BULK DEFORMATION PROCESSES IN METALWORKING

1. Rolling
2. Forging
3. Extrusion
4. Wire and Bar Drawing

Introduction

• Input: bulk materials in a form of cylindrical bars and billets, rectangular billets and slabs or elementary shapes
• Process: large plastic deformation - Rolling, Forging, Extrusion and Wire and Bar drawing under cold, warm and hot working conditions
• Output: work materials for subsequent processes or final products (net shaping)

1. Rolling

• Thickness of a work material is reduced by the compressive forces exerted by two opposing rolls.
  - plates (>6mm or 1/4 in) - ship hull, bridge
  - sheets (<6mm) - car bodies, appliance
  - foil (<0.1mm) - aluminum foil
• Flat (typical) and shape rolling
• Equipment: roll mills (expansive)
• Hot rolling – large deformation, low force, no residual stress and isotropic properties but problems with tolerance and surface finish
• Cold Rolling - strengthen, tight tolerance, better surface

Process Information

• Ingot casting
  - Input: Molten metal
  - Output: Ingot
• Soaking
  - Input: Ingot
  - Output: heated Ingot
• Rolling
  - Input: Heated Ingot
  - Output: bloom, billet or slab
• Cold Rolling
  - light tolerance, better surface and mechanical properties
• Hot Rolling
  - above recrystallization temp. (450°C for Al alloy, 1250°C for steel alloy and 1650°C for refractory alloy) converts the cast structure to a wrought structure
  - Heavy scale forms on the surface.

Flat rolling

Spreading: Conservation of Mass

\[ L_f - L_i = f \left( V_f - V_i \right) \]

\[ t_f - t_i = t_f - t_i \]

\[ R = \frac{d}{2} \]

\[ \mu = \frac{\text{frictional force}}{\text{normal force}} \]

Rolling Analysis I

• Friction at the entrance controls the maximum possible draft.

\[ \mu = \frac{F_f}{F_n} \]

\[ \mu = \left[ \begin{array}{c} 0.1 \text{ for coldworking} \\ 0.2 \text{ for warmworking} \\ 0.3-0.4 \text{ for hotworking} \end{array} \right] \]

• If however depending on lubrication, work and roller materials and temperature.

\[ \mu = \left[ \begin{array}{c} \text{for coldworking} \\ \text{for warmworking} \\ \text{for hotworking} \end{array} \right] \]

• When sticking occurs, \( \mu \) can be as high as 0.7

• Higher the friction and larger the roll radius, the greater the maximum draft and reduction in thickness become.
Rolling Analysis II

- **Roll force**: \( F = \frac{L}{w} \int_0^L pdL = \frac{F_o}{L} \)
  - Newton or lb, \( L \) is in meter or ft and \( N \) is in rpm
- **Contact length**: \( L = \sqrt{R(L - t_f)} \)
- **Torque for each roll**: \( T = 0.5FL \)
- **Power**: \( P = \frac{2\pi NFL}{60,000kW} \)

Problem 19.11

A single-pass rolling operation reduced a 20mm thick plate to 18mm. The starting plate is 200mm wide. Roll radius=250mm and rotational speed=12rev/min. The work material has a strength=600MPa and a strain hardening coefficient =0.22. Determine (a) roll force (b) roll torque and (c) power required for this operation.

(a) Assuming a typical friction coefficient for cold rolling of 0.1
Draft \( d = 20-18 = 2\text{mm} < d_{max} = 0.12(250) = 2.5\text{mm} \)
Contact length \( L = 250(0.2) = 11.18\text{mm} = 0.0112\text{m} \)
True Strain \( \varepsilon = \ln(20/18) = 0.1054 \)
Average flow stress \( f = 600(0.1054)/1.22 = 300\text{MPa} \)
Rolling force \( F = \frac{Y_fL}{2\pi}(0.0112) = 300\text{MN} \)
(b) Torque \( T = \frac{0.5(300,000)(0.0112)}{2\pi} = 3,720 \text{N.m} \)
(c) Power \( P = \frac{2\pi(12/60)(300,000)(0.0112)}{33000/2} = 37,697 \text{W} \)

Rolling

- **Rolling mills**
  - Two-high (basic) – nonreversing and reversing
  - Three-high
  - Four-high
  - Cluster
  - Tandem
- **Shape Rolling**
  - I-beam, L-beam and U-channels, railroad track, round and square bars.
  - Roll-pass design
    - Designing the intermediate shapes and rolls

Intermediate & final rolled form

- Slab
- Billet
- Bar
- Plate, sheet
- Coils
- Rails, I-beams
- L-beams, U-channels

Other Rolling Operations

- **Ring rolling**
- **Thread rolling** – cold thread-making process
  - higher production, better strength, fatigue resistance and less material waste
- **Gear rolling**
  - higher production, better strength, fatigue resistance and less material waste
- **Roll piercing** – making seamless thick-walled tubes

2. Forging

- **Dating from about 5000 B.C.**
- A deformation process achieved by gradual and certain movement of two dies. (forging press or forging hammer)
- Hot or warm forging and sometime cold forging
- Three types
  - Open-die forging – no lateral constraints
  - Impression-die forging – the die surface contains the material but not completely
  - Flashless (closed-die) forging – the material is completely constrained within the die
Impression-die & Flashless forging

- **Impression-die forging**
- **Flashless (closed-die) forging**

![Illustration of Impression-die forging](image1)

![Illustration of Flashless forging](image2)

**Analysis on Open-die forging**

- The true strain for the process: \( \varepsilon = \ln \frac{h_0}{h_f} \)
- Force required: \( F = K_f Y_f A \)
  where \( K_f = 1 + \frac{0.4 \mu D}{h_f} \)

\( Y_f \) is the flow stress, not average flow stress

![Ideal vs Actual](image3)

**Impression and Flashless forging**

- **Force required:** \( F = K_f Y_f A \)

<table>
<thead>
<tr>
<th>Type</th>
<th>Force (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simple w/ flash</td>
<td>6.0</td>
</tr>
<tr>
<td>Complex w/ flash</td>
<td>8.0</td>
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<tr>
<td>Very complex w/ flash</td>
<td>10.0</td>
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<tr>
<td>Flashless</td>
<td></td>
</tr>
<tr>
<td>Coining</td>
<td>6.0</td>
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<tr>
<td>Complex shape</td>
<td>8.0</td>
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</tbody>
</table>

**Impression-die Forging**

- Impression-die forging can achieve **Close tolerance**
- Advantages compared to machining from solid stock:
  - Higher production rates, less waste, Greater strength
  - Favorable grain orientation in the metal
- Limitations:
  - Not capable of close tolerances
  - Machining often required to achieve accuracies and features needed, such as holes, threads, and mating surfaces that fit with other components. Need machining afterward

**Problem 19.14**

A cylindrical part is warm upset forged in an open die. \( D_o=50\text{mm} \) and \( h_o=40\text{mm} \). Coefficient of friction \( \mu=0.2 \). The work material has a flow curve defined by \( K=600\text{MPa} \) and \( n=0.12 \). Determine the force in the operation (a) just as the yield point reached (0.002), and (b) \( h=20\text{mm} \).

(a) \( V=\pi D_o^2 L/4=\pi (50)^2 (40)=78,540\text{mm}^3 \)

For a small strain, \( \varepsilon=\Delta h/h_o=40-h_f/40=0.002 \)

Therefore, \( h_f=39.92\text{mm} \) and \( Y_f=600(0.002)^{0.12}=284.5\text{MPa} \)

\( F=1.1(284.6)(1963.5)=614,693\text{N} \)

(b) \( h_f=20\text{mm} \), \( \varepsilon=\ln(40/20)=0.693 \)

\( Y_f=600(0.693)^{0.12}=574.2\text{MPa} \)

Because the volume stays constant, \( D_f=70.7\text{mm} \)

\( F=1.28(574.2)(3927)=2,892,661\text{N} \)

**Flashless forging**

- Flashless (closed-die) forging
  - A precision forging process
  - Process control more demanding than impression-die forging
  - Best suited to part geometries that are simple and symmetrical
- Forging dies
  - Gravity or Power drop hammers
  - Mechanical, Hydraulic & Screw Presses
Sequence in impression-die forging

Other Deformation Processes
- Upset and Heading
- Swaging and Radial Forging
- Roll Forging
- Orbital Forging
- Hobbing
- Isothermal and Hot Die Forging
- Trimming

Upsetting and Heading

Swaging

Trimming
- Used to reduce diameter of tube or solid rod stock
- Mandrel sometimes required to control shape and size of internal diameter of tubular parts

Cutting operation to remove flash from a work part while work is still hot in impression-die forging. Alternatively grinding or sawing operation is used.