# Project 19: Mechanism of Dwell Fatigue Crack Initiation in Ti-7Al Under Biaxial Tension-Tension Loads

## Thrust Area 2: High Performance Non-Ferrous Alloys

**Spring 2018 Semi-Annual Meeting**
**Colorado School of Mines, Golden, CO**
**April 11-12, 2018**

*Student: Garrison Hommer (CSM)*

*Faculty: Dr. Aaron Stebner (CSM) & Dr. Peter Collins (ISU)*

*Industrial Mentor(s): Dr. Adam Pilchak (AFRL)*

# Project 19: Mechanism of Dwell Fatigue Crack Initiation in Ti-7Al Under Biaxial Tension-Tension Loads Dashboard

- Student: Garrison Homer (Mines)
- Advisor(s): Aaron Stebner (Mines), Adam Pilchak (AFRL)

**Project Duration**

PhD: September 2015 to March 2018

➢Problem: Stress dwell periods are detrimental to fatigue life of Ti alloys. Biaxial tension-tension failure is not predicted from uniaxial data.

➢Objective: Under biaxial tension-tension loads, determine microstructural mechanisms of dwell fatigue and define hard and soft grain orientations.

➢Benefit: Improved life management for biaxially loaded locations.

Recent Progress

- Cyclic evolutions of stress metrics
- Interdependencies of stress metrics, orientations, and loading ratios (i.e., 1:4 and 1:1 X:Y stress)
- Effects of grain neighborhood characteristics on individual grains
- Successfully defended and submitted PhD thesis

**Metrics**

| Description | % Complete | Status |
|---|---|---|
| 1. Planar biaxial specimen design | 100% | ● |
| 2. Literature review | 100% | ● |
| 3. Macroscopic characterization of tension-tension mechanical response | 100% | ● |
| 4. Microstructural mechanisms of dwell fatigue under biaxial tension-tension loads | 100% | ● |
| 5. Provide microstructural data for instantiation of crystal plasticity simulations of Ti dwell fatigue | 100% | ● |

# Major components of this project

- Design of experimental platform
  - Planar biaxial platform for nondestructive 3D grain scale studies via high energy diffraction microscopy (HEDM)
- Application of experimental platform
  - Dwell fatigue in alpha titanium subjected to multiaxial loads

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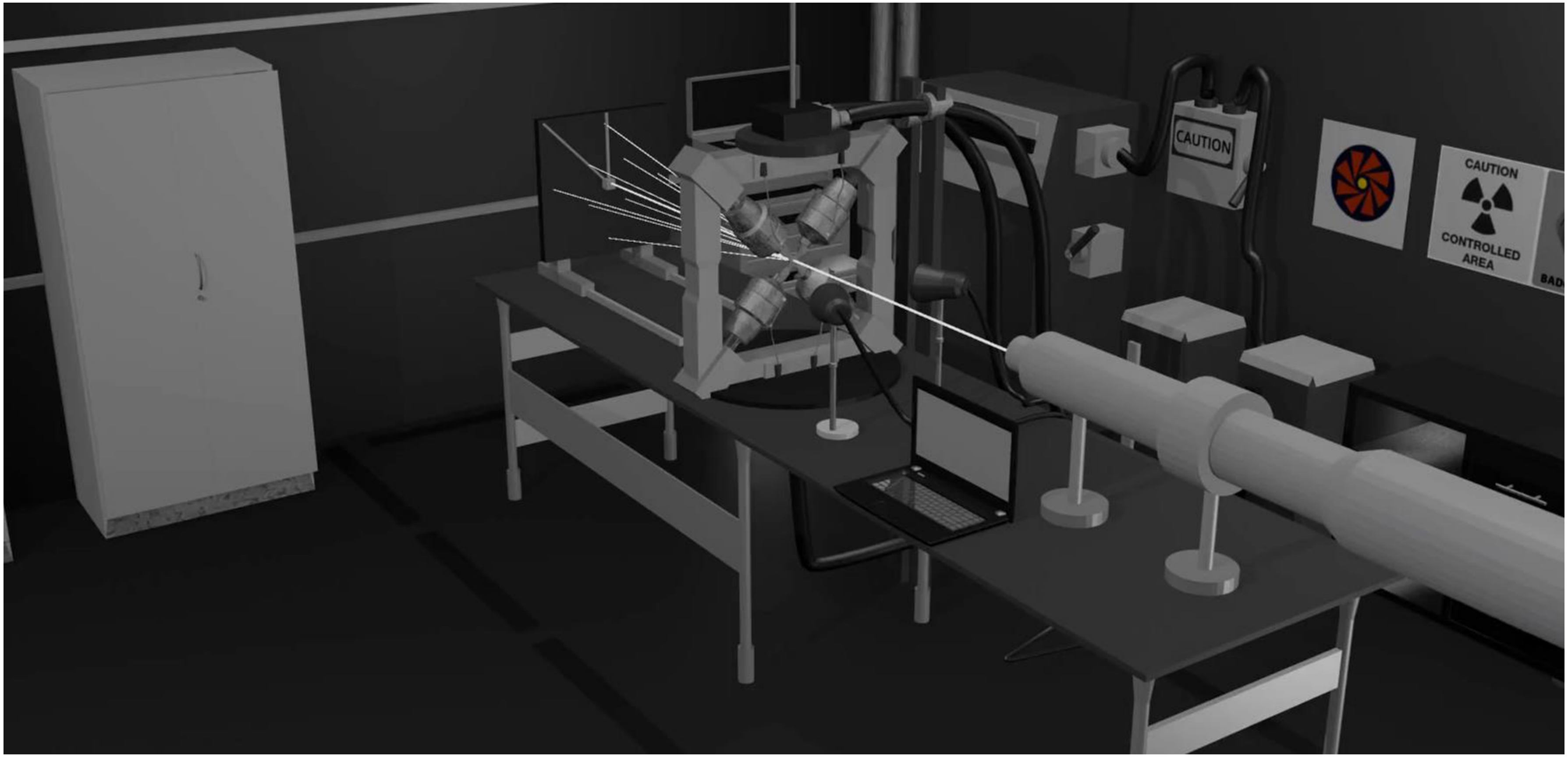
# *In situ* HEDM planar biaxial experiment

● Specimen geometry ●
● Planar biaxial load frame ●

● Synchrotron X-ray diffraction ●
● Data collection & analysis technique ●



*Video courtesy of Harshad Paranjape*

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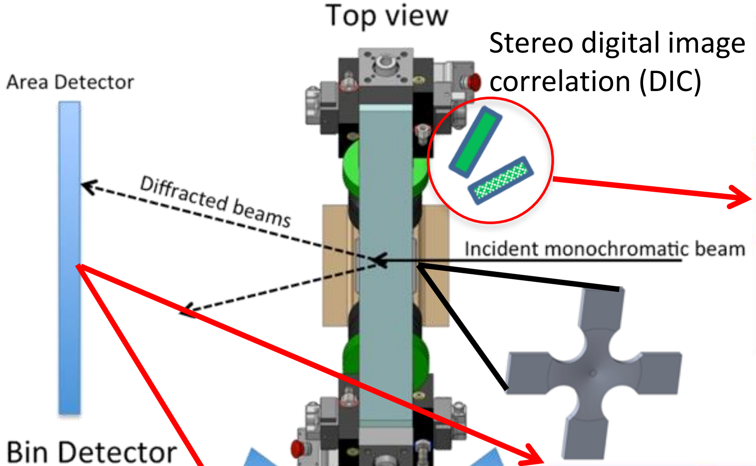
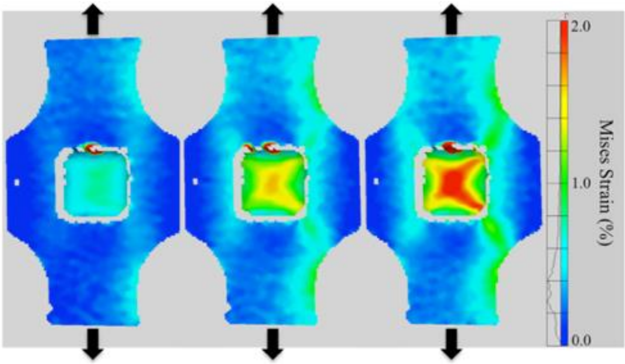
# Multiscale *In situ* HEDM data capabilities



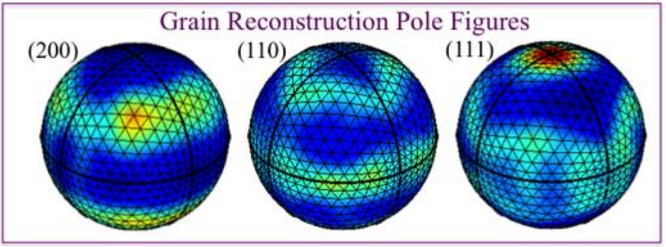
Bin Detector Image every 0.1°

Rotate +/- 180°



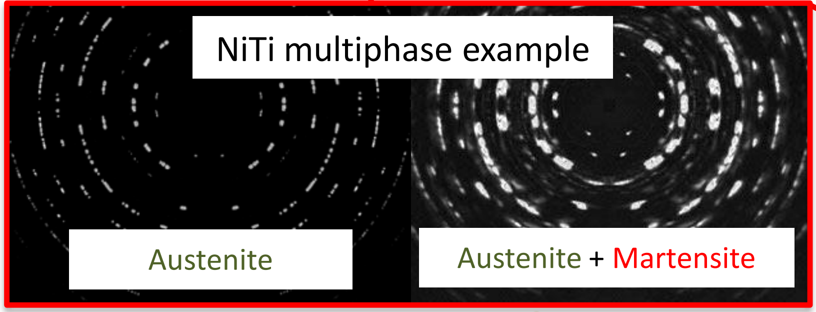
## Macroscopic Data

- Mechanics Loads
- Surface Strains
- Temperature

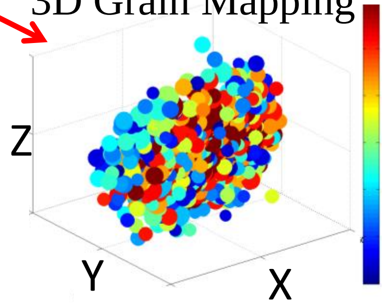

Grain Reconstruction Pole Figures

## Mesoscopic (Powder) Data

- Texture
- Phase Fractions
- Lattice Strain Pole Figures


NiTi multiphase example

3D Grain Mapping



## Microscopic (Crystal) Data

- Center of Mass (x,y,z)
- Volume
- Phase
- Orientation
- Lattice Strain Tensor

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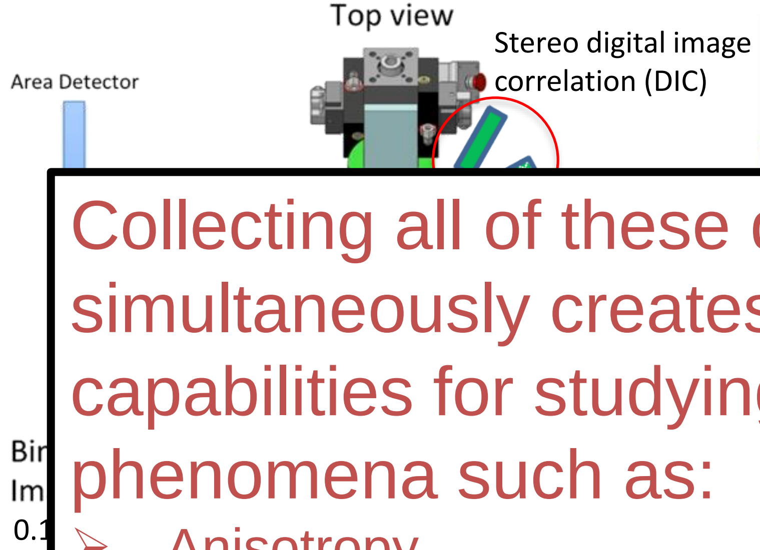
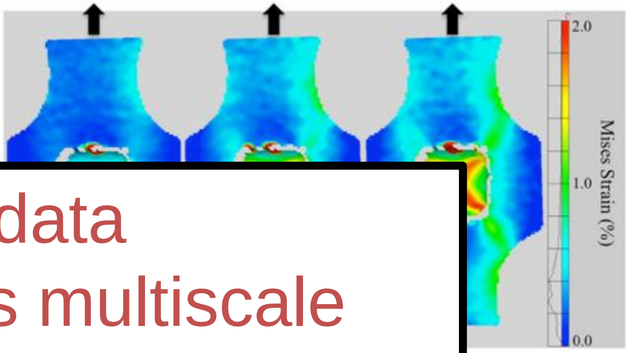
# Multiscale *In situ* HEDM data capabilities





**Macroscopic Data**

- Mechanics Loads
- Surface Strains
- Temperature

Collecting all of these data simultaneously creates multiscale capabilities for studying multiaxial phenomena such as:

- Anisotropy
- Asymmetry
- Path Dependence
- Sheet Metal Formability
- Crystal Mechanics
- Crystal Plasticity
- Model Validation

**Mesoscopic (Powder) Data**

- Texture
- Phase Fractions
- Lattice Strain Pole Figures

**Microscopic (Crystal) Data**

- Center of Mass (x,y,z)
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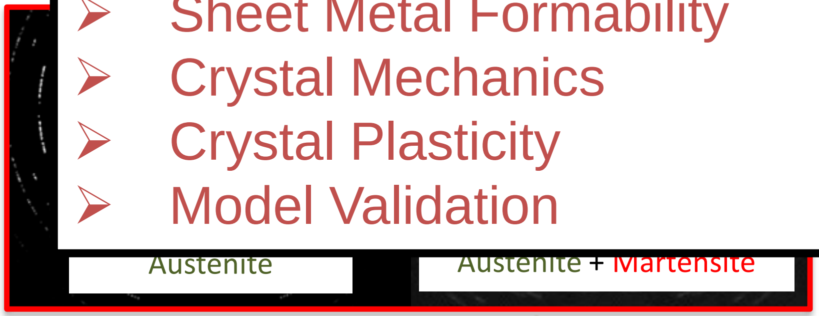

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# Major components of this project

- Design of experimental platform
  - Planar biaxial platform for nondestructive 3D grain scale studies via high energy diffraction microscopy (HEDM)

- **Application of experimental platform**
  - **Dwell fatigue in alpha titanium subjected to multiaxial loads**

# Biaxial Dwell fatigue in Ti-7Al outline

- What is dwell fatigue, why does it affect Ti alloys, and why is this work relevant?
- Material and experimental methods
- Normalized resolved shear stress pole figures (nRSS PFs)
- Plasticity metrics: stress coaxiality angle (SCA) and Mises stress
- Mechanics of cyclic evolutions
- Mechanics of load shedding
- Grain neighborhood effects

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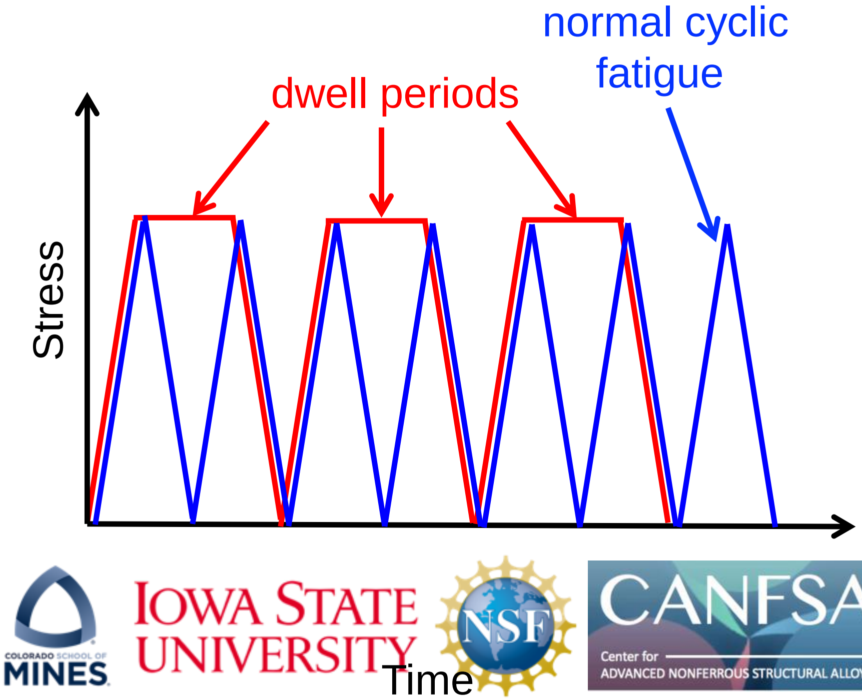
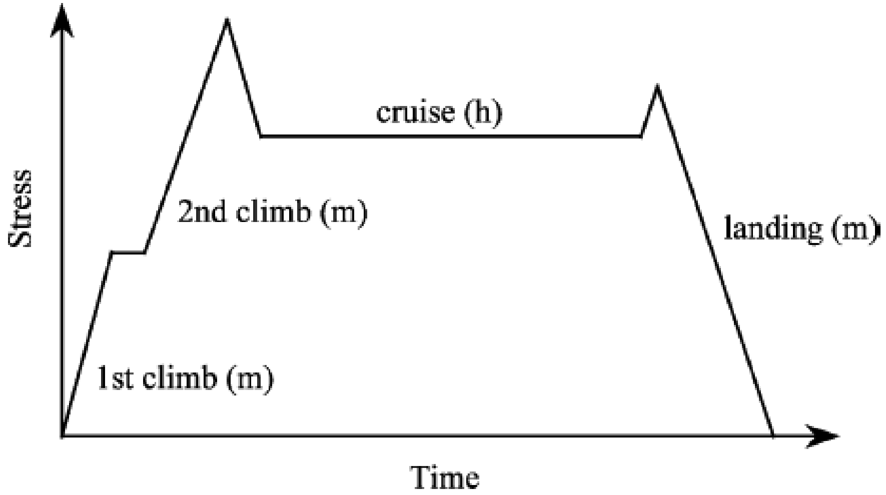
# Cold dwell fatigue reduces lifetime in Ti alloys

- Reduction in fatigue life resulting from stress dwell periods
    - $\sigma_{max}/\sigma_{0.2}$ = 0.92, 1, 1.05 (80 s) life reduction = 2, 5, 30
- Occurs at temperatures ≤ ~200 °C
    - Thermal activation eliminates dwell effect at T > ~200 °C



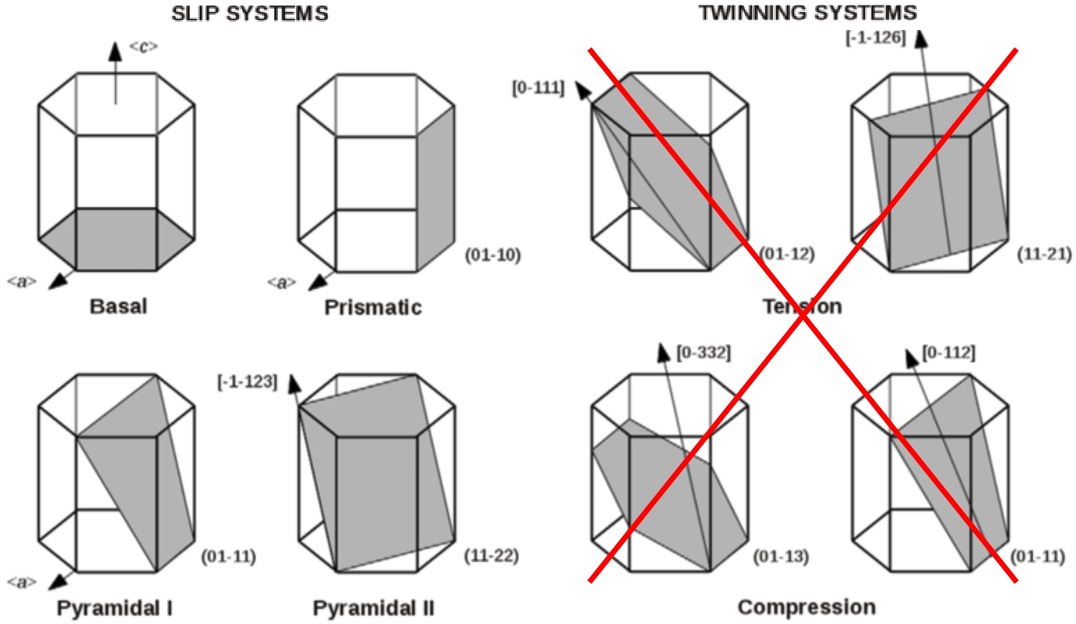


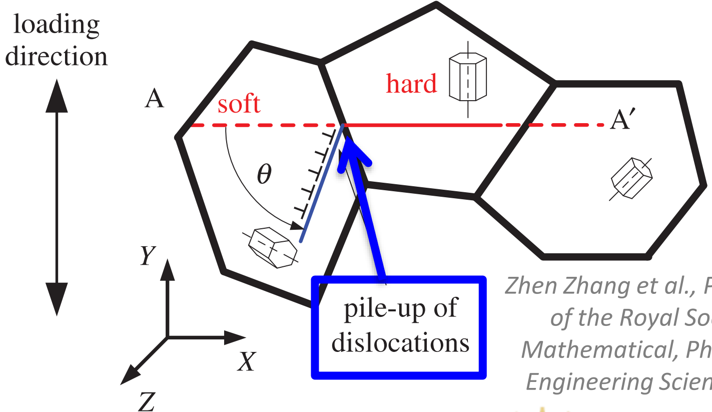
M.R. Bache, International Journal of Fatigue 25 (2003)

# Origin of dwell fatigue in Ti alloys

- α-phase in Ti alloys has HCP crystal structure
- Limited deformation mechanisms at low temperature
  - Twinning suppressed in dwell sensitive alloys by aluminum content ( > 5 wt. % )
  - Strong slip system anisotropy (prism:basal:pyramidal II, 0.9 : 1.0 : 3.0)
  - Less hardening, room temperature creep in soft grains (rate dependence)
  - Local load shedding from plastically soft to plastically hard grains
    - Microvoid formations at dislocation pile-ups lead to failure
    - Soft and hard (plastically) grains relative to full grain stress tensor

*A Luque et al., Modelling and Simulation in Materials Science and Engineering (2015)*





*Zhen Zhang et al., Proceedings of the Royal Society A: Mathematical, Physical and Engineering Science (2015)*

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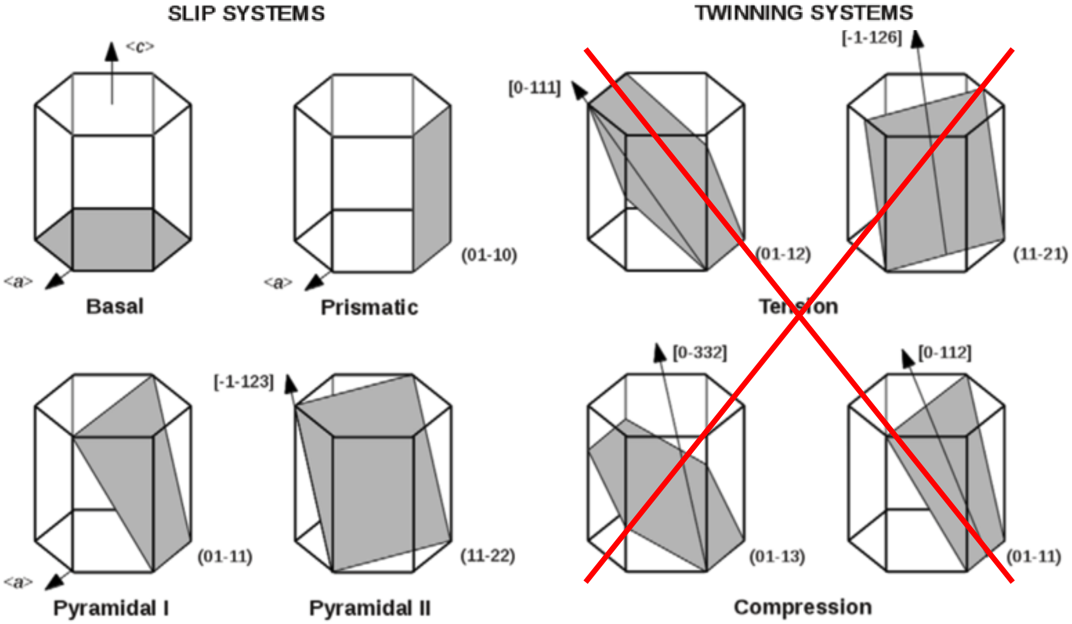
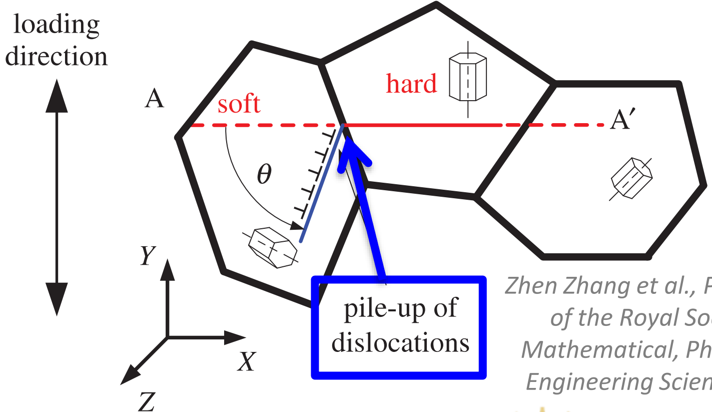
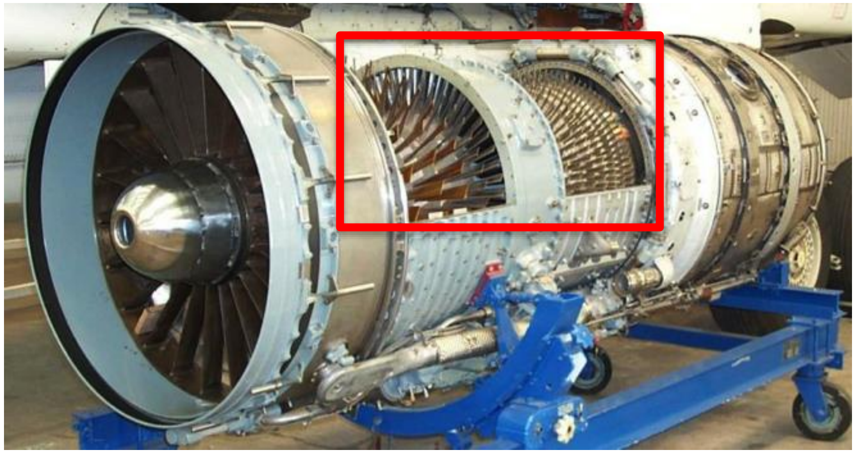




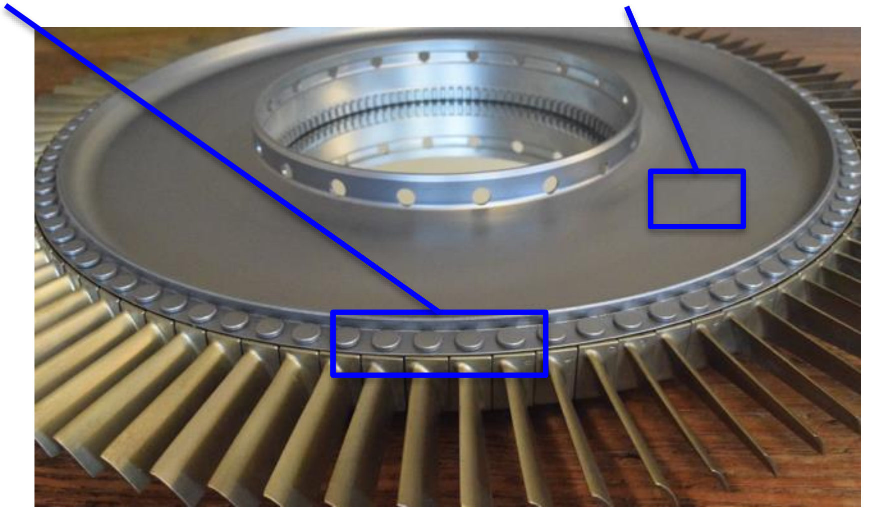
*Zhen Zhang et al., Proceedings of the Royal Society A: Mathematical, Physical and Engineering Science (2015)*

# Ti alloy compressor discs experience biaxial dwell fatigue

- Titanium alloy jet engine turbine compressor discs
- Enhance life prediction
  - Biaxial loading effect on fatigue life not well characterized



*http://www.daviddarling.info/images/Concorde_Olympus_engine.jpg*



*http://www.ashbyinteriors.co.uk/wp-content/uploads/2014/09/DSC_0707-p.jpg*

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# Ti alloy biaxial dwell fatigue goals:

- Define multiaxial hard and soft grain orientations
- Determine microstructural mechanisms
- Investigate grain behaviors as functions of:
  - Cycles
  - Orientation
  - Neighborhood characteristics
- Qualitative life assessment relative to uniaxial dwell fatigue
- Provide insight into observed failure orientations

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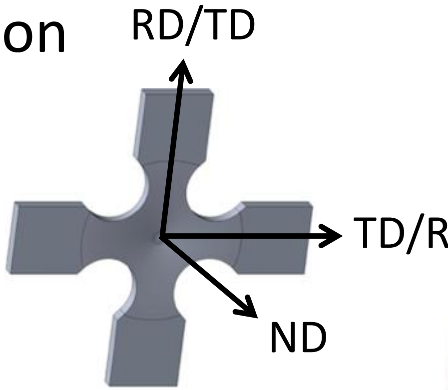
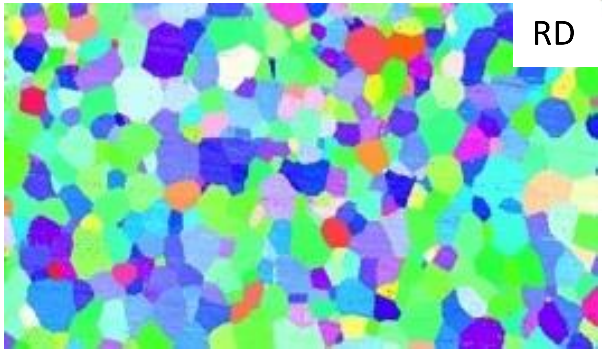
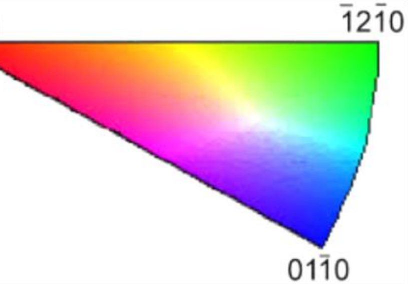
# Material microstructure

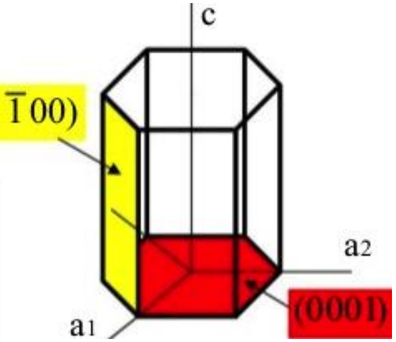
- C-axes oriented in normal direction
- Uniform in-plane texture
- ~100 µm equiaxed grains

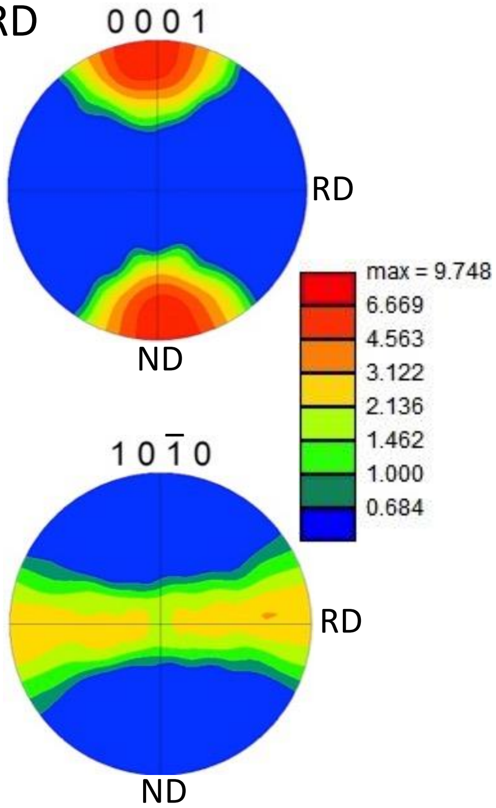


200 µm









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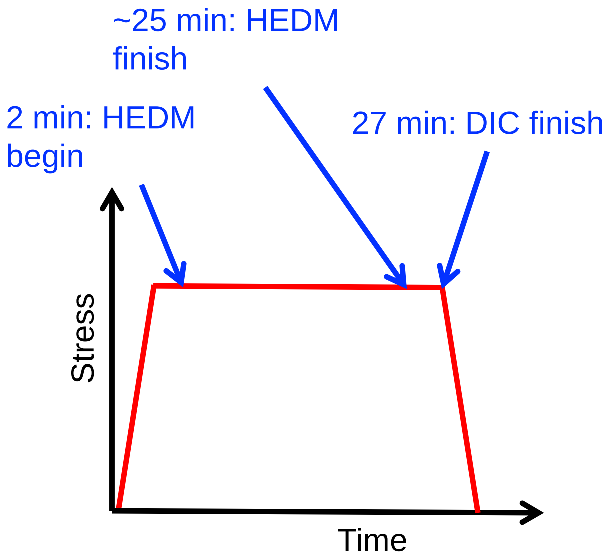
# Methods for *in situ* dwell fatigue at APS

- Tension-tension 1:1 and 1:4 X:Y stress ratio dwell fatigue
  - Used specimens from previous experiments (100 and 310 cycles at ~80 % yield stress)
- 120 second holds in force control
- 1 second load and unload
- ~100 % yield stress
- HEDM data points at load and unload
  - Reference & cycles 1 – 5, 50
  - 1 x 0.8 $\text{mm}^2$ total beam size
    - ~1.2 x 0.8 x 0.5 $\text{mm}^3$ illuminated volume



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- **Normalized resolved shear stress pole figures (nRSS PFs)**
- Plasticity metrics: stress coaxiality angle (SCA) and Mises stress
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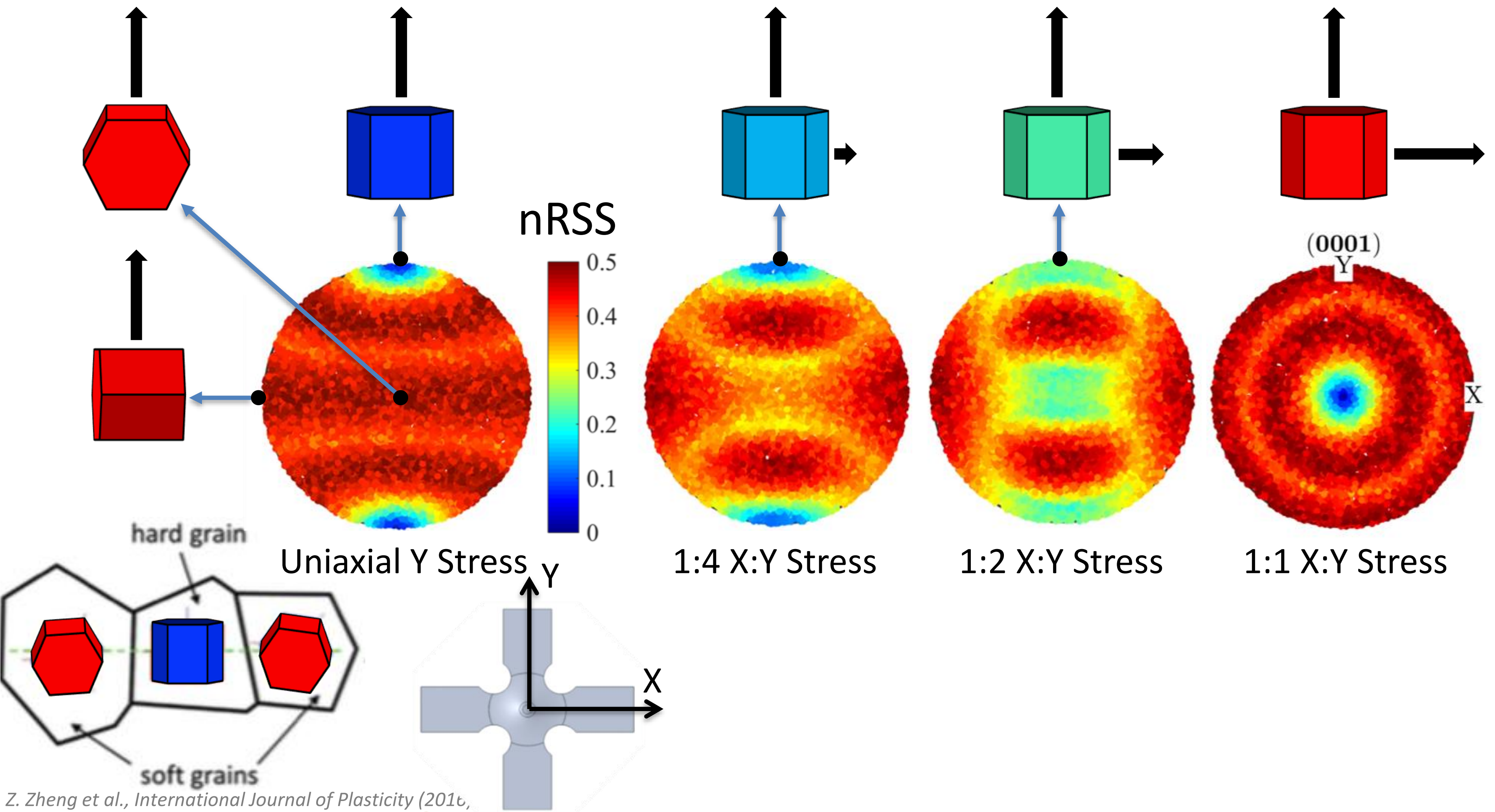
- Mechanics of load shedding
- Grain neighborhood effects

# Composites of Basal-Prismatic *normalized* resolved shear stress on (0001) pole figures (IPFs)



*Z. Zheng et al., International Journal of Plasticity (2016*

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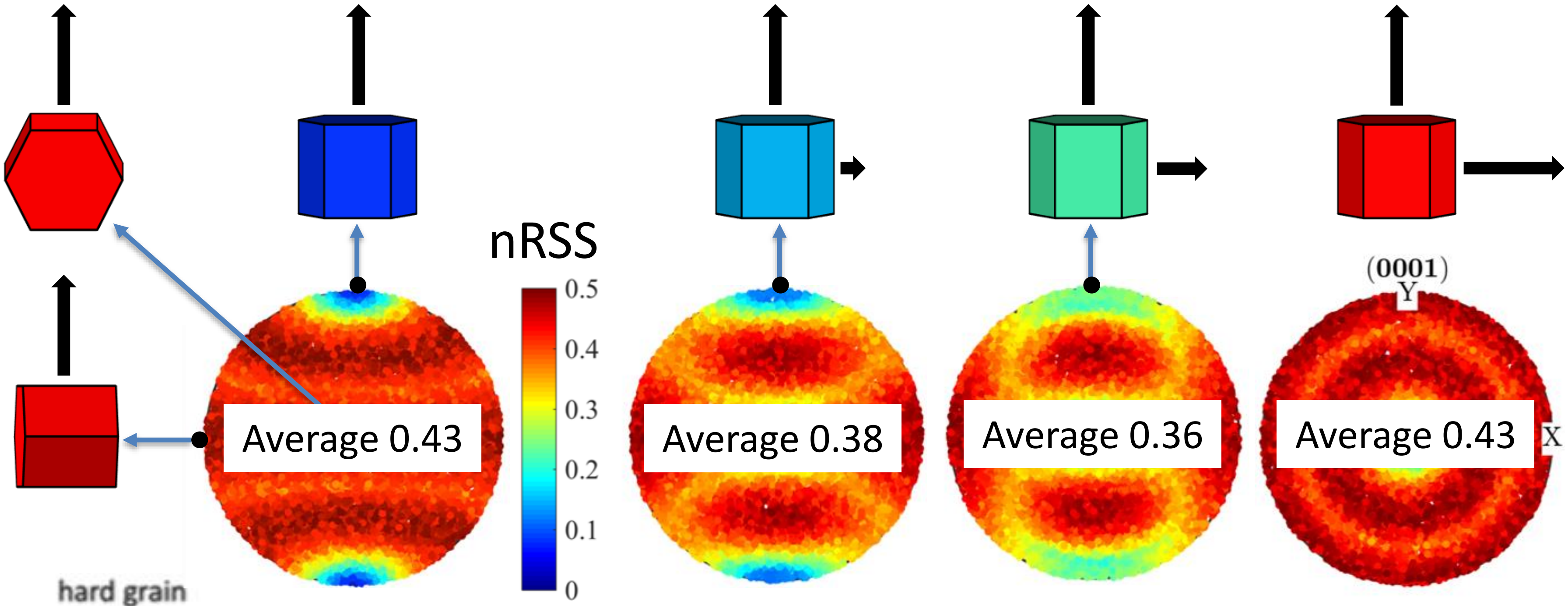
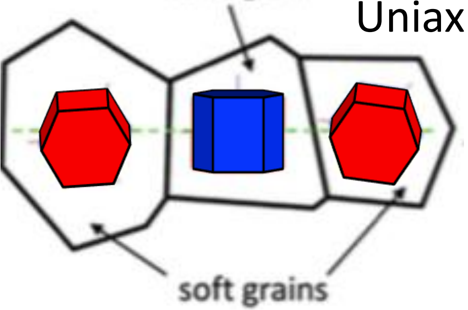


Uniaxial Y Stress

1:4 X:Y Stress

1:2 X:Y Stress

1:1 X:Y Stress



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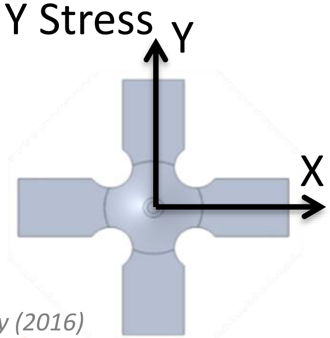
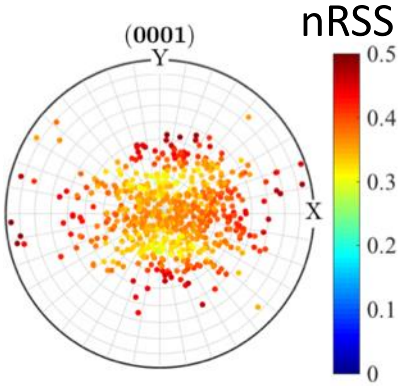


- *Multiaxial loading reduces:*
  - *disparity between hard and soft grains*
  - *average resolved shear stress on a randomly oriented polycrystal*

# Average nRSS in 1:4 and 1:1 X:Y stress ratio specimens

## 1:4

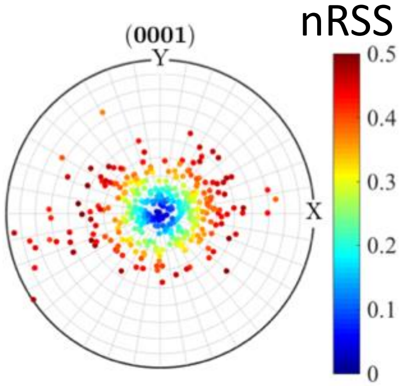
Basal-Prismatic Composite: **0.37**
Standard Deviation: **0.04**

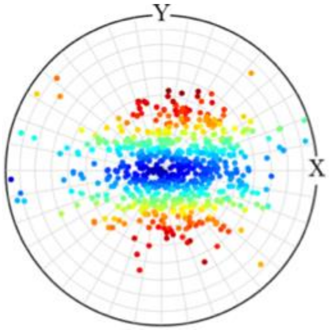


- *1:4*
  - *more plastic deformation*
  - *fewer rogue grain pairs (less load shedding)*
- *1:1*
  - *basal slip dominance*

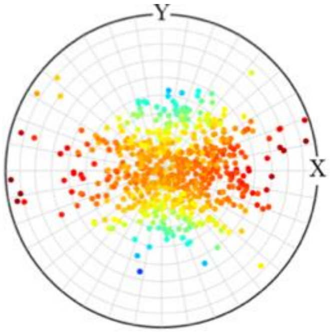
## 1:1

Basal-Prismatic Composite: **0.29**
Standard Deviation: **0.12**

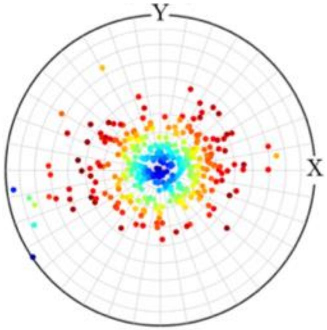




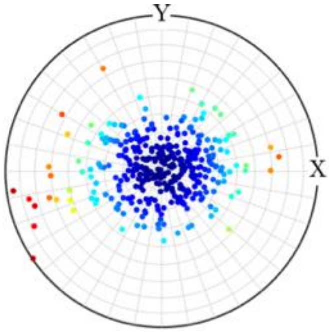
Basal: **0.22**



Prismatic: **0.34**



Basal: **0.29**



Prismatic: **0.09**

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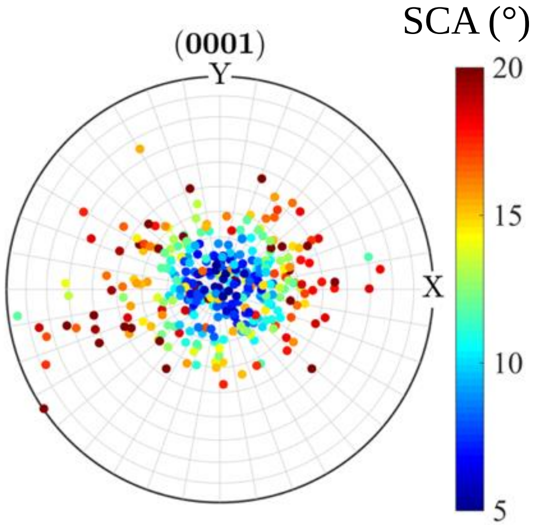
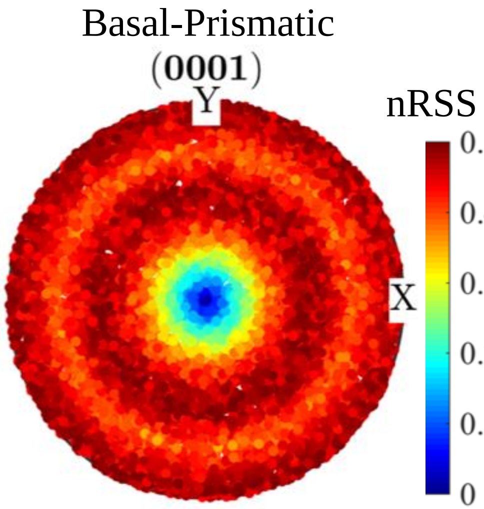
# Stress coaxiality angle (SCA) and Mises stress as metrics for plastic deformation

- Plastic deformation leads to increase in SCA and decrease in Mises stress

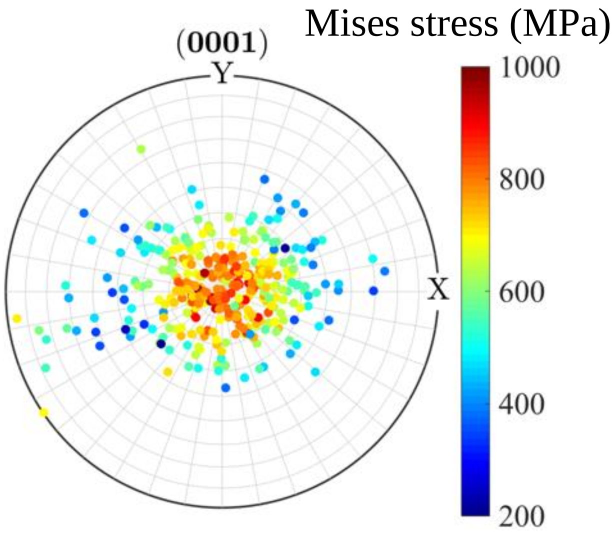
*Stress Coaxiality Angle*:
scalar measure of alignment between applied stress tensor and grain stress tensor

$$\theta = \cos^{-1}\left(\frac{\boldsymbol{\sigma}_{applied} : \boldsymbol{\sigma}_{grain}}{|\boldsymbol{\sigma}_{applied}||\boldsymbol{\sigma}_{grain}|}\right)$$





1:1 stress ratio



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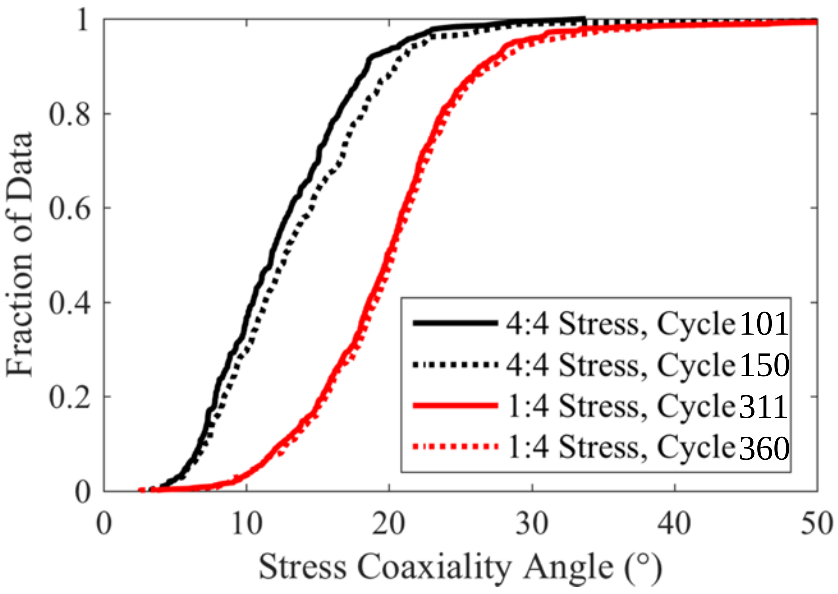
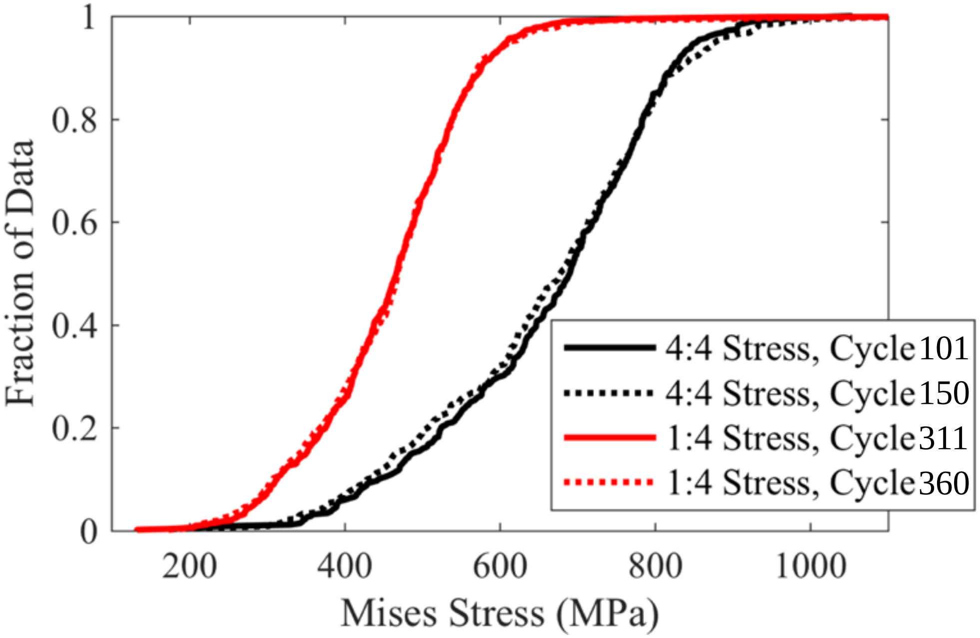
# Empirical cumulative distribution functions (ECDFs) highlight cyclic SCA differences in 4:4 & 1:4 stress ratios



- 1:4 higher median SCA (20.4° ) indicates more plastic deformation than 4:4 (12.4°)
- 1:4 low SCA tail indicates fewer hard behaving grains than 4:4
- 4:4 cyclic shift indicates more cyclic plasticity than 1:4
  - Less plastic shakedown in 1:1, 150 cycles vs. 360
  - Basal slip dominance causes less hardening

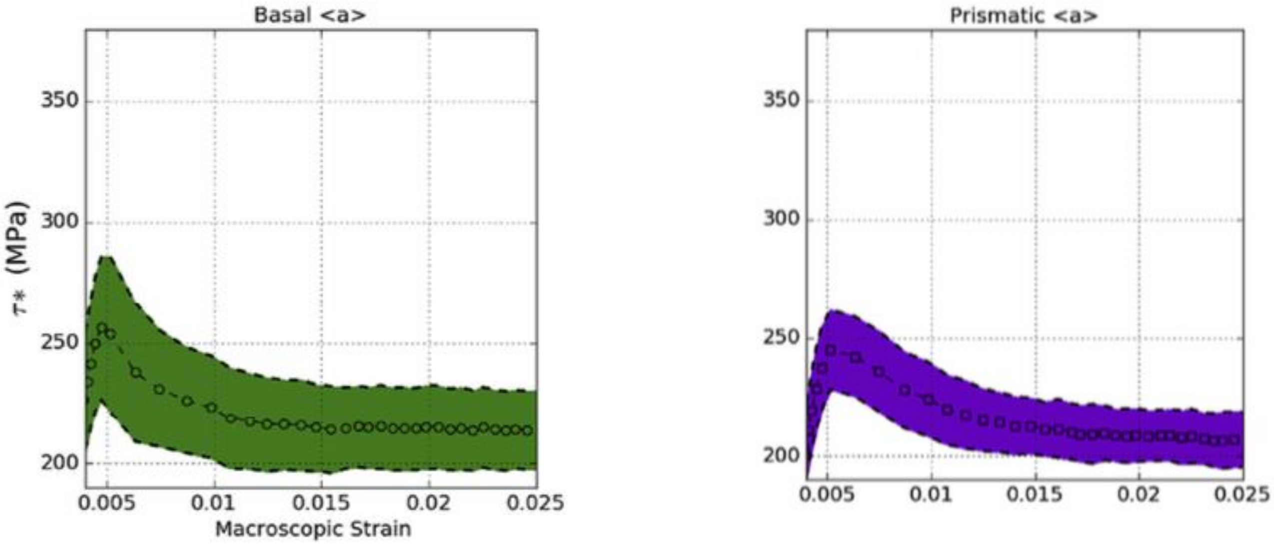
# Mises stress ECDFs highlight greater soft-hard grain disparity in 4:4 stress ratio

- 4:4 ratio has wider distribution
  - Larger disparity between soft and hard grains
- 4:4 ratio cyclic behavior indicative of load shedding
  - Upper tail of 4:4 ratio shifts to higher stress
  - Lower half of 4:4 ratio shifts to lower stress



# Cyclic slip system softening

- Ti$_3$Al precipitates (coherent)
  - Initial strengthening followed by glide plane softening & highly planar slip after shearing
  - Observed in monotonic loading



*Pagan et al., Acta. Mat., 2017*

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- ➢ $Ti_3Al$ precipitates (coherent)
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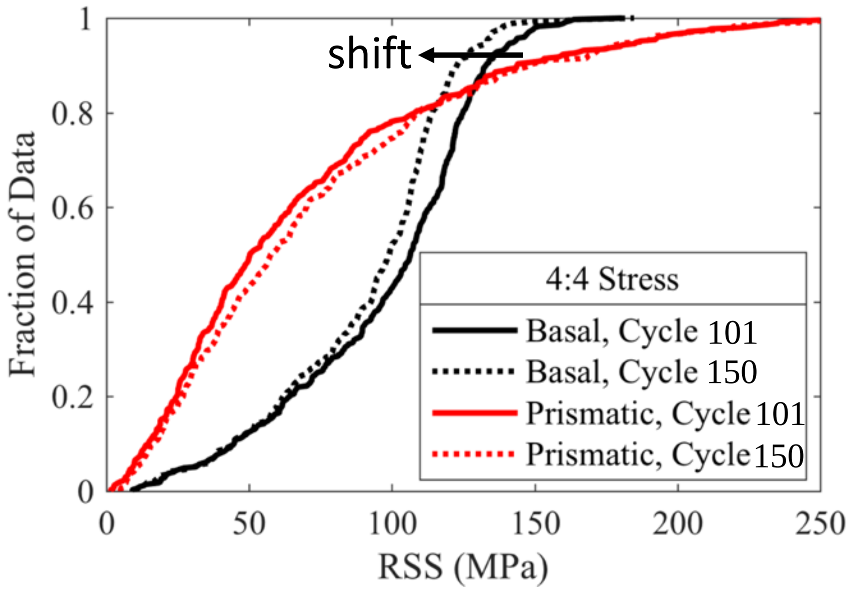
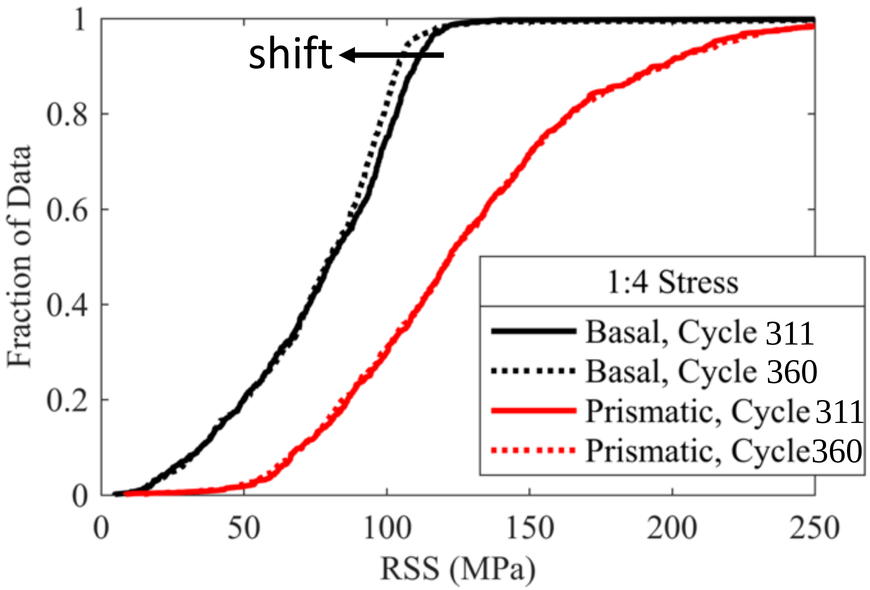
  - ➢ Observed in monotonic loading

➢ *Shift in basal ECDF at high RSS indicates cyclic basal softening*





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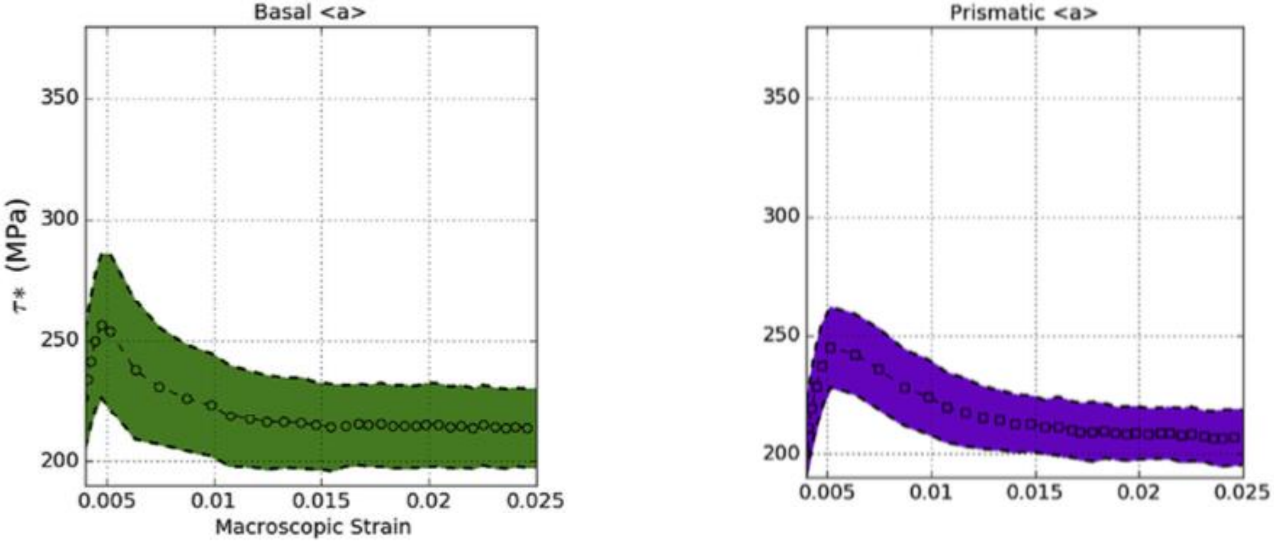
  - Initial strengthening followed by glide plane softening & highly planar slip after shearing
  - Observed in monotonic loading



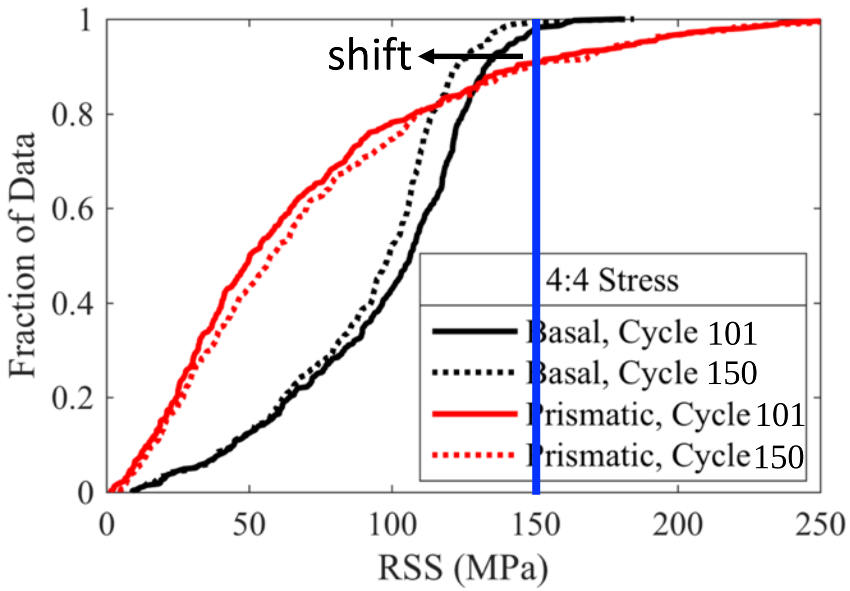
*Pagan et al., Acta. Mat., 2017*

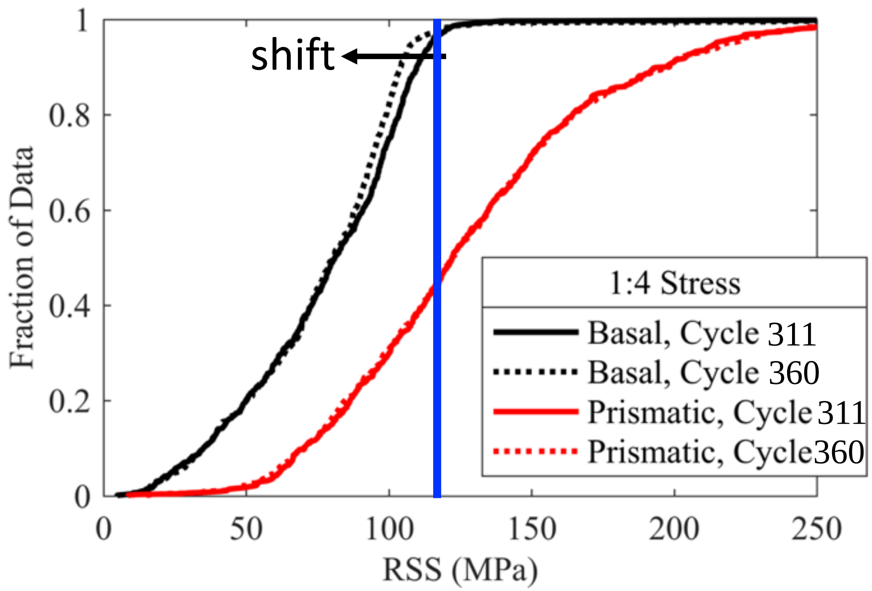
# Cyclic slip system softening

- 4:4 basal CRSS > 1:4 basal CRSS
- 4:4 softening > 1:4 softening
  - 150 vs. 360 cycles
  - Less plastic shakedown in 4:4
  - Less hardening in 4:4

*Cycle 101: more $Ti_3Al$ shearing*

*Cycle 150: more planar slip*





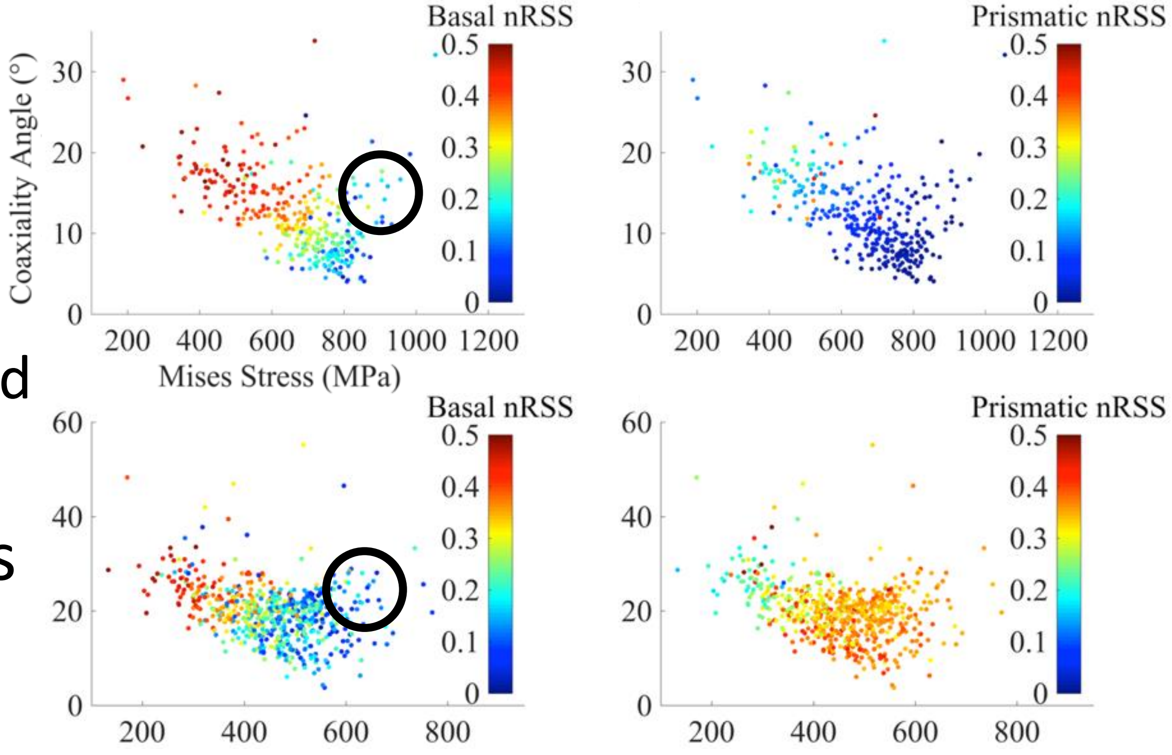
# Biaxial Dwell fatigue in Ti-7Al outline

- What is dwell fatigue, why does it affect Ti alloys, and why is this work relevant?
- Material and experimental methods
- Normalized resolved shear stress pole figures (nRSS PFs)
- Plasticity metrics: stress coaxiality angle (SCA) and Mises stress
- Mechanics of cyclic evolutions
- **Mechanics of load shedding**
- Grain neighborhood effects

# SCA decreases with increasing Mises stress except at highest stresses

- Stronger 1:1 basal nRSS dependence due to texture
    - 1:1 has distinctly hard grains
- Highest Mises stress grains show SCA increase

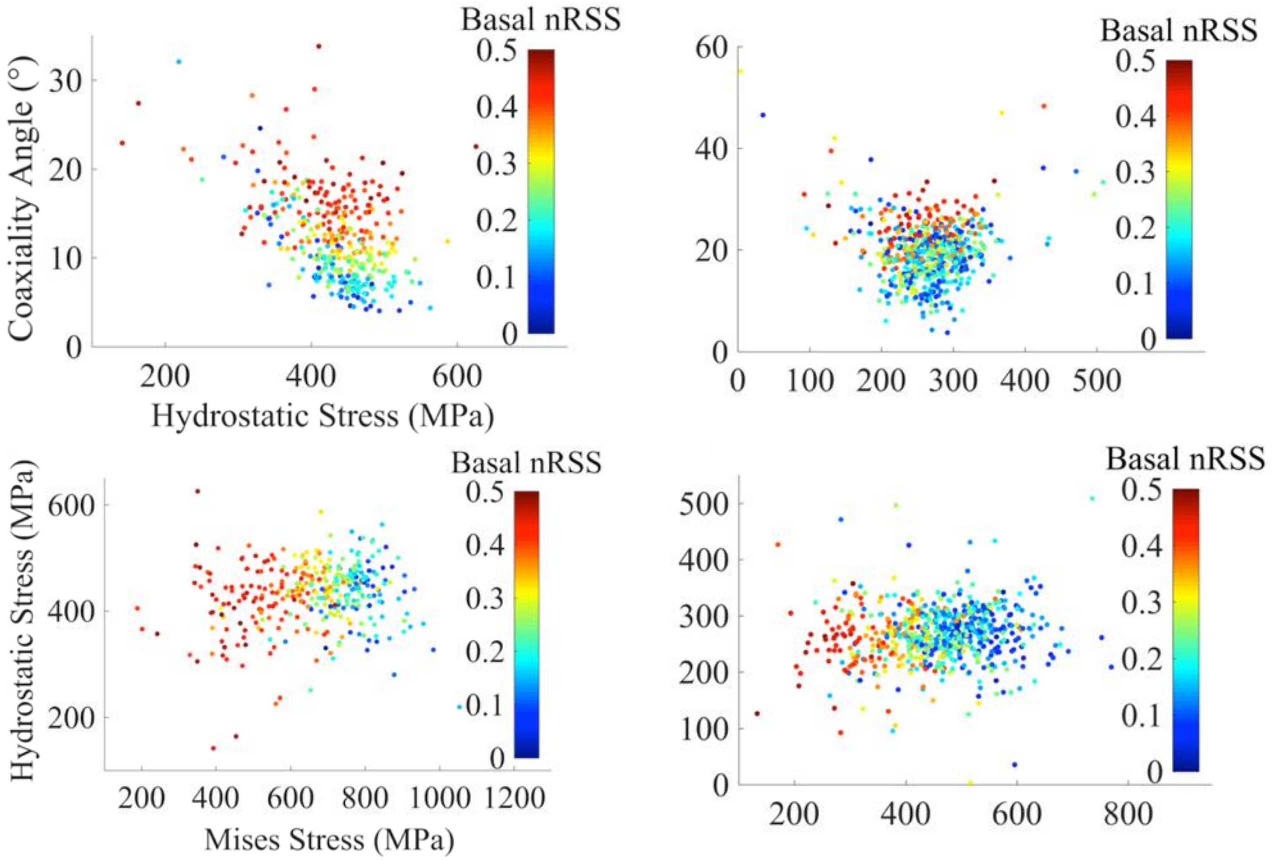
1:1



1:4

# Hydrostatic stress does not trend with SCA, Mises stress, or orientation

- Hydrostatic stress: $\sigma_H = (\sigma_{11} + \sigma_{22} + \sigma_{33}) / 3$

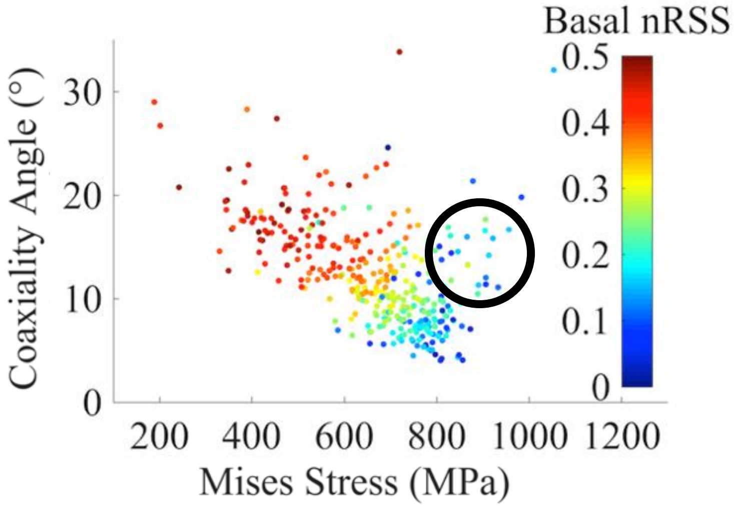


1:1

1:4

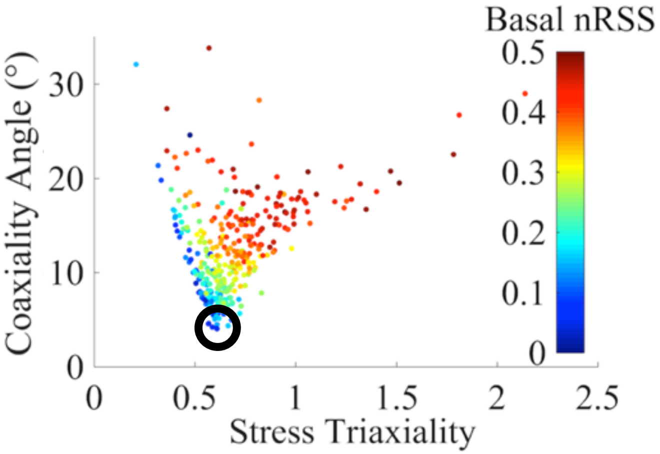
# SCA exhibits strong trends with stress triaxiality and orientation

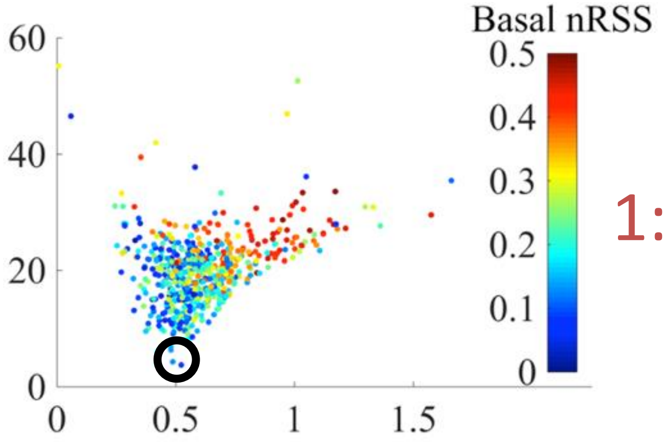
- Stress triaxiality = $\sigma_H / \sigma_{VM}$
- Stress triaxiality at minimum S plane stress elastic calculation ratio
  - Higher indicates load shedding
  - Lower indicates load receiving



- Load shedding onto hard grains increases SCA

1:1





1:4

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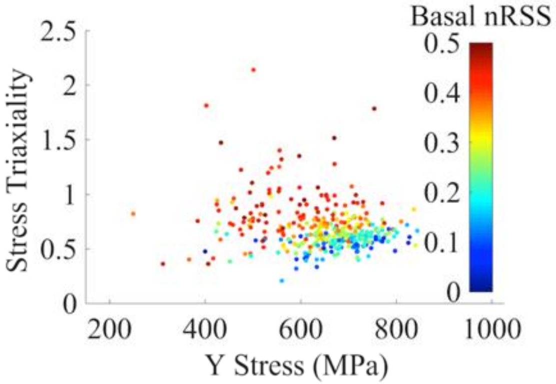
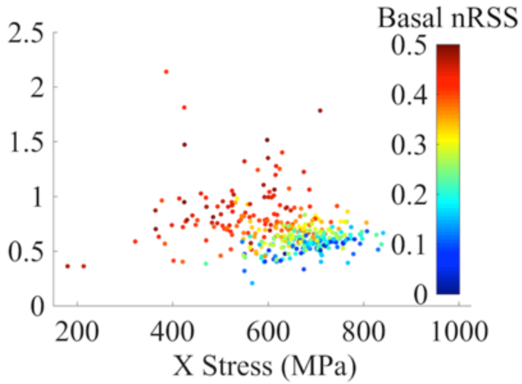
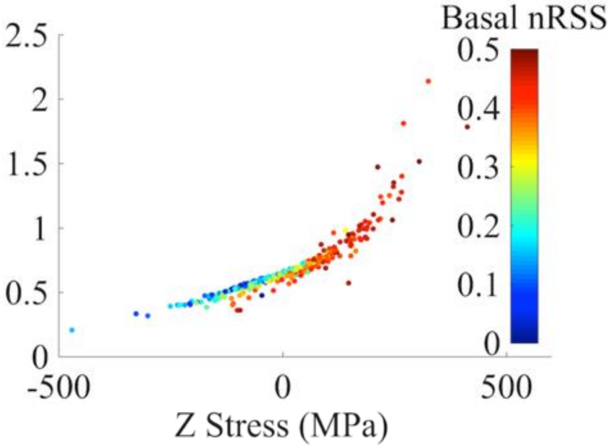
# Out of plane stress trends strongly with stress triaxiality

- X and Y stresses are directly affected by load shedding and receiving
- Z stress is driven by X and Y stresses

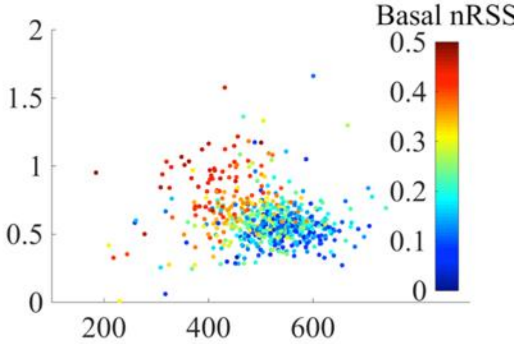
1:1

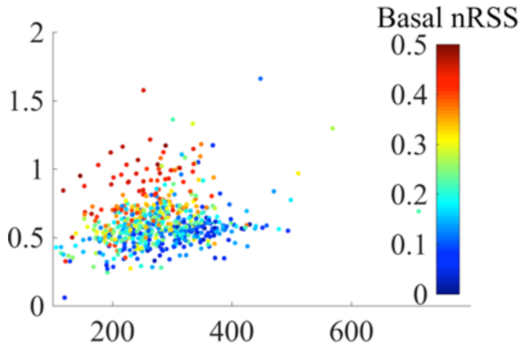


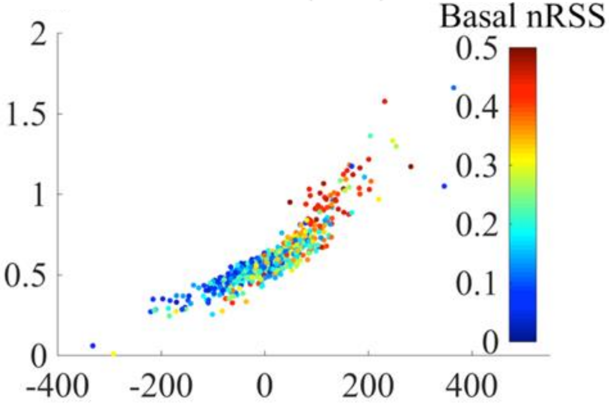




1:4







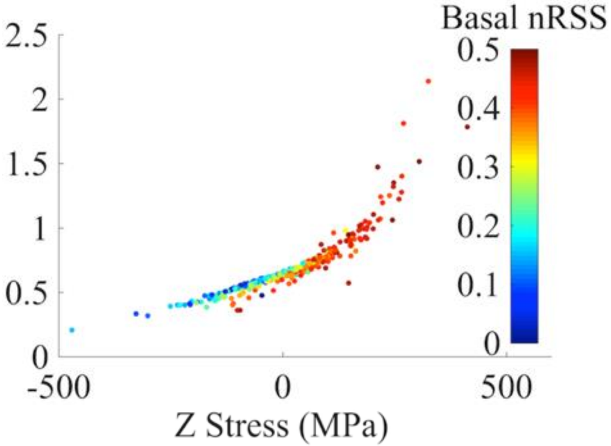
# Out of plane stress trends strongly with stress triaxiality

- X and Y stresses are directly affected by load shedding and receiving
- Z stress is driven by X and Y stresses

- *Mechanism of crack initiation on soft (near) basal planes due to load shedding:*

- *Planar dislocation pileup: microvoids*
- *High stress triaxiality*
- *Decohesion of (near) basal planes*

1:1



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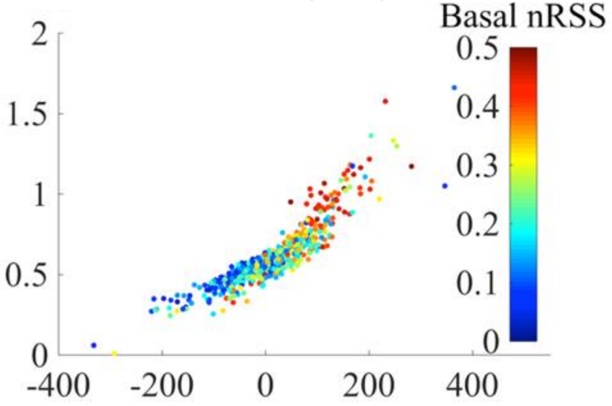


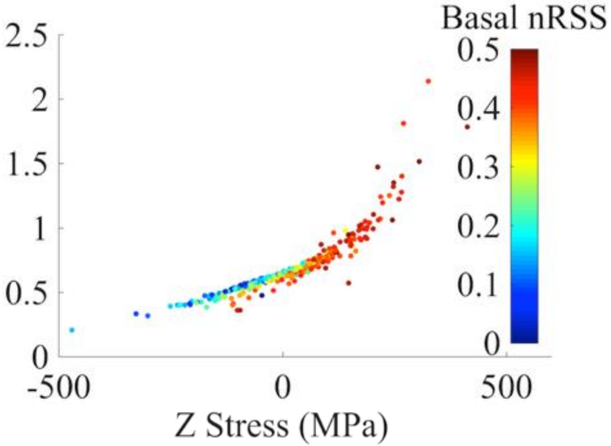
# Out of plane stress trends strongly with stress triaxiality

- X and Y stresses are directly affected by load shedding and receiving
- Z stress is driven by X and Y stresses

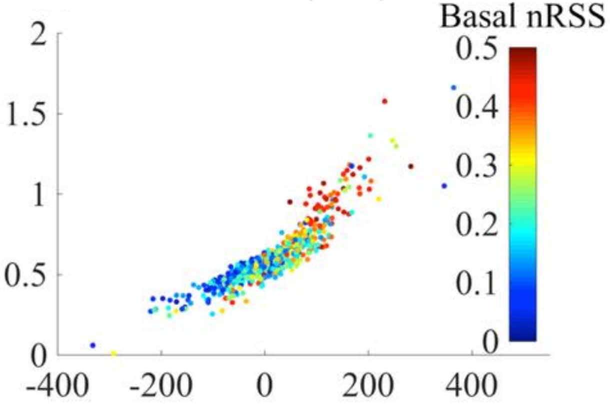
- *Mechanism of crack propagation on hard (near) basal planes due to load shedding:*

- *Initiation in soft neighbor*
- *Additional load shedding*
- *Removal of Z (Poisson) direction constraint*

1:1



1:4



# Biaxial Dwell fatigue in Ti-7Al outline

- What is dwell fatigue, why does it affect Ti alloys, and why is this work relevant?
- Material and experimental methods
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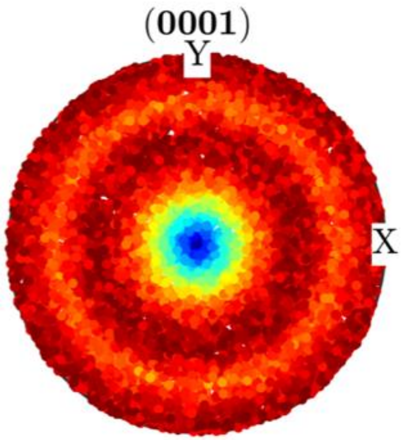
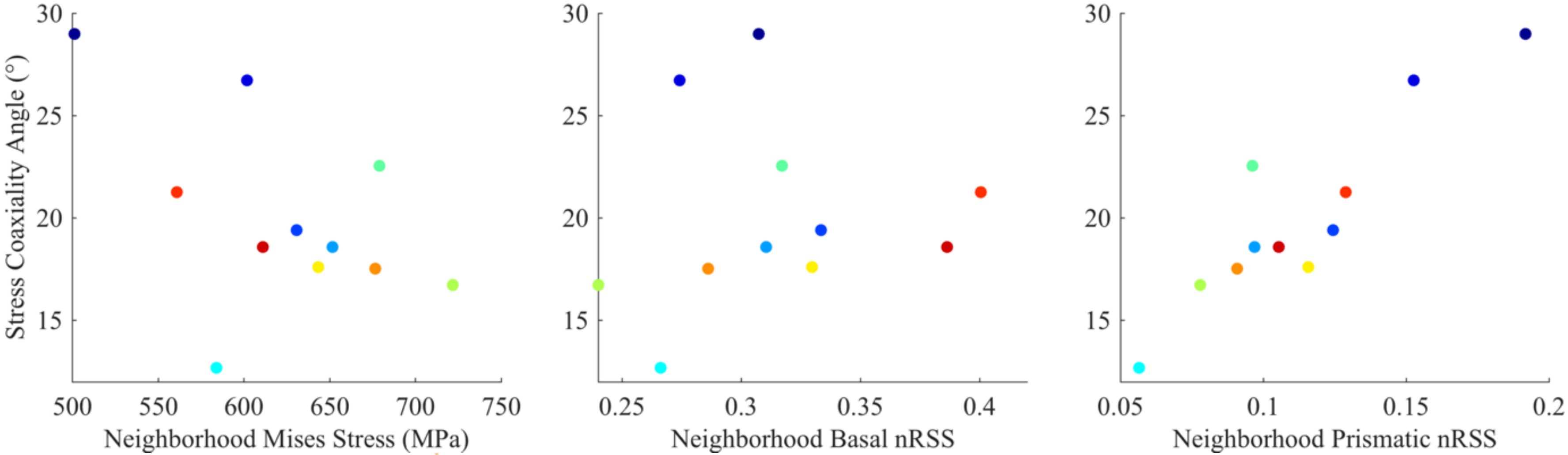
- Mechanics of cyclic evolutions
- Mechanics of load shedding
- **Grain neighborhood effects**

# Neighborhood dependencies of 1:1 soft grains with minimum Mises stress

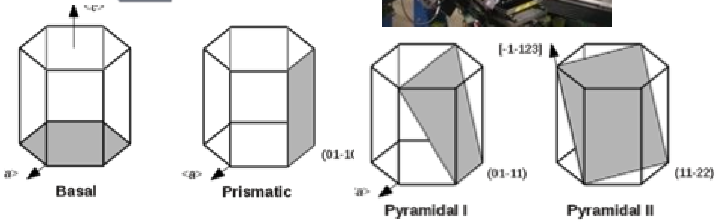
- Selected grains with lowest Mises stress
  - Indicates unconstrained plastic deformation
  - Soft grains in soft neighborhoods
- SCA:
  - Decreases with increasing neighborhood Mises stress
  - Increases with increasing basal nRSS (outliers)
  - Increases with increasing prismatic nRSS
  - Dual slip family activation results in higher SCA than single

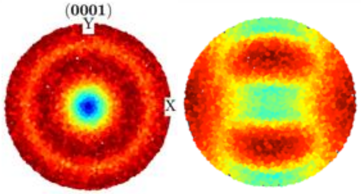


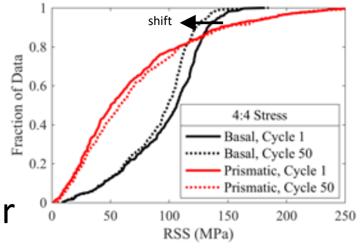


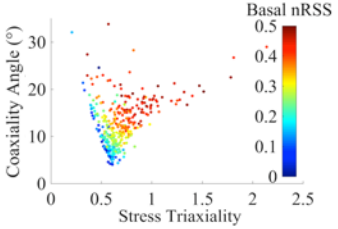
# Summary

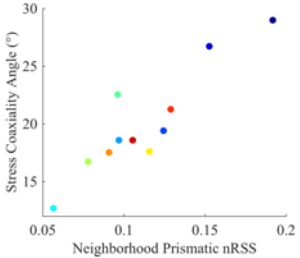
- New experimental platform enables nondestructive multiaxial 3D micromechanical studies
  - Custom planar biaxial load frame & specimen geometry
  - Advanced materials (anisotropy, asymmetry, path dependence)
- Dwell fatigue in Ti-7Al under biaxial tension-tension loads
  - HCP (α) phase is source of dwell fatigue: limited and anisotropic slip systems
  - Improve life management of jet engine turbine compressor discs
  - Defined soft and hard grain orientations (nRSS PFs)
  - Qualitative assessment of lifetime differences between uniaxial and biaxial loading
  - Observed cyclic basal slip system softening
  - Observed mechanics of dwell fatigue (load shedding, stress tensor evolution, grain neighborhood effects)
  - Provided new insight into mechanisms of crack initiation and propagation
  - Hard neighborhoods reduce SCA and increase Mises stress in soft grains (constraint)







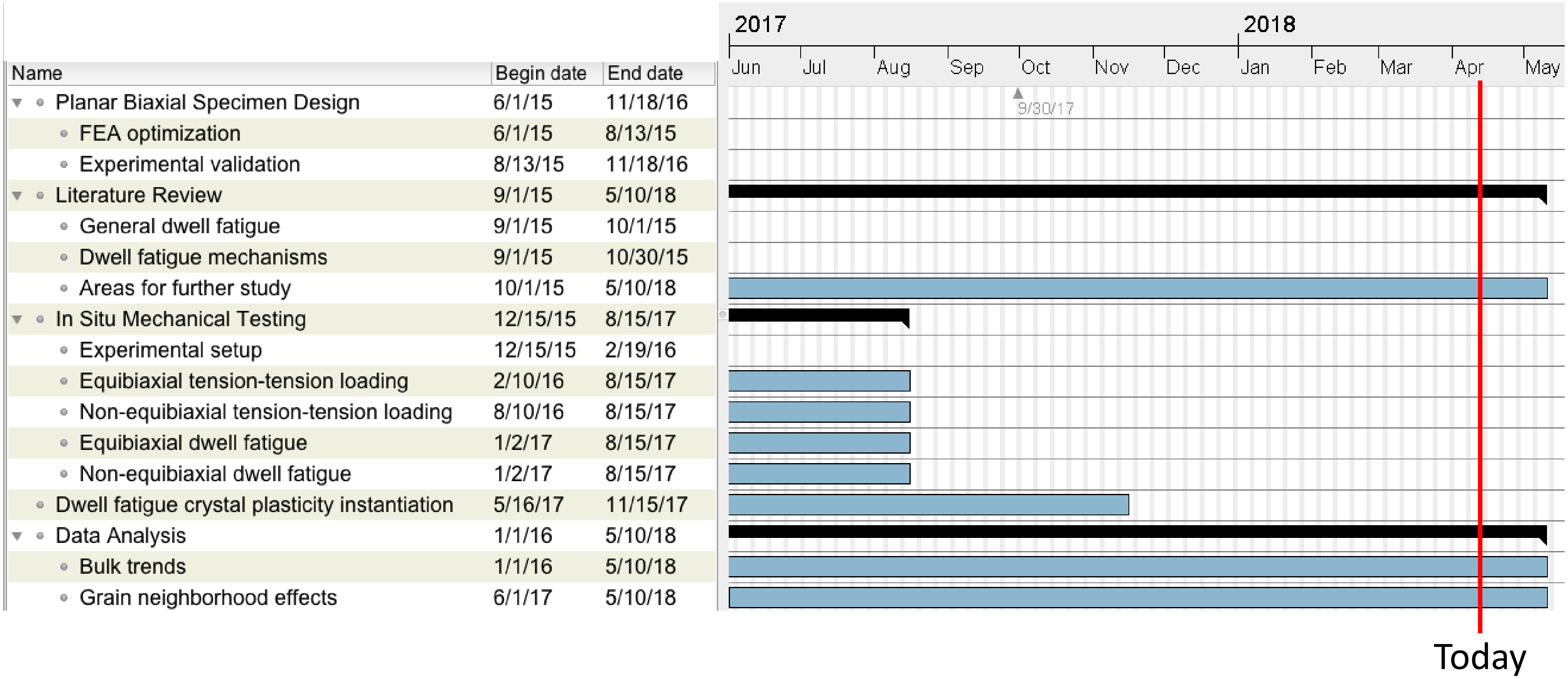




# Future work

- Ti-7Al mechanics publications
- Fractography and microstructural characterization
- Redo experiments with equal cycles between 1:1 and 1:4 stress ratios
- Redo experiments under strain control
- Dwell fatigue lifetime tests
- Design to promote multiaxial stress states in dwell sensitive components
- Incorporate basal softening into models

# Gantt chart



| Name | Begin date | End date |
|---|---|---|
| ▼ Planar Biaxial Specimen Design | 6/1/15 | 11/18/16 |
| FEA optimization | 6/1/15 | 8/13/15 |
| Experimental validation | 8/13/15 | 11/18/16 |
| ▼ Literature Review | 9/1/15 | 5/10/18 |
| General dwell fatigue | 9/1/15 | 10/1/15 |
| Dwell fatigue mechanisms | 9/1/15 | 10/30/15 |
| Areas for further study | 10/1/15 | 5/10/18 |
| ▼ In Situ Mechanical Testing | 12/15/15 | 8/15/17 |
| Experimental setup | 12/15/15 | 2/19/16 |
| Equibiaxial tension-tension loading | 2/10/16 | 8/15/17 |
| Non-equibiaxial tension-tension loading | 8/10/16 | 8/15/17 |
| Equibiaxial dwell fatigue | 1/2/17 | 8/15/17 |
| Non-equibiaxial dwell fatigue | 1/2/17 | 8/15/17 |
| Dwell fatigue crystal plasticity instantiation | 5/16/17 | 11/15/17 |
| ▼ Data Analysis | 1/1/16 | 5/10/18 |
| Bulk trends | 1/1/16 | 5/10/18 |
| Grain neighborhood effects | 6/1/17 | 5/10/18 |

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# Acknowledgements

- Advisors and committee
  - Aaron Stebner, Adam Pilchak, Branden Kappes, John Berger, Peter Collins, Michael Kaufman
- Fellow research group members
  - Ashley Bucsek, Harshad Paranjape, Jinesh Dahal, Zach Brunson, Nathan Johnson, Bryan Marsh, Luis Ham Villa, Andrew Peterson
- Argonne National Lab – Advanced Photon Source (APS) 1-ID Beam Line
  - Jonathan Almer, Peter Kenesei, Ali Mashayekhi, Jun-Sang Park
- MTS Systems Corporation
  - Steve Lemmer, Justin Vignes

## Thank You

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- Center of Advanced Non-Ferrous Structural Alloys (CANFSA)
- National Science Foundation – Civil, Mechanical and Manufacturing Innovation (NSF-CMMI) Award # 1454668

# References, Acknowledgements, and Contact

[1] Véronique Doquet, Vincent De Greef, *Dwell-fatigue of a titanium alloy at room temperature under uniaxial or biaxial tension (2011)*

[2] Zhen Zhang, M.A. Cuddihy, F.P.E. Dunne, *On rate-dependent polycrystal deformation: the temperature sensitivity of cold dwell fatigue (2015)*

[3] J.C. Williams, R.G. Baggerly, N.E. Paton, *Deformation Behavior of HCP Ti-Al Alloy Single Crystals (2002)*

[4]V. Doquet and V. De Greef, “Dwell-fatigue of a titanium alloy at room temperature under uniaxial or biaxial tension,” *Int. J. Fatigue*, vol. 38, pp. 118–129, May 2012.

[5] Bernier, J. V., N. R. Barton, U. Lienert, and M. P. Miller. (2011). *J of Strain Analysis for Engg Design*

[6] Sharma, Hemant, Richard M. Huizenga, Aleksei Bytchkov, Jilt Sietsma, and S. Erik Offerman. (2012). *Acta Mat*

- CANFSA
- NSF-CMMI Award # 1454668
  - Experiment and specimen design
- AFRL
  - Material studies
- Advanced Photon Source (APS) 1-ID Beam Line
  - *In* situ experiments

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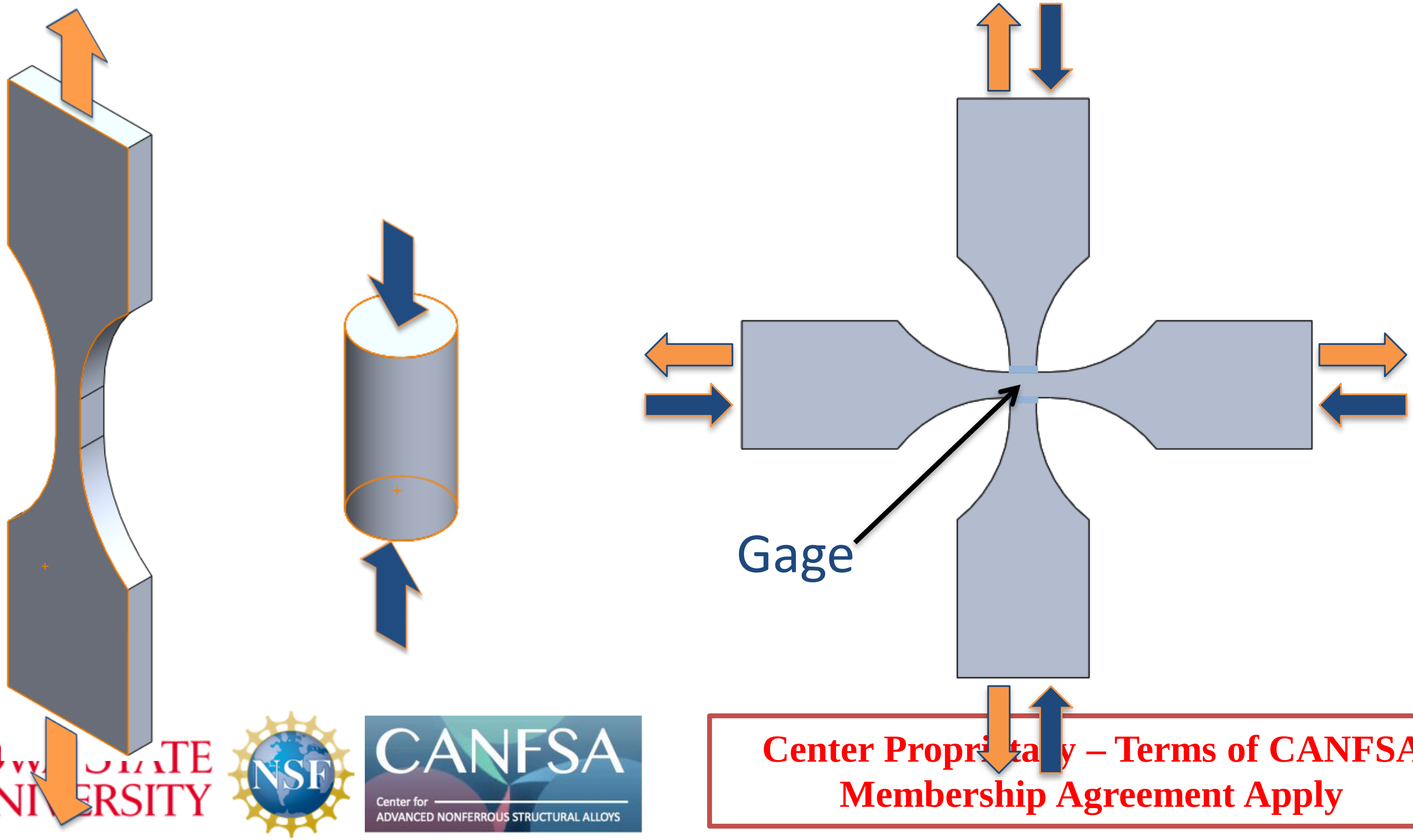
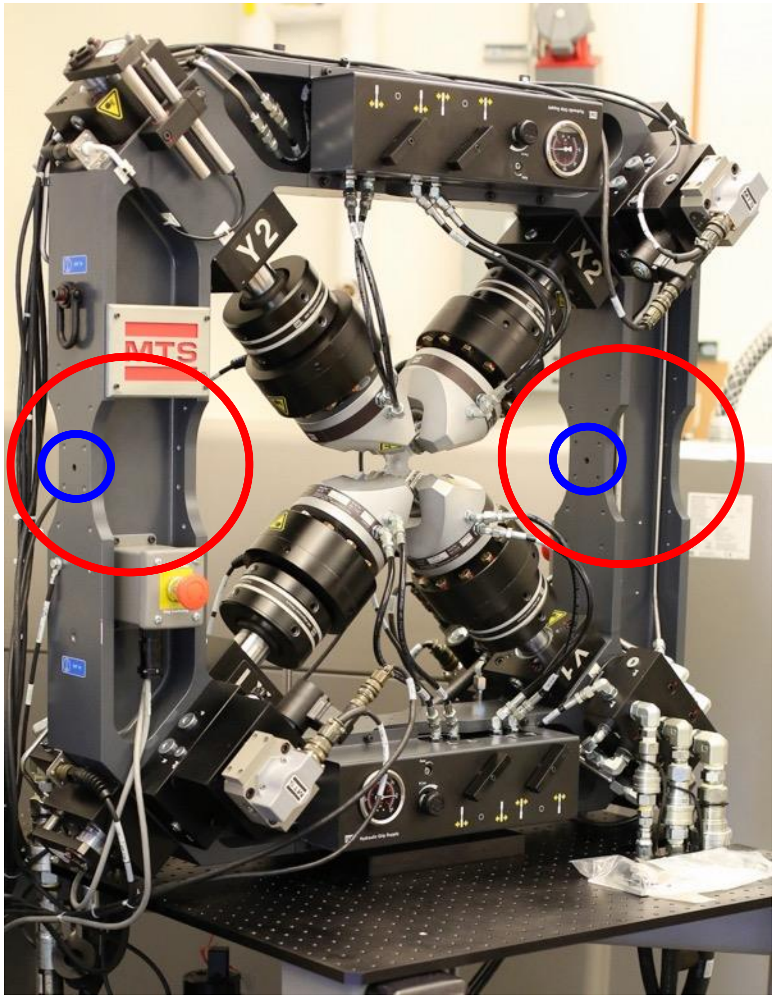
# Planar biaxial loading using cruciform geometry

- Logical extension of uniaxial tension/compression

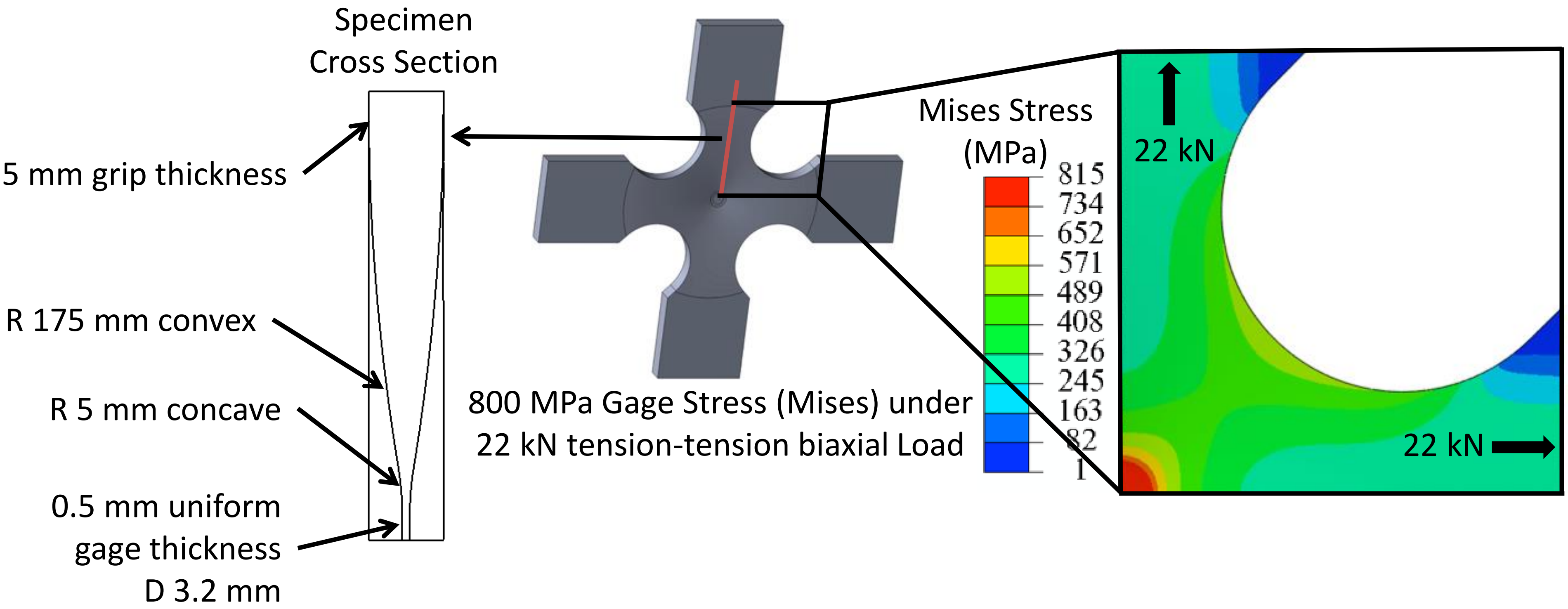


# Custom planar biaxial load frame attributes

- Diffraction
  - Compact (~ 3 x 3 x 0.5 ft, ~500 lbs)
  - Transportable
  - Sample center deviation < 5 µm at maximum load (25 kN per axis)
  - 320° rotation without beam obstruction (260° data with 15° diffraction cone
  - Beam Alignment
- Mechanical
  - 4 Independent hydraulic actuators
  - All ratios of tension/compression
  - 4 alignment fixtures
  - Aligned  for < 30 µε (0.003 %) bending under load



# Specimen geometry: tension, compression and diffraction capable



Specimen
Cross Section

5 mm grip thickness

R 175 mm convex

R 5 mm concave

0.5 mm uniform
gage thickness
D 3.2 mm

800 MPa Gage Stress (Mises) under
22 kN tension-tension biaxial Load

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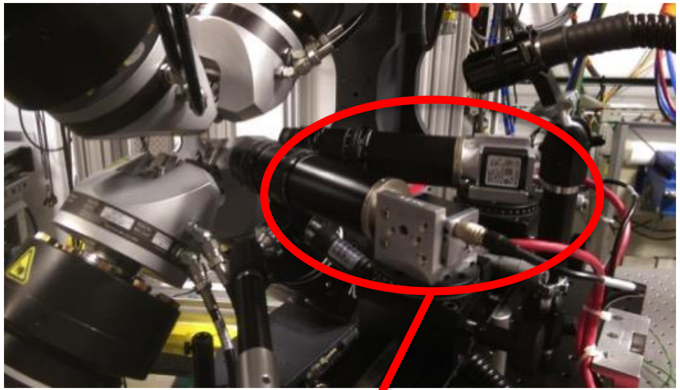
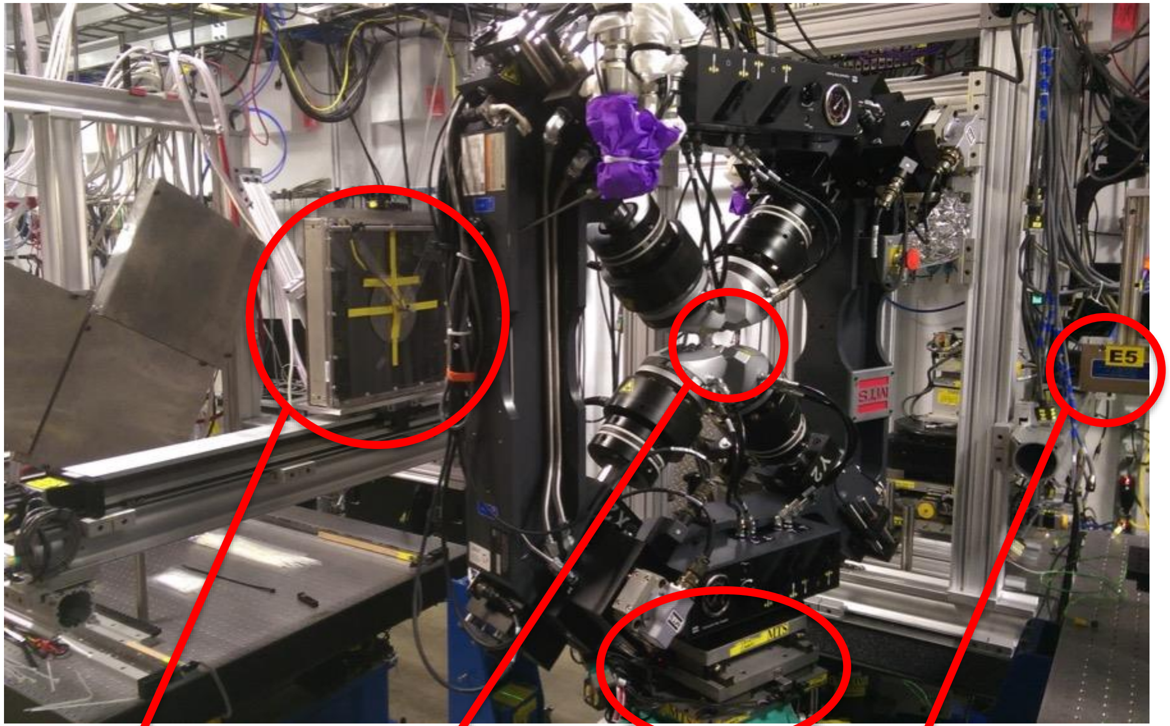
# Experimental setup at the Advanced Photon Source, 1-ID-E beamline



Digital image correlation (DIC)



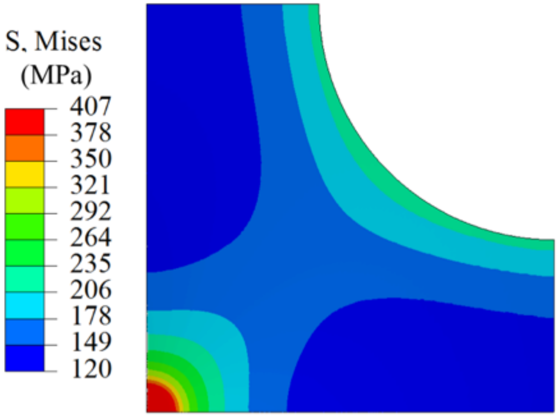
Detector

Specimen

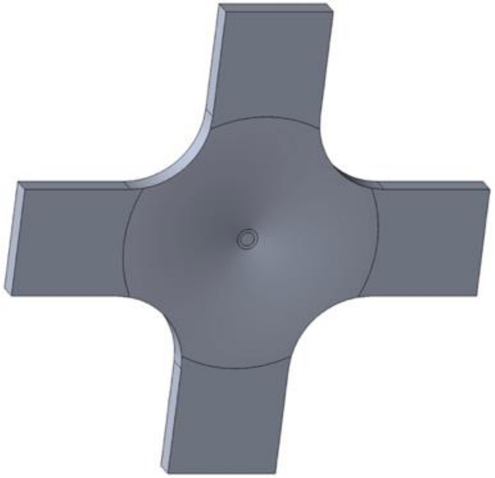
Beam

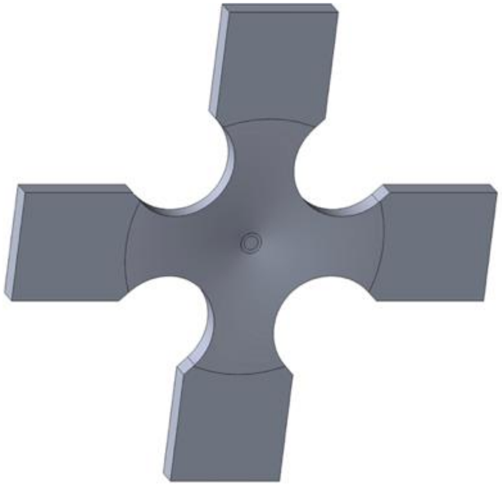
Translation & rotation stages

# Specimen geometry: variable maximum gage stress

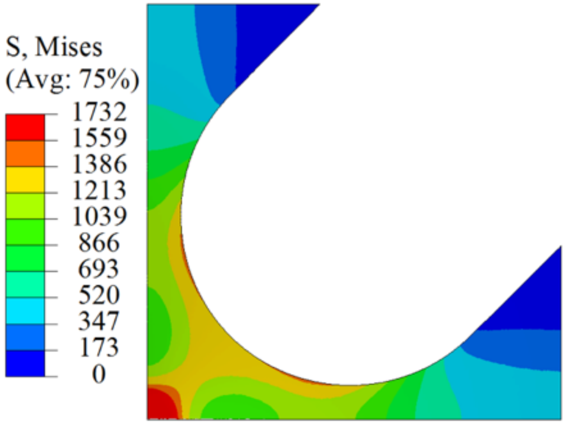


400 MPa 1:1 at 22 kN Load

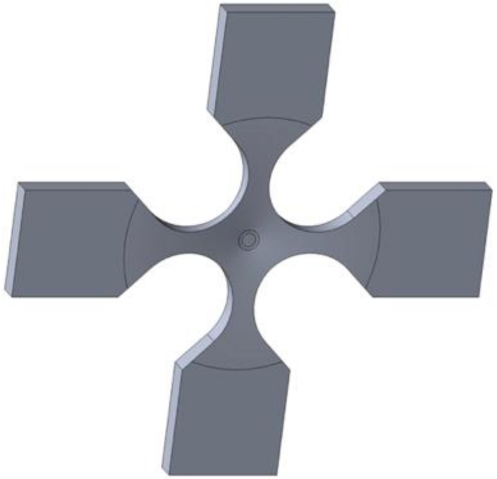




800 MPa Gage Stress (Mises) at 22 kN Load



1700 MPa 1:1 at 22 kN Load



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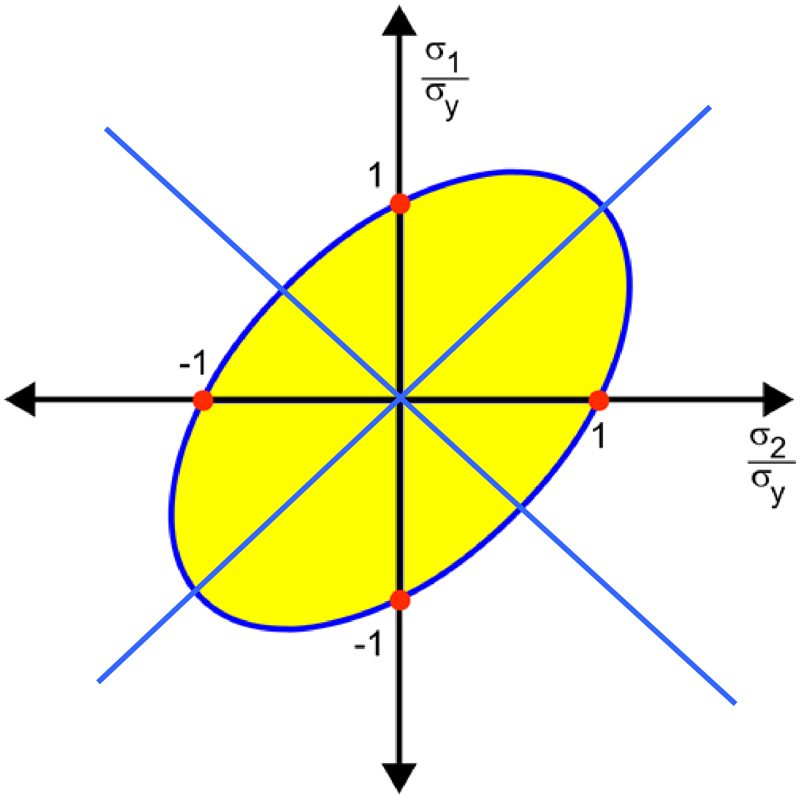
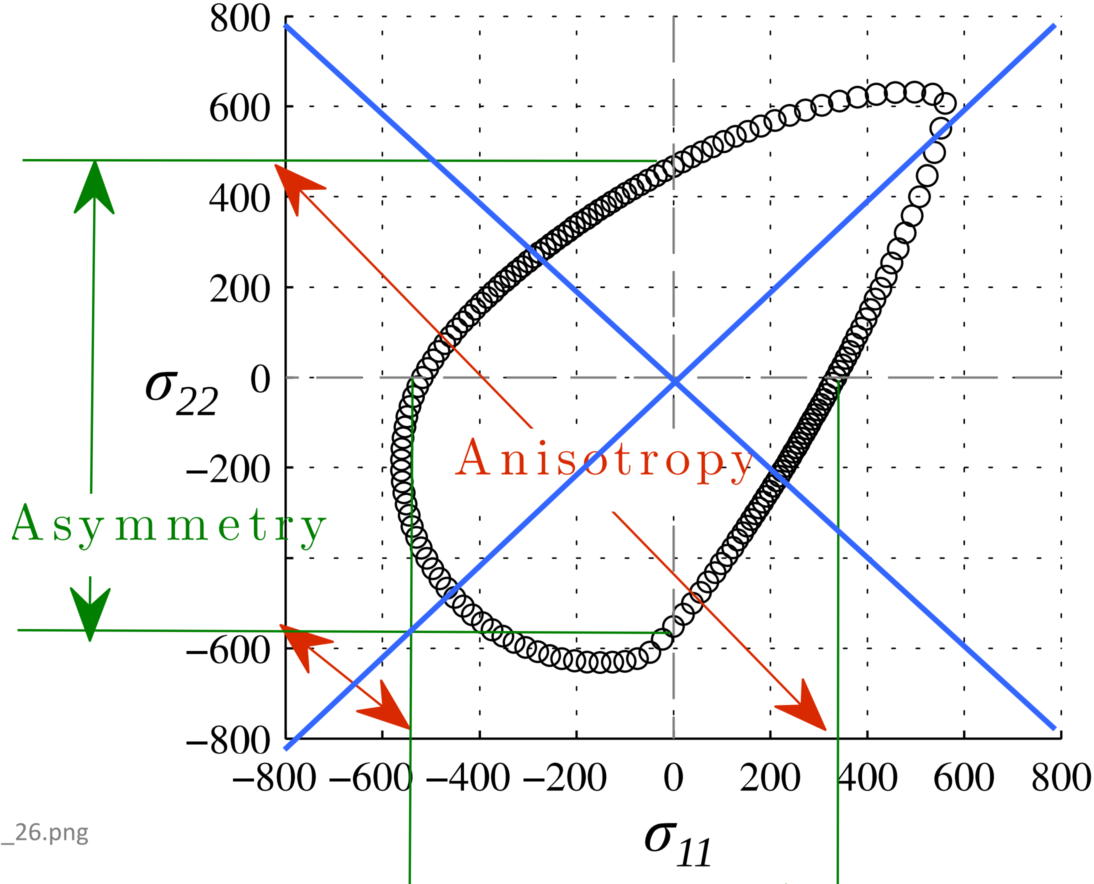
# Planar biaxial can elucidate anisotropy and asymmetry of complete yield locus



http://personal.strath.ac.uk/j.wood/CCOPPS_DBA/resources/figures/N_fig_26.png



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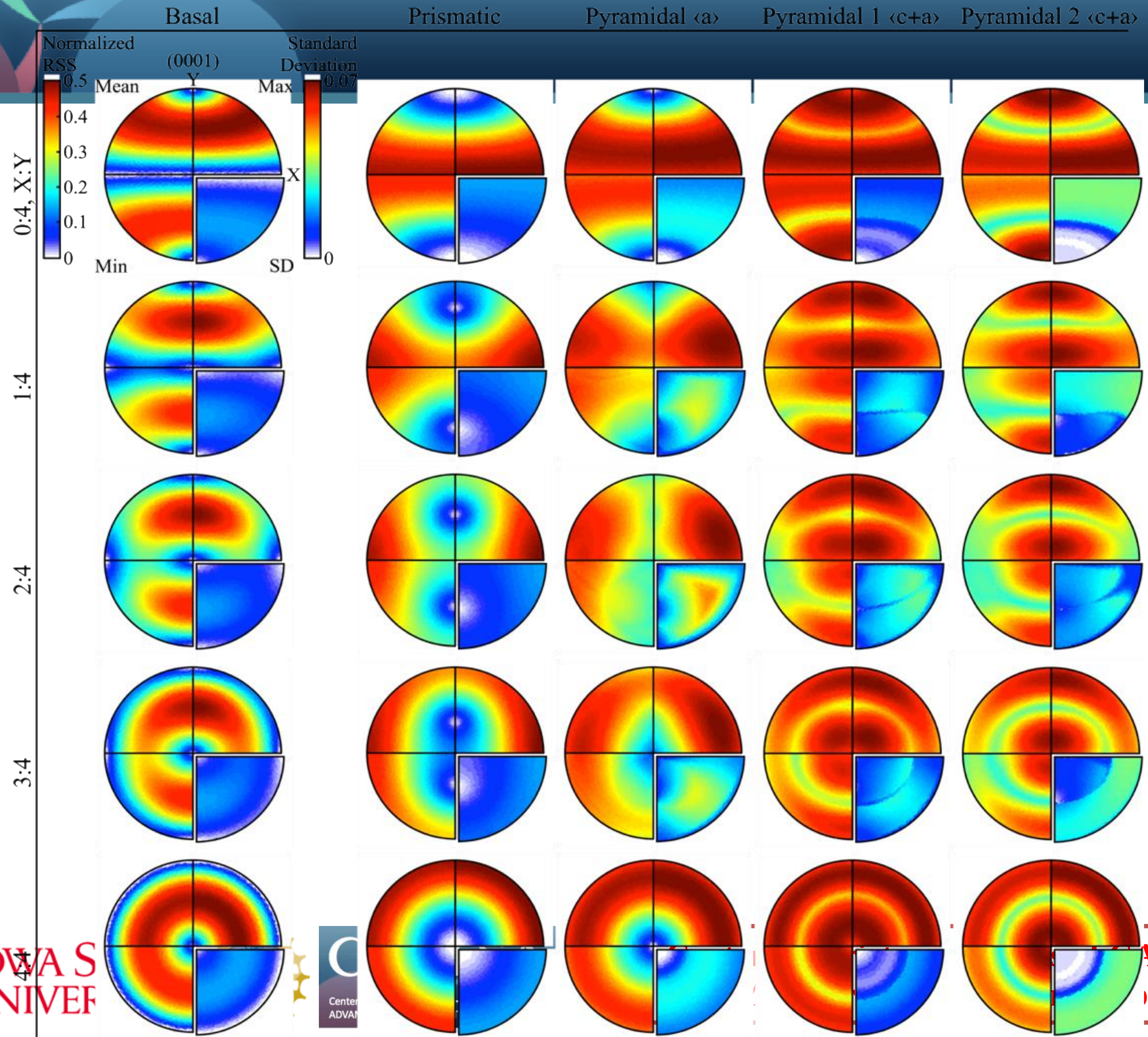
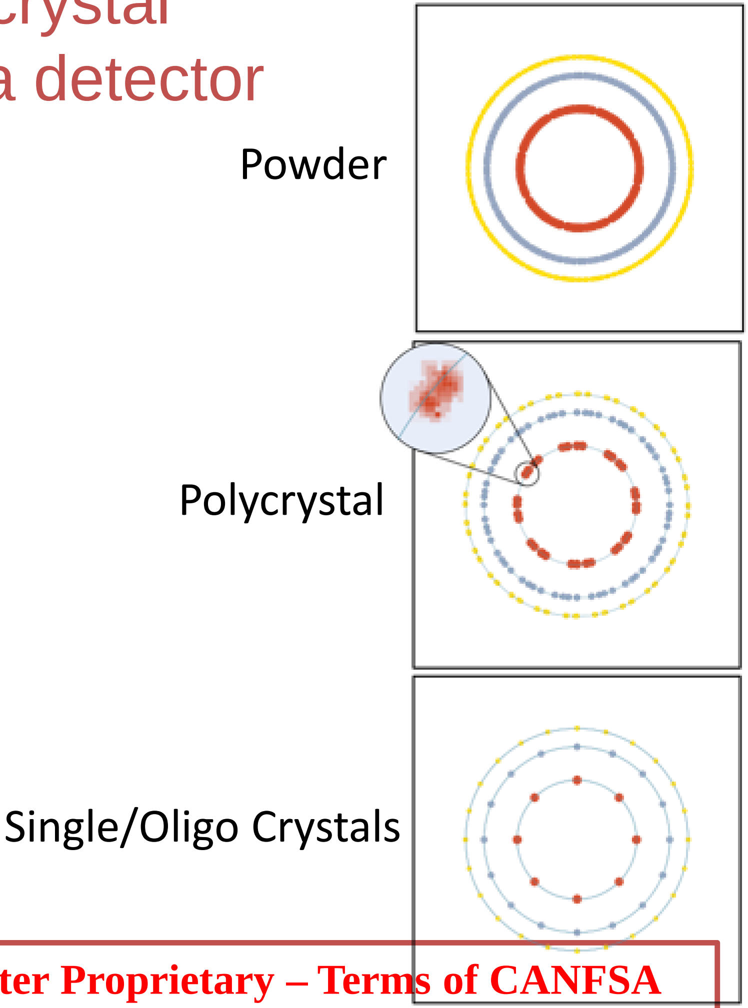
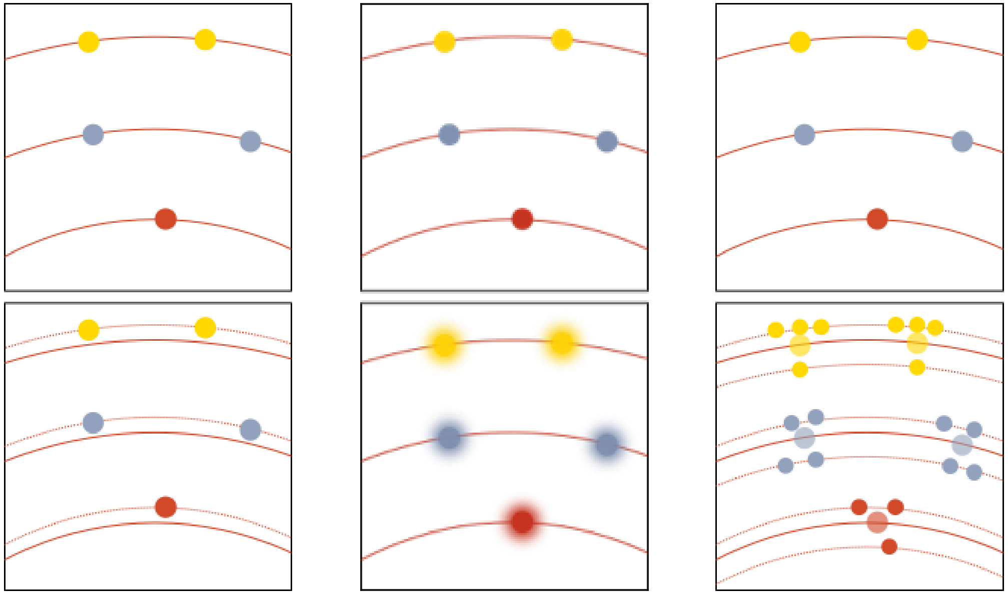

Basal
Prismatic
Pyramidal ‹a›
Pyramidal 1 ‹c+a›
Pyramidal 2 ‹c+a›
Normalized RSS
0.5
0.4
0.3
0.2
0.1
0
(0001)
Y
X
Mean
Max
Min
SD
Standard Deviation
0.07
0
0:4, X:Y
1:4
2:4
3:4
4:4

ANFSA
ly

# Microstructural effects on diffraction patterns

- Diffracted beam from individual polycrystal grains produces spot pattern on area detector





Elasticity

Slip

Phase Trans.

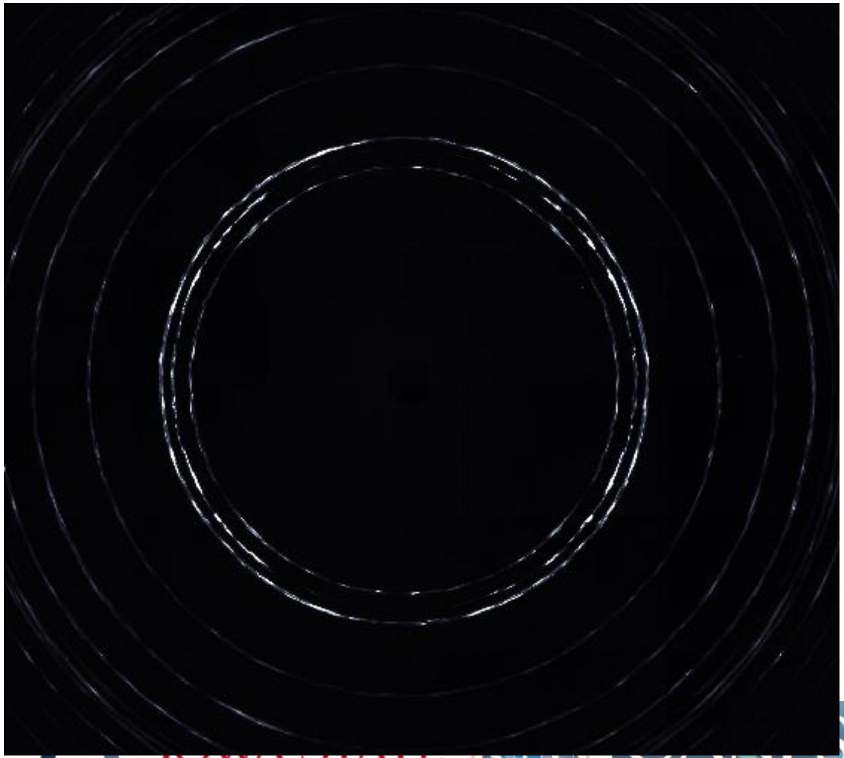
# Bimodal grain size distribution

Powder = small grains

Spots = large grains

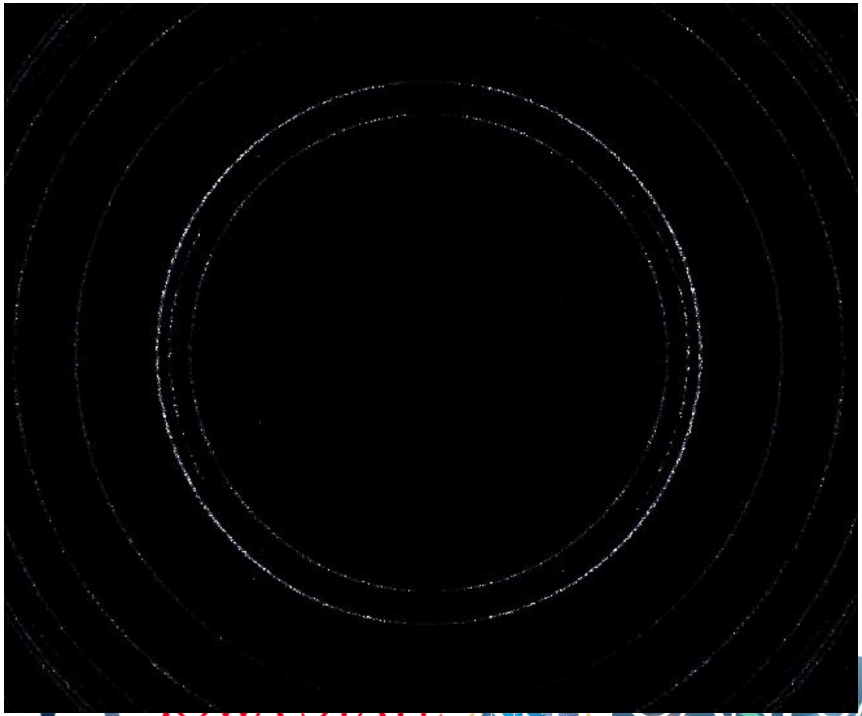
# Ti-7Al diffraction rings: high plastic

- *Highly smeared spots*

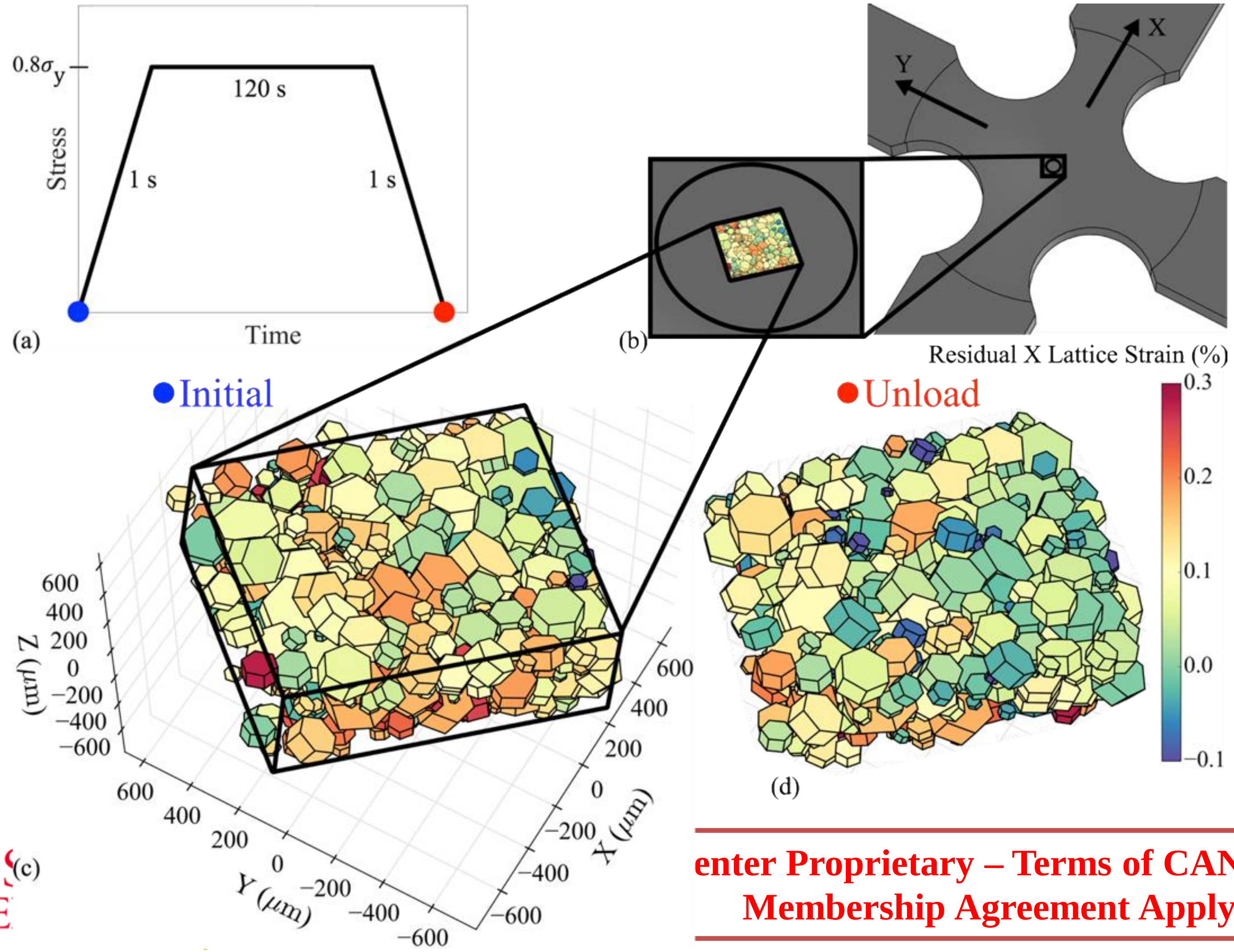


# Ti-7Al diffraction rings: low plastic

- *Distinct spots*
  - *“large” grains (~100 μm)*
- *No smearing*
  - *No plastic deformation*

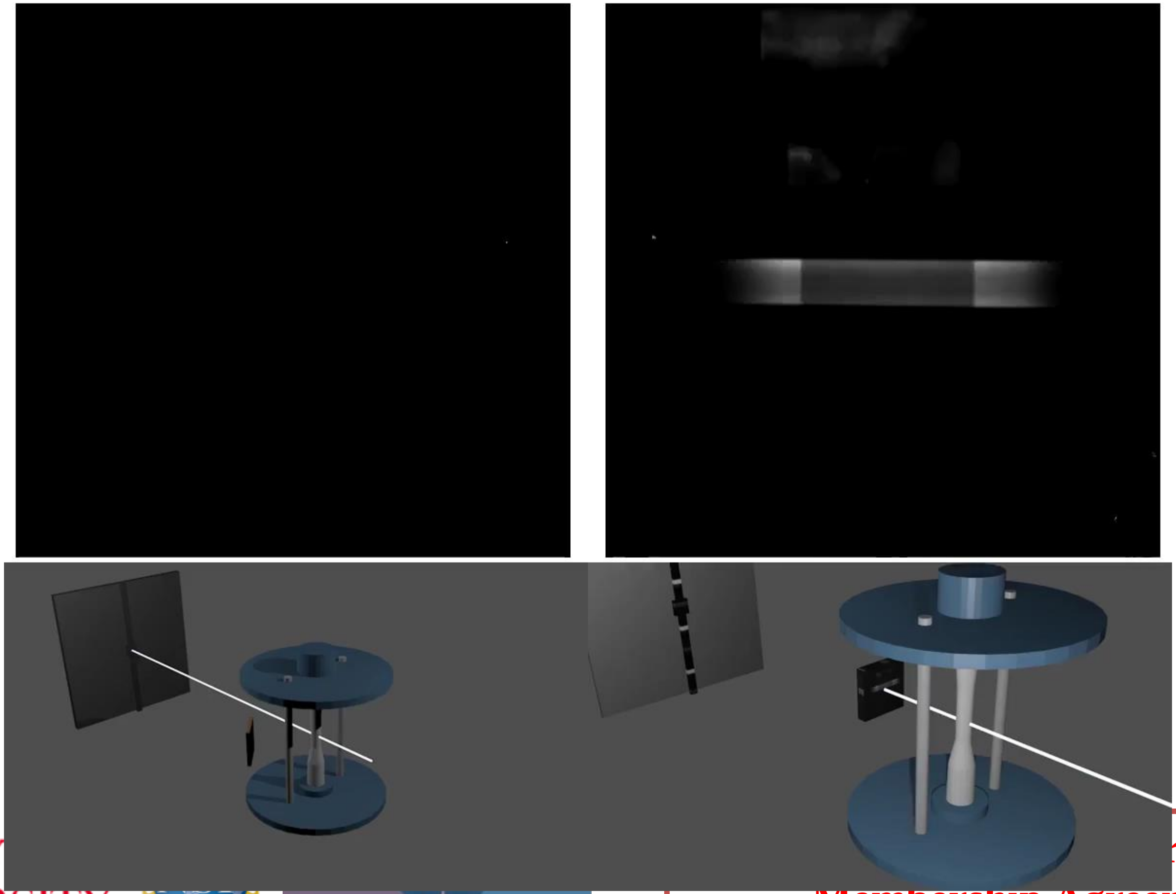


# Beam, specimen and grain



# Far-field vs. near-field HEDM

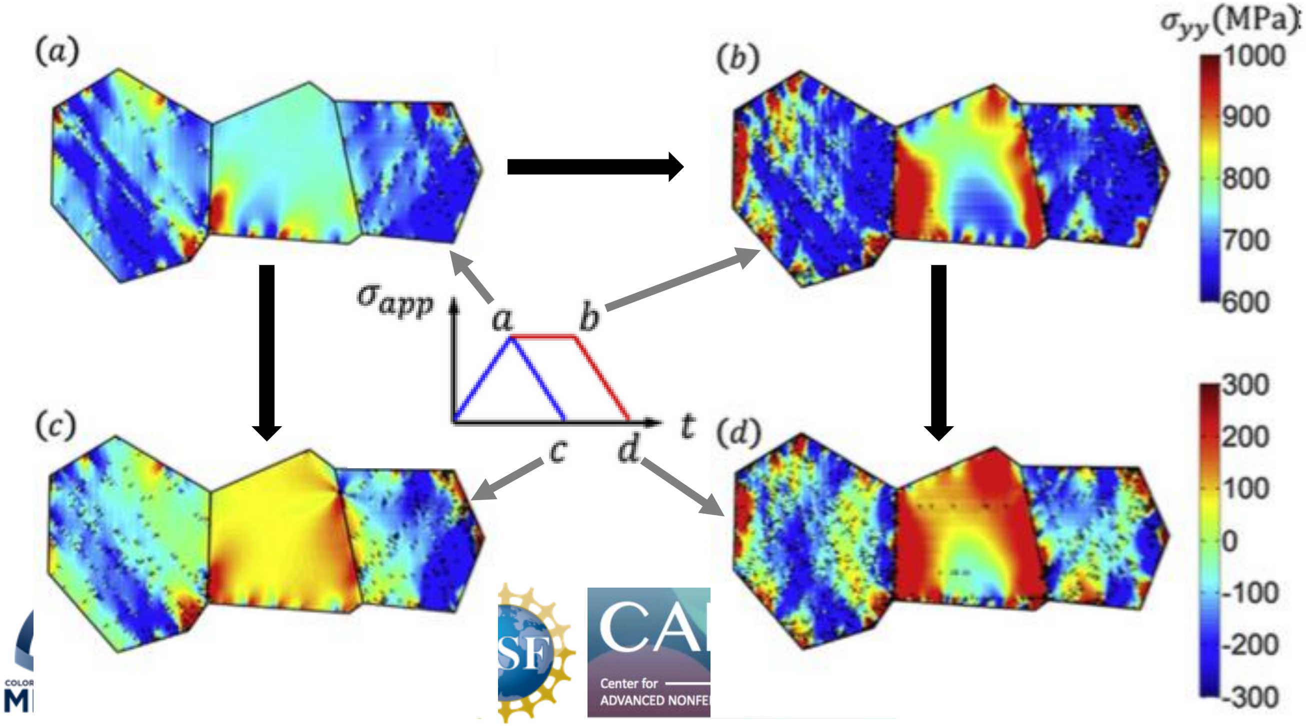
- Far-field: grain strain and orientation
- Near-field: grain morphology

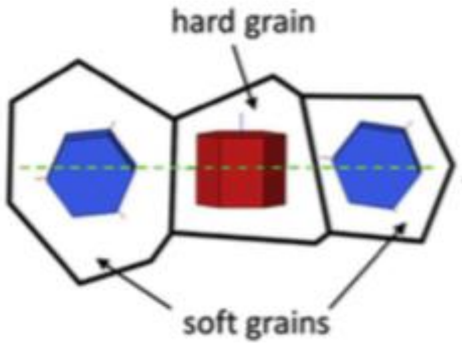


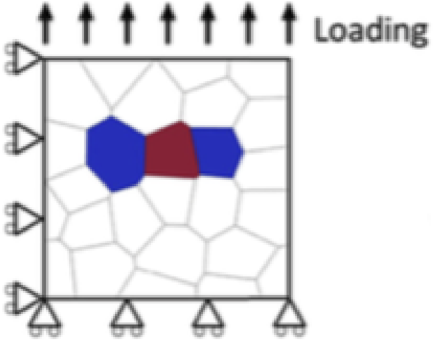
Video courtesy of Dr. Harshad Paranjape

# Model shows soft grain strain relaxation under uniaxial

- ➢ *Z. Zheng et al., International Journal of Plasticity (2016)*
- ➢ Soft grains show residual compressive stresses
- ➢ Hard grains show residual tensile stresses





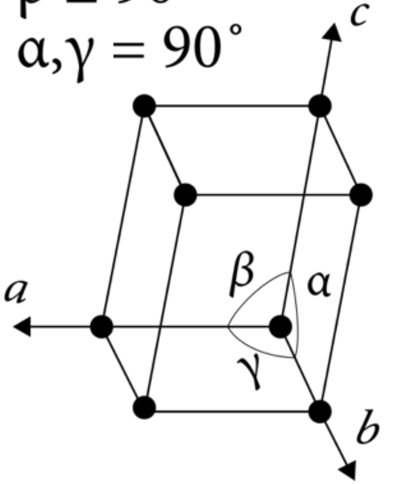


# Origins of anisotropy and asymmetry

- Texture
- Grain shape
- Low symmetry crystal lattices
- Several deformation mechanisms
  - Slip, twinning, phase transformation
  - Asymmetry and anisotropy
  - Path dependence

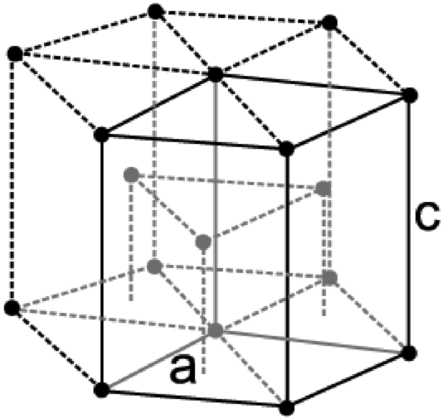
NiTi alloys:
some with monoclinic phase

$\beta \geq 90^\circ$
$\alpha,\gamma = 90^\circ$



http://upload.wikimedia.org/wikipedia/commons/thumb/6/67/Monoclinic_cell.svg/438px-Monoclinic_cell.svg.png

Mg and Ti alloys:
hexagonal close packed (HCP)

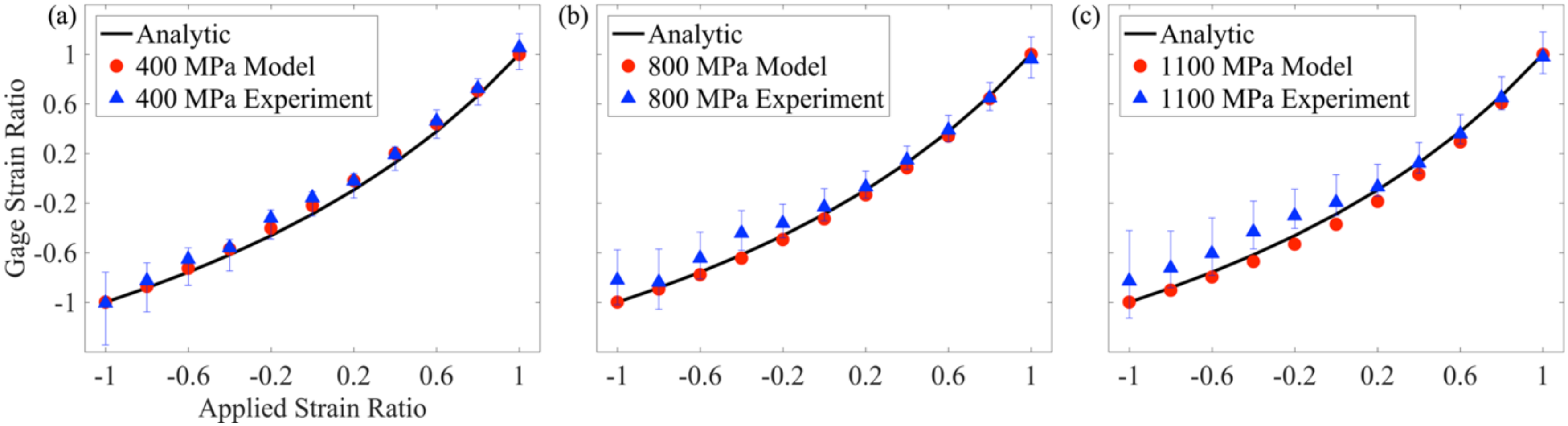


http://lamp.tu-graz.ac.at/~hadley/ss1/problems/kittel1.3/hcp.gif

# HEDM constraints, requirements and limitations

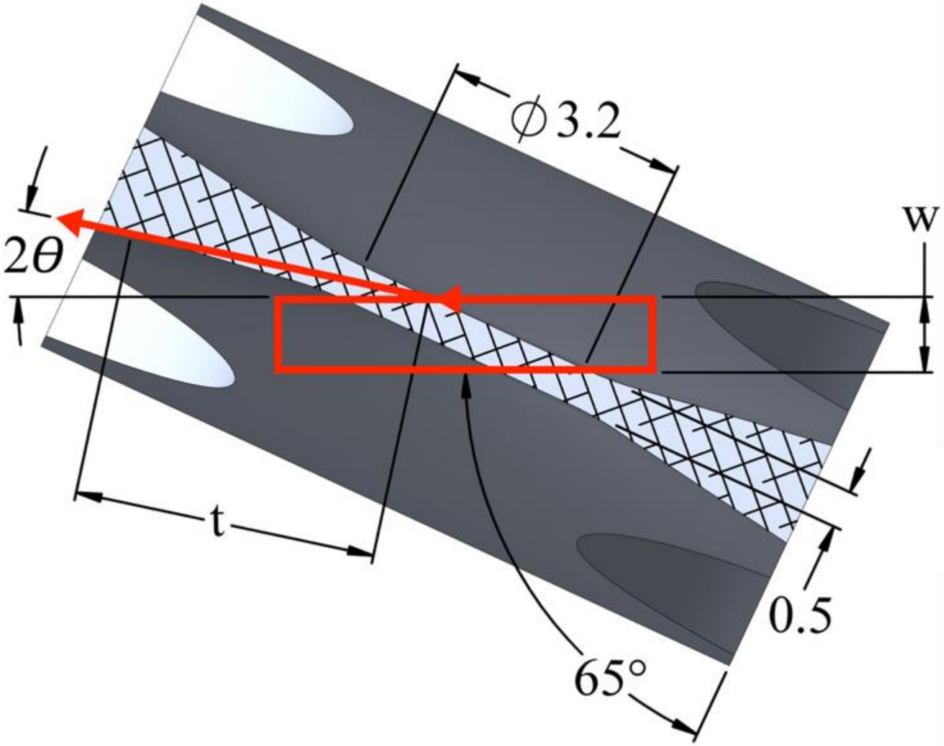
- Load frame
  - Rotation/translation stage weight limit: 600 lbs.
  - Maximize angular range of 2D data sets: 360°
  - Align specimen center with rotation axis
    - Maintain same grains in beam
    - Maintain sample-to-detector distance
- Specimen
  - Maximum penetration depth: 2 – 4 mm
  - No diffracted beam interference
- Material
  - Minimum grain size: ~25 µm
  - Maximum grains in beam: 1000's
  - Grain size uniformity
  - Not heavily deformed

- asdf

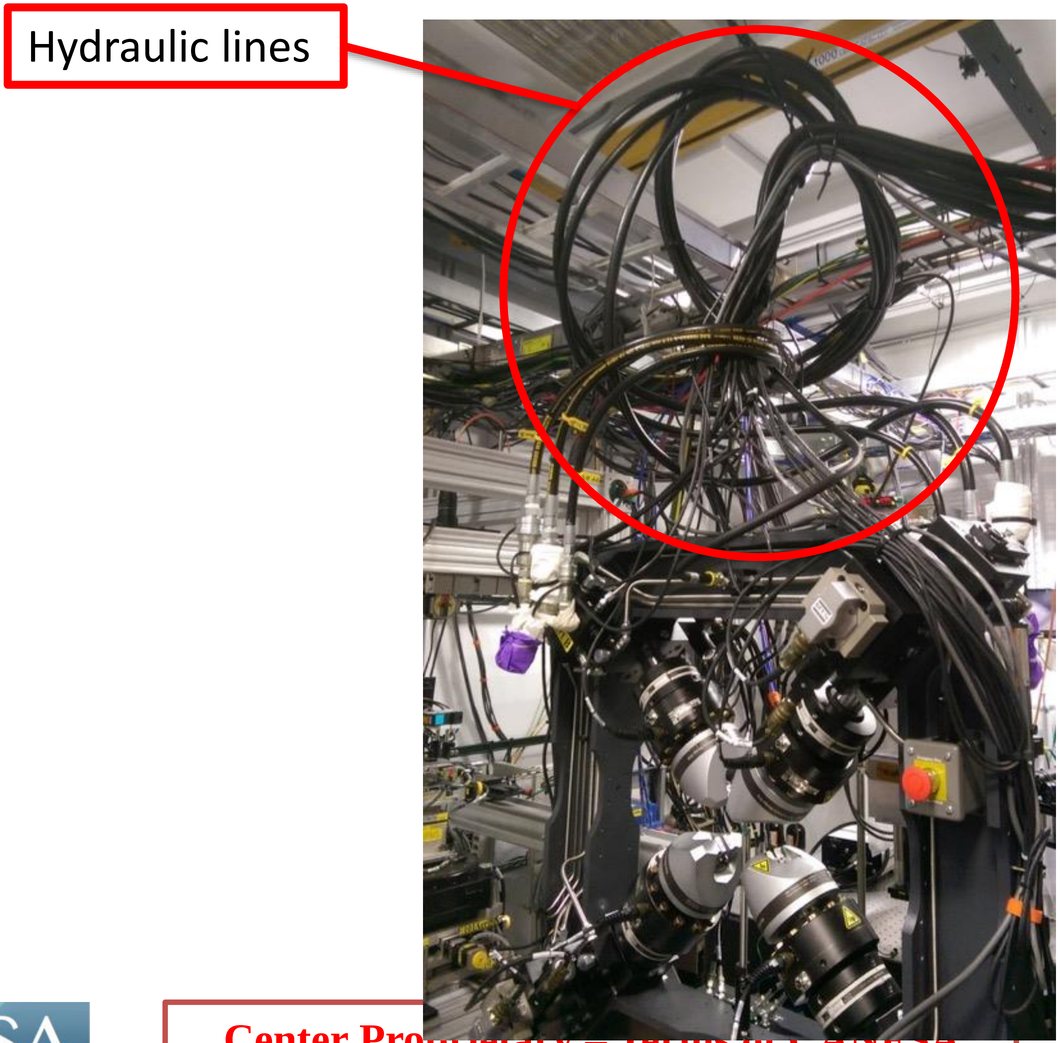

(a)
Analytic
400 MPa Model
400 MPa Experiment
(b)
Analytic
800 MPa Model
800 MPa Experiment
(c)
Analytic
1100 MPa Model
1100 MPa Experiment
Gage Strain Ratio
1
0.6
0.2
-0.2
-0.6
-1
-1
-0.6
-0.2
0.2
0.6
1
Applied Strain Ratio

# Specimen geometry: diffraction capabilities

- Measurable diffraction angle ($2\boldsymbol{\theta}$) function of
  - Beam width (w)
  - Material penetration capability (t)



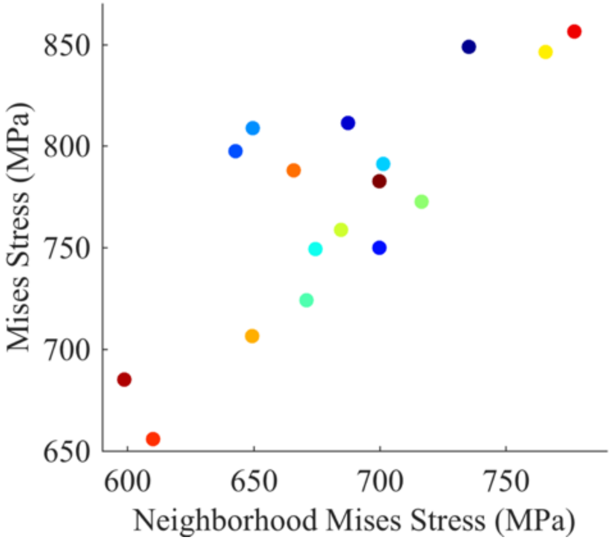
# Experimental setup at the APS

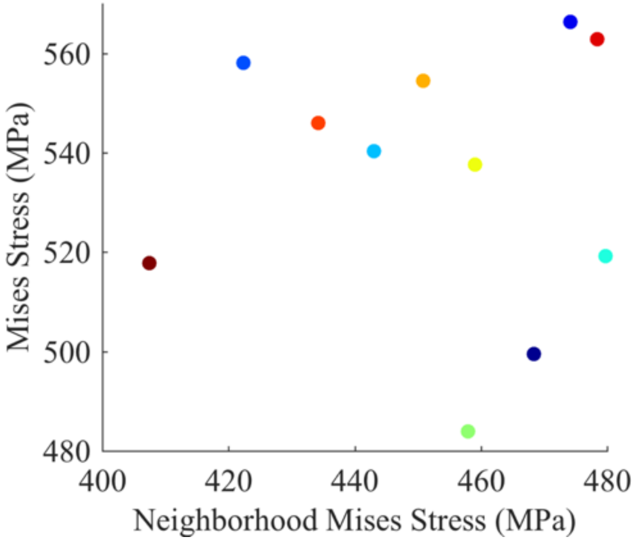


# Neighborhood dependencies of hard orientations with minimum SCA

- Selected grains with low basal nRSS and SCA
  - Low SCA indicates not receiving load
  - Hard grains in hard neighborhoods
- 1:1 Mises stress increases with increasing neighborhood
- 1:4 trend weak, no distinctly hard grains

1:1



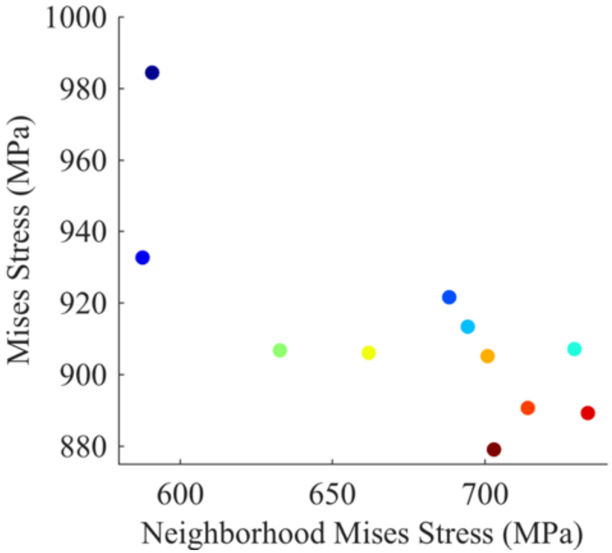


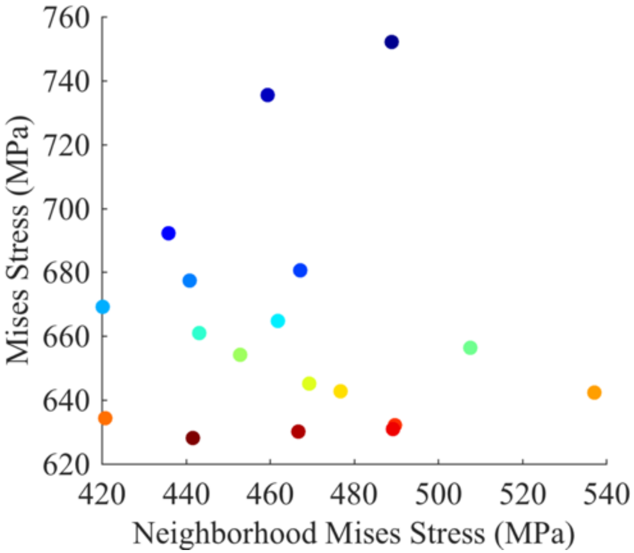
1:4

# Neighborhood dependencies of hard grains with maximum Mises stress

- Selected grains with highest Mises stress
  - Indicates receiving load
  - Hard grains in soft neighborhoods
- 1:1 Mises stress decreases with increasing neighborhood
  - Softer neighborhoods shed more load

1:1





1:4

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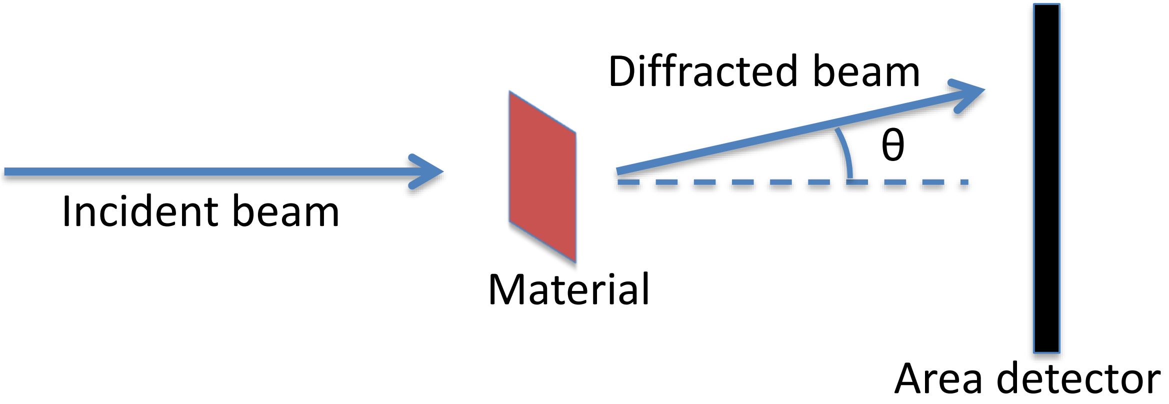
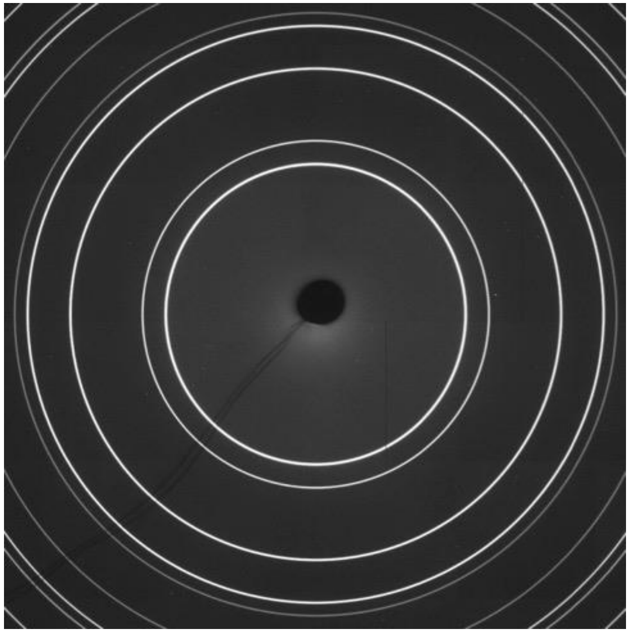
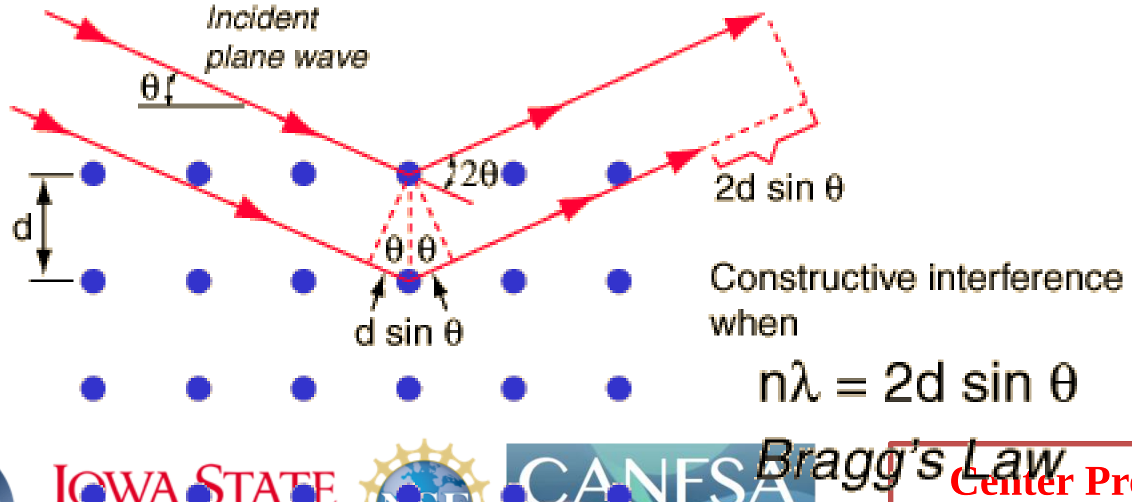
# Diffraction: Bragg's Law

- Probe atomic scale with particle beam



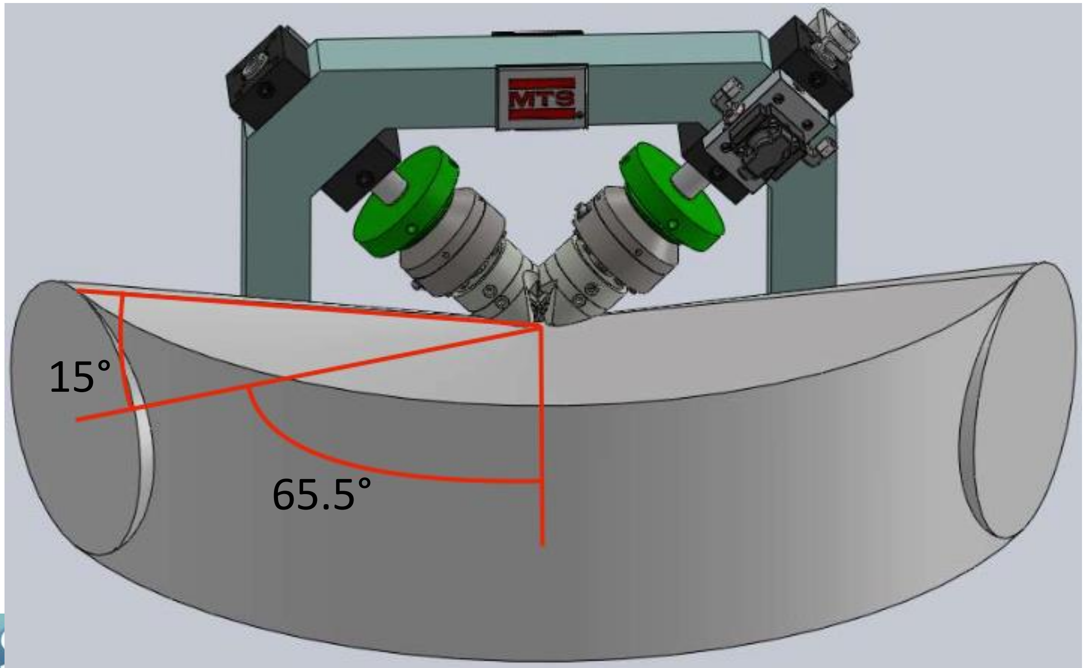




http://hyperphysics.phy-astr.gsu.edu/hbase/quantum/imgqua/bragglaw.gif

# Load frame diffraction capabilities

- 322° total rotation without load frame interference with incident beam
- Minimum 15° diffraction cone for 3D reconstruction techniques
  - 50 – 70 keV X-ray source
- 262° of sample rotation



Membership Agreement Apply