Deformation Processing - Drawing

ver. 1

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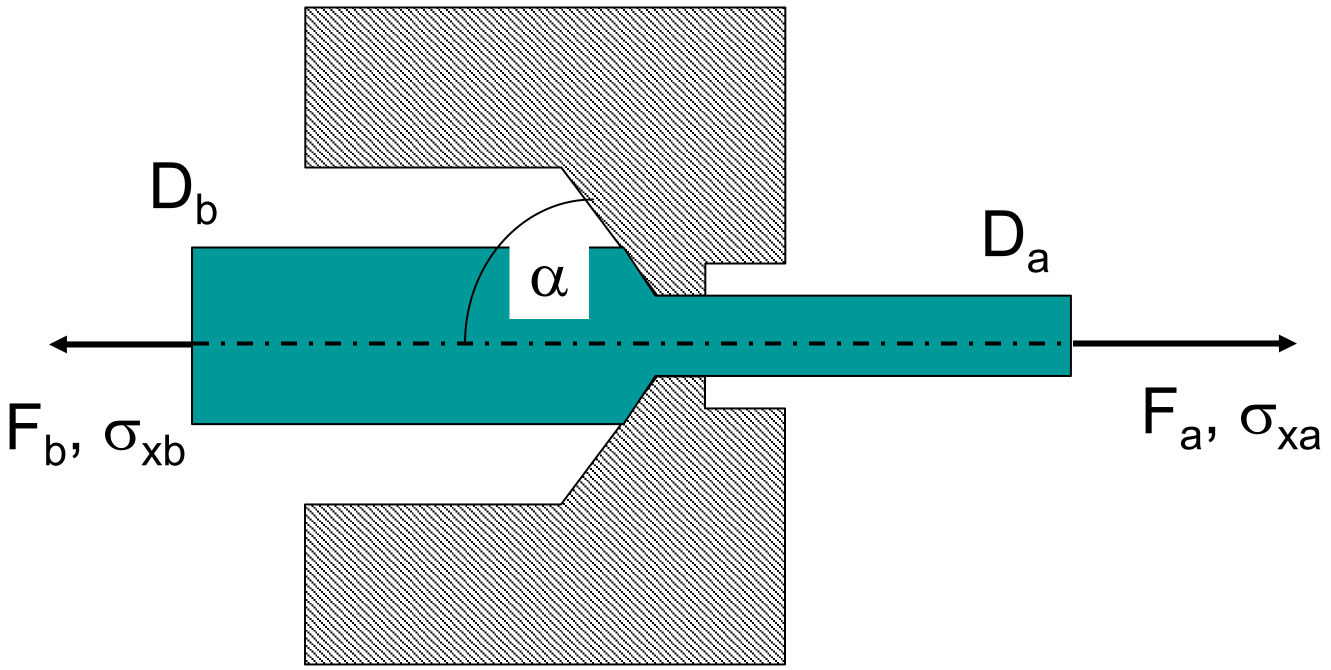
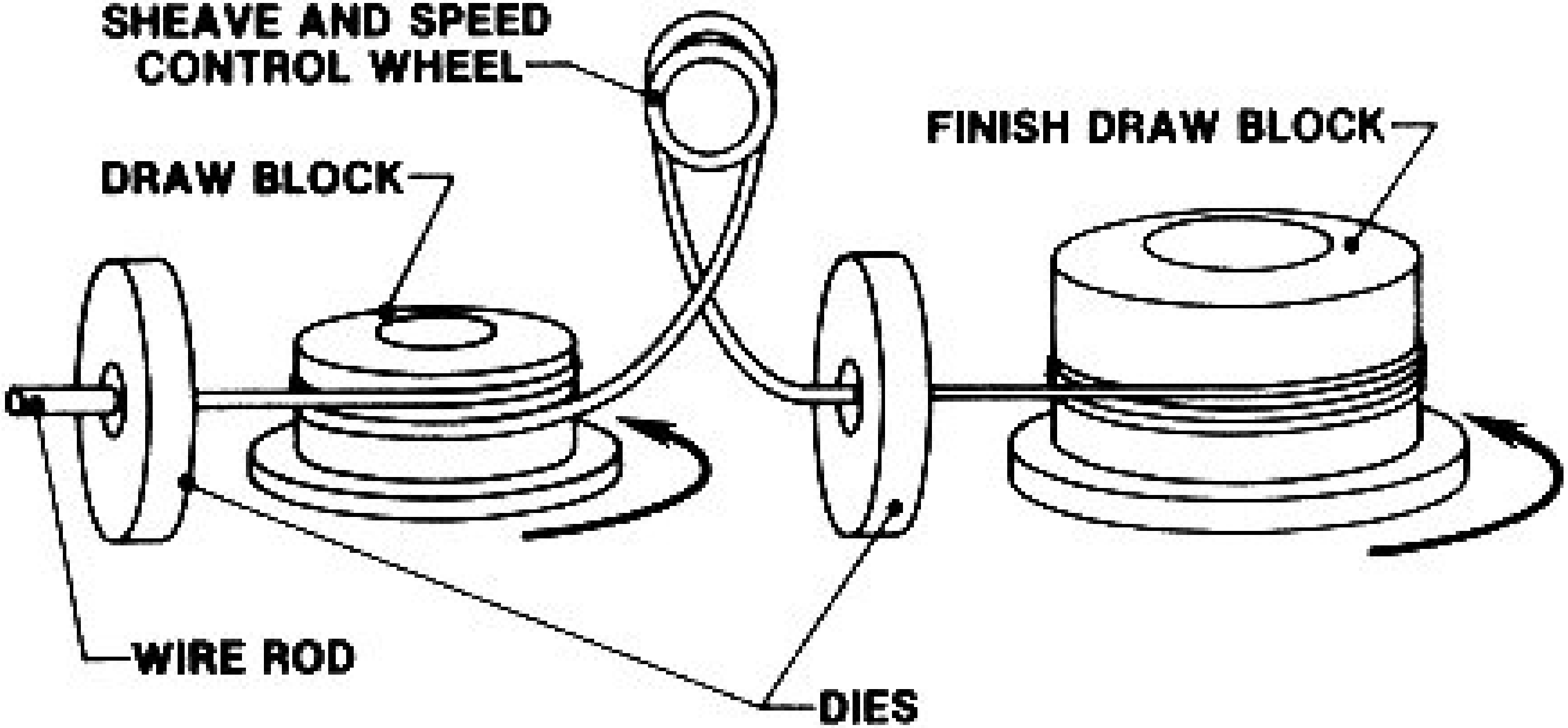
Overview

- Description
- Characteristics
- Mechanical Analysis
- Thermal Analysis
- Tube drawing

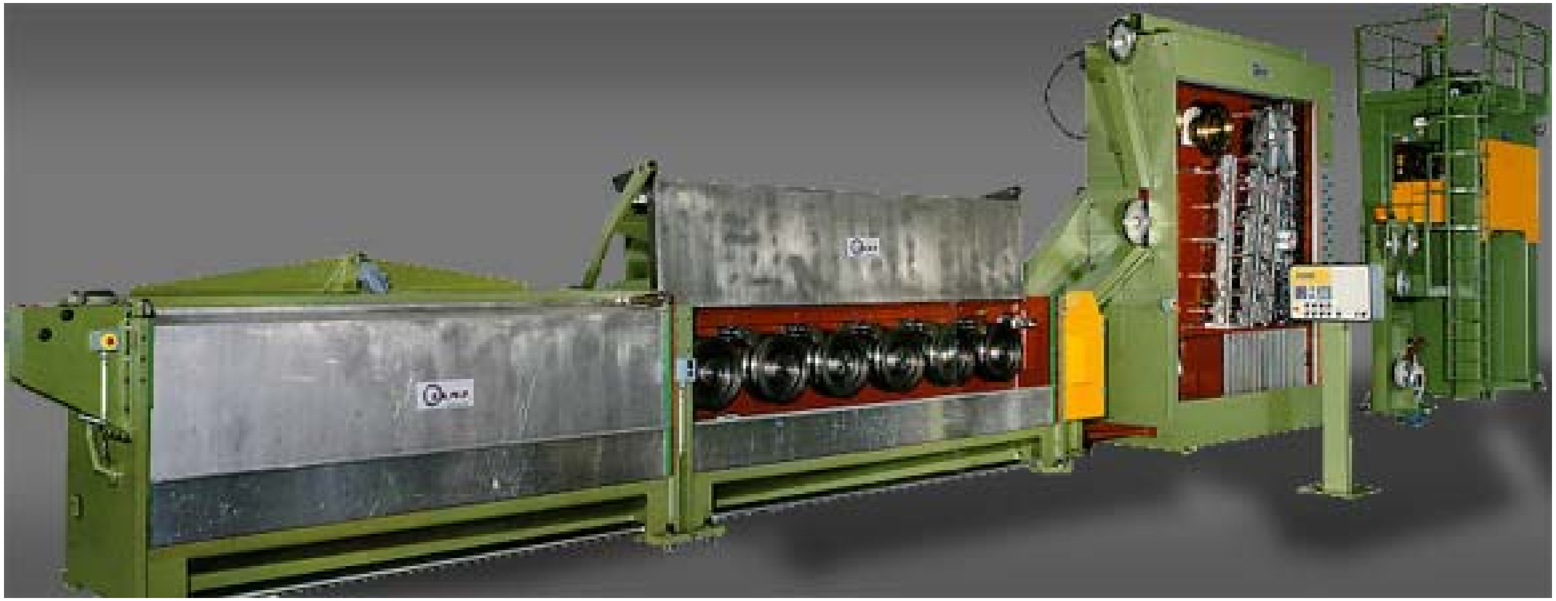
Geometry



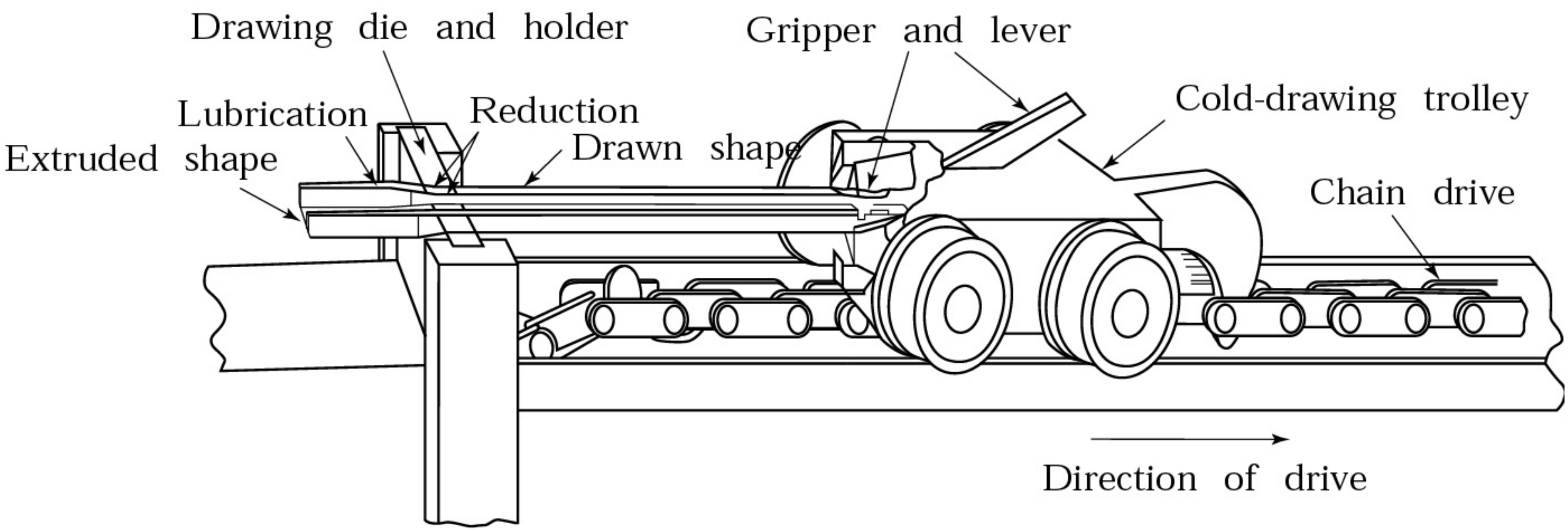
WIRE DRAWING



Equipment



Cold Drawing



A. Durer - Wire Drawing Mill (1489)

Characteristics

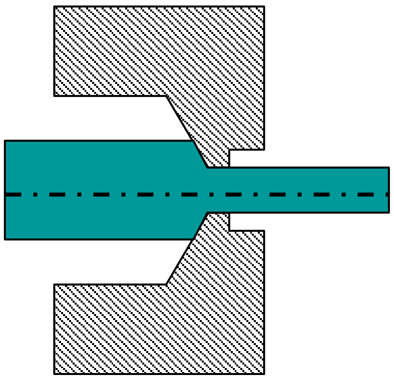
- Product sizes:
  - 0.0002" (5μm) to several inches (100-150 mm)
- Mostly cold ($T < 0.4\ T_{melting}$)
  - below recrystallization point
- Small diameter (wire):
  - uses a capstan
- Diameter > 1 inch (25 mm) (rod):
  - bull blocks on a draw bench
  - length up to 40 feet (12 m)

Characteristics

- Fine wire done through several dies
- Speeds
  - large diameter: 30 feet per minute (9 m/min)
  - small diameter: 300 feet per minute (90 m/min)
  - fine wires: 5,000 feet per minute (60 mph – 100 km/h)

Die Materials

- Large diameter
  - high carbon steel
  - high speed steel
- Moderate diameter
  - tungsten carbide (WC)
- Small diameter
  - diamond inserts

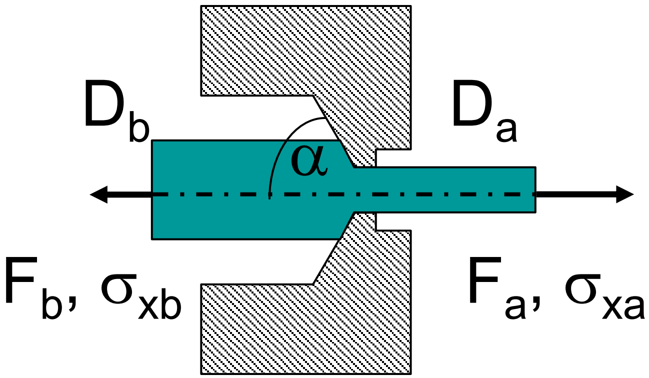


Characteristics

- Lubrication
  - Coatings
  - Oil
- Die angle (α)
  - typically small: 4-6^o

Mechanical analysis (round wire / rod)

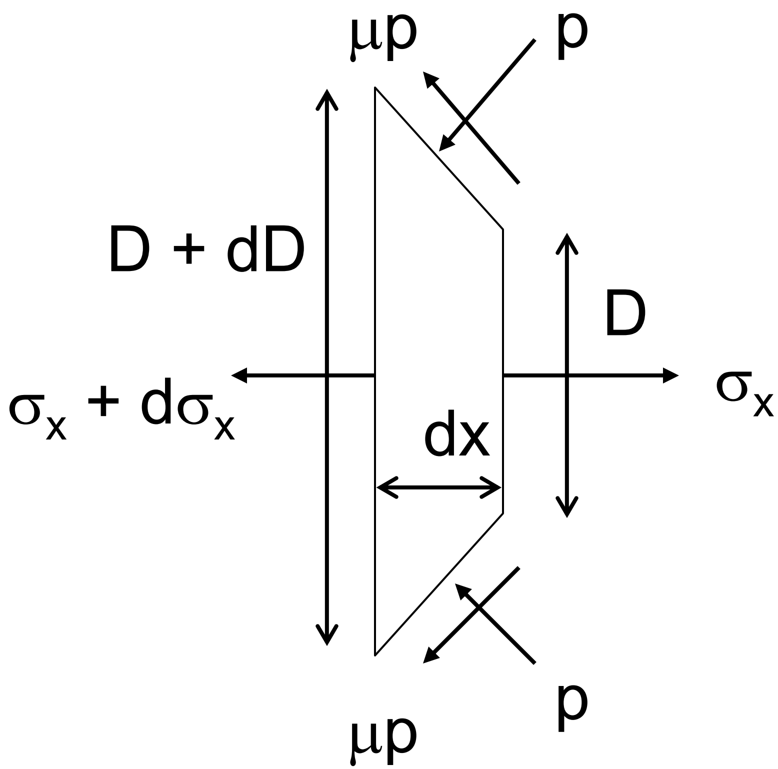
Reduction in area (RA)

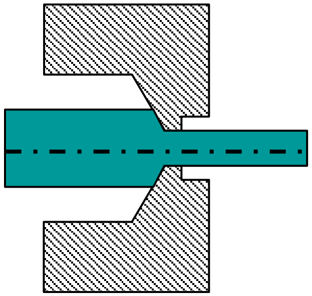


$$RA = \frac{D_b^2 - D_a^2}{D_b^2} = 1 - \left(\frac{D_a}{D_b}\right)^2$$

$$\varepsilon_t = \ln\left(\frac{1}{1-RA}\right) = 2 \cdot \ln\left(\frac{D_b}{D_a}\right)$$

Slab analysis





- Assume p, σ_x are uniform
  - OK for small α, μ

Equilibrium

$$\left(\sigma_x + d\sigma_x\right)\frac{\pi}{4}\left(D + dD\right)^2 - \sigma_x \frac{\pi}{4} D^2$$

$$+ p\frac{\pi D \cdot dx}{\cos\alpha}\sin\alpha + \mu p\frac{\pi D \cdot dx}{\cos\alpha}\cos\alpha = 0$$

Expanding

$$\left(\sigma_x + d\sigma_x\right)\frac{\pi}{4}\left(D^2 + 2DdD + dD^2\right) - \sigma_x \frac{\pi}{4} D^2$$

$$+ p\frac{\pi D \cdot dx}{\cos\alpha}\sin\alpha + \mu p\frac{\pi D \cdot dx}{\cos\alpha}\cos\alpha = 0$$

Equilibrium

small small small

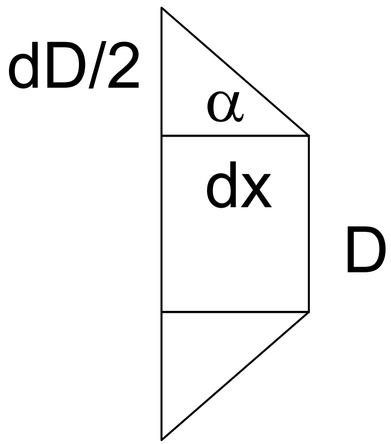
$$\frac{\pi}{4}\left[\left(\sigma_x D^2 + 2\sigma_x DdD + \cancel{\sigma_x dD^2}\right) + \left(d\sigma_x D^2 + \cancel{2d\sigma_x DdD} + \cancel{d\sigma_x dD^2}\right)\right]$$

$$-\sigma_x \frac{\pi}{4} D^2 + p\frac{\pi D \cdot dx}{\cos\alpha}\sin\alpha + \mu p\frac{\pi D \cdot dx}{\cos\alpha}\cos\alpha = 0$$

Eliminating higher order terms, dividing by D & π, multiplying by 4 and canceling

$$2\sigma_x dD + d\sigma_x D + 4p\frac{dx}{\cos\alpha}\sin\alpha + 4\mu p\frac{dx}{\cos\alpha}\cos\alpha = 0$$

Equilibrium



Noting

$$\tan\alpha = \frac{dD/2}{dx} \qquad dx = \frac{dD}{2\tan\alpha}$$

$$2\sigma_x dD + d\sigma_x D + 4p\frac{\sin\alpha}{\cos\alpha}\frac{dD}{2\tan\alpha} + 4\mu p\frac{\cos\alpha}{\cos\alpha}\frac{dD}{2\tan\alpha} = 0$$

or

$$2\sigma_x dD + d\sigma_x D + 2pdD + 2\mu p\frac{dD}{\tan\alpha} = 0$$

Equilibrium

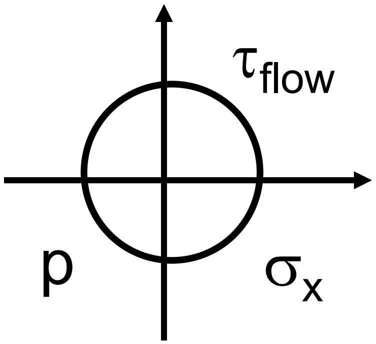
Finally

$$2\sigma_x \cdot dD + D \cdot d\sigma_x + 2p \cdot \left(1 + \frac{\mu}{\tan\alpha}\right) \cdot dD = 0$$

Maximum shear stress (Tresca) criterion

$$\sigma_x + p = 2\tau_{flow} = \sigma_{flow}$$

$$\frac{\mu}{\tan\alpha} \equiv B$$



Differential form

$$\frac{dD}{D} = \frac{dp}{4\tau_{flow} + 2pB}$$

$$\frac{dD}{D} = \frac{d\sigma_x}{2B\sigma_x - 4\tau_{flow}(1+B)}$$

Integrating

$$\int_{D_a}^{D_b} \frac{dD}{D} = \int_{\sigma_{xa}}^{\sigma_{xb}} \frac{d\sigma_x}{2B\sigma_x - 4\tau_{flow}(1+B)}$$

In[1]:= $$\int_{Da}^{Db} \frac{1}{D}\, dD$$

Out[1]= $$\mathrm{If}\Big[\frac{-\mathrm{Im}[Db]\,\mathrm{Re}[Da]+\mathrm{Im}[Da]\,\mathrm{Re}[Db]}{\mathrm{Im}[Da]-\mathrm{Im}[Db]} \ge 0 \;\&\&\; \Big(\Big(\mathrm{Re}\Big[\frac{Da}{-Da+Db}\Big] \ge 0 \;\&\&\; \frac{Da}{-Da+Db} \ne 0\Big) \;||\; \mathrm{Re}\Big[\frac{Da}{Da-Db}\Big] \ge 1 \;||\; \mathrm{Im}\Big[\frac{Da}{-Da+Db}\Big] \ne 0\Big),\; -\mathrm{Log}[Da]+\mathrm{Log}[Db],$$
$$\mathrm{Integrate}\Big[\frac{1}{D},\, \{D, Da, Db\},\, \mathrm{Assumptions} \to !\Big(\frac{-\mathrm{Im}[Db]\,\mathrm{Re}[Da]+\mathrm{Im}[Da]\,\mathrm{Re}[Db]}{\mathrm{Im}[Da]-\mathrm{Im}[Db]} \ge 0 \;\&\&\; \Big(\Big(\mathrm{Re}\Big[\frac{Da}{-Da+Db}\Big] \ge 0 \;\&\&\; \frac{Da}{-Da+Db} \ne 0\Big) \;||\; \mathrm{Re}\Big[\frac{Da}{Da-Db}\Big] \ge 1 \;||\; \mathrm{Im}\Big[\frac{Da}{-Da+Db}\Big] \ne 0\Big)\Big)\Big]\Big]$$

Integration Result

$$-\mathrm{Log}[Da]+\mathrm{Log}[Db]$$

In[2]:= $$\int_{\sigma xa}^{\sigma xb} \frac{1}{2B\sigma - 4\tau_f(1+B)}\, d\sigma$$

$$\mathrm{If}\Big[\frac{\mathrm{Im}[\sigma xb]\,\mathrm{Re}[\sigma xa]-\mathrm{Im}[\sigma xa]\,\mathrm{Re}[\sigma xb]}{\mathrm{Im}[\sigma xa]-\mathrm{Im}[\sigma xb]} \le 0 \;\&\&$$
$$\Big(\mathrm{Im}\Big[\frac{B\,\sigma xa-2(1+B)\tau_f}{B(\sigma xa-\sigma xb)}\Big] \ne 0 \;||\; \mathrm{Re}\Big[\frac{B\,\sigma xa-2(1+B)\tau_f}{B(\sigma xa-\sigma xb)}\Big] \le 0 \;||$$
$$\Big(\mathrm{Re}\Big[\frac{B\,\sigma xa-2(1+B)\tau_f}{B(\sigma xa-\sigma xb)}\Big] \ge 1 \;\&\&\; \Big(1+\mathrm{Re}\Big[\frac{-B\,\sigma xa+2(1+B)\tau_f}{B(\sigma xa-\sigma xb)}\Big] \le 0 \;||\; \mathrm{Im}\Big[\frac{-B\,\sigma xa+2(1+B)\tau_f}{B(\sigma xa-\sigma xb)}\Big] \ne 0\Big)\Big)\Big),$$
$$\frac{-\mathrm{Log}[2B\,\sigma xa-4(1+B)\tau_f]+\mathrm{Log}[2B\,\sigma xb-4(1+B)\tau_f]}{2B},\; \mathrm{Integrate}\Big[\frac{1}{2B\sigma-4(1+B)\tau_f},$$
$$\{\sigma, \sigma xa, \sigma xb\},\, \mathrm{Assumptions} \to !\Big(\frac{\mathrm{Im}[\sigma xb]\,\mathrm{Re}[\sigma xa]-\mathrm{Im}[\sigma xa]\,\mathrm{Re}[\sigma xb]}{\mathrm{Im}[\sigma xa]-\mathrm{Im}[\sigma xb]} \le 0 \;\&\&$$
$$\Big(\mathrm{Im}\Big[\frac{B\,\sigma xa-2(1+B)\tau_f}{B(\sigma xa-\sigma xb)}\Big] \ne 0 \;||\; \mathrm{Re}\Big[\frac{B\,\sigma xa-2(1+B)\tau_f}{B(\sigma xa-\sigma xb)}\Big] \le 0 \;||\; \Big(\mathrm{Re}\Big[\frac{B\,\sigma xa-2(1+B)\tau_f}{B(\sigma xa-\sigma xb)}\Big] \ge 1 \;\&\&$$
$$\Big(1+\mathrm{Re}\Big[\frac{-B\,\sigma xa+2(1+B)\tau_f}{B(\sigma xa-\sigma xb)}\Big] \le 0 \;||\; \mathrm{Im}\Big[\frac{-B\,\sigma xa+2(1+B)\tau_f}{B(\sigma xa-\sigma xb)}\Big] \ne 0\Big)\Big)\Big)\Big)\Big]\Big]$$

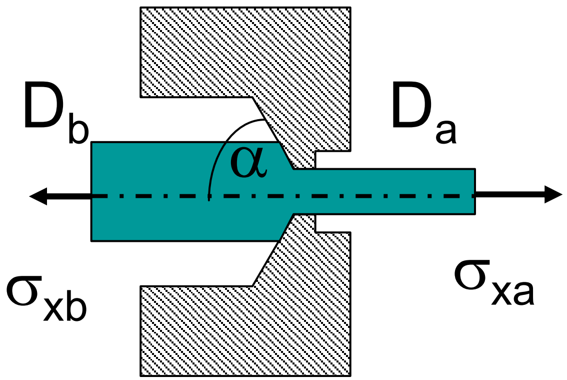
Integration result :

$$\frac{-\mathrm{Log}[2B\,\sigma xa-4(1+B)\tau_f]+\mathrm{Log}[2B\,\sigma xb-4(1+B)\tau_f]}{2B}$$

Drawing stress

$$\frac{\sigma_{xa}}{2\tau_{flow}} = \frac{1+B}{B}\left[1-\left(\frac{D_a}{D_b}\right)^{2B}\right] + \frac{\sigma_{xb}}{2\tau_{flow}}\left(\frac{D_a}{D_b}\right)^{2B}$$

- where:
  - σ_{xb} = back stress (tension)
  - σ_{xa} = pulling stress (tension)

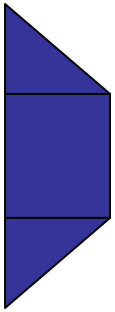


Strain hardening (cold – below recrystallization point)

- For round parts - Tresca

$$2\tau_{flow} = \sigma_{flow} = \overline{Y} = \frac{K\varepsilon^n}{n+1}$$

average flow stress:
due to shape of element

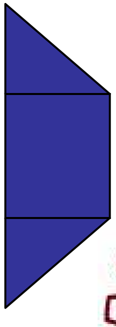


Strain rate effect
(hot – above recrystallization point)

$$2\tau_{flow} = \sigma_{flow} = \bar{Y} = C\dot{\bar{\varepsilon}}^{m}$$

- For a round part (derived for extrusion)

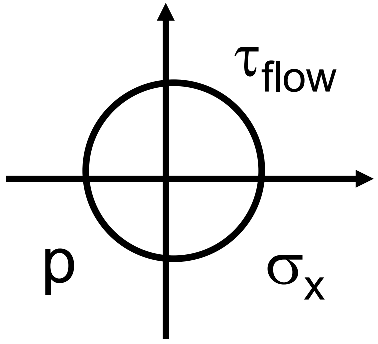
$$\dot{\bar{\varepsilon}} = \frac{6 v_b D_b^2 \cdot \tan\alpha}{D_b^3 - D_a^3} \cdot \ln\left(\frac{A_b}{A_a}\right)$$



  - average strain rate due to shape of element
  - v_b = velocity of “b” side
  - A = area

Value for p

$$p = Y - \sigma$$

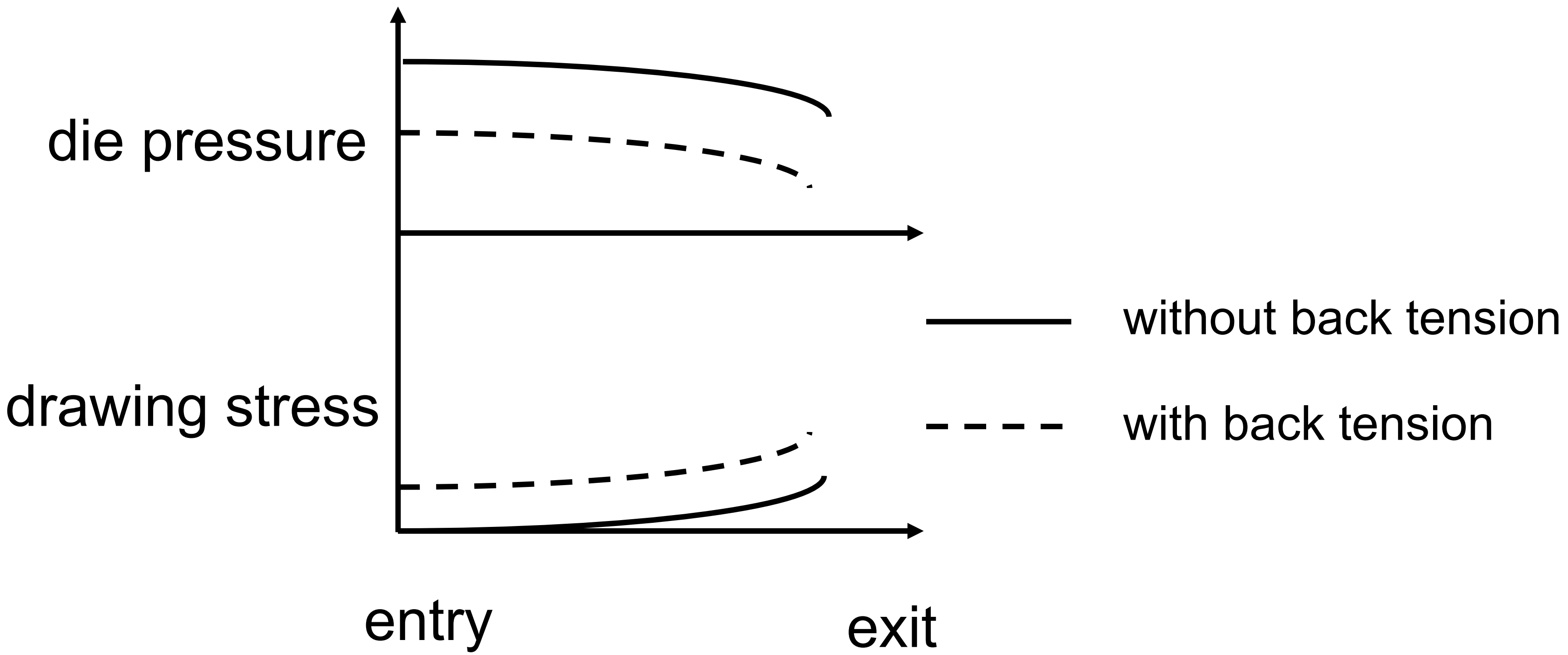


or

$$p = 2\tau_{flow} - \sigma$$

maximum at entrance

Effect of back tension



Maximum RA

- Solve previous equations with:

  $\alpha = 6^o$ (typical value)

  $\mu = 0.1$

  $\therefore B = 1$

  $\sigma_{xb} = 0$

  For failure: draw stress = material flow {yield} stress

$$\sigma_{xa} = \sigma = K\varepsilon^n \qquad 2\tau_{flow} = \sigma_{flow} = \bar{Y} = \frac{K\varepsilon^n}{n+1}$$

here, say K = 760 MPa, and n = 0.19

Maximum RA

$$\frac{K\varepsilon^n}{\dfrac{K\varepsilon^n}{n+1}} = \left(\frac{1+B}{B}\right)\cdot\left(1-\left(\frac{D_a}{D_b}\right)^{2B}\right)$$

$$\frac{0.19+1}{1} = \left(\frac{1+1}{1}\right)\cdot\left(1-\left(\frac{D_a}{D_b}\right)^{2}\right)$$

- Yields RA = 0.6
  - must be solved for each μ, α, σ_{xb}

Energy / unit volume (u)

$u = F\,V / A_a\,V = \sigma_{xa}$

(with no back stress)

V= volume

Rod/Wire Drawing Analysis

- Ideal deformation

  External work = Work of ideal plastic deformation

$$\sigma_d \left(A_f L\right) = u \left(A_f L\right)$$

$$\sigma_d = u = \int_0^{\varepsilon_t} \sigma_t \, d\varepsilon_t$$

for $\sigma_t = K\varepsilon_t^n$

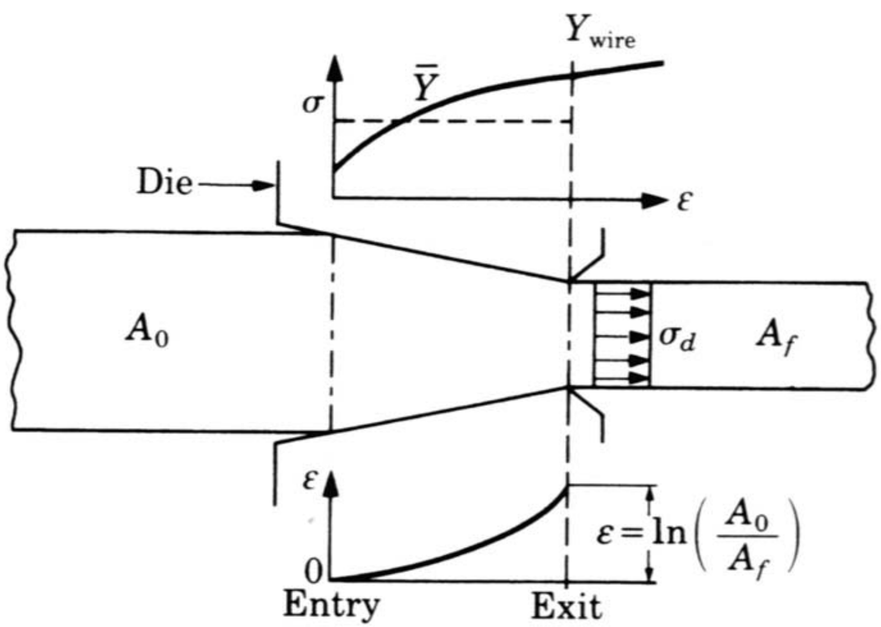
$$\boxed{\sigma_d = \frac{K\varepsilon_t^n}{n+1}\varepsilon_t = \bar{Y}_f \varepsilon_t = \bar{Y}_f \ln\left(\frac{A_0}{A_f}\right)}$$

Rod/Wire Drawing Analysis

- Ideal deformation

  Drawing force, $F_d = \sigma_d A_f$

  Drawing power, $P_d = F_d\, V_f$



Source: S. Kalpakjian & S. Schmidt, 4th ed. 2003

Drawing Limit

- Ideal deformation of a perfectly plastic material

$$\sigma_d = Y \cdot ln\left(\frac{A_o}{A_f}\right)$$

$$\sigma_\varepsilon = Y$$

$$\sigma_d = \sigma_\varepsilon \Rightarrow ln\left(\frac{A_o}{A_f}\right) = 1 \Rightarrow \frac{A_o}{A_f} = e$$

Maximum reduction per pass

$$= \frac{A_o - A_f}{A_o} = 1 - \frac{1}{e} = 0.63 = 63\%$$

Drawing Limit

- Ideal deformation of a strain hardening material

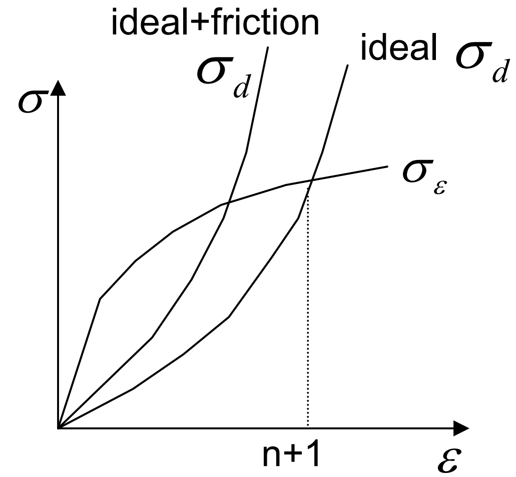
$$\sigma_d = \overline{Y} \cdot ln\left(\frac{A_o}{A_f}\right) = \frac{K\varepsilon^{n+1}}{n+1}$$

$$\sigma_\varepsilon = K\varepsilon^n$$

$$\sigma_d = \sigma_\varepsilon \quad \Rightarrow \quad \varepsilon = n+1$$

Maximum reduction per pass

$$= \frac{A_o - A_f}{A_o} = 1 - e^{-(n+1)}$$



Example Problem

Assuming zero redundant work and frictional work to be 20% of the ideal work, derive an expression for the maximum reduction in area per pass for a wire drawing operation for a material with a true-stress strain curve of $\sigma = K\varepsilon^n$

Total work = Ideal work + frictional work + redundant work

Total work = Ideal work + 0.2 x Ideal work = 1.2 x Ideal work

Or, Total work of deformation = 1.2 [*u* x *volume*] … (1)

In drawing, external work of deformation = σ_d x *volume* … (2)

Equating (1) and (2), we get

σ_d = 1.2*u* or

$$\sigma_d = 1.2\int_0^{\varepsilon_1} \sigma_t \, d\varepsilon_t = 1.2\int_0^{\varepsilon_1} K\varepsilon_t^n \, d\varepsilon_t = 1.2\frac{K\varepsilon_1^{n+1}}{n+1}$$

$$\sigma_d = 1.2\overline{Y}\varepsilon_1 \quad \text{where} \quad \varepsilon_1 = \ln\left(\frac{A_0}{A_f}\right) \qquad \ldots (3)$$

Example Problem

Max reduction occurs when total drawing stress, σ_d = Flow stress of material at die exit, Y

$$\sigma_d = Y$$

$$1.2\bar{Y}\varepsilon_1 = K\varepsilon_1^n$$

$$1.2\frac{K\varepsilon_1^{n+1}}{n+1} = K\varepsilon_1^n$$

$$\varepsilon_1 = \frac{n+1}{1.2} \Rightarrow \ln\frac{A_0}{A_f} = \frac{n+1}{1.2} \Rightarrow \frac{A_0}{A_f} = e^{\frac{n+1}{1.2}}$$

$$\therefore \text{max reduction per pass} = \frac{A_0 - A_f}{A_0} = 1 - e^{-\left(\frac{n+1}{1.2}\right)}$$

Drawing - Ex. 1-1

Determine power, and plot σ_x and p along die length.

- Drawing steel rod from ϕ = 13 mm to ϕ = 12 mm @ 1.5 m/s
- K = 760 MPa, n = 0.19
- $\mu = 0.1$, $\alpha = 4^o$, $\sigma_{xb} = 0$

Drawing - Ex. 1-2

- First, we must see if we can do the process, the limit is

$$\sigma_{xa} = \sigma_{\max} = K\varepsilon^n$$

- RA = 1 - $(D_a/D_b)^2$ = 0.15 = 15%
- ε_t = ln{1/(1-RA)}

  = ln {1/(1-0.15)} = 0.16
- B = $\mu/\tan\alpha$ = 0.1 / tan 4^o = 1.43

Drawing - Ex. 1-3

$$\frac{\sigma_{xa}}{2\tau_{flow}} = \frac{1+B}{B}\left[1-\left(\frac{D_a}{D_b}\right)^{2B}\right] + \frac{\sigma_{xb}}{2\tau_{flow}}\left(\frac{D_a}{D_b}\right)^{2B}$$

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

$$\sigma_{\max} = K\varepsilon^n$$

Drawing - Ex. 1-4

- So, equating the equations (with no back stress) yields

$$1 = \frac{1}{n+1}\left(\frac{1+B}{B}\right)\cdot\left(1-\left(\frac{D_a}{D_b}\right)^{2B}\right)$$

$$1 = \frac{1}{0.19+1}\left(\frac{1+1.43}{1.43}\right)\cdot\left(1-\left(\frac{D_{a-\min}}{13}\right)^{2\times 1.43}\right)$$

Drawing - Ex. 1-5

- Solving gives D_{a-min} = 8.53 mm, so we can do the process and proceed with the analysis

Drawing - Ex. 1-6

$$\frac{\sigma_{xa}}{2\tau_{flow}} = \frac{1+1.43}{1.43}\left[1-\left(\frac{12}{13}\right)^{2\times 1.43}\right]+0=0.35$$

$$2\tau_{flow} = \overline{Y} = \frac{K\varepsilon^n}{n+1} = \frac{760\cdot(0.16)^{0.19}}{0.19+1} = 446MPa$$

Drawing - Ex. 1-7

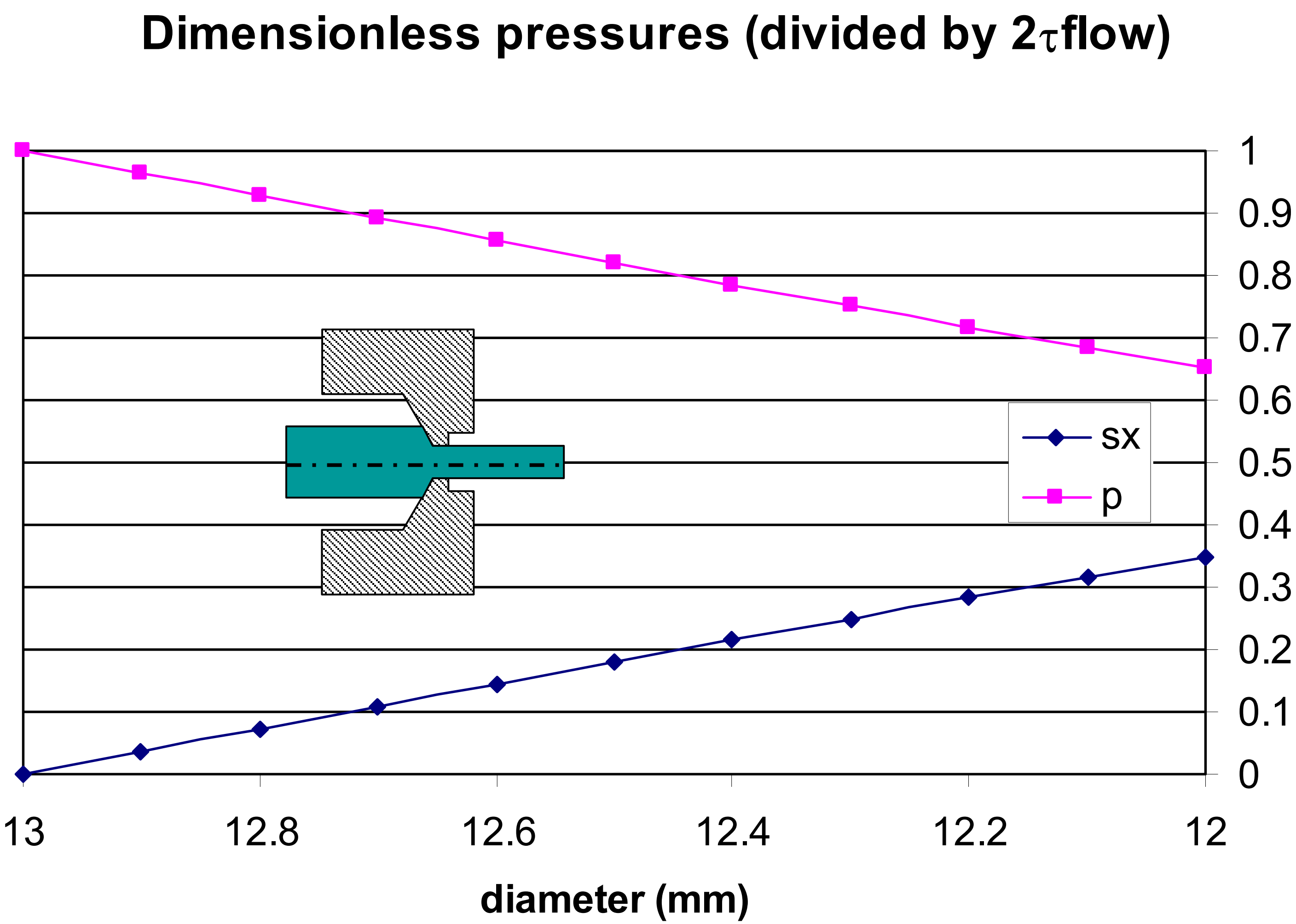
- $\sigma_{xa} = 0.35 \times 2\tau_{flow}$

  $= 0.35 \times 446$ MPa $= 156$ MPa
- $F_{draw} = \sigma_{xa} \times Area = 156 \times \pi(12/2)^2$

  $= 17.6$ kN $= 3938$ lbf
- Power $= F_{draw} \times$ speed

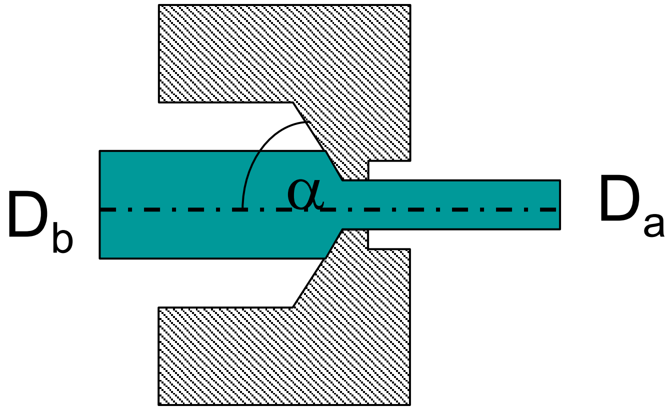
$= 17.6$ kN x 1.5 m/s $= 26.4$ kW $= 35.4$ hp

Drawing - Ex. 1-8



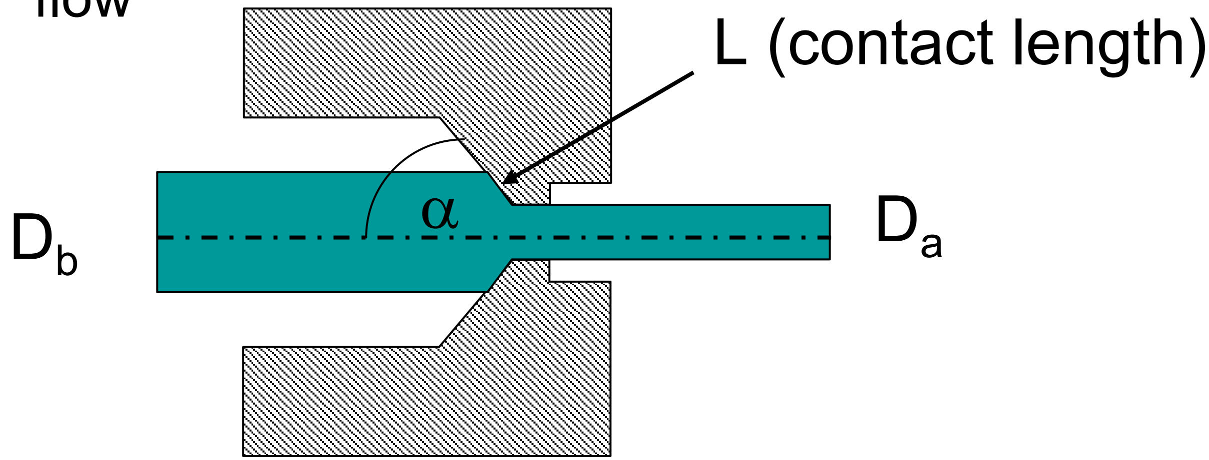
Limits on analysis

- Larger die angles
  - more redundant work
  - σ, p, u will be larger than predicted



Redundant work

- $\Delta = d_m/L$
- $d_m = (D_a + D_b) / 2$
- $p = Q_r \, \sigma_{flow}$



Redundant work factor (Backofen)
(frictionless)

$Q_r = \frac{p}{2\tau_Y}$

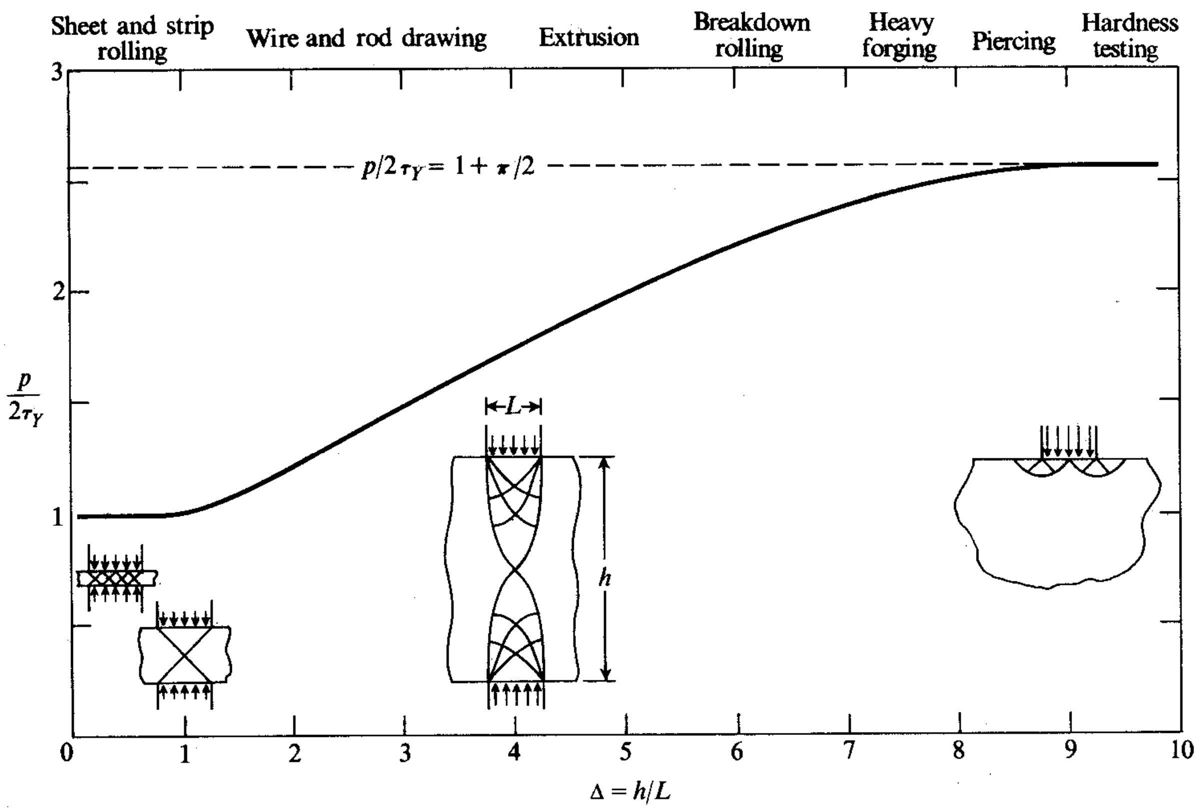
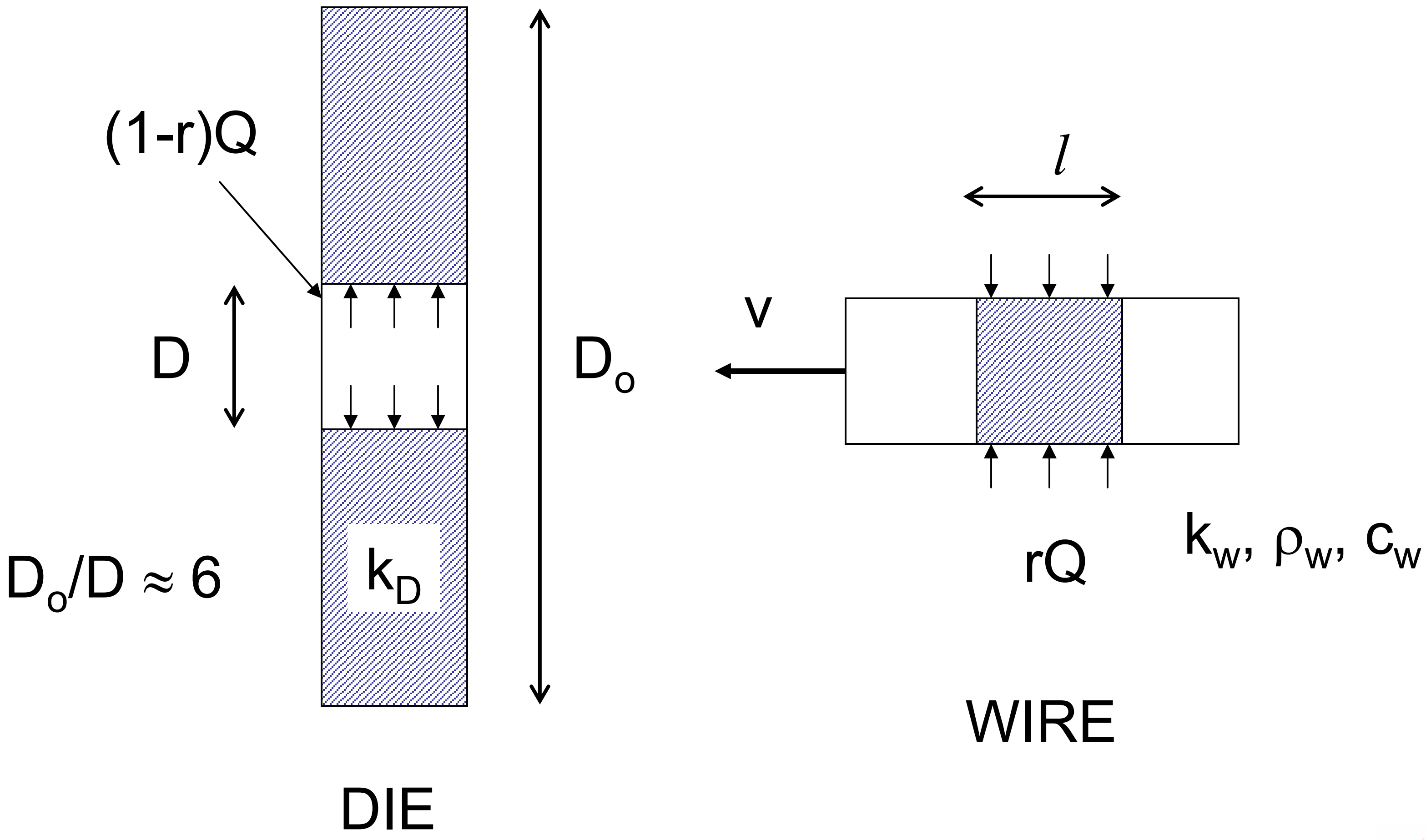


Fig. 7-1. The Δ-dependence of yield pressure for the frictionless plane strain-indentation of a nonstrain-hardening material.

Temperature rise



Temperatures

$$\theta = \theta_o + \theta_s + \theta_f$$

θ_o = ambient (room) temperature

θ_s = temperature rise in the wire due to plastic shear energy, u_s

θ_f = interface temperature rise due to frictional energy, u_f

Specific energies

$u = u_s + u_f$

$u = \sigma_{xa}$

$u_s = 2\tau_{flow}\,\varepsilon$

Specific energies

From the example above (steel rod):

$$u = \sigma_{xa} = 156 \text{ MPa}$$

$$u_s = 2\tau_{flow}\,\varepsilon = 446 * 0.16$$

$$= 71.4 \text{ MPa}$$

$$\therefore\ u_f = u - u_s = 156 - 71.4$$

$$= 84.6 \text{ MPa}$$

Shear temperature (θ_s)

- Since the shear strain is uniform in the wire
- and all the shear energy remains in the rod as heat
- Then, we can obtain the shear temperature in the wire:

$$\theta_s = \frac{u_s}{\rho_w c_w}$$

Material properties

- For this material:
  - k_w = 60 W/m-K
  - ρ_w = 7850 kg/m^3
  - c_w = 500 J/kg-K
  - α_w = 1.53 x 10^{-5} m^2/s
- For a WC die:
  - k_D = 42 W/m-K

Shear temperature (θ_s)

$$\theta_s = \frac{u_s}{\rho_w c_w} = \frac{71.4 \times 10^6}{7850 \times 500} = 18.2^{\circ} C$$

Frictional heat (Q)

Q represents all heat generated by friction

$$Q = u_f \frac{\pi D^2 v}{4}$$

- v = velocity
- (1-r)Q goes into the die

Die and wire temperatures (θ)

ref: Carslaw and Jaeger

- For the die (steady):

$$\theta = \theta_o + \frac{(1-r)Q}{2\pi k_D l} \cdot \ln \frac{D_o}{D}$$

- For the wire (moving):

$$\theta = \theta_o + \theta_s + 1.07\left(\frac{rQ}{\pi D l k_w}\right)\sqrt{\alpha_w l / 2v}$$

Q calculation

$$Q = u_f \frac{\pi D^2 v}{4}$$

$$= 84.6 \times 10^6 \cdot \frac{\pi \cdot 0.012^2 \cdot 1.5}{4}$$

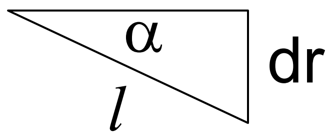
$$Q = 14352\ W$$

Dimensions

- $D = 12$ mm
  - from $D_o / D \approx 6$
  - $D_o = 72$ mm in this example
- l = contact length

  = reduction in radius / sin α

  = 0.5 mm / sin 4^o = 7.17 mm



Die temperature

$$\theta = \theta_o + \frac{(1-r)Q}{2\pi k_D l} \cdot \ln\frac{D_o}{D}$$

$$\theta = 20 + \frac{(1-r)\cdot 14352}{2\pi \cdot 42 \cdot 0.00717} \cdot \ln\frac{72}{12}$$

$$= 20 + 13591 \cdot (1-r)$$

Wire temperature

$$\theta = \theta_o + \theta_s + 1.07 \cdot \left(\frac{rQ}{\pi D l k_w} \right) \cdot \sqrt{\alpha_w l / 2v}$$

$$\theta = 20 + 18.2 + 1.07 \cdot \left(\frac{r \cdot 14352}{\pi \cdot 0.012 \cdot 0.00717 \cdot 60} \right)$$

$$\times \sqrt{1.53 \times 10^{-5} \cdot 0.00717 / 2 \cdot 1.5}$$

$$= 38.2 + 181 \cdot r$$

Heat flow ratio and Temperature

- Equating the previous equations yields:

  $r = 0.99$

- hence

  $\theta = 156^oC = 429\ K$

$T_{melt} = 1500^oC = 1723\ K$

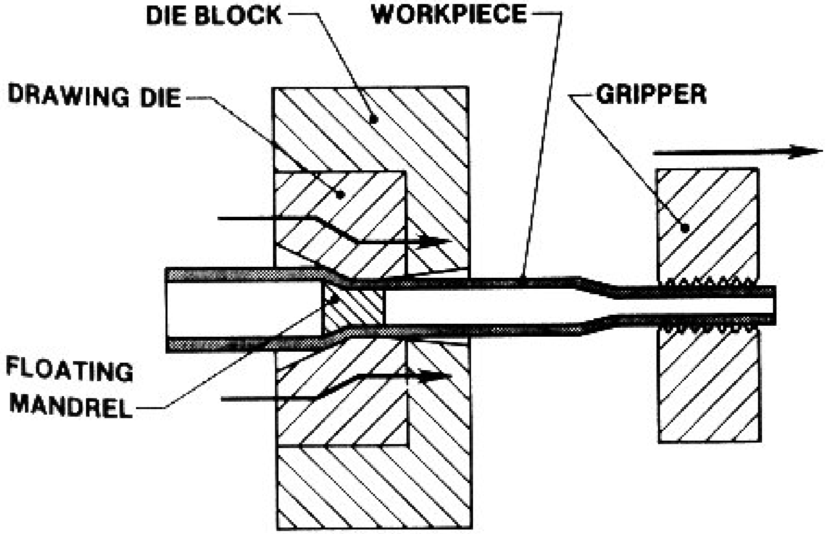
So $\theta/T_{melt} = 0.25$, cold (below recrystallization point

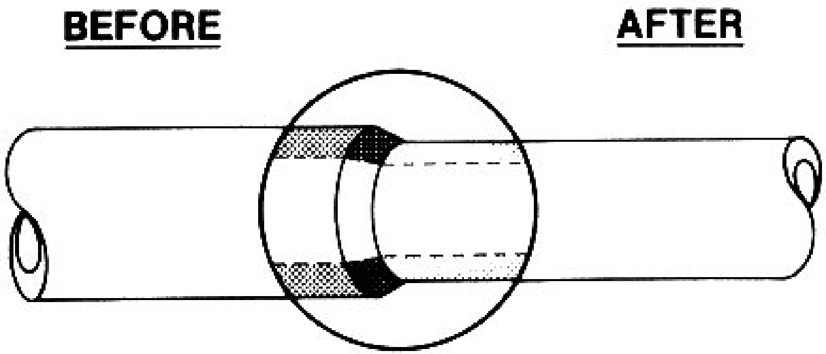
Temperature in practice

- In practice, r ≈ 1
  - all heat goes into wire

$$\theta = \theta_o + \frac{u_s}{\rho_w c_w} + 0.19 \cdot \left(\frac{u_f}{\rho_w c_w} \right) \cdot \sqrt{\frac{D^2 \cdot v}{\alpha_w \cdot l}}$$

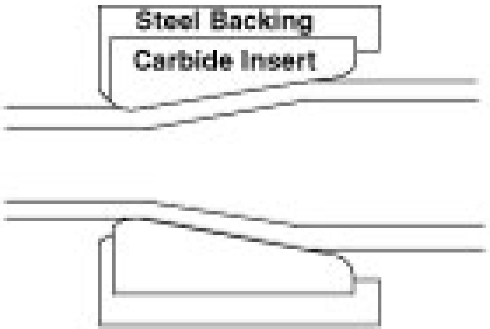
Tube drawing



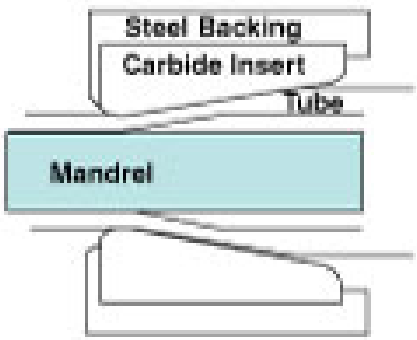


Tube Drawing

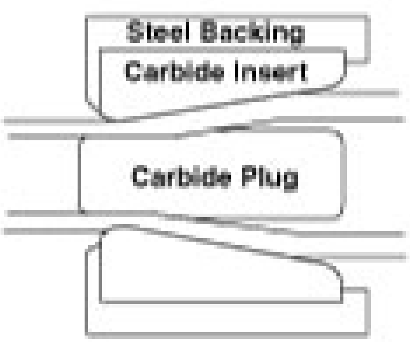
Tube Sinking



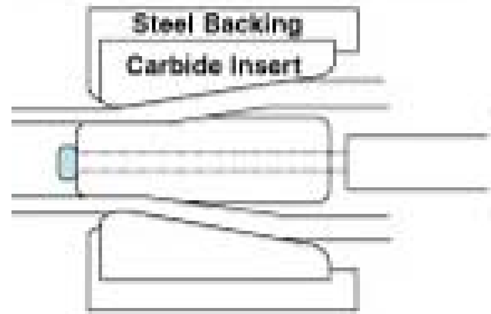
Rod Drawing



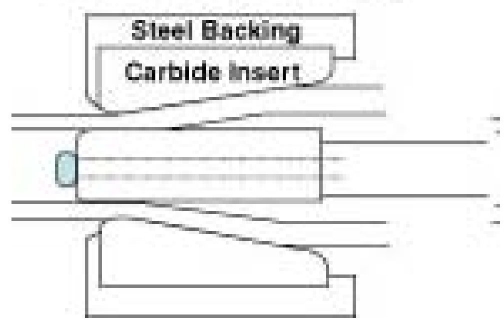
Floating Plug Drawing



Tethered Plug Drawing



Fixed Plug Drawing



Plane strain / Slab analysis

$$\frac{\sigma_{xa}}{2\tau_{flow}} = \frac{1+B^*}{B^*}\left[1-\left(\frac{t_f}{t_i}\right)^{B^*}\right]$$

$$B^* \equiv \frac{\mu_{die} + \mu_{mandrel}}{\tan\alpha - \tan\beta}$$

α= semicone angle of die
β =semicone angle of plug

Tube Drawing – Special Cases

$$B^* \equiv \frac{\mu_{die} + \mu_{mandrel}}{\tan\alpha - \tan\beta}$$

Fixed mandrel- same friction at both interface (plane – tube is modeled as a flat section)

$$B^* \equiv \frac{2\mu}{\tan\alpha}$$

Fixed mandrel (slab – circular tube)

$$B^* \equiv \frac{2\mu}{\tan\alpha} - \mu^2$$

Moving mandrel – No friction at interface of mandrel and tube (plane and slab)

$$B^* \equiv \frac{\mu}{\tan\alpha}$$

Moving mandrel with friction towards exit, takes into account motion between mandrel and tube (B may be negative) (plane)

$$B^* \equiv \frac{\mu_{die} - \mu_{mandrel}}{\tan\alpha}$$

Summary

- Description
- Characteristics
- Mechanical analysis
- Thermal analysis
- Tube drawing