2018 International Mechanical Engineering Congress & Exposition (IMECE), Tampa, Florida, November 3-9, 2017

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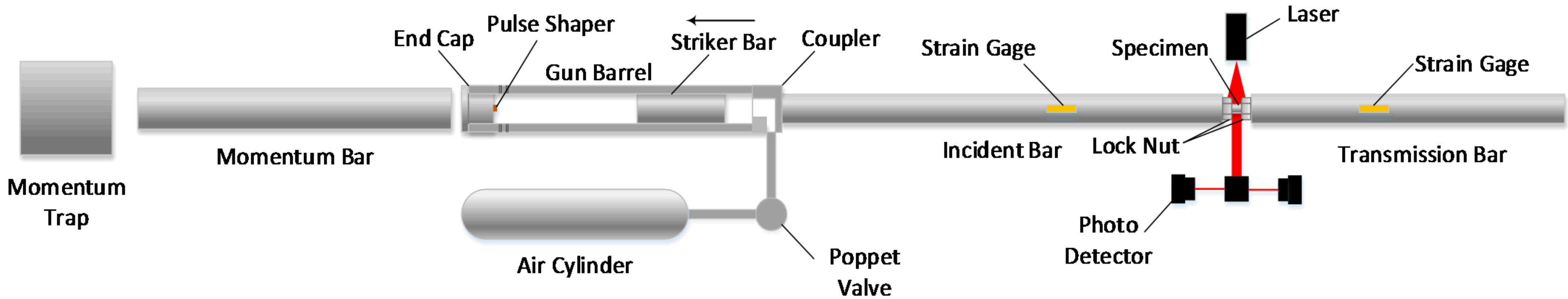

High Strain Rate Tensile Response of A572 and 4140 Steel

Bo Song, Brett Sanborn, Andrew Thompson, Blake Reece, Stephen Attaway, Russell Teeter

U.S. DEPARTMENT OF ENERGY NNSA National Nuclear Security Administration

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A572 and 4140 Steels

- American Society for Testing and Materials (ASTM) **A572 steel**
  - Columbium-Vandium Steel
  - Minimum yield stress of ~400 MPa (quasi-static)
  - Good corrosion resistance
- Used in:
  - Building structures
  - Anchoring systems
  - Bridges
  - Boom sections

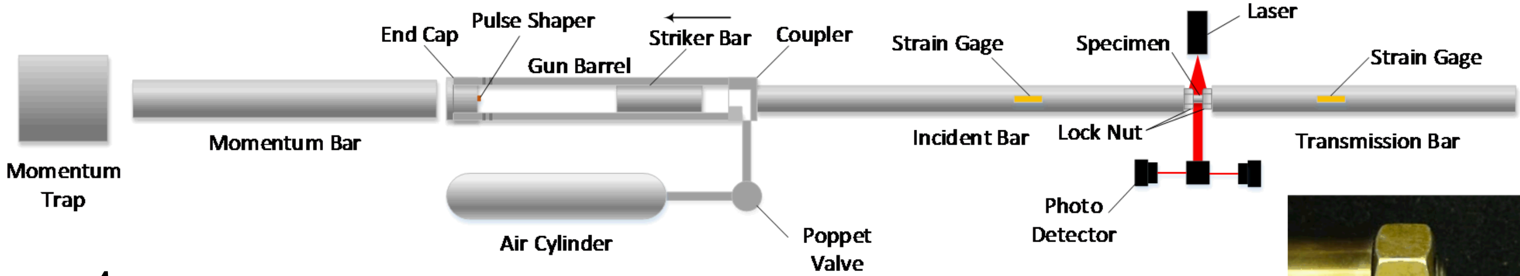
ASTM A572-50 steel beam for a bridge.

www.steel-sections.com

- American Iron and Steel Institute (AISI) **4140 Alloy**
  - Chromium-Molybdenum
  - Yield Strength ~650 MPa (quasi-static)
  - Excellent corrosion resistance
- Used in:
  - Hydraulic Shafts
  - Boring bars
  - Axles
  - Roll Cages
  - Bolts

Scope of Work

- Dynamic tensile material characterization at high strain rates
  - ~500, 1500, 3000 s^{-1}



$$\sigma_E = E\frac{A_0}{A_s}\varepsilon_t$$

$$\varepsilon_E = \begin{cases} c'\dfrac{L_1 - L_2}{L_s} & (\sigma \le \sigma_y) \\ \dfrac{L_1 - L_2 - (1 - c')(L_1 - L_2)_{yield}}{L_s} & (\sigma > \sigma_y) \end{cases}$$

$$c' = \frac{\Delta L_s}{\Delta L + \Delta L_s} = 0.62$$

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DYMAT 23rd Technical Meeting

Dynamic Fracture of Ductile Materials

High Strain Rate Tensile Response of A572 and 4140 Steel

Brett Sanborn[a]*, Bo Song[a], Andrew Thompson[a], Blake Reece[a], Stephen Attaway[a]

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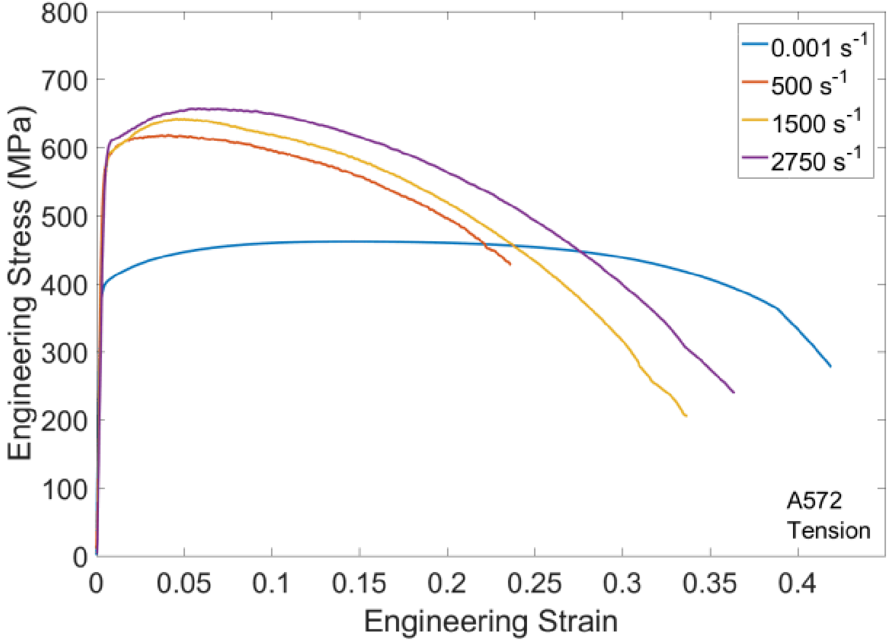
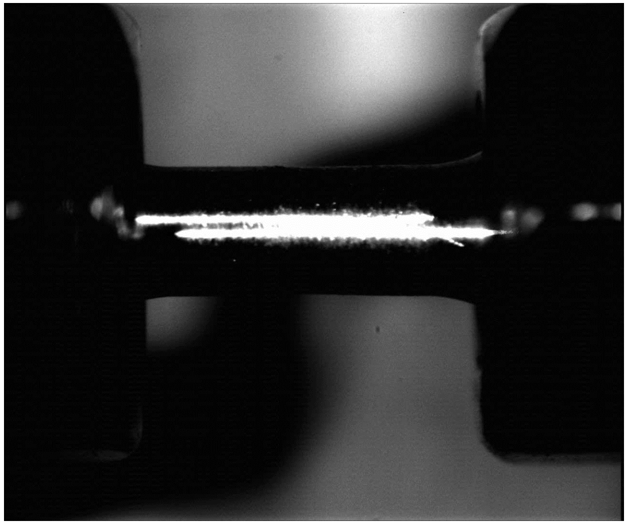
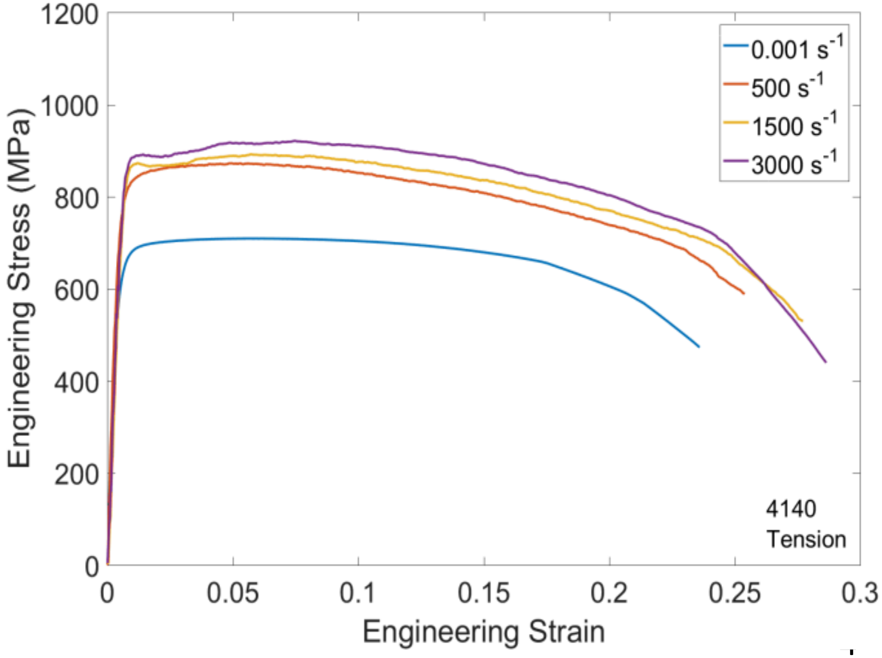
- Rate-dependent material modeling
  - Modified Johnson-Cook model

Experimental Results

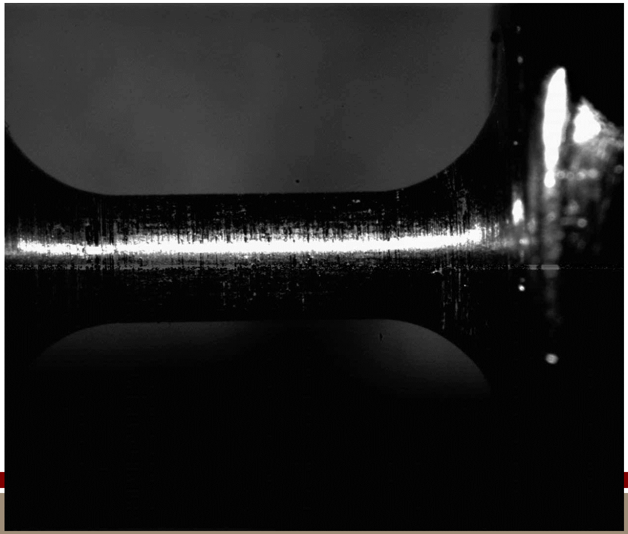


A572 #19

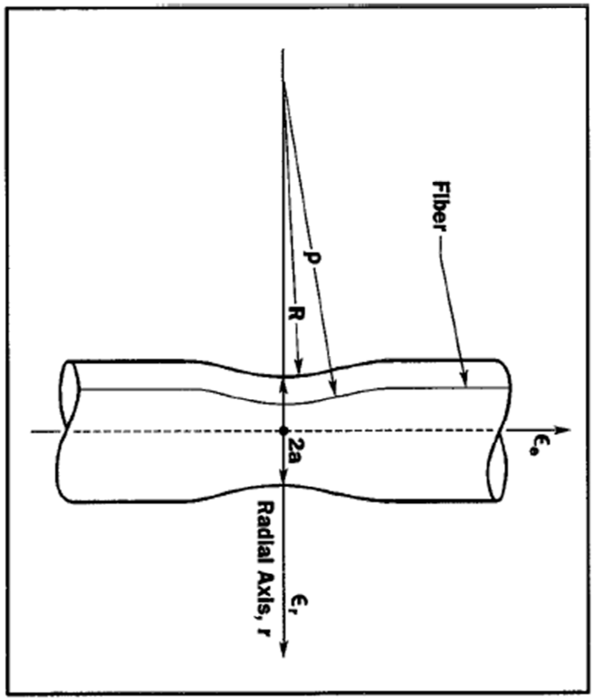




4140 #12



Bridgman Correction for Necking



Bridgman Correction

- Assumptions:
  - Uniform strain distribution in the minimum section
  - A longitudinal grid line deformed into a curve at the neck
- Good for rod

- True strain $\varepsilon_T = ln\frac{A_0}{A}$

- Average true axial stress at the smallest cross section

$$(\sigma_a)_{av} = \frac{F}{A} = \sigma_E \frac{A_0}{A}$$

  - Uniaxial stress correction

$$\sigma_T = k(\sigma_a)_{av}$$

$$k = \left[\left(1 + \frac{2R}{a}\right) ln\left(1 + \frac{a}{2R}\right)\right]^{-1}$$

- Requires instantaneous measurements of minimum cross sectional area, *A,* and radius, *R*.

True Stress-Strain Response

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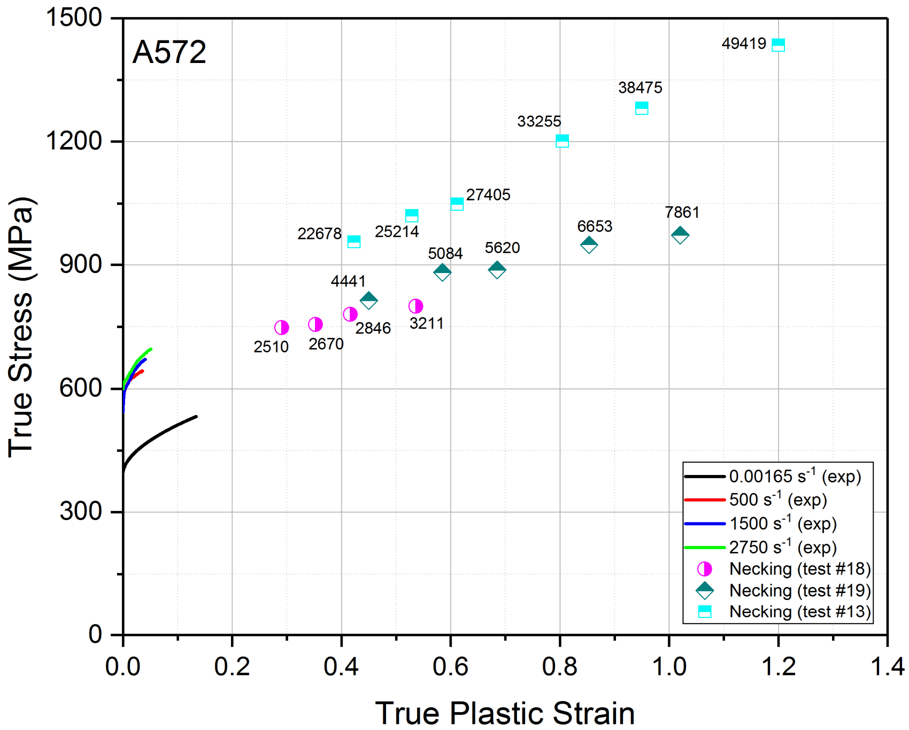
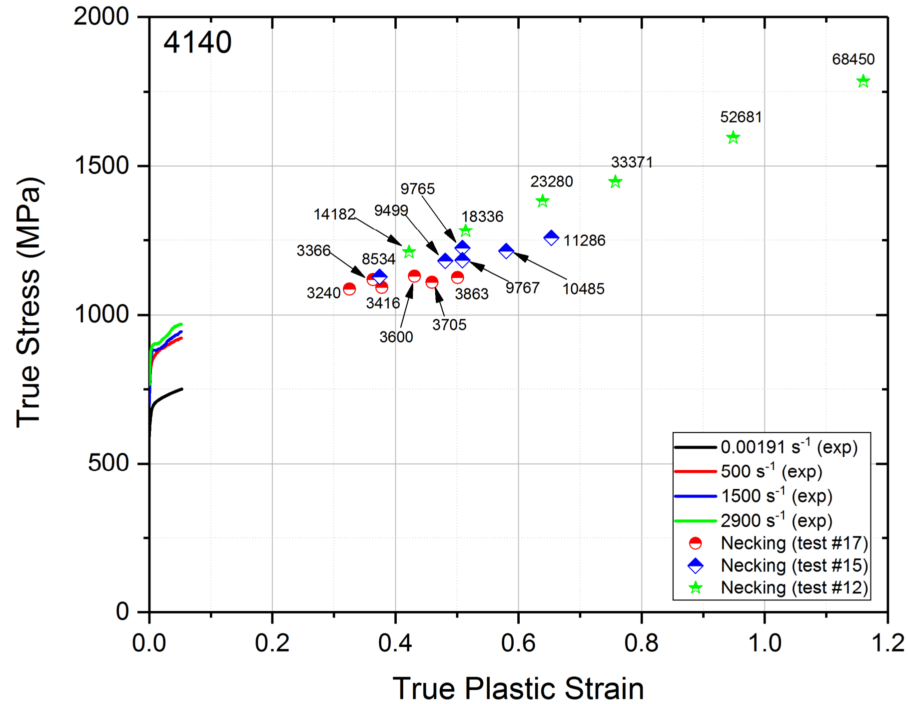




During necking

- True plastic strain becomes significantly higher
  - *More than 10 times elongated*
- Strain rate becomes significantly higher
  - *More than 10 times higher*

Johnson-Cook Model

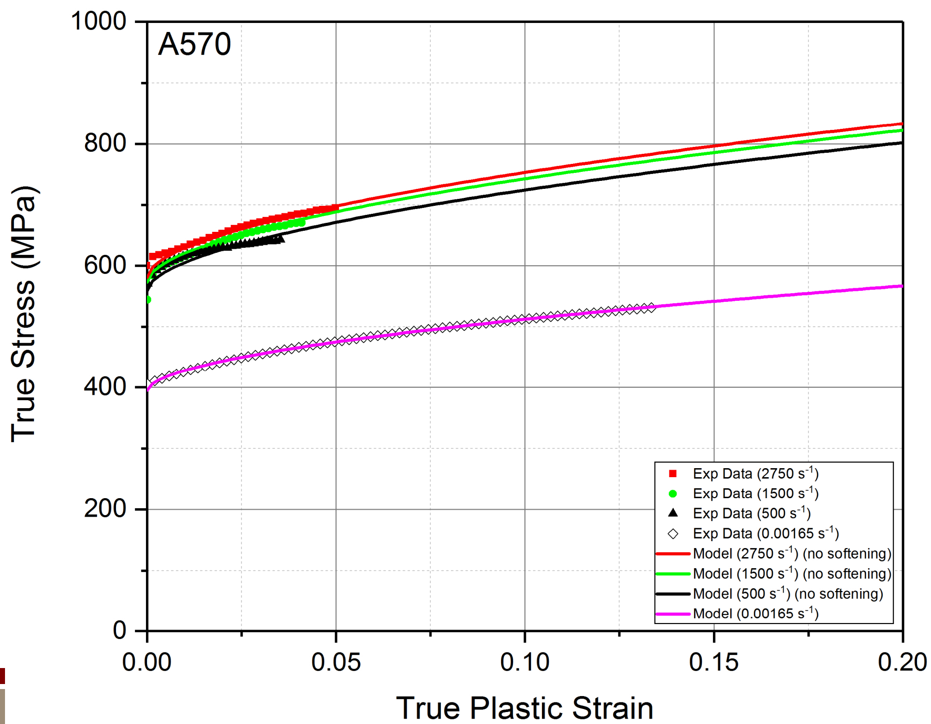
$$\sigma = \left(A + B\varepsilon^n\right)\cdot\left(1 + C\ln\frac{\dot{\varepsilon}}{\dot{\varepsilon}}\right)\cdot\left(1 - T^{*m}\right)$$

$$T^* = \frac{T - T_0}{T_m - T_0}$$

Strain (work) hardening

Strain-rate effect (scaling)

Temperature effect (thermal-softening)



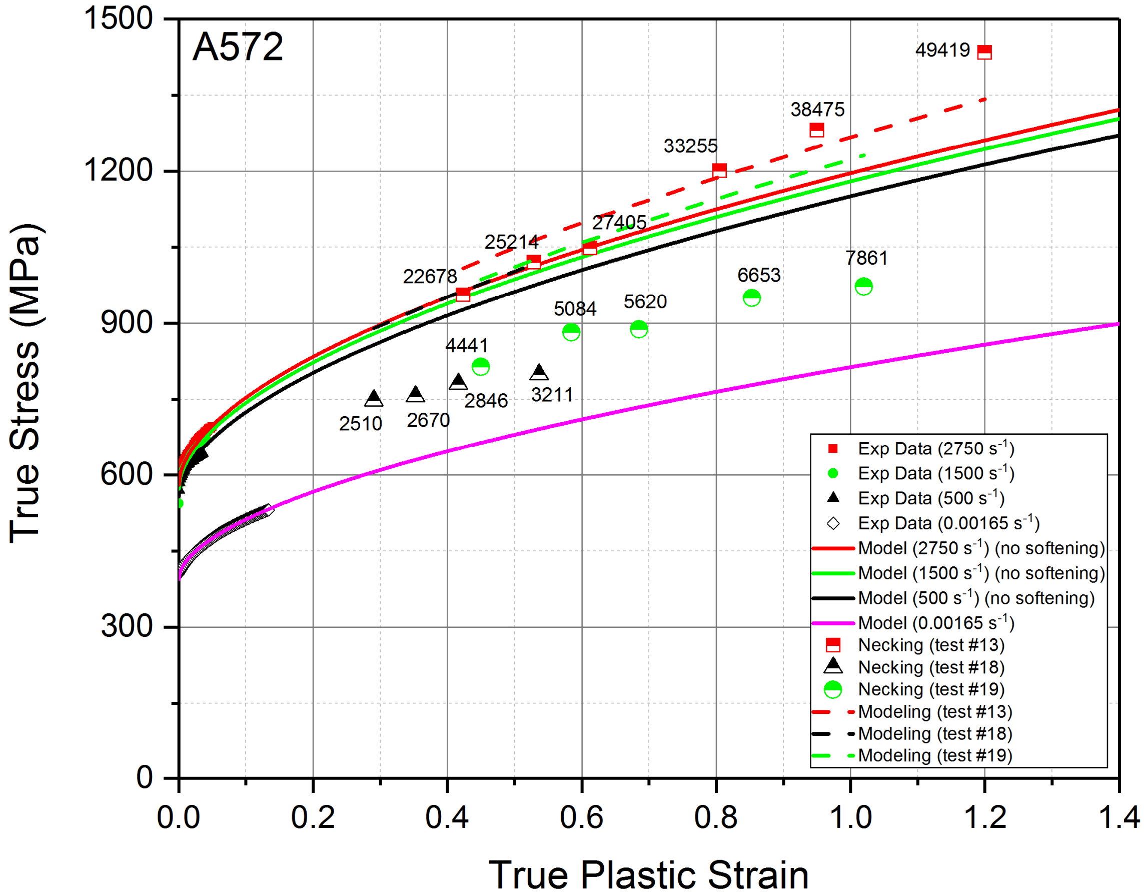
The most difficult part !

- *May be neglected for room-temperature quasi-static tests*
- *What about room-temperature dynamic tests?*

Johnson-Cook Model (Temperature Effect)

$$\sigma = \left(A + B\varepsilon^n\right)\cdot\left(1 + C\ln\frac{\dot{\varepsilon}}{\dot{\varepsilon}}\right)\cdot\left(1 - T^{*m}\right)$$

$$T^* = \frac{T - T_0}{T_m - T_0}$$



What about room-temperature dynamic tests?

- *Adiabatic heating must be considered*
  - *In-situ temperature measurement*
  - *Temperature effect on quasi-static material properties*
  - *Uncertainties?*

$$\Delta T = \frac{\beta}{\rho C}\cdot\int \sigma d\varepsilon$$

Where is "adiabatic"?

Modified Johnson-Cook Model for Thermal Softening

$$\sigma = \left(A + B\varepsilon^{n}\right)\cdot\left(1 + C\ln\frac{\dot{\varepsilon}}{\dot{\varepsilon}}\right)\cdot\left(1 - T^{*m}\right)$$

$$T^{*} = \left(T_{m} - T_{0}\right)\cdot\Delta T = f\left(\varepsilon,\dot{\varepsilon}\right)\propto \varepsilon,\ln\frac{\dot{\varepsilon}}{\dot{\varepsilon}_{0}}$$

$$\sigma = \left(A + B\varepsilon^{n}\right)\cdot\left(1 + C\ln\frac{\dot{\varepsilon}}{\dot{\varepsilon}}\right)\cdot\left(1 - D\left(\varepsilon\cdot\ln\frac{\dot{\varepsilon}}{\dot{\varepsilon}_{0}}\right)^{m}\right)$$

when $\varepsilon = 0 \longrightarrow T^{*} = 0$

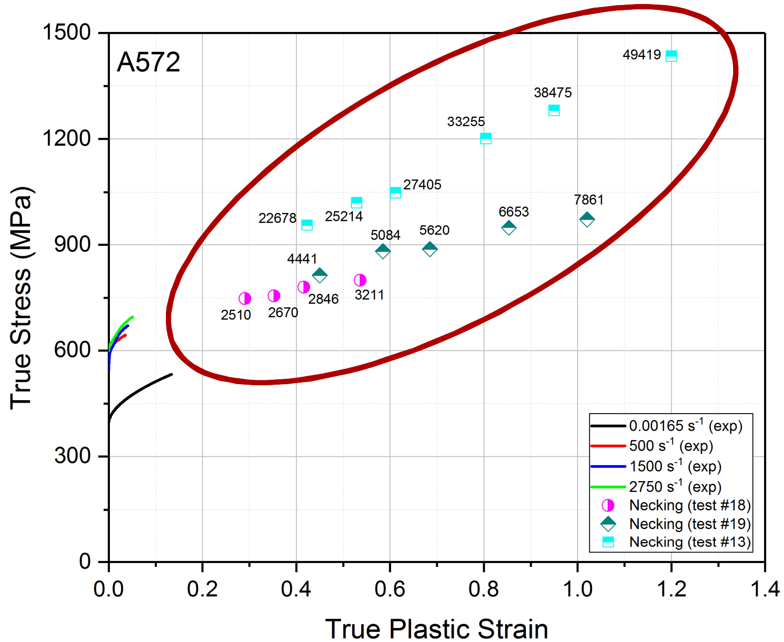
when $\dot{\varepsilon} = \dot{\varepsilon}_{0} \longrightarrow T^{*} = 0$

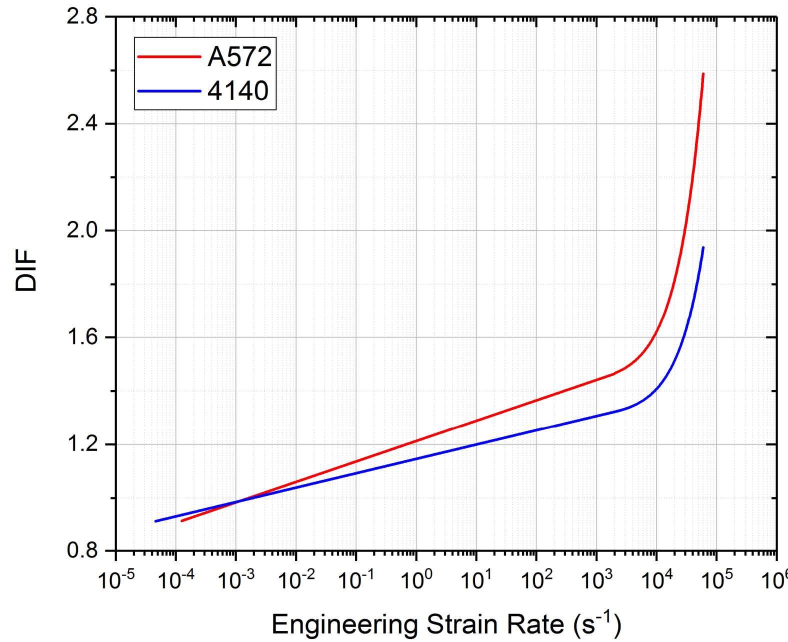
No temperature rise

$\dot{\varepsilon}_{0}$ is reference strain rate which is sufficiently low to be considered isothermal.

Showing adiabatic heating at higher strain rates

Modified Johnson-Cook Model For Strain-Rate Effect

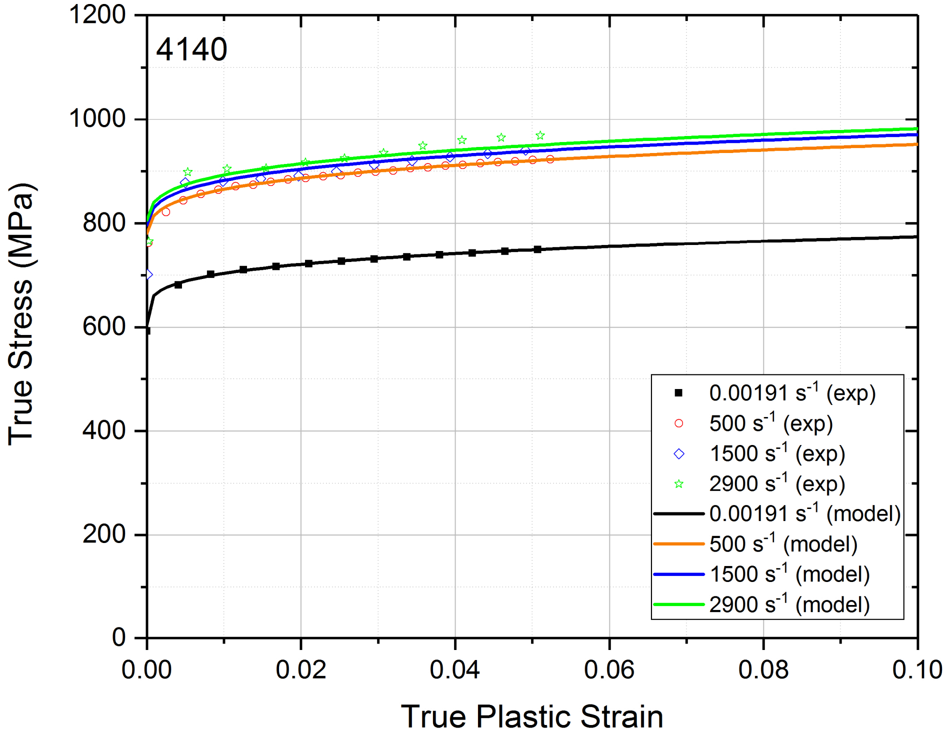


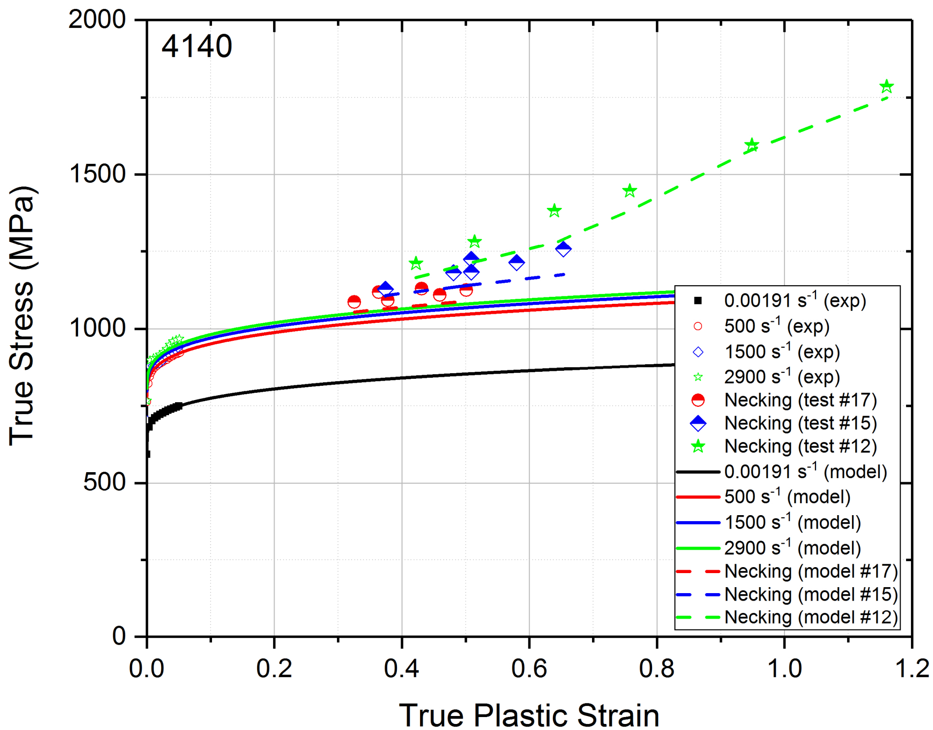


$$\sigma = \left(A + B\varepsilon^{n}\right)\cdot f\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)\cdot\left(1 - D\left(\varepsilon\cdot\ln\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)^{m}\right)$$

$$f\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right) = \begin{cases} 1 + C_0 \ln\left(\dfrac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right) & \dot{\varepsilon} \le \dot{\varepsilon}^{*} \\ C_1 + C_2\cdot\dfrac{\dot{\varepsilon}}{\dot{\varepsilon}_0} & \dot{\varepsilon} > \dot{\varepsilon}^{*} \end{cases} \qquad \dot{\varepsilon}^{*} = 2500 s^{-1}$$

Modified Johnson-Cook Model for A572 Steel



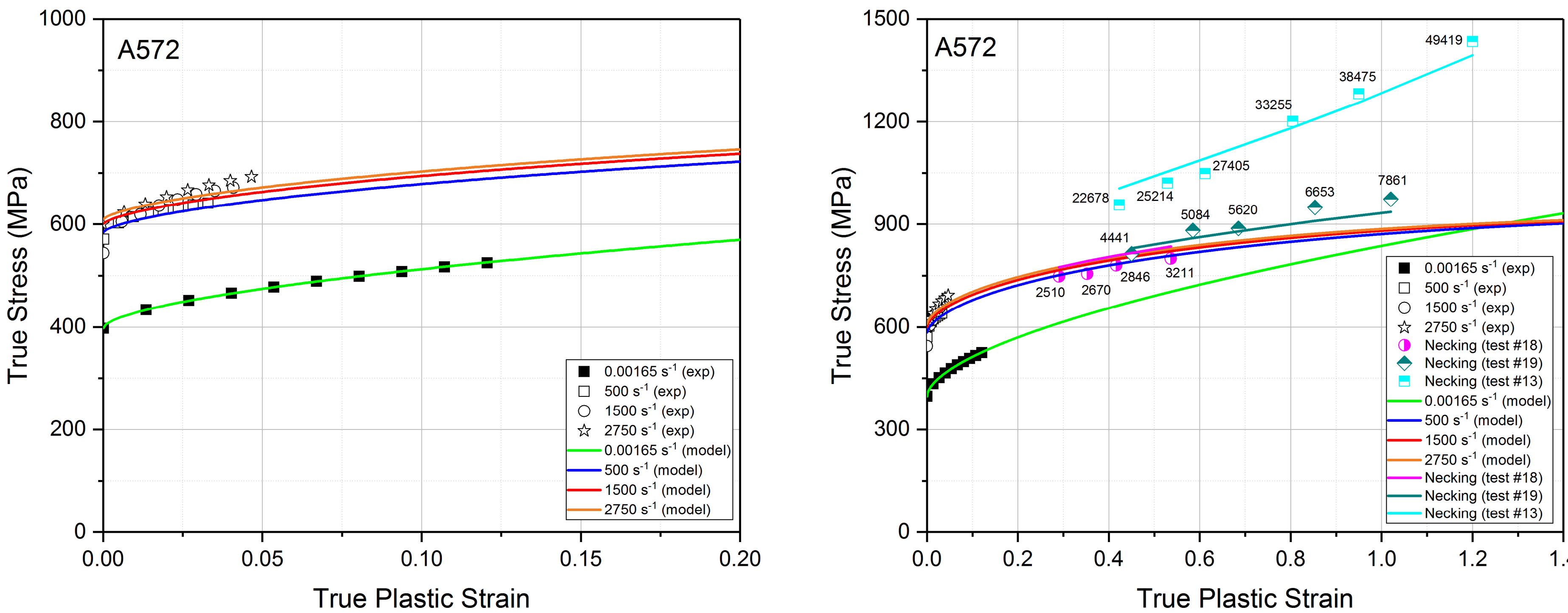


$$A = 605.53 MPa \quad B = 291.31 MPa \quad n = 0.2375 \quad D = 0.04739$$

$$m = 0.01235 \quad C_0 = 0.02327 \quad C_1 = 1.3016 \quad C_2 = 3.0583 \times 10^{-8}$$

$$\dot{\varepsilon}_0 = 0.00191 s^{-1} \quad \dot{\varepsilon}^* = 2500 s^{-1}$$

Modified Johnson-Cook Model for 4140 Steel



$A = 397.82 MPa$ $B = 438.77 MPa$ $n = 0.5821$ $D = 0.08893$

$m = 0.4676$ $C_0 = 0.03714$ $C_1 = 1.4807$ $C_2 = 3.3551 \times 10^{-8}$

$\dot{\varepsilon}_0 = 0.00165 s^{-1}$ $\dot{\varepsilon}^* = 2500 s^{-1}$

Conclusion

- A572 and 4140 steels were characterized in tension using Kolsky tension bar at high strain rates.

- The tensile stress and strain data during necking were obtained through high-speed measurement of necking geometries and corrected with Bridgman correction.

- The experimental data were used to modify Johnson-Cook model to reflect strain-rate and thermal-softening effect prior to and after necking.

$$\sigma = \left(A + B\varepsilon^n\right) \cdot f\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right) \cdot \left(1 - D\left(\varepsilon \cdot \ln\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)^m\right)$$

$$f\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right) = \begin{cases} 1 + C_0 \ln\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right) & \dot{\varepsilon} \le \dot{\varepsilon}^* \\ C_1 + C_2 \cdot \frac{\dot{\varepsilon}}{\dot{\varepsilon}_0} & \dot{\varepsilon} > \dot{\varepsilon}^* \end{cases}$$