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Flow Strength of Shocked Aluminum in the Solid-Liquid Mixed Phase Region

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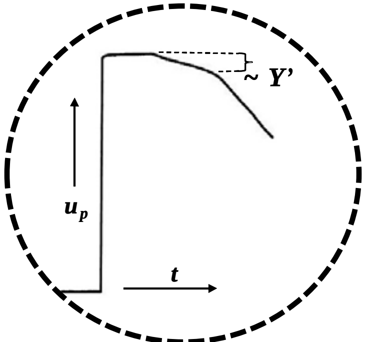
Objective: Determine the flow strength of aluminum at high shock pressure approaching complete melt

- Study the dynamic strength of three types of Aluminum in the solid and liquid mixed phase regions
  - Aluminum materials studied include commercially available 6061-T6, 2024, 1100
- Assess effects of microstructure on dynamic strength properties
- Strength estimated from shock loading and unloading profiles



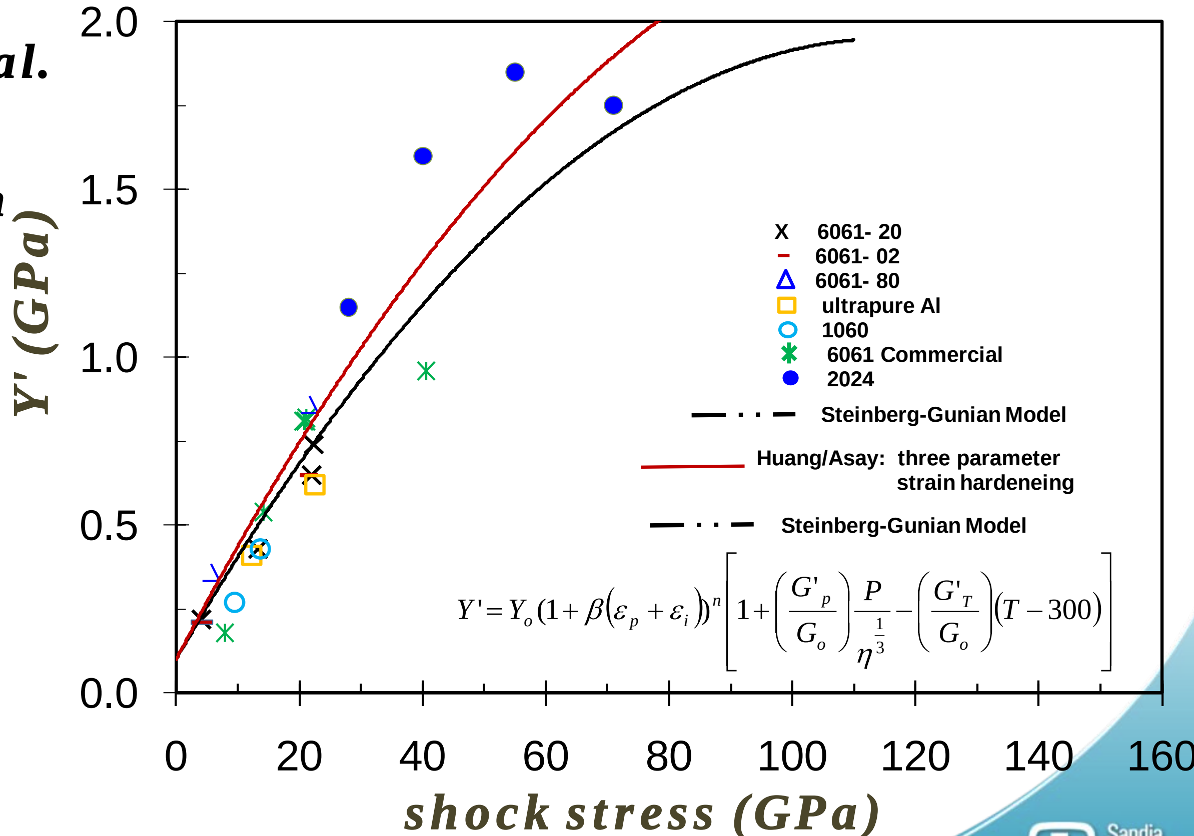
Background: Low Pressure

- ***Extensive low pressure (to ~ 20 GPa) studies show that the relative change in strength (Y′) for several Aluminum materials are similar***

- ***Steinberg model provides reasonable representation to ~ 40 GPa for Y′ (unloading data)***

- ***Studies by Morris et al. on 2024 Al showed a continued increase in Y′ over this range***

- ***Older studies were complicated by lack of reliable window materials at high pressure***



Y′ represents change in shear stress, $\tau_c + \tau_h$

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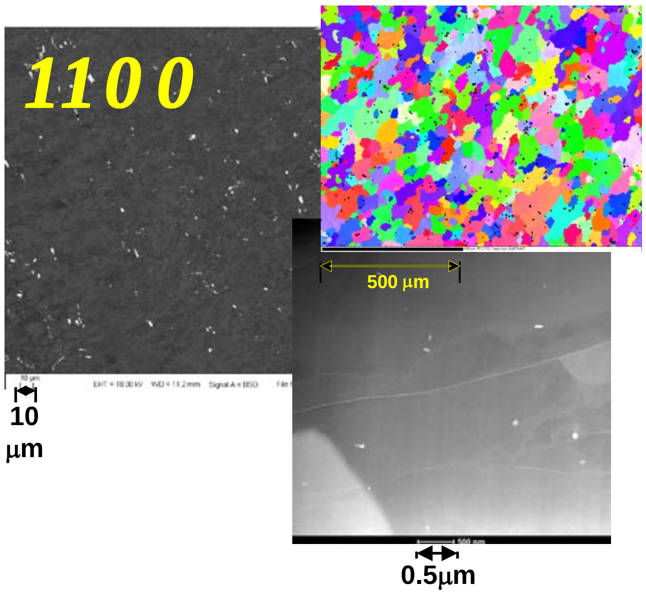
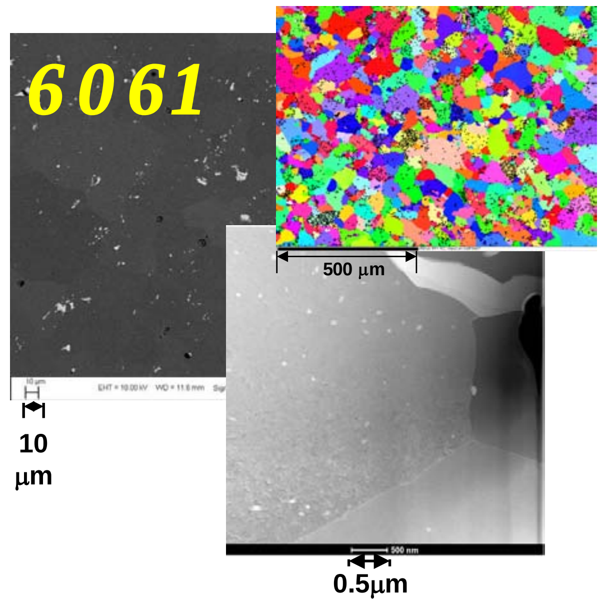
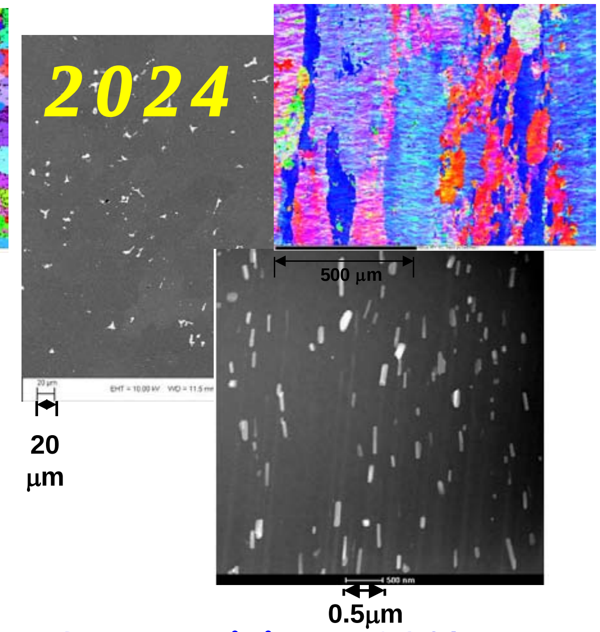
SEM/TEM/EBSD-Transverse View



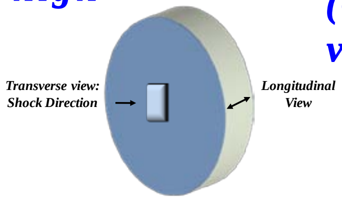




- ***Composition: 99% Al***
  0.03% Si, 0.03 % Fe, 0.01% Cu, 0.01% Zn
- ***Texture:***
  - ***equiaxed (100 µm),***
  - ***columnar (500 µm)***
- ***Bright particles are Fe/Si: 1.2 um avg. circ. diameter***
- ***smaller particles (Cu/Zn) become visible in high magnification***

- ***Composition: 97% Al***
  1.0% Mg, 0.7% Si, 0.7% Fe, 0.3% Cu, 0.2% Cr, 0.1% Mn
- ***Texture:***
  - ***equiaxed (30 µm),***
  - ***flattened (50 µm)***
- ***Bright particles are Fe/Si: 1.1 um avg. circ. diameter***
- ***smaller particles (Cr/Mg/Cu/Mn) become visible in high magnification***

- ***Composition: 93%***
  4.2% Cu, 1.4% Mg, 0.5% Si, 0.5% Fe, 0.5% Mn
- ***Texture:***
  - ***equiaxed (29 µm),***
  - ***columnar 90 µm)***
- ***Bright particles are Fe/Si : 2.8 um avg. circ. diameter***
- ***smaller particles (Mg/Cu/Mn) become visible in high magnification***



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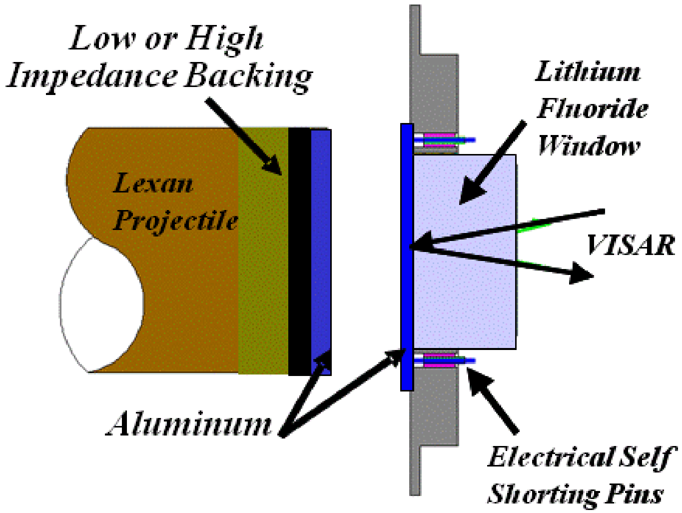
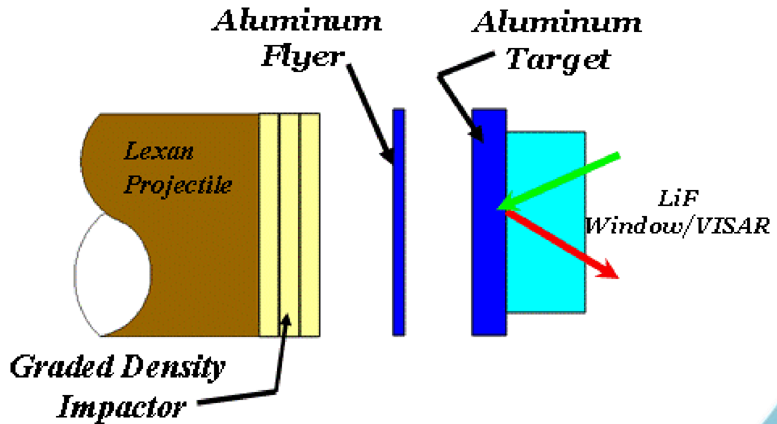
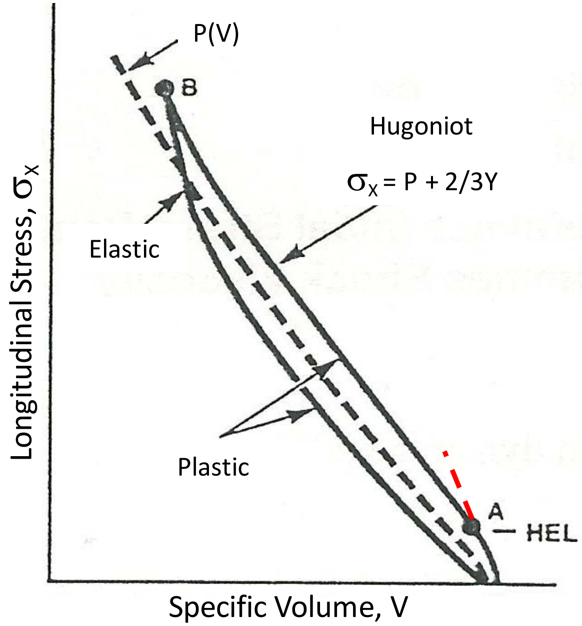
Experimental Method

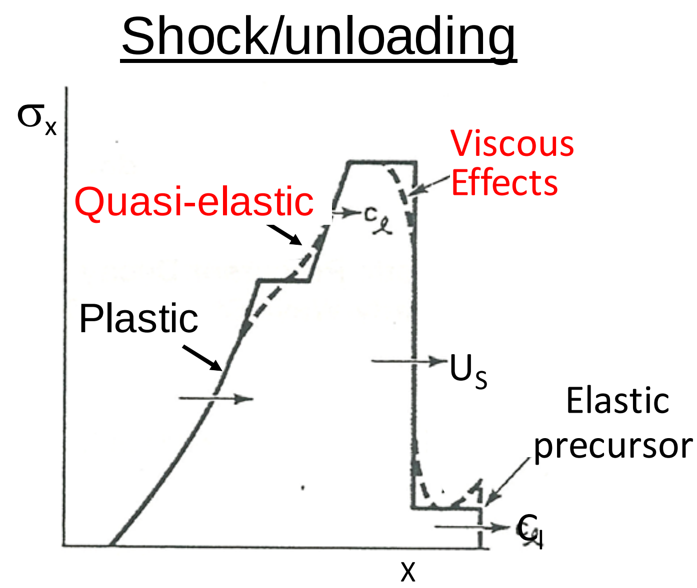
- ***Symmetric impact***
  - *3-10 km/s impact velocity*
  - *Two-Stage pressures: to ~90 GPa*
  - *Three-Stage Pressures: to ~ 160 Gpa*
- ***VISAR diagnostics***
  - *High sensitivity, ultra-clean interferometer diagnostic-techniques used to resolve QE recompression*
- ***Previous difficulties***
  - *Separation of impactor and backing during projectile launch*
  - *Window materials*
  - *Impact velocity limitations (~7km/s)*





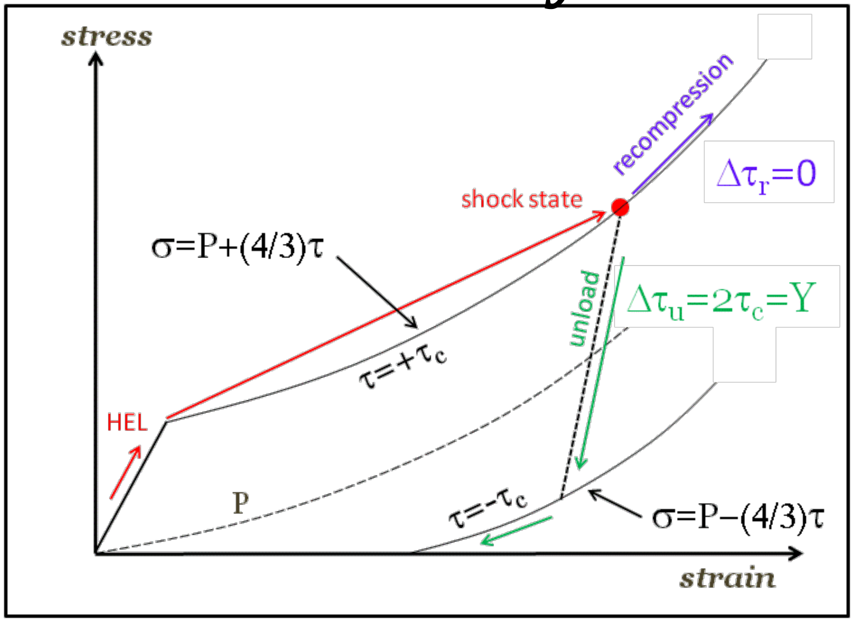
Elastic-plastic response produces specific wave signatures

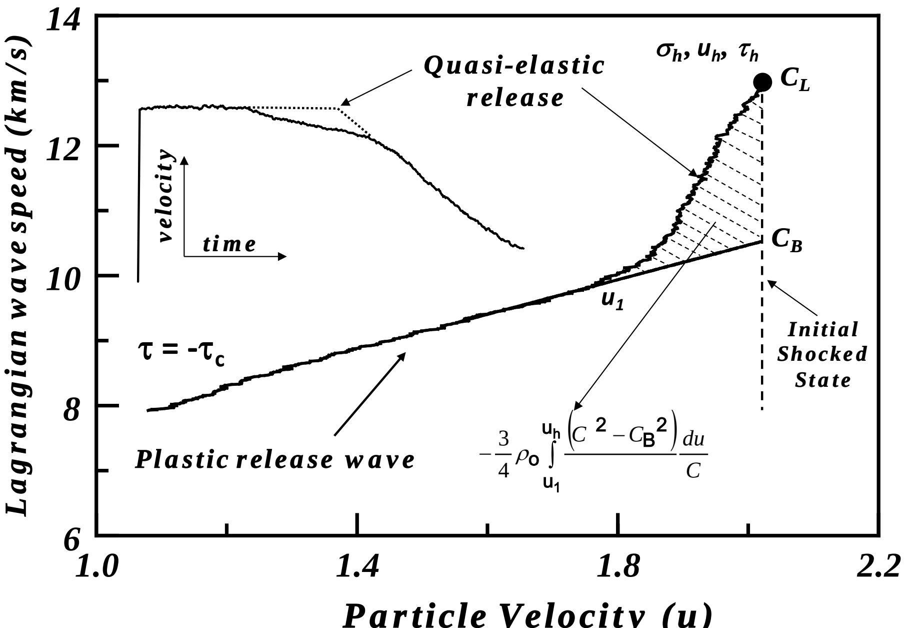




- ***Upon unloading from the shocked state, the response is initially elastic until the onset of reverse yielding, followed by plastic unloading***
- ***most materials deviate from ideal elastic-plastic unloading through a dispersive mechanism resulting in quasi-elastic unloading.***
- ***the strength of the of the material can be determined from the amplitude of the transition from elastic to plastic response during unloading.***

Analysis Methodology: Unloading





Key assumption is that the shock state lies on the upper yield surface

- **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**
  $\Delta\tau_u= 2\tau_c= Y'$
- **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 estimate of Y for unloading:**

$$Y' = \tau_c+\tau_H=-\frac{3}{4}\rho_0\int_{u_1}^{u_H}\left(c^2-c_B{}^2\right)\frac{du}{c}$$

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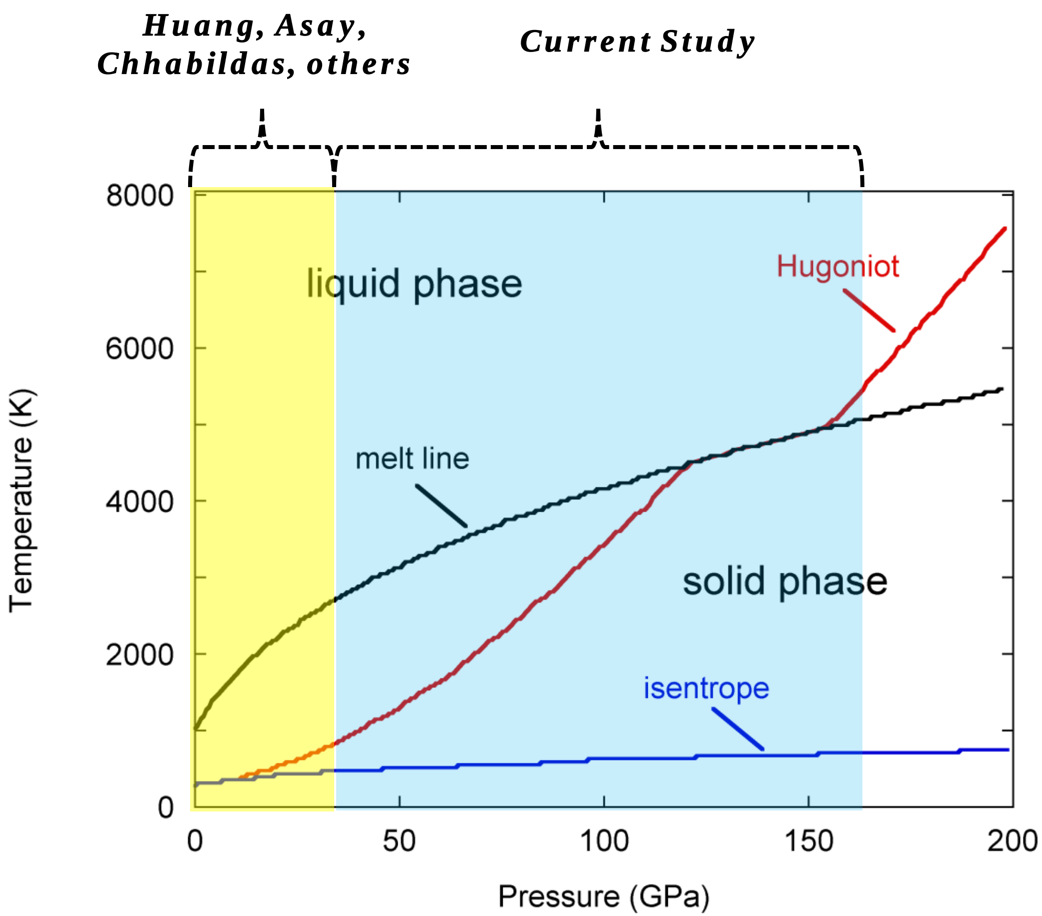
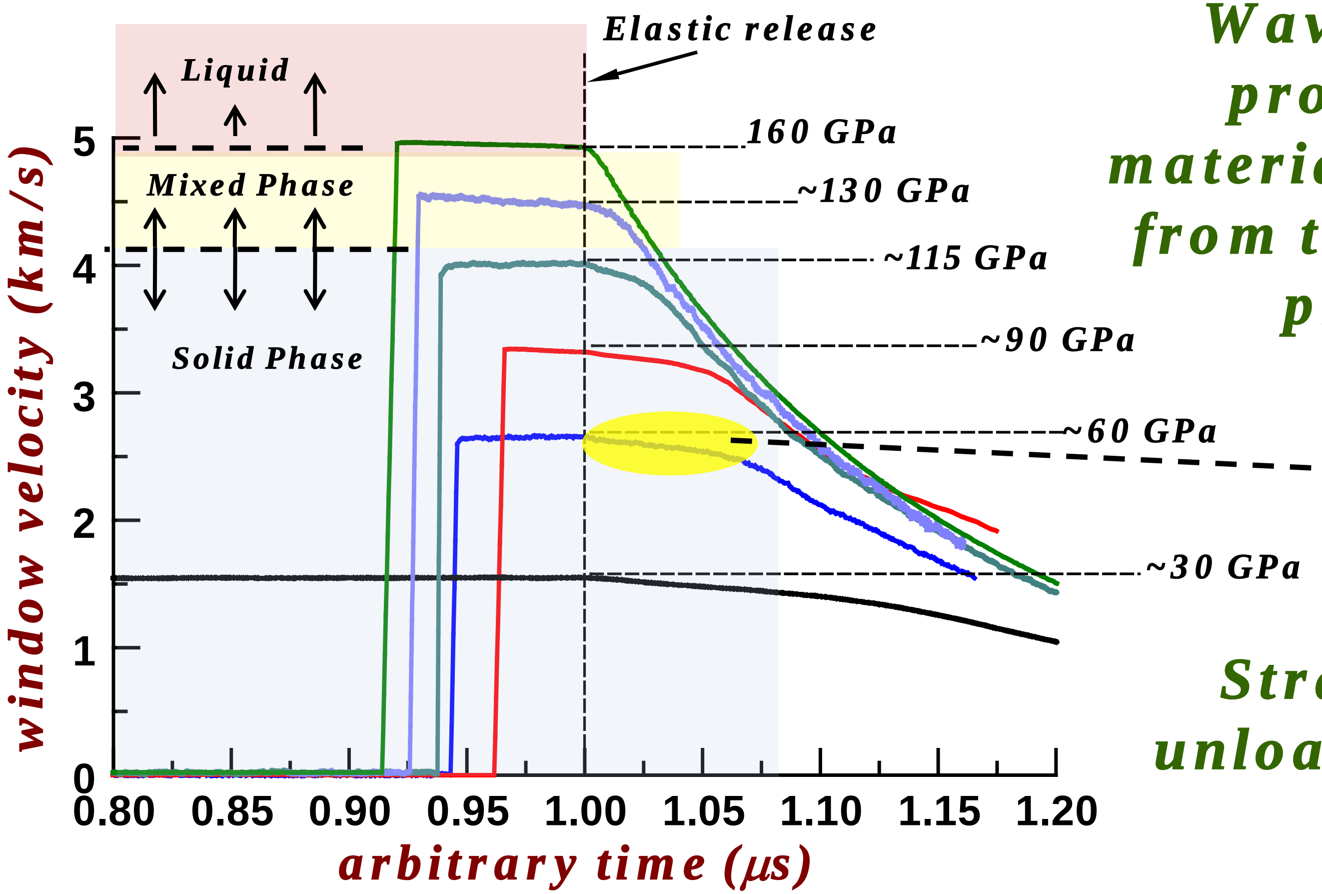
Pressure-temperature phase diagram for Aluminum

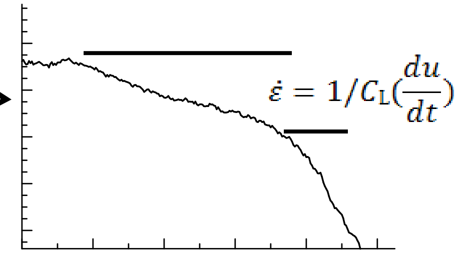
- Material strength in shock induced solid-liquid coexistence regions has not been studied
- Solid-liquid coexistence is expected to influence strength
- Phase boundaries have some uncertainty (~5 GPa) depending on theoretical approach used



Wave Profiles: 6061-T6



Wave profiles may provide evidence material is transforming from the solid to mixed phase to melt



Strain rates in QE unloading: 0.2 x 10^6/s

- **Spatial heterogeneous melting process begins at ~120 GPa**

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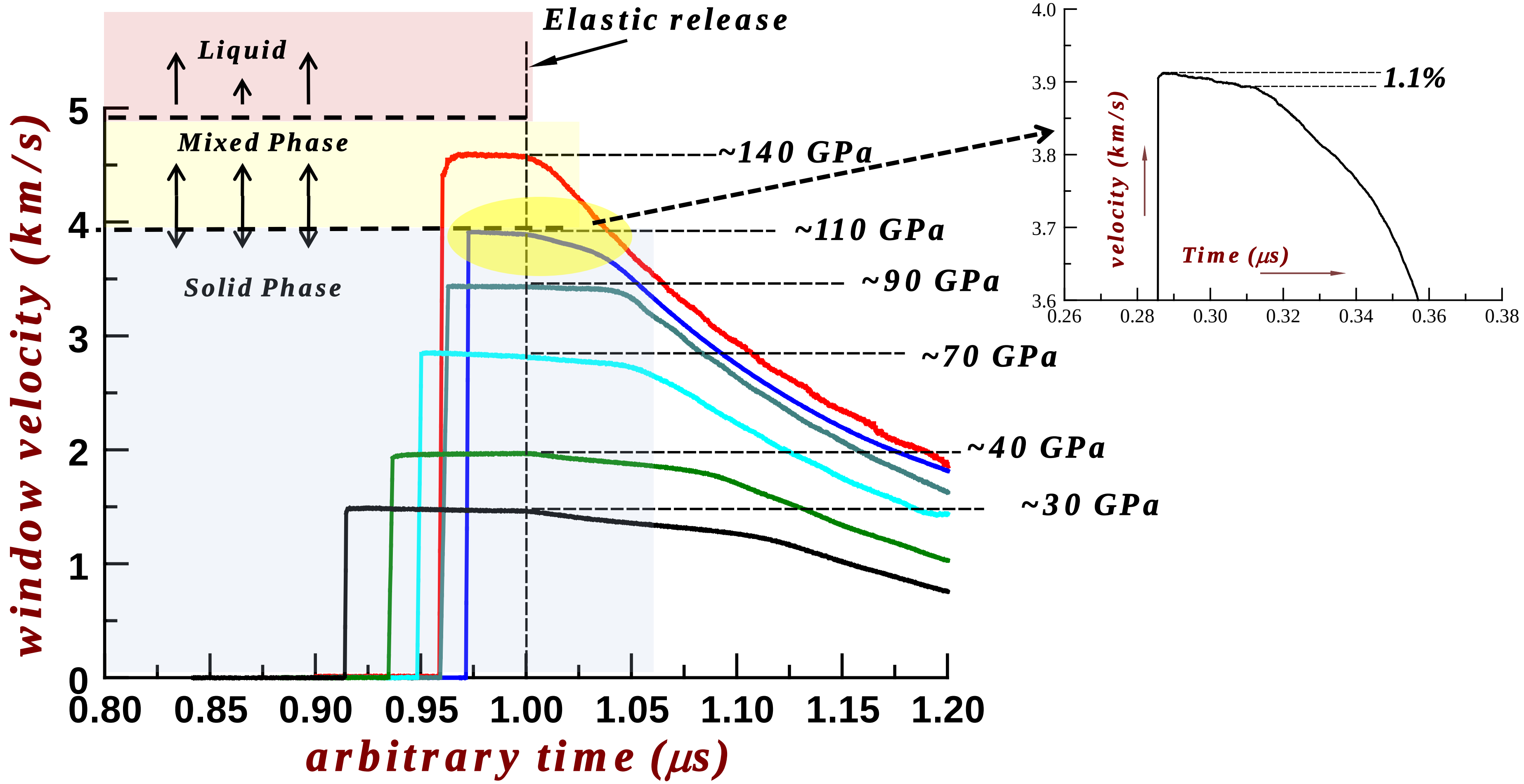
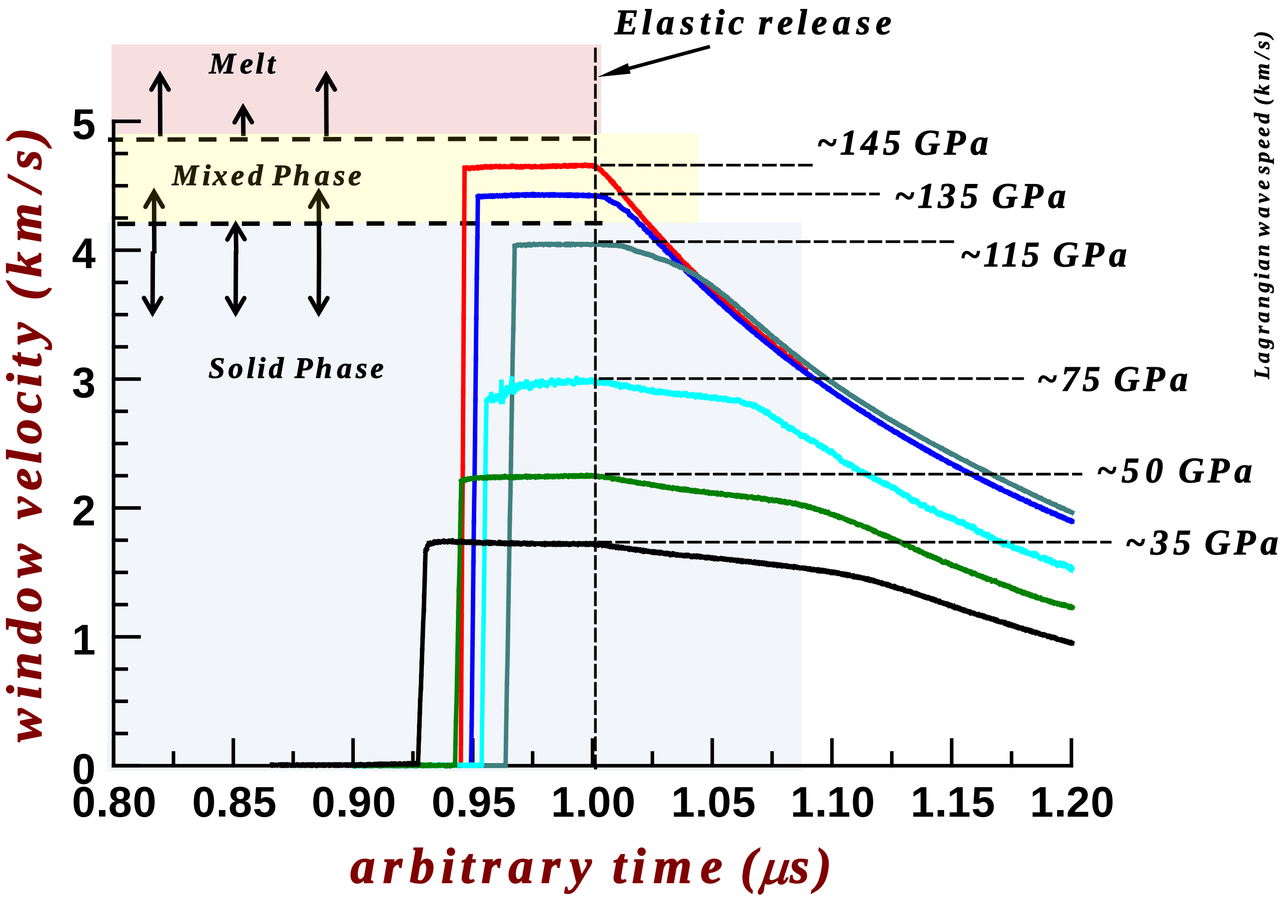
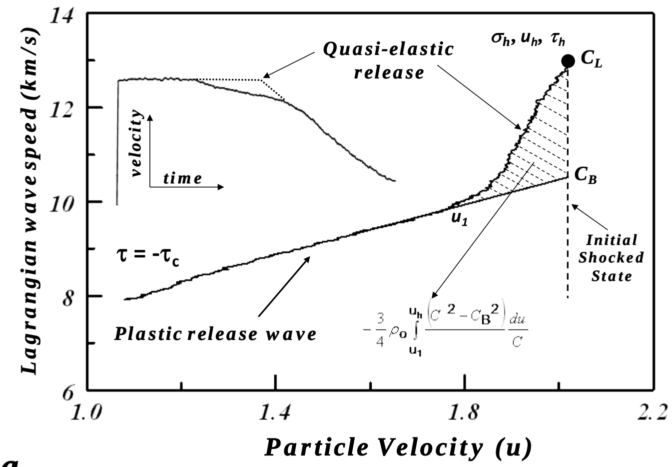
Wave Profiles: 1100



- *Linear particle velocity decline may indicate material is transforming from the solid to mixed phase to melt*
- *Mixed phase may start earlier in 1100*

Wave Profiles: 2024

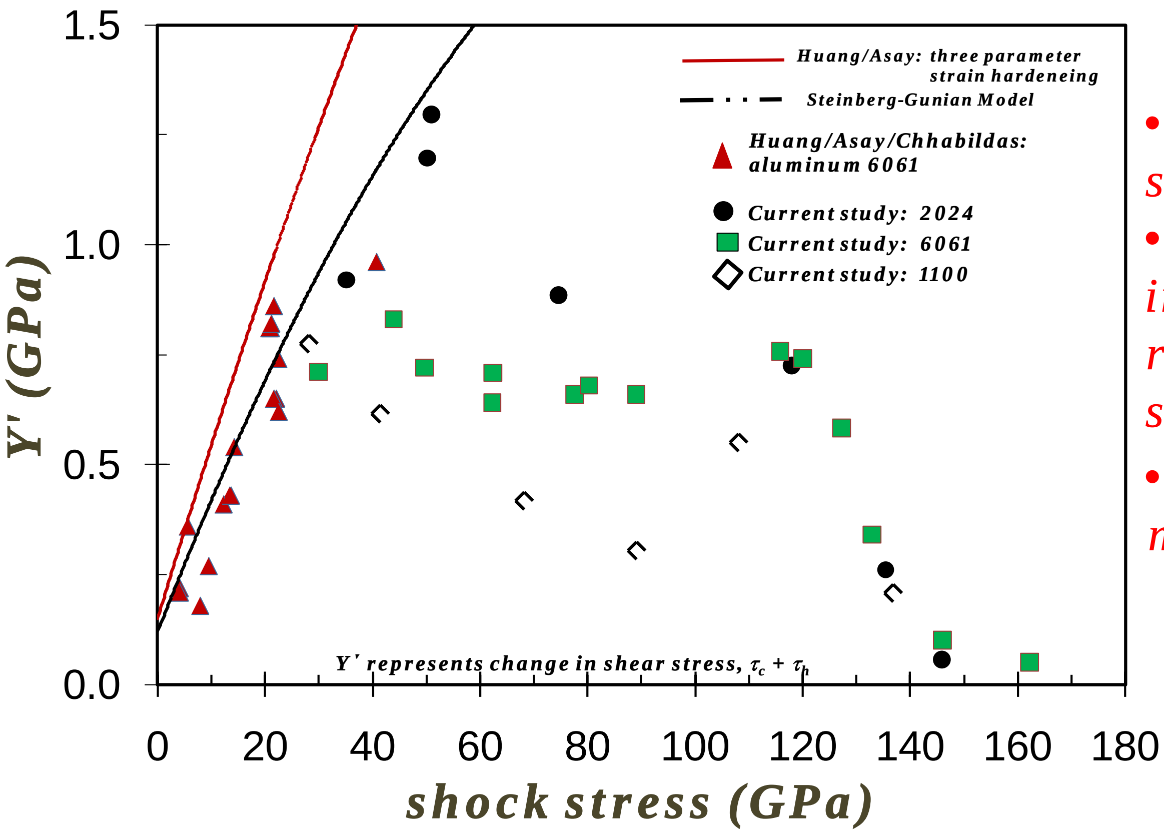




Particle velocity decline not as evident in 2024

- *Easier to work in the wave velocity versus particle velocity plane to estimate the bulk speed in the QE region as bulk wave speed is linear over larger ranges*
- *Wave speeds provide evidence that material is in the mixed phase and approaching melt*

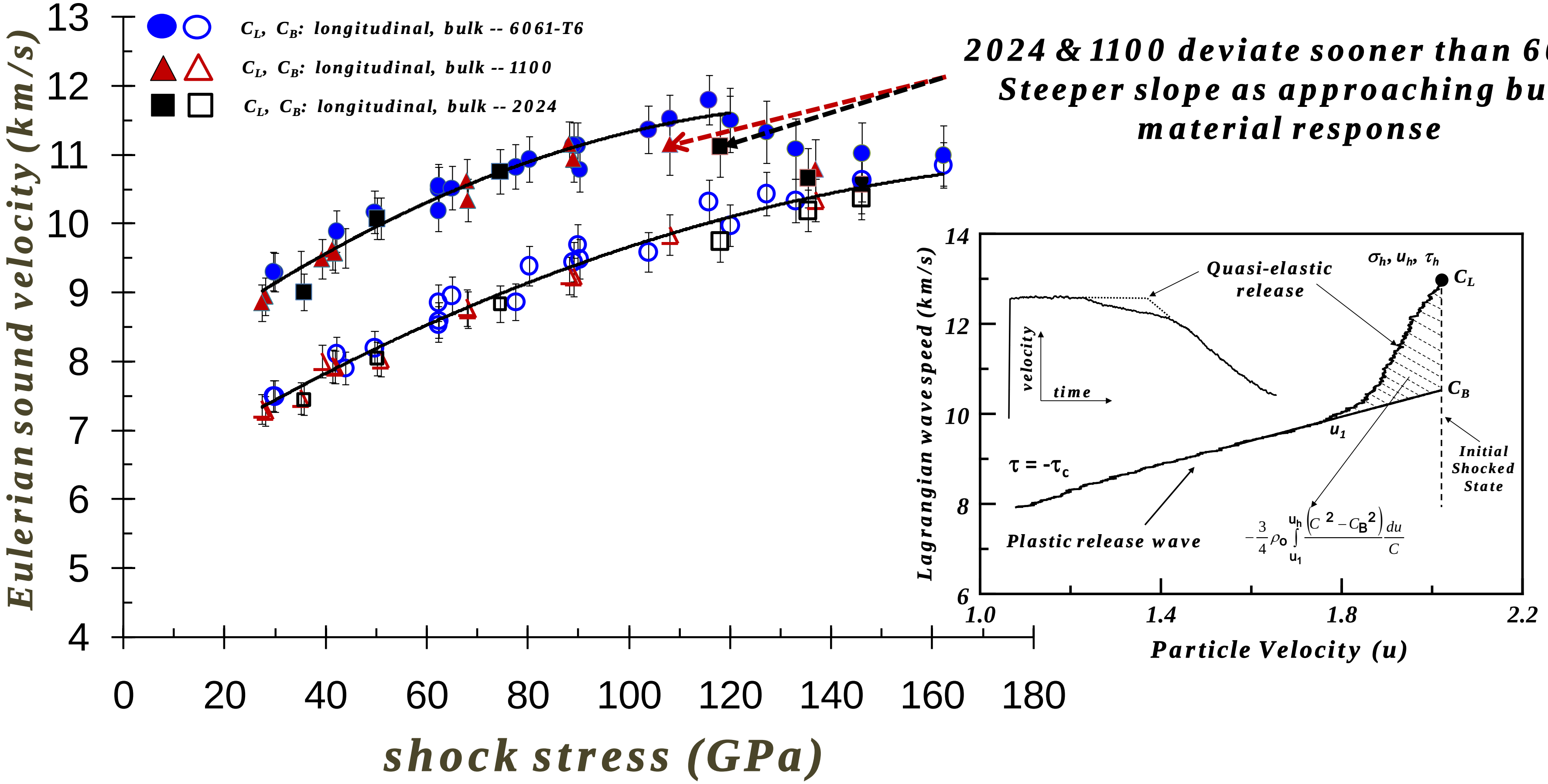
Present study: Y'



- previous data, Y' agree to standard models to about 40 GPa
- all three materials show a break in hardening behavior at ~40 GPa, resulting in no major increase in strength;
- a dip in Y' is observed in all materials between 40 - 60 GPa
  - being most prevalent in 1100

- **an increase in strength from 70-120 GPa is observed for all materials, followed by a rapid relaxation to zero strength near 150 GPa;**
- **The major drop near 120 GPa is consistent with thermodynamic predictions of the onset of melting in Al**

Wavespeeds:

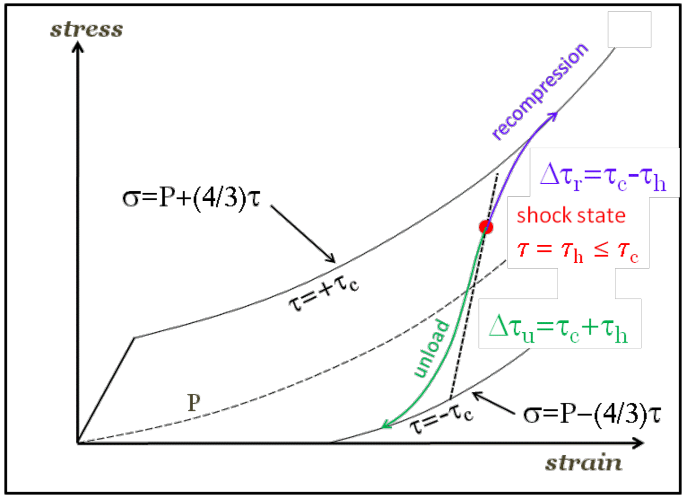


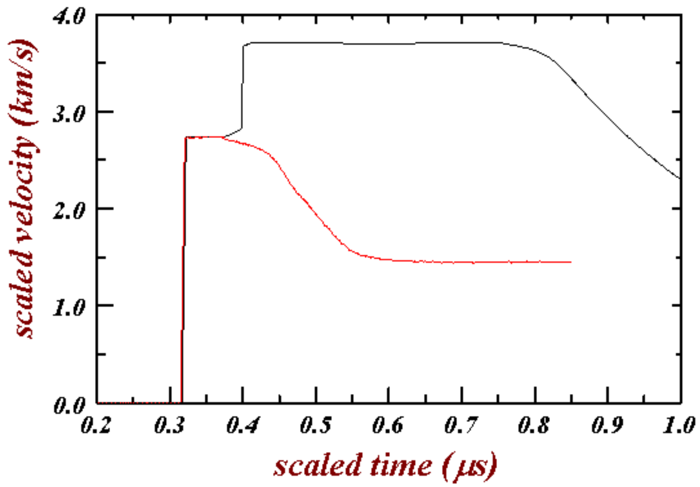
• Wave speeds start transition to bulk at ~120 GPa

• Transition pressure, for change is wave speed, consistent with transition pressure for flow strength to zero in mixed phase

Reloading: Assumption that shock state is NOT on upper yield surface

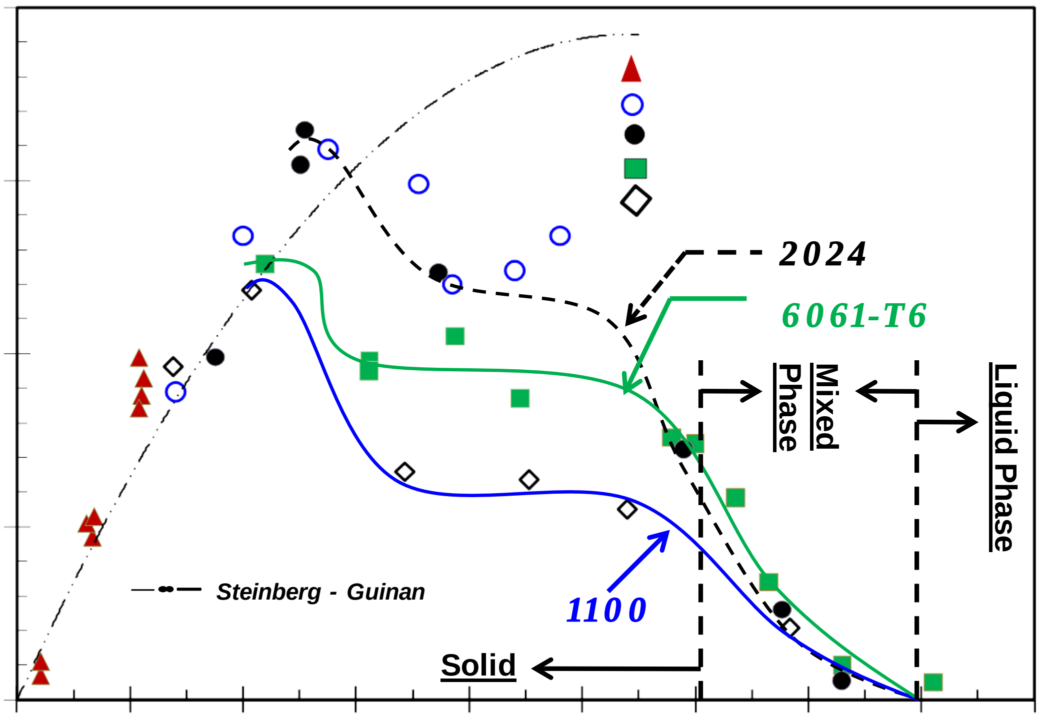
- Evidence suggests that the shock states lie at: $\tau=+\tau_H$ ($\leq \tau_c$)
  - Elastic recompression
- On release, the material unloads elastically to a yield surface $-\tau_c$ below the hydrostat
- Elastic portion of the <u>release</u> gives $\Delta\tau_u=\tau_c+\tau_H\leq Y$
- In order to determine Y must measure both τ_c <u>and</u> τ_H
- Requires both reload and release data: $Y=2\tau_c=\Delta\tau_u+\Delta\tau_r$





Measuring release only could lead to errors up to a factor of 2

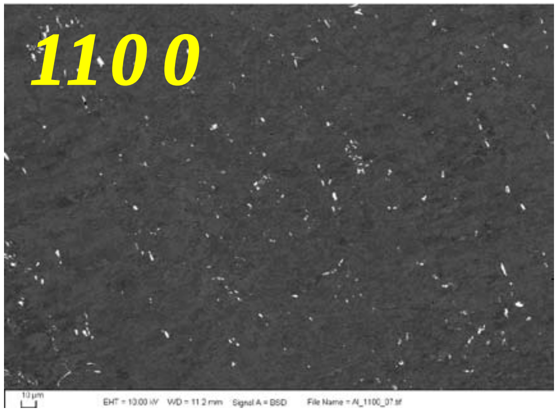
Strength: Y-Yo

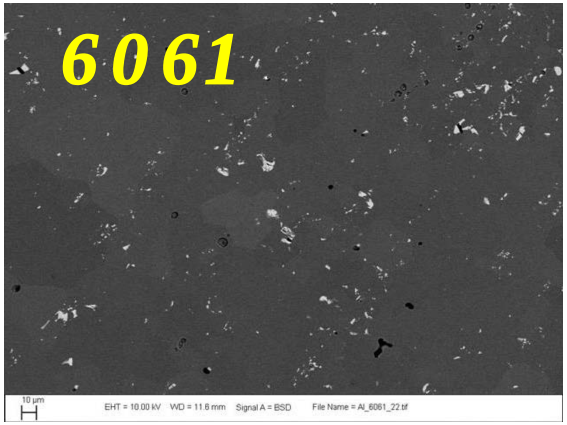


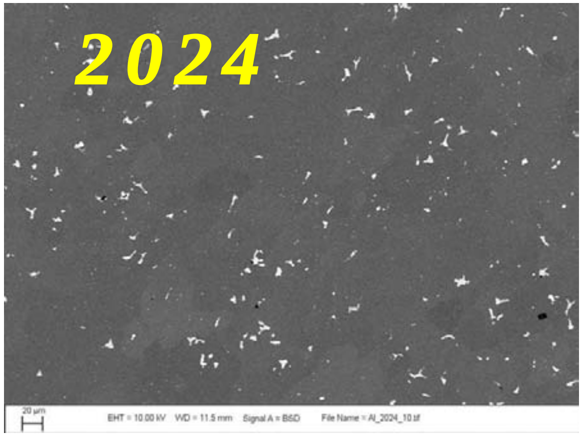
- reloading experiments, indicates standard models under predict strength of material (Less than 40 GPa)
- Increase of strength at 120 GPa is not as evident

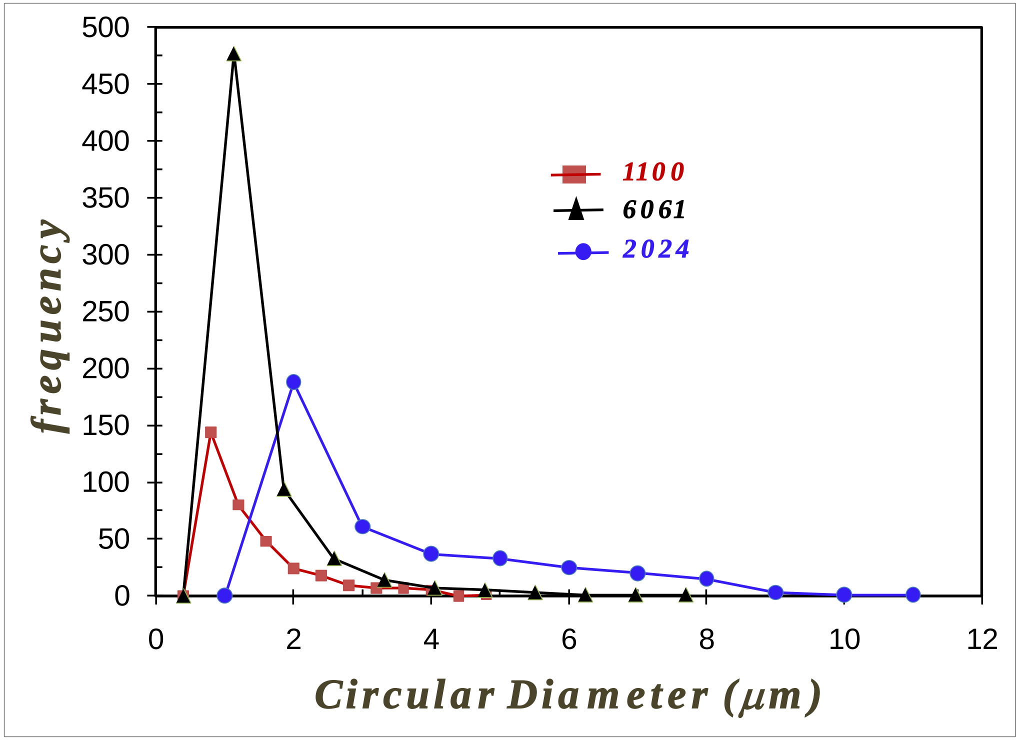
- experiments over 100 GPa, do not include reloading
- 2024 includes reloading estimate attained from 6061
  - older 2024 data is unloading data only

Particle Distributions: SEM



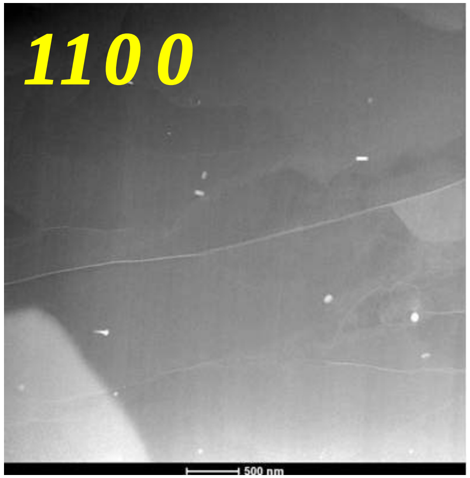


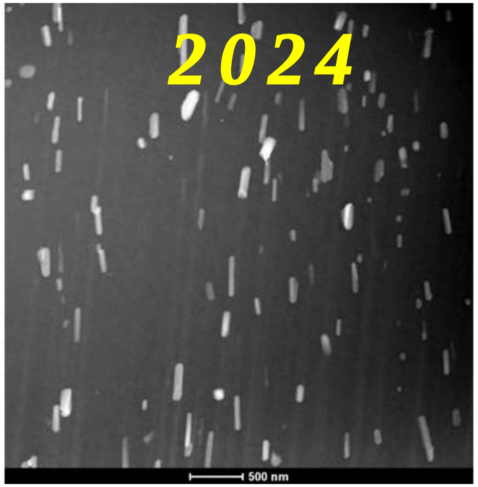




- *treatment of alloys has impurities go to solid solution and randomly distribute:*
  - *not effective in for maintaining strength*
- *Average size of precipitates 1.1 – 2.8 mm*

Particle Distributions: STEM





- ***Higher concentration of finer precipitates within grains will act as an effective means to maintain strength***
    - ***prevents catastrophic interaction of shock with larger precipitates***
    - ***Inhibiting dislocations from flowing results in higher strength—plastic deformation***

Summary

- ***This work is believed to be the first 'in-situ' type measurements to estimate both wave velocities and strength properties of aluminum during shock loading that describe material behavior from the solid to the onset of melt to the liquid phase.***

- ***Reasonable agreement with models to ~ 40 GPa for all materials***
    - ***all materials show a decline of strength above 40 GPa, leading to dramatic deviation from the models***

- ***The rapid strength loss from ~120 - 160 GPa is a clear indication of the onset of melt (120 GPa) and melt completion (160 GPa)***

- ***In depth metallurgical analysis gives insight for assessing effects of microstructure on dynamic strength properties***
    - ***larger precipitates randomly located within the material are ineffective for adding strength at high pressures***
    - ***concentrated, smaller precipitates within the grains, may provide strengthen properties by disrupting dislocations.***

- ***data indicates that the shock state does not lie on the upper yield surface***
    - ***rate independent mesoscale effects? Dislocation flow?***
    - ***elastic response upon recompression***
    - ***reloading: models under predict strength below 40 GPa***

Next Steps:

- ***repeat few experiments at key locations for reproducibility check***
- ***do ultra-pure Al to check precipitate picture***
- ***initiate modeling effort to understand how precipitates could influence high pressure strength of materials***
- ***reshock on 2024 in 60-100 GPa range***
- ***work out technique for reshock with 3-stage***