Some Recent Collaborators

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Adapted from W.L. Johnson
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
Thermoplastic Molding & Hot Embossing

Processing

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

\[ Zr_{41.2} Ti_{13.8} Cu_{12.5} Ni_{10} Be_{22.5} \]
BMG Processing

Amorphous $\text{Zr}_{52.5}\text{Ti}_{5}\text{Al}_{10}\text{Cu}_{17.9}\text{Ni}_{14.6}$
Deformation of Crystalline Metals

Dislocation motion

Animation courtesy of J.N. Florando
Limited Ductility

Compression

True Stress (MPa)

True Strain

E = 97 GPa

E = 96 GPa

σ_{yield} = 1.9 GPa

σ_{yield} = 1.7 GPa

Zr_{40}Ti_{14}Ni_{10}Cu_{12}Be_{24}

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

Tension

True Stress (MPa)

True Strain

Zr_{41.2}Ti_{13.8}Ni_{10.0}Cu_{12.5}Be_{22.5}

Shear Banding
Zr–Ti–Ni–Cu–Be

Shear Step

Sample Face

Pd–Ni–P

Zr–Ti–Ni–Cu–Be
Fracture Events in Metallic Glasses
Localized Adiabatic Heating


Pd–Ni–P

50 µm
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.
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).
Serrated Flow

\[ \sigma_{\text{yield}} = 1.9 \text{ GPa} \]
\[ \sigma_{\text{yield}} = 1.7 \text{ GPa} \]

\[ E = 97 \text{ GPa} \]
\[ E = 96 \text{ GPa} \]

- Zr\textsubscript{40}Ti\textsubscript{14}Ni\textsubscript{10}Cu\textsubscript{12}Be\textsubscript{24}
- Pd\textsubscript{40}Ni\textsubscript{40}P\textsubscript{20}

True Stress (MPa)
True Strain
Mechanics of the Load Train

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


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

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

\[
d\sigma = -\left( \frac{k_{\text{machine}} E}{k_{\text{machine}} + \frac{EA}{L}} \right) d\varepsilon_p
\]

$E$ = sample elastic modulus, $A$ = sample cross-sectional area, $L$ = sample length
Effect of Sample Size

\[ d\sigma = -\left(\frac{k_{machine} E}{k_{machine} + \frac{EA}{L}}\right) d\epsilon_p \]

- For a stiff machine,
  \[ k_{machine} \gg \frac{EA}{L} \]
  \[ d\sigma \approx -E d\epsilon_p \]
  Large

- For a compliant machine,
  \[ k_{machine} \ll \frac{EA}{L} \]
  \[ d\sigma \approx -\frac{k_{machine} L}{A} d\epsilon_p \]
  Small

Stability/Instability Map

Han, Wu, Li, Wei, and Gao *Acta Materialia* 2009
Bilinear Machine Stiffness

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
Precision Alignment

![Graph showing engineering stress vs. engineering strain with data points labeled Gage A1, Gage B1, Gage A2, Gage B2.](image-url)
50 Hz Acquisition
100 kHz Acquisition


\[ \text{A opposes C} \]

\[ \text{B opposes D} \]

\[ \text{Pd}_{40}\text{Ni}_{40}\text{P}_{20} \]
100 kHz Acquisition

A opposes C
B opposes D
100 kHz Acquisition

A opposes C
B opposes D

\( \Delta t = 1.2 \, \text{ms} \)
100 kHz Acquisition

A opposes C
B opposes D
100 kHz and 400 kHz

A opposes C
B opposes D
Implications for Shear Band Velocity

Simultaneous Shear

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

Progressive Shear

\[
\frac{2\sqrt{2} \text{ mm}}{1 \text{ ms}} = 2.8 \text{ m/s}
\]
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
$\text{Zr}_{45}\text{Hf}_{12}\text{Nb}_{5}\text{Cu}_{15.4}\text{Ni}_{12.6}\text{Al}_{10}$
http://dx.doi.org/10.1063/1.4895605

Zr_{45}Hf_{12}Nb_{5}Cu_{15.4}Ni_{12.6}Al_{10}
Load versus Time

Image Correlation

Initial

After Deformation

Large Strains

Camera

Courtesy of M.M. LeBlanc
Load versus Time

Displacement (µm)

Image Number

Load versus Time

Bucknell UNIVERSITY
Zr$_{52.5}$Cu$_{17.9}$Ni$_{14.6}$Al$_{10}$Ti$_5$
FRACTURE

Load (N)

Time (s)

Zr$_{52.5}$Cu$_{17.9}$Ni$_{14.6}$Al$_{10}$Ti$_{5}$
$\text{Zr}_{57}\text{Ti}_{5}\text{Cu}_{20}\text{Ni}_{8}\text{Al}_{10}$
Slaughter, Kertis, Deda, Gu, Wright, and Hufnagel

APL Materials 2014
$Zr_{57}Ti_{5}Cu_{20}Ni_{8}Al_{10}$
Heating Predictions

Temperature rise, $\Delta T$ (K)

Fracture

$\Delta t = 20 \mu s, \Delta T = 4060$ K

Shear

$\Delta t = 6$ ms, $\Delta T = 0.3$ K

$\Delta t = 1$ ns, $\Delta T = 700$ K

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

Shear Step  Sample Face

Zr–Ti–Ni–Cu–Be  5 µm

Fracture Surface

Pd–Ni–P  50 µm
“Plastic corrugation as a result of post–failure deformation by various types of elastic waves.”
Ductile BMG

\[ \text{Zr}_{45}\text{Hf}_{12}\text{Nb}_{5}\text{Cu}_{15.4}\text{Ni}_{12.6}\text{Al}_{10} \]
Antonaglia, Wright, Gu, Byer, Hufnagel, LeBlanc, Uhl, and Dahmen

*Physical Review Letters* 2014
Mean–Field Model with Slip Avalanches


- 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
Antonaglia, Wright, Gu, Byer, Hufnagel, LeBlanc, Uhl, and Dahmen

Physical Review Letters 2014
Antonaglia, Wright, Gu, Byer, Hufnagel, LeBlanc, Uhl, and Dahmen

*Physical Review Letters* 2014

**Figure (c):**

- **Size scaling regime:**
  
  \[ S^{\sigma_p} = S^{1/2} \]

- **Avalanche size (MPa)**

- **Maximum stress drop rate (MPa/s)**

- The graph shows a scaling relationship between the avalanche size and the maximum stress drop rate.
Antonaglia, Wright, Gu, Byer, Hufnagel, LeBlanc, Uhl, and Dahmen

*Physical Review Letters* 2014
Antonaglia, Wright, Gu, Byer, Hufnagel, LeBlanc, Uhl, and Dahmen

*Physical Review Letters* 2014
Shear Transformation Zone

\[ \tau \]

\[ \tau \]
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).
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
Acknowledgments

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