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DYNAMIC TESTING OF MATERIALS

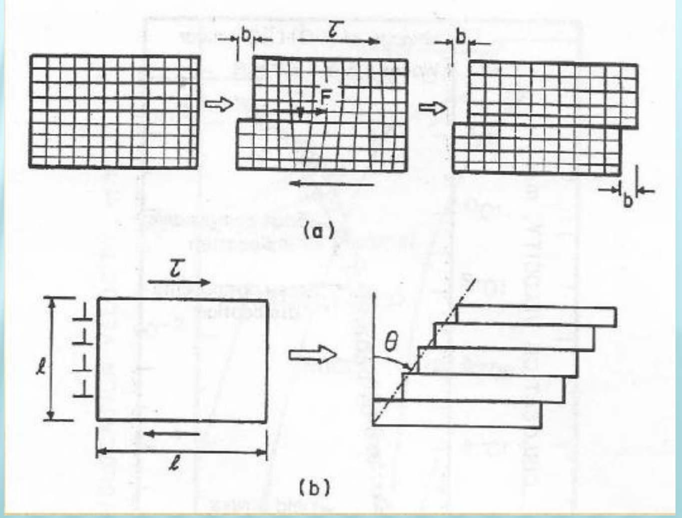
OUTLINE

- Background
- Dynamic Testing
  - Taylor Anvil Test
  - Split-Hopkinson Bar
  - Expanding Ring Technique
  - Dynamic Mechanical Analysis (DMA)
  - Cam Plastometer
- Summary and Conclusions

BACKGROUND

DYNAMIC BEHAVIOR

- Materials respond to external forces by
  - Dislocation generation and motion
  - Mechanical twinning
  - Phase transformation
  - Fracture
  - Viscous glide of polymer chains and shear zones in glasses



PHYSICAL BASED CONSTITUTIVE EQUATIONS

$$\sigma = f(\varepsilon, \frac{d\varepsilon}{dt}, T, deformation\ history)$$

Litonski	1977	$\tau = B(\gamma_0 + \gamma_p)^n (1 - aT)\left[1 + b\left(\frac{d\gamma}{dt}\right)\right]^m$
Johnson-Cook	1983	$\sigma = (\sigma_0 + B\varepsilon^n)\left[1 + C\ln\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right]\left[1 - \left(\frac{T - T_r}{T_m - T_r}\right)^m\right]$
Klopp	1985	$\tau = \tau_0\left(\frac{\gamma}{\gamma_0}\right)^n\left(\frac{T}{T_r}\right)^{-\nu}\left(\frac{\dot{\gamma}_p}{\dot{\gamma}_0}\right)^m \Rightarrow \tau = \tau_0\left(\frac{\dot{\gamma}}{\dot{\gamma}_0}\right)^{1/M}\left(1 + \frac{\gamma}{\gamma_0}\right)^m \exp(-\lambda\Delta T)$
Meyers	1994	$\sigma = (\sigma_0 + B\varepsilon^n)\left[1 + C\log_{10}\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right]\left(\frac{T}{T_r}\right)^{-\lambda}$ $\sigma = (\sigma_0 + B\varepsilon^n)\left[1 + C\log_{10}\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right]e^{-\lambda(T - T_r)}$
Andrade	1994	$\sigma = (\sigma_0 + B\varepsilon^n)\left[1 + C\log\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right]\left[1 - \left(\frac{T - T_r}{T_m - T_r}\right)^m\right]H(T)$ $H(T) = \frac{1}{1 - \{1 - [(\sigma_f)_{rec}/(\sigma_f)_{def}]\}u(T)}$; $u(T) = \begin{cases} 0 & for\ T < T_c \\ 1 & for\ T > T_c \end{cases}$

M.A. Meyers, in “Mechanics and Materials,” John Wiley and Sons, 1999

DYNAMIC TESTING RANGE

STRAIN RATE, s^{-1}	COMMON TESTING METHODS	DYNAMIC CONSIDERATIONS	
10^7, 10^6, 10^5	HIGH VELOCITY IMPACT -Explosives -Normal plate impact -Pulsed laser -Exploding foil -Incl. plate impact (pressure-shear)	SHOCK-WAVE PROPAGATION SHEAR-WAVE PROPAGATION	INERTIAL FORCES IMPORTANT
10^4, 10^3	DYNAMIC-HIGH -Taylor anvil tests -Hopkinson Bar -Expanding ring	PLASTIC-WAVE PROPAGATION	
10^2, 10^1	DYNAMIC-LOW High-velocity hydraulic, or pneumatic machines; cam plastometer	MECHANICAL RESONANCE IN SPECIMEN AND MACHINE IS IMPORTANT	
10^0, 10^{-1}, 10^{-2}, 10^{-3}, 10^{-4}, 10^{-5}	QUASI-STATIC Hydraulic, servo-hydraulic or screw-driven testing machines	TESTS WITH CONSTANT CROSS-HEAD VELOCITY STRESS THE SAME THROUGHOUT LENGTH OF SPECIMEN	INERTIAL FORCES NEGLIGIBLE
10^{-6}, 10^{-7}, 10^{-8}, 10^{-9}	CREEP AND STRESS-RELAXATION -Conventional testing machines -Creep testers	VISCO-PLASTIC RESPONSE OF METALS	

M.A. Meyers, in "Dynamic Behavior of Materials," John Wiley and Sons, 1994

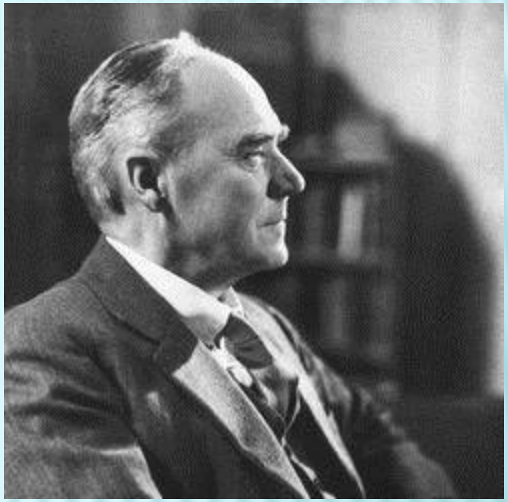
Taylor Anvil Test

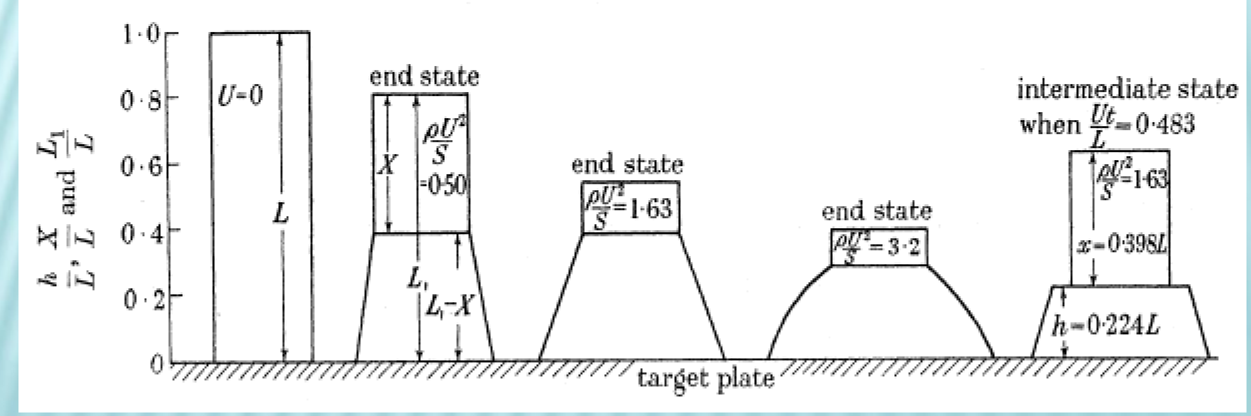
DYNAMIC TESTING

METHODS

-Developed by Geoffrey Ingram Taylor in 1948.

-Taylor showed that dynamic material properties could be deduced from the impact of a projectile against a rigid boundary.

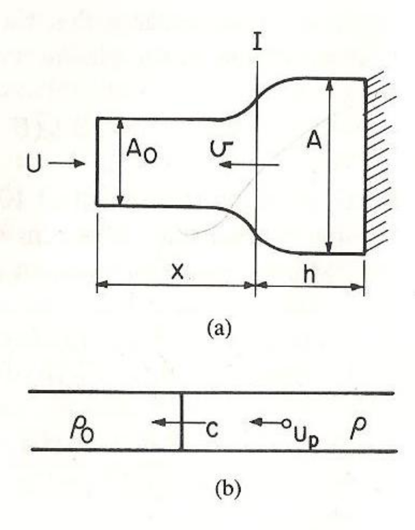


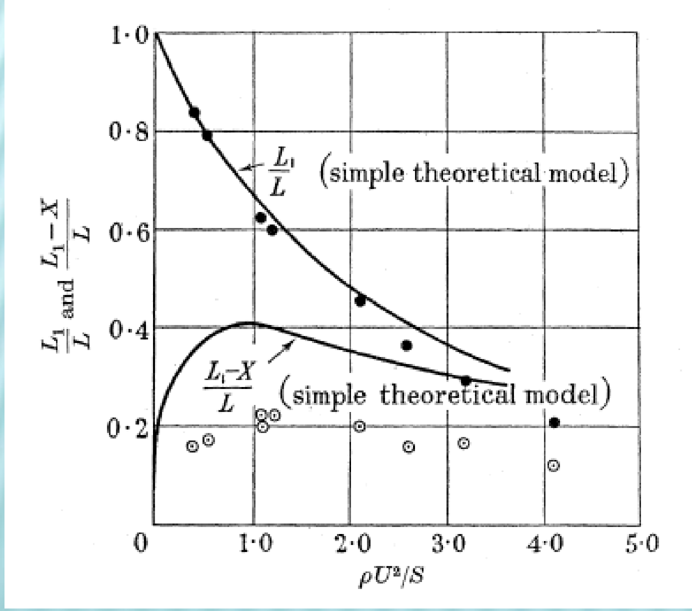


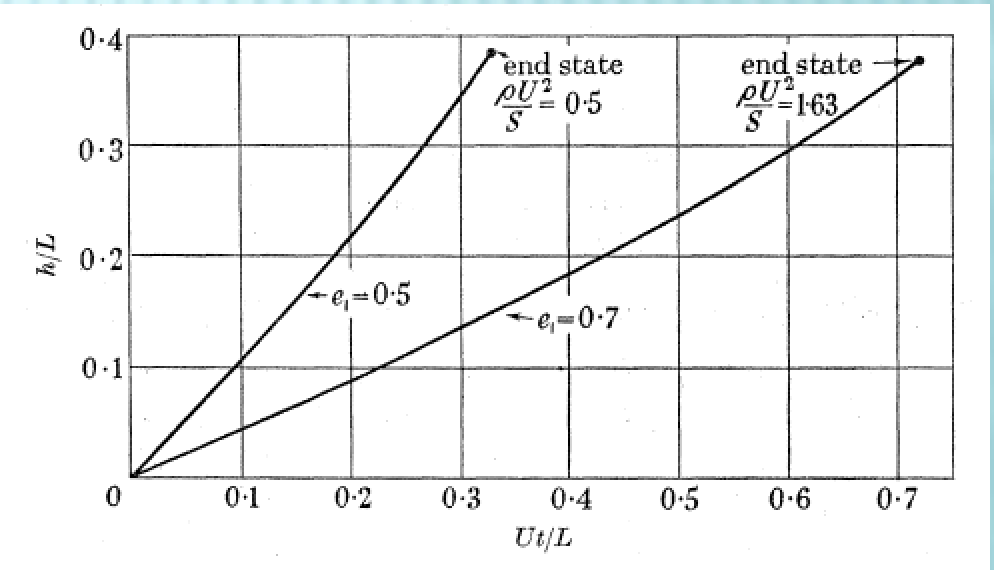
G.I. Taylor, Proc. of the Royal Society of London Vol. 194 (1948) p.289

RESULTS

$$\frac{h/L}{Ut/L} = \frac{h}{Ut} = \frac{1}{U}\frac{h}{t} \cong 1$$







G.I. Taylor, Proc. of the Royal Society of London Vol. 194 (1948) p.289

WILKINS-GUINAN ANALYSIS

$$\frac{L_1}{L_0} = \left(1 - \frac{h}{L_0}\right)\exp\left(-\frac{\rho_0 U^2}{2\sigma_{yd}}\right) + \frac{h}{L_0}$$

L_1: new specimen length

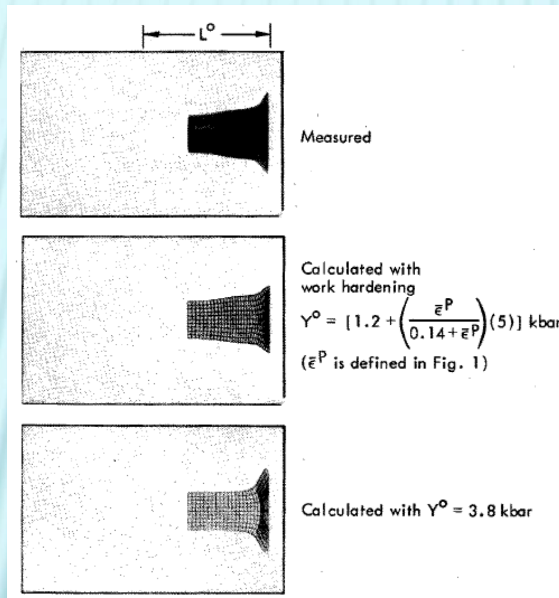
L_0: original length

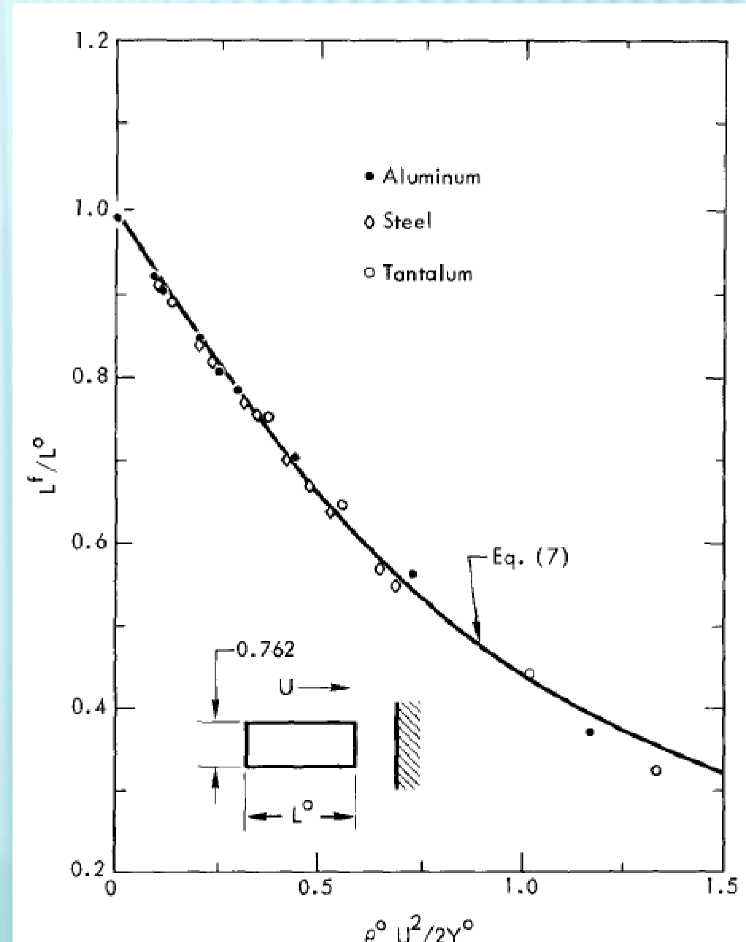
h: thickness of the plastic zone

ρ_0: original density

U: velocity of cylindrical projectile

σ_{yd}: dynamic yield stress

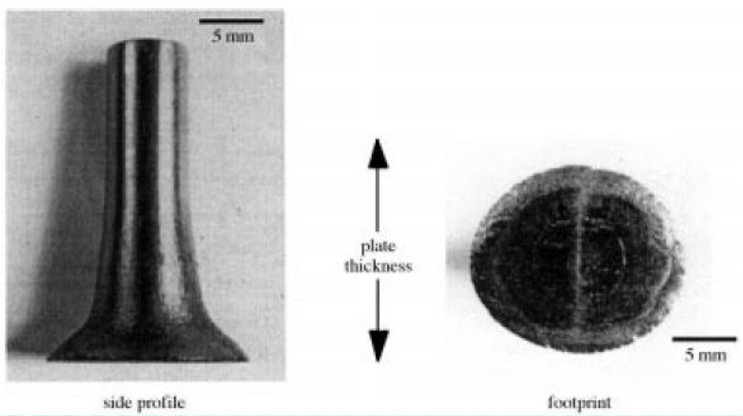


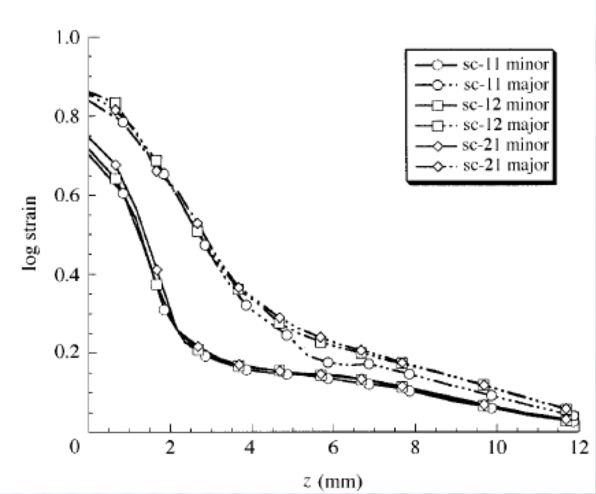


M.L. Wilkins, M.W. Guinan, J. Appl. Phys. 44 (1973) 1200

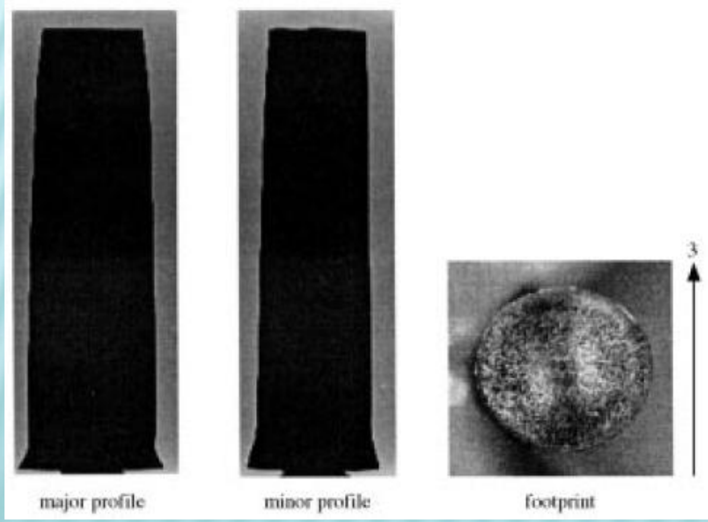
RESULTS

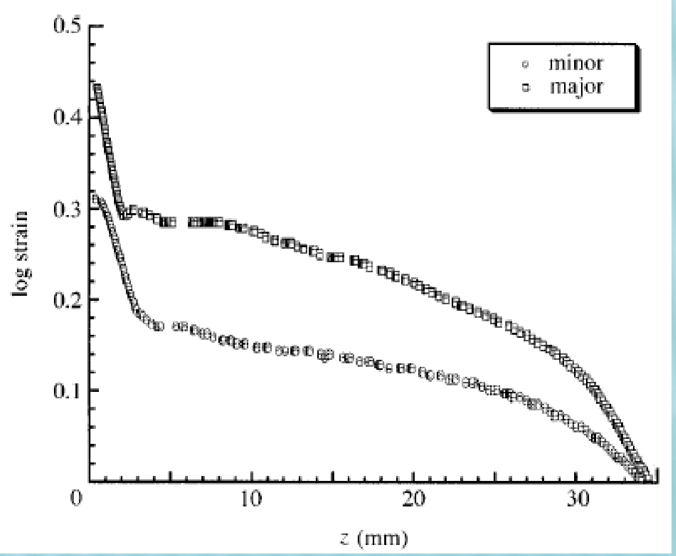
Tantalum Taylor impact specimen





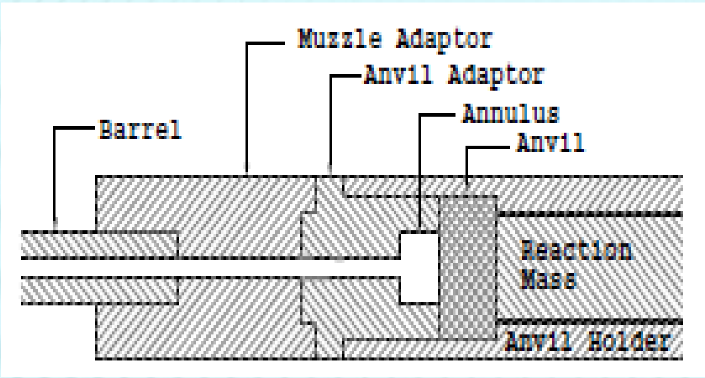
Zirconium Taylor impact specimen

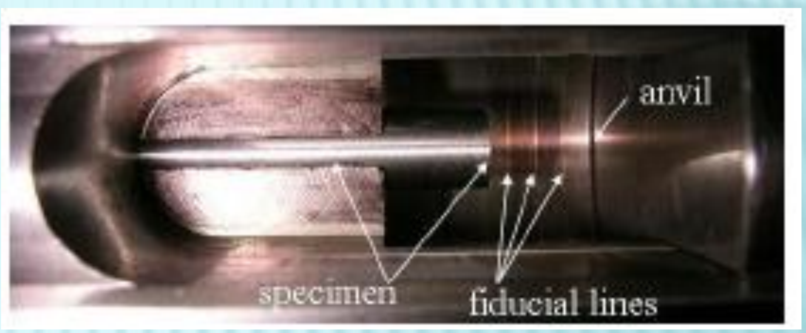


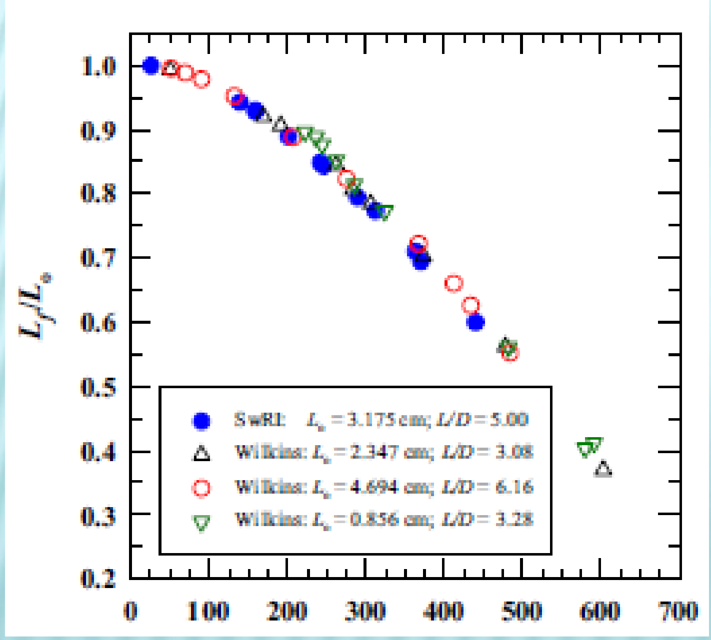


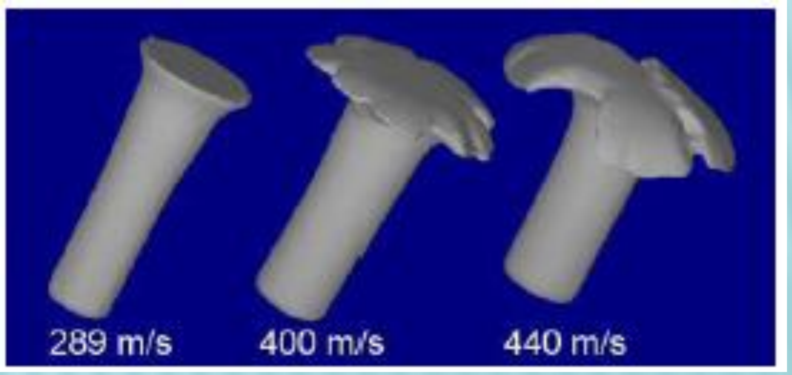
P.J. Maudlin, G.T. Gray III, C.M. Cady, G.C. Kaschner, Phil. Trans. Soc. A 357 (1999) 1707

DEVELOPMENT









C. Anderson Jr., A. Nicholls, I.S.Chocron, R. Ryckman, AIP Conf. Proc. 845 (2005) 1367

Split-Hopkinson Bar

DYNAMIC TESTING

THE HOPKINSON PRESSURE BAR

-First suggested by Bertram Hopkinson in 1914

-Initially utilized as a way to measure stress pulse propagation in a metal bar

-Single bar is struck by bullet or gun-cotton detonation

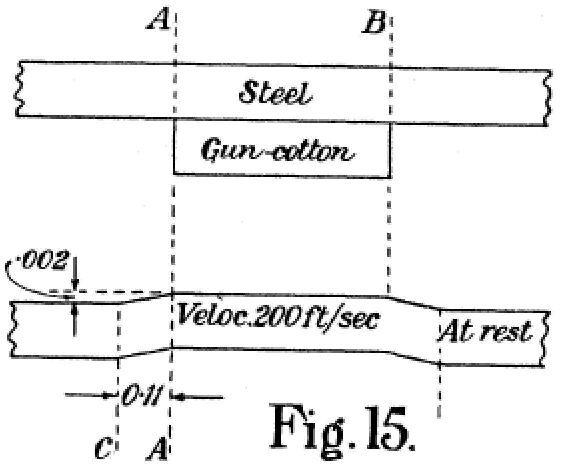


Fig.15.

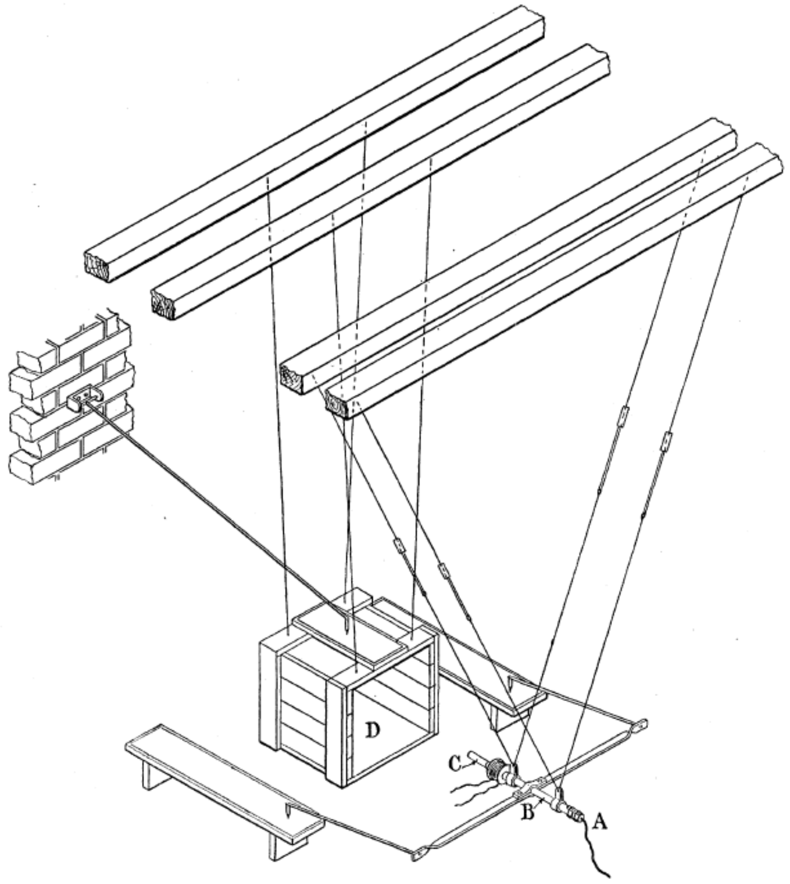


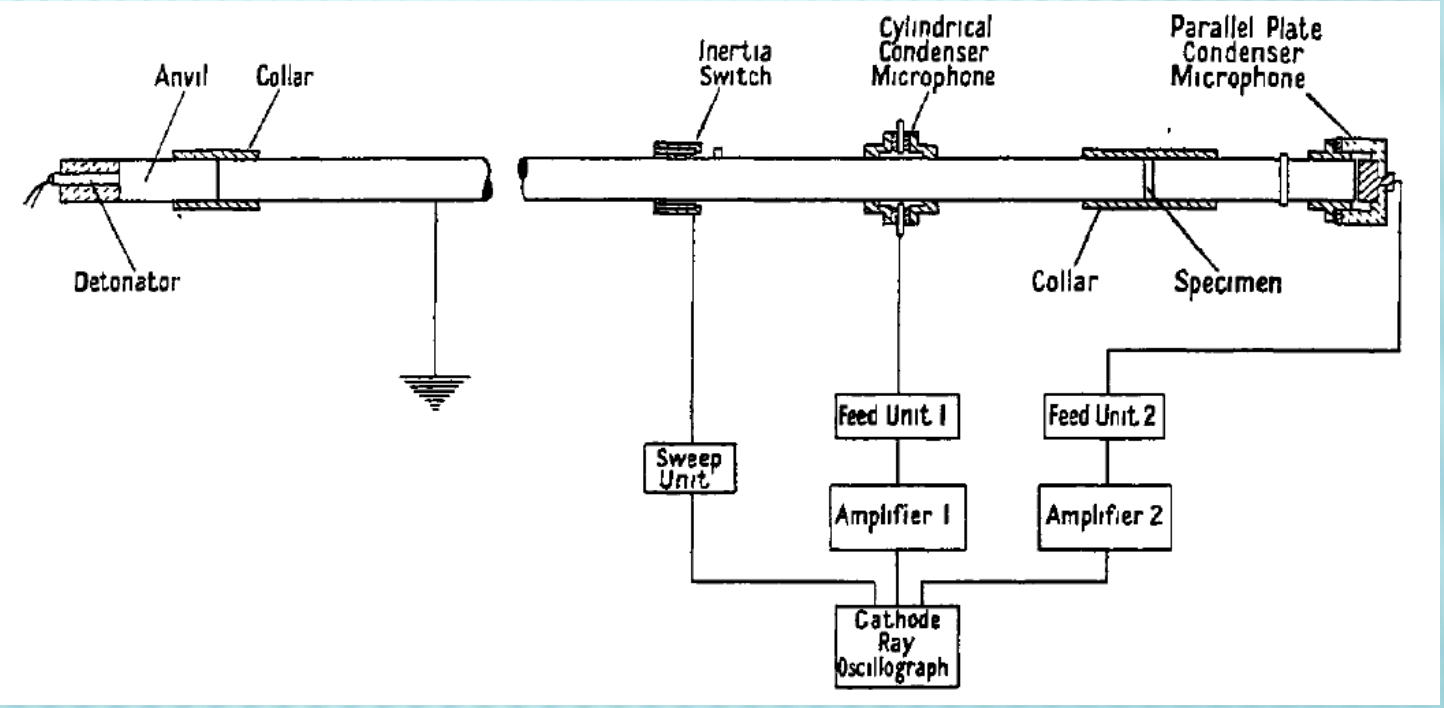
Fig. 12.

B. Hopkinson, Philo. Trans. of the Royal Society of London Vol. 213 (1914) p.437

DEVELOPMENT OF HOPKINSON PRESSURE BAR

-In 1949, H. Kolsky refined Hopkinson’s technique

-Two Hopkinson bars were used in series to determine stress and strain



H. Kolsky, Proc. Phys. Soc. B 62 (1949) 676

COMPRESSION TESTING

L: Original length of the specimen

ε_r: Time-dependent reflected strain in the incident bar

c_0: Elastic longitudinal bar wave velocity

$A_{0/S}$: Cross-sectional area of the transmission bar/specimen

E: Young's modulus of the bar material

ε_t : Time-dependent axial strain in the transmission bar

$$\dot{\varepsilon}(t) = -\frac{2c_0}{L}\varepsilon_r(t)$$

$$\sigma(t) = \frac{A_0}{A_s}E\varepsilon_t(t)$$

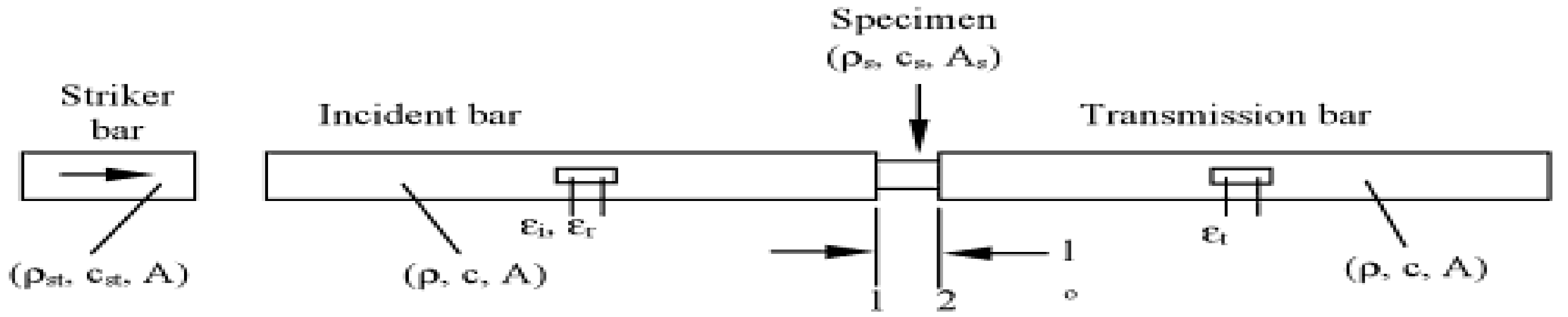
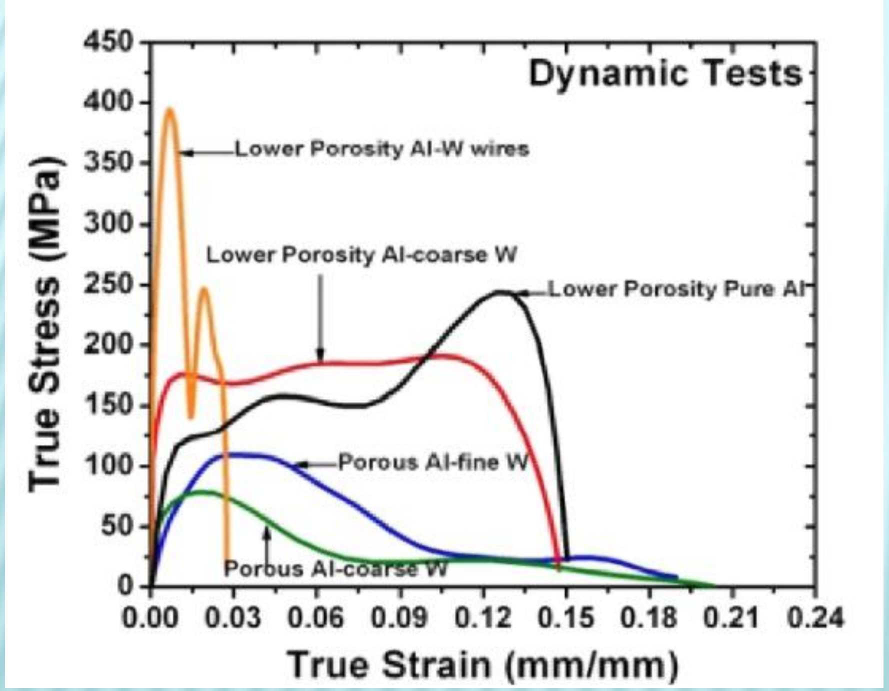


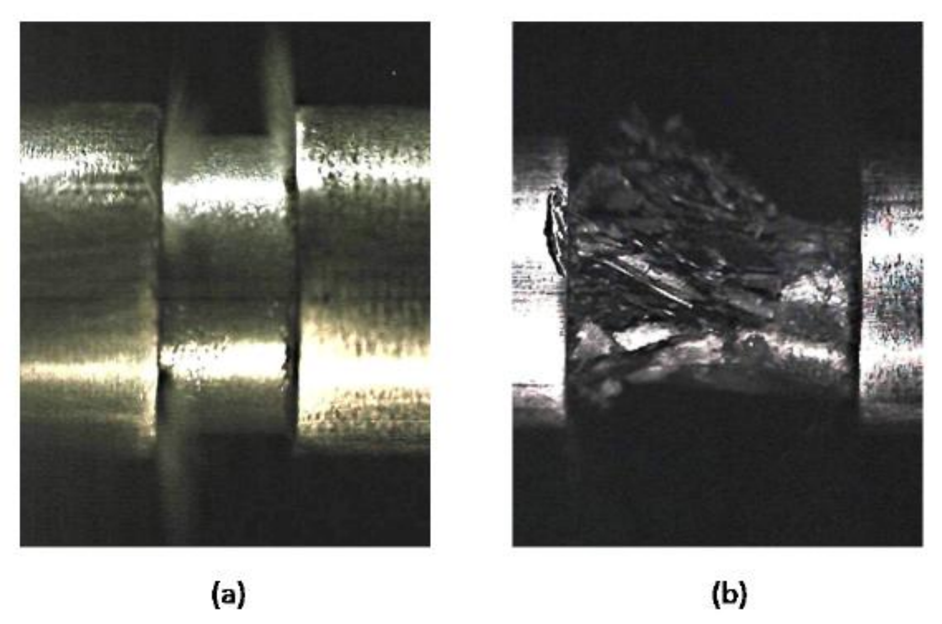
Figure 10.1. *A schematic illustration of the Hopkinson bar set-up*

T. Kundu, in "Advanced Ultrasonic Methods for Material and Structure Inspection ," John Wiley and Sons, 2007

RESULTS

- Unlike quasi-static testing machines, where the machine rigidity is typically much higher than that of the specimen and testing conditions can be controlled just by controlling the machine motion, the loading bars in a SHPB are much less rigid.



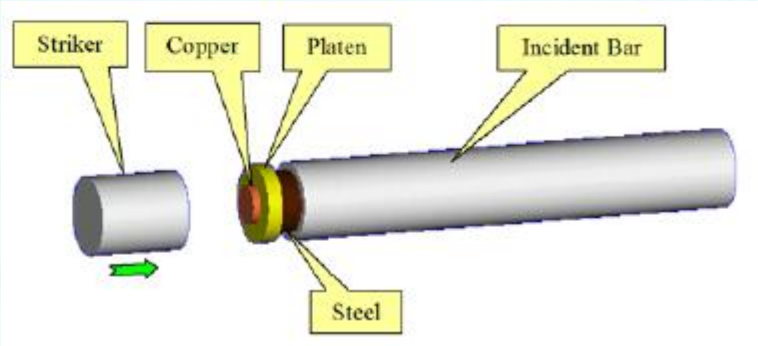


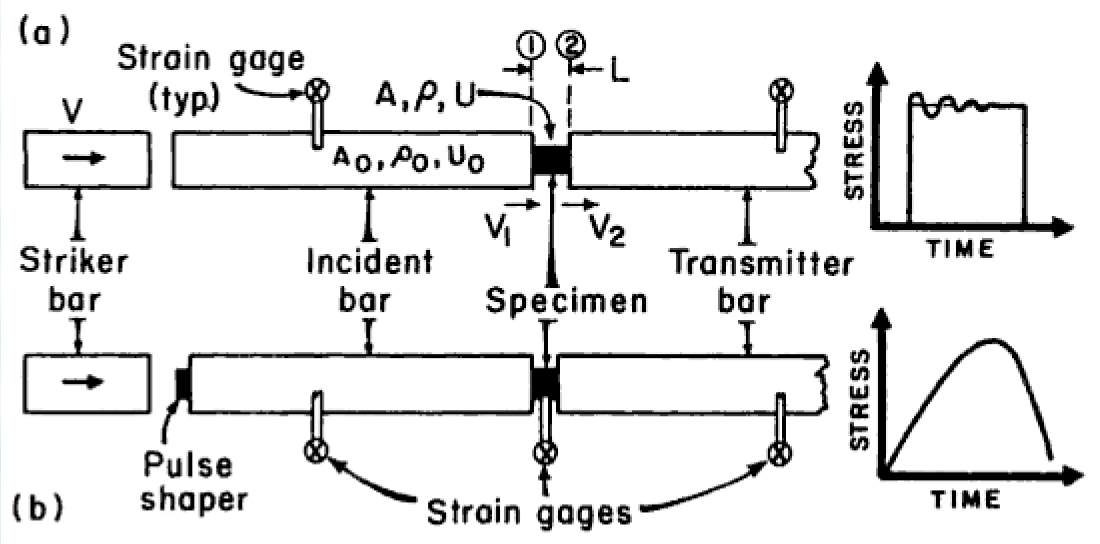
P.-H. Chui, S. Wang, E. Vitali, E. B. Herbold, D. J. Benson, V. F. Nesterenko, AIP Conf. Proc. 1195 (2009) 1345

RESULTS (VIDEO)

- http://bcove.me/vilofpvy

IMPORTANCE OF A PULSE SHAPER

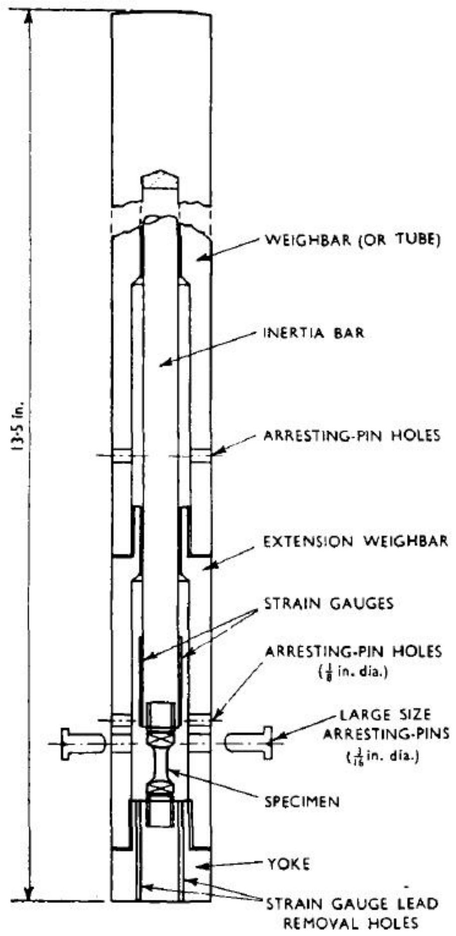


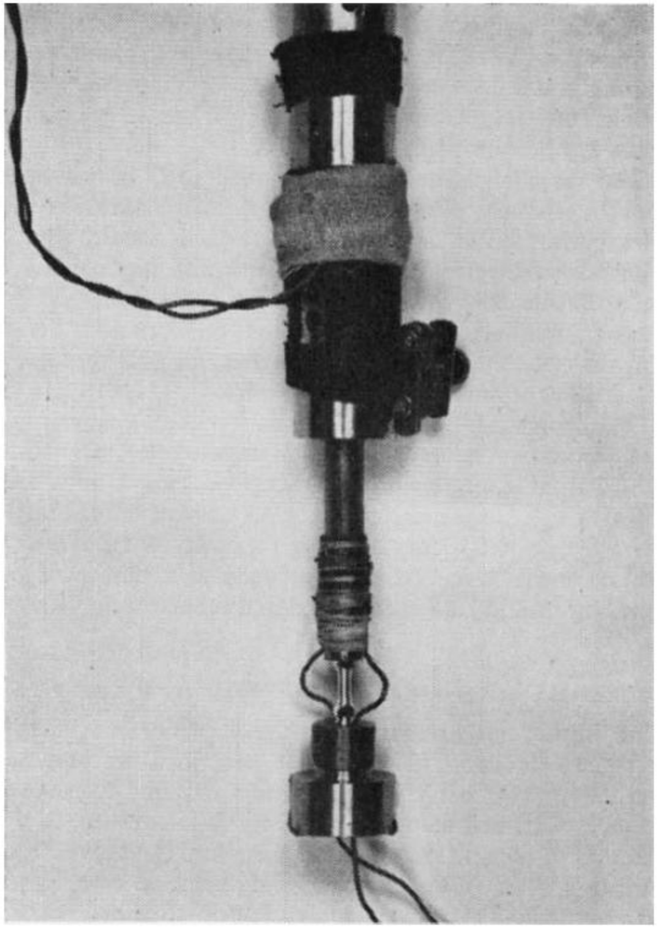


M.A. Meyers, in “Dynamic Behavior of Materials,” John Wiley and Sons, 1994

TENSION TESTING

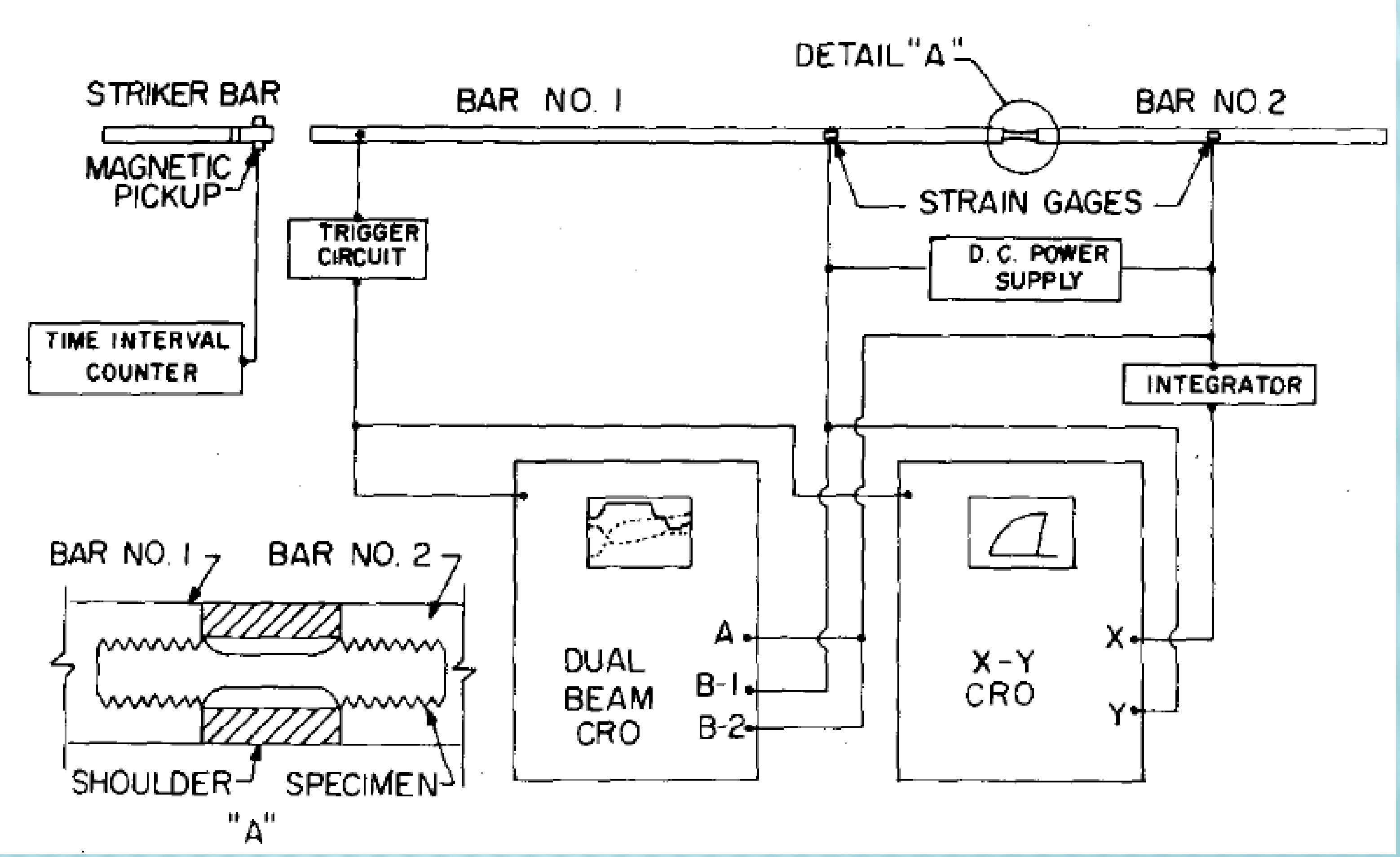
- The first tension bar was designed and tested by Harding et al. in 1960





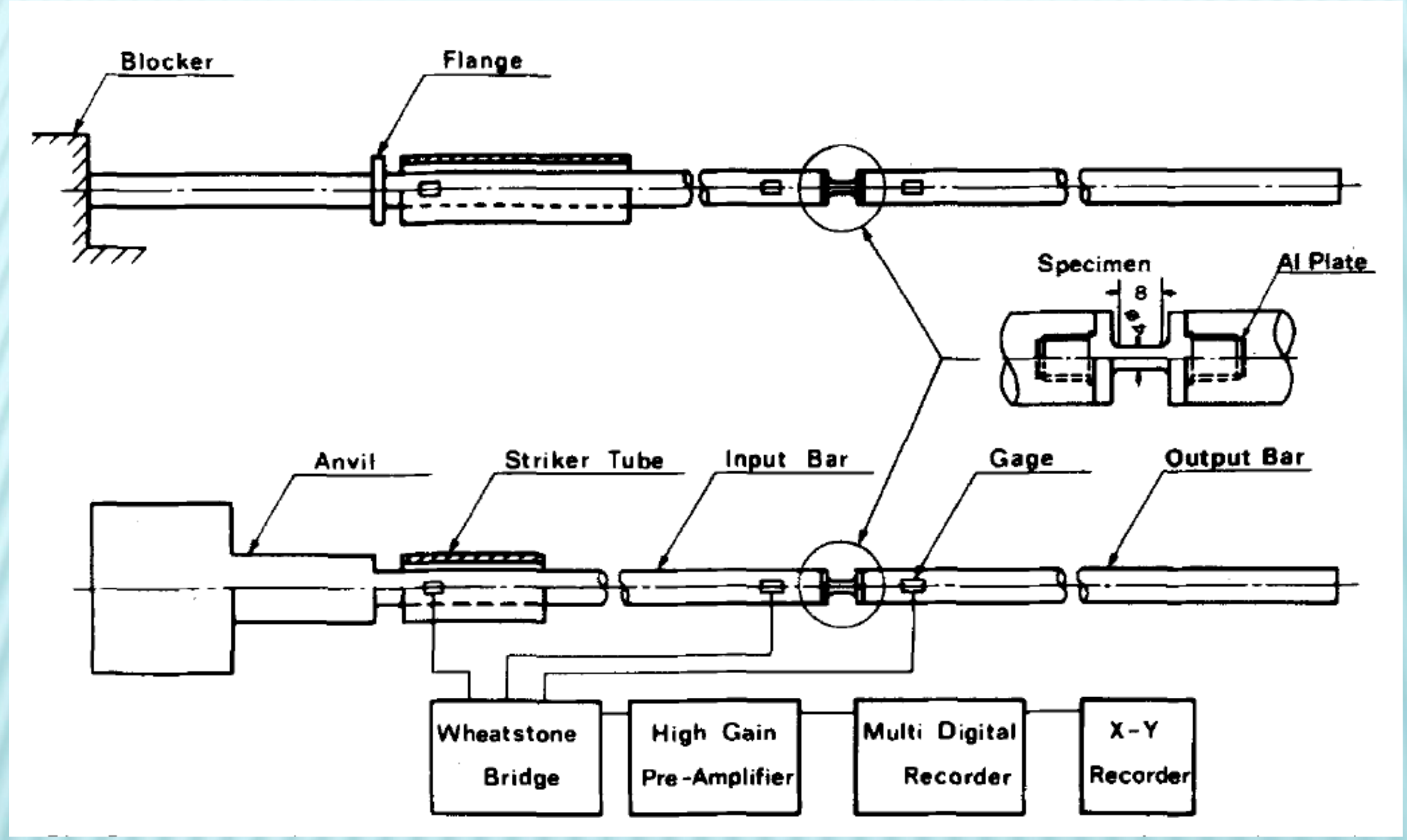
J. Harding, E.O. Wood, J.D. Campbell, J. Mech. Eng. Sci. 2 (1960) 88

DEVELOPMENT



T. Nicholas, Exp. Mech. 21(1981) 177

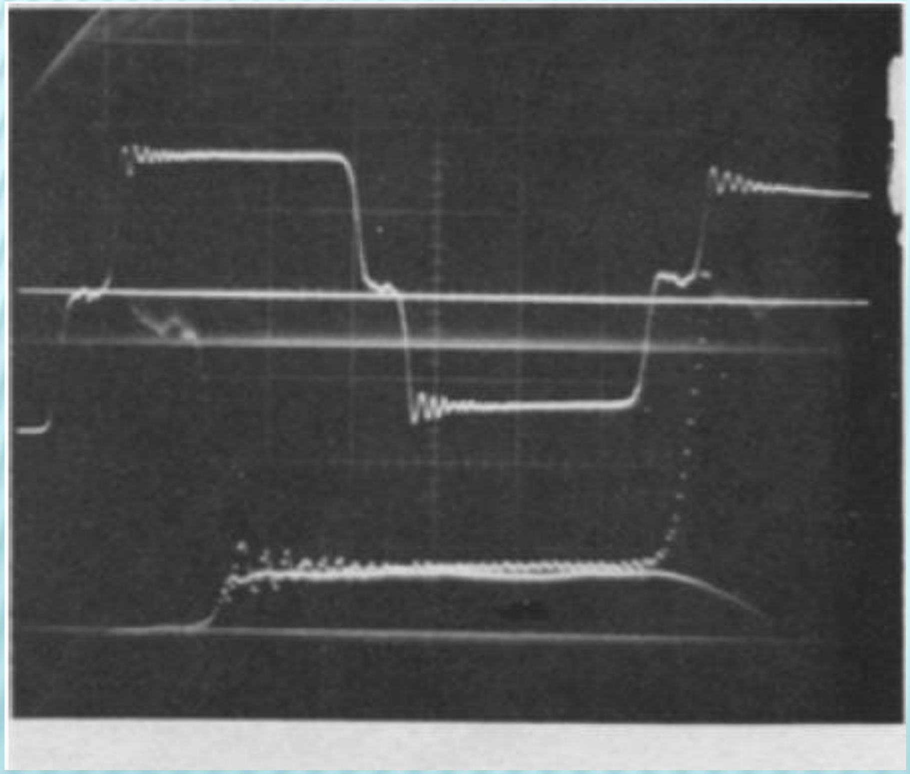
DEVELOPMENT (CONT.)

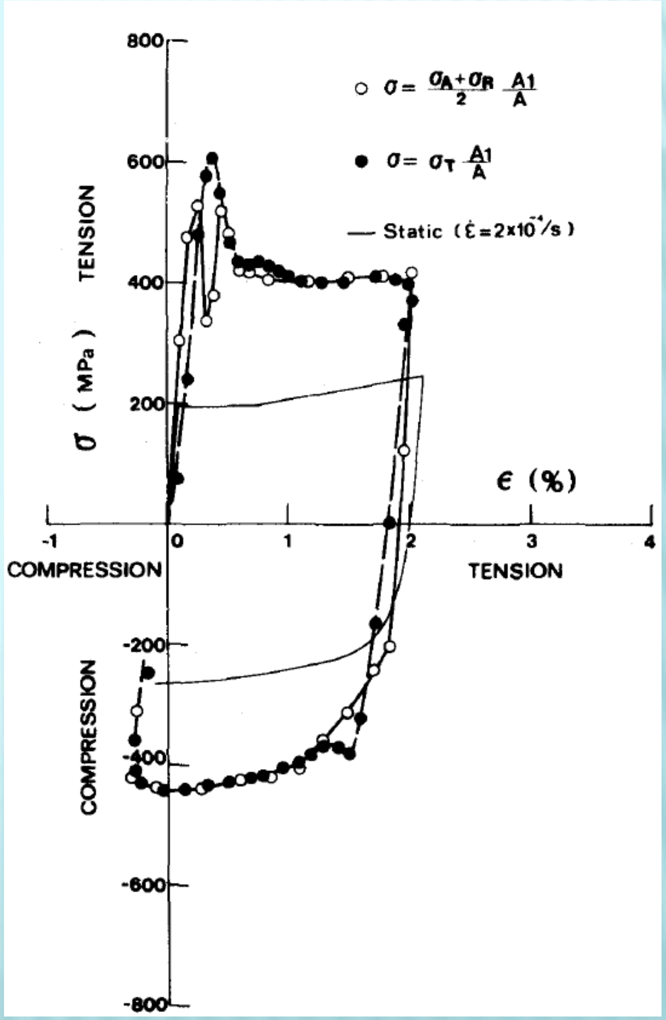


K. Ogawa, Exp. Mech. 24(1984) 81

RESULTS

- Typical oscilloscope trace from a Hopkinson bar tension test and a stress-strain relation obtained by it.



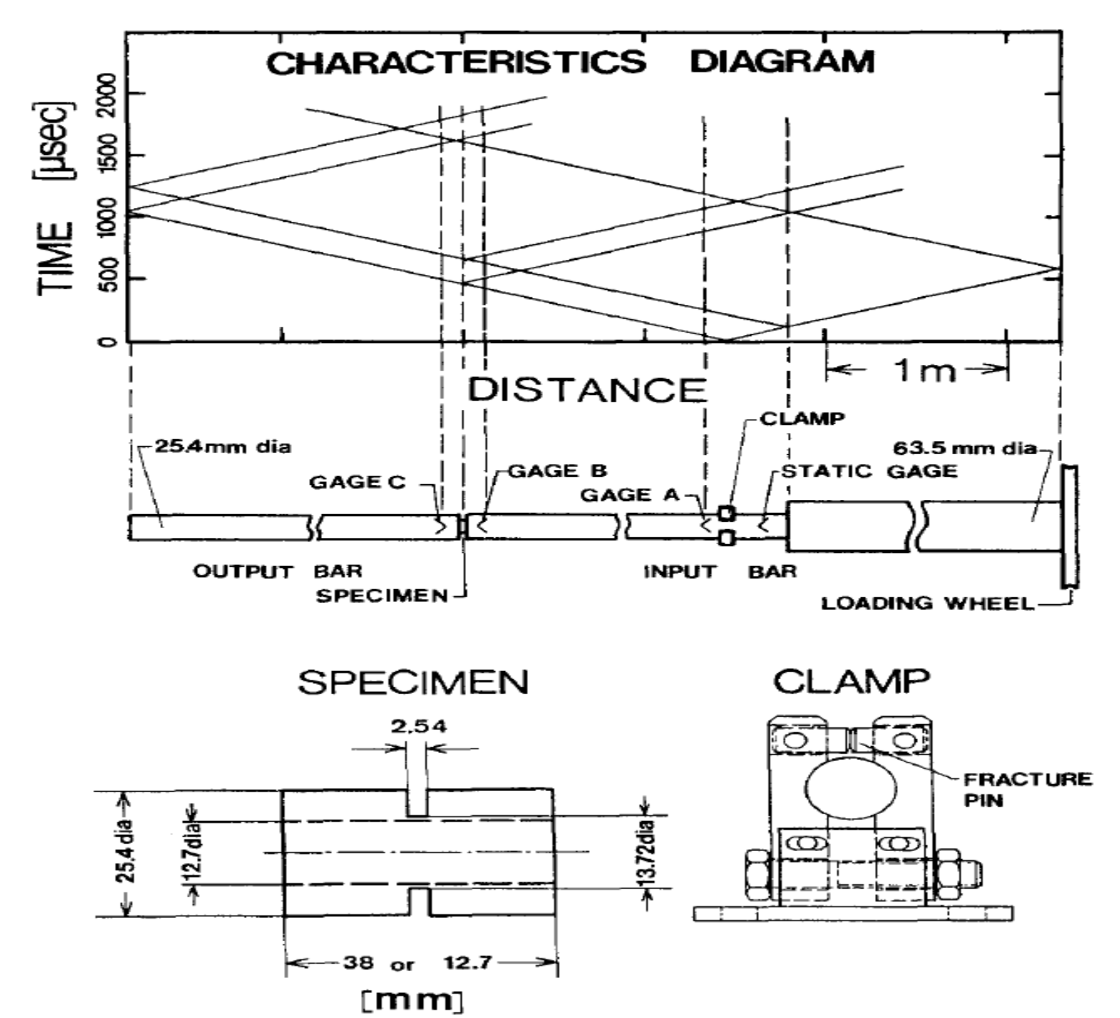


T. Nicholas, Exp. Mech. 21(1981) 177
K. Ogawa, Exp. Mech. 24(1984) 81

TORSION TESTING

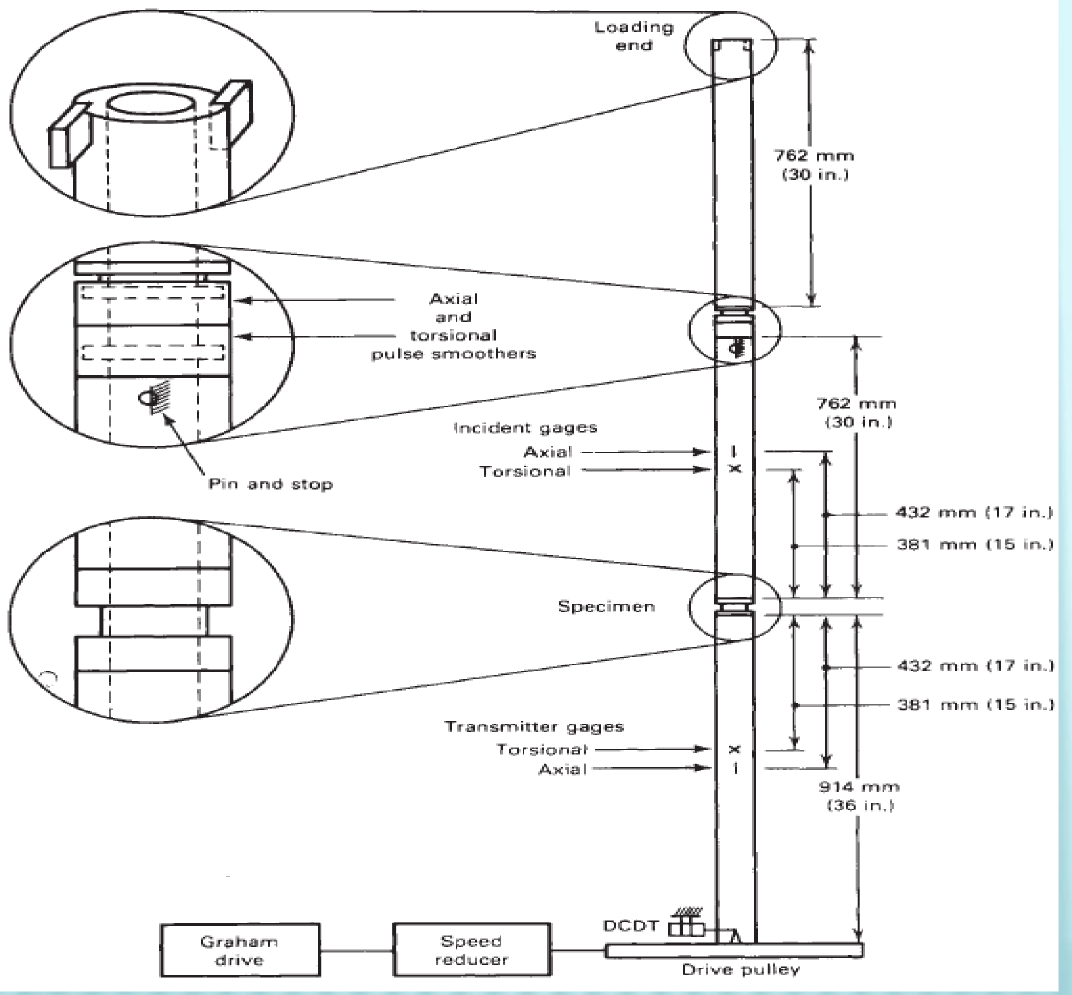
-The stored-torque method involves clamping the midsection of the incident bar, as shown in the figure, while a torque is applied to the free end.

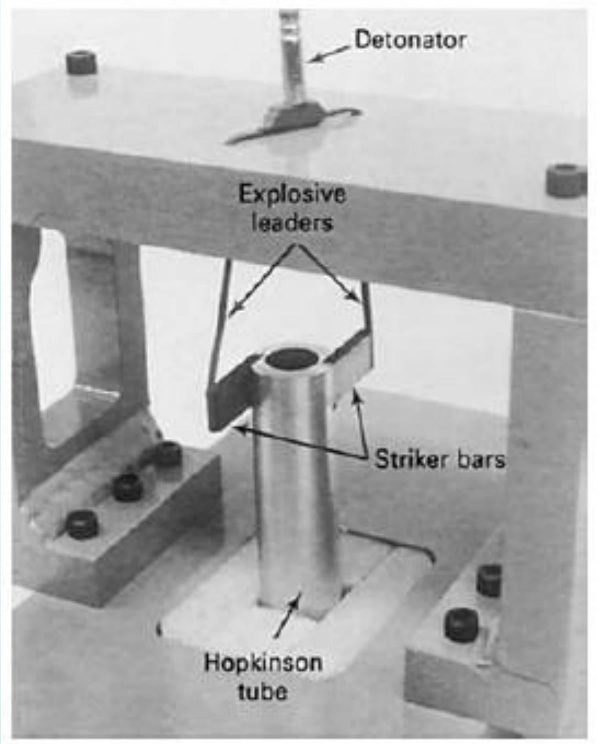
-A characteristics diagram that shows the propagation of the elastic waves in the bars is also shown in the figure here.



A. Gilat, Y.H. Pao, Exp. Mech. 28 (1988) 322

DEVELOPMENT

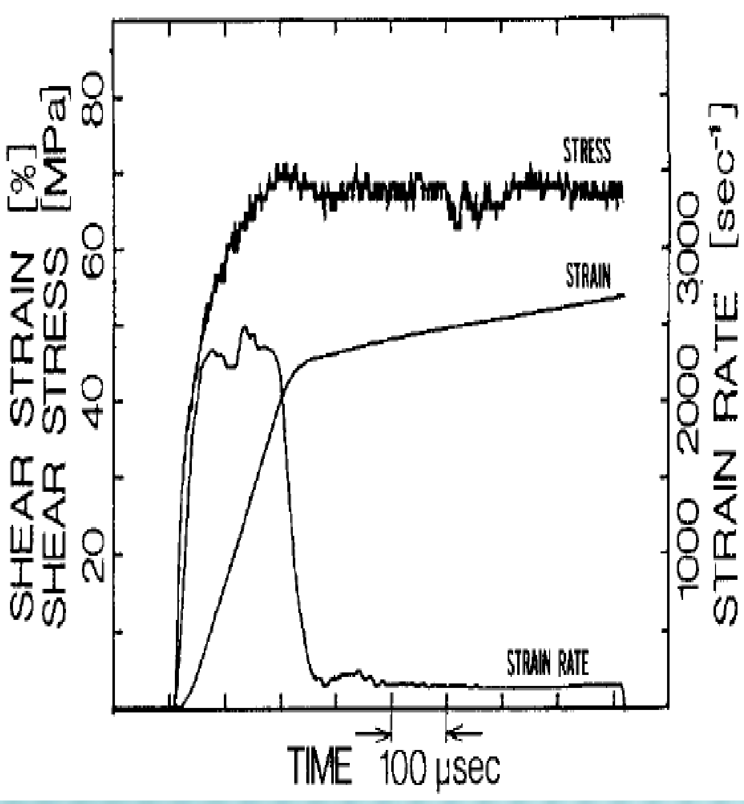


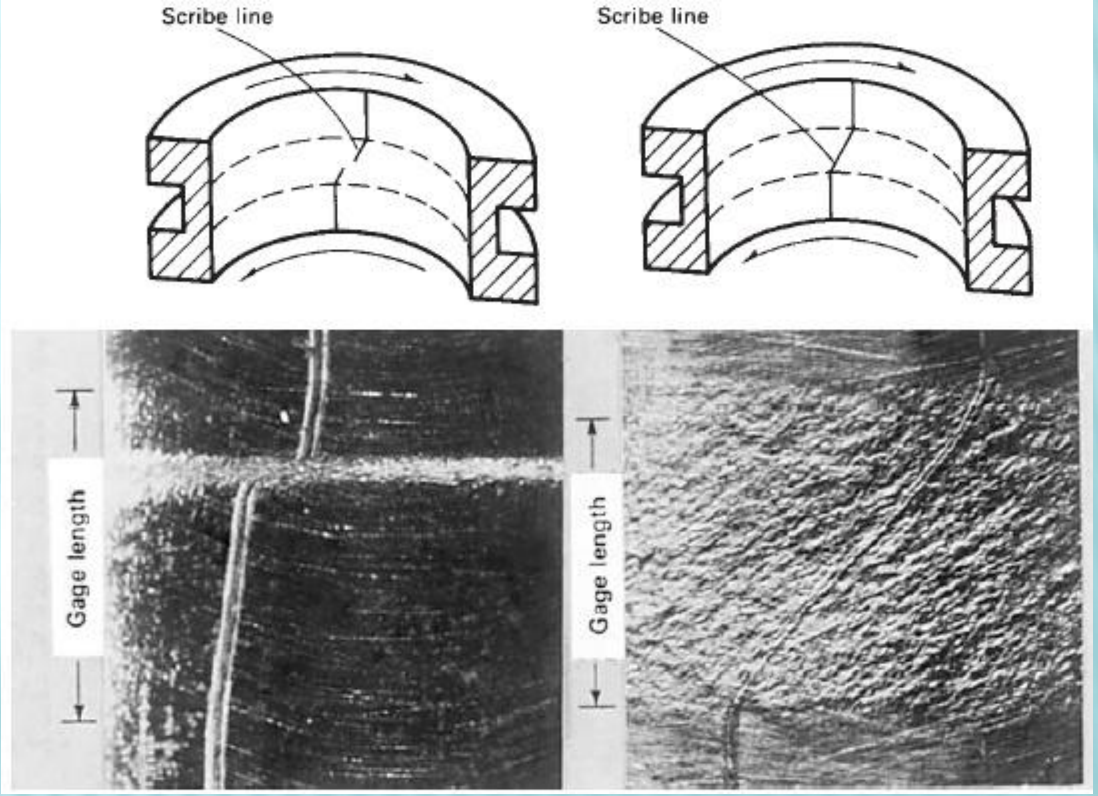


A. Gilat, ASM Handbook 8 (2000) 505

RESULTS

- With continued loading into the plastic range, the strain distribution in the thin-wall tube may not remain homogeneous. For example, depending on the material, shear bands may form. An easy way to detect this is with scribe lines on the inside surface.





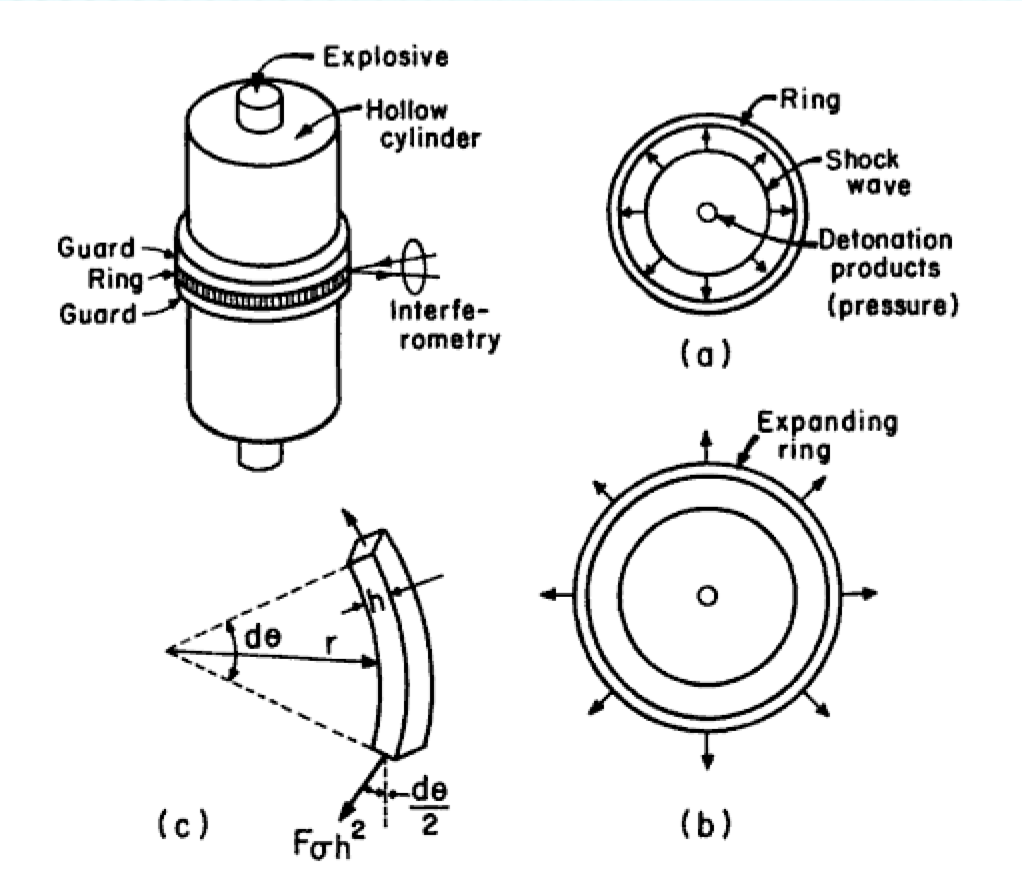
A. Gilat, Y.H. Pao, Exp. Mech. 28 (1988) 322
A. Gilat, ASM Handbook 8 (2000) 505

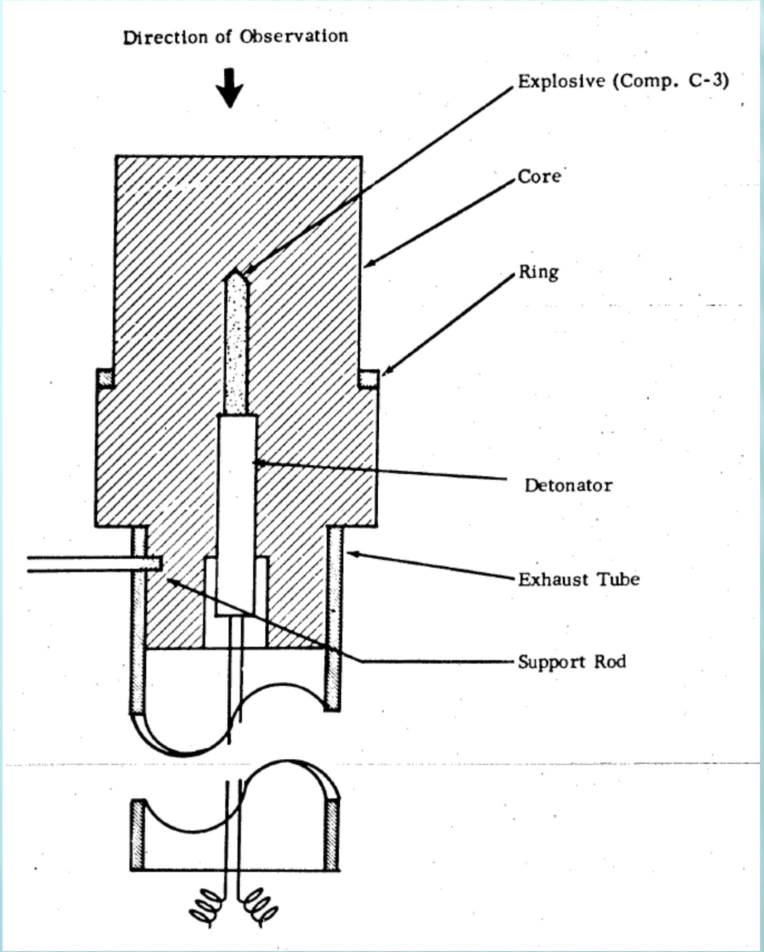
Expanding Ring Technique

DYNAMIC TESTING

METHODS

- Introduced by Johnson, Stein, and Davis in 1962

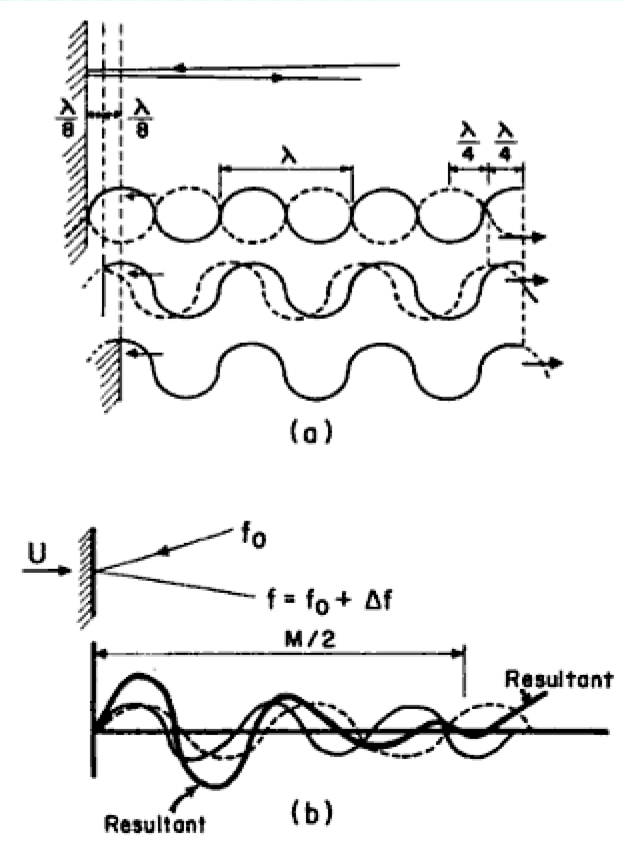


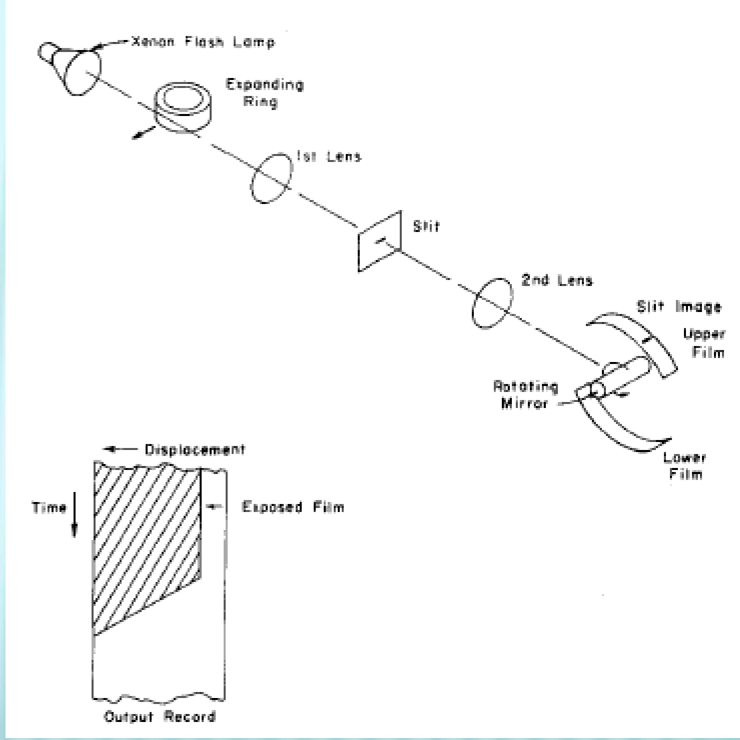


M.A. Meyers, in "Dynamic Behavior of Materials," John Wiley and Sons, 1994

LASER INTERFEROMETRY

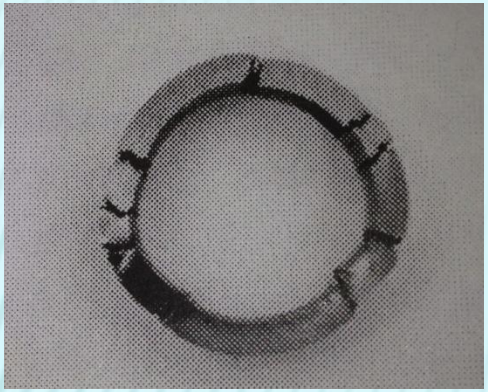
- Laser interferometry is based on interference fringes that appear when different laser beams interact. If two beams either are offset or have slightly different wavelengths, interference patterns will occur as shown in figure on the left.

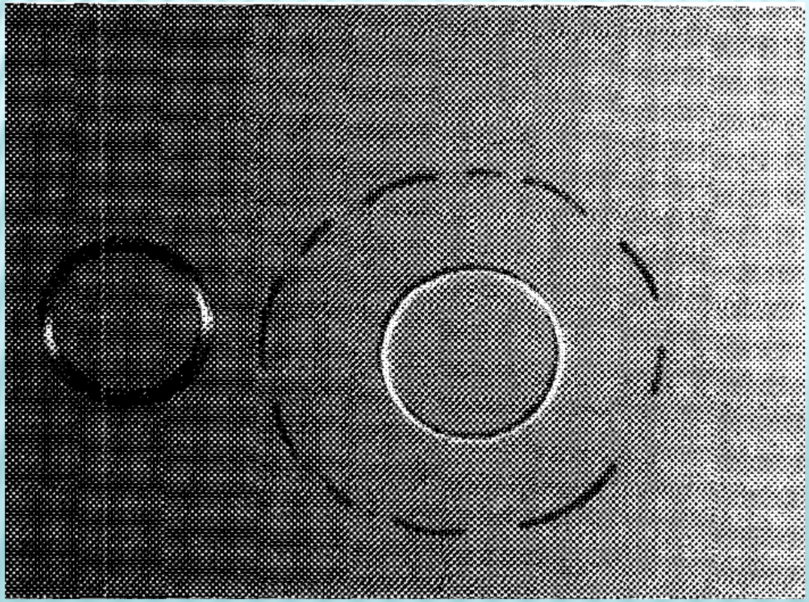




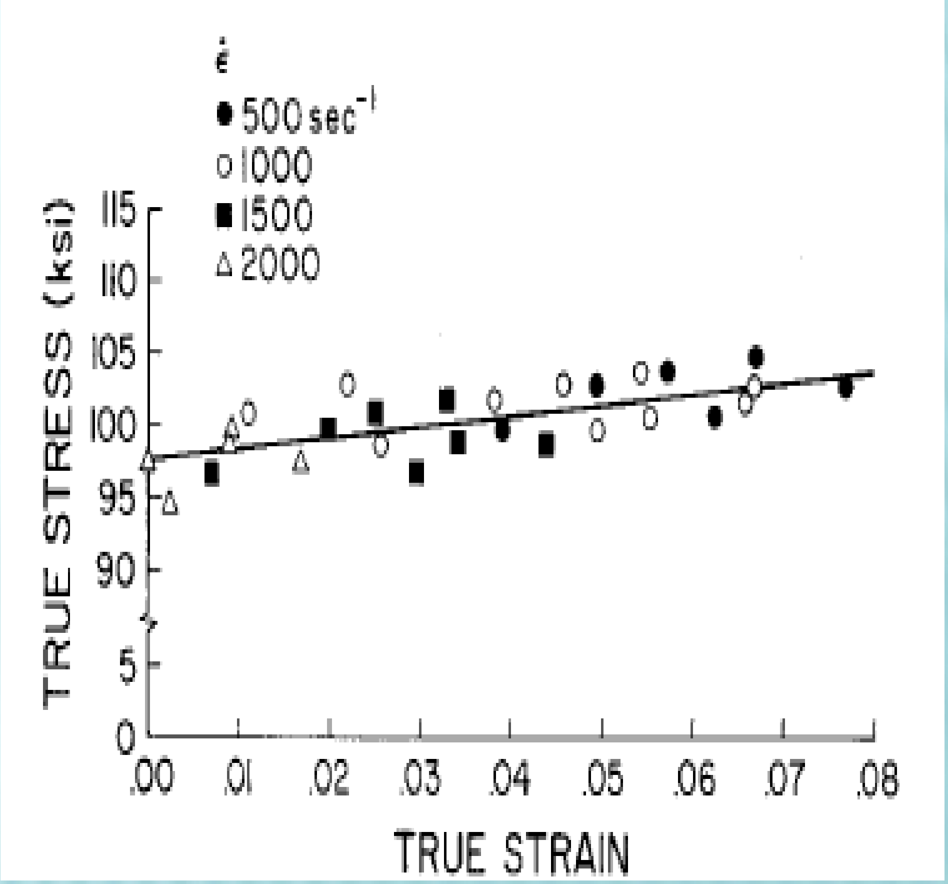
C.R. Hoggatt, R.F. Recht, Exp. Mech. 9 (1969) 441

RESULTS





- Dynamic stress-strain data obtained for 1020 cold-drawn steel.



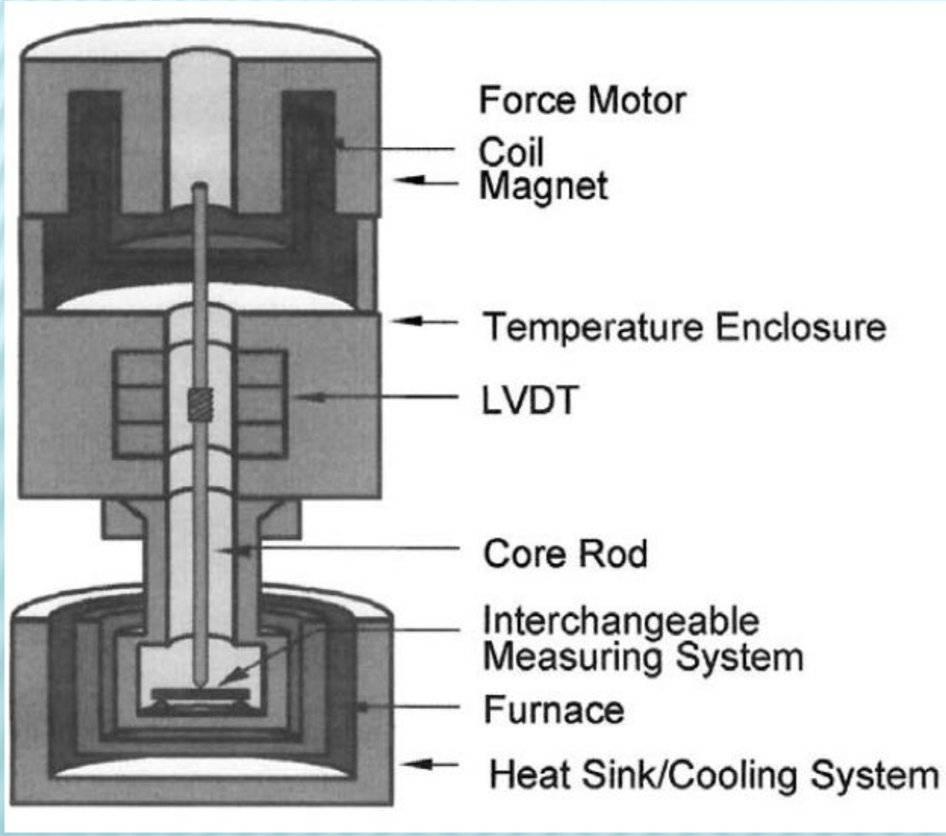
W.H. Gourdin, S.L. Weinland, R.M. Boling, Rev. Sci. Instrum. 60 (1989) 427

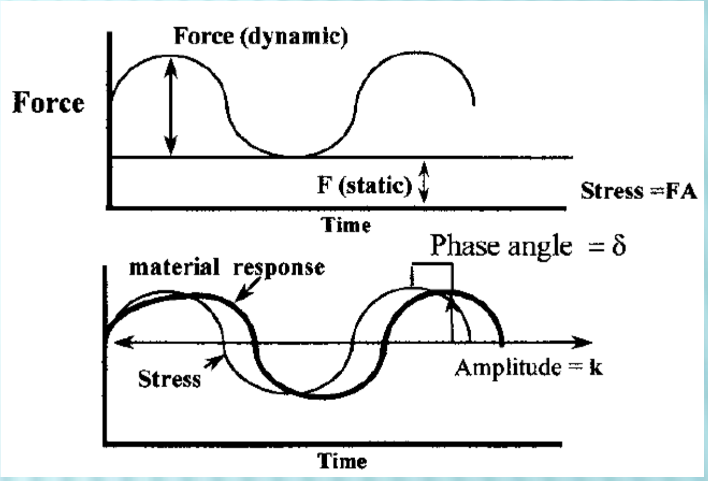
Dynamic Mechanical Analysis (DMA)

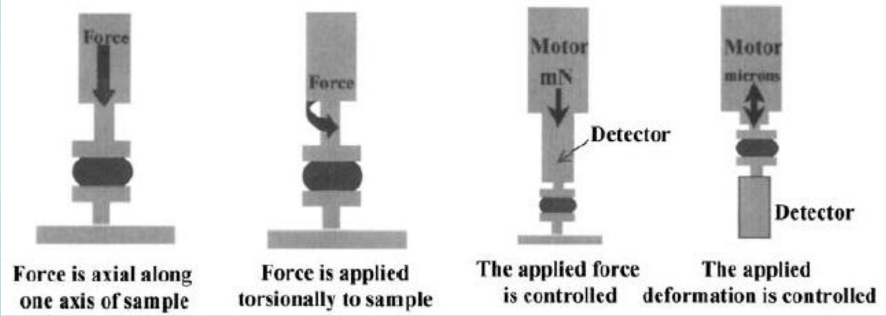
DYNAMIC TESTING

METHODS

- Dynamic mechanical analysis, also known as dynamic mechanical spectroscopy, is a high-velocity hydraulic testing method used to study & characterize materials.



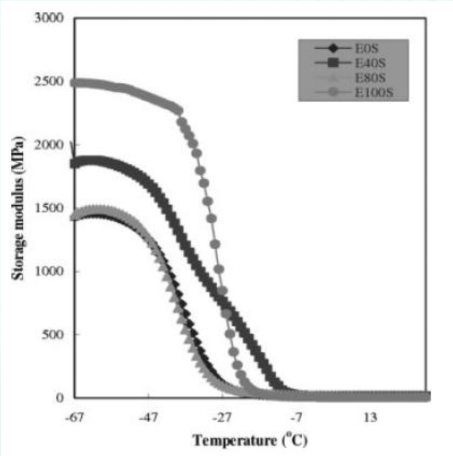


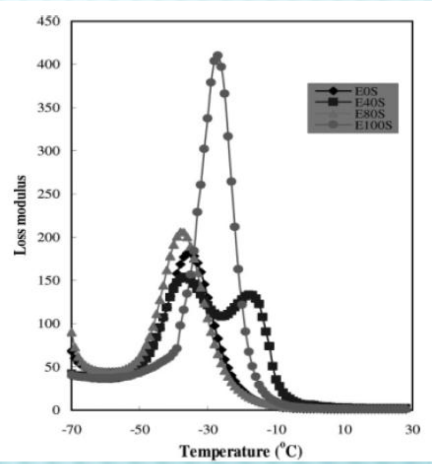


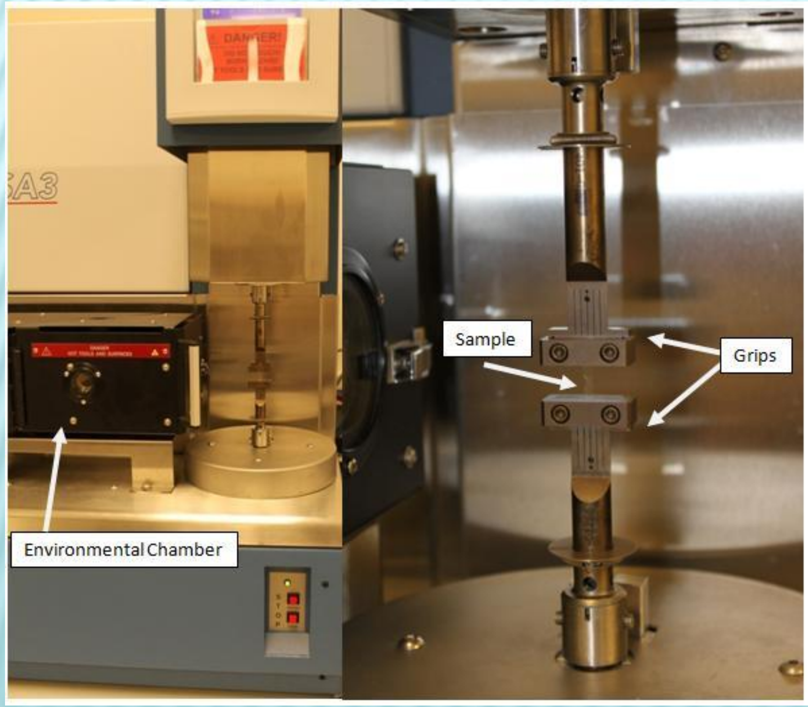
K.P. Menard, in “Dynamic Mechanical Analysis: A Practical Introduction,” CRC Press, 1999

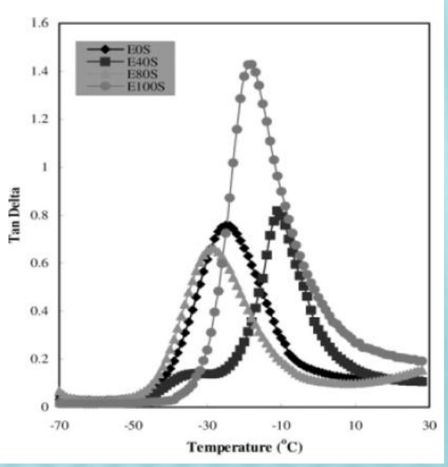
RESULTS

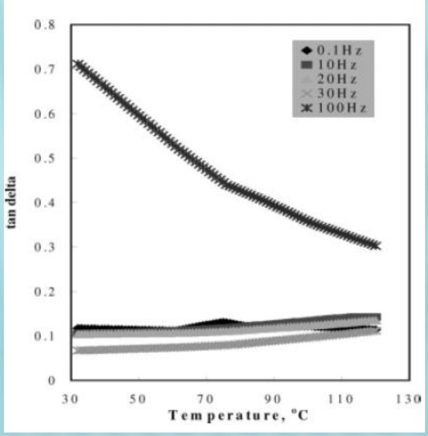
- By gradually increasing the amplitude of oscillations, one can perform a dynamic stress-strain measurement.











T. Nair, M. Kumaran, G. Unnikrishnan, V. Pillai, J. Appl. Poly. Sci. 112 (2008) 72

Cam Plastometer

DYNAMIC TESTING

METHODS

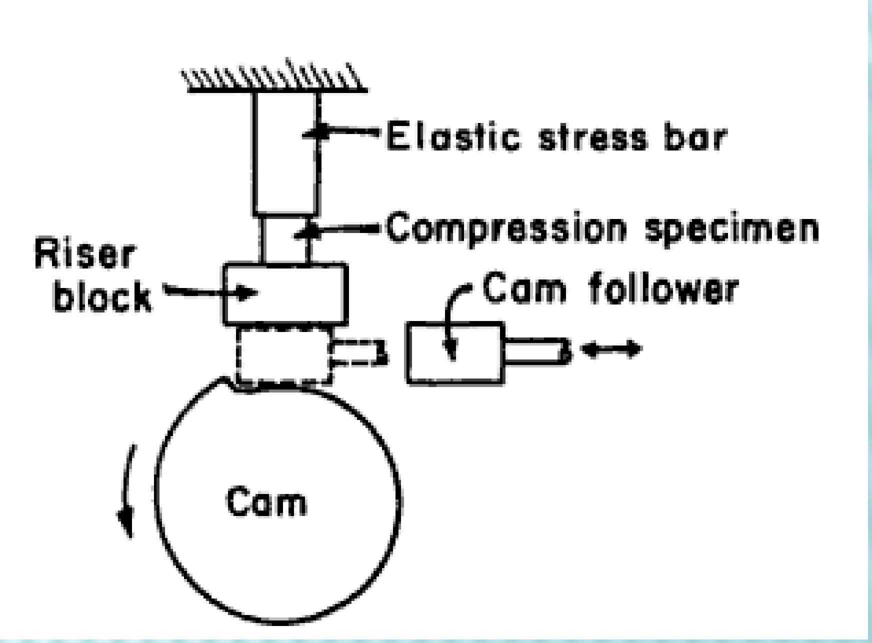
-A cam is rotated at a specific velocity.

-The compression specimen is placed on an elastic bar.

-At a certain moment, the cam follower is engaged.

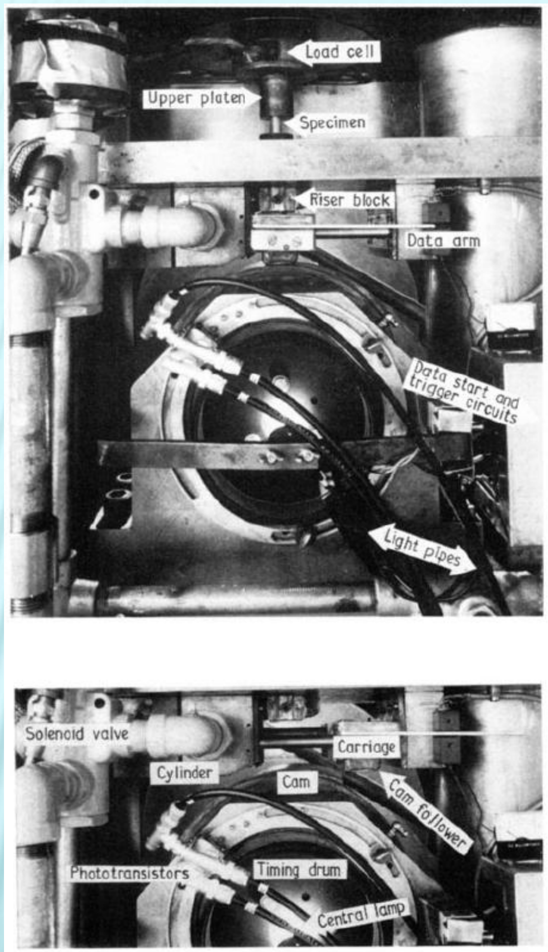
-Within one cycle the specimen is deformed.

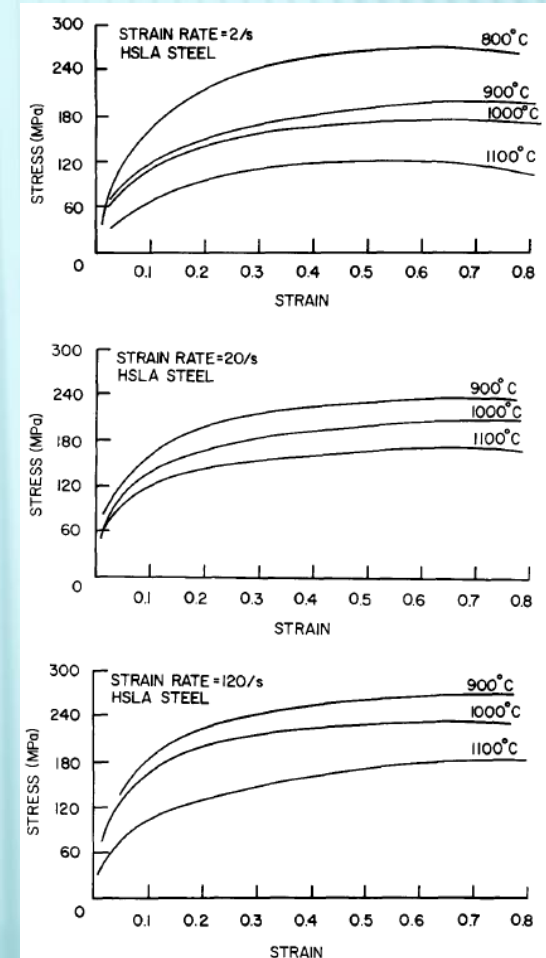
- Strain rates between 0.1 and 100 s^{-1} have been achieved by this method



M.A. Meyers, in “Dynamic Behavior of Materials,” John Wiley and Sons, 1994

RESULTS





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SUMMARY AND CONCLUSIONS

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- In the strain rate range of **10^1-10^3 s^{-1}** machines such as the **cam plastometer** and **DMA** are used.
- In the strain rate range of **10^3-10^5 s^{-1}** the **expanding ring**, the **Hopkinson bar**, and the **Taylor test** are used.
- There are **advantages** and **disadvantages** such as ease of operation, sample preparation, and cost that must be **weighed** for **dynamic testing** of specific materials in **certain strain rate ranges.**
- Thus, the **optimal method** for examination can be determined for **dynamic material properties.**

THANK YOU FOR YOUR ATTENTION

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