Heat Treatment Fundamentals and Processes

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1. Introduction

Heat treatment is the controlled process of heating to a specified temperature, holding that temperature for a specified duration (soaking), and then cooling at a specified rate. The process is typically performed on a metal or alloy to alter its microstructure and phase constituents and thus improve mechanical properties. It may also be performed to increase ductility in order to improve formability and facilitate hot or cold deformation (working) processes such as forging, drawing, extruding, etc. to make mill products. Heat treatment is commonly associated with steels, but it is also conducted on aluminum (Al) alloys, titanium (Ti) alloys, nickel-based superalloys, and other alloy systems. Heat treatment adds significant value that is estimated at ~$15B annually to manufactured metal products. It is a necessary part of the manufacturing process to produce parts for many industries including aircraft, aerospace, automotive, defense, semiconductors, power generation, petrochemical, and heavy equipment. Almost all metal mechanical components are heat treated to achieve either their final properties or shape or both. The magnitude of change in properties depends on the alloy system and a specific alloy's composition. For example, the strength and hardness of steels can be increased significantly depending on the alloying elements and their concentration combined with a heat treatment process. But some alloy systems may not respond to heat treatment with significant increases in strength and hardness if the concentration of alloying elements is too low. On the other hand, almost any metal or alloy can be softened to facilitate deformation if the heat treatment duration is sufficiently long enough. In general, the heat treatment processes to alter microstructure and properties are broadly categorized as (i) annealing, (ii) quench and tempering, (iii) case hardening, and (iv) precipitation hardening. These processes are all performed at elevated temperatures but while the alloy is still in the solid-state. The above categories can be further sub-divided based on purpose, heat treatment temperature, and heat treatment technology. For instance, annealing heat treatment includes stress relief annealing, full annealing, process annealing, and several others. In a second example, normalizing and spheroidizing are special categories of annealing heat treatments for steels. Several methods of case hardening exist including carburizing, nitriding, flame hardening, and induction hardening.

Many engineering handbooks and texts have been published by professional societies such as ASM International or the Heat Treating Society that provide diagrams, cooling curves, data, and micrographs on many ferrous alloys, aluminum (Al) alloys, and other alloy systems. Engineers require knowledge of heat treatment and its effects during the design process in order to ensure that parts meet engineering specifications and design requirements. Since metal and alloys are used in many engineering applications, this knowledge and understanding is useful for civil and structural engineers, mechanical engineers, materials and metallurgical engineers, chemical engineers, and electrical engineers.

In this course, the heat treatment fundamentals and processes of metals are presented. The course first reviews important underlying concepts including metal crystal structures, defects, alloying, diffusion, and phase diagrams that are needed to understand heat treatment processes. Heat treatment of metals and alloys is performed while they are in the solid-state. Changes to their crystal structure, composition, alloying elements, and diffusion are an integral part of almost all heat treatment processes. Equilibrium phase diagrams are a visual map to link temperature, composition, phases, and microstructure. It provides valuable information on solid-state transformations relevant for heat treatment processes of long duration. In the second part, the course provides an overview of different types of heat treatment processes and applications that are important in different industries including annealing processes, quench and tempering, case hardening processes, and precipitation hardening. The effect of heat treatment on microstructure and mechanical properties is examined in each section. The course also discusses relevant equipment for heat treatment processes. Examples are provided for important engineering alloys including steel, copper, aluminum, titanium, and others throughout the discussion.

2. Concepts in Crystal Structures, Defects, Alloying, and Diffusion

2.1. Crystal Structures

Almost all solid metals or alloys are crystalline in nature, where the atoms are arranged in three-dimensional (3-D) periodic arrays over long atomic distances. This long-range order forms when a metal or alloy solidifies during cooling from the liquid state. Ceramics and certain polymers can also form crystalline structures. Materials that do not possess this long-range atomic order are denoted as non-crystalline or amorphous and an example is bulk metallic glass (BMG). Extremely rapid cooling typically forms this category of metals. The properties of conventional engineering metals and alloys are partly dependent on their crystal structure including their spacing, arrangement, and defects. For instance, the theoretical density of a metal is related to its crystal structure, atomic radius, and atomic mass as shown in Example 1 below. In a second illustration, introducing elemental impurities such as in alloying or introducing lattice defects during cold working can significantly alter the mechanical properties of metals. In metals and alloys, the crystal structures are simple, but they can be significantly more complex in ceramics. In context of crystal structures, the periodic arrays are referred to as lattices and consist of unit cells, which are the smallest repeating entity in the lattice. The points in a unit cell and thus lattice represent centers of atoms, which for describing crystal structures are thought of as hard, solid spheres with fixed locations and diameters that is referred to as the hard sphere model. If a perfect lattice is extended in three dimensions, it forms a single crystal with a specific crystallographic orientation. Single crystals may be fabricated for engineering applications and a common example is nickel-based alloy turbine blades. In this application, the advantage of a single crystal is that it gives better creep properties at operating temperatures. However, most alloys consist of many grains (polycrystalline) and thus at a longer length-scale, the microstructure of consists of numerous grains each of which has a lattice structure with a certain crystallographic orientation. The boundaries between grains are locations where the lattice structure is discontinuous and is referred to as a grain boundary.

Metals can be grouped according to their unit cell configurations based upon their 3D geometry. The shape of the unit cell is defined by six degrees-of-freedom in an x, y, z, coordinate system that are referred to as lattice parameters. These parameters are the three edge lengths a, b, and c, and three inter-axial angles, α, β, and γ. In this framework, there are seven crystal systems, which are cubic, tetragonal, hexagonal, orthorhombic, rhombohedral, monoclinic, and triclinic, as depicted in Figure 1. Several of these systems can be further sub-divided based on their symmetry and thus there are 14 different lattice types referred to as Bravais lattices.

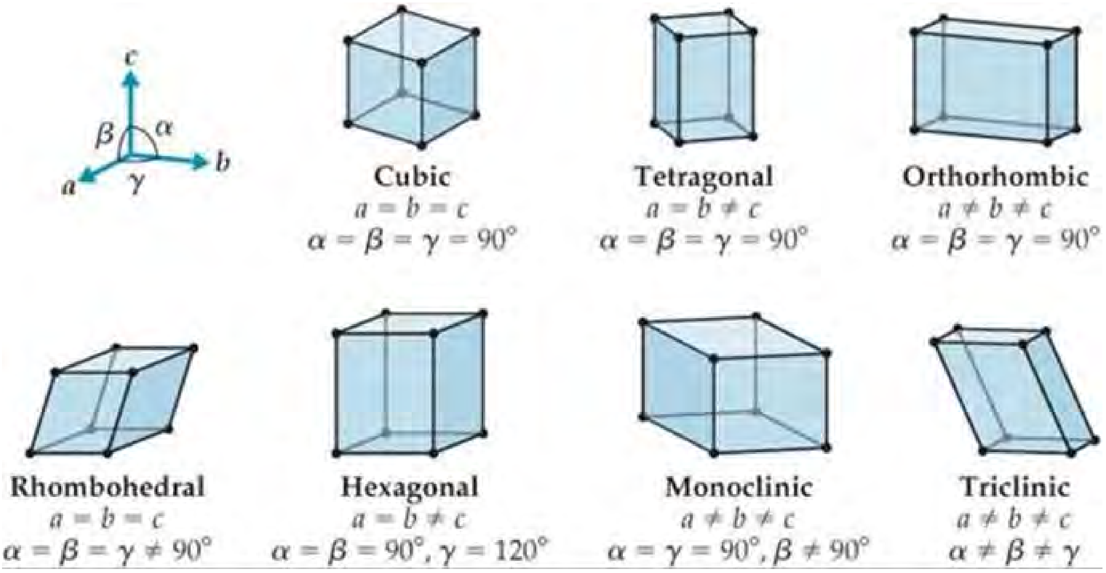

Figure 1. The seven crystal systems and the relationship between the six lattice parameters of edge length, a, b, and c, and inter-axial angles, α, β, and γ.

The simplest and most important crystal system in the context of engineering alloys and heat treatment is the cubic system where the lattice parameters are related by $a = b = c$ and $\alpha = \beta = \gamma = 90°$. The cubic lattice system can be further subdivided into three distinct types of Bravais lattices based on symmetry and the number of atoms in the unit cell. These are simple cubic (SC), body-centered cubic (BCC), and face-centered cubic (FCC). Many common engineering alloys have either BCC or FCC crystal structures. For example, at room temperature and equilibrium, iron (Fe) and low-alloy steels have BCC crystal structures. On the other hand, aluminum (Al) alloys, nickel-based (Ni-based) superalloys, and copper (Cu) alloys have FCC crystal structures. Iron has the important property that it changes crystal structure as the temperature is increased from room or ambient temperature. The ability of an element to exist in more than one crystal state is referred to as **allotropy**. At room temperature and equilibrium, iron has a BCC structure and is known as alpha iron (α-Fe) or alpha ferrite. During slow heating and at higher temperatures it undergoes a solid-state transformation to a metastable FCC crystal structure and is known as gamma iron (γ-Fe) or austenite, and at even higher temperature it undergoes yet another solid-state transformation to a metastable BCC crystal structure known as delta iron (δ-Fe) or delta ferrite. These transformations and the allotropic nature of iron and steels are very important from the perspective of heat treatment as discussed below.

Example 1

The theoretical density of a pure metal can be calculated by the following equation:

$$\rho = \frac{nA}{V_C N_A}, \qquad (1)$$

where *n* is the number of atoms in a unit cell that is related to crystal structure, *A* is the atomic mass of the element, V_C is the volume of the unit cell that is function of the elements' crystal structure and atomic radius, and N_A is Avogadro's number. For aluminum (Al), the crystal structure is face-centered cubic (FCC), the atomic radius is 0.143 nm, and the atomic mass is 26.98 g/mol. In the case of a FCC crystal structure, there are four atoms/unit cell and the volume of the unit cell is given by $16r^3\sqrt{2}$. By substitution,

$$\rho = \frac{nA_{Al}}{\left(16r^3\sqrt{2}\right)N_A} = \frac{\left(4 \text{ atoms/unit cell}\right)\left(26.98 \text{ g/mol}\right)}{\left(16\left(1.43 \times 10^{-8}\,cm\right)^3\sqrt{2}\,/\,\text{unit cell}\right)\left(6.023 \times 10^{23}\,\text{atoms/mol}\right)}$$

$$\rho = 2.708 \text{ g/cm}^3$$

which compares closely with the experimentally measured density of 2.71 g/cm^3.

The second most significant crystal system in context of engineering alloys and heat treatment is the hexagonal system where the lattice parameters are related by $a = b \neq c$ and $\alpha = \beta = 90°$ and $\gamma = 120°$. Titanium and its alloys also exhibit allotropy similar to steels. The ability to heat-treat and variability of microstructure and simultaneously mechanical properties of titanium alloys are largely a function of its allotropic nature. At room temperature and equilibrium, titanium (Ti), has a hexagonal close-packed (HCP) structure. During slow heating and at temperatures greater than the beta transus temperature titanium undergoes a solid-state transformation to a metastable BCC crystal structure. Other engineering metals that have a HCP crystal structure are magnesium (Mg) and zirconium (Zr). Zirconium exhibits allotropy whereas magnesium does not. Table 1 lists some important engineering metals and their equilibrium (room temperature) crystal structures, atomic mass, atomic radii, and measured density.

Table 1. Table of Selected Engineering Metals

Metal	**Crystal Structure (20 °C)**	**Atomic Mass**	**Atomic Radii**	**Measured Density (20 °C)**
		(amu)	**(nm)**	**(g/cm^3)**
Aluminum	FCC	26.98	0.143	2.71
Copper	FCC	63.55	0.128	8.94
Iron	BCC	55.85	0.124	7.87
Magnesium	HCP	24.31	0.160	1.74
Nickel	FCC	58.69	0.125	8.90
Titanium	HCP	47.88	0.145	4.51
Zirconium	HCP	91.22	0.159	6.51

Figure 2 illustrates the hard sphere models for the BCC, FCC, and HCP unit cells with numbers of atoms per unit cell and atomic packing factor (APF). The edge length, a, is $4r/\sqrt{3}$ for the BCC crystal structure, it is $2r/\sqrt{2}$ for the FCC crystal structure, and is $2r$ for the HCP crystal structure. The c/a ratio is 1.6333 for the HCP crystal structure. In the BCC crystal structure, there are 1/8 of an atom at each corner and one full atom in the center for two total atoms per unit cell. In the FCC crystal structure, there are 1/8 of an atom at each corner and ½ of an atom at each face for a total of four atoms per unit cell. In the HCP crystal structure, there are 1/6 of an atom at each corner, ½ of an atom at the end faces, and three atoms in the center for a total of six atoms. This figure illustrates that the three types of unit cells are not completely solid but have free or interstitial space. This is defined by the atomic packing factor (APF), which is ratio of the volume of atoms in the hard sphere model to volume of the unit cell and is given by

$$\text{APF} = \frac{\text{Volume of Atoms in Unit Cell}}{\text{Volume of Unit Cell}} \qquad (2)$$

In the case of hard spheres having the same diameter, the maximum APF for the BCC crystal structure is 0.68, for the FCC structure it is 0.74, and for th re, it is also 0.74. Example 2 illustrates the calculation of A . The concept of the space occupied by th r solid solutions or alloying, diff

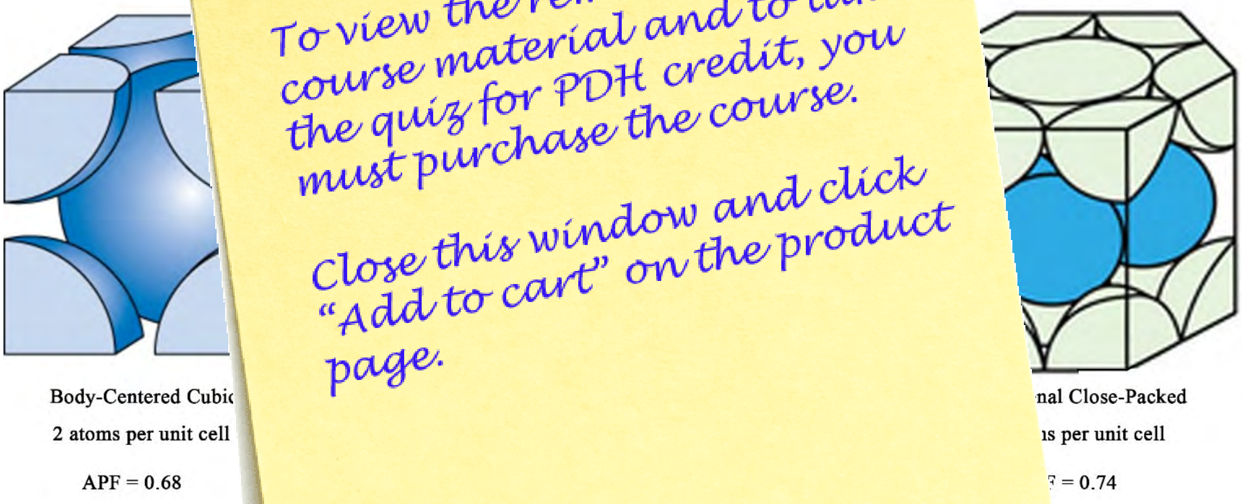

Figure 2. Schemati the body-centered cubic (BCC, face-centered cubic (FCC), and close-packed (HCP) crystal structures. The number of atoms per unit cell and atomic packing factors (APF) are given in the figure.