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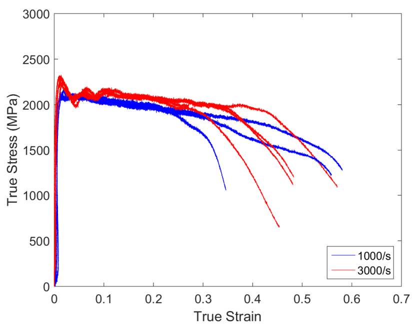

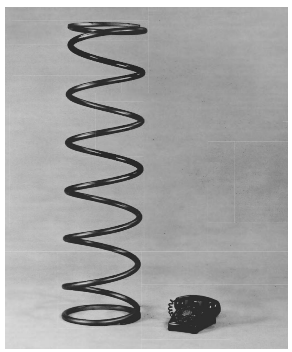

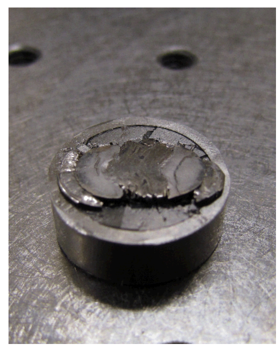

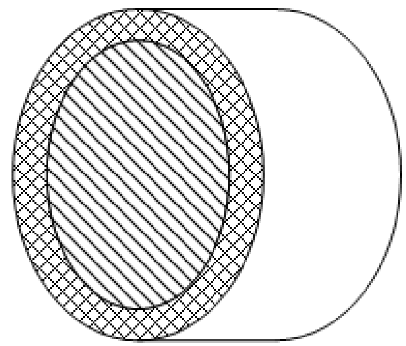

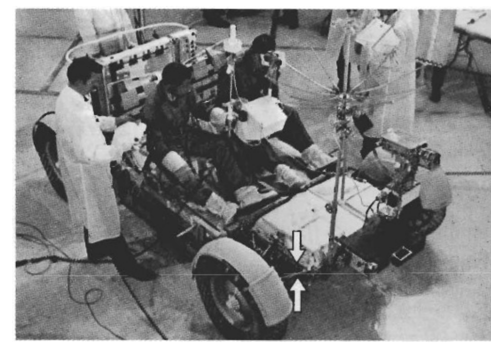

Dynamic Compression Characterization of Vascomax® C250 Alloy

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Introduction

- Maraging steel
  - Martensitic => hard form of steel crystalline structure
  - Aging => refers to the heat treatment process
  - Martensitic + Aging = Mar-Aging

- Vascomax maraging steels are useful in a variety of applications
  - High strength
  - High fracture toughness
  - Stability over a wide range of temperatures

Typical temperatures
Anneal: 820 C
Aging: ~500 C for ~3 hours

	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
C300	0.004	0.0005	0.03	0.02	0.03	4.85	9.27	0.63	0.09	0.003	<0.01	<0.01	0.006	0.01	18.58	BAL

Typical Applications of Vascomax

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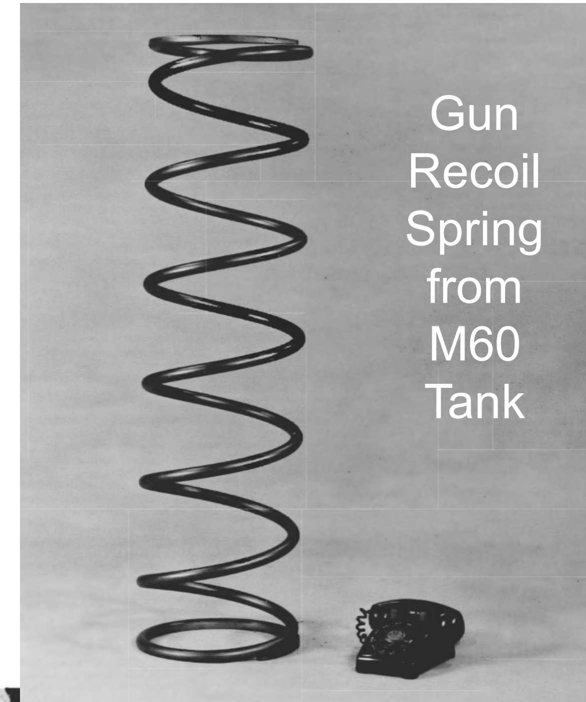
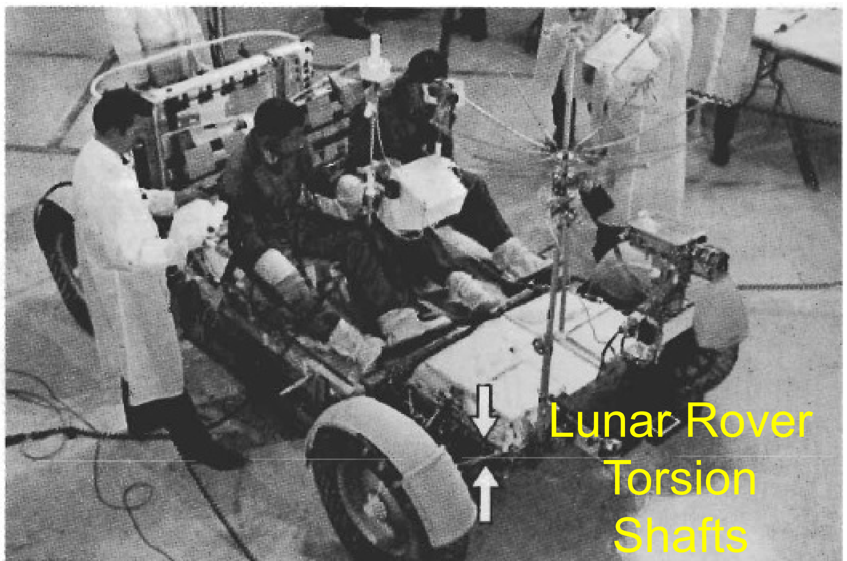
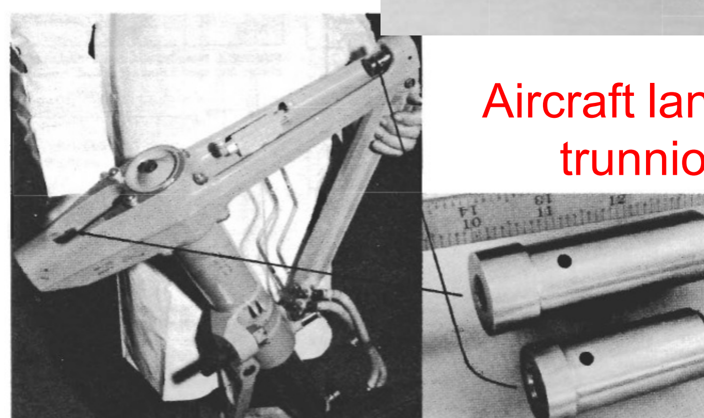
- Typical applications for maraging steels
  - Rocket motor casings
  - Aircraft landing gear
  - Power shafts
  - Munitions

High-rate Impact Loading Scenarios





Aircraft landing gear trunnion pins



http://www.dynamicmetals.net/VascoMaxCatalog.pdf

Compression Experimental Challenges

Specimen Material

Vascomax Steel

C250 (~250 ksi yield strength)

Actual yield strength (QS): 255 ksi / 1.758 GPa

Hardness: RC48

Bar Material

Vascomax Steel

C300 (~300 ksi yield strength)

Actual yield strength (QS): 290 ksi / 2.0 GPa

Hardness: RC52-56

C250 Steel is nearly as strong as the bar material
=
This could cause an indentation and damage the bars

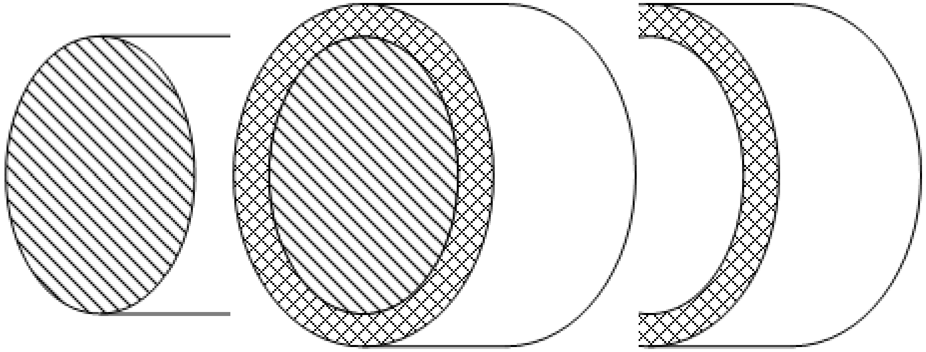
We also want to test C300 which is the same material as the bar!

Tungsten Carbide Platens

- Tungsten Carbide (WC) is a good platen material
- Hardness > RC90
- High Modulus - ~600 GPa
- Limit stress concentration at the end of the bar

Stainless Steel

Problem:
WC is relatively brittle

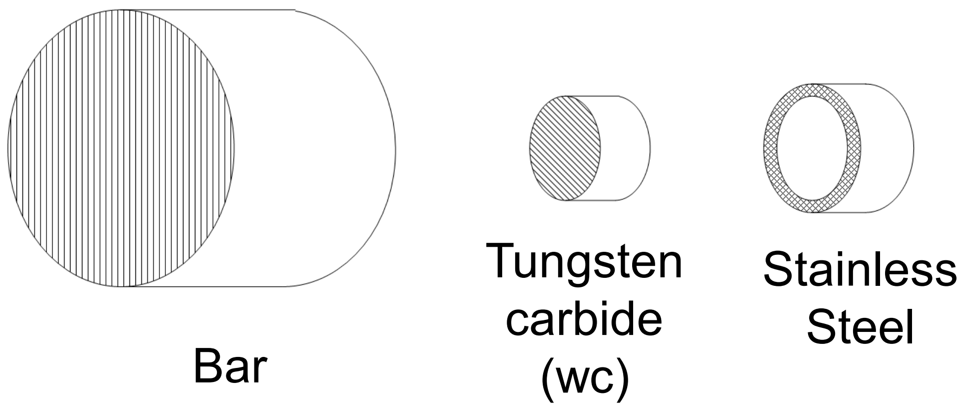


Solution:
Press-fit WC platen into a ductile ring

Platen Design

- Platens must be impedance matched with the bar ends

$$(\rho C A)_{Bar} = (\rho C A)_{Platen*}$$



*Equivalent Stiffness and Density

$$\sigma_{Total} = \sigma_{wc} + \sigma_s$$

$$E_{equiv} A_{total}\varepsilon = E_{wc}A_{wc}\,\varepsilon + E_s A_s \varepsilon$$

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

$$M_{total} = M_{wc} + M_s$$

$$\rho_{equiv} V_{total} = \rho V_{wc} + \rho V_s$$

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

We chose

$$Diam_{wc} = 15\ mm$$

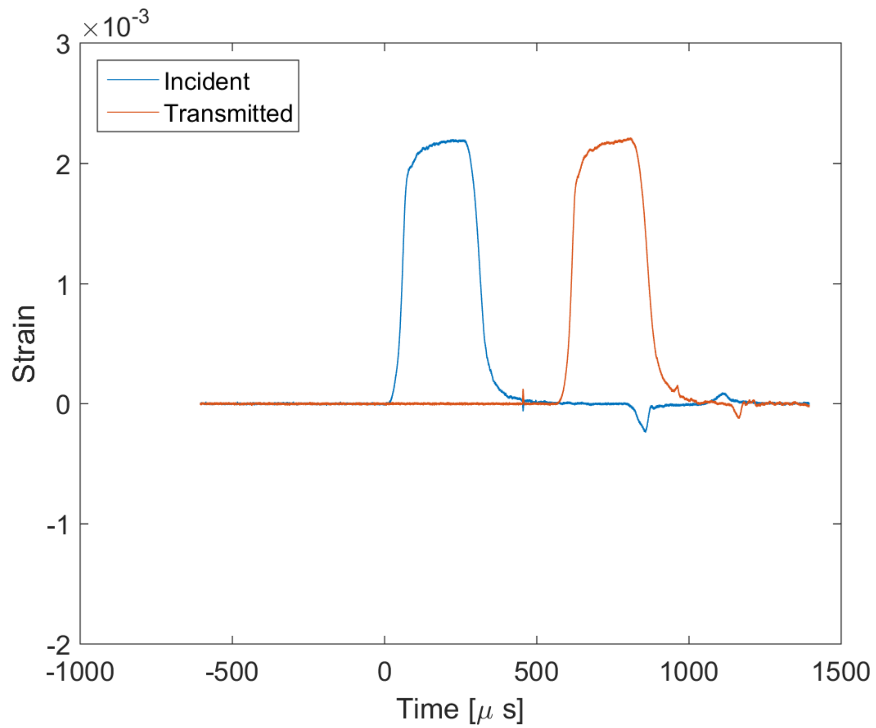
$$Diam_s = 18.02mm\ \text{OD},\ 15\ mm\ \text{ID}$$

$$19750\ \frac{kg}{m*s} \approx 19625\ \frac{kg}{m*s}$$

Solution is not unique

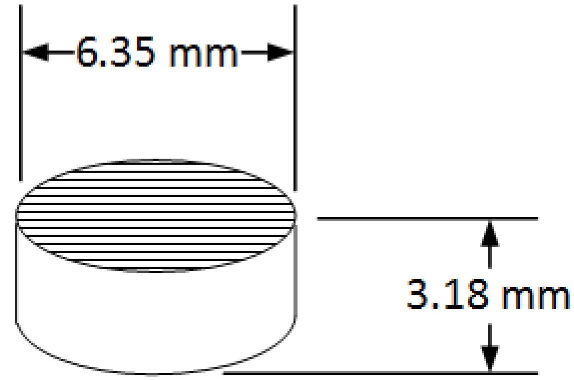
How well did the platen work?

- Experiment with single platen
- Incident and Transmitted signals are similar
- Small reflection at interface (could be slight misalignment)

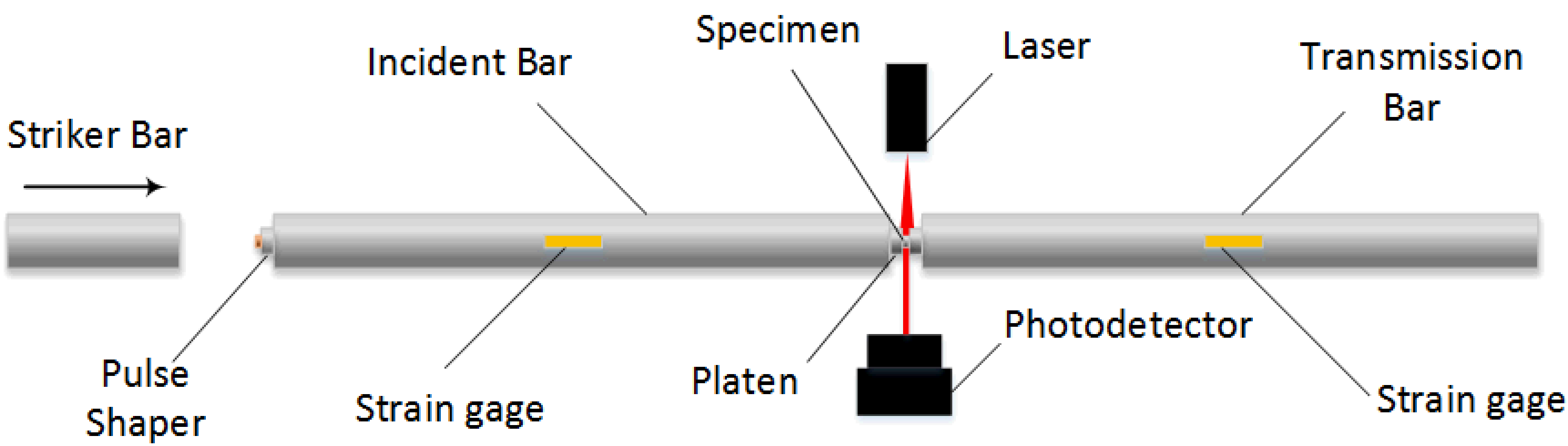


Materials & Experimental Setup

- Material for this study:
  - C250 Steel, RC48
  - 1000 s^{-1}, 3000 s^{-1}
  - 3-4 experiments at each condition



- Compression Kolsky bar
- C300 Steel



Results

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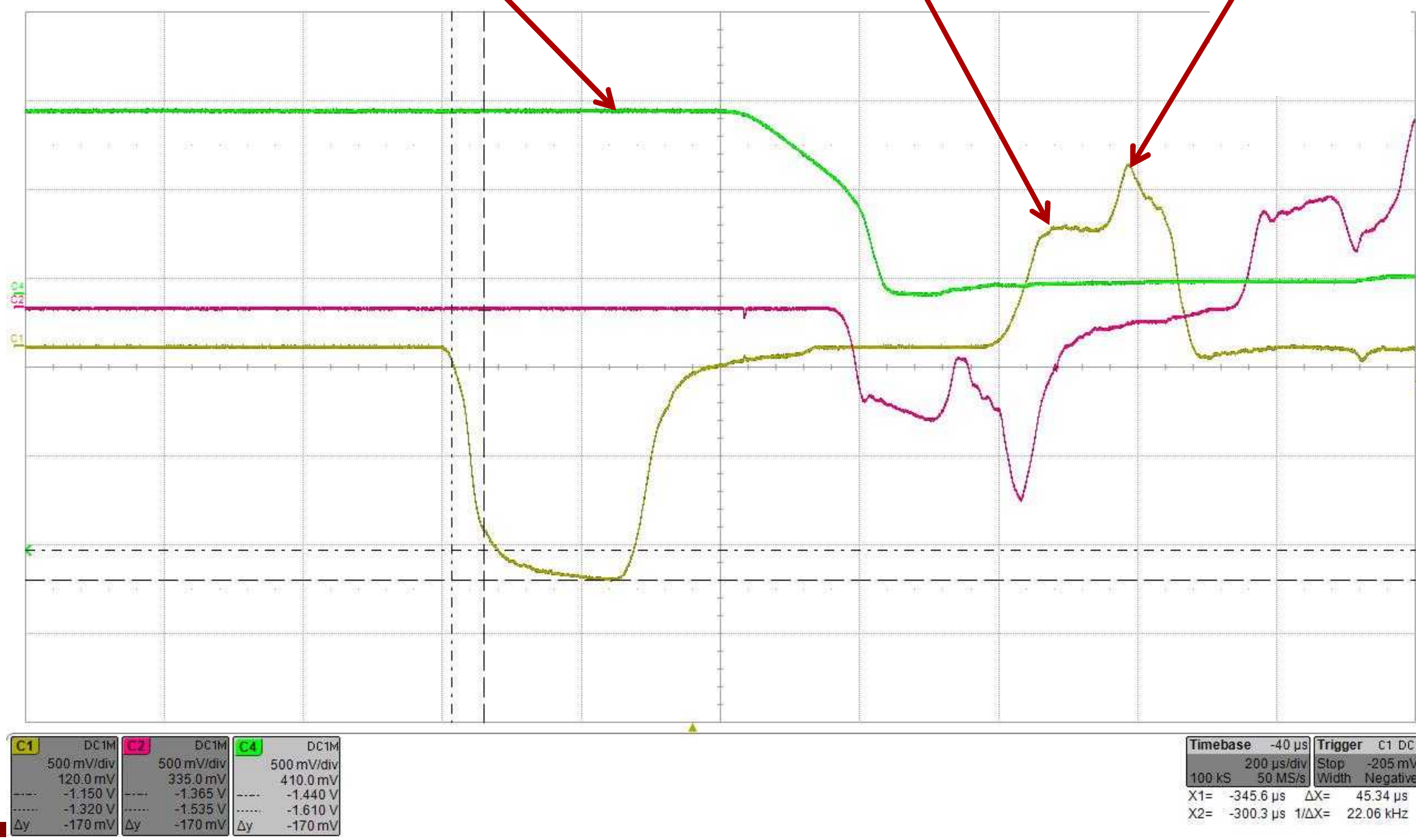
- Typical experimental record
- ~3000/s strain rate

Good laser signal

Flat reflected pulse until fracture occurs

Crushing fragments causes strain rate to increase

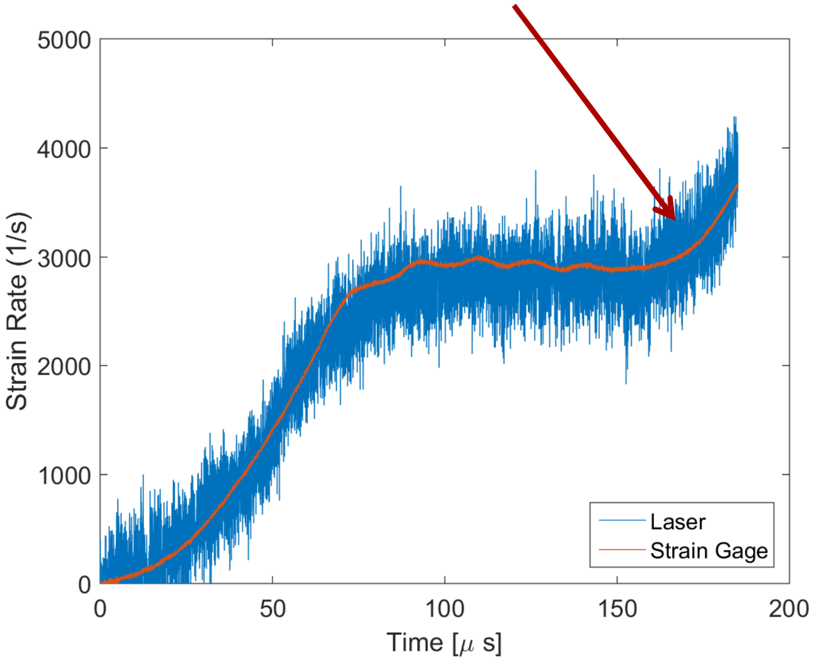


Results

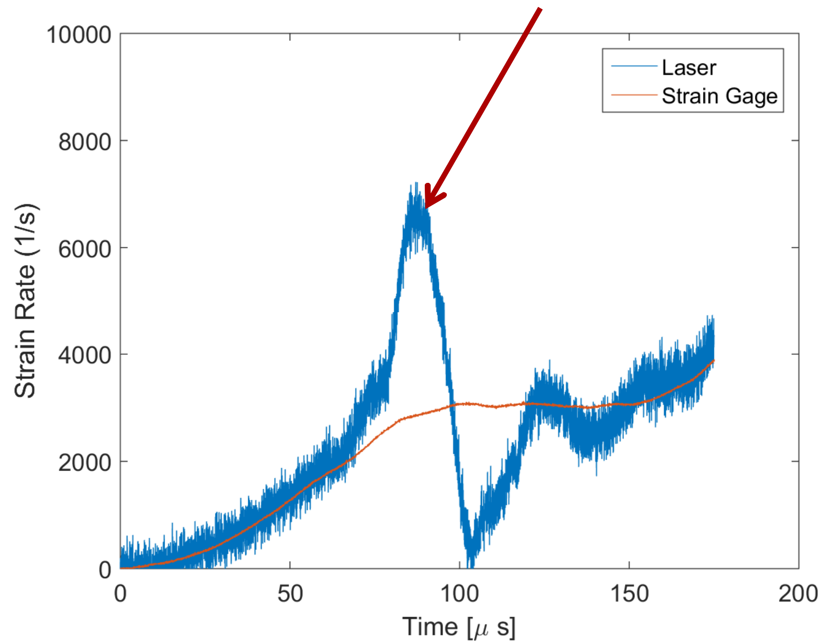
- Another experimental record
- ~3000/s strain rate

Results – Laser signal

Strain rate increases
when fracture occurs



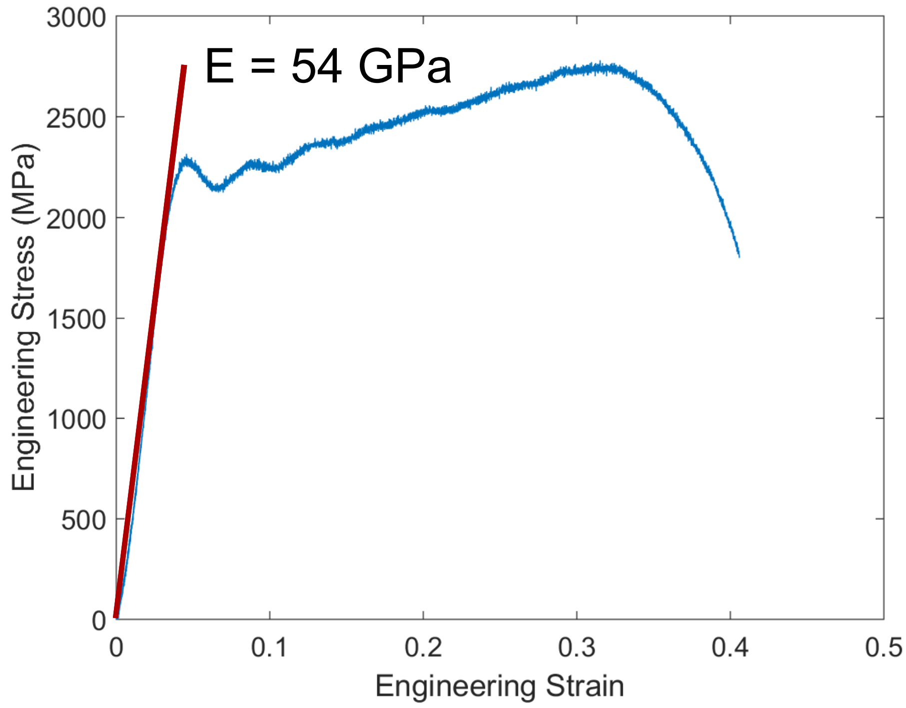
Small bump in laser signal causes
large spike in strain rate curve



- Spike in laser signal was caused by a flash/spark that was picked up on photodetector => Friction between specimen/platen?
- Laser signal is probably not reliable for strain measurement
- When sparks didn't occur, laser and strain gage matched

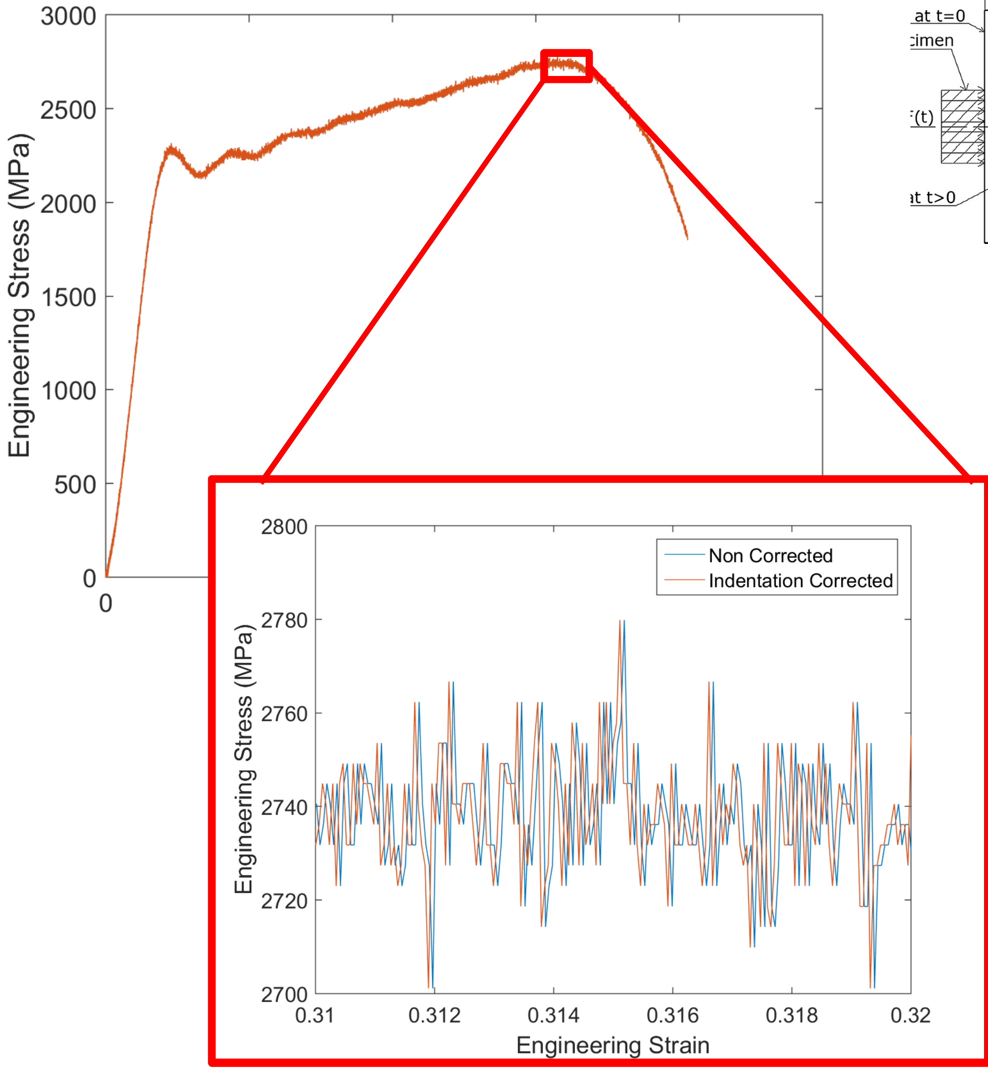
Results – Stress-strain behavior

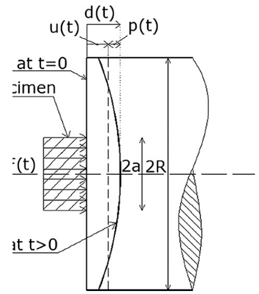
- Stress-strain curve
- At 3000/s, yield stress is 2.3 GPa, ~18% higher than QS value



- Modulus is significantly lower than the expected value of ~189 GPa

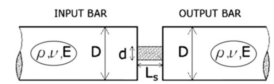
Correcting the Displacement-Indentation





Summary of main results for SHPB

We consider a classical SHPB apparatus where input and output bars are identical with diameter D and with ρ, ν and E the density, Poisson ratio and Young's modulus, respectively, of their material. The geometrical characteristics of the specimen are d, l_s and S_s, corresponding to its diameter, length and cross sectional area, respectively.



At any time throughout the experiment, the strain of the sample is obtained as

$$\epsilon(t) = \epsilon_{SHPB}(t) - \epsilon_{punch.}(t)$$

where

- $\epsilon_{punch.}(t) = 2K_p \frac{\sigma_{SHPB}(t) S_s}{l_s}$
- $\epsilon_{SHPB}(t)$ and $\sigma_{SHPB}(t)$ are the strain and stress, respectively, obtained by standard SHPB formulas.
- $K_p = \frac{16}{3\pi^2} \frac{1-\nu^2}{dE} H_p(\frac{d}{D})$

$$H_p(x) = 2 - (x + \frac{1}{x})E(x) - (x - \frac{1}{x})K(x)$$

$$E(x) = \int_0^{\frac{\pi}{2}} \sqrt{1 - x^2 \sin^2\theta}\, d\theta,\; K(x) = \int_0^{\frac{\pi}{2}} \frac{d\theta}{\sqrt{1 - x^2 \sin^2\theta}}$$

Tabulated results for the function $H_p(x)$ are given in the table underneath.
Values for $0.5 < x \leq 1$ are obtained by linear interpolation.

x	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50	0.60	0.70	0.80	0.90	1.00
$H_p(x)$	1.765	1.648	1.531	1.416	1.301	1.188	1.076	0.967	0.860	0.688	0.516	0.344	0.172	0

K. Safa & G. Gary. “Displacement Correction for Punching at a Dynamically Loaded Bar End.” International Journal of Impact Engineering (2010), Vol. 37, Pg. 371-384

E. Nishida, E. Corona, B. Song. (2015) Data Reduction Uncertainties in Kolsky Bar Experiments on Metals. SEM Conference Proceedings

Mechanical impedance

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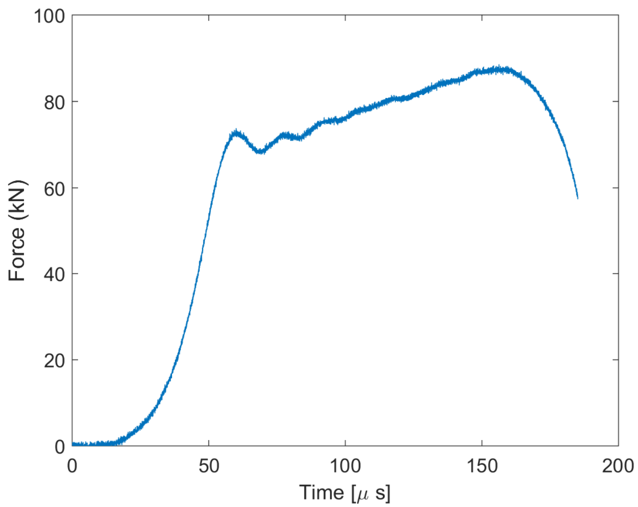
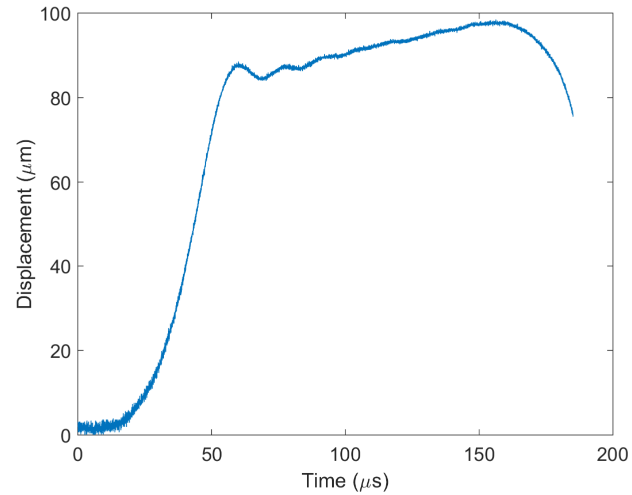
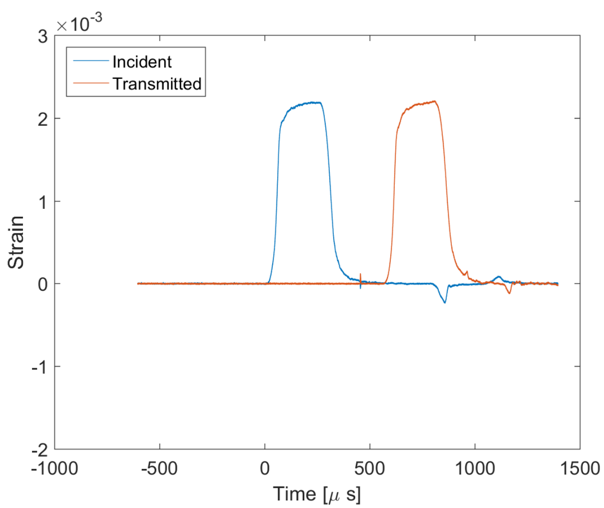
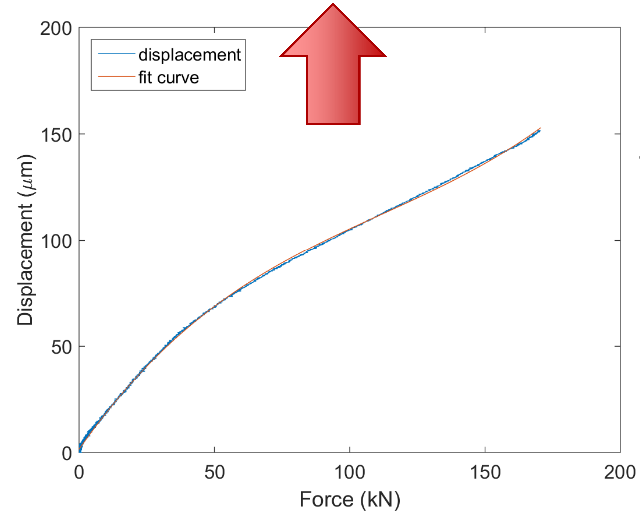
- Max force reached during experiment=> 87 kN





Displacement as a function of Force





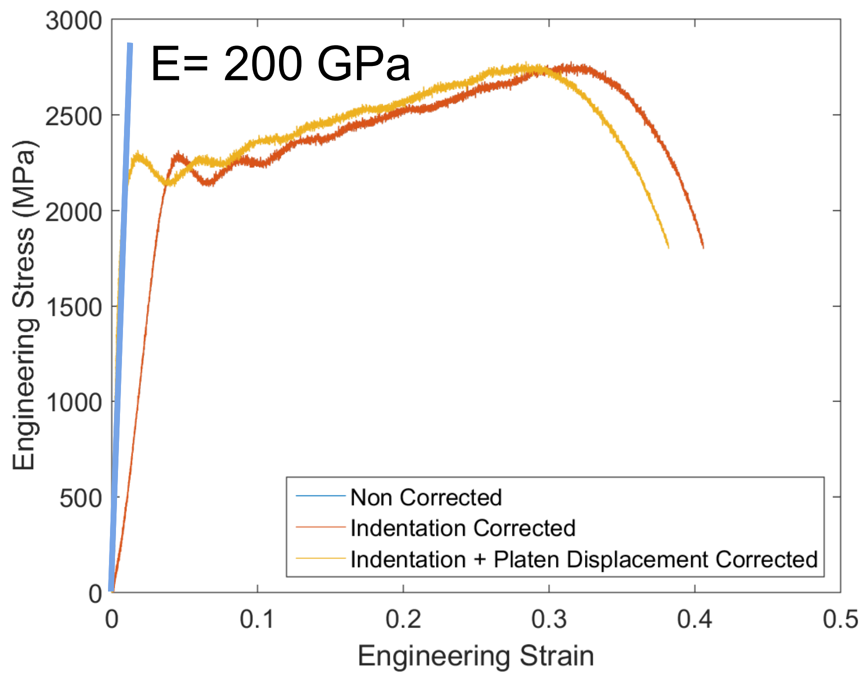
(reflected signal)

d ≈95µm

Stress-strain correction

- Displacement as a function of force is calculated for the experiment

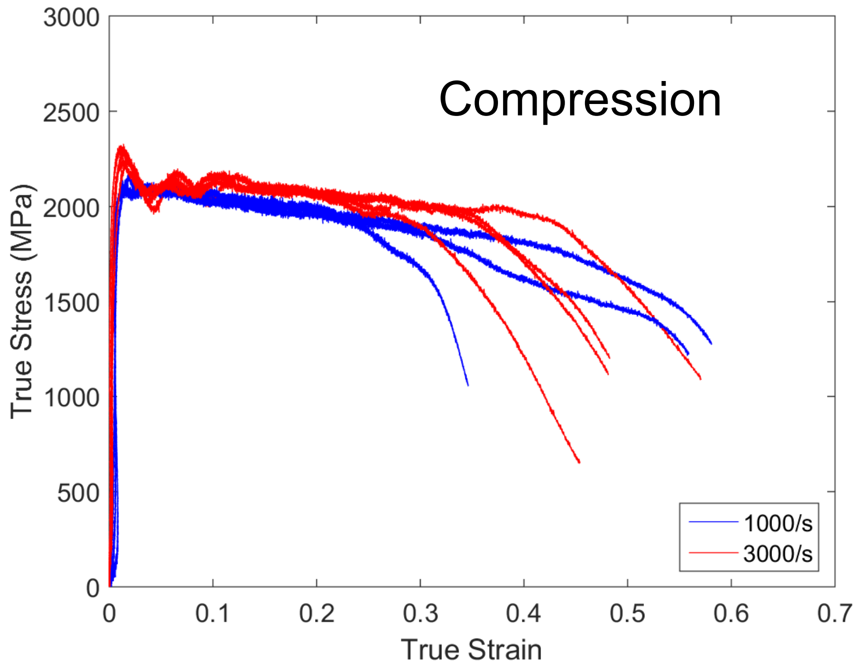
$$\varepsilon_{corrected} = \frac{disp_{strain\ gage} - disp_{indentation} - disp_{interface}}{sample\ length}$$

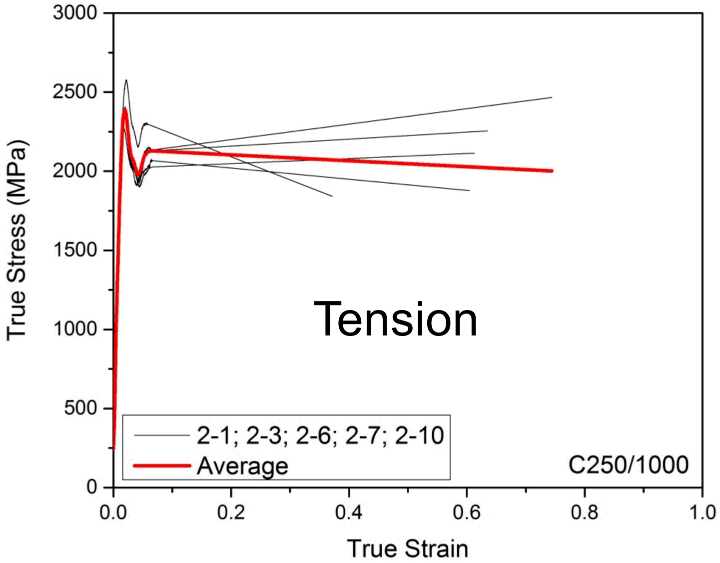


Displacement at the platen is caused by slight impedance mismatch

Strain Rate Comparison

- Yield stress increased from 2.09 ± 15 MPa to 2.23 ± 29 MPa
- 18% higher than nominal QS value for yield stress



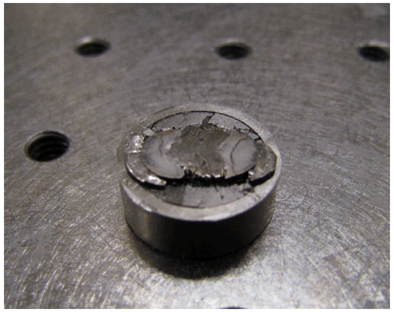


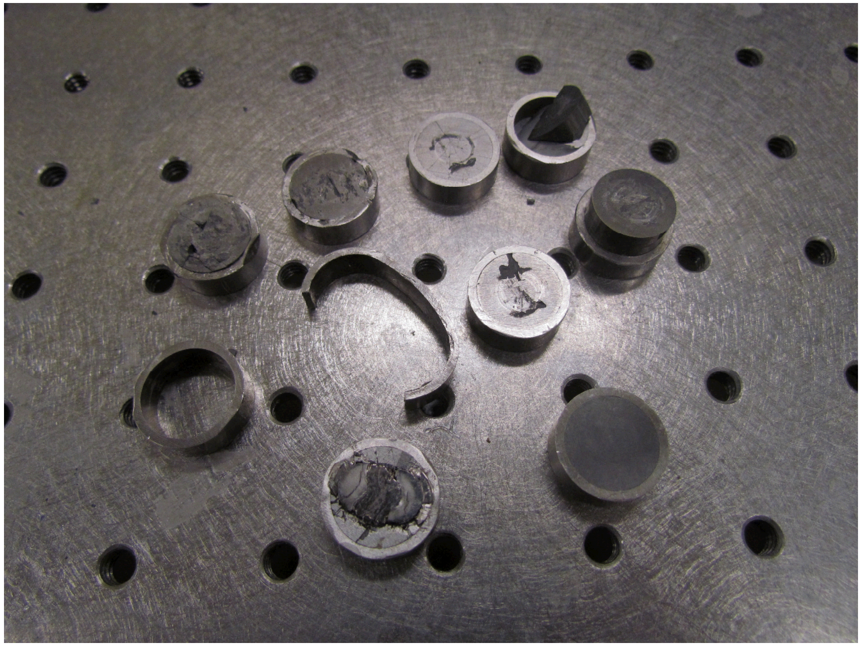
- Yield stresses are similar for compression and tension

B. Song, P.E. Wakeland, M. Furnish. Dynamic Tensile Characterization of Vascomax Maraging C250 and C300 Alloys. J Dyn Behav Mater 2015

Complications

- Platen method is not perfect
- Platens broke/cracked after several uses
- Some samples were embedded into platen
  => Reloading?
- Single loading momentum trap will be used in the future





Conclusions and Future Work

- High strength steels with strengths similar to the bar materials have been studied
- Impedance-matched platens were designed and used to protect bar ends
- Strain must be corrected by displacement and punching correction
- WC platens barely experienced punching force
- Majority of strain correction due to misalignment/platen strain
- Revised platen design and single loading momentum trap must be explored
- Compression properties of C300 steel will be investigated in the future