

# Bulk Deformation - 1

# ME 206

# Manufacturing Processes 1

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



# Outline

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

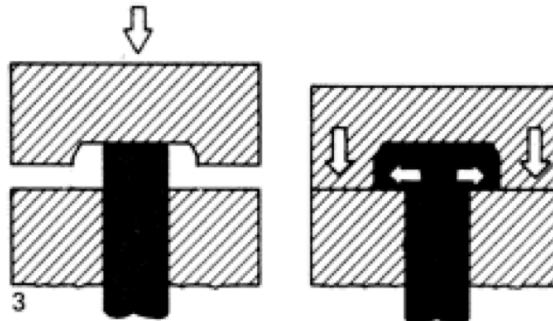


# What is bulk deformation?

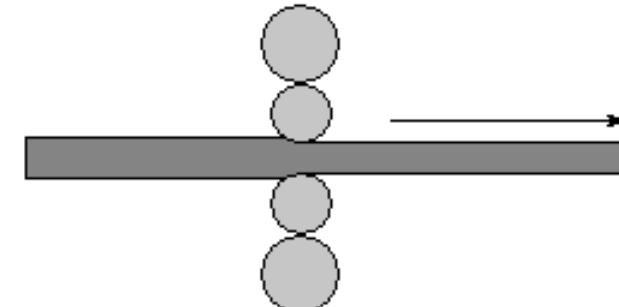
- Bulk deformation (or forming): processes characterized by large amount of plastic deformation (large strains) carried out at elevated or room temperature
- Bulk plastic flow of material under uniaxial or multi-axial stresses dominated by compression
- Mass conserving processes → volume is constant

# Bulk Deformation Processes

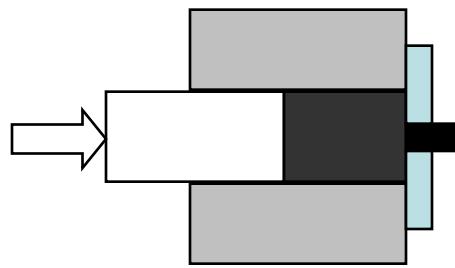
- Examples include: forging, rolling, extrusion, rod drawing etc.



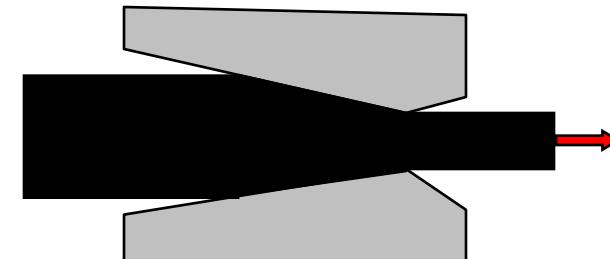
Forging (heading)



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

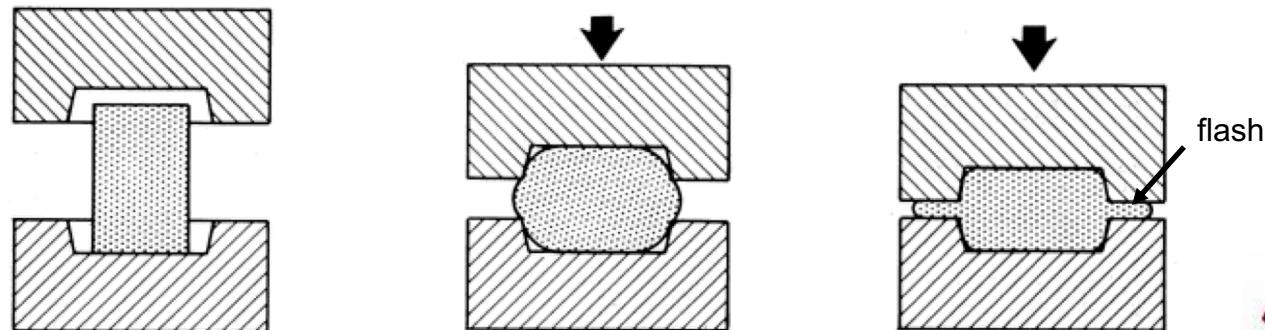
- Easily forms oxide layers (scales) on surface → poor surface finish
- Harder to control dimensions

# 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

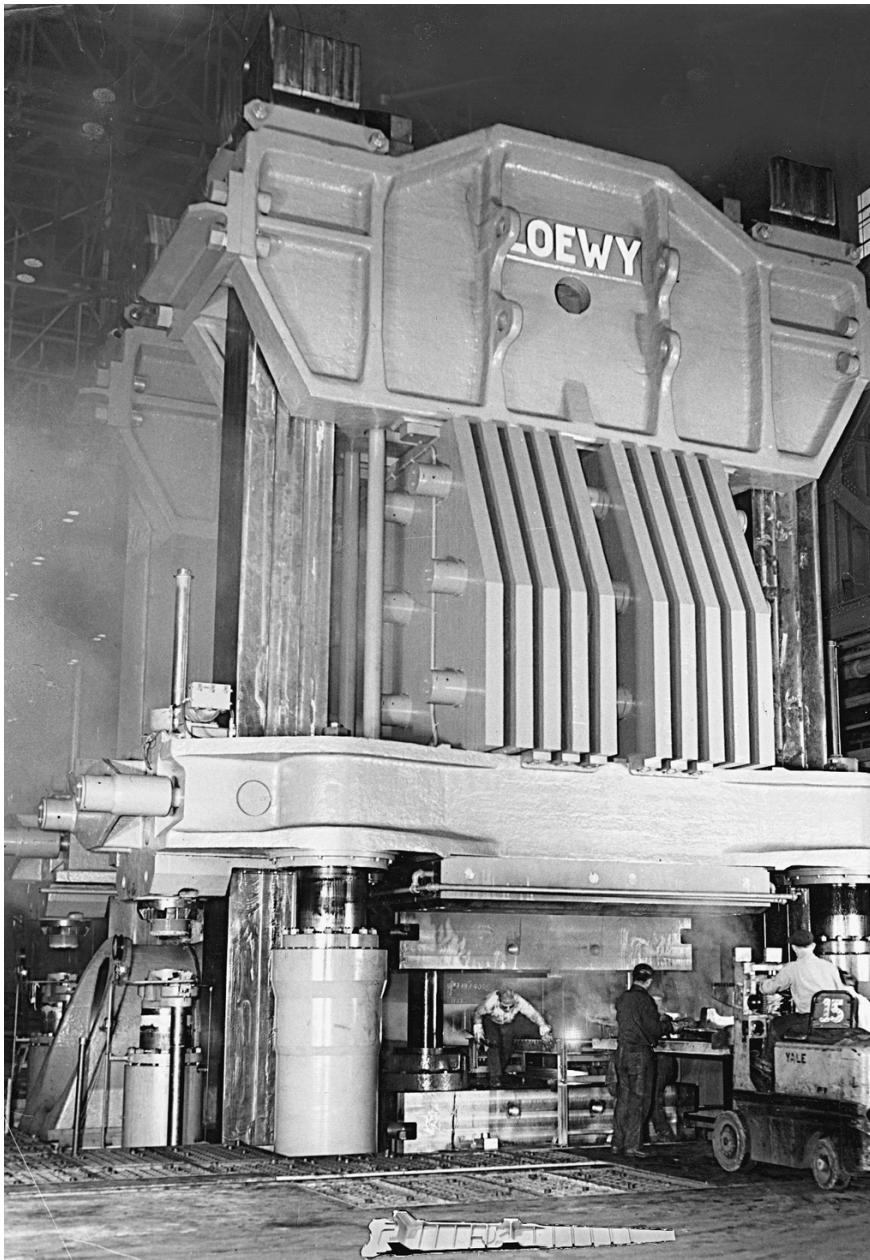
- Large machines
  - hold dies
  - form parts



# Press types

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



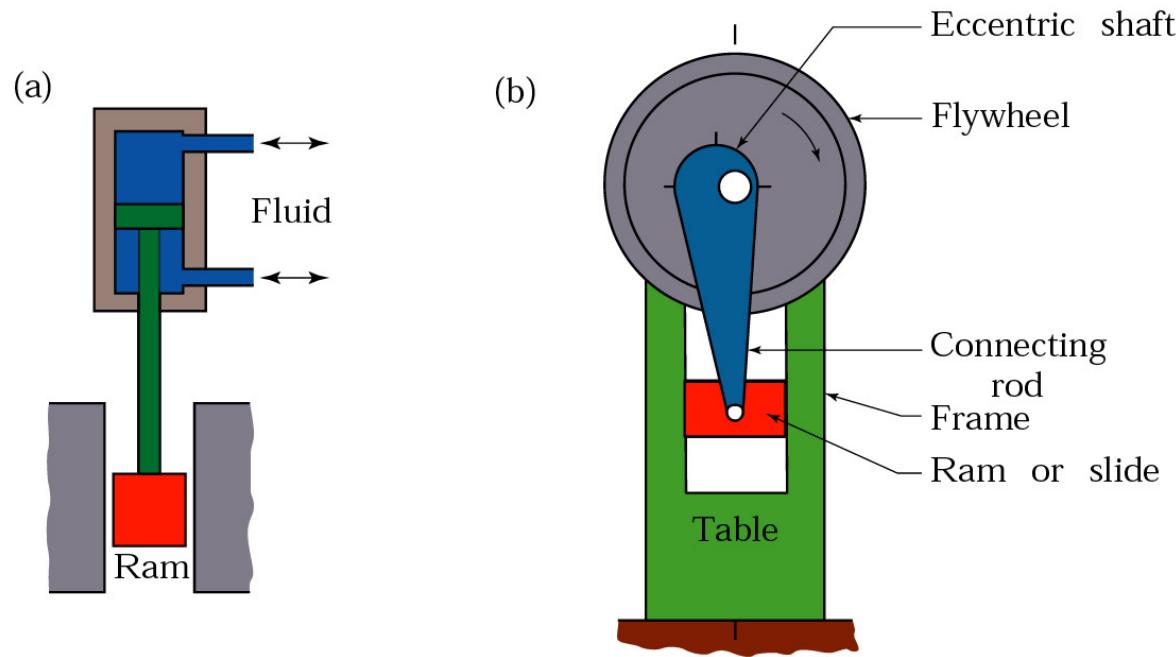


50,000 ton  
press

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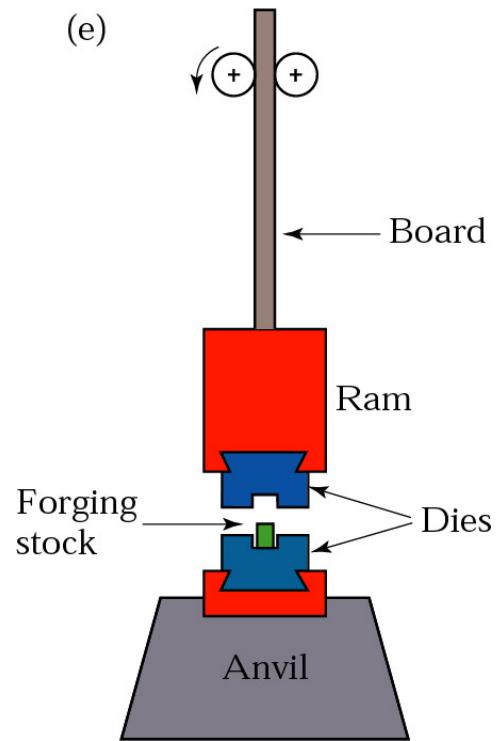
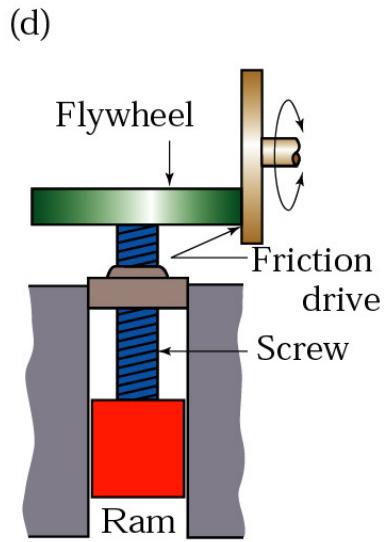
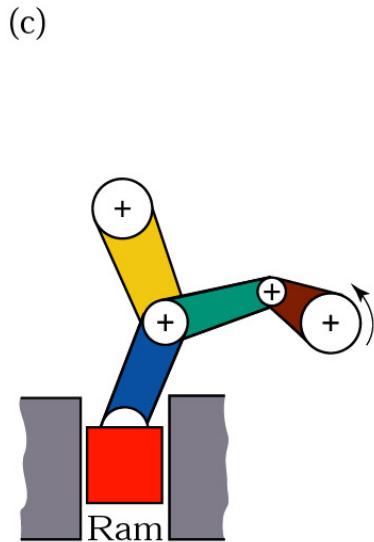


# Forges



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
  - $\text{MoS}_2$
  - glass
  - graphite



# Lubrication purposes

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

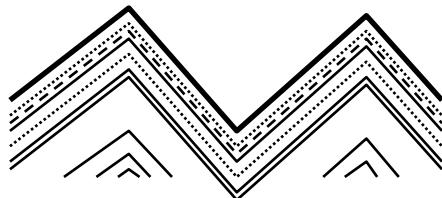
# Forging steps

- 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

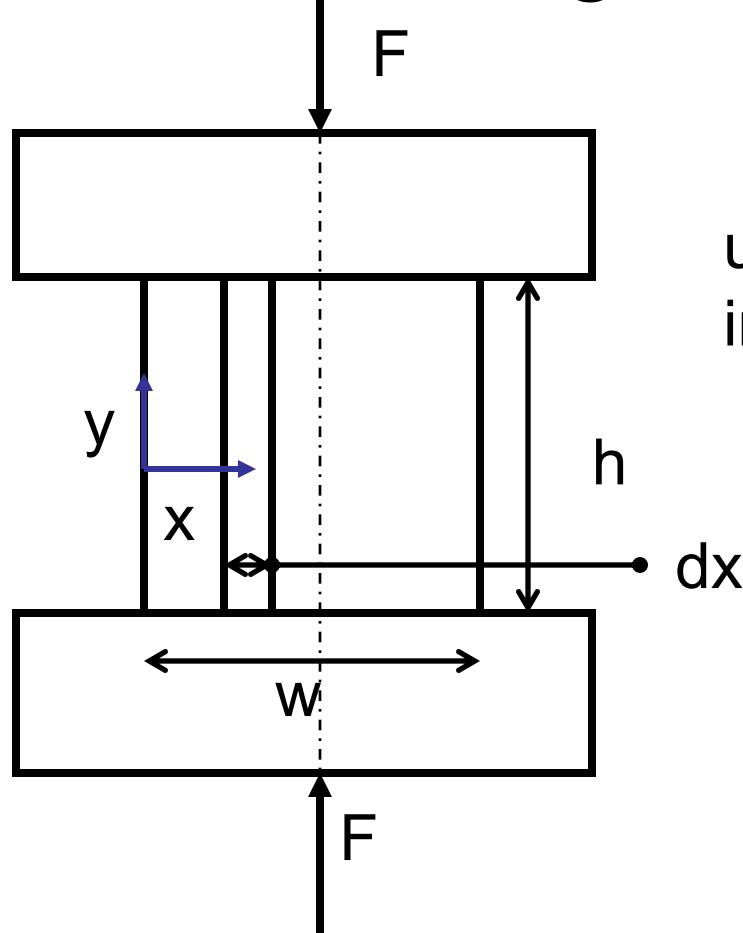
Source: <http://www.forging.org>

# Slab analysis assumptions

- Entire forging is plastic
  - no elasticity
- Material is perfectly plastic
  - strain hardening and strain rate effects later
- Friction coefficient ( $\mu$ ) 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

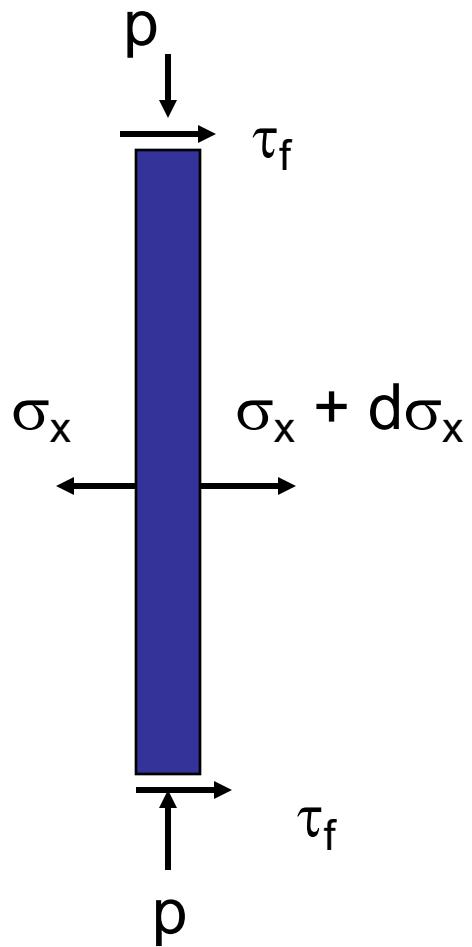


# Open die forging analysis – rectangular part



unit depth  
into figure

# Expanding the $dx$ slice on LHS



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

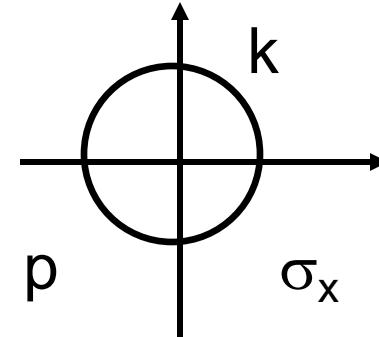
# Force balance in x-direction

$$hd\sigma_x + 2\tau_{friction}dx = 0$$

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

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

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

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

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

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

# Sliding region

$$\int \frac{dp}{p} = \int_0^x \frac{2\mu}{h} dx$$

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



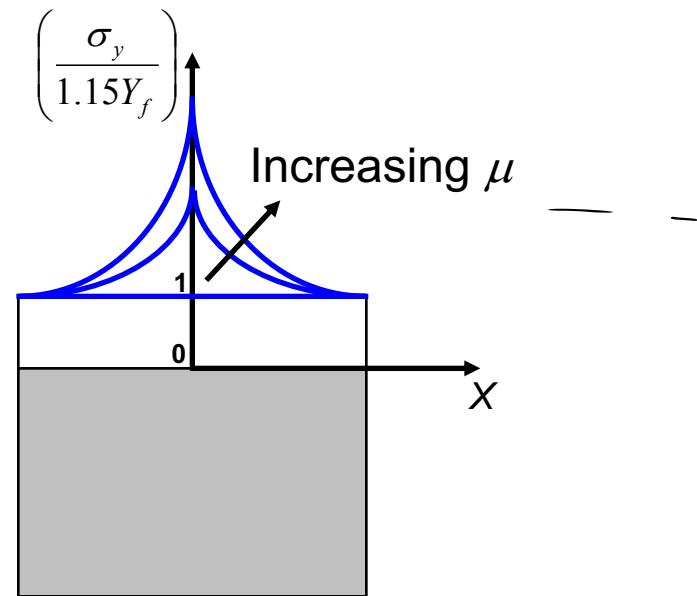
# Forging pressure – sliding region

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

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  $|x| \leq 1$

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

yields

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

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

# Average forging pressure – all sliding approximation

- using the Taylor's series approximation

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

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

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

N.B done on a  
per unit depth basis



# Forging force – all sliding approximation

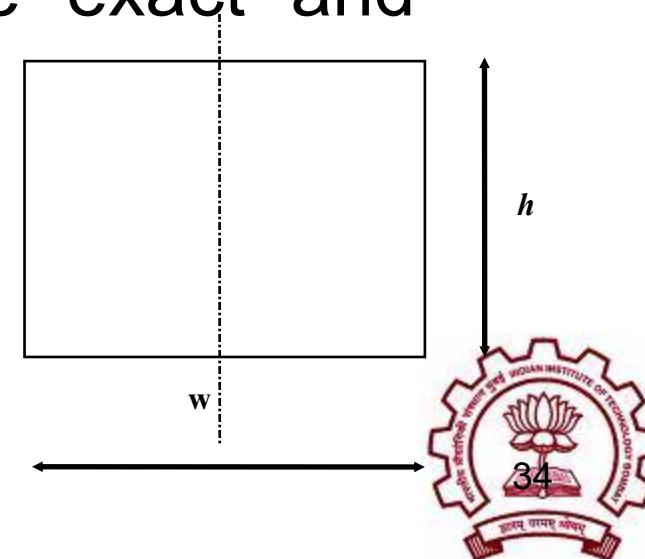
$$F_{forging} = p_{ave} \cdot width \cdot depth$$

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



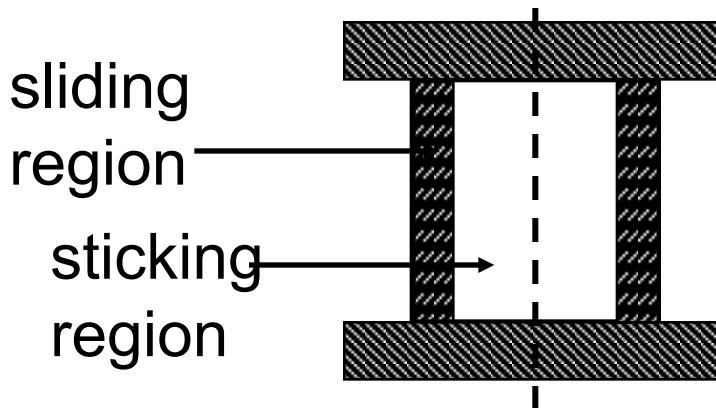
# Example Problem

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  $\mu = 0.3$ . 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  $\tau_f < \tau_{\text{flow}}$
- Sticking if  $\tau_f \geq \tau_{\text{flow}}$ 
  - 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  $\tau_{\text{flow}}$



# Sliding / sticking transition

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

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

- hence:

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



# Sticking region

$$dp = \frac{2\mu}{h} pdx$$

- Using  $p = k/\mu$

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

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

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



# 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  $x_k < x < w/2$ )

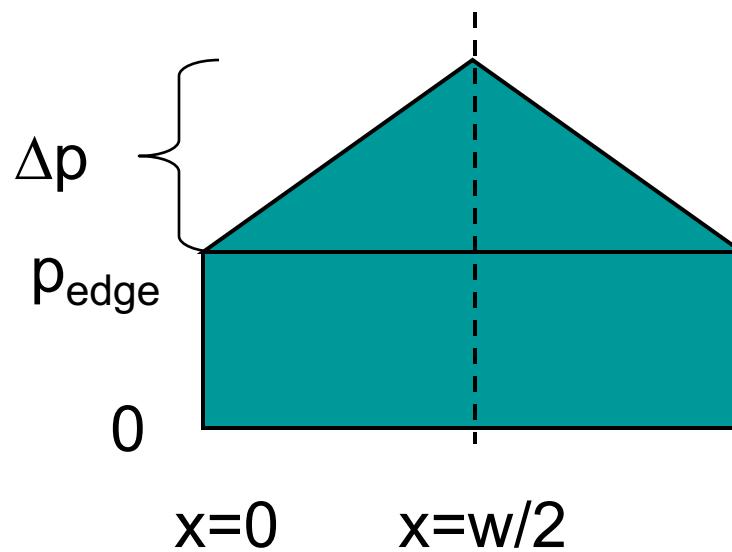
$$\frac{p_x}{2k} = \frac{1}{2\mu} \left( 1 - \ln \left( \frac{1}{2\mu} \right) \right) + \frac{x}{h}$$

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



# Forging pressure – all sticking approximation

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



# Forging pressure – all sticking approximation

$$p_{edge} = 2k$$

$$\int_{2k}^{p_x} dp = \int_0^x \frac{2k}{h} dx \quad p_x - 2k = \frac{2k}{h}(x)$$

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

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



# Average forging pressure – all sticking approximation

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

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

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

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# 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.

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

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



# Material Models

Strain hardening (cold – below recrystallization point)

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

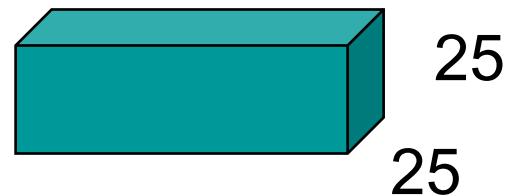
Strain rate effect (hot – above recrystallization point)

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

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

# Forging - Ex. 1-1

- Lead 25 mm x 25 mm x 900 mm
- $\sigma_y = 6.89 \text{ MPa}$
- $h_f = 6.25 \text{ mm}$ ,  $\mu = 0.25$
- 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:

$h_f = 6.25 \text{ mm}$ ,  $w_f = 100$  (conservation of mass)

- Sliding / sticking transition

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

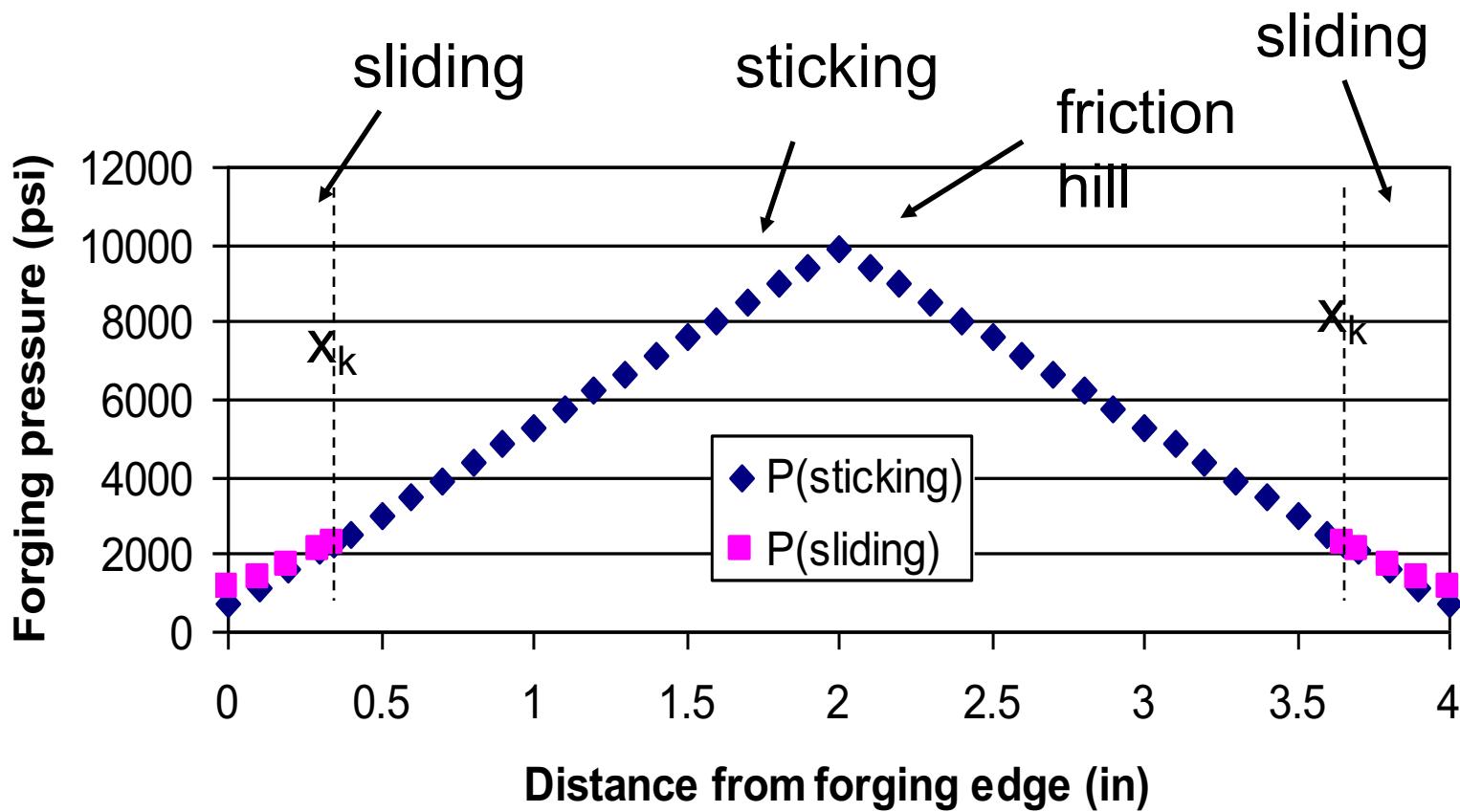


# Forging - Ex. 1-3

- 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

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



# 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:

$F(\text{both}) = 337 \text{ Tonnes}$

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

$F(\text{all sticking}) = 363 \text{ tonnes}$

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

$F(\text{all sliding}) = 496,800 \text{ lbs} = 218 \text{ tons}$

Can we use exact solution for this???

All sticking over-estimates actual value.



# Forging – Effect of friction

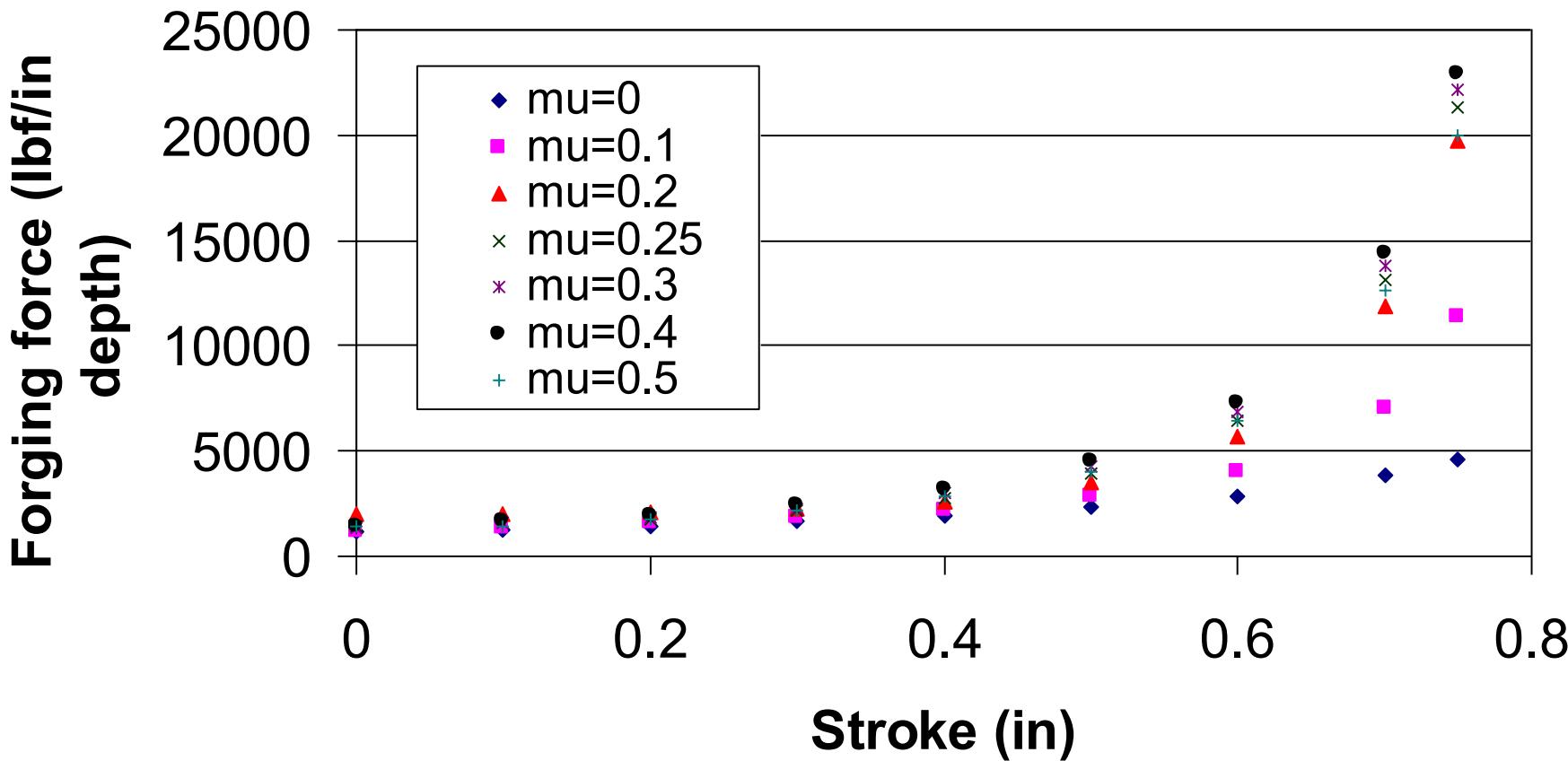
- Effect of friction coefficient ( $\mu$ ) – all sticking

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

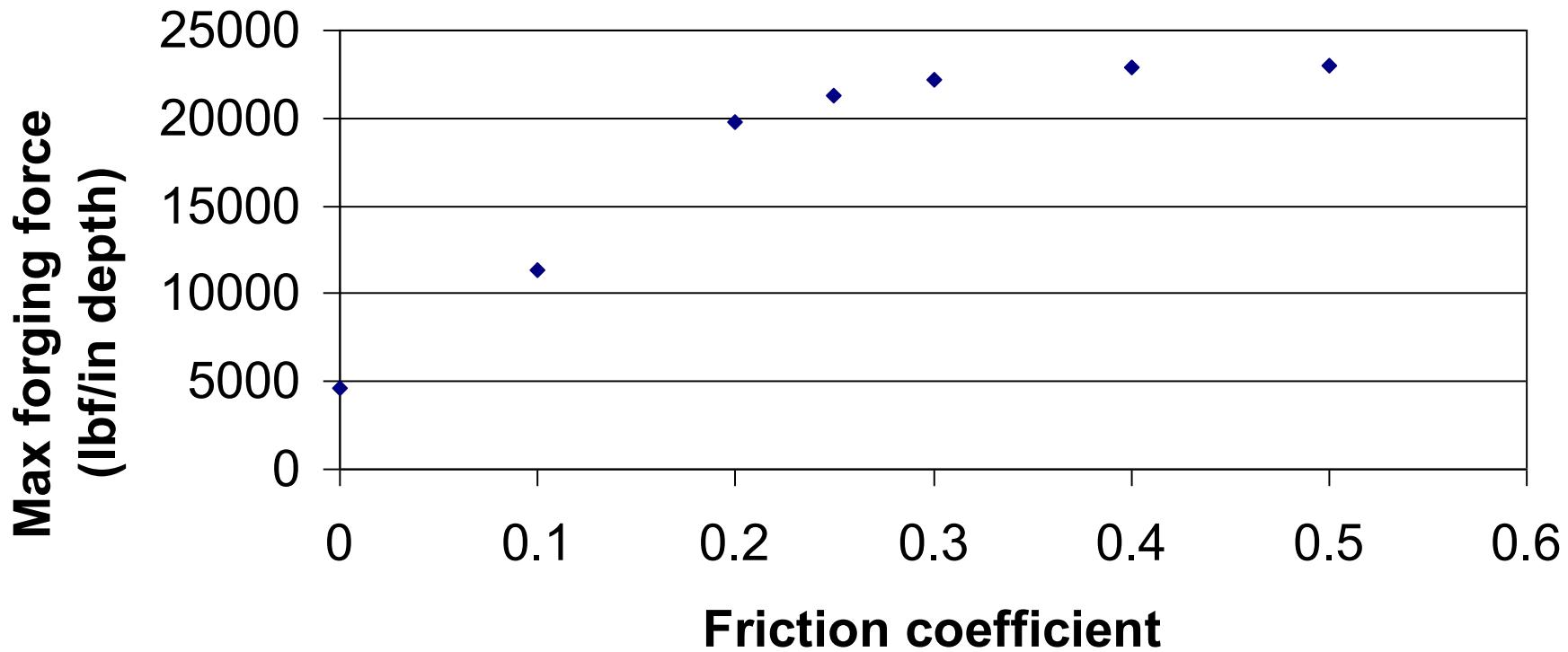
# Forging - Ex. 1-17

## Forging force vs. stroke – all sticking



# Forging - Ex. 1-19

Maximum forging force vs. friction coefficient ( $\mu$ )  
all sticking



# Deformation Work

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

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

Work of ideal plastic deformation,  $W_{ideal}$

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

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

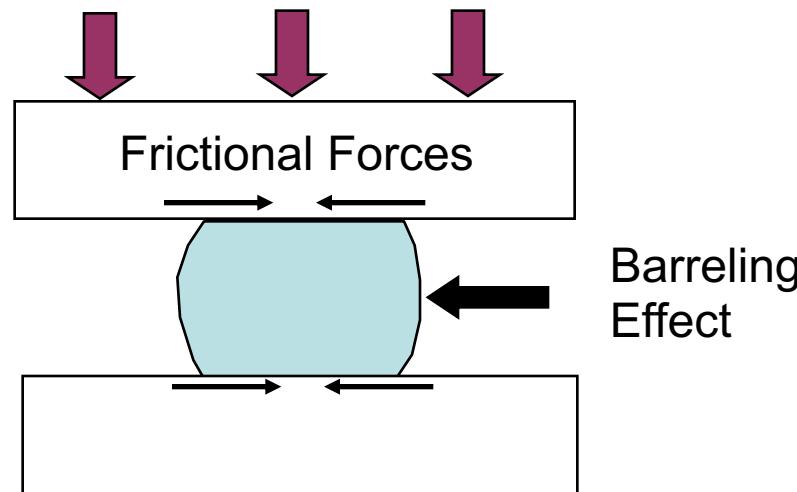
For a true stress-true strain curve  $\sigma_t = K\varepsilon_t^n$  :

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

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

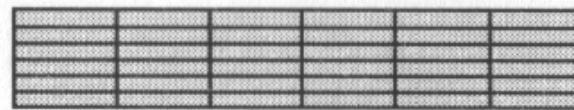
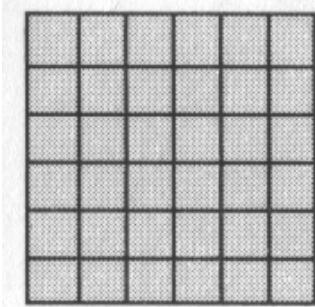
# Deformation Work

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

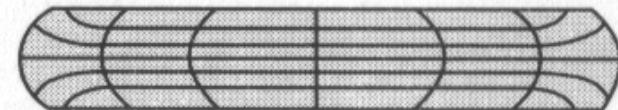


# Deformation Work

Internal shearing of material requires redundant work to be expended

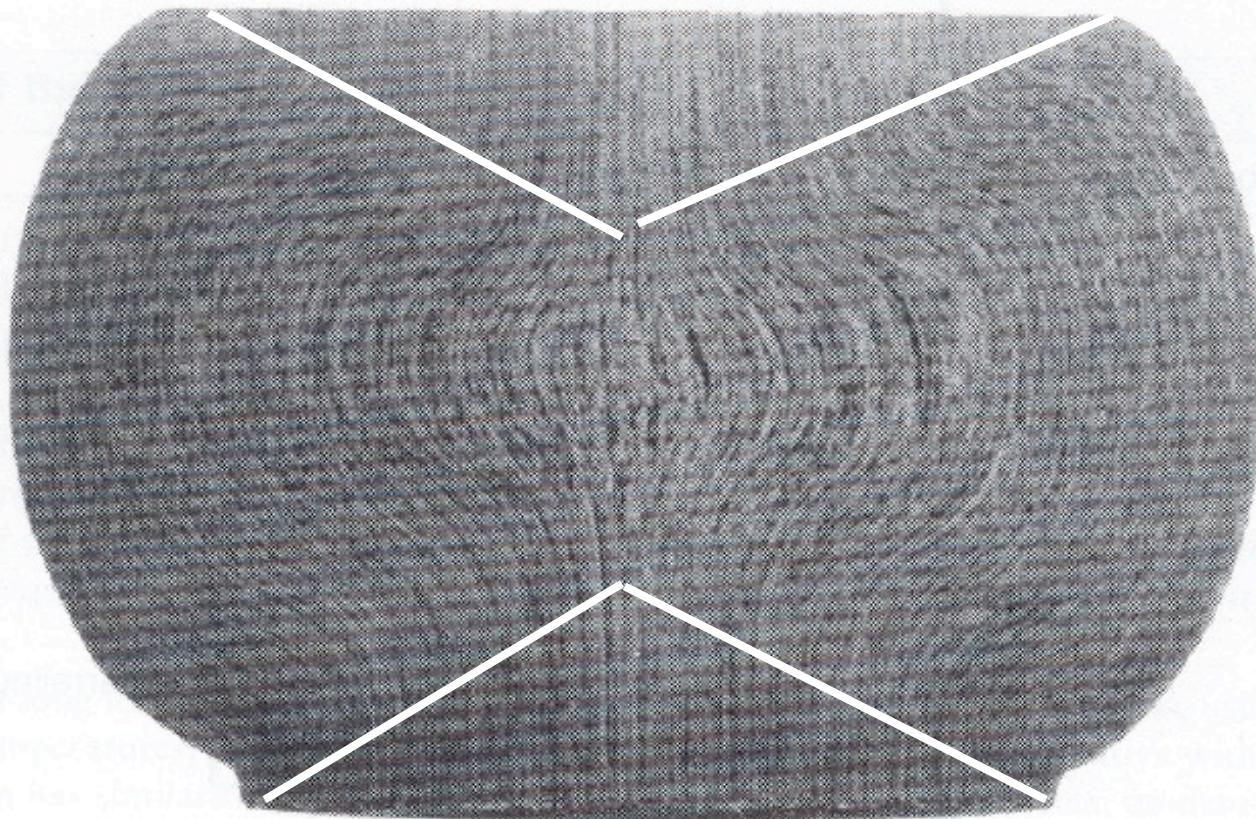


**Ideal Deformation**



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

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

# 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

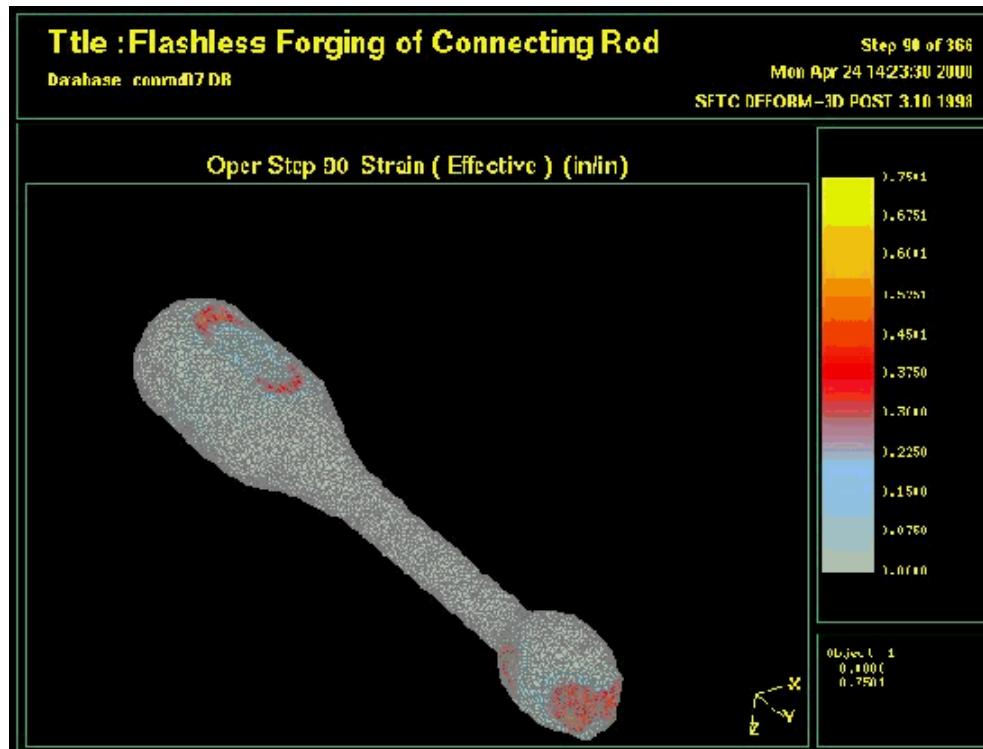
= 3~5 for simple shapes without flash

= 5~8 for simple shapes with flash

= 8~12 for complex shapes with flash

# Other Analysis Methods

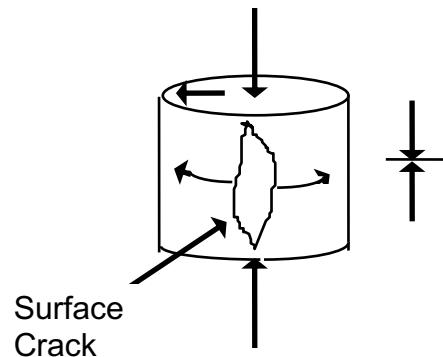
- Complex closed die forging simulated using finite element software



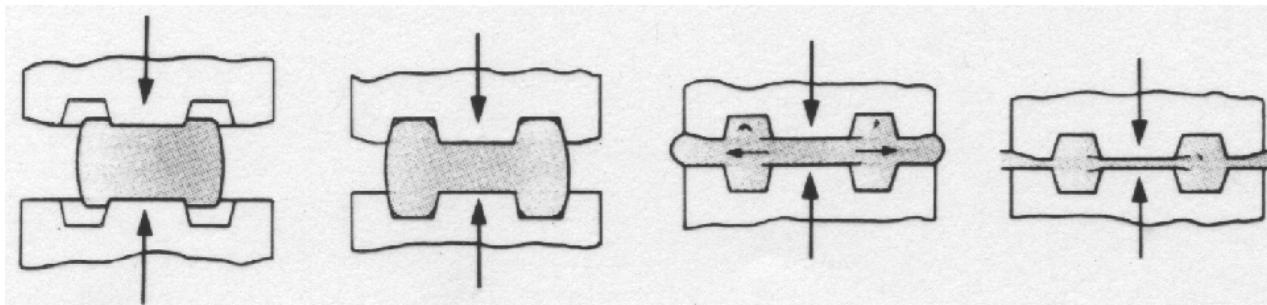
Source: <http://nsmwww.eng.ohio-state.edu/html/f-flashlessforg.htm>

# Forging Defects

- Surface cracking due to tensile stresses

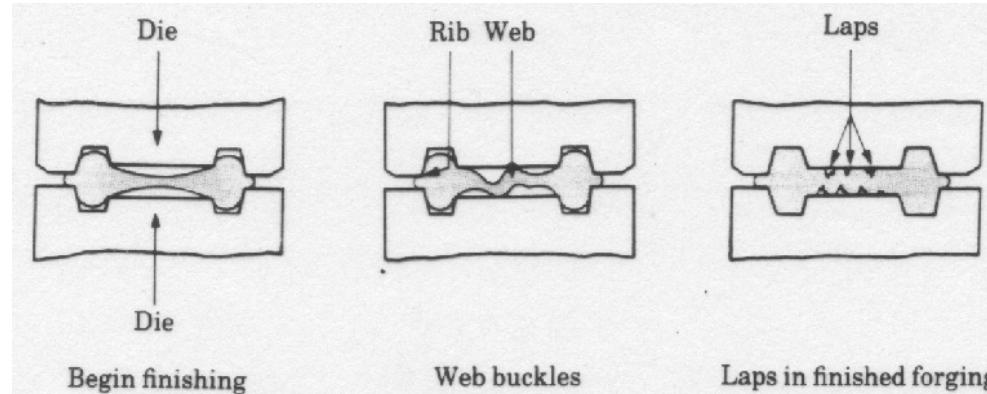


- Internal cracking in thick webs

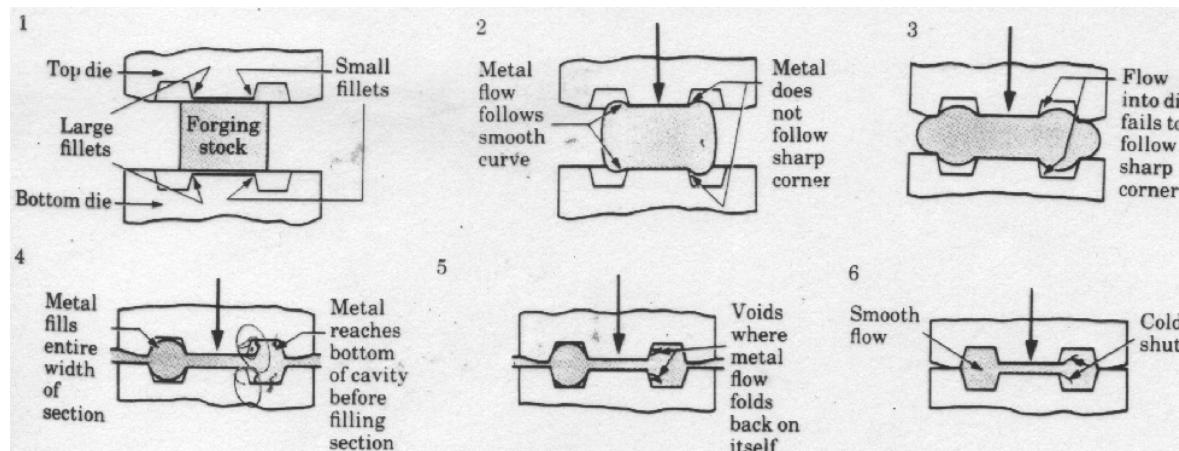


# Forging Defects

- 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