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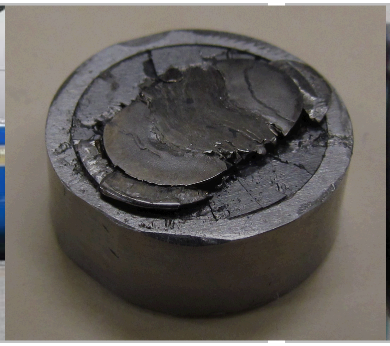

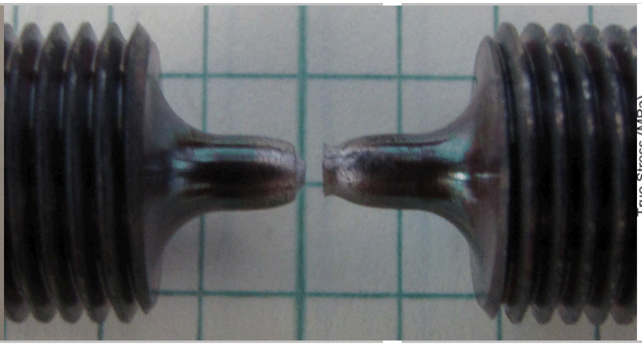

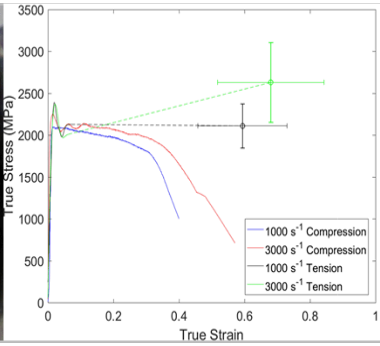

Dynamic Characterization and Stress-Strain Symmetry of Vascomax® C250 Maraging Steel in Compression and Tension

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VascoMax® Maraging Alloys

- **Iron-based steels alloyed with 18% nickel**
- **Maraging C-Type Alloys**

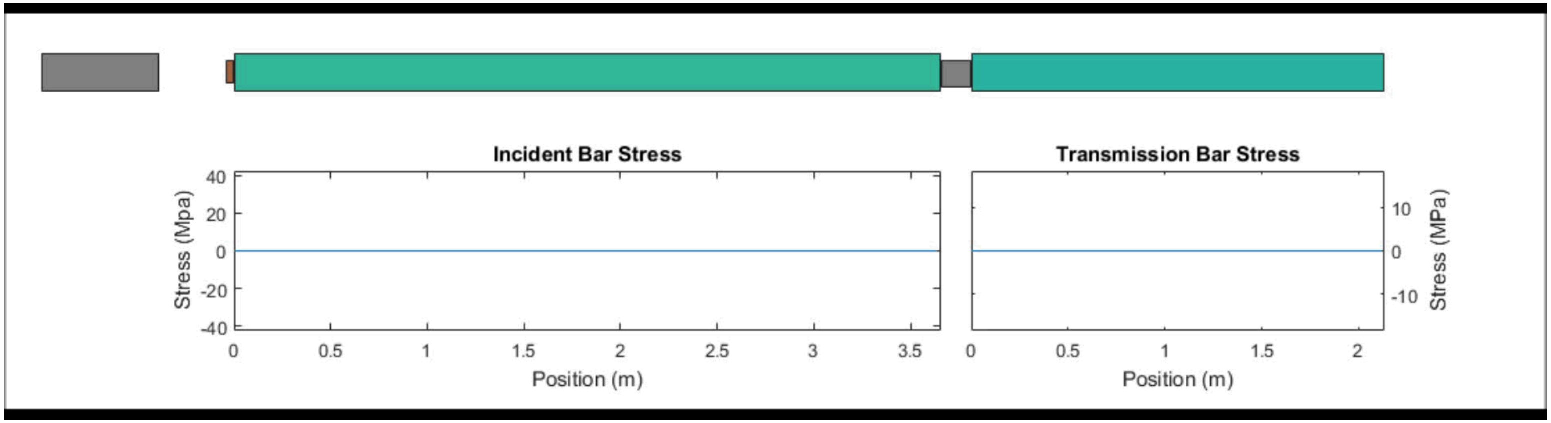
	C	S	Mn	Si	Cr	Mo	Co	Ti	Al	B	Zr	Cu	P	W	Ni	Fe
C250	0.005	0.0004	0.02	0.01	0.02	4.76	7.81	0.42	0.11	0.003	<0.01	<0.01	0.003	<0.01	18.55	BAL

  - **Strengthened steels with 7-12% cobalt, depending on the grade**
  - **C250 – 250 ksi (yield)**

- **Characteristics**
  - **Relatively soft in annealed condition**
  - **Significant hardness increase after a precipitation hardening process**
    - **No protective atmosphere required**
    - **Relatively low furnace temperatures**
      - **Anneal Temp: 820 °C; Aging Temp: 500 °C**

Dynamic properties are important!

Kolsky (split Hopkinson) Bars



$$\sigma = \frac{F_1 + F_2}{2A_s} = \frac{E_0 A_0}{2A_s}\left(\varepsilon_i + \varepsilon_r + \varepsilon_t\right)$$

$$\dot{\varepsilon} = \frac{V_1 - V_2}{l_s} = \frac{C_0}{l_s}\left(\varepsilon_i - \varepsilon_r - \varepsilon_t\right)$$

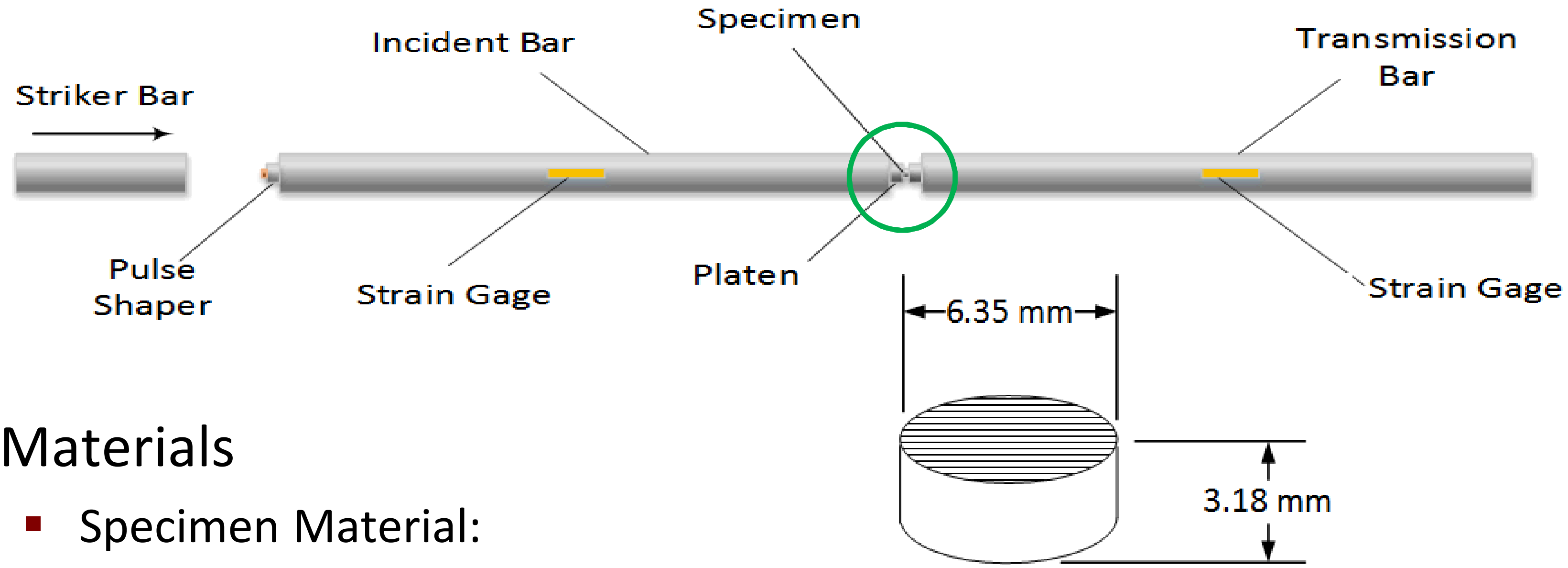
Stress Equilibrium

Constant Strain Rate

$$\varepsilon = \int_0^t \dot{\varepsilon}(\tau)\,d\tau$$

$$\sigma \sim \varepsilon$$

Kolsky (split Hopkinson) Bars for Dynamic Compression



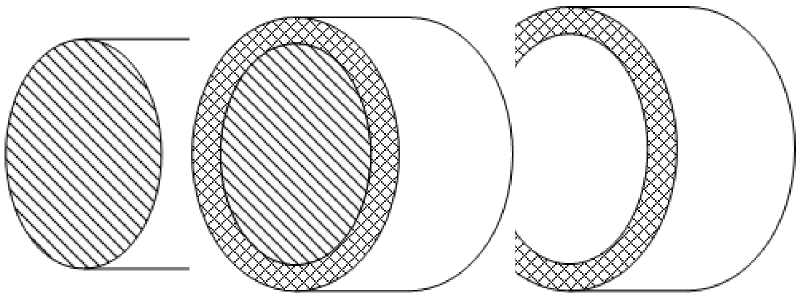
- Materials
  - Specimen Material:
    - Vascomax® C250 maraging steel, RC48
      - QS yield strength: 255ksi (1.758 GPa)
  - Bar Material
    - Vascomax® C300 maraging steel, RC52-56
      - QS yield strength: 290 ksi (2.0 GPa)

Possible indentation and/or damage to the bars

Tungsten Carbide Platen Design

- Tungsten Carbide (WC)
  - High Hardness: >RC90
  - High Modulus: ~600 GPa
  - Brittle
- Confined WC platen
  - Press-fit WC platen into a stainless steel ring
  - Mechanical impedance match to the pressure bars $(\rho CA)_{Bar} = (\rho CA)_{Platen*}$

  or $(\sqrt{\rho E}A)_{Bar} = (\sqrt{\rho E}A)_{Platen*}$



$$\rho_{equiv} = \frac{\rho_{wc}\boldsymbol{A_{wc}} + \rho_s\boldsymbol{A_s}}{\boldsymbol{A_{total}}} \qquad \boldsymbol{E_{equiv}} = \frac{E_{wc}\boldsymbol{A_{wc}} + E_s\boldsymbol{A_s}}{\boldsymbol{A_{total}}}$$

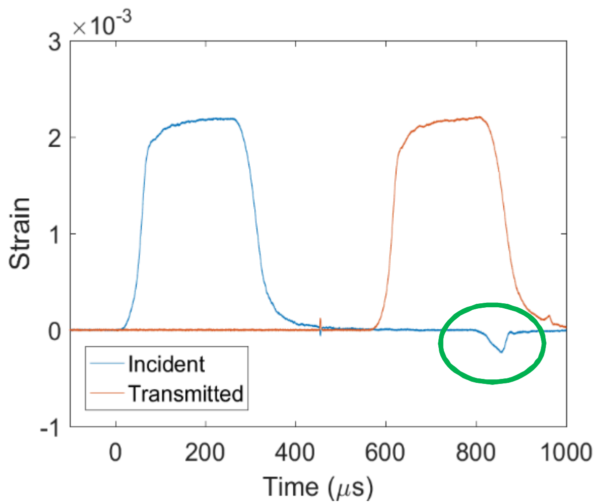
Solution is not unique

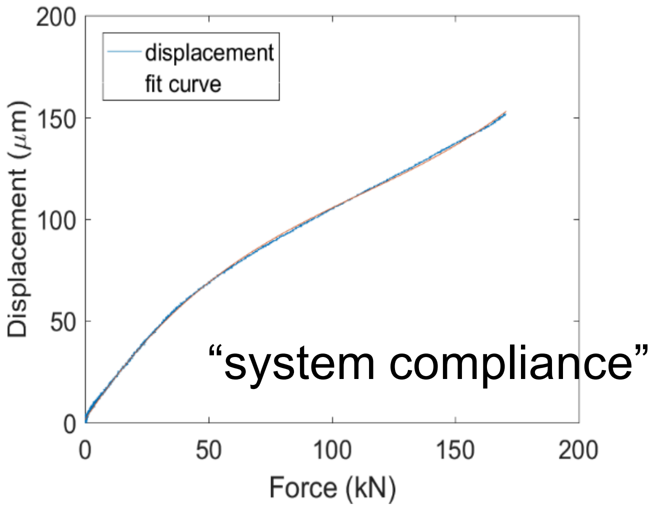
$$Diam_{wc} = 15\ mm \qquad Diam_s = 18.02mm\ \text{OD}, \ 15\ mm\ \text{ID}$$

Pressure Bar ⇨ $19750\ \frac{kg}{s} \approx 19625\ \frac{kg}{s}$ ⇦ Platen

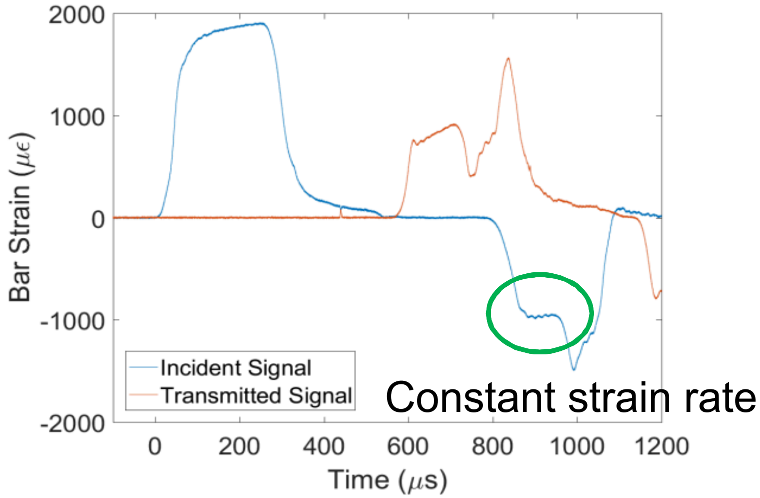
Dynamic Compression Tests

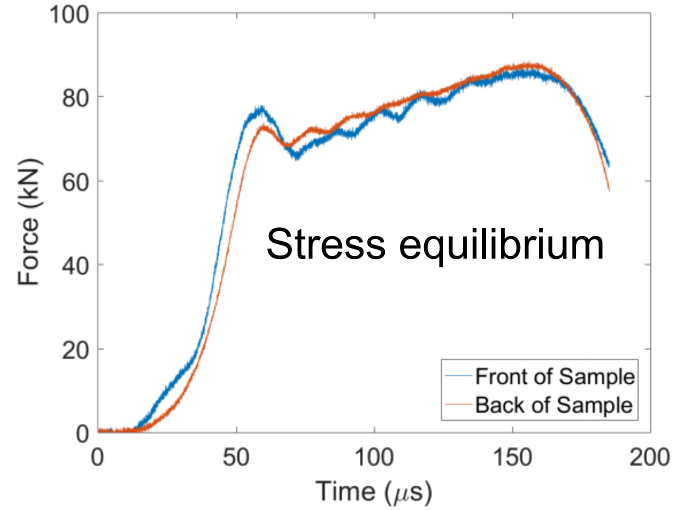
Calibration Test





Actual Test

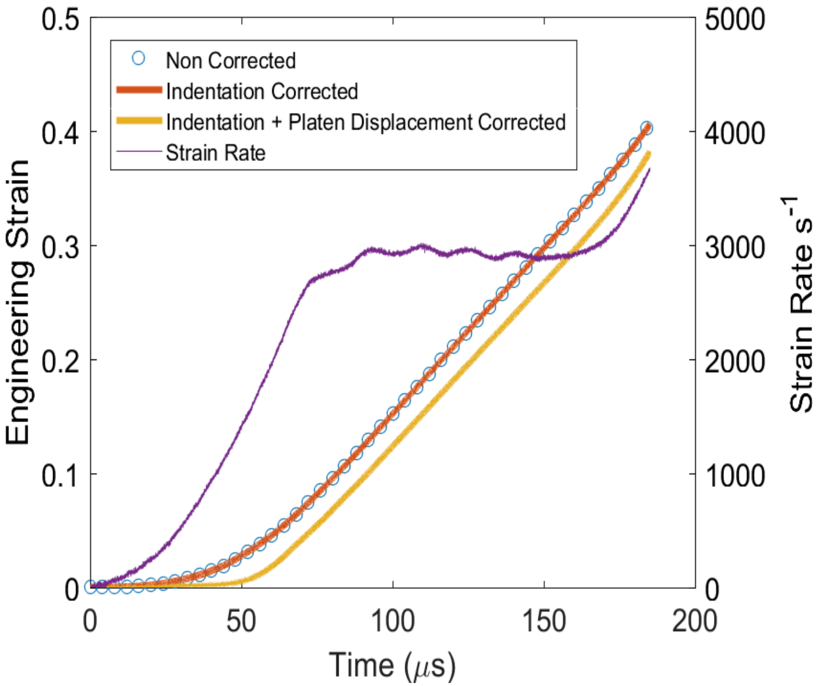


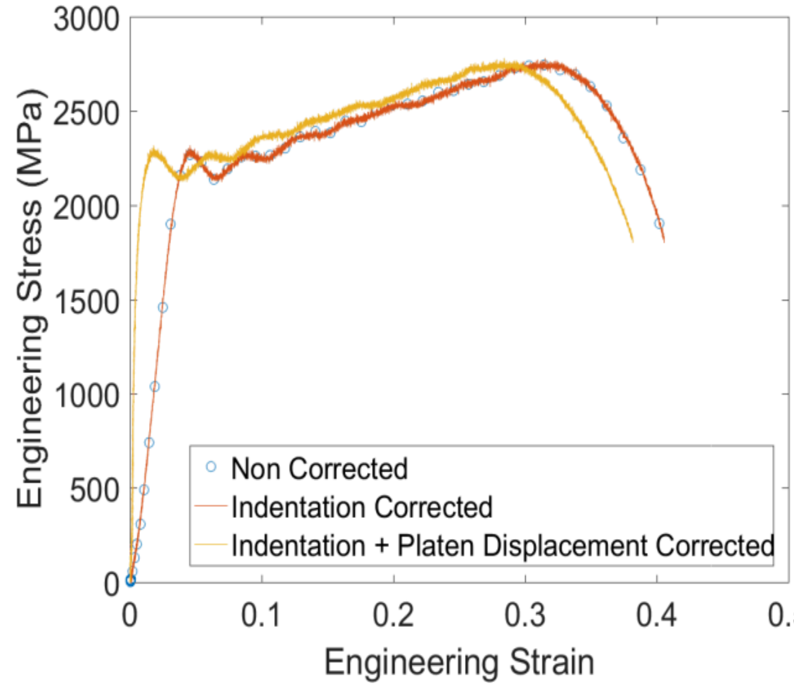


Specimen Strain Correction

- Compliance correction
- Indentation correction: Safa and Gary (2010)

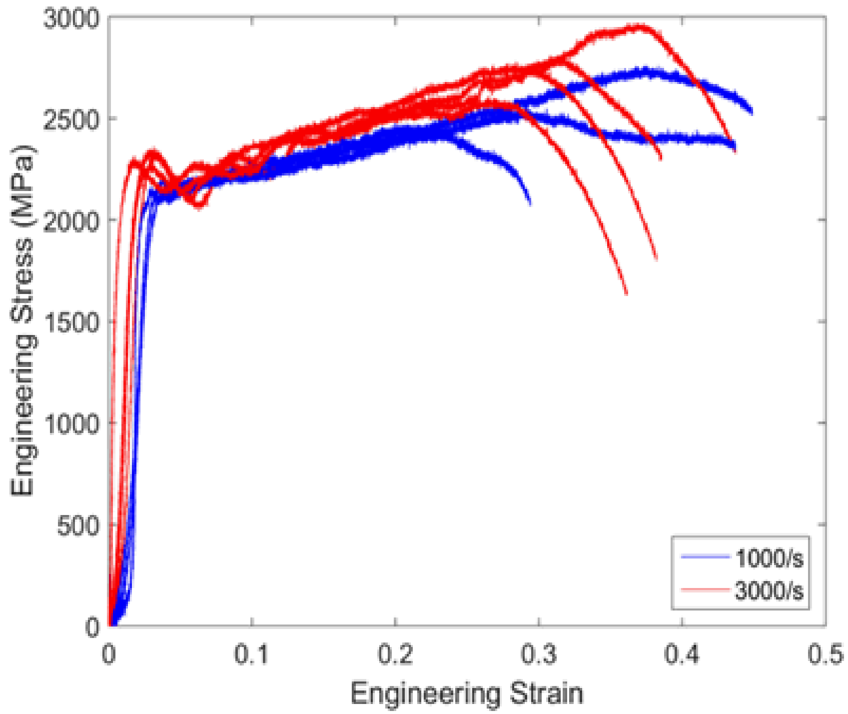
$$\varepsilon(t) = \frac{L_{measure} - L_{platen} - L_{indentation}}{L_{specimen}}$$

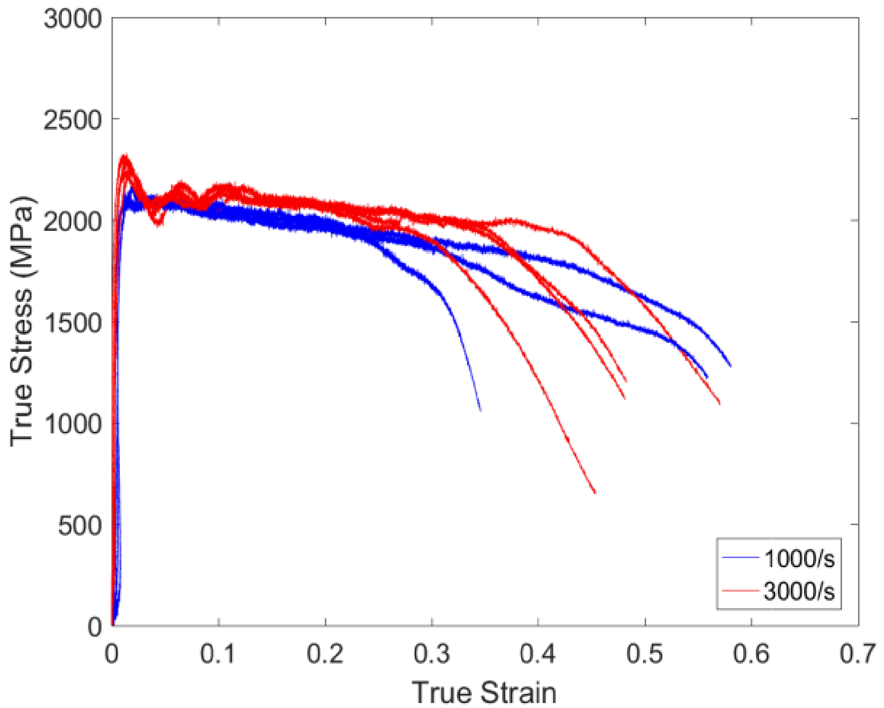




Dynamic Compressive Stress-Strain Curves

(14a)

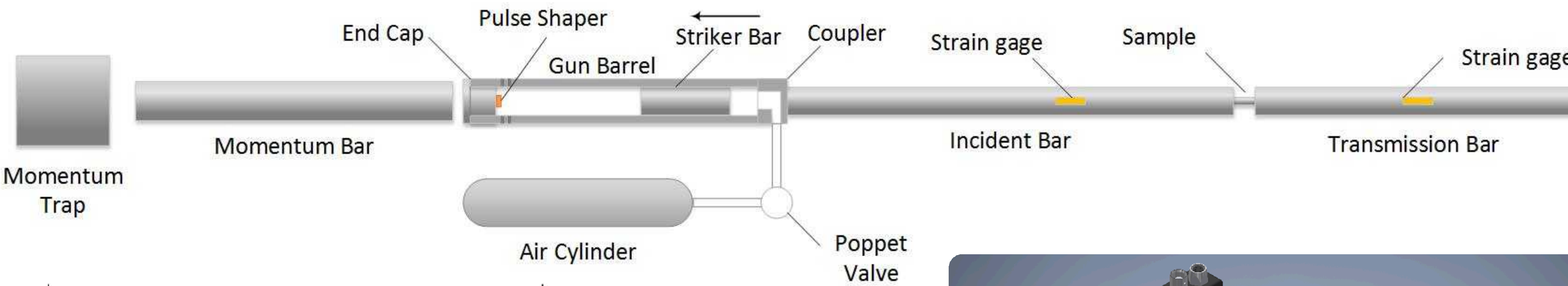


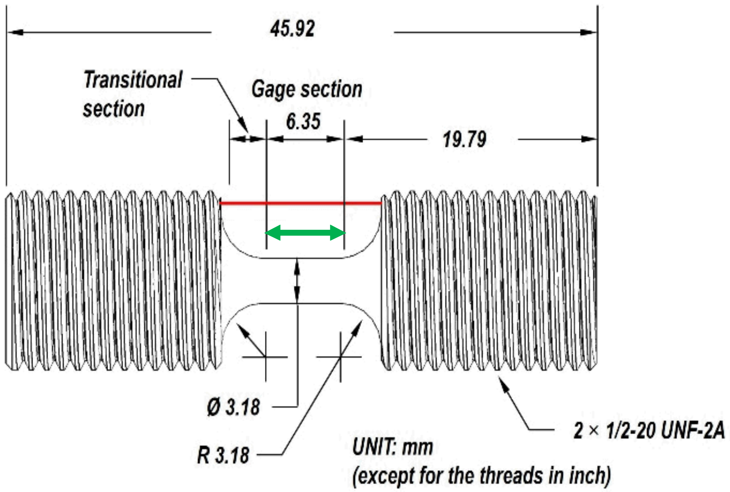


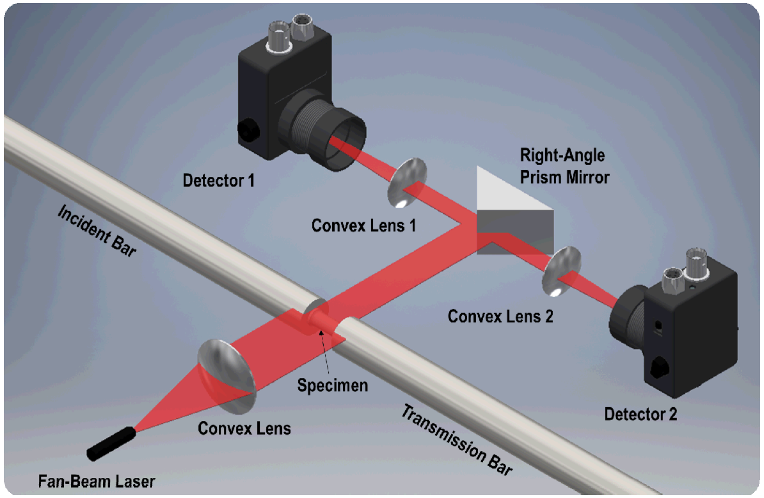
$$\sigma_{True}(t) = \sigma_{Eng} \cdot (1 - \varepsilon_{Eng})$$

$$\varepsilon_{True}(t) = -\ln(1 - \varepsilon_{Eng})$$

Dynamic Tensile Tests







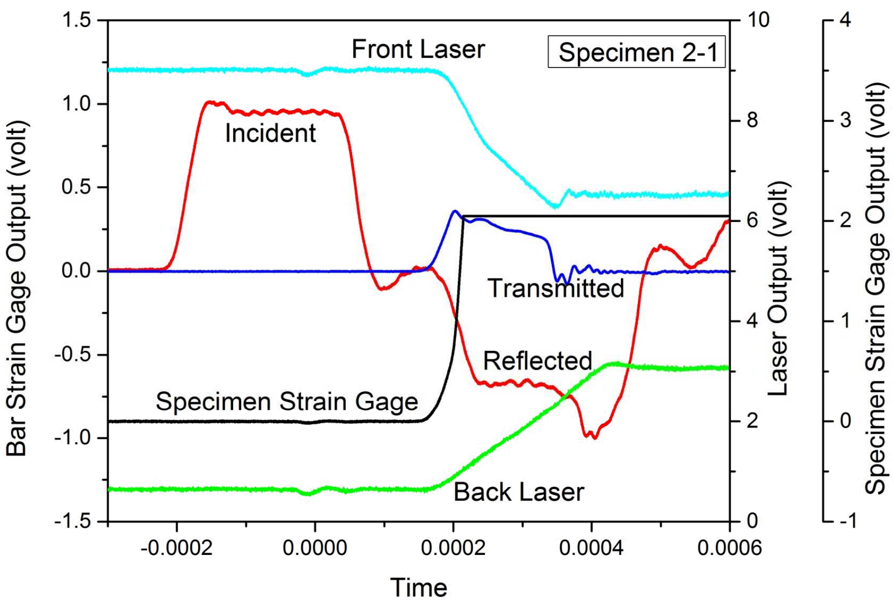
$$\sigma = E_0 \frac{A_0}{A_s} \varepsilon_t$$

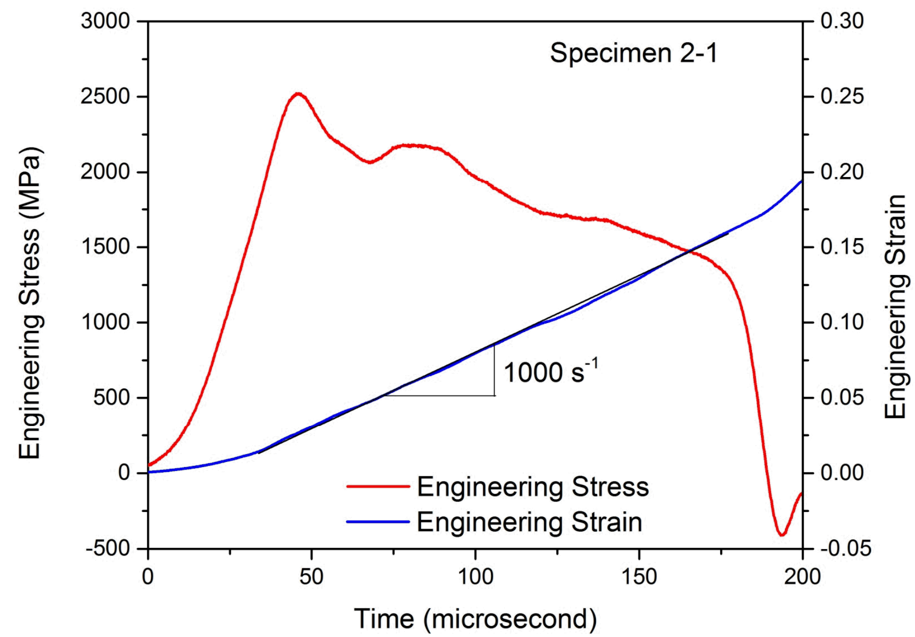
$$\varepsilon = \begin{cases} c' \cdot \dfrac{L_1 - L_2}{L_s} & (\sigma \le \sigma_y) \\ \dfrac{L_1 - L_2 - (1 - c')(L_1 - L_2)_{yield}}{L_s} & (\sigma > \sigma_y) \end{cases}$$

C'=0.62

Song et al., Experimental Mechanics, 2013
Song et al., Journal of Dynamic Behavior of Materials, 2015

Dynamic Tensile Tests

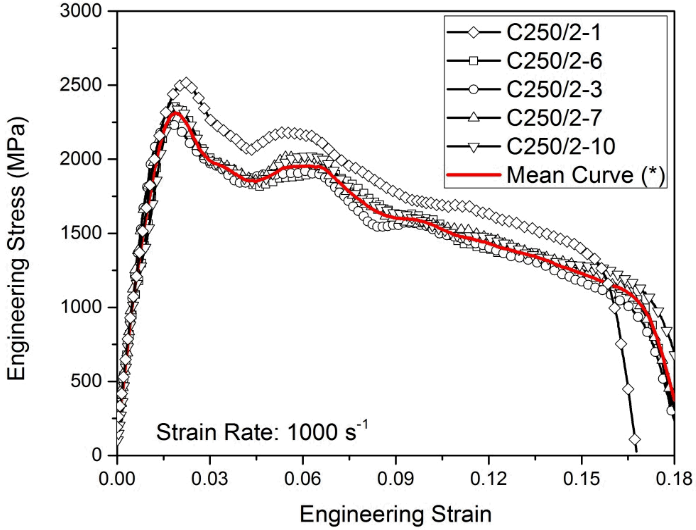


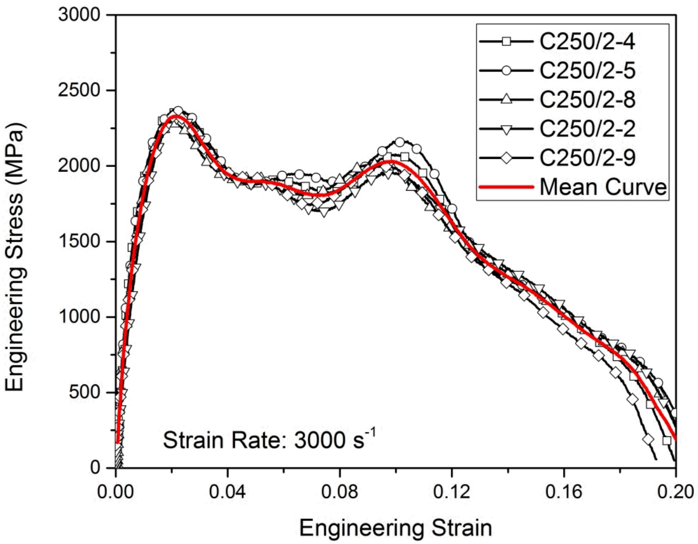


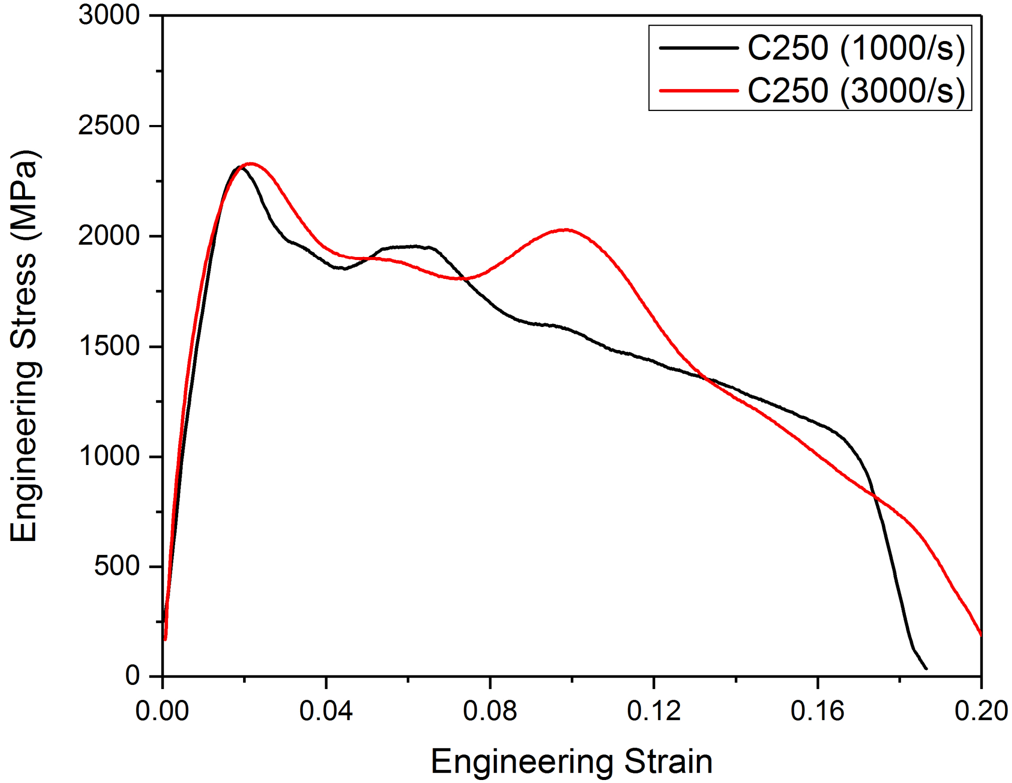
Original Oscilloscope Records

Engineering Stress and Strain Histories

Dynamic Tensile Tests







True Stress-Strain Curves in Tension

Before onset of necking

True Strain $\varepsilon_T = ln(1 + \varepsilon_E)$

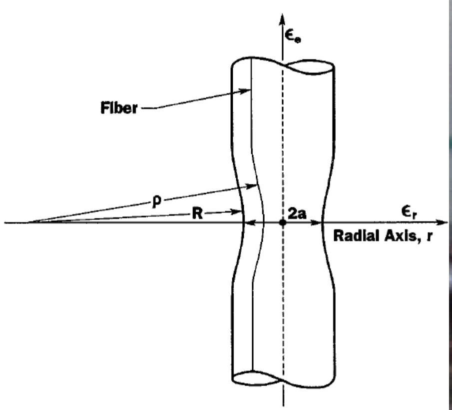
True Stress $\sigma_T = \sigma_E(1 + \varepsilon_E)$

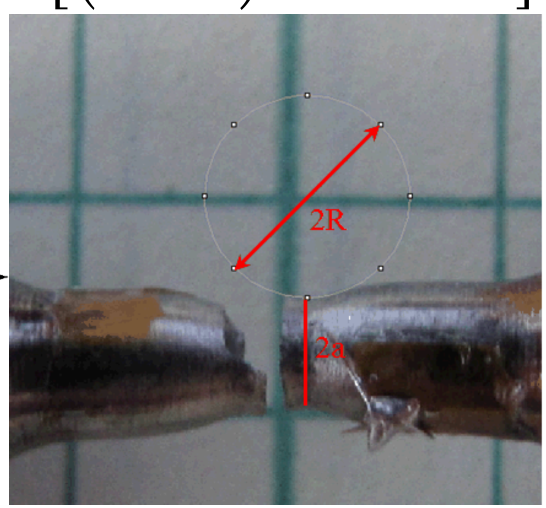
During necking until failure (Bridgman Correction)

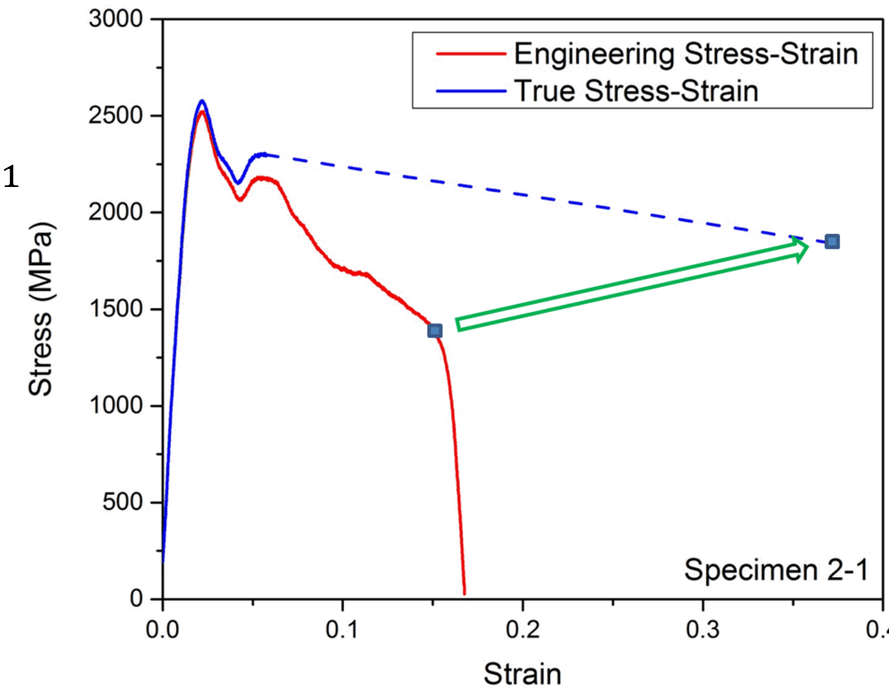
True Strain $\varepsilon_T = ln\frac{A_0}{A}$

True Stress

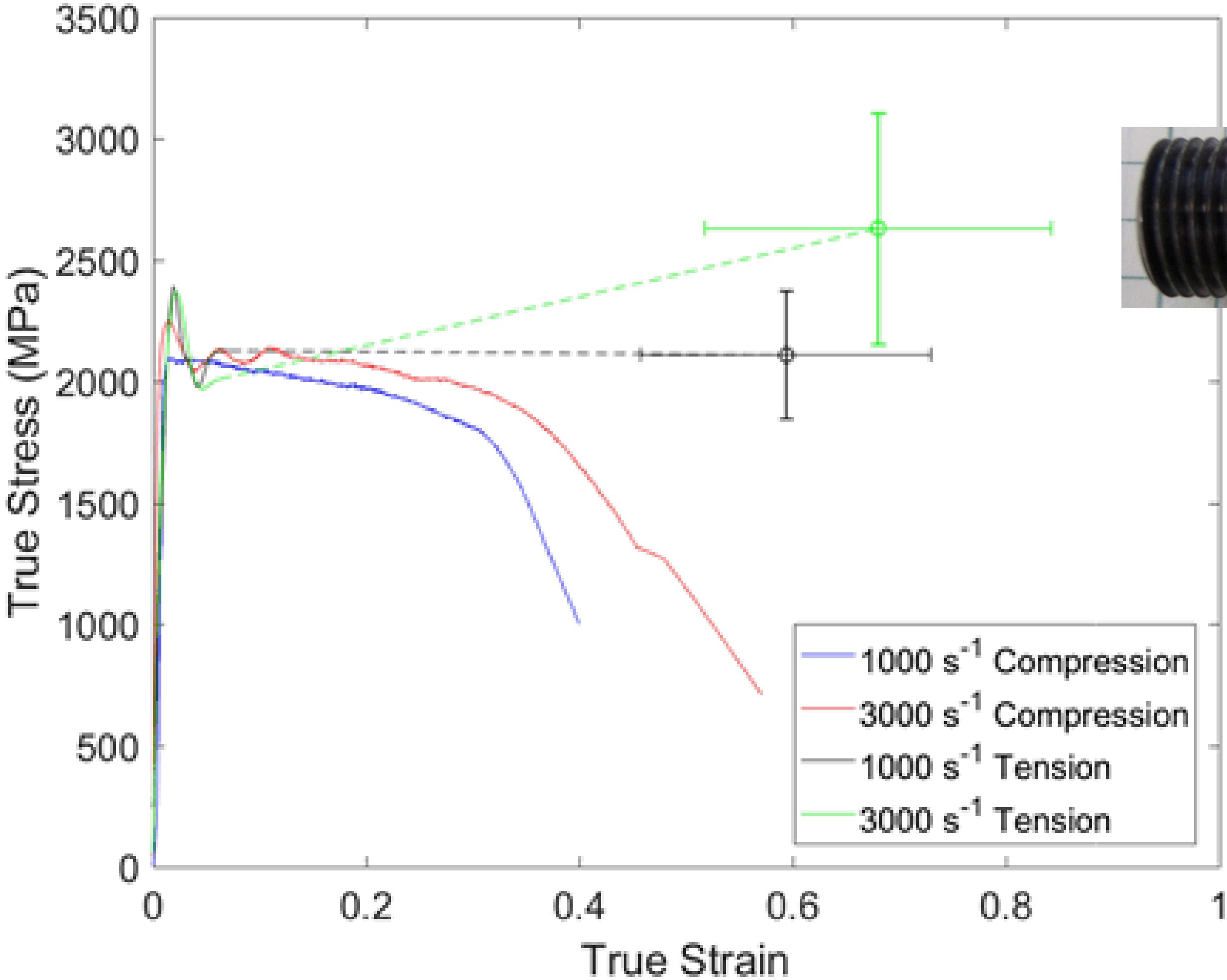
$$\sigma_T = \sigma_E \cdot \frac{A_0}{A} \cdot \left[\left(1 + \frac{2R}{a}\right) ln\left(1 + \frac{a}{2R}\right)\right]^{-1}$$

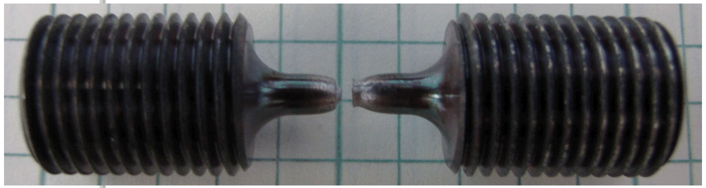


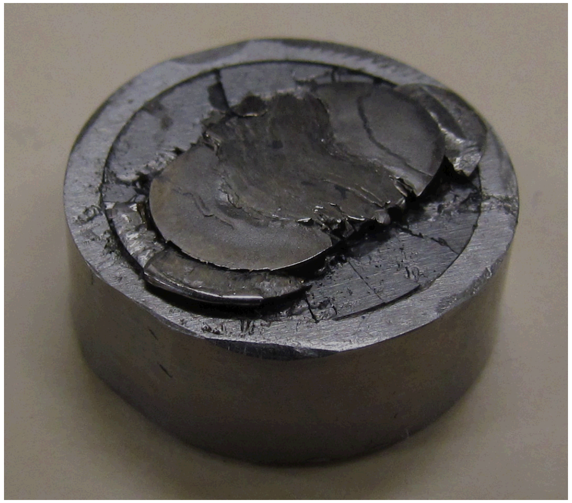




Stress-Strain Symmetry in Compression and Tension







Conclusions

- Vascomax® C250 alloy was dynamically characterized with Kolsky (split Hopkinson) bars at two strain rates: 1000 and 3000 s^{-1}
  - In compression with
    - WC platens
    - Specimen strain correction
  - In tension with
    - Laser extensometer
    - Bridgman correction to calculate true failure stress and strain

- The Vascomax® C250 alloy exhibits
  - Some strain-rate effect
  - Reasonable symmetry in dynamic compression and tension, except for failure strains