Production & Industrial Engineering

General Engineering

Vol. I : Engineering Materials

Comprehensive Theory

with **Solved Examples** and **Practice Questions**

MADE EASY Publications

MADE EASY Publications Pvt. Ltd.

Corporate Office: 44-A/4, Kalu Sarai (Near Hauz Khas Metro Station), New Delhi-110016
E-mail: infomep@madeeasy.in
Contact: 011-45124660, 8860378007
Visit us at: www.madeeasypublications.org

General Engineering : Vol. I – Engineering Materials

First Edition : 2020
Second Edition : 2021

Third Edition : 2022

Contents

Engineering Materials

■■■■

VOLUME I

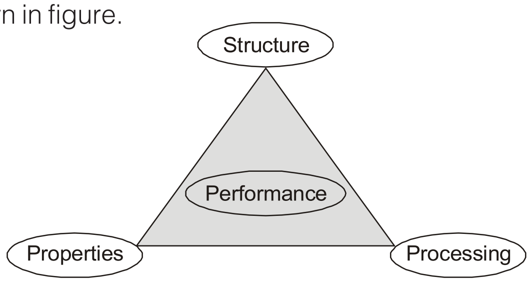
General Engineering

Engineering Materials

INTRODUCTION

Materials are so important in the development of human civilization that the historians have identified early periods of civilization by the name of most significantly used material, e.g.: Stone Age, Bronze Age. This is just an observation made to showcase the importance of materials and their impact on human civilization. It is obvious that materials have affected and controlling a broad range of human activities through thousands of decades.

As engineering materials constitute foundation of technology, it's not only necessary but a must to understand how materials behave like they do and why they differ in properties. This is only possible with the atomistic understanding allowed by quantum mechanics that first explained atoms and then solids starting in the 1930s. The combination of physics, chemistry, and the focus on the relationship between the properties of a material and its microstructure is the domain of Materials Science. The development of this science allowed designing materials and provided a knowledge base for the engineering applications (Materials Engineering). Important components of the subject Materials Science are structure, properties, processing, and performance. A schematic interrelation between these four components is shown in figure.



Interrelation between four components of Material Science

Innovation in engineering often means the clever use of a new material for a specific application. For example: plastic containers in place of age-old metallic containers. It is well learnt lesion that engineering disasters are frequently caused by the misuse of materials. So it is vital that the professional engineer should know how to select materials which best fit the demands of the design - economic and aesthetic demands, as well as demands of strength and durability. Beforehand the designer must understand the properties of materials, and their limitations. Thus it is very important that every engineer must study and understand the concepts of Materials Science and Engineering. This enables the engineer :

- To select a material for a given use based on considerations of cost and performance.
- To understand the limits of materials and the change of their properties with use.
- To be able to create a new material that will have some desirable properties.
- To be able to use the material for different application.

1.1 Classification of Materials

Like many other things, materials are classified in groups, so that our brain can handle the complexity. One can classify them based on many criteria, for example crystal structure (arrangement of atoms and bonds between them), or properties, or use. Metals, Ceramics, Polymers, Composites, Semiconductors, and Biomaterials constitute the main classes of present engineering materials. Following chart describes the basic classification of material:

1. **Metals :** These materials are characterized by high thermal and electrical conductivity; strong yet deformable under applied mechanical loads; opaque to light (shiny if polished). These characteristics are due to valence electrons that are detached from atoms, and spread in an electron sea that glues the ions together, i.e. atoms are bound together by metallic bonds and weaker Van der Waals forces. Pure metals are not good enough for many applications, especially structural applications. Thus metals are used in alloy form i.e. a metal mixed with another metal to improve the desired qualities. E.g.: aluminum, steel, brass, gold.

   Properties of metals :

   1. At ordinary temperature they are usually solid.
   2. To some extent they are malleable and ductile.
   3. They are usually good electrical and thermal conductors.
   4. Most of the metals form alloys.
   5. Their freshly cut surface arc lustrous.
   6. When struck they produce typical metallic sound.

Metals are typically classified according to their uses in engineering as under :

(i) **Pure metals :** They are obtained by refining the ore. Generally, it is very difficult to produce pure metal. Again, pure metals are mostly, not of any use to the engineers. But by specialized and expensive techniques, very pure metals (99.99% pure) can be obtained e.g., copper and aluminium

(ii) **Alloyed metals :** Metals are alloyed by combining two or more metals. The combination so formed is called an alloy. The properties of an alloy can be totally different from its basic metals. For example. 18.8 stainless steel, which contains 18% chromium, 8% nickel in low carbon steel (carbon less than 0.15%) is extremely tough exceedingly ductile and highly resistant to corrosion. These properties are quite different from the behaviour of original carbon steel.

(iii) **Ferrous metals :** Iron is the principal constituent of such metals. Ferrous alloys contain significant amount of non-ferrous metals. In engineering, ferrous alloys are extremely important They can be classified on the basis of the percentage of carbon and other alloying elements present. The important groupings according to the percentage of carbon present are :

(a) **Mild steels :** The carbon present range from 0.15% to 0.25%. These steels have good weldability and are moderately strong. The cost of production is low.

(b) **Medium carbon steels :** These steels contain carbon between 0.3% to 0.6%, their weldability is comparatively lesser but their strength is high.

(c) **High carbon steels :** The carbon content range from 0.65% to 1.5%. The weldability is poor and these steels become hard and tough by heat treatment.

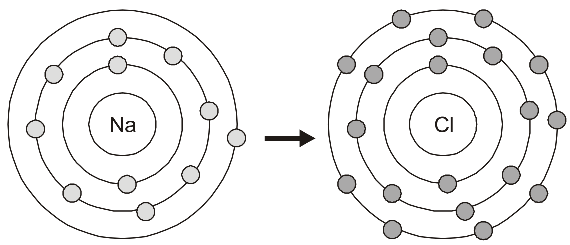
If carbon content is up to 1.5% and silica up to 0.5% manganese up to 1.5% along with traces of other elements, the steel so formed is called as plain carbon steel.

(d) **Cast irons :** These iron contain carbon between 2% to 4%. These iron as ferrous casting alloys. The cost of production is quite low.

Secondary or physical forces and energies are also found in many solid materials; they are weaker than the primary ones, but nonetheless influence the physical properties of some materials.

1.3.1 Ionic Bond

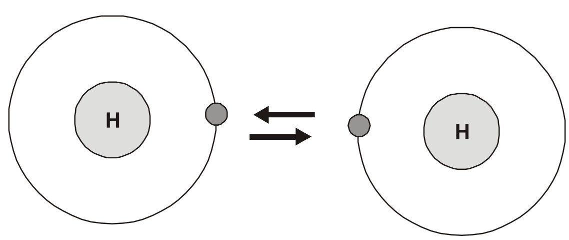
This bond exists between two atoms when one of the atoms is negative (has an extra electron) and another is positive (has lost an electron). Then there is a strong, direct Coulomb attraction. Basically ionic bonds are non-directional in nature. An example is NaCl. In the molecule, there are more electrons around Cl, forming Cl^- and fewer electrons around Na, forming Na^+. Ionic bonds are the strongest bonds. In real solids, ionic bonding is usually exists along with covalent bonding.



Schematic representation of ioning bonding. Here Na is giving an electron to Cl to have stable structure.

1.3.2 Covalent Bond

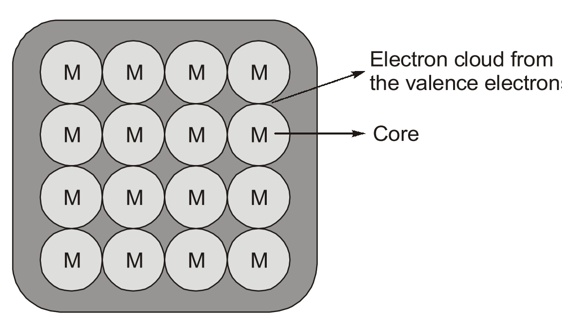
In covalent bonding, electrons are shared between the atoms, to saturate the valency. The simplest example is the H_2 molecule, where the electrons spend more time in between the nuclei of two atoms than outside, thus producing bonding. Covalent bonds are stereo-specific, i.e., each bond is between a specific pair of atoms, which share a pair of electrons (of opposite magnetic spins). Typically, covalent bonds are very strong, and directional in nature The hardness of diamond is a result of the fact that each carbon atom is covalently bonded with four neighboring atoms, and each neighbor is bonded with an equal number of atoms to form a rigid three-dimensional structure.



Schematic representation of covalent bond in Hydrogen molecule (sharing of electrons)

1.3.3 Metallic Bond

Metals are characterised by high thermal and electrical conductivities. Thus, neither covalent nor ionic bonding are realized because both types of bonding localize the valence electrons and preclude conduction. However, strong bonding does occur in metals. The valence electrons of metals also are delocalized. Thus metallic bonding can be viewed as metal containing a periodic structure of positive ions surrounded by a sea of delocalized electrons. The attraction between the two provides the bond, which is non-directional.



Metallic Bonding

Example 1.16 What it the composition in weight percent, of an alloy that consists of 5 at % Cu and 95 at % Pi?

Take A_{Cu} = 63.54 g/mol; A_{Pt} = 195.09 g/mol

Solution :

Assume :

$$C'_{Pt} = \text{at \% of platinum;}$$
$$C'_{Cu} = \text{at \% of copper;}$$

Now, weight percent composition of platinum

$$C'_{Pt} = \frac{C'_{Cu}A_{Cu}}{C'_{Cu}A_{Cu} + C'_{Pt}A_{Pt}} \times 100$$

$$= \frac{5 \times 63.54}{5 \times 63.54 + 95 \times 195.09} \times 100 = 1.69 \text{ wt \%}$$

$$C_{Cu} = \frac{C'_{Pt}A_{Pt}}{C'_{Cu}A_{Cu} + C'_{Pt}A_{Pt}} \times 100$$

$$= \frac{95 \times 195.09}{5 \times 63.54 + 95 \times 195.09} \times 100 = 98.314 \text{ wt \%}$$

Example 1.17 Determine the approximate density of a Ti – 6A*l* – 4V titanium alloy that has a composition of 90 wt% Ti, 6 6 wt% A*l* and 4 wt% V.

Take,
$$A_{Ti} = 47.90 \text{ g/mol}; \rho_{Ti} = 4.54 \text{ g/cm}^3;$$
$$A_{Al} = 26.98 \text{ g/mol}; \rho_{Al} = \rho \text{ g/cm}^3;$$
$$A_V = 50.94 \text{ g/mol}: \rho_V = 6.11 \text{ g/cm}^3$$

Solution :

We know that, average density of titanium alloy can be expressed as

$$\rho_{alloy} = \frac{100}{\frac{C_{Ti}}{\rho_{Ti}} + \frac{C_{Al}}{\rho_{Al}} + \frac{C_V}{\rho_V}}$$

where, C_{Ti}, C_{Al} and C_V are in weight percent and ρ_{Ti}, ρ_{Al}, ρ_V are in g/cm^3

$$= \frac{100}{\frac{90}{4.54} + \frac{6}{2.7} + \frac{4}{6.11}} = 4.405 \text{ g/cm}^3$$

1.7 Mechanical Properties of Material

Property of a material (or Material property) is a factor that influences qualitatively or quantitatively the response of a given material to imposed stimuli and constraints, e.g. forces, temperatures, etc.

Mechanical properties include those characteristics of material that describe its behaviour under the action of external forces. Different mechanical properties are :

1. Elasticity
2. Plasticity
3. Toughness
4. Resilience
5. Tensile strength
6. Yield strength
7. Impact strength
8. Ductility
9. Malleability
10. Brittleness
11. Hardness
12. Fatigue
13. Creep
14. Wear resistance

Remember

- **Stress** $= \dfrac{\text{Internal resistance or applied load}}{\text{Area of cross section opposing load}}$
- **Young's modulus or modulus of elasticity (*E*)**

$$E = \frac{\text{Tensile or compressive stress}}{\text{Corresponding strain}} = \frac{\sigma}{\epsilon}$$

- **Strength :** The resistance offered by a material on application of external force is called strength.
- **Hardness :** Hardness is the resistance offered by surface of the material on indentation.
- **Stiffness :** The ability of material to resist elastic deformation or deflection is called stiffness.
- **Elasticity :** The property of a material by virtue of which material regains its original form after removal of load is elasticity.
- **Plasticity :** Plasticity is just opposite to elasticity which means ability of the material to undergo permanent deformation.
- **Ductility :** Measure of amount of plastic deformation a material can undergo under tensile forces without fracture.
- **Resilience :** It is the strain energy that can be absorbed by the material without plastic deformation upto elastic limit.
- **Toughness :** Toughness is the maximum strain energy that can be absorbed by the material upto fracture.
- **Malleability :** It is the property of the material to be plastically deformed into a flat sheet.
- **Fatigue :** The behaviour of the material under fluctuating loads.
- **Creep :** The permanent deformation of a material over a period of time at a constant load and at elevated temperature is called creep.
- **Isotropy :** When the properties of a material are dependent on the direction.

1.8 Phase Diagram

- Phase diagrams are an important tool in the armory of an materials scientist.
- In the simplest sense a phase diagram demarcates regions of existence of various phases. (Phase diagrams are maps)
- Phase diagrams are also referred to as "equilibrium diagrams" or "constitutional diagrams". This usage requires special attention: through the term used is "equilibrium", in practical terms the equilibrium is not global equilibrium but Microstructural level equilibrium.
- Broadly two kinds of phase diagrams can be differentiated : those involving time and those which do not involve time.
- In this section, we shall deal with the phase diagrams not involving time.
  - This type can be further sub classified into:
  - Those with composition as a variable (e.g. *T* vs. %Composition)
  - Those without composition as a variable (e.g. *P* vs. *T*)
- Time-Temperature-Transformation (TTT) diagrams and Continuous-Cooling-Transformation (CCT) diagrams involve time.

Example 1.22 A 0.40 percent *C* plain carbon steel is slowly cooled from 950°C to a temperature slightly above 727°C. Calculate :

(i) the wt % austenite present in the steel.

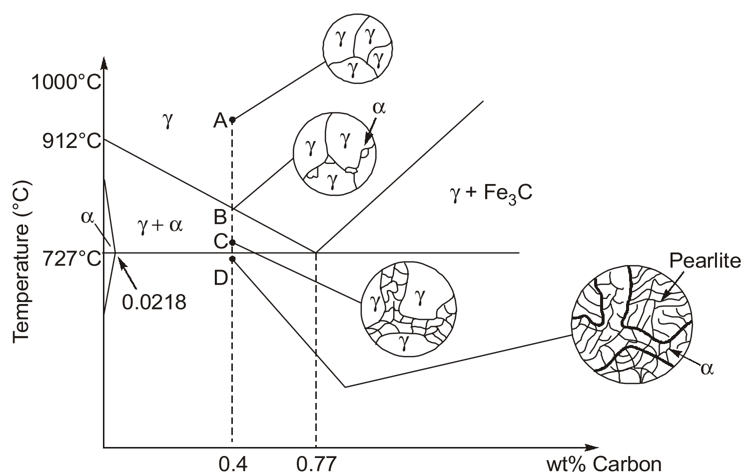
(ii) the wt % proeutectoid ferrite present in the steel.

Solution :

Referring to figure below and using tie line at point '*C*'; we get

(i) $$\text{wt. \% of Austenite} = \frac{0.40-0.0218}{0.77-0.0218}\times 100\% = 50.55\%$$

(ii) $$\text{wt\% of proeutectoid ferrite} = \frac{0.77-0.40}{0.77-0.0218}\times 100\% = 49.45\%$$



Example 1.23 A 0.40% *C* plain carbon steel is slowly cooled from 950°C to a temperature just slightly below 727°C. Calculate :

(i) the wt % proeutectoid ferrite present in the steel.

(ii) the wt % eutectoid ferrite and weight percent eutectoid cementite present in the steel.

Solution:

Refer Fig. 9.33.

The weight percentage proeutectoid ferrite present in the steel just below 727°C will be

$$= \frac{0.40-0.0218}{0.77-0.0218}\times 100\% = 50.55\%$$

Now, $$\text{wt. \% total ferrite} = \frac{6.67-0.40}{6.67-0.0218}\times 100\% = 94.31\%$$

$$\text{wt.\% total cementite} = \frac{0.40-0.0218}{6.67-0.0218}\times 100\% = 5.69\%$$

$$\text{wt.\% eutectoid ferrite} = \text{total ferrite} - \text{proeutectoid ferrite}$$
$$= (94.31-50.55)\% = 43.76\%$$

$$\text{wt. eutectoid cementite} = \text{wt\% total cementite} = 5.69\%$$

(**Note:** Formation of proeutectoid cementite was not possible during cooling.]

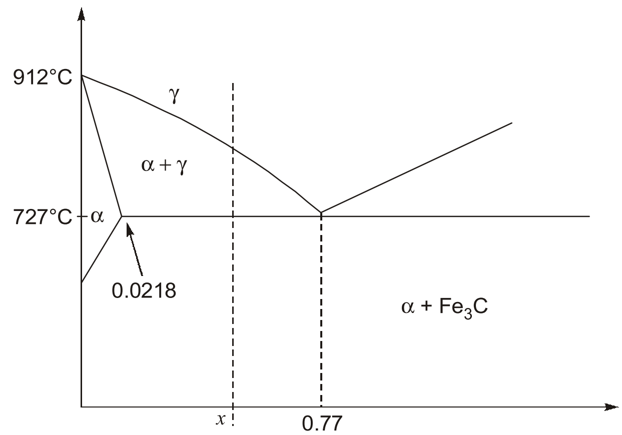
Example1.24 A Hypoeutectoid plain-carbon steel that was slow-cooled from the austenite region to room temperature contains 82 wt. % eutectoid ferrite. Assuming no change in structure just below the eutectoid temperature to room temperature, what is the carbon content of the steel?

Solution :

Let, x = the wt. % carbon the Hypoeutectoid steel.

We also know that,

Eutectoid ferrite = total ferrite – proeutectoid ferrite



Using above figure and applying lever rule,

$$0.091 = \frac{6.67 - x}{6.67 - 0.0218} - \frac{0.77 - x}{0.77 - 0.0218}$$

$\Rightarrow$ $0.091 = 0.15042(6.67 - x) - 1.3365(0.77 - x)$

$\Rightarrow$ $x = 0.0985\%$ C.

Student's Assignments 1

Q.1 BCC metals possesses following characteristics over FCC metals.
(a) higher strengths, higher ductility
(b) higher strengths, lower ductility
(c) lower strengths, higher ductility
(d) lower strengths, lower ductility

Q.2 Motion of dislocation in screw dislocation and edge dislocations are termed as
(a) climb and glide respectively
(b) glide and climb respectively
(c) glide and glide respectively
(d) climb and climb respectively

Q.3 For removing the oxygen trapped in steel structure, which of the following element is added?
(a) Silica (b) Manganese
(c) Cobalt (d) Nickel

Q.4 Which of the following operation is performed on the material for predicting strain aging time?
(a) Skin rolling (b) Notching
(c) Machining (d) Alloying

Q.5 What will be the effect of grain refinement on creep resistance?
(a) Creep resistance decreases
(b) Creep resistance increase
(c) Remains unaffected
(d) It may increase or decrease

Q.6 Which one of the following is incorrect?
(a) FCC materials have only one slip plane
(b) FCC materials have only one slip direction
(c) FCC materials have 12 slip systems
(d) Cu is an exception which has three slip planes

Q.7 Which one of the following statement is incorrect?
(a) For an edge dislocation, Burger vector is perpendicular to the dislocation line.
(b) In screw dislocation motion of dislocation is referred as glide.
(c) Direction of slip is represented by Burger vector.
(d) Both (a) and (b)

Q.8 A 10 mm diameter Brinell ball produced an indentation of diameter $\sqrt{1.99}$ mm in a steel alloy when a load of 4.9 kN is used. The Brinell hardness number is_______. (Take $g = 9.8$ m/s^2)

Q.9 A material having face central cubic structure has atomic radius of element as 2Å, then the volume vacant per unit cell will be _____ $\times 10^{-24}$ cm^3.

Q.10 What is the main purpose of tempering?
(a) Reducing ductility and toughness
(b) Reducing the after effect of cold working
(c) Increasing the machinability
(d) Reducing hardness and brittleness

Q.11 Consider the following statements:
1. Bainite cannot be produced by continuous cooling.
2. Austempering is the process of producing bainite.

Which of the above statements is/are correct?
(a) 1 only (b) 2 only
(c) both 1 and 2 (d) neither 1 nor 2

Q.12 Consider the following statements for Iron carbon diagram:
1. Ledeburite can be produced by cooling liquid metal contains approx 4.3% carbon at a temperature of 1150°C.
2. Pearlite is a phase mixture of a-iron and Fe_3C produced primarily by diffusion.
3. At peritectic point mixture of two solid phases produce another solid phase.

Which of the above statements are correct?
(a) 1 and 2 (b) 1 and 3
(c) 2 and 3 (d) 1, 2 and 3

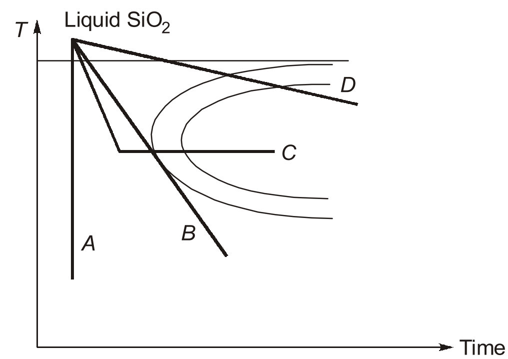
Q.13 Match **List-I** (Iron phases) with **List-II** (Maximum temperature) and select the correct answer using the codes given below the lists:

List-I	List-II
A. γ-Iron	1. 910°C
B. δ-Iron	2. 768°C
C. α-Iron	3. 1535°C
	4. 1410°C
	5. 1590°C
	6. 1452°C

Codes:

	A	B	C
(a)	5	6	1
(b)	4	6	2
(c)	6	4	2
(d)	4	3	1

Q.14 Consider the following processes on T-T-T diagram. Which one of the following process has highest probability of getting metallic glass used in transformer cores to minimize the eddy current loss, on cooling of liquid metal(liquid SiO_2)?



(a) Process (d) (b) Process (c)
(c) Process (b) (d) Process (a)

Q.15 Match **List-I** (Types of cast iron) with **List-II** (Carbon%) and select the correct answer using the codes given below the lists:

List-I	List-II
A. Gray iron	1. 2.8 - 3.3%
B. White iron	2. 1.8 - 3.6%
C. High strength gray iron	3. 3.0 - 4.0%
D. Nodular iron	4. 2.5 - 4.0%

Codes:

	A	B	C	D
(a)	3	1	2	4
(b)	4	1	2	3
(c)	3	4	1	2
(d)	4	2	1	3

Student's Assignments 2

Q.16 What are the type of fractures if cleavages appear on surface and dimples appear on surface respectively?
(a) Ductile and brittle (b) Brittle and ductile
(c) Brittle and shear (d) Shear and ductile

Q.17 Consider the following statements regarding hydrogen embrittlement:

1. BCC and FCC crystals are most susceptible to hydrogen embrittlement, but HCP metals are generally not susceptible.
2. Hydrogen embrittlement increases by slow strain rates.

Which of the above statement(s) is/are correct?
(a) 1 only
(b) 2 only
(c) Both 1 and 2
(d) Neither 1 nor 2

Q.18 Which of the following is correct statement regarding plastics?
1. Polyethylene and polystyrene are thermoplastics whereas epoxy and bakelite are thermosetting plastic.
2. Polyethylene, polytetrafluoro ethylene and polyster are thermoplastics whereas phenol formaldehyde is thermosetting plastic.

(a) 1 only
(b) 2 only
(c) both (1) and (2)
(b) Neither (1) nor (2) correct.

Q.19 The planar density (in atoms/nm^2) of the plane located on FCC structure and it has Miller indices (0 1 1) is________. [Assume lattice parameter, a = 0.5 nm]

Q.20 Which of the following are correct regarding advantage of Gas carburizing?
1. Heat consumed in process is less.
2. Closer quality limits can be achieved
3. This process can also be used for high carbon steel.

(a) 1 and 2 only (b) 2 and 3 only
(c) 1 and 3 only (d) 1, 2 and 3 only

Q.21 An alloy of two metals A and B is having the composition as 60 wt% A and 40 wt% B. At a certain temperature T, it consists of 66 wt% α-phase and 34 wt% of β-phase. The α-phase has the composition of 87 wt% A and 13 wt% B. The composition of b-phase is __________ wt% of A. (Correct upto two digits)

ANSWERS

1. (b)	**2.** (a)	**3.** (a)	**4.** (a)
5. (a)	**6.** (d)	**7.** (b)	**8.** (318.18)
9. (47.058)	**10.** (d)	**11.** (c)	**12.** (a)
13. (d)	**14.** (d)	**15.** (d)	**16.** (b)
17. (b)	**18.** (a)	**19.** (5.65)	**20.** (a)
21. (7.59)			

HINTS

3. (a)

Silica is added in steel to remove the trapped oxygen from structure. It forms SiO_2, which is sludge and it can be easily removed.

4. (a)

Skin rolling operation is performed on the material for predicting the strain aging time.

5. (a)

Grain refinement increases the grain boundaries which decreases the creep resistance.

6. (d)

For FCC material:

Material	Slip plane	Slip direction	No. of slip system
Cu, Al, Ni, Ag, Au	{111}	< 110 >	12

7. (b)

In screw dislocation motion of dislocation is referred as climb and in edge dislocation movement of dislocation is referred as glide.
In edge dislocation Burger vector is perpendicular to the dislocation line while in screw dislocation Burger vector is parallel to the dislocation line.
Unit plastic deformation is called slip and it always appear in the direction of applied load. Direction of slip is represented by Burger vector.

8. (318.18)(315 to 320)

$$\text{BHN} = \frac{P\text{ (in kg)}}{\frac{\pi D}{2}\left[D - \sqrt{D^2 - d^2}\right]}$$

$$= \frac{\left(\frac{4900}{9.8}\right)}{\frac{\pi \times 10}{2}\left[10 - \sqrt{10^2 - \left(\sqrt{1.99}\right)^2}\right]}$$

$$= \frac{7 \times 500 \times 2}{22 \times 10\left[10 - \sqrt{100 - 1.99}\right]}$$

$$= \frac{700}{22\left[10 - \sqrt{98.01}\right]}$$

$$= \frac{700}{22[10 - 9.9]} = \frac{700}{22 \times 0.1} = 318.182$$

9. **(47.058) (46.8 to 47.2)**

Atomic radius $= 2Å$

Side of unit cell, $a = (2\sqrt{2})r$ [for FCC material]

Volume of vacant space per unit cell

$= (0.26)a^3 = (0.26)(3 \times 2\sqrt{2})r^3$

$= (0.26) \times 16 \times (\sqrt{2}) \times (2 \times 10^{-10})^3$

$= 47.058 \times 10^{-30}\ m^3$

$= 47.058 \times 10^{-24}\ cm^3$

10. **(d)**

After hardening resulting microstructure is extremely hard and brittle. So, tempering is performed for reducing hardness and brittleness and for increasing ductility or toughness.

11. **(c)**

Austenite sample is quenched at a rate greater than or equal to critical cooling rate to a temperature below the nose but above martensite start line. This temperature is maintained for substantial period of time so that transformation line enters into TTT curve. This produces bainite. Bainite cannot be produced by continuous cooling. This process of producing bainite is called austempering.

12. **(a)**

1. Eutectic reaction:

$$L \xrightarrow[4.3\%\ C]{1150°C} \underbrace{\gamma - \text{iron} + Fe_3C}_{\text{Ledeburite}}$$

2. Eutectoid reaction:

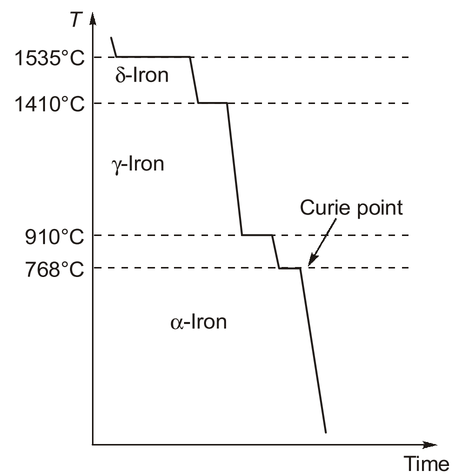
$$\gamma - \text{iron} \xrightarrow[0.8\%\ C]{725°C} \underbrace{\alpha - \text{iron} + Fe_3C}_{\text{Pearlite}}$$

Pearlite is having plate like structure of a-iron and Fe_3C. It is phase mixture of a-iron and Fe_3C. It is mainly produced by diffusion.

3. Peritectic reaction:

$$\underbrace{\delta - \text{iron}}_{\text{Solid}} + \underbrace{L}_{\text{Liquid}} \xrightarrow[0.18\%\ C]{1493°C} \underbrace{\gamma - \text{iron}}_{\text{solid}}$$

13. **(d)**



14. **(d)**

Upon quenching liquid metals at a very fast rate (10^6 °C/sec) the metal will also convert into glass called metallic glass and is used in transformer cores to minimize the eddy current losses.

17. **(b)**

BCC and HCP crystals are most susceptible to hydrogen embrittlement but FCC metals are generally not susceptible.

18. **(a)**

Polyvinyl chloride (PVC), polypropylene (PP), polyethylene (PE) and polystyrene (PS) are thermoplastics, known as B1G-4 plastics. Other well known thermoplastics are polytetrafluoro ethylene, acrylic etc. The commonly used thermosetting plastics are epoxy, polyster and phenol formaldehyde (Bakelite) etc. Most of these thermosetting plastics are used as matrix in composite materials.

19. **(5.65)(5.6 to 5.7)**

$$\text{Planar density} = \frac{\text{No. of atoms}}{\text{Area of plane}}$$