METALLURGY FOR INSPECTION PERSONNEL
PRESENTED BY

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ASNT NDT LEVEL III
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WHAT IS STEEL?

Steel is an alloy of Iron and other elements, including Carbon. When carbon is the primary alloying element, its content in the steel is between 0.002% and 2.1% by weight. The following elements are always present in steel: Carbon, Manganese, Phosphorous, Sulfur, Silicon, and traces of Oxygen, Nitrogen and Aluminum.

Alloying elements intentionally added to modify the characteristics of steel include: Manganese, Nickel, Chromium, Molybdenum, Boron, Titanium, Vanadium and Niobium.
Alloy?

- An alloy is a metallic solid solution composed of two or more elements.

- An alloy will contain one or more of the three:
  - a solid solution of the elements (a single phase)
  - a mixture of metallic phases (two or more solutions)
  - an intermetallic compound with no distinct boundary between the phases.

- Solid solution alloys give a single solid phase microstructure, while partial solutions give two or more phases that may or may not be homogeneous in distribution, depending on the thermal (heat treatment) history of the material.

- An intermetallic compound will have another alloy or pure metal embedded within another pure metal. Alloys are used as their properties are superior to those of the pure component elements.
CAST IRON

- Alloys with a higher than 2.1% carbon (depending on other element content and possibly on processing) are known as Cast Iron.

- Because they are not malleable even when hot, they can be worked only by casting, and they have lower melting point and good castability.

- Steel is also distinguishable from wrought iron, which can contain a small amount of carbon, but it is included in the form of slag inclusions.
CLASSIFICATION OF STEELS

- **Steel Grades**: used to classify various steels by their composition and physical properties have been developed by a number of standards organizations.

- Steel specified by purpose of use (application) and mechanical properties.

- Steel specified by chemical composition.

- To inhibit corrosion, at least 11% chromium is added to steel so that a hard oxide forms on the metal surface; this is known as stainless steel.
Iron is found in the Earth's crust only in the form of an ore, usually an iron oxide, such as Magnetite, Hematite etc. Iron is extracted from Iron Ore by removing the oxygen and combining the ore with a preferred chemical partner such as carbon.
IRON & STEEL MAKING

BASIC RAW MATERIAL

- IRON ORE ( Oxides of Iron )
- CARBON ( COKE )
- LIME STONE
BLAST FURNACE

Blast Furnace
Produces molten pig iron from iron ore.
Blast Furnace

- 0.5 inch thick steel shell
- Refractory lining 8 to 24 inches
- 80 to 100 feet diameter
- 400 to 500 feet high
- Operation for 5 to 6 years
- Maintenance 8 to 12 months
- Steel plant has 5 to 6 furnaces running and 1 under maintenance
Raw Material (Charge) in the Blast Furnace

- Iron ore (Oxides of Iron)
  Hematite ($\text{Fe}_2\text{O}_3$) or Magnetite ($\text{Fe}_3\text{O}_4$)
  Impurities (Sulphur, Silica & Phosphorous) associated with iron ore

- Coke (Carbon)

- Limestone (Flux)

- Hot air (1000°C)
Reactions in the Blast Furnace

- \( C + O_2 = CO_2 + \text{Heat} \)
- \( CO_2 + C = 2CO \)
- \( CaCO_3 = CaO + CO_2 \)
- \( 3Fe_2O_3 + CO = CO_2 + 2Fe_3O_4 \)
- \( Fe_3O_4 + CO = CO_2 + 3FeO \)
- \( FeO + CO = CO_2 + Fe \) or
- \( FeO + C = CO + Fe \) (Pig Iron)
- \( FeS + CaO + C = CaS + FeO + CO \) (Slag)
- \( CaO + SiO_2 = CaSiO_3 \)
<table>
<thead>
<tr>
<th>Element</th>
<th>Composition</th>
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<tbody>
<tr>
<td>Iron (Fe)</td>
<td>= 93.5 - 95.0%</td>
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<tr>
<td>Silicon (Si)</td>
<td>= 0.30 - 0.90%</td>
</tr>
<tr>
<td>Sulfur (S)</td>
<td>= 0.025 - 0.050%</td>
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<tr>
<td>Manganese (Mn)</td>
<td>= 0.55 - 0.75%</td>
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<tr>
<td>Phosphorus (P)</td>
<td>= 0.03 - 0.09%</td>
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<tr>
<td>Titanium (Ti)</td>
<td>= 0.02 - 0.06%</td>
</tr>
<tr>
<td>Carbon (C)</td>
<td>= 4.1 - 4.4%</td>
</tr>
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Distinction between an Impurity & an Alloying Element.

- **Impurity**: Is something the presence of that element will be responsible for deterioration in the properties of the material in which it is present. e.g. S & P in steel.

- **Alloying Element**: Is the element the presence of which will enhance the properties of the material in which it is present. e.g. Mn, Si, Cr & Ni in steel.
Steel Making

- Conversion of Pig Iron into Steel: Processes
- Bessemer converter
- Electric Arc Furnace
Bessemer Converter
Construction

- 0.5 inch thick steel shell
- Refractory lining (acidic / basic)
- Mounted on trunnions for tilting
- Nozzles for hot oxygen at bottom
Charge

- Liquid Pig Iron

- Alloying Elements (on reaching required carbon content)
BASIC OXYGEN STEEL MAKING PROCESS (BOP)

- A process for converting pig iron from a blast furnace into steel.
- The molten pig iron is loaded into a refractory-lined tilting furnace (Bessemer converter) at about 1250°C.
- Oxygen is blown into the furnace from the base and spiegel is added to introduce the correct amount of carbon.
- Impurities (especially silicon, phosphorus, and manganese) are removed by the converter lining to form a slag.
- Finally, the furnace is tilted so that the molten steel can be poured off.
Process

- Oxygen oxidizes impurities Sulfur & Phosphorous.
- Oxygen oxidizes excess carbon content.
- Addition of alloying elements.
- Chemical analysis.
Electric Arc Furnace

- Melting of either Pig Iron blocks, direct reduced iron or scrap called charge in the electric arc furnace by striking an arc between a charge and graphite electrodes.
Construction

- Spherical hearth and cylindrical shell of 0.5 inch thick steel
- Refractory lining (resin bonded magnesia-carbon bricks)
- Mounted on trunnions for tilting
- Water-cooled dome-shaped swinging roof
Typical Electric Arc Furnace

- Power cables
- Graphite electrodes
- Scrap steel
- Refractory lining
Process

- Scrap charging
- Melting
- Sampling and chemical analysis of the melt
- Oxidizing slag formation
- Oxidation of C, P, Mn, Si, Al.
- Sampling and temperature measurement
- De-slagging
- Basic slag formation
- Deoxidizing ("killing")
- Alloying
- Tapping the steel
- Refractory lining maintenance.
Charging: Scrap, Direct reduced iron, Pig Iron blocks

The scrap is charged commonly from the furnace top. The roof with the electrodes is swung aside before the scrap charging.
Melting :

Melting process starts at low voltage (short arc) between the electrodes and the scrap. The arc during this period is unstable.

In order to improve the arc stability small pieces of the scrap are placed in the upper layer of the charge. The electrodes descend melting the charge and penetrating into the scrap forming bores. The molten metal flows down to the furnace bottom.

When the electrodes reach the liquid bath the arc becomes stable and the voltage may be increased (long arc). The electrodes are lifting together with the melt level. Most of scrap (85%) melt during this period.

Temperature of the arc reaches 6300°F (3500°C).
Oxidizing stage

At this stage excessive carbon, phosphorous, silicon and manganese oxidize. The process is similar to that in Basic Oxygen furnace.

Basic oxidizing slag composed of lime (CaO) and iron ore (FeO) is used during the oxidizing period.

Gaseous oxygen may be blown into the melt for additional oxidizing.

Iron oxide causes increase of Oxygen content in the molten steel.
Oxygen dissolved in the melt oxidizes carbon, phosphorous, silicon and manganese.

Carbon monoxide partially burns in the atmosphere: The formed oxides are absorbed by the slag. CO bubbles floating up through the melt result in refining of the steel from non-metallic inclusions and hydrogen removal.

Gaseous products CO and CO$_2$ are removed by the exhausting system.

The oxidizing slag enriched with phosphorous and other oxides formed during this period is removed from the furnace to a slag pot (de-slagging).
Reducing stage

New slag composed mainly of lime (CaO), CaF2 (as slag fluidizer) is added at this stage for formation of basic reducing conditions.

The function of this slag is refining of the steel from sulfur and absorption of oxides, formed as a result of deoxidation ("killing").

The excessive oxygen dissolved in the melt during oxidizing period is removed by metallic deoxidizers Mn, Si, Al.

Basic reducing slag is favorable for desulfurization.

Oxide and sulfide non-metallic inclusions are absorbed by the slag.
Alloying elements (Cr, Ni, Mo, V, etc.) are added after deoxidation.

In many cases the processes of “killing” (deoxidation), desulfurization, alloying and final heating are performed outside of the furnace - Ladle refining.
Ladle Furnace (LF)

- Molten steel in a ladle may be treated (refined) in a device called Ladle Furnace (LF).

Molten steel treated in Ladle Furnace is covered by a layer of desulfurizing slag. During the treatment process argon is blown through the bottom porous plug providing continuous metal stirring. Stirring results in distribution of heat produced by the arcs, chemical homogenization and desulfurization of the steel by the slag.

Alloying elements may be added through the addition hopper.

If deep desulfurization is required active desulfurizing agents Ca, Mg, CaSi are injected into the melt through the injection lance or in form of cored wire. Besides refining operations Ladle Furnace (LF) may serve as a buffer station before Continuous casting.
Ladle Refining (ladle metallurgy, secondary refining)

- Ladle refining is post steel making technological operations, performed in the ladle prior to casting with the purposes of desulfurization, degassing, temperature and chemical homogenization, deoxidation and others.
- Ladle refining may be carried out at atmospheric pressure, at vacuum, may involve heating, gas purging and stirring.
- Sulfur refining (desulfurization) in the ladle metallurgy is performed by addition of fluxes (CaO, CaF$_2$ and others) into the ladle and stirring the steel together with the slag, absorbing sulfur.
- In the production of high quality steel the operation of vacuum treatment in ladle is widely used.
According to the degree of de-oxidation Carbon steels may be subdivided into three groups:

- Killed steels
- Semi-killed steels
- Rimmed steels
Killed steels - completely deoxidized steels, solidification of which does not cause formation of carbon monoxide (CO). Ingots and castings of killed steel have homogeneous structure and no gas porosity (blowholes).
Semi-killed steels - incompletely deoxidized steels containing some amount of excess oxygen, which forms carbon monoxide during last stages of solidification.
Rimmed steels - partially deoxidized or non-deoxidized low carbon steels evolving sufficient amount of carbon monoxide during solidification. Ingots of rimmed steels are characterized by good surface quality and considerable quantity of blowholes.
Types of Pouring

- Bottom pouring (up-hill)
- Top pouring (down-hill)
Figure 6: Ingot casting
Ingot Casting

A: Cavity formation.
B: Rimmed ingot in big-end-down mold.
C: Killed-steel ingot in big-end-up mold.
Continuous Casting
Advantages

- Improved yield,
- Quality,
- Productivity &
- Cost efficiency.
Operation:

- Liquid steel flows out of the ladle
- Into the tundish, and then
- Into a water-cooled copper mould.
- Solidification begins in the mould, and continues through the First Zone and Strand Guide.
- In this configuration, the strand is straightened,
- Torch-cut,
- Discharged for intermediate storage or hot charged for finished rolling.
Steel ingot structure

- “Bridges”
- Shrinkage cavity
- Shrinkage porosity
- Columnar grains
- Small equiaxed grains
- Large equiaxed grains
- Bottom cone

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Structure of killed steel ingot

- Structure consists of five zones:
- Zone of small equi-axed grains
- The thin layer of small crystals forms when a melt comes to a contact with a wall of a cold metallic mold. The crystals (grains) have no favorable direction (equi-axed) and their chemical composition is close to that of the liquid steel. Heat liberated as a result of crystallization depresses the nucleation and crystal growth.
Zone of columnar grains

Columnar grains start to grow when a stable and directed heat flow is formed as a result of heat transfer through the zone of small equi-axed grains. Direction of the columnar grains growth is opposite to the direction of heat flow. Columnar grains continue to grow until the heat flow decreases due to the following causes:

- Large width of the solidified metal;
- Heating the mold wall;
- Formation of an air gap between the ingot and the mold wall. The air gap is a result of shrinkage caused by solidification.
- When the temperature of the melt, adjacent to the solidification front, increases due to the liberation of the latent heat, constitutional undercooling will end and the columnar grains growth will stop.
Zone of large equiaxed grains

Low temperature gradient (low heat flow) and low cooling rate of the solute-enriched liquid in the central zone of the ingot result in formation of equiaxed grains.

This process is slow due to slow heat extraction therefore the number of nuclei (seed crystals) is low and the grains size is large.

Zone of large equiaxed grains is enriched by the impurities (sulfur, phosphorous, carbon).
Bottom cone

- This cone-shaped zone is a mixture of small equi-axed grains grown as a result of the contact with a bottom of a cold metallic mold and crystals and crystals fragments, which from other ingot zones. Bottom cone is characterized by negative segregation of the impurities.
Shrinkage cavity zone

Shrinkage cavity is located in the top part of the ingot (which is later discarded) where last portion of liquid solidifies. The mold design should provide upwards direction of solidification at its last stage. Below the shrinkage cavity the zone of shrinkage porosity is located. This zone forms when the feeding of solidifying metal by the residual liquid is insufficient. Isolated pockets of liquid metal separated from the liquid pool by “bridges” form their own shrinkage cavities (shrinkage pores). The mold shape, which is wider in upper levels and thermal isolation of the “hot top” favor to diminish the shrinkage porosity.
Solidification

Solidification is a comprehensive process of transformation of the melt of an alloy into a solid piece of the alloy, involving crystallization of the liquid phase, segregation of impurities and alloying elements, liberation of the gases dissolved in the melt, shrinkage cavities and porosity formation.

Structure of ingots and castings

- Fine and homogeneous grain structure is the most desirable for the common castings and ingots.
- It is achieved when the crystallization proceeds under the following conditions:
Grain structure of ingot

Columnar grains

Large equiaxed grains

Small equiaxed grains

(from Bower T.F. and Flemings M.C., Trans. AIME, 239, 1620 (1967))
Process

- Formation of a large number of stable nuclei;
- Fast extraction of latent crystallization heat and the superheat of the liquid.
- These conditions are realized when a melt comes to a contact with a wall of a cold metallic mold. Small equi-axed grains (chill crystals) form at this stage. Latent crystallization heat, liberating from the crystallizing metal, decreases the undercooling of the melt and depresses the fast grains growth.
At this stage some of small grains, having favorable growth axis, start to grow in the direction opposite to the direction of heat flow. As a result **columnar crystals (columnar grains)** form. Length of the columnar grains zone is determined by the **constitutional undercooling**. When the temperature of the melt, adjacent to the solidification front, increases due to the liberation of the latent heat, constitutional undercooling will end and the columnar grains growth will stop.
Further cooling of the molten alloy in the central zone of the ingot will cause formation of large equiaxed grains.

Formation of the grain zones of an ingot is presented in the figure.

The crystals, growing as a result of solidification of ordinary alloys, are in dendrite form.
Segregation

- Composition of solidified alloy is not uniform. Concentrations of impurities and alloying elements are different in different parts of the casting. This difference is a result of different solubility of impurities in liquid and solid phases at the equilibrium temperature.

- Segregation is a result of separation of impurities and alloying elements in different casting regions.
Gas pores

- Gas pores, entrapped in the solid structure of a casting, arise from different origins:

- Gas (hydrogen) dissolved in the liquid during melting (from damp materials, atmosphere, oils, etc). When the melt cools down and solidifies, hydrogen solubility decreases and it is forced out from the melt. The gas bubbles are trapped by the dendrites, forming gas porosity.
Gas pores, called blowholes, may be a result of chemical reaction occurring in the solidifying alloy. If a liquid steel was not deoxidized by deoxidizers (aluminum, silicon), oxygen and carbon, which are dissolved in the steel, form carbon monoxide by the reaction: \( C + O \rightarrow CO \). The bubbles of CO, trapped by the dendrites, form blowholes. Surface blowholes may form as a result of the decomposition of some constituents of mold dressing.
Shrinkage

Shrinkage is a contraction of alloy volume caused by:

- Contraction of the melt when it cools down to the liquidus temperature;
- Contraction of the alloy owing its solidification (cooling from liquidus temperature to solidus temperature). All metals except bismuth have higher density in solid state, than in liquid.
- Contraction of the solid alloy cooling from the solidus temperature to the ambient temperature.
Steel / Carbon Steel

- Alloy of iron, carbon and manganese
Properties of Steel

- Strength
- Ductility
- Toughness
- Hardness
- Wear/corrosion resistance
- Weldability
- Impact strength
- Creep resistance
Modification of properties of steel

- Change carbon content
- Add alloying elements
- Heat treatment
Carbon content

- **Improves:**
  - Strength
  - Hardness

- **Lowers:**
  - Ductility
  - Weldability
Alloying elements

- Mn: hardenability, ductility, wear resistance
- Ni: impact strength, toughness, corrosion resistance
- Cr: hardenability, strength, wear resistance
- W: hardness at elevated temperature
- V: strength, hardness, impact resistance, creep resistance
- Mo: hardenability, strength at elevated temperature
- Si: strength, elasticity
- Ti: strength, corrosion resistance
- Co: strength at high temperature, magnetic permeability
Heat treatment

- Hardening & Tempering:
  - Improve strength, hardness, toughness

- Normalising:
  - Reduce stresses, improve strength

- Annealing:
  - Reduce stresses, restore strength and ductility
Classification of Steels

- Carbon content
- Alloying element content
- Application
- Shape and surface
Carbon content

- **Low carbon steel**: $C < 0.25\%$
- **Medium carbon steel**: $0.25\% < C < 0.70\%$
- **High carbon steel**: $> 0.70\%$
- **Cast Iron**: $> 2.0\%$
Alloying element content

- **Low alloy steel**: $<5\%$
- **Medium alloy steel**: $5\% < A < 10\%$
- **High alloy steel**: $>10\%$
Application

- High strength low alloy steel
- Bearing steel
- Stainless steel
- Electrical steel
- Tool steel
- High speed steel
Shape & surface

- **Flat product**: plates, hot-rolled strip and sheets, and cold-rolled strip and sheets (hot/cold rolled)

- **Long product**: bars, rods and wires, structural shapes and rails, channels, angles, tees, zees, I-beams and tubes

- Billet, bloom, beam & slab

- Bars, rods
Steel Forming Processes

- Forming processes convert solidified steel into products useful for the fabricating and construction industries. The objectives are to obtain a desired shape, to improve cast steel’s physical properties (which are not suitable for most applications), and to produce a surface suitable for a specific use.
The major forming processes are carried out hot, at about 1,200°C, because of steel’s low resistance to plastic deformation at this temperature. This requires the use of reheating furnaces of different designs.

Cold forming is often applied as a secondary process for making special steel products such as sheet or wire.
There are a number of steel-forming processes including:

- Forging
- Rolling
- Pressing
- Piercing
- Drawing
- Extruding
Forging

Hammer forging

Hammer
Punch
Workpiece
Die
Anvil

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Rolling
Drawing
Extrusion
Hot Rolling
Cold rolling of steel strip

Tandem cold rolling mill

Uncoiler → Entry looper → Continuous annealing furnace → Exit looper → Recoiler

Uncoiler → Cleaning → Continuous annealing furnace → Exit looper → Recoiler

Temper rolling mill

Uncoiler → → Recoiler

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Hot Rolling
Tube manufacture (by welding)

A: Welding of steel strip along longitudinal seam.

B: Welding of steel strip along spiral seam.

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Tube manufacture (seamless)

C: Cross-rolling a solid round onto a revolving piercer.

D: Push-rolling a square bloom onto a stationary piercer.

E: Three-roll mill for reducing large-diameter tubes.
Fundamentals of Metallurgy

- Crystal structure
- Solidification: Crystals and grains
- Solid Solution: Phase diagram
Metallic Crystalline Structures

- There are 14 different types of crystal unit cell structures or lattices are found in nature. However most metals and many other solids have unit cell structures described as:
  - Body Centre Cubic (BCC)
  - Face Centred Cubic (FCC)
  - Hexagonal Close Packed (HCP).
Crystal lattice examples

Cubic body centered (bcc)  Fe, V, Nb, Cr
Cubic face centered (fcc)  Al, Ni, Ag, Cu, Au
Hexagonal                  Ti, Zn, Mg, Cd
Body-Centred Cubic (BCC) Structure

- The body-centred cubic unit cell has atoms at each of the eight corners of a cube (like the cubic unit cell) plus one atom in the centre of the cube.
- Each of the corner atoms is the corner of another cube so the corner atoms are shared among eight unit cells.
- The bcc unit cell consists of a net total of two atoms; one in the centre and eight eighths from corners atoms.
Body Centered Cubic (BCC)
Some of the materials that have a BCC structure include: lithium, sodium, potassium, chromium, barium, vanadium, alpha-iron and tungsten.

Metals which have a BCC structure are usually harder and less malleable.
The face centred cubic structure has atoms located at each of the corners and the centres of all the cubic faces. Each of the corner atoms is the corner of another cube so the corner atoms are shared among eight unit cells. Additionally, each of its six face centred atoms is shared with an adjacent atom. The FCC unit cell consists of a net total of four atoms; eight eighths from corners atoms and six halves of the face atoms.
Face Centered Cubic (FCC)
Some of the metals that have the FCC structure include:
- aluminium, copper, gold, iridium, lead, nickel, platinum and silver.
Hexagonal Close Packed (HCP) Structure

- Another common close packed structure is the hexagonal close packed. The hexagonal structure of alternating layers is shifted so its atoms are aligned to the gaps of the preceding layer. The atoms from one layer nest themselves in the empty space between the atoms of the adjacent layer just like in the FCC structure. However, instead of being a cubic structure, the pattern is hexagonal.
Hexagonal Close Packed (HCP)
The HCP structure is very common for elemental metals and some examples include:
beryllium, cadmium, magnesium, titanium, zinc and zirconium.
Comparatively low ductility.
Similarities and Difference Between the FCC and HCP Structure

- The face centred cubic and hexagonal close packed structures both have a same packing factor, consist of closely packed planes of atoms, and have a same coordination number.
- The difference between the fcc and hcp is the stacking sequence. The hcp layers cycle among the two equivalent shifted positions whereas the fcc layers cycle between three positions.
- The hcp structure contains only two types of planes with an alternating ABAB arrangement. The atoms of the third plane are in exactly the same position as the atoms in the first plane. However, the fcc structure contains three types of planes with a ABCABC arrangement. The atoms in rows A and C are no longer aligned. Cubic lattice structures allow slippage to occur more easily than non-cubic lattices, so hcp metals are not as ductile as the fcc metals.
Stable Room Temperature Crystal Structures for Elemental Metals

<table>
<thead>
<tr>
<th>Metal</th>
<th>Crystal Structure</th>
<th>Atomic Radius (nm)</th>
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</thead>
<tbody>
<tr>
<td>Aluminium</td>
<td>FCC</td>
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</tr>
<tr>
<td>Cadmium</td>
<td>HCP</td>
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<tr>
<td>Chromium</td>
<td>BCC</td>
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<tr>
<td>Cobalt</td>
<td>HCP</td>
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<td>Copper</td>
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</table>
Crystal Defects

- A perfect crystal, with every atom of the same type in the correct position, does not exist. All crystals have some defects. Defects contribute to the mechanical properties of metals.

- Adding alloying elements to a metal is one way of introducing a crystal defect.

- Nevertheless, the term “defect” will be used, just keep in mind that crystalline defects are not always bad. There are basic classes of crystal defects:
POINT DEFECT

- Point defects, which are places where an atom is missing or irregularly placed in the lattice structure. Point defects include lattice vacancies, self-interstitial atoms, substitution impurity atoms, and interstitial impurity atoms.
LINEAR DEFECTS

- Linear defects, which are groups of atoms in irregular positions. Linear defects are commonly called dislocations.
PLANAR DEFECTS

- Planar defects, which are interfaces between homogeneous regions of the material. Planar defects include grain boundaries, stacking faults and external surfaces.
Solidification

- Normally when a material begins to solidify, multiple crystals begin to grow in the liquid and a polycrystalline (more than one crystal) solid forms.
- The moment a crystal begins to grow is known as nucleation and the point where it occurs is the nucleation point.
- The final sizes of the individual crystals depend on the number of nucleation points. The crystals increase in size by the progressive addition of atoms and grow until they impinge upon adjacent growing crystal.
a) Nucleation of crystals
b) Crystal growth
c) Irregular grains form crystals grow together,
d) Grain boundaries as seen in a microscope.
Effect of grain size on material properties

- Rapid cooling generally results in more nucleation points and smaller grains a fine grain structure which will have higher strength, hardness and low ductility.

- Slow cooling generally results in larger grains which will have lower strength, hardness and ductility.

- The normal grain size varies between 1µm to 1000 µm.
Alloy

The term alloy is used to describe a mixture of atoms in which the primary constituent is a metal. The primary metal is called the base, the matrix, or the solvent. The secondary constituents are often called solutes.

- Binary alloy. two types of atoms forming the mixture
- Ternary alloy. three types of atoms forming the mixture
- Quaternary alloy. four types of atoms forming the mixture
- Quinary alloy. five types of atoms forming the mixture

Because the percentage of each constituent can be varied, with any mixture the entire range of possible variations is called a SYSTEM.
Different atomic mechanisms of alloy formation, showing pure metal, substitutional, interstitial, and a combination of the two.
Substitutional,Interstitial, and a combination of the two.

- **Substitutional**: Bronze (Cu-Sn), Brass (Cu-Zn)
- **Interstitial**: Steel (Fe-C)
- **A combination of the two**: Stainless Steel (Fe-C-Cr-Ni)
Solid Solution

- Alloy structure may be a single phase or a multi phase.

- **Phase** is a uniform part of an alloy, having a certain chemical composition and structure, and which is separated from other alloy constituents by a phase boundary.

- An alloy phase may be in form of *valence compound* (substance formed from two or more elements), with a fixed ratio determining the composition) or in form of solid solution.

- **Solid solution** is a phase, where two or more elements are completely soluble in each other.
Phase Diagrams

- The phase diagram is simply a map showing the structure of phases present as the temperature and overall composition of the alloy are varied. It is a very useful tool for understanding and controlling the structures of poly-phase materials.
A binary phase diagram shows the phases formed in differing mixtures of two elements over a range of temperatures. When an alloy exhibits more than two phases, a different type of phase diagram must be used, such as a ternary diagram for three phase alloys.
Iron carbon equilibrium diagram

- The iron-carbon equilibrium diagram is a plot of transformation of iron with respect to carbon content and temperature. This diagram is also called iron-iron carbon phase diagram.
- The important metallurgical terms, used in the diagram:
  - Ferrite (BCC)
  - Cementite ($\text{Fe}_3\text{C}$)
  - Pearlite (mixture of ferrite and cementite)
  - Austenite (FCC)
The Iron-carbon phase diagram illustrates the phase changes in steels and iron-carbon alloys as a function of temperature and carbon content. Key points and phases include:

- **A3, A2** temperatures marking the start of the transformation from austenite to pearlite.
- **A1** temperature marking the start of the transformation to sorbite.
- **AcM** temperature marking the start of martensitic transformation.
- **L** phase for liquid.
- **L + Fe3C** phase for liquid plus cementite.
- **L + δ** phase for liquid plus ferrite.
- **Austenite + cementite + ledeburite** phase at certain carbon contents.
- **Cementite + pearlite + transformed ledeburite** phase at lower carbon contents.

Temperature and carbon contents are indicated in various segments of the diagram, with specific points labeled in Fahrenheit and Celsius.
Iron-Iron Carbon Equilibrium Diagram
Ferrite (α): Virtually pure iron with BCC crystal structure. It is stable at all temperatures up to 910 °C. The carbon solubility in ferrite depends upon the temperature; the maximum being 0.02% at 723 °C.

Cementite: Iron carbide (Fe3C), a compound iron and carbon containing 6.67% carbon by weight.

Pearlite: A fine mixture of ferrite and cementite arranged in lamellar form. It is stable at all temperatures below 723°C.
Austenite (γ): Austenite is a FCC structure. It is stable at temperatures above 723 °C depending upon carbon content. It can dissolve upto 2% carbon.

The maximum solubility of carbon in the form of Fe3C in iron is 6.67%. Addition of carbon to iron beyond this percentage would result in formation of free carbon or graphite in iron.

At 6.67% of carbon, iron transforms completely into cementite or Fe3C (Iron Carbide).
Generally carbon content in structural steels is in the range of 0.12 - 0.25%.

Upto 2% carbon, we get a structure of ferrite + pearlite or pearlite + cementite depending upon whether carbon content is less than 0.8% or beyond 0.8%.

Beyond 2% carbon in iron, hard and brittle cast iron is formed.
Microstructures of structural steel are formed by the slow cooling
It is important to note that steel of 0.20% carbon ends up in pearlite + ferrite microstructure, only when it is cooled very slowly from higher temperature during manufacture. When the rate of cooling is faster, the normal pearlite + ferrite microstructure may not form, instead some other microstructure called Bainite or Martensite may result.
The Steel Section of the Iron - Carbon Diagram
Variation in microstructure in steels

- Austenite
- Austenite + Ferrite
- Ferrite + pearlite
- Cementite + Pearlite
Changes that occur in a 1.2 % Carbon alloy as it is cooled from 1000 degrees

1. 1.2 % Carbon is dissolved in a solid solution of FCC austenite

2. As cooling continues the cementite soaks up the Carbon until at 723 degrees there is only the eutectoid composition of carbon left which changes to pearlite.

3. This gives us a steel containing Cementite (Fe₃C) and the layered structure pearlite.
Changes that occur in a 0.83 % Carbon alloy as it is cooled from 1000 degrees.

Due to their being so much Carbon dissolved in the FCC austenite structure the BCC Ferrite cannot begin to form.

Below 723 deg. the excess Carbon is taken into the cementite (Fe₃C) as the cementite grows in thin layers. It draws the Carbon from all around it allowing the austenite to form Ferrite. This ends up a Lamellar structure with alternate layers of Ferrite and Cementite in the ratio of 7 parts ferrite to one part Cementite (Fe₃C).
Changes that occur to a 0.4 % Carbon alloy upon cooling from 1000 degrees

1. Austenite and carbon in a solid solution with the C atoms between the F.C.C. lattice

2. At point U, austenite begins to change from its FCC structure to a BCC structure known as Ferrite. BCC structure has no room for C atoms so they all move into the remaining FCC structure.

3. At 723 degrees the BCC ferrite has pushed all the Carbon into the remaining FCC austenite. At 723 degrees this carbon rich austenite changes to pearlite— which is a layered structure of 7 parts ferrite to 1 part cementite (Fe₃C). As Cementite has 1 Carbon atom to 3 iron atoms, this is where the Carbon ends up.
Thermal Processing

- Heat treatment
- Strengthening mechanism
Heat Treatment of Steels

Heat treatment of a metal or alloy is a technological procedure, including controlled heating and cooling operations, conducted for the purpose of changing the alloy microstructure and resulting in achieving required properties.
Heat Treatment Processes

- Annealing
- Normalizing
- Hardening & Tempering
- Case hardening
- Nitriding
- Carburizing
- Carbonitriding
- Cyaniding
Annealing & Stress Relief

- **Annealing** is a heat treatment procedure involving heating the alloy and holding it at a certain temperature (annealing temperature), followed by controlled cooling.

**Annealing results in:**
- relief of internal stresses,
- Softening and high ductility,
- chemical homogenizing and
- transformation of the grain structure into more stable state.

- Annealing temperature and the control cooling rate depend on the alloy composition and the type of the annealing treatment.
Recrystallization Annealing

Recrystallization annealing is a process of heating a cold worked metal to a temperature above the recrystallization temperature followed by soaking for a time required for the grain structure transformation.

Recrystallization annealing is widely used as an intermediate softening treatment between stages of cold work (cold rolling, drawing).

Combination of recrystallization annealing and cold work allows to control the microstructure grains size.
Stress Relief (Recovery)

- Stress relief (recovery) – a relatively low temperature process of reducing internal mechanical stresses, caused by cold work, casting or welding.

- The stress relief temperature is lower than the recrystallization temperature
Normalizing

- Normalizing is a process in which a steel is heated to about 100°F (55°C) above the upper critical temperature, followed by soaking and cooling in still air at room temperature.

- Normalizing treatment is similar to the full annealing treatment. The difference is in the cooling method and rate – full annealing involves slow controlled cooling if the furnace or in some medium providing slow cooling rate.

- As normalizing requires less time, it is more economically efficient heat treatment method than full annealing.
Normalizing relieves internal stresses caused by cold work while grain growth is limited by the relatively high cooling rate therefore the mechanical properties (strength, hardness) of a normalized steel are better than in an annealed steel.

Since the cooling rate in the normalizing heat treatment is not controlled, the resulting structure is dependent on the thickness of the steel part, therefore the effect of increased mechanical properties is greater in thin parts.

Quality of surface after machining of a normalized part is also better than in an annealed part. This effect is caused by increased ductility of annealed steel favoring formation of tearing on the machined surface.
Hardening & Tempering

- **Hardening** is a heat treatment process involving heating a steel above the phase transformation temperature (upper critical temperature, $A_3$), followed by soaking and then rapid cooling (quenching either in oil or water).
- When steel is heated above the upper critical temperature, its structure becomes entirely austenitic.
- Then the article is cooled at a rate exceeding the critical rate value.
- **Critical cooling rate** is a function of the chemical composition and the grain size of austenite.
- If the critical cooling rate is not achieved, a mixture of ferrite and cementite forms.
Cooling in water usually provides cooling rate higher than the critical value.

The structure forming as a result of quenching in water is called **martensite** (supersaturated solid solution of carbon in α-iron).

Martensite is hard and brittle phase, having hardness varying between 500 HB to 710 HB depending on the carbon content.

The temperature interval at which the austenite-martensite transformation occurs is about 250°C - 200°C.

**Hardening temperature** is the temperature to which a steel is heated before quenching.
Tempering

- **Tempering** is a heat treatment operation involving reheating hardened steel to a certain temperature below the lower critical point \( A_1 \) followed by soaking and then cooling.
- The steel structure after hardening consists mainly of martensite which is hard and brittle. Tempering is carried out in order to change the martensite structure and obtain a desired combination of strength and ductility.
- The object of tempering is also to reduce the internal stresses caused by quenching.
Tempering Temperature Ranges

- Tempering at temperatures 150°C - 250°C.
- Tempering at temperatures 300°C - 400°C.
- Tempering at temperatures 400°C but lower than $A_1$.

Determined by:
- Carbon content
- Component size
Microstructure of quenched 0.95% carbon steel.
(a) Martensitic structure (1000x).
(b) Bainitic structure (550x).
Effects of carbon content on the microstructures of plain-carbon steels.
(a) Ferrite grains and pearlite (gray streaks) in a white matrix of a steel containing 0.4% C. 1000x.
(b) Microstructure (all pearlite grains) of a steel containing 0.77% C. 2000x.
(c) Microstructure of a steel containing 0.77% C with all cementite in the spheroidal form. 1000x.
(d) Microstructure of a steel containing -1.0% C containing pearlite with excess cementite bounding the grains. 1000x
Case Hardening

- **Case hardening** is the diffusion heat treatment operation which involves two stages:
  - Heating a steel part to a temperature above the upper critical temperature in a medium, containing an element capable to saturate the surface layer of the part through diffusion;
  - Heat treatment of the part in order to obtain the desired combination of mechanical properties of the hard outer “case” and the ductile “core”.

- As a medium for the case hardening solid, liquid and gaseous substances may be used.
- The most widely used case hardening methods are:
  - Carburizing
  - Nitriding
  - Carbonitriding
Carburizing medium

- Charcoal or other carbon-containing solids mixed with sodium carbonate and barium carbonate accelerating the process of dissolving the carbon in steel.

- Kerosene or benzene – liquid carbonizing mediums, which are usually used in dispersed form;

- Methane (CH4), propane (C3H8) – gaseous carbonizing mediums.
- Thickness of the hard layer formed in the gaseous carburizing may reach 0.15” (4mm).

- Heat treatment after carburizing involves hardening-tempering treatments with purpose of controlling structure and properties of both the hard layer and the ductile core.

- The process is carried out in a furnace (batch or continuous) at the temperature 900°C - 950°C for 3-4 hrs.
Nitriding

- **Nitriding** is the process of diffusion enrichment of the surface layer of a part with nitrogen.

- **Gas nitriding** is carried out at 500°C - 600°C for 40-100 hrs. in the atmosphere of Ammonia, which dissociates to Hydrogen and nitrogen. The latter diffuses into the steel forming nitrides of iron, aluminum, chromium and vanadium.
Ion nitriding (plasma nitriding) is a surface hardening heat treatment, in which nitrogen is delivered to the workpiece surface in form of ionized gas (plasma).

The case formed as a result of nitriding has a hardness of about 1100 HV which is higher than the hardness after carburizing.

Nitrided part possess also better wear resistance, increased fatigue strength, enhanced toughness and good resistance to corrosion.

No additional heat treatment is required after nitriding.
Carbonitriding

- **Carbonitriding** is the process of diffusion enrichment of the surface layer of a part with carbon and nitrogen.

- **Gaseous carbonitriding** is carried out in gaseous medium, consisting of carburizing gas (methane, propane) with addition of 3-8% of Ammonia.
There are two principal methods of the gaseous carbonitriding:

- Low temperature gaseous carbonitriding, conducted at (500°C - 600°C). The steel surface is enriched mostly with nitrogen in this process.

- High temperature gaseous carbonitriding, conducted at (800°C - 950°C). The steel surface is enriched mostly with carbon in this process. This process is followed by heat treatment.
Cyaniding

- **Cyaniding** is the carbonitriding process, conducted in molten salt, containing 20-25% of sodium cyanide (extremely toxic substance).

- The process is carried out at the temperatures (820°C - 860°C) for 1 hour.

- Carbonitrided parts possess better (than carburized parts) wear resistance.
Strengthening Structural Steels

- Cooling rate of steel from austenite region to room temperature produces different microstructures, which impart different mechanical properties.

- The grain size of crystal is an important parameter in strengthening of steel.
Weldability

- Weldability of steel is closely related to the amount of carbon in steel. Weldability is also affected by the presence of other elements. The combined effect of carbon and other alloying elements on the weldability is given by “carbon equivalent value (Ceq)”, which is given by:

  \[
  \text{Ceq} = \%C + \frac{\% \text{Mn}}{6} + \left(\% \text{Cr} + \% \text{Mo} + \% \text{V}\right)/5+\left(\% \text{Ni} + \% \text{Cu}\right)/15
  \]

- The steel is considered to be weldable without preheating, if Ceq < 0.42%.
- However, if carbon is less than 0.12% then Ceq can be tolerated upto 0.45%.
QUESTIONS...
Consider three different compositions of elements A and B, on phase diagrams and how their microstructures will differ because of their positions on the phase diagram.

First a eutectic alloy, which is an alloy with composition right at the eutectic point.

Then compositions on both sides of the eutectic point.

An alloy with a composition that lies to the left of the eutectic point on the phase diagram is called a hypoeutectic alloy, and an alloy with a composition that lies to the right of the eutectic point is called hypereutectic alloy.

The microstructure can be controlled by manipulating the speed of cooling the alloy, but this will be covered in heat treatments.
EUTECTIC ALLOYS
HYPOEUTECTIC ALLOYS
DIFFUSION

- Diffusion is the migration of atoms from a region of high concentration to a region of low concentration. In a homogeneous material, atoms are routinely moving around but the movement is random (i.e. there is always an equal number of atoms moving in all directions). In an inhomogeneous material, all the atoms are moving near randomly, but there is a migration of atoms to areas where their concentrations are lower. In other words, there is a net diffusion.
Atom diffusion can occur by the motion of host or substitutional atoms to vacancies (vacancy diffusion), or interstitial impurities atoms to different interstitial positions (interstitial diffusion).

In order to move, an atom must overcome the bond energy due to nearby atoms. This is more easily achieved at high temperatures when the atoms are vibrating strongly.
PHASE TRANSFORMATION
STEEL AND CAST IRON
NON-FEROUS METALS
Dendrites

In metals, the crystals that form in the liquid during freezing generally follow a pattern consisting of a main branch with many appendages. A crystal with this morphology slightly resembles a pine tree and is called a dendrite, which means branching. The formation of dendrites occurs because crystals grow in defined planes due to the crystal lattice they create. The figure to the right shows how a cubic crystal can grow in a melt in three dimensions, which correspond to the six faces of the cube.
Anisotropy and Isotropy

- In a single crystal, the physical and mechanical properties often differ with orientation. When the properties of a material vary with different crystallographic orientations, the material is said to be anisotropic.
When the properties of a material are the same in all directions, the material is said to be **isotropic**. For many polycrystalline materials the grain orientations are random before any working (deformation) of the material is done. Therefore, even if the individual grains are anisotropic, the property differences tend to average out and, overall, the material is isotropic. When a material is formed, the grains are usually distorted and elongated in one or more directions which makes the material anisotropic.
HEAT TREATMENT OF STEEL

- Alloys that were allowed to solidify by slow cooling produce different microstructures.

- It is possible to modify the microstructure of an alloy by subjecting it to various thermal treatments.

- The focus will be on metals but it should be noted that heat-treatment is also used on ceramics and composites to modify their properties.
Heat-treating is a term used to describe all of the controlled heating and cooling operations performed on a material in the solid state for the purpose of altering its microstructure and/or properties.
The major objectives of the different kinds of thermal treatments are:

- Soften the material for improved workability.
- Increase the strength or hardness of the material.
- Increase the toughness or resistance to fracture of the material.
- Stabilize mechanical or physical properties against changes that might occur during exposure to service environments.
- Insure part dimensional stability.
- Relieve undesirable residual stresses induced during part fabrication.
Depending on the thermal treatment used, the atomic structure and/or microstructure of a material may change due to movement of dislocations, an increase or decrease in solubility of atoms, an increase in grain size, the formation of new grains of the same or different phase, a change in the crystal structure, and others mechanisms.
HEAT TREATMENT PROCESSES

- **Age Hardening** is a relatively low-temperature heat treatment process that strengthens a material by causing the precipitation of components or phases of alloy from a supersaturated solid solution condition.
Annealing is a softening process in which metals are heated and then allowed to cool slowly. The purpose of annealing is to soften the material for improve machinability, formability, and sometimes to control magnetic properties.
Normalising is much like annealing, but the cooling process is much faster. This results in increased strength but less ductility in the metal. Its purpose is to refine grain structure, produce more uniform mechanical properties, and sometimes to relieve internal and surface stresses.
Precipitation Heat Treatment is the three step process of solution treating, quenching, and age hardening to increase the strength or hardness of an alloy.
Solution Heat Treatment involves heating the material to a temperature that puts all the elements in solid solution and then cooling very rapidly to freeze the atoms in place.
Stress Relieving is a low temperature heat treat process that is used to reduce the level of residual stresses in a material.
Tempering involves gently heating a hardened metal and allowing it to cool slowly will produce a metal that is still hard but also less brittle. This process is known as tempering.
Quenching is the rapid cooling of a hot material. The medium used to quench the material can vary from forced air, oil, water and others. Many steels are hardened by heating and quenching. Quenching results in a metal that is very hard but also brittle.
STRENGTHENING MECHANISM
METAL FORMING
FURNACE & FURNACE ATMOSPHERE
CORROSION