Materials

Give me matter, and I will construct a world out of it.

Immanuel Kant

Materials in Manufacturing

- Metals
  - Ferrous – steels and cast iron (¾ of metals used)
  - Nonferrous – aluminum, titanium, nickel...
- Ceramics
  - A compounds of metallic (semi-metallic) and nonmetallic
- Polymers
  - Thermoplastic
  - Thermosetting
  - Elastomers
- Composites – Matrix & Second phases
- Thermomechanical Behavior
  - Elastic, plastic, fatigue, thermal
  - Electrical, Magnetic, Optical, Chemical

Manufacturing Processes

- Process Operation
  - Shaping
  - Property Enhancing
  - Assembly Operation
- Operation
- Operation

Solidification Processes

- Starting material is heated sufficiently to transform it into a liquid or highly plastic state
- Examples: Casting for metals, molding for plastics
Sand Casting

Figure 3.22 Schematic illustration of the sand casting process.

Deformation Processing

- Starting workpart is shaped by application of forces that exceed the yield strength of the material
- Examples: (a) forging, (b) extrusion and etc.

Forging and Extrusion

Figure 3.23 An example of the steps in forging a connecting rod for an internal combustion engine, and the die used.

Particulate Processing

1. Starting materials: powders of metals or ceramics
2. Pressing (to enhance the formability, powder is mixed with liquid or a binder phase)
3. Sintering

Figure 3.24 The extrusion process. (a) Schematic illustration of the forward or direct extrusion process; (b) Examples of cross-sections commonly extruded.
Material Removal Processes

- Excess material removed from the starting workpiece so what remains is the desired geometry
- Machining such as (a) turning, (b) drilling, and (c) milling and grinding and nontraditional processes

Other Processing Operation

- Property Enhancing Processes
  - Heat Treatment: Improve physical properties of the material without changing its shape
  - Alloying
  - Composites
- Surface Processing
  - Cleaning
  - Surface treatment and
  - Coating deposition

Tolerance vs. Surface Roughness

Figure 3.25 Schematic illustration of a typical extruder.

Figure 3.26 A plot of achievable tolerance versus surface roughness for assorted manufacturing operations.
Table 3.8 Commercially available forms of materials.

<table>
<thead>
<tr>
<th>Material</th>
<th>Available forms&lt;sup&gt;a&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td>B, F, I, P, S, T, W</td>
</tr>
<tr>
<td>Ceramics</td>
<td>B, p, s, T</td>
</tr>
<tr>
<td>Copper and brass</td>
<td>B, f, I, P, s, T, W</td>
</tr>
<tr>
<td>Elastomers</td>
<td>b, P, T</td>
</tr>
<tr>
<td>Glass</td>
<td>B, P, s, T, W</td>
</tr>
<tr>
<td>Graphite</td>
<td>B, P, s, T, W</td>
</tr>
<tr>
<td>Magnesium</td>
<td>B, I, P, S, T, w</td>
</tr>
<tr>
<td>Plastics</td>
<td>B, f, P, T, w</td>
</tr>
<tr>
<td>Precious metals</td>
<td>B, F, I, P, t, W</td>
</tr>
<tr>
<td>Steels and stainless steels</td>
<td>B, I, P, S, T, W</td>
</tr>
<tr>
<td>Zinc</td>
<td>F, I, P, W</td>
</tr>
</tbody>
</table>

<sup>a</sup> B=bar and rod; F=foil; I=ingot; P=plate and sheet; S=structural shapes; T=tubing; W=wire. Lowercase letters indicate limited availability. Most of the metals are also available in powder form, including prealloyed powders.

2-2 Statistical Significance of Material Properties

Gaussian or normal distribution

Mean \( \bar{x} = \frac{x_1 + x_2 + \cdots + x_N}{N} = \frac{1}{N} \sum_{i=1}^{N} x_i \)

Standard deviation \( \sigma = \sqrt{\frac{1}{N} \sum_{i=1}^{N} (x_i - \bar{x})^2} \).

UTS for 1000 samples of 1020 steel

the mean stress of 63.42ksi and the standard deviation of 2.594ksi
Stress and Strain Diagram

- **Engineering Stress & Strain**
  - Original Area, $A_o$
  \[ \sigma = \frac{F}{A_o}, \; \varepsilon = \frac{\delta}{L_o} \]

- **True Stress and Strain**
  - Instantaneous Current Area, $A$
  \[ \sigma = \frac{F}{A}, \; \varepsilon = \int_{A_o}^{A} \frac{dl}{l} = \ln \frac{L}{L_o} \]

Characteristics

- Ductile and Brittle
- Perfectly elastic: $\sigma = E\varepsilon$
- Perfectly plastic: $\sigma = Y$
- Elastic and Perfectly Plastic
  - Flow curve: $K = Y$, $n = 0$
- Elastic and Strain hardening
  - Flow curve: $K > Y$, $n > 0$
- Nonlinear
- Temperature-dependent

Figure 3.5 Typical stress-strain curve for a ductile material.

Figure 3.6 Typical stress-strain behavior for ductile metal showing elastic and plastic deformations and yield strength $S_y$.

2-3 Strength and Cold Work
Strength and Cold Work

- Cold working \( \varepsilon = \varepsilon_e + \varepsilon_p \)
- Reduction in area \( R = \frac{A_0 - A_f}{A_0} = 1 - \frac{A_f}{A_0} \)
- Cold Work Factor \( W = \frac{A_0 - A_f}{A_0} \)
- True Stress and Strain in plastic region \( \sigma = \sigma_0 \varepsilon^m \)

At the ultimate point: \( m = \varepsilon_u \)

In plastic Volume stays constant: \( \frac{1}{V_o} = \frac{A_o}{A} \)

\[ \text{Hardness} \]

- For steels with \( 200 < H_B < 450 \)
  \[ S_u = \begin{cases} 0.495H_B & \text{kpsi} \\ 3.41H_B & \text{MPa} \end{cases} \]

- Cast Iron
  \[ S_u = \begin{cases} 0.23H_B - 12.5 & \text{kpsi} \\ 1.58H_B - 86 & \text{MPa} \end{cases} \]

Comparison of Brittle and Ductile Materials

Testing of Brittle Materials

- Brittle Materials deform elastically until fracture
  - Failure occurs at the outer fibers of specimen when tensile strength are exceeded.
  - Cleavage - separation rather than slip occurs along certain crystallographic planes
- Three Point Bend Test
- Four Point Bend Test
- Transverse Rupture Strength, \( TRS = \frac{1.5FL}{bt^2} \)
Impact Properties

- Definition of Impact load
  - The time of application is less than the third of the lowest natural frequency of the part or structure
  - Charpy (more common) and Izod Tests
- Charpy (more common) and Izod Tests

Density of Materials

Figure 3.11 Density for various metals, polymers, and ceramics at room temperature (20°C, 68°F).

Modulus of Elasticity

Figure 3.12 Modulus of elasticity for various metals, polymers, and ceramics at room temperature (20°C, 68°F).
### Table 3.3 Poisson’s ratio for various metals, polymers, and ceramics at room temperature (20°C, 68°F).

<table>
<thead>
<tr>
<th>Material</th>
<th>Poisson’s Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metals</td>
<td></td>
</tr>
<tr>
<td>Aluminum and its alloys&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.33</td>
</tr>
<tr>
<td>Aluminum</td>
<td>0.33</td>
</tr>
<tr>
<td>Brass</td>
<td>0.33</td>
</tr>
<tr>
<td>Bronze</td>
<td>0.33</td>
</tr>
<tr>
<td>Copper</td>
<td>0.33</td>
</tr>
<tr>
<td>Iron</td>
<td>0.26</td>
</tr>
<tr>
<td>Iron, pure</td>
<td>0.20</td>
</tr>
<tr>
<td>Iron, wrought</td>
<td>0.30</td>
</tr>
<tr>
<td>Magnesium alloys</td>
<td>0.33</td>
</tr>
<tr>
<td>Steels</td>
<td>0.30</td>
</tr>
<tr>
<td>Zn alloys</td>
<td>0.27</td>
</tr>
</tbody>
</table>

**Polymers**

- Aetal (polymethylmethacrylate) | 0.40
- Polyethylene, high density | 0.35
- Phenolic formaldehyde | 0.50
- Rubber | 0.50

**Ceramics**

- Alumina (Al₂O₃) | 0.28
- Graphite, high strength | 0.20
- Cemented carbides | 0.19
- Silicon carbide (SiC) | 0.19
- Silicon nitride (Si₃N₄) | 0.26

<sup>a</sup>Structural alloys

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### Poisson’s Ratio

The material characteristic quantity of heat energy given up or taken on when body changes temperature.

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### Linear Thermal Expansion Coefficient

- **Metals**

<table>
<thead>
<tr>
<th>Material</th>
<th>Linear thermal expansion coefficient, α (x 10⁻⁶/°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alloys</td>
<td></td>
</tr>
<tr>
<td>Aluminum</td>
<td>23 x 10⁻⁶</td>
</tr>
<tr>
<td>Alloys</td>
<td></td>
</tr>
<tr>
<td>Brass</td>
<td>24 x 10⁻⁶</td>
</tr>
<tr>
<td>Copper</td>
<td>26 x 10⁻⁶</td>
</tr>
<tr>
<td>Iron</td>
<td>27 x 10⁻⁶</td>
</tr>
<tr>
<td>Iron, pure</td>
<td>28 x 10⁻⁶</td>
</tr>
<tr>
<td>Steel, high speed</td>
<td>29 x 10⁻⁶</td>
</tr>
<tr>
<td>Steel, low speed</td>
<td>30 x 10⁻⁶</td>
</tr>
<tr>
<td>Steel, stainless</td>
<td>31 x 10⁻⁶</td>
</tr>
<tr>
<td>Cast iron</td>
<td>32 x 10⁻⁶</td>
</tr>
</tbody>
</table>

- **Polymers**

<table>
<thead>
<tr>
<th>Material</th>
<th>Linear thermal expansion coefficient, α (x 10⁻⁶/°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nylon</td>
<td>44 x 10⁻⁶</td>
</tr>
<tr>
<td>Polyethylene, high density</td>
<td>45 x 10⁻⁶</td>
</tr>
<tr>
<td>Polyethylene, low density</td>
<td>46 x 10⁻⁶</td>
</tr>
<tr>
<td>Polystyrene, high density</td>
<td>47 x 10⁻⁶</td>
</tr>
<tr>
<td>Polystyrene, low density</td>
<td>48 x 10⁻⁶</td>
</tr>
<tr>
<td>Polypropylene</td>
<td>49 x 10⁻⁶</td>
</tr>
<tr>
<td>PTFE</td>
<td>50 x 10⁻⁶</td>
</tr>
</tbody>
</table>

---

### Specific Heat Capacity

- **Metals**

<table>
<thead>
<tr>
<th>Material</th>
<th>Specific heat capacity, c_p (J/g·°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alloys</td>
<td></td>
</tr>
<tr>
<td>Aluminum</td>
<td>900</td>
</tr>
<tr>
<td>Alloys</td>
<td></td>
</tr>
<tr>
<td>Brass</td>
<td>950</td>
</tr>
<tr>
<td>Copper</td>
<td>980</td>
</tr>
<tr>
<td>Iron</td>
<td>1000</td>
</tr>
<tr>
<td>Iron, pure</td>
<td>1030</td>
</tr>
<tr>
<td>Steel, high speed</td>
<td>1050</td>
</tr>
<tr>
<td>Steel, low speed</td>
<td>1070</td>
</tr>
<tr>
<td>Steel, stainless</td>
<td>1090</td>
</tr>
<tr>
<td>Cast iron</td>
<td>1100</td>
</tr>
</tbody>
</table>

- **Polymers**

<table>
<thead>
<tr>
<th>Material</th>
<th>Specific heat capacity, c_p (J/g·°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nylon</td>
<td>1300</td>
</tr>
<tr>
<td>Polyethylene, high density</td>
<td>1350</td>
</tr>
<tr>
<td>Polyethylene, low density</td>
<td>1400</td>
</tr>
<tr>
<td>Polystyrene, high density</td>
<td>1450</td>
</tr>
<tr>
<td>Polystyrene, low density</td>
<td>1500</td>
</tr>
<tr>
<td>Polypropylene</td>
<td>1550</td>
</tr>
<tr>
<td>PTFE</td>
<td>1600</td>
</tr>
</tbody>
</table>

---

### Figure 3.13 Thermal conductivity for various metals, polymers, and ceramics at room temperature (20°C, 68°F).

- **Thermal Conductivity**

<table>
<thead>
<tr>
<th>Material</th>
<th>Thermal conductivity, k (W/m·°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metals</td>
<td></td>
</tr>
<tr>
<td>Aluminum</td>
<td>125</td>
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<tr>
<td>Alloys</td>
<td></td>
</tr>
<tr>
<td>Brass</td>
<td>125</td>
</tr>
<tr>
<td>Copper</td>
<td>125</td>
</tr>
<tr>
<td>Iron</td>
<td>125</td>
</tr>
<tr>
<td>Iron, pure</td>
<td>125</td>
</tr>
<tr>
<td>Steel, high speed</td>
<td>125</td>
</tr>
<tr>
<td>Steel, low speed</td>
<td>125</td>
</tr>
<tr>
<td>Steel, stainless</td>
<td>125</td>
</tr>
<tr>
<td>Cast iron</td>
<td>125</td>
</tr>
</tbody>
</table>

---

### Figure 3.14 Linear thermal expansion coefficient for various metals, polymers, and ceramics at room temperature (20°C, 68°F).

- **Linear Thermal Expansion Coefficient**

<table>
<thead>
<tr>
<th>Material</th>
<th>Linear thermal expansion coefficient, α (x 10⁻⁶/°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metals</td>
<td></td>
</tr>
<tr>
<td>Aluminum</td>
<td>23 x 10⁻⁶</td>
</tr>
<tr>
<td>Alloys</td>
<td></td>
</tr>
<tr>
<td>Brass</td>
<td>24 x 10⁻⁶</td>
</tr>
<tr>
<td>Copper</td>
<td>26 x 10⁻⁶</td>
</tr>
<tr>
<td>Iron</td>
<td>27 x 10⁻⁶</td>
</tr>
<tr>
<td>Iron, pure</td>
<td>28 x 10⁻⁶</td>
</tr>
<tr>
<td>Steel, high speed</td>
<td>29 x 10⁻⁶</td>
</tr>
<tr>
<td>Steel, low speed</td>
<td>30 x 10⁻⁶</td>
</tr>
<tr>
<td>Steel, stainless</td>
<td>31 x 10⁻⁶</td>
</tr>
<tr>
<td>Cast iron</td>
<td>32 x 10⁻⁶</td>
</tr>
</tbody>
</table>

---

### Figure 3.15 Specific heat capacity for various metals, polymers, and ceramics at room temperature (20°C, 68°F).

- **Specific Heat Capacity**

<table>
<thead>
<tr>
<th>Material</th>
<th>Specific heat capacity, c_p (J/g·°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metals</td>
<td></td>
</tr>
<tr>
<td>Aluminum</td>
<td>900</td>
</tr>
<tr>
<td>Alloys</td>
<td></td>
</tr>
<tr>
<td>Brass</td>
<td>950</td>
</tr>
<tr>
<td>Copper</td>
<td>980</td>
</tr>
<tr>
<td>Iron</td>
<td>1000</td>
</tr>
<tr>
<td>Iron, pure</td>
<td>1030</td>
</tr>
<tr>
<td>Steel, high speed</td>
<td>1050</td>
</tr>
<tr>
<td>Steel, low speed</td>
<td>1070</td>
</tr>
<tr>
<td>Steel, stainless</td>
<td>1090</td>
</tr>
<tr>
<td>Cast iron</td>
<td>1100</td>
</tr>
</tbody>
</table>

---
Table 3.6 Specific heat capacity for various metals, polymers, and ceramics at room temperature (20°C, 68°F).

<table>
<thead>
<tr>
<th>Material</th>
<th>Specific heat capacity, ( C_p )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>kJ/kg°C</td>
</tr>
<tr>
<td>Metals</td>
<td></td>
</tr>
<tr>
<td>Aluminum and its alloys</td>
<td>0.9</td>
</tr>
<tr>
<td>Aluminum tin</td>
<td>0.96</td>
</tr>
<tr>
<td>Babbitt, lead-based white metal</td>
<td>0.15</td>
</tr>
<tr>
<td>Babbitt, tin-based white metal</td>
<td>0.21</td>
</tr>
<tr>
<td>Brasses</td>
<td>0.39</td>
</tr>
<tr>
<td>Bronze</td>
<td>0.38</td>
</tr>
<tr>
<td>Copper</td>
<td>0.38</td>
</tr>
<tr>
<td>Copper lead</td>
<td>0.32</td>
</tr>
<tr>
<td>Iron, cast</td>
<td>0.42</td>
</tr>
<tr>
<td>Iron, porous</td>
<td>0.46</td>
</tr>
<tr>
<td>Iron, wrought</td>
<td>0.46</td>
</tr>
<tr>
<td>Magnesium alloys</td>
<td>1.0</td>
</tr>
<tr>
<td>Steels(^a)</td>
<td>0.45</td>
</tr>
<tr>
<td>Zinc alloys</td>
<td>0.4</td>
</tr>
<tr>
<td>Polymers</td>
<td></td>
</tr>
<tr>
<td>Thermoplastics</td>
<td>1.4</td>
</tr>
<tr>
<td>Rubber, natural</td>
<td>2.0</td>
</tr>
<tr>
<td>Ceramics</td>
<td></td>
</tr>
<tr>
<td>Graphite</td>
<td>0.8</td>
</tr>
<tr>
<td>Ceramicized Carborundum</td>
<td>0.7</td>
</tr>
</tbody>
</table>

\(^a\)Aluminum bronze up to 0.48 kJ/kg°C (0.12 Btu/lbm²°F).
\(^b\)Rising up to 0.55 kJ/kg°C (0.13 Btu/lbm²°F) at 200°C (392°F).

\[ Q = C_p m \Delta T \]

where \( Q \) = quantity of Heat, J

\( C_p \) = specific heat of material, \(J/kg°C\)

\( m \) = mass of body, kg

\( \Delta T \) = temperature change, °C

Specific Elastic Modulus

Figure 3.17 Modulus of elasticity plotted against density.

Specific Strength

Figure 3.18 Strength plotted against density.

Modulus of Elasticity vs. Strength

Figure 3.19 Modulus of elasticity plotted against strength.
Wear Constant

\[ W = K_A p \]

where \( K_A \) = Archard Wear Constant (removed volume/distance)

\( A \) = Area of Contact, \( m^2 \)

\( p \) = limiting pressure, \( Pa \)

**Figure 3.20** Archard wear constant plotted against limiting pressure.

**Modulus of Elasticity vs. Cost**

**Objectives**

- Learn common engineering materials
- Understand why each behave as it is
2.5 Engineering Materials

- Metals – metallic bonds,
  - Crystalline structure (BCC, FCC or HCP)
  - High thermal and electrical conductivity
- Ceramics – Ionic and/or covalent bonds
  - High hardness, Stiffness, brittleness
- Polymers – Secondary bonds (van der Waals)
  - Glassy and/or crystalline
  - Thermoplastic – a long chain of mer in a linear structure
  - Thermosetting – a rigid three dimensional structure
  - Elastomer – large molecules with coiled structures
- Composites

Crystalline Structure

- Macroscopic Structures - Crystalline and Noncrystalline
- Crystalline structure
  - Unit cell – Face Center Cubic (FCC), Body Center Cubic (BCC), Hexagonal Closed Pack (HCP)
  - Allotropic – Fe (BCC @18°C to FCC @912°C to BCC @1400°C)
  - Imperfection
    - Point defect – vacancy, iron-pair vacancy, interstitialcy, displaced ion
    - Line defect – edge and screw dislocation
    - Surface defect – grain boundary
Deformation

- Elastic deformation – recoverable small atomic movement
- Plastic deformation - critical resolve shear stress; slip plane
  - Slip – slip plane and direction
    - Slip system – a combination of the densest packed plane and the densest packed direction
    - BCC (48), FCC(12), HCP(3)
    - A slip plane containing a dislocation requires less shear stress.
  - Dislocation motion reduces the slip force.
- Twinning – Magnesium, Zinc, Tin (HCP)

Plastic deformation in a perfect crystal

\[
\tau = \tau_{\text{max}} \sin \left( \frac{2\pi}{b} \right)
\]

\[
\frac{d\tau}{dx} = \frac{2\pi}{b} \tau_{\text{max}} \cos \left( \frac{2\pi}{b} \right)
\]

\[
\left( \frac{d\tau}{dx} \right)_{x=0} = \frac{2\pi}{b} \tau_{\text{max}}
\]

- distance between slip plane
- distance between equilibrium position

\[
\frac{dx}{dx} = \frac{dx}{dy} \frac{dy}{dx} = \frac{G}{a}
\]

Because \( \gamma = \frac{x}{a} \)

Therefore, \( \tau_{\text{max}} = \frac{Gb}{2a} = \frac{G}{2\pi} \)

**Reason for discrepancy:** mainly Dislocation

Deformation of a crystal structure

Original Lattice  Elastic Deformation  Plastic Deformation

Dislocations

Edge Dislocation

Screw Dislocation

Strain Hardening due to dislocation interactions
Effect of Dislocation in Deformation

Deformation is easier with dislocation: a lower stress
Because slip occurs consecutively rather than simultaneously

Work hardening (strain hardening)

- Dislocation can entangle and interfere with other dislocations or impede by barriers such as grain boundaries, impurities and inclusions in the material.
- Entanglement and impediments increase the shear stress required for slip.
- **Grains and Grain Boundaries**
  - Empirical Hall-Petch Relation:
    \[ Y = Y_0 + kd^{-1/2} \]
    where \( Y \) = a basic yield stress, \( d \) = grain diameter
  - Smaller the grain sizes, higher the Yield strength.
- Texture – development of anisotropy during plastic deformation
- Creep - grain boundary sliding at high temperature
- Hydrogen embrittlement - attacks Grain Boundary

Noncrystalline (Amorphous)

- Glass, plastics (mixture) and rubbers
- Amorphous metals – fast cooling from liquid to solid
- Two important features
  - Absence of a long range order
  - Differences in melting and thermal expansion

Volume changes in a pure metal

![Volume changes in a pure metal diagram](image)
**Phase Diagram**

From Kalpakjian & Schmidt

**Ferrous Materials**

**HEAT TREATMENT OF METALS**

1. Annealing
2. Martensite Formation in Steel
3. Precipitation Hardening
4. Surface Hardening
5. Heat Treatment Methods
Introduction

- Heat Treatment: Heating and cooling procedure to manipulate structural changes (affect materials properties) for mostly metals.
- Also for glass ceramics, tempered glass, powder metals and ceramics
- Before shaping
  - To soften a metal for forming
- After forming
  - To relieve strain hardening
- Final finish
  - To achieve final strength and hardness.

Principal Heat Treatment

- Annealing
- Martensite formation in steel
- Tempering of martensite
- Precipitation hardening
- Surface hardening

1. Annealing

- **Heating** the metal to a high enough temperature for a certain time and **cooling** slowly.
- Reasons
  - To reduce hardness and brittleness
  - To alter microstructure
  - To soften metal for improved machinability or formability
  - To recrystallize the cold worked metals
  - To relieve residual stresses

Annealing

- Full annealing – heating ferrous metals into the austenite region and slow cooling to form coarse pearlite.
- Normalizing – similar to full annealing but cooling at faster rate (e.g.: in air) to form fine pearlite (higher strength and hardness).
- Process anneal – annealing to allow additional deformation processes.
- Anneal – similar except no subsequent deformation process
- Recovery anneal – retain most of strain hardening but toughness improved.
- Stress-relief annealing – to relieve residual stress.
2. Martensitic Transformation

- Martensite - Body Centered Tetragonal
  - Nonequilibrium transformation of austenite under conditions of rapid cooling.
  - The extreme hardness results from the lattice strain created by carbon atoms trapped in the BCT structure, thus providing a barrier to slip
- Bainite – fine needle-like structure consisting of ferrite and fine carbide regions.
- Time-Temperature-Transformation (TTT) diagram
### TTT Curve for .8%C steels

- **Austenite, \( \gamma \)**
- **Coarse Pearlite, \( P \)**
- **Fine Pearlite, \( P \)**
- **Bainite, \( B \)**
- **Martensite, \( M \)**

- \( M_s \)
- \( M_f \)

**Heat Treatment Process**

- **Austenizing**
  - Heating the steels to a high enough temperature until they convert to at least partial austenite.

- **Quenching**
  - Media: brine (salt water), fresh water, oil, and air
  - Dependency on mass and geometry

- **Tempering**
  - Heat treatment to reduce brittleness on martensite (tempered martensite)
  - Precipitation of fine carbide particle
  - BCT \( \rightarrow \) BCC

### Hardenability

- **Jominy end-quench test**

- **Cooling rate at 700°C (°C/s)**

**3. Precipitation Hardening**

- **Strengthening Heat treatment**
  - Solution Treatment: Alloy is heated to a temperature \( T_s \) above the solvus line into the alpha phase region and held for a period sufficient to dissolve the beta phase

- **Quenching**
  - To room temperature to create a supersaturated solid solution

- **Precipitation treatment**
  - Cause precipitation of fine particles of the beta phase at \( T_p \)
  - **Aging**
    - Natural aging: aging at room temperature
    - Artificial aging: aging at elevated temperature
  - **Overaging (similar to annealing)**
Precipitation Hardening

4. Surface Hardening

- Thermochemical process to alter the surface
- Carburizing
  - Pack carburizing – with carbonaceous materials in a chamber (thickness of 0.6-3.8mm)
  - Gas carburizing - hydrocarbon fuel in a chamber (thickness of 0.13-0.75mm)
  - Liquid carburizing – molten salt bath with chemicals (thickness of 0.13-0.75mm)
- Chromizing – requires higher temperature and longer treatment
  - Not only harder and wear resistant but also corrosion resistant

4. Surface Hardening

- Nitriding (Steels with 0.85-1.5% Al & 5% or more Cr, which form fine nitride compounds particles) (thickness of 0.025-0.05mm)
  - Gas Nitriding – heated in an ammonia atmosphere at 510°C
  - Liquid Nitriding – dipped into molten cyanide salt bath at 510°C
- Carbonitriding – heating in a furnace of carbon & ammonia (thickness of 0.07-0.5mm)
- Borizing – on tool steels, nickel- & cobalt based alloys and Cast iron
  - High hardness and Low friction

Surface Hardening

- Selective Surface Hardening
  - Flame Hardening
  - Induction Heating – high frequency alternating current
  - High Frequency Resistance Heating
  - Electron Beam (EB) Heating - Electron beam focused onto a small area, resulting in rapid heat buildup
    - Involves localized surface hardening of steel austenitizing in less than a second
    - With removal of the beam, heated area is immediately quenched to surrounding metal
    - Disadvantage: For best results, it is performed in a vacuum, so production rates are slow
  - Laser (Light amplification by stimulated emission of radiation) Beam (LB) Heating - High-density beam of coherent light focused onto a small area along a defined path
    - With removal of the beam, heated area is immediately quenched to surrounding metal
    - Laser beams do not require a vacuum to achieve best results

Induction heating
5. Heat Treatment Methods

- Furnace
  - Fuel Fired
  - Electric Heating
  - Batch and Continuous furnace
  - Atmospheric control furnaces
    - Desirable in conventional heat treatment to avoid excessive oxidation or decarburization
    - Include C and/or N rich environments for diffusion into work surface
  - Vacuum furnaces
    - Radiant energy is used to heat the workparts
    - Disadvantage: time needed each cycle to draw vacuum