Bulk Deformation - 1

ME 206

Manufacturing Processes 1

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Outline

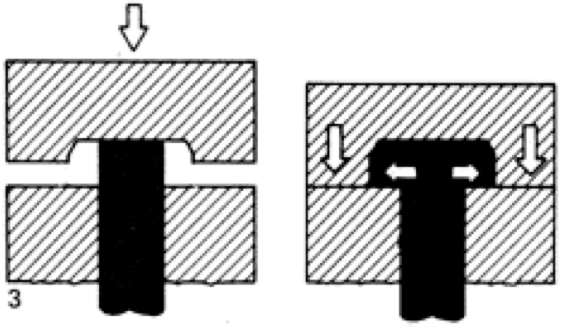
- What is bulk deformation?
- Cold vs hot working
- Forging introduction
- Forging analysis
- Forging defects

What is bulk deformation?

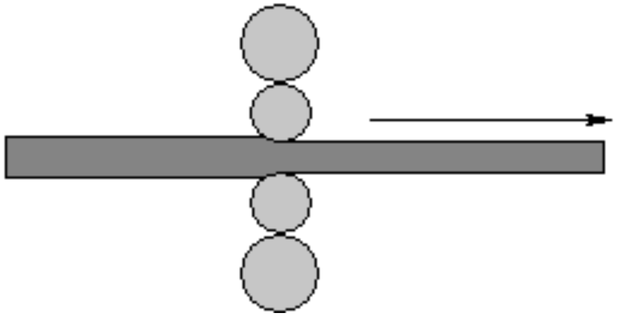
- Bulk deformation (or forming): processes characterized by large amount of plastic deformation (large strains) carried out at elevated or room temperature
- Bulk plastic flow of material under uniaxial or multi-axial stresses dominated by compression
- Mass conserving processes → volume is constant

Bulk Deformation Processes

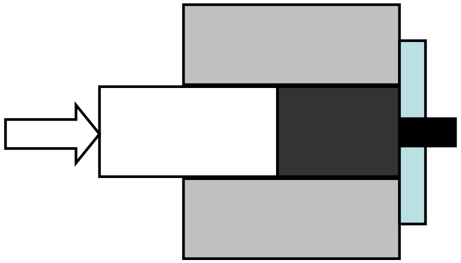
- Examples include: forging, rolling, extrusion, rod drawing etc.



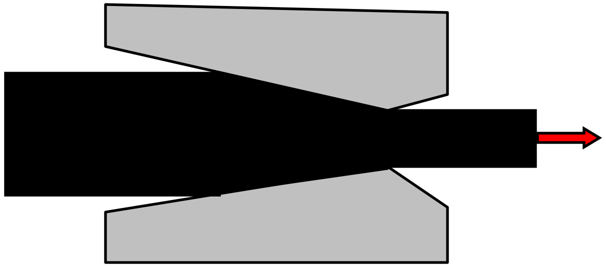
Forging (heading)



Rolling



Extrusion



Rod Drawing

Cold vs Hot Working

- Many bulk deformation processes carried out at elevated temperatures

- Cold working: $T < 0.3T_m$
  - Usually a finishing step

- Warm working: $T = 0.3 \sim 0.5T_m$
  - Intermediate or final step

- Hot working: $T > 0.5T_m$
  - Initial step

Cold Working

Advantages

- Better dimensional control
- Superior surface finish
- Strain hardening of surface layer can be beneficial

Limitations

- Greater material strength → higher forces
- Stronger tooling required
- Lower ductility → small deformations
- Lower malleability → harder to shape material
- Anisotropic surface properties

Hot Working

Advantages

- Lower yield strength → lower forces
- High ductility → larger strains possible
- Higher malleability → easy to shape metal

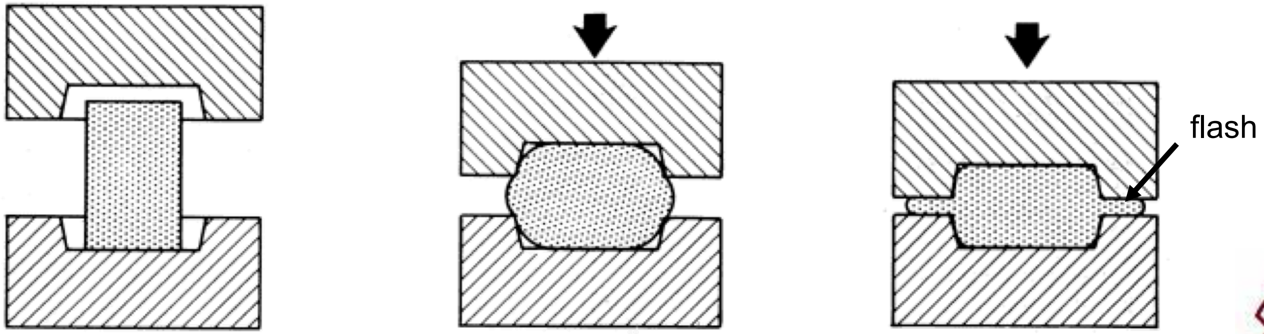
Limitations

- Easily forms oxide layers (scales) on surface → poor surface finish
- Harder to control dimensions

Forging

- Shape change via compressive forces
- Types of forging processes
  - Open die forging (upsetting)

  - Closed or impression die forging



Open Die Forging

- Carried out between flat dies
- Parts weighing few lbs ~ 150 tons e.g. solid shafts, spindles/rotors, rings, etc.
- Often carried out in steps
- Wide range of ferrous and non-ferrous metals

Stepped shaft

Spindles

Source: http://www.forging.org

Closed Die Forging

- Carried out between shaped dies
- Parts weighing few ounces ~ 25 tons e.g. crankshafts,connecting rods, aircraft parts etc.
- Most engineering metals: carbon steels, stainless steels, aluminum, bronze, etc.

Aircraft bulkhead

Connecting rods

Source: http://www.forging.org

Forgings

- Coins
- Landing gear
- Crank shafts
- Turbine shafts

Forging presses

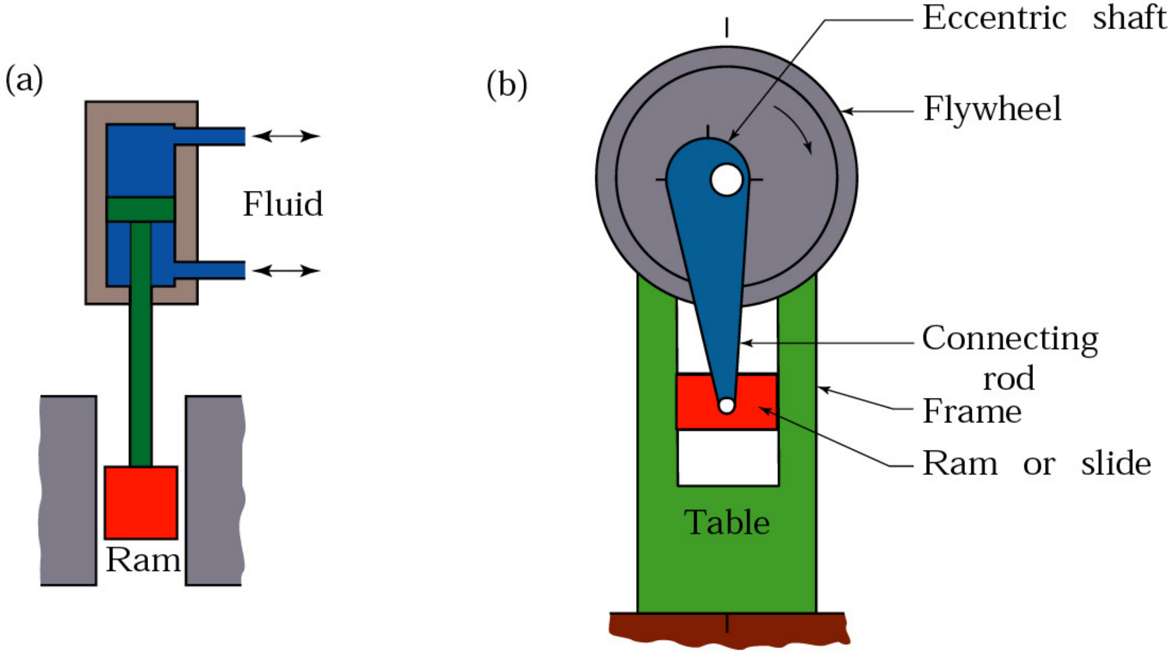
- Large machines
  - – hold dies
  - – form parts

Press types

- Servo-hydraulic presses
- Servo-electrical presses
- Mechanical presses
- Screw presses
- Hammers
  - gravity drop
  - power drop
  - counter blow (two rams)
  - high pressure gas

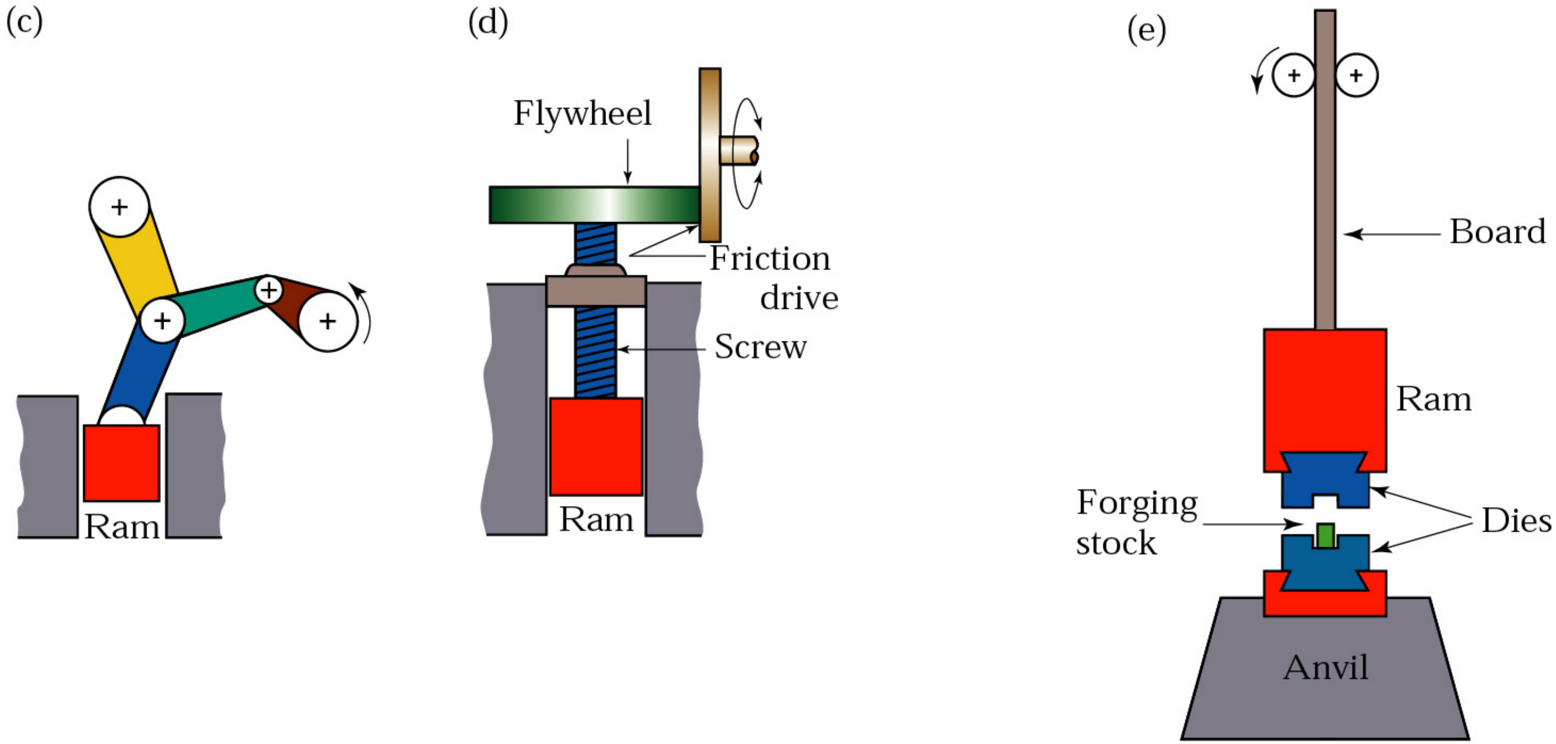
50,000 ton press

Forges



Schematic illustration of the principles of various forging machines. (a) Hydraulic press. (b) Mechanical press with an eccentric drive; the eccentric shaft can be replaced by a crankshaft to give the up-and-down motion to the ram. (continued)

Forges



Schematic illustration of the principles of various forging machines. (c) Knuckle-joint press. (d) Screw press. (e) Gravity drop hammer.

Forging steps

- Prepare slug
  - saw
  - flame cut
  - shear
- Clean slug surfaces
  - shot blast
  - flame

Forging steps

- For hot forging
  - – heat up and descale forging
  - – make sure press is hot
- Lubricate
  - – oil
  - – soap
  - – MoS_2
  - – glass
  - – graphite

Lubrication purposes

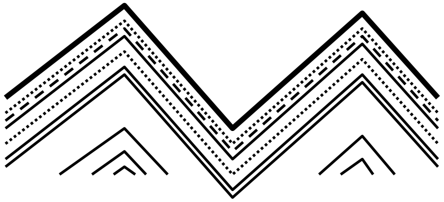
- Reduce friction
- Reduce die wear
- Thermally insulate part
  - to keep it warm

Forging steps

- Forge
- Remove flash
  - trim
  - machine
- Check dimensions
- Post processing, if necessary
  - heat treat
  - machine

Effect on grain structure

- Large grains are broken up.
- Grains can be made to flow.



Dies

- Final part shape determined by die accuracy
- Multiple parts can be made in one die
- Progressive shaping can be done in one die set
- Need to be stronger than highest forging stress

Forging Analysis

- Simple stress analysis possible for open die forging process

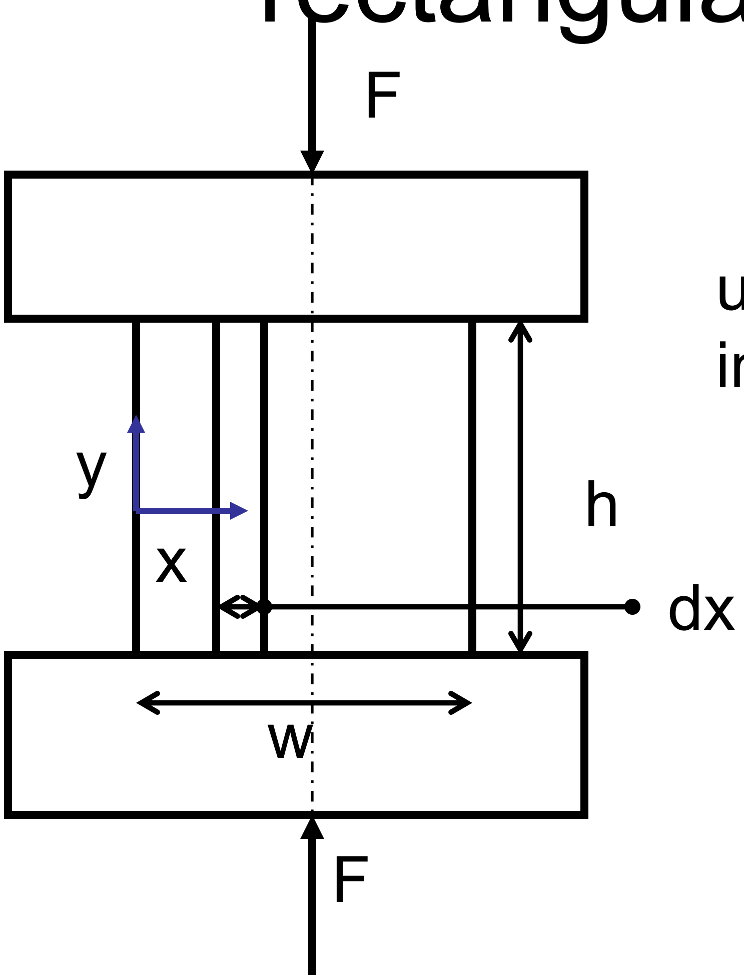
- Analysis method called "slab" analysis
- Applicable to plane strain compression with low sliding friction

Source: http://www.forging.org

Slab analysis assumptions

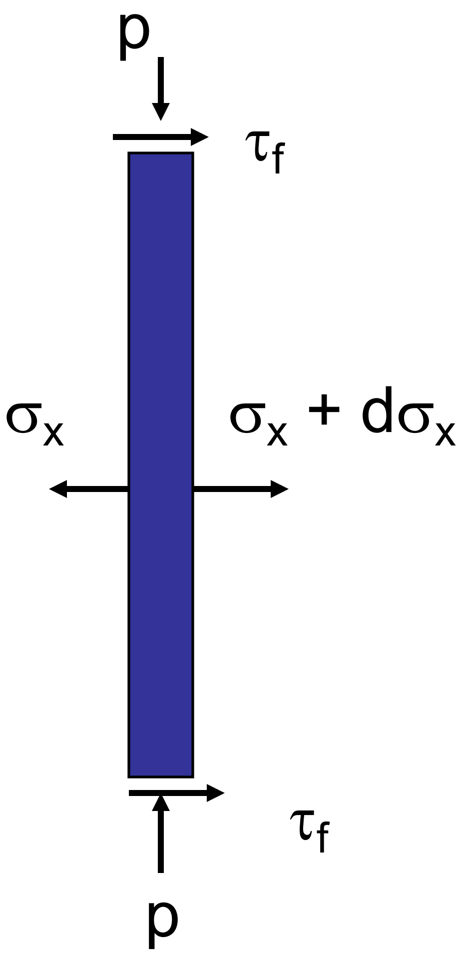
- Entire forging is plastic
  - no elasticity
- Material is perfectly plastic
  - strain hardening and strain rate effects later
- Friction coefficient (μ) is constant
  - all sliding, to start
- Plane strain
  - no z-direction deformation
- In any thin slab, stresses are uniform
- Three conditions exist: All sliding; Sliding-sticking transition and Fully sticking

Open die forging analysis – rectangular part



unit depth
into figure

Expanding the dx slice on LHS



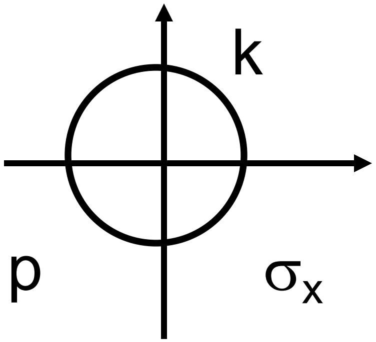
- p = die pressure
- σ_x, $d\sigma_x$ from material on side
- $\tau_{friction}$ = friction force = μp

Force balance in x-direction

$$h\,d\sigma_x + 2\tau_{friction}\,dx = 0$$

$$d\sigma_x = -\frac{2\tau_{friction}}{h}\,dx$$

Mohr's circle



$$\sigma_x + p = 2k = \frac{2}{\sqrt{3}}\sigma_{flow} = 1.15 \cdot \sigma_{flow}$$

(distortion energy (von Mises) criterion, plane strain)

N.B. all done on a per unit depth basis

Force balance

Differentiating, and substituting into Mohr's circle equation

$$d(2k) = d(\sigma_x + p) \qquad \therefore\ dp = -d\sigma_x$$

$$d\sigma_x = -\frac{2\tau_{friction}}{h}dx \qquad \therefore\ dp = \left(\frac{2\tau_{friction}}{h}\right)dx$$

noting: $\tau_{\text{friction}} = \mu p$

$$dp = \frac{2\mu}{h}p\,dx \longrightarrow \frac{dp}{p} = \frac{2\mu}{h}dx$$

Sliding region

$$\int_{2k}^{p_x} \frac{dp}{p} = \int_{0}^{x} \frac{2\mu}{h} dx$$

- Noting: @ x = 0, $\sigma_x = 2k = 1.15\ \sigma_{flow}$

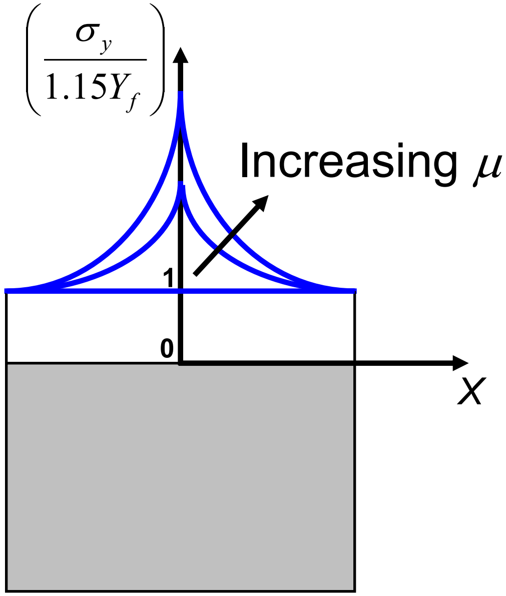
Forging pressure – sliding region

$$\ln p_x - \ln(2k) = 2\mu \frac{x}{h}$$

Sliding region result ($0 < x < x_k$)

$$\frac{p_x}{2k} = \exp\left(\frac{2\mu x}{h}\right)$$

$$p_x = 1.15 \cdot \sigma_{flow} \cdot \exp\left(\frac{2\mu x}{h}\right)$$



N.B done on a
per unit depth basis

Forging pressure – approximation

- Taking the first two terms of a Taylor's series expansion for the exponential about 0, for $|x| \leq 1$

$$\exp(x) = 1 + x + \cancelto{0}{\frac{x^2}{2!}} + \cancelto{0}{\frac{x^3}{3!}} + \cdots + \frac{x^n}{n!} = \sum_{k=0}^{n} \frac{x^k}{k!}$$

yields

$$\frac{p_x}{2k} = \left(1 + \frac{2\mu x}{h}\right) \qquad p_x = 1.15 \cdot \sigma_{flow} \cdot \left(1 + \frac{2\mu x}{h}\right)$$

Average forging pressure – all sliding approximation

- using the Taylor's series approximation

$$\frac{p_{ave}}{2k}=\frac{\int_0^{\frac{w}{2}}\frac{p_x}{2k}dx}{\frac{w}{2}}=\frac{\int_0^{\frac{w}{2}}\left(1+\frac{2\mu x}{h}\right)dx}{\frac{w}{2}}=\frac{\left.\left(x+\frac{2\mu x^2}{2h}\right)\right|_0^{\frac{w}{2}}}{\frac{w}{2}}$$

$$\frac{p_{ave}}{2k}=\left(1+\frac{\mu w}{2h}\right)$$

$$p_{ave}=1.15\cdot\sigma_{flow}\cdot\left(1+\frac{\mu w}{2h}\right)$$

N.B done on a
per unit depth basis

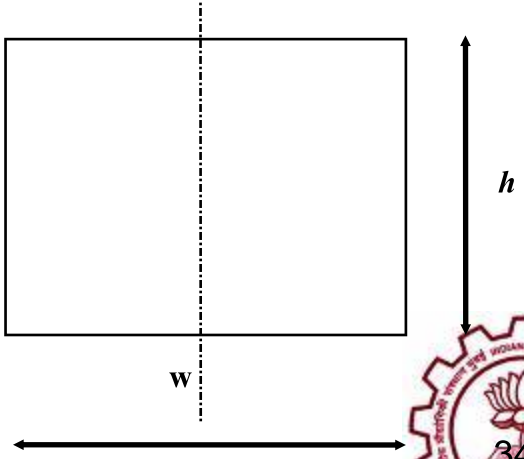
Forging force – all sliding approximation

$$F_{forging} = p_{ave} \cdot width \cdot depth$$

$$F_{forging} = 1.15 \cdot \sigma_{flow} \cdot \left(1 + \frac{\mu w}{2h}\right) \cdot w \cdot depth$$

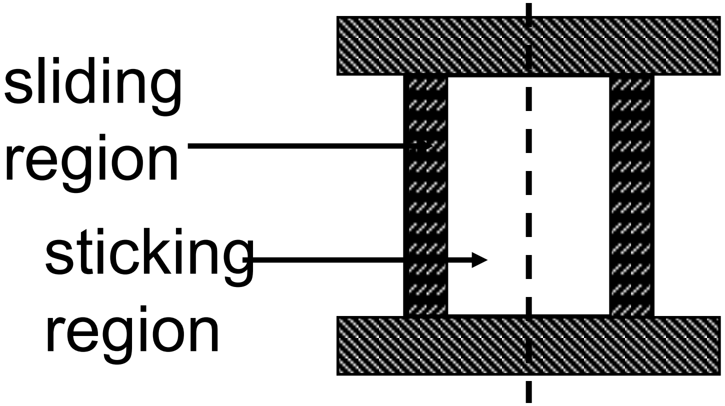
Example Problem

A rectangular workpiece has the following original dimensions: w = 100 mm, h = 25 mm, and depth d= 20 mm and is being open die forged in plane strain. The true stress-true strain curve of the metal is given by $\sigma_t = 400\varepsilon_t^{0.5}$ MPa and the coefficient of friction is μ = 0.3. Calculate the forging force required to reduce the height by 20%. Use both the “exact” and the average pressure methods.



Slab - die interface

- Sliding if $\tau_f < \tau_{flow}$
- Sticking if $\tau_f \geq \tau_{flow}$
  - can't have a force on a material greater than its flow (yield) stress
  - deformation occurs in a sub-layer just within the material with stress τ_{flow}



Sliding / sticking transition

- Transition will occur at x_k
- using $k = \mu p$, in:

$$\frac{p_x}{2k} = \exp\left(\frac{2\mu x}{h}\right) \qquad \frac{k}{2\mu k} = \exp\left(\frac{2\mu x_k}{h}\right)$$

- hence:

$$\frac{x_k}{h} = \frac{1}{2\mu}\ln\frac{1}{2\mu}$$

Sticking region

$$dp = \frac{2\mu}{h} p dx$$

- Using p = k/ μ

$$dp = \frac{2\mu}{h}\frac{k}{\mu}dx$$

$$\int_{p_{x_k}}^{p_x} dp = \int_{x_k}^{x} \frac{2k}{h} dx$$

$$p_x - p_{x_k} = \frac{2k}{h}\left(x - x_k\right)$$

Sticking region

We know that

- at $x = x_k$, $p_{x_k} = k/\mu$

- and $$\frac{x_k}{h} = \frac{1}{2\mu}\ln\frac{1}{2\mu}$$

Forging pressure - sticking region

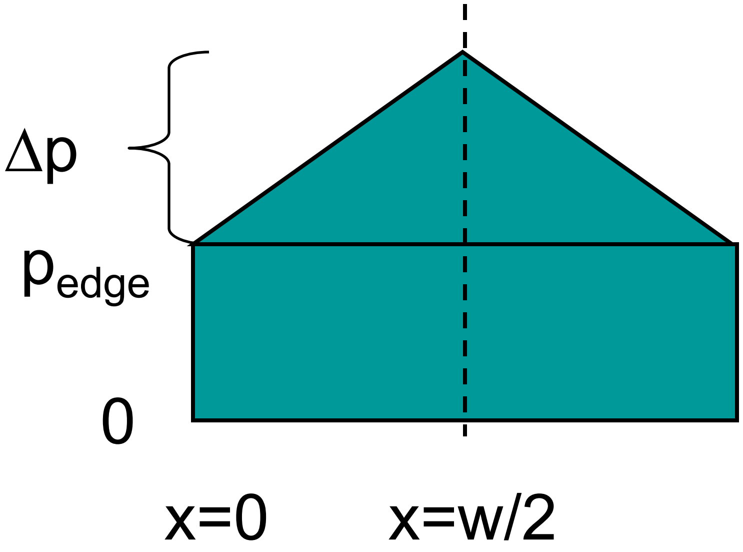
Combining (for $x_k < x < w/2$)

$$\frac{p_x}{2k} = \frac{1}{2\mu}\left(1 - \ln\left(\frac{1}{2\mu}\right)\right) + \frac{x}{h}$$

$$p_x = 1.15 \cdot \sigma_{flow} \cdot \left[\frac{1}{2\mu}\left(1 - \ln\left(\frac{1}{2\mu}\right)\right) + \frac{x}{h}\right]$$

Forging pressure – all sticking approximation

- If $x_k << w$, we can assume all sticking, and approximate the total forging force per unit depth (into the figure) by:



Forging pressure – all sticking approximation

$$p_{edge} = 2k$$

$$\int_{2k}^{p_x} dp = \int_{0}^{x} \frac{2k}{h} dx$$

$$p_x - 2k = \frac{2k}{h}\left(x\right)$$

$$\therefore \frac{p_x}{2k} = \left(1 + \frac{x}{h}\right)$$

$$p_x = 1.15 \cdot \sigma_{flow} \cdot \left(1 + \frac{x}{h}\right)$$

Average forging pressure – all sticking approximation

$$\frac{p_{ave}}{2k} = \frac{\int_{0}^{\frac{w}{2}} \frac{p_x}{2k}\,dx}{w/2} = \frac{\int_{0}^{\frac{w}{2}} \left(1+\frac{x}{h}\right)dx}{w/2} = \frac{\left.\left(x+\frac{x^2}{2h}\right)\right|_{0}^{\frac{w}{2}}}{w/2}$$

$$\frac{p_{ave}}{2k} = \left(1+\frac{w}{4h}\right)$$

$$p_{ave} = 1.15 \cdot \sigma_{flow} \cdot \left(1+\frac{w}{4h}\right)$$

Forging force – all sticking approximation

$$F_{forging} = p_{ave} \cdot width \cdot depth$$

$$F_{forging} = 1.15 \cdot \sigma_{flow} \cdot \left(1 + \frac{w}{4h}\right) \cdot w \cdot depth$$

Sticking and sliding

- If you have both sticking and sliding, and you can't approximate by one or the other,
- Then you need to include both in your pressure and average pressure calculations.

$$F_{forging} = F_{sliding} + F_{sticking}$$

$$F_{forging} = \left(p_{ave} \cdot A\right)_{sliding} + \left(p_{ave} \cdot A\right)_{sticking}$$

Material Models

Strain hardening (cold – below recrystallization point)

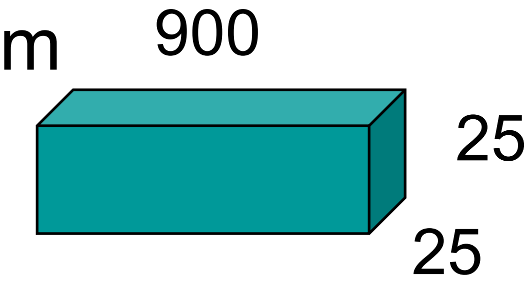
$$\sigma_{flow} = Y = K\varepsilon^{n}$$

Strain rate effect (hot – above recrystallization point)

$$\sigma_{flow} = Y = C\left(\dot{\varepsilon}\right)^{m}$$

$$\dot{\varepsilon} = \frac{1}{h}\frac{dh}{dt} = \frac{v}{h} = \frac{\text{platen velocity}}{\text{instantaneous height}}$$

Forging - Ex. 1-1



- Lead 25 mm x 25 mm x 900 mm
- $\sigma_y = 6.89$ MPa
- $h_f = 6.25$ mm, $\mu = 0.25$
- Show effect of friction on total forging force.
- Use the slab method.
- Assume it doesn't get wider in 900 mm direction.
- Assume cold forging.

Forging - Ex. 1-2

- At the end of forging:

h_f = 6.25 mm, w_f = 100 (conservation of mass)

- Sliding / sticking transition

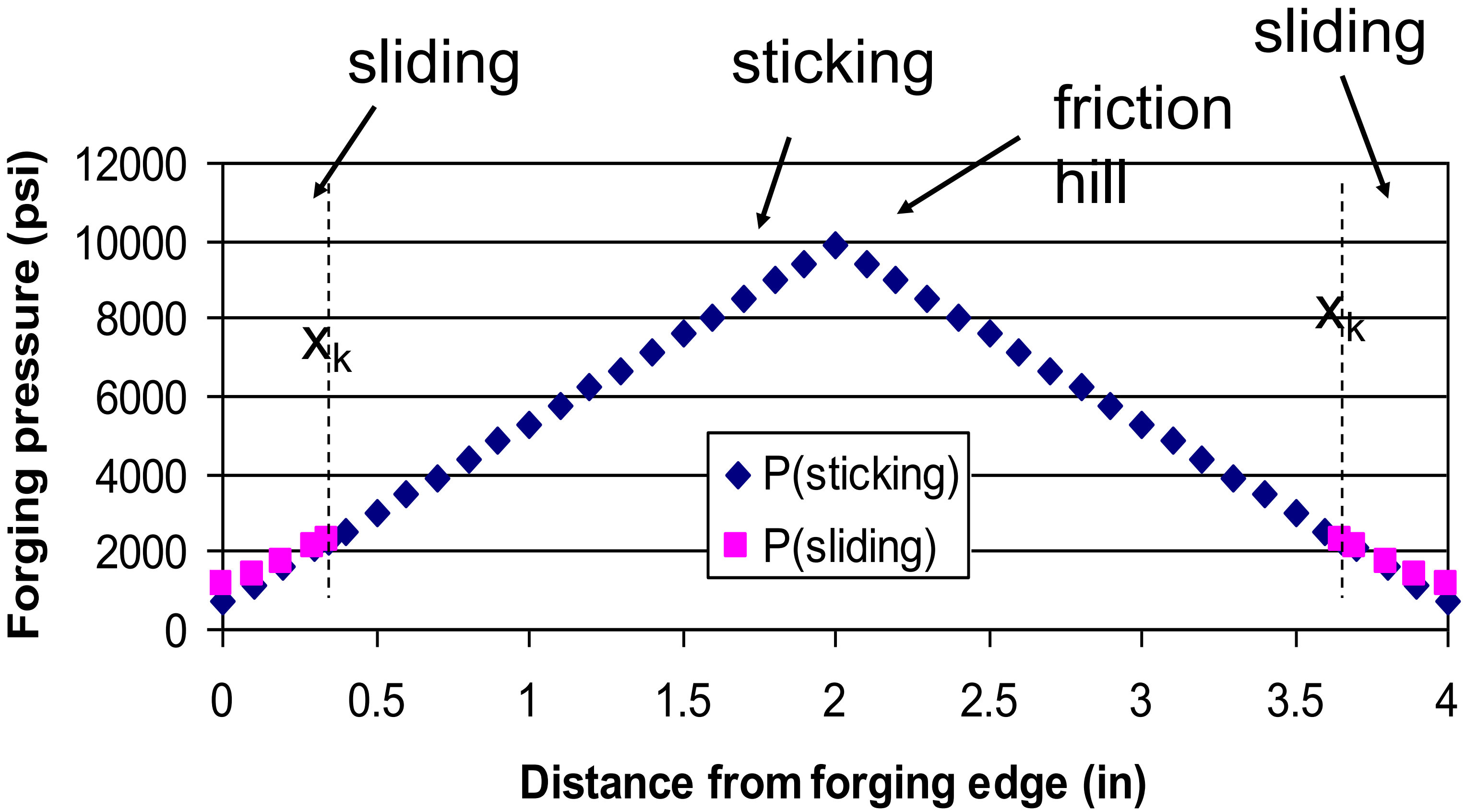
$$\frac{x_k}{h} = \frac{1}{2\mu}\ln\frac{1}{2\mu}$$

Forging - Ex. 1-3

- Sliding region:

$$p_x = 1.15 \cdot \sigma_{flow} \cdot \exp\left(\frac{2\mu x}{h_f}\right)$$

Forging - Ex. 1-5



Forging - Ex. 1-6

- Friction hill
  - forging pressure must be large (8.7x) near the center of the forging to "push" the outer material away against friction

Forging - Ex. 1-7

- Determine the forging force from:

$$Force = \iint p \cdot dA$$

- since we have plane strain

$$\frac{F}{unit\ depth} = \int_0^x p_x dx$$

Forging - Ex. 1-8

- We must solve separately for the sliding and sticking regions

$$F_{forging} = 2\left(\left(\int_{0}^{x_k} p_x dx\right).depth\right)_{sliding} + 2\left(\left(\int_{x_k}^{w/2} p_x dx\right).depth\right)_{sticking}$$

Forging - Ex. 1-16

or since the part is 36” deep:

F(both) = 337 Tonnes

$$F_{forging} = 1.15 \cdot \sigma_{flow} \cdot \left(1 + \frac{w}{4h}\right) \cdot w \cdot depth$$

F(all sticking) = 363 tonnes

$$F_{forging} = 1.15 \cdot \sigma_{flow} \cdot \left(1 + \frac{\mu w}{2h}\right) \cdot w \cdot depth$$

F(all sliding) = 496,800 lbs = 218 tons

Can we use exact solution for this???

All sticking over-estimates actual value.

Forging – Effect of friction

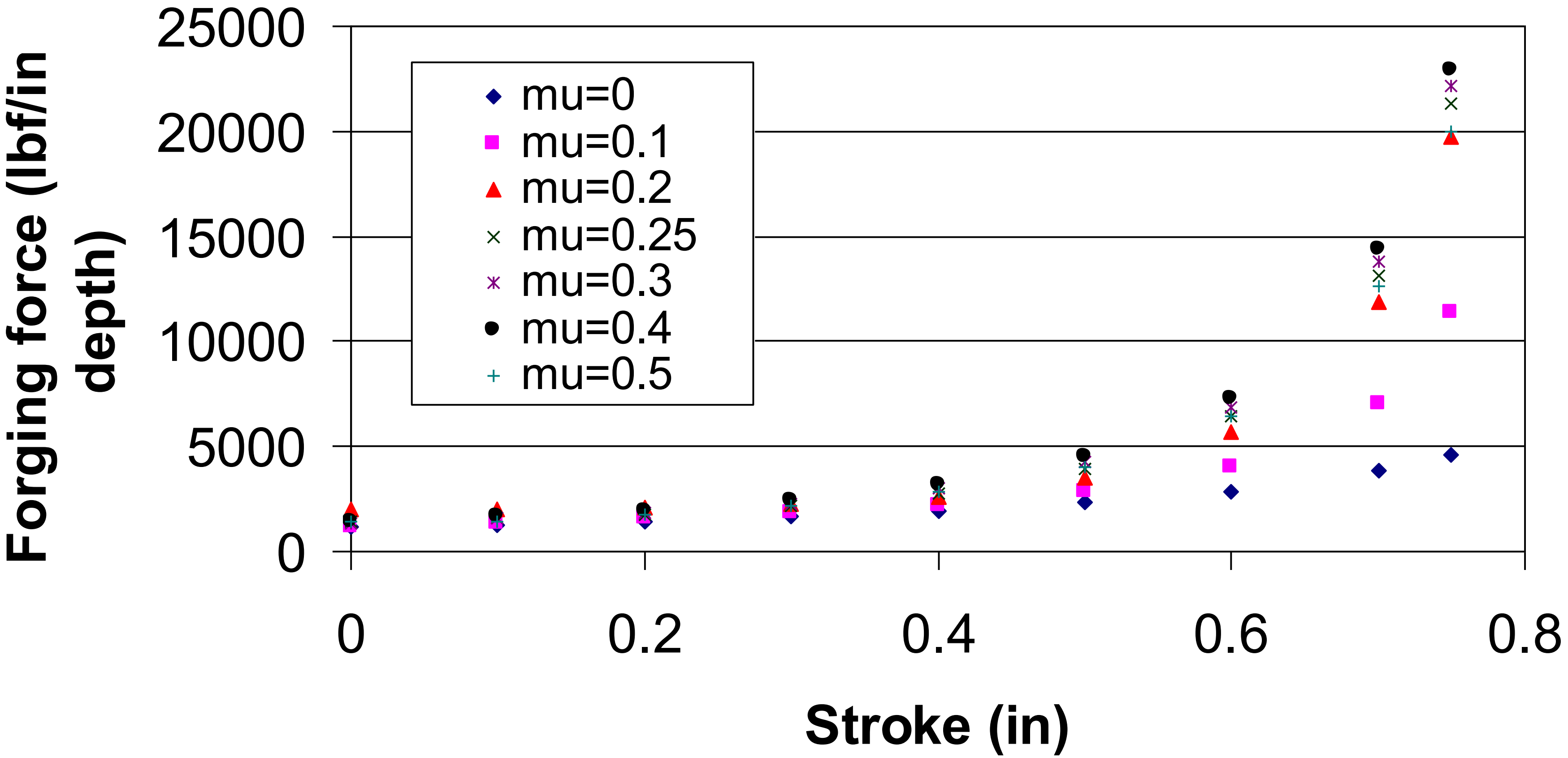
- Effect of friction coefficient (μ) – all sticking

Friction coefficient	Fmax (lbf/in depth)	xk	Stick/slide
0	4600	2	slide
0.1	11365	2	slide
0.2	19735	0.573	both
0.25	21331	0.347	both
0.3	22182	0.213	both
0.4	22868	0.070	both
0.5	23000	0	stick

- Friction is very important

Forging - Ex. 1-17

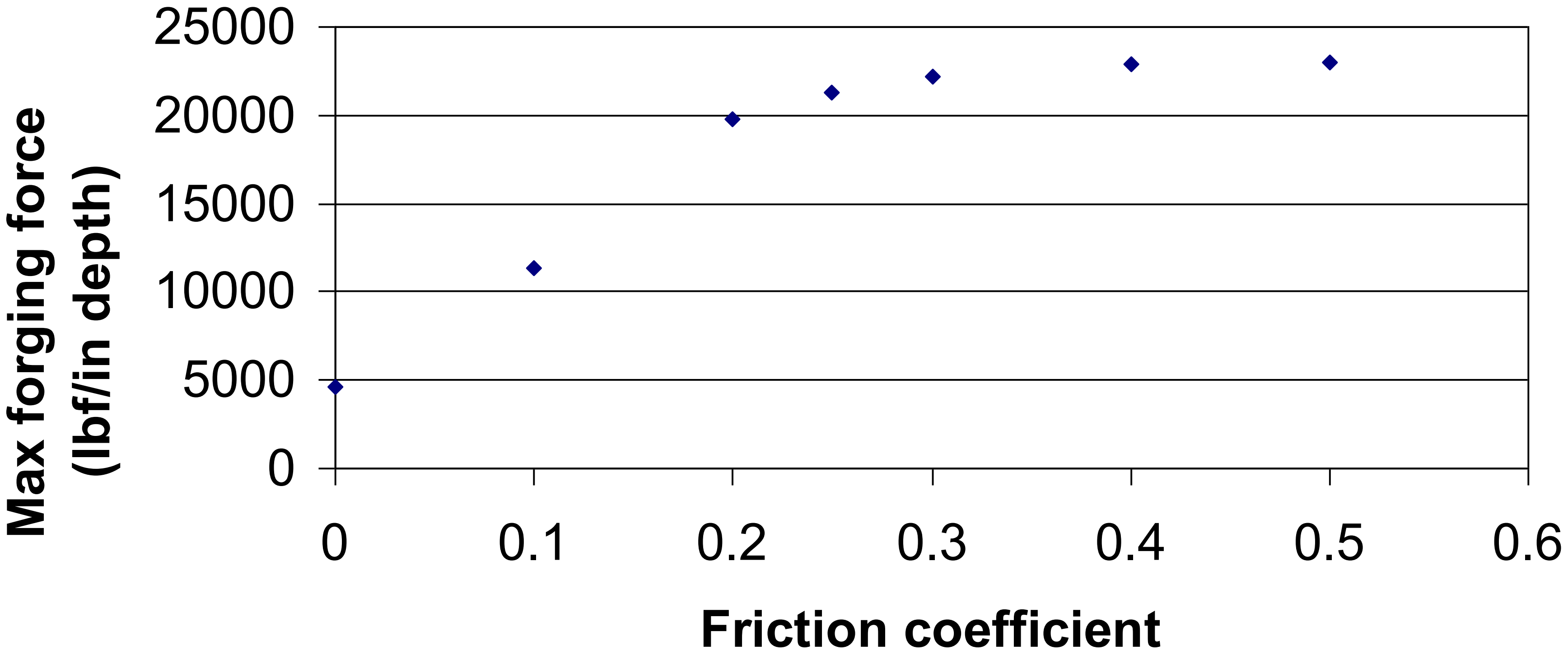
Forging force vs. stroke – all sticking



Forging - Ex. 1-19

Maximum forging force vs. friction coefficient (μ)

all sticking



Deformation Work

In general, work done in bulk deformation processes has three components

Total work, $W = W_{ideal} + W_{friction} + W_{redundant}$

Work of ideal plastic deformation, W_{ideal}

= (area under true stress-true strain curve)(volume)

$$= (\text{volume})\left(\int_0^{\varepsilon_t} \sigma_t \, d\varepsilon_t\right)$$

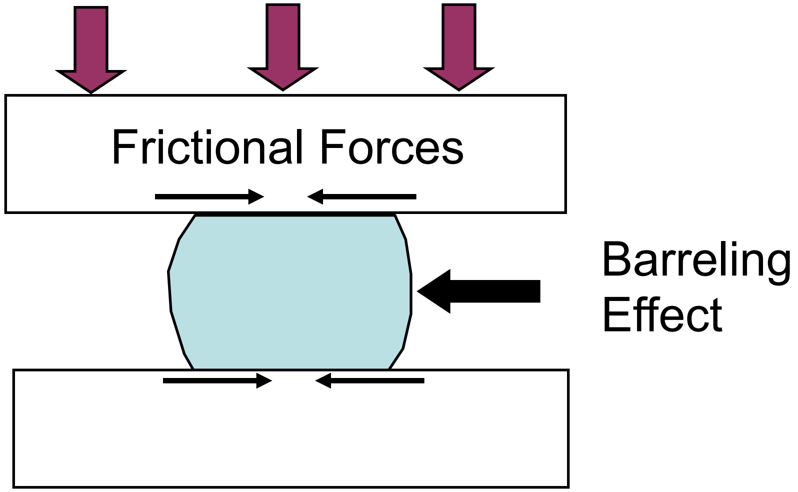
For a true stress-true strain curve $\sigma_t = K\varepsilon_t^n$:

$$\boxed{W_{ideal} = (\text{volume})\left(\frac{K\varepsilon_t^{n+1}}{n+1}\right) = (\text{volume})\bar{Y}_f \varepsilon_t}$$

$\bar{Y}_f = \text{Avg. flow stress}$

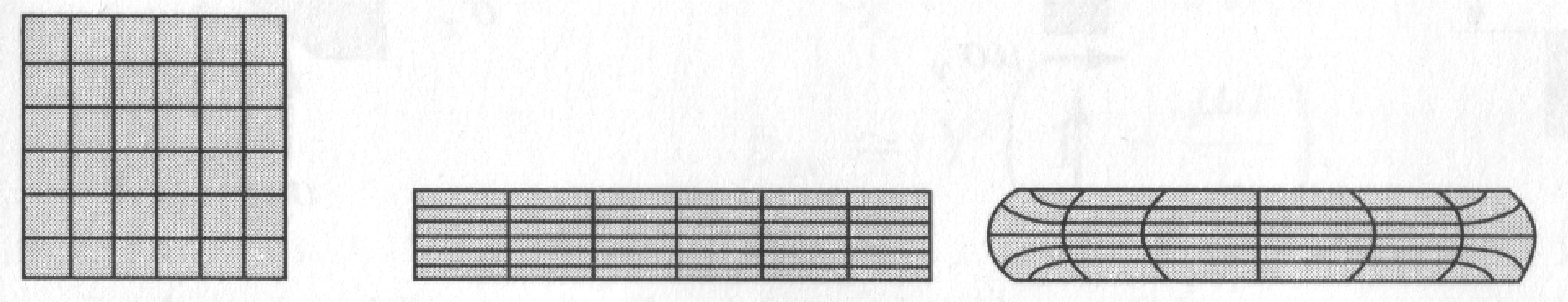
Deformation Work

Friction between dies and workpiece causes inhomogeneous (non-uniform) deformation called barreling



Deformation Work

Internal shearing of material requires redundant work to be expended



Ideal Deformation

Redundant Deformation

Redundant Zone

Closed/Impression Die Forging

- Analysis more complex due to large variation in strains in different parts of workpiece

- Approximate approaches

  - Divide forging into simple part shapes e.g. cylinders, slabs etc. that can be analyzed separately

  - Consider entire forging as a simplified shape

Closed/Impression Die Forging

Steps in latter analysis approach

- ***Step 1***: calculate average height from volume *V* and total projected area A_t of part (including flash area)

$$h_{avg} = \frac{V}{A_t} = \frac{V}{Lw}$$

- ***Step 2***:

$$\varepsilon_{avg} = \text{avg. strain} = \ln\left(\frac{h_i}{h_{avg}}\right)$$

$$\dot{\varepsilon}_{avg} = \text{avg. strain rate} = \frac{v}{h_{avg}}$$

Closed/Impression Die Forging

- ***Step 3***: calculate flow stress of material Y_f for cold/hot working

- ***Step 4***:

$$\text{Avg. forging load} = F_{avg} = K_p Y_f A_t$$

K_p = pressure multiplying factor

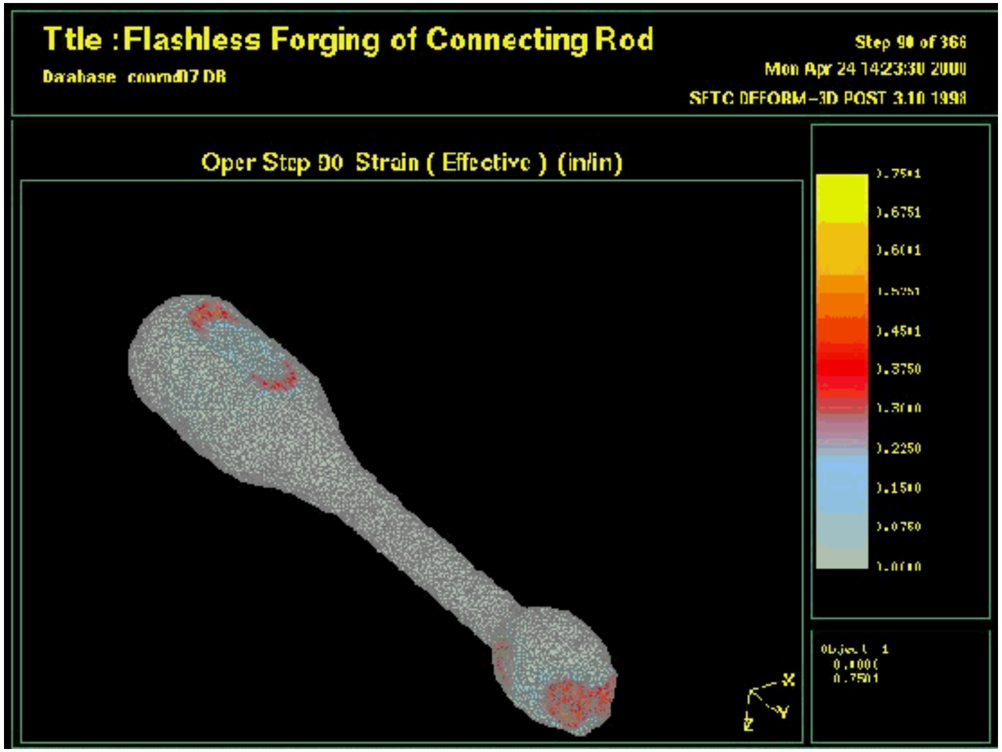
= 3~5 for simple shapes without flash

= 5~8 for simple shapes with flash

= 8~12 for complex shapes with flash

Other Analysis Methods

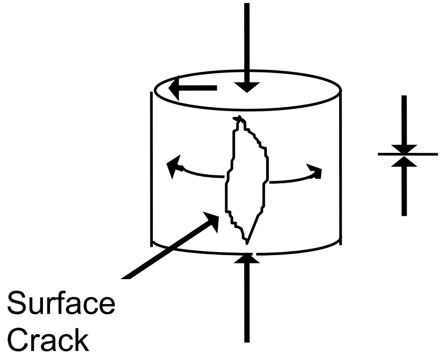
- Complex closed die forging simulated using finite element software



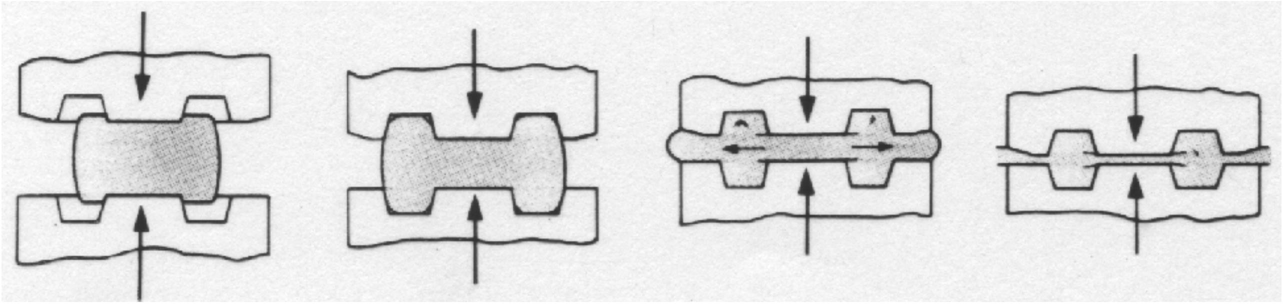
Source: http://nsmwww.eng.ohio-state.edu/html/f-flashlessforg.html

Forging Defects

- Surface cracking due to tensile stresses

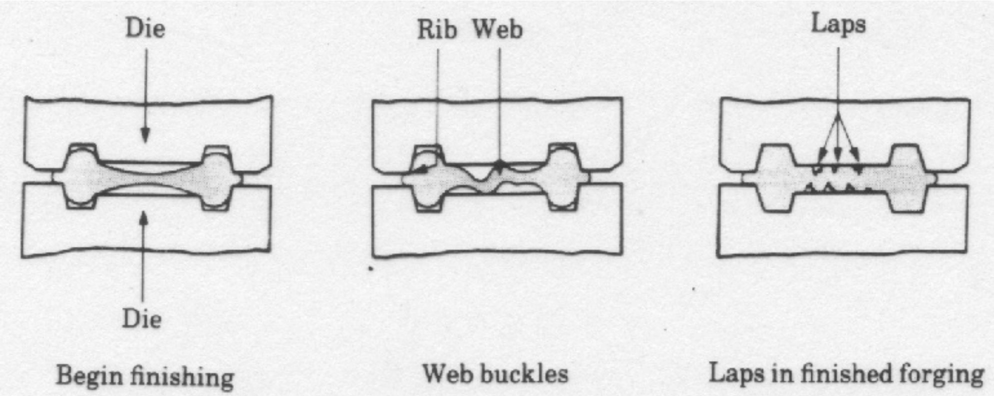


- Internal cracking in thick webs

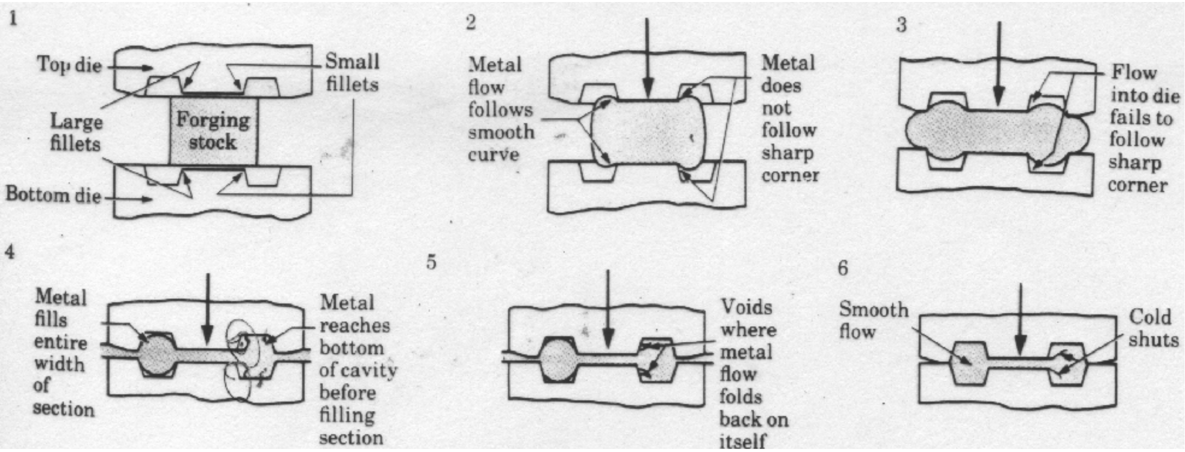


Forging Defects

- Laps due to buckling of thin webs



- Cold shuts due to small radii fillets in die



Summary

- What is bulk deformation?
- Cold vs hot working
- Forging analysis
  - Slab analysis
- Forging defects