# Steels and Stainless Steels

An Online Continuing Education Course for Engineers

**Course Number: MA-4005**

**Credit: 4 Hours / 4 PDH / 4 CPD**

# Steels and Stainless Steels

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## 1. Introduction

Steels and stainless steels are the most commonly used types of engineering alloys. Steels consist of iron and additions of small concentrations of carbon and other alloying elements to obtain the desired mechanical properties. In general, steels and stainless steels can be alloyed, heat-treated, and processed to achieve a wide range of strength, ductility, and toughness. Steels' versatility combined with its comparatively low cost to make, process and form, make it the most important engineering alloy. There are generally two main categories of steels that are carbon steels and tool steels. Carbon steels can be further sub-divided into plain carbon steels and alloy steels. Stainless steels are ferrous alloys with the addition of ~11 wt.% - 12 wt.% chromium and other elements such as nickel and molybdenum to increase corrosion resistance. This property leads to stainless steels' use in demanding environments where corrosion and oxidation may cause mechanical property degradation.

The raw materials and recycled scrap to make steels and stainless steels are generally abundant and inexpensive. Over 1.6 billion metric tons of carbon steel, tool steel, and stainless steel are produced annually, which is a significantly greater quantity than any other engineering alloy. In general steels and stainless steels are available in many forms and shapes including sheet, plate, bar, rod, channel, etc. Steels and stainless steels may be drawn, extruded, rolled, cast, forged and 3D printed. Hence, steels and stainless steels are used in many industries including automotive, defense, power generation, petrochemical, heavy equipment and machinery, refineries, ships, railways, weapons, buildings, construction, power tools, household appliances, commercial kitchens, food processing, and surgical instruments.

Many engineers require knowledge of steel and stainless steel fundamentals, properties, microstructures, and applications to ensure that a component or structure does not fail. For example, civil and structural engineers must select steels with sufficiently high strength for buildings so that deformation does not occur. A mechanical engineer may decide between stainless steels with different strengths and corrosion resistance for use in a petrochemical process. A biomedical engineer may decide on different types of stainless steels for a surgical instrument. Materials engineers and manufacturing engineers must understand how to make steels and stainless steels and then heat-treat components and fabricate structures.

This course first reviews important fundamental aspects of steels and stainless steels, including crystallographic structures, alloying, impurities, and common alloying elements. The second part of the course covers iron-carbon and iron-chromium phase diagrams, including details on the most common phases that form in steels and stainless steels. This section of the course covers both equilibrium and non-equilibrium phases and microstructures. We also discuss the topics of sensitization and stabilization related to the undesirable presence of chromium carbides in stainless steels. In the third part of the course, we discuss different types of heat treatment processes relevant to many steels and stainless steels. We cover annealing, quenching and tempering, and precipitation hardening. In this section, we also discuss the hardenability of steels and stainless steels. In the fourth part of the course, we discuss categories of carbon steels, tool steels and stainless steels and their mechanical properties and applications. We also discuss carbon steel, tool steel, and stainless steel numbering systems in this section. Examples are provided throughout the discussion.

## 2. Steel and Stainless Steel Fundamentals

### *2.1. Crystal Structures*

In steels and stainless steels, the crystal structures are simple. In general, metals and alloys 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, $\alpha$, $\beta$, and $\gamma$. 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.

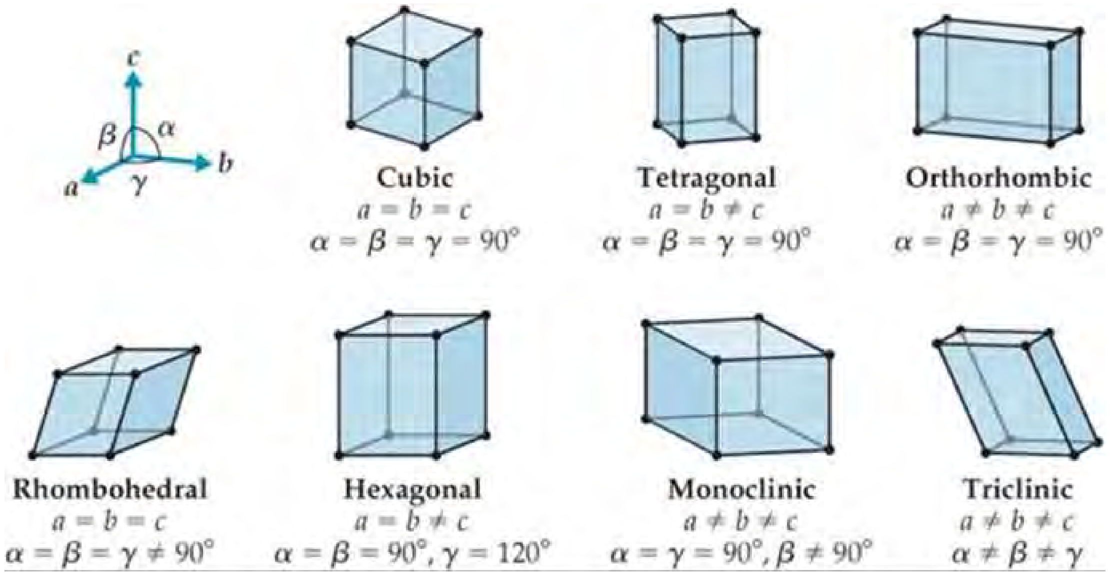

**Figure 1.** The seven crystal systems and the relationship between the six lattice parameters of edge length, $a$, $b$, and $c$, and inter-axial angles, $\alpha$, $\beta$, and $\gamma$.

The most important crystal system in the context of steels and stainless steels 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). Of these three, both the BCC and FCC crystal structures are important for steels and stainless steels. The second most important crystal system for steels and stainless steels is the tetragonal system where the lattice parameters are related by $a = b \neq c$ and $\alpha = \beta = \gamma = 90°$. This crystal structure system is essentially an elongated cube. The tetragonal system can be further sub-divided into primitive tetragonal and body-centered tetragonal (BCT). The BCT crystal structure is important for steels and stainless steels.

The crystallographic structures of steels and stainless steels are based upon that of iron. Iron has the important property that it changes crystal structure as the temperature is increased from the room or ambient temperature. The crystal structure can also depend on the rate of cooling from an elevated 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 crystal structure and is known as alpha iron ($\alpha$-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 ($\gamma$-Fe) or austenite. At even higher temperature, iron undergoes yet another solid-state transformation to a metastable BCC crystal structure known as delta iron ($\delta$-Fe) or delta ferrite. Steels and stainless can also exist in a metastable BCT crystal structure, which is referred to as martensite. Martensite forms due to a displacive transformation with no diffusion of the iron or carbon atoms during very rapid cooling from elevated temperatures. These transformations and the allotropic nature of iron are very important from the perspective of alloying, heat treatment, and altering mechanical properties. It is this property that facilitates the many different types of steels and stainless steels with a broad range of physical and mechanical properties. In turn, this makes steels and stainless steels one of the most useful engineering alloys.

The steel or stainless steel crystal structure also dictates the free space between atoms, which is referred to as the interstitial space. Figure 2 illustrates the hard sphere models for the BCC and FCC 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, and it is $2r/\sqrt{2}$ for the FCC 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. This figure illustrates that the two 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 the ratio of the volume of atoms in the hard sphere model to the volume of the unit cell and is given by

$$\mathrm{APF} = \frac{\text{Volume of Atoms in Unit Cell}}{\text{Volume of Unit Cell}} \qquad (1)$$

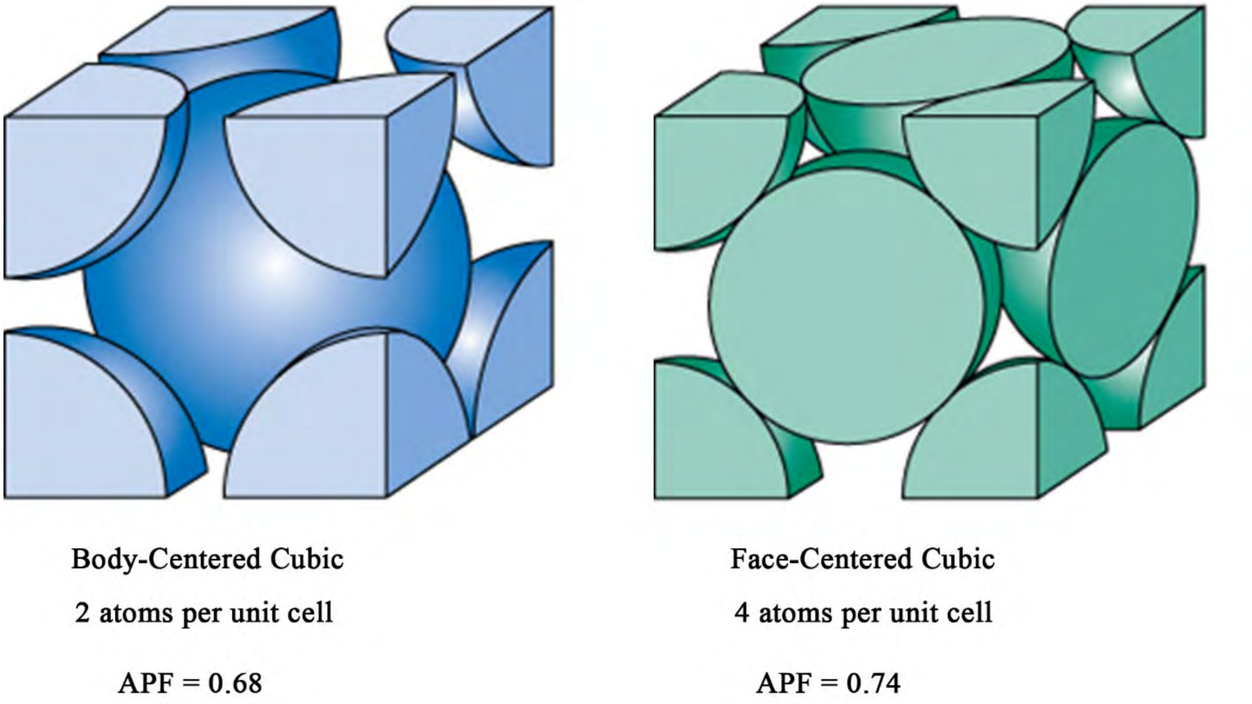

**Figure 2.** Schematics of the hard sphere models for the body-centered cubic (BCC) and face-centered cubic (FCC) crystal structures. The number of atoms per unit cell and atomic packing factors (APF) is given in the figure.

In the case of hard spheres having the same diameter, the maximum APF for the BCC crystal structure is 0.68, and for the FCC structure, it is 0.74. The APF of the BCT crystal structure depends on the ratio of the long edge length-to-short edge length or *c*/*a*. Example Problem 1 illustrates the calculation of APF for the BCC crystal structure. The concept of space occupied by the host atoms and also interstitial space is an important concept for steels and stainless steels. Pure iron is very soft and ductile. However, adding very small quantities of carbon makes steel, which is harder and not as ductile as pure iron. The carbon added to pure iron occupies the interstitial spaces. These spaces are slightly larger in the FCC crystal structure compared to the BCC crystal structure, and thus the amount of carbon that can be in solid solution is influenced by heat treatment and the allotropy property of iron.

## Example Problem 1

The atomic packing factor (APF) for a BCC structure, such as iron at room temperature, can be calculated by equation (1):

$$\text{APF} = \frac{\text{Volume of Atoms in Unit C}}{\text{V}}$$

Where the volum … sphere volume $V_s$, and the volume of the unit … e are two atoms per unit cell in a BCC crystal st … $r$ is the atomic radius. The volume of the unit c … hich is $4r/\sqrt{3}$ for an FCC crystal structure. By

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$$\text{APF} = \frac{V_s}{V_c} = \quad \frac{}{3\sqrt{3}} r^3$$

$$\text{APF} = 0.68.$$