University of Basrah
College of Engineering
Mechanical Engineering Department
MANUFACTURING PROCESSES (ME337), 3rd Year (2019-2020)
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3. Wire and Bar Drawing Conventional and Non-Conventional Processes

3.1. Wire and Bar Drawing – Conventional Process

Introduction:

- It is an operation in which the cross-section of a bar, rod or wire is reduced by pulling it through a die opening.
- The difference between extrusion and drawing is: the w.p. is pulled in drawing, whereas it is pushed in extrusion.
- Bar drawing is the term used for large diameter bar and rod stock (it usually involves stock that is too large in cross-section to be coiled). Round bar stock may be 1 to 10cm in diameter or even larger.
- Wire drawing applies to small diameter stock. Wire sizes down to 0.03mm (0.001in) are possible in wire drawing.
- Bar drawing is accomplished as a ***single-draft*** operation: the stock is pulled through one die opening (it is in the form of a straight cylindrical piece rather than coiled due to large diameter of stock).
- Wire is drawn from coils consisting of several hundred (or even several thousand) feet of wire and is passed through a series of draw dies
- In wire drawing, no. of dies varies typically between 4 and 12.
- The term ***continuous drawing*** is used to describe this type of operation.
- The drawing process is described in figure (3-30).

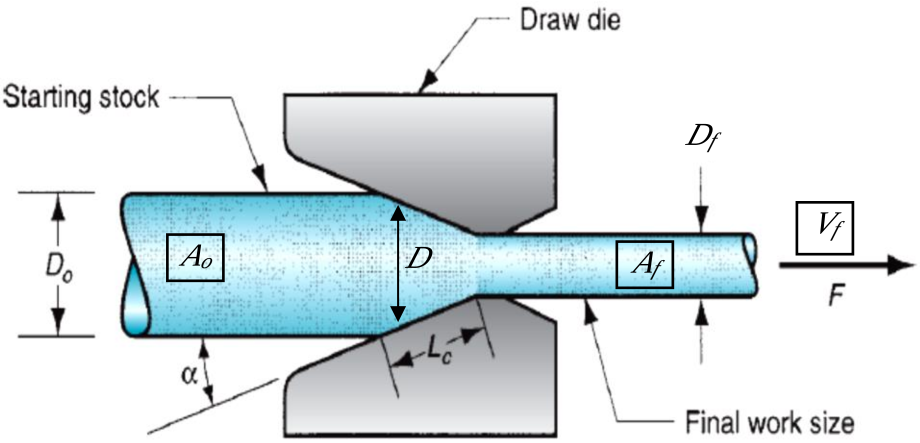


Figure (3-30) Drawing Process

Analysis of Drawing:

1- Area Reduction:

- From figure (3-30), the reduction in area can be:

$$r = \frac{A_o - A_f}{A_o}$$

r: area reduction (drawing reduction)

A_o: original area of w.p.

A_f: final area of w.p.

2- Draft:

$$d = D_o - D_f$$

d: draft

D_o: original diameter of w.p.

D_f: final diameter of w.p.

3- True Strain:

- For ideal deformation (no friction or redundant work occurred during drawing process), the true strain will be:

$$\varepsilon = \ln \frac{A_o}{A_f} = \ln \frac{1}{1 - r}$$

4- True Stress:

- For ideal deformation (no friction or redundant work occurred during drawing process), the true stress will be:

$$\sigma = \bar{Y}_f \varepsilon = \bar{Y}_f \ln \frac{A_o}{A_f}$$

$$\bar{Y}_f = \frac{K \varepsilon^n}{n + 1}$$

- For processes that including gradual deformation and strain hardening like drawing and extrusion, the average flow stress is used instead of flow stress.

$\bar{Y}_f$: average flow stress

5- Actual Draw Stress (σ_d):

- Due to friction between w.p. and die in drawing process and the w.p. experiences inhomogeneous deformation (redundant work), then:

$$\sigma_d > \sigma$$

- Variables that influence draw stress are:
  (a) A_o / A_f ratio
  (b) Die angle α
  (c) Friction coefficient (μ) at the w.p.-die interface

Thus, the actual draw stress will be according to the following equation:

$$\sigma_d = \bar{Y}_f \left(1 + \frac{\mu}{\tan \alpha}\right) \emptyset \ln \frac{A_o}{A_f}$$

σ_d: actual draw stress

μ: die-w.p. friction coefficient

α: die angle (half-angle)

$\emptyset$: is a factor that accounts for inhomogeneous deformation (redundant work)

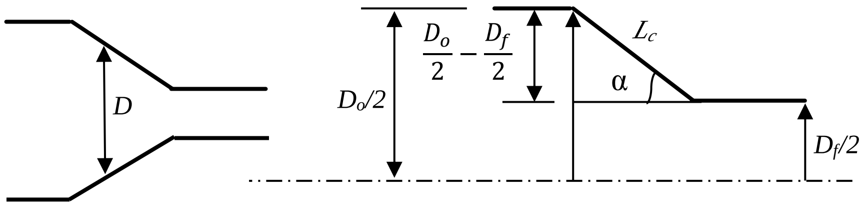
$$\emptyset = 0.88 + 0.12 \frac{D}{L_c} \qquad \text{for round cross-section}$$

D: average diameter of w.p.

L_c: contact length of w.p. with draw die

$$D = \frac{D_o + D_f}{2}$$

$$L_c = \frac{D_o - D_f}{2 \sin \alpha}$$



6- Draw Force:

$$F_d = \sigma_d A_f = A_f \bar{Y}_f (1 + \frac{\mu}{\tan \alpha}) \emptyset \ln \frac{A_o}{A_f}$$

7- Draw Power:

$$P_d = F_d V_f$$

V_f: final velocity of w.p. at exit (drawing velocity)

8- Die Pressure:

- The die pressure along the die contact length can be obtained from:

$$p_{die} = Y_f - \sigma$$

p_{die}: die pressure

σ: tensile stress in the deformation zone at a particular diameter

Y_f: flow stress of the w.p. at a particular diameter

$Y_f = K\varepsilon^n$

$\sigma = 0.0$ at the die entry

$\sigma = \sigma_d$ at the die exit

9- Drawing Analysis at Elevated Temperature:

- As we have seen, the flow stress of metals is a function of the strain rate.
- In drawing, the average true-strain rate in the deformation zone can be given by (as in hot extrusion):

$$\dot{\bar{\varepsilon}} = \frac{6\, V_o}{D_o} \ln \frac{A_o}{A_f}$$

V_o: w.p. feeding velocity
$\dot{\bar{\varepsilon}}$: average true-strain rate

- **Flow Stress:**

$$\bar{Y}_f = C\dot{\bar{\varepsilon}}^m$$

- **True Stress:**

$$\boldsymbol{\sigma = \bar{Y}_f \varepsilon = C\dot{\varepsilon}^m \ln \frac{A_o}{A_f}}$$

- **Actual Draw Stress:**

$$\boldsymbol{\sigma_d = C\dot{\varepsilon}^m \left(1 + \frac{\mu}{tan\ \alpha}\right) \emptyset \ln \frac{A_o}{A_f}}$$

- **Draw Force:**

$$\boldsymbol{F_d = \sigma_d A_f}$$

- **Draw Power:**

$$\boldsymbol{P_d = F_d V_f}$$

Example (10):

Wire is drawn through a draw die with entrance angle = 15°. Starting diameter is 2.5mm and final diameter = 2.0 mm. The coefficient of friction at the work–die interface = 0.07. The metal has a strength coefficient K = 205 MPa and a strain-hardening exponent n = 0.20. Determine the actual draw stress and corresponding draw force in this operation.

Solution:

1- Draw stress:

$$\sigma_d = \bar{Y}_f \left(1 + \frac{\mu}{tan\ \alpha}\right) \emptyset \ln \frac{A_o}{A_f}$$

$$\bar{Y}_f = \frac{K\varepsilon^n}{n+1}$$

$$\varepsilon = \ln \frac{A_o}{A_f} = \ln \frac{D_o^2}{D_f^2} = \ln \frac{2.5^2}{2^2} = 0.446$$

$$\bar{Y}_f = \frac{205\ (0.446)^{0.2}}{1.2} = 145.4 MPa$$

$$\emptyset = 0.88 + 0.12 \frac{D}{L_c}$$

$$\mathrm{D} = \frac{D_o + D_f}{2} = \frac{2.5 + 2}{2} = 2.25 mm$$

$$L_c = \frac{D_o - D_f}{2\ sin\ \alpha} = \frac{2.5 - 2}{2\ sin\ 15} = 1.0 mm$$

$$\emptyset = 0.88 + 0.12 \frac{2.25}{1.0} = 1.15$$

$\therefore \sigma_d = 145.4\left(1+\frac{0.07}{tan\ 15}\right)(1.15)(0.446) = 94.1MPa$ **Answer**

2- Draw force:

$F_d = \sigma_d A_f = (94.1)\frac{\pi}{4}2^2 = 295.6N$ **Answer**

Example (11):

A round rod of annealed 302 stainless steel is being drawn from a diameter of 10mm to 8mm at a speed of 0.5m/s (drawing speed). Assume that the frictional and redundant work together constitute 40% of the ideal work of deformation. (a) Calculate the power required in this operation, and (b) Calculate the die pressure at the exit of the die.

Take: K=1300MPa, n=0.3

Solution:

(a) $P_d = F_d V_f$

$F_d = \sigma_d A_f$

Multiplying draw stress with 1.4 to include the frictional and redundant work effects. Thus:

$\sigma_d = 1.4(\bar{Y}_f \varepsilon) = 1.4(\bar{Y}_f \ln\frac{A_o}{A_f})$

$$\varepsilon = \ln\frac{10^2}{8^2} = 0.446$$

$$\bar{Y}_f = \frac{K\varepsilon^n}{n+1} = \frac{1300(0.446)^{0.3}}{1.3} = 784.875MPa$$

$\therefore \sigma_d = 1.4(784.875)(0.446) = 490.1MPa$

$F_d = \sigma_d A_f = (490.1)\frac{\pi}{4}8^2 = 24635.1N$

$\therefore P_d = F_d V_f = 24635.1(0.5) = 12.3kW$ **Answer**

(b) $p_{die} = Y_f - \sigma$

$\sigma = \sigma_d = 490.1MPa$ at the die exit

$Y_f = K\varepsilon^n = 1300(0.446)^{0.3} = 1020.3MPa$

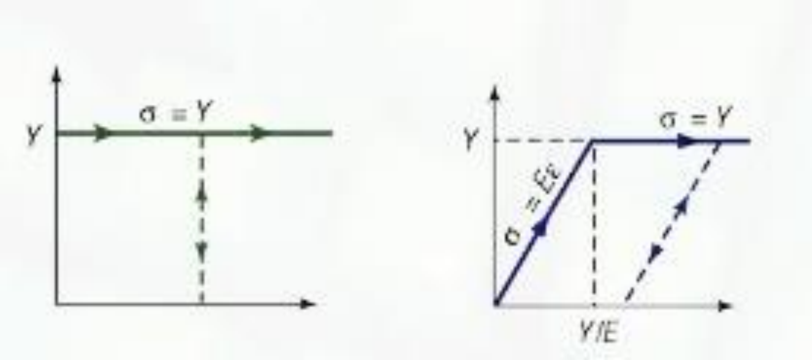
$p_{die} = Y_f - \sigma = 1020.3 - 490.1 = 530.2MPa$ **Answer**

Example (12):

Bar stock of initial diameter = 90 mm is drawn with a draft = 15 mm. The draw die has an entrance angle = 18°, and the coefficient of friction at the work-die interface = 0.08. The metal behaves as a perfectly plastic material with yield stress = 105 MPa. Determine (a) area reduction, (b) draw stress, (c) draw force required for the operation, and (d) power to perform the operation if exit velocity = 1.0 m/min.

Solution:

- The perfectly plastic curve is:



(a) $d=D_o - D_f$ ➡ $D_f=D_o - d=90-15=75mm$

$r = \frac{A_o - A_f}{A_o} = 1 - \frac{75^2}{90^2} = 0.3056$ **Answer**

(b) $\sigma_d = \bar{Y}_f(1 + \frac{\mu}{\tan\alpha})\emptyset \ln\frac{A_o}{A_f}$

$$\varepsilon = \ln\frac{A_o}{A_f} = \ln\frac{90^2}{75^2} = 0.365$$

$$\emptyset = 0.88 + 0.12\frac{D}{L_c}$$

$$\mathrm{D} = \frac{D_o + D_f}{2} = \frac{90 + 75}{2} = 82.5mm$$

$$L_c = \frac{D_o - D_f}{2\ sin\ \alpha} = \frac{90 - 75}{2\ sin\ 18} = 24.271mm$$

$$\emptyset = 0.88 + 0.12\frac{82.5}{24.271} = 1.2879$$

Since the material is perfectly plastic, then;

n=0.0, K=Y (yield strength) =105MPa

$$\bar{Y}_f = \frac{K\varepsilon^n}{n+1} = \frac{105(0.365)^0}{1+0} = 105MPa$$

$\therefore \sigma_d = 105\left(1+\frac{0.08}{tan\ 18}\right)(1.2879)(0.365) = 61.5MPa$ **Answer**

(c) $F_d = \sigma_d A_f = (61.5)\frac{\pi}{4}75^2 = 271.7kN$ **Answer**

(d) $P_d = F_d V_f = 271.7\left(\frac{1}{60}\right) = 4.53kW$ **Answer**

Maximum Reduction per Pass:

- As reduction increases ⟶ σ_d increases.
- If reduction is large enough ⟶ σ_d exceeds the w.p. strength ⟶ w.p. will elongate rather than new w.p. being squeezed.
- For successful drawing ⟶ σ_d < yield strength of w.p.
- To determine maximum reduction in one pass under certain assumptions:
  1. Perfectly plastic (n=0), ideal deformation (no friction and no redundant work).
  2. Maximum $\sigma_d =$ Y (yield strength of w.p.)

$$\sigma_d = \bar{Y}_f \ln\frac{A_o}{A_f}$$

And setting $\bar{Y}_f = Y$ (yield strength) because n=0

$$Y = Y\ln\frac{A_o}{A_f} \longrightarrow 1 = \ln\frac{A_o}{A_f} \longrightarrow 1 = \varepsilon_{max} \longrightarrow \frac{A_o}{A_f} = e^1 = 2.7183$$

$\therefore r_{max} = \frac{A_o - A_f}{A_o} = 1 - \frac{A_f}{A_o} = 1 - \frac{1}{2.7183} = 0.632$ (theoretical max. reduction)

- **In practice:** maximum reduction is **less than** theoretical one due to:
  1. Friction and redundant work reduce the max. reduction.
  2. Strain hardening increases max. reduction because exiting w.p. be stronger than starting w.p.

Drawing Practice:

- Drawing is usually performed as a cold-working operation.
- It is most used to produce round cross-sections but squares and other shapes are also drawn.
- Wire drawing is an important industrial process which includes: **electrical wire and cables, wire stock for fences, coat hangers and shopping carts. Rod stock to produce nails, screws, rivets, springs**…

- Advantages of drawing in these application include:
  1. **Close dimensional control**
  2. **Good surface finish**
  3. **Improved mechanical properties such as strength and hardness**
  4. **In case of bar drawing to provide stock for machining, the operation improves the machinability of bar.**

Drawing Equipment:

1. **Bar Drawing**
   - It is accomplished on a machine called a "draw bench" as stated in figure (3-31).
   - From figure (3-31), carriage is used to pull the bar through draw die. It is powered by hydraulic cylinders or motor-driven chains.
   - Die stand in figure (3-31) contains the draw die and often designed to hold more than one die.

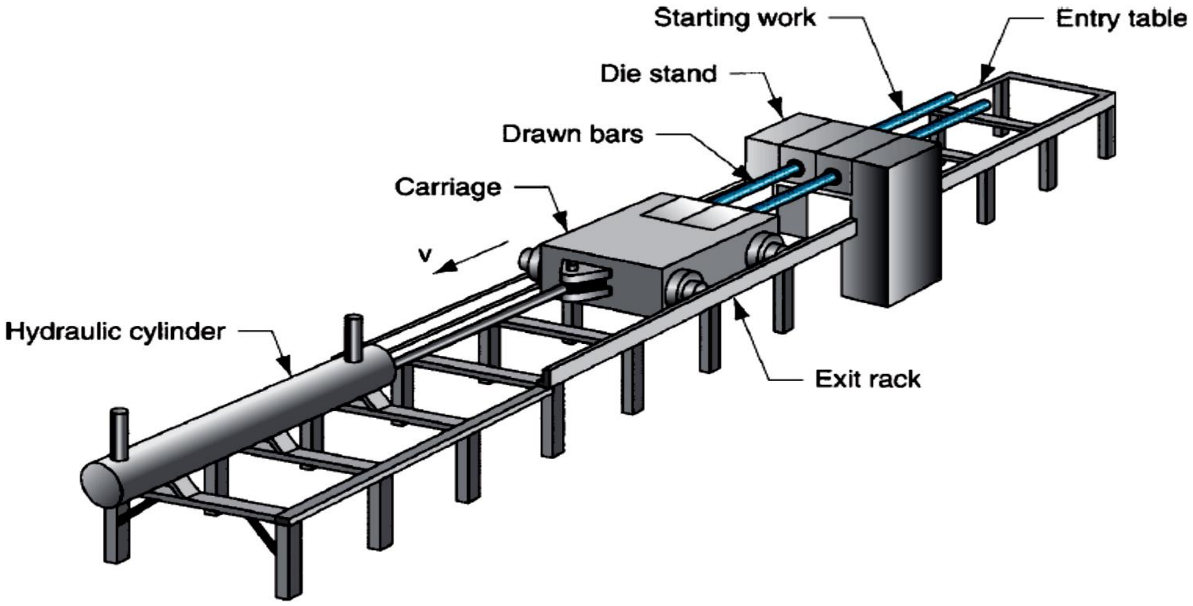


Figure (3-31) hydraulically operated draw bench for drawing metal bars

2- Wire Drawing

- It is done on continuous drawing machine as shown in figure (3-32).
- It consists of multiple draw dies separated by accumulated drums between dies.
- Each drum called a **“capstan”** is motor-driven.
- Capstan function is: **(1) produce proper pull force to draw the wire, (2) maintain a modest tension on wire as it proceeds to the next draw die.**
- Each die provides a certain amount of reduction in the wire.

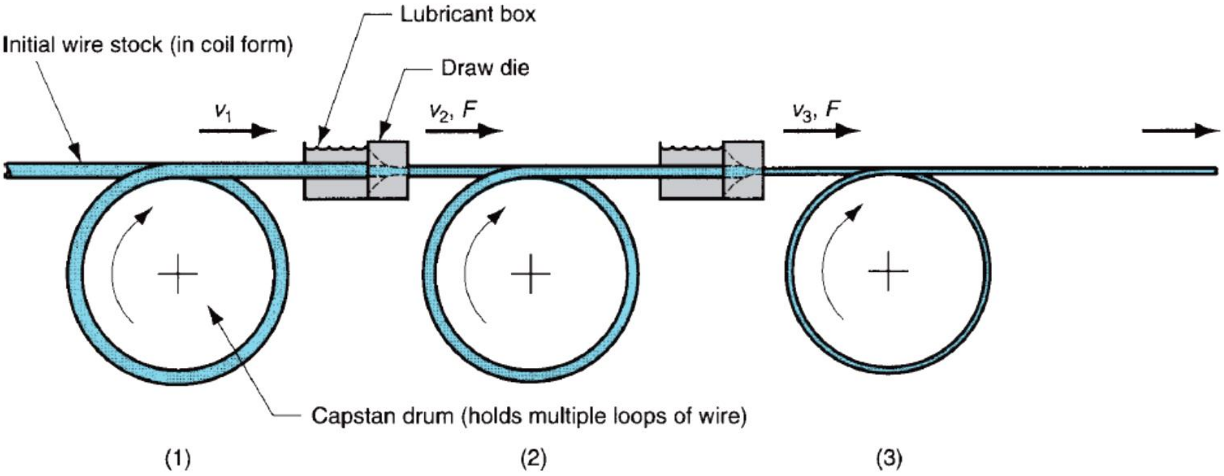


Figure (3-32) continuous drawing of wire

Draw Die:

- Figure (3-33) explains the draw die for round cross-sections. It is consisted of four regions as follows:
  - **(1) Entry:** is usually a bell-shaped mouth that does not contact the w.p. its purpose is to funnel the lubricant into the die and prevent scoring of w.p. and die surfaces.
  - **(2) Approach:** is where the drawing process occurs. It is cone-shaped with an angle, namely, die angle (half angle) normally ranging from about 6° to 20°.
  - **(3) Bearing Surface (land):** determines the size of final drawn stock.
  - **(4) Back Relief:** is the exit zone. It is provided with a back relief angle (half angle) of about 30°.

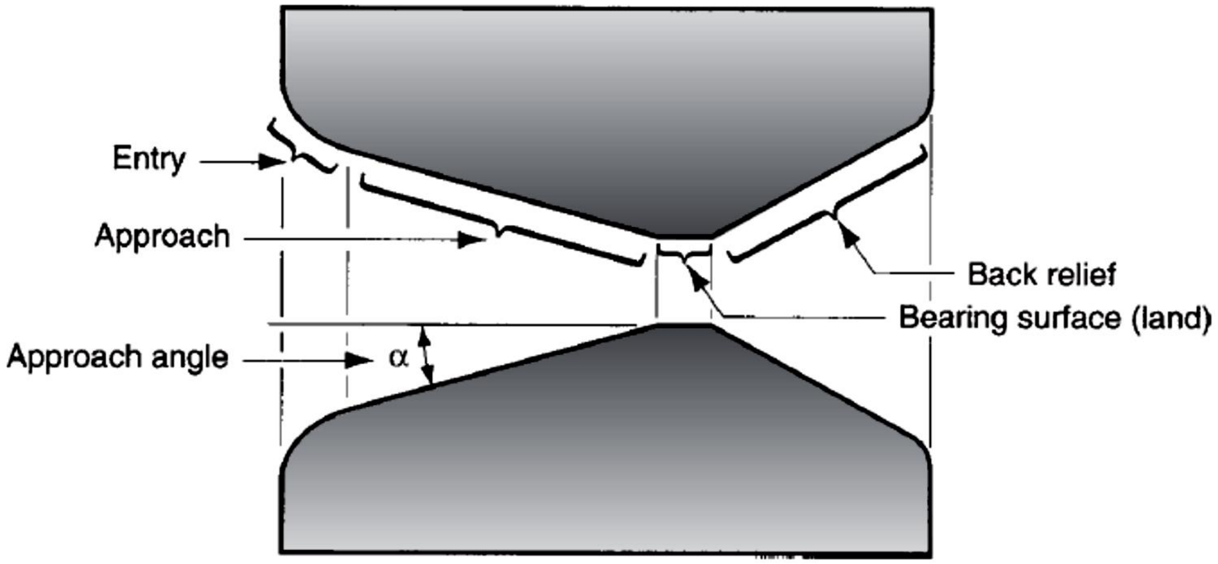


Figure (3-33) draw die for drawing of round rod or wire

Preparation of the W.P.:

1- **Annealing:** it is to increase the ductility of w.p. to accept deformation during drawing.
2- **Cleaning:** is required to prevent damage of w.p. surface and draw die. It involves removal of surface contaminants (e.g., scale and rust).
3- **Pointing:** involves the reduction in diameter of starting end of w.p. so that it can be inserted through the draw die. This is usually accomplished by rolling or turning. The pointed end of w.p. is then gripped by carriage jaws or other device to initiate the drawing process.

Tube Drawing:

- Drawing can be used to reduce the diameter or wall thickness of seamless tubes and pipes, after the initial tubing has been produced by some other process such as extrusion.
- Tube drawing can be carried out either with or without a mandrel.

(1) No mandrel also called **"tube sinking"** is used as shown in figure (3-34). The problem with it is that it lacks control over the inside diameter and wall thickness of tube.

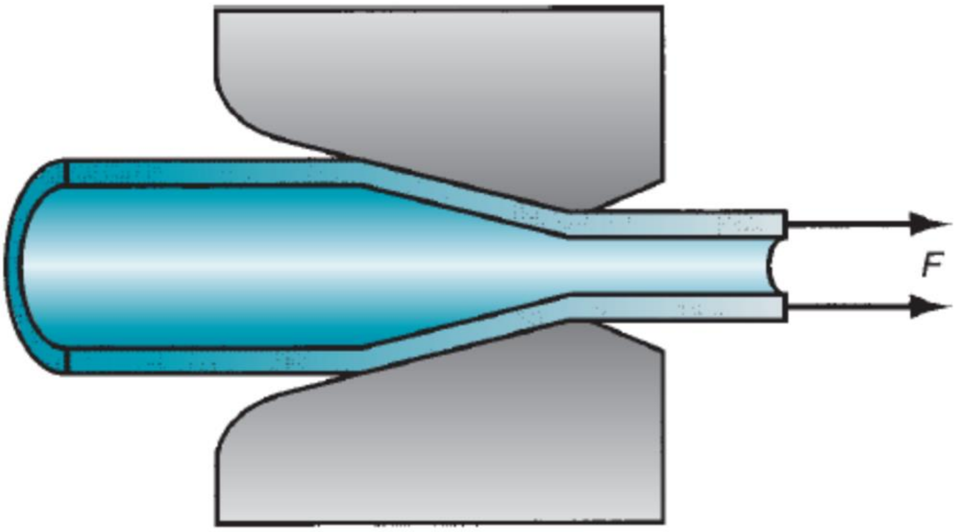


Figure (3-34) tube drawing with no mandrel.

(2) With mandrel: it is shown as in figure (3-35).

(a) **Fixed Mandrel:** it is attached to a long support bar to maintain inside diameter and wall thickness. There is restriction of the length of tube that can be drawn due to practical limitations on length of the support bar.

(b) **Floating Plug:** whose shape is designed so that it finds a natural position in the reduction zone of die. This method removes the limitations on w.p. length.

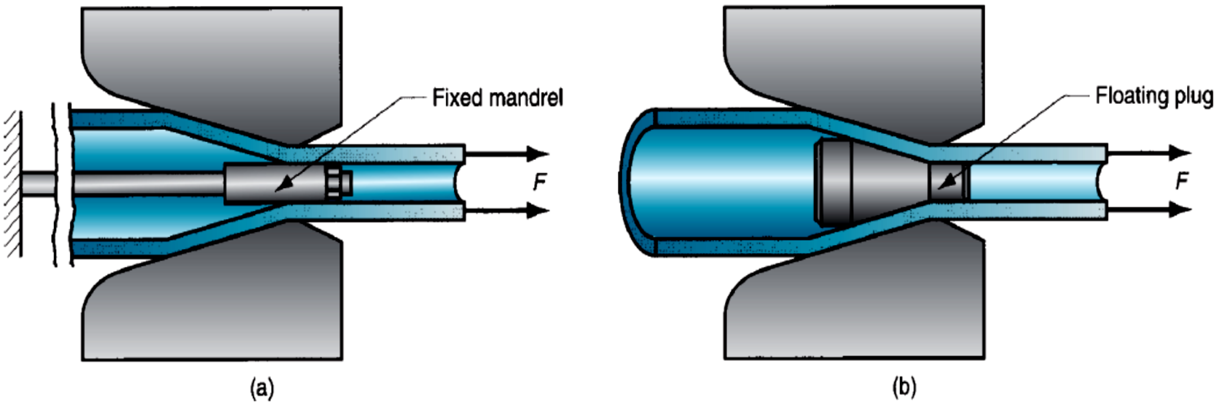


Figure (3-35) tube drawing with mandrel: (a) fixed mandrel (b) floating plug

3.2. Dieless Drawing Processes – Non-Conventional Processes

Introduction:

- Dieless wire/tube drawing process is utilized in initiating continuous deformation depending on local heating and intensive local cooling.
- The temperature range in this process should not be less than ($0.4 - 0.5T_m$).
- The strain rate ranges must be in low levels ($10^{-5} – 10^{-1}$)s^{-1}.
- To accomplish dieless drawing process (DLD), three major components must be integrated; heating unit, cooling unit and drawing device.
- At elevated temperatures, yield strength, modulus of elasticity, ultimate tensile strength and flow stress are decreased,
- Ductility and toughness (specific energy dispersed up to fracture) are increased at high temperature.
- Consequently, a significant reduction in cross-section area of the wire/tube will occur depending on feeding and drawing velocities of the wire/tube.
- The drawing force and suitable reduction ratio are depended on feeding and drawing velocities of the wire/tube.

Types of DLD Process:

- There are three different kinds of DLD processes, namely Variants A, B, and C as shown in figure (3-36).
- In type A and B, the heating/cooling units are moving and the wire/tube is fixed at one side.
- In type C, the heating/cooling units are fixed and the wire/tube is moved (continuous drawing process).

Heating Ways in DLD Process:

- There are four ways for heating the wire/tube during the DLD process without contact: **(1) molten polymer (2) electrical resistant (3) high frequency induction (4) laser power.**
- Among these ways, the high frequency induction heating is the better for the DLD process.

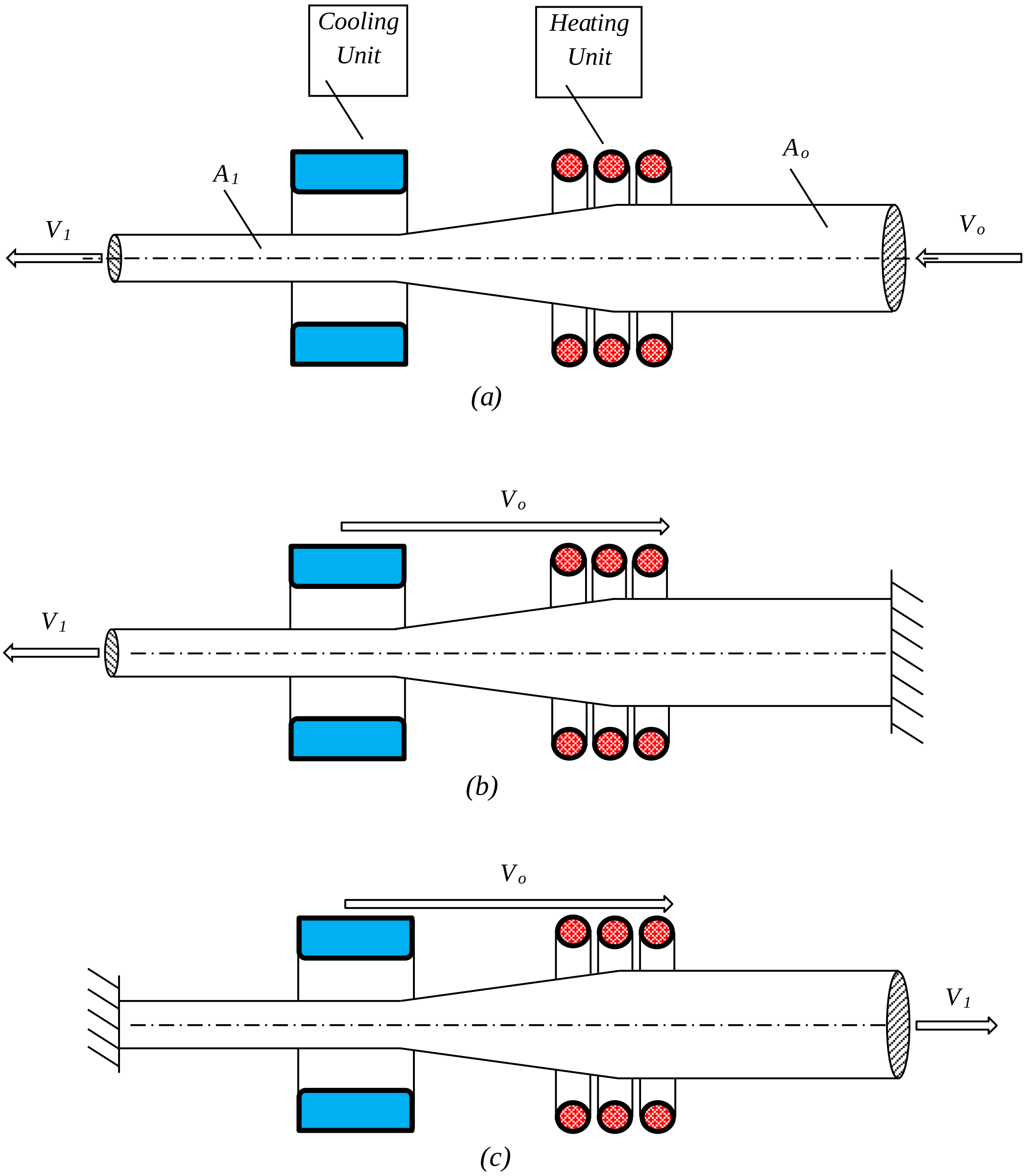


Figure (3-36) DLD types ; (a) Continuous process, V_o: feeding velocity, V_1: drawing velocity, A_o: original cross-section area, A_1: final cross-section area, and (b), (c) Non Continuous process, V_o: velocity of heating/cooling unit, V_1: drawing velocity.

Cooling Ways in DLD Process:

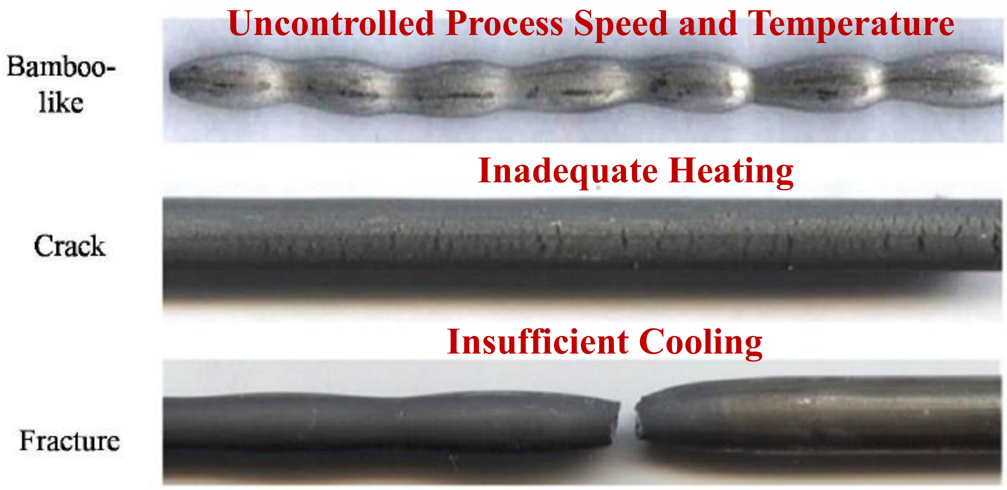
- There are different fluids that are used in the cooling units (to gradient the high temperature range and prevent further deformation) such as water, compressed air, argon and liquid-CO_2.

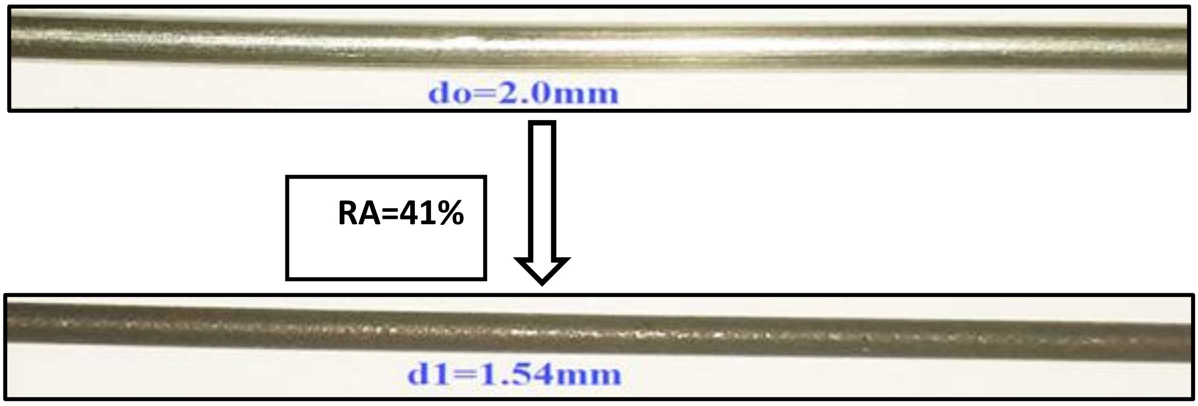
Advantages of DLD Process:

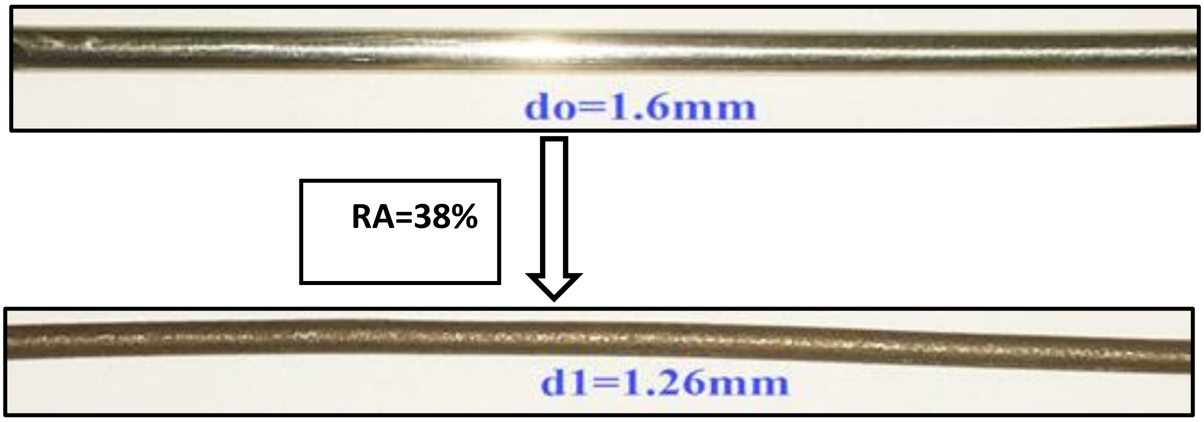
- Eliminating of friction forces.
- Lowering of drawing force and energy consumption.
- Considerable area reduction in single drawing pass.
- Needless of pre-cleaning/lubricating.
- Allowing for variable sections to be manufactured.
- Refinement of grain size – possibly related to thermal cycling and reduction in area - for steel or any microstructural transformation in materials, so better mechanical properties can be imparted to the product after drawing

Disadvantages of DLD Process:

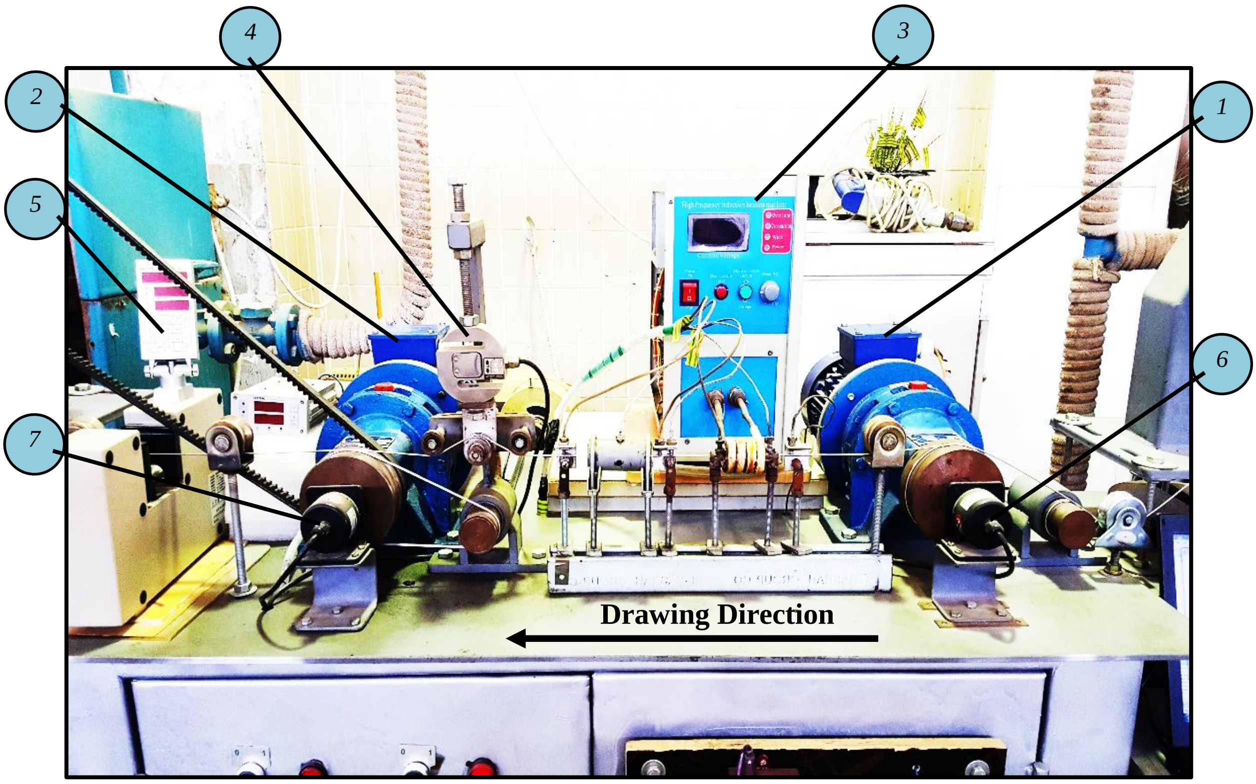
- Final sizes - particularly in massive reduction ratios - are unstable to some degrees.
- Uneven shape (bamboo-like).
- Slow forming time due to low deforming speeds.







Continuous Dieless Wire drawing Machine: General View; (1) DLD Machine, (2) Computer, (3) Air Compressor, (4) Cooling Tower



Continuous DLD Machine: Main Parts; (1) Motor-gearbox-1, (2) Motor-gearbox-2, (3) Induction Heater, (4) Load Cell, (5) Laser Diameter Gauge, (6) Encoder-1, (7) Encoder-2

Kinematics of DLD Process:

(1) Continuous DLD Process:

- The kinematic of DLD process is governed by the volume constancy principle, which determines the reduction ratio of area (RA), where:

$$A_o V_o = A_1 V_1 \qquad \text{and} \qquad RA = \frac{A_o - A_1}{A_o} = 1 - \frac{A_1}{A_o} = 1 - \frac{V_o}{V_1}$$

(2) Non-Continuous DLD Process:

(a) The heating-cooling unit speed is in opposite direction to the drawing speed:

$$A_o V_o = A_1 (V_1 + V_o) \qquad \text{and} \qquad RA = \frac{A_o - A_1}{A_o} = 1 - \frac{A_1}{A_o} = \frac{V_1}{V_1 + V_o}$$

(b) The heating-cooling unit speed is in the same direction with the drawing speed:

$$A_o(V_o - V_1) = A_1 V_o \quad \text{and} \quad RA = \frac{A_o - A_1}{A_o} = 1 - \frac{A_1}{A_o} = \frac{V_1}{V_o}$$