Project 33B-L: In-Situ Studies of Strain Rate Effects on Phase Transformation and Microstructural Evolution in Multi-Principal Element Alloys

Spring Meeting April 7th – 9th

Student: John Copley (Mines)
Faculty: Amy Clarke (Mines)
Industrial Mentors: Clarissa Yablinsky (LANL), Paul Wilson (Boeing), John Foltz (ATI)
Other Participants: Francisco Coury (UFSCAR), Jonah Klemm-Toole (Mines)

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Project 33B-L: In-Situ Studies of Strain Rate Effects on Phase Transformation and Microstructural Evolution in Multi-Principal Element Alloys

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- Student: John Copley (Mines)
- Advisor(s): Amy Clarke (Mines)

Project Duration
MS: September 2018 to August 2020

- Problem: The effects of strain rate and temperature on the TRIP/TWIP behavior exhibited by MPEAs are not well understood.
- Objective: Determine the relationship between alloying, strain rate and strain state effects on the evolution of deformation twins and deformation induced phase changes.
- Benefit: Improved understanding of TRIP/TWIP behavior seen in other materials, alloy design for specific applications, especially blast resistance.

Recent Progress

- High rate ($\dot{\varepsilon} \approx 10^3 s^{-1}$) tensile tests with simultaneous XRD at the APS
  - In-situ observation of FCC→HCP phase transformation during straining
  - Mechanical data showing improved UTS and elongation with increased strain rate
- Preparation for in-situ quasi-static deformation with XRD experiments at CHESS (postponed due to COVID-19)

Metrics

Description	% Complete	Status
1. Literature review	75%	●
2. Quasi-Static Testing	30%	●
3. Dynamic Testing	80%	●
4. Ex-situ microstructure characterization and diffraction	35%	●

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Industrial Relevance

- Understanding of TRIP/TWIP of MPEAs during high rate deformation
  - New strategies to design deformation mechanisms
  - Drive development of alloys for blast-resistance and performance in extreme environments

- Fundamental understanding of TRIP/TWIP
  - Applications to more commonly used Advanced High Strength Steels and some Ti alloys

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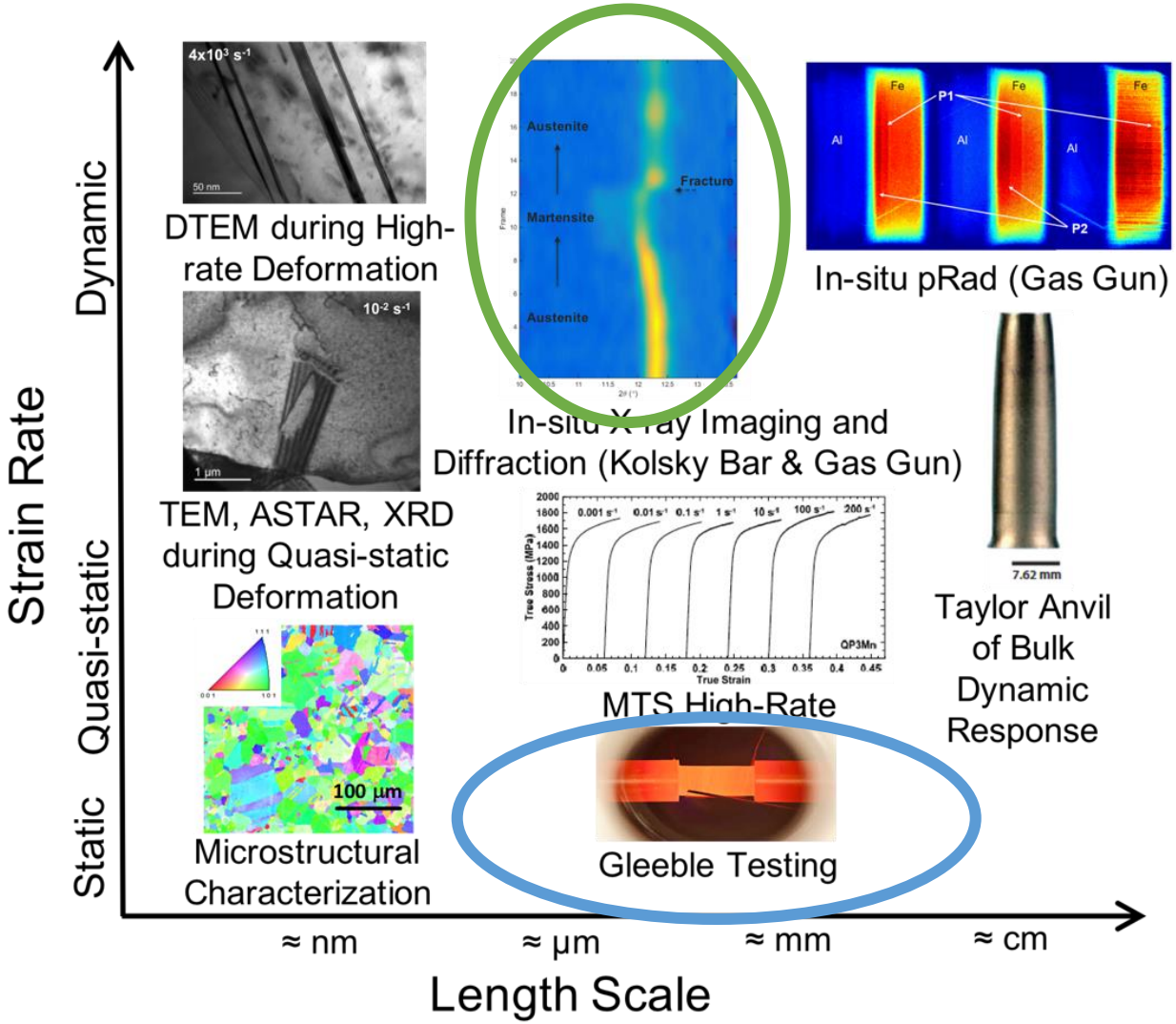
Project Vision



State-of-the-art, multi-scale microstructural characterization with electrons, x-rays, and protons of TRIP/TWIP in MPEAs for blast resistance

Figure courtesy of Dr. Amy Clarke

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Multi-Principal Element Alloys

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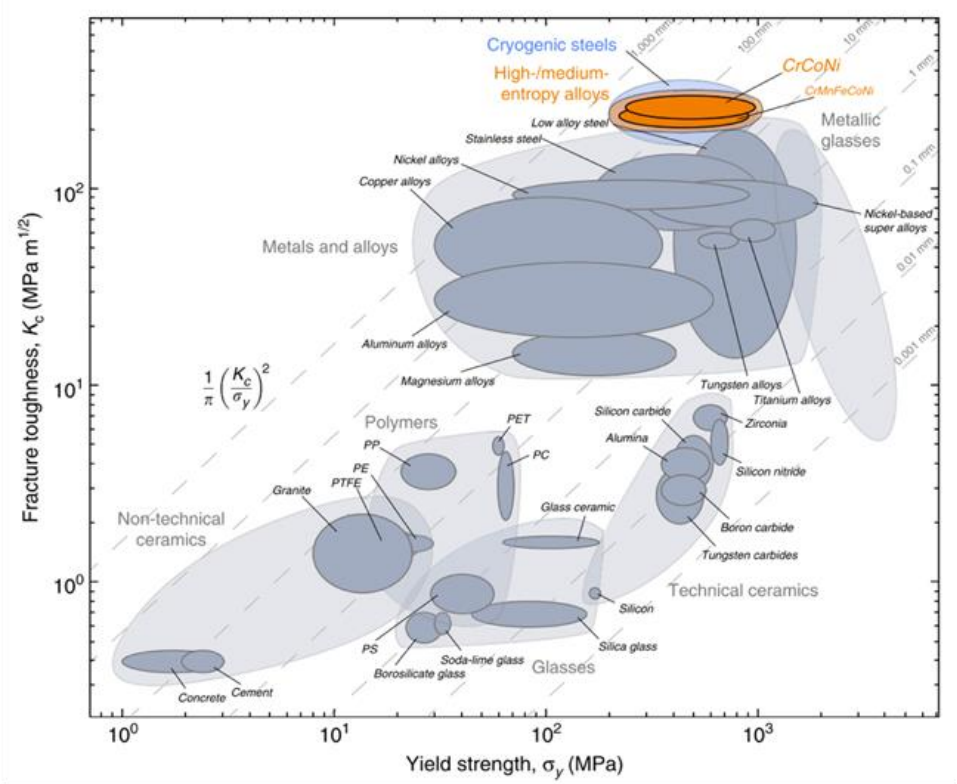
- No definable main element
  - Equiatomic, or
  - Several (>2) components present in very high concentrations
- Almost infinite combinations
- MPEA vs HEA
  - Broader definition than HEAs
    - Strength and toughness do not scale with entropy
  - CoCrNi Family
    - Fails HEA criteria
    - Toughest known CCAs



B. Gludovatz, et al., Nature Communications, 2016, 7:10602

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Twinning and Transformation Induced Plasticity

- Deformation accommodated by change in local atomic stacking
- Increased work hardening rates
  - Burgers vectors are not conserved at twin or phase interfaces
  - The "Dynamic" Hall-Petch Effect
  - High work hardening rates delay instability
- Delayed Instability
  - Increased UTS, elongation
  - Improved toughness

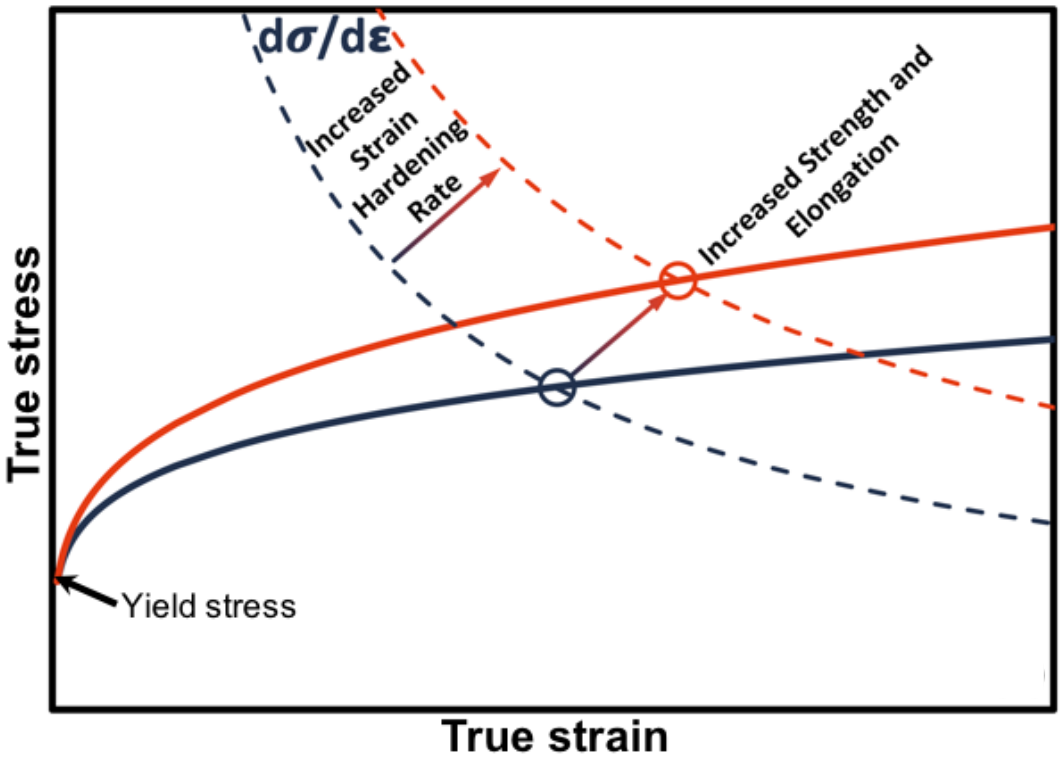

Figure courtesy of Dr. Kester Clarke

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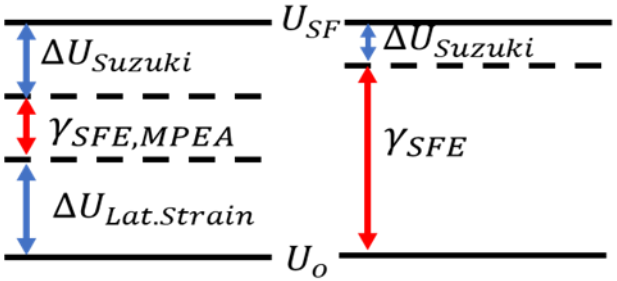
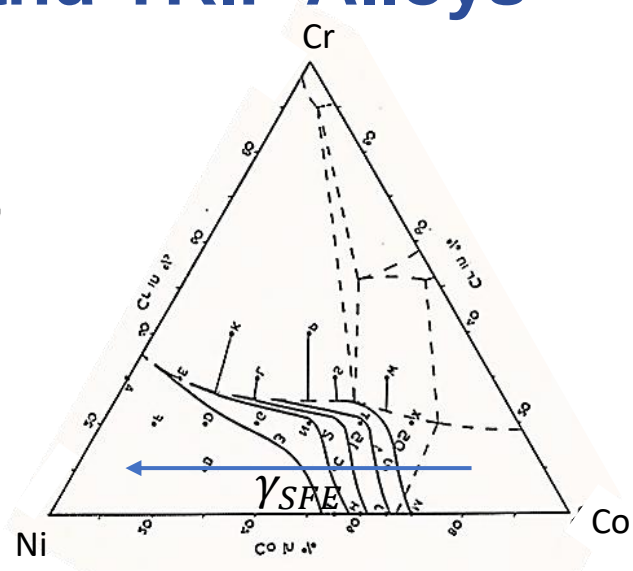
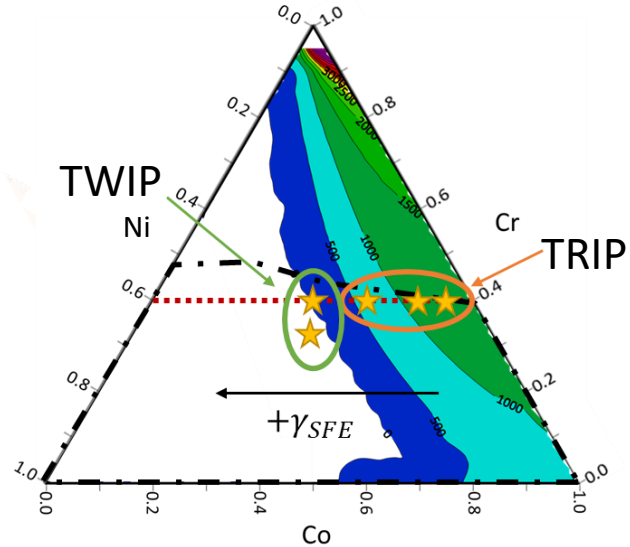
Project Review: Identifying Potential TWIP and TRIP Alloys







TWIP Potential:

- TWIP related to γ_{SFE}
  - Low γ_{SFE} expected in MPEAs
    - Suzuki Interaction
    - Lattice Distortion Energy
- γ_{SFE} correlated with T_0
- $Co_{33}Cr_{33}Ni_{33}$ and $Co_{27.5}Cr_{45}Ni_{27.5}$ exhibit deformation twinning

TRIP Potential:

- TRIP must occur below T_0
  - High T_0 → TRIP possible at elevated T
  - Low T_0 → TWIP or slip may be favored

From: E.H. Koster et al. Stacking Fault Energies of Ni-Co-Cr Alloys, The Philosophical Magazine, Series 8, Vol 10 (1964)

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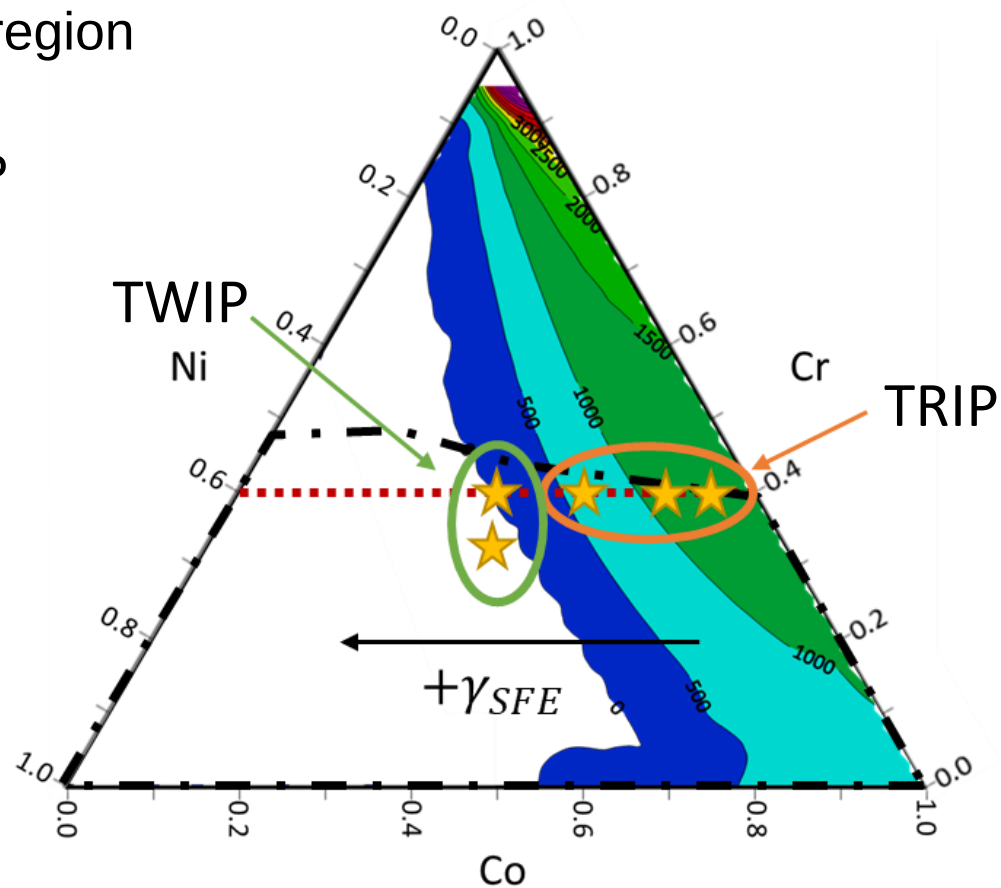
Alloy Selection for TRIP and TWIP Effects

- $Co_X Cr_{40} Ni_{60-X}$
  - X=30, 40, 50 at%
    - Inside single phase FCC region
    - Large range in T_0
    - Range from TRIP to TWIP
- CoCrNi

Alloy	$T_0(°C)$
$CoCrNi$	N/A
$Co_{30}Cr_{40}Ni_{30}$	N/A
$Co_{40}Cr_{40}Ni_{20}$	407
$Co_{50}Cr_{40}Ni_{10}$	864
$Co_{55}Cr_{40}Ni_{5}$	967



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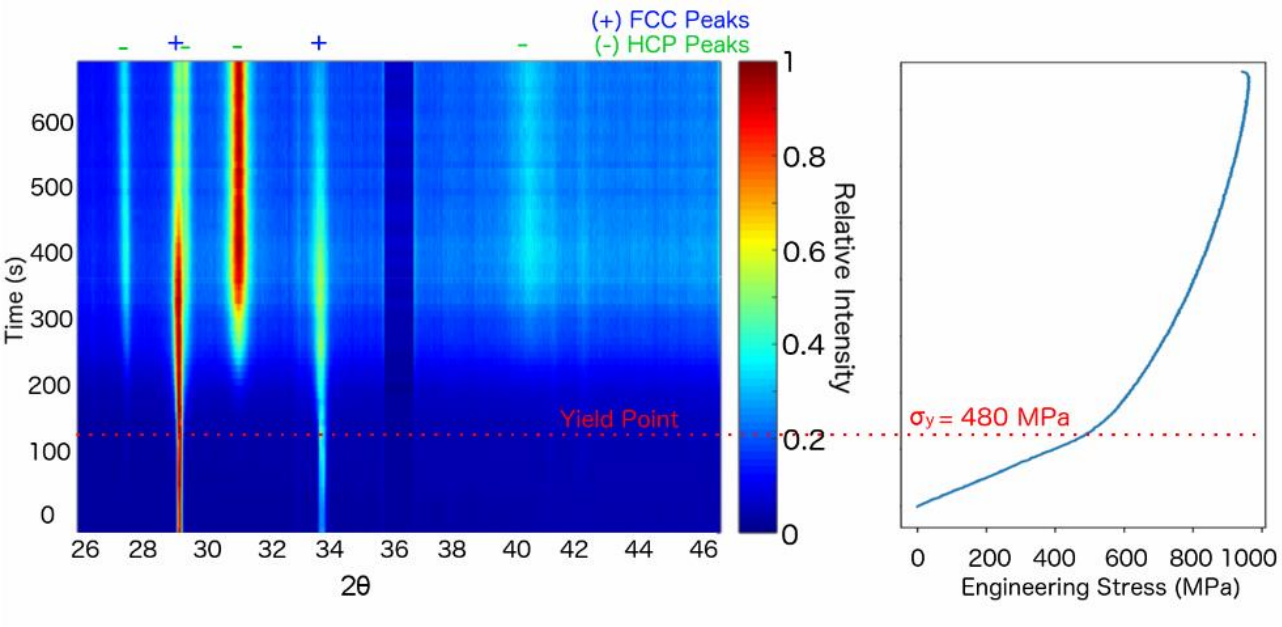
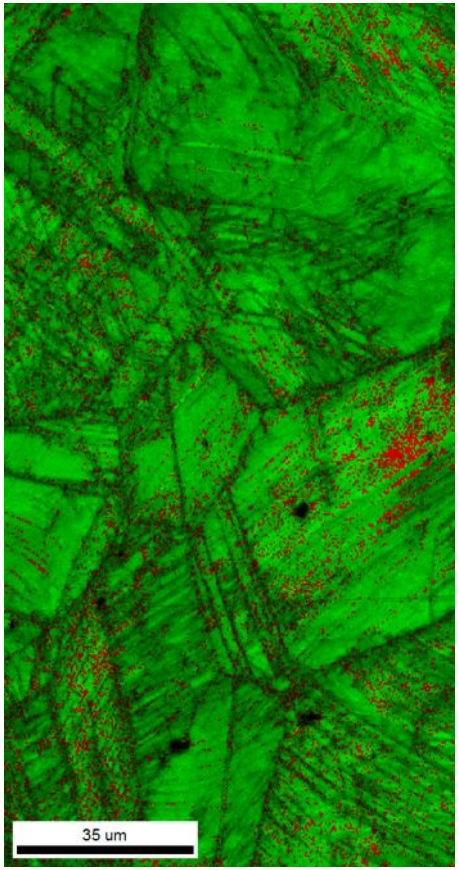
Project Review: Evidence of TRIP in $Co_{55}Cr_{40}Ni_5$





HCP, FCC

Post-mortem EBSD showing nearly 100% transformation (FCC→HCP) during deformation

- In-situ quasi-static deformation at 60°C with synchrotron x-ray diffraction, XRD (performed by Dr. Francisco Coury)
- TRIP observed from -100 to 450°C, *before being suppressed above 450°C*

F.G. Coury, D. Santana, Y. Guo, J. Copley, L. Otani, S. Fonseca, G. Zepon, C. Kimimami, M.J. Kaufman, A.J. Clarke, 2019 Scripta Materialia, 173:70-74

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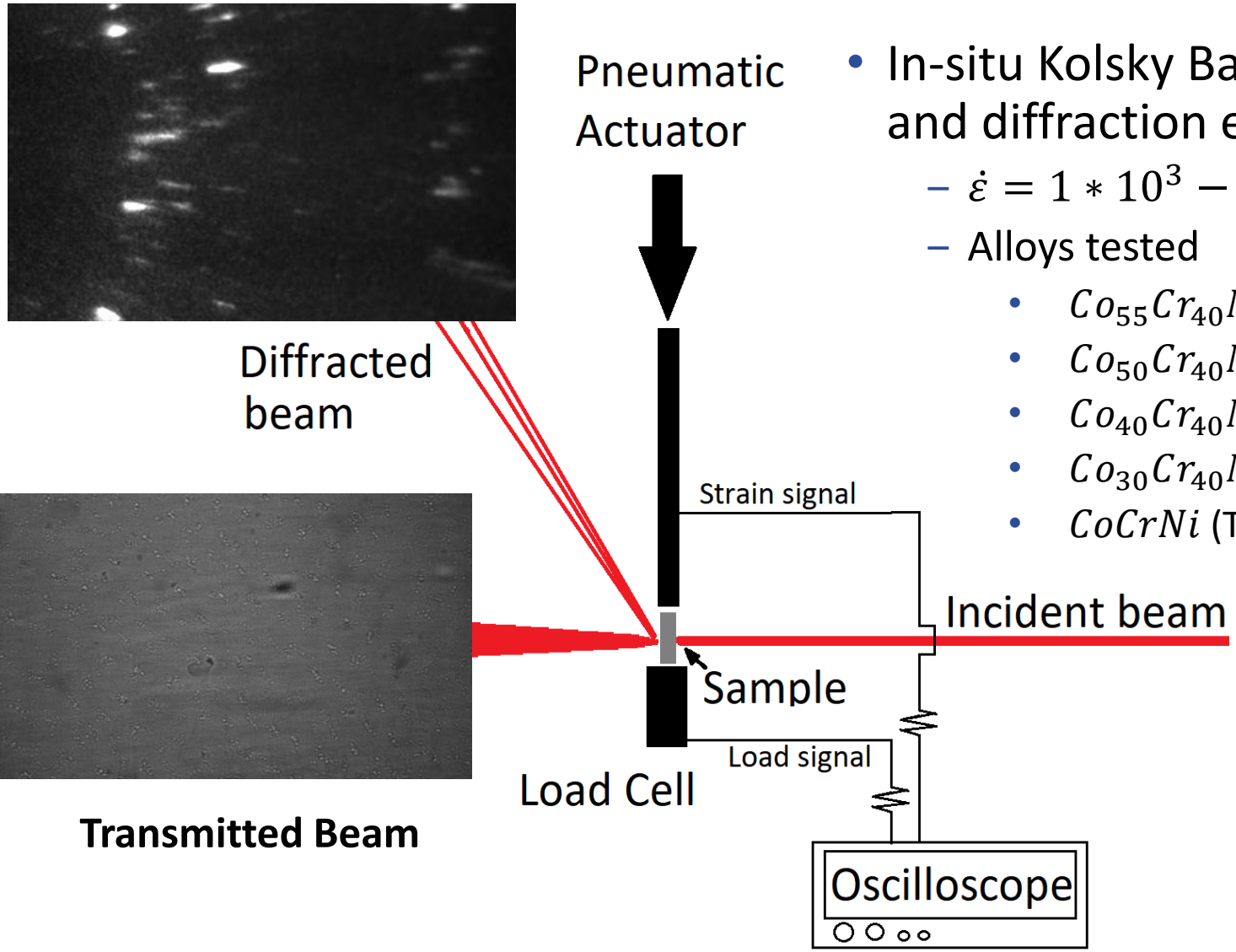
In-situ Dynamic Testing at APS



- In-situ Kolsky Bar, X-ray imaging and diffraction experiments
  - $\dot{\varepsilon} = 1 * 10^3 - 2 * 10^3\ s^{-1}$
  - Alloys tested
    - $Co_{55}Cr_{40}Ni_5$ (TRIP)
    - $Co_{50}Cr_{40}Ni_{10}$ (TRIP)
    - $Co_{40}Cr_{40}Ni_{20}$ (TRIP)
    - $Co_{30}Cr_{40}Ni_{20}$ (TWIP)
    - $CoCrNi$ (TWIP)

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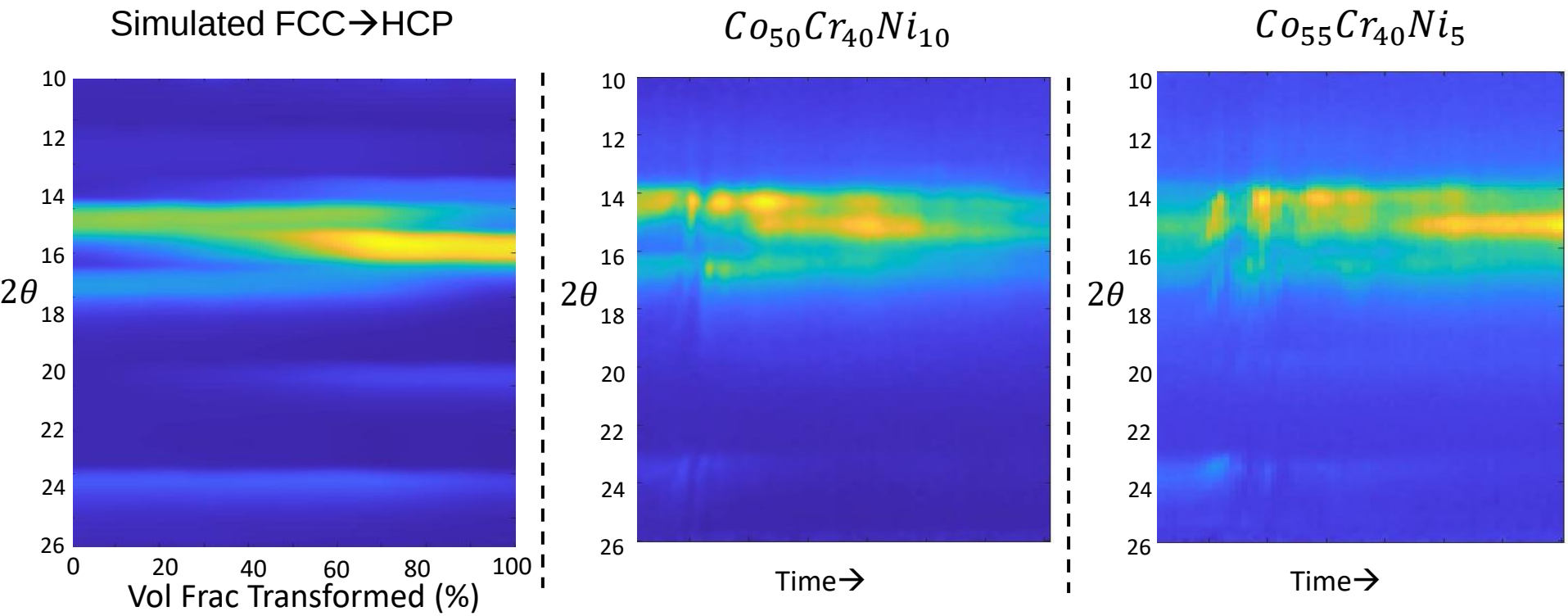
Observation of TRIP in Co50 and Co55 During High Rate Deformation



- TRIP and TWIP observed during high rate deformation
- Co50 & Co55 both show evolution of new peak (attributed to HCP $\{10\bar{1}0\}$)
- CoCrNi, Co30 & Co40 do not show evidence of this new peak

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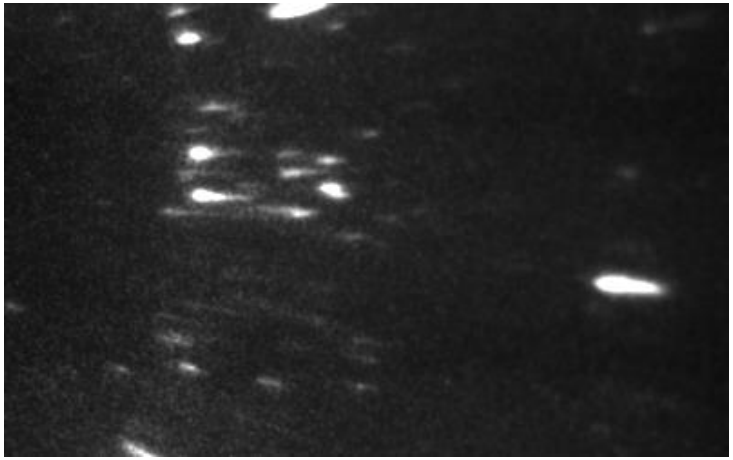
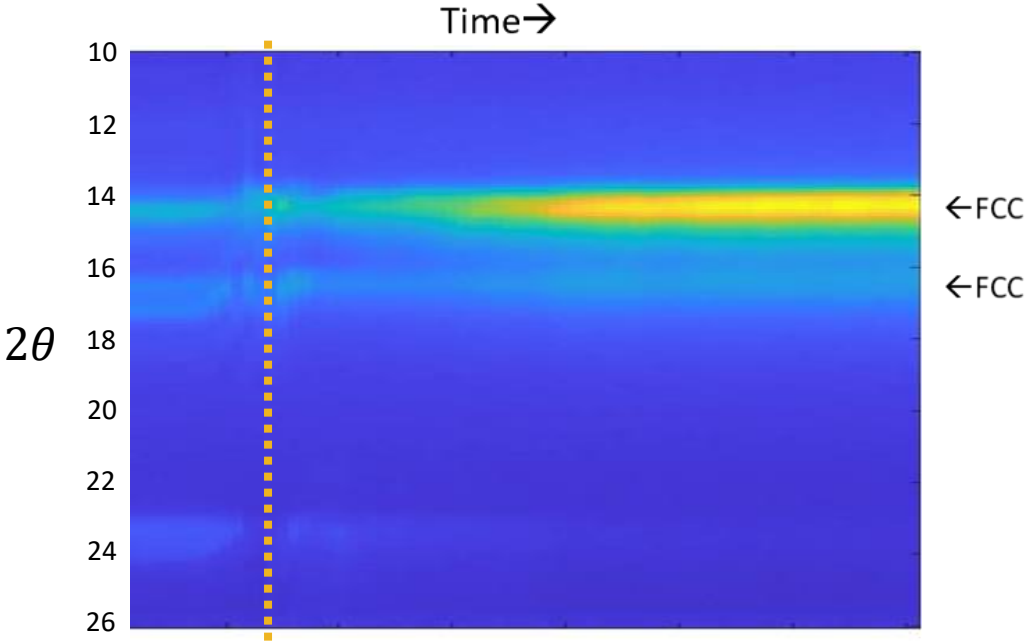
Suppression of TRIP in Co40 During High Rate Deformation

- Co40 did not exhibit TRIP during deformation at high rate deformation at either $1 * 10^3 \; or \; 2 * 10^3 \; s^{-1}$ but does at lower strain rates.



- Believed to be a result of adiabatic heating:
  - In Co55 TRIP suppressed between $450°C - 600°C$
    - 50-70% of T_0
  - Equivalent range in Co40 is $70°C - 200°C$



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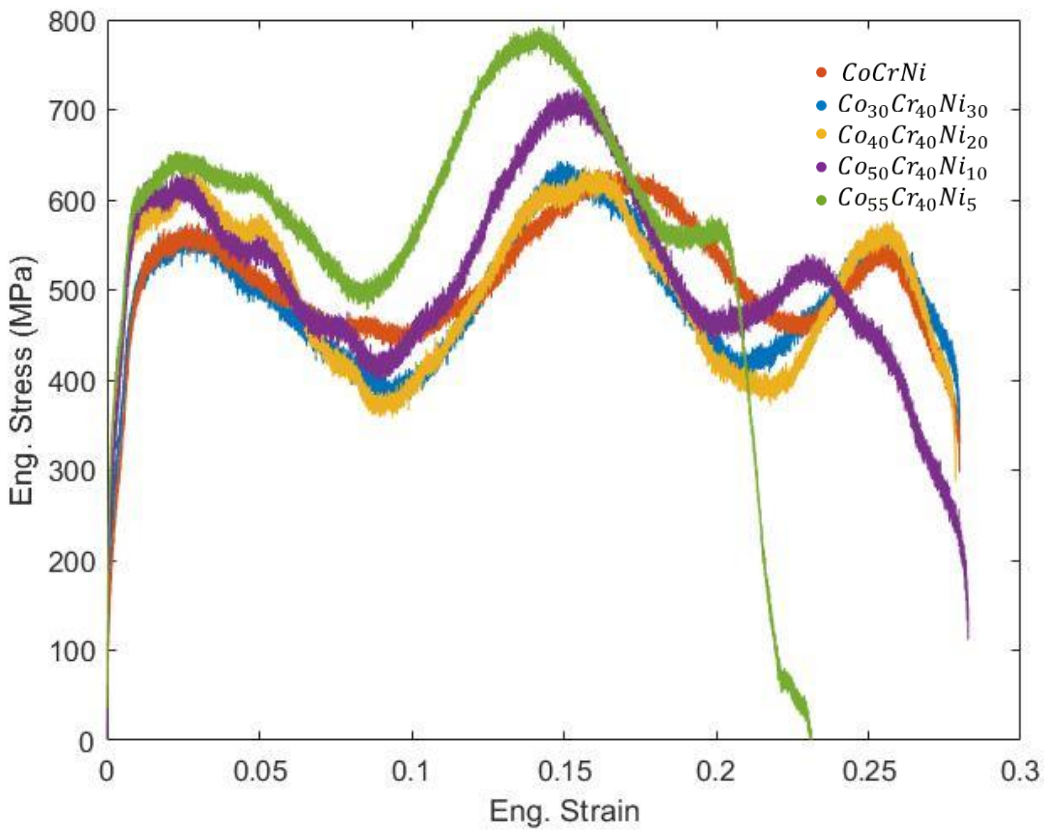
Initial Assessment of Mechanical Behavior

- Tests performed using 30psi & 75psi
  - Strain rates of approximately $1 * 10^3 s^{-1}$ & $2 * 10^3 s^{-1}$
- All alloys exhibited similar behavior at $10^3 s^{-1}$
  - Co55 shows greatest difference from others, with higher UTS and lower ductility
- Thank you to Ben for writing the MATLAB code that processes the data



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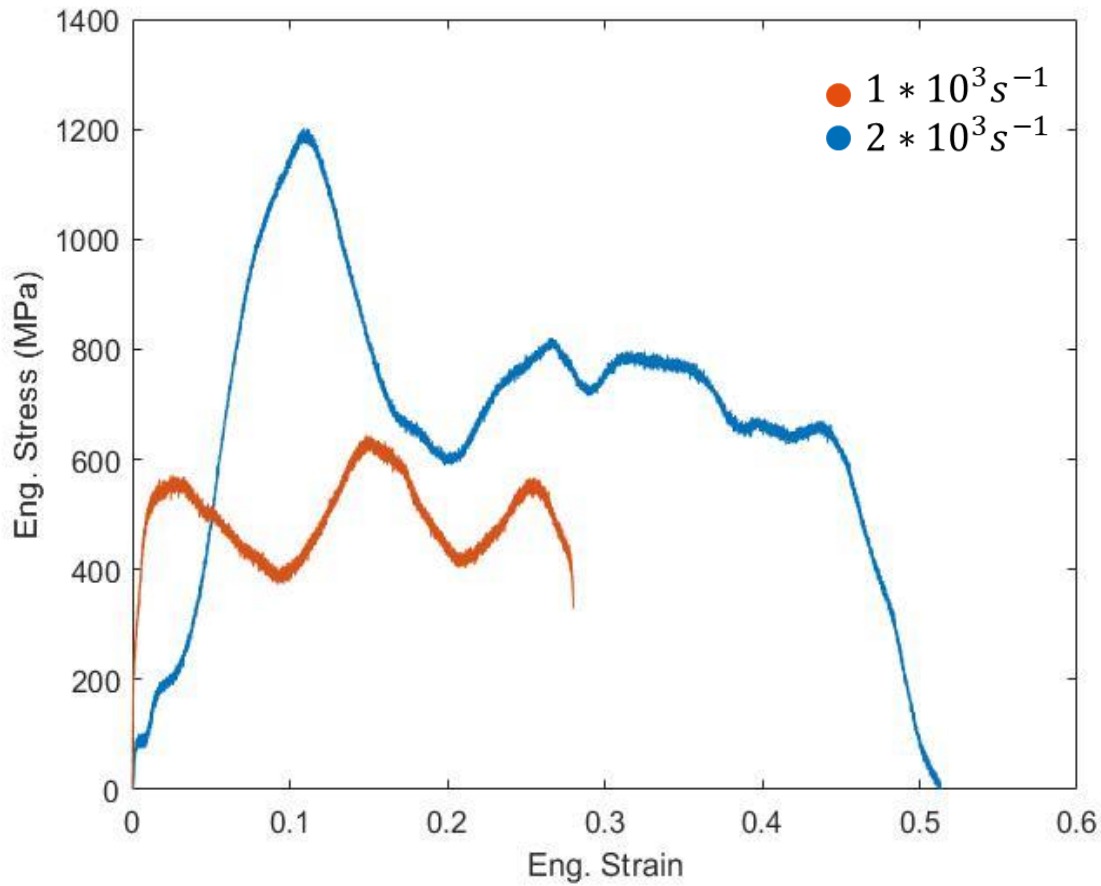
Strain Rate Effects on Mechanical Properties

- Processing of high rate deformation is ongoing
- Initial assessment indicates that increased strain rate results in both increased UTS and elongation
- This behavior is consistent with reported cryogenic testing of CoCrNi alloys



Mechanical response of Co30 TWIP alloy at two strain rates

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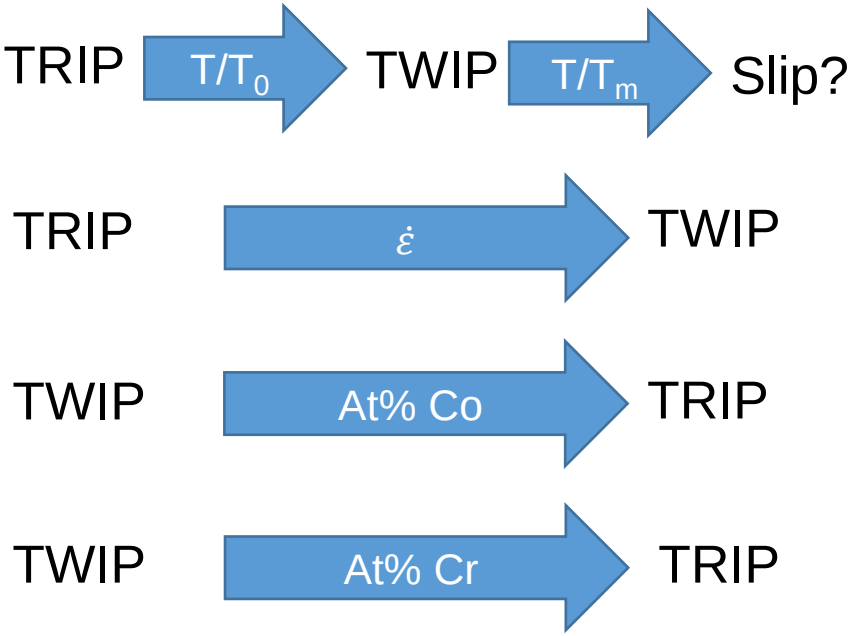
TRIP and TWIP Observed in CoCrNi

- TRIP behavior seen:
  - At low and high strain rates ($10^{-2} to\ 10^{3}\ s^{-1}$)
  - Temperatures from -100°C to 450°C
- TWIP behavior seen:
  - At low and high strain rates ($10^{-2}\ to\ 10^{3} s^{-1}$)
- Increased $\dot{\varepsilon}$ shows improved mechanical performance



Alloy composition in CoCrNi can be controlled to activate specific deformation mechanisms given knowledge of use conditions.

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Continuing Work

- Processing mechanical and diffraction data from APS
  - Matching diffraction to strain, not just time
  - Evaluating $\dot{\varepsilon}$ and alloying effects on phase fraction at different strains
- A deeper dive into the thermodynamics of TRIP and TWIP
  - Thermo-Calc modelling of other TRIP/TWIP alloys with known behavior to compare to CoCrNi
- Quasi-static testing at CHESS (delayed due to COVID-19)
  - Testing of thermal effects on FCC→HCP transformation
    - Where does T/T_0 suppress TRIP?
    - How does T/T_0 change the transformed fraction at similar strains?
- Mechanical testing at Mines
  - Strain rates $10^{-2} - 10^{2} s^{-1}$
  - Interrupted testing
- Post-mortem XRD and EBSD to observe microstructural evolution

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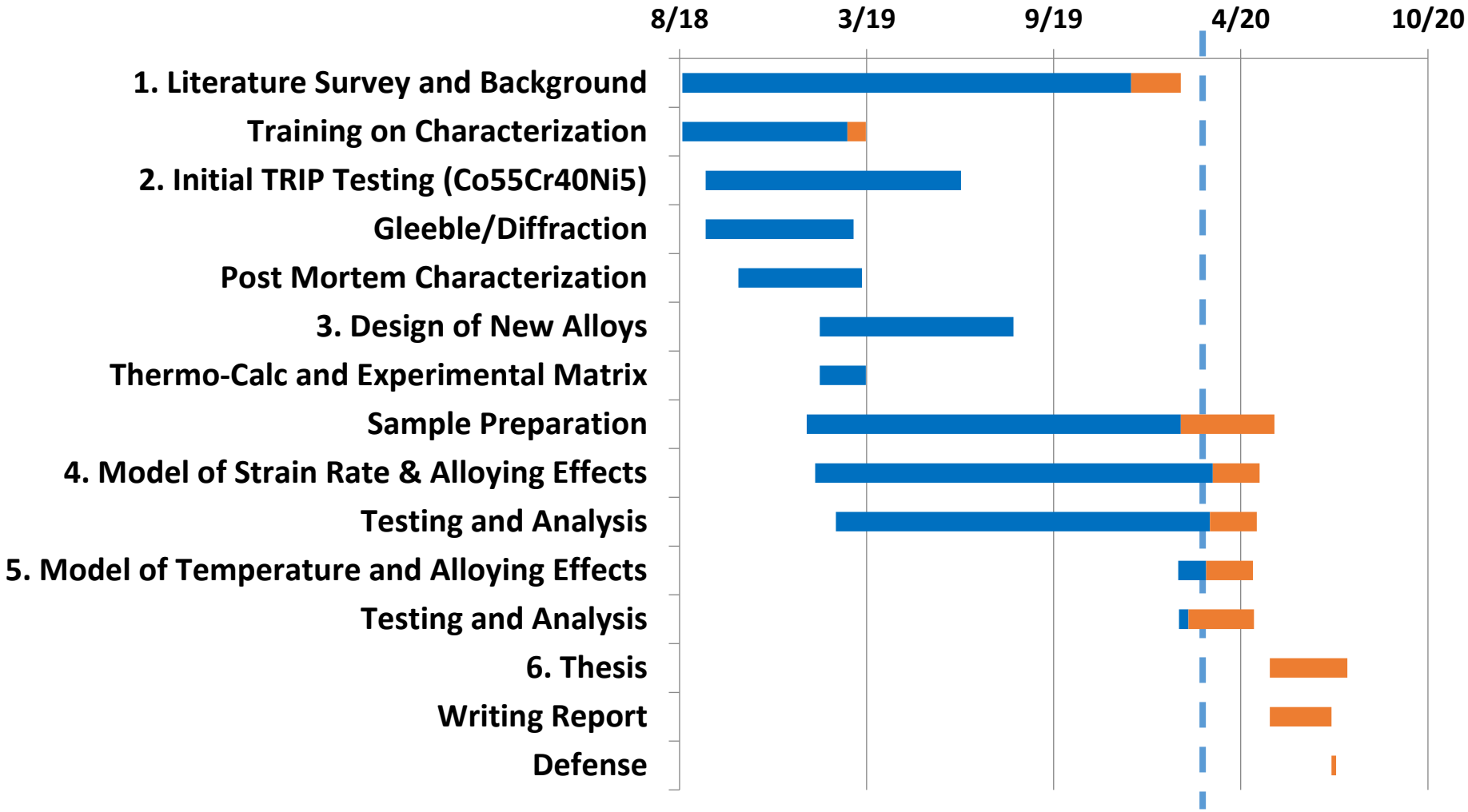
Progress



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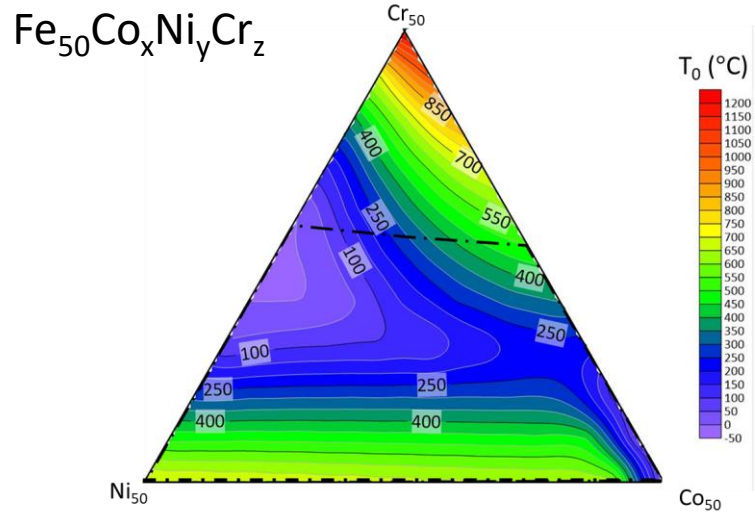
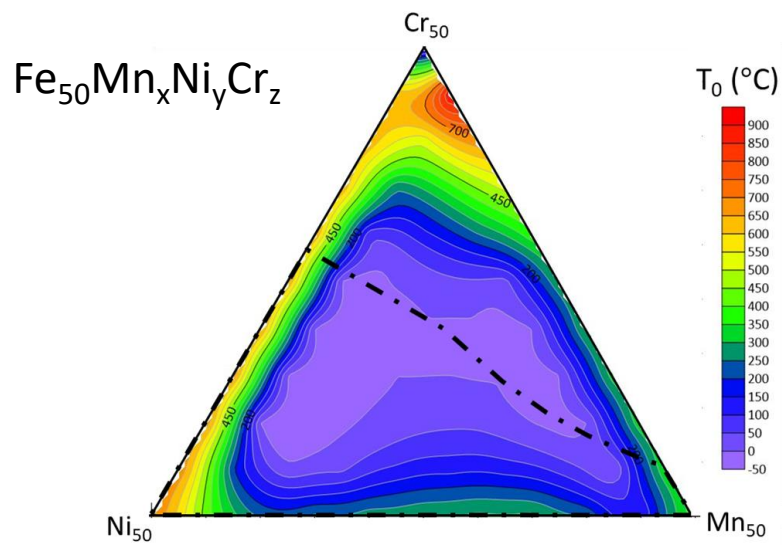
Challenges and Opportunities

- Challenges:
  - High rate deformation data is messy
  - Coupling of thermodynamic effects (T/T_0) and kinetic effects (T/T_m and $\dot{\varepsilon}$) makes it difficult to determine the causes of switches between TRIP/TWIP/slip
- Opportunities
  - TRIP and TWIP offer a pathway to materials that overcome the strength-ductility tradeoff
  - Understanding of designing TRIP and TWIP into CoCrNi can be extended to other alloy systems, especially Fe-rich MPEAs





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Thank you!

John Copley
jacopley@mines.edu

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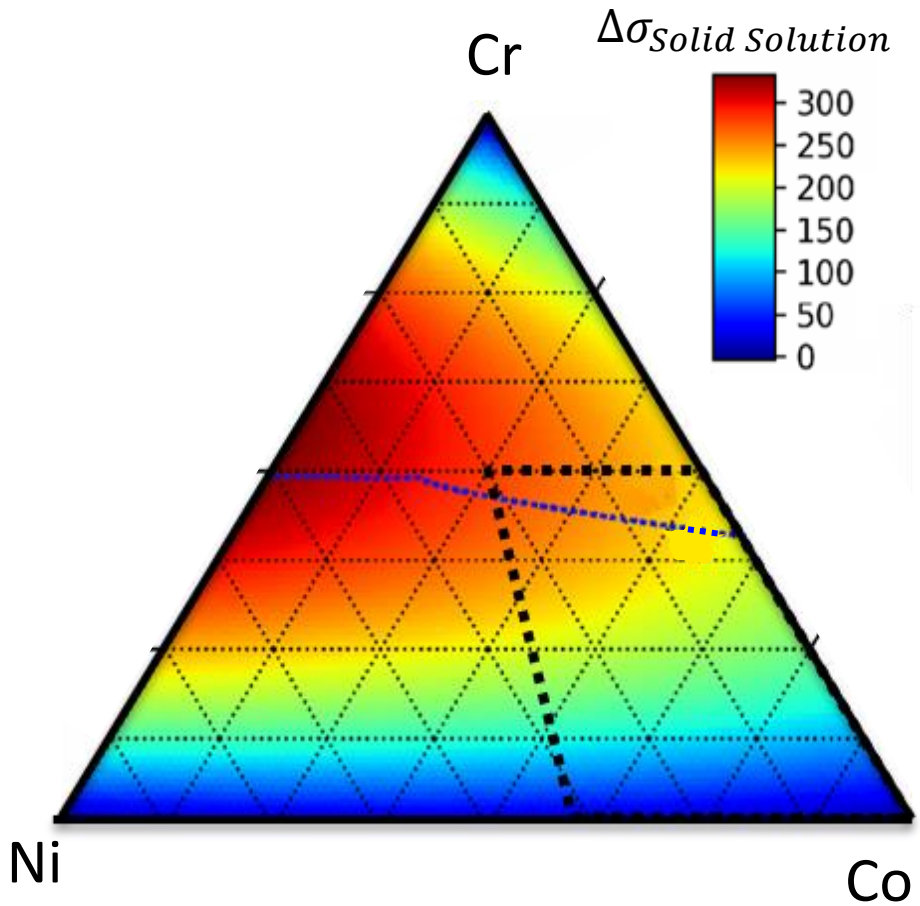
MPEAs and Solid Solution Strengthening

- Initial HEA/MPEA studies:
  - Equiatomic compositions
  - Solid solid solution strengthening
- Effective Atomic Radii for Strengthening (EARS)
  - Atoms in solution do not have the radii conventionally used to predict strength
  - EARS radii act as better strength predictors
  - Shows that optimal properties are not correlated with maximum entropy



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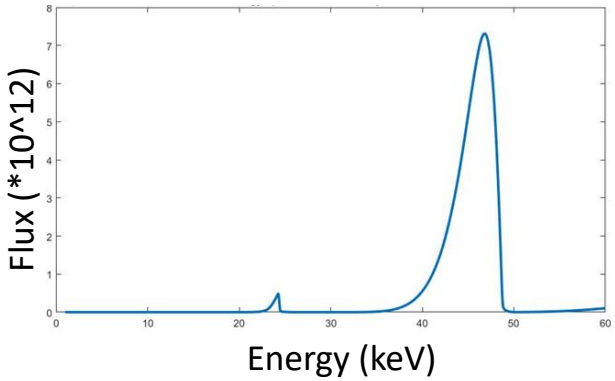
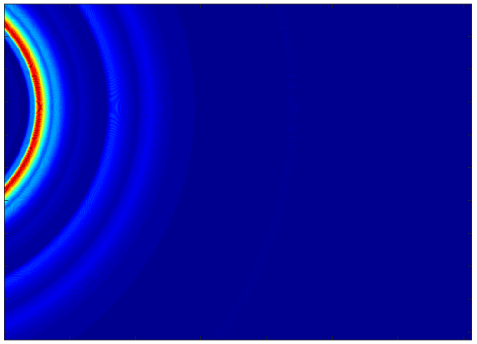
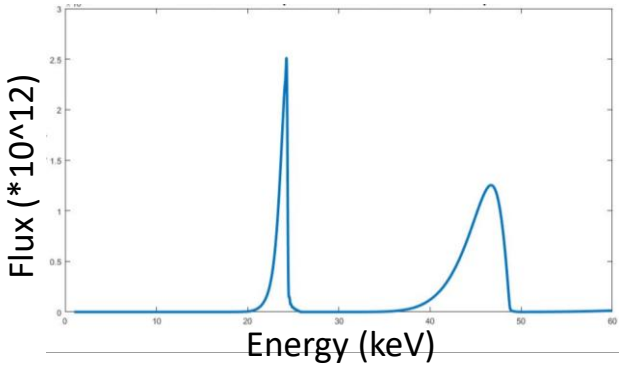
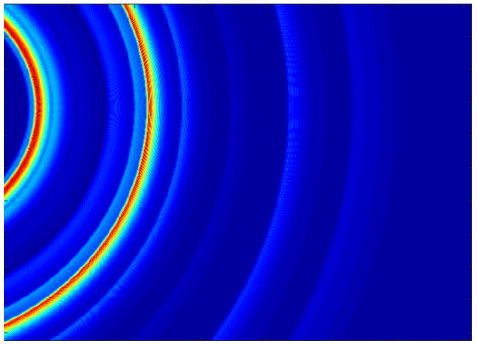
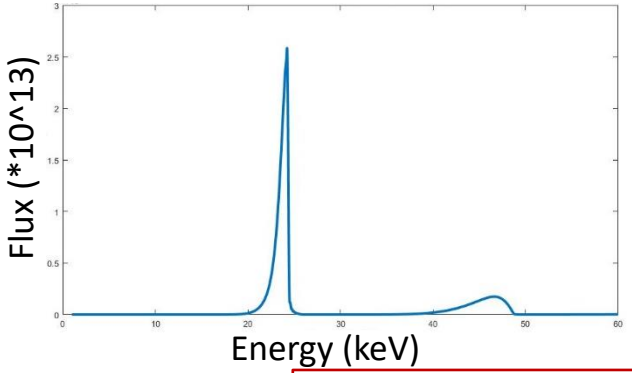
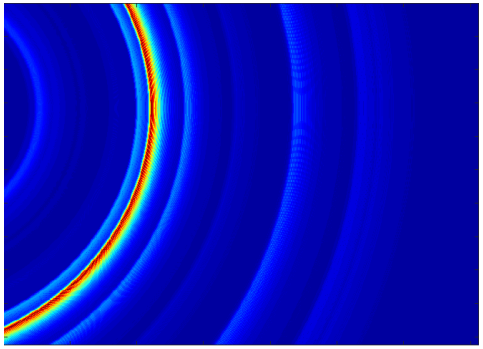
Project Review: Sample Geometry Effects

Thickness	Modified Energy Spectrum	Ratio of I_{1st}: I_{2nd}	
500μm		1:10 Tilting of the sample improved ratio by having some thinner sections	
250μm		2:1	
100μm		10:1	

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