Mechanical properties and testing

- The mechanical behavior of a material reflects the relationship between its response or deformation to an applied load or force. Key mechanical design properties are stiffness, strength, hardness, ductility, and toughness.
- The mechanical properties of materials are ascertained by performing carefully designed laboratory experiments that replicate as nearly as possible the service conditions.

Stress

- Stress is internal resistive force per unit area developed inside a material under loading condition.
- Unit of stress is N/m^2, which is similar as unit of pressure.
- Pressure always acts normal to the surface and applied externally on the body, but stress is developed inside the material or body and it acts normal or along the internal surface of body.
- Pressure is a scaler quantity and stress is second order tensor quantity.
- A tensor is a quantity which has magnitude, direction, and a plane in which it acts.
- $\text{engineering stress or stress} = \dfrac{force}{original\ cross\ sectional\ area}$
- $\text{true stress} = \dfrac{force}{actual\ cross\ sectional\ area}$

Strain

- **Strain** is simply the measure of how much an object is stretched or deformed. Strain occurs when force is applied to an object. Strain deals mostly with the change in length of the object.
- For ***engineering strain or strain*** If the original length of the body L_0changes by ΔL , then stress can be expressed as

$$\text{strain} = \frac{change\ in\ length}{original\ length} = \frac{\Delta L}{L_0}$$

- It is also a second order tensor quantity.
- *true strain* is defined as the natural log of the ratio of current length and the original length.

$$\text{true strain} = \ln \frac{L}{L_0}$$

Stress Strain Diagrams

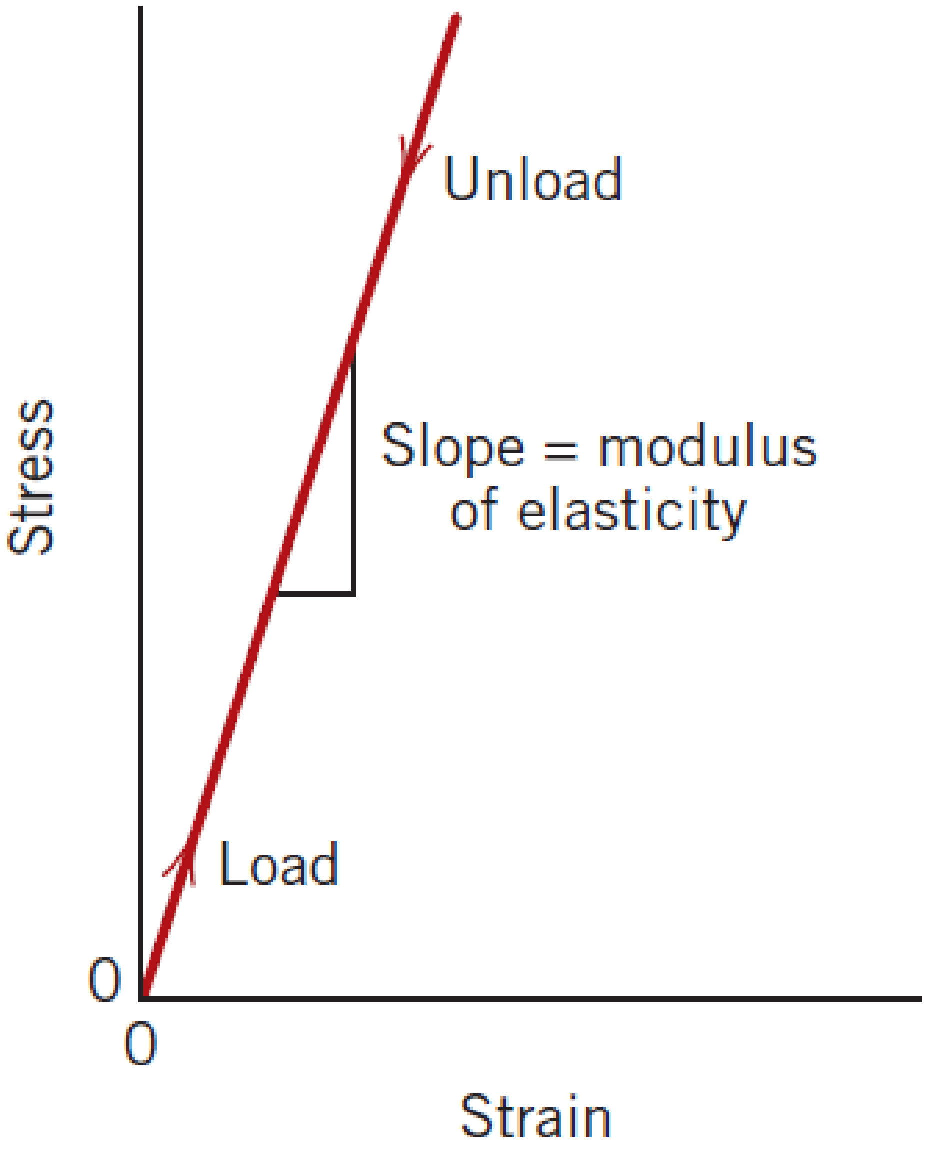
- **It is a tool for understanding material behavior under load.**
- It is a graph that represents how a part behaves under an **increasing load** and used by engineers when selecting materials for specific designs.
- Stress-strain diagrams are generated experimentally through the performance of controlled **tensile test** using fabricated test specimens.
- The **applied load and displacement** are monitored during the test, and are used to calculate stress and strain, respectively.

Stress-strain diagram region

- A stress-strain diagram generally contains **three regions:**
  1. **Elastic region:** This portion is generally represented as a **linear relationship** between stress and strain. If the load is released the specimen **will return** to its original dimensions.
  2. **Plastic region:** In this portion, the specimen begins to **yield**. The **maximum strength** of the specimen occurs in this zone. The specimen endures some **permanent deformation** that remains after the load is released.
  3. **Rupture:** The point at which a specimen **breaks into two parts.**

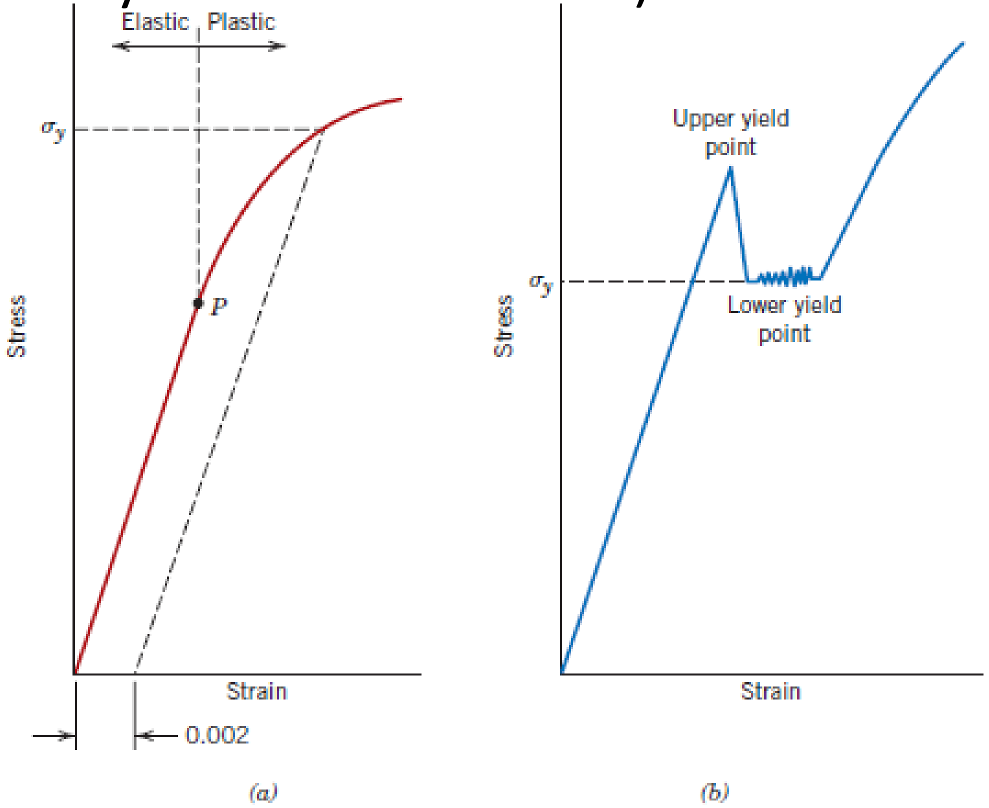
Stress strain diagram important points

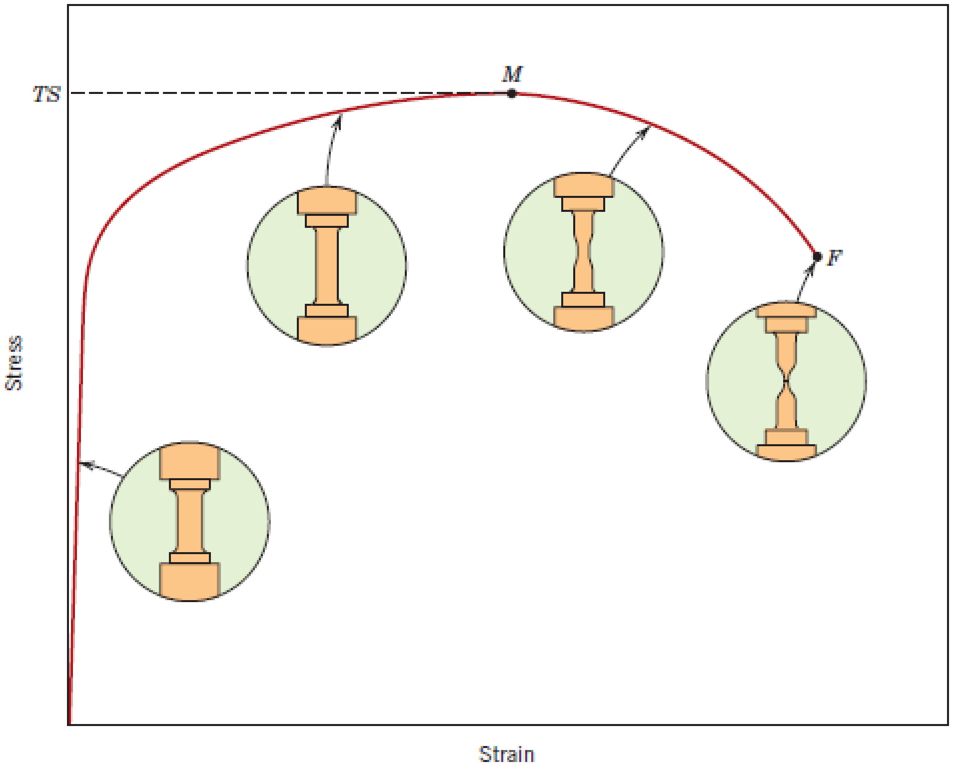
- **Proportionality limit**-it is the point in the stress strain graph up to which stress is directly **proportional** to strain. Up to this point hook's law is applicable.
- $\sigma = E\varepsilon$
- This is known as Hooke's law, and the constant of proportionality *E* (GPa or psi) is the **modulus of elasticity,** or *Young's modulus*.
- **Elastic Limit:** The limit in which the material will return its original shape when the load is removed.
- Most of the time these two points(elastic and proportionality point) are very close and treated as same point.



- **Yield Point:** Yield point is the point at which the material will have an appreciable elongation **OR** a slight increase in stress above the elastic limit will result in permanent deformation. This behavior is called yielding for ductile materials (**In Engineering, the transition from elastic behavior to plastic behavior**).
- Less ductile materials such as aluminum and medium to high carbon steels do not have a well defined yield point. For these materials the yield strength is typically determined by **"offset method"** by which a line is drawn parallel to linear portion of the curve and intersecting at some value most commonly 0.2%. (generally from 0.1% to 0.2%).
  - **Upper yield point:** which corresponds to the load reached just before yield starts.
  - **Lower yield point:** which corresponding to the load required maintain yield. Lower yield point should be used to determine the **yield strength of the material.**

Figure 6.10 (*a*) Typical stress–strain behavior for a metal showing elastic and plastic deformations, the proportional limit *P*, and the yield strength σ_y, as determined using the 0.002 strain offset method. (*b*) Representative stress–strain behavior found for some steels demonstrating the yield point phenomenon.



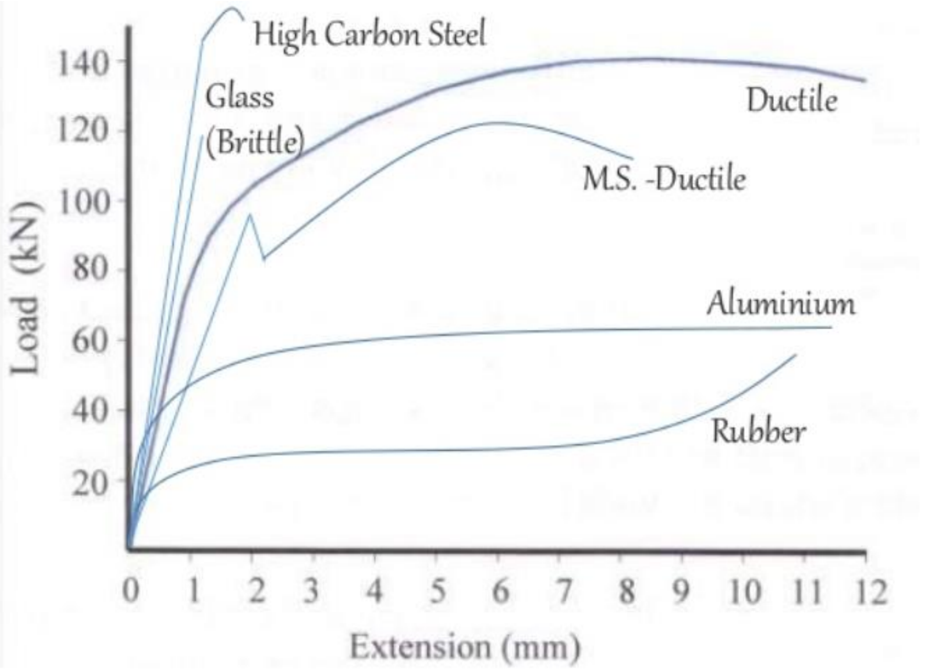


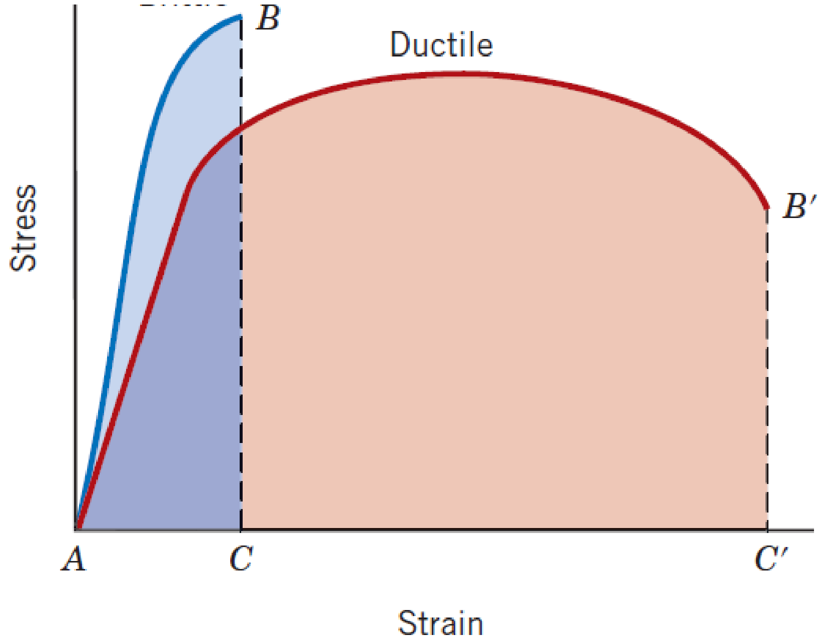
Typical Engineering stress–strain behavior to fracture, point *F*. The tensile strength *TS* is indicated at point *M*. The circular insets represent the geometry of the deformed specimen at various points along the curve.

- **Ultimate stress(strength) point or tensile strength** this is the maximum stress or strength of the material. After this point cross section of specimen start decreasing, this phenomenon is known as necking.
- **Fracture point** is the point where material ruptured. fracture ultimately occurs at the neck. The fracture strength corresponds to the stress at fracture.
- For engineering stress strain curve it has magnitude below the ultimate strength point(UT). But for true engineering stress strain curve it is above the UT.
- **Strain Hardening:** The stress must be **increased** to keep elongating the specimen, until the **maximum** value has been reached. This is due to a property of the material known as **strain hardening.**

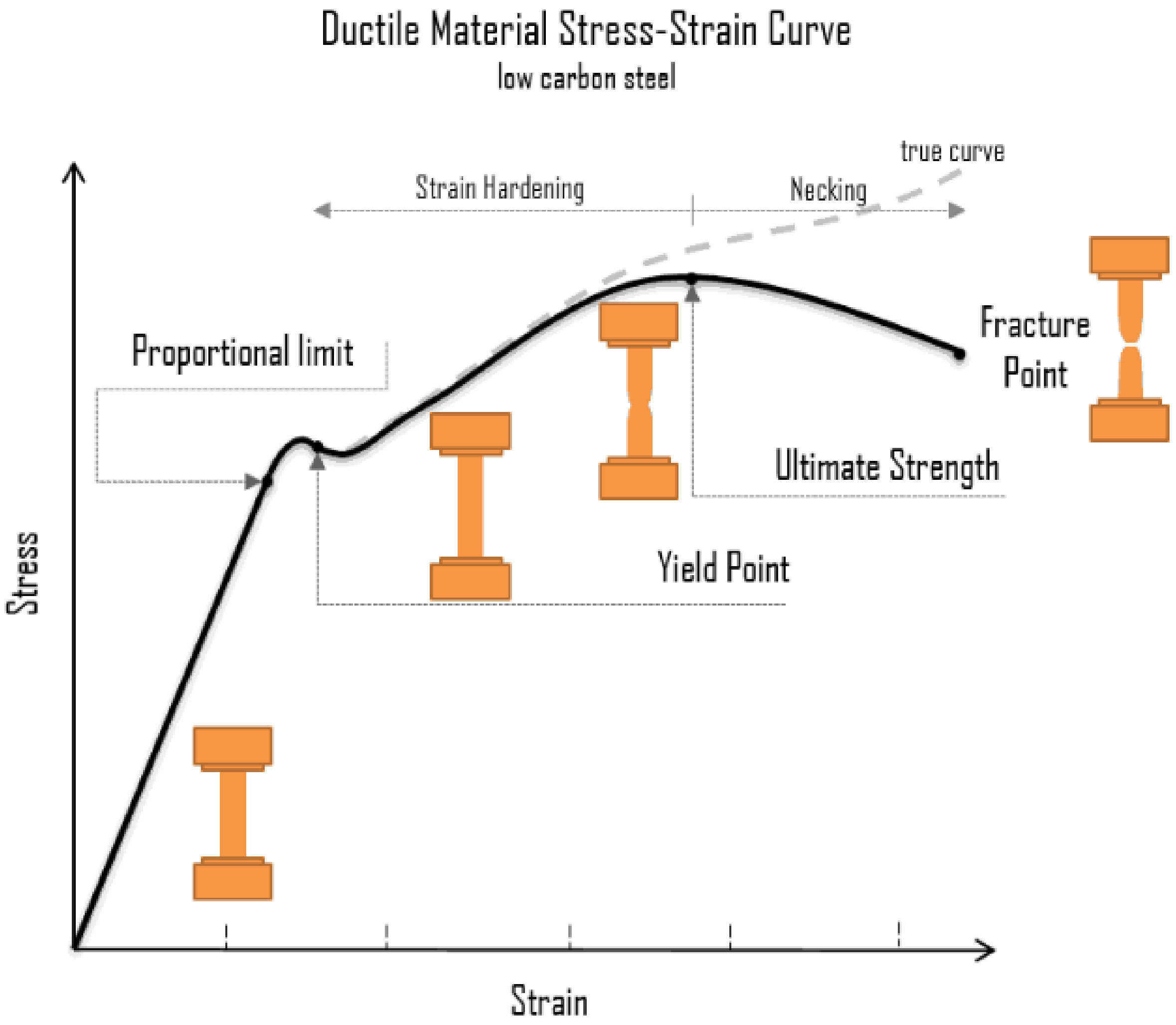
Stress strain diagram for different material

- Stress strain diagram is different for different material , but it is seen that some material elongate more before its rupture and some hardly elongates.
- A **ductile material** is one having relatively large tensile strain up to the point of rupture like structural **steel and aluminum.**
- whereas **brittle materials** has a relatively small strain up to the point of rupture like **cast iron and concrete**.

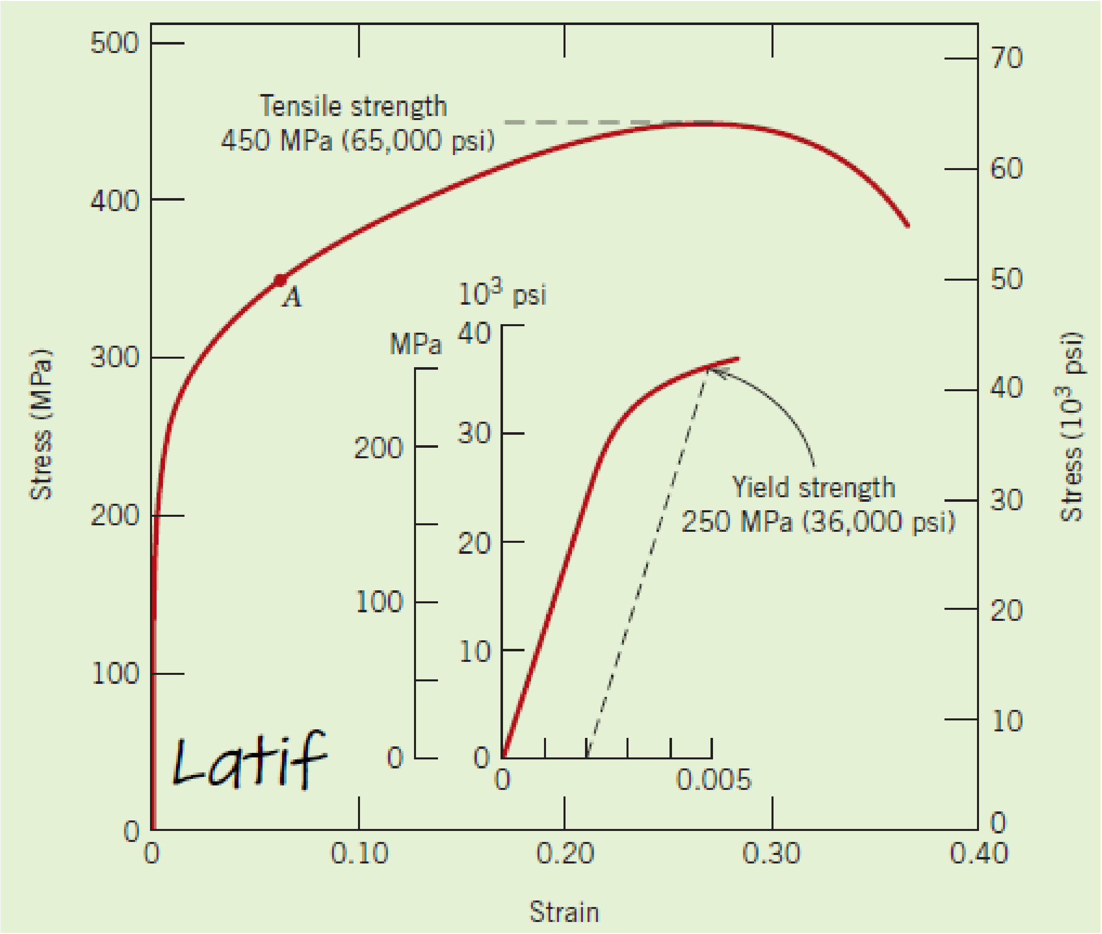




Ductile material



Stress and strain curve for low carbon steel



Stress and strain curve for brasss

Brittle materials

- **Brittle materials:** such as **cast iron, glass, concrete and carbon fiber (composite materials)** are characterized by the fact that rupture occurs without any prior change in the rate of deformation.
- These do not have a yield point and do not strain harden, which means that ultimate strength and breaking strength are at same point.
- we note the absence of **any necking of the specimen** in the case of the **brittle materials** and observe that rupture occurs along the surface perpendicular to the load. And we conclude that **normal stresses** are responsible for the **failure of brittle materials**.

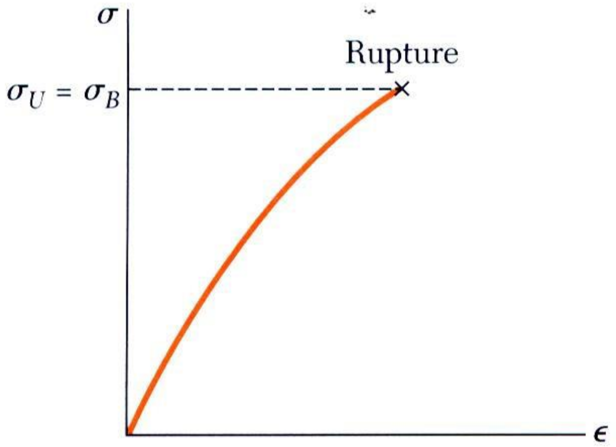
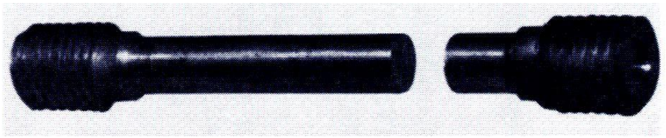


Fig. 2.11 Stress-strain diagram for a typical brittle material.



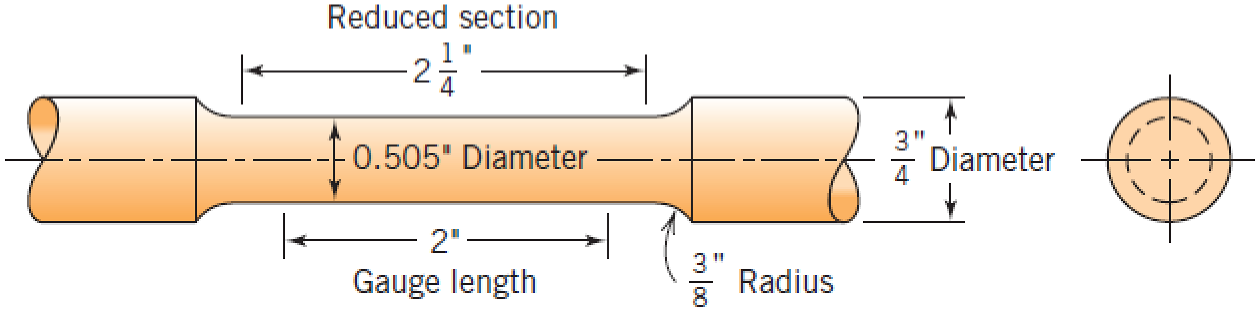
Why Material testing is required ?

- To test mechanical properties like ultimate tensile strength, yield strength , elongation , toughness etc. which is used as a design input.
- Make informed choices in using raw materials.
- To check properties of material after heat treatment, welding , brazing and other operations.
- Ensure batch and production quality.
- As a part of maintenance and to prevent failure in usage.

Type of material testing

- Destructive testing / mechanical testing
  - The material is physically tested to destruction or indentation.
  - To measure the strength, hardness, toughness etc.
  - Example: tensile test, impact test, hardness test etc.
- Non-destructive test (NDT)
  - Samples or finished product are tested without spoiling the product.
  - Radiography, dye penetration tests etc.

Tensile test

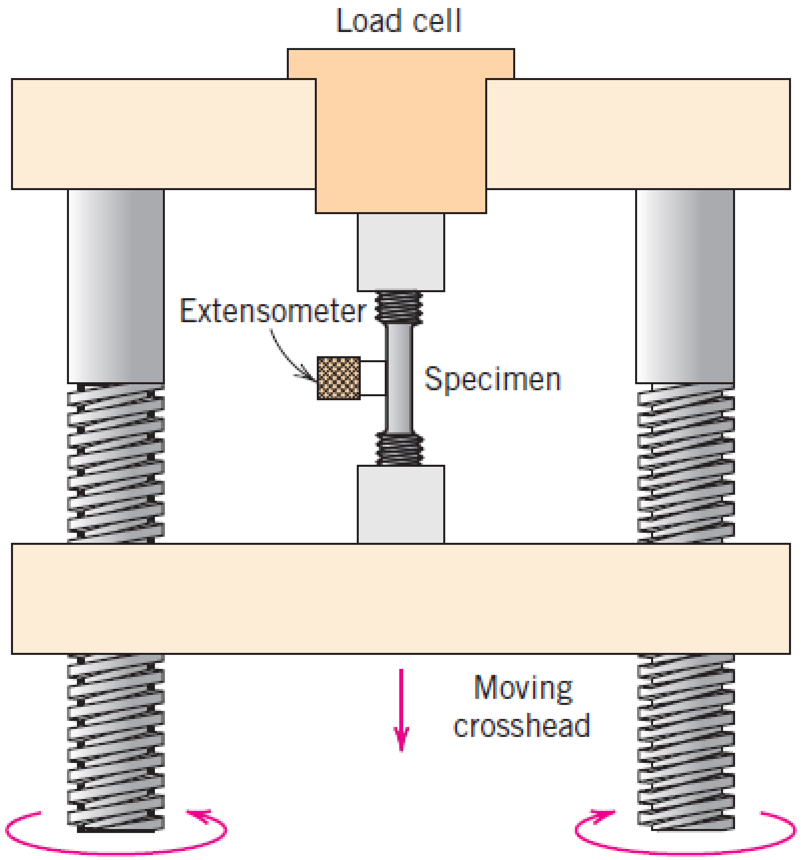


A standard tensile specimen with circular cross section

- Is perform on a universal testing machine (UTM).
- Uses load cell and extensometer to measure force exerting in specimen and percentage elongation respectively.
- The load v/s elongation is then plotted and studied.
- Variables such as strain, stress, elasticity, tensile strength, ductility and shear strength are measured and computed.
- Test specimen can be round or flat.

Universal Testing Machine

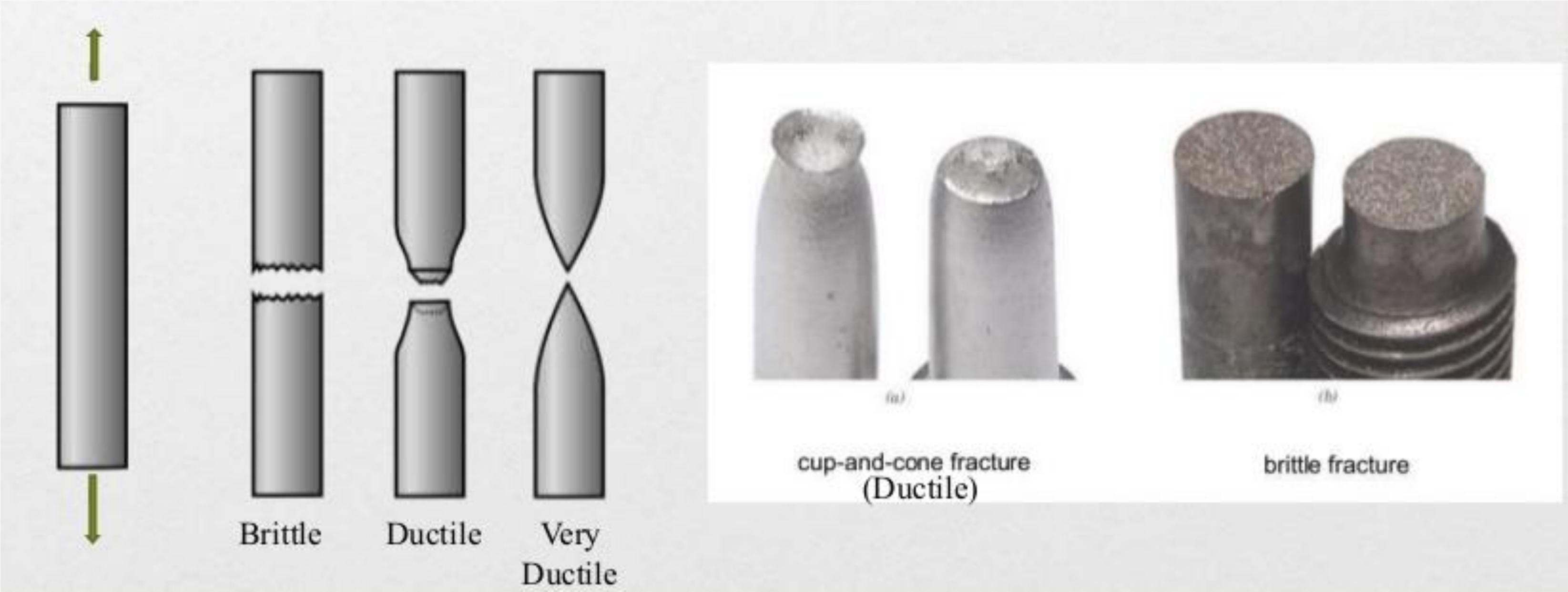
- Is used to test the tensile strength and compressive strength of materials.
- The "universal" part of the name reflects that it can perform many standard tensile and compression tests on materials, components, and structures (in other words, that it is versatile).



Schematic representation of the apparatus used to conduct tensile stress–strain tests.

Fractured surface of tensile test

- Cup and cone fracture signifies a ductile material.
- A shear fracture indicates a brittle material.



Properties determined by the tensile testing

- Strength (stress and strain curve after computation)
- Ductility
- Elasticity
- Stiffness
- Malleability
- Modulus of toughness
- Modulus of resilience

Hardness testing

- **Hardness** : is a measure of a material’s resistance to localized plastic deformation (e.g., a small dent or a scratch).
- Quantitative hardness techniques have been developed over the years in which a small indenter is forced into the surface of a material to be tested, under controlled conditions of load and rate of application.
- The depth or size of the resulting indentation is measured, which in turn is related to a hardness number; the softer the material, the larger and deeper the indentation, and the lower the hardness index number.
- Measured hardness values are only relative (rather than absolute), and care should be exercised when comparing values determined by different techniques.

Types of hardness testing

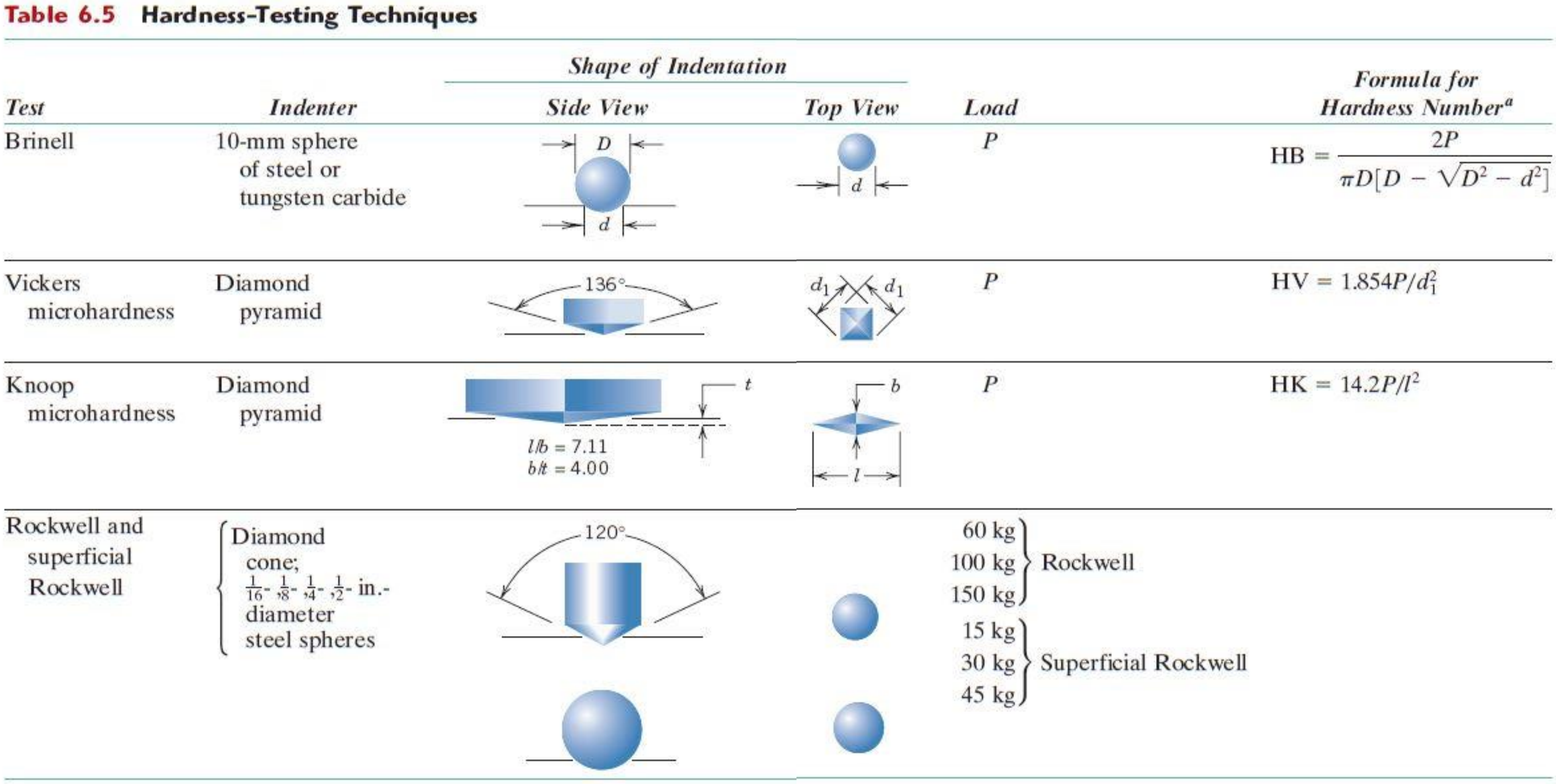


Table 6.5 Hardness-Testing Techniques

Test	Indenter	Shape of Indentation: Side View	Shape of Indentation: Top View	Load	Formula for Hardness Number[a]
Brinell	10-mm sphere of steel or tungsten carbide			P	$\mathrm{HB} = \dfrac{2P}{\pi D[D - \sqrt{D^2 - d^2}]}$
Vickers microhardness	Diamond pyramid			P	$\mathrm{HV} = 1.854P/d_1^2$
Knoop microhardness	Diamond pyramid	$l/b = 7.11$ $b/t = 4.00$		P	$\mathrm{HK} = 14.2P/l^2$
Rockwell and superficial Rockwell	Diamond cone; $\frac{1}{16}$-, $\frac{1}{8}$-, $\frac{1}{4}$-, $\frac{1}{2}$-in.-diameter steel spheres			60 kg, 100 kg, 150 kg } Rockwell 15 kg, 30 kg, 45 kg } Superficial Rockwell	

Rockwell Hardness Tests

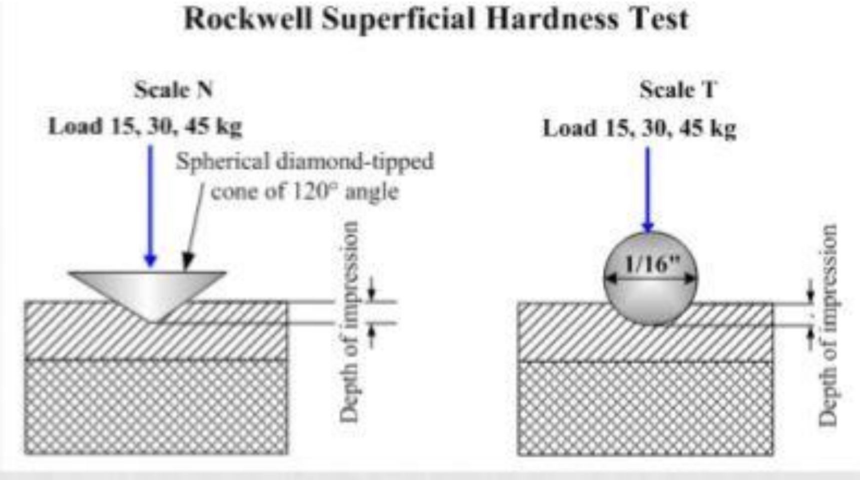
- The Rockwell tests constitute the most common method used to measure hardness because they are so simple to perform and require no special skills.
- Several different scales may be utilized from possible combinations of various indenters and different loads, which permit the testing of virtually all metal alloys.
- Indenters include spherical and hardened ***steel balls*** having diameters Of $\frac{1}{16}$, $\frac{1}{8}$, $\frac{1}{4}$ and $\frac{1}{2}$ in. (1.588, 3.175, 6.350, and 12.70 mm), and a ***conicaldiamond*** (Brale) indenter, which is used for the hardest materials. (diagrams are shown in upcoming slides)
- A hardness number is determined by the difference in depth of penetration resulting from the application of an ***initial minor load*** followed by a larger ***major load***; utilization of a minor load enhances test accuracy.

Rockwell Hardness Tests

- Based on the magnitude of both major and minor loads, there are two types of tests: ***Rockwell*** and ***superficial Rockwell***.
- For Rockwell, the minor load is 10 kg, whereas major loads are 60, 100, and 150 kg.
- For superficial tests, 3 kg is the minor load; 15, 30, and 45 kg are the possible major load values. These scales are identified by a 15, 30, or 45 (according to load), followed by N, T, W, X, or Y, depending on indenter.
- ***Superficial*** tests are frequently performed on ***thin specimens***.
- When specifying Rockwell and superficial hardnesses, both hardness number and scale symbol must be indicated. The scale is designated by the symbol HR followed by the appropriate scale identification.
- For example, 80 HRB represents a Rockwell hardness of 80 on the B scale, and 60 HR30W indicates a superficial hardness of 60 on the 30W scale.

  (scales are shown in next slide)

Rockwell Hardness Tests



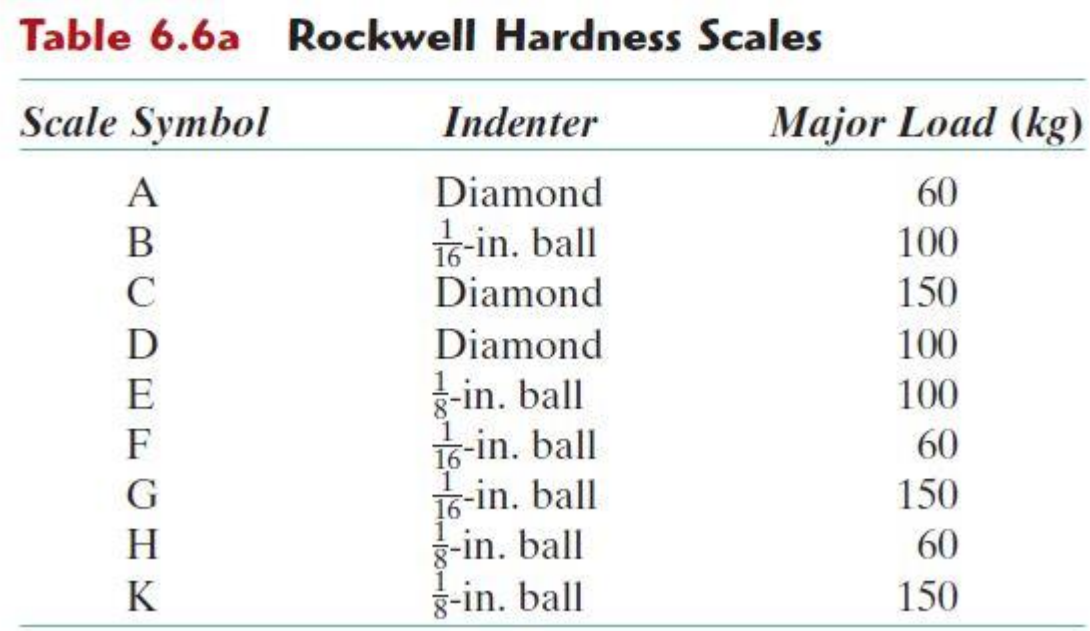


Table 6.6a **Rockwell Hardness Scales**

Scale Symbol	*Indenter*	*Major Load (kg)*
A	Diamond	60
B	$\frac{1}{16}$-in. ball	100
C	Diamond	150
D	Diamond	100
E	$\frac{1}{8}$-in. ball	100
F	$\frac{1}{16}$-in. ball	60
G	$\frac{1}{16}$-in. ball	150
H	$\frac{1}{8}$-in. ball	60
K	$\frac{1}{8}$-in. ball	150

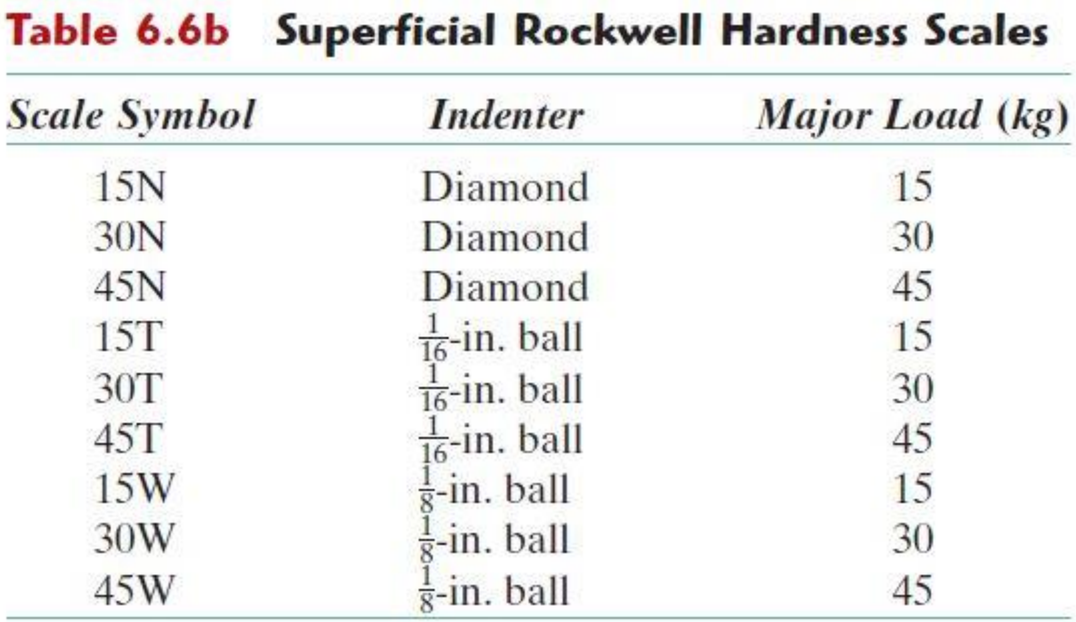


Table 6.6b **Superficial Rockwell Hardness Scales**

Scale Symbol	*Indenter*	*Major Load (kg)*
15N	Diamond	15
30N	Diamond	30
45N	Diamond	45
15T	$\frac{1}{16}$-in. ball	15
30T	$\frac{1}{16}$-in. ball	30
45T	$\frac{1}{16}$-in. ball	45
15W	$\frac{1}{8}$-in. ball	15
30W	$\frac{1}{8}$-in. ball	30
45W	$\frac{1}{8}$-in. ball	45

Brinell Hardness Tests

- In Brinell tests, as in Rockwell measurements, a hard, ***spherical indenter*** is forced into the surface of the metal to be tested.
- The diameter of the hardened steel (or tungsten carbide) indenter is 10.00 mm (0.394 in.).
- Standard loads range between 500 and 3000 kg in 500-kg increments; during a test, the load is maintained constant for a specified time (between 10 and 30 s).
- The Brinell hardness number, HB, is a function of both the magnitude of the **load** and the **diameter of the resulting indentation**.
- Formula for hardness number is shown in table 6.5.
- For tensile strength as a function of the HB for cast iron, steel, and brass. The same proportionality relationship does not hold for all metals

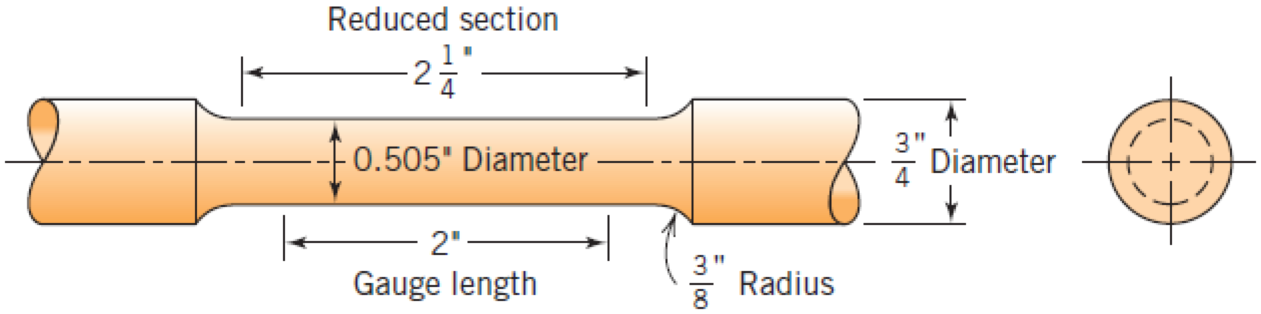
$$TS(\text{MPa}) = 3.45 \times \text{HB}$$

$$TS(\text{psi}) = 500 \times \text{HB}$$

Knoop and Vickers Micro indentation Hardness Tests

- For each test, a very **small diamond indenter** having **pyramidal geometry** is forced into the surface of the specimen. Applied loads are much smaller than for Rockwell and Brinell, ranging between 1 and 1000 g.
- The resulting impression is **observed under a microscope and measured**; this measurement is then converted into a hardness number.
- Careful specimen surface preparation (grinding and polishing) may be necessary to ensure a well-defined indentation that may be accurately measured.
- The Knoop and Vickers hardness numbers are designated by HK and HV, respectively and and hardness scales for both techniques are approximately equivalent.
- Knoop is used for testing brittle materials such as ceramics.

creep



- Time-dependent and permanent deformation of materials when subjected to a constant load or stress.
- For metals it becomes important only for temperatures greater than about 0.4 T_m($T_m$is the absolute melting temperature).
- A typical creep test consists of subjecting a specimen to a constant load or stress while maintaining the temperature constant.
- Deformation or strain is measured and plotted as a function of elapsed time.
- For metallic materials, most creep tests are conducted in uniaxial tension using a specimen having the same geometry as for tensile tests (shown in Figure). On the other hand, uniaxial compression tests are more appropriate for brittle materials.

Creep curve

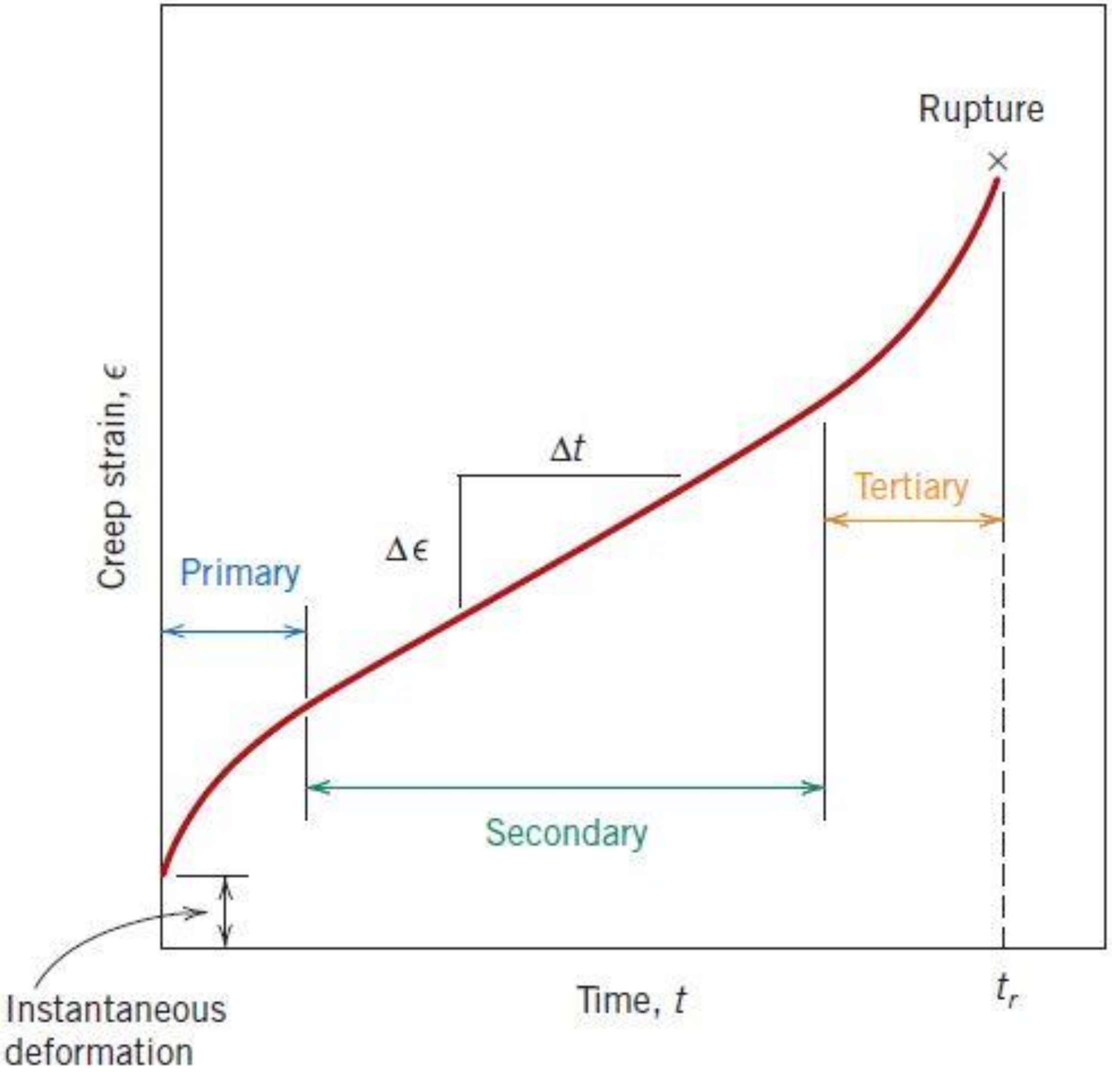


Figure 8.28 Typical creep curve of strain versus time at constant load and constant elevated temperature. The minimum creep rate $\Delta\epsilon/\Delta t$ is the slope of the linear segment in the secondary region. Rupture lifetime t_r is the total time to rupture.

- Upon application of the load there is an instantaneous deformation, as indicated in the figure, which is totally elastic.
- The resulting creep curve consists of three regions, each of which has its own distinctive strain–time feature.
- ***Primary*** *or* ***transient creep*** occurs first, typified by a continuously decreasing creep rate; that is, the slope of the curve diminishes with time. This suggests that the material is experiencing an increase in creep resistance or strain hardening.
- ***Secondary creep****,* sometimes termed ***steady-state creep****,* the rate is constant; that is, the plot becomes linear. This is often the stage of creep that is of the longest duration.
- The constancy of creep rate is explained based on a balance between the competing processes of strain hardening and recovery, recovery being the process whereby a material becomes softer and retains its ability to experience deformation.
- Finally, for ***tertiary creep****,* there is an acceleration of the rate and ultimate failure. This failure is frequently termed *rupture* and results from microstructural and/or metallurgical changes.
- Possibly the most important parameter from a creep test is the slope of the secondary portion of the creep curve, this is often called the minimum or *steady-state creep rate*

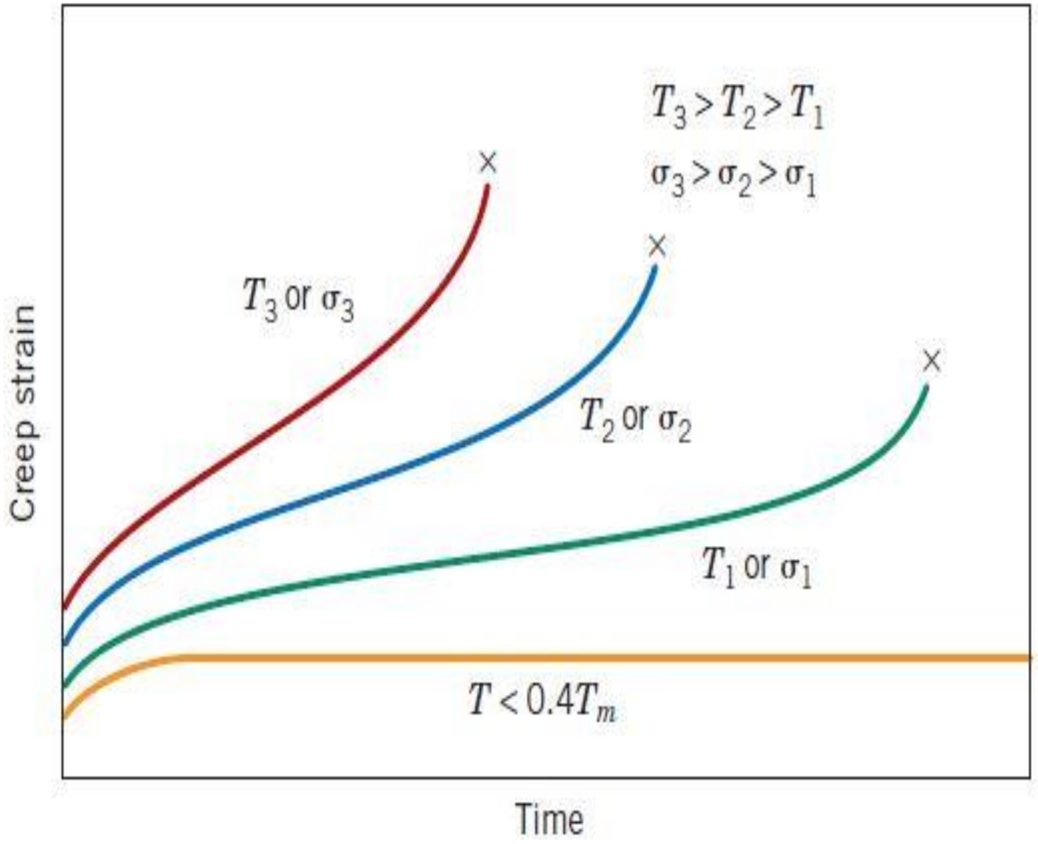
Stress and temperature effect on creep

With either increasing stress or temperature, the following will be noted:

(1) The instantaneous strain at the time of stress application increases,

(2) The steady-state creep rate is increased, and

(3) The rupture lifetime is diminished.



Fatigue

- **Fatigue** is a form of failure that occurs in structures subjected to dynamic and fluctuating stresses (e.g., bridges, aircraft, and machine components). Under these circumstances it is possible for failure to occur at a stress level considerably lower than the tensile or yield strength for a static load.
- The term *fatigue* is used because this type of failure normally occurs after a lengthy period of repeated stress or strain cycling.
- The surface which has undergone fatigue fracture appears brittle without gross deformation at fracture (in the macroscale).
- On a macroscopic scale the fracture surface is usually normal to the direction of the principal tensile stress.
- Fatigue failure is usually initiated at a site of stress concentration (E.g. a notch in the specimen or an acicular inclusion).

Cyclic stresses

- The applied stress may be axial (tension–compression), flexural (bending), or torsional (twisting) in nature.
- Three different fluctuating stress–time modes are possible.

1. ***Completely reversed cycle of stress(repeated stress cycle):*** the amplitude is symmetrical about a mean zero stress level, for example, alternating from a maximum tensile stress to a minimum compressive stress of equal magnitude.
2. ***purely tensile cycle or purely compressive cycle:*** the maxima and minima are asymmetrical relative to the zero-stress level.
3. *Random cycle*: the stress level may vary randomly in amplitude and frequency.

Important parameters

- *mean stress* σ_m, defined as the average of the maximum and minimum stresses in the cycle.

$$\sigma_m = \frac{\sigma_{\max} + \sigma_{\min}}{2}$$

- *Range of stress* σ_r , defined as the difference between maximum and minimum value of stresses in the cycle.

$$\sigma_r = \sigma_{\max} - \sigma_{\min}$$

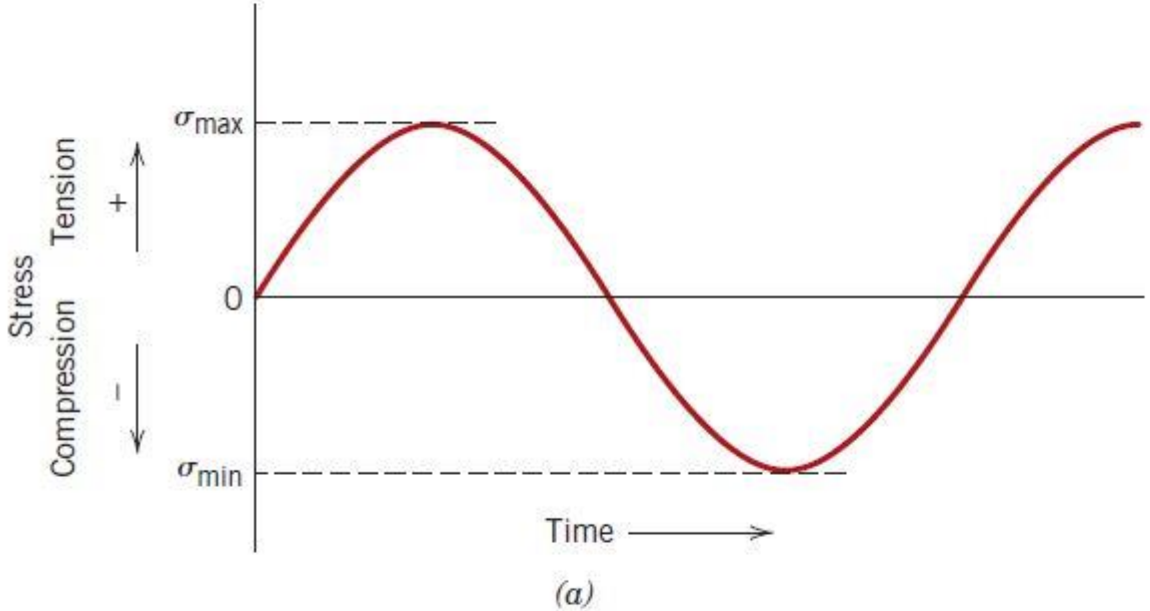
- *Stress amplitude* is just one-half of this range of stress.

$$\sigma_a = \frac{\sigma_r}{2} = \frac{\sigma_{\max} - \sigma_{\min}}{2}$$

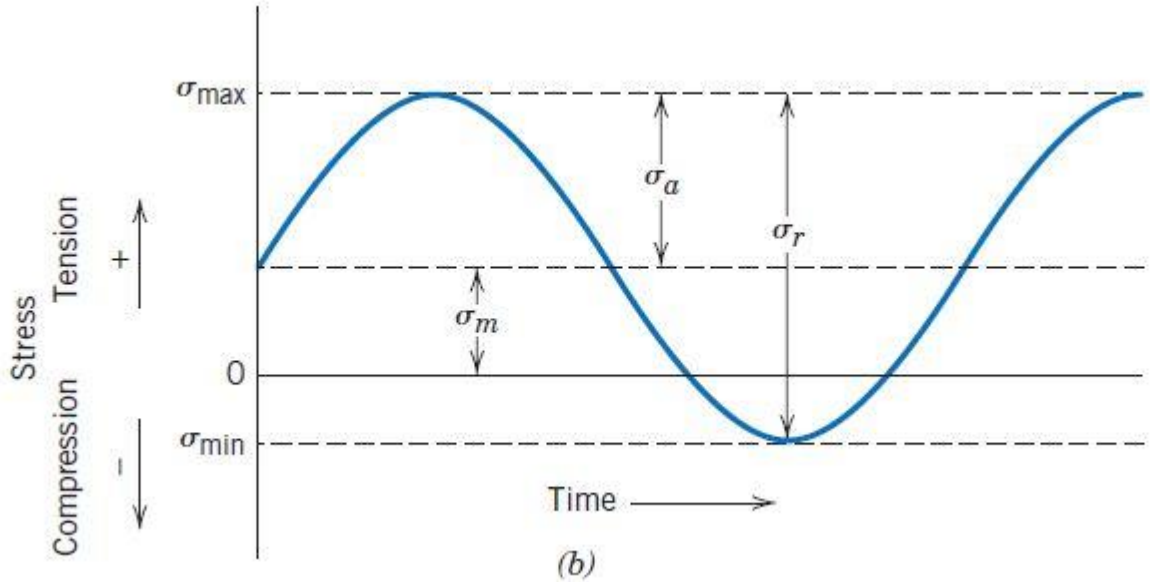
- *stress ratio R* is just the ratio of minimum and maximum stress amplitudes.

$$Stress\ ratio \rightarrow R = \frac{\sigma_{\min}}{\sigma_{\max}}$$

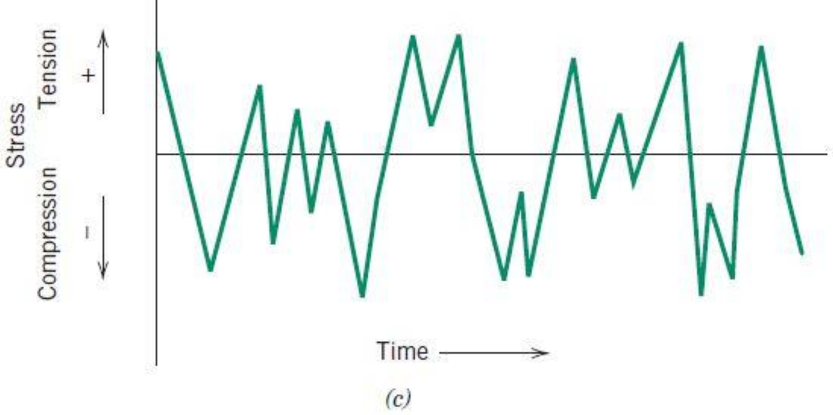
$$Amplitude\ ratio \rightarrow A = \frac{\sigma_a}{\sigma_{\mathrm{m}}} = \frac{1-R}{1+R}$$



(*a*) Reversed stress cycle, in which the stress alternates from a maximum tensile stress to a maximum compressive stress of equal magnitude.



(*b*) Repeated stress cycle, in which maximum and minimum stresses are asymmetrical relative to the zero-stress level



(*c*) Random stress cycle.

S-N curve

- Engineering fatigue data is usually plotted as a S-N curve. Here S is the stress and N the number of cycles to failure (usually fracture). The x-axis is plotted as log(N).
- The stress plotted could be one of the following: σ_a, σ_{max}, σ_{min}. Each plot is for a constant σ_m, R or A.
- It should be noted that the stress values plotted are nominal values and does not take into *account local stress concentrations.*
- Most fatigue experiments are performed with $\sigma_m = 0$ *(e.g. rotating beam tests).*
- Typically the stress value chosen for the stress is low ($< \sigma_y$) and hence S-N curves deal with fatigue failure at a large number of cycles ($> 10^5$ cycles). These are the **high cycle fatigue** tests.
- It is to be noted that the nominal stress $< \sigma_y$, but microscopic plasticity occurs, which leads to the accumulation of damage.
- As obvious, if the magnitude of Stress increases the fatigue life decreases.
- **Low cycle fatigue** ($N < 10^4$ or 10^5 cycles) tests are conducted in controlled cycles of elastic + plastic strain *(strain control mode, instead of stress control).*

- Broadly two kinds of S-N curves can be differentiated for two classes of materials.
  (1) those where a stress below a threshold value gives a 'very long' life (this stress value is called the *Fatigue Limit / Endurance limit*). Steel and Ti come under this category.
  (2) those where a decrease in stress increases the fatigue life of the component, but no distinct fatigue life is observed. Al, Mg, Cu come under this category.
- Thus, fatigue will ultimately occur regardless of the magnitude of the stress. For these materials, the fatigue response is specified as **fatigue strength,** which is defined as the stress level at which failure will occur for some specified number of cycles.
- From a application point of view having a sharp fatigue limit is useful (as keeping service stress below this will help with long life (i.e. large number of cycles) for the component).

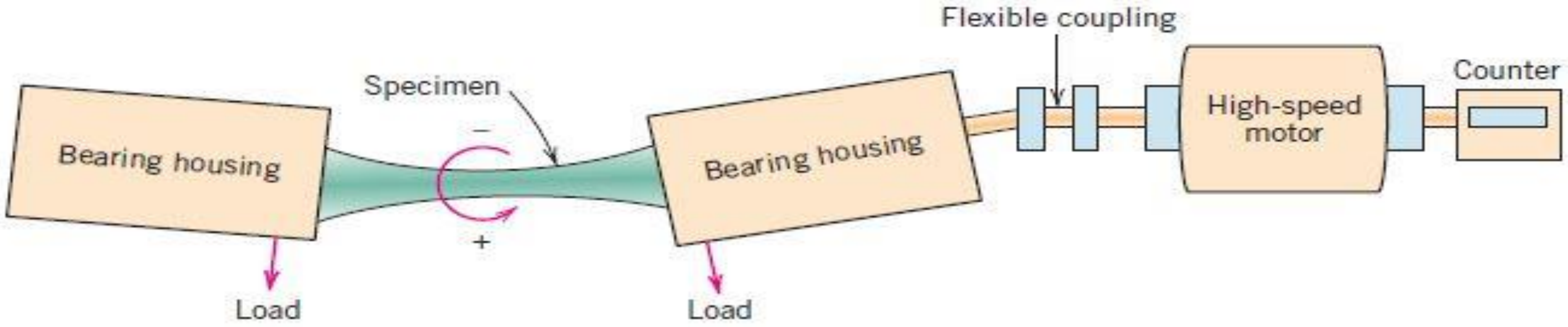
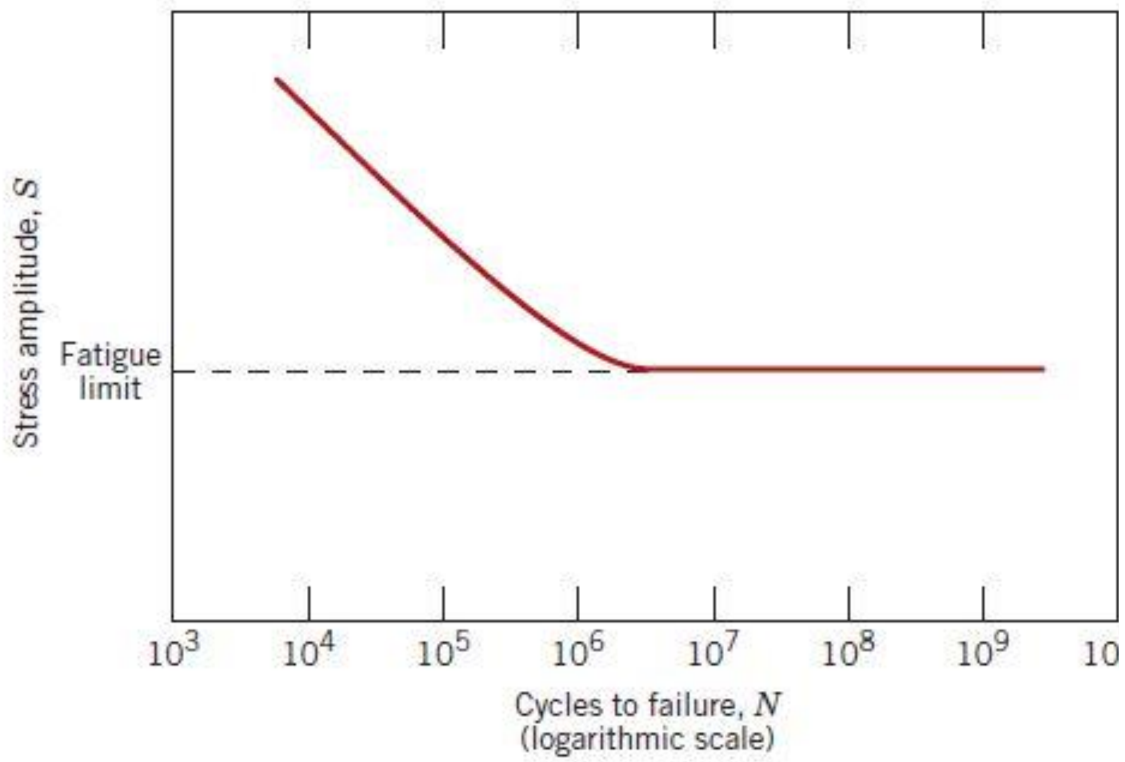
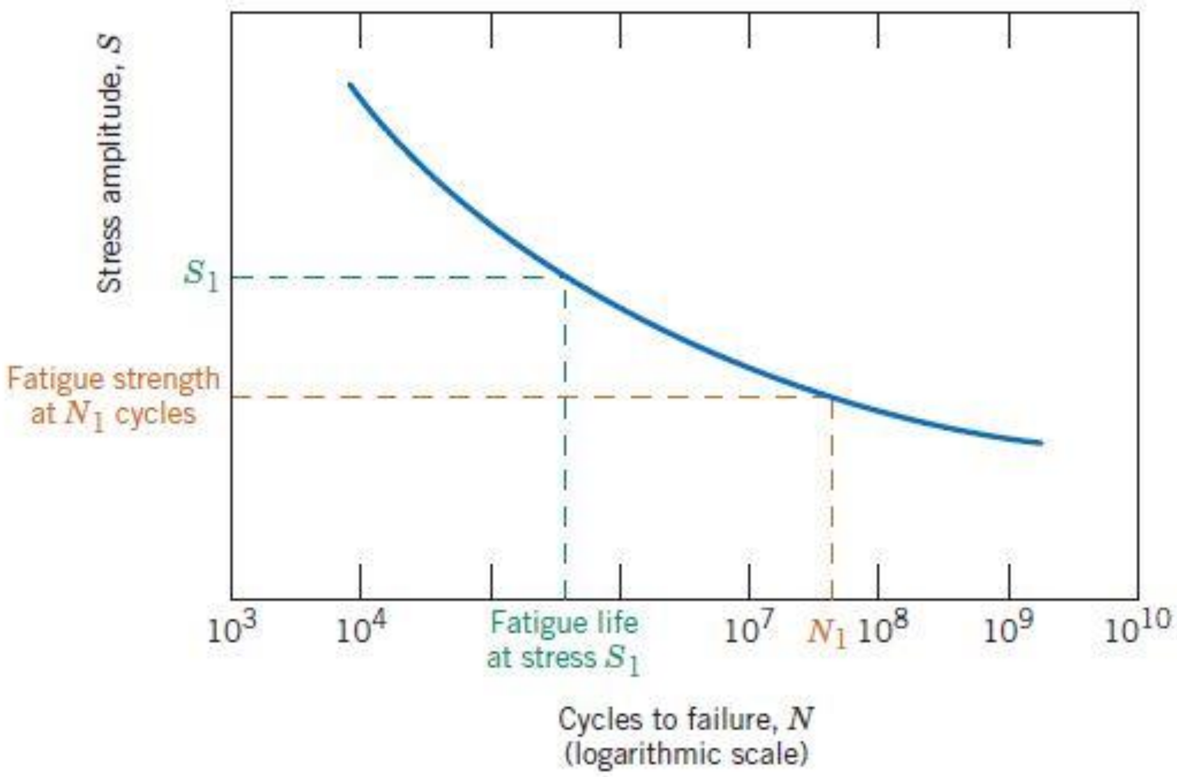


Figure 8.18 Schematic diagram of fatigue-testing apparatus for making rotating-bending tests. (From *KEYSER, MATERIALS SCIENCE IN ENGINEERING, 4th, © 1986.* Electr-



(a)

Steel, Ti show fatigue limit



(b)

Al, Mg, Cu show no fatigue limit

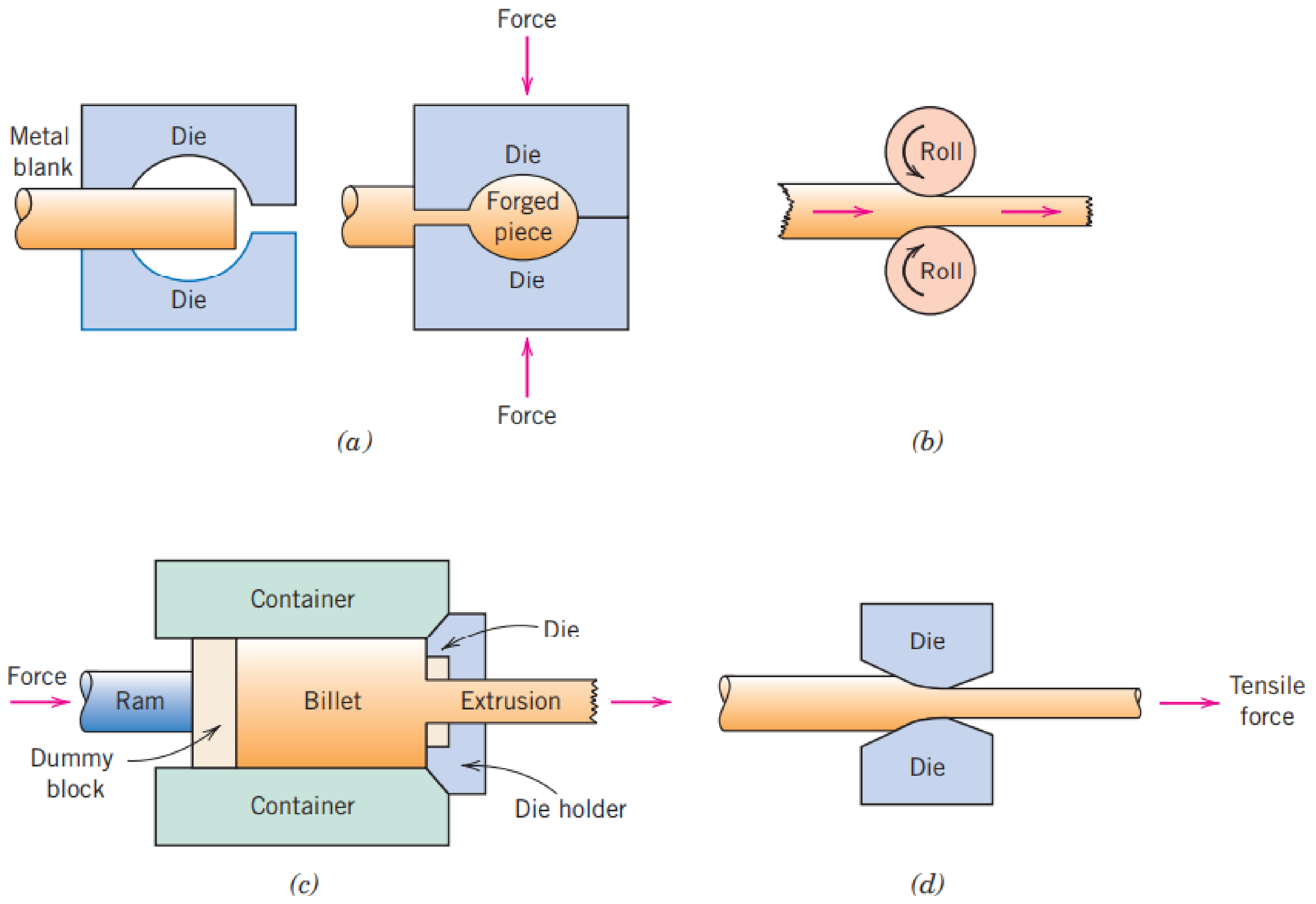
(Might show a limit, but prohibitive to conduct such long time tests!)

Forming (metal forming)

- Forming operations are those in which the shape of a metal piece is changed by *plastic deformation*.
- for example, forging, rolling, extrusion, and drawing are common forming techniques.
- the deformation must be induced by an external force or stress, the magnitude of which must exceed the yield strength of the material.
- Most metallic materials are especially amenable to these procedures, being at least moderately ductile and capable of some permanent deformation without cracking or fracturing.

Cold and hot working in Forming operation

- Recrystallization temperature : the minimum temperature at which the completed recrystallisation of cold worked matal occurs within a specified period of approximately one hour.
- Recrystallization temperature depends on the amount of cold work a material has already recived . The higher the cold work, the lower would be the Recrystallization temperature .
- When deformation is achieved at a temperature above that at which recrystallization occurs, the process is termed *hot working* otherwise, it is *cold working*. (recrystallization temperature is important term here, above which is hot working and below is cold working).
- With most of the *forming techniques*, both *hot- and cold-working* procedures are possible.



Metal deformation during (a) Forging (b) Rolling (c) Extrusion (d) Drawing

Advantage of Cold working

- Better accuracy , close tolerances.
- Better surface finish.
- Strain hardening increases strength and hardness.
- Grain flow during deformation can cause desirable directional properties in product.
- No heating of work required

Disadvantage of Cold working

- Equipment of higher forces and power required.
- Surface of starting work piece must be free from scale and dust.
- Ductility and strain hardening limit the amount of forming that can be done.
- In some operations, metals must be annealed to allow further deformation.
- Some metals are simply not ductile enough to be cold worked.

Advantage of Hot working

- The porosity of metal is largely eliminated. (this increases the hardness and toughness)
- The grain structure of metal is refined.
- The impurities like slag are squeezed into fibres and distributed throughout the metal.
- The mechanical properties such as toughness , percentage elongation, percentage reduction in area and resistance to shock and vibration improved due to refinement of grains.

Disadvantage of hot working

- It requires expensive tools.
- It produces *poor surface finish,* due to the rapid oxidation and scale formation on the metal surface.
- Due to poor surface finish , close tolerance can’t be maintained.

Phase diagram

SOLUBILITY LIMIT

For many alloy systems and at some specific temperature, there is a maximum concentration of solute atoms that may dissolve in the solvent to form a solid solution; this is called a **solubility limit.**

PHASES

- A phase may be defined as a homogeneous portion of a system that has uniform physical and chemical characteristics.

- Sometimes, a single-phase system is termed *homogeneous.*

- *Systems composed* of two or more phases are termed *mixtures or heterogeneous systems.*

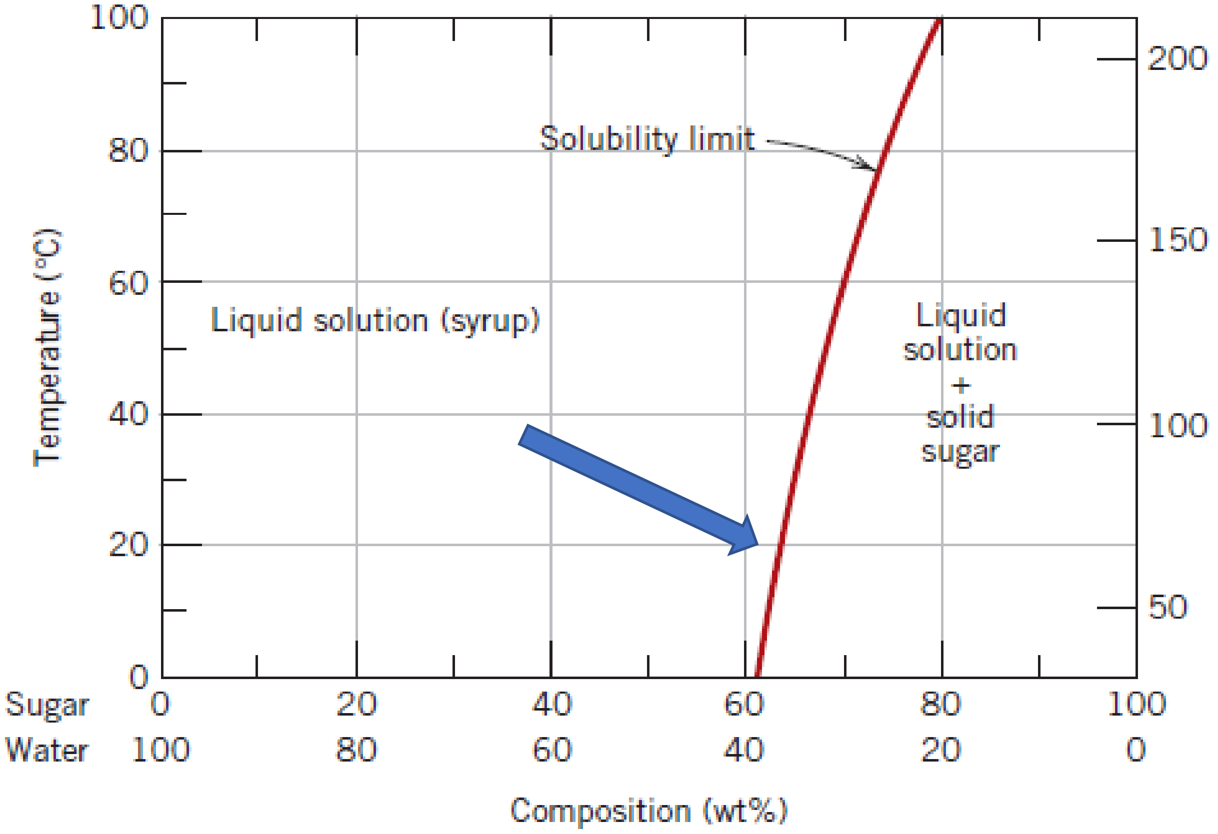
Equilibrium

- Equilibrium is another essential concept that is best described in terms of a thermodynamic quantity called the **free energy.**
- free energy is a function of the internal energy of a system, and also the randomness or disorder of the atoms or molecules (or entropy).
- A system is at equilibrium if its free energy is at a minimum under some specified combination of temperature, pressure, and composition.
- The (macroscopic) characteristics of the system do not change with time — the system is stable.
  - A change in T, P or C for the system will result in an increase in the free energy and possible changes to another state whereby the free energy is lowered.

phase equilibrium

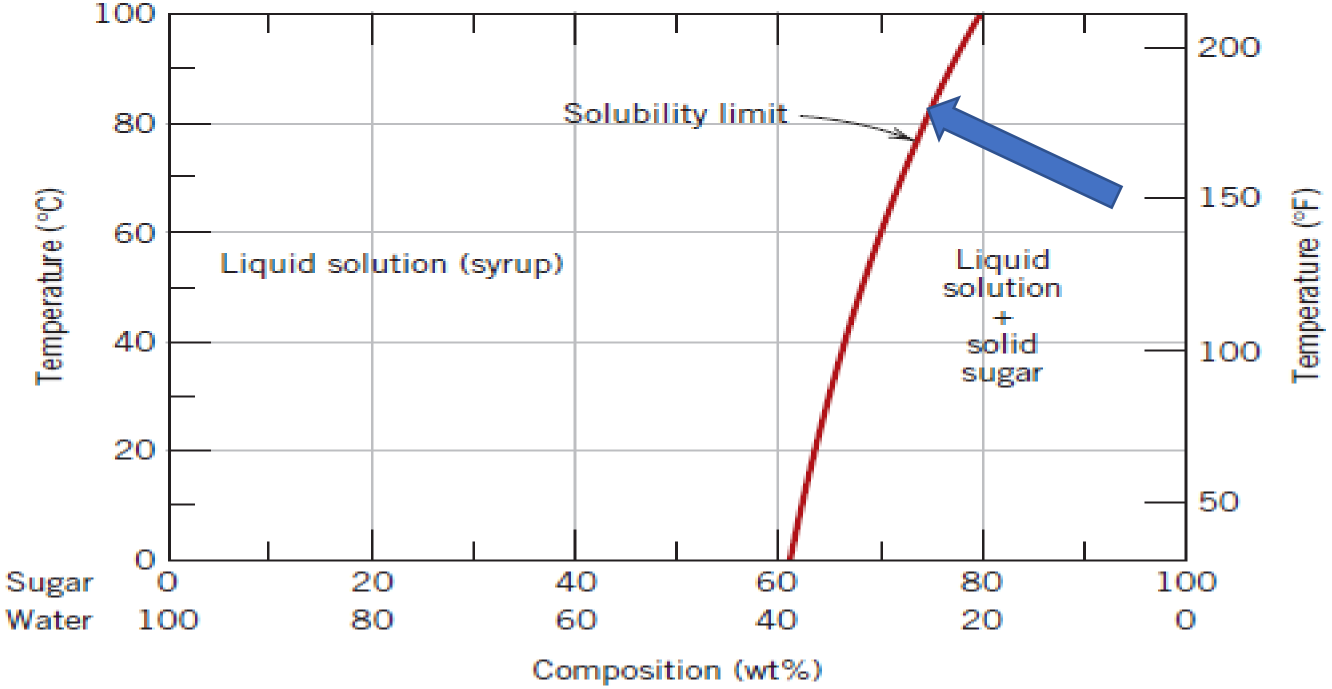
- Refers to equilibrium as it applies to systems (more than one matter, like Fe-C system) in which more than one phase may exist.
- Phase equilibrium is reflected by a constancy with time in the phase characteristics of a system.
- Much of the information about the control of the phase structure of a particular system is conveniently and concisely displayed in what is called a **phase diagram,** also often termed an *equilibrium diagram.*
- Now, there are three externally controllable parameters that will affect phase structure—*temperature*, *pressure,* and *composition* and phase diagrams are constructed when various combinations of these parameters are plotted against one another.

Example of phase equilibrium



Suppose that a sugar–water syrup is contained in a closed vessel and the solution is in contact with solid sugar at 20^{o}C. If the system is at equilibrium, the composition of the syrup is 65 wt% sugar 35wt% water, and the amounts and compositions of the syrup and solid sugar will remain constant with time.

- If the temperature of the system is suddenly raised—say, to 100°C—this equilibrium or balance is temporarily upset in that the solubility limit has been increased to 80 wt% sugar . Thus, some of the solid sugar will go into solution in the syrup. This will continue until the new equilibrium syrup concentration is established at the higher temperature.



Gibbs Phase Rule

Phase diagrams and phase equilibrium are subject to the laws of thermodynamics.

Gibbs phase rule is a criterion that determines how many phases can coexist within a system at equilibrium.

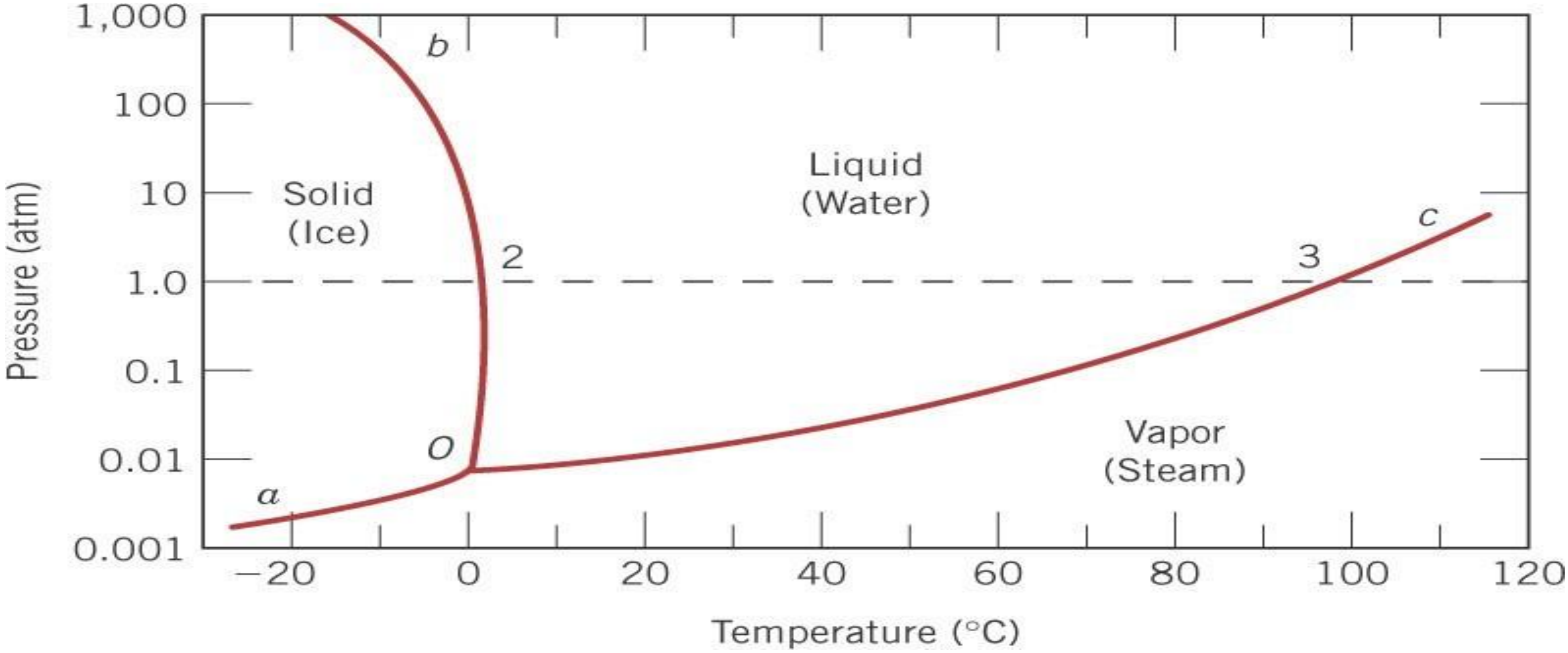
$$P + F = C + N$$

- P: No. of phases present
- F:degrees of freedom (temperature, Pressure, Composition)
- C: components or compounds
- N: non-compositional variables

ONE-COMPONENT (OR UNARY) PHASE DIAGRAMS

- Perhaps the simplest and easiest type of phase diagram to understand is that for a one-component system, in which ***composition is held constant*** (i.e., the phase diagram is for a pure substance).
- This means that ***pressure*** and ***temperature*** are the variables.
- Sometimes also called a *pressure -temperature (or P–T) diagram.*

Example of One Component Phase Diagram (water)



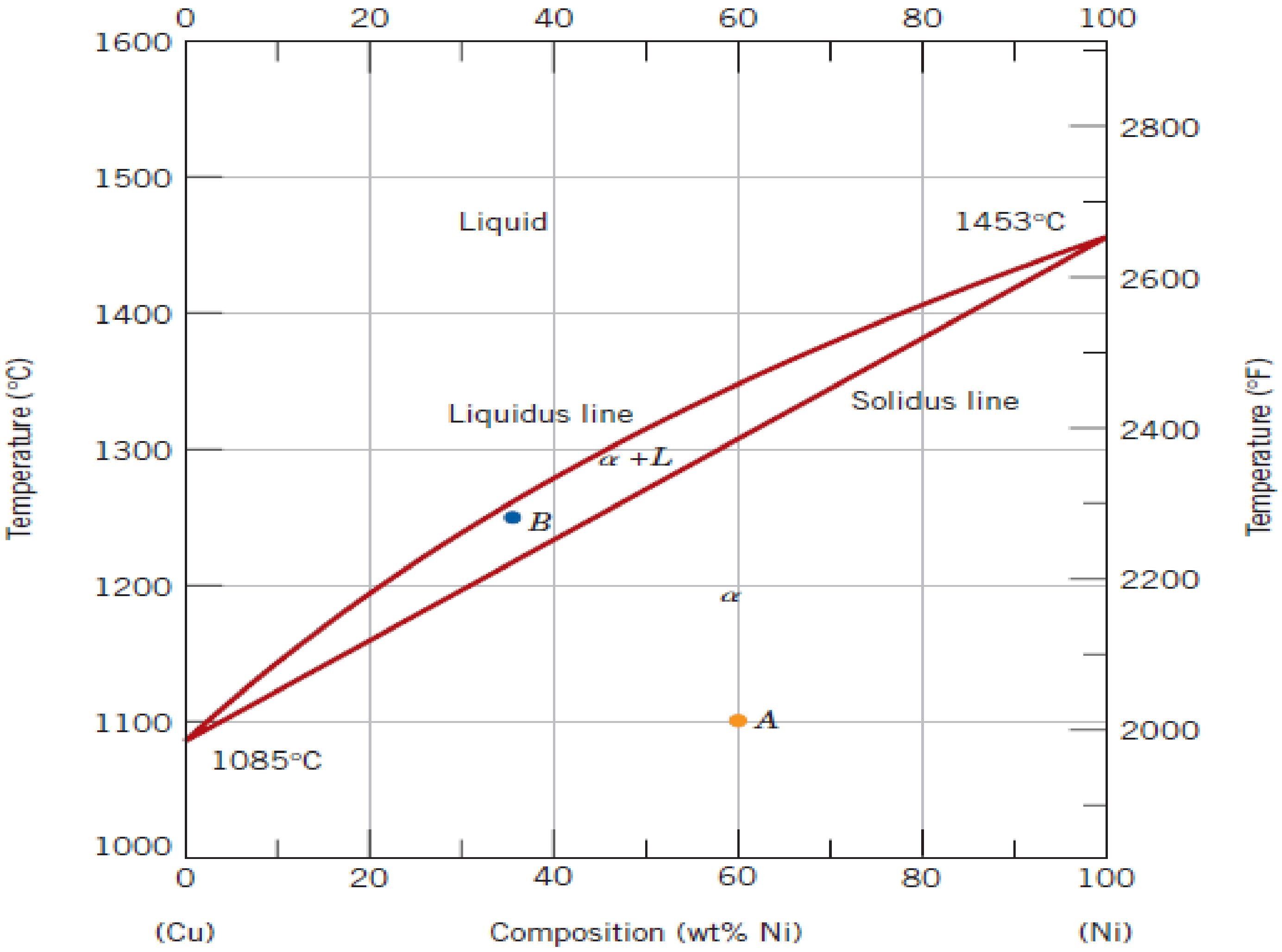
Binary Phase Diagrams

- Another type of extremely common phase diagram is one in which **temperature** and **composition** are variable parameters, and pressure is held constant—normally 1 atm.
- There are various type of binary phase diagram

1. **Solid solution type** (components are complete soluble in solid and liquid state for all proportion)
2. **Eutectic type** (components are complete soluble in liquid phase in all proportion and partially soluble in solid state(for very less proportion of component it is completely soluble and most of the proportion it makes phase mixture.))
3. **Peritectic type** (it also has eutectic point but it has named on peritectic point)

- The copper–nickel system en example of *Solid solution type* binary phase diagram which is termed ***isomorphous*** because of this complete liquid and solid solubility of the two components at any composition.

Example of Binary Phase Diagram (Cu-Ni system)



- Three different phase regions, or fields, appear on the diagram, an alpha (α) field, a liquid (*L) field, and a two-phase* α+ *L* field which is known as *mushy zone.*
- The liquid *L is a homogeneous liquid solution composed of both copper and* nickel.
- The *phase* α *is a substitutional solid solution consisting of both Cu and Ni* atoms, and having an FCC crystal structure.
- There are 2 important line , liquidus and solidus line which are shown in figure.
- the line separating the *L* and α+ *L phase fields is termed the liquidus line.*
- the line separating the α and α+ *L phase fields is termed the solidus line.*

INTERPRETATION OF PHASE DIAGRAMS

For a binary system of known composition and temperature that is at equilibrium, at least three kinds of information are available:

(1)the phases that are present,
(2)the compositions of these phases,
(3) the percentages or fractions of the phases.

Point (1) is very simple to compute, One just locates the temperature–composition point on the diagram and notes the phase(s) with which the corresponding phase field is labeled. Go to the figure and consider the point A, you will notice that point A lies in the α phase and you can get the corresponding percentage of the composition.

- For an alloy having composition and temperature located in a two-phase region, the situation is more complicated. In all two-phase regions $\alpha + L$ (and in two-phase regions only), one may imagine a series of horizontal lines, one at every temperature; each of these is known as a **tie line**, or sometimes as an **isotherm.**
- **These tie** lines extend across the two-phase region and terminate at the phase boundary lines on either side.

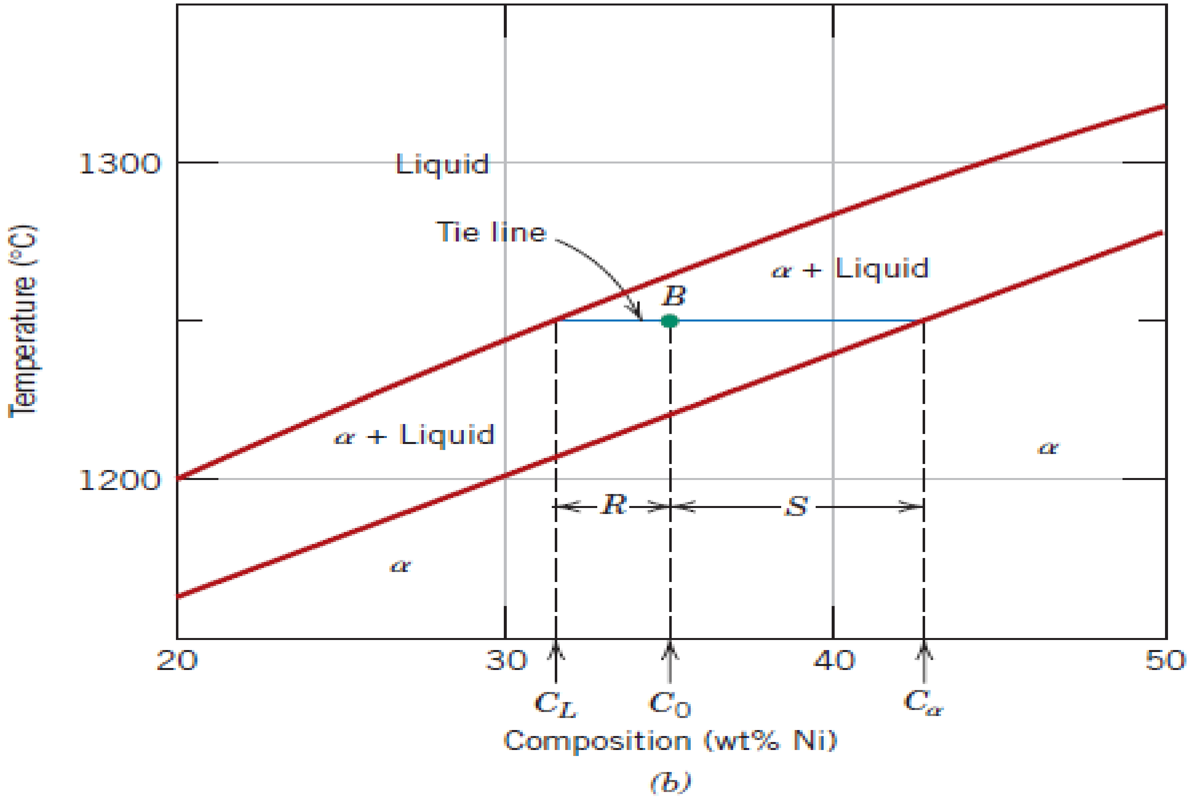
Lever rule

If the composition and temperature position is located within a two-phase region, things are more complex. The tie line must be utilized in conjunction with a procedure that is often called the **lever rule (or the *inverse lever rule), which is applied*** as follows:

1. The tie line is constructed across the two-phase region at the temperature of the alloy.
2. The overall alloy composition is located on the tie line.
3. The fraction of one phase is computed by taking the length of tie line from the overall alloy composition to the phase boundary for the *other phase, and* dividing by the total tie line length.
4. The fraction of the other phase is determined in the same manner.
5. If phase percentages are desired, each phase fraction is multiplied by 100

Example

- Consider the figure shown below*, in which at 1250°C both α (solid)* and *L (liquid)* phases are present for a 35 wt% Ni–65 wt% Cu alloy. The problem is to compute the fraction of each of the α *and liquid phases.*



The tie line has been constructed that was used for the determination of *α and L phase compositions.*

Let the overall alloy composition be located along the tie line and denoted as

C_o

mass fractions be represented by *and* W_α *for the α and* W_L *phases.*

From the lever rule, *may* W_L *be computed according to*

$$W_L = \frac{C_\alpha - C_0}{C_\alpha - C_L}$$

Composition need be specified in terms of only one of the constituents for a binary alloy; for the preceding computation, weight percent nickel will be used (i.e., $C_0 = 35$ wt% Ni, $C_\alpha = 42.5$ wt% Ni, and $C_L = 31.5$ wt% Ni), and

$$W_L = \frac{42.5 - 35}{42.5 - 31.5} = 0.68$$

Similarly, for α the phase,

$$W_\alpha = \frac{C_0 - C_L}{C_\alpha - C_L}$$

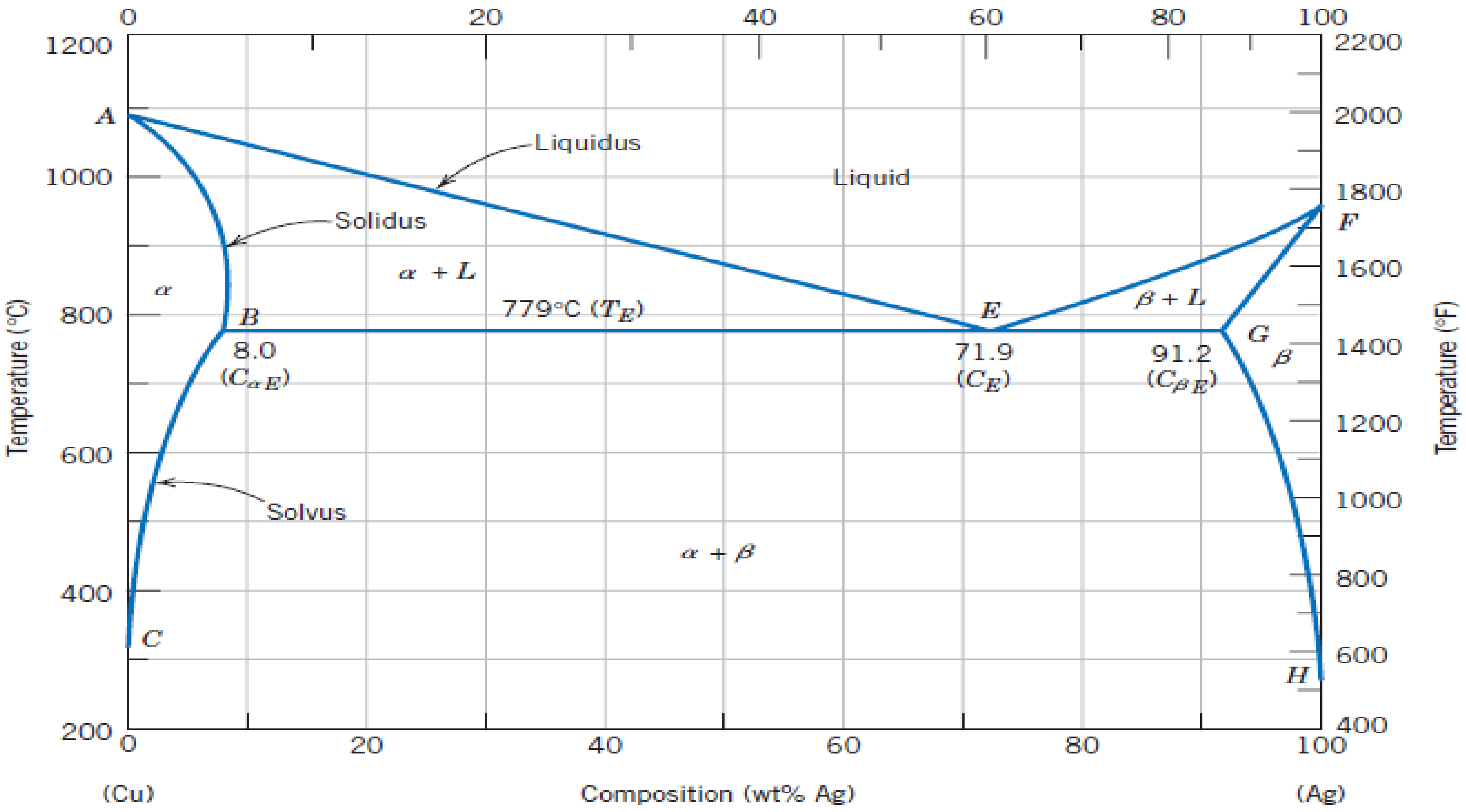
$$= \frac{35 - 31.5}{42.5 - 31.5} = 0.32$$

Of course, identical answers are obtained if compositions are expressed in weight percent copper instead of nickel.

Thus, the lever rule may be employed to determine the relative amounts or fractions of phases in any two-phase region for a binary alloy if the temperature and composition are known and if equilibrium has been established.

BINARY EUTECTIC SYSTEMS

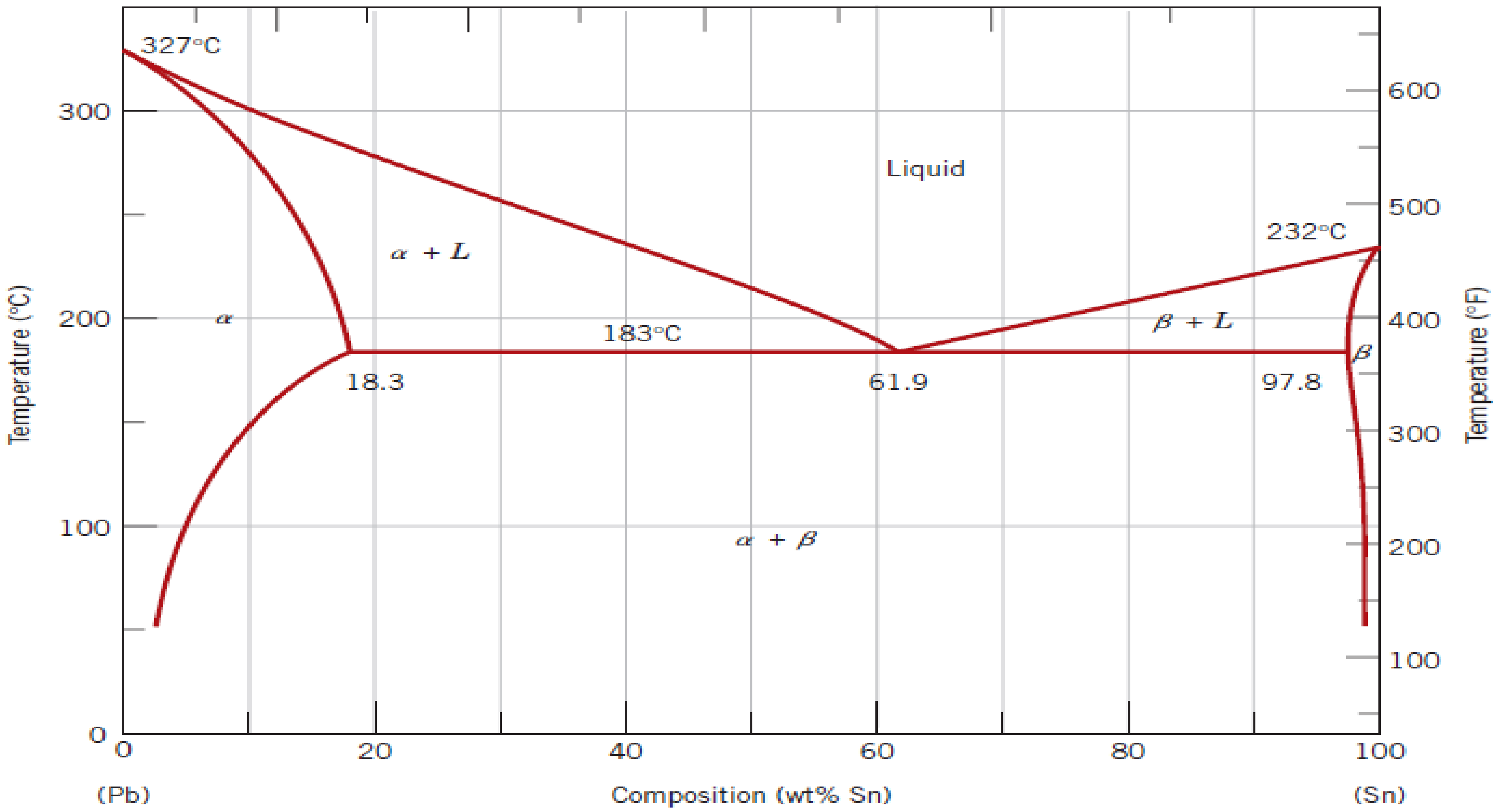
- Another type of common and relatively simple phase diagram found for binary alloys is shown in Figure below for the copper–silver system.
- Three single-phase regions are found on the diagram:α , β , and liquid.
- The α *phase is a solid solution rich in copper,* it has silver as the solute component and an FCC crystal structure.
- The β -phase solid solution also has an FCC structure, but copper is the solute.
- Pure copper and pure silver are also considered to be α *and* β *phases, respectively.*


0
20
40
60
80
100
1200
1000
800
600
400
200
2200
2000
1800
1600
1400
1200
1000
800
600
400
A
Liquidus
Liquid
Solidus
F
α
α + L
779°C (T_E)
β + L
B
E
8.0
($C_{\alpha E}$)
71.9
(C_E)
91.2
($C_{\beta E}$)
G
β
Solvus
α + β
C
H
Temperature (°C)
Temperature (°F)
0
20
40
60
80
100
(Cu)
Composition (wt% Ag)
(Ag)

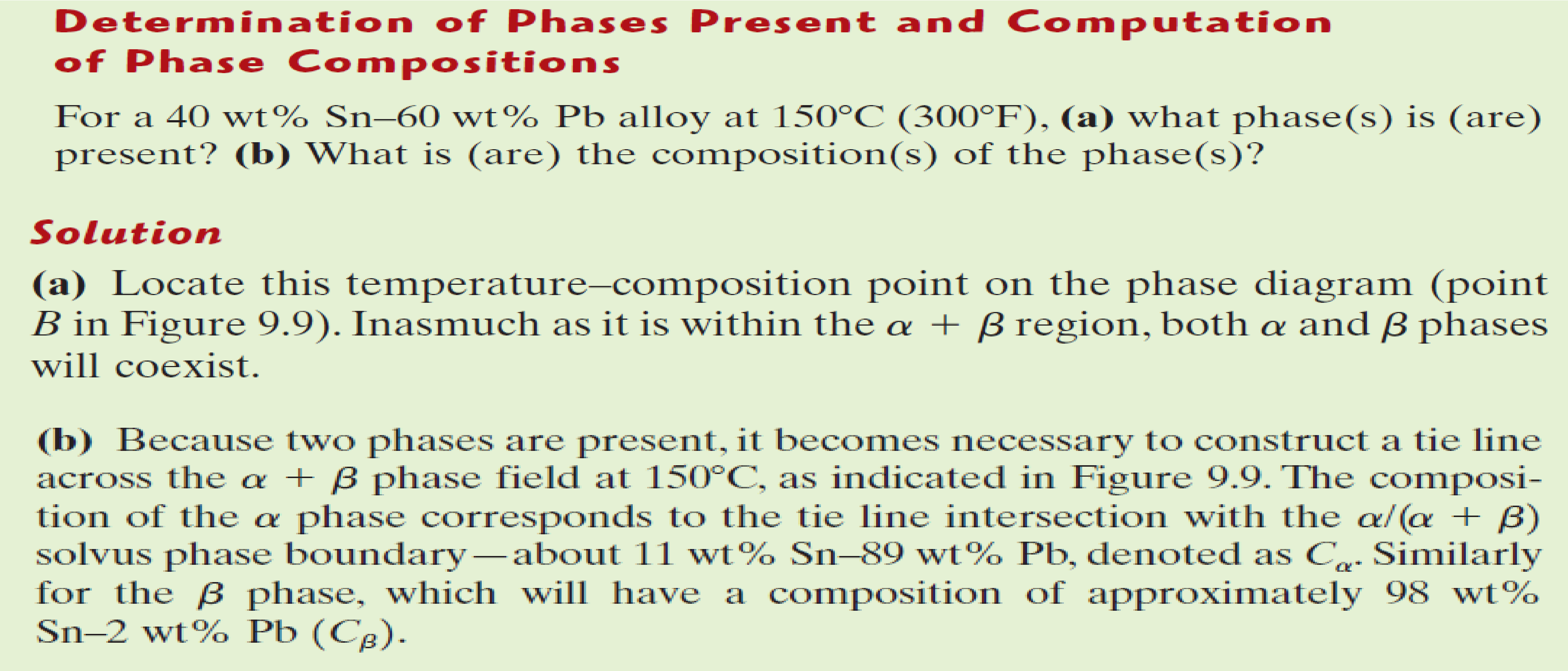
- The solid solubility limit line separating the α *and* α+ β *phase regions is termed a* ***solvus line.*** Similarly boundary GH is also a solvus line (α+ β and β).
- The boundary AB *between the* α *and* α+ *L fields is the* ***solidus line.*** Similarly boundary GF is also the solidus line (β + *L and* β).
- ***liquidus line*** separates α+ *L and L for AE and* β + *L and* β for *EF.*
- liquidus lines meet at the point *E on the phase diagram, through which also* passes the horizontal isotherm line *BEG. Point E is called an* ***invariant point ,*** which has ***zero degree of freedom.***
- *An important reaction takes place at point E, which is called* ***eutectic reaction*** *(eutectic means easy melting) (C shows composition.)*

$$L(C_E) \underset{\text{heating}}{\overset{\text{cooling}}{\rightleftharpoons}} \alpha(C_{\alpha E}) + \beta(C_{\beta E})$$

Sn-Pb system (eutectic type)



Example



Determination of Phases Present and Computation of Phase Compositions

For a 40 wt% Sn–60 wt% Pb alloy at 150°C (300°F), **(a)** what phase(s) is (are) present? **(b)** What is (are) the composition(s) of the phase(s)?

Solution

(a) Locate this temperature–composition point on the phase diagram (point *B* in Figure 9.9). Inasmuch as it is within the $\alpha + \beta$ region, both α and β phases will coexist.

(b) Because two phases are present, it becomes necessary to construct a tie line across the $\alpha + \beta$ phase field at 150°C, as indicated in Figure 9.9. The composition of the α phase corresponds to the tie line intersection with the $\alpha/(\alpha + \beta)$ solvus phase boundary—about 11 wt% Sn–89 wt% Pb, denoted as C_α. Similarly for the β phase, which will have a composition of approximately 98 wt% Sn–2 wt% Pb (C_β).

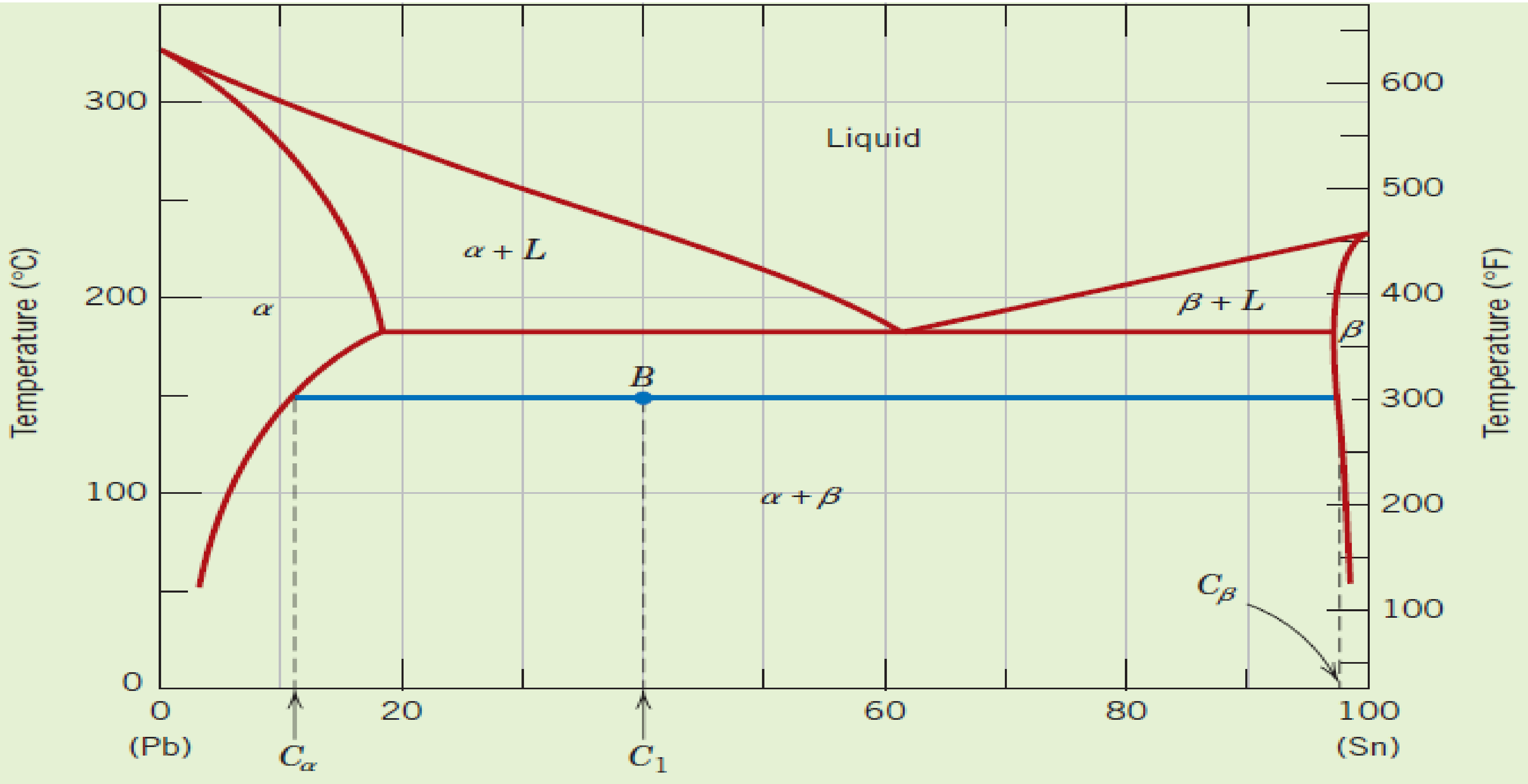


Figure 9.9 The lead–tin phase diagram. For a 40 wt% Sn–60 wt% Pb alloy at 150°C (point *B*), phase compositions and relative amounts are computed in Example Problems 9.2 and 9.3.

EXAMPLE PROBLEM 9.3

Relative Phase Amount Determinations—Mass and Volume Fractions

For the lead–tin alloy in Example Problem 9.2, calculate the relative amount of each phase present in terms of **(a)** mass fraction and **(b)** volume fraction. At 150°C take the densities of Pb and Sn to be 11.23 and 7.24 g/cm^3, respectively.

Solution

(a) Because the alloy consists of two phases, it is necessary to employ the lever rule. If C_1 denotes the overall alloy composition, mass fractions may be computed by subtracting compositions, in terms of weight percent tin, as follows:

$$W_\alpha = \frac{C_\beta - C_1}{C_\beta - C_\alpha} = \frac{98 - 40}{98 - 11} = 0.67$$

$$W_\beta = \frac{C_1 - C_\alpha}{C_\beta - C_\alpha} = \frac{40 - 11}{98 - 11} = 0.33$$

(b) To compute volume fractions it is first necessary to determine the density of each phase using Equation 4.10a. Thus

$$\rho_\alpha = \frac{100}{\dfrac{C_{\mathrm{Sn}(\alpha)}}{\rho_{\mathrm{Sn}}} + \dfrac{C_{\mathrm{Pb}(\alpha)}}{\rho_{\mathrm{Pb}}}}$$

where $C_{\mathrm{Sn}(\alpha)}$ and $C_{\mathrm{Pb}(\alpha)}$ denote the concentrations in weight percent of tin and lead, respectively, in the α phase. From Example Problem 9.2, these values are 11 wt% and 89 wt%. Incorporation of these values along with the densities of the two components leads to

$$\rho_\alpha = \frac{100}{\dfrac{11}{7.24\ \mathrm{g/cm^3}} + \dfrac{89}{11.23\ \mathrm{g/cm^3}}} = 10.59\ \mathrm{g/cm^3}$$

Similarly for the β phase:

$$\rho_\beta = \frac{100}{\dfrac{C_{\mathrm{Sn}(\beta)}}{\rho_{\mathrm{Sn}}} + \dfrac{C_{\mathrm{Pb}(\beta)}}{\rho_{\mathrm{Pb}}}}$$

$$= \frac{100}{\dfrac{98}{7.24\ \mathrm{g/cm^3}} + \dfrac{2}{11.23\ \mathrm{g/cm^3}}} = 7.29\ \mathrm{g/cm^3}$$

Now it becomes necessary to employ Equations 9.6a and 9.6b to determine V_α and V_β as

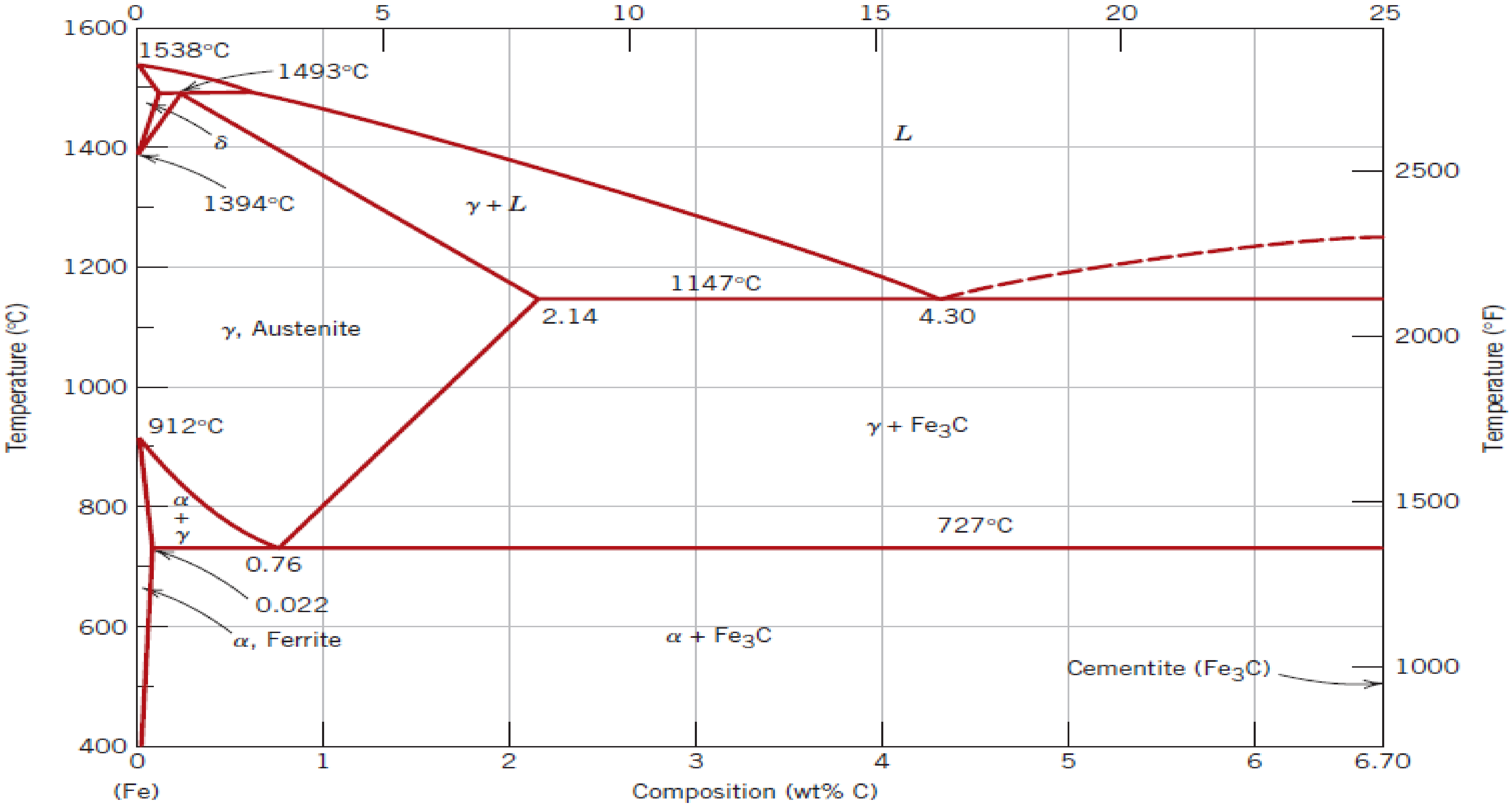
$$V_\alpha = \frac{\dfrac{W_\alpha}{\rho_\alpha}}{\dfrac{W_\alpha}{\rho_\alpha} + \dfrac{W_\beta}{\rho_\beta}}$$

$$= \frac{\dfrac{0.67}{10.59\ \text{g/cm}^3}}{\dfrac{0.67}{10.59\ \text{g/cm}^3} + \dfrac{0.33}{7.29\ \text{g/cm}^3}} = 0.58$$

$$V_\beta = \frac{\dfrac{W_\beta}{\rho_\beta}}{\dfrac{W_\alpha}{\rho_\alpha} + \dfrac{W_\beta}{\rho_\beta}}$$

$$= \frac{\dfrac{0.33}{7.29\ \text{g/cm}^3}}{\dfrac{0.67}{10.59\ \text{g/cm}^3} + \dfrac{0.33}{7.29\ \text{g/cm}^3}} = 0.42$$

THE IRON–IRON CARBIDE PHASE DIAGRAM (IRON-CORBON PHASE DIAGRAM) (PERITECTIC TYPE)



Something about *pure iron*...

- If we go along the vertical left axis , we will have 100% iron, so concentrate first on the pure iron(where carbon percentage is zero).
- Pure iron, upon heating, experiences two changes in crystal structure before it melts.
- At *room temperature* ,the stable form below 912^{o}C, called **ferrite,** or **α-iron,** has a **BCC** crystal structure.
- Ferrite experiences a polymorphic transformation to **austenite, or γ-iron,** at 912^{o}C (1674^{o}F), which has FCC crystal structure.
- This austenite persists to 1394^{o}C (2541^{o}F), at which temperature the FCC austenite reverts back to a ***BCC*** phase known as ***δ-ferrite***, which finally melts at 1538^{o}C (2800^{o}F).

Important points about Fe-C diagram

- The composition axis in Figure 9.24 extends only to 6.70 wt% C; at this concentration the intermediate compound iron carbide, or **cementite (Fe_3C),** is formed, which is represented by a vertical line on the phase diagram.
- Thus, the iron–carbon system may be divided into two parts: an iron-rich portion, as in Figure and the other (not shown) for compositions between 6.70 and 100 wt% C (pure graphite).

- In practice, all steels and cast irons have carbon contents less than 6.70 wt% C; therefore, we consider only the iron–iron carbide system.
- Carbon is an interstitial impurity in iron and forms a solid solution with each of α- and δ-ferrites, and also with austenite, as indicated by the α, δ, and γ *single phase* fields in Figure.

α-ferrite in Fe-C diagram

- In the BCC α -ferrite, only small concentrations of carbon are soluble; the maximum solubility is 0.022 wt% at 727°C (1341°F). The limited solubility is explained by the shape and size of the BCC interstitial positions, which make it difficult to accommodate the carbon atoms.
- Even though present in relatively low concentrations, carbon significantly influences the mechanical properties of ferrite.
- This particular iron–carbon phase is relatively soft, may be made magnetic at temperatures below 768°C (1414°F), and has a density of 7.88 g/cm3.

Austenite (γ) in Fe-C

- The austenite, or γ *phase of iron, when alloyed with carbon alone, is not stable* below 727ºC (1341ºF), as indicated in Figure.
- The maximum solubility of carbon in austenite, 2.14 wt%, occurs at 1147ºC (2097ºF). This solubility is approximately 100 times greater than the maximum for BCC ferrite, because the FCC interstitial positions are larger therefore, the strains imposed on the surrounding iron atoms are much lower.

δ- ferrite in Fe-C

- The -ferrite is virtually the same as δ-ferrite, except for the range of temperatures over which each exists.
- Because the δ -ferrite is stable only at relatively high temperatures, it is of no technological importance.

Cementite (Fe_3C) in Fe-C

- Cementite forms when the solubility limit of carbon in α -ferrite is exceeded below 727°C (1341°F) (for compositions within the $\alpha+Fe_3C$ *phase region).* see the diagram for percentage of component.
- Cementite will also coexist with the γ *phase between 727*°and 1147°C (γ $+Fe_3C$ *phase region*).
- Mechanically, cementite is very hard and brittle; the strength of some steels is greatly enhanced by its presence.

Important reactions in Fe-C

- **Eutectic reaction**: when liquid phase changes into two solid phase (γ and cementite) at ***4.30 wt% C and 1147^{o}C***.
- These temperature and composition are known as eutectic temperature and composition.
- It forms the phase mixture known as ledeburite.

$$L \underset{\text{heating}}{\overset{\text{cooling}}{\rightleftharpoons}} \gamma + \mathrm{Fe_3C}$$

Important reactions in Fe-C

- **Eutectoid reaction:** when a solid phase changes into two solid phases. eutectoid invariant point exists at a composition of ***0.76 wt% C*** and a temperature of ***727^{o}C***.
- upon cooling, the solid γ *phase is transformed into* α*-iron and cementite.*
- It forms the phase mixture known as **pearlite**.

$$\gamma(0.76\ \mathrm{wt\%\ C}) \underset{\text{heating}}{\overset{\text{cooling}}{\rightleftharpoons}} \alpha(0.022\ \mathrm{wt\%\ C}) + \mathrm{Fe_3C}(6.7\ \mathrm{wt\%\ C})$$

Important reactions in Fe-C

- **Peritectic reaction**: This reaction appears at ***1493ºC*** and at ***0.18%C*** where a mixture of liquid and solid converts into another solid phase upon cooling .
- This reaction appears in alloys where there is large difference in the melting point.
- Due to the presence of this point it is called peritectic phase diagram.

$$L + \delta \xrightarrow{cooling} \gamma$$

$$L + \delta \xleftarrow{heating} \gamma$$

Pearlite in Fe-C

- Pearlite is the phase mixture of α ferrite and cementite. *(**pearlite is not a phase**)*.
- The microstructure for the eutectoid steel (0.76 wt% C) that is slowly cooled through the eutectoid temperature(727^{o}C) consists of alternating layers or lamellae of the two phases(α ferrite and cementite) that form simultaneously during the transformation.

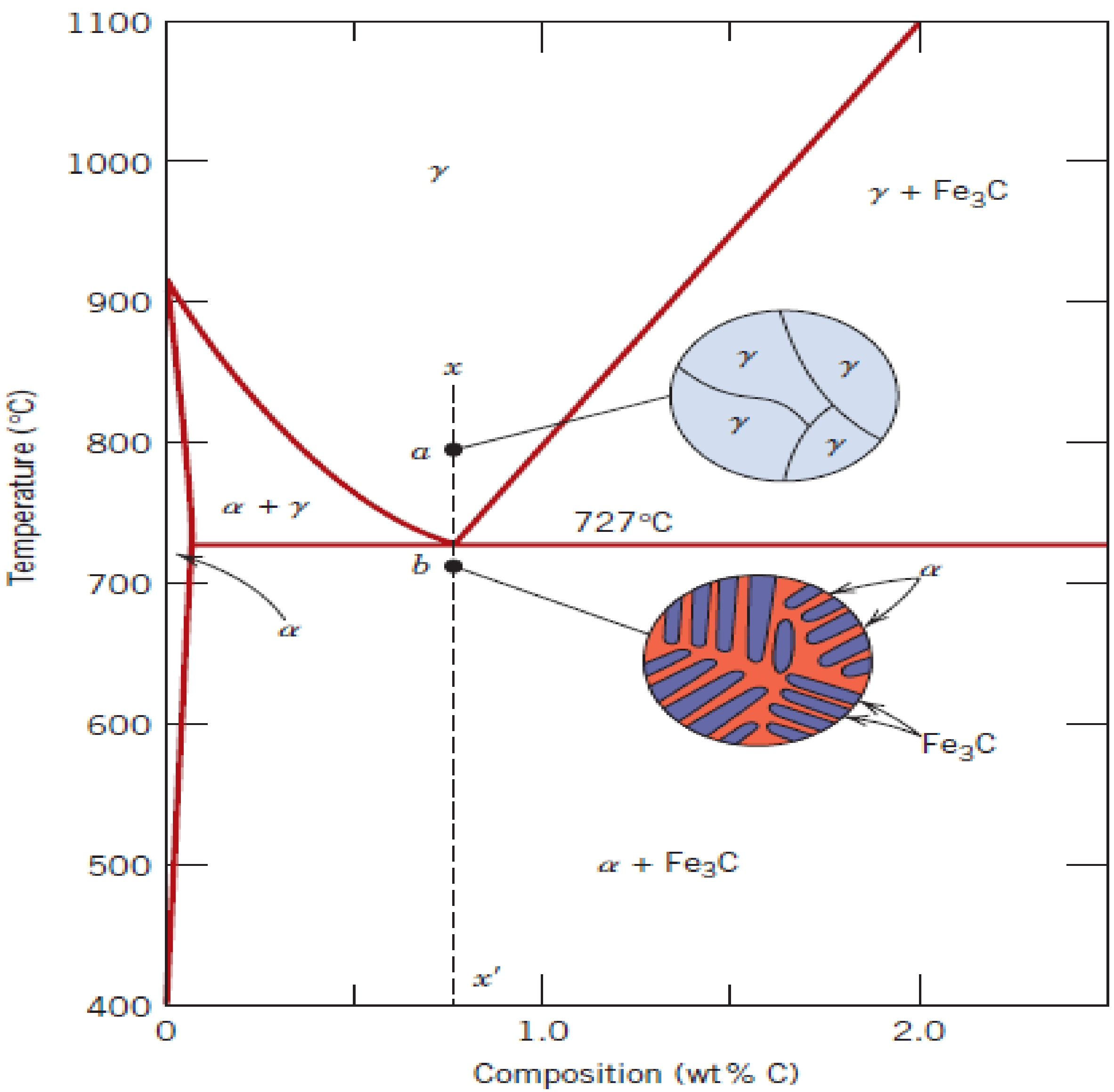


Figure 9.26 Schematic representations of the microstructures for an iron–carbon alloy of eutectoid composition (0.76 wt% C) above and below the eutectoid temperature.

ledeburite

- It is also a phase mixture , not a phase.
- It is formed when liquid at eutectic composition (4.3%wt of C) is cooled through eutectic temperature(1147^{o}C).
- It is a phase mixture of γ austenite and cementite.

Name of steel	Limit of %wt of C
Hypo- eutectiod	Upto .76
Hyper-eutectoid	.76 to 2.14
Hypo-eutectic	2.14 to 4.3
Hyper-eutectic	4.3 to 6.67

Thank you