Introduction

- Metal Forming uses plastic deformation to change the shape of metal workpieces
  - Materials (metals) – plastic deformation
  - External loads – Typically compressive
  - Sometimes stretch the metal (tensile), bend the metal (tensile and compressive), shear stresses
  - Shape - die and tools

Classification

- Bulk Deformation
- Sheet Metal Forming – High surface area-to-volume ratio
  - Parts are called stampings
  - Usual tooling: punch and die

Introduction

- Bulk Deformation Process
  - Rolling
  - Forging
  - Extrusion
  - Drawing
- Sheet metal forming
  - Bending
  - Drawing
  - Shearing
  - (Stamping)

Material Properties in Metal Forming

- Desirable material properties:
  - Yield strength ?
  - Ductility ?
  - Second phase or Inclusion ?
- These properties are affected by temperature:
  - When work temperature is raised, ductility increases and yield strength decreases while loosing on surface finish and dimension accuracy.
- Other factors:
  - Strain rate and friction

Theories of Failure

- The limit of the stress state on a material
  - Ductile Materials - Yielding
  - Brittle Materials - Fracture
- In a tensile test, Yield or Failure Strength of a material.
- In a multiaxial state of stress, how do we use Yield or Failure Strength?

Yielding: Ductile Materials

A. Maximum Shear Stress Theory
   (Tresca Criterion)

In a tension specimen:
$$\tau_{\text{max}} = \frac{S_y}{2}$$

The diameter of the Mohr circle = $$S_y$$

For Plane Stress: \(\sigma_i = S_y\) \(\sigma_j\) have same signs.
$$\sigma_i - \sigma_j = S_y$$ \(\sigma_i\), \(\sigma_j\) have opposite signs.

Kwon
Ductile Materials

B. Maximum Distortion Energy Theory (von Mises Criterion)

For the three principal stresses, 
\[
\sigma_1, \sigma_2, \sigma_3 \quad \text{where} \quad \sigma_1 > \sigma_2 > \sigma_3
\]

\[
u = \frac{1}{3} \left[ \left( \sigma_1 - \sigma_3 \right) + \left( \sigma_1 - \sigma_2 \right) + \left( \sigma_2 - \sigma_3 \right) \right]
\]

After taking out the hydrostatic stress \((\sigma_0 = (\sigma_1 + \sigma_2 + \sigma_3)/3)\)

Now substitute \(\sigma_1, \sigma_2, \sigma_3\) with \((\sigma_1 - \sigma_0), (\sigma_2 - \sigma_0), (\sigma_3 - \sigma_0)\)

For plane stress: \(\nu = \frac{1}{2} \left[ \sigma_1 - \sigma_3 + \sigma_2 \right]

\[
\text{In a biaxial case, the same amount of distortion energy}
\]

\[
\sigma_1 - \sigma_2 = \frac{1}{1 - \nu} \sigma
\]

\[
\text{Hydrostatic stress}
\]

\[
\text{Stress Tensor:}
\]

\[
\text{To find Principal Stresses:}
\]

\[
\text{Yield function:}
\]

\[
\text{Plasticity}
\]

- Flow theory (Classical theory)
  - The current strain rates depend on the stress.
- Deformation theory (Hencky theory)
  - The total strain is related to the stress.
  - Ideal for nonlinear elasticity
  - Still work for monotonically increasing stresses everywhere in a body
- Pressure-independent – Hydrostatic pressure does not affect dislocation motion.
- Bauschinger effect
  - The different behaviors in tension and compression

Problem #1

\[
d = 100 \text{mm} \quad \sigma_y = 170 \text{MPa}
\]

\[
\sigma = \frac{P}{A} = \frac{1.5(600)}{4.88(10^{-3})} = -191 \text{MPa}
\]

\[
\sigma_y = 91.1 \times 10^2 \text{MPa}
\]

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\[
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- Maximum Distortion Energy Theory
  \[
  f(J_1, J_2, J_3) = \min \frac{1}{2} \left( \sigma_1 - \sigma_0 \right)^2 + \frac{1}{2} \left( \sigma_2 - \sigma_0 \right)^2 + \frac{1}{2} \left( \sigma_3 - \sigma_0 \right)^2
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  \[
  \text{Based on uniaxial yielding:}
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  f(\sigma) = \sigma_0 = \sigma
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2. Behavior in Metal Forming

- The stress-strain relationship beyond elastic range assuming no unloading at anytime and anywhere.
  \[ \sigma = K \varepsilon^n \]
- Flow stress – The instantaneous value of stress required to continue deforming the material.
  \[ f = K \varepsilon^n \]
- Average Flow Stress
  \[ \bar{f} = \frac{K \varepsilon^n}{1 + n} \]
- For any metal, \( K \) and \( n \) in the flow curve depend on temperature

3. Temperature in Metal Forming

- **Cold Working** – Performed at room temperature or slightly above
  - Near net shape or net shape
  - Better accuracy, closer tolerances & surface finish
  - Strain hardening increases strength and hardness
  - Grain flow during deformation can cause desirable directional properties in product
  - No heating of work required
  - Higher forces and power required
  - Surfaces must be free of scale and dirt
  - Ductility and strain hardening limit the amount of forming

- **Warm Working**
  - Performed at above room temperature but below recrystallization temperature
  - \( 0.3T_m \), where \( T_m = \) melting point (absolute temperature)
  - Lower forces and power than in cold working
  - More intricate work geometries possible
  - Need for annealing may be reduced or eliminated
  - Isothermal Forming – eliminate surface cooling especially highly alloyed steels and Ti and Ni alloys

- **Hot Working**
  - Deformation process at temperatures above recrystallization temperature \((0.5T_m)\)
  - A perfectly plastic material - Strain hardening exponent is zero (theoretically)
    - Lower forces and power required
    - Metals become ductile
    - Strength properties are generally isotropic
    - No work hardening of part
    - Part can be subsequently cold formed
    - Lower dimensional accuracy
    - Higher total energy required
    - Poorer surface finish including oxidation (scale), shorter tool life

4. Effect of Strain Rate

- Sensitive to strain-rate at elevated temperatures
- Strain rate: \( \dot{\varepsilon} = \frac{V}{h} \)
- Relationship: \( Y_f = C \dot{\varepsilon}^n \)
- A more complete relationship: \( Y_f = A \dot{\varepsilon}^{n_1} \dot{\varepsilon}^{n_2} \)
- Evaluation of strain rate is complicated by
  - Workpart geometry
  - Variations in strain rate on the part
- Strain rate can reach \( 1000 \text{ s}^{-1} \) or more for some metal forming operations
Effect of temperature on flow stress

- Increasing temperature decreases $C$, increases $m$
- At room temperature, effect of strain rate is almost negligible

5. Friction and Lubrication

- Friction – retard metal flow and increase power and wear
  - Lubrication – reduce friction & heat, improve surface finish
    - Choosing a Lubricant – Type of operation, reactivity, work materials, cost and ease of applications
      - Cold working – mineral oil, fats, fatty oils, water-based emulsions, soaps and coating
      - Hot working – mineral oil, graphite and glass

<table>
<thead>
<tr>
<th>Categories</th>
<th>Temp. Range</th>
<th>Strain-rate Sensitivity exponent</th>
<th>Coefficient of Friction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cold Working</td>
<td>$&lt;0.3T_m$</td>
<td>$0.05 &lt; m &lt; 0.1$</td>
<td>0.1</td>
</tr>
<tr>
<td>Warm Working</td>
<td>$0.3T_m - 0.5T_m$</td>
<td>$0.05 &lt; m &lt; 0.4$</td>
<td>0.2</td>
</tr>
<tr>
<td>Hot Working</td>
<td>$0.5T_m - 0.75T_m$</td>
<td>$0.05 &lt; m &lt; 0.4$</td>
<td>0.4-0.5</td>
</tr>
</tbody>
</table>