Blastalloy TRIP-180

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Revolutionary Research . . . Relevant Results

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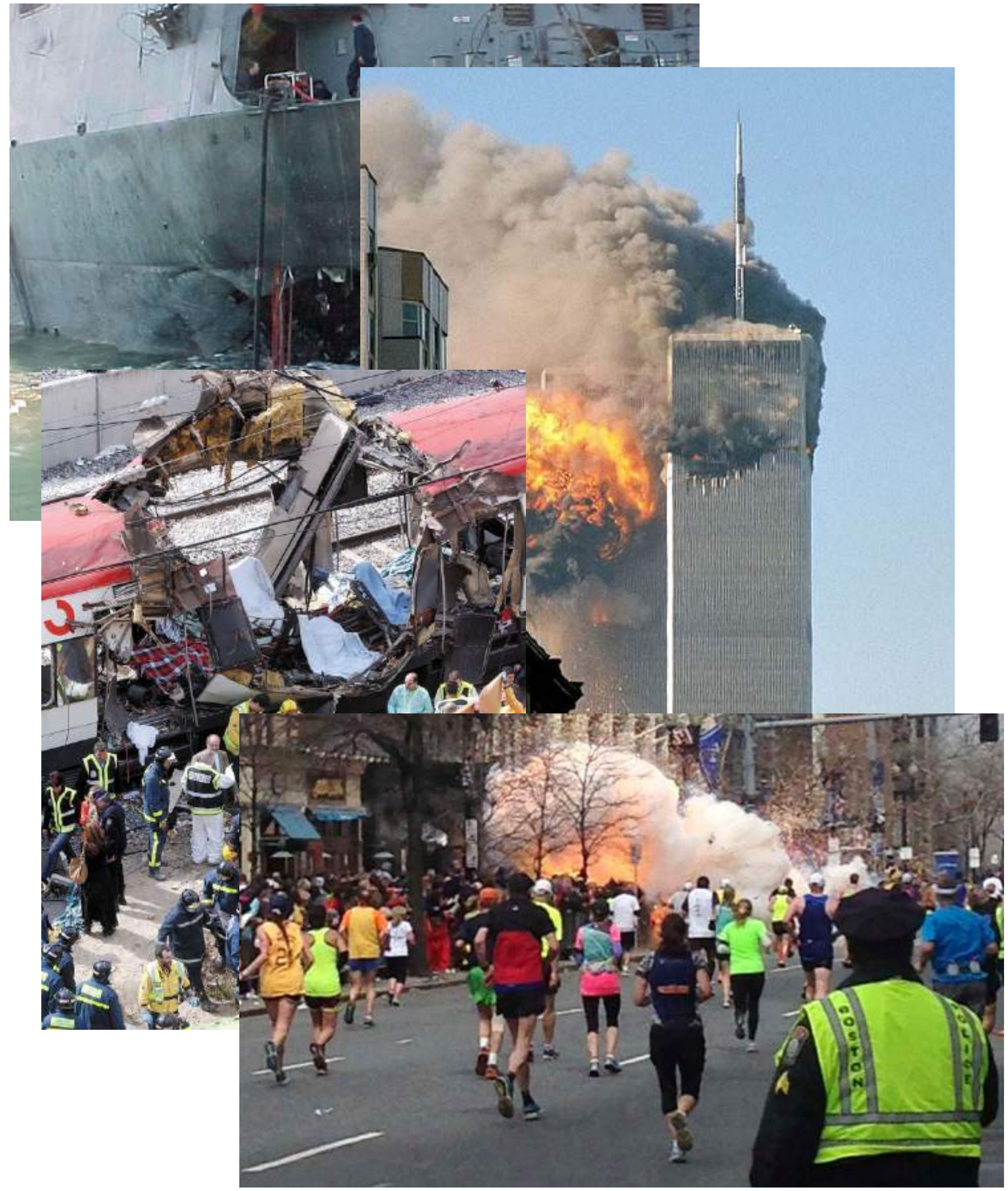
Outline

- Background
- TRIP-180 Design
- Performance in Shear
- Design and Modeling
- LEAP Analysis
- Future Work

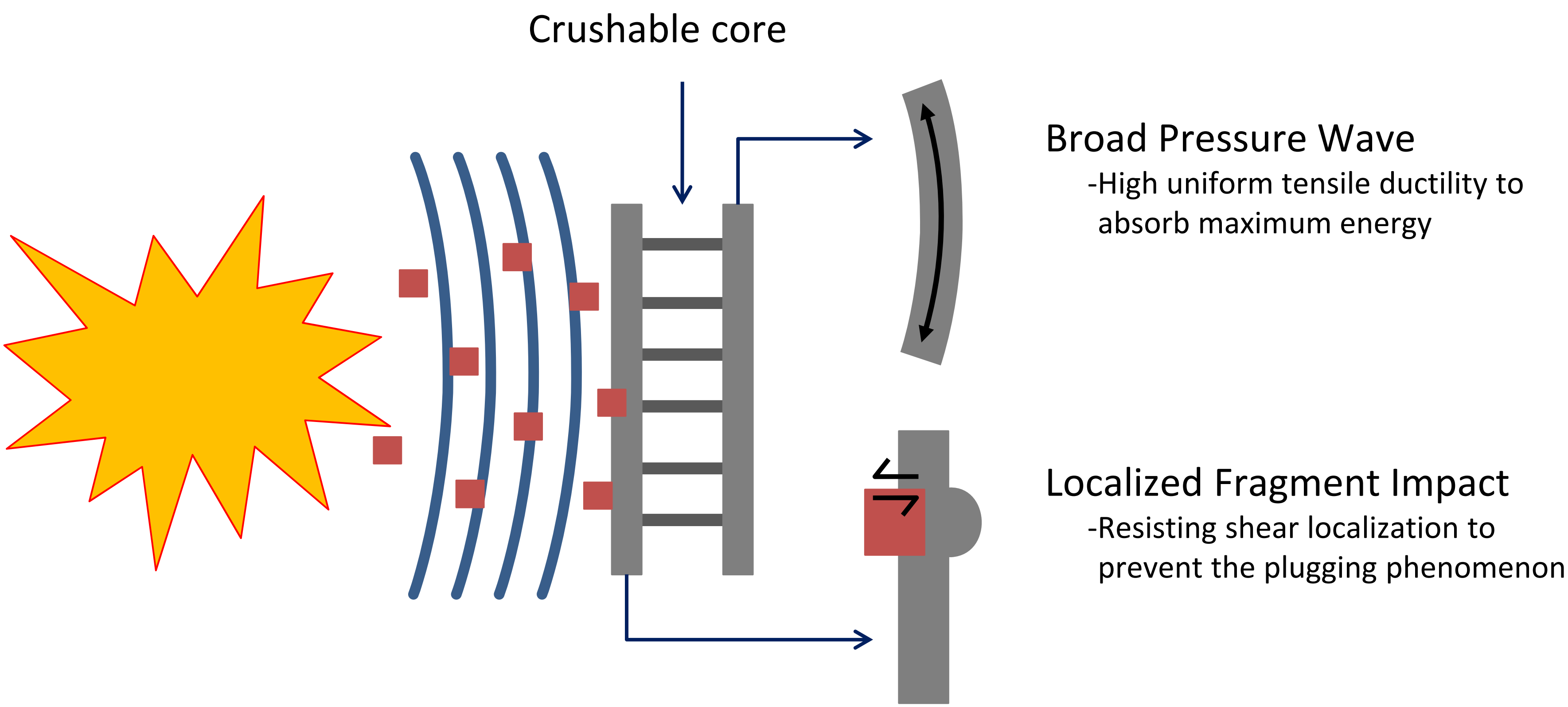
Motivation

- Increase in terrorist activities abroad and domestically
  - USS Cole
  - September 11, 2001
  - Madrid Commuter Train Bombings
  - Boston Marathon Bombs
- Need for higher performance materials to resist explosions



http://en.wikipedia.org/wiki/USS_Cole_bombing
http://en.wikipedia.org/wiki/9/11
http://www.britannica.com/EBchecked/topic/1279086/Madrid-train-bombings-of-2004
http://www.aei-ideas.org/wp-content/uploads/2013/04/Boston-Marathon-Bombing.jpg

Blast/Fragment Protection Overview



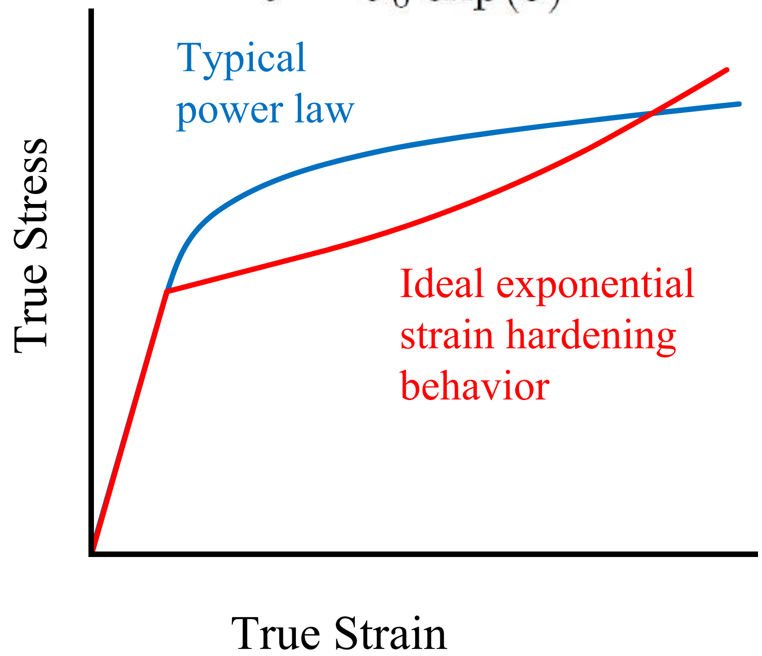
Optimizing Performance using TRIP

- **TR**ansformation **I**nduced **P**lasticity
- Martensitic transformation is exploited to boost mechanical properties
- Austenite stabilized at room temperature by addition of:
  - Nickel
  - Chromium

Criterion for necking instability:

$$\frac{d\sigma}{d\varepsilon} = \sigma$$

$$\sigma = \sigma_0 \exp(\varepsilon)$$

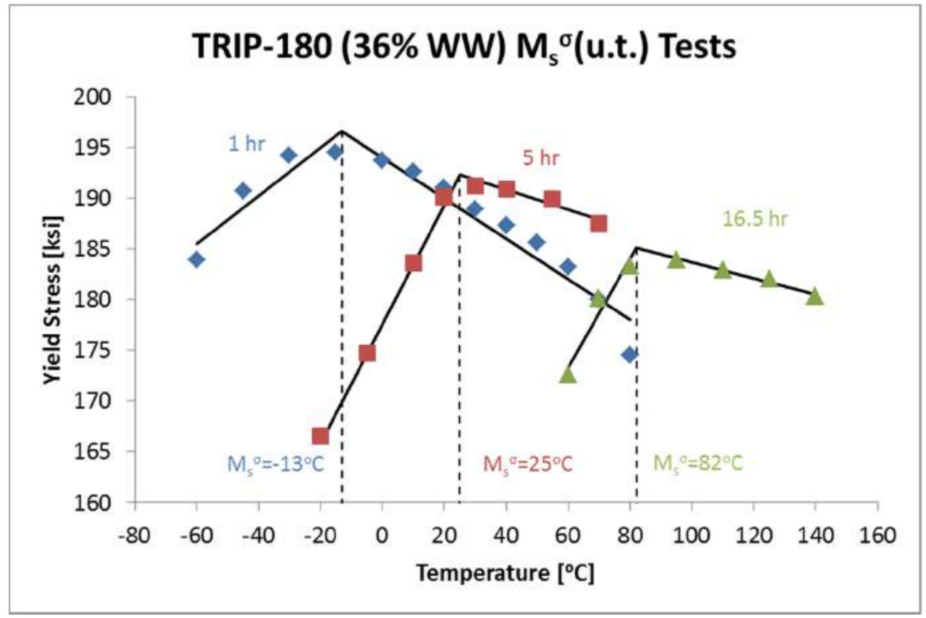


Quantifying Austenite Stability

- The M_s^σ temperature is defined as the maximum temperature at which an elastic stress causes martensitic transformation

- Transition from stress-assisted transformation to strain-induced transformation

- Stability given by the Olson-Cohen relation:



$$\Delta G_{tot} = \Delta G_{ch} + \Delta G_{\sigma}$$

$$\Delta G_{crit} = -G_n - W_{sol}^{f}$$

$$\Delta G_{ch} + W_f^{sol} = -G_n - \Delta G_{\sigma}$$

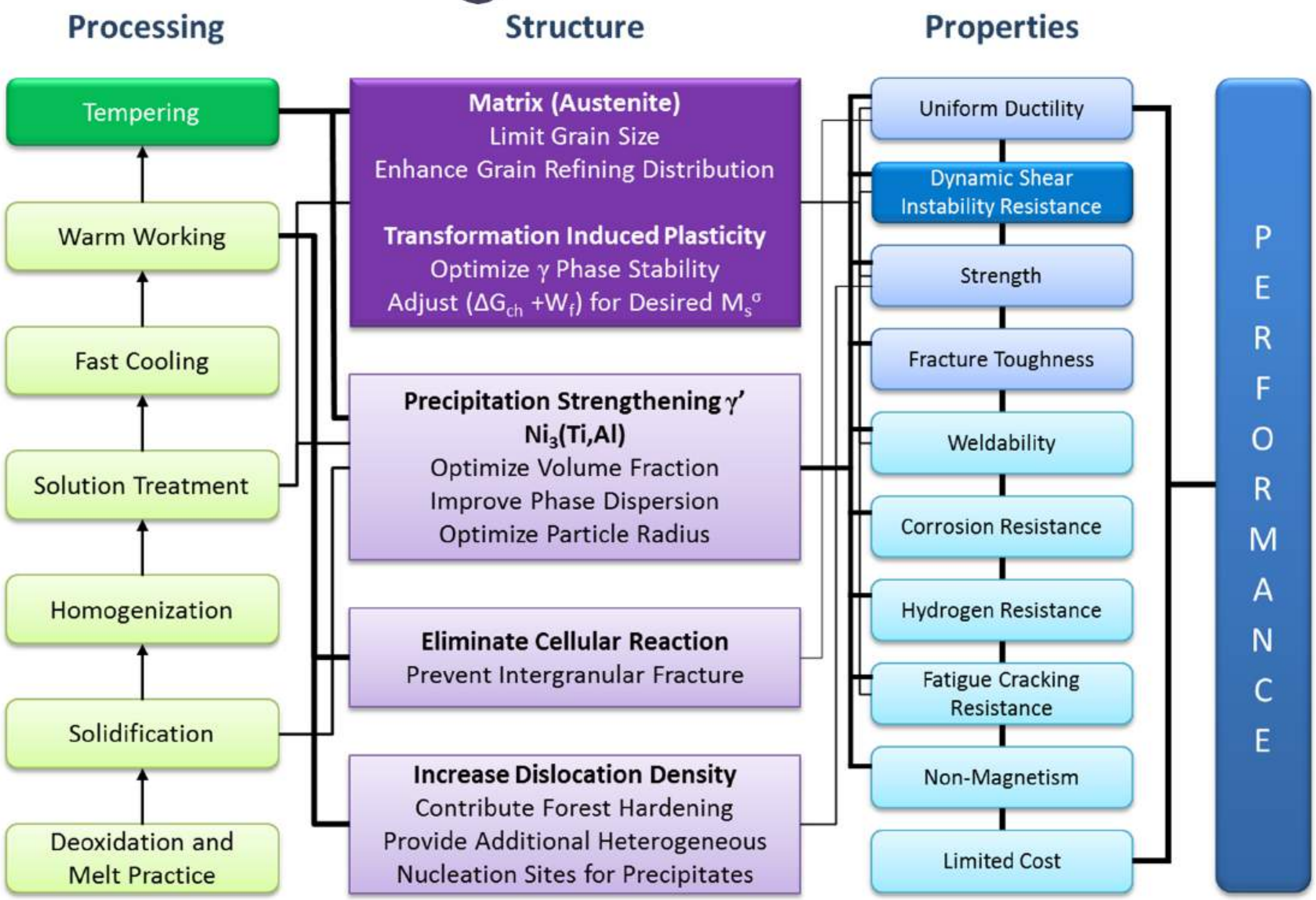
$$\text{when} \quad \sigma = \sigma_y \quad \text{and} \quad T = M_s^{\sigma}$$

OLSON, G. B., "Mechanically-induced phase transformations in alloys," *Encyclopedia of Materials Science and Engineering*, pp. 2929–2932, 1986.
FEINBERG, Z. D., *Design and Optimization of an Austenitic TRIP Steel for Blast and Fragment Protection*. PhD thesis, Northwestern University, 2012.

TRIP-180 Design: New Objectives

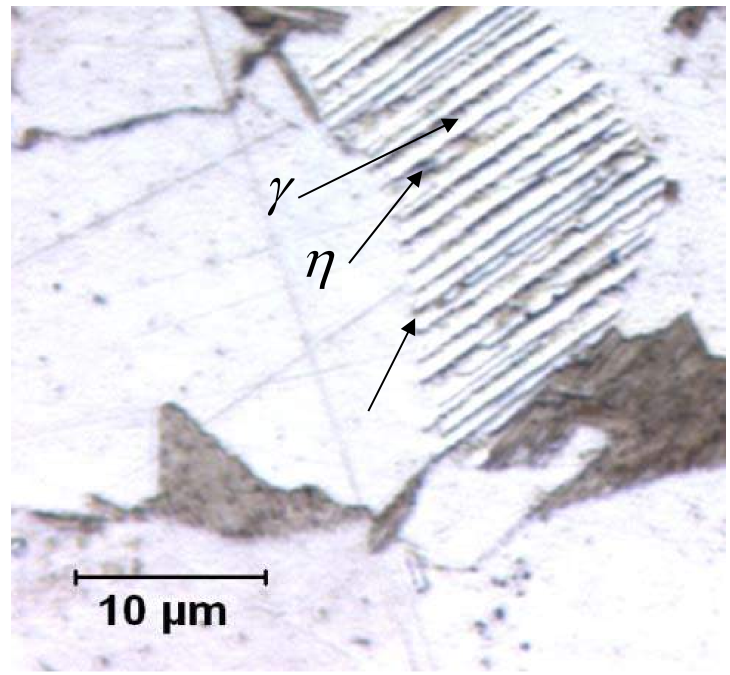
Primary Objectives	**Secondary Objectives**
Uniform Tensile Ductility: $\varepsilon_u > 30\%$	Nonmagnetic: $T_{curie} < 0°C$
Yield Strength: 120 ksi	Weldable
Optimized austenite stability: $M_s^\sigma(sh)$	Corrosion Resistant
Dynamic shear instability resistance: maximize γ_i^a	Hydrogen Resistant: $K_{ISCC}/K_{IC} > 0.5$
Sufficient fracture toughness: $K_{IC} \geq 90$ ksi/in$^{0.5}$	Fatigue Cracking Resistant
	Limited Cost
	γ' Phase Fraction: > 0.10

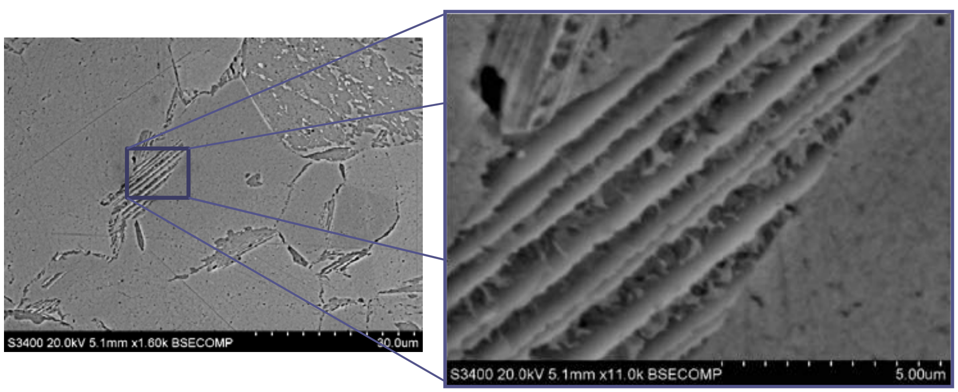
Systems Design Chart



η Cellular Precipitation

- Cellular reaction causes a decrease in ductility
- Cellular reaction requires precipitation and concurrent boundary migration



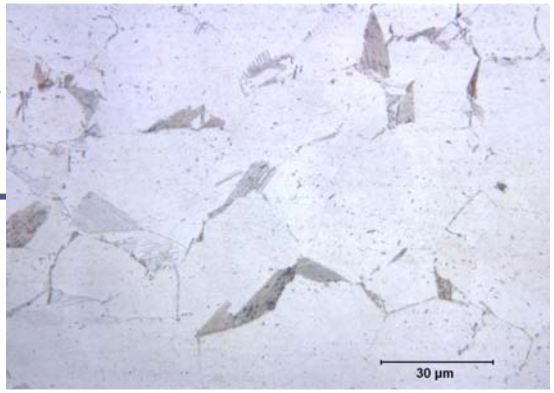


FEINBERG, Z. D., *Design and Optimization of an Austenitic TRIP Steel for Blast and Fragment Protection*. PhD thesis, Northwestern University, 2012.

Eliminating the Cellular Precipitation

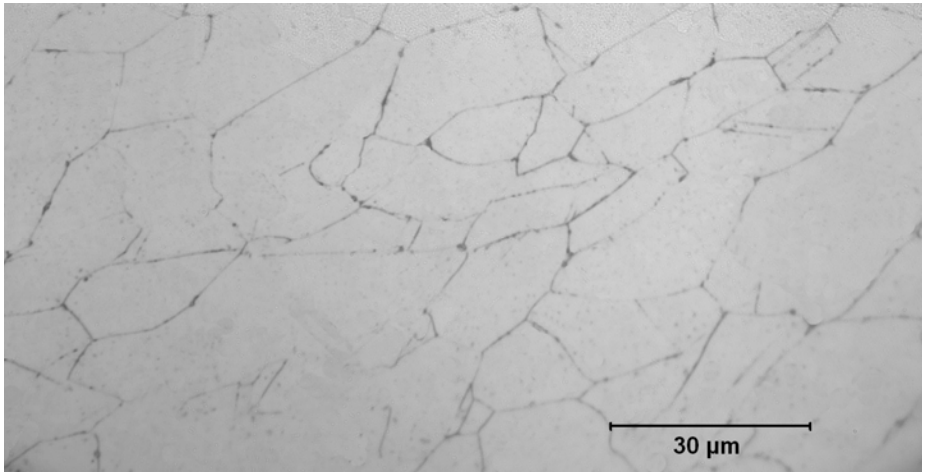
- Two-Step Temper
  - Demonstrated limited improvement in fracture ductility
- Warm Working
  - Introduces dislocations
    - Increases strength
    - Provides heterogeneous nucleation sites for γ’ resisting η cellular reaction
  - Avoids η formation
    - Inhibits intergranular fracture
    - Increases fracture ductility
  - TRIP-120 warm worked at 450°C to 23% and 36% reductions of area

750°C 10hr



Warm Working

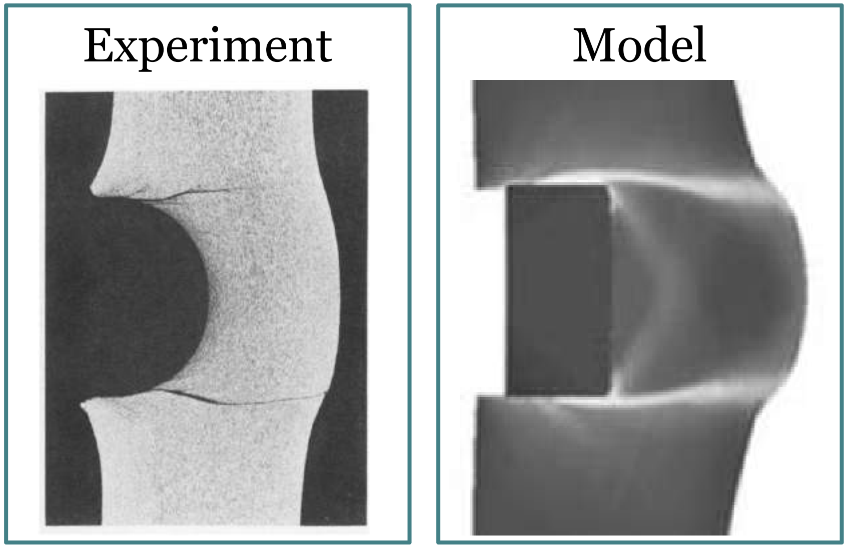
TRIP-180 WW 36% 700C, 1hr

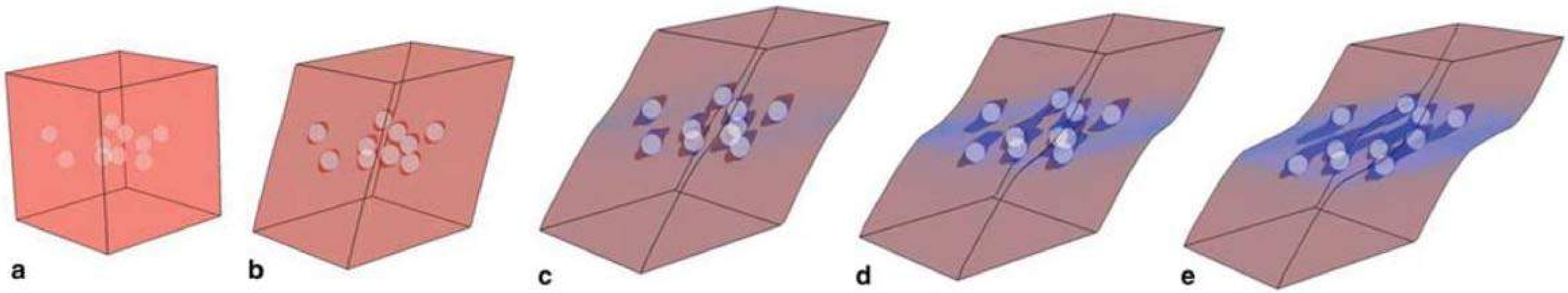


FEINBERG, Z. D., *Design and Optimization of an Austenitic TRIP Steel for Blast and Fragment Protection*. PhD thesis, Northwestern University, 2012.

Fragment Penetration: Shear Localization

- Failure through plastic shear instability and flow localization
- Plugging mode of failure
- Causes submicron microvoid nucleation
- Creates instability where deformation is localized and failure occurs prematurely





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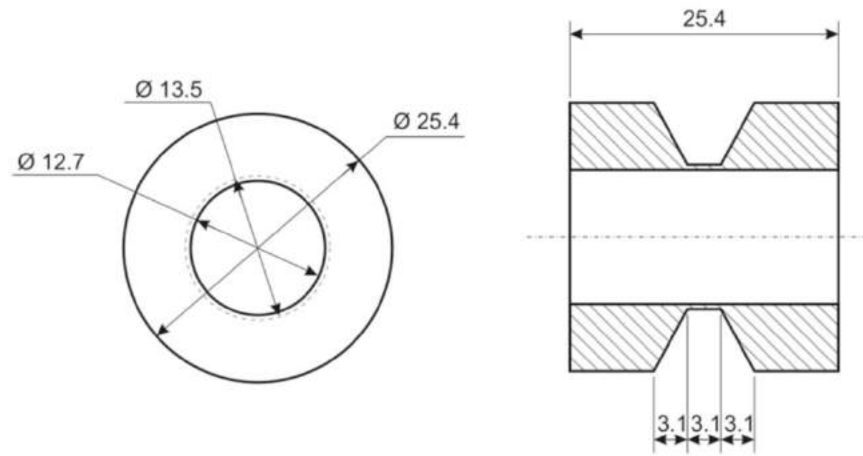
VERNEREY, F. J. *et al.*., "The 3-D computational modeling of shear-dominated ductile failure in steel," *JOM*, vol. 58, pp. 45–51, Dec. 2006.

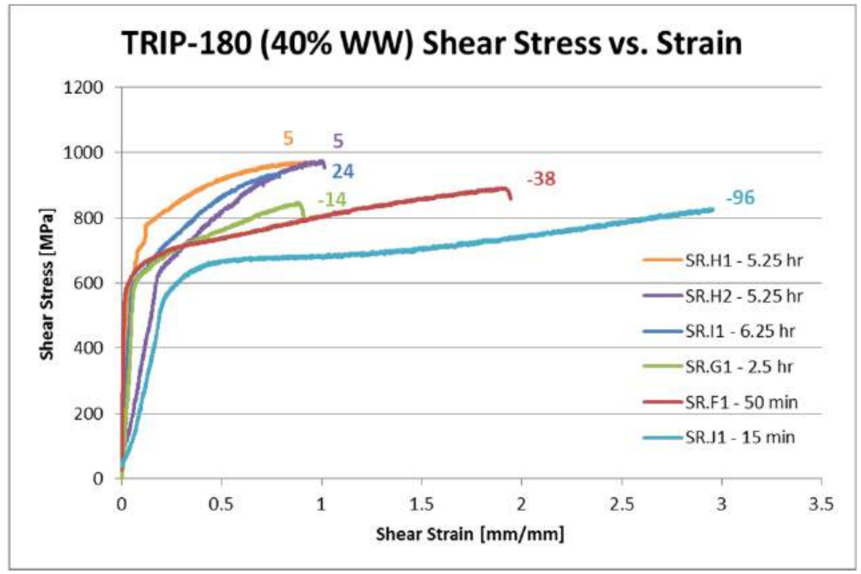
Quasi-Static Shear: Test Setup

- Thin walled Kolsky specimens
    - Uniform shear throughout gauge section
- Performed at Illinois Institute of Technology
- Analyze data from previous tests
- Perform new round of testing correcting buckling failure



Quasi-Static Shear: Results

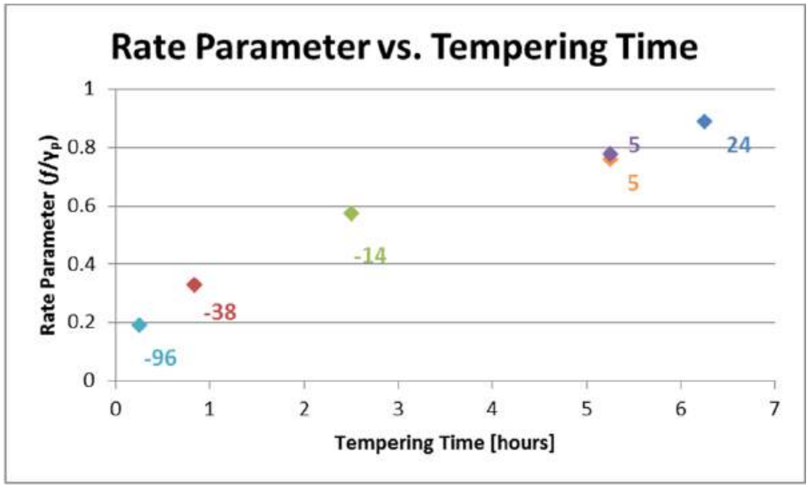
- Remade grips to be concentric
- Inserted hardened drive shaft through center of sample
- Failure in pure shear

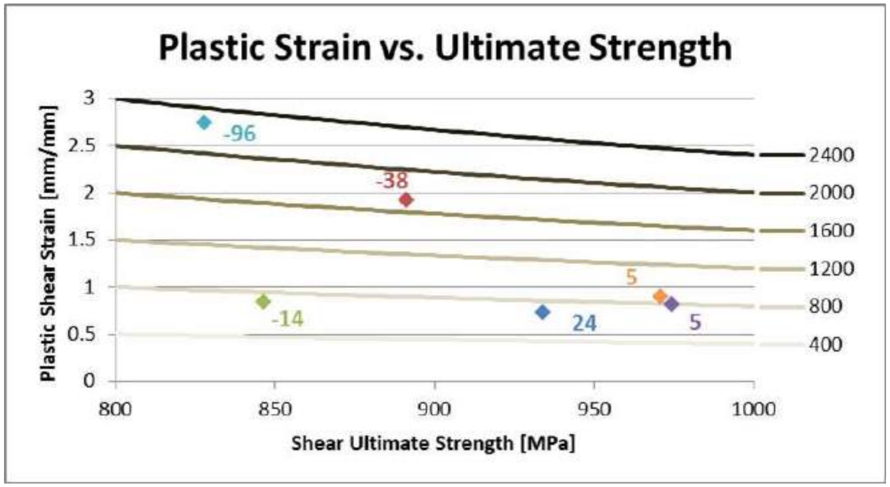


Tempering Time	15 (min)	50 (min)	2.5	5.25	5.25	6.25	hr
M_s^σ(sh)	-96	-38	-14	5	5	24	C
Shear Yield Stress (τ_y)	79.3	78.6	83.8	82.5	92.4	84.3	ksi
Shear Instability Strain (γ_{in})	2.96	1.94	0.91	0.93	1.01	0.79	in/in
Plastic Strain ($\gamma_p = \gamma_{in} - \gamma_y$)	2.75	1.93	0.85	0.90	0.82	0.74	in/in
Martensite Fraction (f)	0.528	0.637	0.487	0.686	0.639	0.655	
Transformation Rate Parameter (f/γ_p)	0.192	0.330	0.575	0.760	0.778	0.889	

Quasi-Static Shear: Performance

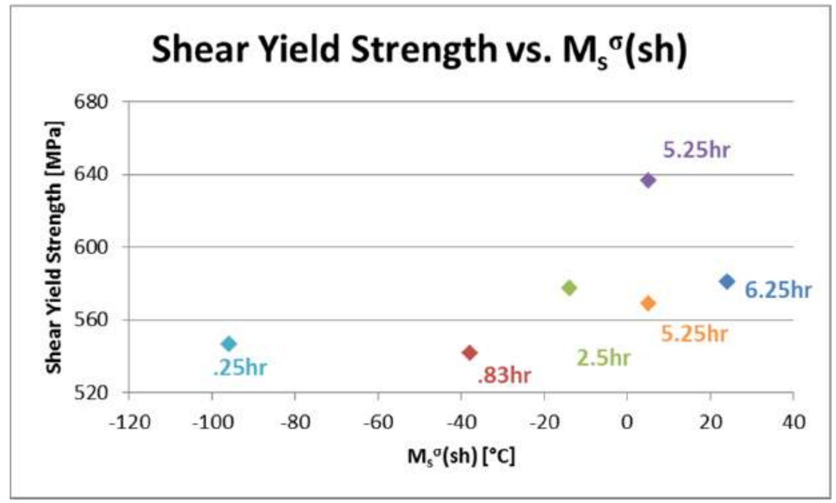
- Longer tempering
  - More unstable
  - More transformation per strain
- Ultimate plastic strain times strength is a measure of penetration resistance

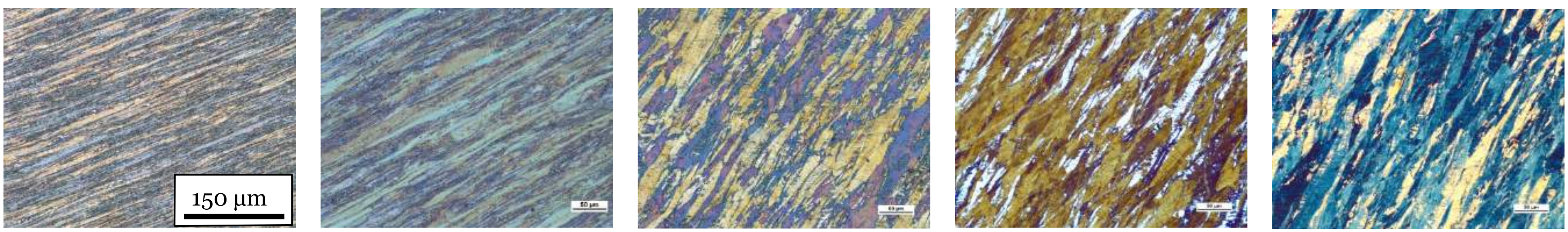




Quasi-Static Shear: Calibrating Stability

- Peak yield strength at $M_s^{\sigma}(sh)=5^{o}C$
- Recalibrate M_s^{σ} model $M_s^{\sigma}(sh)=22^{o}C$

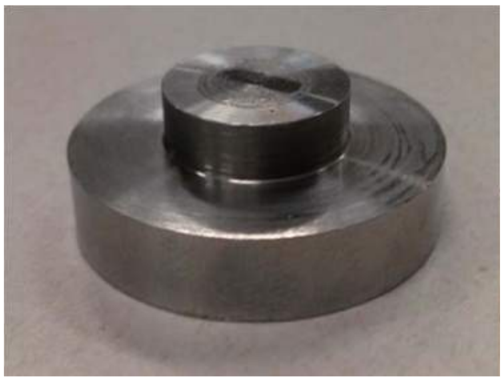




Strain-Induced ← → Stress-Assisted

Time	15 min	50 min	2.5 hr	5.25 hr	6.25 hr	
$M_s^{\sigma}(sh)$	-96°C	-38°C	-14°C	5°C	24°C	old
$M_s^{\sigma}(sh)$	-107°C	-37°C	-18°C	22°C	29°C	new

Dynamic Shear HAT Type Tests
Stored Energy Split-Hopkinson Bar

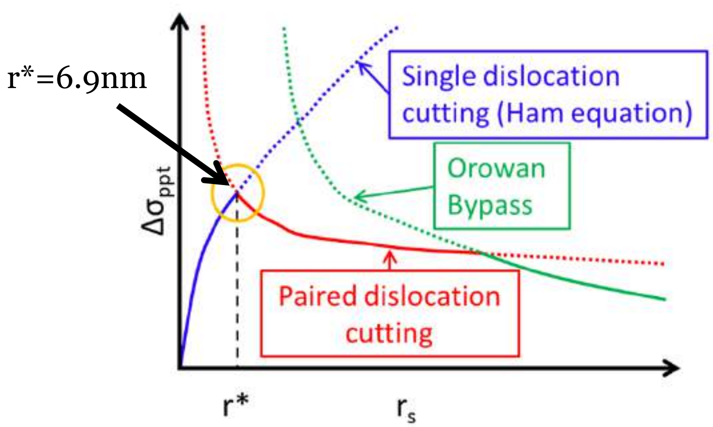


Modeling: Strength

- γ‘: $L1_2$ structure, $Ni_3(Ti,Al)$
- Ham strengthening model

$$\Delta\tau = \frac{\gamma_0}{2b}\left[\left(\frac{8\gamma_0 r_s f}{\pi G b^2}\right)^{\frac{1}{2}} - f\right]$$

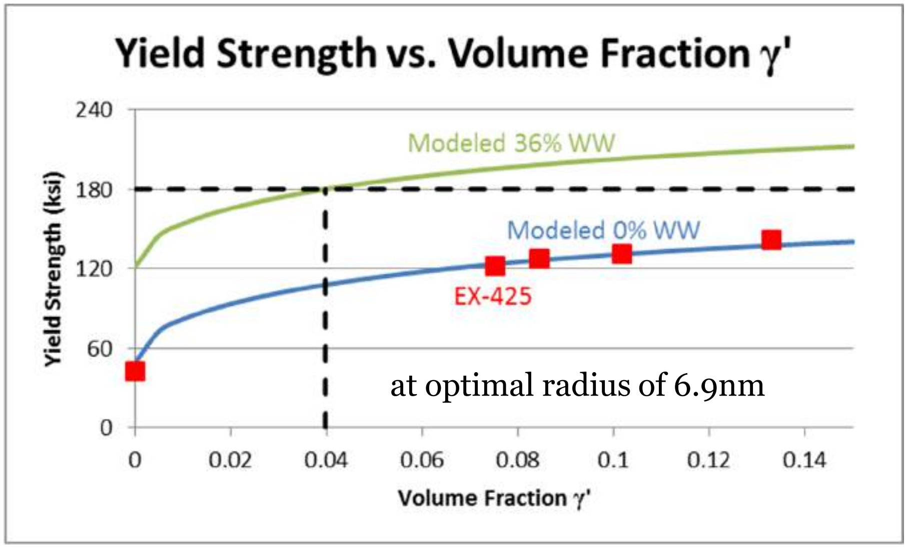
$$\Delta\sigma = M\Delta\tau$$



- Warm Working

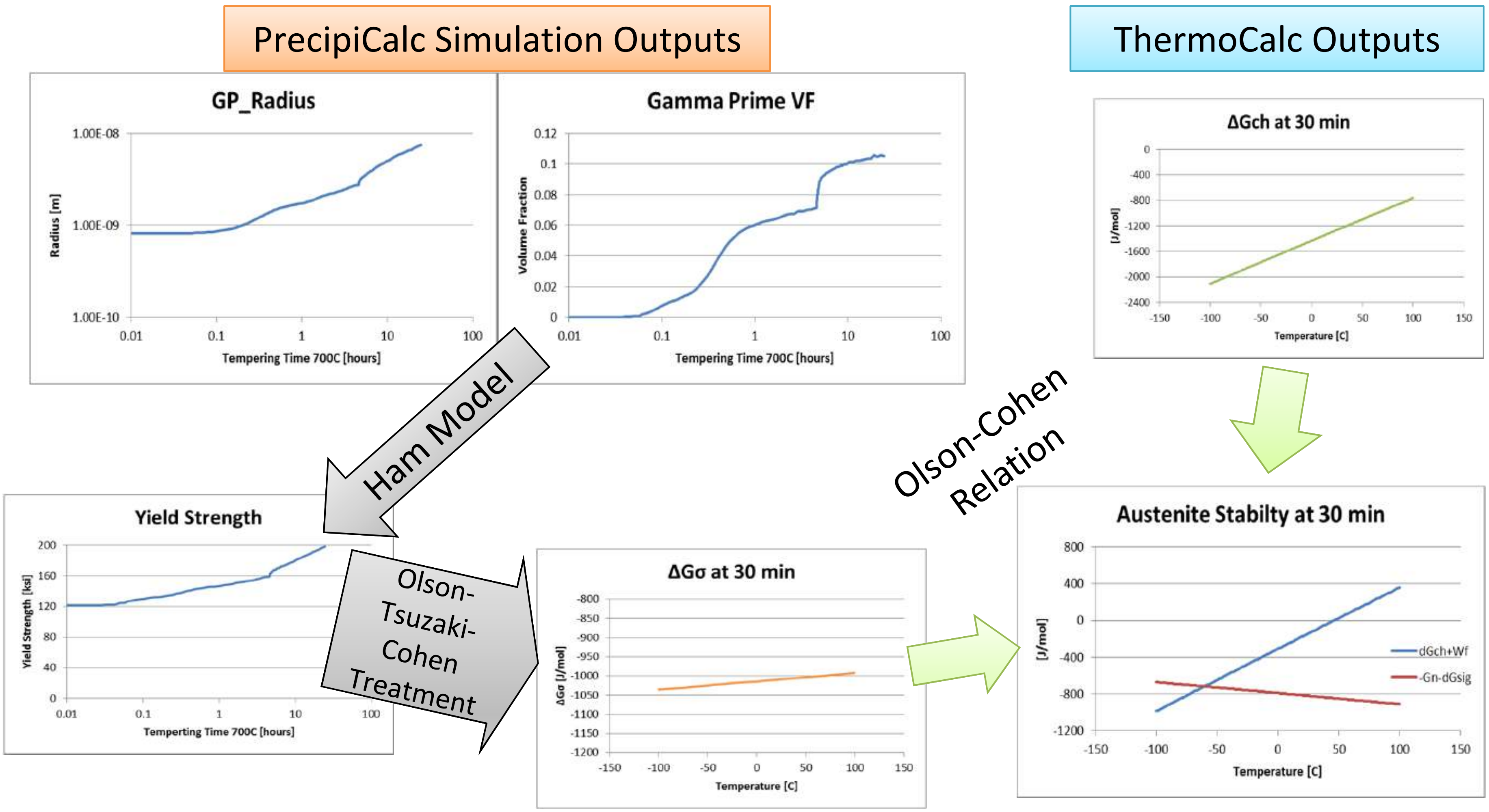
$$\Delta\sigma_{\perp} = C\epsilon^{n}$$

- Models determine required Al and Ti content



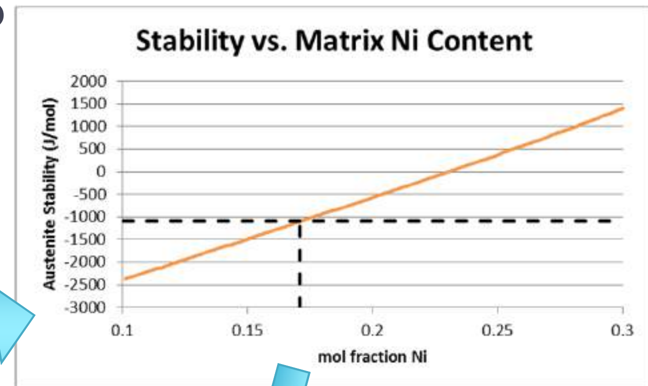
CHIOU, S. T., AND LEE, W. S., “Plastic deformation and fracture response of 304 stainless steel subjected to dynamic shear loading,” *Mat Sci and Tech*, vol. 19, pp. 1261–1265, Sept. 2003.
KOBAYASHI, H., AND DODD, B., “A numerical analysis for the formation of adiabatic shear bands including void nucleation and growth,” *Int jour of imp eng*, vol. 8, no. 1, pp. 1–13, 1989.
RANC, N., *et al.*, “Temperature field measurement in titanium alloy during high strain rate loading - Adiabatic shear bands phenomenon,” *Mechanics of Materials*, vol. 40, pp. 255–270, Apr. 2008.
SADHUKHAN, P., *Computational Design and Analysis of High Strength Austenitic TRIP Steels for Blast Protection Applications*. PhD thesis, Northwestern University, 2008.

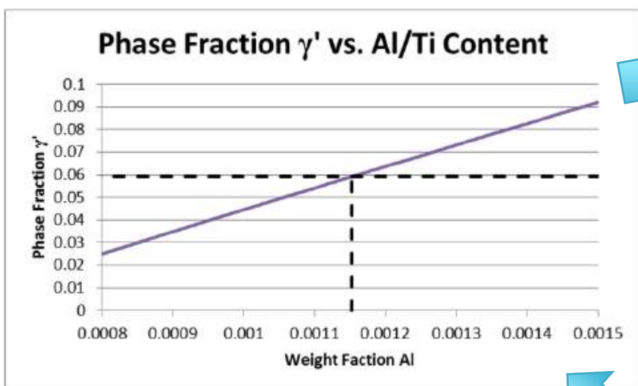
Modeling: M_s^σ Temperature

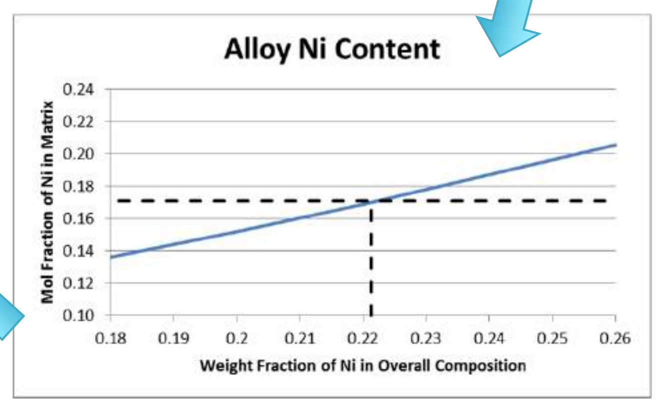


Computational Design: Reducing Warm Working

- M_s^{σ} (sh)= 25°C
- σ_y = 122 ksi
- ThermoCalc and PrecipiCalc iterations



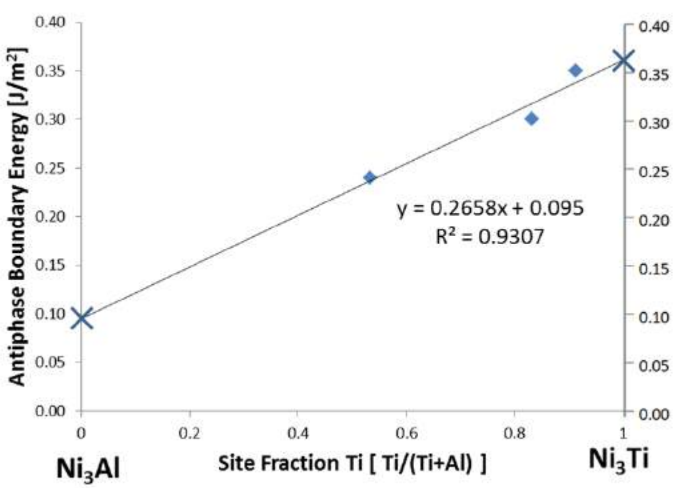


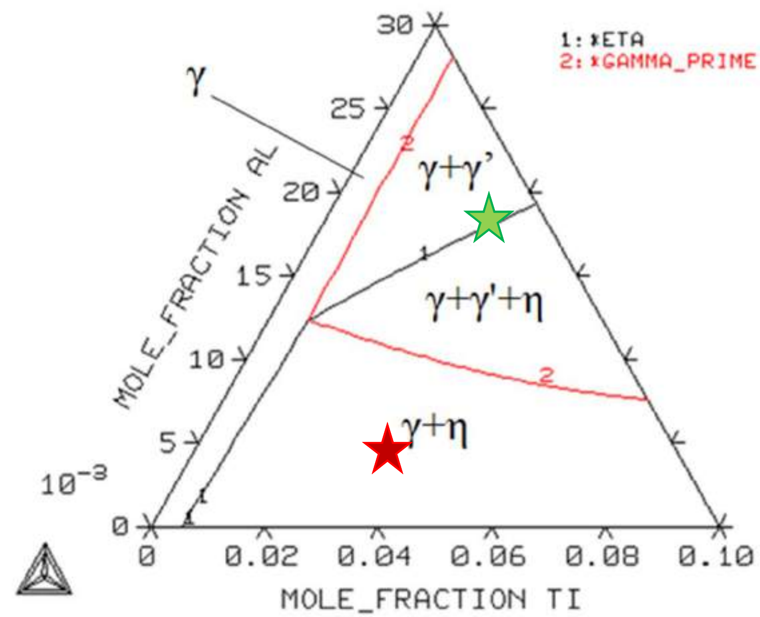


wt%	Ni	Al	Ti	Cr	Mo	V	C	B	N	γ' fraction
10% ww	23.542	0.1937	3.6	4.3	1.245	0.319	0.01	0.0125	0.001	0.101

Computational Design: Eliminating Warm Working

- Thermodynamically and kinetically favoring γ’ over η
- $M_s^{\sigma}(sh) = 25^{o}C$
- σ_y = 114 ksi

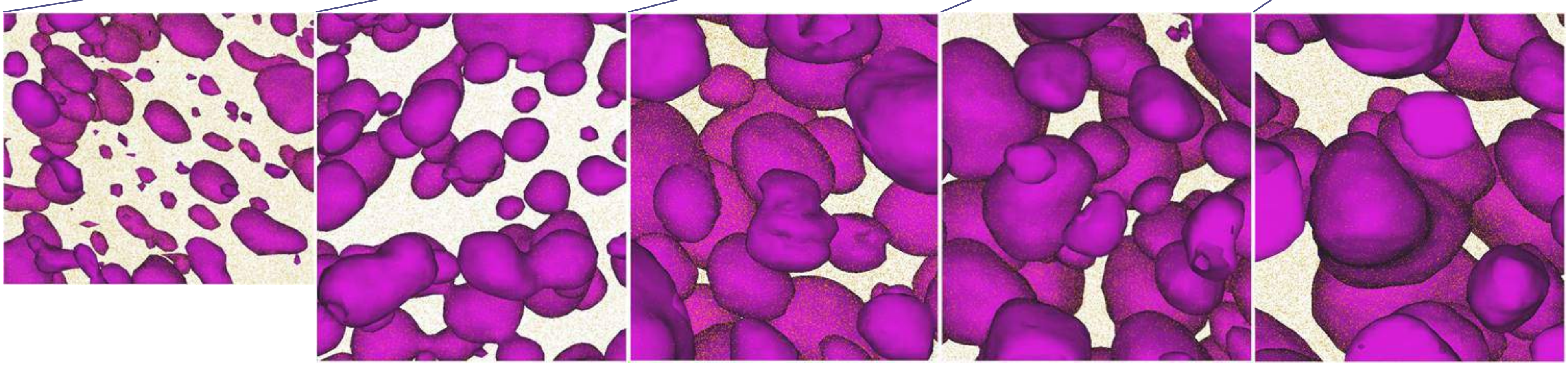




wt%	Ni	Al	Ti	Cr	Mo	V	C	B	N	γ' fraction
0% ww	23.542	0.194	3.60	4.30	1.245	0.319	0.01	0.0125	0.001	0.106

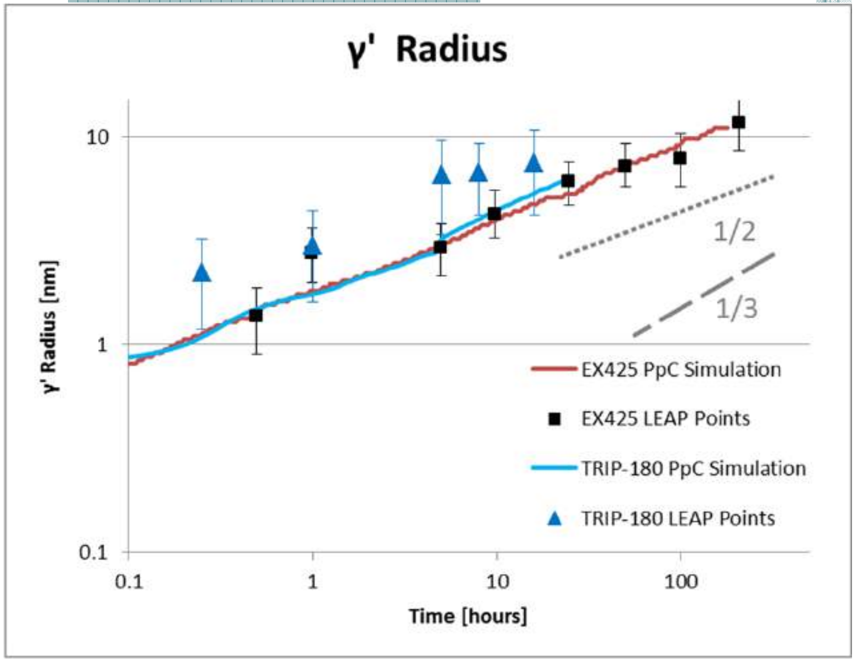
LEAP Precipitate Analysis

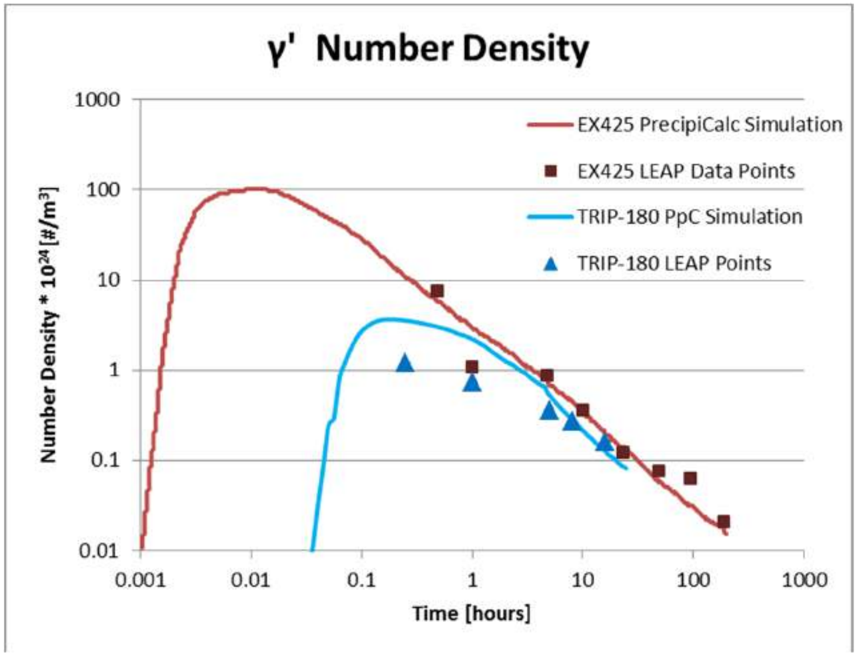
Time at 700C	15 min	1 hr	5 hr	8 hr	16 hr
Radius [nm]	2.206	3.196	6.509	6.726	7.446
Phase Fraction	0.034	0.099	0.111	0.003	0.116
Num Density [#/m³]	1.207	0.728	0.359	0.268	0.161

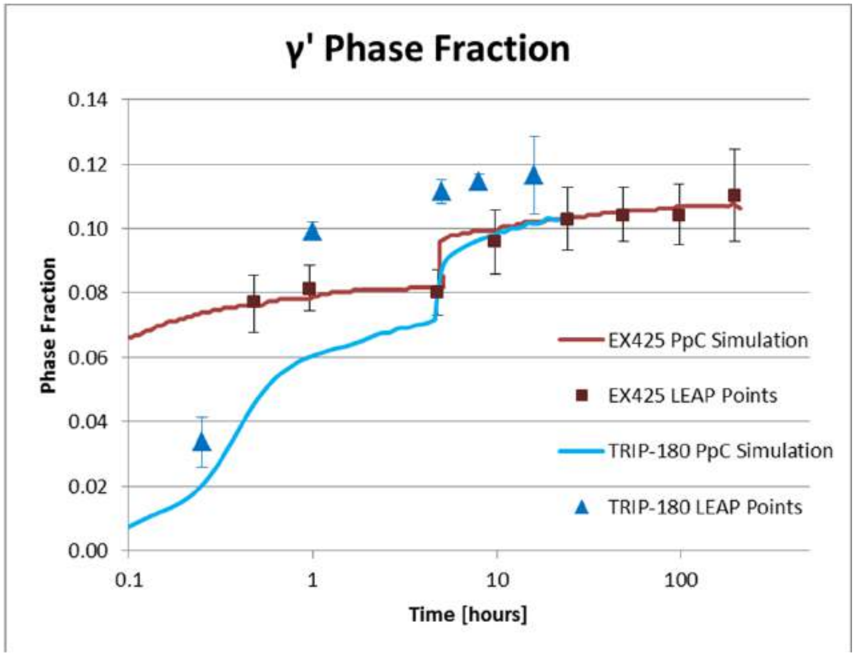


45% Ni, Ti, Al isoconcentration surface

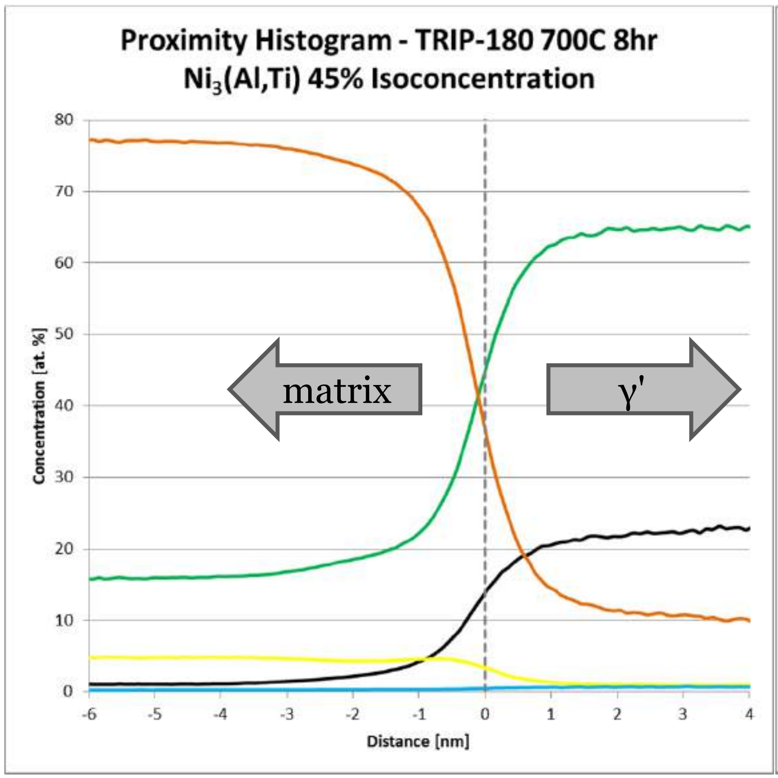
Comparison to EX425 and Current Models

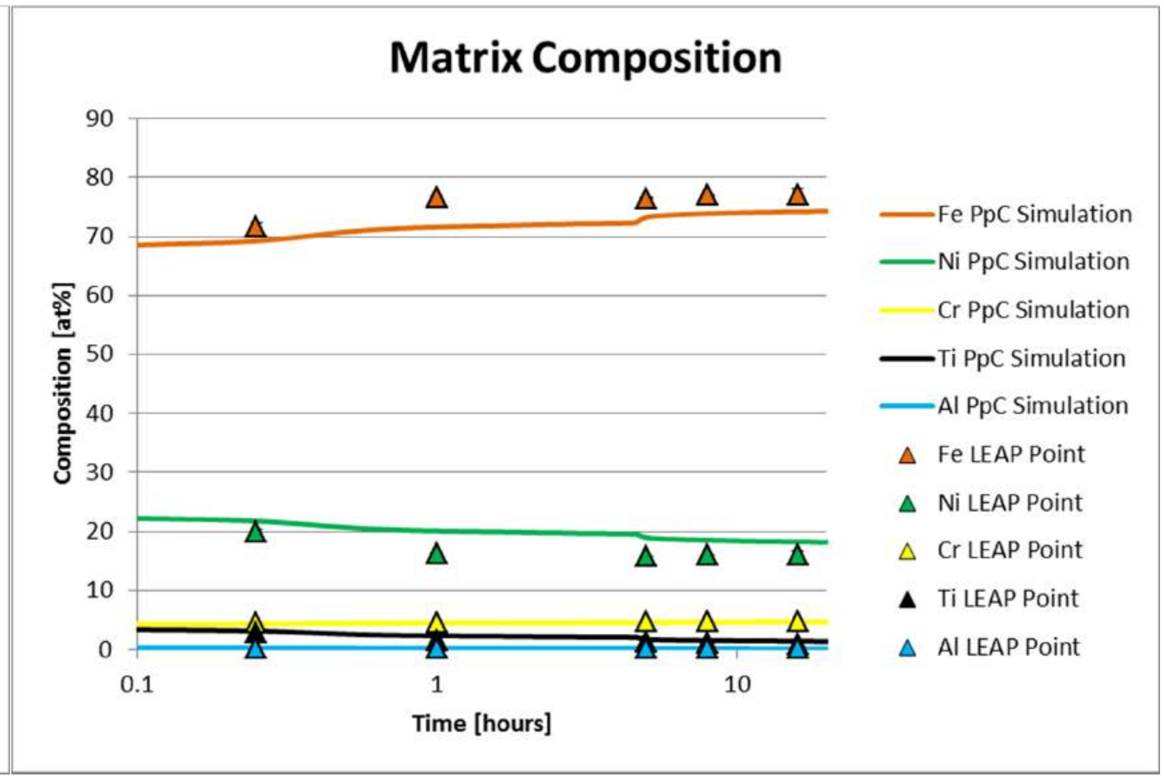






Matrix Composition Evolution





Future Work

- Perform higher accuracy composition analysis using LEAP
- Refine existing models and software package input to match experimental evaluation
- Perform calibration on Split-Hopkinson Bar
- Develop and execute test plan for dynamic shear HAT type tests

Thank You!

Any Questions?

Revolutionary Research . . . Relevant Results

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