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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**

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

<table>
<thead>
<tr>
<th>Model</th>
<th>Year</th>
<th>Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Litonski</td>
<td>1977</td>
<td>[ \tau = B(\gamma_0 + \gamma_p)^n (1 - aT)^m \left[ 1 + b \left( \frac{d\gamma}{dt} \right)^m \right] ]</td>
</tr>
<tr>
<td>Johnson-Cook</td>
<td>1983</td>
<td>[ \sigma = (\sigma_0 + B\varepsilon^n) \left[ 1 + C \ln \left( \frac{\dot{\varepsilon}}{\dot{\varepsilon}_0} \right) \right] \left[ 1 - \left( \frac{T - T_r}{T_m - T_r} \right)^m \right] ]</td>
</tr>
<tr>
<td>Klopp</td>
<td>1985</td>
<td>[ \tau = \tau_0 \left( \frac{\gamma}{\gamma_0} \right)^n \left( \frac{T}{T_r} \right)^\mu \left( \frac{\dot{\gamma}}{\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 \left( - \lambda \Delta T \right) ]</td>
</tr>
<tr>
<td>Meyers</td>
<td>1994</td>
<td>[ \sigma = (\sigma_0 + B\varepsilon^n) \left[ 1 + C \log_{10} \left( \frac{\dot{\varepsilon}}{\dot{\varepsilon}<em>0} \right) \right] \left( \frac{T}{T_r} \right)^\lambda ]   [ \sigma = (\sigma_0 + B\varepsilon^n) \left[ 1 + C \log</em>{10} \left( \frac{\dot{\varepsilon}}{\dot{\varepsilon}_0} \right) \right] e^{-\lambda(T-T_r)} ]</td>
</tr>
<tr>
<td>Andrade</td>
<td>1994</td>
<td>[ \sigma = (\sigma_0 + B\varepsilon^n) \left[ 1 + C \log \left( \frac{\dot{\varepsilon}}{\dot{\varepsilon}<em>0} \right) \right] \left[ 1 - \left( \frac{T - T_r}{T_m - T_r} \right)^m \right] H(T) ]   [ H(T) = \frac{1}{1 - \left( 1 - \left( \frac{\sigma_f}{\sigma_f} \right)</em>{\text{ref}} / \left( \sigma_f \right)_{\text{def}} \right) u(T)} ]   [ u(T) = \begin{cases} 0 &amp; \text{for } T &lt; T_c \ 1 &amp; \text{for } T &gt; T_c \end{cases} ]</td>
</tr>
</tbody>
</table>

M.A. Meyers, in “Mechanics and Materials,” John Wiley and Sons, 1999
# Dynamic Testing Range

<table>
<thead>
<tr>
<th>Strain Rate, s⁻¹</th>
<th>Common Testing Methods</th>
<th>Dynamic Considerations</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^7$</td>
<td>High Velocity Impact</td>
<td>Shock-Wave Propagation</td>
</tr>
<tr>
<td></td>
<td>- Explosives</td>
<td></td>
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<tr>
<td></td>
<td>- Normal plate impact</td>
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<tr>
<td></td>
<td>- Pulsed laser</td>
<td></td>
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<tr>
<td></td>
<td>- Exploding foil</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Incl. plate impact</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(pressure-shear)</td>
<td></td>
</tr>
<tr>
<td>$10^5$</td>
<td>Dynamic-High</td>
<td>Shear-Wave Propagation</td>
</tr>
<tr>
<td></td>
<td>- Taylor anvil tests</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Hopkinson Bar</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Expanding ring</td>
<td></td>
</tr>
<tr>
<td>$10^3$</td>
<td>Dynamic-Low</td>
<td>Plastic-Wave Propagation</td>
</tr>
<tr>
<td></td>
<td>High-velocity hydraulic, or pneumatic machines; cam plastometer</td>
<td></td>
</tr>
<tr>
<td>$10^2$</td>
<td>Quasi-Static</td>
<td>Mechanical Resonance in Specimen and Machine is Important</td>
</tr>
<tr>
<td></td>
<td>Hydraulic, servo-hydraulic or screw-driven testing machines</td>
<td></td>
</tr>
<tr>
<td>$10^1$</td>
<td></td>
<td>Tests with constant cross-head velocity stress the same throughout length of specimen</td>
</tr>
<tr>
<td>$10^0$</td>
<td>Creep and Stress-Relaxation</td>
<td>Viscous-Plastic Response of Metals</td>
</tr>
<tr>
<td></td>
<td>- Conventional testing machines</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Creep testers</td>
<td></td>
</tr>
</tbody>
</table>

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.

\[ \frac{h}{L} \frac{U_t}{L} = \frac{h}{U t} = \frac{1}{U t} \frac{h}{L} \approx 1 \]
\[ \frac{L_1}{L_0} = \left( 1 - \frac{h}{L_0} \right) \exp \left( - \frac{\rho_0 U^2}{2\sigma_{yd}} \right) + \frac{h}{L_0} \]

\( L_1 \): new specimen length

\( L_0 \): original length

\( h \): thickness of the plastic zone

\( \rho_0 \): original density

\( U \): velocity of cylindrical projectile

\( \sigma_{yd} \): dynamic yield stress

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

Tantalum Taylor impact specimen

Zirconium Taylor impact specimen

DYNAMIC TESTING

Split-Hopkinson Bar
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

B. Hopkinson, Philo. Trans. of the Royal Society of London Vol. 213 (1914) p.437
In 1949, H. Kolsky refined Hopkinson’s technique

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

COMPRESSION TESTING

$L$: Original length of the specimen

$\varepsilon_r$: 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

$\varepsilon_t$: 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**

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.
RESULTS (VIDEO)

- http://bcove.me/vilofpvy
IMPORTANCE OF A PULSE SHAPER

The first tension bar was designed and tested by Harding et al. in 1960.
- Typical oscilloscope trace from a Hopkinson bar tension test and a stress-strain relation obtained by it.
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.

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, ASM Handbook 8 (2000) 505
- Introduced by Johnson, Stein, and Davis in 1962

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

Dynamic Mechanical Analysis (DMA)

DYNAMIC TESTING
Dynamic mechanical analysis, also known as dynamic mechanical spectroscopy, is a high-velocity hydraulic testing method used to study & characterize materials.
- By gradually increasing the amplitude of oscillations, one can perform a dynamic stress-strain measurement.
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.

RESULTS

In the strain rate range of $10^1$-$10^3 \text{ s}^{-1}$ machines such as the cam plastometer and DMA are used.

In the strain rate range of $10^3$-$10^5 \text{ s}^{-1}$ 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
REFERENCES

- B. Hopkinson, Philo. Trans. of the Royal Society of London Vol. 213 (1914) p.437
- C.R. Hoggatt, R.F. Recht, Exp. Mech. 9 (1969) 441