Extrusion

ver. 1
Overview

• Equipment
• Characteristics
• Mechanical Analysis
  – direct extrusion
  – indirect extrusion
• Redundant work
• Defects
Geometry (90° die)

D1

D2

p

dead zone
45° angle
Equipment
Extrusion
Equipment

1. Hydraulic power unit
2. Tie rods
3. Butt shear
4. Extrusion platen
5. Container shifting cylinders
6. Swiveling operator's console
7. Die slide
8. Container
9. Container housing
10. Billet loader
11. Press base
12. Billet loader cylinders
13. Pressing stem
14. Crosshead
15. Side cylinder
16. Cylinder platen
17. Main cylinder

Prof. Ramesh Singh, Notes by Dr. Singh/ Dr. Colton
Extrusions

Prof. Ramesh Singh, Notes by Dr. Singh/ Dr. Colton
Characteristics

• Similar to closed die forging

• Forging
  – slug (bulk) is forging
  – flash (extrusion) is waste

• Extrusion
  – extrusion (flash) is part
  – billet (bulk) is waste
Types

- Direct
- Indirect
- Tubular
- Hydrostatic
- Cold Impact
Types

1 – direct
2 – indirect
3 – heading (forging also)
Flow types

- “Laminar”
- “Turbulent”
  - redundant work
  - can bring outside of billet into center
  - leaving the skin keeps outside scale out of final extrusion
Steel extrusion

- $T_{\text{processing}} = 2100$ to $2400^\circ\text{F} (1150$ – $1315^\circ\text{C})$
- $T_{\text{melting}} = 2500$ - $2800^\circ\text{F} (1370$ – $1540^\circ\text{C})$
- Die $\approx 400^\circ\text{F} (205^\circ\text{C})$
- Obviously “Hot”
  - above recrystallization point
- Lubricants
  - glass (viscous lube ) 0.001” thick
  - MoS$_2$
  - graphite
Mechanical Analysis

- Dead zone
- 45° angle
- External friction
- Internal friction

Prof. Ramesh Singh, Notes by Dr. Singh/ Dr. Colton
Assumptions

• Metal deforms uniformly
  – $D_1$ to $D_2$
• No redundant work
• Can’t use slab analysis
  – die angles too great
  – friction too high
• Dead zone sets up at 45 degrees
Upper bound analysis

- Work input by external forces = plastic work expended

\[ \dot{W}_{\text{pressure}} = \dot{W}_{\text{internal friction}} + \dot{W}_{\text{plastic work to compress}} + \dot{W}_{\text{external friction}} \]
Rate of work = Power

• Work rate = Power
• Work rate = Area • stress • velocity
Pressure work input

- Power = $A \cdot p \cdot v$
  - ram moves at velocity, $v_{ram}$

$$\dot{W}_p = \frac{\pi D_1^2}{4} \cdot p \cdot v_{ram}$$
Internal “frictional” work input

- Work determined by integrating rate of frictional work dissipation at each cross section from $D_2$ to $D_1$
  - $\tau_{\text{friction}} = \tau_{\text{flow}}$
  - $v_i$ is in x-direction

$$\dot{W}_f = \tau_{\text{flow}} \cdot \left( \pi \int_{D_2}^{D_1} v_i D dL \right)$$

$dL = dD/\sqrt{2}$
Internal “frictional” work input

- Volumetric flow rate

\[ Q = A_i v_{ram} = A_i v_i \]
- where \( D \), \( A_i \), \( v_i \) are instantaneous

\[ v_i = \left( \frac{D_i}{D} \right)^2 v_{ram} \]
Internal “frictional” work input

\[ \dot{W}_f = \frac{\pi \nu_{ram} \tau_{flow} D_1^2}{\sqrt{2}} \int_{D_2}^{D_1} \frac{dD}{D} \]

\[ \dot{W}_f = \frac{\pi \nu_{ram} \tau_{flow} D_1^2}{\sqrt{2}} \cdot \ln \frac{D_1}{D_2} \]
Plastic work to compress input

• Power = \( u_p \times \text{Area} \times \text{velocity} \)

\[
\text{Energy} / \text{volume} = u_p = \int \sigma \, d\varepsilon = \bar{Y}_f \varepsilon = 2 \tau_{\text{flow}} \varepsilon
\]

\[
\varepsilon = 2 \ln \frac{D_1}{D_2}
\]

• hence

\[
\therefore \quad \dot{W}_{pw} = \left(4 \tau_{\text{flow}} \cdot \ln \frac{D_1}{D_2} \right) \cdot \left(\frac{\pi D_1^2}{4}\right) \cdot v_{\text{ram}}
\]
Total work input (without external friction)

\[
\frac{\pi D_1^2}{4} \cdot p \cdot v_{ram} = \frac{\pi D_1^2}{4} \cdot v_{ram} \left( 4\tau_{flow} \cdot \ln\frac{D_1}{D_2} \right) \\
+ \frac{\pi D_1^2}{4} \cdot v_{ram} \cdot \frac{4\tau_{flow}}{\sqrt{2}} \cdot \ln\frac{D_1}{D_2}
\]

• reducing

\[
\frac{p}{2\tau_{flow}} = 3.414 \cdot \ln\frac{D_1}{D_2}
\]
Extrusion ratio \((r_e)\)

- Reduction in area (RA) is large
  - it is not sensitive for classification
- Use \(r_e\) instead

\[
r_e = \left(\frac{D_1}{D_2}\right)^2 = \frac{1}{1 - RA}
\]
Extrusion pressure (without external friction)

\[
\frac{p}{2\tau_{\text{flow}}} = 3.414 \cdot \ln \left( \frac{D_1}{D_2} \right) = 1.707 \cdot \ln \left( \frac{D_1}{D_2} \right)^2
\]

\[
\frac{p}{2\tau_{\text{flow}}} = 1.707 \cdot \ln r_e
\]
Billet - wall friction

- Assume limiting case:
  friction stress = shear flow stress

\[ \tau_f = \tau_{\text{flow}} \]
Additional pressure due to billet - wall friction

\[ \Delta p \cdot \frac{\pi \cdot D_1^2}{4} = \tau_{flow} \cdot \pi \cdot D_1 \cdot x \]

\[ \frac{\Delta p}{2\tau_{flow}} = \frac{2x}{D_1} \]
Direct extrusion pressure

\[
\frac{p_x}{2\tau_{flow}} = \frac{p}{2\tau_{flow}} + \frac{\Delta p}{2\tau_{flow}} = \frac{p}{2\tau_{flow}} + \frac{2x}{D_1}
\]

\[
\frac{p_x}{2\tau_{flow}} = 3.414 \cdot \ln \frac{D_1}{D_2} + \frac{2x}{D_1}
\]

\[
\frac{p_x}{2\tau_{flow}} = 1.707 \cdot \ln r_e + \frac{2x}{D_1}
\]
Strain hardening (cold – below recrystallization point)

- Not plane strain (Tresca)

\[ 2\tau_{\text{flow}} = \sigma_{\text{flow}} = \bar{Y} = \frac{K\varepsilon^n}{n + 1} \]

average flow stress: due to shape of element
Example – 1-1

- You are forward, cold extruding Al-1100 (K = 140 MPa, n = 0.25), 10-cm diameter billet to a diameter of 5-cm at 1 m/min. The billet is initially 25 cm long.
- The ram is made of a high-strength steel with a yield stress of 1.5 GPa.
- Determine the extrusion force and power.
- Determine the safety factor for indenting the ram.
Example – 1-2

• The equations we use are:

\[ \frac{p_x}{2\tau_{\text{flow}}} = 3.414 \cdot \ln \frac{D_1}{D_2} + \frac{2x}{D_1} \]

\[ 2\tau_{\text{flow}} = \bar{Y} = \frac{K\varepsilon^n}{n + 1} \]

because

\[ u_p = \int \sigma d\varepsilon = \int K\varepsilon^n d\varepsilon = \frac{K\varepsilon}{n + 1} \]

\[ \varepsilon = 2 \ln \left( \frac{D_1}{D_2} \right) \]
Example – 1-3

• We need to determine the dead-zone length to subtract from the initial billet length.

• so $X = 0.25 - 0.025 = 22.5$ cm
Example – 1-4

- Substituting values

\[ \varepsilon = 2 \ln \left( \frac{D_1}{D_2} \right) = 2 \ln \left( \frac{10}{5} \right) = 1.39 \]

\[ 2\tau_{flow} = \bar{Y} = \frac{K\varepsilon^n}{n + 1} = \frac{140 \times (1.39)^{0.25}}{0.25 + 1} = 121.6 \text{ MPa} \]

\[ p_x = 2\tau_{flow} \times \left( 3.414 \cdot \ln \frac{D_1}{D_2} + \frac{2x}{D_1} \right) \]

\[ P_{extrusion, \ max} = 121.6 \times \left( 3.414 \cdot \ln \frac{10}{5} + \frac{2 \times 22.5}{10} \right) = 834 \text{ MPa} \]
Example – 1-5

\[ F_{\text{extrusion}} = P_{\text{extrusion}} \times Area = 834 \times 10^6 \times \frac{\pi}{4} (0.1)^2 = 6.6 \text{ MN} \]

\[ \text{Power} = F \times \text{speed} = 6.6 \text{ MN} \times 1 \text{ m/min} \times \text{min/60 sec} = 110 kW \]

- Safety factor against indenting the ram
  - to determine the “press-fit” failure, we would need the dimensions of the extrusion die and its material

\[ n = \frac{\sigma_y}{\sigma_{\text{extrusion}, \text{max}}} = \frac{1.5 \text{ GPa}}{0.834 \text{ GPa}} = 1.8 \]
Redundant work

- $\Delta = \frac{d_m}{L}$
- $d_m = \frac{(D_1 + D_2)}{2}$
- $p = Q_r \sigma_{\text{flow}}$

![Diagram of contact length](image)
Redundant work factor
(Backofen)
(friotionless)

\[ Q_r = \frac{p}{2\tau_y} \]

Fig. 7-1. The \( \Delta \)-dependence of yield pressure for the frictionless plane strain-indentation of a nonstrain-hardening material.
Defects

- Surface materials drawn into center
  - pipe, tail pipe

- Surface materials extruded
  - eliminate by leaving skin
Chevron Cracking
Chevron cracking defect

- Hydrostatic tension
  - outer layer in compression
  - inner layer in tension, if entire part is not plastic

- eliminate by using a fluid
  - hydrostatic compression
  - reduces friction
Defects

• Surface speed cracking
  – high friction
  – temperature
  – speed
Summary

• Equipment
• Characteristics
• Mechanical Analysis
  – direct extrusion
• Redundant work
• Defects