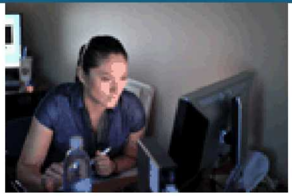
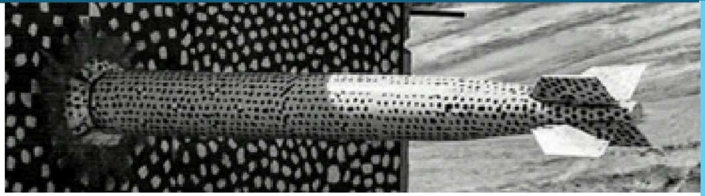
SAND2019-9843C

A Modified Johnson-Cook Model for Dynamic Response of Metals with an Explicit Strain- and Strain-rate-dependent Thermosoftening Effect





PRESENTED BY

Bo Song, Brett Sanborn

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A Classic Johnson-Cook Model

Based on scaling

$$\sigma = \left(A + B\cdot\varepsilon^{n}\right)\cdot\left(1 + C'\cdot\ln\dot{\varepsilon}\right)\cdot\left[1 - T^{*m}\right]$$

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

T_0 Room temperature

T_m Melting temperature

Work Hardening

Strain-rate Strengthening

Temperature Effect

"Temperature Rise" due to "adiabatic heating"

"Adiabatic Thermo-softening"

A general practice:

- Use very low rate data as a reference strain rate (isothermal condition)
- Room-temperature tests at various strain rates
- Quasi-static tests at various temperatures

Johnson GR, Cook WH (1983) A constitutive model and data for metals subjected to large strains, high strain rates and high temperatures. In: Proceedings of the 7th International Symposium on Ballistics, The Hague, The Netherlands, pp.541-7.

Revisit of Classic Johnson-Cook Model – Strain Rate Effect

$$\sigma = \left(A + B\cdot\varepsilon^{n}\right)\boxed{\left(1 + C'\cdot\ln\dot{\varepsilon}\right)}\cdot\left[1-\left(\frac{T-T_0}{T_m-T_0}\right)^{m}\right]$$

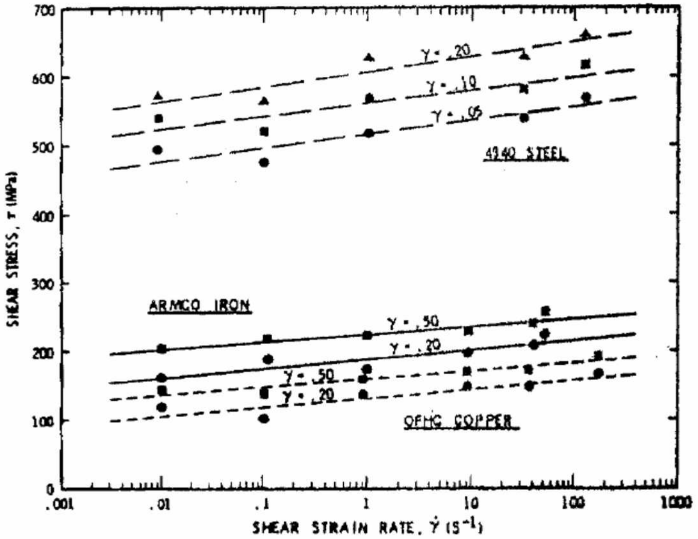
At $\varepsilon = 0$ *ε is plastic strain*

A represents yield strength

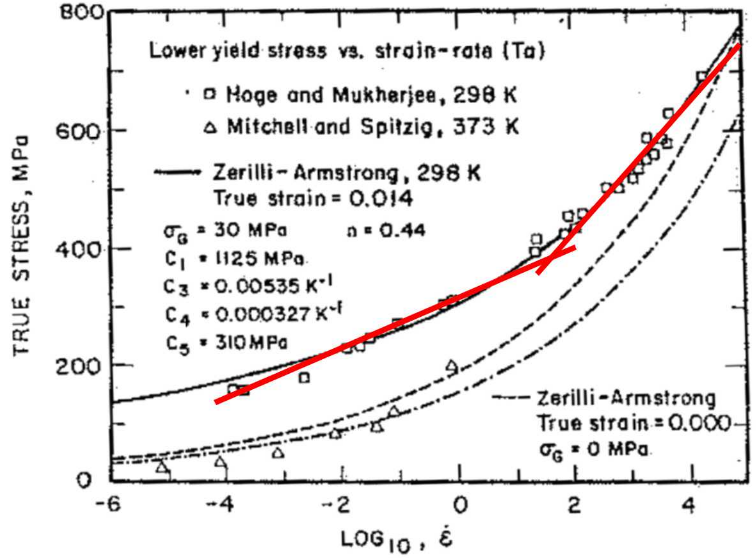
$T = T_0$ No temperature rise

$$\sigma = A\cdot\left(1 + C'\cdot\ln\dot{\varepsilon}\right) = A\cdot\left(1 + C\cdot\ln\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)$$

Strain rate effect – linear to logarithm of strain rate, which may not be true for many materials.



Johnson and Cook, 1983.



M. Meyers, Dynamic Behavior of Materials, 1994.

Revisit of Classic Johnson-Cook Model – Adiabatic Thermosoftening

$$\sigma = \left(A + B \cdot \varepsilon^n\right) \cdot \left(1 + C' \cdot \ln \dot{\varepsilon}\right) \cdot \boxed{\left[1 - \left(\frac{T - T_0}{T_m - T_0}\right)^m\right]}$$

Implicit to Strain and Strain Rate

Determination of Temperature Rise

Determination of Thermosoftening

Fraction of Plastic Work Converted to Heat

Adiabatic/Heat Transfer

Is temperature effect independent of strain rate?

Proposed Modification of J-C Model with Explicit Thermo-softening

$$\sigma = \left(A + B \cdot \varepsilon^{n}\right) \cdot \underbrace{f\left(\dot{\varepsilon}\right)} \cdot \underbrace{g\left(\varepsilon, \dot{\varepsilon}\right)}$$

A better description of strain-rate effect

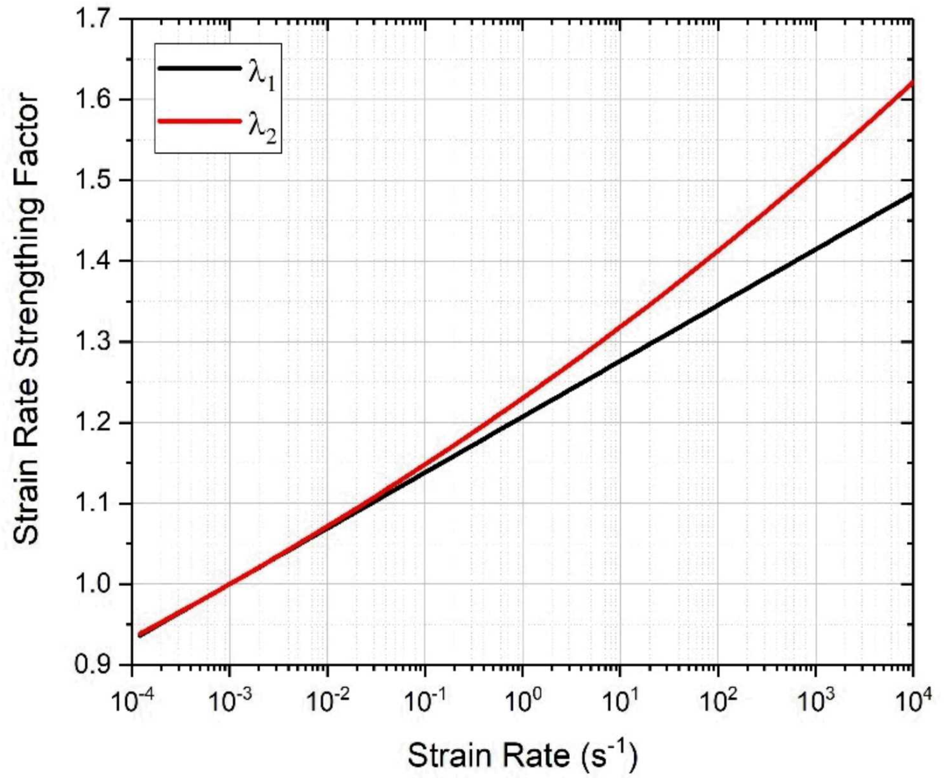
An explicit description of strain and strain-rate-dependent thermo-softening

- A power-law form
  - ✓ Zerilli and Armstrong, 1987
  - ✓ Litonski 1977
  - ✓ Vinh et al. 1979
  - ✓ Klopp et al. 1985

$$f\left(\dot{\varepsilon}\right) = \lambda_2 = \left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)^{\alpha}$$

VS

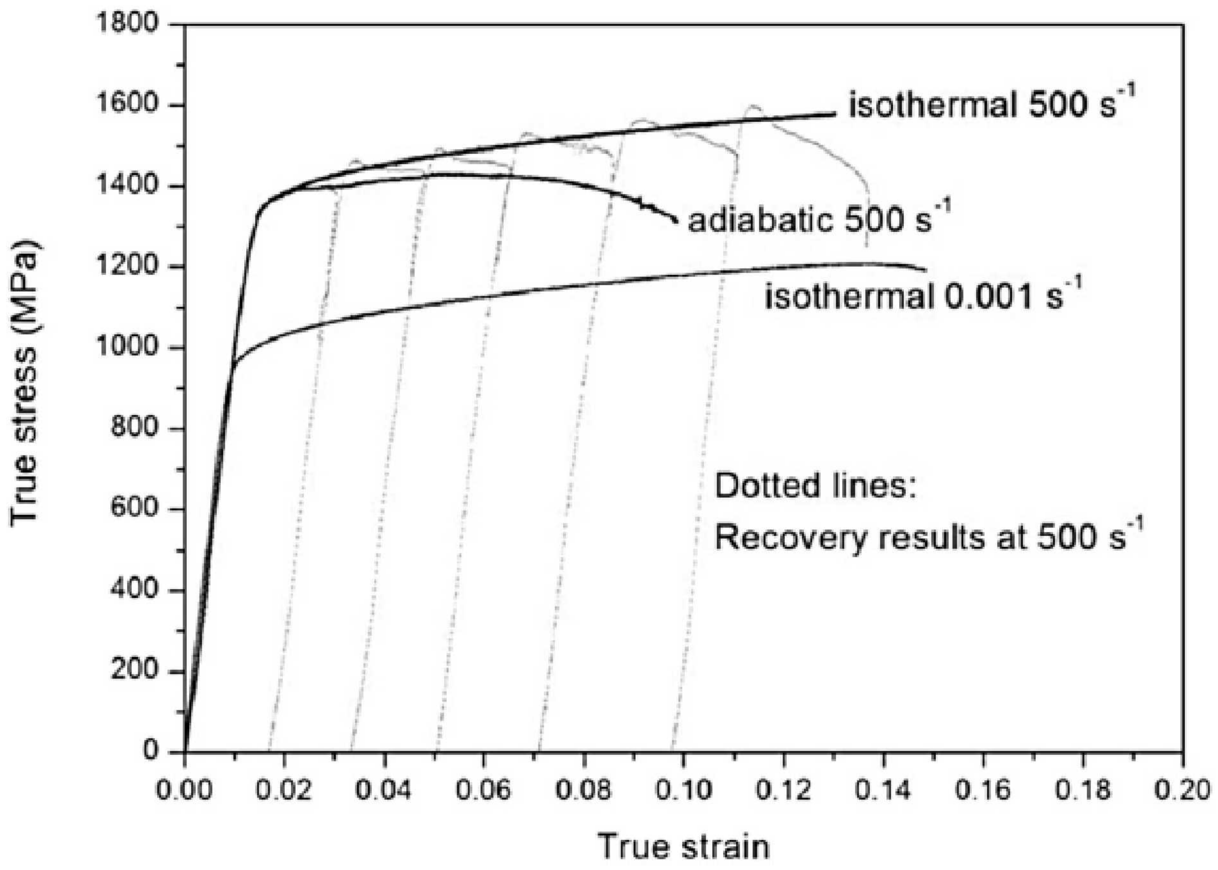
$$f\left(\dot{\varepsilon}\right) = \lambda_1 = 1 + C \cdot \ln\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)$$

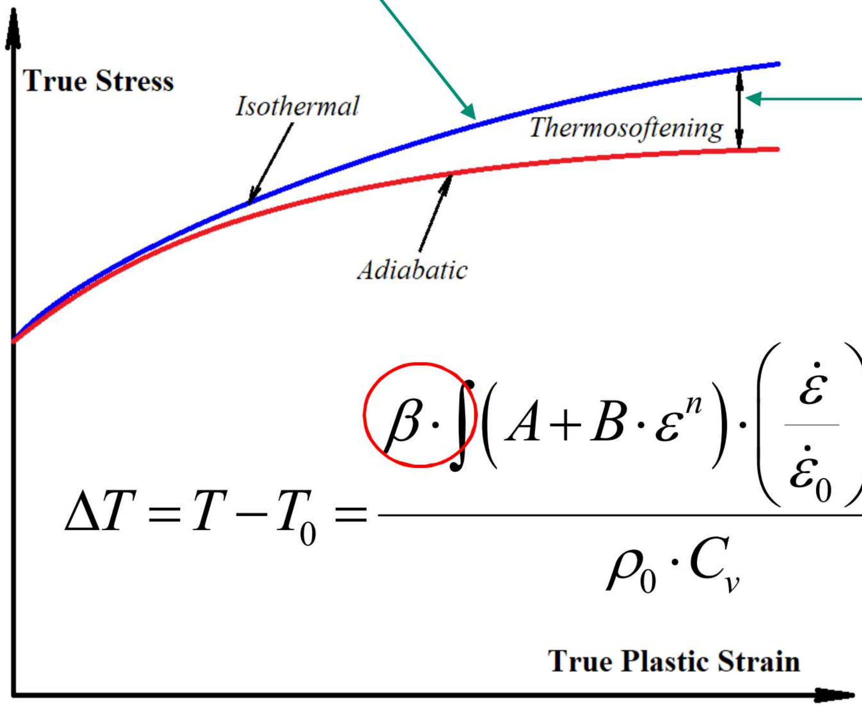


Proposed Modification of J-C Model – Thermo-softening

Zhang et al. (2015) The constitutive responses of Ti-6.6Al-3.3Mo-1.8Zr-0.29Si alloy at high strain rates and elevated temperatures, Journal of Alloys and Compounds, 647:97-104.

$$\sigma = \left(A + B \cdot \varepsilon^{n}\right) \cdot \left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)^{\alpha} \cdot \boxed{\left[1 - \left(\frac{T - T_0}{T_m - T_0}\right)^{m}\right]}$$





$$\Delta T = T - T_0 = \frac{\beta \cdot \int \left(A + B \cdot \varepsilon^{n}\right) \cdot \left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)^{\alpha} d\varepsilon}{\rho_0 \cdot C_v}$$

Taylor-Quinney Coefficient

Phenomenological TQ Coefficient, β

Plastic Work, *W* → **Heat, *Q*** → **Heat for Temperature Rise, *ΔT***

TQ Coefficient, β_0

Internal Energy

Heat Transfer, Q_T (conduction, convection, radiation)

Taylor-Quinney coefficient $\beta_0 = \frac{d\dot{Q}}{d\dot{W}}$

$$\Delta T = T - T_0 = \frac{Q - Q_T}{\rho_0 \cdot C_v} = \frac{\beta_0 \cdot W - Q_T}{\rho_0 \cdot C_v} = \frac{\beta_0 \cdot \int \sigma d\varepsilon - Q_T}{\rho_0 \cdot C_v}$$

Phenomenological Fraction of plastic work converted to heat

$$\Delta T = T - T_0 = \frac{\beta \cdot W}{\rho_0 \cdot C_v} = \frac{\beta \cdot \int \sigma d\varepsilon}{\rho_0 \cdot C_v}$$

0% Heat for specimen temperature rise 100%

Isothermal → Adiabatic

100% Heat Transfer (conduction in majority) 0%

Farren WS, Taylor GI (1925) The heat developed during plastic extension of metals, Proc. Royal Soc., pp423-451.
Taylor GI, Quinney H (1934) The latent energy remaining in a metal after cold working, Proc. Royal Soc., pp307-326

Taylor-Quinney Coefficient

Phenomenological TQ Coefficient, β

Plastic Work, *W* → **Heat, *Q*** → **Heat for Temperature Rise, *ΔT***

TQ Coefficient, β_0

Internal Energy

Heat Transfer, Q_T
(conduction, convection, radiation)

$$\Delta T = T - T_0 = \frac{Q - Q_T}{\rho_0 \cdot C_v} = \frac{\beta_0 \cdot W - Q_T}{\rho_0 \cdot C_v} = \frac{\beta_0 \cdot \int \sigma d\varepsilon - Q_T}{\rho_0 \cdot C_v}$$

<u>Isothermal:</u> $Q_T = Q = \beta_0 \cdot W$

$$\beta = 0$$

$$\beta = \beta_0 - \frac{Q_T}{W} = \beta_0 - \frac{Q_T}{\int \sigma d\varepsilon}$$

$$\beta = \beta_0$$

$$\Delta T = T - T_0 = \frac{\beta \cdot W}{\rho_0 \cdot C_v} = \frac{\beta \cdot \int \sigma d\varepsilon}{\rho_0 \cdot C_v}$$

<u>Adiabatic:</u> $Q_T = 0$

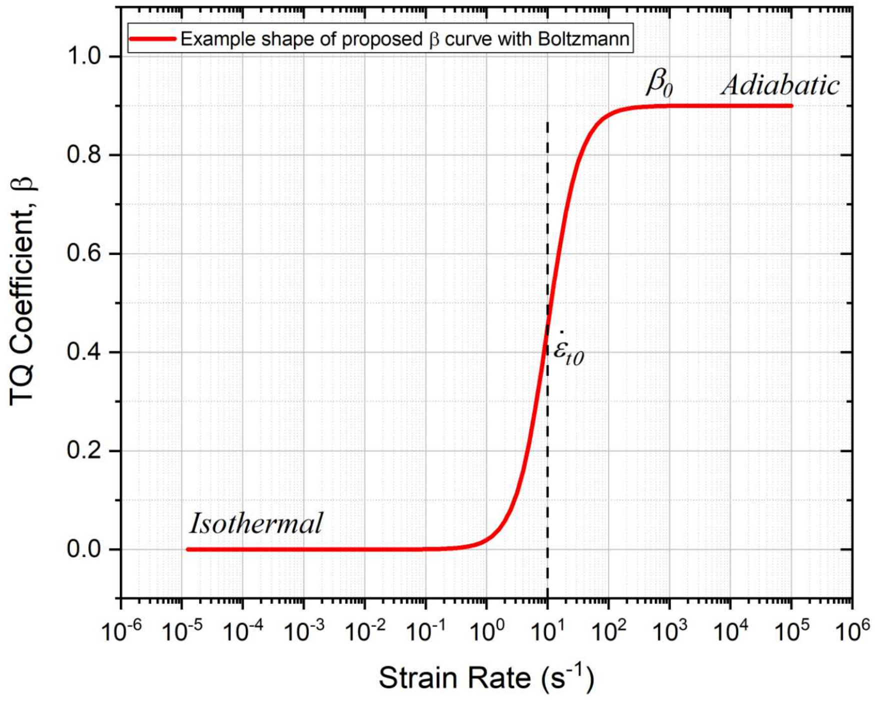
Determination of Temperature Rise with Taylor-Quinney Coefficient

$$\Delta T = T - T_0 = \frac{\beta_0 \cdot \int \sigma d\varepsilon - Q_T}{\rho_0 \cdot C_v} = \frac{\beta \cdot \int \sigma d\varepsilon}{\rho_0 \cdot C_v}$$

β is easier than β_0 due to unknown heat transfer at lower strain rates.

$$0 \le \beta \le \beta_0 \le 1$$

Strain Rate Effect



Boltzmann Function

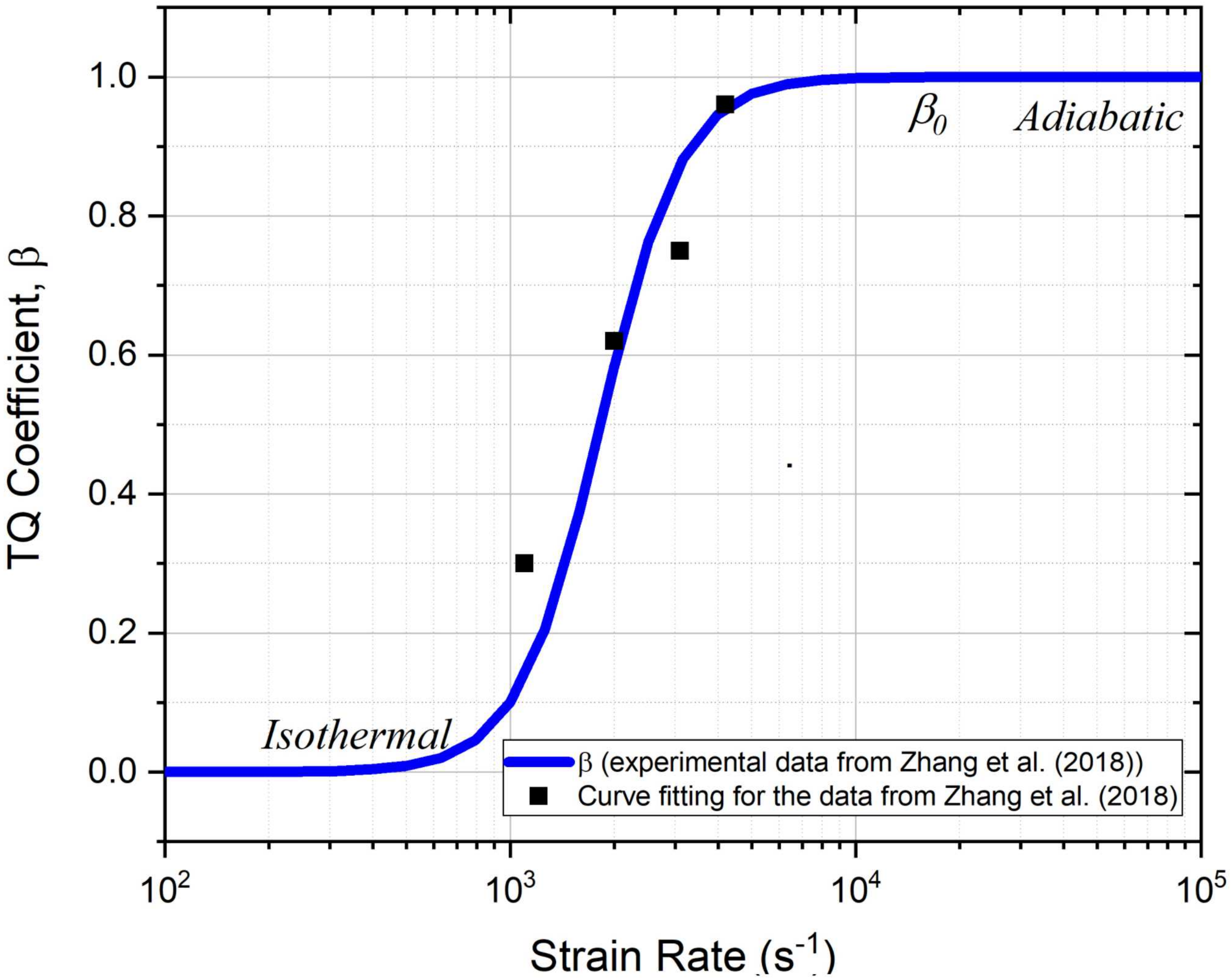
$$\beta(\dot{\varepsilon}) = \frac{\beta_0}{1 + \exp\left[-\frac{\ln \dot{\varepsilon} - \ln \dot{\varepsilon}_{t0}}{\delta}\right]} \Rightarrow \beta(\dot{\varepsilon}) = \frac{\beta_0}{1 + \left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_{t0}}\right)^{-\frac{1}{\delta}}}$$

Boltzmann Description of Taylor-Quinney Coefficient

Zhang T, Guo Z-R, Yuan F-P, Zhang H-S (2018) Investigation on the plastic work-heat conversion coefficient of 7075-T651 aluminum alloy during an impact process based on infrared temperature measurement technology, Acta Mech Sinica, 34:327-333.

$$\beta(\dot{\varepsilon}) = \frac{\beta_0}{1 + \exp\left[-\frac{\ln\dot{\varepsilon} - \ln\dot{\varepsilon}_{t0}}{\delta} \right]}$$

$$\beta(\dot{\varepsilon}) = \frac{\beta_0}{1 + \left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_{t0}} \right)^{-\frac{1}{\delta}}}$$



Proposed Modification of J-C Model

$$\sigma = \left(A + B\cdot\varepsilon^{n}\right)\cdot f\left(\dot{\varepsilon}\right)\cdot g\left(\varepsilon,\dot{\varepsilon}\right)$$

Explicit Strain- and Strain-rate- Dependent Thermo-softening Effect

Power-law Strain-rate Effect

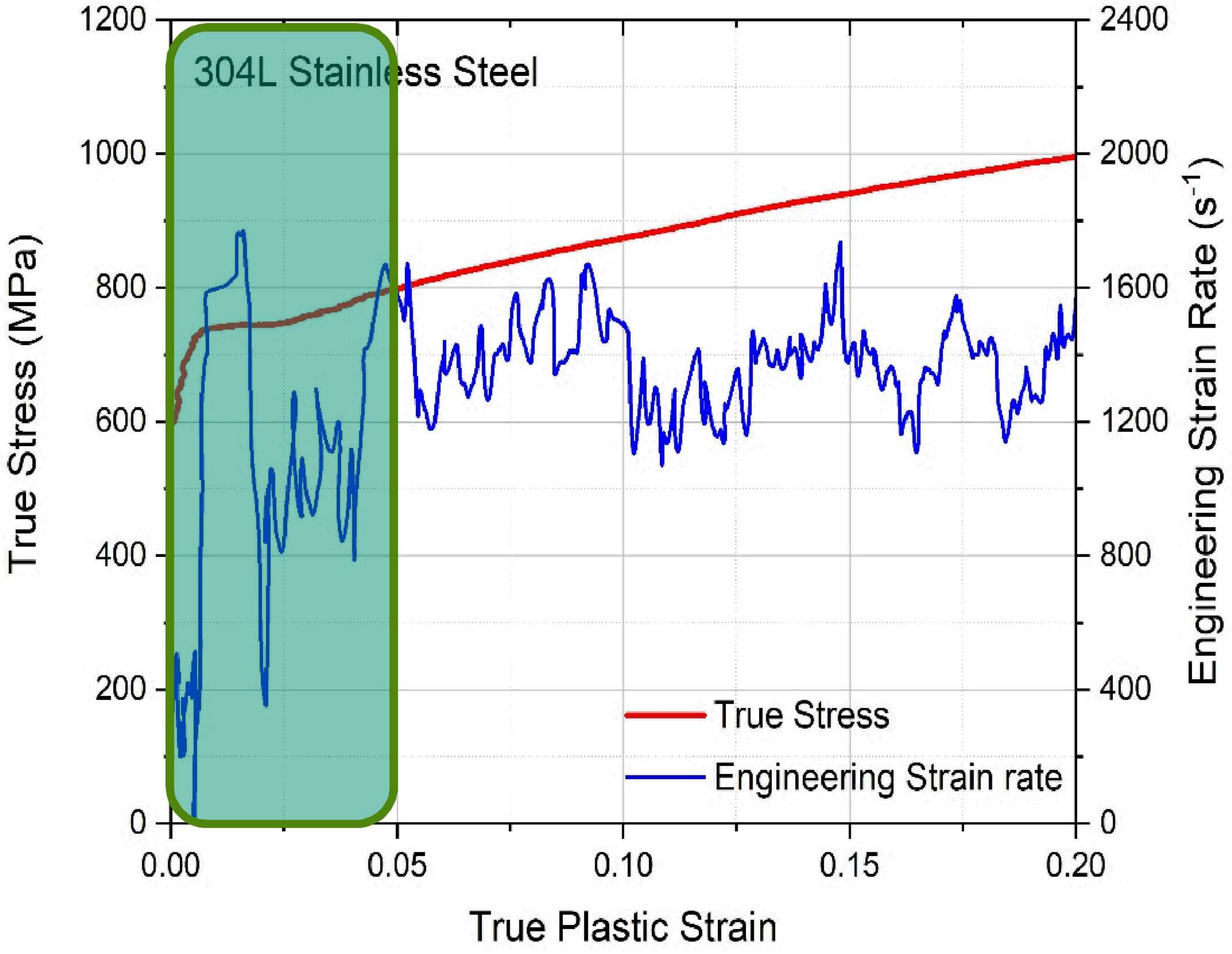
$$\sigma = \left(A + B\cdot\varepsilon^{n}\right)\cdot\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)^{\alpha}\cdot\left\{1-\left[\frac{D\cdot\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)^{\alpha}\cdot Y\left(\varepsilon\right)}{1+\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_{t0}}\right)^{-\frac{1}{\delta}}}\right]^{m}\right\}$$

where

$$Y\left(\varepsilon\right)=\left(A+\frac{B}{n+1}\cdot\varepsilon^{n}\right)\cdot\varepsilon$$

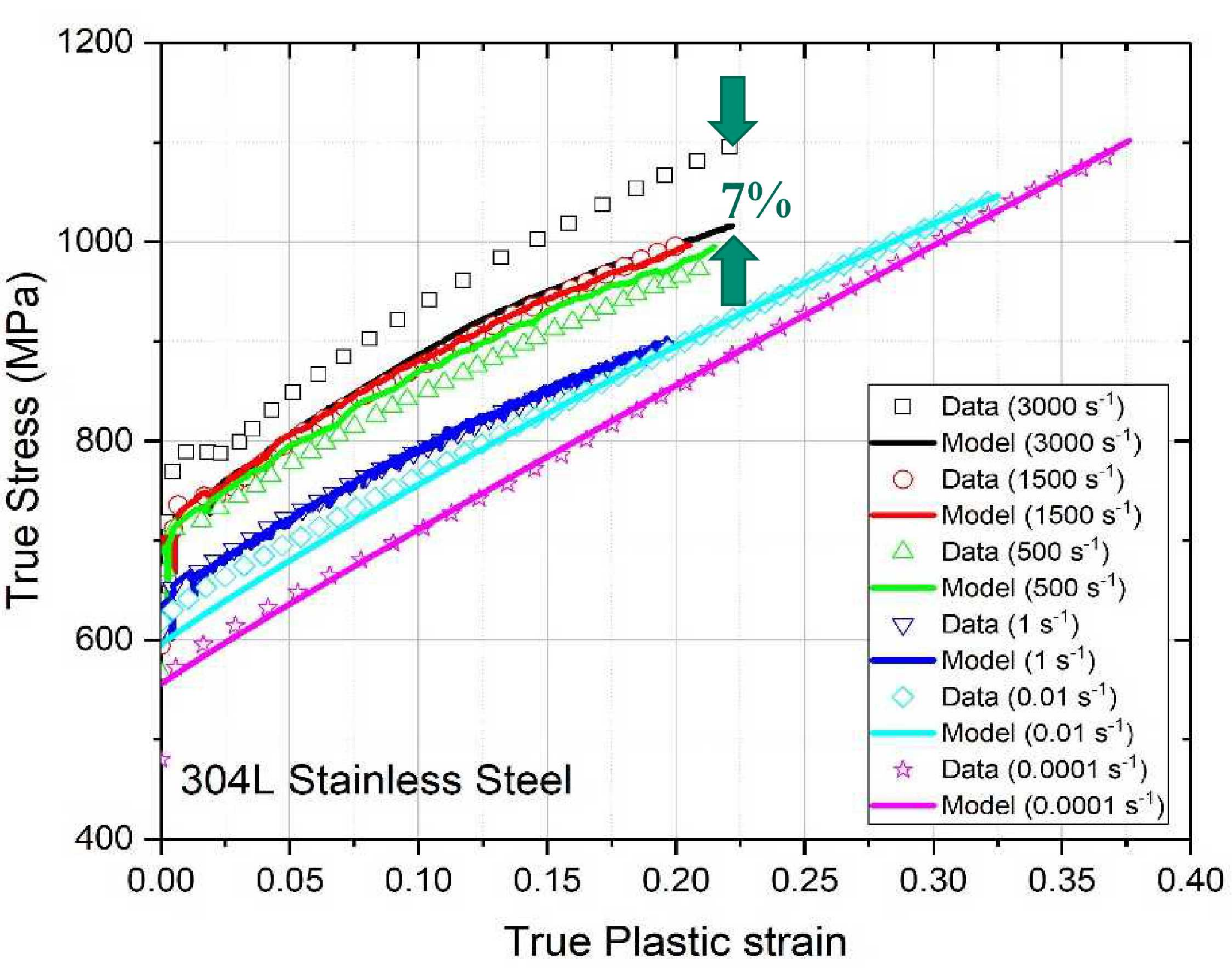
Determination of Strain-Rate-Effect

Constant strain rates are preferred. However, in reality, it takes time/strain for strain rate to ramp up.



Song B, Sanborn B, Heister JD, Everett RL, Martinez TL, Groves GE, Johnson EP, Kenney DJ, Knight ME, Spletzer MA, Haulenbeek KK, McConnell C (2019) An apparatus for tensile characterization of materials within the upper intermediate strain rate regime, Exp Mech, DOI:10.1007/s11340-019-00494-3.

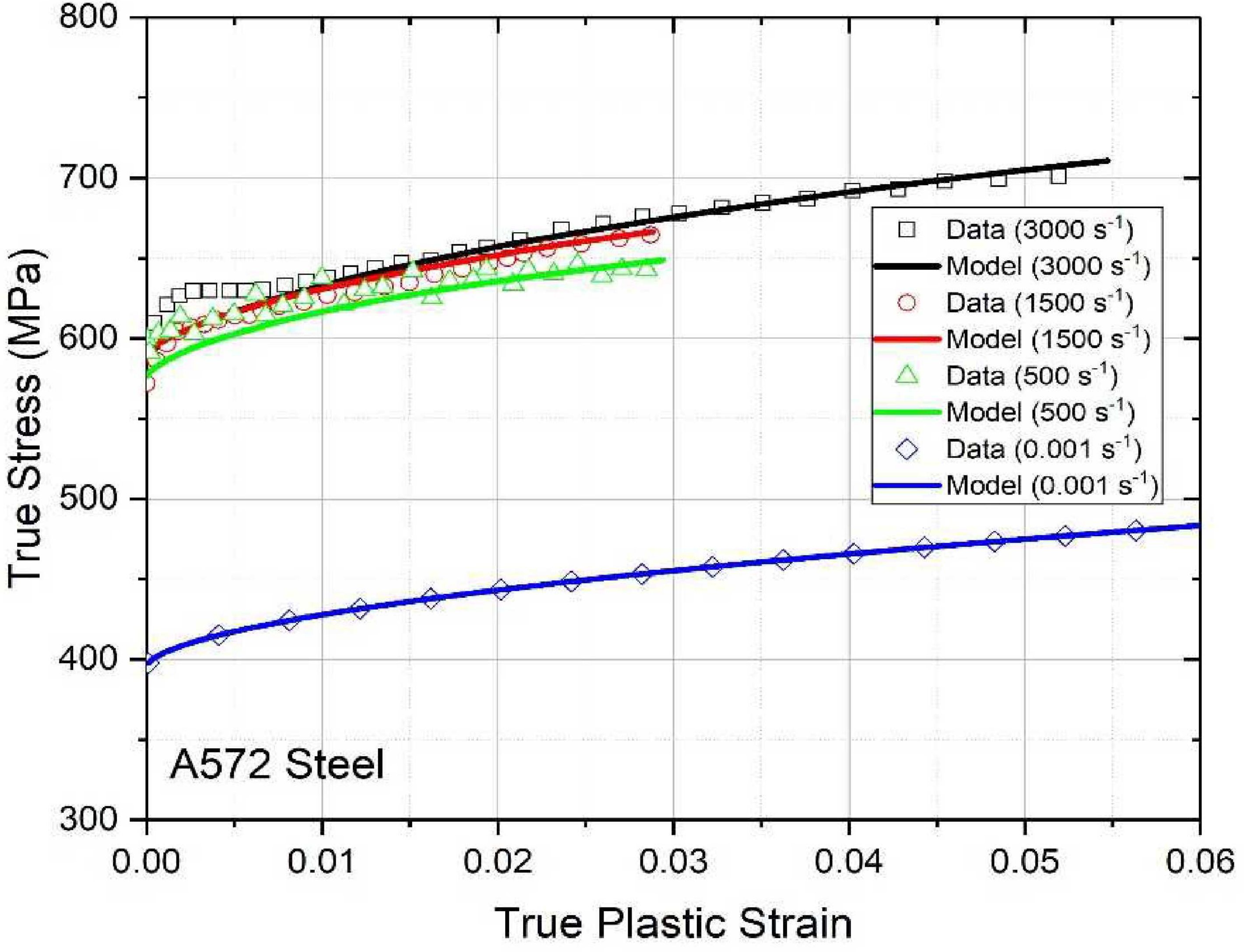
Modified J-C Model for 304L Stainless Steel



Constants	*304L Stainless Steel*
A	555.47 MPa
B	1378.87 MPa
n	0.9497
α	0.01503
D	9.4431×10^{-4}
δ	0.5327
m	1.3263
$\dot{\varepsilon}_0$	$1\times10^{-4}\ s^{-1}$
$\dot{\varepsilon}_{t0}$	$0.012\ s^{-1}$

Song B, Sanborn B, Heister JD, Everett RL, Martinez TL, Groves GE, Johnson EP, Kenney DJ, Knight ME, Spletzer MA, Haulenbeek KK, McConnell C (2019) An apparatus for tensile characterization of materials within the upper intermediate strain rate regime, Exp Mech, DOI:10.1007/s11340-019-00494-3.

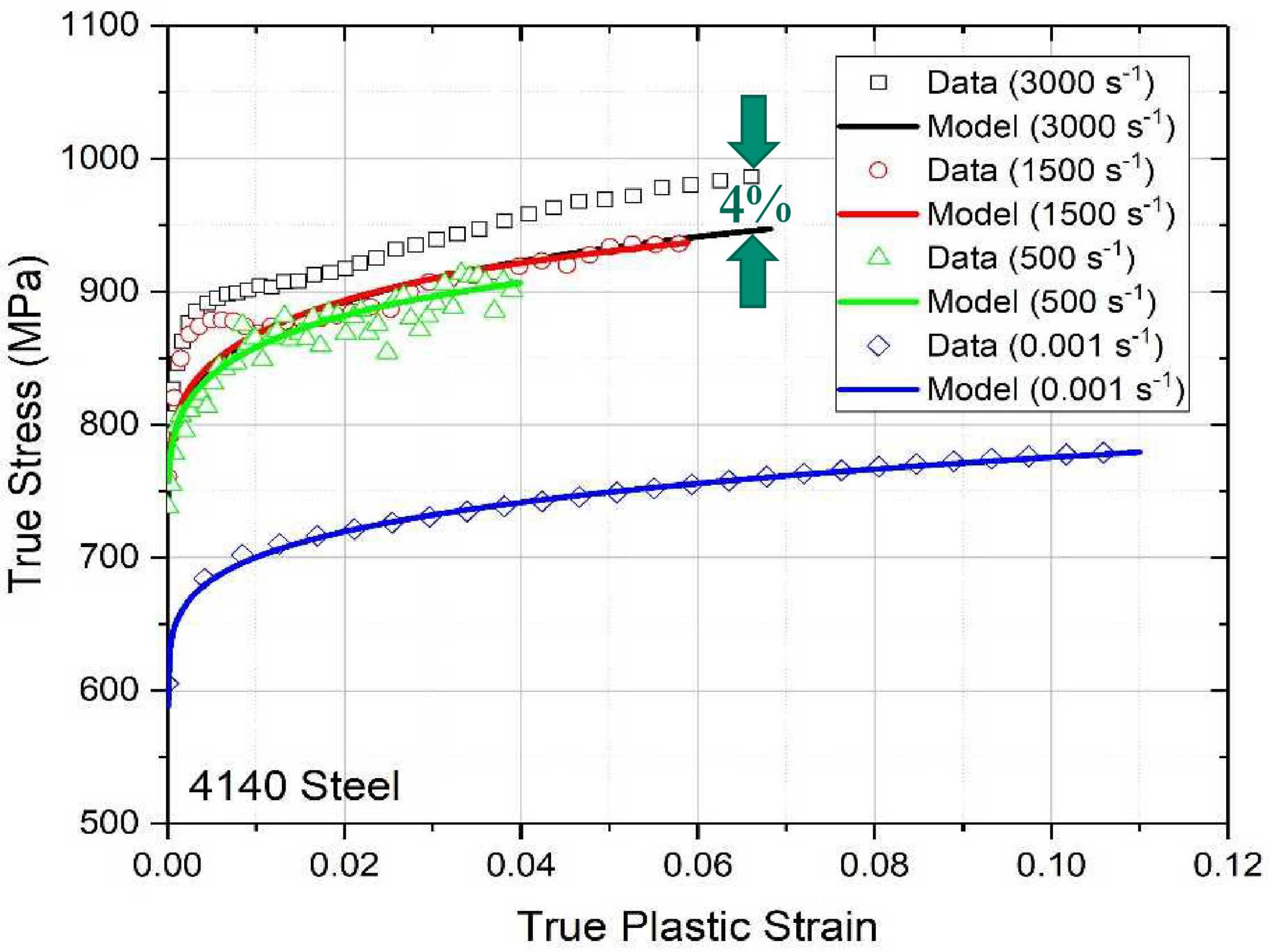
Modified J-C Model for A572 Steel



Constants	*A572 Steel*
A	394.98 MPa
B	418.33 MPa
n	0.5522
α	0.03157
D	2.6460×10^{-6}
δ	0.7173
m	0.3098
$\dot{\varepsilon}_0$	1×10^{-3} s^{-1}
$\dot{\varepsilon}_{t0}$	128 s^{-1}

Sanborn B, Song B, Thompson A, Reece B, Attaway S (2017) High strain rate tensile response of A572 and 4140 steel, Proc Eng, 197:33-41.

Modified J-C Model for 4140 Steel



Constants	*4140 Steel*
A	562.41 MPa
B	330.62 MPa
n	0.1654
α	0.01968
D	1.589×10^{-7}
δ	0.7111
m	0.3388
$\dot{\varepsilon}_0$	1×10^{-3} s^{-1}
$\dot{\varepsilon}_{t0}$	73 s^{-1}

Sanborn B, Song B, Thompson A, Reece B, Attaway S (2017) High strain rate tensile response of A572 and 4140 steel, Proc Eng, 197:33-41.

Bridgman Correction for True Stress-Strain Response During Necking

- True strain

$$\varepsilon_T = ln\frac{A_0}{A}$$

- Average true axial stress at the smallest cross section

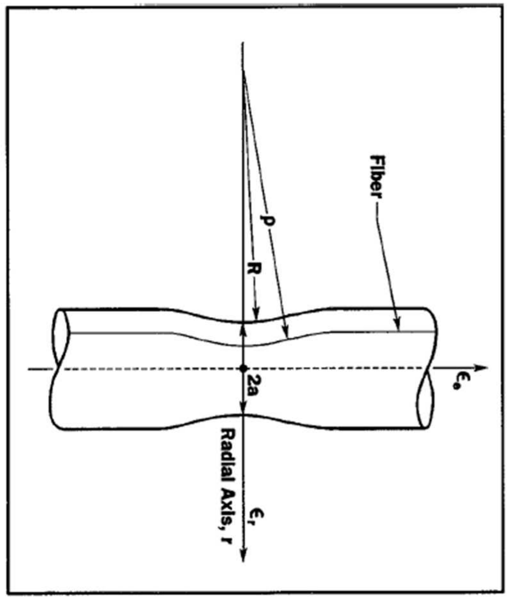
$$(\sigma_a)_{av} = \frac{F}{A} = \sigma_E\frac{A_0}{A}$$

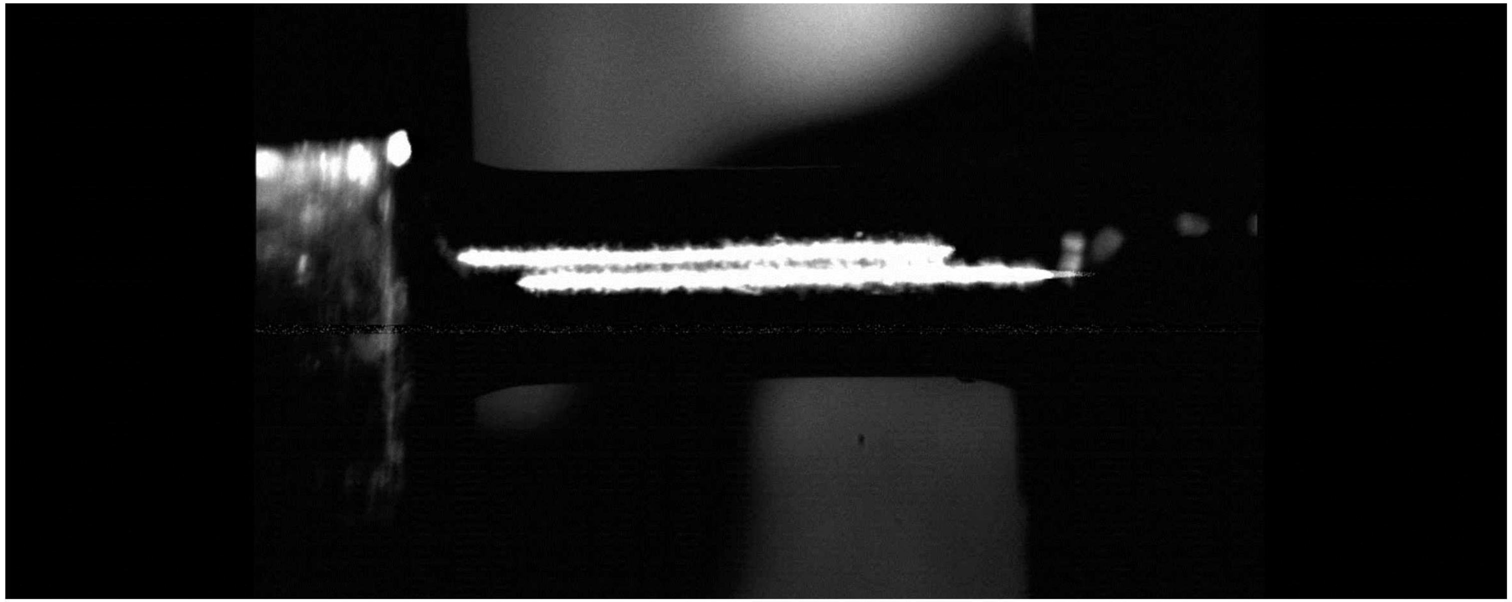
  - Uniaxial stress correction

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

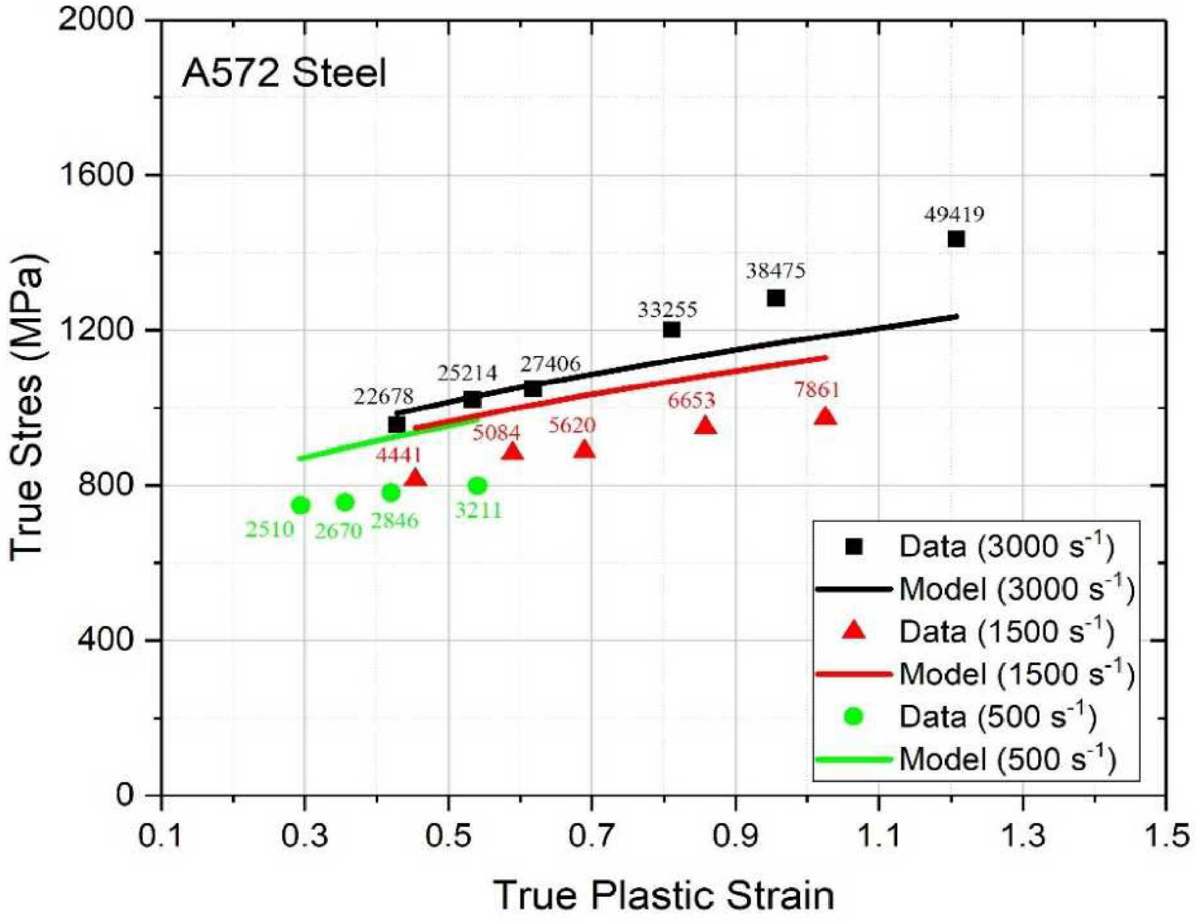
$$k = \left[\left(1 + \frac{2R}{a}\right) ln\left(1 + \frac{a}{2R}\right)\right]^{-1}$$

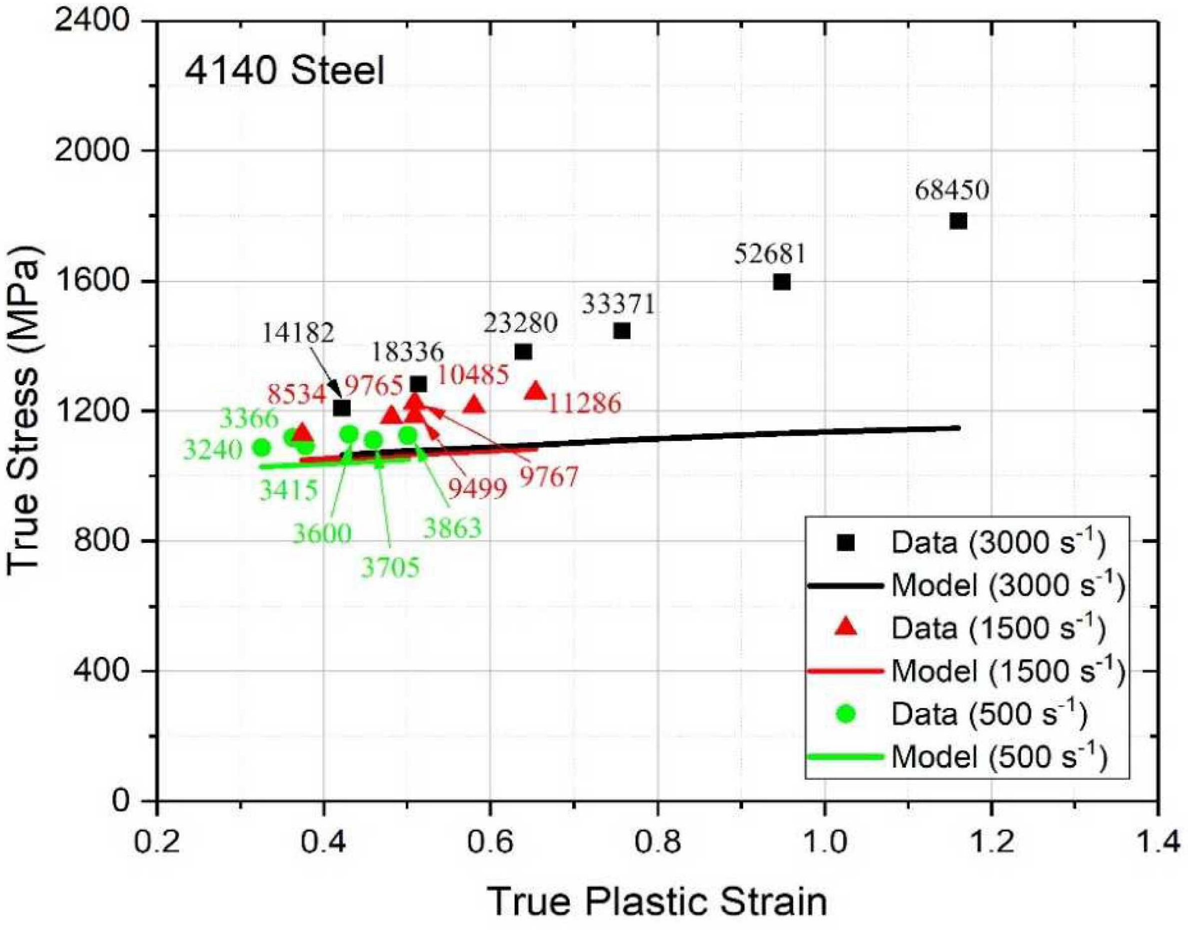
- Requires instantaneous measurements of minimum cross sectional area, *A,* and radius, *R.*





Modified J-C Model for True Stress-Strain Response During Necking





Uncertainties:

- Description of strain rate effect
- Experimental data corrected with Bridgman method

Song, B., Sanborn, B., Thompson, A., Reece, B., Attaway, S., and Teeter, R., High strain rate tensile response of A572 and 4140 steel, In: 2017 ASME International Mechanical Engineering Congress & Exposition (IMECE), November 3-9, 2017, Tampa, FL

Conclusions

- The Johnson-Cook model was modified with
  - power-law strain rate effect
  - explicit strain- and strain-rate-dependent thermosoftening using
    - a Boltzmann description of phenomenological Taylor-Quinney Coefficient

$$\sigma = \left(A + B \cdot \varepsilon^n\right) \cdot \left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)^{\alpha} \cdot \left\{1 - \left[\frac{D \cdot \left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)^{\alpha} \cdot Y(\varepsilon)}{1 + \left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_{t0}}\right)^{-\frac{1}{\delta}}}\right]^m\right\} \qquad Y(\varepsilon) = \left(A + \frac{B}{n+1} \cdot \varepsilon^n\right) \cdot \varepsilon$$

- The modified Johnson-Cook model was tested for three different materials – 304L stainless steel, A572 and 4140 steels
  - the model described the tensile stress-strain response prior to necking better than that during necking
    - Description of strain rate effect
    - Uncertainties of Bridgman correction