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Determining Strength at Ultrahigh Strain Rates

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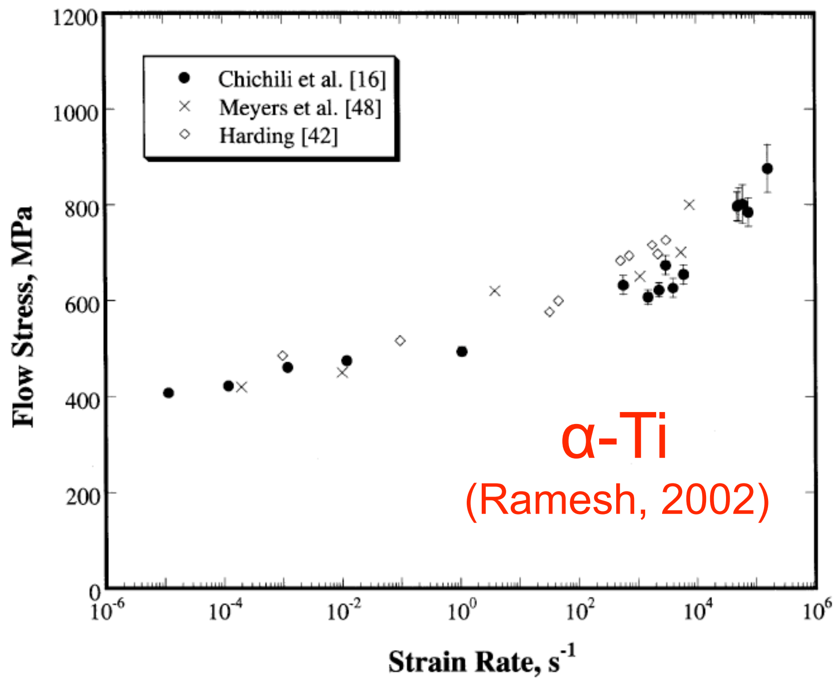
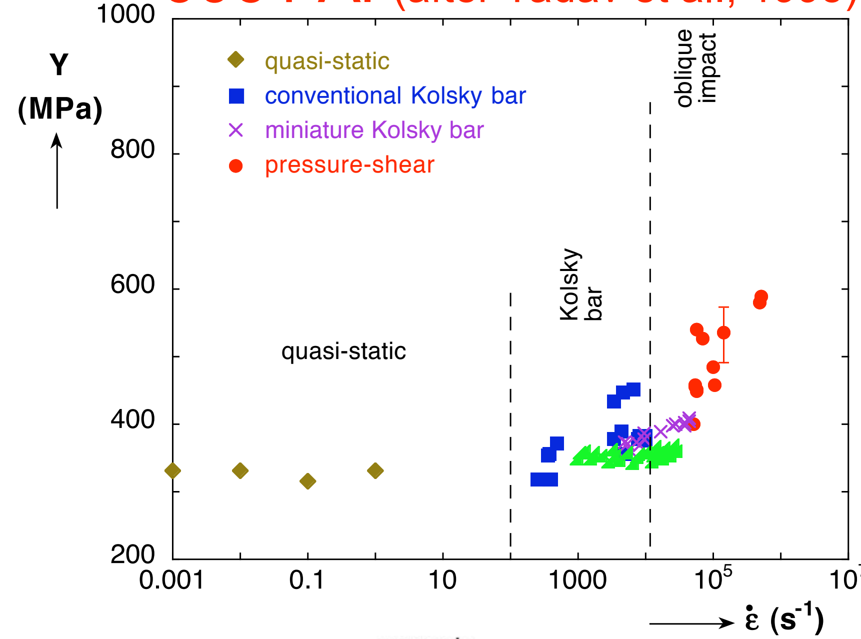
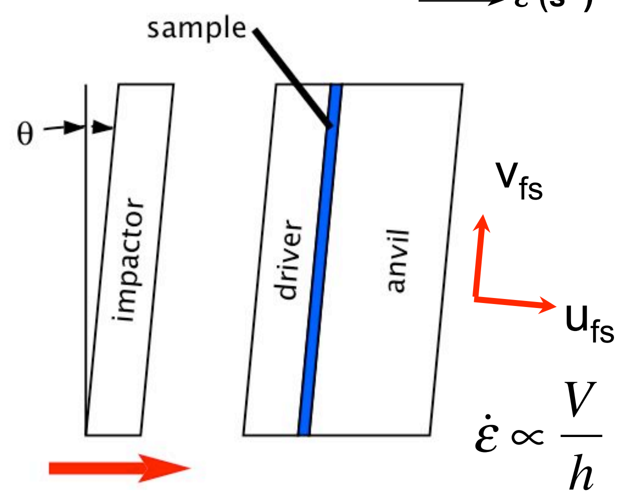
The Mechanics Viewpoint: Strain Rate Dependence



6061 Al (after Yadav et al., 1995)

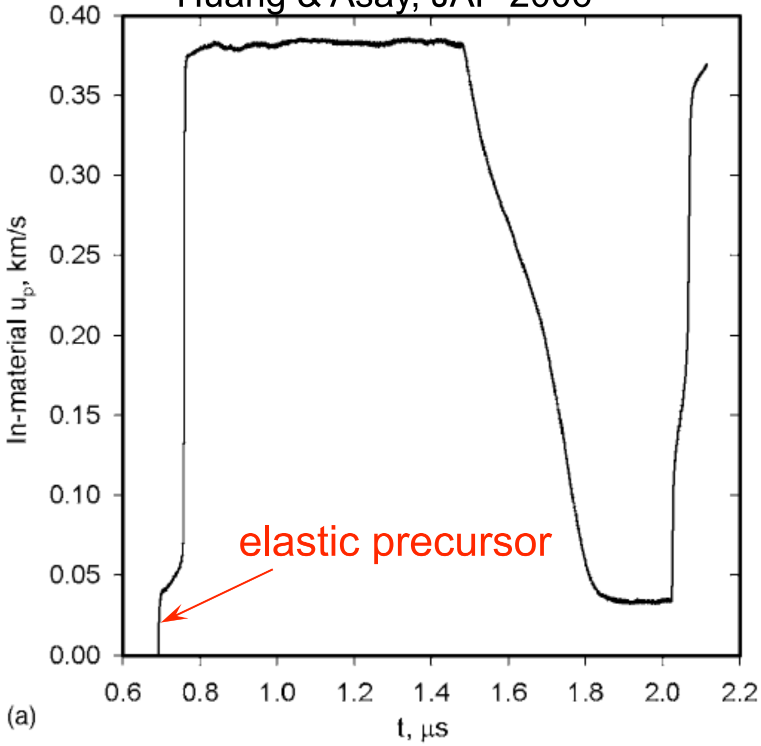


Purdue U., W. Chen

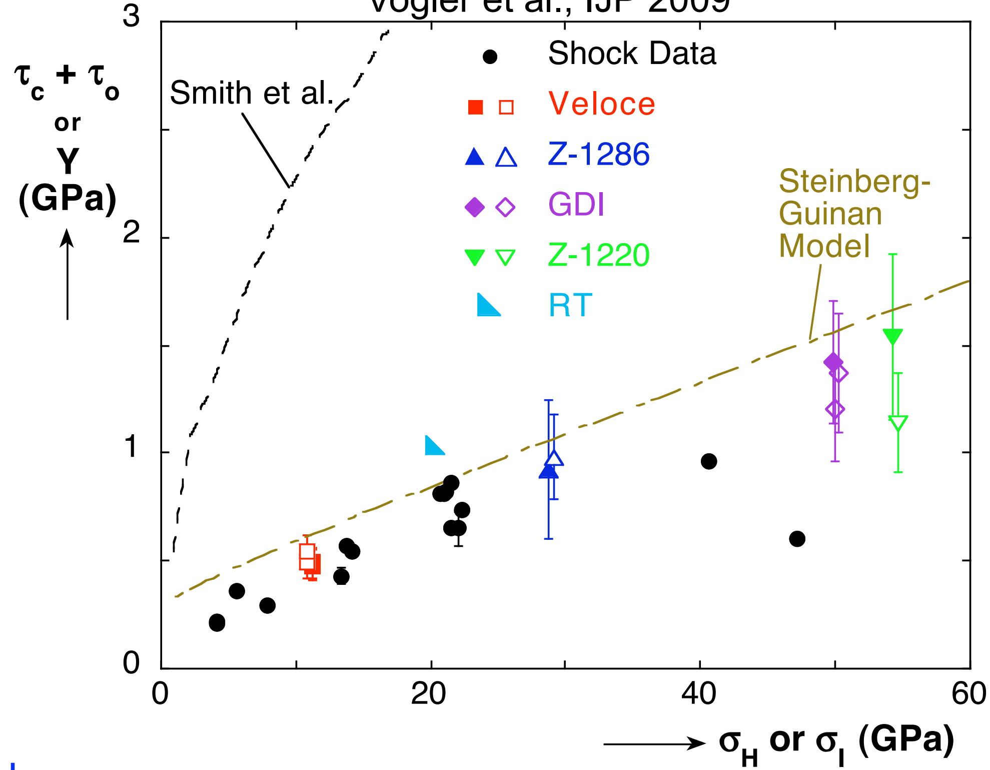


The Shock Physics Viewpoint: Pressure Dependence

Huang & Asay, JAP 2006



Vogler et al., IJP 2009



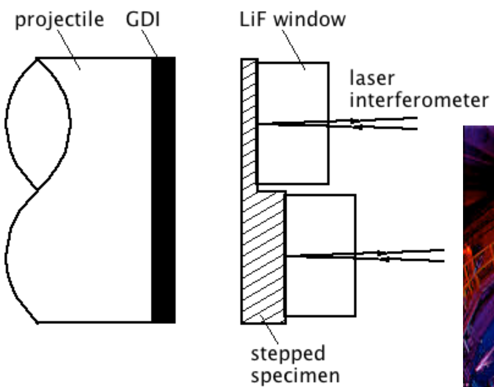
- elastic limit of 6061-T6 aluminum in shock experiments suggests minimal rate dependence

Steinberg-Guinan Strength Model (rate-independent version):

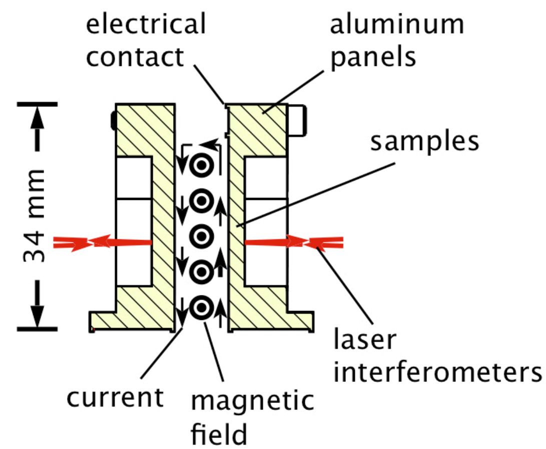
$$\frac{Y}{Y_o} = \left(1+\beta(\varepsilon_p+\varepsilon_i)\right)^n \frac{G(P,T)}{G_o} \qquad G(P,T) = G_o + \frac{\partial G}{\partial P}\frac{P}{\eta^{1/3}} + \frac{\partial G}{\partial T}(T-T_o)$$

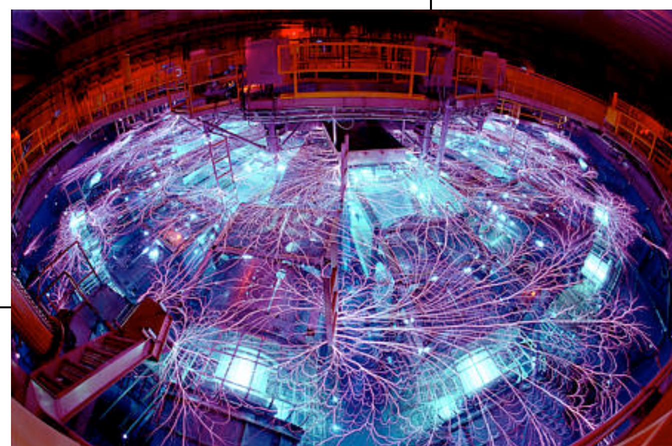
Ramp Loading Techniques Can Access Rates of 10^6 s^{-1} and Above

Graded Density Impactor, Barker, 1984

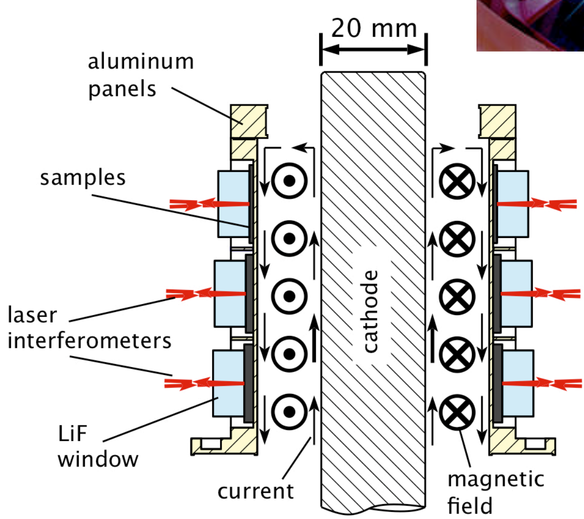


Magnetic Loading - Veloce

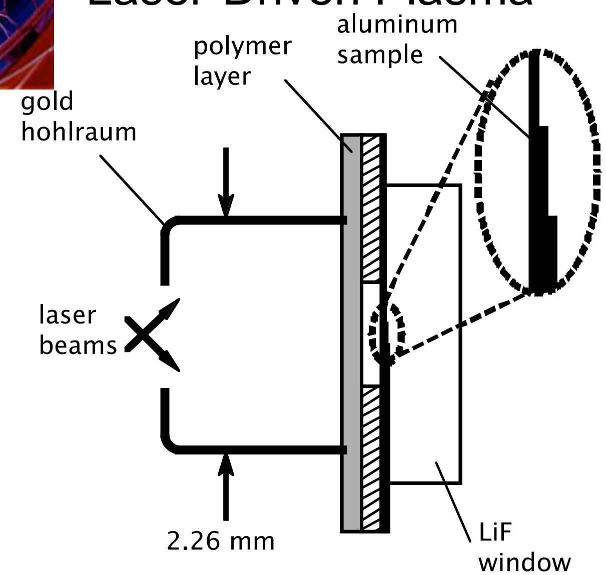




Magnetic Loading - Z

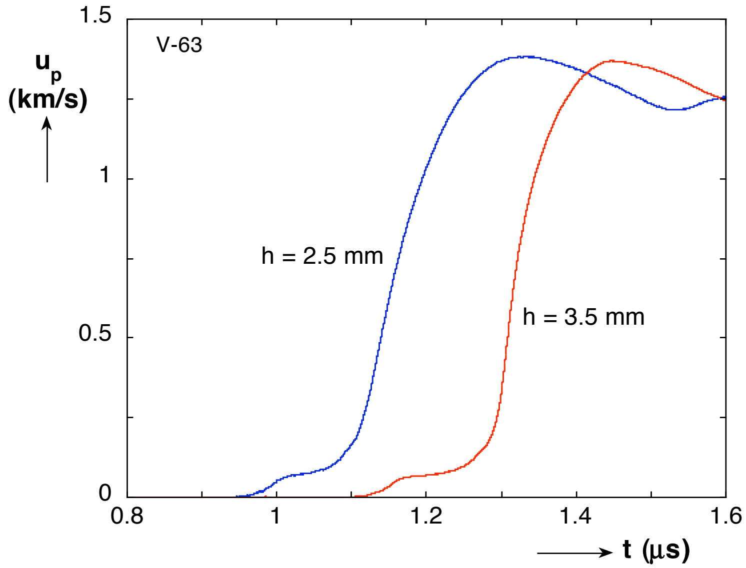


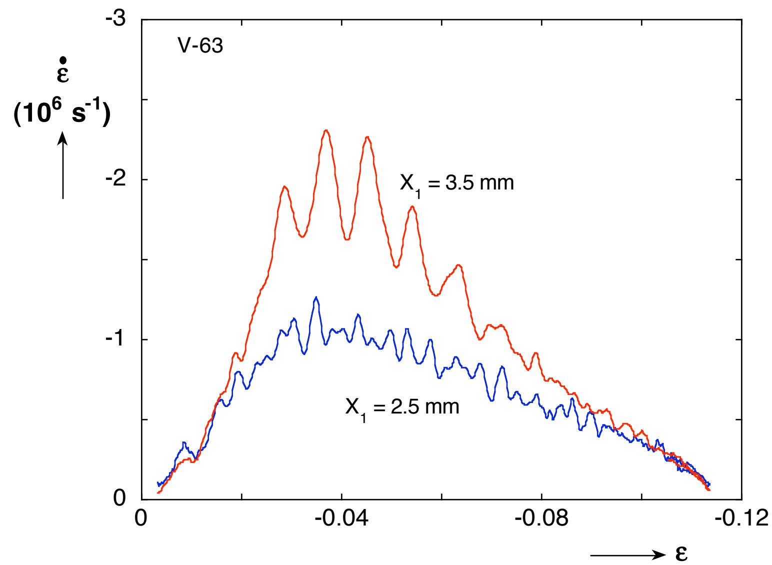
Laser-Driven Plasma

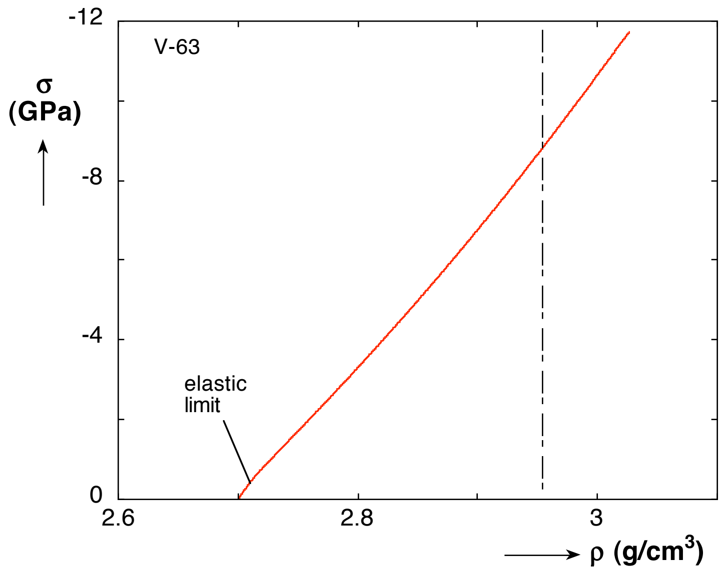


Smith et al., 2007

Results for an Experiment on Veloce



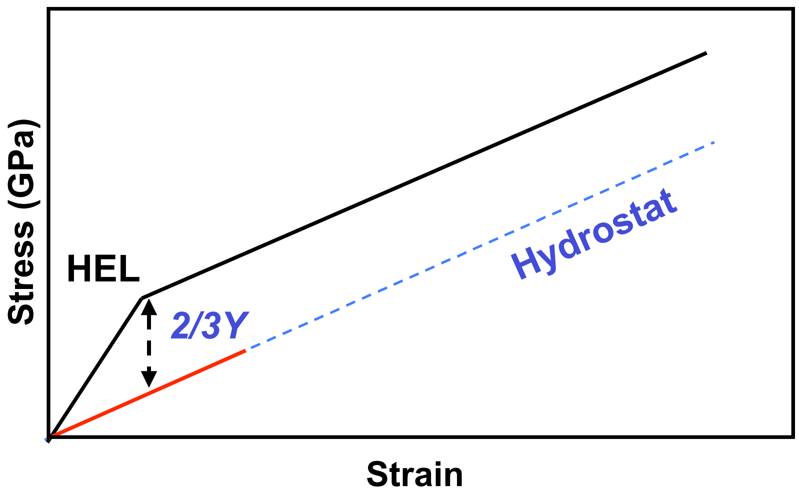




- free surface velocities measured for multiple sample thicknesses with VISAR
- iterative characteristics analysis used to determine uniaxial strain material response, $\sigma = \sigma(\varepsilon)$
- estimate strain rate based on velocity measurements - relatively constant for 2.5 and 3.5 mm

Comparison to Hydrostat

Fowles, G. R. (1961). "Shock wave compression of hardened and annealed 2024 aluminum," *J. Appl. Phys.* ***32, 1475-1487.***



$$Y = 1.5(\sigma_x(\rho,T) - P(\rho,T))$$

compare shock state to hydrostatic state at same density (with appropriate thermal corrections)

applied to ramp loading: Al - Barker (1984), Smith et al. (2007)
Mo - Reisman et al. (2001)
W - Chhabildas & Barker (1988)
diamond - Bradley et al. (2009)

good: simple, continuous measurement, compliments other techniques
bad: difference of two large numbers, uncertainties in hydrostat

The Issue of Temperature

- temperature along the isentrope calculated using thermodynamic relationships and the EOS
- non-isentropic processes occur in experiments (viscosity, strength, etc.)
- therefore, must account for irreversible processes
- focus on heating due to plastic work

Calculation of Temperature Change Due to Plastic Work

some preliminary equations:

deviatoric stress

$$\sigma'_{ij} = \sigma_{ij} - \tfrac{1}{3}\delta_{ij}\sigma_{kk}$$
$$= \sigma_{ij} - \tfrac{1}{3}\delta_{ij}\bar{\sigma}$$

mean stress

flow stress

$$Y = -\tfrac{3}{2}\sigma'_{11}$$
$$= \tfrac{3}{2}\left(-\sigma_{11} - P\right)$$

rate of deformation tensor

$$D_{ij} = \frac{1}{2}\left(\frac{dv_i}{dx_j} + \frac{dv_j}{dx_i}\right)$$

work equations:

rate of work $$\frac{dW}{dt} = \sigma_{ij}D_{ij} = \frac{dW_V}{dt} + \frac{dW_D}{dt}$$

volumetric rate of work

$$\frac{dW_V}{dt} = -P\,D_{ii}$$

deviatoric rate of work

$$\frac{dW_D}{dt} = \sigma'_{ij}D'_{ij}$$
$$= \tfrac{2}{3}Y\frac{\dot{\rho}}{\rho}$$

assumption: deviatoric elastic strain energy is small

$$\frac{dW_D}{dt} \approx \frac{dW_P}{dt}$$

Calculation of Temperature Change Due to Plastic Work (2)

temperature calculation along the quasi-isentrope:

Taylor-Quinney factor (assumed= 1)

$$dT = \frac{1}{c_v}\left(\frac{dW_V}{\rho} + \frac{dW_P}{\rho}\right) = \frac{1}{c_v}\left(\frac{bT}{\rho^2}d\rho + \beta\frac{2Y}{3\rho^2}d\rho\right)$$

temperature change along the isentrope

heating due to plastic work

$$b = \left.\frac{\partial P}{\partial T}\right|_V = 3\alpha K_T$$

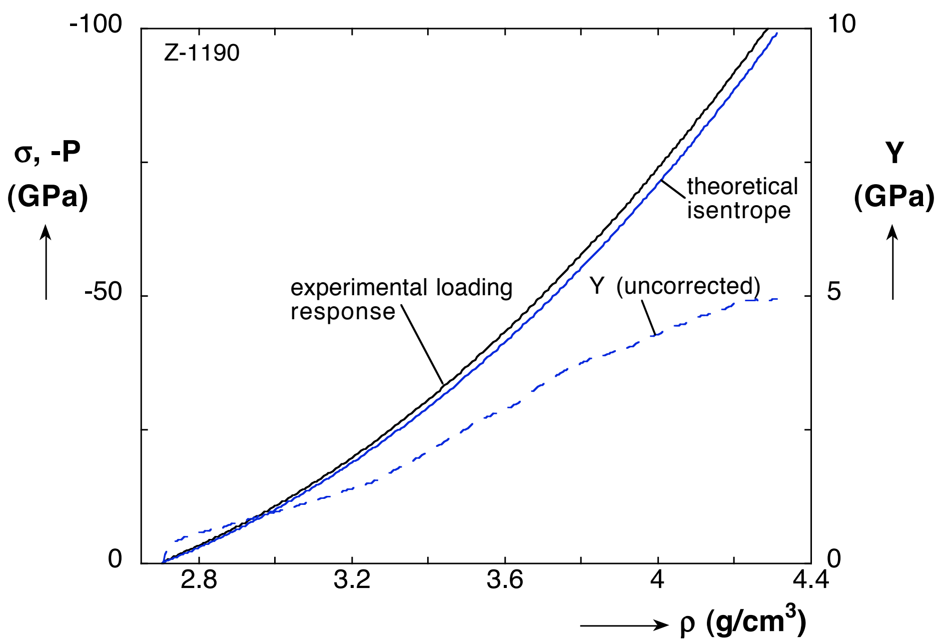
pressure calculation:

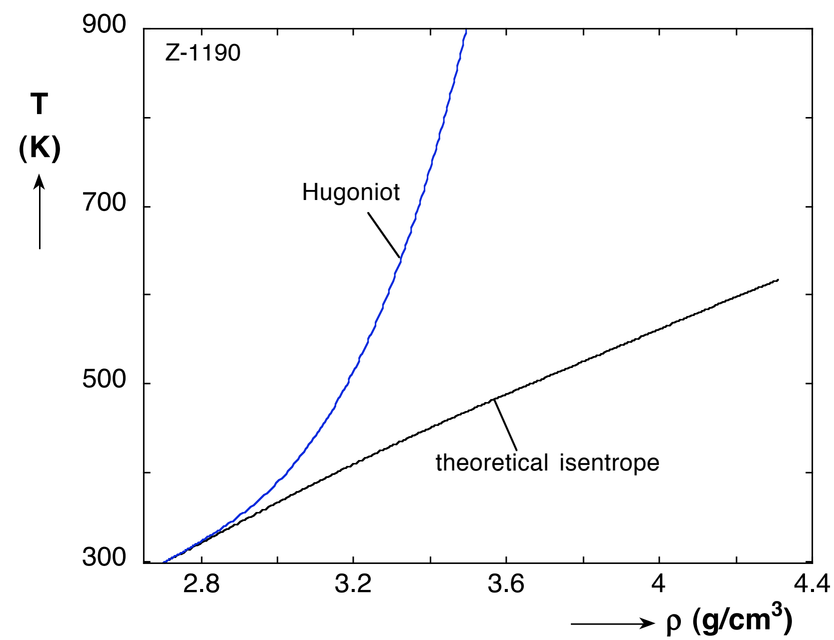
$$dP = \frac{K_S}{\rho}d\rho + \beta\frac{b}{c_v\rho}dW_P = \frac{K_S}{\rho}d\rho + \beta\frac{2bY}{3c_v\rho^2}d\rho$$

$$\Gamma = \frac{b}{c_v\rho}$$

Strength Calculations from Al Results of Davis (2006)

- Experimental data - Davis, J.-P. (2006). *J. Appl. Phys.* ***99, 103512.***
- Sesame 3700 EOS - Kerley, G. I. (1987). *Int. J. Impact Eng.* ***5, 441-449.***





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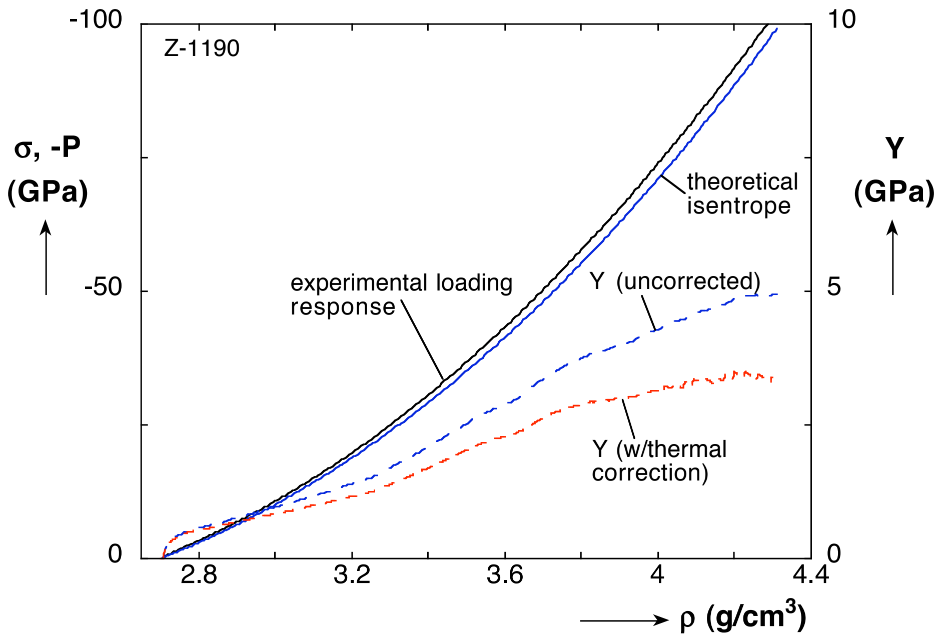
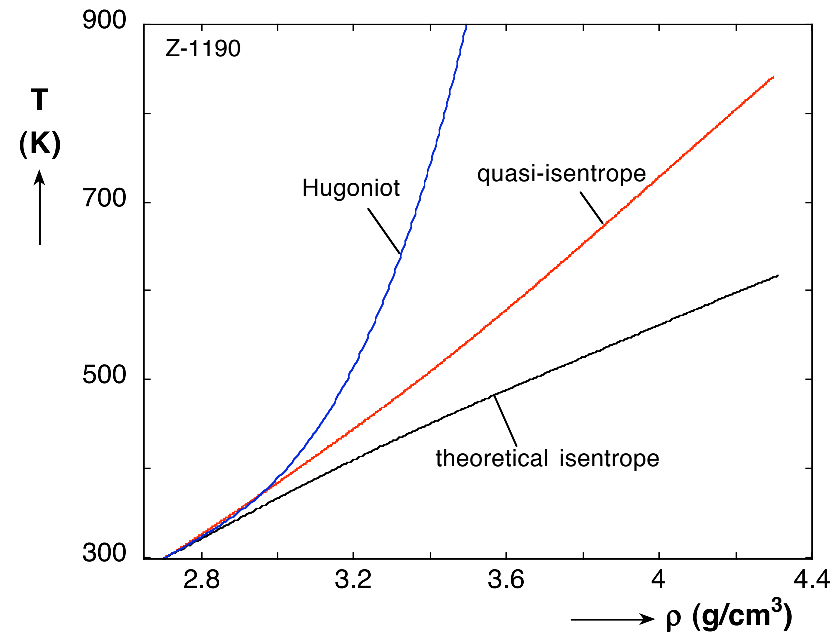
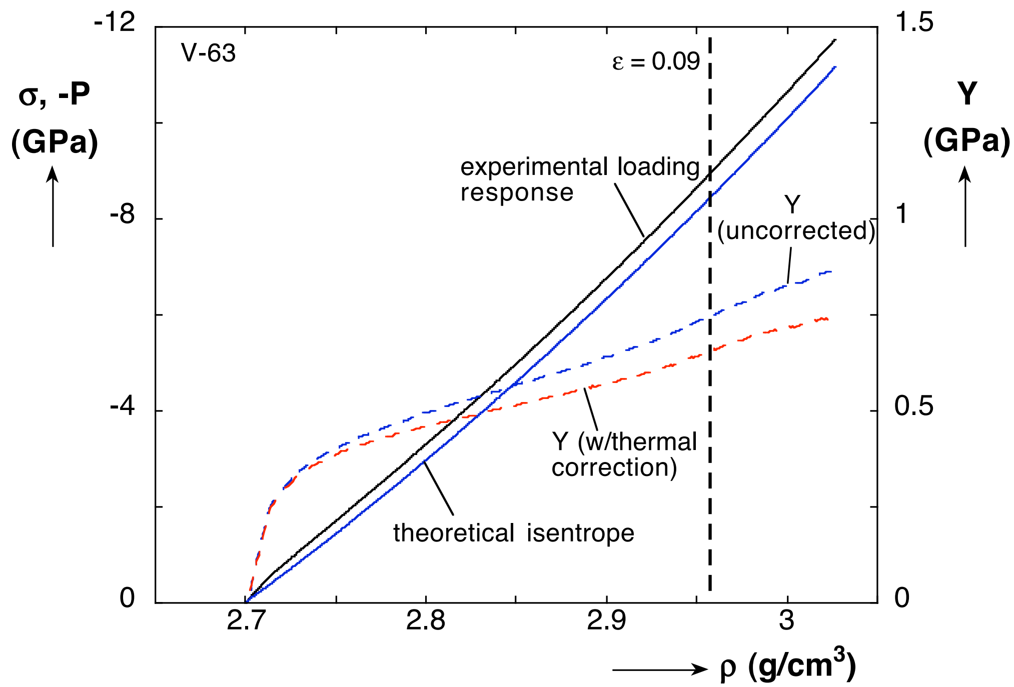




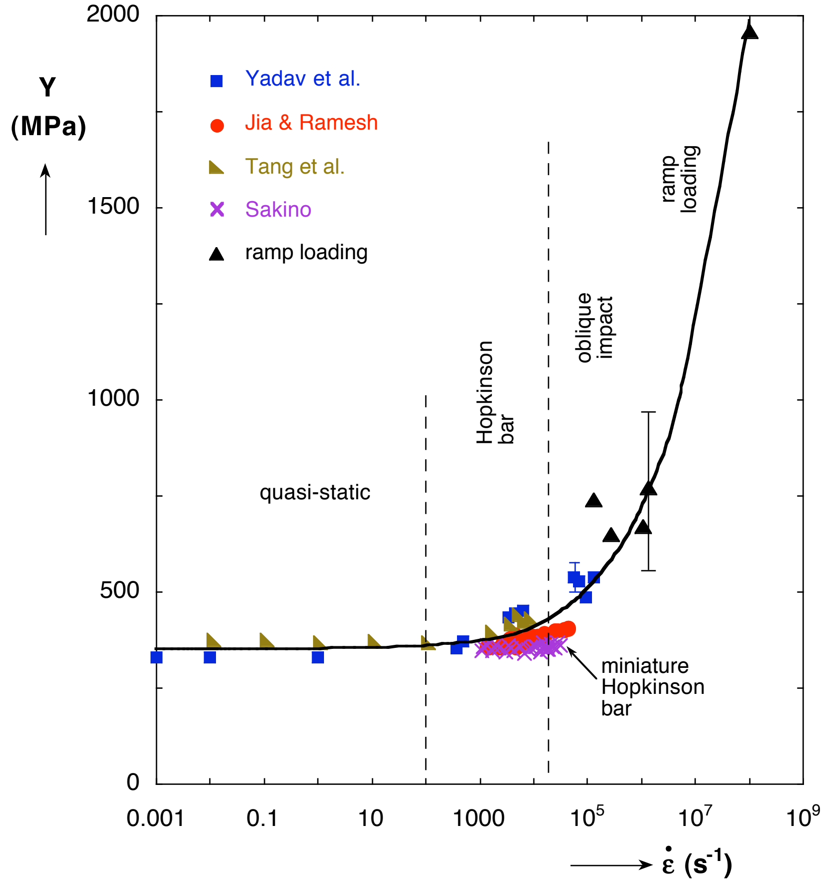
heating due to plastic work has significant effect on apparent strength and temperature

Velocities and Strain Rates for Veloce Experiment



- Y ≈ 0.66 GPa
- P ≈ 8.5 GPa
- temperature rise due to plastic work about 10% effect on Y but miniscule effect on quasi-isentrope

Strain Rate Dependence - Initial Take



- ramp loading results extend strength data for aluminum above 10^6 s^{-1}
- data consistent with strong rate sensitivity beginning around 10^4 s^{-1}

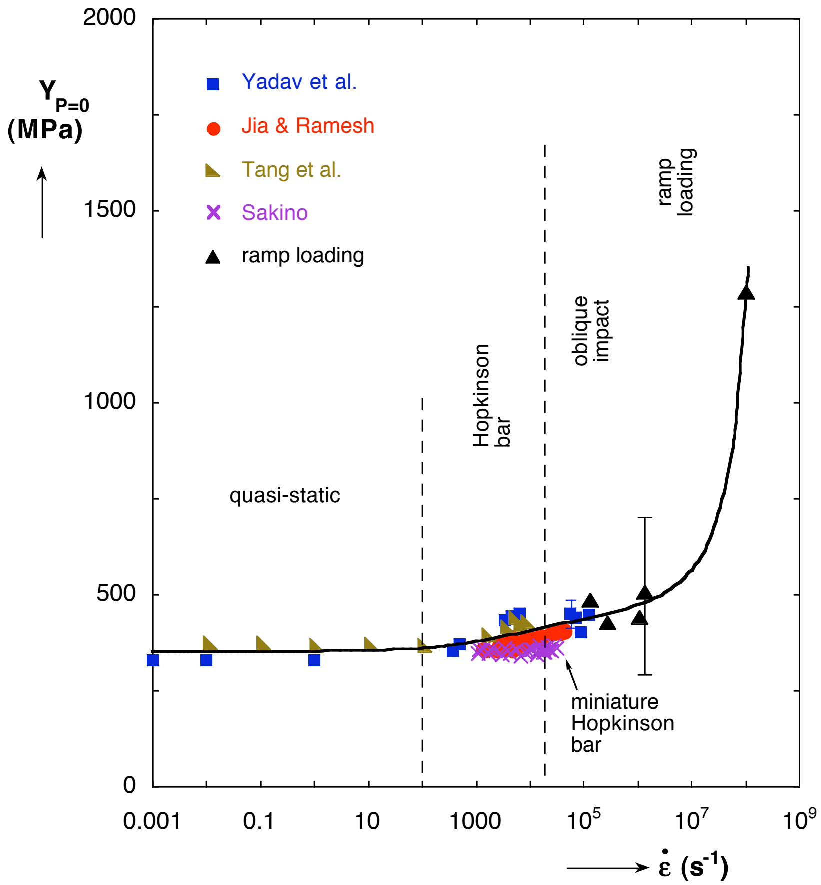
The Effect of Pressure

- range of pressures for different techniques:
  - negligible for quasi-static regime
  - negligible for Hopkinson bar experiments
  - ~3 GPa for pressure-shear experiments
  - ~8.5 GPa for ramp loading experiments
- theoretical arguments suggest strain rate should scale with shear modulus, which increases with pressure
- estimate zero-pressure flow stress using

$$Y_{P=0} = \frac{G_o}{G(P)} Y$$

- lowers Y by about 34% for ramp loading and about 17% for pressure-shear

Strain Rate Dependence
- The Effect of Pressure



- zero-pressure flow strengths suggest that strong strain rate sensitivity doesn't occur until ~10^7 s^{-1}
- scaling is very simplistic and may not be entirely accurate

Pressure Effects in Other Materials

- pressure ~constant in pressure-shear experiments (3-5 GPa),
- thus, pressure effect will be less in most other materials (which will have higher bulk modulus than aluminum)
- for ramp loading to a constant strain level, pressure effects in aluminum, copper, and tantalum are comparable (at ε=0.09, P=9, 16, and 20 GPa, respectively)

Conclusions

- ramp loading can be used to extend strength measurements to strain rates well above those for other techniques
- must account for heating due to plastic work to obtain correct strength value
- when comparing ramp loading results to quasi-static and Hopkinson bar data, it is necessary to account for the mean stress (hydrostatic pressure)
- in pressure-shear experiments, this effect is non-negligible for aluminum but small for most other materials
- data suggests strong rate sensitivity doesn’t occur in 6061-T6 aluminum until strain rates of ~10^7 s^{-1}