Materials Science & Structure of Matter

Professor Maury Balik
Other Disciplines FE Specifications

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We are grateful to NCEES for granting us permission to copy short sections from the FE Handbook to show students how to use Handbook information in solving problems. This information will normally appear in these slides in outlined boxes like this one.
Textbooks for review

William D. Callister, Jr.
*Materials Science and Engineering: An Introduction*

James F. Shackelford
*Materials Science for Engineers*

Lawrence H. Van Vlack
*Elements of Materials Science and Engineering*
Structure of matter

Which of the following materials has ionic bonds?

(a) Sodium fluoride
(b) Iron
(c) Carbon (diamond)
(d) Silicon crystal

Ionic bonding: transfer of electron(s)
Covalent bonding: sharing of electrons
Metallic bonding: atoms give up electrons to form an "electron sea"

ATOMIC BONDING
Primary Bonds
- Ionic (e.g., salts, metal oxides)
- Covalent (e.g., within polymer molecules)
- Metallic (e.g., metals)

Atomic solids
- Metals and ceramics
- Melting produces individual atoms

Molecular solids:
- Polymers (and all organic compounds)
- Melting produces individual molecules
- Secondary bonding between molecules
Amorphous materials like glass:

(a) are composed of a single element.
(b) have no apparent crystal structures.
(c) are electrically conductive.
(d) are composed of large rectangular crystals.

Crystalline: 3-D periodic structure, unit cell
--- Metals, most ceramics

Amorphous: no periodic structure
--- Glass, thermoset polymers, some thermoplastic polymers

Semi-crystalline: crystalline + amorphous regions
--- Some thermoplastic polymers

from p. 70

**Amorphous Materials**
Amorphous materials such as glass are non-crystalline solids

Thermoplastic polymers are either semicrystalline or amorphous.

Below the glass transition temperature ($T_g$) the amorphous material will be a brittle solid.

The volume temperature curve as shown above is often used to show the difference between amorphous and crystalline solids.
Diffusion

The activation energy for Al in a Cu solvent is 1.6 x 10^8 J/kmol. What is the diffusion coefficient, D, at 575 °C if the constant of proportionality, D₀, is 7 x 10⁻⁶ m²/s?

(a) 4.04 x 10⁻⁴⁷ m²/s
(b) 2.04 x 10⁻²⁰ m²/s
(c) 9.75 x 10⁻¹⁶ m²/s
(d) 2.31 x 10⁻⁵ m²/s

from p. 65

DIFFUSION

Diffusion Coefficient

\[ D = D_0 \ exp\left(-\frac{Q}{RT}\right) \]

where

- \( D \) = diffusion coefficient
- \( D_0 \) = proportionality constant
- \( Q \) = activation energy
- \( R \) = gas constant [8.314 J/(mol*K)]
- \( T \) = absolute temperature

1. Convert kmol to mol
2. Convert T from °C to K
3. Calculate \( D = D_0 \ exp\left(-\frac{Q}{RT}\right) \)
The diffusion coefficient for carbon in $\alpha$-Fe is $2.4 \times 10^{-12}$ m$^2$/sec at 500 °C and $1.7 \times 10^{-10}$ m$^2$/sec at 900 °C. The activation energy for diffusion of carbon in $\alpha$-Fe is most nearly

(a) 40 kJ/mol
(b) 60 kJ/mol
(c) 80,000 kJ/mol
(d) 80 kJ/mol

1. $Q$ and $D_o$ have the same values at each temp.
2. Write 2 equations for $D_1$ at $T_1$ and $D_2$ at $T_2$
3. Combine the 2 equations to eliminate $D_o$

$$D_1 = D_o \exp \left( \frac{-Q}{RT_1} \right)$$

$$D_2 = D_o \exp \left( \frac{-Q}{RT_2} \right)$$

dividing:

$$\frac{D_1}{D_2} = \exp \left[ \frac{Q}{R} \left( \frac{1}{T_2} - \frac{1}{T_1} \right) \right]$$

4. Convert temperatures to K
5. Solve for $Q$
6. Convert $Q$ from J/mol to kJ/mol

from p. 65

**DIFFUSION**

Diffusion Coefficient

$$D = D_o \exp^{-\frac{Q}{RT}}$$

where

$D$ = diffusion coefficient

$D_o$ = proportionality constant

$Q$ = activation energy

$R$ = gas constant [8.314 J/(mol•K)]

$T$ = absolute temperature
The test depicted in the figure is called a

(a) compression test  
(b) toughness test  
(c) resilience test  
(d) tensile test

Key mechanical properties obtained from a tensile test curve:
- Elastic modulus
- Ductility (also called percent elongation): Permanent engineering strain after failure
- Ultimate tensile strength (also called tensile strength): Maximum engineering stress
- Yield strength: Engineering stress at which permanent deformation is first observed, calculated by 0.2% offset method.

adapted from Callister 7th ed. Figure 6.11
Stress-strain (tensile) test

**Equations:**

$$\sigma = \frac{F}{A_o}$$  \hspace{1cm}  $$\varepsilon = \frac{L - L_o}{L_o}$$  \hspace{1cm}  $$\% \text{ strain} = 100 \varepsilon$$

- $\sigma$ = engineering stress
- $\varepsilon$ = engineering strain
- $E$ = elastic modulus (Young's modulus)
- $F$ = applied force
- $A_o$ = initial cross-sectional area
- $L_o$ = initial length
- $L$ = stretched length
- $\Delta L = L - L_o$ = change in length

**In the initial elastic region:**  
$$\sigma = E \varepsilon$$

$$\sigma_T = \frac{F}{A}$$  \hspace{1cm}  $$\varepsilon_T = \ln \frac{L}{L_o} = \ln(1 + \varepsilon)$$

- $\sigma_T$ = true stress
- $\varepsilon_T$ = true strain
- $A$ = actual cross-sectional area
The modulus of elasticity for the material shown in the figure is most nearly

(a) 50 GPa
(b) 100 GPa
(c) 150 GPa
(d) 200 GPa

1. Calculate the slope of the linear region.
2. Easiest to use the points (.002, 100) and (0,0).
3. Convert units from MPa to GPa.
The 0.2% offset yield strength for the material shown in the figure is most nearly

(a) 50 MPa
(b) 100 MPa
(c) 160 MPa
(d) 190 MPa

1. Draw a straight line parallel to initial elastic region, starting at $\varepsilon = 0.002$ (0.2% $\varepsilon$).
2. Point of intersection with $\sigma - \varepsilon$ curve is the 0.2% offset yield strength.
Mechanical properties

A tensile specimen has an elastic modulus of 50 GPa. If the length of the specimen before being stressed is 280 mm, its length when stressed elastically by 380 MPa is most nearly

(a) 281 mm
(b) 282 mm
(c) 283 mm
(d) 284 mm

1. Convert modulus to MPa.
2. Using $\varepsilon = \sigma / E$, calculate $\varepsilon$.
3. Using $\Delta L = \varepsilon L_0$, calculate $\Delta L$.
4. Add $\Delta L$ to the original length.

from p. 67

The elastic modulus (also called modulus, modulus of elasticity, Young's modulus) describes the relationship between engineering stress and engineering strain during elastic loading. Hooke's Law applies in such a case.

$$\sigma = E \varepsilon$$

where $E$ is the elastic modulus.

from p. 65

Engineering strain

$$\varepsilon = \frac{\Delta L}{L_0}$$

$\varepsilon$ = engineering strain
$\Delta L$ = change in length
$L_0$ = initial length
A metal with high hardness will generally have:

(a) high yield strength.
(b) high ductility.
(c) good formability.
(d) high impact toughness.

Hardness is the resistance to indentation. Hardness is directly related to tensile strength and yield strength.

Ductility is inversely related to hardness, tensile strength and yield strength.

RELATIONSHIP BETWEEN HARDNESS AND TENSILE STRENGTH
For plain carbon steels, there is a general relationship between Brinell hardness and tensile strength as follows:

\[
\begin{align*}
TS(\text{psi}) & \approx 500 \text{ BHN} \\
TS(\text{MPa}) & \approx 3.5 \text{ BHN}
\end{align*}
\]
Hardenability of steel

Heat-treatable steels generally have high hardenabilities. Comparing a 1040 steel with a 4340 steel, how much deeper can the 4340 steel be hardened to a level of $R_C = 50$?

(a) 50 mm  
(b) 34 mm  
(c) 30 mm  
(d) 3 mm

Jominy bar is heated to a high temperature then quenched on one end.  
Cooling rate decreases with distance from quenched end.  
Hardness decreases with decreasing cooling rate.

From graph:
1. 1040 has $R_C = 50$ at a depth of 2 mm  
2. 4340 has $R_C = 50$ at a depth of 32 mm  
3. Difference is 30 mm

Hardness: Resistance to penetration. Measured by denting a material under known load and measuring the size of the dent.  
Hardenability: The "case" with which hardness can be obtained.  
Cooling rate at 700°C, °C/sec
Other mechanical properties

The Charpy Impact Test measures

(a) the energy required to fracture a material
(b) the elastic modulus of a material
(c) the ultimate tensile strength of a material
(d) the ductility of a material

from p. 69

Impact Test
The Charpy Impact Test is used to find energy required to fracture and to identify ductile to brittle transition.

Impact tests determine the amount of energy required to cause failure in standardized test samples. The tests are repeated over a range of temperatures to determine the ductile to brittle transition temperature.
A particular steel alloy has a fracture toughness of 54.8 MPa-m$^5$ and is exposed to a stress of 1030 MPa. Assuming that the geometric factor $Y = 1$, the minimum length of an interior crack that would cause brittle failure is most nearly

(a) .724 mm  
(b) .901 mm  
(c) 1.45 mm  
(d) 1.80 mm

1. Calculate $a = (1/\pi)(K_{IC}/Y\sigma)^2$
2. $a = 9.01 \times 10^{-4}$ m = 0.901 mm
3. Since it is an interior crack, crack length = $2a = 1.80$ mm
Other mechanical properties

Failure of materials undergoing cyclic loading and unloading is measured by

(a) a creep test
(b) a fatigue test
(c) a tensile test
(d) a Charpy Impact Test

from p. 67

- Creep: Time-dependent deformation under load. Usually measured by strain rate. For steady-state creep this is:
  \[
  \frac{d\varepsilon}{dt} = A\sigma^n e^{-\frac{Q}{RT}}
  \]
  \[
  A = \text{pre-exponential constant}
  
  n = \text{stress sensitivity}
  
  Q = \text{activation energy for creep}
  
  R = \text{ideal gas law constant}
  
  T = \text{absolute temperature}
  
- Fatigue: Time-dependent failure under cyclic load. Fatigue life is the number of cycles to failure. The endurance limit is the stress below which fatigue failure is unlikely.

Fatigue: cyclic loading

Creep: deformation at constant load, usually at elevated temperature.
A micrograph of a sample of molybdenum has 17 grains in an area of 59 x 59 mm in a micrograph taken at a magnification of 250x. The ASTM grain size of this sample is

1. Calculate the number of grains per unit area, accounting for magnification. Then scale to an area of 0.0645 mm$^2$.

\[
\frac{17 \text{ grains}}{(59/250)^2 \text{ mm}^2} = \frac{N \text{ grains}}{0.0645 \text{ mm}^2}
\]

2. Calculate $N_{(0.0645 \text{ mm}^2)}$.

\[
N_{(0.0645 \text{ mm}^2)} = N_{(0.0645 \text{ mm}^2)} = 19.7
\]

3. Calculate $n$. Round to nearest integer.

\[
n = 1 + \frac{\log N}{\log 2} = 5.3
\]
Thermal and mechanical processing of metals

The mechanical deformation of a material at a temperature above its recrystallization temperature is called:

(a) hot working
(b) grain growth
(c) cold working
(d) strain aging

from p. 65

Cold working (plastically deforming) a metal increases strength and lowers ductility.

Raising temperature causes (1) recovery (stress relief), (2) recrystallization, and (3) grain growth. Hot working allows these processes to occur simultaneously with deformation.

adapted from Callister 7th ed. Figure 7.22
Thermal and mechanical processing of metals

Compared to a cold-worked steel part, an equally deformed hot-worked steel part will have:

(a) greater hardness.
(b) greater toughness.
(c) higher yield strength.
(d) less ductility.

Toughness is the ability of a material to resist fracture. Related to impact strength. It is a function of both strength and ductility, but primarily ductility.

from p. 65

Cold working (plastically deforming) a metal increases strength and lowers ductility.

Raising temperature causes (1) recovery (stress relief), (2) recrystallization, and (3) grain growth. Hot working allows these processes to occur simultaneously with deformation.
Thermal and mechanical processing of metals

Which of the following properties describes martensite?
1. high hardness
2. formed by quenching austenite
3. high ductility

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

M = martensite. Formed by rapid quenching of austenite (γ).
Has high strength & hardness. Low ductility.
Phase diagram basics

BINARY PHASE DIAGRAMS
Allows determination of (1) what phases are present at equilibrium at any temperature and overall alloy composition, (2) the compositions of those phases and (3) the wt% of those phases.

Eutectic reaction: liquid $\square$ solid 1 + solid 2
Eutectoid reaction: solid $\square$ solid 1 + solid 2
Peritectic reaction: liquid + solid $\square$ solid
Peritectoid reaction: solid 1 + solid 2 $\square$ solid

Solid phases (Greek letters): $\alpha$, $\beta$, $\gamma$, etc.
Liquid phases: Liquid, L

In a 2-phase region at a fixed $T$, phase compositions are found at ends of the tie line. $x_\alpha = 11\%$ Sn, $x_\beta = 98\%$ Sn

Phase amounts are given by lever rule:

\[
\text{wt}\% \alpha = 100 \left( \frac{x_\beta - x}{x_\beta - x_\alpha} \right) = 100 \left( \frac{98 - 65}{98 - 11} \right) = 37.9\%
\]

\[
\text{wt}\% \beta = 100 \left( \frac{x - x_\alpha}{x_\beta - x_\alpha} \right) = 100 \left( \frac{65 - 11}{98 - 11} \right) = 62.1\%
\]

Overall alloy composition = 65% Sn

eutectic point at $T = 183\, ^\circ C$, 61.9% Sn

from Callister 7th ed. Figure 9.8
Phase diagrams

At 150 °C, the phase amounts present at equilibrium in a Pb/Sn alloy containing 30 wt% Pb are most nearly

(a) 77% α, 23% β
(b) 77% β, 68% α
(c) 32% β, 68% α
(d) 32% α, 68% β

1. Draw a tie line at 150 °C for a 70% Sn (or 30% Pb) alloy
2. Use lever rule to obtain phase amounts

from Callister 7th ed. Figure 9.8
At 200 °C, the composition of the phase(s) present at equilibrium in a Pb/Sn alloy containing 40 wt% Sn are most nearly

(a) α 18% Sn, L 56% Sn
(b) α 56% Sn, L 18% Sn
(c) α 18% Sn, β 56% Sn
(d) Liquid 60% Sn

1. Draw a tie line at 200 °C for a 40% Sn alloy.
2. Read compositions of each phase at ends of tie line.
The transformation occurring at 727 °C and 0.77 %C is a

(a) eutectic reaction
(b) eutectoid reaction
(c) peritectic reaction
(d) peritectoid reaction

1. Eutectoid: $\gamma \rightarrow \alpha + \text{carbide (Fe}_3\text{C)}$
2. Eutectic at 4.3%C, 1148 °C
3. Peritectic at 0.25%C, 1493 °C
An Fe-C alloy with 0.395 wt% carbon is austenitized at 1000 °C and very slowly cooled to 728 °C. The amount (in wt%) of austenite present in the microstructure at 728 °C is most nearly

(a) 25 wt%
(b) 40 wt%
(c) 50 wt%
(d) 100 wt%

1. Draw a tie line at 728 °C for a .395% C alloy.
2. Use the compositions listed on the diagram for 727 °C (close enough).
3. Use lever rule to calculate the wt% austenite (γ phase).
Mechanical properties of polymers

The elastic modulus of an amorphous thermoplastic polymer is lowest

(a) at its glass transition temperature
(b) above its glass transition temperature
(c) below its glass transition temperature
(d) in the glassy state

Polymers

Polymers are classified as thermoplastics that can be melted and reformed. Thermosets cannot be melted and reformed.

The above curve shows the temperature dependent strength (σ) or modulus (E) for a thermoplastic polymer.

Thermoplastics: not chemically crosslinked
Thermosets: are chemically crosslinked
A substance often added to polymers to improve their resistance to ultraviolet radiation is

(a) a plasticizer
(b) glass fibers
(c) carbon black
(d) a flame retardant

from p. 70

**Polymer Additives**

Chemicals and compounds are added to polymers to improve properties for commercial use. These substances, such as plasticizers, improve formability during processing, while others increase strength or durability.

Examples of common additives are:

- **Plasticizers**: vegetable oils, low molecular weight polymers or monomers
- **Fillers**: talc, chopped glass fibers
- **Flame retardants**: halogenated paraffins, zinc borate, chlorinated phosphates
- **Ultraviolet or visible light resistance**: carbon black
- **Oxidation resistance**: phenols, aldehydes
Composites

A rod of composite material consisting of a magnesium matrix (80 vol%, $E_{\text{Mg}} = 45$ GPa) and continuous carbon fibers (20 vol%, $E_{\text{Carb}} = 700$ GPa) aligned along the rod length is pulled in tension. What is the elastic modulus of the rod?

(a) 55 GPa  
(b) 176 GPa  
(c) 225 GPa  
(d) 310 GPa

Use equation for longitudinal loading:

$$E_c = E_{\text{Mg}} f_{\text{Mg}} + E_{\text{Carb}} f_{\text{Carb}}$$

$f_{\text{Mg}} = .8$, $f_{\text{Carb}} = .2$

From p. 68

**COMPOSITE MATERIALS**

- $\rho_c = \sum f_i \rho_i$  
- $C_c = \sum f_i C_i$  
- $\left[ \sum f_i \frac{E_i}{E} \right]^{-1} \leq E_c \leq \sum f_i E_i$  
- $\sigma_c = \sum f_i \sigma_i$

- $\rho_c$ = density of composite  
- $C_c$ = heat capacity of composite per unit volume  
- $E_c$ = Young’s modulus of composite  
- $f_i$ = volume fraction of individual material  
- $c_i$ = heat capacity of individual material per unit volume  
- $E_i$ = Young’s modulus of individual material  
- $\sigma_c$ = strength parallel to fiber direction

$E_c$ : longitudinal loading (parallel to fiber direction)  
$E_c$ : transverse loading (normal to fiber direction)

$\rho_c$, $C_c$ are independent of fiber orientation
Electrical properties of materials

A cylindrical silicon specimen has a diameter of 7 mm and is 57 mm long. A current of .25 A passes through in the axial direction, and a voltage of 24 V is measured across two probes separated by 45 mm. The electrical conductivity of this specimen is most nearly

(a) 0.0648 (Ω·m⁻¹)
(b) 0.0154 (Ω·m⁻¹)
(c) 61.7 (Ω·m⁻¹)
(d) 15.4 (Ω·m⁻¹)

Ohm's Law: \( V = IR \)
1. Calculate \( R = V/I \)
2. Convert diameter & length to m
3. Calculate \( A = \pi d^2/4 \)
4. Calculate \( \rho = RA/L \)
5. Calculate \( \sigma = 1/\rho \)

Resistivity of a material within a resistor
\[ \rho = \frac{RA}{L} \]
\( \rho \) = resistivity of the material
\( R \) = resistance of the resistor
\( A \) = cross-sectional area of the resistor
\( L \) = length of the resistor

Conductivity is the reciprocal of the resistivity

Resistivity
For a conductor of length \( L \), electrical resistivity \( \rho \), and cross-sectional area \( A \), the resistance is
\[ R = \frac{\rho L}{A} \]

For metallic conductors, the resistivity and resistance vary linearly with changes in temperature according to the following relationships:
\[ \rho = \rho_0\left[1 + \alpha(T - T_0)\right], \text{ and} \]
\[ R = R_0\left[1 + \alpha(T - T_0)\right], \text{ where} \]
\( \rho_0 \) = resistivity at \( T_0 \)
\( R_0 \) = resistance at \( T_0 \)
\( \alpha \) = temperature coefficient

Ohm's Law: \( V = IR \)\( v(t) = i(t) \cdot R \)
Electrical properties of materials

The electrical conductivity of aluminum is $3.8 \times 10^7$ (Ω-m)$^{-1}$. An aluminum wire 10 m long must experience a voltage drop of less than 1.0 V when a current of 5 A is passed through it. The minimum diameter of the wire needed is most nearly

(a) 1.29 mm
(b) 0.647 mm
(c) 6.47 mm
(d) 10.2 mm

Ohm's Law: $V = IR$

1. Calculate $R = V/I$
2. Calculate $\rho = 1/\sigma$
3. Calculate $A = \rho L/R$
4. Calculate diameter from $A$: $d = \sqrt{4A/\pi}$
5. Convert diameter to mm

from p. 65

Resistivity of a material within a resistor

$$\rho = \frac{RA}{L}$$

$\rho$ = resistivity of the material
$R$ = resistance of the resistor
$A$ = cross-sectional area of the resistor
$L$ = length of the resistor

Conductivity is the reciprocal of the resistivity

$$\sigma = 1/\rho = \text{conductivity}$$
Electrical properties of materials

A parallel plate capacitor with an area of 6.45 $\times$ $10^{-4}$ m$^2$ and a plate separation of 2 mm is charged with a potential of 10 V. If the material between the plates has a dielectric constant of 6, the charge on the capacitor is most nearly

(a) $1.71 \times 10^{-10}$ F  
(b) $1.71 \times 10^{-11}$ F  
(c) $1.71 \times 10^{-10}$ C  
(d) $1.71 \times 10^{-11}$ C

1. Calculate $\varepsilon = \kappa \varepsilon_0$
2. Convert $d$ to m
3. Calculate $C = \varepsilon A/d$
4. Calculate $q = CV$

**Electrical**
- Capacitance: The charge-carrying capacity of an insulating material
- Charge held by a capacitor
  \[ q = CV \]
  \[ q = \text{charge} \]
  \[ C = \text{capacitance} \]
  \[ V = \text{voltage} \]
- Capacitance of a parallel plate capacitor
  \[ C = \frac{\varepsilon A}{d} \]
  \[ C = \text{capacitance} \]
  \[ \varepsilon = \text{permittivity of material} \]
  \[ A = \text{cross-sectional area of the plates} \]
  \[ d = \text{distance between the plates} \]
- $\varepsilon$ is also expressed as the product of the dielectric constant ($\kappa$) and the permittivity of free space ($\varepsilon_0 = 8.85 \times 10^{-12}$ F/m)
Electrical properties of materials

Silicon doped with boron is

(a) an n-type extrinsic semiconductor
(b) a p-type extrinsic semiconductor
(c) an n-type intrinsic semiconductor
(d) a p-type intrinsic semiconductor

Intrinsic semiconductors (no dopants): Si, Ge
Extrinsic semiconductors are Si or Ge which are "doped" with small amounts of impurity atoms.

Periodic Table on p. 60
Group # = # of valence electrons. Si, Ge: Group 4
Dopants:

Group 3 elements: B, Al, Ga
- add holes: positive carriers (p-type)
Group 5 elements: P, As, Sb
- add electrons: negative carriers (n-type)
Corrosion

If the zinc coating on galvanized steel is scratched and the steel below it exposed to a corrosive environment, the steel is not attacked. Which of the following mechanisms is responsible for this?

(a) The Zn coating acts as an inhibitor.
(b) The Zn coating acts as the cathode and provides anodic protection.
(c) The Zn coating acts as a sacrificial anode and provides cathodic protection.
(d) The steel becomes positive.

When dissimilar metals are in contact and exposed to an electrolyte, the more anodic material preferentially corrodes.

The anode is oxidized (loses electrons)
The cathode is reduced (gains electrons)
Corrosion

In a galvanic cell consisting of Cu and Al electrodes in an electrolyte

(a) Cu is the anode.
(b) Cu is oxidized.
(c) Al is the cathode.
(d) Al is oxidized.

<table>
<thead>
<tr>
<th>Reaction</th>
<th>$E_o$ (volts)</th>
</tr>
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<tbody>
<tr>
<td>$2\text{Hg} \rightarrow \text{Hg}_2^{2+} + 2\text{e}^-$</td>
<td>-0.788</td>
</tr>
<tr>
<td>$\text{Fe}^{3+} \rightarrow \text{Fe}^{2+} + \text{e}^-$</td>
<td>-0.771</td>
</tr>
<tr>
<td>$4\text{(OH)}^- \rightarrow \text{O}_2 + 2\text{H}_2\text{O} + 4\text{e}^-$</td>
<td>-0.401</td>
</tr>
<tr>
<td>$\text{Cu} \rightarrow \text{Cu}^{2+} + 2\text{e}^-$</td>
<td>-0.337</td>
</tr>
<tr>
<td>$\text{Sn}^{2+} \rightarrow \text{Sn}^{4+} + 2\text{e}^-$</td>
<td>-0.150</td>
</tr>
<tr>
<td>$\text{H}_2 \rightarrow 2\text{H}^+ + 2\text{e}^-$</td>
<td>0.000</td>
</tr>
<tr>
<td>$\text{Pb} \rightarrow \text{Pb}^{2+} + 2\text{e}^-$</td>
<td>+0.126</td>
</tr>
<tr>
<td>$\text{Sn} \rightarrow \text{Sn}^{2+} + 2\text{e}^-$</td>
<td>+0.136</td>
</tr>
<tr>
<td>$\text{Ni} \rightarrow \text{Ni}^{2+} + 2\text{e}^-$</td>
<td>+0.250</td>
</tr>
<tr>
<td>$\text{Co} \rightarrow \text{Co}^{2+} + 2\text{e}^-$</td>
<td>+0.277</td>
</tr>
<tr>
<td>$\text{Cd} \rightarrow \text{Cd}^{2+} + 2\text{e}^-$</td>
<td>+0.403</td>
</tr>
<tr>
<td>$\text{Fe} \rightarrow \text{Fe}^{2+} + 2\text{e}^-$</td>
<td>+0.440</td>
</tr>
<tr>
<td>$\text{Cr} \rightarrow \text{Cr}^{3+} + 3\text{e}^-$</td>
<td>+0.744</td>
</tr>
<tr>
<td>$\text{Zn} \rightarrow \text{Zn}^{2+} + 2\text{e}^-$</td>
<td>+0.763</td>
</tr>
<tr>
<td>$\text{Al} \rightarrow \text{Al}^{3+} + 3\text{e}^-$</td>
<td>+1.662</td>
</tr>
</tbody>
</table>

When dissimilar metals are in contact and exposed to an electrolyte, the more anodic material preferentially corrodes.

The anode is oxidized (loses electrons)
The cathode is reduced (gains electrons)
Copper has a thermal expansion coefficient of \(1.7 \times 10^{-5} \, ^\circ\text{C}^{-1}\). If a copper rod having a length of 50 mm is heated from 25 to 800 °C, its length at 800 °C is most nearly

(a) 50.7 mm  
(b) 50.3 mm  
(c) 49.7 mm  
(d) 49.3 mm

1. Calculate the strain at a \(\Delta T\) of 775 °C.  
2. Calculate the change in length from the strain.  
3. Add the change in length to the original length.
Adding entrained air to concrete

(a) increases compressive strength
(b) increases curing time
(c) decreases workability
(d) increases durability

Water-cement (W/C) ratio is the primary factor affecting the strength of concrete. The figure above shows how W/C expressed as a ratio of weight of water and cement by weight of concrete mix affects the compressive strength of both air-entrained and non-air-entrained concrete.

Water content affects workability. However, an increase in water without a corresponding increase in cement reduces the concrete strength. Superplasticizers are the most typical way to increase workability. Air entrainment is used to improve durability.