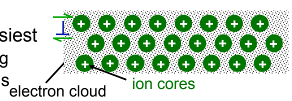
Chapter 7: Deformation & Strengthening Mechanisms

ISSUES TO ADDRESS...

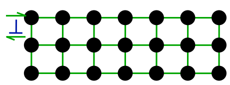
- Why are the number of _______________ present greatest in metals?
- How are strength and _____________________ related?
- Why does heating alter strength and other properties?

Dislocations & Materials Classes

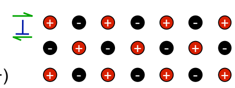
- __________ (Cu, Al):
  Dislocation motion easiest
  - non-directional bonding
  - close-packed directions for slip



- _____________________
  (Si, diamond): Motion difficult
  - directional (angular) bonding



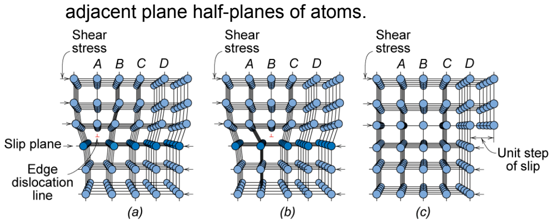
- __________________ (NaCl):
  Motion difficult
  - need to avoid nearest ________ of like sign (- and +)



Dislocation Motion

Dislocation motion & plastic _____________

- Metals - plastic __________ occurs by slip – an edge dislocation (extra half-plane of atoms) slides over adjacent plane half-planes of atoms.



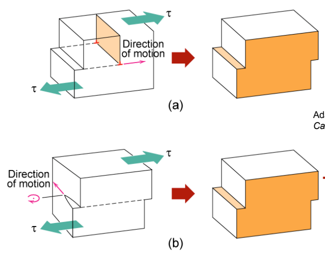
Adapted from Fig. 7.1, *Callister & Rethwisch 8e.*

- If dislocations can't move, plastic ___________ doesn't occur!

Dislocation Motion

- A dislocation moves along a slip plane in a slip __________ perpendicular to the dislocation line
- The slip direction is the same as the __________ direction

Edge __________



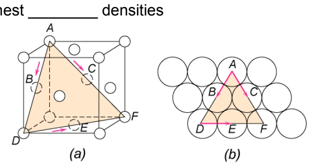
Adapted from Fig. 7.2, *Callister & Rethwisch 8e.*

__________ dislocation

Deformation Mechanisms

Slip System

- __________ - plane on which easiest ______ occurs
  - Highest planar ________ (and large interplanar spacings)
- Slip ______________ - directions of movement
  - Highest _______ densities



Adapted from Fig. 7.6, *Callister & Rethwisch 8e.*

- FCC Slip occurs on {111} _________ (close-packed) in <110> directions (close-packed)
  - => total of 12 slip systems in FCC
- For BCC & HCP there are other slip _________.

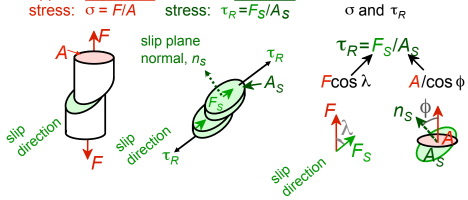
Stress and Dislocation Motion

- Resolved __________________
  - results from applied ________________

Applied _______ stress: $\sigma = F/A$

Resolved _______ stress: $\tau_R = F_S/A_S$

Relation between σ and τ_R

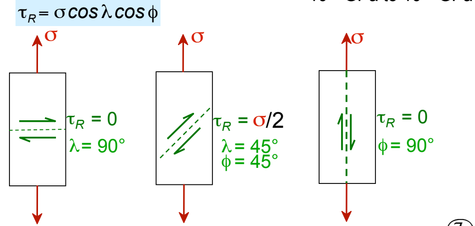


$$\tau_R = \sigma \cos\lambda \cos\phi$$

Critical Resolved Shear Stress

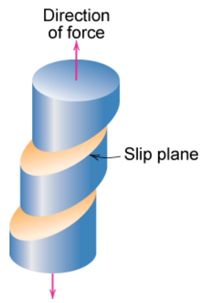
- Condition for __________ motion: $\tau_R > \tau_{CRSS}$ ← typically 10^{-4} GPa to 10^{-2} GPa
- Ease of __________ motion depends on _________________ orientation

$\tau_R = \sigma \cos\lambda \cos\phi$



τ maximum at $\lambda = \phi = 45°$

Single Crystal Slip

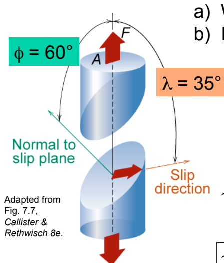


Adapted from Fig. 7.8, *Callister & Rethwisch 8e.*

Adapted from Fig. 7.9, *Callister & Rethwisch 8e.*

Ex: Deformation of single crystal

a) Will the single crystal yield?
b) If not, what stress is needed?



Adapted from Fig. 7.7, *Callister & Rethwisch 8e.*

τ_{crss} = __________

$\tau = \sigma \cos\lambda \cos\phi$

$\sigma = 45$ MPa

$\tau = (45 \text{ MPa}) (\cos 35°)(\cos 60°)$

$= (45 \text{ MPa}) (0.41)$

$\tau = 18.4 \text{ MPa} < \tau_{crss} =$ ______

$\sigma =$ __________

So the ____________________ will not cause the crystal to yield.

Ex: Deformation of single crystal

What stress *is* necessary (i.e., what is the ______________, σ_y)?

$\tau_{crss} = 20.7\text{ MPa} = \sigma_y \cos\lambda \cos\phi = \sigma_y(0.41)$

$$\therefore \sigma_y = \frac{\tau_{crss}}{\cos\lambda\cos\phi} = \frac{20.7\text{ MPa}}{0.41} = 50.5\text{ MPa}$$

So for deformation to occur the ___________ must be greater than or equal to the ___________

$\sigma \geq \sigma_y = 50.5\text{ MPa}$

Chapter 7 - 10

Slip Motion in Polycrystals

- ________ stronger than single crystals – grain boundaries are barriers to dislocation motion.
- Slip planes & directions (λ, ϕ) change from one grain to another.
- _________ from one grain to another.
- The grain with the largest τ_R yields first.
- Other (less favorably oriented) grains yield later.

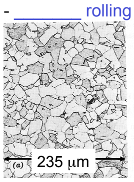
Adapted from Fig. 7.10, *Callister & Rethwisch 8e.* (Fig. 7.10 is courtesy of C. Brady, National Bureau of Standards [now the National Institute of Standards and Technology, Gaithersburg, MD].)

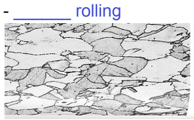
Chapter 7 - 11

Anisotropy in σ_y

- Can be induced by rolling a ___________ metal

- _______ rolling - ______ rolling





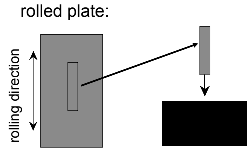
Adapted from Fig. 7.11, *Callister & Rethwisch 8e.* (Fig. 7.11 is from W.G. Moffatt, G.W. Pearsall, and J. Wulff, *The Structure and Properties of Materials*, Vol. I, *Structure*, p. 140, John Wiley and Sons, New York, 1964.)

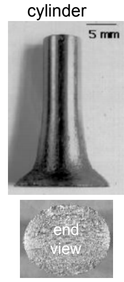
- __________ since grains are equiaxed & _______ oriented.
- ____________ since rolling affects grain _________ and shape.

Chapter 7 - 12

Anisotropy in Deformation

1. Cylinder of ________ machined from a rolled plate:
2. Fire cylinder at a target.
3. Deformed cylinder





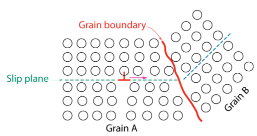
Photos courtesy of G.T. Gray III, Los Alamos National Labs. Used with permission.

plate thickness direction

- The noncircular end view shows ___________ deformation of rolled material.

Four Strategies for Strengthening: 1: Reduce Grain Size

- Grain boundaries are barriers to slip.
- Barrier "strength" ___________ with increasing angle of misorientation.
- _________ grain size: more barriers to slip.



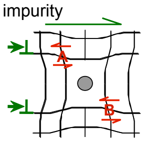
Adapted from Fig. 7.14, *Callister & Rethwisch 8e.* (Fig. 7.14 is from *A Textbook of Materials Technology*, by Van Vlack, Pearson Education, Inc., Upper Saddle River, NJ.)

- Hall-Petch Equation: $\sigma_{yield} = \sigma_o + k_y d^{-1/2}$

Four Strategies for Strengthening: 2: Form Solid Solutions

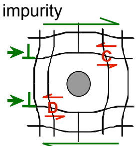
- Impurity atoms distort the _____ & generate lattice strains.
- These strains can act as barriers to ___________ motion.

- Smaller substitutional impurity



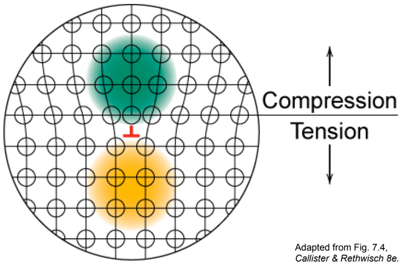
Impurity generates local stress at **A** and **B** that opposes dislocation motion to the right.

- Larger substitutional impurity



Impurity generates local stress at **C** and **D** that opposes dislocation motion to the right.

Lattice Strains Around Dislocations

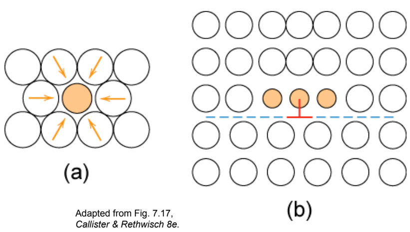


Adapted from Fig. 7.4, *Callister & Rethwisch 8e.*

Chapter 7 - 16

Strengthening by Solid Solution Alloying

- Small ___________ tend to concentrate at dislocations (regions of _______ strains) - partial cancellation of dislocation compressive strains and impurity atom tensile strains
- Reduce mobility of ___________ and increase strength

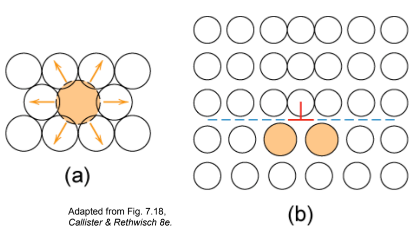


Adapted from Fig. 7.17, *Callister & Rethwisch 8e.*

Chapter 7 - 17

Strengthening by Solid Solution Alloying

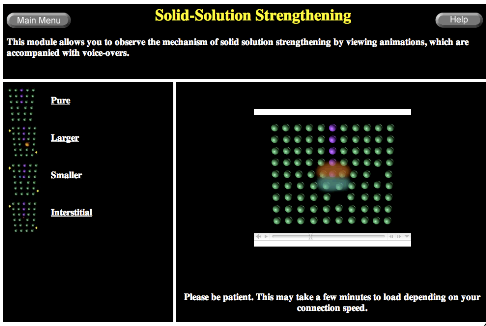
- Large ______________ tend to concentrate at ____________ (regions of tensile strains)



Adapted from Fig. 7.18, *Callister & Rethwisch 8e.*

Chapter 7 - 18

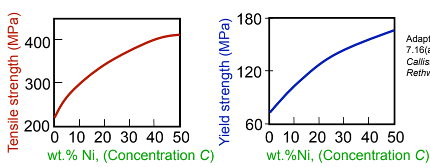
VMSE Solid-Solution Strengthening Tutorial



Chapter 7 - 19

Ex: Solid Solution Strengthening in Copper

- Tensile strength & yield strength increase with wt% Ni.



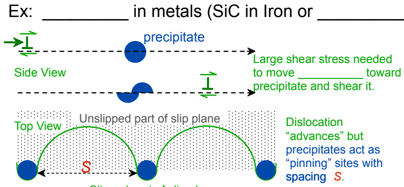
Adapted from Fig. 7.16(a) and (b), *Callister & Rethwisch 8e.*

- _________ relation: $\sigma_y \sim C^{1/2}$
- __________ increases σ_y and *TS*.

Chapter 7 - 20

Four Strategies for Strengthening: 3: ____________ Strengthening

- Hard ____________ are difficult to shear.
  Ex: _________ in metals (SiC in Iron or ___________).



- Result: $\sigma_y \sim \frac{1}{S}$

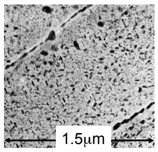
Chapter 7 - 21

Application: Precipitation _____________

- Internal wing structure on Boeing 767

Adapted from chapter-opening photograph, Chapter 11, *Callister & Rethwisch 3e.* (courtesy of G.H. Narayanan and A.G. Miller, Boeing Commercial Airplane Company.)

- Aluminum is strengthened with ____________ formed by alloying.

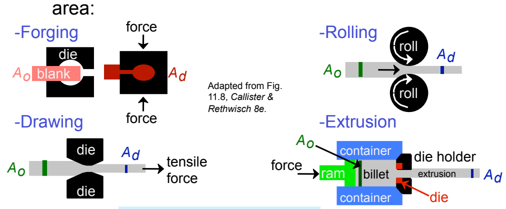


Adapted from Fig. 11.26, *Callister & Rethwisch 8e.* (Fig. 11.26 is courtesy of G.H. Narayanan and A.G. Miller, Boeing Commercial Airplane Company.)

Chapter 7 - 22

Four Strategies for Strengthening: 4: Cold Work (Strain __________)

- Deformation at room temperature (for most metals).
- Common ______________ reduce the cross-sectional area:



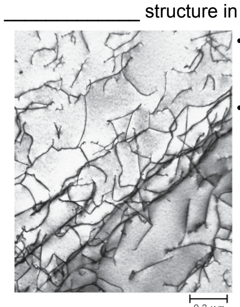
Adapted from Fig. 11.8, *Callister & Rethwisch 8e.*

$$\%CW = \frac{A_o - A_d}{A_o} \times 100$$

Chapter 7 - 23

Dislocation Structures Change During Cold Working

- ____________ structure in Ti after cold ________.



- Dislocations entangle with one another during _________.
- ___________ motion becomes more difficult.

Fig. 4.6, *Callister & Rethwisch 8e.* (Fig. 4.6 is courtesy of M.R. Plichta, Michigan Technological University.)

Chapter 7 - 24

Dislocation Density Increases During Cold Working

Dislocation density = $\frac{\text{total dislocation length}}{\text{unit volume}}$

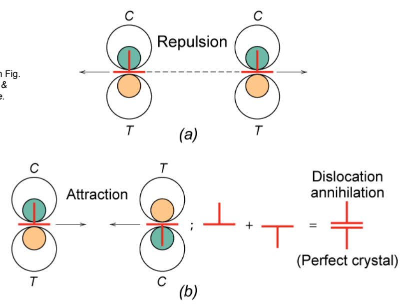
- Carefully grown ______________
  - → ca. 10^3 mm^{-2}
- Deforming sample __________ density
  - → 10^9-10^{10} mm^{-2}
- Heat treatment ___________ density
  - → 10^5-10^6 mm^{-2}

• Yield stress _________ as ρ_d increases:

Chapter 7 - 25

Lattice Strain Interactions Between Dislocations

Adapted from Fig. 7.5, *Callister & Rethwisch 8e.*

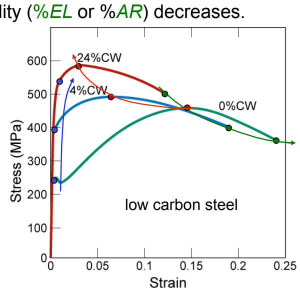


Chapter 7 - 26

Impact of Cold Work

As cold work is increased

- ________ strength (σ_y) increases.
- Tensile strength (*TS*) ____________.
- Ductility (*%EL* or *%AR*) decreases.

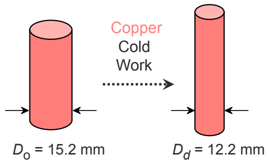


Adapted from Fig. 7.20, *Callister & Rethwisch 8e.*

Chapter 7 - 27

Mechanical Property Alterations Due to ________________

- What are the values of yield strength, tensile strength & ________ after cold working Cu?



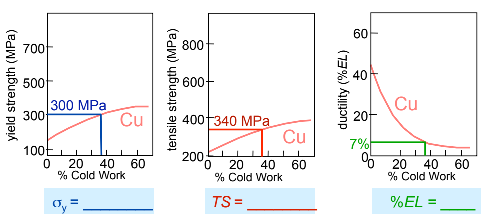
$$\%CW = \frac{\frac{\pi D_o^2}{4} - \frac{\pi D_d^2}{4}}{\frac{\pi D_o^2}{4}} \times 100$$

$$= \frac{D_o^2 - D_d^2}{D_o^2} \times 100$$

$$\%CW = \frac{(15.2\,\text{mm})^2 - (12.2\,\text{mm})^2}{(15.2\,\text{mm})^2} \times 100 = 35.6\%$$

Mechanical Property Alterations Due to Cold Working

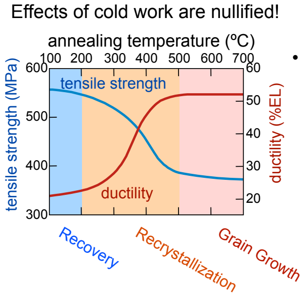
- What are the values of yield strength, _______________ & ductility for Cu for %CW = 35.6%?



Adapted from Fig. 7.19, *Callister & Rethwisch 8e.* (Fig. 7.19 is adapted from *Metals Handbook: Properties and Selection: Iron and Steels*, Vol. 1, 9th ed., B. Bardes (Ed.), American Society for Metals, 1978, p. 226; and *Metals Handbook: Properties and Selection: Nonferrous Alloys and Pure Metals*, Vol. 2, 9th ed., H. Baker (Managing Ed.), American Society for Metals, 1979, p. 276 and 327.)

Effect of Heat Treating After Cold Working

- 1 hour treatment at T_{anneal}... decreases *TS* and increases *%EL*.
- Effects of cold work are nullified!



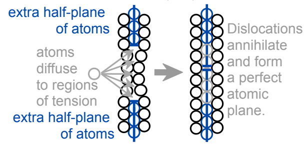
- Three Annealing stages:
  1. ____________
  2. ____________
  3. Grain Growth

Adapted from Fig. 7.22, *Callister & Rethwisch 8e.* (Fig. 7.22 is adapted from G. Sachs and K.R. van Horn, *Practical Metallurgy, Applied Metallurgy, and the Industrial Processing of Ferrous and Nonferrous Metals and Alloys*, American Society for Metals, 1940, p. 139.)

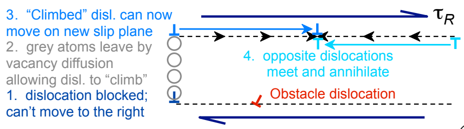
Three Stages During Heat Treatment: 1. Recovery

Reduction of _____________ density by annihilation.

- Scenario 1
  Results from
  ____



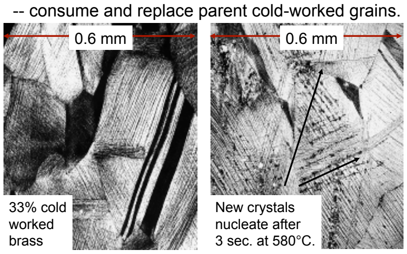
- Scenario 2



Chapter 7 - 31

Three Stages During Heat Treatment: 2. _______________

- New grains are formed that:
  -- have low ___________ densities
  -- are small in _______
  -- consume and replace parent cold-worked grains.

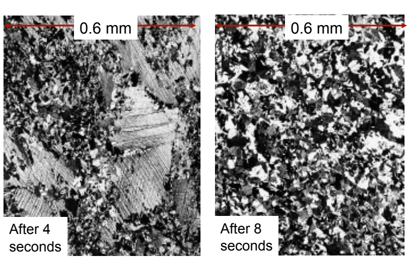


Adapted from Fig. 7.21(a),(b), *Callister & Rethwisch 8e.* (Fig. 7.21(a),(b) are courtesy of J.E. Burke, General Electric Company.)

Chapter 7 - 32

As Recrystallization Continues…

- All _______________ are eventually consumed/replaced.

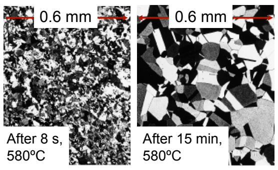


Adapted from Fig. 7.21(c),(d), *Callister & Rethwisch 8e.* (Fig. 7.21(c),(d) are courtesy of J.E. Burke, General Electric Company.)

Chapter 7 - 33

Three Stages During Heat Treatment: 3. Grain Growth

- At longer times, average grain size increases.
  - -- Small ____________ (and ultimately disappear)
  - -- Large __________ continue to grow



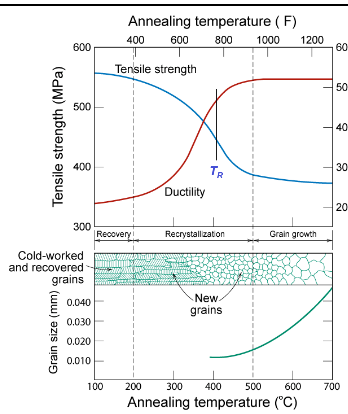
Adapted from Fig. 7.21(d),(e), *Callister & Rethwisch 8e.* (Fig. 7.21(d),(e) are courtesy of J.E. Burke, General Electric Company.)

- Empirical Relation:

$$d^n - d_o^n = Kt$$

exponent typ. ~ 2; grain diam. at time t.; coefficient ________ on ______________; elapsed time

Chapter 7 - 34



T_R = recrystallization temperature

Adapted from Fig. 7.22, *Callister & Rethwisch 8e.*

Chapter 7 - 35

Recrystallization Temperature

T_R = ____________ temperature = temperature at which ____________________________ completion in 1 h.

$$0.3T_m < T_R < 0.6T_m$$

For a specific metal/alloy, T_R depends on:

- %CW -- T_R decreases with increasing %CW
- Purity of ________ -- T_R decreases with increasing purity

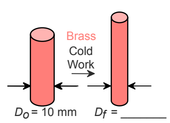
Chapter 7 - 36

Diameter Reduction Procedure - Problem

A cylindrical rod of ________________________ in diameter is to be cold worked by drawing. The circular cross section will be maintained during deformation. A cold-worked tensile strength in excess of _________________ and a ductility of at least 15 %*EL* are desired. Furthermore, the final diameter must be 7.5 mm (0.30 in). Explain how this may be accomplished.

Diameter Reduction Procedure - Solution

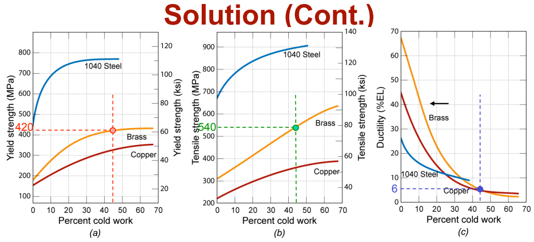
What are the consequences of directly drawing to the final diameter?



$$\%CW = \left(\frac{A_o - A_f}{A_o}\right) x\,100 = \left(1 - \frac{A_f}{A_o}\right) x\,100$$

$$= \left(1 - \frac{\pi D_f^2/4}{\pi D_o^2/4}\right) x\,100 = \left(1 - \left(\frac{7.5}{10}\right)^2\right) x\,100 = 43.8\%$$

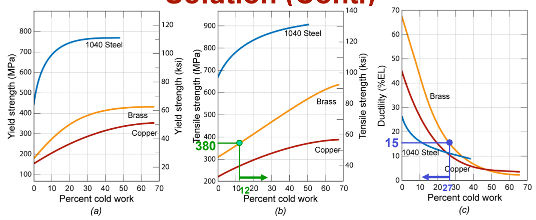
Diameter Reduction Procedure – Solution (Cont.)



Adapted from Fig. 7.19, *Callister & Rethwisch 8e.*

- For %CW = 43.8%
  - σ_y = ________
  - *TS* = _________ __ 380 MPa
  - %*EL* = _____ __ 15
- This doesn't satisfy criteria… what other options are possible?

Diameter Reduction Procedure – Solution (Cont.)



Adapted from Fig. 7.19, *Callister & Rethwisch 8e.*

For *TS* _ _________ → > 12 %CW

For *%EL* > 15 → _ _______

∴ our working range is limited to 12 < %CW < ___

Diameter Reduction Procedure – Solution (cont.)

Cold work, then _______, then ________ again

- For objective we need a cold work of 12 < %CW < 27
  - We'll use 20 %CW
- Diameter after first cold work stage (but before 2nd cold work stage) is calculated as follows:

$$\%CW = \left(1 - \frac{D_{f2}^{\,2}}{D_{02}^{\,2}}\right) x\,100 \;\Rightarrow\; 1 - \frac{D_{f2}^{\,2}}{D_{02}^{\,2}} = \frac{\%CW}{100}$$

$$\frac{D_{f2}}{D_{02}} = \left(1 - \frac{\%CW}{100}\right)^{0.5} \;\Rightarrow\; D_{02} = \frac{D_{f2}}{\left(1 - \frac{\%CW}{100}\right)^{0.5}}$$

$$\text{Intermediate diameter} = D_{f1} = D_{02} = 7.5\,\text{mm} \Big/ \left(1 - \frac{20}{100}\right)^{0.5} = 8.39\,\text{mm}$$

Diameter Reduction Procedure – Summary

Stage 1: _________ – reduce diameter from 10 mm to 8.39 mm

$$\%CW_1 = \left(1 - \left(\frac{8.39\,\text{mm}}{10\,\text{mm}}\right)^2\right) x\,100 = 29.6$$

Stage 2: ____________ (allow recrystallization)

Stage 3: _________ – reduce diameter from 8.39 mm to 7.5 mm

$$\%CW_2 = \left(1 - \left(\frac{7.5}{8.49}\right)^2\right) x\,100 = 20 \;\overset{\text{Fig 7.19}}{\Rightarrow}$$

Therefore, all criteria satisfied

Cold Working vs. Hot Working

- Hot working → deformation above T_R
- Cold working → deformation below T_R

Grain Size Influences Properties

- Metals having ______ grains – relatively strong and tough at low temperatures
- Metals having ______ grains – good creep resistance at relatively ______ temperatures

Summary

- Dislocations are observed primarily in metals and alloys.
- Strength is increased by making dislocation motion difficult.
- Strength of metals may be increased by:
  -- decreasing grain size
  -- solid solution strengthening
  -- precipitate hardening
  -- cold working
- A cold-worked metal that is heat treated may experience recovery, recrystallization, and grain growth – its properties will be altered.