# Module 4

Types of Strengthening mechanisms: - work hardening, equation - precipitation strengthening and over ageing dispersion hardening. Cold working: Detailed discussion on strain hardening; recovery; re-crystallization, effect of stored energy; recrystallization temperature - hot working Bauschinger effect and attributes in metal forming. Alloy steels:- Effects of alloying elements on steel: dislocation movement, polymorphic transformation temperature, alpha and beta stabilizers, formation and stability of carbides, grain growth, displacement of the eutectoid point, retardation of the transformation rates, improvement in corrosion resistance, mechanical properties Nickel steels, Chromium steels etc. - Enhancement of steel properties by adding alloying elements: - Molybdenum, Nickel, Chromium, Vanadium, Tungsten, Cobalt, Silicon, Copper and Lead. High speed steels:- Mo and W types, effect of different alloying elements in HSS Cast irons: Classifications; grey, white, malleable and spheroidal graphite cast iron etc, composition, microstructure, properties and applications. Principal Non ferrous Alloys: - Aluminum, Copper, Magnesium, Nickel, study of composition, properties, applications, reference shall be made to the phase diagrams whenever necessary.

Types of Strengthening Mechanisms

- Generally, ductility is sacrificed when an alloy is strengthened.

- Frequently alloy selection depends on the capacity of a material to be tailored with the mechanical characteristics required for a particular application.

- Because macroscopic plastic deformation corresponds to the motion of large numbers of dislocations, the ability of a metal to plastically deform depends on the ability of dislocations to move.

- Since hardness and strength (both yield and tensile) are related to the ease with which plastic deformation can be made to occur, by reducing the mobility of dislocations.

- The mechanical strength may be enhanced by constraining the dislocation motion,

- The greater is the facility with which the dislocations move in a metal, the softer and weaker it becomes.

- All strengthening techniques rely on this simple principle: restricting or hindering dislocation motion renders a material harder and

Strengthening by Grain Size Reduction

- The size of the grains, or average grain diameter, in a polycrystalline metal influences the mechanical properties.

- Adjacent grains normally have different crystallographic orientations and, a common grain boundary, as indicated in **Figure**.

- During plastic deformation, slip or dislocation motion must take place across this common boundary—say, from grain A to grain B in **Figure**.

- The grain boundary acts as a barrier to dislocation motion for two reasons:

  1. Since the two grains are of different orientations, a dislocation passing into grain B will have to change its direction of motion; this becomes more difficult as the crystallographic misorientation increases.

  2. The atomic disorder within a grain boundary region will result in a discontinuity of slip planes from one grain into the other.

Grain Boundary

Slip Plane
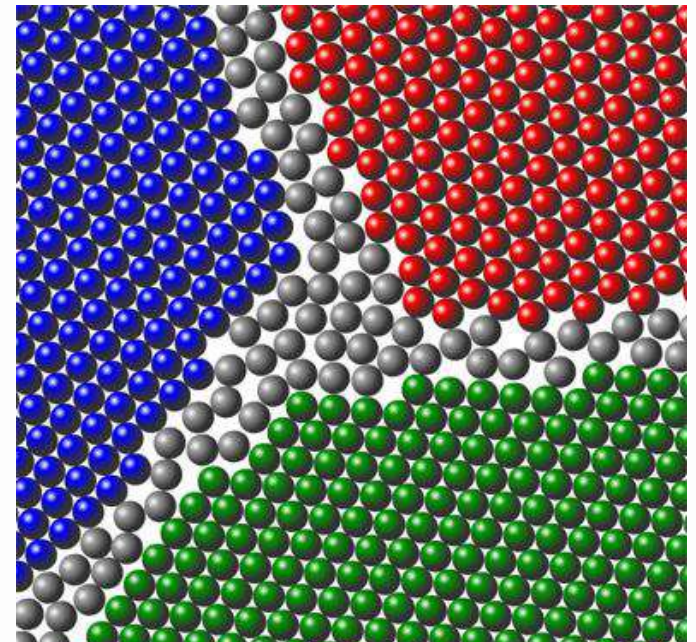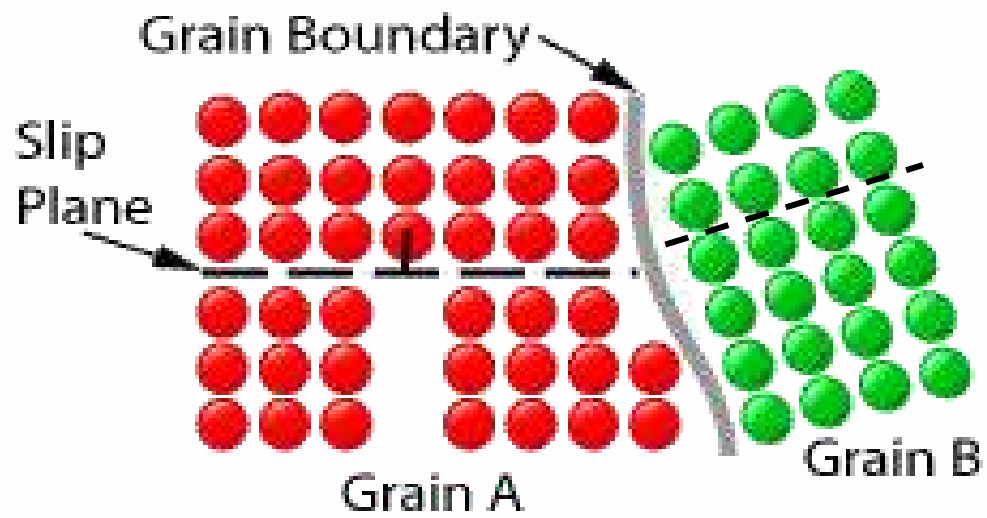
Grain A

Grain B

- For high-angle grain boundaries, the dislocations does not traverse grain boundaries during deformation; but, dislocations tend to "pile up" (or back up) at grain boundaries.
- These pile-ups introduce stress concentrations ahead of their slip planes, which generate new dislocations in adjacent grains.
- A fine-grained material (one that has small grains) is harder and stronger than one that is coarse grained, since the fine grained material has a greater total grain boundary area to stop the dislocation motion.
- The yield strength σ_y varies with grain size according to

$$\sigma_y = \sigma_0 + k_y d^{-1/2}$$

- This expression is termed as Hall-Petch equation, d is the average grain diameter, and σ_0 and k_y are constants for a particular material.
- This Equation is not valid for both very large (i.e., coarse) grain and extremely fine grain polycrystalline materials.
- Grain size may be regulated by the rate of solidification from the liquid phase, and also by plastic deformation followed by an appropriate heat treatment.
- It should also be mentioned that grain size reduction improves not only strength, but also the toughness of many alloys.

Solid-Solution Strengthening

- Alloying metals with impurity atoms that go into either substitutional or interstitial solid solutions can strengthen and harden metals. This is called solid-solution strengthening.

- High-purity metals are almost always softer and weaker than alloys composed of the same base metal.

- Increasing the concentration of the impurity atoms result in an increase in tensile and yield strengths of a material.


(a)

(b)
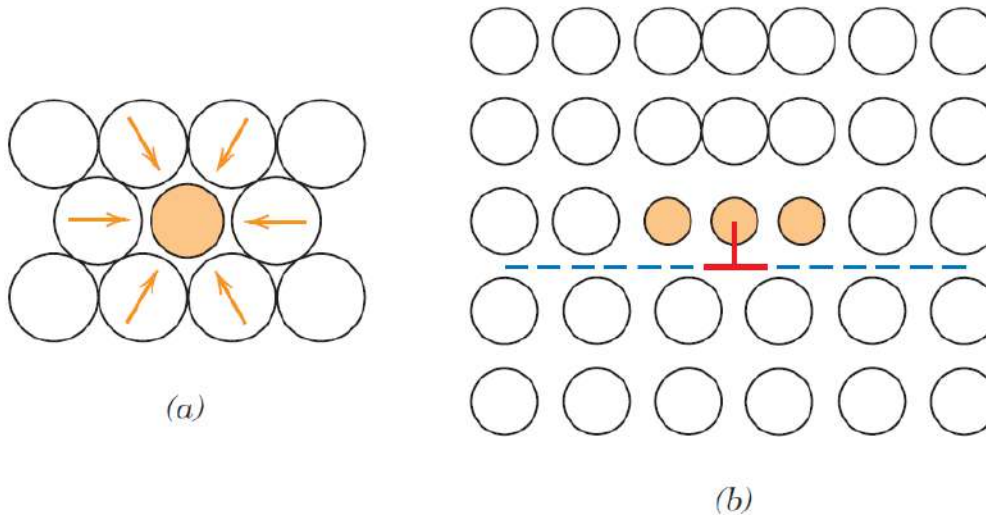
(a) tensile lattice strains imposed on host atoms by a smaller substitutional impurity

- Alloys are stronger than pure metals because impurity atoms that go into solid solution ordinarily impose lattice strains on the surrounding host atoms.

- Lattice strain field interactions between dislocations and these impurity atoms can restrict the dislocation movements.

- An impurity atom that is smaller than a host atom for which it substitutes exerts tensile strains on the surrounding crystal lattice, and a larger substitutional atom imposes compressive strains in its vicinity.

- These solute atoms in the neighborhood of the dislocations reduces the overall strain energy—that is, to cancel some of the strain in the lattice surrounding a dislocation.

- To accomplish this, a smaller impurity atom is located where its tensile strain will partially nullify some of the dislocation's compressive strain.

- The resistance to slip is greater when impurity atoms are present because the overall lattice strain must increase if a dislocation is torn away from them.

- There is a lattice strain interactions between the impurity atoms and dislocations that are in motion during plastic deformation.

- Thus, a greater applied stress is necessary to first initiate and then continue plastic deformation for solid-solution alloys, as opposed to pure metals; this is evidenced
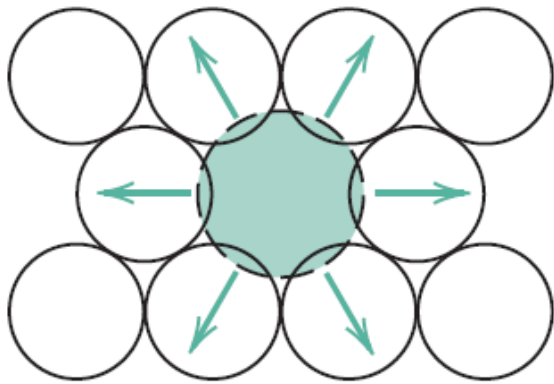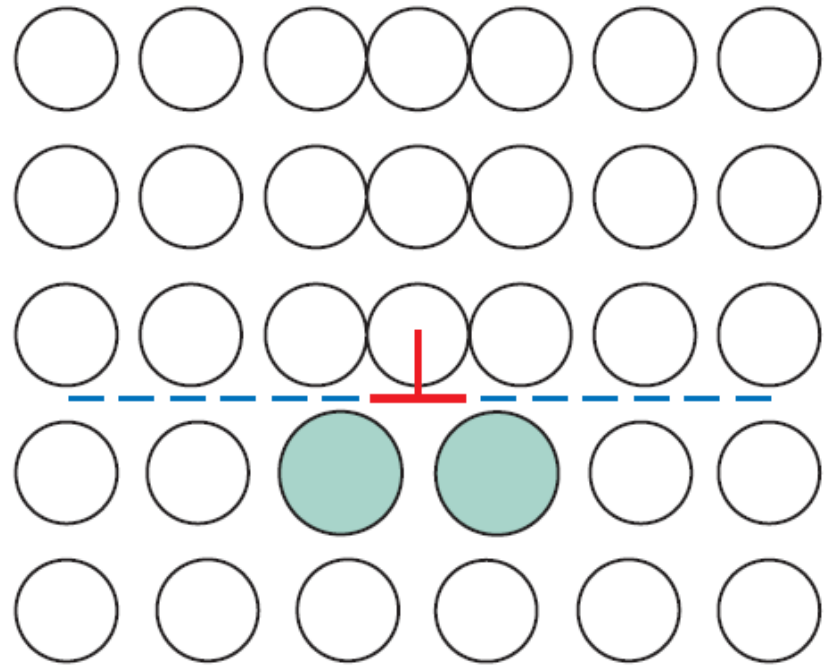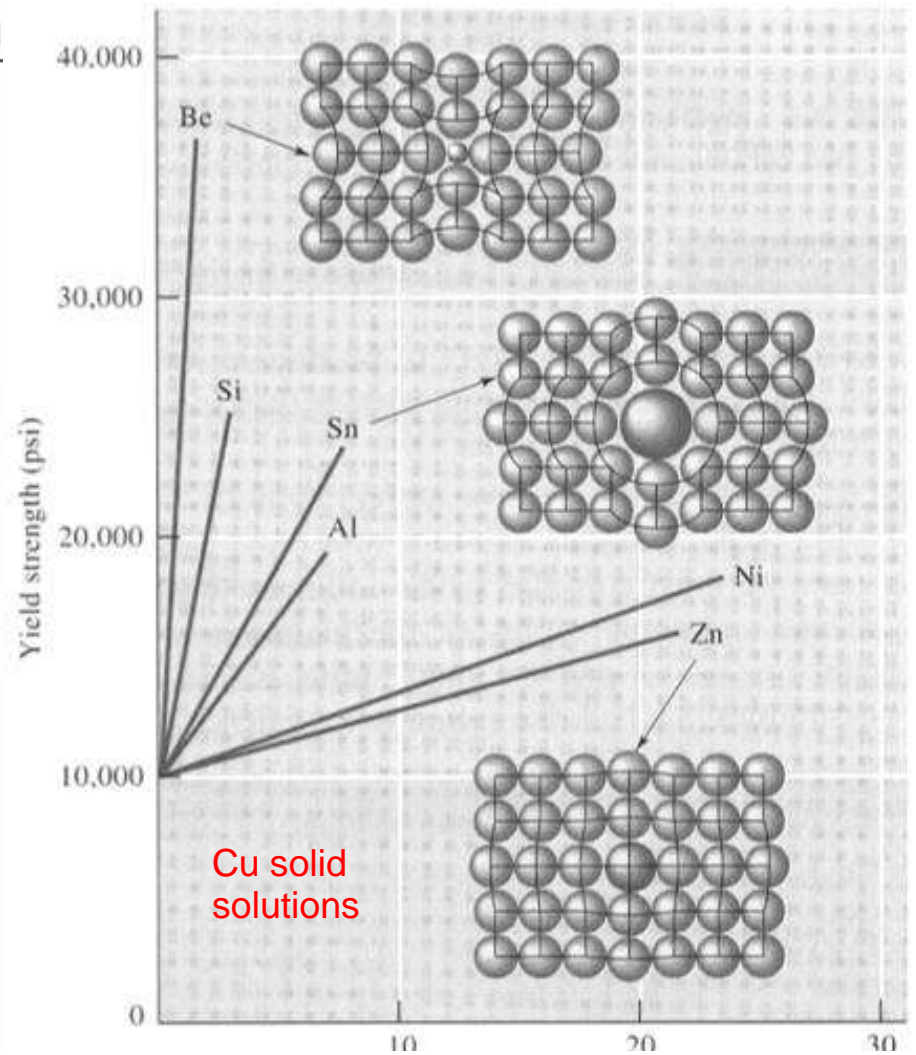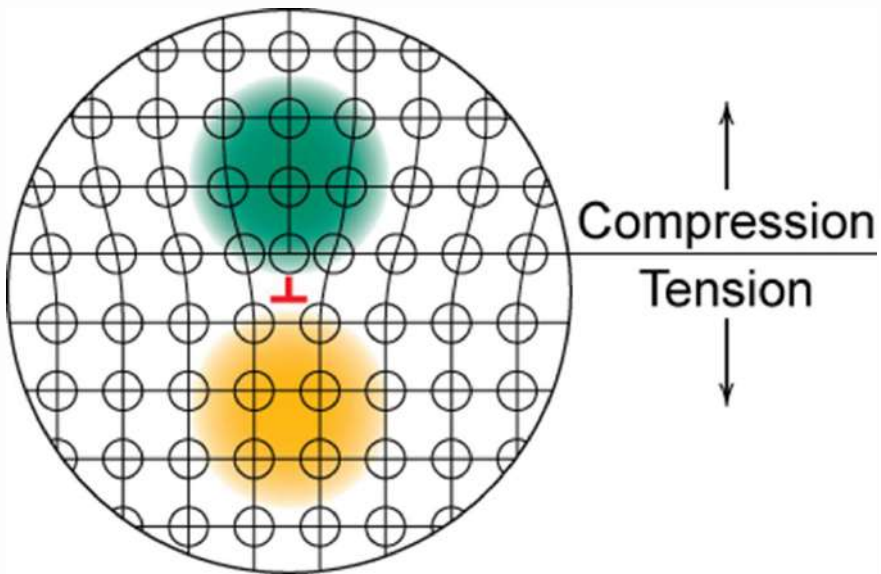
(a) Representation of compressive strains imposed on host atoms by a larger substitutional impurity atom. (b) Possible locations of larger impurity atoms relative to an edge dislocation such that there is partial cancellation of impurity–dislocation lattice strains.

Compression
Tension

Yield strength (psi)

40,000

Be

30,000

Si
Sn

20,000
Al

Ni
Zn

10,000

Cu solid
solutions

0

10   20   30

Work Hardening or strain hardening

- **Strain hardening** is the phenomenon whereby a ductile metal becomes harder and stronger as it is plastically deformed. Sometimes it is also called *work hardening.*

- If the temperature at which deformation takes place is "cold" relative to the absolute melting temperature of the metal, **cold working.**

- Most metals strain harden at room temperature.

- Metals that cannot be heat treated can be strengthened using strain or work hardening

- It is sometimes convenient to express the degree of plastic deformation as *percent cold work* rather than as strain. Percent cold work (%CW) is defined as
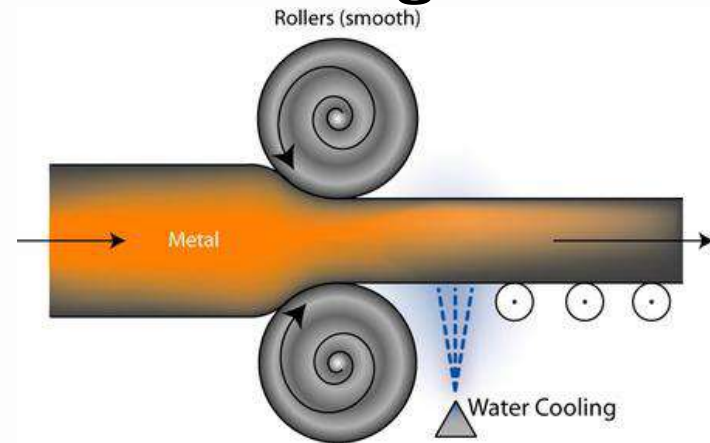
$$\% \, CW = \left(\frac{A_0 - A_d}{A_0} \right) \times 100$$

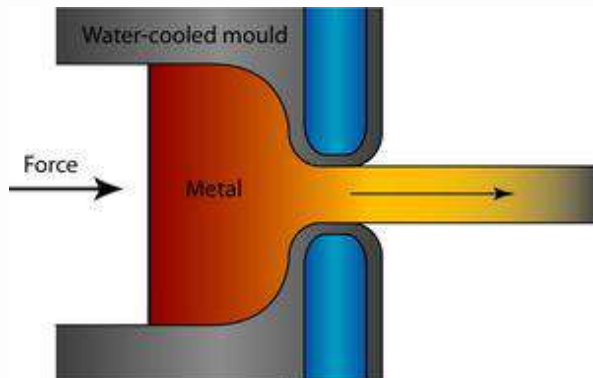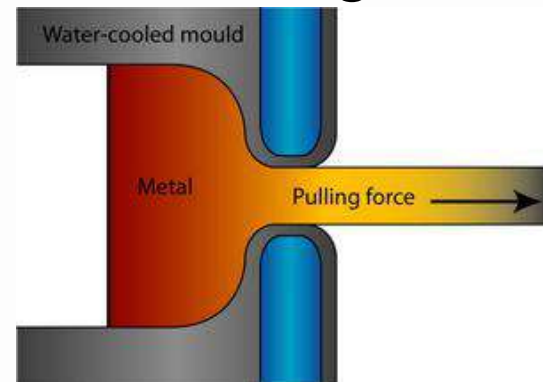where is the A_0 original area of the cross section that

Forging
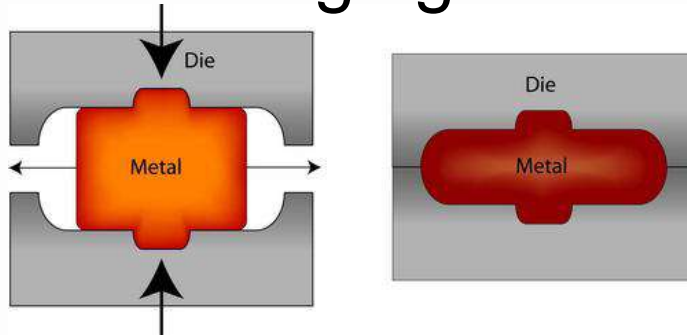
Rolling

Extrusion

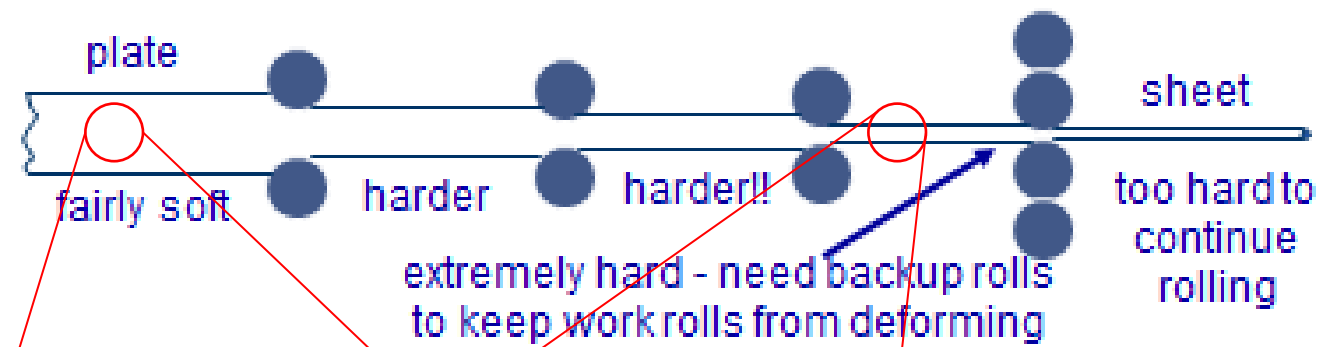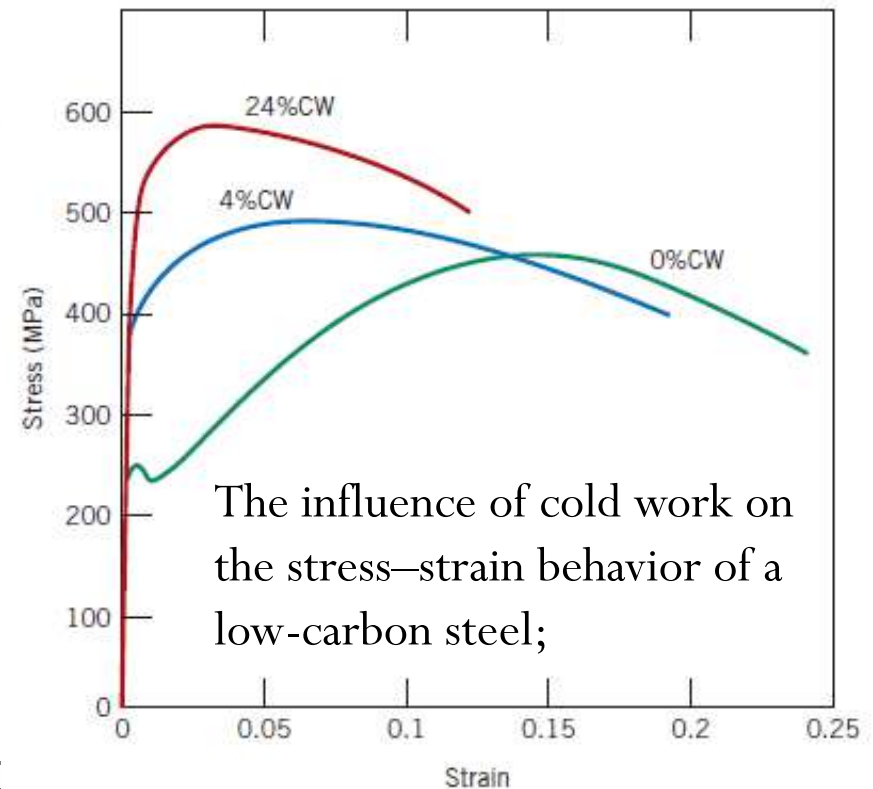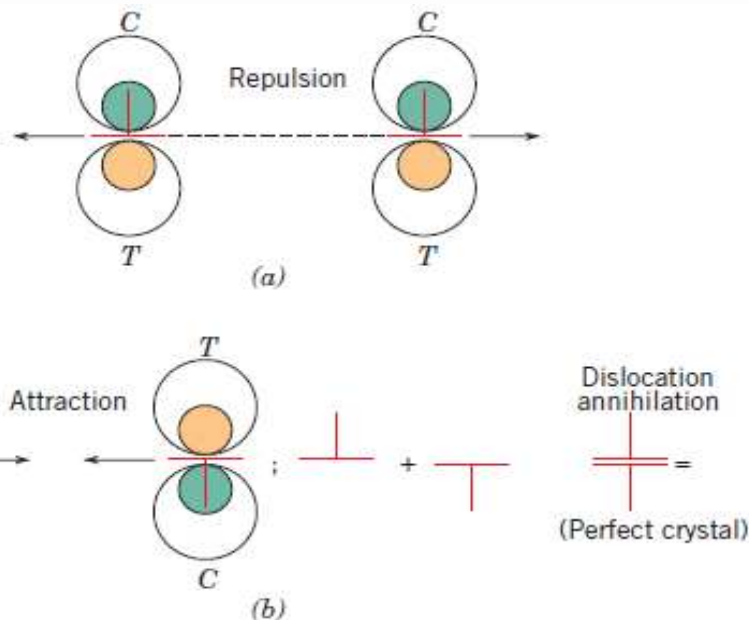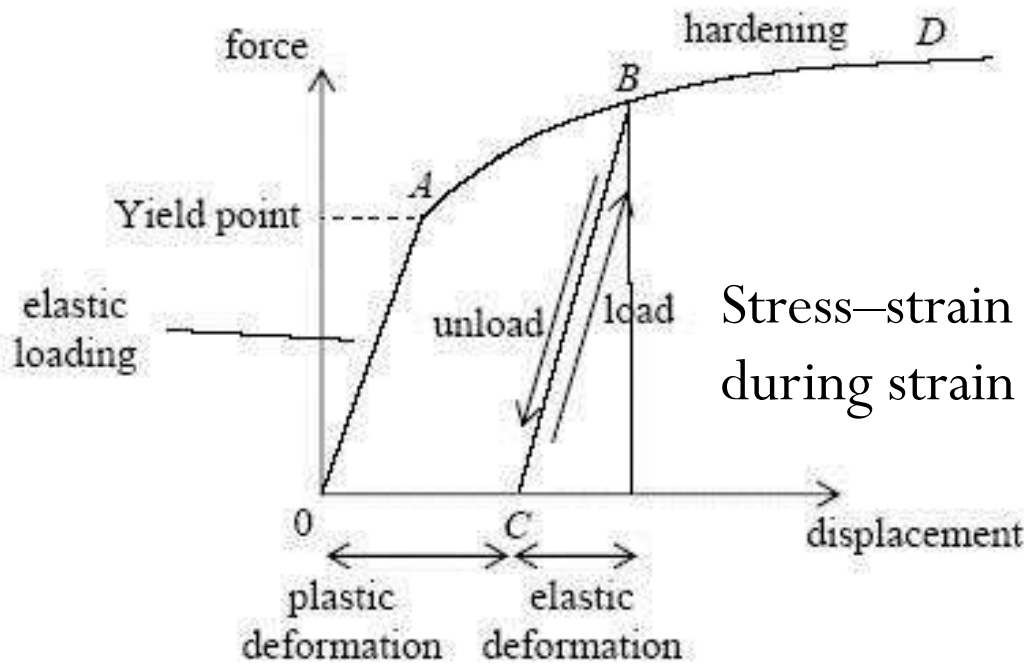

Drawing
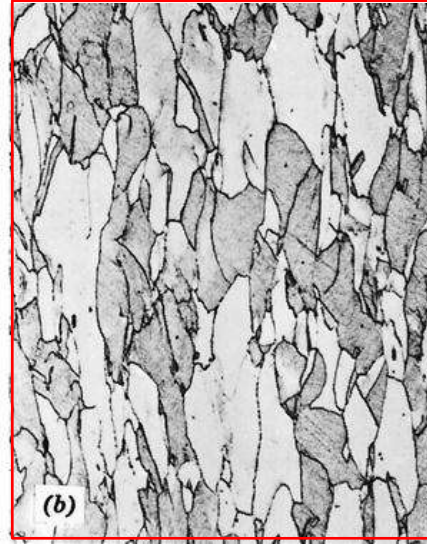
- During plastic deformation, severe distortion of the crystal lattice take place, which leads to the generation of heat.
- When the distortion of grains take place; this distortion will be highest at slip planes and grain boundaries.

Stress–strain behavior during strain hardening

The influence of cold work on the stress–strain behavior of a low-carbon steel;

- There is an increase in yield and tensile strength with increasing cold work.

- The price for this enhancement of hardness and strength is in the ductility of the metal.

- In strain hardening, the metal with yield strength σ_{y0} is plastically deformed to a point initially and the stress is released, then reapplied with a resultant new higher yield strength.

- The strain-hardening phenomenon is explained on the basis of dislocation–dislocation strain field interactions.

- The dislocation density in a metal increases with deformation or cold work, due to dislocation multiplication or the formation of new dislocations.

- Consequently, the average distance of separation between dislocations decreases—the dislocations are positioned closer together.

- On the average, dislocation–dislocation strain interactions are repulsive. The net result is that the motion of a dislocation is hindered by the presence of other dislocations.

- As the dislocation density increases, this resistance to dislocation motion by other dislocations becomes more pronounced. Thus, the imposed stress necessary to deform a metal increases with increasing cold work.

- Strain hardening is often utilized commercially to enhance the mechanical properties of metals during fabrication procedures.

- Compute the ductility (%EL) of a cylindrical copper rod if it is cold worked such that the diameter is reduced from 15.2 mm to 12.2 mm

Precipitation Hardening

- The strength and hardness of some metal alloys may be enhanced by the formation of extremely small uniformly dispersed particles of a second phase within the original phase matrix;

- This structure is accomplished by phase transformations that are induced by appropriate heat treatments. The process is called **precipitation hardening** because the small particles of the new phase are termed "precipitates.

- "Age hardening" is also used to designate this procedure because the strength develops with time, or as the alloy ages even if the alloy is not subjected to heat treatment.

- Examples of alloys that are hardened by precipitation treatments include aluminum–copper, copper–beryllium, copper–tin, and magnesium–aluminum; some ferrous alloys are also precipitation hardenable.
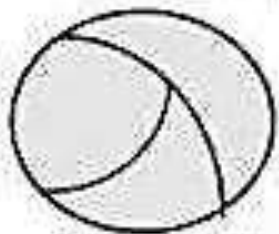
solution heat treatment

- Precipitation hardening is accomplished by two different heat treatments. The first is a **solution heat treatment** in which all solute atoms are dissolved to form a single phase solid solution.

- The treatment consists of heating the alloy to a temperature T_0 within the α phase field and waiting until all the β phase that may have been present is completely dissolved.

- At this point, the alloy consists only of an α phase of composition

- Then the material cooled rapidly or quenched to room temperature, to the extent that any diffusion and the accompanying formation of any of the phase are prevented.

- Thus, a nonequilibrium situation exists in which only the α-phase solid solution supersaturated with B atoms.

- At this stage diffusion rates at are extremely slow, such that the single phase is retained at this temperature
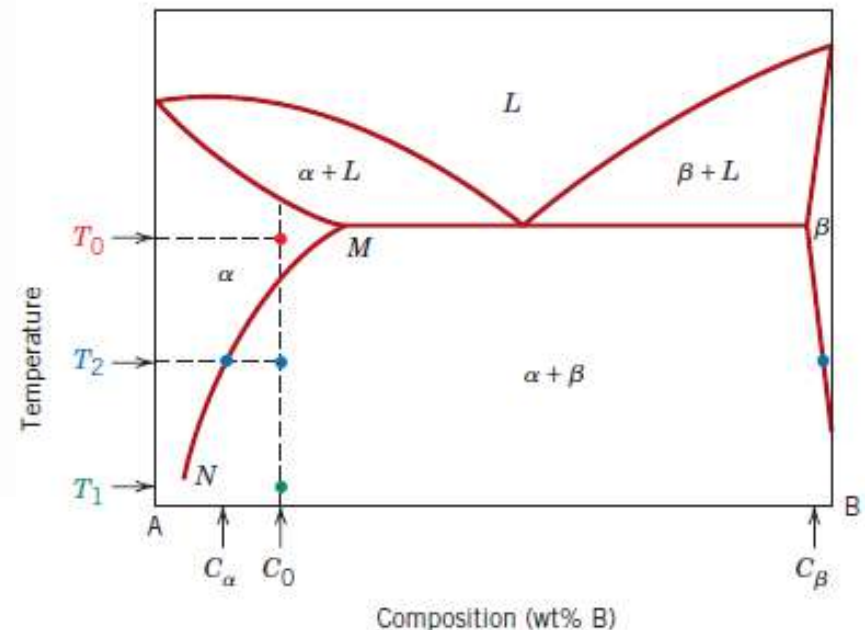
Precipitation treatment

- For the second or **precipitation heat treatment,** the supersaturated α-solid solution is ordinarily heated to an intermediate temperature within the α+β two-phase region, at which temperature diffusion rates become appreciable.
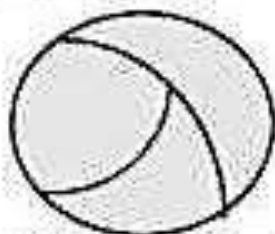
- The precipitate, β phase begins to form as finely dispersed particles in α-phase, the process is sometimes termed "aging."

- After the appropriate aging time at the alloy is cooled to room temperature; normally, this cooling rate is not an important consideration.

- The character of the β particles, and subsequent strength and hardness of the alloy, depend on both the precipitation temperature and the aging time at this temperature.

- For some alloys, aging occurs spontaneously at room temperature over

- extended time periods.

- With increasing time, the strength or hardness increases, reaches a maximum, and finally diminishes. This reduction in strength and hardness that occurs after long time periods is known as **overaging.**

- In some cases, the strength and hardness found to be increasing over the passage of time even if the alloy is kept at room temperature. Therefore the process is called **age hardening.**

- If the aging happens within a short period of time after quenching, the process in known as **natural aging.**

- If the quenching follows heat treatment to achieve aging, the process is called **Artificial**

Solution heat treatment

Quench

Precipitation heat treatment

T_0

T_2

T_1

Temperature

Time

700

600

500

400

300

200

100

Temperature, C

L

$\alpha + L$

α

① Solution Treat

Quench

② Age

③

$\alpha + \theta$

Al 2 4 6 8

Weight Percent Copper

① Copper in Solution

α

② Copper in Supersaturated Solution

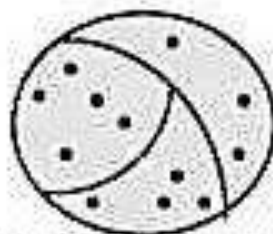③ Copper Precipitates
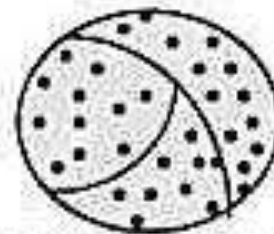
α

θ

Quench

Quench

Age
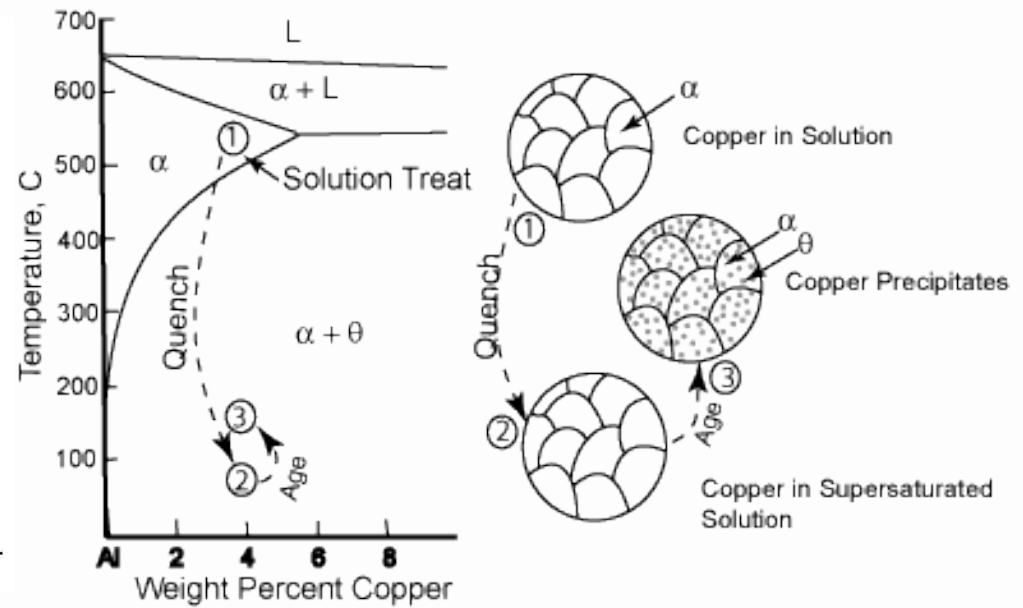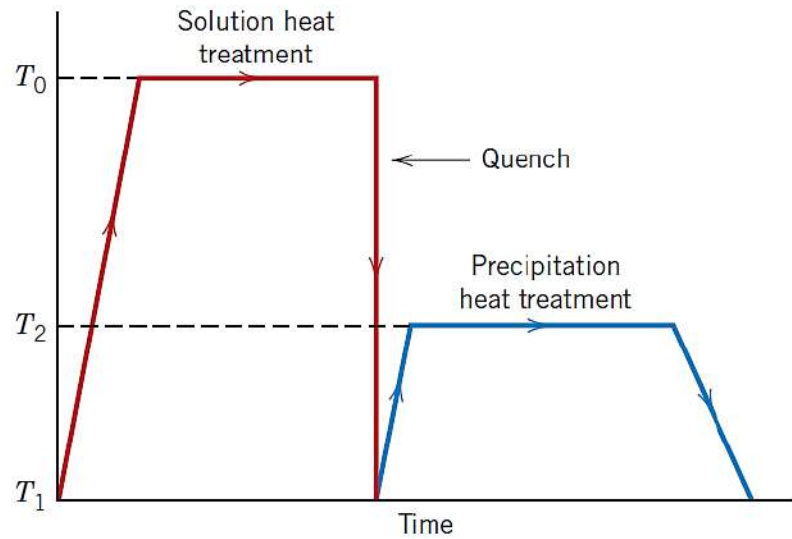
Solutionized   After Quench   Heat Treatment - Growth   Highest Strength   Over-aged
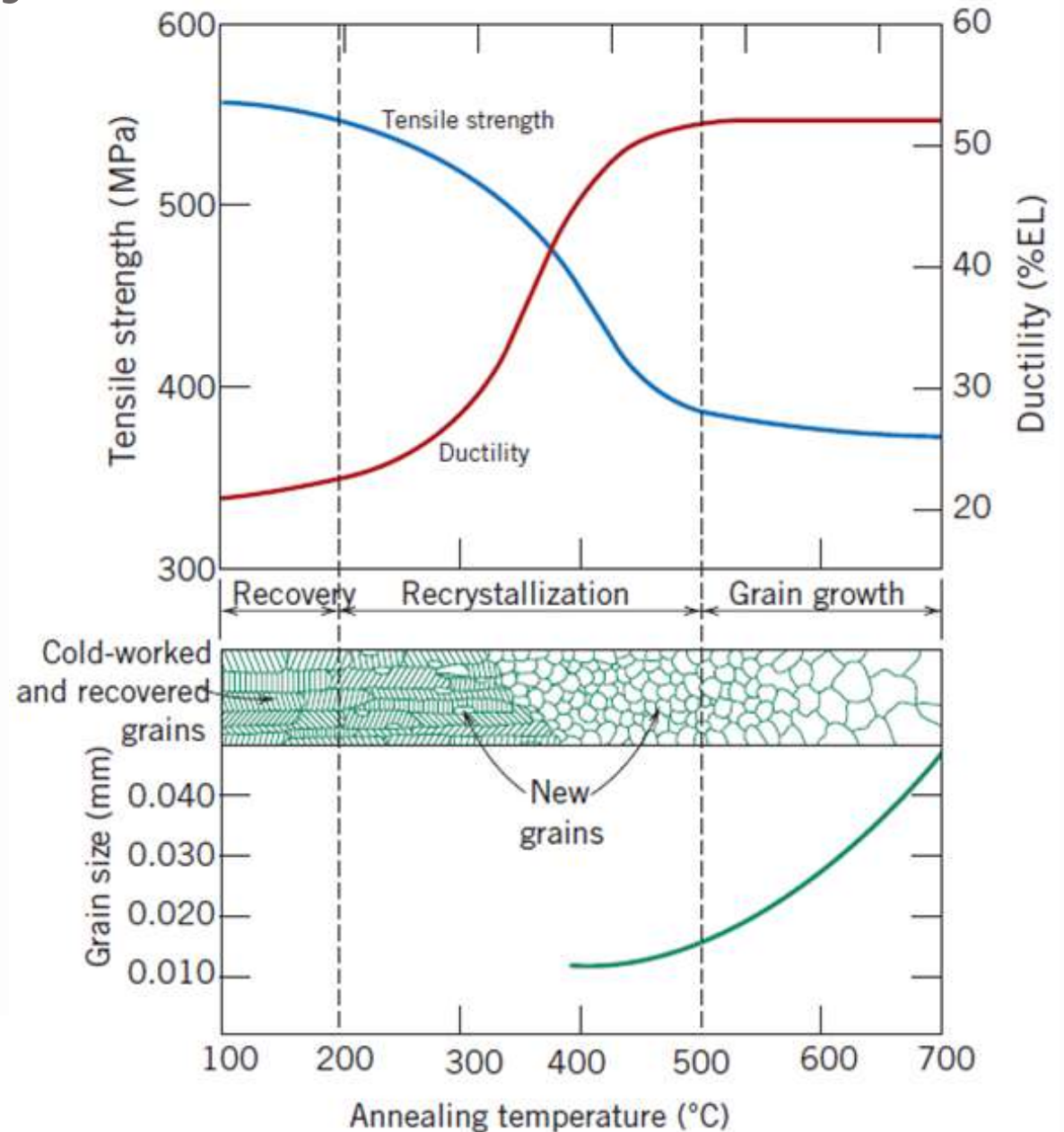
Recovery, Recrystallization, and Grain Growth

- When plastically deforming a poly-crystalline metal specimen at temperatures that are low relative to its absolute melting temperature produces microstructural and property changes that include
  - A Change in Grain Shape,
  - Strain Hardening,
  - An Increase in Dislocation Density.

- Some fraction of the energy expended in deformation is stored in the metal as strain energy, which is associated with tensile, compressive, and shear zones around the newly created dislocations.

- Furthermore, other properties such as electrical conductivity and corrosion resistance may be modified as a consequence of plastic deformation.

- These properties and structures may revert back to the precold-worked states by appropriate heat treatment (sometimes termed an annealing treatment).

- Such restoration results from two different processes that occur at elevated temperatures: recovery and recrystallization, which may be followed by grain growth.

RECOVERY

- During recovery, some of the stored internal strain energy is relieved by virtue of dislocation motion (in the absence of an externally applied stress), as a result of enhanced atomic diffusion at the elevated temperature.

- There is some reduction in the number of dislocations, and dislocation configurations are produced having low strain energies.

- The physical properties such as electrical and thermal conductivities are recovered to their precold-worked states.

Recovery, Recrystallization, and Grain Growth

Recrystallization & Growth
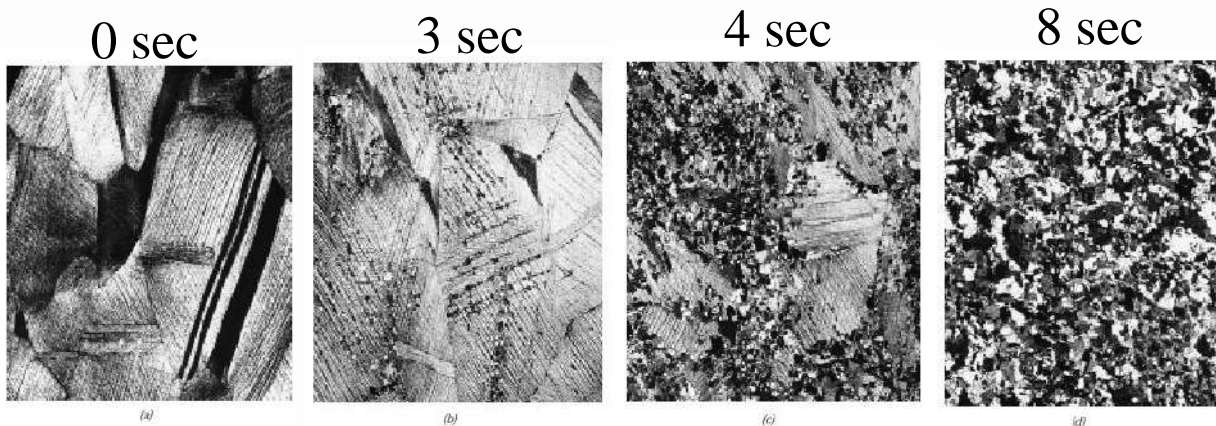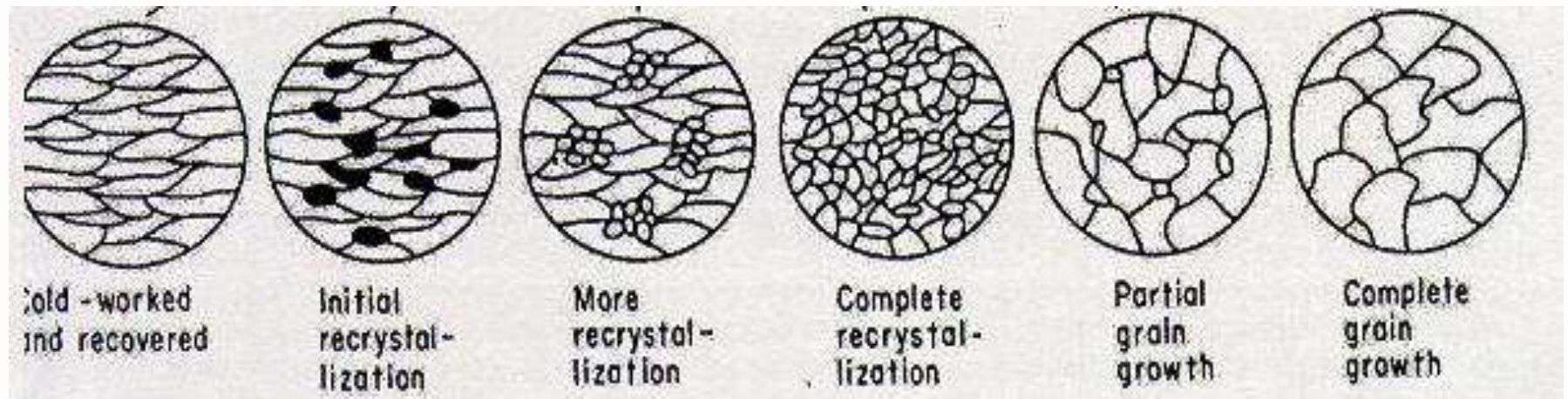
Cold worked brass at re-crystalization temperature 580°C

Recrystallization

- Once the recovery is complete, the grains are still in a relatively high strain energy state.

- Recrystallization is the formation of a new set of strain-free and equiaxed grains (i.e., having approximately equal dimensions in all directions) that have low dislocation densities and are characteristic of the precold-worked condition.

- The driving force to produce this new grain structure is the difference in internal energy between the strained and unstrained material.

- The new grains form as very small nuclei and grow until they completely consume the parent material, processes that involve short-range diffusion.

- Also, during recrystallization, the mechanical properties that were changed as a result of cold working are restored to their precold-worked values; that is, the metal becomes softer, weaker, yet more ductile. Some heat treatments are designed to allow recrystallization to occur with these modifications in the mechanical characteristics.

- Recrystallization is a process the extent of which depends on both time and temperature. The degree (or fraction) of recrystallization increases with time.

- The influence of temperature is demonstrated in **Figure 3.19**, which plots tensile strength and ductility (at room temperature) of a brass alloy as a function of the temperature and for a constant heat treatment time of 1 h. The grain structures

Cold Working and Annealing
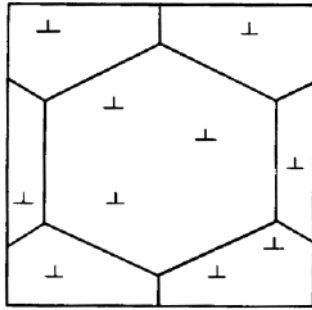
(a)
Starting material with low dislocation density
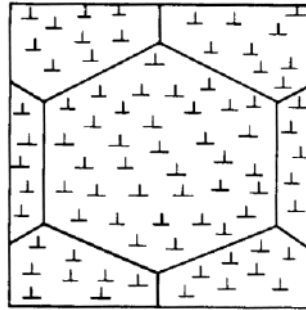
(b)
Cold-worked material has greatly increased dislocation density
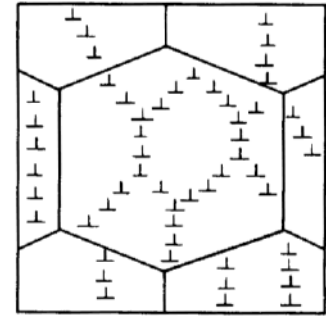
(c)
Annealing leads to recovery
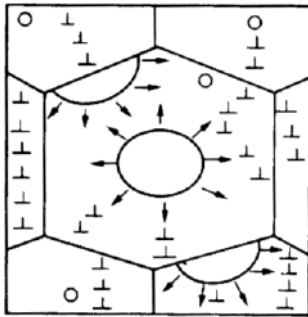
(d)
Further annealing leads to nucleation and growth of new grains
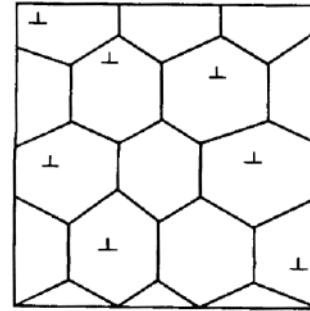
(e)
Fully recrystallized metal with new (smaller) strain-free grains

- The recrystallization behavior of a particular metal alloy is sometimes specified in terms of a *recrystallization temperature*, the temperature at which recrystallization just reaches completion in 1 h.
- Typically, it is between one-third and one-half of the absolute melting temperature of a metal or

- **prior cold work**
  - Increasing the percentage of cold work enhances the rate of recrystallization, with the result that the recrystallization temperature is lowered, and approaches a constant or limiting value at high deformations.
  - There exists some critical degree of cold work below which recrystallization cannot be made to occur; normally, this is between 2% and 20% cold work.
- **Time of annealing**
  - Increasing the annealing time decreases the crystallization temperature.
  - The complete recrystallization of a deformed material can be achieved by keeping the material at lower temperatures for longer periods.
- **Annealing temperature**
  - If the recrystallization is carried out at higher temperatures it gets completed soon.
  - The recrystallization temperature is more sensitive to temperature changes than time.
- **The purity of the alloy**
  - Recrystallization proceeds more rapidly in pure metals than in alloys. During recrystallization, grain-boundary motion occurs as the new grain nuclei form and then grow. It is believed that impurity atoms preferentially segregate at and interact with these recrystallized grain boundaries so as to diminish their (i.e., grain boundary) mobilities; this results in a decrease of the recrystallization rate and raises the recrystallization temperature, sometimes quite substantially.
  - For pure metals, the recrystallization temperature is normally 0.3Tm, where Tm is the absolute

- **Initial Grain size**
  - For an equal amount of cold working, more strain hardening is introduced to a fine grained material than a coarse grained material.
  - A fine grain structure prior to cold working has many grain boundaries, and more distorted regions provide more nucleation sites promoting rapid crystallization..
- **Temperature of deformation**
  - Plastic deformation operations are often carried out at temperatures above the recrystallization temperature in a process termed hot working. The material remains relatively soft and ductile during deformation because it does not strain harden, and thus large deformations are possible.
- **Amount of recovery prior to crystallization**
  - If the deformed metal had been recovered for long, crystallization will be delayed.
  - As the strain energy is relieved during recovery, the driving force for

Grain growth

- After recrystallization is complete, the strain-free grains will continue to grow if the metal specimen is left at the elevated temperature; this phenomenon is called **grain growth**.

- Grain growth does not need to be preceded by recovery and recrystallization; it may occur in all polycrystalline materials, metals and ceramics alike.

- An energy is associated with grain boundaries, as grains increase in size, the total boundary area decreases, leads to a reduction in the total energy; this is the driving force for grain growth.

- The opposing force is rigidity of the lattice, and the rigidity decreases as the temperature increases and the grain growth will be rapid.

- Factors favor rapid nucleation leads to fine grains and slow nucleation leads to large grains.

- **prior cold work**
  - Increasing the percentage of cold work enhances the rate of nucleation and thereby finer grains.
  - There exists some critical degree of cold work at which large grains will form up on annealing, due to the less number of distorted regions that can act as nucleation sites.
  - If a few number of grains are formed during recrystallization, lead to a coarse grained structure.
- **Time of annealing**
  - Increasing the annealing time above the recrystallization temperature, favors the grain growth.
  - If the material is removed soon after recrystallization, the resulting material will have a fine grained structure.
- **Annealing temperature**
  - If the recrystallization is carried out at lower temperatures above recrystallization temperature, finer the grains will be.
  - At lower recrystallization temperatures, diffusion will be slow ; results in fine grained structure.
- **The purity of the alloy**
  - Recrystallization proceeds more rapidly in pure metals than in alloys. The grain growth will decrease as the amount of impurity present is high.

Atomic diffusion across boundary

Direction of grain boundary motion

Annealing

Cold working — Recovery — Recrystallization — Grain growth

Ductility

Hardness

Strength

Electrical conductivity

Property

Internal Stress
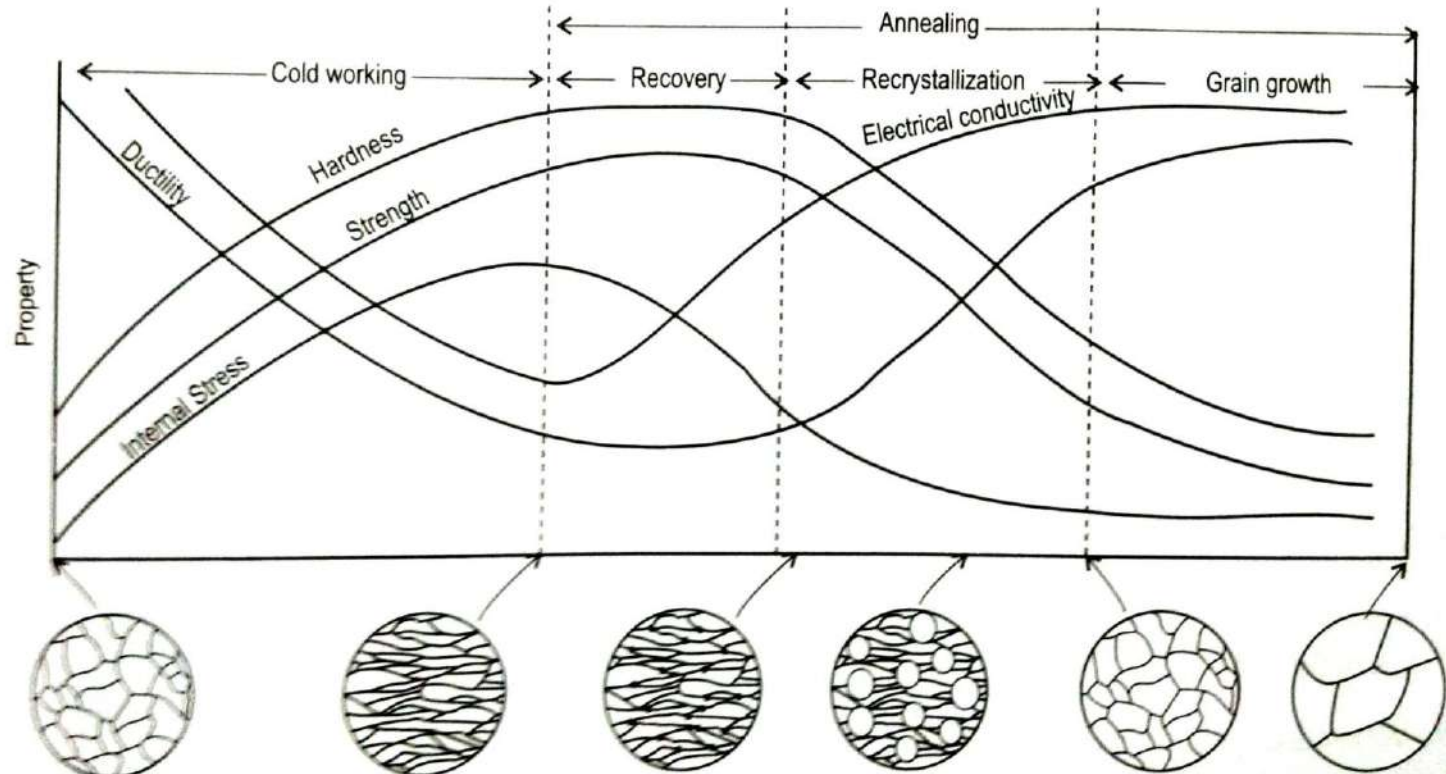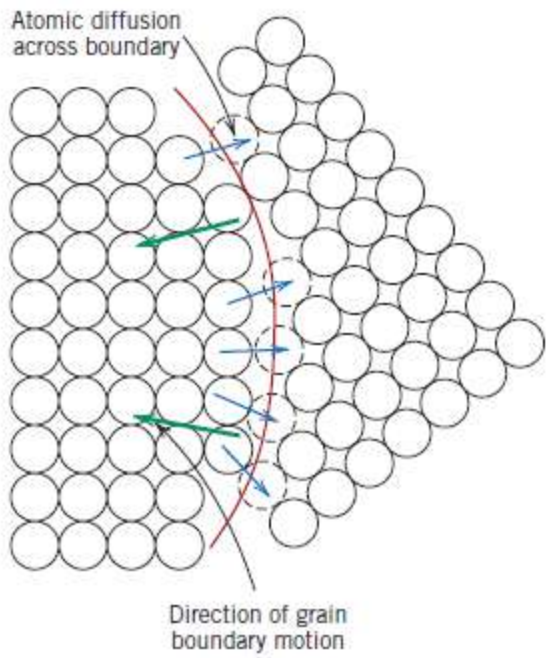
Effects of Alloying Elements

- *Barrier to Dislocation movement*

- *Polymorphic transformation temperature*

- *Strengthening of ferrite*

- *Formation and stability of carbides*

- *Displacement of the eutectoid point*

- *Retardation of the transformation rates*

- *Lowering of critical cooling rate*

- *Improvement in corrosion resistance*

Main Alloying Elements in Steel

- Manganese
- Chromium
- Nickel
- Molybdenum
- Titanium
- Phosphorus
- Silicon
- Copper

- Sulphur
- Cobalt
- Aluminium
- Vanadium
- Tungsten
- Lead
- Colubium
- Boron

Effects of alloying elements on Steel

- Different alloying elements added to the basic system of iron and carbon, and what they do to change the properties or effectiveness of steel.

Carbon

- The presence of carbon in iron is necessary to make steel.
- Carbon is essential to the formation of cementite and also the formation of other microstructures pearlite, spheroidite, bainite, and martensite.
- Martensite being the hardest of the micro-structures, and the structure sought by knife makers.
- The hardness of steel (or more accurately, the hardenability) is increased by the addition of more carbon, up to about 0.65 percent.
- Wear resistance can be increased in amounts up to about 1.5 percent. Beyond this amount, increases of carbon reduce toughness and increase brittleness.
- The steels of interest to knifemakers generally contain between 0.5 and 1.5 percent carbon. They are described as follows:
- Low Carbon: Under 0.4 percent
- Medium Carbon: 0.4 - 0.6 percent

Manganese (Mn)

- Added to steel to improve hot working properties and increase strength, toughness and hardenability.

- Improves ductility and wear resistance.

- Eliminates formation of harmful iron sulfides, increasing strength at high temperatures.

- Manganese, like nickel, is an austenite forming element

- Usually present in quantities from 0.5% to 2%

Chromium (Cr)

- Chromium is added to the steel to increase resistance to oxidation.

- This resistance increases as more chromium is added.

- 'Stainless Steel' has approximately 12% chromium

- When added to low alloy steels, improves hardenability and strength.

- Resists abrasion and wear (with high carbon).

Nickel (Ni)

- Added in large amounts, over about 8%, to high chromium stainless steel to form the most important class of corrosion and heat resistant steels, the austenitic stainless steels.

- Increases toughness and strength at both high and low temperatures.

- Improves resistance to oxidation and corrosion.

- Increases toughness at low temperatures when added in smaller amounts to alloy steels.

- Strengthens unquenched or annealed steels.

- Quantity addition is from 1 to 4%

Molybdenum (Mo)

- When added to chromium-nickel austenitic steels, improves resistance to pitting corrosion especially by chlorides and sulphur chemicals.
- When added to low alloy steels, it improves high temperature strengths and hardness.
- When added to chromium steels it greatly diminishes the tendency of steels to decay in service or in heat treatment.
- Increases hardenability and strength.
- Enhances corrosion resistance in stainless steel.
- Forms abrasion resisting particles.
- used in small quantities from 0.10 to 0.40%.

Titanium (Ti)

- Improves strength and corrosion resistance, limits austenite grain size.

- The main use of titanium as an alloying element in steel is for carbide stabilisation.

- It combines with carbon to form titanium carbides, which are quite stable and hard to dissolve in steel.

- Reduces martensitic hardness and hardenability in medium Cr steels.

- Prevents formation of austenite in high Cr steels.

Phosphorus (P)

- Phosphorus is usually added with sulphur to improve machinability in low alloy steels

- When added in small amounts, aids strength and corrosion resistance.

- Phosphorus additions are known to increase the tendency to cracking during welding.

- Strengthens low-carbon steel.

- Increases resistance to corrosion.

Silicon (Si)

- Improves strength, elasticity, acid resistance and promotes large grain sizes, which cause increasing magnetic permeability.

- Used as a deoxidising (killing) agent in the melting of steel.

- Silicon contributes to hardening of the ferritic phase in steels.

- Alloying element for electrical and magnetic sheet.

- Increase hardenability of steels.

- Strengthens low-alloy steels.

- Used in the range of 1.5% to 2.5%

Copper (Cu)

- Copper is normally present in stainless steels as a residual element.

- It is added to a few alloys to produce precipitation hardening properties.

- Improves corrosion resistance.

- Usually 0.15 to 0.25% added

Other Alloying Elements

- Sulphur (S)
  - When added in small amounts improves machinability
  - used in the range 0.06 to 0.30%.

- Cobalt (Co)
  - Improves strength at high temperatures and magnetic permeability.

- Aluminum (Al)
  - Dexodises and limits austenite grain growth
  - Alloying element in nitriding steel.

Alloying element	Range of percentage	Important functions
Sulphur	< 0.33	Improves machinability, reduces weldability and ductility
Phosphorus	<0.12	Improves machinability, reduces impact strength at low temperature.
Silicon	1.5 to 2.5	Removes oxygen from molten metal, improves strength and toughness, increase hardenability, magnetic permeability
Manganese	0.5 to 2.0	Increases hardenability, reduces adverse effects of sulphur.
Nickel	1.0 to 5.0	Increases toughness, increases impact strength at low temperatures
Chromium	0.5 to 4.0	Improves resistance to oxidation and corrosion. Increases high temperature strength
Molybdenum	0.1 to 0.4	Improves hardenability, enhances the effect of other alloying elements, eliminat temper brittleness, improves red hardness and wear resistance.
Tungsten	2.0 to 3.0	Improves hardenability, enhances the effect of other alloying elements, eliminate temper brittleness, improves red hardness and wear resistance.
Vanadium	0.1 to 0.3	Improves hardenability, increases wear and fatigue resistance, elastic limit.
Titanium	< 1.0	Improves strength and corrosion resistance.
Copper	0.15 to 0.25	Improves corrosion resistance, increases strength and hardness
Aluminium	0.01 to 0.06	Removes oxygen from molten metal
Boron	0.001 to 0.05	Increases hardenability
Lead	< 0.35	Improves machinability