Notes on Chapter 3: Structure and Manufacturing Properties

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Based on notes by Prof. Junlan Wang
Crystal Structures of Metals

Metals are characterized by the metallic bond

- A complete outer shell can not be formed by electron sharing or transfer
- Positive ions are surrounded by wandering, universally shared valence electrons
- Electrons are highly mobile
- High electrical and thermal conductivity
- Bond strength, material strength, and melting point vary
- Positive ions can move within the structure without the breaking of discrete bonds

Metals solidify into crystalline structures

Some metals can exist in the solid state in two or more lattice forms (allotrophic or polymorphic)

The change from one lattice form to another is called an allotropic transformation.
Common Crystal Structures for Metals

FIGURE 3.2 The **body-centered cubic (bcc)** crystal structure: (a) hard-ball model; (b) unit cell; and (c) single crystal with many unit cells. Common bcc metals include chromium, titanium, and tungsten. *Source: After W.G. Moffatt.*

**High strength, moderate ductility**

FIGURE 3.3 The **face-centered cubic (fcc)** crystal structure: (a) hard-ball model; (b) unit cell; and (c) single crystal with many unit cells. Common fcc metals include aluminum, copper, gold and silver. *Source: After W.G. Moffatt.*

**Low strength, high ductility**

FIGURE 3.4 The **hexagonal close-packed (hcp)** crystal structure: (a) unit cell; and (b) single crystal with many unit cells. Common hcp metals include zinc, magnesium and cobalt. *Source: After W.G. Moffatt.*

**Low ductility, Brittle**
Plastic Deformation in Crystals

Permanent deformation of a single crystal under a tensile load. The highlighted grid of atoms emphasizes the motion within the lattice. (a) Deformation by **slip**. The $b/a$ ratio influences the magnitude of the shear stress required so that the slip planes tend to align themselves in the direction of pulling. (b) Deformation by **twinning** of a “twin” around a line of symmetry subjected to shear. Note that the tensile load results in a shear stress.
Crystal Defects

Point

Linear

Planar (GB, phase boundary)

Volume or bulk

FIGURE 3.9  Various defects in a single-crystal lattice. Source: After W.G. Moffatt.

FIGURE 3.10  (a) Edge dislocation, a linear defect at the edge of an extra plane of atoms. (b) Screw dislocation, a helical defect in a three-dimensional lattice of atoms. Screw dislocations are so named because the atomic planes form a spiral ramp.
Movement of an edge dislocation across the crystal lattice under a shear stress. Dislocations help explain why the actual strength of metals is much lower than that predicted by atomic theory.
Density of Dislocation and Strain Hardening

Very pure single crystals: $0 - 10^3 \text{ mm}^{-2}$
Annealed single crystals: $10^5 - 10^6$
Annealed polycrystals: $10^7 - 10^8$
Highly cold-worked metals: $10^{11} - 10^{12}$

strain-hardening: increase of overall strength due to dislocation entanglement and impediments by barriers (GB, impurities, inclusions, etc).
Development of Grain Structure

A small particle of solid forms from the liquid, as the metal solidifies.

Lattice structure that forms is characteristic of a given material.

Metal solidifies as atoms attach themselves to the small particle (nucleation and growth).

Basic crystalline unit is called a unit cell and is repeated throughout the material.

Grains are small continuous volumes of solid.

Surfaces that divide grains are called grain boundaries.

**FIGURE 3.12** Schematic illustration of the various stages during solidification of molten metal. Each small square represents a unit cell. (a) Nucleation of crystals at random sites in the molten metal. Note that the crystallographic orientation of each site is different. (b) and (c) Growth of crystals as solidification continues. (d) Solidified metal.
Grains

Smallest unit in a metal that can be observed by a light microscope

Grain structure impacts mechanical and physical properties

- Hall-Petch Equation

\[ Y = Y_i + k d^{-1/2} \]

Grain size number is important for a design engineer

- ASTM grain size specification
  - \( N = 2^{n-1} \)
  - \( N \) is the number of grains per square inch at 100X
Summary

Crystal structures of Metals

- Metallic bonding
- Three crystal lattices
  - FCC, BCC, HCP
- Ideal shear and tensile strength of metals

Plastic deformation of metals

- Slip vs twinning
- Mechanisms of strain hardening

Grain formation during solidification

- Grain size characterization
Manufacturing Properties of Metals
Outline

Polycrystalline metals

- Tensile strength, GB effect, plastic deformation

Cold, hot, warm working and recrystallization

Fracture and Failure of metals

Physical and chemical properties

Categories of metals and alloys

- Ferrous, Nonferrous, Superalloys, Refractory, others
Tensile Stress in Polycrystalline Material

FIGURE 3.13 Variation of tensile stress across a polycrystalline metal specimen subjected to tension. Note that the strength exhibited by each grain depends on its orientation.
Grain Boundary Effect

Interfere with dislocation movement

Grain boundary sliding → creep

Grain boundary embrittlement

Corrosion

FIGURE 3.14 Embrittlement of copper by lead and bismuth at 350°C (660°F). Embrittlement has important effects on the strength, ductility, and toughness of materials. Source: After W. Rostoker.
Plastic Deformation

Deformation of grain

Increasing strength with increasing deformation

Anisotropy (texture)
- Preferred orientation
- Mechanical fibering
  - Alignment of impurities, inclusions, voids

FIGURE 3.15 Plastic deformation of idealized (equiaxed) grains in a specimen subjected to compression, such as is done in rolling or forging of metals: (a) before deformation; and (b) after deformation. Note the alignment of grain boundaries along a horizontal direction.
Effect of Recovery, Recrystallization and Grain Growth

**Recovery**
- Stress relieve in highly deformed region

**Recrystallization**
- Formation of equi-axed, stress-free grains
- 0.3-0.5 $T_m$
- Decrease dislocation density
- Lowers metal strength, increase ductility
- Depends on prior cold work

**Grain Growth**
- Adverse effect on mechanical properties
- Orange-peel effect (rough surface)

*FIGURE 3.17* Schematic illustration of the effects of recovery, recrystallization, and grain growth on mechanical properties and shape and size of grains. Note the formation of new grains during recrystallization. *Source: After G.*
Recrystallization vs Prior Cold Work

Under same cold work, less time with increasing temperature

More prior cold work, lower temperature for recrystallization

Higher amount of deformation, smaller resulting grain size during recrystallization

Anisotropy due to preferred orientation persists during recrystallization; requires higher temperature to remove

**FIGURE 3.18** Variation of strength and hardness with recrystallization temperature, time, and prior cold work. Note that the more a metal is cold worked, the less time it takes to recrystallize, because of the higher stored elastic energy.

**FIGURE 3.19** The effect of prior cold work and critical elongation (strain) on the recrystallized grain size of alpha brass.
Orange peel effect

FIGURE 3.20 Surface roughness on the cylindrical surface of an aluminum specimen subjected to compression. Source: A. Mulc and S. Kalpakjian.
Hot working: above recrystallization temperature
Cold working: below recrystallization temperature
Warm working: intermediate temperature

<table>
<thead>
<tr>
<th>Process</th>
<th>$T/T_m$</th>
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<td>Cold working</td>
<td>$&lt; 0.3$</td>
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<tr>
<td>Warm working</td>
<td>0.3 to 0.5</td>
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<tr>
<td>Hot working</td>
<td>$&gt; 0.6$</td>
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TABLE 3.2 Homologous Temperature Ranges for Various Processes.

Homologous Temperature
Cold, Warm, Hot Working

Hot worked product:
- Less dimensional accuracy
- Uneven thermal expansion/contraction
- Rougher surface appearance and finish
- Oxidation layer
Two types of Failure: Fracture (brittle, ductile) and Buckling

FIGURE 3.22 Schematic illustration of the types of fracture in tension: (a) brittle fracture in polycrystalline metals; (b) shear fracture in ductile single crystals (see also Fig. 3.5a); (c) ductile cup-and-cone fracture in polycrystalline metals (see also Fig. 2.2); (d) ductile fracture in polycrystalline metals, with 100% reduction of area.

FIGURE 3.21 Schematic illustration of types of failure in materials: (a) necking and fracture of ductile materials; (b) buckling of ductile materials under a compressive load; (c) fracture of brittle materials in compression; (d) cracking on the barreled surface of ductile materials in compression. (See also Fig. 6.1b)
Ductile Fracture Surface

Fibrous pattern with dimples

FIGURE 3.23  Surface of ductile fracture in low-carbon steel, showing dimples. Fracture is usually initiated at impurities, inclusions, or preexisting voids in the metal. Source: K.-H. Habig and D. Klaffke. Photo courtesy of BAM, Berlin, Germany.
Figure 3.24 Sequence of events in necking and fracture of a tensile-test specimen: (a) early stage of necking; (b) small voids begin to form within the necked region; (c) voids coalesce, producing an internal crack; (d) rest of cross-section begins to fail at the periphery by shearing; (e) final fracture surfaces, known as cup-(top fracture surface) and-cone (bottom surface) fracture.
Effect of Inclusions on Void Nucleation

Bond strength between inclusion and matrix

Hardness of inclusion

FIGURE 3.25 Schematic illustration of the deformation of soft and hard inclusions and their effect on void formation in plastic deformation. Note that hard inclusions, because they do not comply with the overall deformation of the ductile matrix, can cause voids.
Brittle and Intergranular Fracture

Little or no plastic deformation

Happens along a crystallographic plane (cleavage plane) where normal stress is highest

BCC and hcp metals

FIGURE 3.28 Typical fracture surface of steel that failed in a brittle manner. The fracture path is granular (through the grains). Compare this with the ductile fracture surface shown in Figure 3.23.

Source: Courtesy of Packer Engineering.

FIGURE 3.29 Intergranular fracture, at two magnifications. Grains and grain boundaries are visible in this micrograph. The fracture path is along the grain boundaries. Source: Courtesy of Packer Engineering.
Defects, Fracture Mode & Fatigue Fracture

Effect of defect

\[ \sigma \propto \frac{1}{\sqrt{\text{Crack length}}} \]

Fracture mode

- Fatigue fracture
  - Characteristics: bench mark
  - Improving fatigue strength
    - Introduce compressive residual stress
    - Surface hardening
    - Fine surface finishing
    - Materials free of inclusions, voids, impurities

**FIGURE 3.30** Three modes of fracture. Mode I has been studied extensively, because it is the most commonly observed in engineering structures and components. Mode II is rare. Mode III is the tearing process; examples include opening a pop-top can, FIGURE 3.31. Typical fatigue fracture surface on metals, showing **beach marks**. Most components in machines
Physics Properties of Materials

**Density**: depends on atomic weight, atomic radius and packing (little dependence on alloying elements)

**Melting point**: strong dependence on alloying elements

**Specific heat**: little dependence on alloying elements

**Thermal conductivity**: significant effect from alloying elements

**Thermal expansion coefficient (CTE)**: \( \propto \frac{1}{T_m} \), minor alloying effect

**Electrical and magnetic properties**: strong alloying effect

- Electrical conductivity, resistivity, piezoelectricity
- Magnetostriction

**Oxidation and corrosion resistance**
# Physical Properties of Materials

<table>
<thead>
<tr>
<th>METAL</th>
<th>Density (kg/m³)</th>
<th>Melting Point (°C)</th>
<th>Specific Heat (J/kg K)</th>
<th>Thermal Conductivity (W/m K)</th>
<th>Coefficient of Thermal Expansion (μm/m°C)</th>
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**NONMETALLIC**

| Ceramics                | 2300-5500       | —                   | 750-950                 | 10-17                         | 5.5-13.5                                 |
| Glasses                 | 2400-2700       | 580-1540            | 500-850                 | 0.6-1.7                       | 4.6-70                                   |
| Graphite                | 1900-2200       | —                   | 840                     | 5-10                          | 7.86                                     |
| Plastics                | 900-2000        | 110-330             | 1000-2000               | 0.1-0.4                       | 72-200                                   |
| Wood                    | 400-700         | —                   | 2400-2800               | 0.1-0.4                       | 2-60                                     |
General Properties of Ferrous Alloys
Alloys with iron as base metal

Carbon and alloy steels
- Carbon steels
- Alloy steels

Stainless steels
- High corrosion resistance, high strength and ductility, high Cr content

Tool and die steels
- High speed, hot-worked, cold-worked, shock resisting

FIGURE 3.33 Effect of carbon content on the mechanical properties of carbon steel.
General Properties of Non-ferrous Metals

Al and Al alloys
- High strength-to-weight ratio, resistance to corrosion, high thermal and electrical conductivity, non toxicity, reflectivity, appearance
- Alloy elements: copper, zinc, magnesium, silicon, manganese and lithium
- Wrought aluminum alloys (4 figure number), cast (5 figure number)

Mg and Mg alloys
- Lightest engineering metal available
- Light-weight applications, minimize inertial forces
- Low strength – use as alloys with other metals
- Potential fire hazard
Non-ferrous Metals and Alloys (cont.)

Cu and Cu alloys

- Superior conductor of electricity and heat, resistance to corrosion
- Easy processing: machining, forming, casting, joining..
- Most common Cu alloys: Brass (Cu+Zn), Bronze (Cu+Sn)

Ni and Ni alloys

- High strength, toughness, corrosion resistance
- Important alloying element in stainless steel and Ni-based alloys
- High temperature applications
Super alloys: Heat-resistance or high-temperature alloys

- Iron base, Ni base, Co base
- Service temperature > 1000 °C

Ti and Ti alloys

- High strength-to-weight ratio
- High corrosion resistance under room and high temperature
- Alloying elements: Al, V, Mo, Mg, … for strength, workability
Refractory Metals

- High melting point metals: Mo, Nb, W ($T_m = 3410 \, ^\circ C$), Ta ($T_m = 3000 \, ^\circ C$)

Others

- Low melting point metals – Pb, Zn, Sn
- Precious metals: Au, Ag, Pt

Special Metals and Alloys

- SMA: shape-memory alloys, eg., Ni(55%)/Ti (45%) alloy
- Amorphous alloys ~ Metallic glass (Fe, Ni, Cr with C, P, B, Si)
- Nanomaterials

- Metal foams
Summary

GB effect of polycrystalline metals

Recovery, recrystallization, grain growth

- Cold, hot, warm working

Failure and fracture

- Ductile vs brittle

Physical properties and their importance

General properties and applications of most common Ferrous and Non-ferrous metals and alloys

- Strength, toughness, hardness, ductility, creep, resistance to temperature and oxidation