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New Strength Data on Aluminum to 160 GPa

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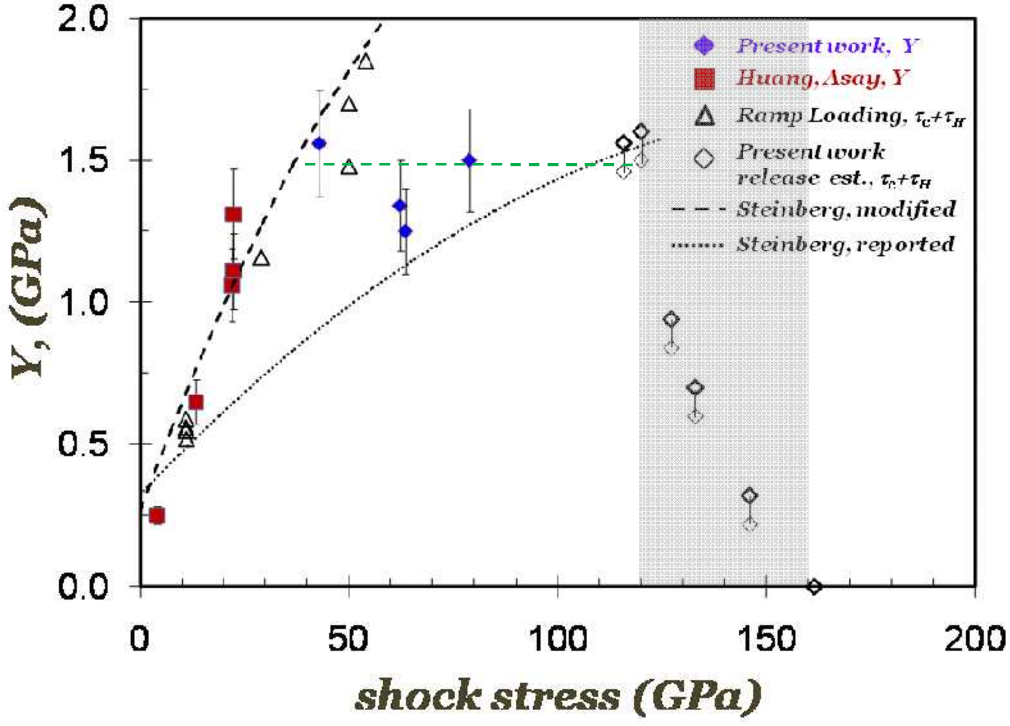

JOWOG 32 Mat
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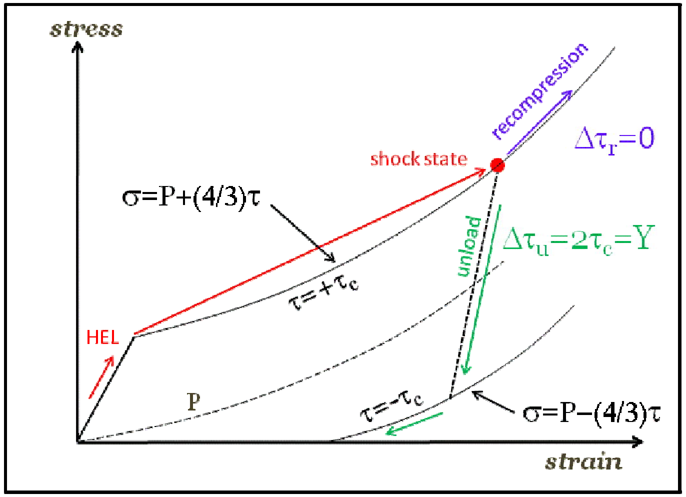
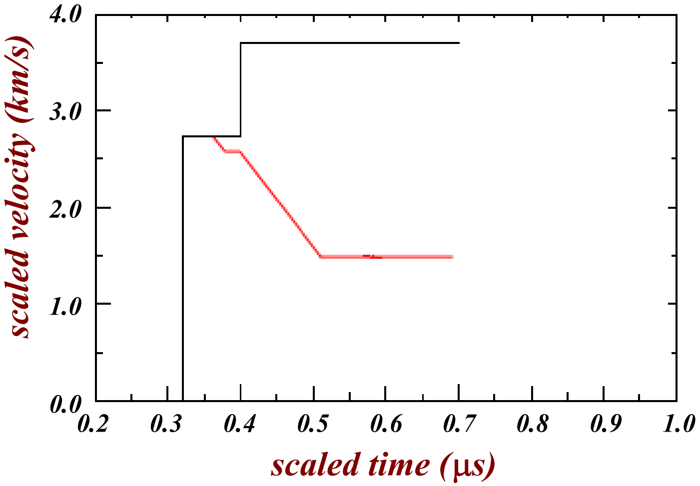
Elastic-plastic theory assumes shock states lie on the upper yield surface

- According to elastic-plastic theory for uniaxial strain:
  - On shock loading, the material first loads elastically to the HEL
  - Shock states lie on a yield surface $\tau=+\tau_c$
  - On release, the material unloads elastically to a yield surface $\tau=-\tau_c$
  - Elastic portion of the release gives $\Delta\tau_u=2\tau_c=Y$
  - Key assumption is that the shock state lies on the upper yield surface
  - $\Delta\tau_r=0$ on reload
    - » inconsistent with experimental data showing quasi-elastic compression on reloading





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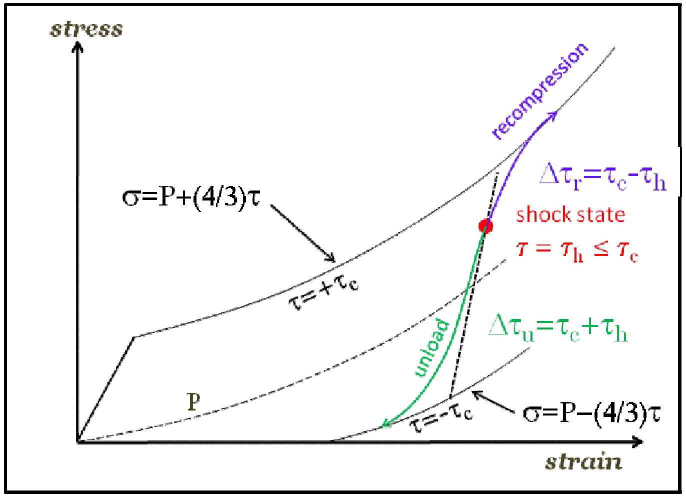
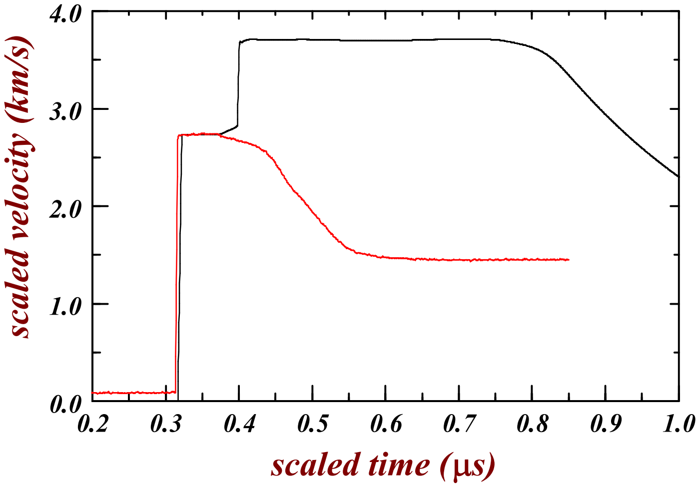
Measured strength can be off by up to a factor of two if E-P assumption is invalid

- **If the shock state is NOT on the upper yield surface:**
  - **Evidence suggests that the shock states lie at $\tau=+\tau_H$ ($\leq \tau_c$)**
  - **On release, the material unloads elastically to a yield surface $-\tau_c$ below the hydrostat**
  - **Elastic portion of the release gives $\Delta\tau_u=\tau_c+\tau_H\leq Y$**
  - **In order to determine Y must measure both τ_c and τ_H**
  - **Requires both reload and release data: $Y=2\tau_c=\Delta\tau_u+\Delta\tau_r$**
  - **Measuring release only can lead to errors up to a factor of 2**

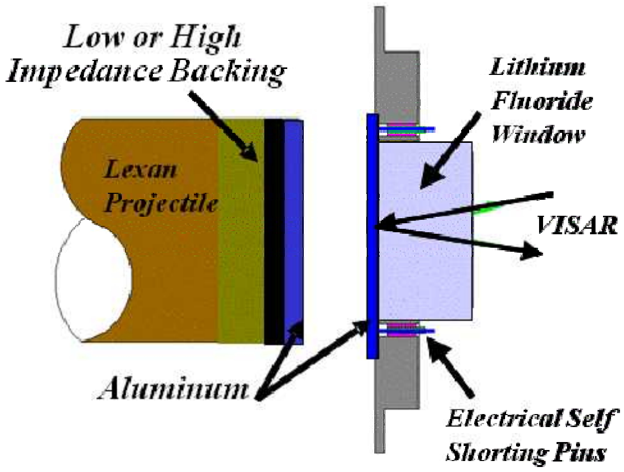




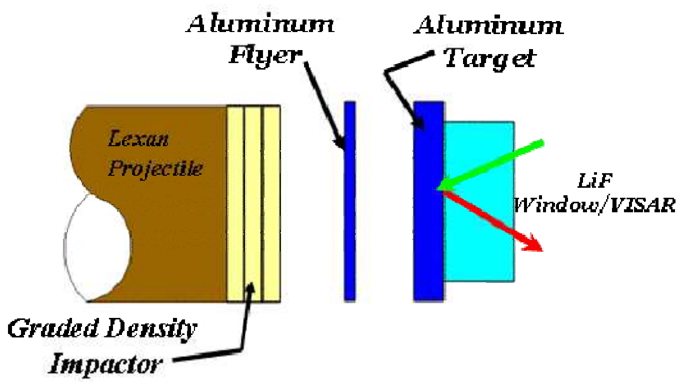
Experimental techniques used for unloading and reloading experiments to 160 GPa

- Symmetric impact conditions
  - 3-10 km/s impact velocity
  - Low impedance backing material or free surface generate release
  - High impedance backing generates reload
- VISAR diagnostics
  - High sensitivity (0.047 – 1.79 km/s/fr) used to resolve QE recompression
  - Particle velocity uncertainty of 0.1 – 1.0%
- Previous difficulties
  - Separation of impactor and backing material compromises reloading data

2-stage configuration

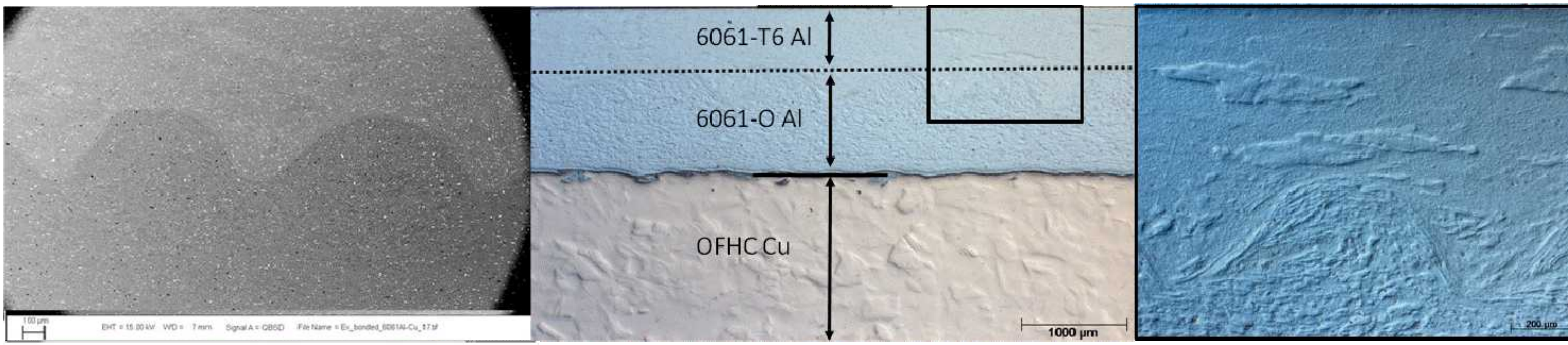


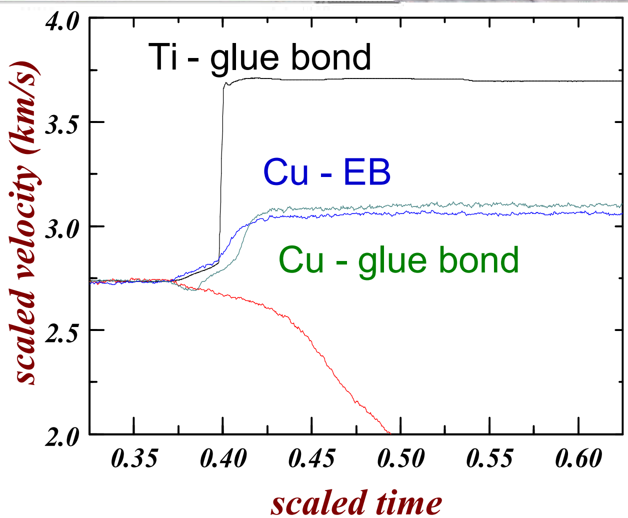
3-stage configuration



Explosively bonded (EB) impactors improve performance over epoxy bonds

- **EB Cu backed Al used as impactors in the reload configuration**
- **No evidence of bond separation as observed previously with epoxy bonding**





•Material supplied to SNL by B. Jensen (LANL)
•Material fabricated by High Energy Metals, Inc. (Sequim, WA)

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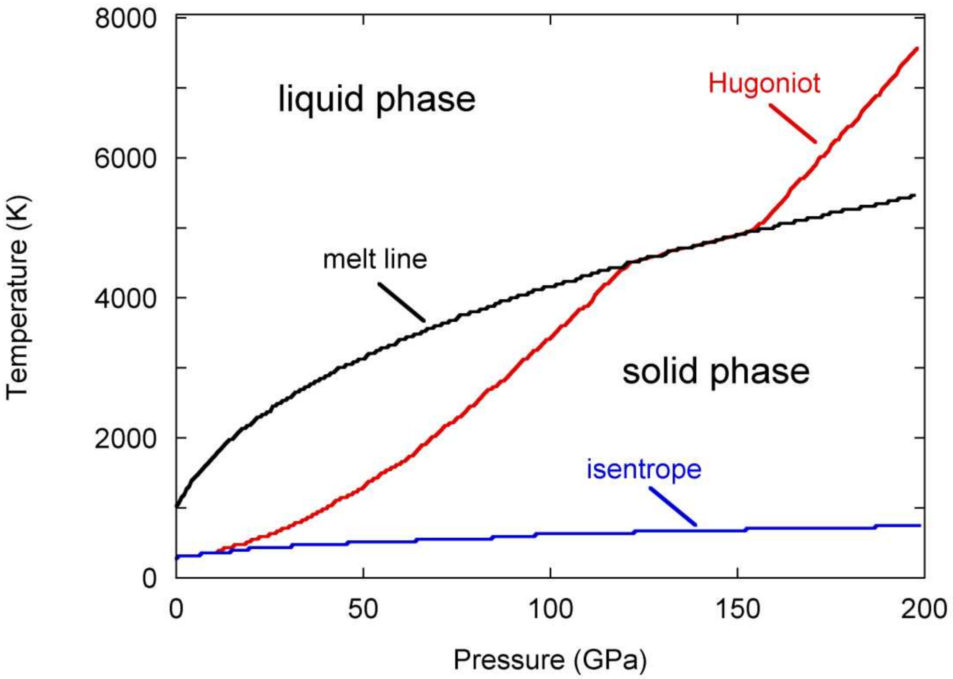
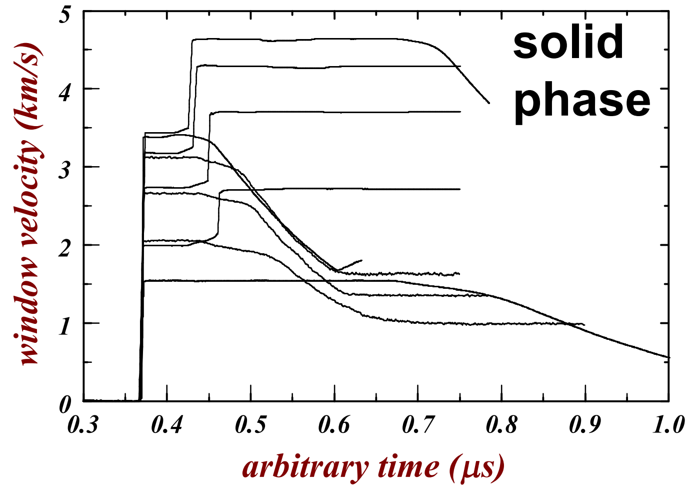
Shock loaded aluminum has a mixed phase region between 120-160 GPa

- **Material strength in shock induced solid-liquid coexistence regions has not been studied**
- **Solid-liquid coexistence is expected to influence strength**
- **Experimentally determined phase boundaries have some uncertainty (~5 GPa)**

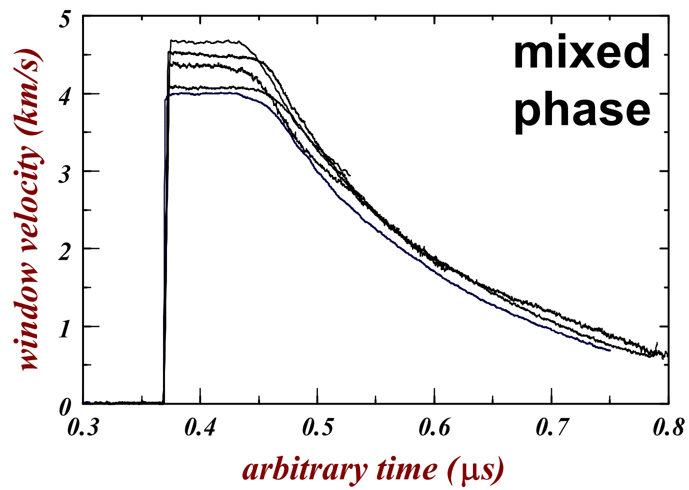


QE response observed in both unloading and reloading data

- **Two-stage shots**
  - Unload/reload pairs performed at nearly identical shock conditions
  - QE release (reload) portion of profile provides $\Delta\tau_u$ ($\Delta\tau_r$)



- **Three-stage shots**
  - Reload has not yet been performed in the three-stage configuration
  - However, release only at high pressures (115 – 161 GPa) provides a good estimate of strength as will be shown

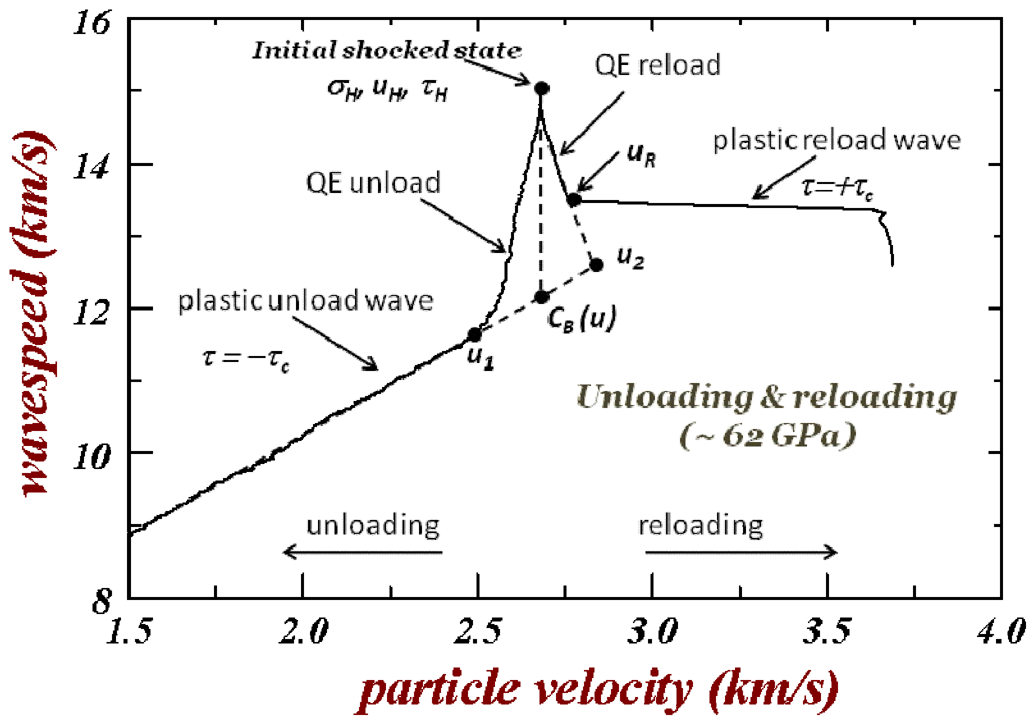


Δτ is determined for unloading (reloading) from the QE portion of each wave profile

- **Wave speed is calculated from the recorded VISAR profiles**
- **The resolved shear stress is given by**

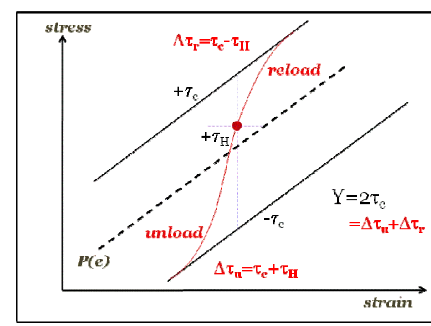
$$d\tau = \frac{3}{4}\rho_0\left(c^2 - c_B^{\,2}\right)de$$

- **Integrating with respect to *u* gives:**



unload: $$\Delta\tau_u = \tau_c + \tau_H = -\frac{3}{4}\rho_0\int_{u_1}^{u_H}\left(c^2 - c_B^{\,2}\right)\frac{du}{c_L}$$

reload: $$\Delta\tau_r = \tau_c - \tau_H = \frac{3}{4}\rho_0\int_{u_H}^{u_2}\left(c^2 - c_B^{\,2}\right)\frac{du}{c_L}$$



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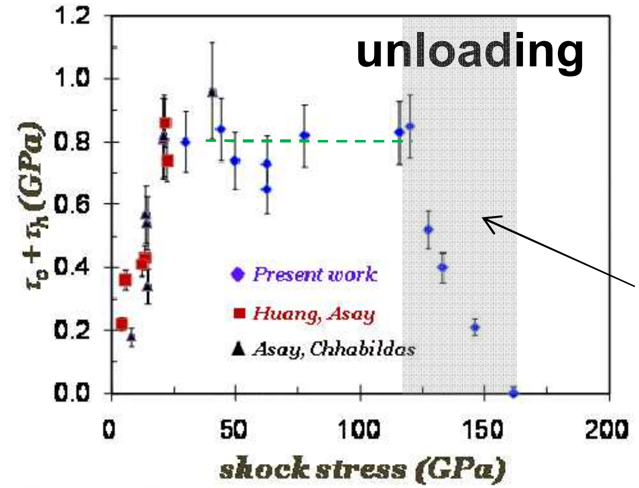
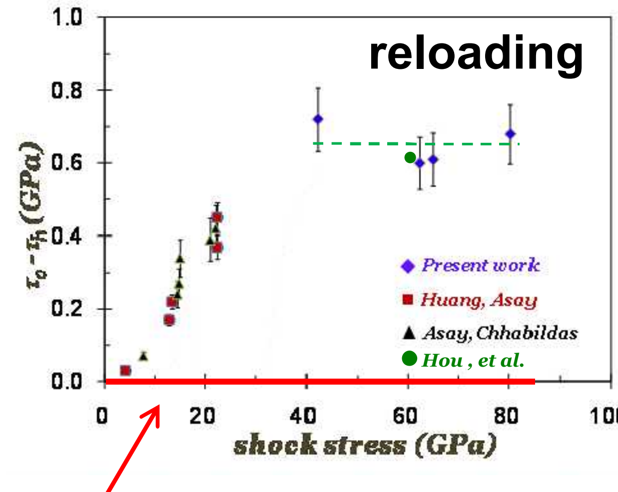
Measured $\Delta\tau$ shows a complex response above 40 GPa

- **Data is plotted with previous lower stress data**
  - Data agree in overlap region (<40 GPa)
  - Essentially constant values seen between 40 GPa and onset of melt (~120 GPa)
  - Steady decline of $\Delta\tau_u$ in the mixed phase region
- **Reloading data is not consistent with EP response**
- **Taking sum and difference gives τ_c and τ_h**



mixed phase region



EP response
($\tau_h = \tau_c$)

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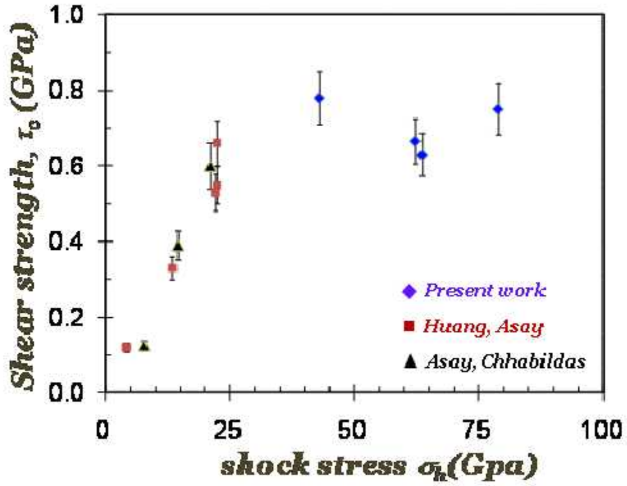
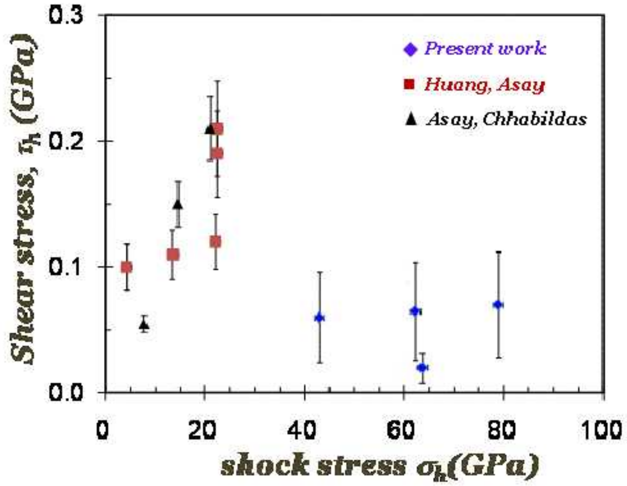
$\tau_h \neq \tau_c$ indicates failure of EP assumption

- Clearly the shock state is not on the upper yield surface ($\tau_h = \tau_c$)
- Strength ($Y=2\tau_c$) shows plateau above 40 GPa
- Corresponds to a collapse in τ_h toward the hydrostat
  - Note that while ~75% reduced from the peak value, $\tau_h > 0$
  - τ_h is expected to decay to zero in mixed phase region
    - » Small error in approximating $\Delta\tau_u = \tau_c + \tau_h \approx \tau_c$
    - » Allows release data to approximate strength in the mixed phase region
    - » Different than EP assumption where $\Delta\tau_u = 2\tau_c$





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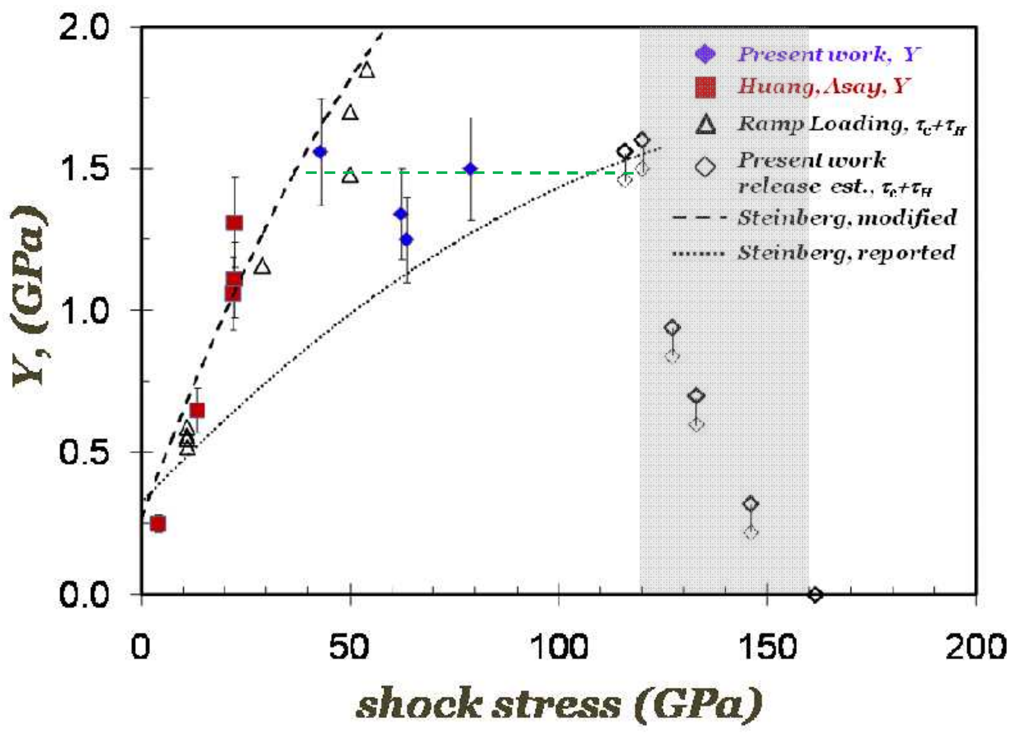
By measuring both τ_c and τ_h strength is determined without the EP assumption

- **When reloading data are considered, τ_c and τ_h are determined**
- **Strength, $Y = 2(\tau_c) \geq (\tau_c+\tau_h)$**
- **Resulting strength data are not well fit by the reported Steinberg model**
- **A modified model reported by Huang and Asay is a good fit to 40 GPa**
- **No strength models predict plateau**



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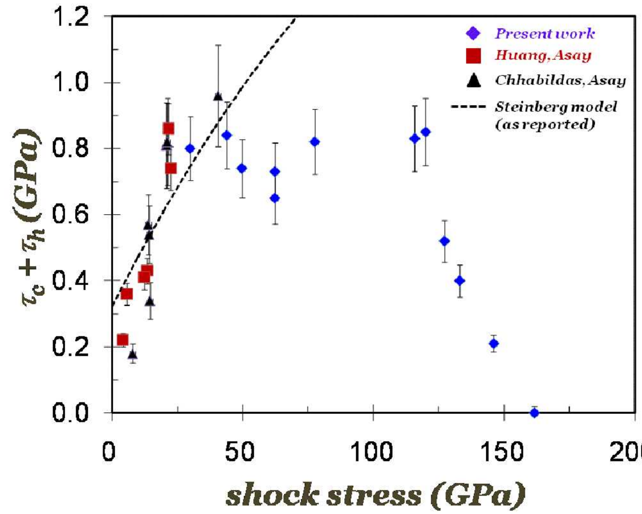
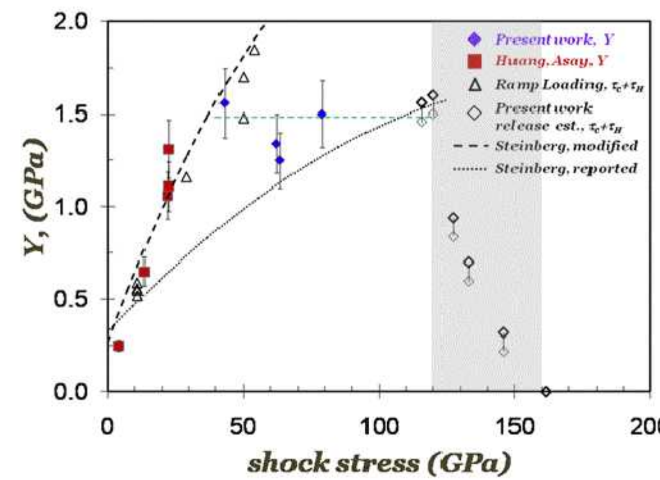
Discrepancies in the data have serious implications to existing strength models

- Steinberg model (and others) often based on unloading wave profile data $Y=(\tau_c+\tau_h)$
- Results presented here show that the EP assumptions are invalid in Al (for σ > 40 GPa)
  - Reloading data must be considered $Y=2(\tau_c)$
- Existing strength models may be off by as much as a factor of two
- New experimental data are required to correct or verify existing models



unloading data only



unloading and release data

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Strength of aluminum was measured using both reloading and release experiments

- Utilizing reloading and release data, the shear components τ_c and τ_h were measured
- EP assumption that the shock state lies on the upper yield surface shown to be false for aluminum
- Measured strength is almost two times larger than estimates using release data only
- Existing strength models based on release data alone need to be revisited
- Initial properties of aluminum appear to influence high pressure response in contrast to low pressure response