Metallic Glasses: Experimental Challenges and Opportunities

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Mechanical Engineering & Chemical Engineering, Bucknell University

Kavli Institute of Theoretical Physics

October 14, 2014

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Some Recent Collaborators

Prof. Karin Dahmen, James Antonaglia

ILLINOIS

Prof. Todd Hufnagel, Stephanie Slaughter

JOHNS HOPKINS
WHITING SCHOOL
of ENGINEERING

Xiaojun Gu, Rachel Byer, Bucknell

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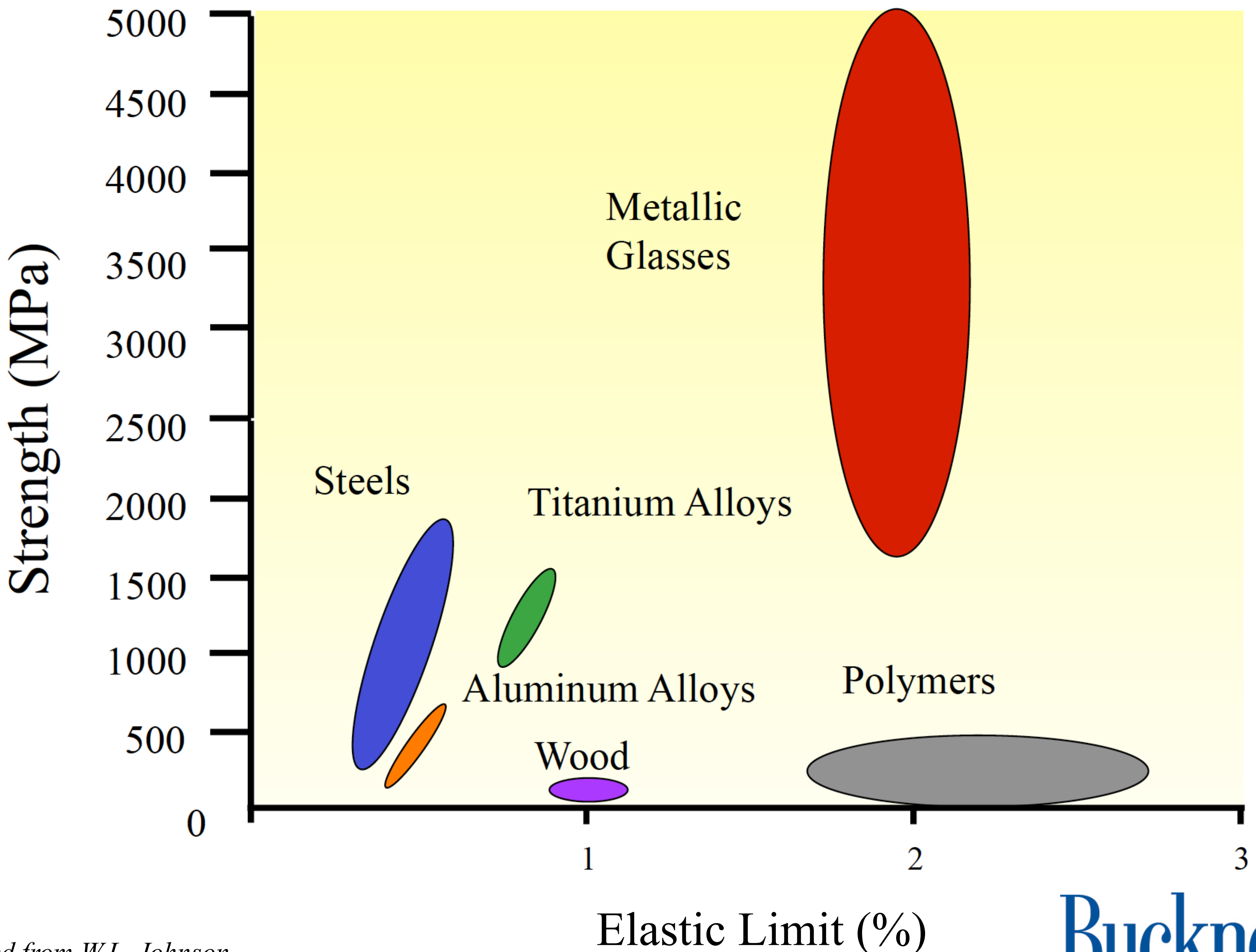

Adapted from W.L. Johnson

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Engineering Advantages

- Near–net–shape casting
- 40 nm as–cast surface finish, superior to CNC machined parts
- Can be injection molded
- Surgical tools, optical mirrors, miniature clamps, sports equipment, projectiles, electronic casings

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9:41 AM
Popular Near Me
fotopedia
Fotopedia Paris
Travel
(601)
Musée du Louvre
Education
(49)
PAR
Paris Travel Guide
Lonely Planet
Travel
(1,360)
RICK STEVES
AUDIO
EUROPE
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Wish List
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SketchBook Mobile
Entertainment
(4,827)
Day One
(Journal / Diary)
Lifestyle
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BADLAND
Games
(58)
Monkey Boxing
Games
(147)
Temple Run: Oz
Games
(2,051)
Draw Something 2™
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New & Noteworthy
See All
Couch-to-5K
Health & F...
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Etsy
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BADLAND
GeoDash
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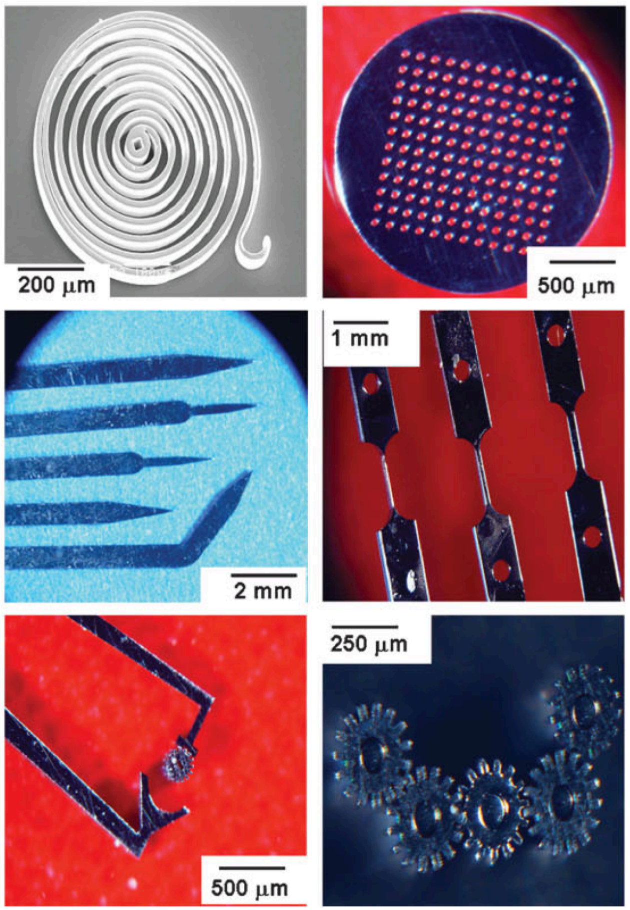
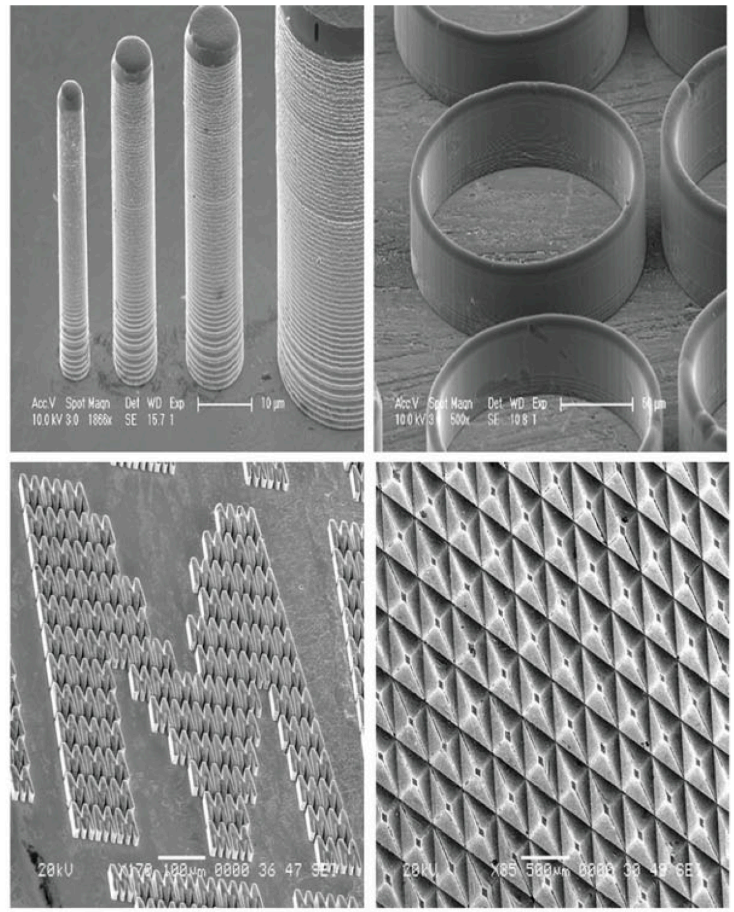
Top Charts
Near Me

Thermoplastic Molding & Hot Embossing





J. Schroers, *Advanced Materials*, 2009

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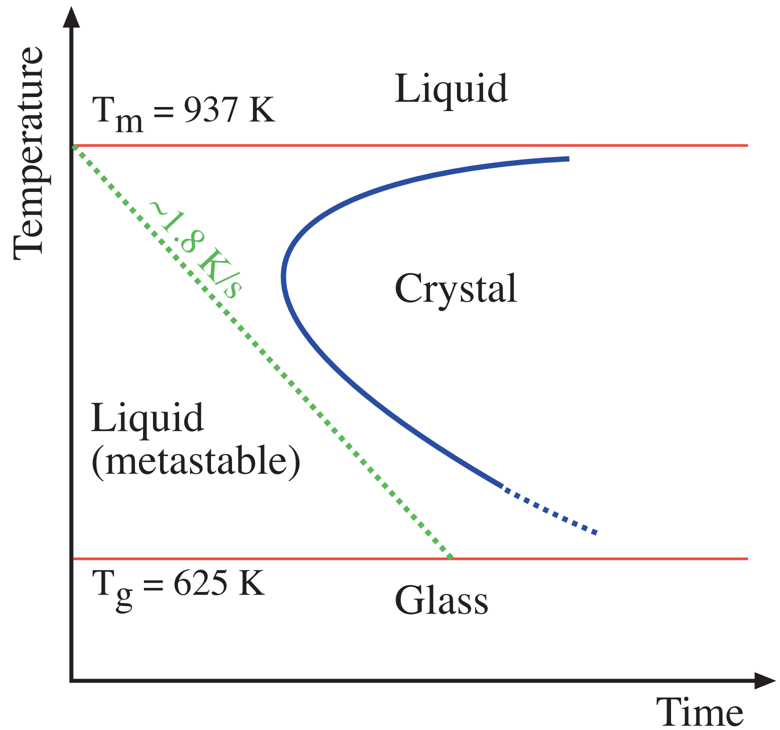
Processing

- Multi–component alloys
- Large atomic radii differences
- Large T_g/T_m
- Strong liquids



$Zr_{41.2}Ti_{13.8}Cu_{12.5}Ni_{10}Be_{22.5}$

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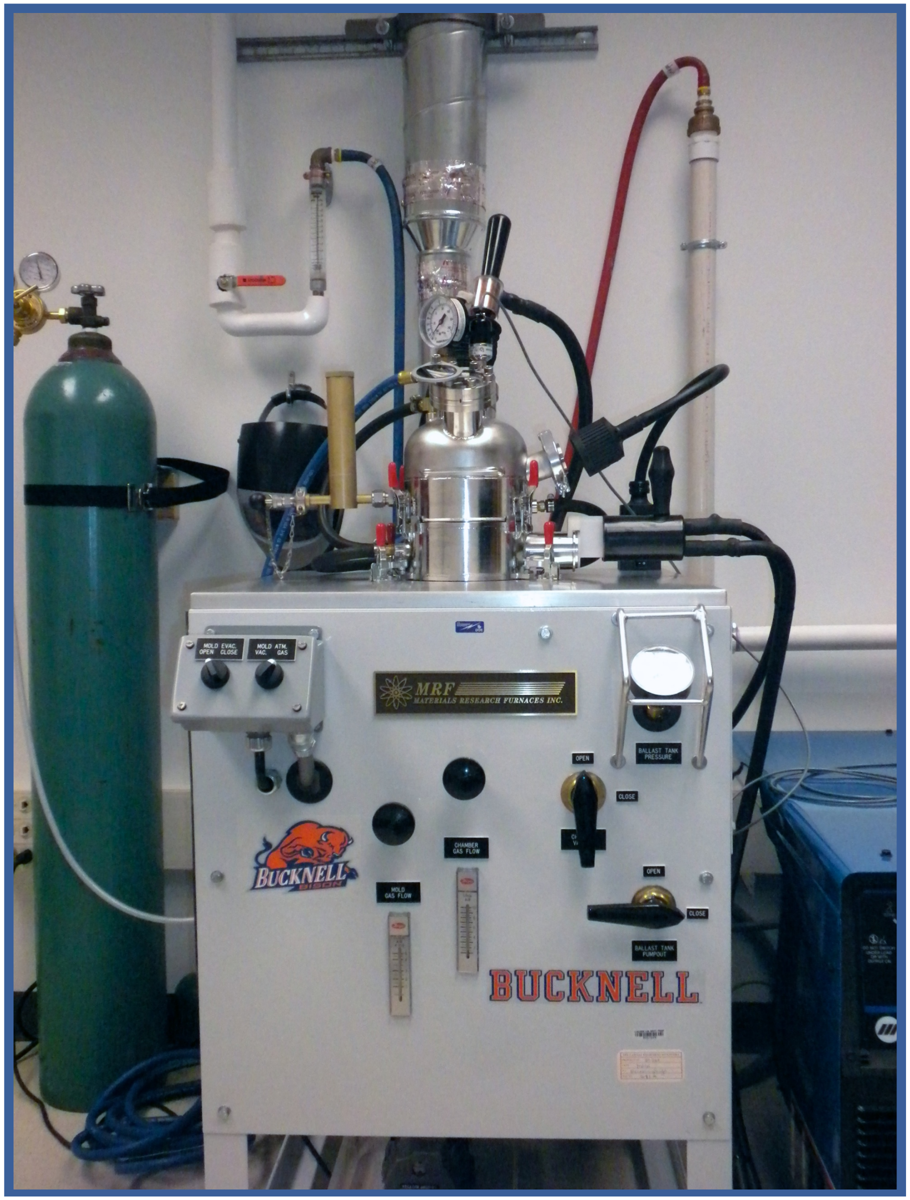
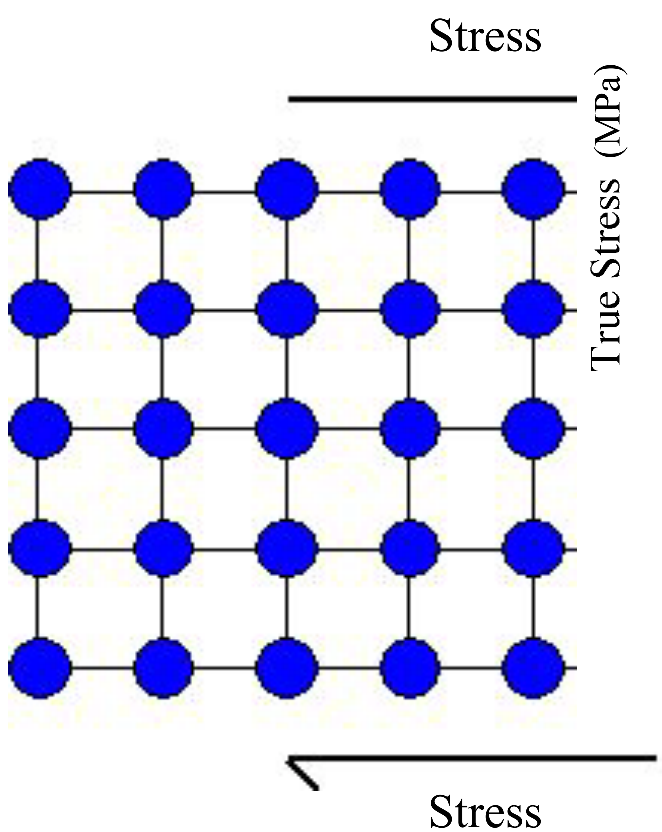
BMG Processing

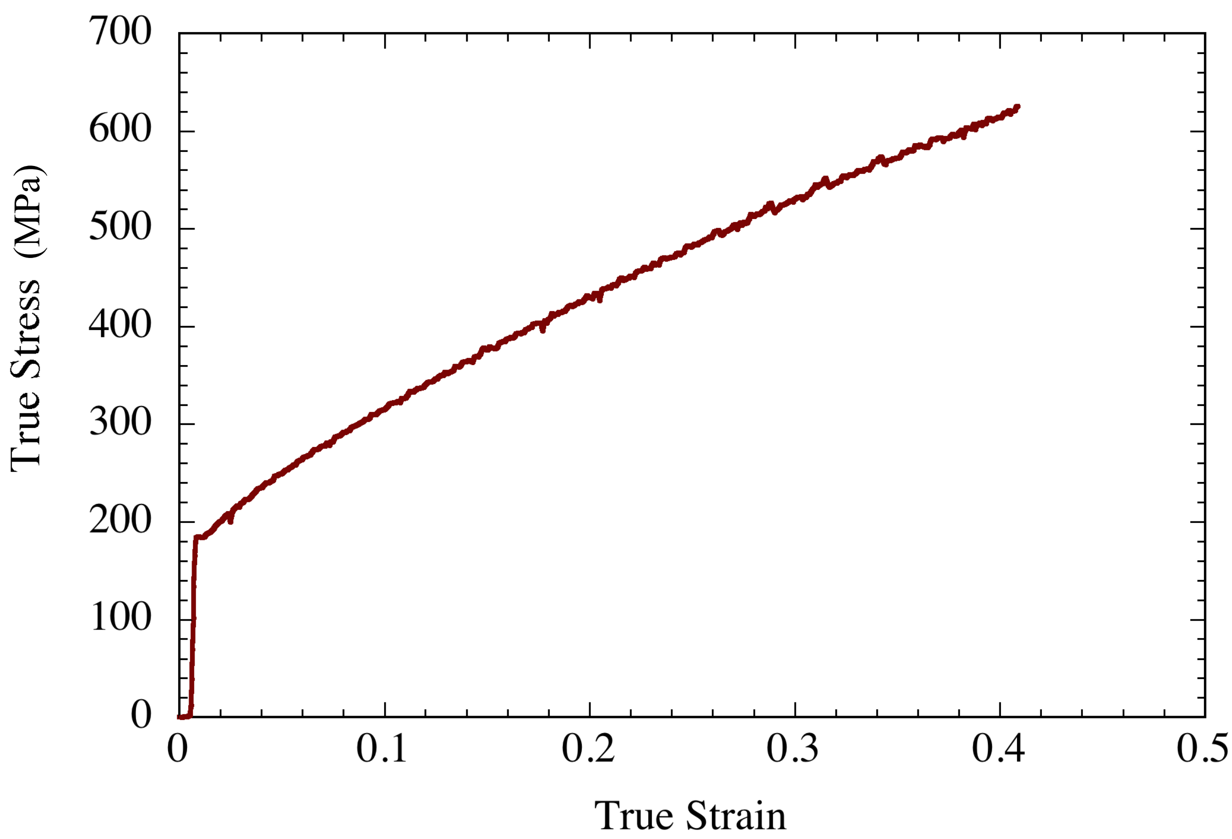


Amorphous $Zr_{52.5}Ti_{5}Al_{10}Cu_{17.9}Ni_{14.6}$

Deformation of Crystalline Metals

Dislocation motion





Animation courtesy of J.N. Florando

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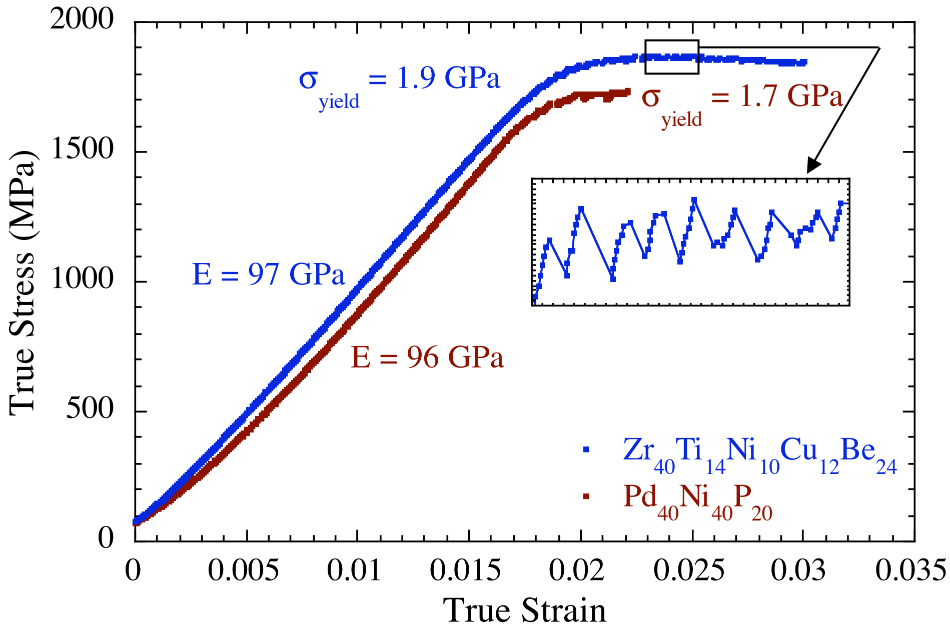
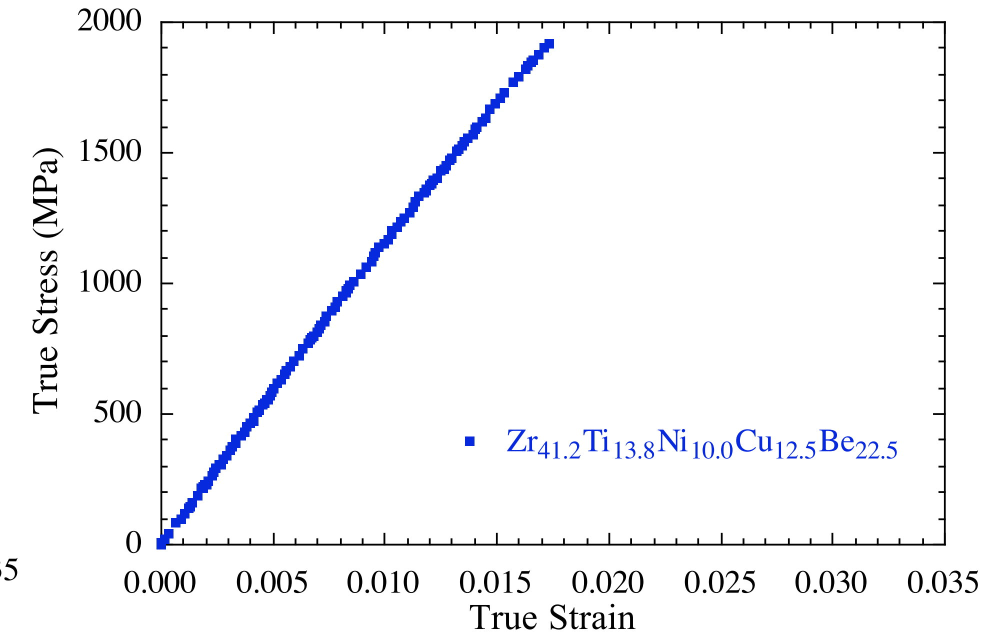
Limited Ductility

Compression



Tension



H.A. Bruck, 1995.

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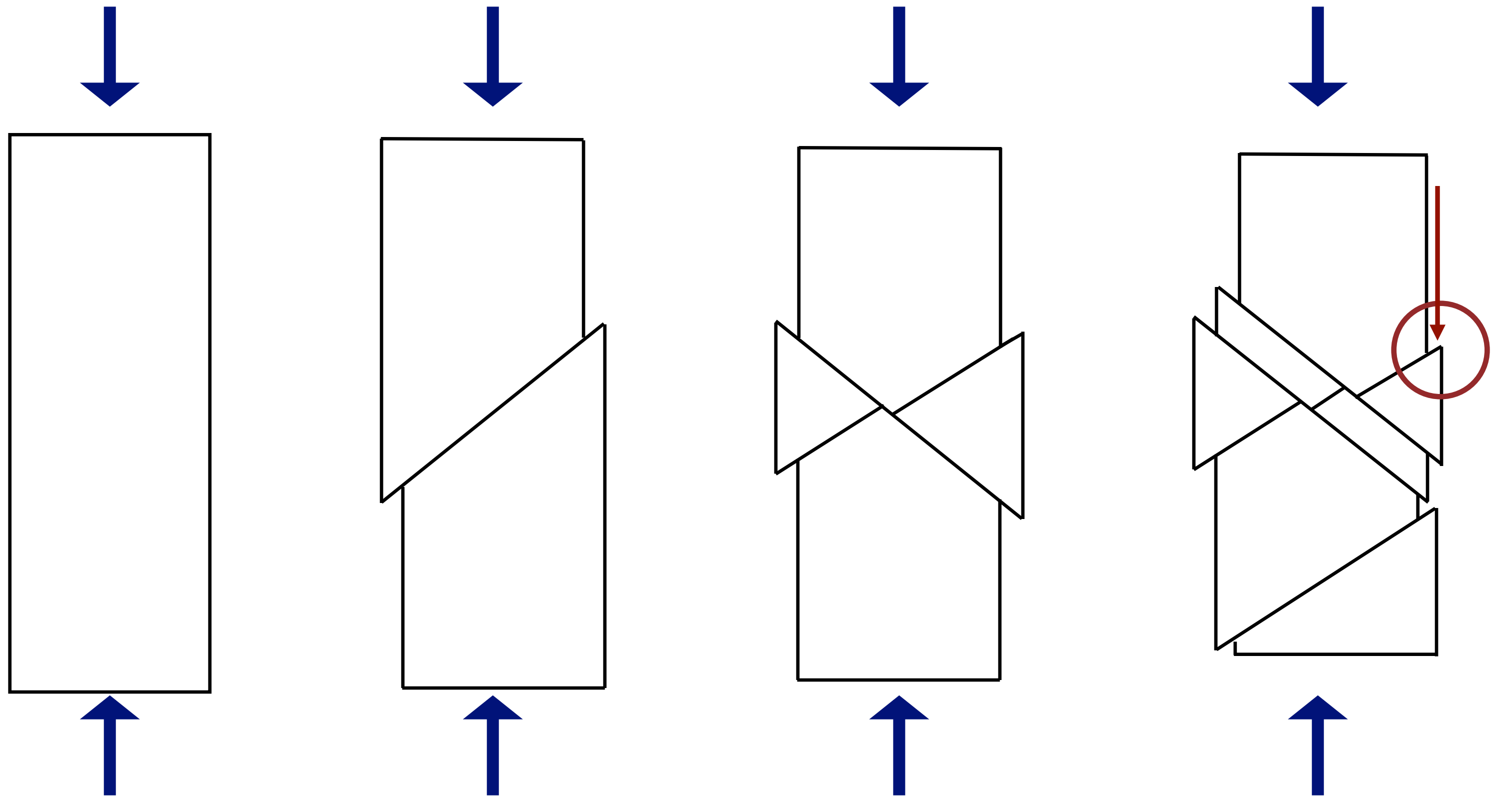
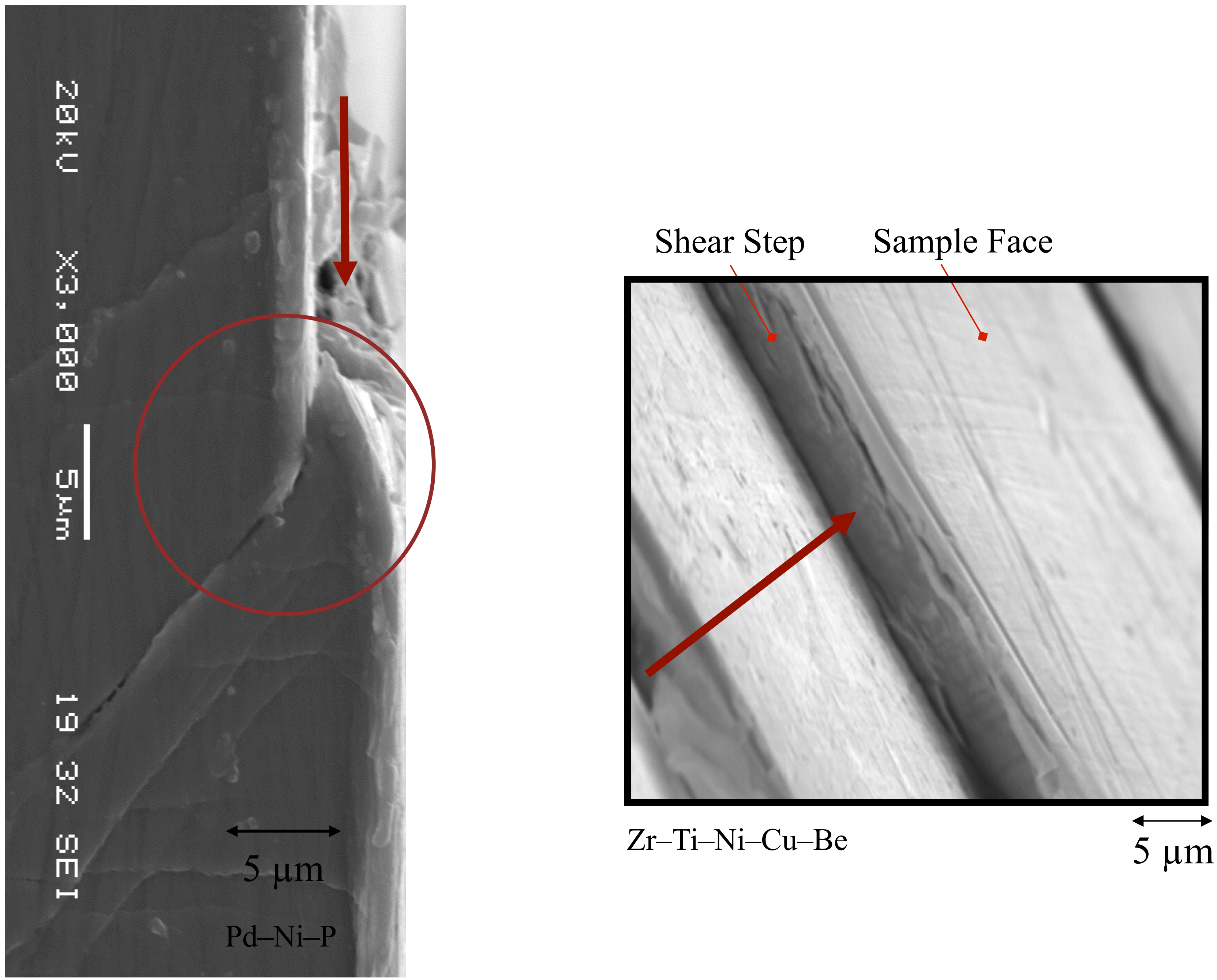
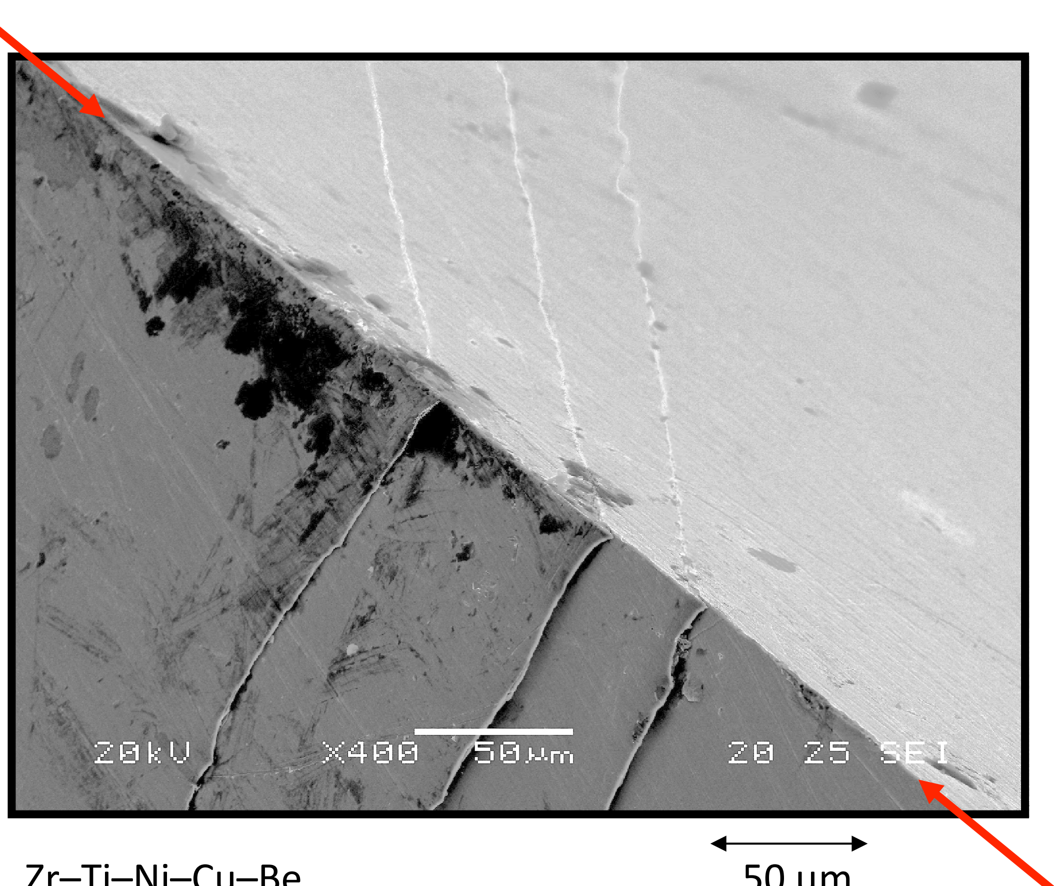
Shear Banding

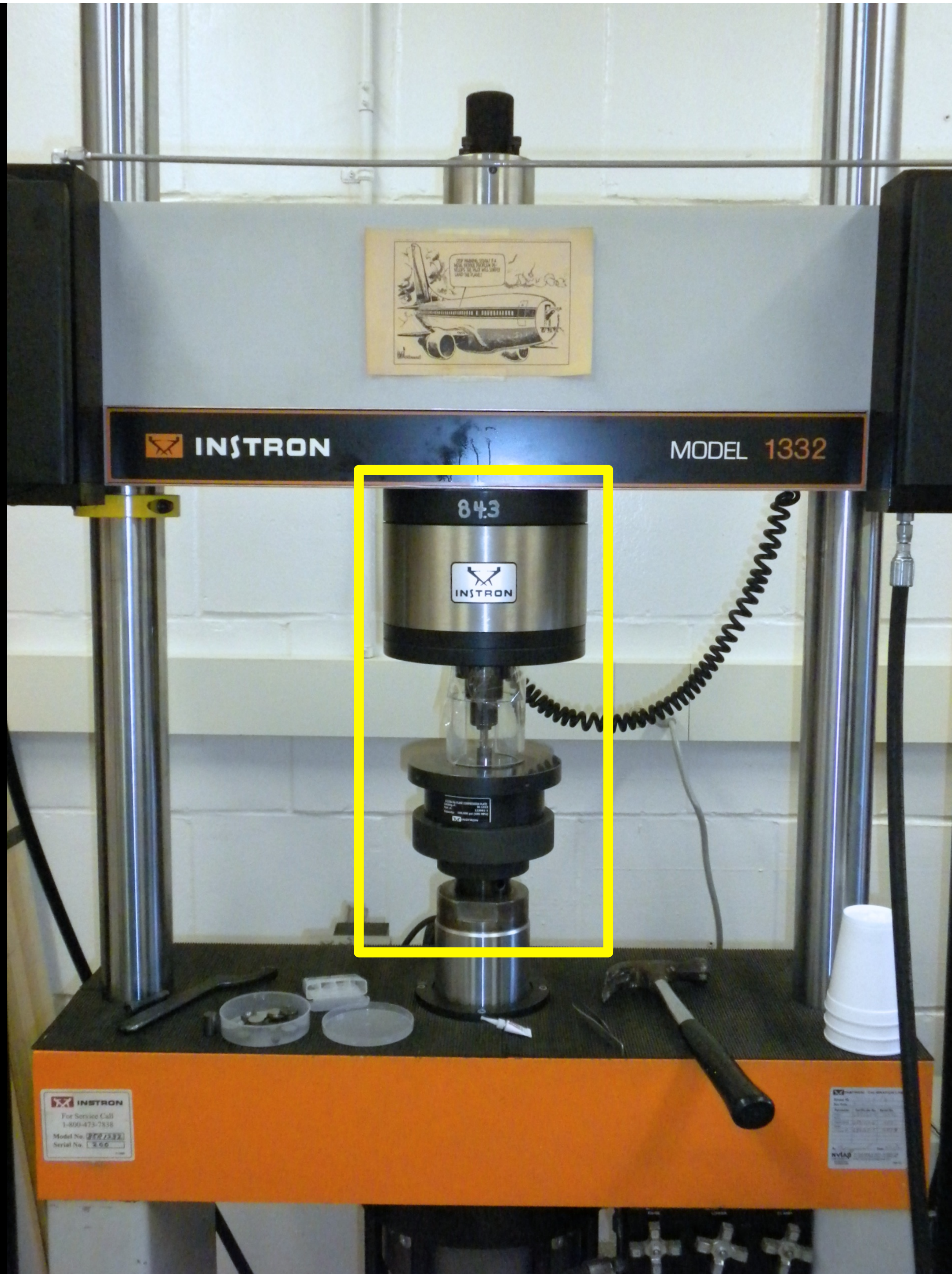



5 µm
Pd–Ni–P
Shear Step
Sample Face
Zr–Ti–Ni–Cu–Be
5 µm



Zr–Ti–Ni–Cu–Be

50 µm


INSTRON
MODEL 1332
843
INSTRON
INSTRON


84.3
INSTRON
PLANE COMPRESSION PLATE
Catalog #: W-1322
Part #: 123981-1
Capacity: 100,000 psi (690 MPa)
INSTRON

Fracture Events in Metallic Glasses

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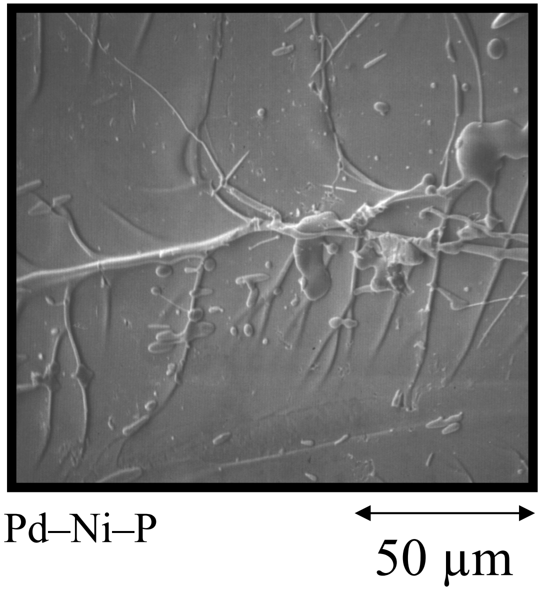
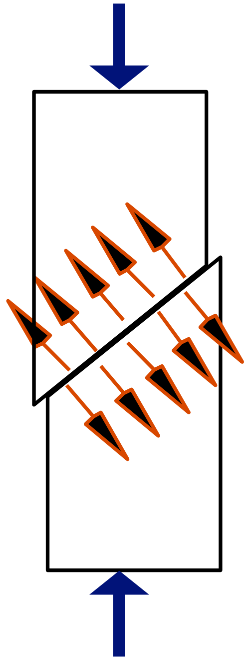
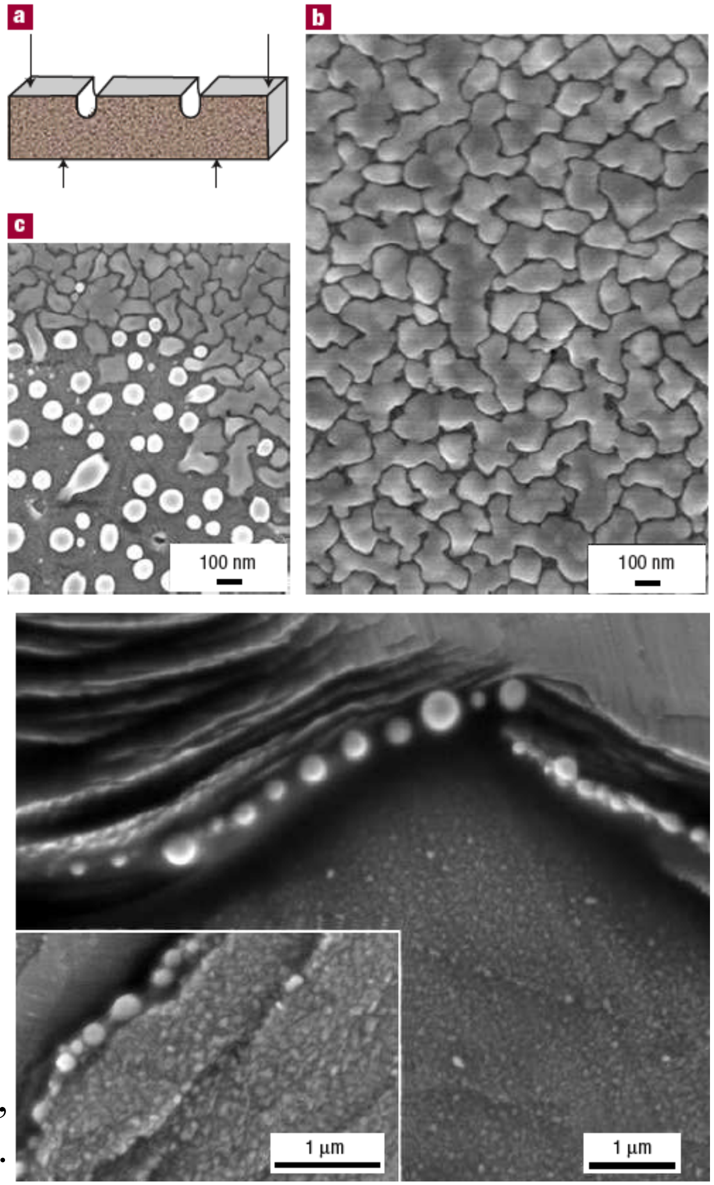
Localized Adiabatic Heating



Pd–Ni–P





J.J. Lewandowski and A.L. Greer, *Nature Materials*, **5** 15 (2006).

Key Experimental Challenge

- Shear bands are localized in both space **and** time; therefore, they are difficult to observe and characterize experimentally.

Key questions

* How fast do they travel?

* What is their mode of propagation?

* Are they hot?

* What is their relationship to fracture?

* What is the fundamental nature of the microscopic deformation mechanism?

Other Considerations

- The finite stiffness of the load frame is known to limit ductility.
- Specimen bending and a low specimen aspect ratio may lead to ductilities that are not indicative of the true material response.
- Stochastic behavior due to casting flaws is expected.

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Some of the Opportunities

- We can use high–speed data and image acquisition to characterize the shear bands.
- This provides some of the answers, but not all of them.
- We can apply the mean field model of slipping weak spots to our macroscopic mechanical measurements to discern some of the remaining answers (some later and more from Karin Dahmen next week).

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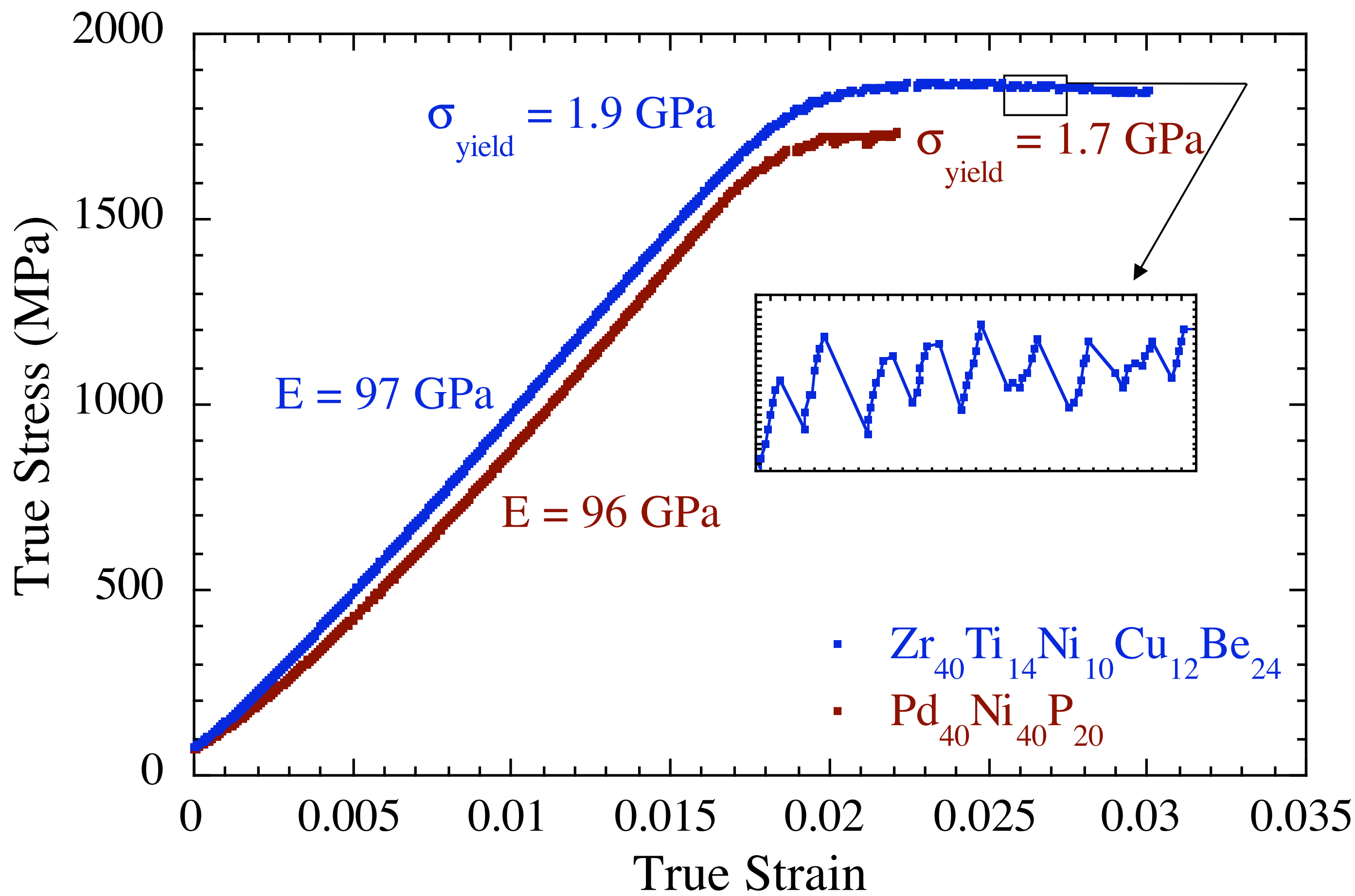
Serrated Flow



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Mechanics of the Load Train

Bharathula, Lee, Wright, and Flores with an acknowledgement to W.D. Nix
Acta Materialia 2010.

$k_{machine}$

$k_{sample} = \frac{EA}{L}$

Plastic element

• A sudden plastic strain increment causes the load in the load train to drop.

• For stable deformation, the applied stress σ should drop as much as possible for a plastic strain increment $d\varepsilon_p$.

$$d\sigma = -\left(\frac{k_{machine}\, E}{k_{machine} + \frac{EA}{L}} \right) d\varepsilon_p$$

$E \equiv$ sample elastic modulus, $A \equiv$ sample cross–sectional area, $L \equiv$ sample length

Effect of Sample Size

$$d\sigma = -\left(\frac{k_{machine}\,E}{k_{machine} + \frac{EA}{L}}\right) d\varepsilon_p$$

$k_{machine}$

$k_{sample} = \frac{EA}{L}$

Plastic element

- For a stiff machine,

$$k_{machine} >> \frac{EA}{L} \qquad d\sigma \approx -E\,d\varepsilon_p$$

Large

- For a compliant machine,

$$k_{machine} << \frac{EA}{L} \qquad d\sigma \approx -\frac{k_{machine}\,L}{A}\,d\varepsilon_p$$

Small

Bharathula, Lee, Wright, and Flores *Acta Materialia* 2010.

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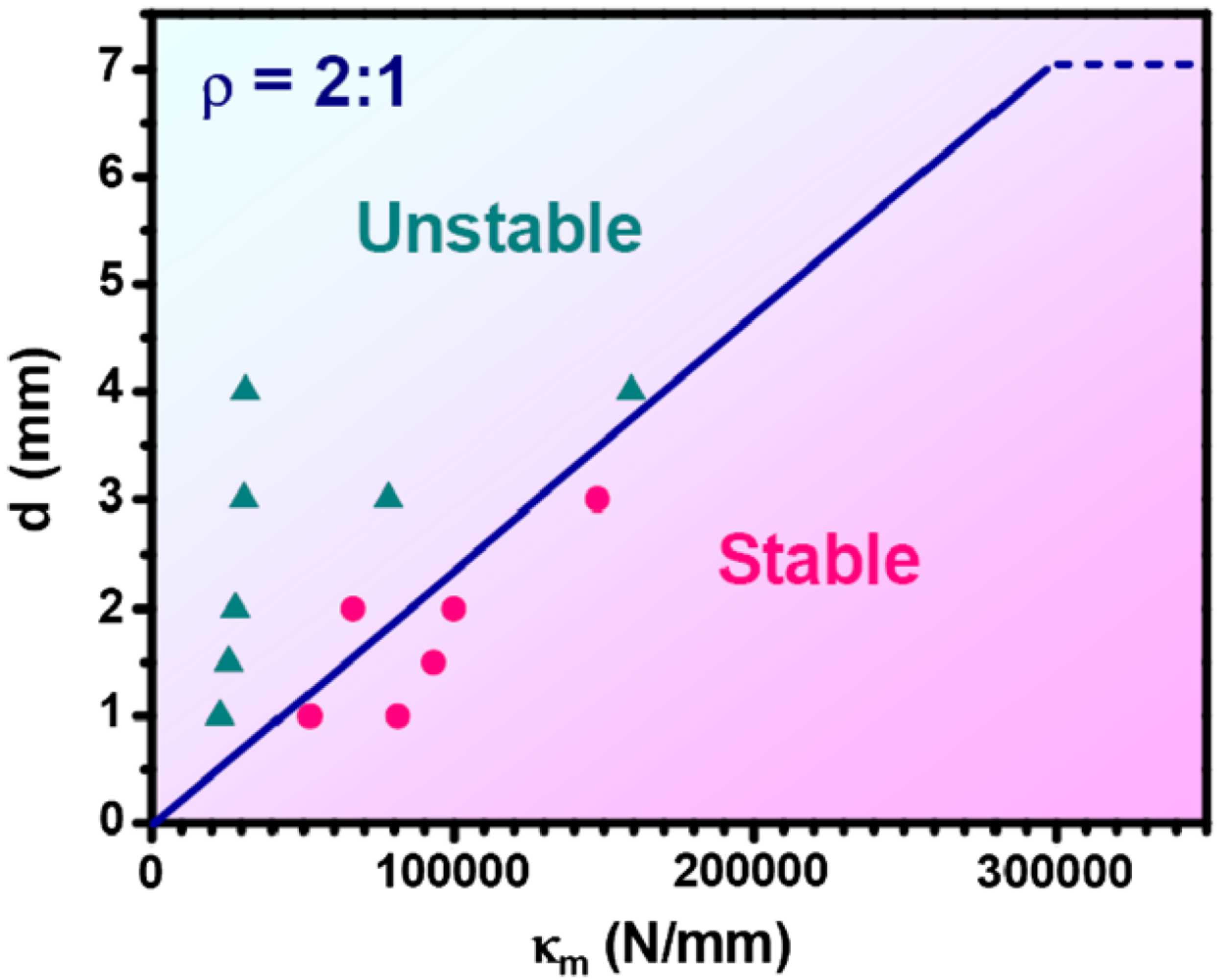
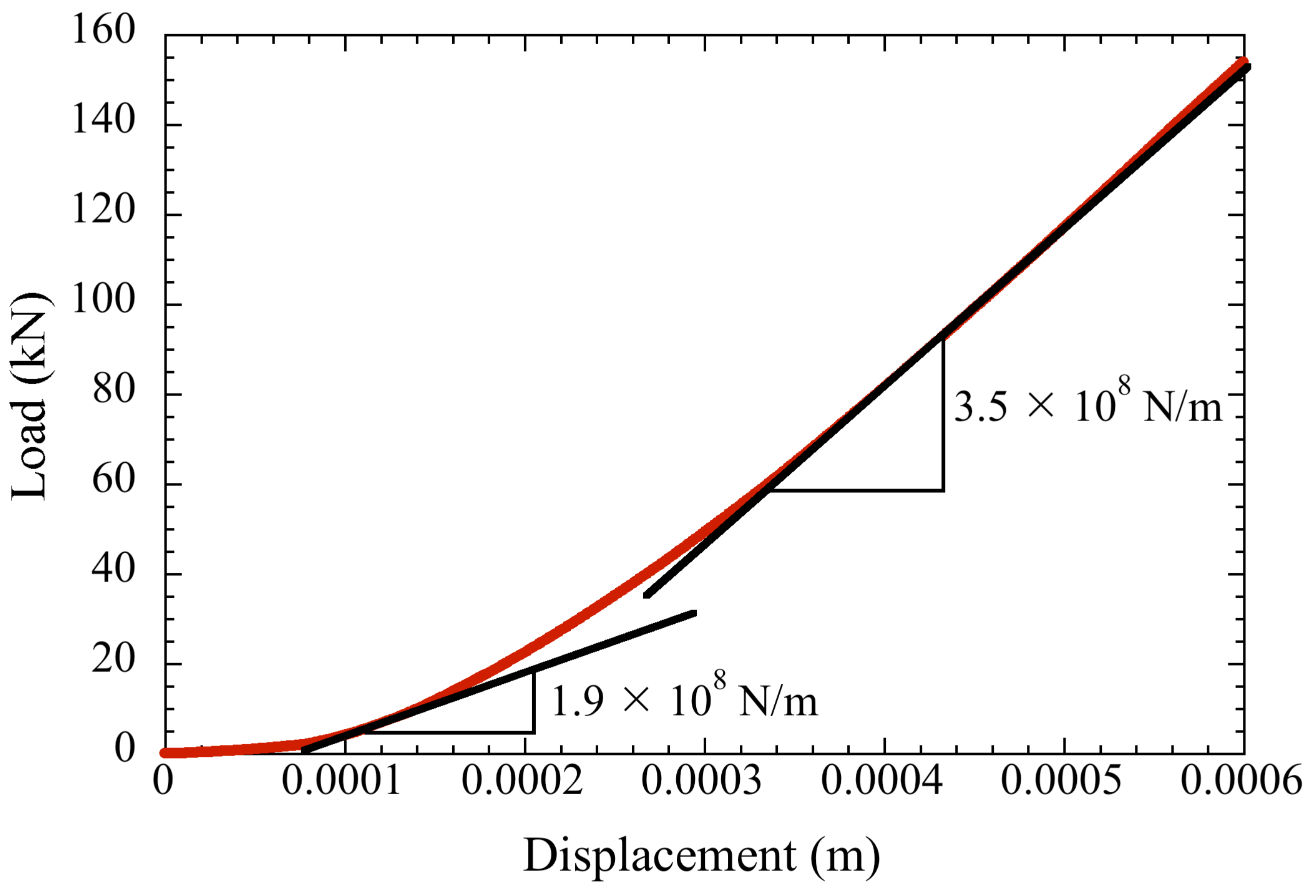
Stability/Instability Map

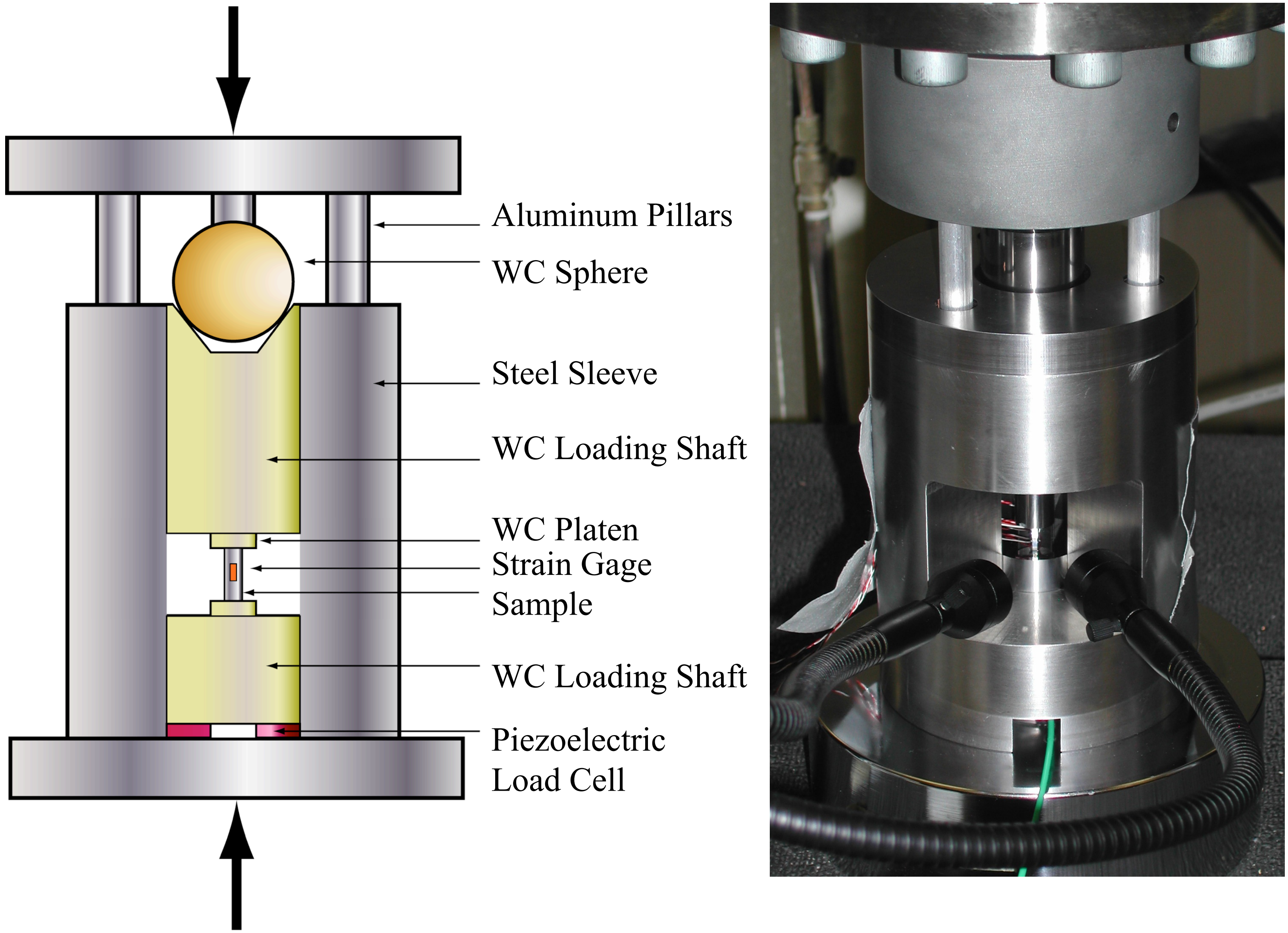


Han, Wu, Li, Wei, and Gao *Acta Materialia* 2009

Bilinear Machine Stiffness

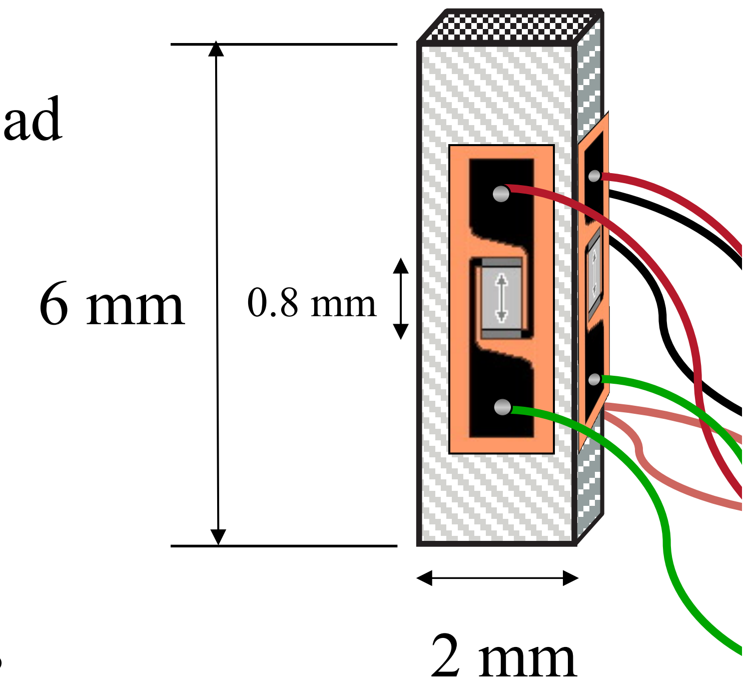


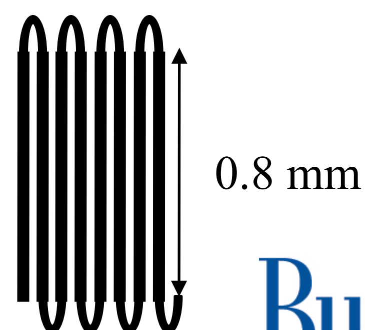
Wright et al. *Acta Materialia* 2009.


Aluminum Pillars
WC Sphere
Steel Sleeve
WC Loading Shaft
WC Platen
Strain Gage
Sample
WC Loading Shaft
Piezoelectric
Load Cell

Experimental

- Data simultaneously acquired at 50 Hz, 100 kHz, and sporadically at 400 kHz
- Load acquired using a 250 kN Instron load cell and a Kistler piezoelectric load cell (180 kHz bandpass)
- Displacement acquired using an MTS extensometer
- Data from four strain gages acquired simultaneously
- Bending minimized by use of a subpress
- Smallest bandwidth filter: –3 dB above 100 kHz on strain gage amplifier





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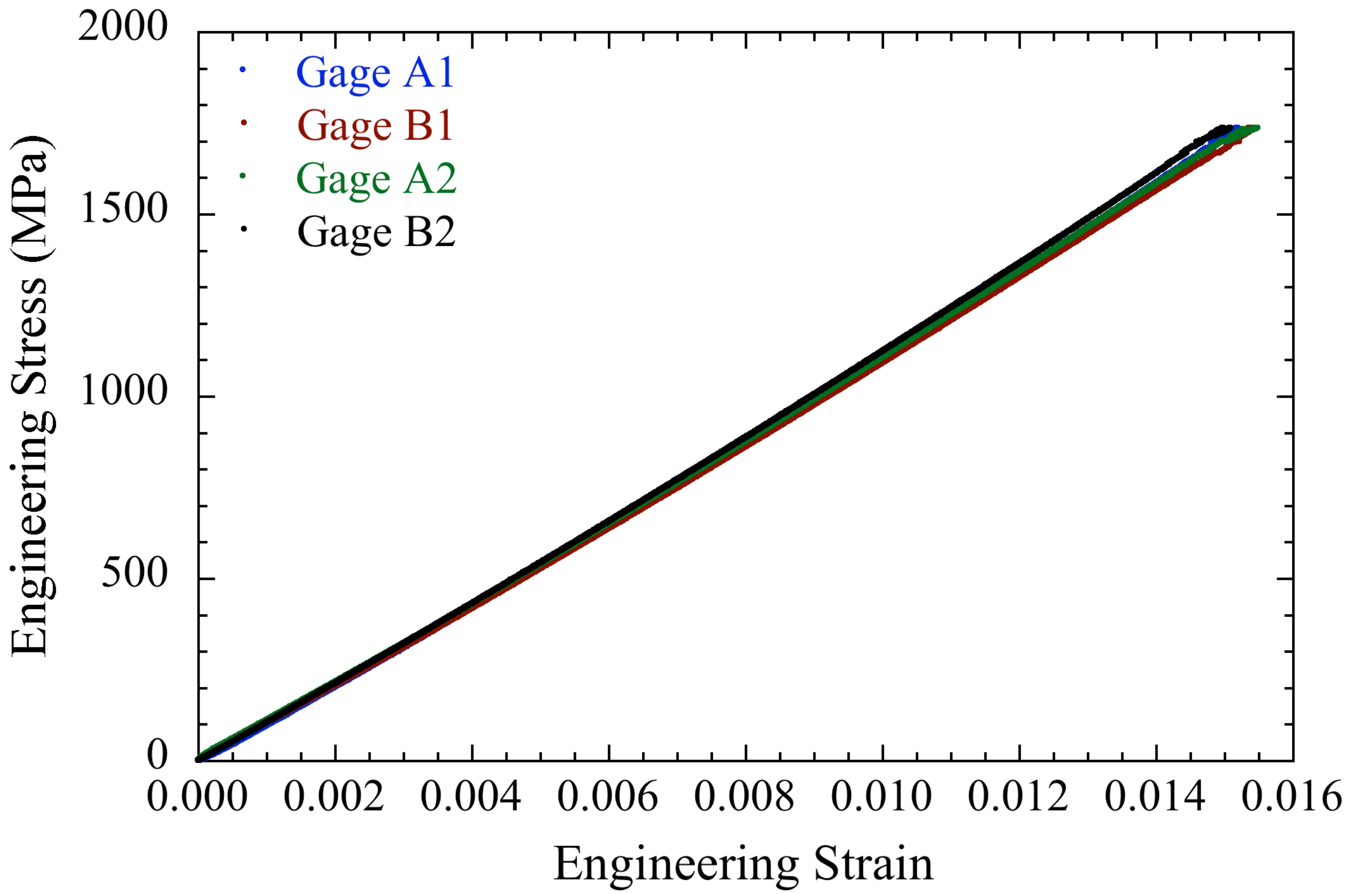
Precision Alignment



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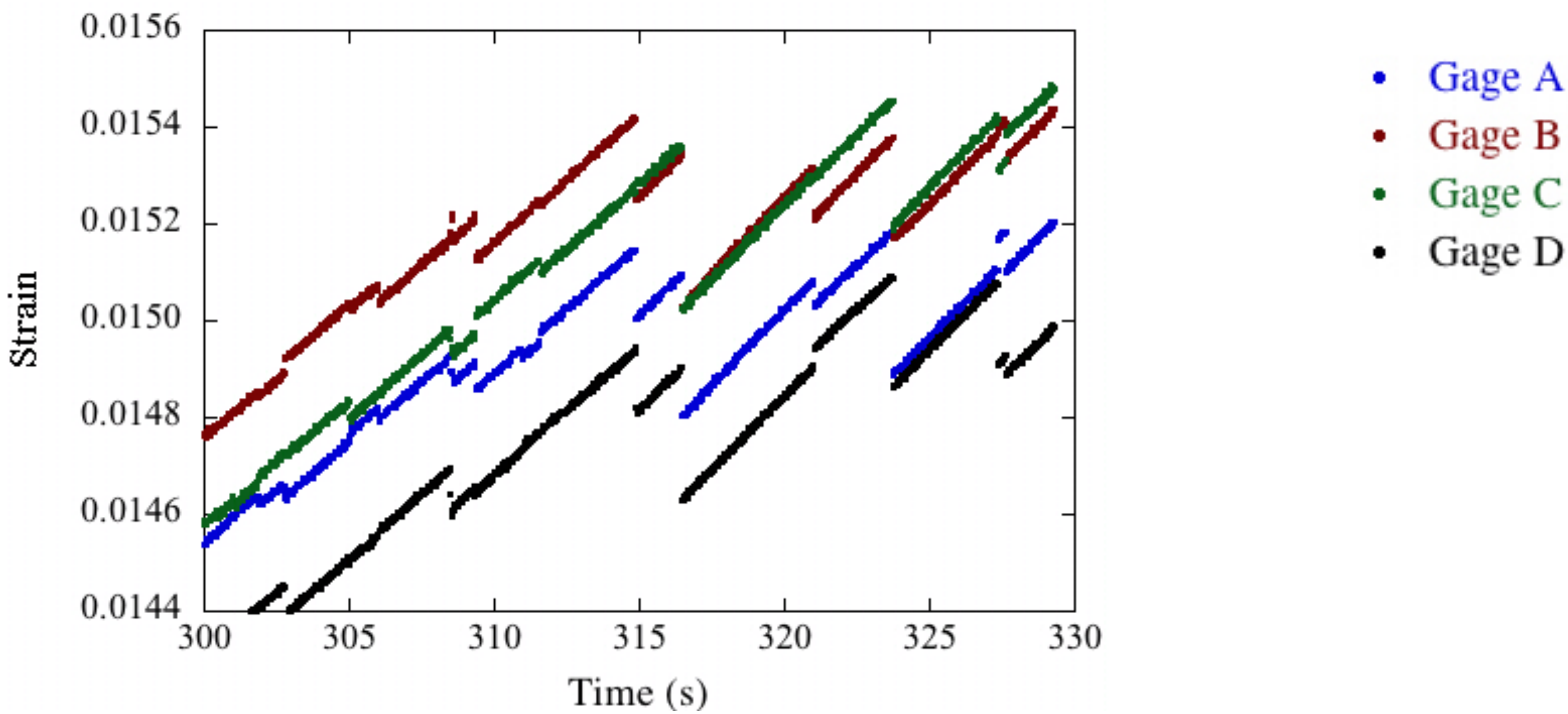
50 Hz Acquisition



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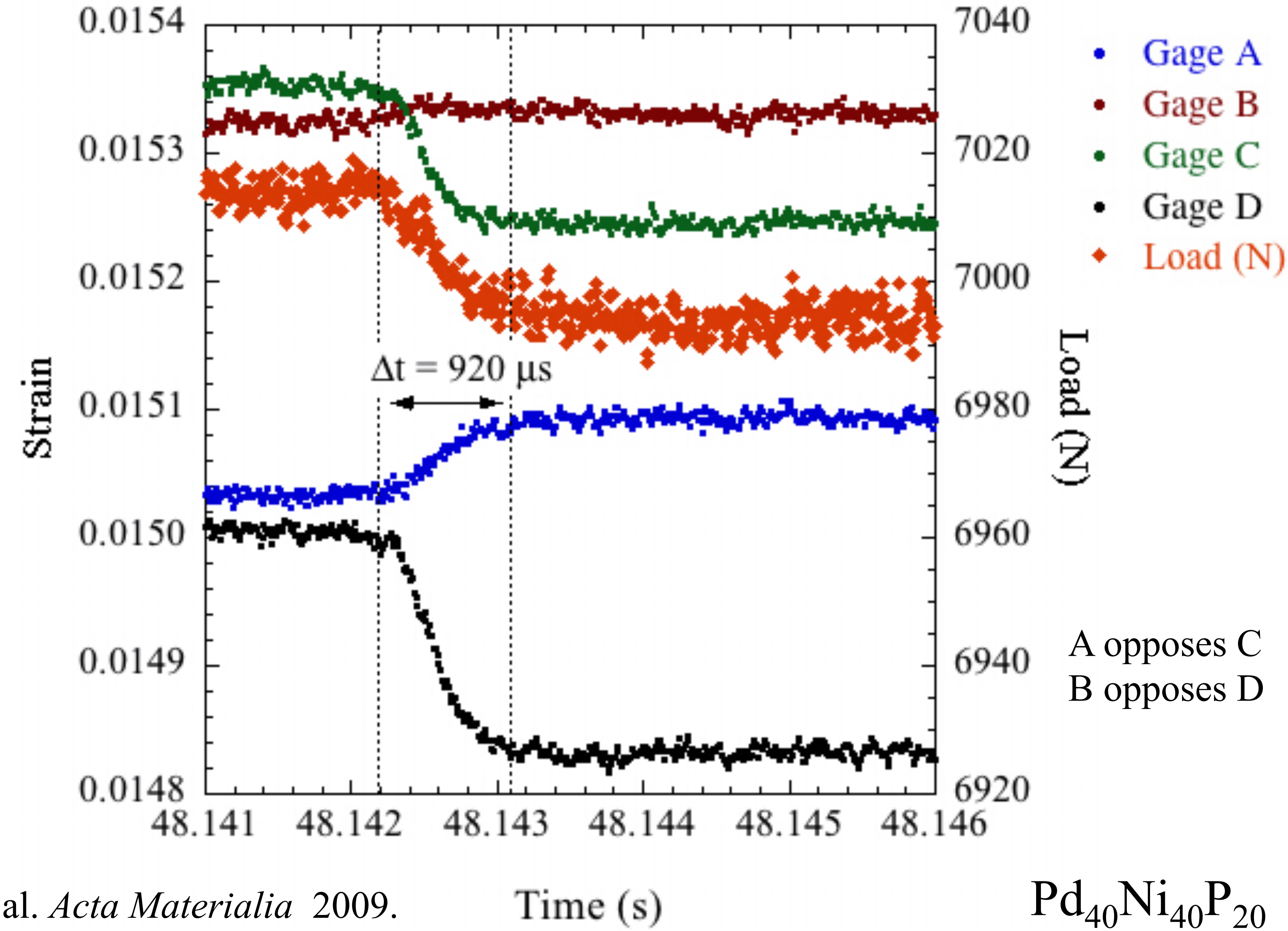
100 kHz Acquisition

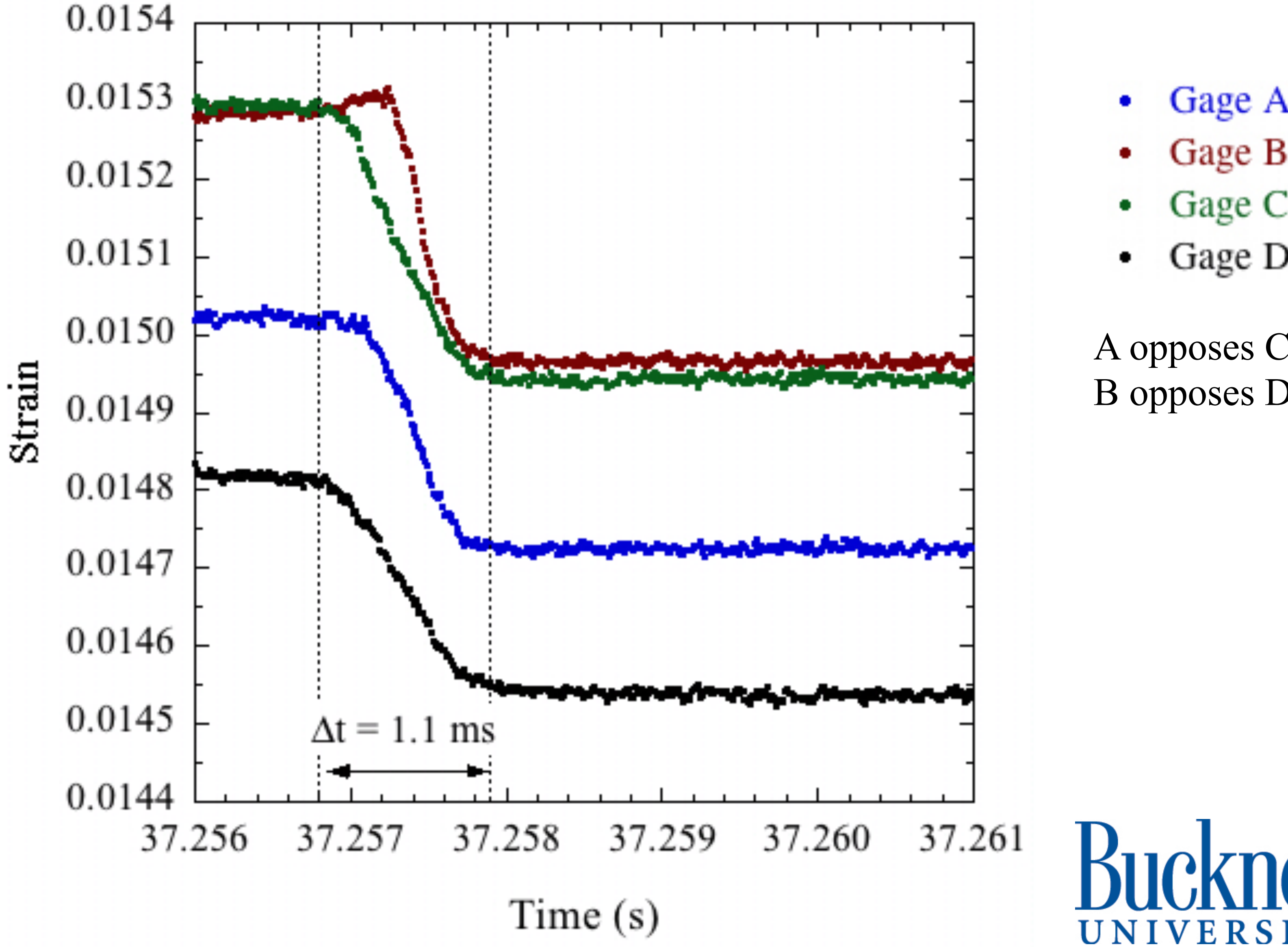


A opposes C
B opposes D

Wright et al. *Acta Materialia* 2009.

$Pd_{40}Ni_{40}P_{20}$

100 kHz Acquisition



A opposes C
B opposes D

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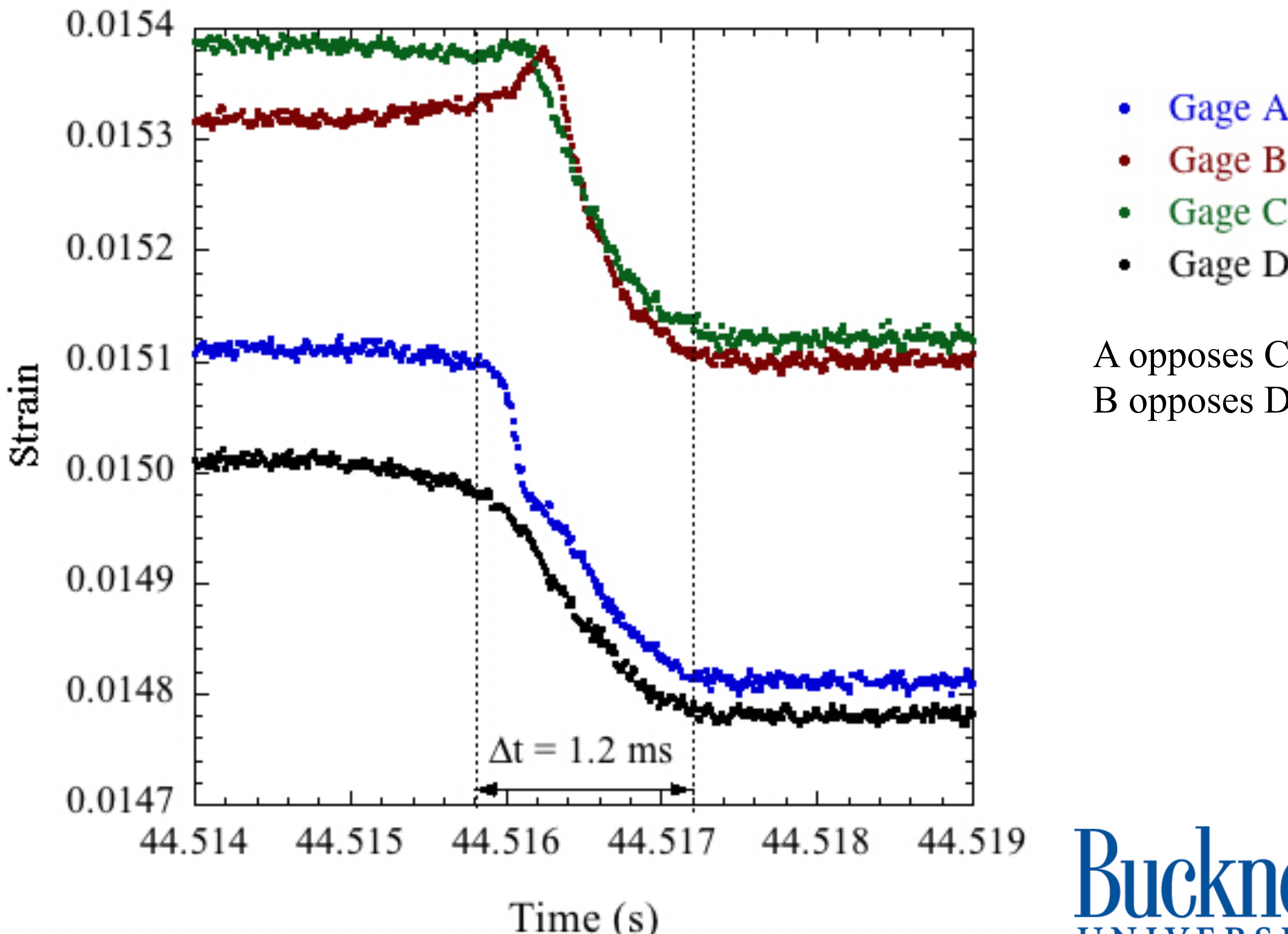
100 kHz Acquisition



A opposes C
B opposes D

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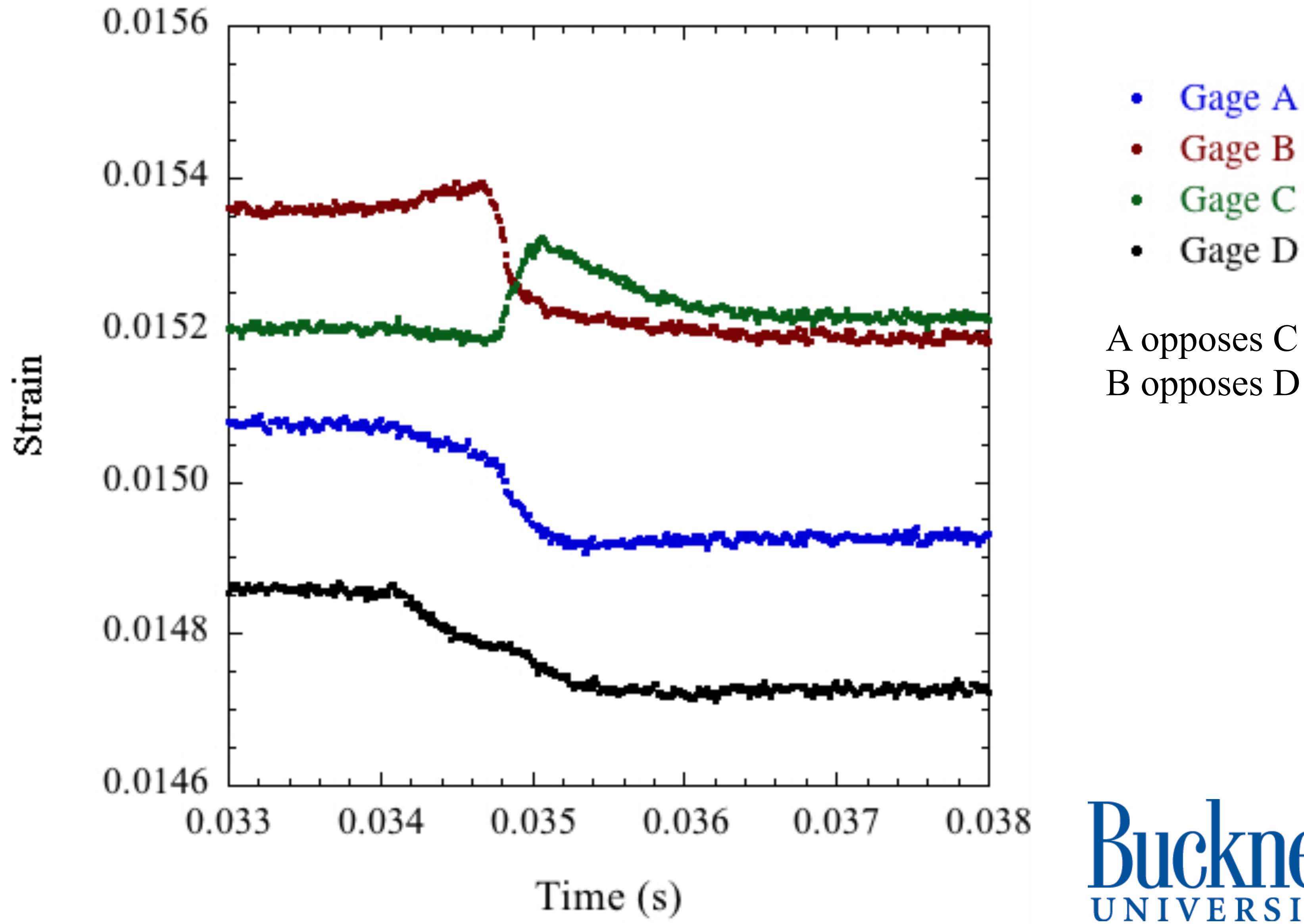
100 kHz Acquisition



A opposes C
B opposes D

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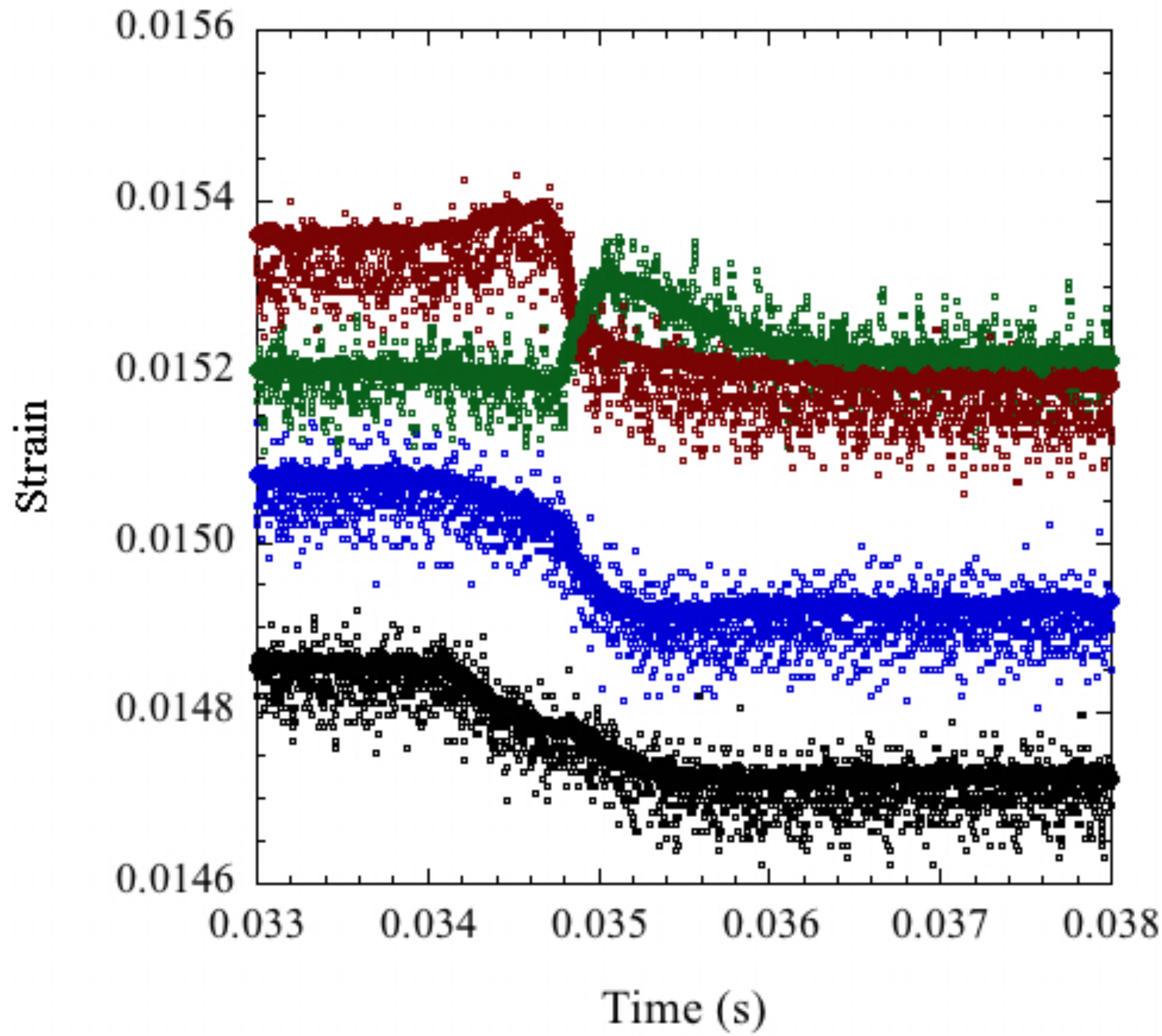
100 kHz and 400 kHz



A opposes C
B opposes D

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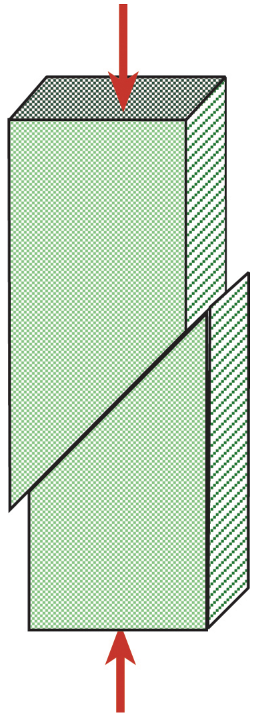
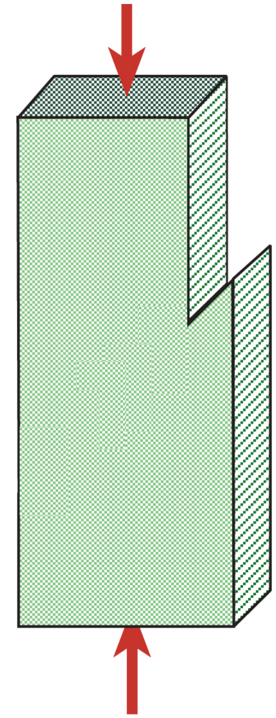
Implications for Shear Band Velocity

Simultaneous Shear



$$\frac{0.002\ \text{mm}}{1\ \text{ms}} = 0.002\ \text{m/s}$$

Progressive Shear



$$\frac{2\sqrt{2}\ \text{mm}}{1\ \text{ms}} = 2.8\ \text{m/s}$$

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Vision Research Phantom 310

- Rectangular specimen dimensions are 6 mm × 2 mm × 1.5 mm with precision tolerances
- Vision Research Phantom 310 camera, black and white, 1280 × 800 pixels maximum resolution, 500 kHz maximum sampling rate, 32 GB memory
- Data from the piezoelectric load cell is acquired using a data acquisition board synched and time-stamped to the same clock as the camera
- During fracture, 80 kHz sampling rate, 64 × 200 pixels, 2 μs exposure
- During serrated flow, 12.5 kHz sampling rate, 224 pixels × 624 pixels, 10 μs exposure

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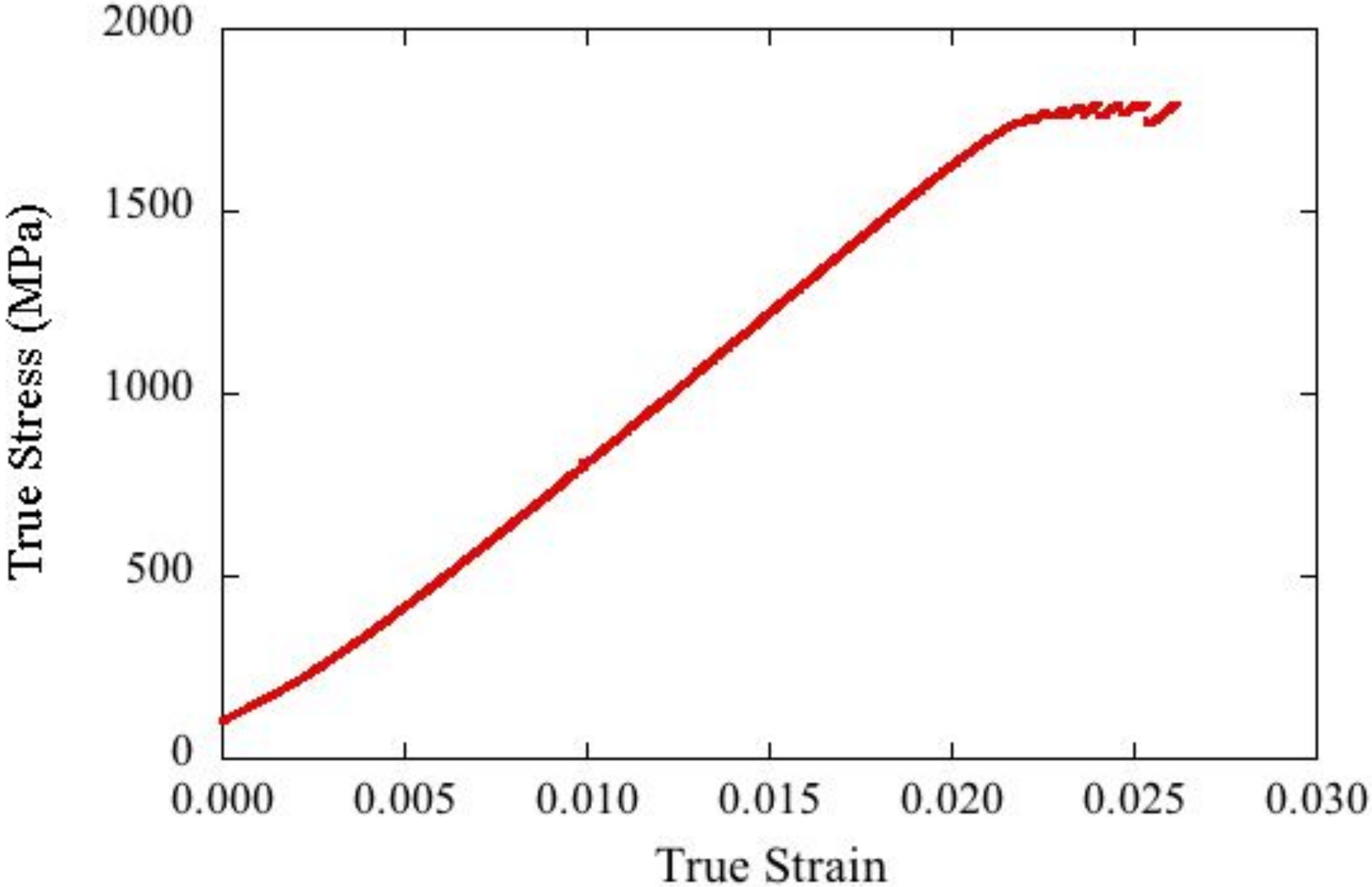

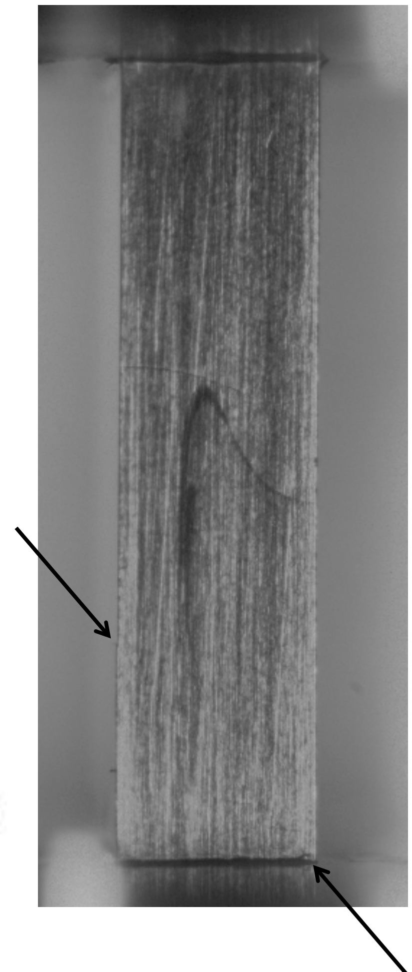

$Zr_{45}Hf_{12}Nb_5Cu_{15.4}Ni_{12.6}Al_{10}$

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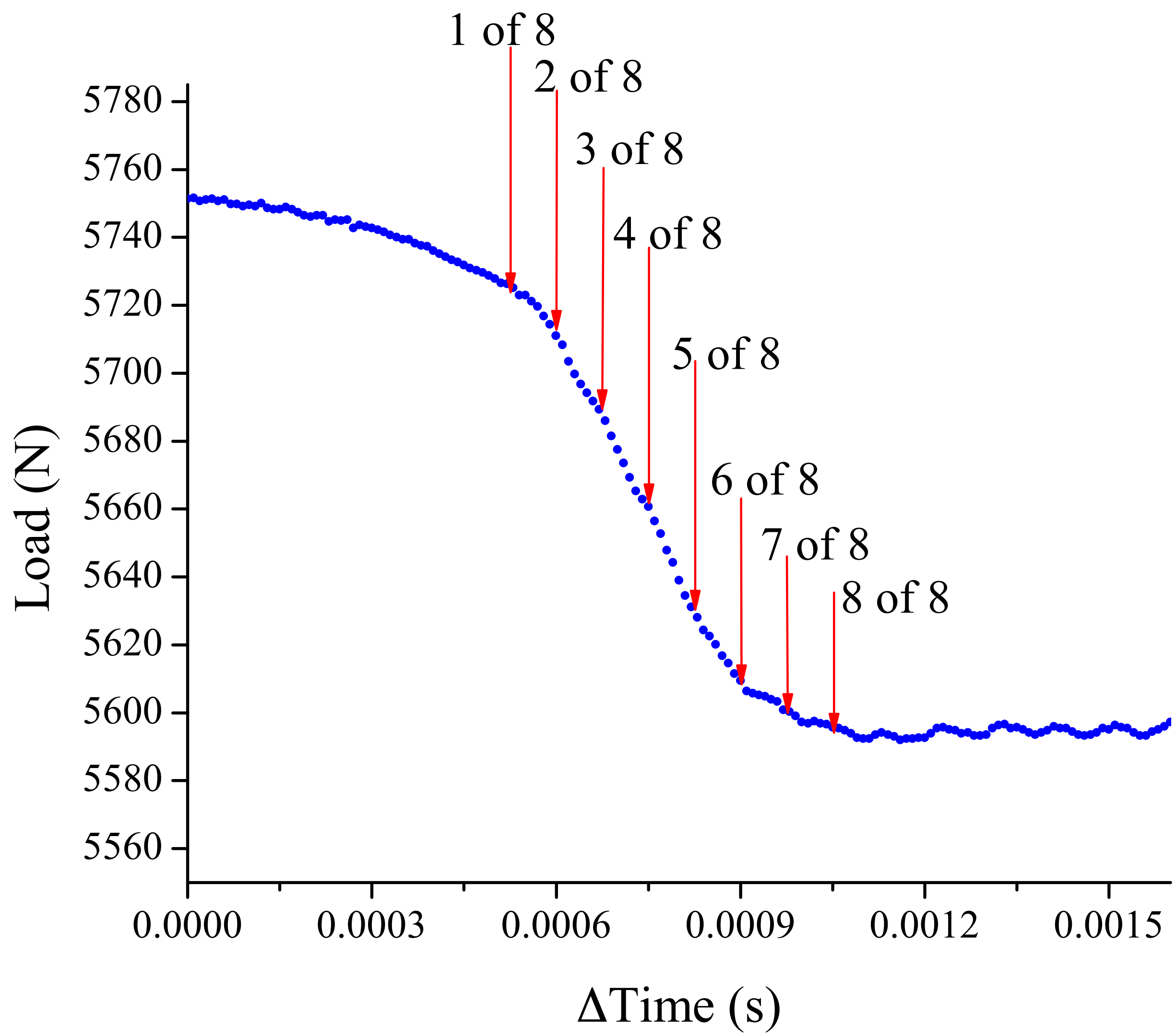
http://dx.doi.org/10.1063/1.4895605

$Zr_{45}Hf_{12}Nb_5Cu_{15.4}Ni_{12.6}Al_{10}$

Load versus Time



Wright, Byer, and Gu *Applied Physics Letters* 2013.

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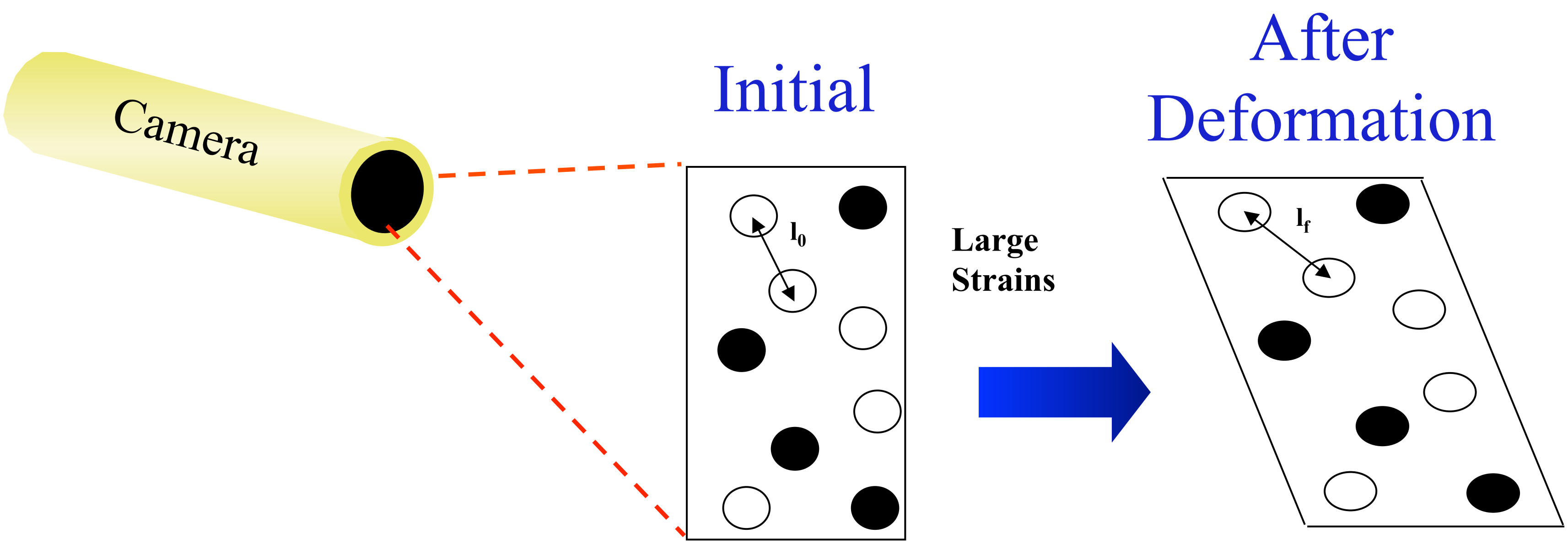
Image Correlation



Courtesy of M.M. LeBlanc

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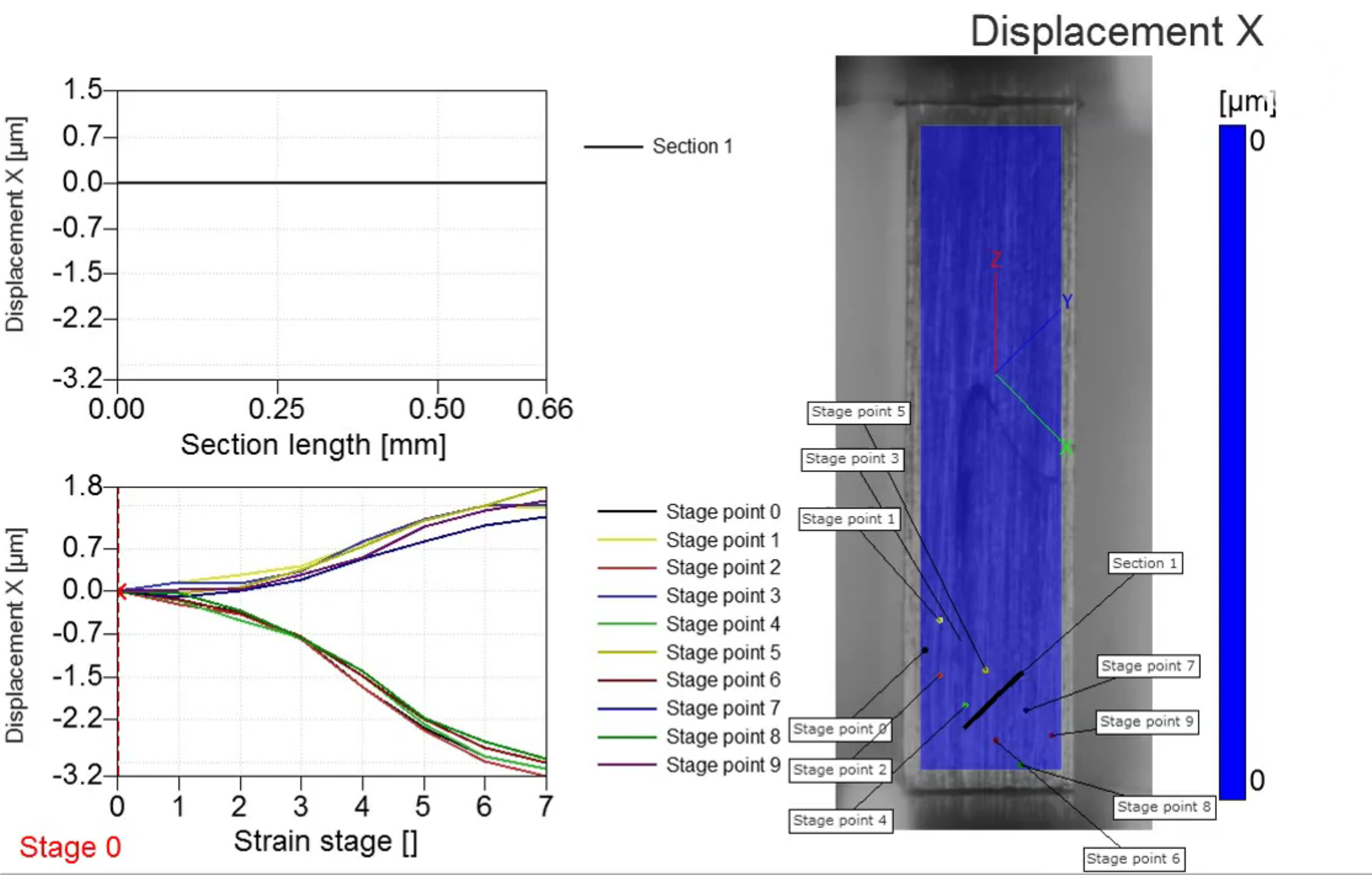
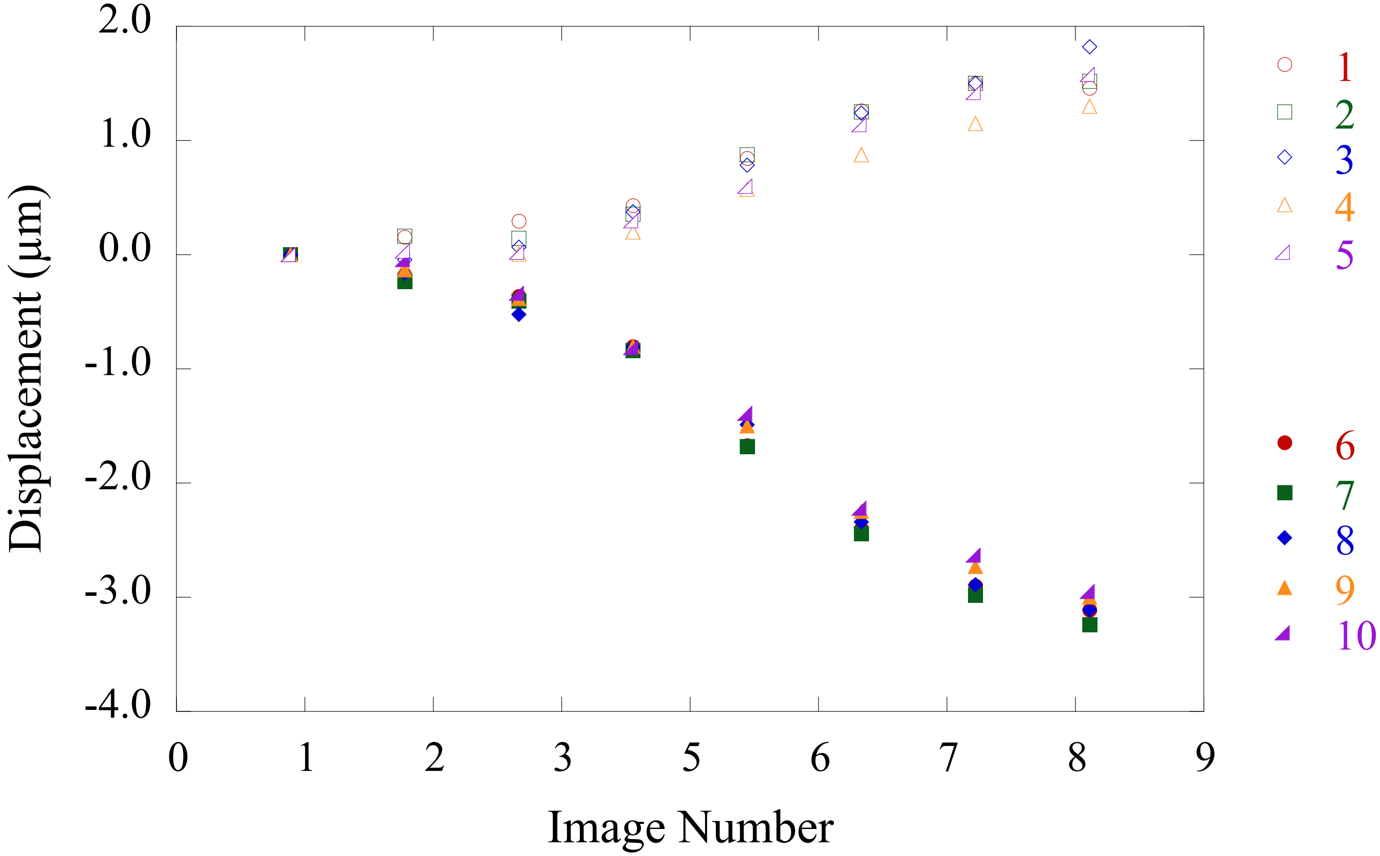
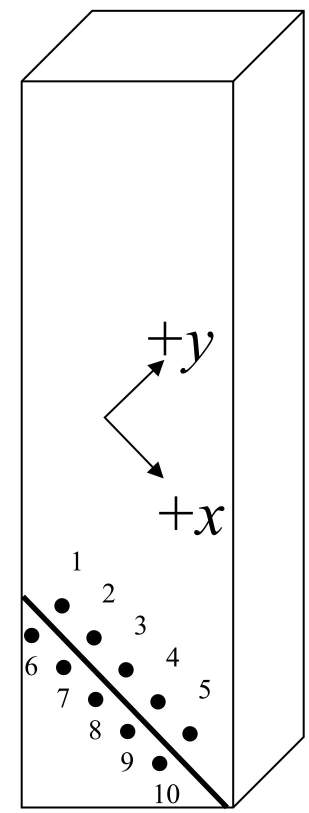


ARAMIS

www.gom.com

Load versus Time





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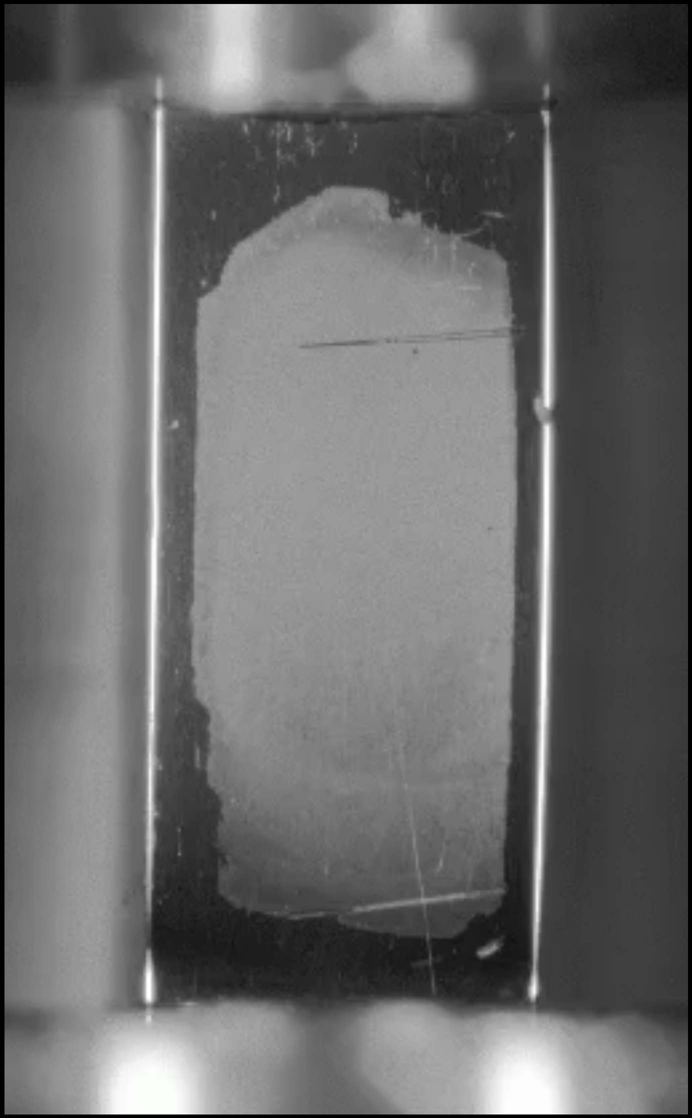
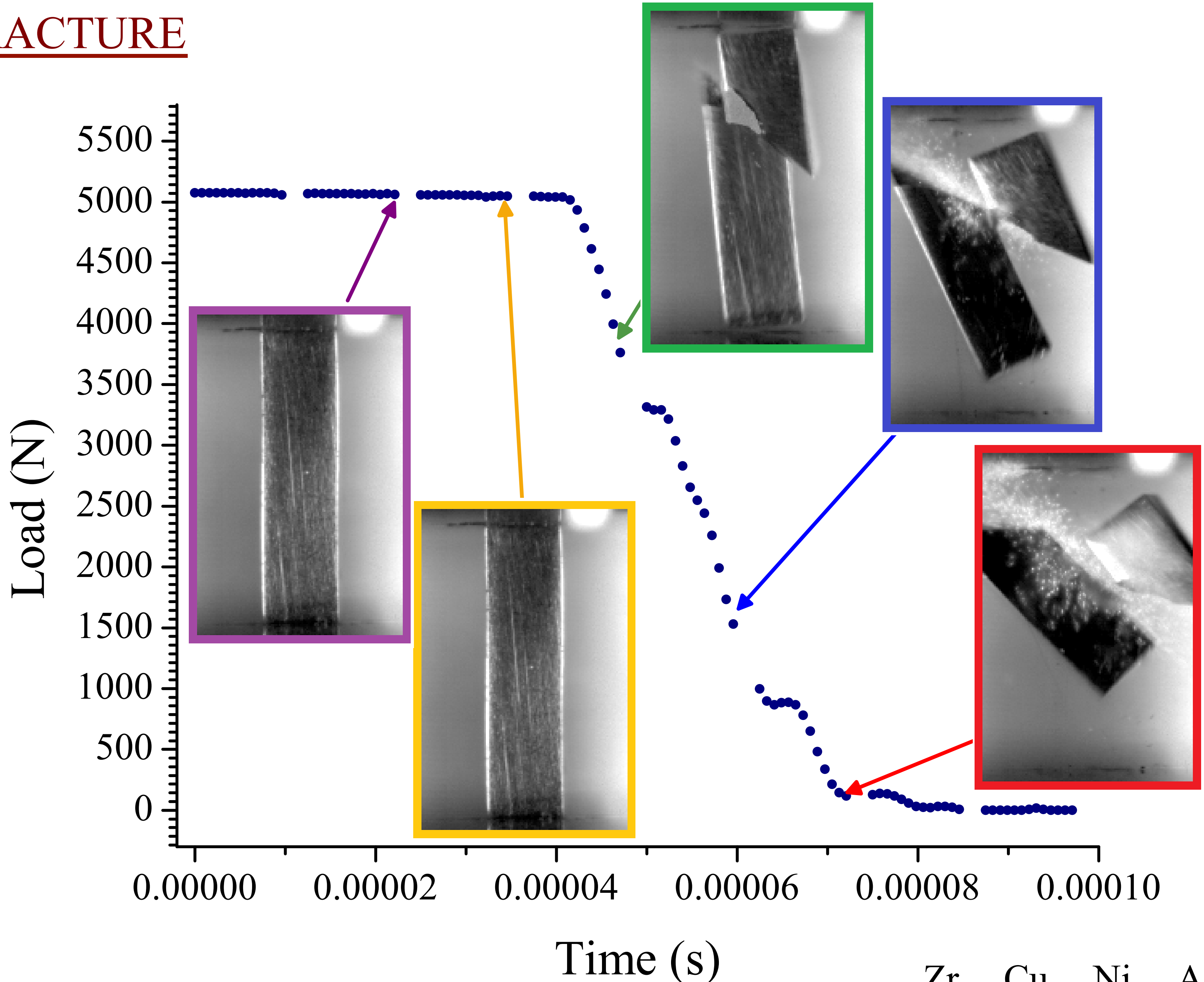
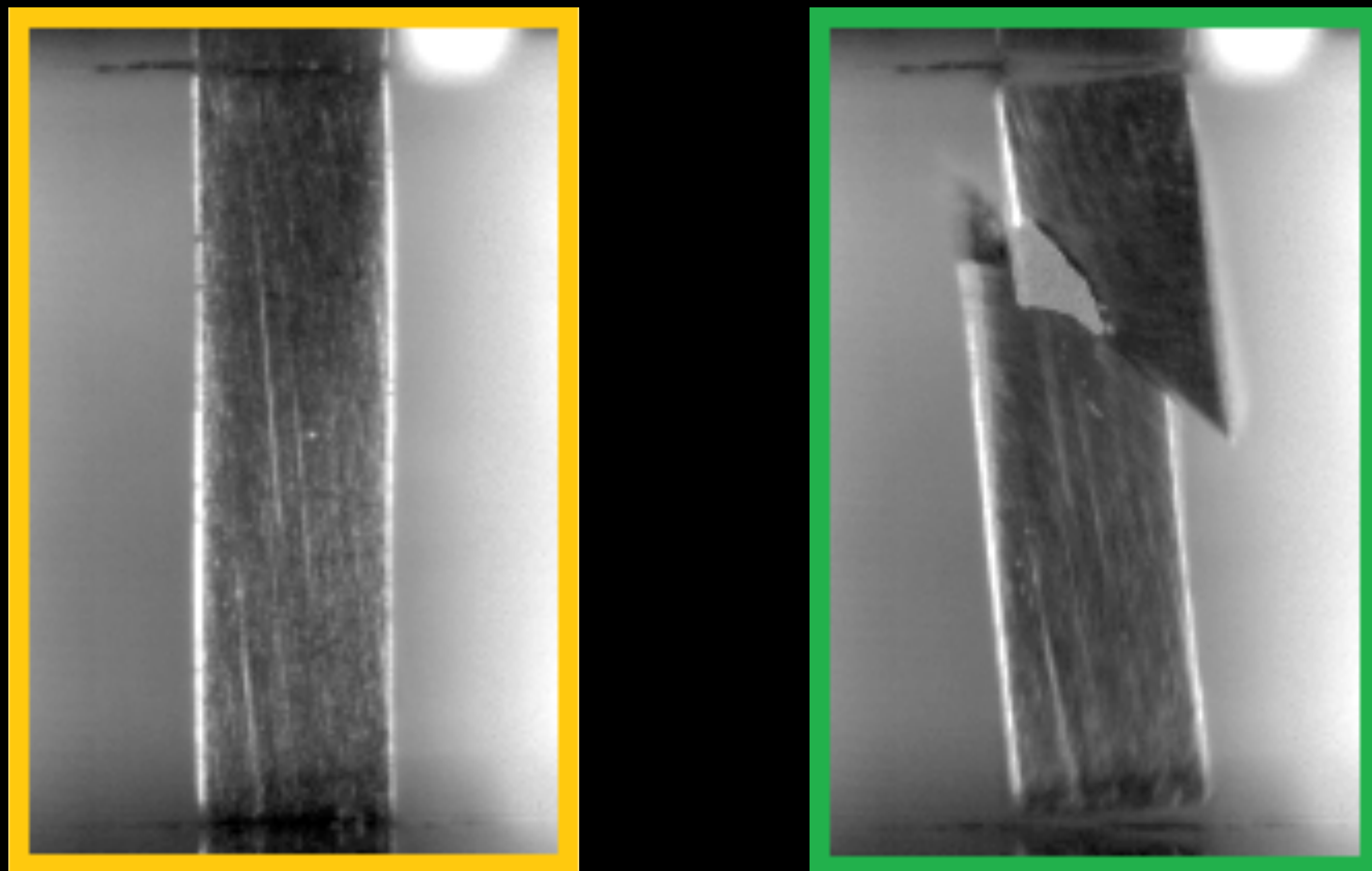


FRACTURE

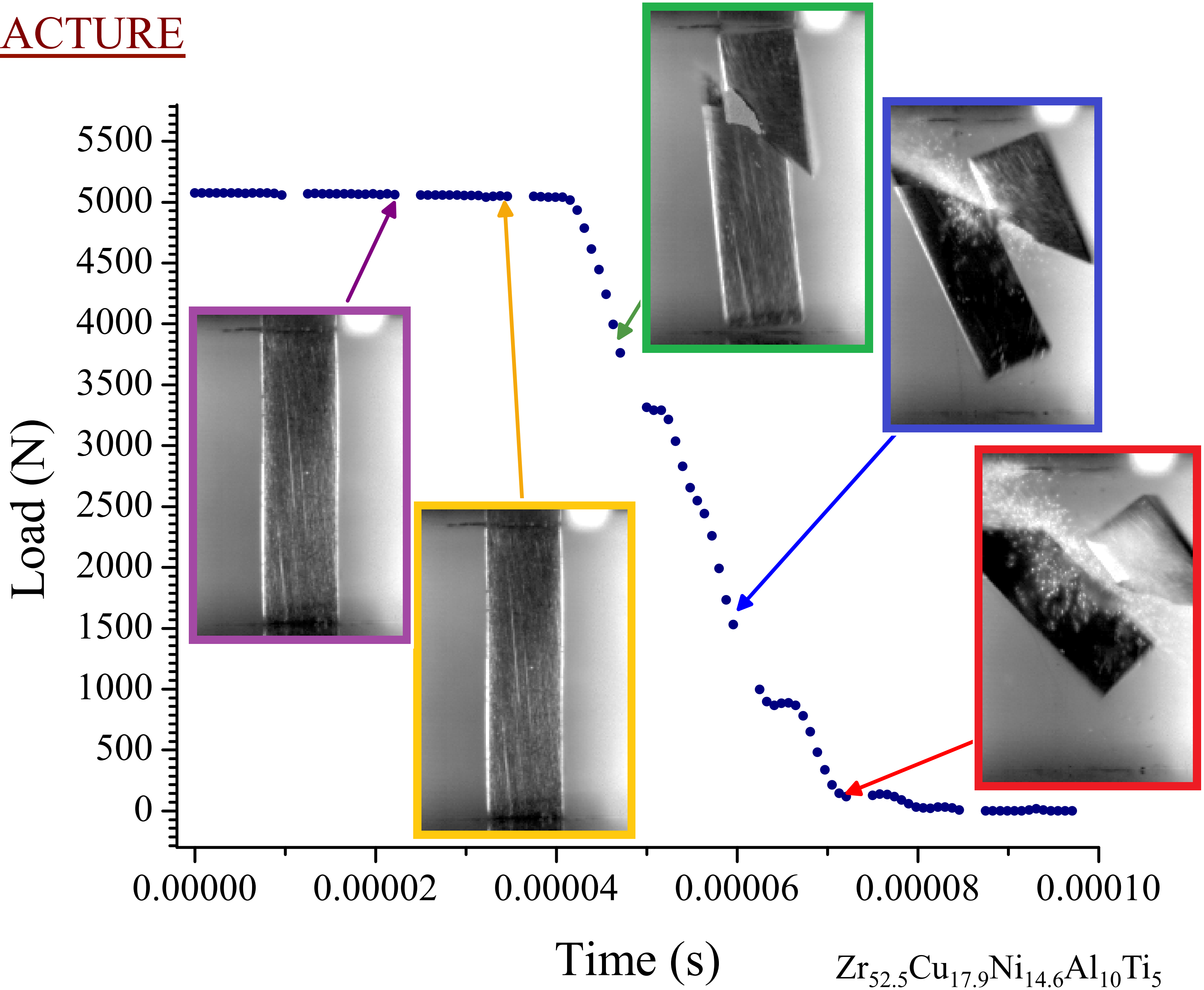


$Zr_{52.5}Cu_{17.9}Ni_{14.6}Al_{10}Ti_5$

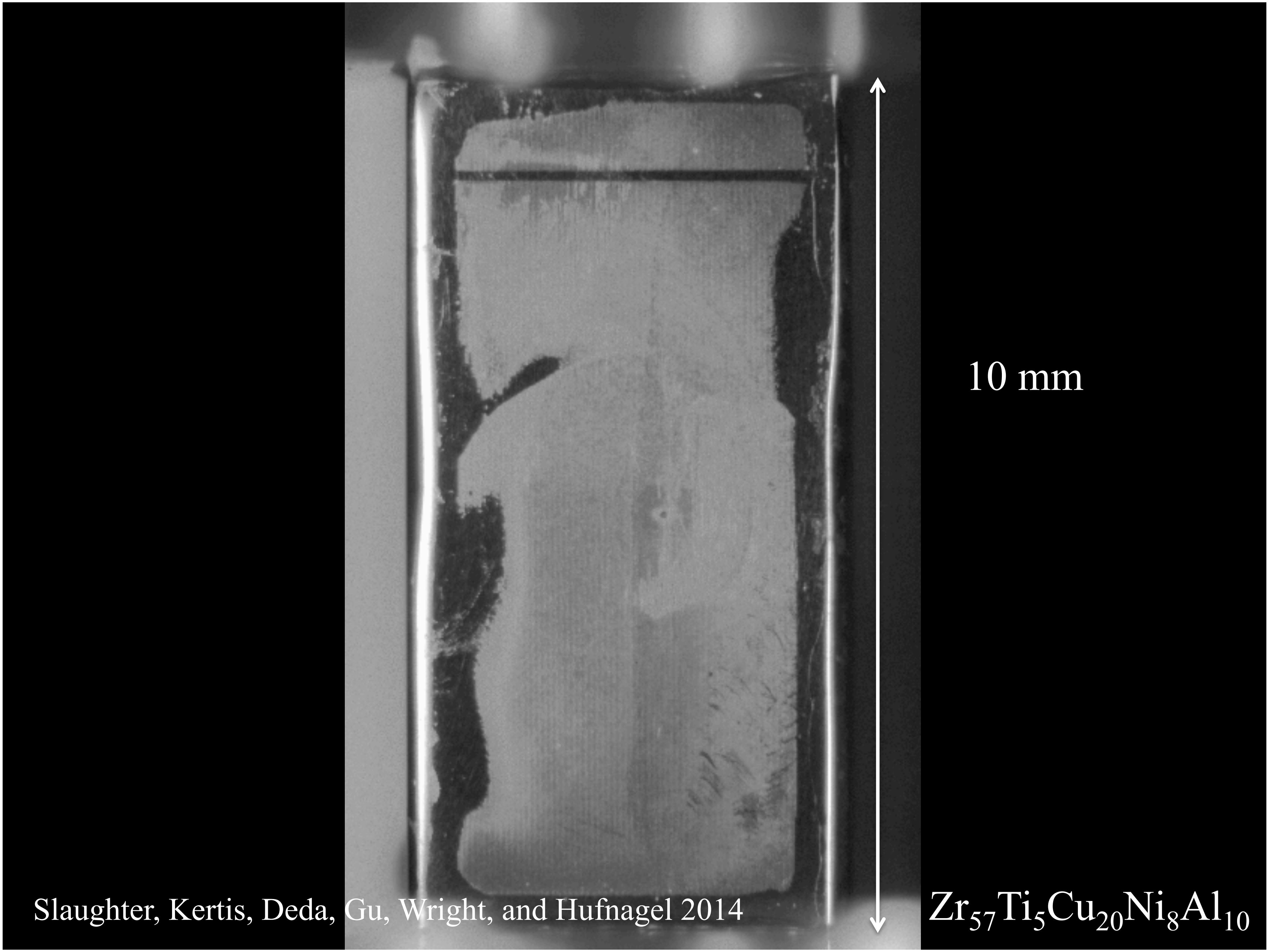


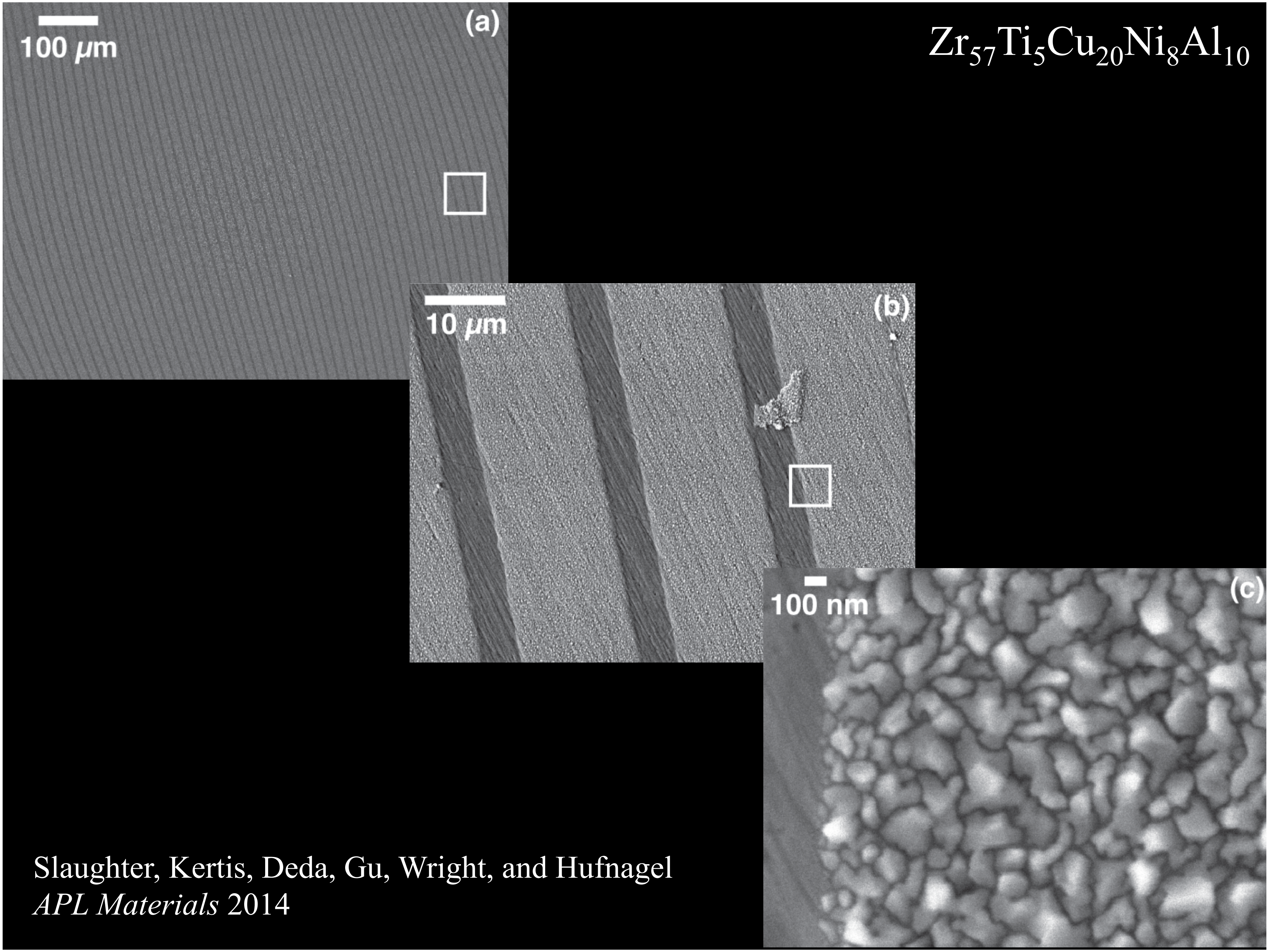
$Zr_{52.5}Cu_{17.9}Ni_{14.6}Al_{10}Ti_5$

FRACTURE



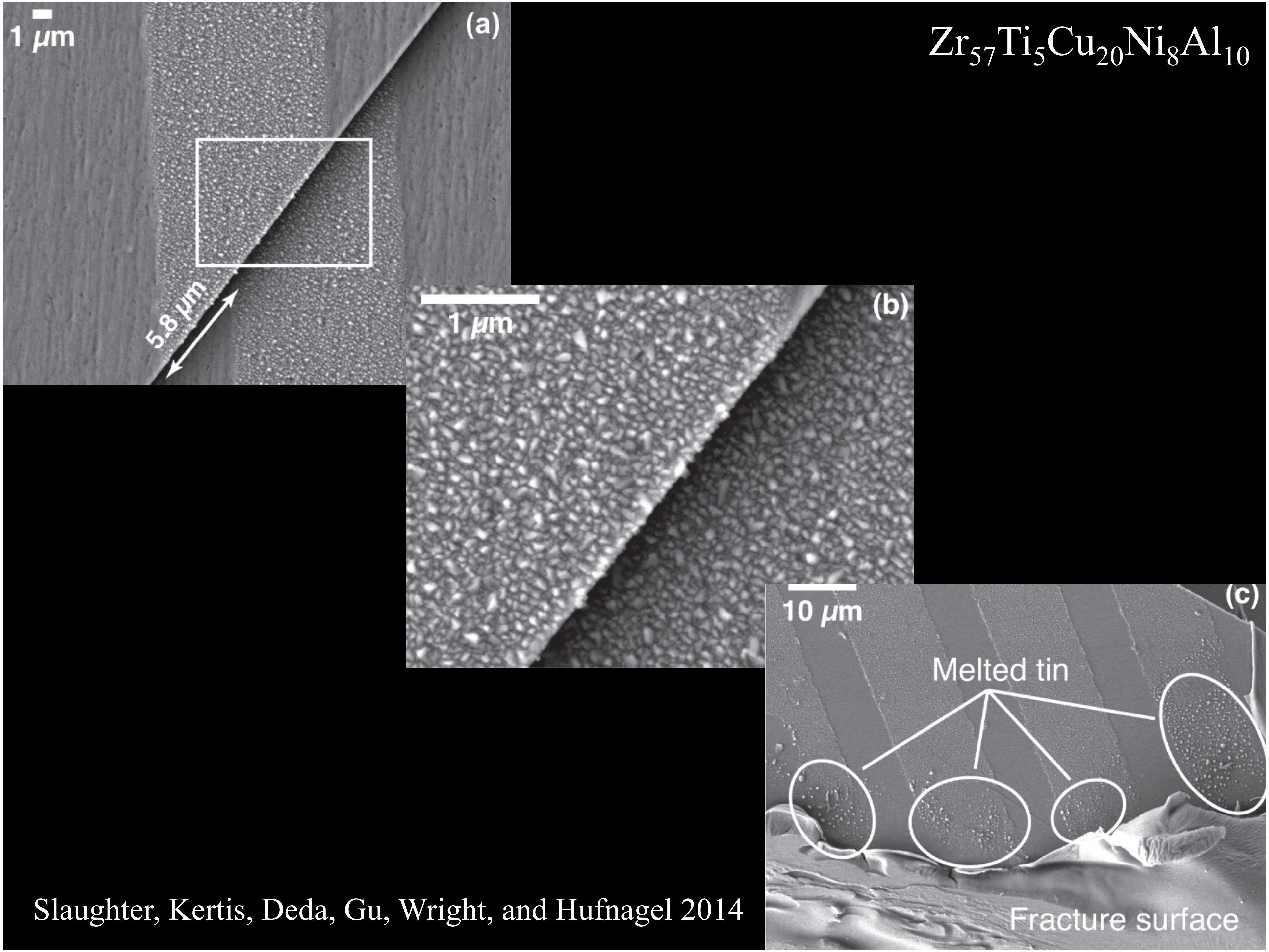
$Zr_{52.5}Cu_{17.9}Ni_{14.6}Al_{10}Ti_5$


10 mm
Slaughter, Kertis, Deda, Gu, Wright, and Hufnagel 2014
$Zr_{57}Ti_5Cu_{20}Ni_8Al_{10}$



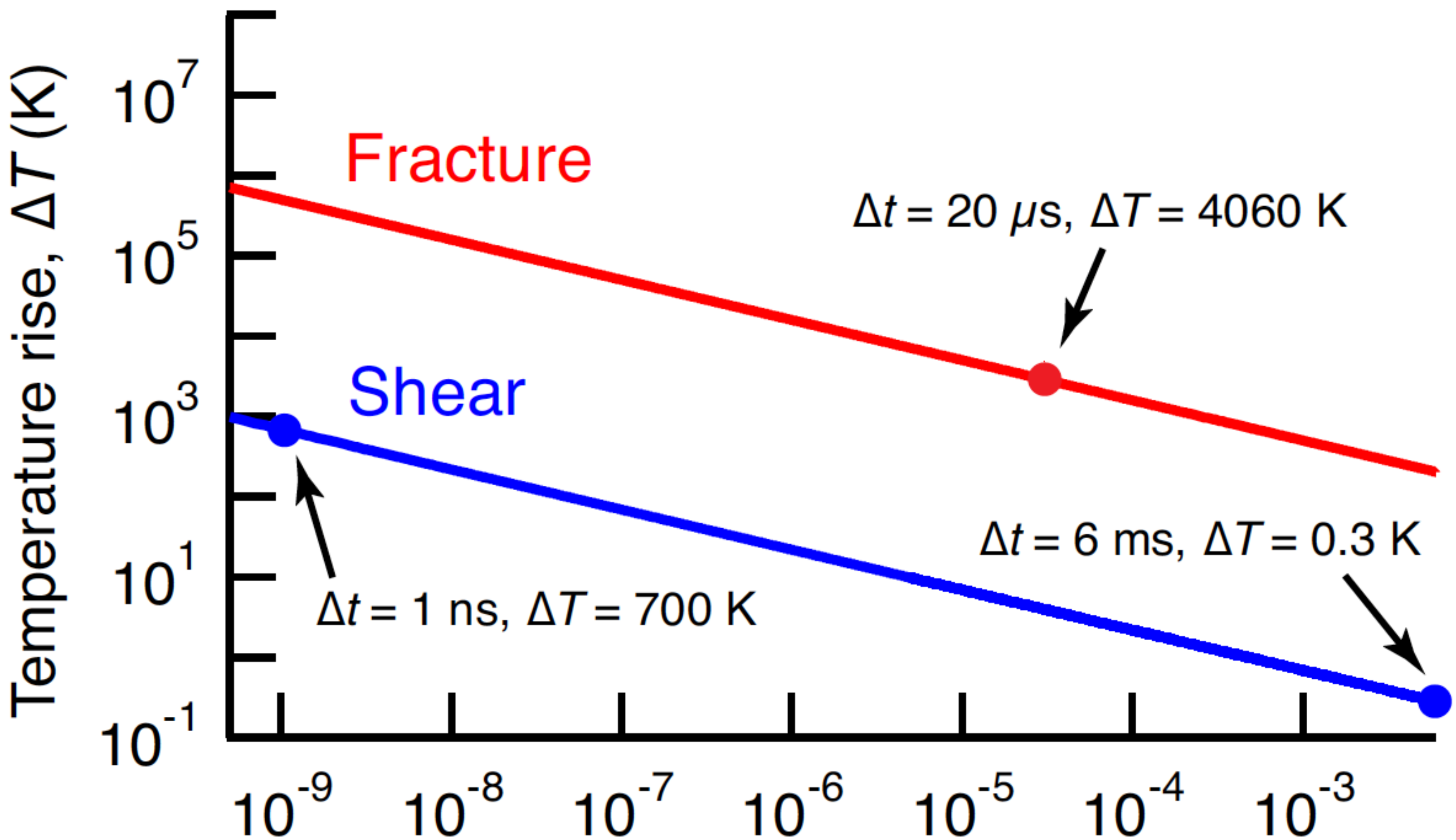
Slaughter, Kertis, Deda, Gu, Wright, and Hufnagel
APL Materials 2014

$Zr_{57}Ti_5Cu_{20}Ni_8Al_{10}$



Slaughter, Kertis, Deda, Gu, Wright, and Hufnagel 2014

Heating Predictions



Slaughter, Kertis, Deda, Gu, Wright, and Hufnagel *APL Materials* 2014

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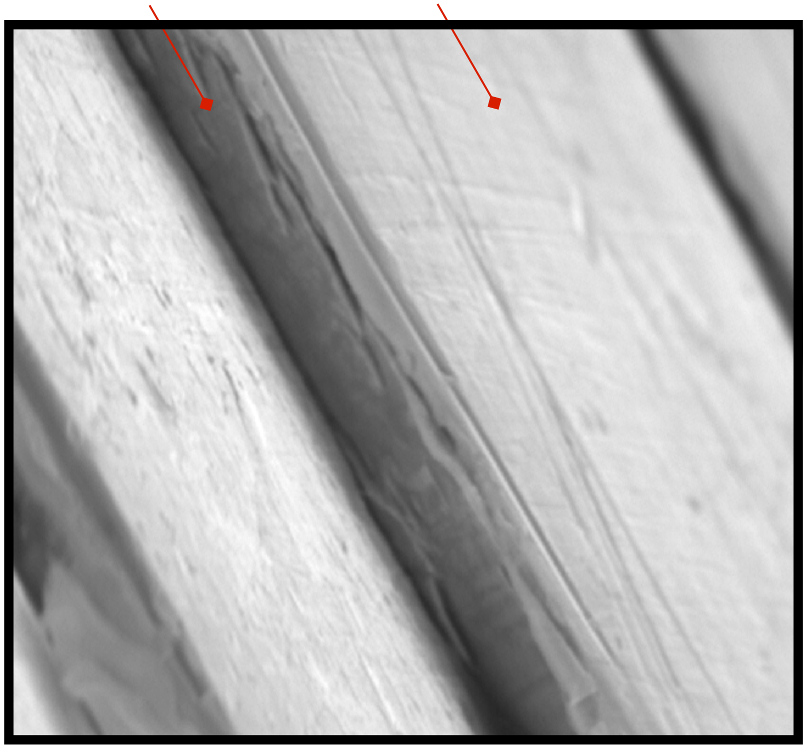
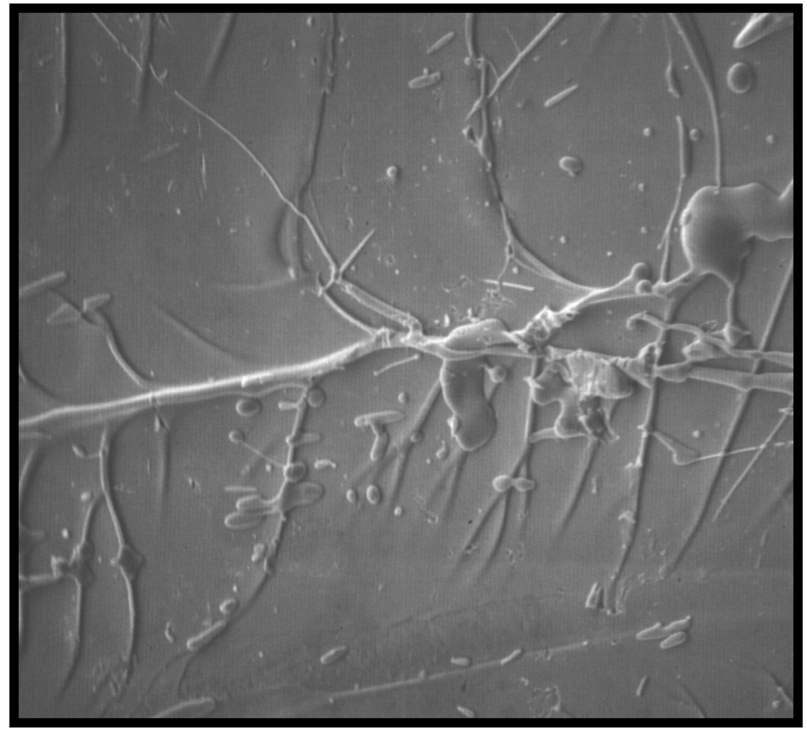
Deformed Surfaces



Zr–Ti–Ni–Cu–Be



Pd–Ni–P

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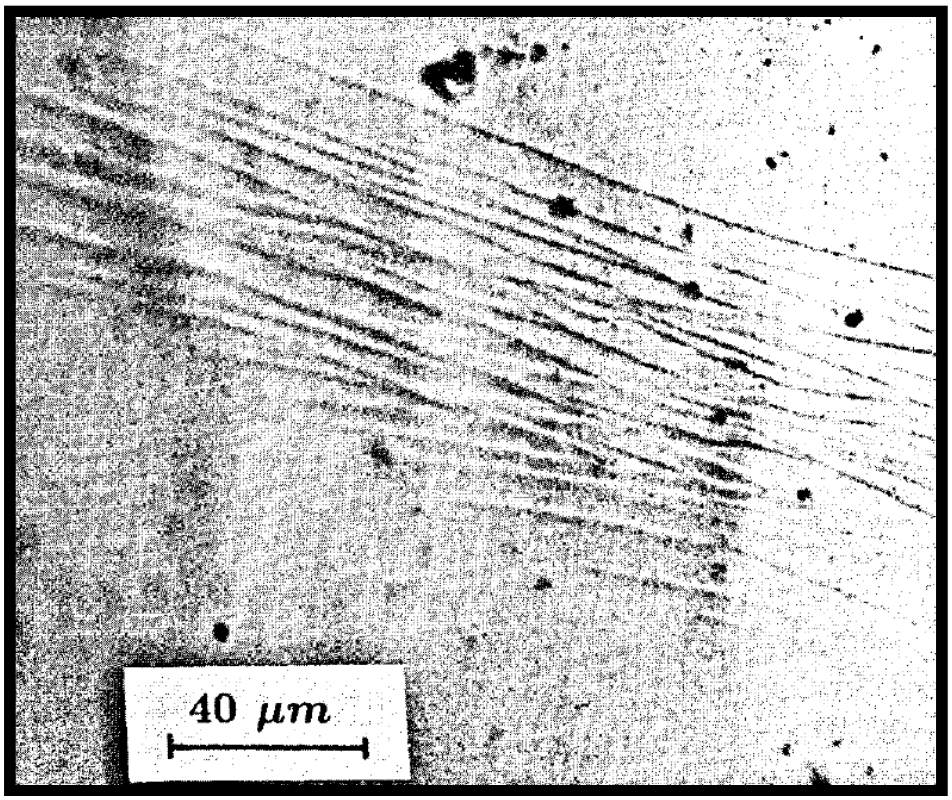
Bengus et al. *International Journal of Rapid Solidification*, 1993, Volume 8, pp. 21–31



"Plastic corrugation as a result of post–failure deformation by various types of elastic waves."

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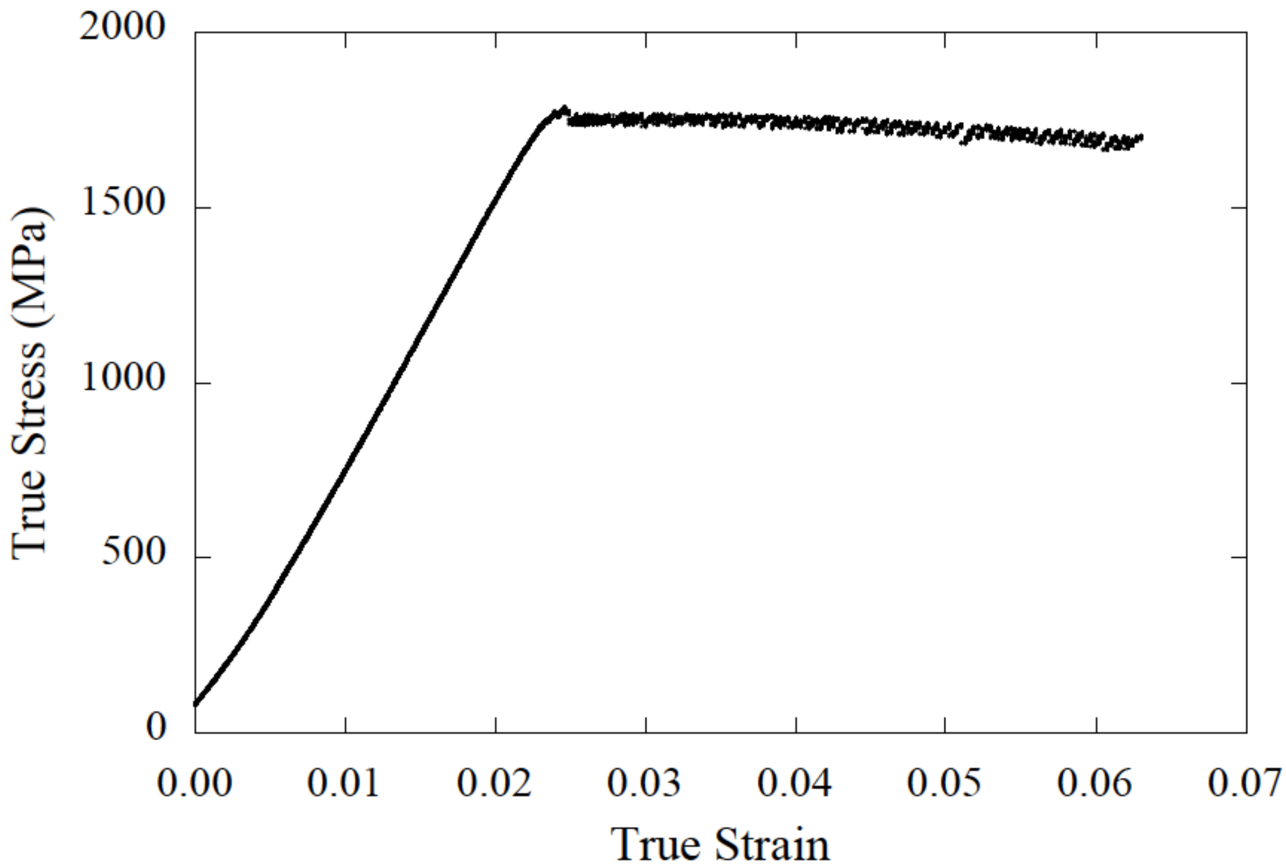
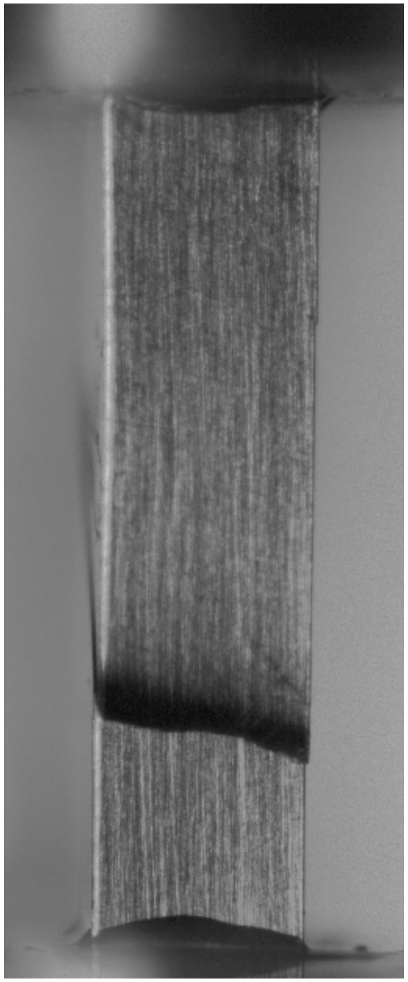
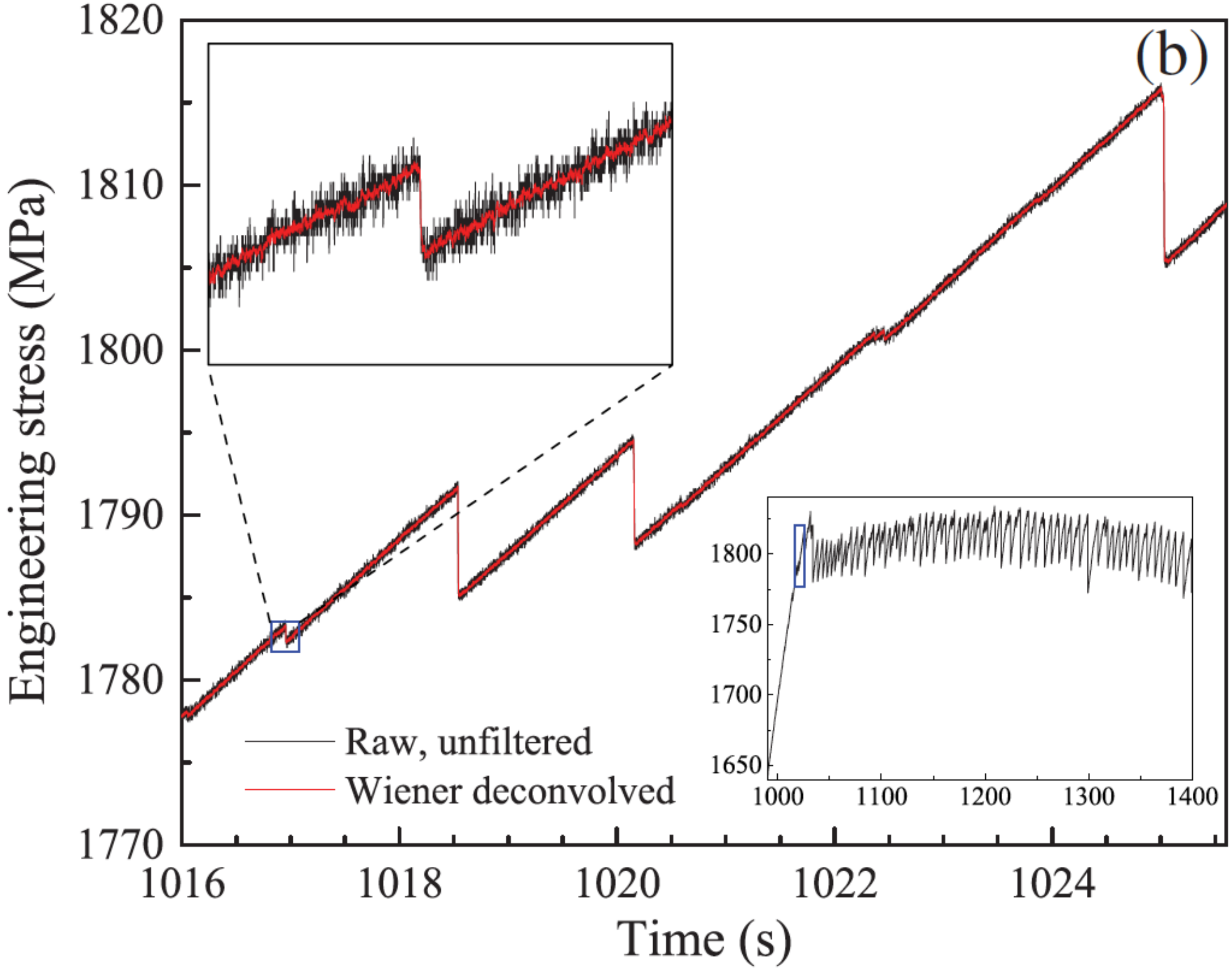
Ductile BMG





$Zr_{45}Hf_{12}Nb_5Cu_{15.4}Ni_{12.6}Al_{10}$



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Mean–Field Model with Slip Avalanches

K. A. Dahmen, Y. Ben-Zion, and J. T. Uhl *Phys. Rev. Lett.* **102**, 175501 (2009)

- Material loads elastically until a local failure stress is reached
- Local slip continues until a local arrest stress is attained
- Subsequent slip events in the same region require a lower activation stress (defined by a weakening parameter, epsilon)
- Local activation stress can be inhomogeneous (details of distribution do not affect scaling)
- Slip at one point can increase stress at other points, causing them to slip as well and leading to an avalanche of slip events
- The slip avalanche stops when the stress at each point is below the local failure stress

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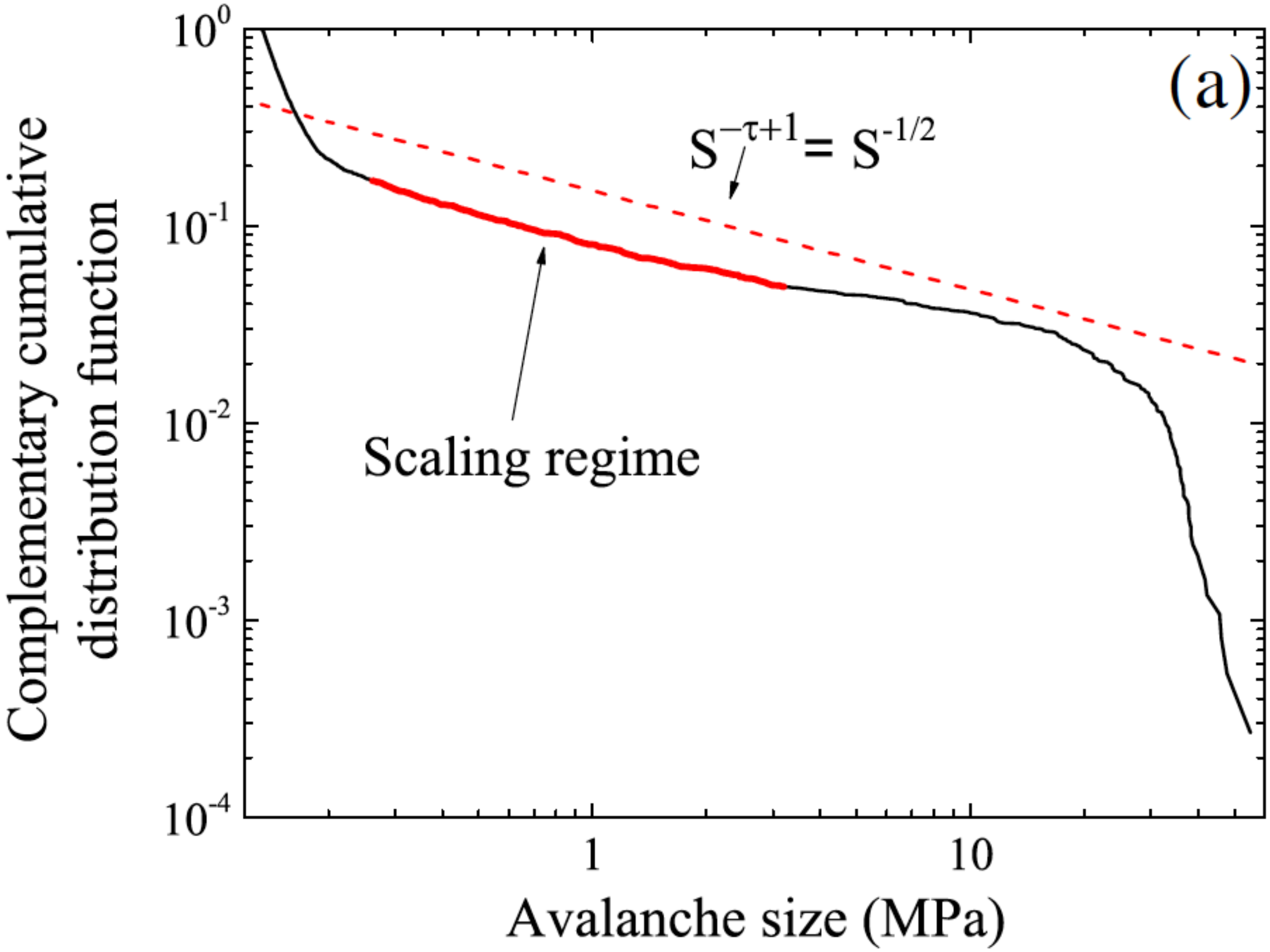

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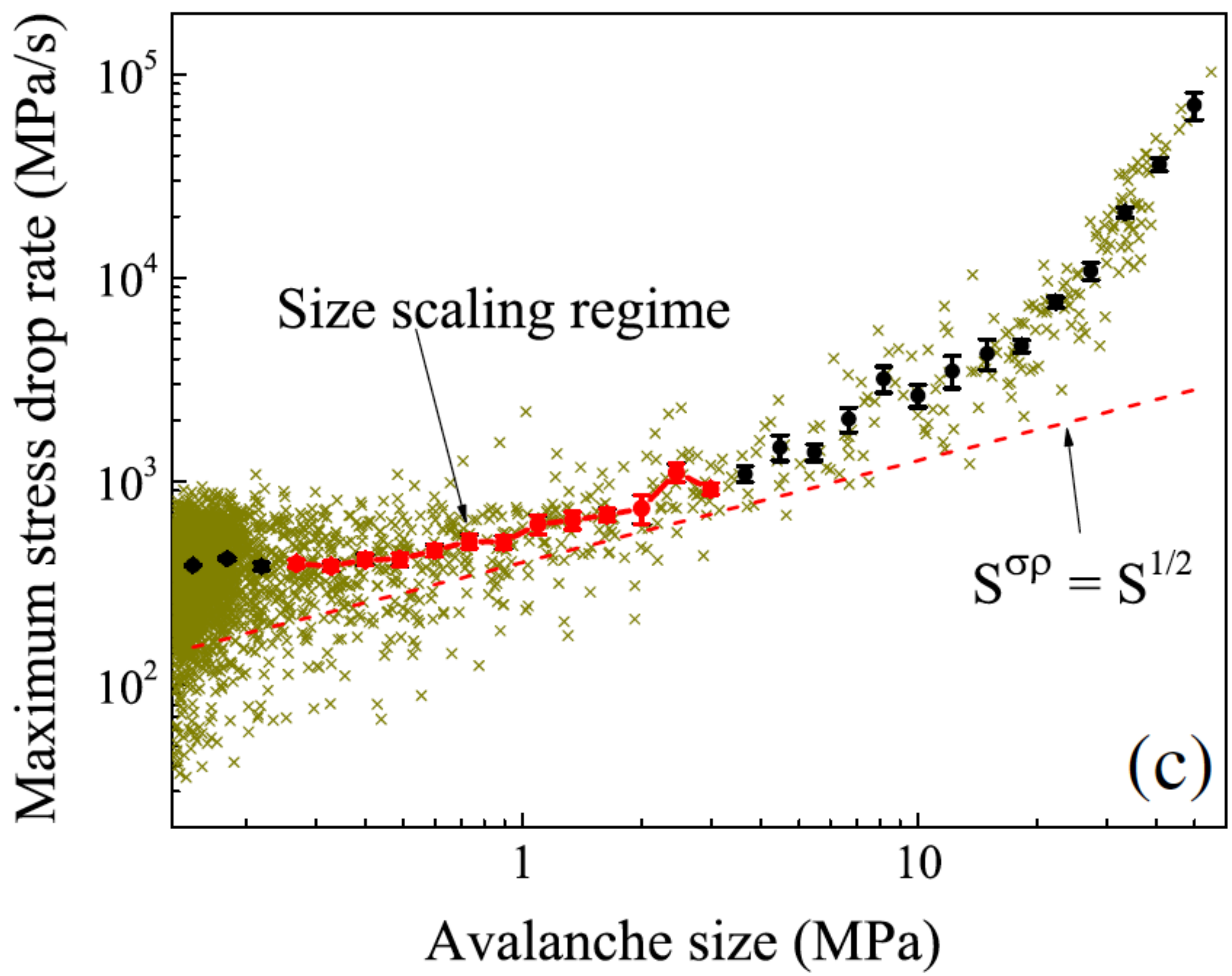

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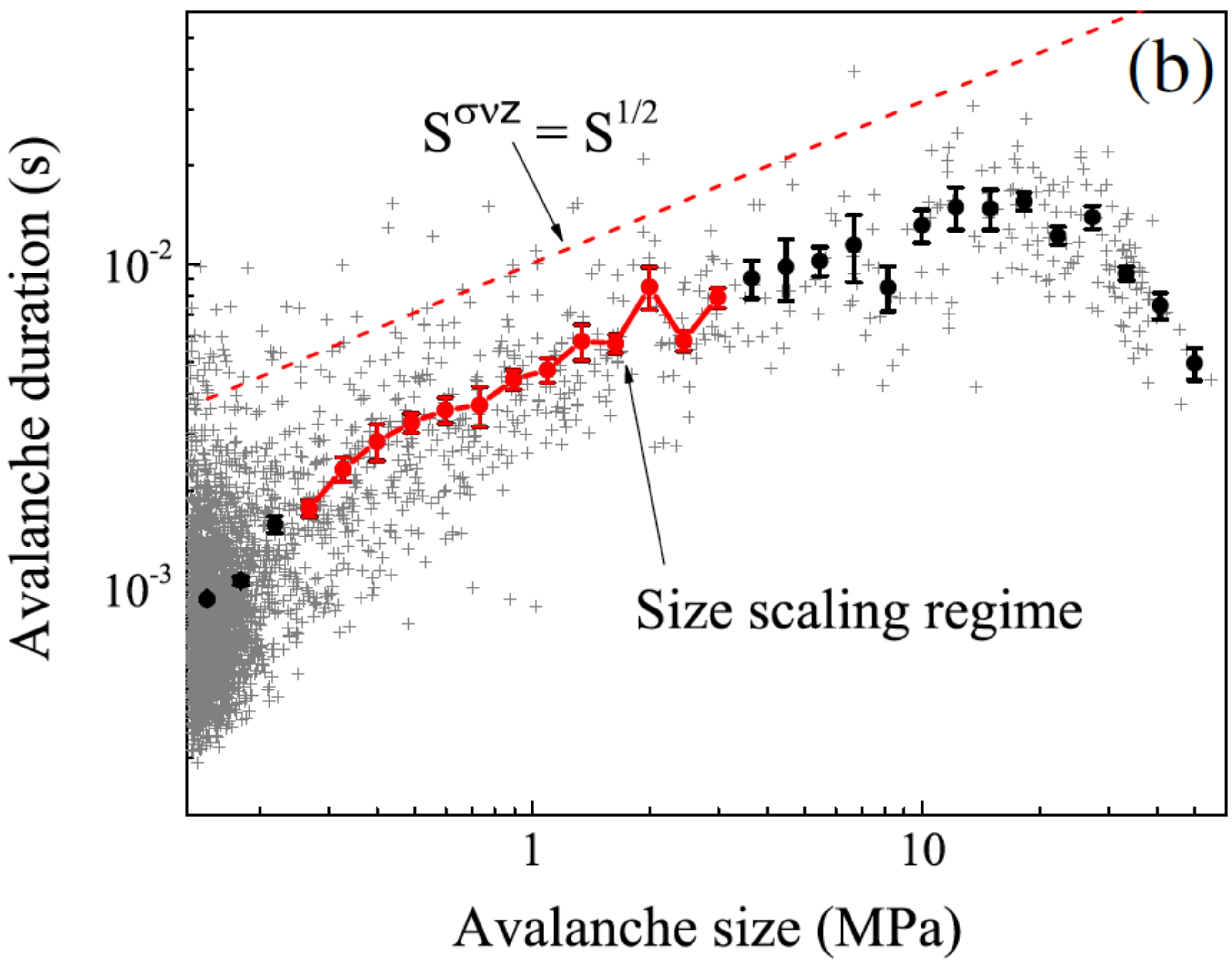

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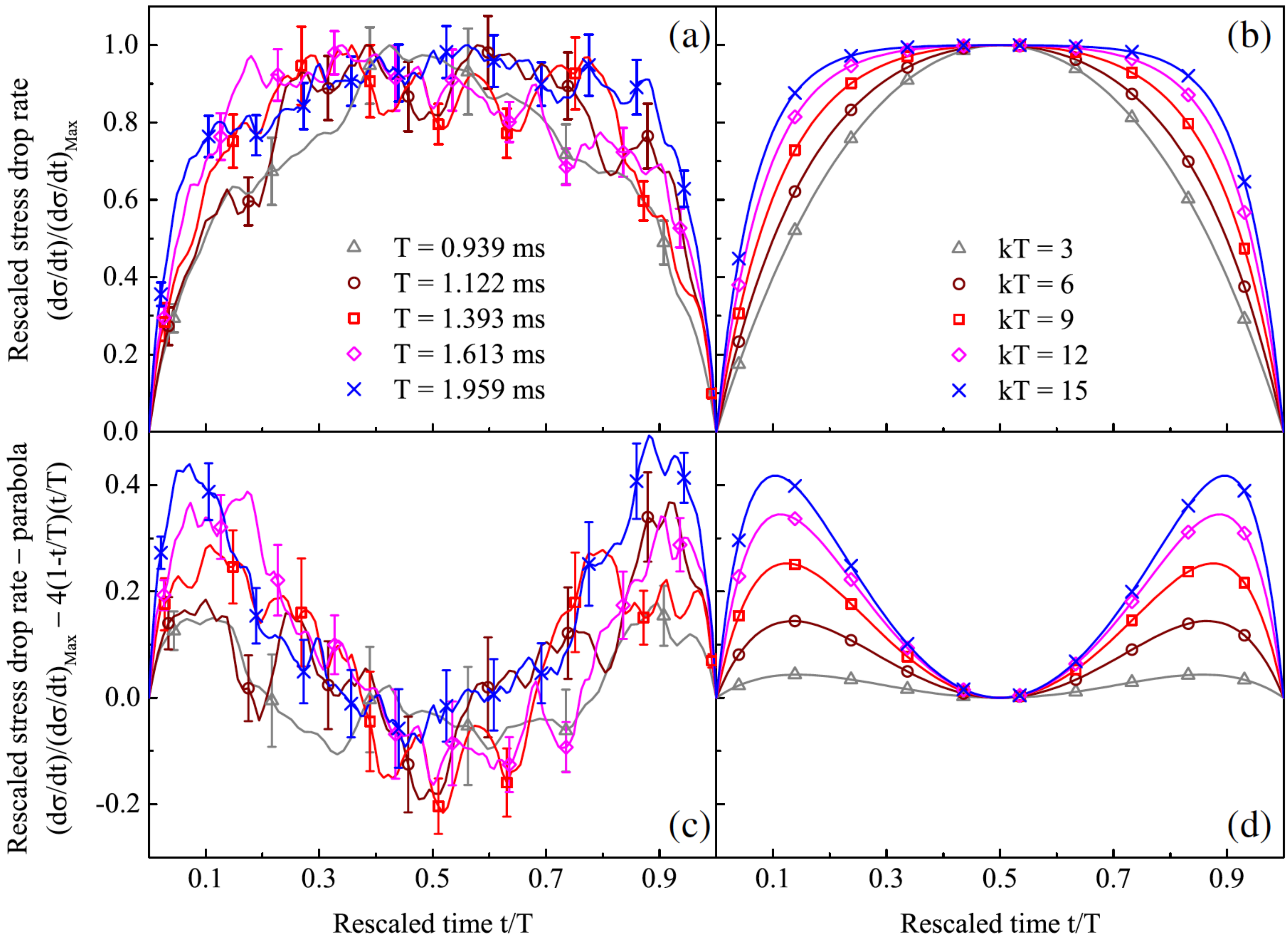

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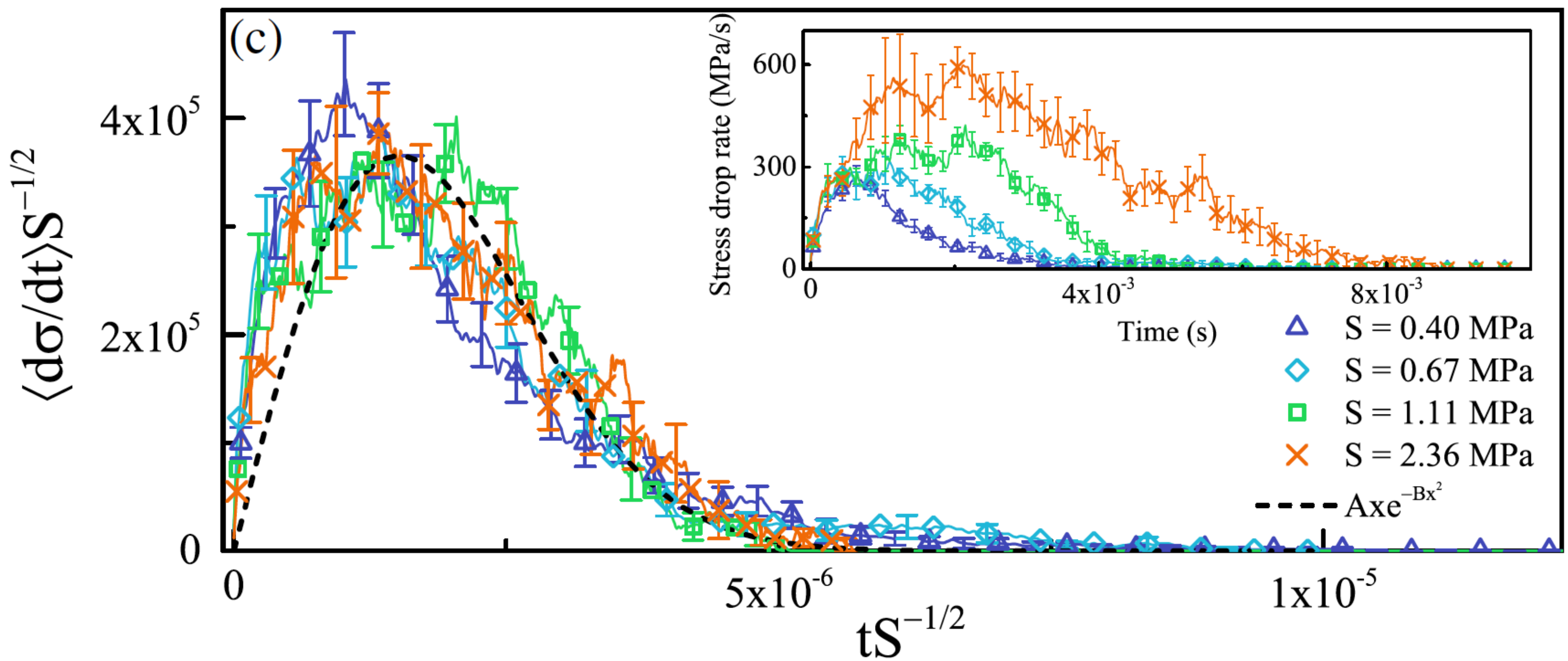

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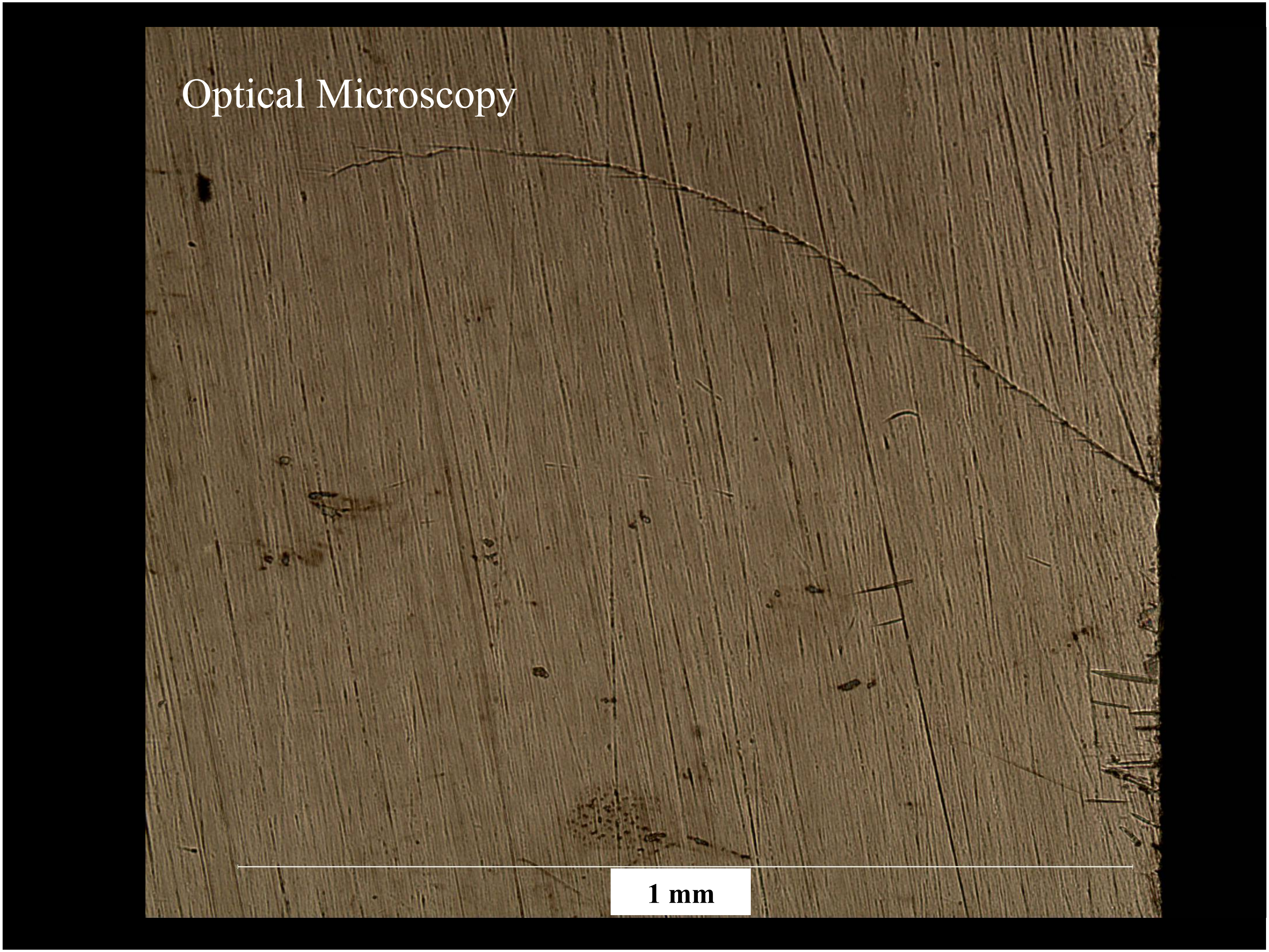
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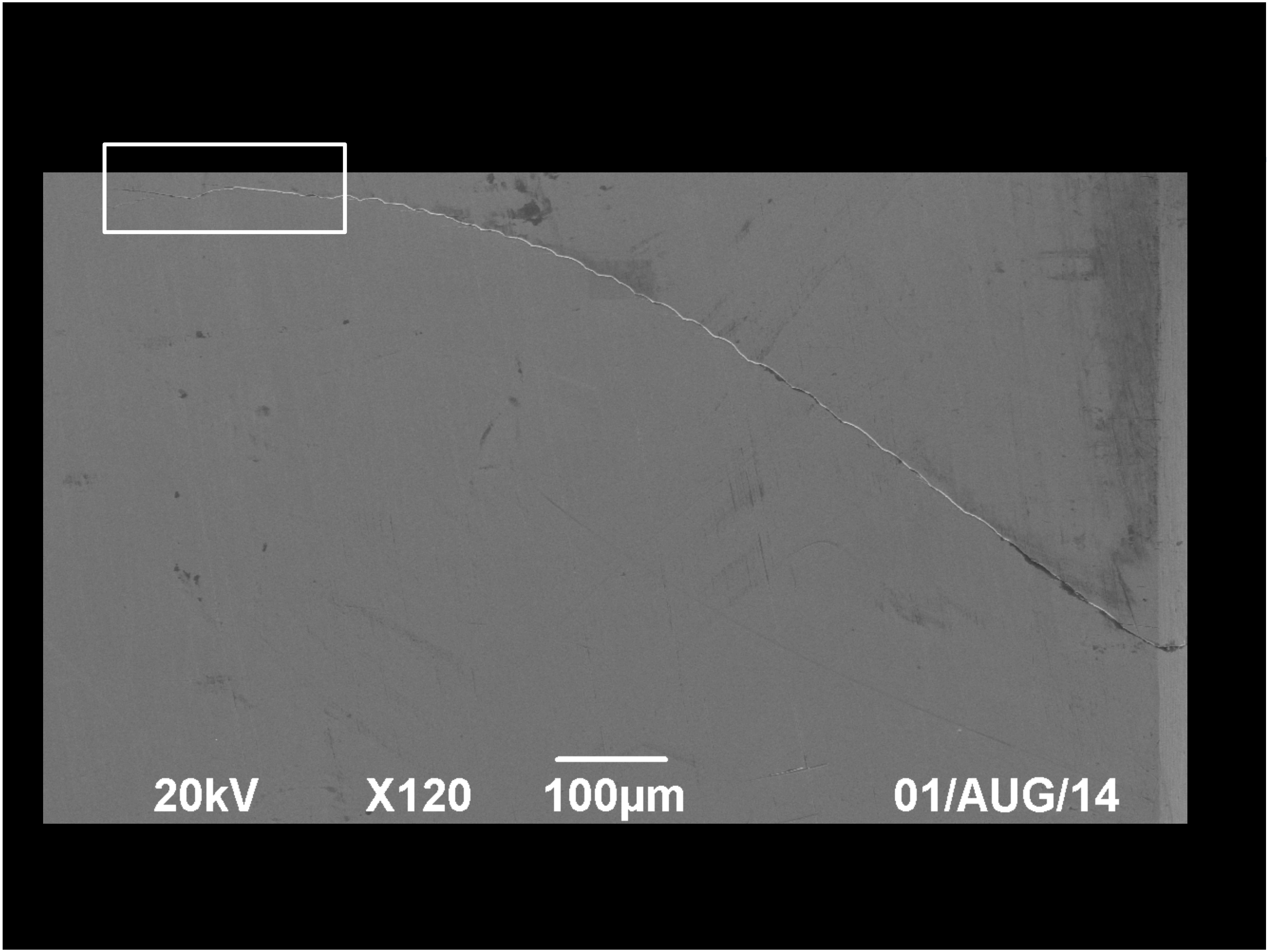
1 mm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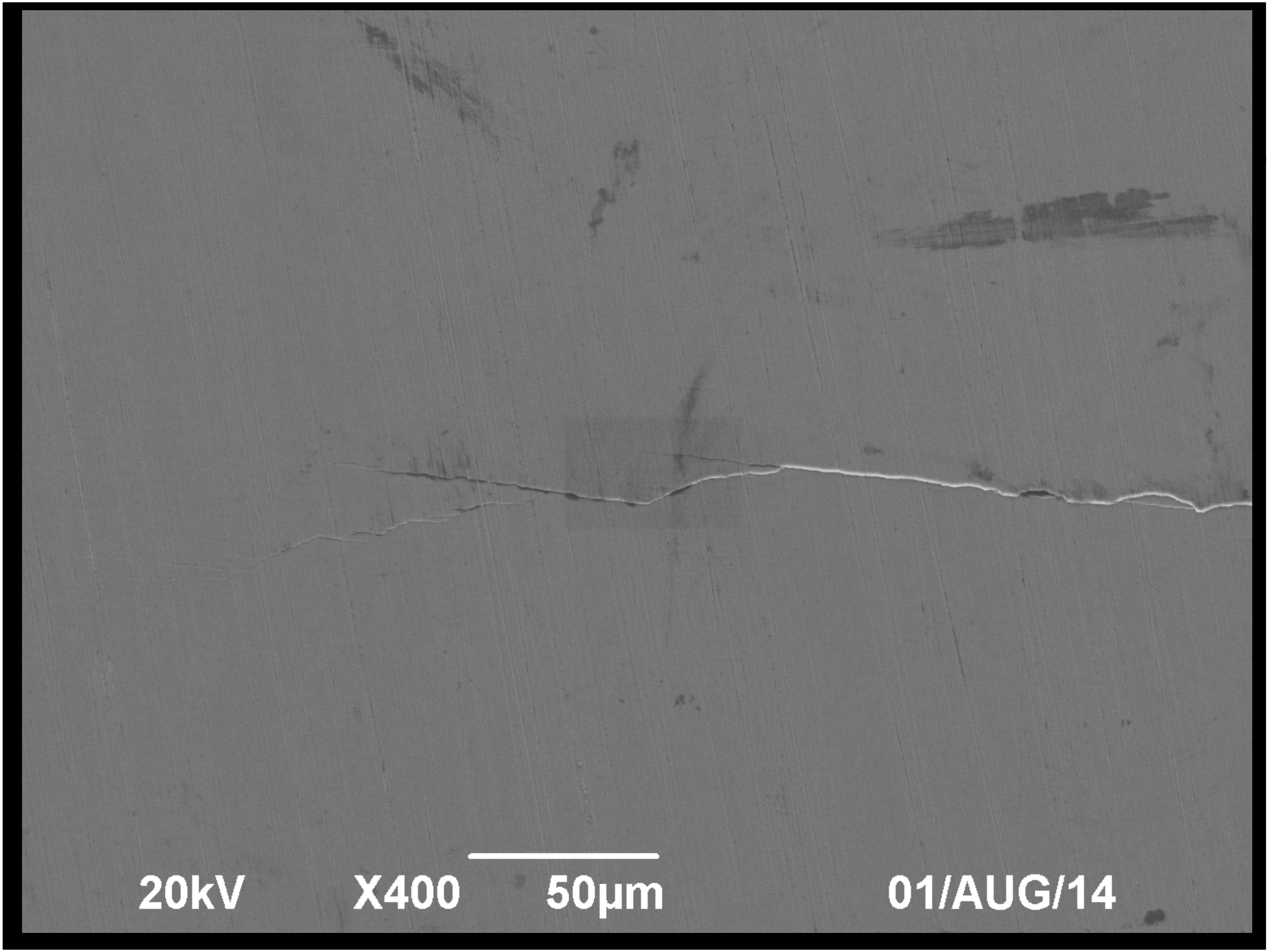
X120
100µm
01/AUG/14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50µm
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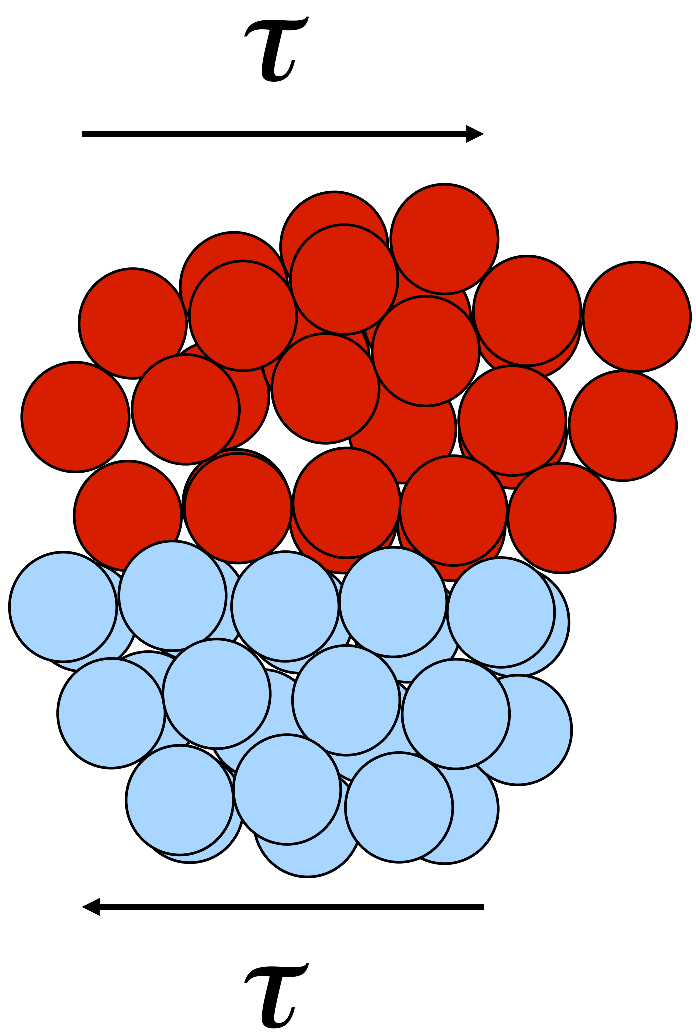
Shear Transformation Zone



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Implications

- Shear banding arises from the collective slip of coupled STZs as demonstrated by agreement with the mean field model for both slip statistics and dynamics

- Two scaling regimes predicted by the mean field model (progressive & simultaneous)

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Implications

- No trend in increasing size or decreasing duration as a function of strain for this alloy
- The largest serrations shed the load most quickly
- No serrations have a force drop rate sufficient to cause melting except for the failure event

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