Universal Quake Statistics: From Compressed Nanocrystals to Earthquakes", Scientific Reports, 2015, 5, p. 16493.**

Publications (Cont'd)

27. P. F. Yu, L. J. Zhang, H. Cheng, H. Zhang, Q. Jing, M. Z. Ma, P. K. Liaw, G. Li, and R. P. Liu, "Special Orientation Relationships of CuZr2 in the Annealed Zr64.5Cu35.5 Metallic Glass", Metallurgical and Materials Transactions a-Physical Metallurgy and Materials Science, 2015, 46A(5), pp. 1855-1859.

28. T. T. Zuo, X. Yang, P. K. Liaw, and Y. Zhang, "Influence of Bridgman Solidification on Microstructures and Magnetic Behaviors of a Non-equiatomic FeCoNiAlSi High-entropy Alloy", Intermetallics, 2015, 67, pp. 171-176.

29. S. H. Chen, K. C. Chan, G. Wang, F. F. Wu, L. Xia, J. L. Ren, J. Li, K. A. Dahmen, and P. K. Liaw, "Loading-rate-independent Delay of Catastrophic Avalanches in a Bulk Metallic Glass", Scientific Reports, 2016, 6, p. 21967.

30. X. Tong, G. Wang, J. Yi, J. L. Ren, S. Pauly, Y. L. Gao, Q. J. Zhai, N. Mattern, K. A. Dahmen, P. K. Liaw, and J. Eckert, "Shear Avalanches in Plastic Deformation of a Metallic Glass Composite", International Journal of Plasticity, 2016, 77, pp. 141-155.

Publications (Cont'd)

31. W. J. Wright, Y. Liu, X. J. Gu, K. D. Van Ness, S. L. Robare, X. Liu, J. Antonaglia, M. LeBlanc, J. T. Uhl, T. C. Hufnagel, and K. A. Dahmen, "Experimental Evidence for both Progressive and Simultaneous Shear During Quasistatic Compression of a Bulk Metallic Glass", Journal of Applied Physics, 2016, 119(8), p. 084908.

32. P. F. Yu, H. Cheng, L. J. Zhang, H. Zhang, Q. Jing, M. Z. Ma, P. K. Liaw, G. Li, and R. P. Liu, "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, pp. 283-291.

33. P. F. Yu, H. Cheng, L. J. Zhang, H. Zhang, M. Z. Ma, G. Li, P. K. Liaw, and R. P. Liu, "Nanotwin's Formation and Growth in an AlCoCuFeNi High-entropy Alloy", Scripta Materialia, 2016, 114, pp. 31-34.

2014 TMS meetings San Diego, CA, USA, February 16-20, 2014 Presentations

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.**
3. **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, and T. Egami.**
4. **Characterization of Inhomogeneous Deformation and Serrated Flows in Bulk Metallic Glasses, X. Xie, J. Antonaglia, J. W. Qiao, G. Y. Wang, Y. Zhang, Y. Yokoyama, K. Dahmen, and P. K. Liaw.**
5. **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.**
6. **Ultra Grain Refinement in High Entropy Alloys: N. Tsuji, I. Watanabe, N. Park, D. Terada, A. Shibata, Y. Yokoyama, P. K. Liaw.**

2014 TMS meetings San Diego, CA, USA, February 16-20, 2014 Presentations (Cont'd)

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.
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. Mechanical Behavior of an Al0.1CoCrFeNi High Entropy Alloy, M. Komarasamy, N. Kumar, Z. Tang, R. Mishra, and P. K. Liaw.
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.
12. 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.

2014 TMS Meeting, San Diego, CA, USA, February 16-20, 2014

Presentations (Cont'd)

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.**
14. **2014 TMS Meeting, San Diego, CA, USA, February 16-20, 2014 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.**
15. **2014 TMS Meeting, San Diego, CA, USA, February 16-20, 2014 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.**
16. **2014 TMS Meeting, San Diego, CA, USA, February 16-20, 2014 The Hot Corrosion Resistance Properties of AlxFeCoCrNi, S. Y. Yang, M. Habibi, L. Wang, S. M. Guo, Z. Tang, P. K. Liaw, L. X. Tan, C. Guo, and M. Jackson.**

2014

Presentations (Cont'd)

1. 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.
2. Beihang University, Beijing, China, June 10, 2014 (Invited) Characterization of Serrated Flows in High-Entropy Alloys and Bulk-Metallic Glasses, P. K. Liaw.
3. 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.
4. 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.
5. 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.
6. 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)

7. 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.
8. University of California, Los Angeles, California, US, October 17th, 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.
9. 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.
10. 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. **Mechanical Response of Zr-based BMG after Mechanical Rejuvenation by High-Pressure Torsion, Koichi Tsuchiya; Fanqiang Meng; Yoshihiko Yokoyama; Karin Dahmen; Peter Liaw.**
2. **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.**
3. **Temperature Evolution in Bulk Metallic Glasses Under Different Loading Conditions, Xie Xie; Junwei Qiao; Gongyao Wang; Yoshihiko Yokoyama; Karin Dahmen; Peter Liaw.**
4. **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.**
5. **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

6. **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.**
7. **Al-Co-Cr-Fe-Ni Phase Equilibria and Properties, Zhi Tang, Oleg Senkov, Chuan Zhang, Fan Zhang, Carl Lundin, and Peter Liaw.**
8. **Fatigue Behavior of an Al0.1CoCrNiFe High Entropy Alloy, Bilin Chen, Xie Xie, Shuying Chen, Ke An, and Peter Liaw.**
9. **Flow and Fracture Behavior of a High Entropy Alloy, Yong Zhang, Peter Liaw, and John Lewandowski.**
10. **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.**
11. **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.**
12. **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)

13. Sputter Deposition Simulation of High Entropy Alloy via Molecular Dynamics Methodology, Yunche Wang, Chun-Yi Wu, Nai-Hua Yeh, and Peter Liaw.
14. 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.
15. The Characterization of Serrated Plastic Flow in High Entropy Alloys, Shuying Chen; Xie Xie; James Antonaglia; Junwei Qiao; Yong Zhang; Karin Dahmen; Peter Liaw.
16. 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

1. **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.**
2. **The Serrated Flows in High Entropy Alloys, Shuying Chen; Xie Xie; James Antonaglia; Junwei Qiao; Yong Zhang; Karin Dahmen; Peter Liaw.**
3. **The Study of the Serrated Flow in Bulk Metallic Glasses, Xie Xie; Abid Khan; Junwei Qiao; Yong Zhang; Gongyao Wang; Karin Dahmen; Peter Liaw.**
4. **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)

5. **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.**
6. **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.**
7. **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)

8. **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.**
9. **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.**
10. **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

1. **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.**
2. **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.**
3. **Nanoindentation for Bulk Metallic Glasses, Xie Xie; Guangfeng Zhao; Peizhen Li; Shuying Chen; Fuqian Yang; Karin Dahmen; Peter Liaw.**
4. **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)

5. **Serrated Plastic Flow in CoFeMnNi, CoCrFeMnNi, and CoCrFeNi High Entropy Systems: Joseph Licavoli; Karin Dahmen; Paul Jablonski; Michael Gao; Peter Liaw; Jeffrey Hawk.**
6. **Serrated Flows in High Entropy Alloys (HEAs), Shuying Chen; Peter Liaw; Xie Xie; Karin Dahmen; Yong Zhang; Junwei Qiao.**
7. **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.**
8. **Exploring the Structure-composition Design Space in Multi-component Alloy Systems Using Nature Inspired Optimization Algorithms: Aayush Sharma; Rahul Singh; Peter Liaw; Ganesh Balasubramanian.**
9. **Time-dependent Mechanical Properties of Metallic Glass via Molecular Dynamics Simulations: Yunche Wang; Nai-Hua Yeh; Peter Liaw.**
10. **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)

11. **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.**
12. **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.**
13. **A Bragg-Williams Model of Ordering in High-entropy Alloys: Louis Santodonato; Peter Liaw.**
14. **Nano-sized Precipitate Stability and Its Controlling Factors in a NiAlstrengthened Ferritic Alloy: Zhiqian Sun; Gian Song; Jan Ilavsky; Gautam Ghosh; Peter Liaw.**
15. **Exploration of High Entropy Alloys for Sustainable Energy Storages: Jingke Mo; Yunzhu Shi; Peter Liaw; Feng-Yuan Zhang.**
16. **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)

16. 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.
17. Intergranular Strain Evolution near Fatigue Crack Tips in Polycrystalline Materials: Yanfei Gao; Rozaliya Barabash; Peter Liaw.
18. 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.
19. 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.
20. 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.
21. 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)

23. **Microstructural Characterization and Phase Evolution of Al1.5CrFeMnTi and Al2CrFeMnTi: Rui Feng; Chanho Lee; Peiyong Chen; Michael Gao; Chuan Zhang; Fan Zhang; Peter Liaw.**
24. **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.**
25. **A Novel, Single Phase, Refractory CrMoNbV High-entropy Alloy: Rui Feng; Michael Widom; Michael Gao; Peter Liaw.**
26. **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.**
27. **Microstructural Characterization in AlxCrFeMnTix advanced Light Weight High-Entropy Alloys: Chanho Lee; Peiyong Chen; Rui Feng; Michael Gao; Fan Zhang; Chuan Zhang; Peter Liaw.**
28. **Microstructural Characterization of a Ni2HfAl-Precipitate- Strengthened Ferritic Alloy: Shao-Yu Wang; Gian Song; Peter K. Liaw.**

2016, 2015, 2014 other invited lectures at conferences:

1. 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", Karin Dahmen and Peter Liaw.

2. 2016 Conference on avalanches, plasticity and nonlinear response in nonequilibrium solids, Kyoto, Japan, Universal Slip Statistics in theory and experiments, 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, Peter K. Liaw, Thorsten Becker, Georg Dresen, and Karin Dahmen.

3. Annual Symposium of the Center for Advanced Study, University of Illinois at Urbana Champaign, Universal slip statistics: from nanocrystals to earthquakes, National Academy of Sciences, Karin Dahmen, Jonathan Uhl, and Yehuda Ben-Zion.

4. Frontiers In Physics, Pattern Formation, and Complex Materials Far From Equilibrium: Universal slip statistics: from nanocrystals to earthquakes, National Academy of Sciences, Karin Dahmen, Jonathan Uhl, and Yehuda Ben-Zion.

2016, 2015, 2014 other invited lectures at conferences, cont'd:

5. Universal slip statistics: from nanocrystals to earthquakes, KITP conference on Complexity in mechanics: 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, Peter K. Liaw, Thorsten Becker, Georg Dresen, and Karin Dahmen

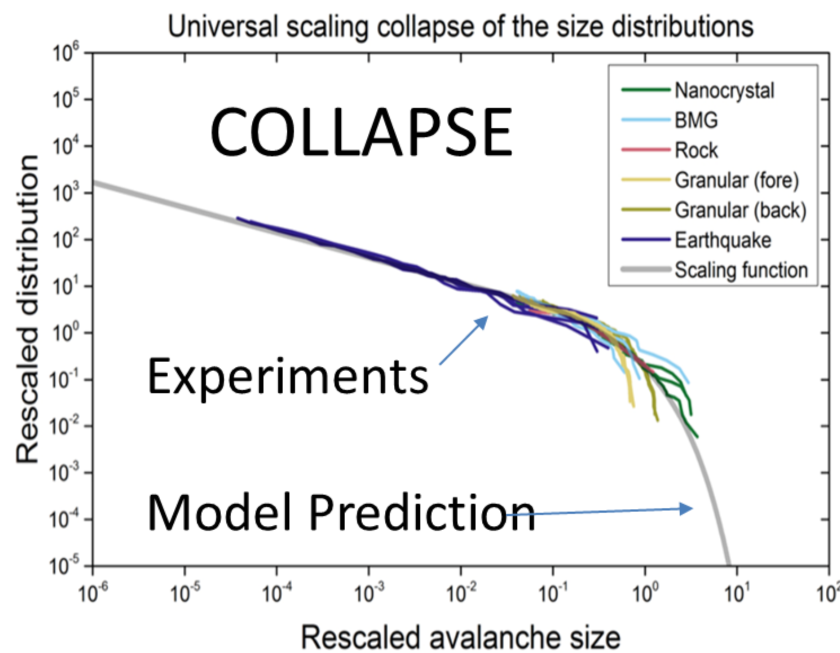
6. Conference Keynote Presentation at "Deformation, Damage, and Life Prediction of Structural Materials“,, Tuned-critical quake statistics; from nanocrystals to bulk metallic glasses to earthquakes”, Karin Dahmen, Jonathan Uhl, Peter Liaw, Wendelin Wright, Todd Hufnagel, Julia Greer.

In addition to these conference talks there were more than 9 Invited Colloquia presented at Universities and National Labs, including Argonne National Lab, Cornell University, University of Wisconsin Madison, Penn State University, Notre Dame University, Toronto University, University of Vancouver, University of Victoria, and Duke University.

Conclusion and Future Use of 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**
- **Nano-crystals, Microcrystals**
- **Bulk Metallic Glasses**
- **Granular Materials**
- **Rocks**
- **Earthquakes**



2. **Planned Future Work:**

- Compare more quantities with the model predictions
- Extract information on the **microstructure** of materials
- Possibly **materials testing and creep-life prediction**

Conclusions for High Entropy Alloys

- For LEAs (Ni and CoNi), MEAs (CoFeNi and CoCrFeNi), and HEA (CoCrFeMnNi) with a single FCC structure, large serration phenomena are only found in MEAs and HEA, which is in remarkable agreement with the predictions of a simple MFT model.
- The MFT theory thereby provides the first quantitative explanation for the observed serration statistics and their dependence on temperature, strain rate, and composition of LEAs, MEAs, and HEAs.
- The results of this study can be used for (1) materials evaluation and (2) alloys design with prescribed serration properties in desired temperature and strain-rate ranges.

Thank you for your attention!

Tensile deformation at different temperatures and comparison to theory

Experiment: Chi Lee, Che-Wei Tsai, Jien Wie Yeh, Peter Liaw,
Theory and Data Analysis: Robert Carrol, Michael LeBlanc, Jonathan T. Uhl, Karin Dahmen,
Scientific Reports 2015

I. Experimental Procedure

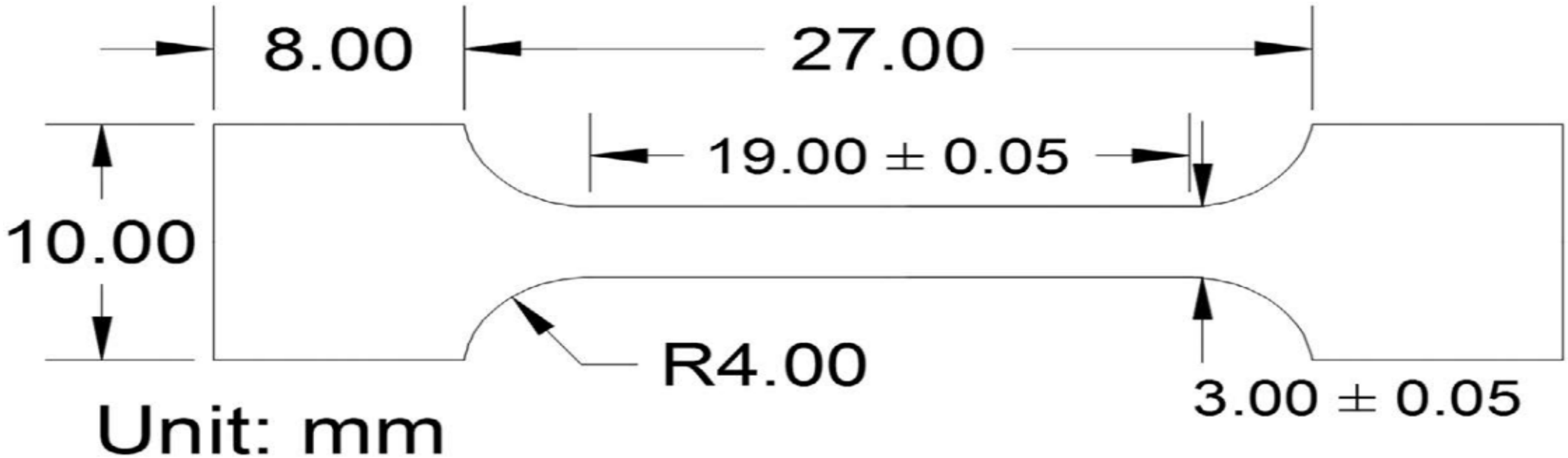
1. CoCrFeMnNi cut into strips
2. Strips tensile-stretched at different temperatures
3. Stress data recorded

II. Data Analysis

Size[1] distributions compiled and compared with theory

1. http://www.instron.com/fileuniverse/live/images/Sitewide/Detail2_5900_Extend_Main_Retrofit_Image.jpg 2. Courtesy of Dr. Jien-Wei Yeh

Three or four test specimen were used for each condition.



Thickness: 1 mm

Dimensions of the tensile specimen used in all experiments.

All numbers are in mm. R indicates the radius of curvature.

R. Carroll, C. Lee, C. W. Tsai, J. W. Yeh, J. Antonaglia, B. A. Brinkman, M. LeBlanc, X. Xie, S. Chen, P. K. Liaw and K. A. Dahmen, "Experiments and Model for Serration Statistics in Low-Entropy, Medium-Entropy, and High-Entropy Alloys", Scientific reports, 2015, 5, pp. 16997.

Slip Avalanches in High Entropy Alloys and other Materials

Karin Dahmen
University of Illinois
At Urbana Champaign

Group:

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

Undergrad Students:
Robert Carroll, Jim Antonaglia, Aya Nawano, Ryan Swindeman, Matthew Wraith, Jeliasko Jeliaskov
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:
Y. Ben-Zion, J.T. Uhl

Earthquakes:
D.S. Fisher, S.Ramanathan

Magnets: J.P. Sethna

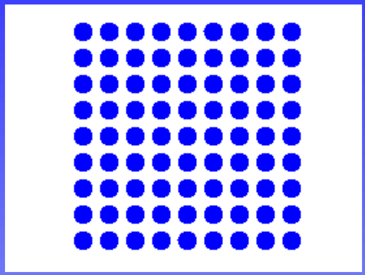
Experiments:

Nanocrystals/HEAs
J. Greer, A. Jennings, R. Maass (Caltech, UIUC), **Jimmy Zuo,** Yang Hu, **Jien-Wie Yeh, P. Liaw, Shuying Chen, Haoyan Diao, Joseph Licavoli, Jeff Hawk, Paul Jablonski, and Michael Gao**

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, S. Backhus, R. Ecke,

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



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