Study of the strength of molybdenum under high pressure using magnetically applied pressure-shear (MAPS) loading*

SAND2015-9910C

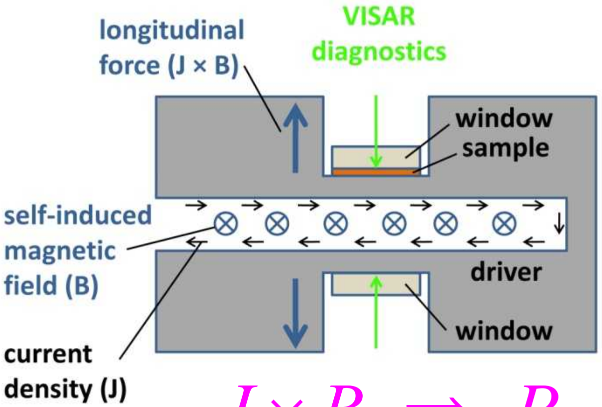
Jow Ding[1], C. Scott Alexander[2], & Jim Asay[3]

[1]Washington State University
[2] Sandia National Lab
[3] Consultant

*** Work sponsored by Sandia National Labs**

Presented at the 19th APS Topical Conference

Uniaxial Compression By Magnetically Generated One-Dimensional Ramp Wave Loading



$$J \times B \Rightarrow P$$

Drive Panel: pure aluminum

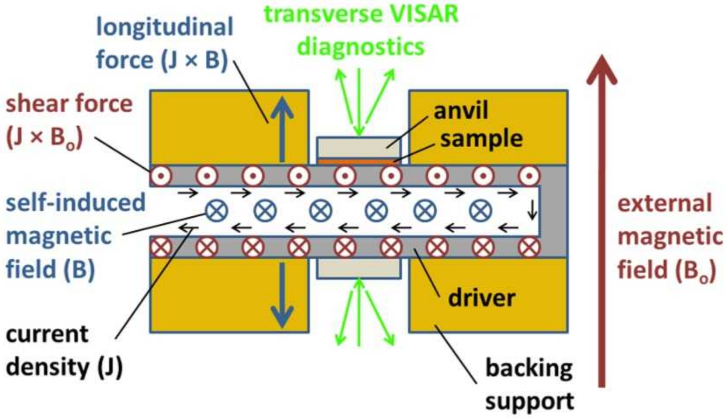
Driver has negligible strength, which is adequate for generating a pure pressure wave.

For ramp wave experiments:

- **Understanding and accurate prediction of the driver response is a critical for development and analysis of the experiments.**

- **Aluminum driver: Strength is not an issue; Can be adequately modeled as a hydrodynamic material.**

Magnetically Applied Pressure Shear (MAPS) Experiments (Two-Dimensional Ramp Wave Loading)



$$J \times B \Rightarrow P$$

$$J \times B_0 \Rightarrow S$$

Drive Panel: molybdenum
Driver must have substantial strength in order to apply the necessary shear traction to the test sample.

Need to:

- **Understand the inelastic behavior of molybdenum under high-strain-rate, high-pressure, and mixed-mode compression-shear loading.**
- **Develop a working model for simulating the response of molybdenum driver under such loading.**

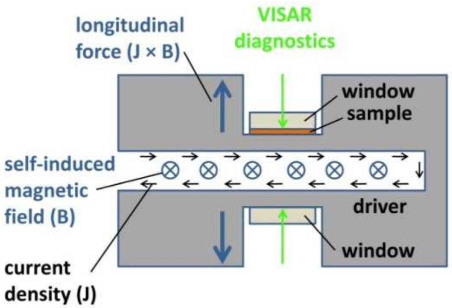
Main Purposes

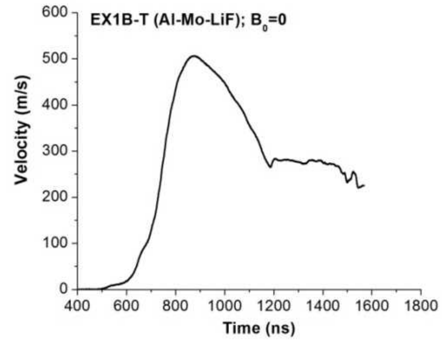
To demonstrate:

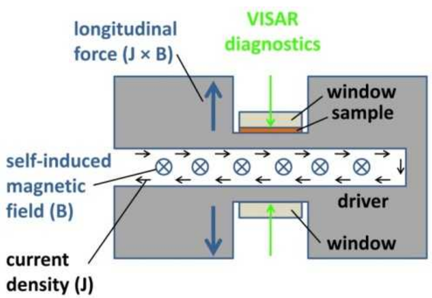
- **Uniaxial compression data are not discriminative enough to distinguish different types of inelastic material behavior.**

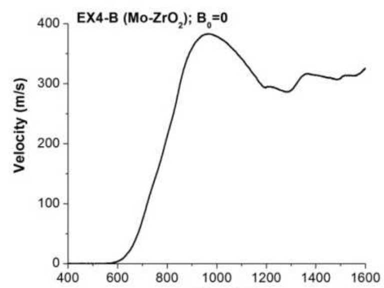
- **MAPS experiments provides valuable insights on the inelastic material behavior under complex, high pressure, high strain rate loadings.**

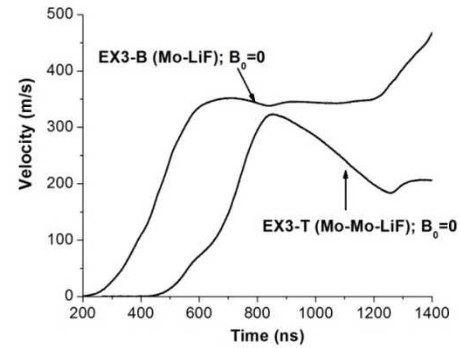
Overview of the Longitudinal Data

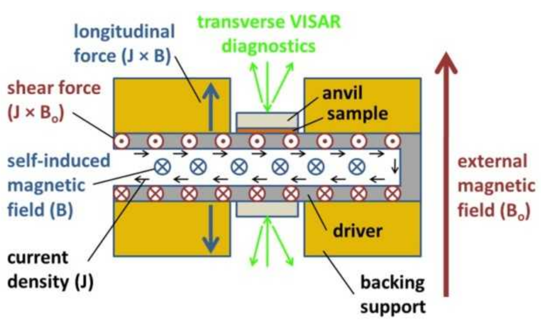


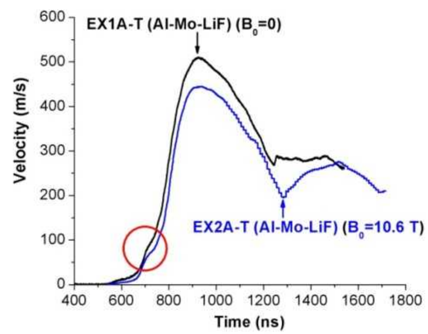


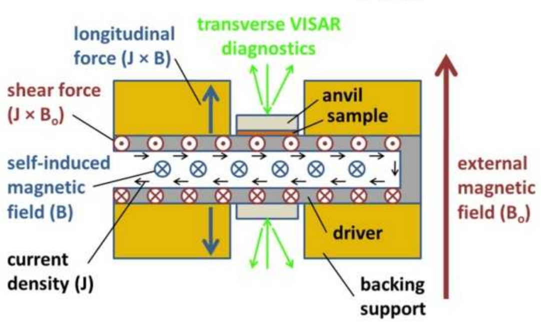


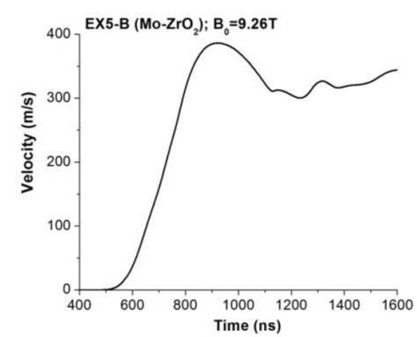












Mechanical Strength Model

$$\dot{\sigma}_{ij}^{'} = 2G\dot{\varepsilon}_{ij}^{e}{}'$$

$$\dot{\varepsilon}_{ij}^{p} = \dot{\bar{\varepsilon}}^{p}(\sigma_{ij}^{'}/|\sigma_{ij}^{'}|)$$ and $$\dot{\bar{\varepsilon}}^{p} = A[\bar{\sigma} - Y)]^{n}$$

($\dot{\bar{\varepsilon}}^{p} = (\frac{2}{3}\dot{\varepsilon}_{ij}^{p}\dot{\varepsilon}_{ij}^{p})^{1/2}$, $\bar{\sigma} = |\sigma_{ij}^{'}| = (\frac{3}{2}\sigma_{ij}^{'}\sigma_{ij}^{'})^{1/2}$, Y :threshold stress)

Modified Steinberg, Cochran, and Guinan model

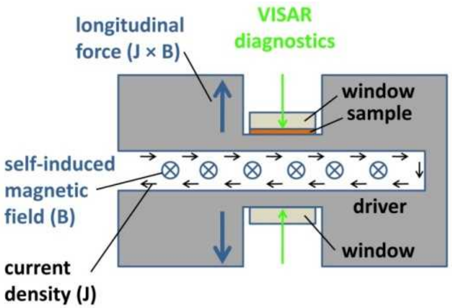
$$G = G_0[1 + (\frac{G_P^{'}}{G_0})\frac{P}{\eta^{1/3}}][1 - (\frac{\theta - \theta_{\text{room}}}{\theta_{\text{melt}} - \theta_{\text{room}}})^{m}]$$

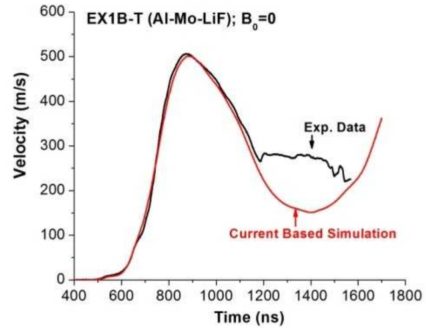
$$Y = Y_0[1 + \beta(\bar{\varepsilon}^{p} + \bar{\varepsilon}_{i}^{p})]^{q}[1 + (\frac{G_P^{'}}{G_0})\frac{P}{\eta^{1/3}}][1 - (\frac{\theta - \theta_{\text{room}}}{\theta_{\text{melt}} - \theta_{\text{room}}})^{m}]$$

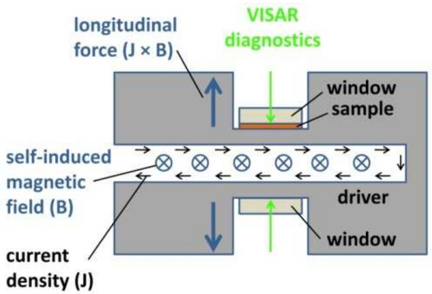
Magnetic annealing can be incorporated through a static recovery function

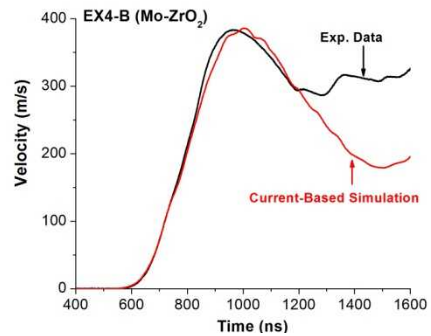
An isotropic hardening/softening model

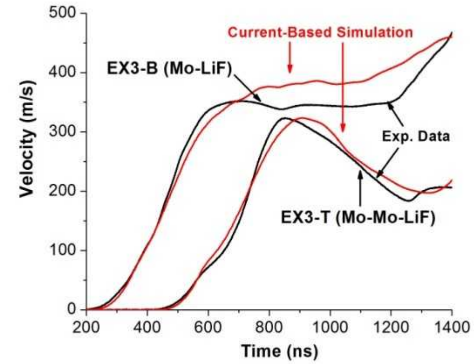
Comparison of the Longitudinal Data With Simulation

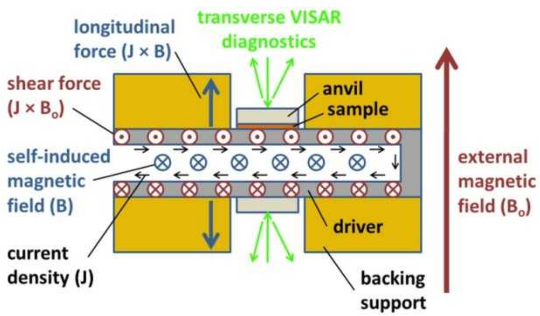


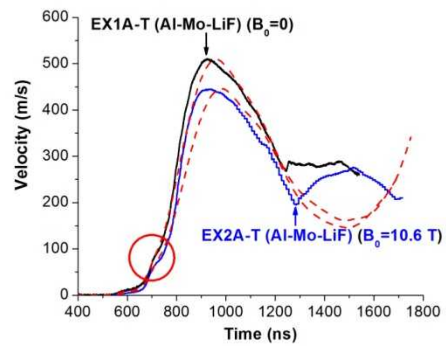


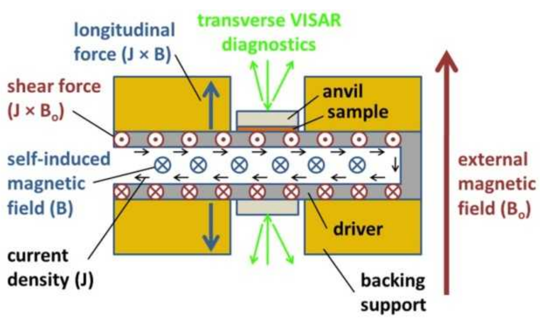


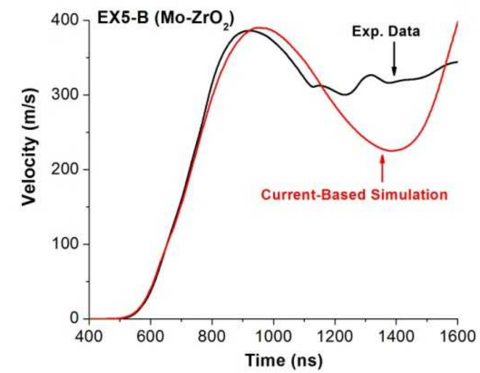




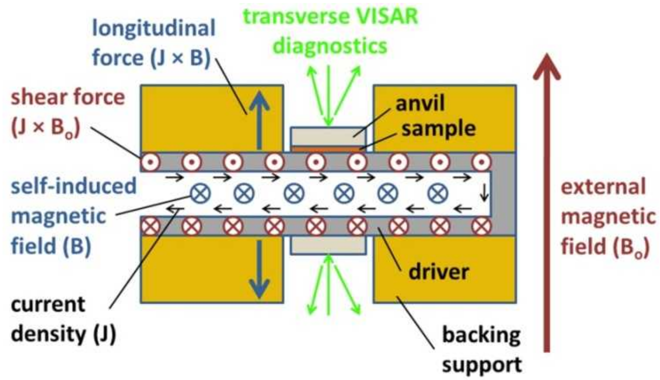


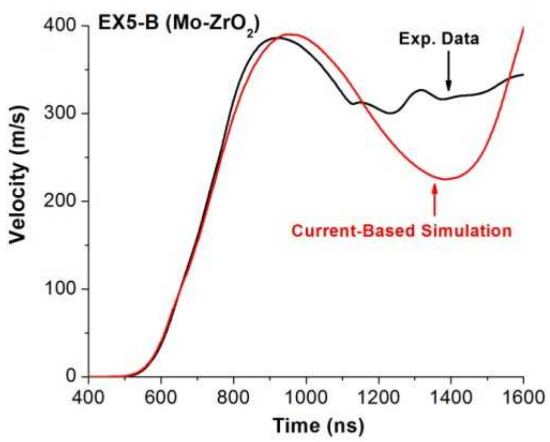


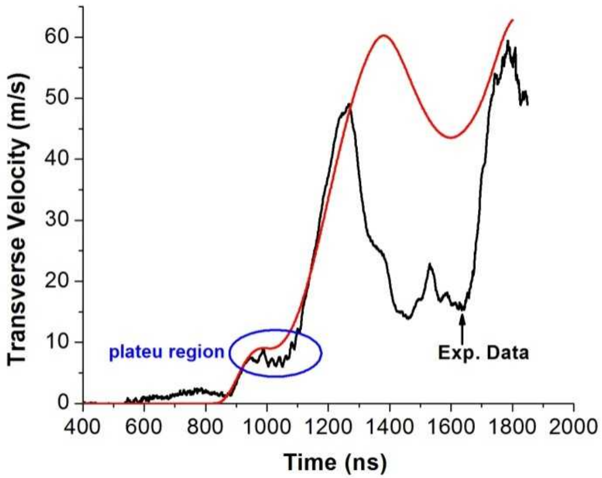




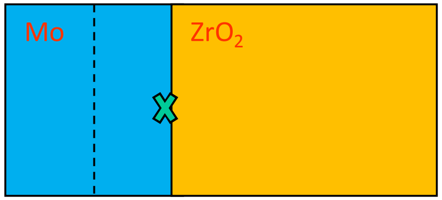
Comparison of the Compression-Shear Data With Simulation



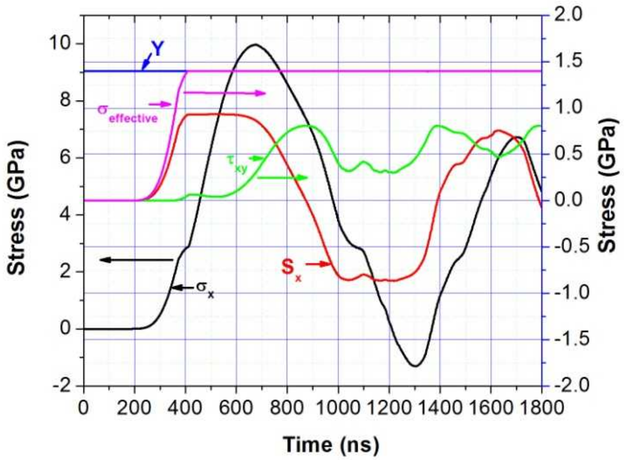


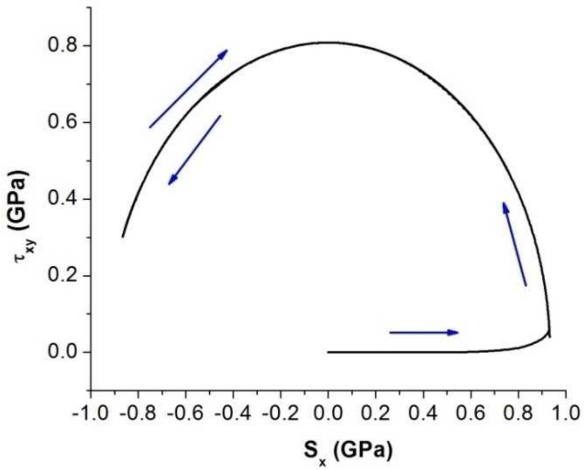


Loading Path Based on Rate-Independent Elastic Perfect Plastic Analysis & Implication of the Plateau Region



$$\underset{\sim}{\sigma}' = \begin{bmatrix} \frac{2}{3}(\sigma_x - \sigma_y) & \tau_{xy} & 0 \\ \tau_{xy} & -\frac{1}{3}(\sigma_x - \sigma_y) & 0 \\ 0 & 0 & -\frac{1}{3}(\sigma_x - \sigma_y) \end{bmatrix} = \begin{bmatrix} S_x & \tau_{xy} & 0 \\ \tau_{xy} & -\frac{1}{2}S_x & 0 \\ 0 & 0 & -\frac{1}{2}S_x \end{bmatrix}$$



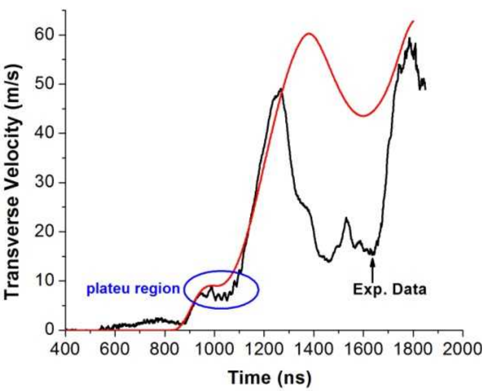


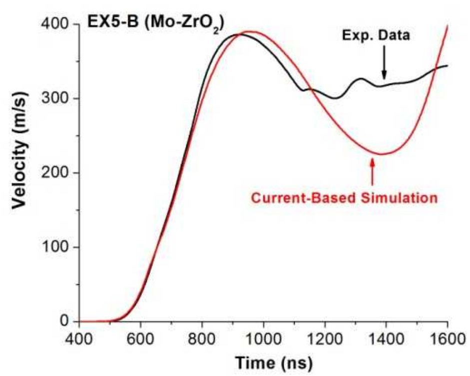
loading

unloading

reverse loading

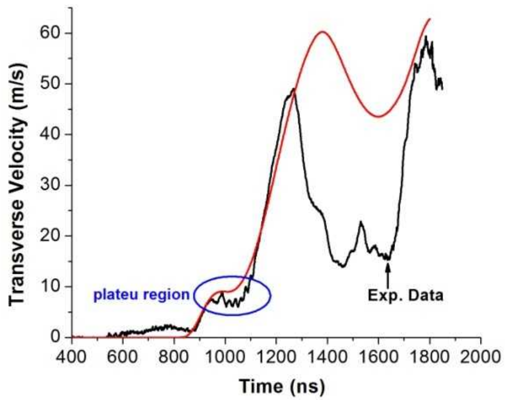
reloading



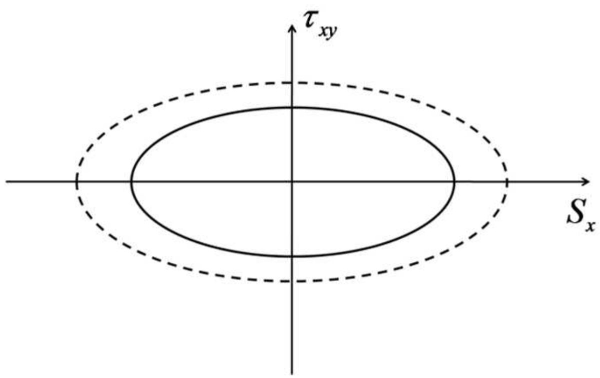


Peak transverse response is a direct measurement of material strength

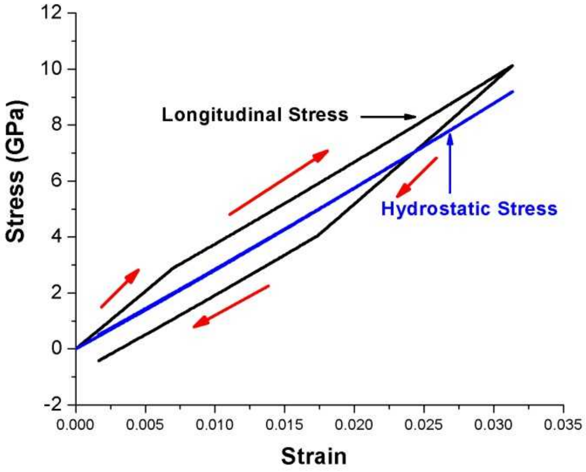
Implication of the Later Part of the Transverse Data



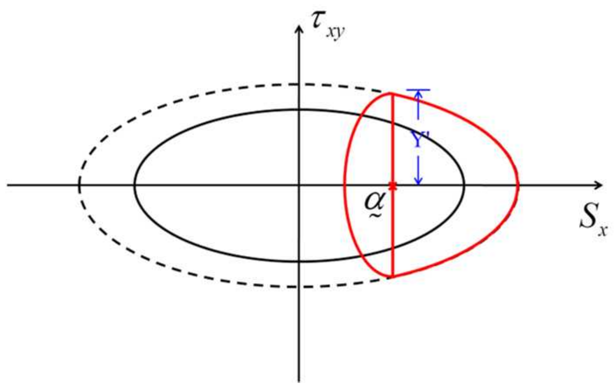
Isotropic hardening/softening



Simulated stress-strain relation



Viscoplasticity Model With Tension-Compression Asymmetry (one possible explanation)

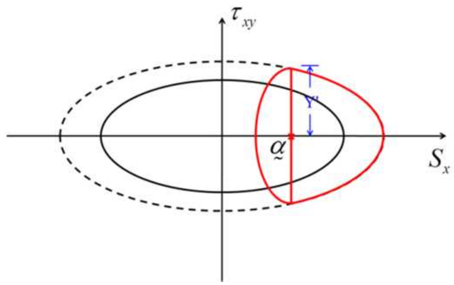


Translation and distortion of the potential surface

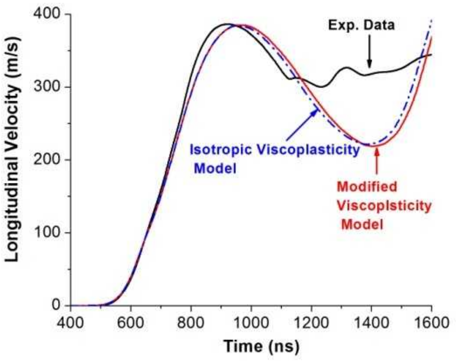
Right side: $$\sqrt{\frac{1}{2}(S_x^2 + S_y^2 + S_z^2 + 2\tau_{xy}^2)} = Y'$$

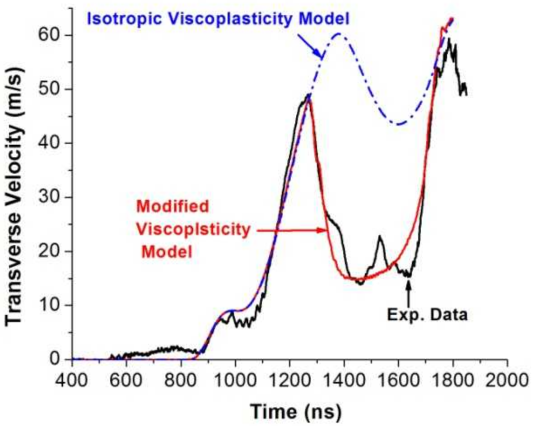
Left side: $$\sqrt{\frac{1}{2}[(H(S_x - \alpha_x))^2 + (H(S_y - \alpha_y))^2 + (H(S_z - \alpha_z))^2 + 2\tau_{xy}^2]} = Y'$$

Viscoplasticity Model With Tension-Compression Asymmetry
(one possible explanation)

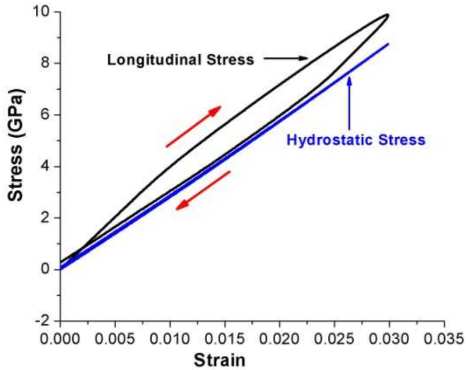


Simulated velocity profiles





Simulated stress-strain relation



Conclusions

- **MAPS experiment is challenging in terms of both the technique and theoretical understanding. Further study is still needed and in progress.**

- **Uniaxial compression data are not discriminative enough to distinguish different types of inelastic material behavior.**

- **MAPS experiments provides valuable insights on the inelastic material behavior under complex, high pressure, high strain rate loadings.**