University of Basrah
College of Engineering
Mechanical Engineering Department
MANUFACTURING PROCESSES (ME337), 3rd Year (2019-2020)
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4. Forging Processes

Introduction:

- It is a deformation process in which the w.p. is compressed between two dies, using either impact or gradual pressure to form the part.
- Forging is carried out in many different ways:
  (1) **By working temperature:** hot or warm to reduce strength and increase ductility of w.p. Cold forging to increase strength by strain hardening.
  (2) **By applied pressure:** either impact or gradual pressure is applied in forging process. The forging machine that applies an impact load is called a “forging hammer” while one that applies a gradual pressure is called a “forging press”.
  (3) **By forging dies used:** the flow of metal in forging dies is either constrained or not constrained. By this classification, there are three types of forging operations as shown in figure (3-37): **(a) open-die forging, (b) impression-die forging and (c) flashless forging**

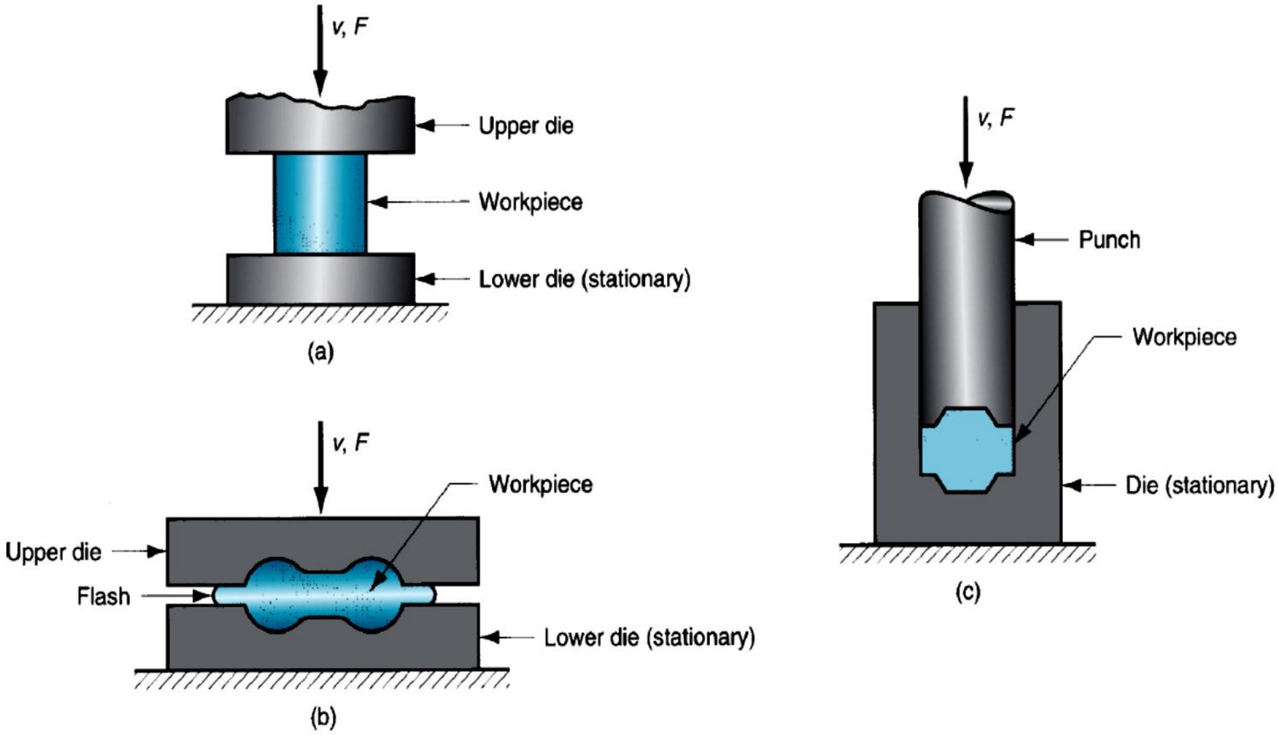


Figure (3-37) three types of forging operation: (a) open-die forging, (b) impression-die forging, (c) flashless forging

Open-Die Forging:

- W.P. is compressed between two flat (or almost flat) dies, thus allowing the metal to flow without constraint in a lateral direction.
- Simple case of open-die involves w.p. of cylindrical cross-section between two flat dies.
- This operation, known as "**upsetting**" or "**upset forging**", reduces height of w.p. and increases its diameter.

Analysis of Open-Die Forging:

(1) Ideal Deformation:

- Under ideal conditions (no friction between w.p. and die surfaces, homogeneous deformation, radial flow of material is uniform throughout its height) as illustrated in figure (3-38).

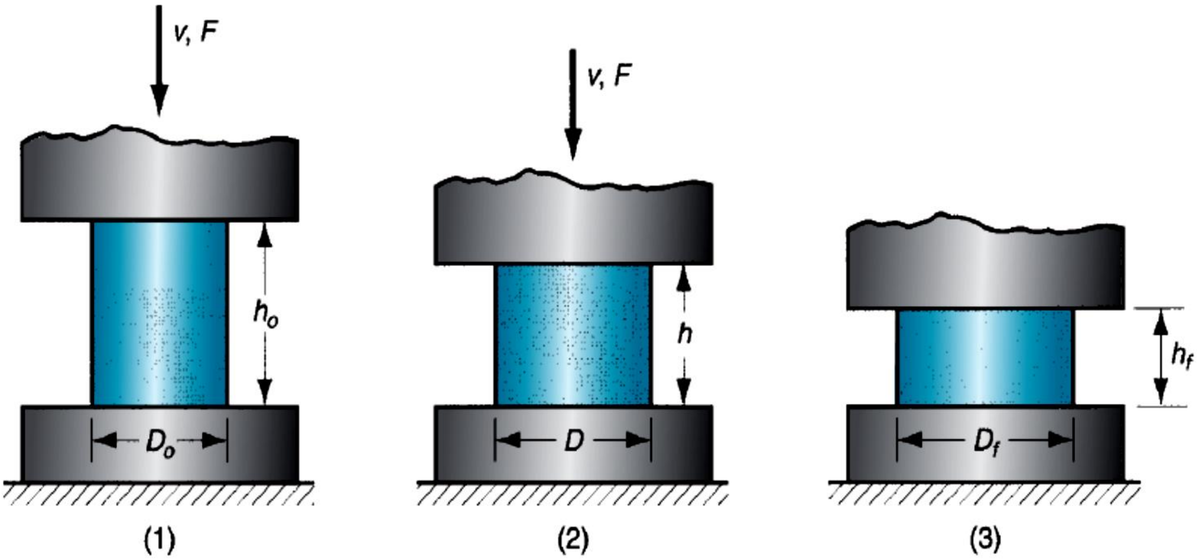


Figure (3-38) homogeneous deformation in open-die forging: (1) start process (2) partial compression and (3) final size

- **True strain:**

$$\varepsilon = \ln \frac{h_o}{h}$$

h_o: starting height of w.p.

h: height at some intermediate point in the process

- **True strain rate:**

$$\dot{\varepsilon} = -\frac{v}{h}$$

v**:** velocity of moved die or punch.
-*ve sign*: indicates the decrease in height

- **Engineering strain rate:**

$$\dot{e} = -\frac{v}{h_o}$$

- **Forging force:**

$$F_{fg} = Y_f A$$

F_{fg}: forging force required to continue the compression at any given height h.

Y_f: flow stress corresponding to the true strain (ε**).**

A: corresponding cross-sectional area obtained from volume constancy.

- **Flow stress:**

$$Y_f = K\varepsilon^n$$

- **Volume constancy:**

$$V_o = V$$
$$A_o h_o = Ah$$

V_o: original volume of w.p.

V: volume of w.p. at any point during deformation

- **Reduction in height:**

$$RH = \frac{h_o - h}{h_o}\%$$

Notes:

- Area A continuously increases as h is reduced.
- $\boldsymbol{Y_f}$ also increases as a result of strain hardening except when metal is perfectly plastic (as in hot working). In this case **$n=0.0$, Y_f=yield strength of w.p.**
- F_{fg} is maximum at end of forging process, when A and Y_f are maximum.
- Because volume is constant during forging process, then, when h is decreased, the diameter of w.p. is increased.

(2) Actual Deformation:

- Because friction opposes the flow of metal at the die surfaces, this creates the barreling effect as shown in figure (3-39).

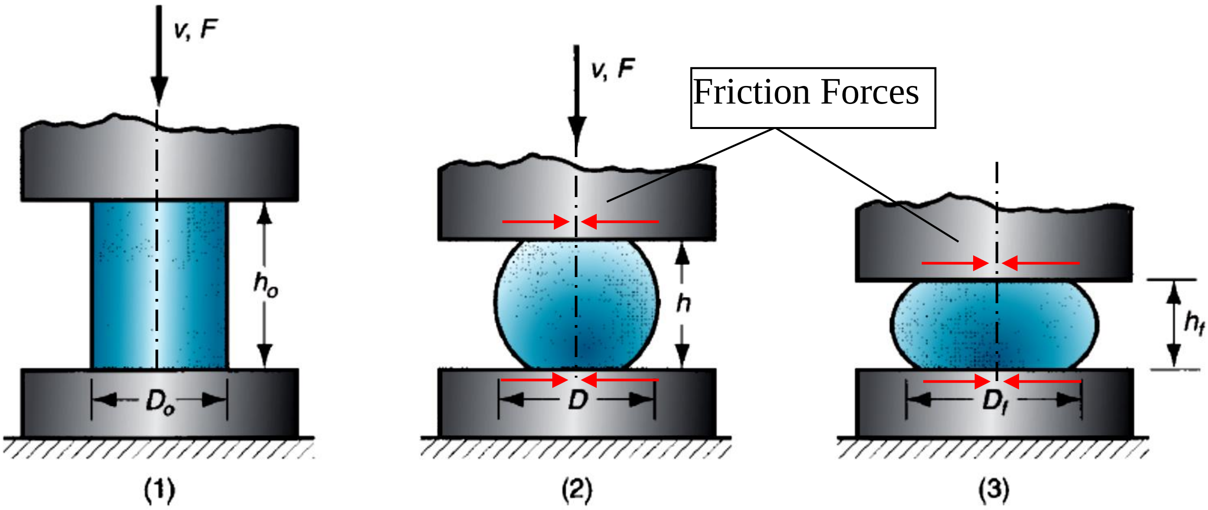


Figure (3-39) actual deformation: (1) start of process, (2) partial deformation and (3) final shape

- Barreling effect is more pronounced when performed on hot w.p. with cold dies.
- This is because higher friction coefficient in hot working and heat transfer at and near the die surfaces which cools the w.p. and increases its resistance to deformation.
- The hotter metal in the middle of w.p. flows more readily than the cooler metal at the ends.
- Barreling is more significant as D/h ratio increases due to greater contact area of w.p.-die interface.
- A shape factor K_f is used to account for friction effect and D/h ratio:

$$\boldsymbol{K_f = 1 + \frac{0.4\mu D}{h}}$$

And actual forging force will be:

$$\boldsymbol{F_{fg} = K_f Y_f A}$$

μ: coefficient of friction

D: instantaneous diameter during forging operation

h: instantaneous height during forging operation

Example (13):

A cylindrical workpiece is subjected to a cold upset forging operation. The starting piece is 75mm in height and 50mm in diameter. It is reduced in the operation to a height of 36mm.The w.p. has a flow curve defined by K=350MPa and n=0.17. Assume a coefficient of friction of 0.1. Determine the force as the process begins, at intermediate heights of 62mm, 49 mm, and at the final height of 36 mm.

Solution:

(1) At h=75mm, D=50mm (at the moment contact with upper die)

$F_{fg} = K_f Y_f A$

$$K_f = 1 + \frac{0.4\mu D}{h} = 1 + \frac{0.4(0.1)(50)}{75} = 1.027$$

$A = \frac{\pi}{4} 50^2 = 1963.5mm^2$

$\varepsilon = \ln\frac{h_o}{h} = \ln\frac{75}{75} = 0$

$\therefore Y_f = K\varepsilon^n = 0$

$\therefore F_{fg} = K_f Y_f A = 0$ **Answer**

(2) At the start of yielding, h is slightly less than 75mm and the true strain is approximately 0.2% at yielding and diameter is still approximately =50mm.

$\varepsilon = \frac{0.2}{100} = 0.002$

$Y_f = K\varepsilon^n = 350(0.002^{0.17}) = 121.7MPa$ and $A = \frac{\pi}{4} 50^2 = 1963.5mm^2$

$$K_f = 1 + \frac{0.4\mu D}{h} = 1 + \frac{0.4(0.1)(50)}{75} = 1.027$$

$$\therefore F_{fg} = K_f Y_f A = 1.027(121.7)(1963.5) = 245.41kN$$ **Answer**

(3) At h=62mm

$$\varepsilon = \ln\frac{h_o}{h} = \ln\frac{75}{62} = 0.1904$$

$$Y_f = K\varepsilon^n = 350(0.1904^{0.17}) = 264MPa$$

To find *D*, from volume constancy:

$$V_o = V \Longrightarrow A_o h_o = Ah \Longrightarrow \frac{\pi}{4}50^2(75) = \frac{\pi}{4}D^2(62) \Longrightarrow D = 55mm$$

$$A = \frac{\pi}{4}55^2 = 2375.8mm^2$$

$$K_f = 1 + \frac{0.4\mu D}{h} = 1 + \frac{0.4(0.1)(55)}{62} = 1.035$$

$$\therefore F_{fg} = K_f Y_f A = 1.035(264)(2375.8) = 649.2kN$$ **Answer**

(4) At h=49mm

$$\varepsilon = \ln\frac{h_o}{h} = \ln\frac{75}{49} = 0.426$$

$$Y_f = K\varepsilon^n = 350(0.426^{0.17}) = 302.7MPa$$

To find *D*, from volume constancy:

$$V_o = V \Longrightarrow A_o h_o = Ah \Longrightarrow \frac{\pi}{4}50^2(75) = \frac{\pi}{4}D^2(49) \Longrightarrow D = 61.9mm$$

$$A = \frac{\pi}{4}61.9^2 = 3009.3mm^2$$

$$K_f = 1 + \frac{0.4\mu D}{h} = 1 + \frac{0.4(0.1)(61.9)}{49} = 1.051$$

$$\therefore F_{fg} = K_f Y_f A = 1.051(302.7)(3009.3) = 957.4\,kN$$ **Answer**

(5) At h=36mm

$$\varepsilon = \ln\frac{h_o}{h} = \ln\frac{75}{36} = 0.734$$

$$Y_f = K\varepsilon^n = 350(0.734^{0.17}) = 332.1MPa$$

To find *D*, from volume constancy:

$$V_o = V \Longrightarrow A_o h_o = Ah \Longrightarrow \frac{\pi}{4}50^2(75) = \frac{\pi}{4}D^2(36) \Longrightarrow D = 72.2mm$$

$$A = \frac{\pi}{4}72.2^2 = 4094.2mm^2$$

$$K_f = 1 + \frac{0.4\mu D}{h} = 1 + \frac{0.4(0.1)(72.2)}{36} = 1.08$$

$$\therefore F_{fg} = K_f Y_f A = 1.08(332.1)(4094.2) = 1468.5\ kN$$ **Answer**

Example (14):

A cylindrical specimen made of annealed 4135 steel has a diameter of 15.24cm and is 10.16cm high. It is upset, at room temperature, by open-die forging with flat dies to a height of 5.08cm. Assuming that the coefficient of friction is 0.2, calculate the upsetting force (forging force) required at the end of the stroke. Take material properties, *K=1015MPa, n=0.17.*

Solution:

h_o = 10.16cm = 0.1016m, D_o = 15.24cm = 0.1524m

$$F_{fg} = K_f Y_f A \quad , \quad K_f = 1 + \frac{0.4\mu D}{h}$$

At the end of forging stroke: h=5.08cm=0.0508m

To find D, from volume constancy:

$$V_o = V \Longrightarrow A_o h_o = Ah$$

$$\frac{\pi}{4}(15.24)^2(10.16) = \frac{\pi}{4}D^2(5.08) \Longrightarrow D = 21.55cm = 215.5mm \Longrightarrow$$

$$\therefore A = \frac{\pi}{4}215.5^2 = 36474.1\ mm^2$$

$$\therefore K_f = 1 + \frac{0.4(0.2)(21.55)}{5.08} = 1.339$$

$$\varepsilon = \ln\frac{h_o}{h} = \ln\frac{10.16}{5.08} = 0.693$$

$$\therefore Y_f = K\varepsilon^n = 1015(0.693)^{0.17} = 953.7MPa$$

$$\therefore F_{fg} = K_f Y_f A = 1.339(953.7)(36474.1) = 46.577MN$$ **Answer**

Example (15):

A hydraulic forging press is capable of exerting a maximum force = 1,000,000 N. A cylindrical workpart is to be cold upset forged. The starting part has diameter = 30 mm and height = 30 mm. The flow curve of the metal is defined by K = 400 MPa and n = 0.2. Determine the maximum reduction in height to which the part can be compressed with this forging press, if the coefficient of friction = 0.1.

Solution:

F_{fg} = 1MN, D_o=30mm, h_o=30mm, K=400MPa, μ=0.1, n=0.2, h=?, D=?

From forging force relation:

$$F_{fg} = K_f Y_f A \quad , \quad K_f = 1 + \frac{0.4\mu D}{h} \quad , \quad \varepsilon = \ln\frac{h_o}{h}$$

$$V_o = V \quad , \quad A_o h_o = Ah \quad , \quad \therefore A = \frac{A_o h_o}{h} \quad , \quad D = \sqrt{\frac{4A}{\pi}}$$

$$A = \frac{A_o h_o}{h} = \frac{\frac{\pi}{4}(30^2)(30)}{h} = \frac{21205.8}{h}, \qquad Y_f = K\varepsilon^n = 400\left(\ln\frac{30}{h}\right)^{0.2}$$

$$K_f = 1 + \frac{0.4(0.1)D}{h} = 1 + \frac{0.04D}{h}$$

$$F_{fg} = \left(1 + \frac{0.04D}{h}\right)\left(400\left(\ln\frac{30}{h}\right)^{0.2}\right)\left(\frac{21205.8}{h}\right) = 1$$

By trial and error, we will assume a value for h that will match the F_{fg} of 1MN.

1. Try *h* = 15mm

$$A = \frac{21205.8}{h} = \frac{21205.8}{15} = 1413.72mm^2 \quad , \quad D = \sqrt{\frac{4(1413.72)}{\pi}} = 42.4mm$$

$$Y_f = 400\left(\ln\frac{30}{15}\right)^{0.2} = 371.73MPa\ , \quad K_f = 1 + \frac{(0.04)(42.4)}{15} = 1.113$$

$$\therefore F_{fg} = (1.113)(371.73)(1413.72) = 584906.14N$$

It is too low compared with 1MN.

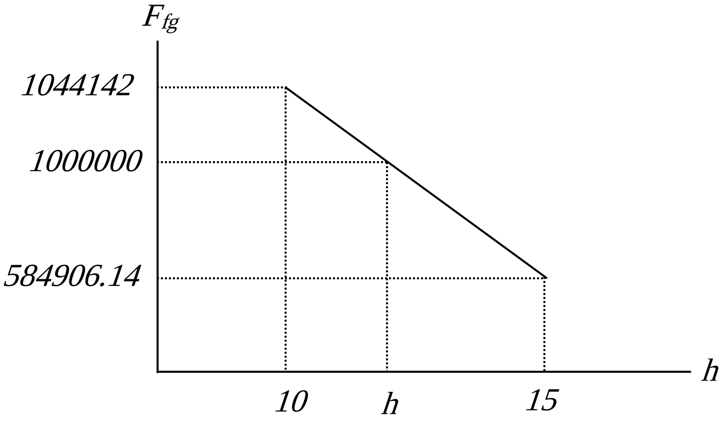
2. Try *h* = 10mm

$$A = \frac{21205.8}{h} = \frac{21205.8}{10} = 2120.6mm^2 \quad , \quad D = \sqrt{\frac{4(2120.6)}{\pi}} = 51.96mm$$

$$Y_f = 400\left(\ln\frac{30}{10}\right)^{0.2} = 407.6MPa\ , \quad K_f = 1 + \frac{(0.04)(51.96)}{10} = 1.208$$

$\therefore F_{fg} = (1.208)(407.6)(2120.6) = 1044142N$ it is slightly high.

By linear interpolation: between *h=10 and h=15*



$$\frac{h-10}{15-10}=\frac{1044142-1000000}{1044142-584906.14}\ ,\ \therefore h=10.48mm$$

$$A=\frac{21205.8}{h}=\frac{21205.8}{10.48}=2023.45mm^2\ ,\ D=\sqrt{\frac{4(2023.45)}{\pi}}=50.76mm$$

$$Y_f=400\left(\ln\frac{30}{10.48}\right)^{0.2}=404.1MPa\ ,\ K_f=1+\frac{(0.04)(50.76)}{10.48}=1.194$$

$\therefore F_{fg}=(1.194)(404.1)(2023.45)=976305.32N$ it is slightly low.

Another linear interpolation: between *h=10 and h=10.48*

$$\frac{h-10}{10.48-10}=\frac{1044142-1000000}{1044142-976305.32}\ ,\quad \therefore h=10.31mm$$

$$A=\frac{21205.8}{h}=\frac{21205.8}{10.31}=2056.82mm^2\ ,\ D=\sqrt{\frac{4(2056.82)}{\pi}}=51.17mm$$

$$Y_f=400\left(\ln\frac{30}{10.31}\right)^{0.2}=405.3MPa\ ,\ K_f=1+\frac{(0.04)(51.17)}{10.31}=1.199$$

$\therefore F_{fg}=(1.199)(405.3)(2056.82)=\mathbf{999521.34N}$ **it is accepted. Answer**

Example (16):

A cold heading operation is performed to produce the head on a steel nail. The strength coefficient for this steel is 600 MPa, and the strain hardening exponent is 0.22. Coefficient of friction at the die-work interface is 0.14. The wire stock out of which the nail is made is 5 mm in diameter. The head is to have a diameter of 9.5 mm and a thickness of 1.6 mm. The final length of the nail is 120 mm. (a) What length of stock must project out of the die in order to provide sufficient volume of material for this upsetting operation? (b) Compute the maximum force that the punch must apply to form the head in this open-die operation.

Solution:

(a) For the nail head: $D_o=5mm$, D=9.5mm, h=1.6mm, then

$$V = Ah = \frac{\pi}{4}9.5^2(1.6) = 113.4mm^3$$

From volume constancy: $V = V_o = A_o h_o \quad \therefore h_o = \frac{V}{A_o}$

$A_o = \frac{\pi}{4}5^2 = 19.63mm^2$, $\therefore h_o = \frac{113.4}{19.63} = \mathbf{5.78mm}$ **Answer**

(b) Forging Force:

$$A = \frac{\pi}{4}9.5^2 = 70.88mm^2$$

$$Y_f = 600\left(\ln\frac{5.78}{1.6}\right)^{0.22} = 633.97MPa\ , \quad K_f = 1 + \frac{(0.4)(0.14)(9.5)}{1.6} = 1.333$$

$\therefore F_{fg} = (1.333)(633.97)(70.88) = \mathbf{59899N \cong 59.9kN}$ **Answer**

Example (17):

A hot upset forging operation is performed in an open die. The initial size of the w.p. is: D_o = 25mm, and h_o = 50 mm. The part is upset to a diameter D= 50 mm. The work metal at this elevated temperature yields at 85 MPa (n = 0, K=yield strength). Coefficient of friction at the die-work interface = 0.4. Determine (a) final height of the part, and (b) maximum force in the operation.

Solution:

(a) $h=?$

From volume constancy: $V=V_o$, $Ah=A_oh_o \quad \Longrightarrow \quad h = \frac{A_o h_o}{A}$

$\therefore h = \frac{A_o h_o}{A} = \frac{\frac{\pi}{4}25^2(50)}{\frac{\pi}{4}50^2} = \mathbf{12.5mm}$ **Answer**

(b) F_{fg}? , μ=0.4

$$F_{fg} = K_f Y_f A\ ,\quad K = 85MPa,\ Y_f = 85\left(\ln\frac{50}{12.5}\right)^0 = 85MPa$$

$$A = \frac{\pi}{4}50^2 = 1963.5mm^2,\ K_f = 1 + \frac{0.4(0.4)(50)}{12.5} = 1.64$$

$$F_{fg} = (1.64)(85)(1963.5) = \mathbf{273712N}$$ **Answer**