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Fundamentals of Metals

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Module 1: Structure of Metals

Learning Objectives

By the end of this section, you will be able to:

- **Identify** the five primary types of atomic bonding and their defining characteristics.
- **Distinguish** between the three most common lattice structures (BCC, FCC, and HCP) and their impact on material properties.
- **Evaluate** how grain size, orientation, and polymorphism influence the dimensional stability and strength of engineering metals.
- **Identify** microscopic and macroscopic defects and explain the mechanical process of slip in crystalline structures.

Executive Summary: The performance of engineering materials is fundamentally dictated by their atomic arrangement. From the primary chemical bonds to the microscopic lattice structures and unavoidable defects, every level of a material's architecture determines its suitability for high-stress environments like nuclear facilities.

Atomic Bonding and States of Matter

Matter exists in three states—solid, liquid, and gas—determined by atomic or molecular interactions. In engineering, solids are the primary focus. These are held together by forces arising from the **valence electrons** in the outer shells of atoms.

The Five Primary Bonding Types

The nature of the attractive forces defines the bond type and the material's resulting conductivity and strength.

- **Ionic Bond:** Electrons are wholly transferred from one atom to another; elements are held by the attraction of **opposite polarity**.
- **Covalent Bond:** Atoms **share electrons** to complete their outer shells.
- **Metallic Bond:** Electrons are **free to move** throughout the metal, creating a "sea of electrons" that allows for high conductivity.
- **Molecular (van der Waals) Bond:** Weak attractions caused by temporary shifts in electron orbits.
- **Hydrogen Bond:** Similar to molecular bonds, occurring due to the ease with which hydrogen atoms displace their charge.

Table 1: Material and Bond Examples

Material	Bond Type
Sodium Chloride	Ionic
Diamond	Covalent
Sodium	Metallic
Solid H2	Molecular
Ice	Hydrogen

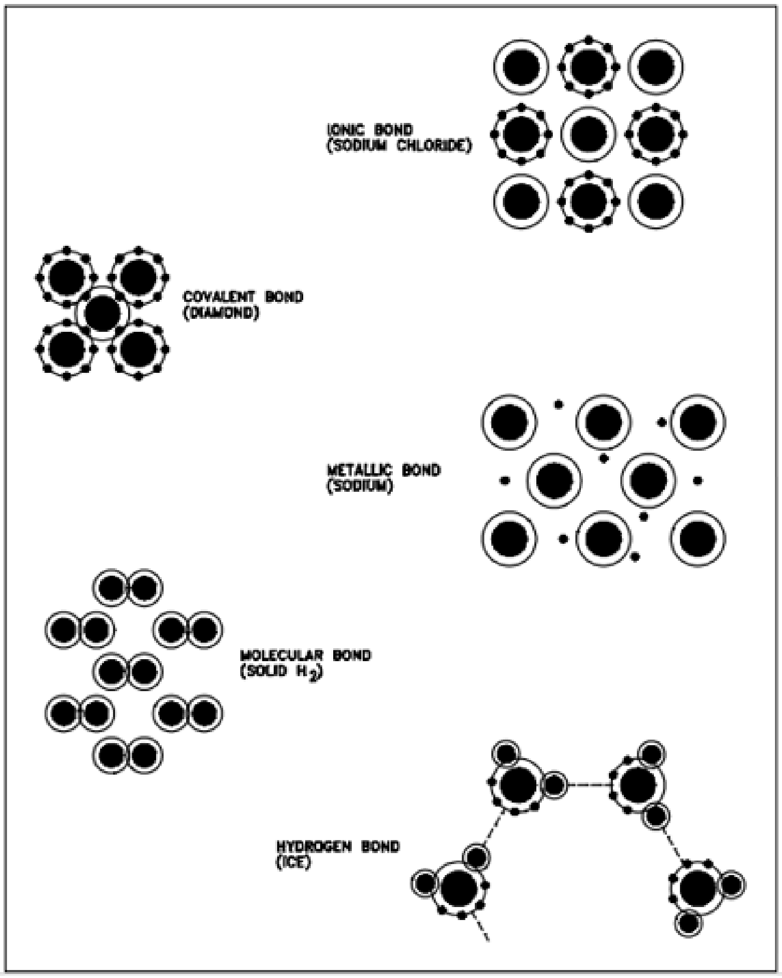

Figure 1: Bonding Types

Order in Microstructures: Lattices

Solids are classified as either **Amorphous** (no regular arrangement, no sharp melting point) or **Crystalline** (regular, repeating three-dimensional arrays called **lattices**).

Common Lattice Types

There are three patterns most common to engineering metals:

1. **Body-Centered Cubic (BCC):** Eight atoms at corners, one at the body center.
2. **Face-Centered Cubic (FCC):** Eight atoms at corners, one at the center of each of the six faces.
3. **Hexagonal Close-Packed (HCP):** Two hexagonal layers with a three-atom "close-packed" middle layer.

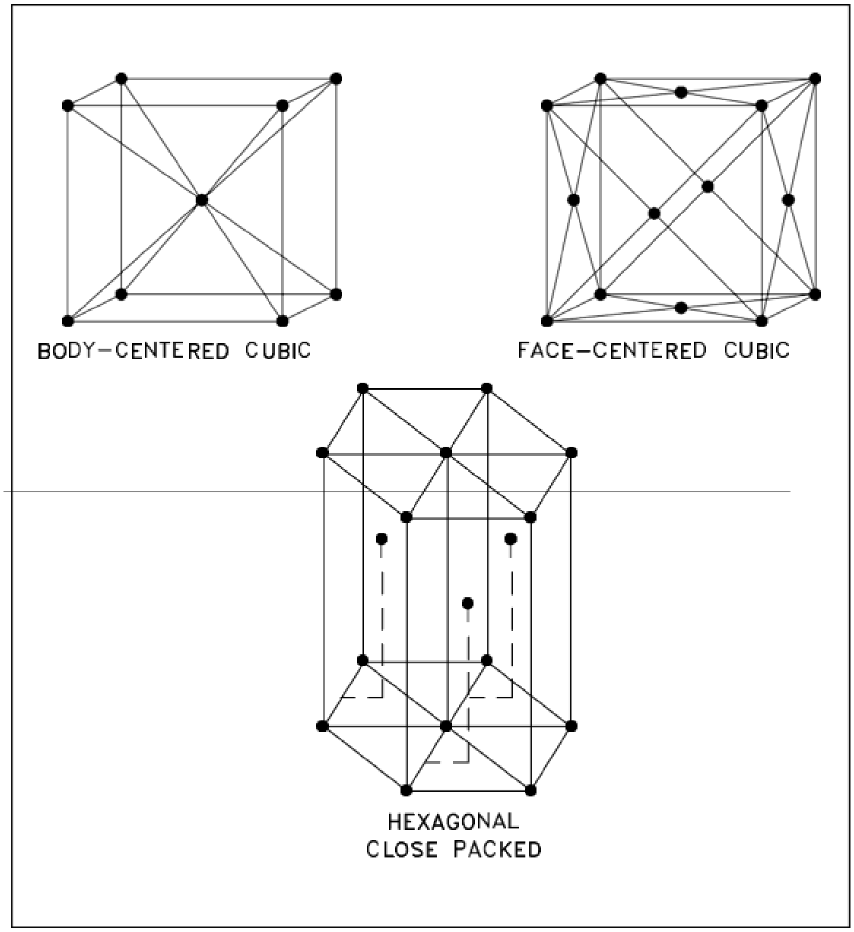

Figure 2: Common Lattice Types

Mechanical Property Correlation

- **BCC Metals:** High strength, low ductility (e.g., Ferrite, Chromium, Tungsten).
- **FCC Metals:** Lower strength, high ductility (e.g., Austenite, Aluminum, Copper).
- **HCP Metals:** Low ductility (e.g., Zirconium, Magnesium).

Grain Structure and Boundaries

A **grain** is a region of continuous crystal lattice. **Grain boundaries** are the regions of misfit (1-3 atom diameters wide) between grains of different orientations.

- **Small Grain Size:** Increases tensile strength and ductility.
- **Large Grain Size:** Improves resistance to **creep** (permanent deformation over time under constant stress).

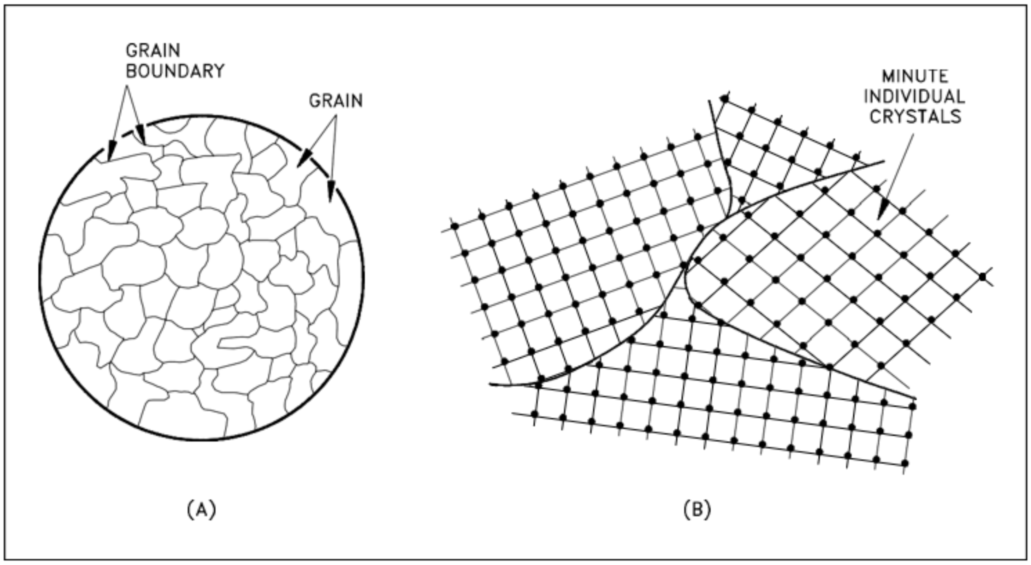

Figure 3: Grains and Boundaries (a) Microscopic (b) Atomic

Grain Orientation

- **Random Orientation:** Obtained via cross-rolling; properties are uniform in all directions.
- **Preferred Orientation:** Grains align with the rolling direction. In materials like **uranium**, this can cause catastrophic dimensional changes during reactor operation.

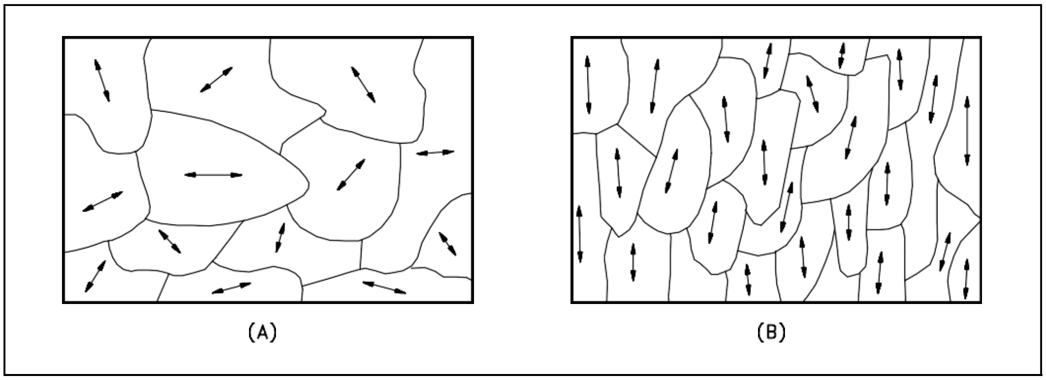

Figure 4: Grain Orientation (a) Random (b) Preferred

Polymorphism

Polymorphism is the ability of a metal to exist in multiple crystalline forms depending on temperature.

Uranium Phases

Uranium exists in three phases, but the **Alpha Phase** (Room Temp to 663°C) is problematic because it expands non-uniformly (shrinks in one axis, expands in others). This **anisotropic expansion** prevents pure uranium from being used as fuel.

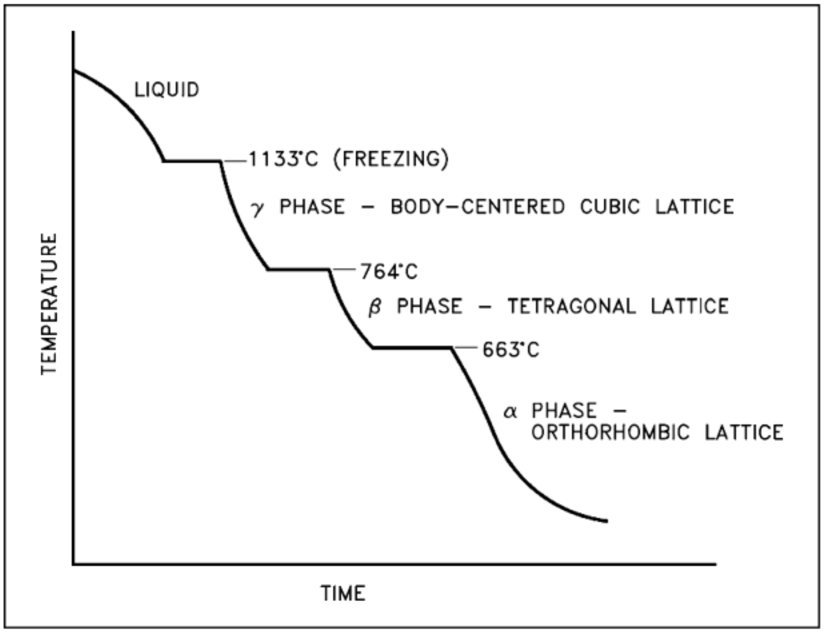

Figure 5: Cooling Curve for Unalloyed Uranium

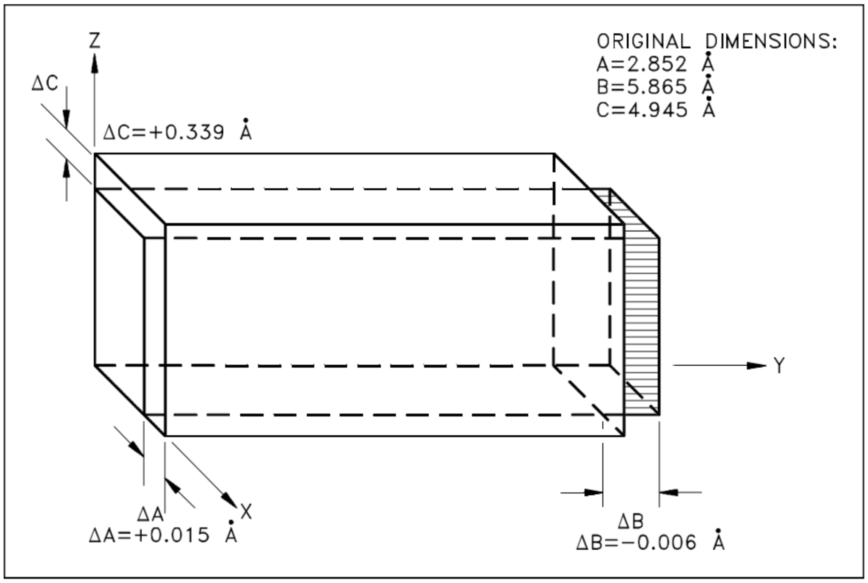

Figure 6: Change in Alpha Uranium Upon Heating From 0 to 300°C