Metallurgical Processes

By

Professor Issam S. Jalham

Industrial Engineering Department School of Engineering University of Jordan Amman - Jordan

Metallurgy

Metallurgy is the technology of extracting metals from their ores and adapting them for use and the science or study of the behavior, structure, properties, and composition of metals that leads to development of alloy properties.

Branches of metallurgy:

- 1. Extractive metallurgy, which is freeing the metal atoms from a combined state.
- 2. Physical metallurgy, which is the study of properties and composition of metals.
- Powder metallurgy, which is the technology of producing useful metal shapes from metallic powder (P/M)

Definitions

• The physical world is composed of matter and energy. Matter is defined as anything that occupies space

- Matter is anything occupies space & composed of atoms
- Energy is the ability to do work

• Einstein's discoveries leading to this atomic age revealed that matter and energy are related. A small amount of matter releases a tremendous amount of energy under certain conditions.

Definitions cont.

- ★An element is Matter composed of a single kind of atoms.
- ★A compound is composed of two or more elements combined chemically.
- ★A mixture is two or more elements or compounds physically combined in the same way in which two fine powders are mixed together
- ★ The molecule is defined as the smallest particle of any substance that can exist free and still exhibit all the chemical properties of that substance. A molecule can consist of one or more atoms

Definitions cont.

- *Iron*: pure iron or contains less than .02 wt % carbon.
- Steel: iron + (contains 0.02 < carbon <2.0 wt %)
- Cast Iron: Iron + (contains 2.0 < carbon < 6.69 wt %)
- *Ferrous alloys*: iron based alloys
- *Non-ferrous alloys*: non iron based alloys
- *Plain carbon steel*: contains only residual concentrations of impurities other than carbon and a little Mn.
- *Alloy steel*: when more alloying elements are intentionally added in specific concentrations

THE PERIODIC TABLE

Columns: Similar Valence Structure



Electropositive elements: Readily give up electrons to become + ions. Electronegative elements: Readily acquire electrons to become - ions.

Bohr model

BOHR ATOM



Nucleus: Z = # protons

= 1 for hydrogen to 94 for plutonium N = # neutrons

Atomic mass $A \approx Z + N$

Wave-mechanical model

ELECTRON ENERGY STATES

Electrons...

- have discrete energy states
- tend to occupy lowest available energy state.

POSITION: PROBABILITY DISTRIBUTION

<u>OCCUPIRD ENERGY STATE (CONFIGURATION)</u>: ACCORDING TO QUANTUM NUBERS & ENERGY STATE

QUANTUM NUMBERS:

- 1. PRINCIPAL NUMBER
- 2. SECONDARY NUMBER
- 3. MAGNETIC NUMBER
- 4. SPIN NUMBER

STABLE ELECTRON CONFIGURATIONS

Stable electron configurations...

- have complete s and p subshells
- tend to be unreactive.

Ζ	Element	Configuration
2	He	1s ²
10	Ne	1s ² 2s ² 2p ⁶
18	Ar	1s ² 2s ² 2p ⁶ 3s ² 3p ⁶
36	Kr	1s ² 2s ² 2p ⁶ 3s ² 3p ⁶ 3d ¹⁰ 4s ² 4p ⁶

SURVEY OF ELEMENTS

• Most elements: Electron configuration not stable.

<u>Element</u>	Atomic #	Electron configuration		
Hydrogen	1	1s ¹		
Helium	2	1s ² (stable)		
Lithium	3	1s ² 2s ¹		
Beryllium	4	1s ² 2s ²		
Boron	5	1s ² 2s ² 2p ¹		
Carbon	6	1s ² 2s ² 2p ²		
•••		•••		
Neon	10	1s ² 2s ² 2p ⁶ (stable)		
Sodium	11	1s ² 2s ² 2p ⁶ 3s ¹		
Magnesium	12	1s ² 2s ² 2p ⁶ 3s ²		
Aluminum	13	1s ² 2s ² 2p ⁶ 3s ² 3p ¹		
•••		•••		
Argon	18	<u>1s²2s²2p⁶3s²3p⁶ (stable)</u>		
	•••	• • •		
Krypton	36	1s ² 2s ² 2p ⁶ 3s ² 3p ⁶ 3d ¹⁰ 4s ² 4 ⁶ (stable)		

• Why? Valence (outer) shell usually not filled completely.

Types of bonds:

- Primary bonds
 - -Metallic
 - -Covalent
 - -lonic
- Secondary bonds
 -Vander waals forces
- Mixed bonds

METALLIC BONDING

• Arises from a sea of donated valence electrons (1, 2, or 3 from each atom).



• Primary bond for metals and their alloys

IONIC BONDING

- Occurs between + and ions.
- Requires electron transfer.
- Large difference in electronegativity required.
- Example: NaCl



COVALENT BONDING

- Requires shared electrons
- Example: CH4
 - C: has 4 valence e, needs 4 more
 - H: has 1 valence e, needs 1 more
 - Electronegativities are comparable.



SECONDARY BONDING

Arises from interaction between dipoles

• Fluctuating dipoles



Permanent dipoles-molecule induced



SUMMARY: BONDING

<u>Type</u>	Bond Energy	<u>Comments</u>
lonic	Large!	Nondirectional (ceramics)
Covalent	Variable large-Diamond small-Bismuth	Directional semiconductors, ceramics polymer chains)
Metallic	Variable large-Tungsten small-Mercury	Nondirectional (metals)
Secondary	smallest	Directional inter-chain (polymer) inter-molecular

SUMMARY: PRIMARY BONDS

Ceramics

(lonic & covalent bonding):

Metals

(Metallic bonding):

Large bond energy large T_m large E small α

Variable bond energy moderate T_m moderate E moderate α

Polymers

(Covalent & Secondary):



Directional Properties Secondary bonding dominates small T small E large α

METALLIC CRYSTALS

- **1. SIMPLE CUBIC CRYSTAL STRUCTURE**
- 2. BODY CENTERED CUBIC CRYSTAL STRUCTURE (BCC)
- 3. FACE CENTERED CUBIC STRUCTURE (FCC)
- 4. HEXAGONAL CLOSE-PACKED CRYSTAL STRUCTURE (HCP)
- **5. TRICLINIC**
- 6. MONOCLINIC
- 7. ORTHORHOMBIC
- 8. RHOMBOHEDRAL
- 9. TETRAGONAL
 - Simple
 - Body centered tetragonal (BCT)

SIMPLE CUBIC STRUCTURE (SC)

- Rare due to poor packing (only Po has this structure)
- Close-packed directions are cube edges.



 Coordination # = 6 (# nearest neighbors)



(Courtesy P.M. Anderson)

ATOMIC PACKING FACTOR



• APF for a simple cubic structure = 0.52



BODY CENTERED CUBIC STRUCTURE (BCC)

- Close packed directions are cube diagonals.
 - --Note: All atoms are identical; the center atom is shaded differently only for ease of viewing.



• Coordination # = 8



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ATOMIC PACKING FACTOR: BCC

• APF for a body-centered cubic structure = 0.68



FACE CENTERED CUBIC STRUCTURE (FCC)

- Close packed directions are face diagonals.
 - --Note: All atoms are identical; the face-centered atoms are shaded differently only for ease of viewing.
 - Coordination # = 12





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ATOMIC PACKING FACTOR: FCC

• APF for a body-centered cubic structure = 0.74



FCC STACKING SEQUENCE

- ABCABC... Stacking Sequence
- 2D Projection

A sites B sites C sites



• FCC Unit Cell



HEXAGONAL CLOSE-PACKED STRUCTURE (HCP)

- ABAB... Stacking Sequence
- 3D Projection



2D Projection
Top layer
Middle layer
Bottom layer

- Coordination # = 12
- APF = 0.74

AREA DEFECTS: GRAIN BOUNDARIES

Grain boundaries:

- are boundaries between crystals.
- are produced by the solidification process, for example.
- have a change in crystal orientation across them.
- impede dislocation motion.

In the grain: atoms of the same direction and same energy

Metal Ingot

Schematic







- Mean linear intercept method
- ASTM Method
 N = 2 ⁿ⁻¹
- N = 1- 5 coarse grained structure
- N = 5 8 Fine grained structure
- 70% falls in the range

Crystalline changes during heating

• Allotropy (Iron)



Standards and Specifications of metals and alloys

- Classification of materials and alloys is very important as it is:
- 1. Necessary not to repeat the conduction of experiments every time to explore the properties of the same alloy
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Methods of steel classification

The main methods of steel classification are:

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The widely used method of classification is by analysis.

ASTM, DIN, GOST

Individual work

Iron – Carbon/Cementite Phase Diagram


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ASTM, DIN, GOST

Individual work

Iron – Carbon/Cementite Phase Diagram



Solid phases in iron carbon diagram

- <u>Alpha Ferrite</u>: This phase is an interstitial solid solution of carbon in the BCC iron crystal lattice, reaching a maximum solid solubility of 0.02% at 723 °C. The solubility of carbon in alpha ferrite decreases to 0.005% at 0 °C.
- <u>Gamma Austenite</u>: This phase is an interstitial solid solution of carbon in the FCC iron crystal lattice, reaching a maximum solid solubility of 2.0 % at 1128 °C. The solubility of carbon in austenite decreases to 0.8% at 723 °C.
3. <u>Cementite (Fe3C)</u>: It is an intermetalic compound which has negligible solubility limit and a composition of 6.67% C & 93.7% Fe. It is also hard and brittle.

 <u>Delta Ferrite</u>: It is an interstitial solid solution of carbon in the BCC delta iron crystal lattice, reaching a maximum solid solubility of 0.09 % at 1465 °C.

Reactions in iron carbon diagram

1. Eutectic



3. Peritectic

 $\delta (0.09\% C) + L (0.53\% C) \longrightarrow \gamma$

1459 ° C

Development of Microstructure

Eutectoid alloy
Hypo-eutectoid
Hyper eutectoid

IRON-CARBON (Fe-C) PHASE DIAGRAM

(eutectoid alloy structure)



Pearlite Formation



- Austenite precipitates
 Fe3C at Eutectoid
 Transformation
 Temperature (727°C).
- When slow cooled, this is Pearlite (looks like Mother of Pearl)

Diffusion of Carbon in Pearlite



- Schematic representation of the formation of pearlite from austenite
 - direction of arrows indicates carbon diffusion



- Micrograph of eutectoid steel, showing pearlite microstructure.
 - α ferrite (light)
 - Fe₃C (dark) ⁵

Morphology of Pearlite



(a) coarse pearlite

(b) fine pearlite 3000X

HYPO EUTECTOID STEEL



HYPERE UTECTOID STEEL



controston (21.10).



A diagram showing the relationship between carbon content, microstructure and mechanical properties of plain carbon steels in the *normalised* condition. Typical uses of these steels are also indicated.

The influence of alloying element

- On phase diagram:
- 1. Altering the position of the boundaries
- 2. Altering the shape of the phase field.

- The extent of influence depends on:
- 1. The type of alloying element
- 2. The concentration of alloying element

ALLOYING STEEL WITH MORE ELEMENTS

Teutectoid changes:



Ceutectoid changes:





The effect of chromium on the austenite range of steel. (Machine Tools and Machining Practices)

Heat treatment

Heat treatment can be classified into:

Heat treatment of ferrous alloys
 Heat treatment of non ferrous alloys
 Heat treatment of cast iron
 Heat treatment of welding



Heat treatment of ferrous alloys

It is the procedure for producing metals or alloys with different or demanded properties by heating them to predetermined temperature, then cooling them using different media (different cooling rates) which leads to different microstructure and different properties of the alloys without changing the product shape.

<u>Steels</u> are particularly suitable for heat treatment, since they respond well to heat treatment and the commercial use of steels exceeds that of any other material. Steels are heat treated for one of the following reasons:



2. <u>Hardening</u>

3. Material Modification

Softening: Softening is done to reduce strength or hardness, remove residual stresses, improve toughnesss, restore ductility, refine grain size or change the electromagnetic properties of the steel. Restoring ductility or removing residual stresses is a necessary operation when a large amount of cold working is to be performed, such as in a cold-rolling operation or wiredrawing. <u>Annealing</u> — full Process, spheroidizing, normalizing and tempering austempering, martempering are the principal ways by which steel is softened.

Hardening: Hardening of steels is done to increase the strength and wear properties. One of the pre-requisites for hardening is sufficient carbon and alloy content. If there is sufficient Carbon content then the steel can be directly hardened. Otherwise the surface of the part has to be Carbon enriched using some diffusion treatment hardening techniques.

2. Normalizing

- 3. Hardening
- 4. Tempering

5. Treatments using isothermal transformation (I-T) diagrams

Annealing:

Full anneal It is heating the part in the furnace to about 28 °C above A3 before 0.8% C and to about 28 °C above A1 after 0.8% C, then cooling very slowly in the furnace or in an insulating material. The microstructure becomes coarse pearlite and ferrite.

Purpose:

1. For easier machining of tool steels that have more than 0.8%C

2. For welding when iron contains less than 0.8%C * Tensile strength of Hypoeutectoid alloy = (40 000 x % of ferrite + 120 000 x % of pearlite) In the microstructure

Microstructure after Full annealing:



Spherodize anneal: It is heating the material to a temperature close to 704 ℃ (lower than A1), holding it for four hours then cooling in the furnace. The microstructure is spherical or globular carbide grains in the steel rather than lamellar structure.

Purpose:

To improve the machinability of high carbon steels (0.8 – 1.7 % C).

* When spherodize low carbon steels(), their machinability gets poorer, since they become gummy and soft causing edge build up

Microstructure after spherodize annealing:



Stress relief anneal: It is heating of low carbon steel to 510 °C after getting stressed by cold working such as rolling, pressing, welding...etc.

<u>Purpose:</u> elimination of the cold working effect.

<u>The microstructure</u>: the distored grains reform or recrystallize into new softer ones after the annihliation of dislocations. The pearlite and some other forms of iron carbide remain unaffected by this heat treatment.

EFFECT OF HEATING AFTER %CW

- 1 hour treatment at Tanneal... decreases TS and increases %EL.
- Effects of cold work are reversed!



Recovery, Recrystallization and Grain Growth

- ★ <u>Recovery</u> is a low-temperature effect in which there is little or no visible change in the microstructure. Electrical conductivity is increased, and often a decrease in hardness is noted.
- Re-crystallization releases much larger amounts of energy than does recovery. The flattened, distorted grains are sometimes reformed to some extent during recovery into polygonal grains, while some rearrangement of defects such as dislocations takes place. Recrystallization not only releases much larger amounts of stored energy but new, larger grains are formed by the nucleation of stressed grains and the joining of several grains to form larger ones.
- **X** <u>Grain growth</u> is the process of joining of adjacent grains. Grain boundaries migrate to new positions, which changes the orientation of the crystal structure.

<u>Process anneal:</u> It is the anneal, between a series of cold working operations, reforms the grains to the original soft and ductile conditions. It is carried out in a closed container with inert gas to prevent oxidation of the surface.

<u>Purpose:</u> to be able to continue the forming process by eliminating the cold working effect. Normalizing: It is heating the piece to 56 ℃ above A3 then cooling it in still air. When the content of carbon is more than 0.8%, a higher temperatures are required. The resultant microstructure is fine pearlite.

Purpose:

- **1.** To correct the irregular grain structure after casting or forging
- 2. To improve machinability of low carbon steel because it becomes gummy when annealed

Microstructure Normalizing:



<u>Hardening:</u> It is heating the piece to a temperature above A3 before 0.8% C and to a temperature above A1 after 0.8 % C then suddenly cooling it with a high rate of cooling. The microstructure formed is martensite.

<u>Purpose:</u> to increase the strength and wear properties.

<u>Martensite</u>

- Diffusionless transformation of FCC to BCT (more volume!)
- **×** Lenticular structure
- **X** Very hard & very brittle.
- × Unstable
- Martensite Transformation depends on:
- 1. Mass of the part
- 2. Hardenability of the material
- 3. Severity of quenching media





Hardenability: It is the Ability of an alloy to be hardened by the formation of martensite.

- This is dependent upon the chemical composition of the steel alloy.
- The addition of Nickel, Chromium and Molybdenum will slow the transformation to other phases and allow more martensite to form.
- Most heat treatable steels are alloys rather than plain carbon steels.

Hardenability Testing

• Jominy end quench test is used to measure hardenability.



• Hardness versus distance from the quenched end.



PREDICTING HARDNESS PROFILES

• Ex: Round bar, 1040 steel, water quenched, 2" diam.



Heat Treatments abbreviations

- A Furnace Annealed Slow cooled
- N Normalized Air cooled.
- O Oil Quenched
- WQ Water quenched.
- WT(370)–Water quenched, tempered at 370°C for 1 hour.
- WT(705)–Water quenched, tempered at 705°C for 1 hour.
Tempering: It is heating the piece of steel that was hardened by quenching to a temperature below A1 (about 200 − 450 °C). At this temperature martensite transforms the equilibrium structure of ferrite and cementite.

<u>Purpose:</u> It is done for the hardened structure to increase their toughness properties and their ductility and to relief the structure from the stressed state of the distored lattice.

Isothermal Transformation (I-T) Diagrams:

- It is the heat treatment process that uses the Temperature – Time - Transformation (TTT) curves. (I-T diagrams are also called the Bain S-Curve or T-T-T (time-temperature-transformation) diagrams)
- **TTT Curve**: It is a graphical representation of the cooling of the specimen that relates the microstructure to temperature and time.
- <u>Purpose</u>: this process assumes that the temperature of the piece is held constant for a period of time before cooling.

Construction of the TTT Diagram

When plotting an I-T diagram, three facts should be kept in mind:

1. When austenite is cooled below the A1 line to a particular temperature and held at that temperature, it will begin to transform in a given time and will complete the transformation after a given time peculiar to that steel.

2. Martensite is formed only at relatively low temperatures and almost instantaneously.

3. If austenite transforms at any point in the transformation to a structure that is stable at room temperature, rapid cooling will not change the product already transformed, but the remaining untransformed austenite will form martensite.

Construction of the TTT Diagram

- ★ Data for isothermal transformation diagrams are obtained by heating large numbers of small steel specimens of a specific kind of steel to the austenitization temperature (Figure below). They are then abruptly transferred to furnaces or molten salt baths that have been heated to predetermined temperatures below the critical line A1.
- ★ To study the transformation at 1200°F (649°C), a set of specimens is held at 1200°F (649°C) constant temperature (isothermal). At regular time intervals a specimen is removed and rapidly quenched in iced brine. Microscopic examination will then show martensite if transformation has not yet started, but will show martensite and pearlite (in this case) if transformation has started, and only pearlite if transformation is complete. A mark is placed on the graph, indicating the time and temperature.

Construction of the TTT Diagram

• This procedure is repeated at other temperatures until the entire graph is plotted for that particular steel (Figure 3). The vertical scale on the left represents temperature and the horizontal scale on the bottom represents time. It is plotted on a log scale that corresponds to 1 minute, 1 hour, 1 day, and 1 week. The letters Ms can be found at a specific temperature for each kind of steel. Ms represents the temperature at which austenite begins to transform to martensite during cooling. The Mf temperature is the point at which the transformation of austenite to martensite is completed or near 100 percent during cooling. This is sometimes replaced by a percentage of transformation.



Method of plotting I-T diagram. Austenitized specimens are placed in a furnace or salt bath and held at a specific temperature. They are removed at specific time intervals and quenched in brine. Each specimen, having been marked for its time period, is then prepared and checked with a microscope for its lack of transformation products (it would be fully martensite in that case) or its percentage of transformation and at what time interval transformation began and ended. Probably many more specimens would be used for a single temperature plot than this diagram shows.

What About Cooling Rates?

- Faster cooling gives "non-equilibrium microconstituents"...
 - -Bainite
 - -Martensite
 - -And more!
- To know what microconstituents are present, you must look at cooling curve diagrams

<u>General Demonstration:</u> Isothermal Diagrams

ISOTHERMAL TRANSFORMATION DIAGRAMS

- Fe-C system, Co = 0.77wt%C
- Transformation at T = 675C.



COOLING HISTORY Fe-C SYSTEM

- Eutectoid composition, Co = 0.77wt%C
- Begin at T > 727C
- Rapidly cool to 625C and hold isothermally.



NON-EQUIL TRANSFORMATION PRODUCTS: Fe-C

-- α lathes (strips) with long rods of Fe₃C --diffusion controlled. Isothermal Transf. Diagram 800 Austenite (stable) ١E T(°C) Α 100% pearlite | -----pearlite/bainite boundary 600 100% bainite В 400 Α

100°/0

105

time (s)

50%

10³

Bainite:

200

10-1

10

٠





OTHER PRODUCTS: Fe-C SYSTEM (1)

--heat bainite or pearlite for long times --reduces interfacial area (driving force) Isothermal Transf. Diagram 800 Austenite (stable) T(°C) ١F Α 100% spheroidite 600 Spheroidite 100% spheroidite B 400-Α ×00°/0 200 . 50°/° 10³ 10⁵time (s) 10-1 10

-- α crystals with spherical Fe₃C

--diffusion dependent.

• Spheroidite:



60 μ**m**

OTHER PRODUCTS: Fe-C SYSTEM (2)



Martentite needles Austenite

- γ to M transformation..
 - -- % transf. depends on T only.

COOLING EX: Fe-C SYSTEM (1)



COOLING EX: Fe-C SYSTEM (2)



COOLING EX: Fe-C SYSTEM (3)



Critical cooling rates

- **X** <u>Different alloys can affect the shape of the I-T diagrams</u>:
- **1.** An increase in carbon content moves the S-curve to the right (increases the time before transformation takes place).
- 2. Grain size also has an effect on hardenability (the property that determines the depth and distribution of hardness induced by quenching a ferrous alloy). Larger-grain carbon steels also take more time to transform. This also moves the S-curve to the right.
- 3. The addition of alloy to the steel also moves the S-curve to the right.
- ★ A plain low carbon steel cannot be hardened for practical purposes because the nose of the diagram is at or falls short of the zero time line, and it would be impossible to avoid cutting into it with the quenching or cooling curve (shown before).

Isothermal heat treatment methods

1. Isothermal annealing is done by quenching from above the critical range to the desired annealing temperature in the upper portion of the I-T diagram and holding at the anneal temperature for a length of time sufficient to produce complete transformation (Figure 9). This method produces a more uniform microstruc-ture than conventional annealing, in which the steel is very slowly cooled.

2. Another method of hardening and tempering is a form of isothermal quenching called austempering (Figure 7), in which a part is austenitized and quenched into a lead or salt bath held at a temperature of approximately 600°F (316°C) to produce a desired microstructure of lower bainite. It is held at this temperature for several hours until 0 complete transformation has taken place. This type of hardening eliminates the need for tempering

3. Martempering (Figure 8), in which the austenitized part is brought to slightly over the Ms temperature and held for a few minutes in order to equalize the interior and exterior temperatures to avoid stresses. Then the quench is continued to the Mf temperature, followed by conventional tempering.

4. Spherodizing



Continuous cooling curves

<u>There</u> are two main types of transformation diagram that are helpful in selecting the optimum steel and processing route to achieve a given set of properties. These are

- 1. time-temperature transformation (TTT) and
- 2. continuous cooling transformation (CCT) diagrams.

<u>CCT</u> diagrams are generally more appropriate for engineering applications as components are cooled (air cooled, furnace cooled, quenched etc.) from a processing temperature as this is more economic than transferring to a separate furnace for an isothermal treatment.

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Factors influence the succefullness of the heat treatment process:

- 1. The quenching media (includes the severity of the media). The severity from high to low can be ranked as follows: 5% caustic soda, 20% brine, cold water, warm water, mineral oil, animal oil, vegetable oil, air, insulating material or furnace.
- 2. The composition of the alloy (shifting of critical cooling rate to the right)
- **3.** The size and shape of the specimen (Figure below)

Quenching media

Quenching describes the sudden immersion of a heated metal into cold water or oil. It is used make the metal very hard. to Quenching process is typically by cooling at a comparatively high rate. This is done to avoid problems like internal microstructure that are not desired, ensuring uniform mechanical property, minimal residual stress, warpage avoidance.

Types of quenching

- A. LIQUID QUENCHING
- 1. still-bath
- 2. flush quenching
- B. Dry quenching
- C. Polymer quenching

In still-bath quenching, you cool the metal in a tank of liquid. The only movement of the liquid is that caused by the movement of the hot metal, as it is being quenched

In flush quenching, the liquid is sprayed onto the surface and into every cavity of the part at the same time to ensure uniform cooling.

Heat treatment equipment:

- **1.** Furnaces
- Types of furnaces:
- Electric
- Gas
- Oil-fueled

Sizes: small to very largectric Temperature: up to 1371C. Auxiliary parts: Temperature controller Temperature recording system

Important factors: soaking time&soaking temp.

Disadvantages of small electric furnaces:

Oxidation at high temperature which leads to the decarburization of the surface of the metal.

Overcoming this problem:

- 1. Inert gas environment
- 2. Wrapping the metal in stainless steel foil
- 3. Packing In cast iron chips
- 4. Wrapping with a paste of boric acid and water

2. Pot Furnaces (High temperature salt baths)

Disadvantages:

The difference between the temperature of surface and the temperature of the core (rate of heating) leads to cracking or distorsion

Overcoming this problem:

Bath of solid salt prevents rapid heating

- 1. Overheating (coarse grains and poor quality)
- 2. Extreme overheating (damage of the grain boundaries)
- **3.** Shape of the part (hole and sharp shoulders leads to a crack development)
- 4. Quench cracks

Heat treatment of non ferrous alloys

NONFERROUS ALLOYS



Main methods of the heat treatment of <u>ferrous:</u>

- **1. Solution heat treatment**
- 2. Precipitation heat treatment (aging) Requisite features of the phase diagram for precipitation hardening:
- **1.** An appreciable maximum solubility of one component in the other.
- 2. Solubility limit that rapidly decreases in concentration of the major component with temperature reduction

PRECIPITATION HARDENING



Hardening and strengthening mechanism



Schematic depiction of several stages in the formation of the equilibrium precipitate (θ) phase. (a) A supersaturated α solid solution. (b) A transition, θ'' , precipitate phase. (c) The equilibrium θ phase, within the α matrix phase. Actual phase particle sizes are much larger than shown here.



Logarithm of aging time

Schematic diagram showing tensile strength and hardness as a function of the logarithm of aging time at constant temperature during the precipitation heat treatment.

Casting process and metallurgy
Casting:

Molten metals are cast into molds and allowed to solidify for the purpose of producing the desired product by using different techniques(Processes).

Casting Processes:

- 1. Sand casting
- 2. Shellmolding
- 3. Plaster mold casting
- 4. Ceramic-mold casting
- 5. Evaporated pattern casting (lost-foam process)
- 6. Investment casting (lost wax process)

Casting Processes (cont.):

- 7. Permanent mold casting
- Pressure casting
- Die casting
- Vacuum casting
- Slush casting
- 8. Centrifugal casting
- 9. Squeeze casting & semisolid metal forming
- **10.** Composite mold casting operations



Schematic illustration of a sand mold, showing various

features.

Risering system design

<u>Riser</u> is a part of gating system that forms the reservoir of molten metal necessary to compensate for losses due to shrinkage as the metal solidifies.

- <u>Risers</u> are only effective if three conditions are met:
- **1.** The riser cools after the casting
- 2. The riser has enough material compensate for the casting shrinkage
- 3. The casting <u>directionally solidifies</u> towards the riser

In general we have two methods for finding riser's size :

Method 1 :

To calculate the minimum size of a riser is to use Chvorinov's rule by setting the solidification time for the riser to be longer than that of the casting. Any time can be chosen but 25% longer is usually a safe choice, which is written as follows:

$$t_{riser} = 1.25t_{casting}$$

• Or

$$\left(\frac{V}{A}\right)_{\rm riser}^n = 1.25 \left(\frac{V}{A}\right)_{\rm casting}^n$$

Steps in Sand Casting



Shell molding

Shell molding first was developed in the 1940s and has grown significantly because it can produce many types of castings with close dimensional tolerances and a good surface finish at low cost. Shell-molding applications include small mechanical parts requiring high precision, such as gear housings, cylinder heads, and connecting rods. The process also is used widely in producing high-precision molding cores. The capabilities of shell-mold casting are given in Table 11.2.

In this process, a mounted pattern made of a ferrous metal or aluminum is (a) heated to a range of 175° to 370°C, (b) coated with a parting agent (such as silicone), and (c) clamped to a box or chamber. The box contains fine sand, mixed with 2.5 to 4% of a thermosetting resin binder (such as phenol-formaldehyde) that coats the sand particles. Either the box is rotated upside down (Fig. 11.9) or the sand mixture is blown over the pattern, allowing it to coat the pattern.



FIGURE 11.9 The shell-molding process, also called the dump-box technique.

investment casting

A variation of the investment-casting process is ceramic-shell casting. It uses the same type of wax or plastic pattern, which is dipped first in ethyl silicate gel and subsequently into a fluidized bed of finegrained fused silica gel and subsequently into coarser-grained silica or zircon flour. The pattern then is dipped into coarser -grained silica to build up additional coatings and develop a proper thickness so that the pattern can withstand the thermal shock due to pouring. The rest of the procedure is similar to investment casting. This process is economical and is used extensively for the precision casting of steels and high-temperature alloys.



FIGURE 11.13 Schematic illustration of the investment casting (lost-wax) process. Castings produced by this method can be made with very fine detail and from a variety of metals. *Source*: Courtesy of Steel Founders' Society of America.

DIE- CASTING

The *die casting* process, developed in the early 1900s, is a further example of permanent-mold casting. Typical parts made by die casting are motor housings, engine blocks, business-machine and appliance components, hand tools, and toys. The weight of most castings ranges from less than 90 g to about 25 kg. Equipment costs, particularly the cost of dies, are somewhat high, but labor costs are generally low, because the process is now semi- or fully automated. Die casting is economical for large production runs. The capabilities of die casting are given in Table 11.2.

In this process, the molten metal is forced into the die cavity at pressures ranging from 0.7 to 700 MPa. The European term *pressure-die casting* (or simply die casting), which is described in this section, is not to be confused with the term *pressure casting* described in Section 11.3.4. There are two basic types of die-casting machines: hot-chamber and cold-chamber.



FIGURE 11.17 Schematic illustration of the hot-chamber die-casting process.

Centrifugal casting

As its name implies, the *centrifugal-casting* process utilizes inertial forces (caused by rotation) to distribute the molten metal into the mold cavities—a method that was first suggested in the early 1800s. There are three types of centrifugal casting: true centrifugal casting, semicentrifugal casting, and centrifuging.

True centrifugal casting. In *true centrifugal casting*, hollow cylindrical parts (such as pipes, gun barrels, bushings, engine-cylinder liners, bearing rings with or without flanges, and streetlamp posts) are produced by the technique shown in Fig. 11.20. In this process, molten metal is poured into a rotating mold. The axis of rotation is usually horizontal but can be vertical for short workpieces. Molds are made of steel, iron, or graphite and may be coated with a refractory lining to increase mold life. The mold surfaces can be shaped so that pipes with various external designs can be cast. The inner surface of the casting remains cylindrical, because the molten metal is distributed uniformly by the centrifugal forces. However, because of density differences, lighter elements (such as dross, impurities, and pieces of the refractory lining) tend to collect on the inner surface of the casting. Consequently, the properties of the casting can vary throughout its thickness.



FIGURE 11.21 (a) Schematic illustration of the semicentrifugal casting process. Wheels with spokes can be cast by this process. (b) Schematic illustration of casting by centrifuging. The molds are placed at the periphery of the machine, and the molten metal is forced into the molds by centrifugal force.

Main Ferrous casting alloys

- 1. Gray cast iron
- 2. Ductile cast iron
- 3. White cast iron
- 4. Malleable
- 5. Compacted graphite iron (between flake raphite and nodular graphite cast iron)
- 6. Cast steels
- 7. Cast stainless steel

Micrographs of different types of cast iron





FIGURE 23. White cast iron, etched (500 \times).





FIGURE 21. Nodular cast iron, unetched $(500 \times)$.



FIGURE 22. Micrograph of malleable cast iron, unetched $(100 \times)$. (By permission, from *Metals Handbook*, Volume 7, Copyright American Society for Metals, 1972)

Non ferrous casting alloys

- 1. Al-base alloys
- 2. Mg-base alloys
- 3. Cu-base alloys
- 4. Zn-base alloys
- 5. High temperature base alloys such as Ti....etc.

Casting Metallurgy

The Development of the Microstructure

- 1. When a pure metal solidifies, each crystal begins to form independently from a nucleus or 'centre of crystallisation'.
- 2. The nucleus will be a simple unit of the appropriate crystal lattice, and from this the crystal will grow.
- The crystal develops by the addition of atoms according to the **3**. lattice pattern it will follow, and rapidly begins to assume visible proportions in what is called a 'dendrite' (Gk 'dendron', a tree). This is a sort of crystal skeleton, rather like a backbone from which the arms begin to grow in other directions, depending upon the lattice pattern. From these secondary arms, tertiary arms begin to sprout, somewhat similar to the branches and twigs of a fir-tree. In the metallic dendrite, however, these branches and twigs conform to a rigid geometrical pattern. A metallic crystal grows in this way because heat is dissipated more quickly from a point, so that it will be there that the temperature falls most quickly leading to the formation of a rather elongated skeleton (Fig. 3.10).



Fig. 3.10 The early stages in the growth of a metallic dendrite.



Plate 3.1 Dendritic growth.

This iron dendrite grew from a nucleus at 'n' in a molten mixture of iron and copper. After all the available iron had been used up the dendrite ceased to grow, and the molten copper solidified as the matrix in which the iron dendrite remains embedded. (In fact the iron dendrite will contain a little dissolved copper—in 'solid solution'—whilst the copper matrix will contain a very small amount of dissolved iron). \times 300..

Large Ingots

In a large ingot the crystal size may vary *considerably from the outside* surface to the centre (Fig. 3.13). This is due to the variation which exists in the temperature gradient as the ingot solidifies and heat is transferred from the metal to the mould. When metal first makes contact with the mould the latter is cold, and this has a chilling effect which results in the formation of small crystals at the surface of the ingot. As the mould warms up, its chilling effect is reduced, so that the formation of nuclei will be retarded as solidification proceeds. Thus crystals towards the centre of the ingot will be larger. In an intermediate position the rate of cooling is favourable to the formation of elongated columnar crystals, so that we are frequently able to distinguish three separate zones in the crystal structure of an ingot, as shown in Fig. 3.13. More recent research into rapid solidification processes (RSP) has been carried out with the object of obtaining metals and alloys with extremely tiny crystals, and in some cases retaining the amorphous structure of the original liquid at ambient temperatures (9.110).

PLANES OF WEAKNESS DUE -TO CORNERS



Defects in castings

- **1.** Blow-holes and porosity
- 2. Shrinkage
- 3. Segregation of impurities (the presence of low melting segregates along grain boundaries increase the tendency for hot tearing)
- 4. Incomplete casting
- 5. Line and point defects

Annealing of castings

- The most suitable treatment for a large casting involves heating it slowly up to a temperature about 40°C above its upper critical (thus the annealing temperature depends upon the carbon content of the steel), holding it at that temperature only just long enough for a uniform temperature to be attained throughout the casting and then allowing it to cool slowly in the furnace. This treatment not only introduces the improvements in mechanical properties associated with fine grain but also removes mechanical strains set up during solidification.
- As the lower critical temperature (723°C) is reached on heating, the patches of pearlite transform to austenite but these new crystals of austenite are very small since each patch of pearlite gives rise to many new austenite crystals. It is upon this fact that the complete success of this type of annealing process depends. As the temperature rises, the Widmanstatten-type plates of ferrite are dissolved by the austenite until, when the upper critical temperature is reached, the structure consists entirely of finegrained austenite. Cooling causes reprecipitation of the ferrite, but, since the new austenite crystals are small, the precipitated ferrite will also be distributed as small particles. Finally, as the lower critical temperature is reached, the remaining small patches of austenite will transform to pearlite. The structural changes taking place during annealing are illustrated dia-grammatically in Fig. 11.9.



Fig. 11.9 Structural changes occurring during the annealing of a steel casting (approx 0.35% carbon). The as-cast Widmanstätten structure is reheated to some temperature above its upper critical and then allowed to cool in the furnace.

Normalizing of castings

- X Normalising resembles the 'full' annealing of castings described in 11.53 in that the maximum temperature attained is similar. It is in the method of cooling that the processes differ. Whilst, in annealing, cooling is retarded, in normalising the steel is removed from the furnace and allowed to cool in still air. This relatively rapid method of cooling limits grain growth in normalising, whilst the ferrite/cementite lamellae in pearl-ite will also be much finer. For both reasons the mechanical properties are somewhat better than in an annealed component. Moreover, the surface finish of a normalised article is often superior to that of an annealed one when machined, since the high ductility of the latter often gives rise to local tearing of the surface.
- ★ The type of structure obtained by normalising will depend largely upon the thickness of cross-section. Thin sections will give a much finer grain than thick sections, the latter differing little in structure from an annealed section.

Joining processes

Observations:

- 1. Products made of one component such as paper clips, nails, steel ball
- 2. Products made of two components such as kitchen knives, cooking spots,etc.
- 3. Products made of more than two components such as computers, cars, ... etc

Reasons behind assembly operations:

- **1.** Product may be impossible to manufacture as a single piece
- 2. More economic to manufacture the product as individual parts
- **3.** Different properties may be desirable (automotive brake shoes-surface and bulk)
- 4. For maintenance purposes
- 5. For transportation purposes

Examples of WELDING PROCESSES

- **1.** Arc Welding
- 2. Resistance Welding
- 3. Oxyfuel Gas Welding
- 4. Solid State Welding

What is an Electric Arc?

An electric arc is a discharge of electric current across a gap in a circuit

- It is sustained by an ionized column of gas (plasma) through which the current flows
- To initiate the arc in AW, electrode is brought into contact with work and then quickly separated from it by a short distance

A pool of molten metal is formed near electrode tip, and as electrode is moved along joint, molten weld pool solidifies in its wake



Figure 31.1 Basic configuration of an arc welding process.

Two Basic Types of AW Electrodes

- Consumable consumed during welding process
 - -Source of filler metal in arc welding
- Nonconsumable not consumed during welding process

-Filler metal must be added separately

Weldability of ferrous alloys

1.	Plain carbon steel
2.	Medium carbon steel
3 .	High carbon steel
4.	Low alloy steel
5.	High alloy steel
6 .	Stainless steel
7.	Cast iron

good Fair poor Fair **good**(under controlled conditions) weldable Varied weldability

Defects in welds

Defect	Figure
Porosity	Caused by gases released during melting of the weld area but trapped during solidification, chemical reactions, Contaminants
Slag inclusions	Compounds such as oxides ,fluxes, and electrode- coating materials that are trapped in the weld Zone
Incomplete fusion & penetration	(a) (b) Weld Incomplete fusion from oxide or dross at the center of a joint, especially in aluminum Metal (c) Weld Incomplete fusion find a groove weld
Weld profile	(a) Underfill Inclusions Crack Incomplete penetration (b) Porosity Overlap Undercut (c) Good weld
Cracks	
Residual stresses	

Three welding distinct zones:

- 1. Base metal
- 2. Heat Affected Zone (HAZ)
- 3. Weld metal

The metallurgy of the second and third zones strongly depend on:

- 1. The type of metal joined
- 2. The type of joining process
- 3. The filler metal used
Why Post-Weld Heat Treat?

The fast cooling rates associated with welding often produce martensite

- During postweld heat treatment, martensite is tempered (transforms to ferrite and carbides)
 - +Reduces hardness
 - +Reduces strength
 - +Increases ductility
 - +Increases toughness
- Residual stress is also reduced by the postweld heat treatment

Postweld Heat Treatment and Hydrogen Cracking

- Postweld heat treatment (~ 1200°F) tempers any martensite that may have formed
 - +Increase in ductility and toughness
 - +*Reduction in strength and hardness*
- Residual stress is decreased by postweld heat treatment
- Rule of thumb: hold at temperature for 1 hour per inch of plate thickness; minimum hold of 30 minutes

Multipass Welds

- Heat from subsequent passes affects the structure and properties of previous passes
 - -Tempering
 - -Reheating to form austenite
 - -Transformation from austenite upon cooling
- Complex Microstructure

Knife-Line Attack in the HAZ



- $Cr_{23}C_6$ precipitate in HAZ
 - Band where peak temperature is 800-1600°F
- Can occur even in stabilized grades
 - Peak temperature dissolves titanium carbides
 - Cooling rate doesn't allow them to form again

Review and Introduction

Terms and definitions

Metallurgy

Metallurgy is the technology of extracting metals from their ores and adapting them for use and the science or study of the behavior, structure, properties, and composition of metals that leads to development of alloy properties.

Branches of metallurgy.

- **1. Extractive metallurgy**, which is freeing the metal atoms from a combined state.
- **2. Physical metallurgy**, which is the study of properties and composition of metals.
- 3. Powder metallurgy, which is the technology of producing useful metal shapes from metallic powder (P/M)

Definitions

• The physical world is composed of **matter and energy**. Matter is defined as anything that occupies space

- Matter is anything occupies space & composed of atoms
- Energy is the ability to do work

• Einstein's discoveries leading to this atomic age revealed that matter and energy are related. A small amount of matter releases a tremendous amount of energy under certain conditions. • An **element is** Matter composed of a single kind of atoms.

• A **compound** is composed of two or more elements combined chemically.

• A **mixture** is two or more elements or compounds physically combined in the same way in which two fine powders are mixed together

• The molecule is defined as the smallest particle of any substance that can exist free and still exhibit all the chemical properties of that substance. A molecule can consist of one or more atoms



Iron: pure iron or contains less than .02 wt % carbon.

Steel: iron + (contains 0.02 < carbon <2.0 wt %)

Cast Iron: Iron + (contains 2.0 < carbon < 6.69 wt %)

Ferrous alloys: iron based alloys

Non-ferrous alloys: non iron based alloys

Plain carbon steel: contains only residual concentrations of impurities other than carbon and a little Mn.

Alloy steel: when more alloying elements are intentionally added in specific concentrations

Background

THE PERIODIC TABLE

Columns: Similar Valence Structure



Readily give up electrons to become + ions.

Electronegative elements Readily acquire electrons to become - ions. Subatomic structure

Bohr model

BOHR ATOM



ELECTRON DESCRIPTION: FIXED POSITION FIXED ENERGY DISCRETE ORBITS

Nucleus: Z = # protons = 1 for hydrogen to 94 for plutonium N = # neutrons

Atomic mass $A \approx Z + N$

What's wrong with Bohr's model of the atom?

Chemistry > Bohr Model of the atom

2 Answers



The main problem with Bohr's model is that it works very well for atoms with only one electron, like H or He+, but not at all for multi-electron atoms. Bohr was able to predict the difference in energy between each energy level, allowing us to predict the energies of each line in the emission spectrum of hydrogen, and understand why electron energies are quantized.

Bohr's model breaks down when applied to multielectron atoms. It does not account for sublevels (s,p,d,f), orbitals or elecrtron spin. Bohr's model allows classical behavior of an electron (orbiting the nucleus at discrete distances from the nucleus.

The application of Schrodinger's equation to atoms is able to explain the nature of electrons in atoms more accurately.



Defects of the Bohr's model are as follows -

1) According the the uncertainty principle, the exact position and momentum of an electron is indeterminate and hence the concept of definite paths (as given by Bohr's model) is out if question. Thus the concept of orbitals is thrown out.

2) It couldn't be extended to multi-electron systems. Systems that could work would be $H, He^{+1}, Li^{+2}, Be^{+3}$ etc.

Also, the Bohr's theory couldn't explain the fine structure of hydrogen spectrum and splitting of spectral lines due to an external electric field (Stark effect) or magnetic field (Zeeman effect).

It couldn't explain why some lines on the spectra where brighter than the others, i.e., why are some transitions in the atom more favourable than the others.

Wave-mechanical model

ELECTRON ENERGY STATES

Electron Description

POSITION: PROBABILITY DISTRIBUTION

- have discrete energy states
- tend to occupy lowest available energy state.

OCCUPIRD ENERGY STATE (CONFIGURATION): ACCORDING TO QUANTUM NUBERS & ENERGY STATE

QUANTUM NUMBERS:

PRINCIPAL NUMBER
 SECONDARY NUMBER
 MAGNETIC NUMBER
 SPIN NUMBER



STABLE ELECTRON CONFIGURATIONS

Stable electron configurations...

have complete s and p subshells
tend to be unreactive.

Ζ	Element	Configuration
2	He	1s ²
10	Ne	$1s^{2}2s^{2}p^{6}$
18	Ar	1s ² 2s ² 2p ⁶ 3s ² 3p ⁶
36	Kr	1s ² 2s ² 2p ⁶ 3s ² 3p ⁶ 3d ¹⁰ 4s ² 4p ⁶

Not STABLE ELECTRON CONFIGURATIONS

• Most elements: Electron configuration not stable.

Element	Atomic #	Electron configuration
Hydrogen	1	1s ¹
Helium	2	1s ² (stable)
Lithium	3	1s ² 2s ¹
Beryllium	4	1s ² 2s ²
Boron	5	1s ² 2s ² 2p ¹
Carbon	6	1s ² 2s ² 2p ²
•••		•••
Neon	10	1s ² 2s ² 2p ⁶ (stable)
Sodium	11	1s ² 2s ² 2p ⁶ 3s ¹
Magnesium	12	1s ² 2s ² 2p ⁶ 3s ²
Aluminum	13	1s ² 2s ² 2p ⁶ 3s ² 3p ¹
•••		•••
Argon	18	1s ² 2s ² 2p ⁶ 3s ² 3p ⁶ (stable)
•••		•••
Krypton	36	1s ² 2s ² 2p ⁶ 3s ² 3p ⁶ 3d ¹⁰ 4s ² 4 ⁶ (stable)

• Why? Valence (outer) shell usually not filled completely.

Atomic Bonds



 Primary bonds -Metallic -lonic -Covalent Secondary bonds -Vander waals forces (London Forces) Mixed bonds

Primary bond for metals and their alloys

METALLIC BONDING

• Arises from a sea of donated valence electrons (1, 2, or 3 from each atom).



IONIC BONDING

- Occurs between + and ions.
- Requires electron transfer.
- Large difference in electronegativity required.
- Example: NaCl



COVALENT BONDING

- Requires shared electrons
- Example: CH4
 - C: has 4 valence e, needs 4 more
 - H: has 1 valence e, needs 1 more
 - Electronegativities are comparable.



SECONDARY BONDING

Arises from interaction between dipoles

• Fluctuating dipoles



Permanent dipoles-molecule induced



SUMMARY: BONDING

Type	Bond Energy	Comments
Ionic	Large!	Nondirectional (ceramics)
Covalent	Variable large-Diamond small-Bismuth	Directional semiconductors, ceramics polymer chains)
Metallic	Variable large-Tungsten small-Mercury	Nondirectional (metals)
Secondary	smallest	Directional inter-chain (polymer) inter-molecular





Metallurgical Processes

By

Professor Issam S. Jalham

Industrial Engineering Department School of Engineering University of Jordan Amman - Jordan

1	Course title	Metallurgical Processes
2	Course number	0946513
	Credit hours	3
3	Contact hours (theory, practical)	3 theory + 0 practical (1 hr-3 times per week-16 weeks)
4	Prerequisites/corequisites	0906411
5	Program title	Industrial Engineering
6	Program code	
7	Awarding institution	University of Jordan
8	School	School of Engineering
9	Department	Industrial Engineering
10	Level of course	Fifth year
11	Year of study and semester (s)	2020-2021 Summer semester
12	Final Qualification	BSc
13	Other department (s) involved in teaching the course	none
14	Language of Instruction	English
15	Teaching methodology	□Blended ⊠Online
16	Electronic platform(s)	☑Moodle ☑Microsoft Teams □Skype□Zoom□Others
17	Date of production/revision	28 June 2020

Course Description

This course demonstrates the basic principles of metallurgical processes. As an introduction, there will be a definition of metallurgy terms, classification of metals and alloys, and an overview of the ironiron carbon diagram and the influence of alloying elements on it. On the other hand, a general idea of the heat treatment of steels will be introduced. Moreover, the heat treatment of ferrous and non-ferrous alloys, cast iron, and welding will be demonstrated. Case studies will be given to support the knowledge.

Objectives

This course is designed for use in industrial and manufacturing engineering courses. The main objectives of this course is to provide the students with the necessary knowledge about metallurgical processes. The student will be shown how to select the proper method of heat treatment for the intended product, to select the machines and tools, determine the right operations and to calculate time and other parameters of each operation.

Learning Outcomes:

Successful completion of the course should lead to the following:

- The student should be able to understand the significance of Designing and Planning of metallurgical processes and the terms related to this subject.
- The student should be able to understand how to calculate the parameters of each operation
- The student should be able to understand and select the proper metallurgical process for the intended steel
- The student should be able to differentiate between the heat treatment of ferrous and non-ferrous alloys.
- The student should be able to understand the metallurgical process of cast iron
- The student should be able to understand the metallurgical process of welding

Relationship of the Course content to the Student Learning Outcomes

- an ability to identify, formulate, and solve complex engineering problems by applying principles of engineering, science, and mathematics
- an ability to apply engineering design to produce solutions that meet specified needs with consideration of public health, safety, and welfare, as well as global, cultural, social, environmental, and economic factors
- ³ ability to communicate effectively with a range of audiences
- an ability to recognize ethical and professional responsibilities in engineering situations and make informed judgments, which must consider the impact of engineering solutions in global, economic, environmental, and societal contexts
- an ability to function effectively on a team whose members together provide leadership, create a collaborative and inclusive environment, establish goals, plan tasks, and meet objectives
- ⁶ an ability to develop and conduct appropriate experimentation, analyze and interpret data, and use engineering judgment to draw conclusions
- $_{\rm 7}$ ability to acquire and apply new knowledge as needed, using appropriate learning $_{\rm v}$ strategies

Week #	Торіс	
1	Introduction	
2	Notes on specifications(BS, ASTM, AISI, SAE, DIN, GOST, and UNS)	
3-4	Conventional Heat treatment methods of steels	
5-8	Heat treatment methods of steels using I-T Diagrams	
9-10	Heat treatment methods of non-iron base alloys	
11-13	Heat treatment methods of castings and	
14-15	Heat treatment methods of welding	
16-16	Project defense	

Evaluation Methods				
Evaluation Activity	Mark	Topic(s)	Period (Week)	Platform
Midterm exam or Assignment	30% (26-11-2020)	Covers all topics	In due	e-learning and
Course project	20% (23-12-2020)		course	NIICrosoft teams
Final exam	50%			

Course Requirements

students should have:

- 1. a computer, internet connection, webcam, account on a specific software/platform
- 2. access to library (books and periodicals)

Course Policies

All the following points should comply with the university regulations:

A- Attendance policies:

B- Absences from exams and submitting assignments on time:

C- Health and safety procedures:

D- Honesty policy regarding cheating, plagiarism, misbehavior

E- Grading policy:

F- Available university services that support achievement in the course

References

- A- Required book(s), assigned reading and audio-visuals:
- 1. Raymond A. Higgins, Engineering Metallurgy, Part 1 : Applied Physical Metallurgy, Latest edition.
- B- Recommended books, materials and media:
- 1. Herman W. Pollack, Materials science and Metallurgy, prentice Hall Corp., 1981 or Latest edition
- 2. William D. Callister, Jr., 3rd edition (or latest), John Wiley & Sons Inc., 1994 or Latest edition
Project-based learning (PBL) Rubrics



Final product/ outcome of the project How the students will submit their work?

- Video
- Constructive model
- Art
- Fact sheet
- Brochure
- Poster
- Power point presentation
- Assignment (written account)



هذا المُنحَنى البسيط يُسَمّى (تأثير دانينج-كروغر)Dunning-Kruger Effect..للعالِمَين (دايفيد دانينغ) و(جاستن كروغر). - المُنحَنى يُوَضِّح العِلاقَة النِسبيّة بين "ثِقَةِ الإنسان بنفسه" (وهو المِحوَر الرأسي) و"خِبراتِه ومَعَارفِه في مجال ما" (وهو المِحوَر الأفقى)...ويمكننا إجمال ما يُفسّره في ٣ جوانب رئيسية: ١- الجانب الأيسَر من المُنحنى: (الثقة الزائدة بالنفس). يمكنكم ببساطة ملاحظة أنه في الوقت الذي تكون خِبراتُ الإنسان ومعارفُه في مجال ما تساوي (صفر%) فإنّ ثِقَتَه بنفسه تكون (100%) تقريبا!...ما يعنى أن الجاهل يَستَشعِر ثِقةً لا مثيل لها في آرائه وأطروحاته ولا يَشْكَ مُطلقاً في قدراته وعِلمِه وصِحَة آرائه...وهي مرحلة الوَهم ومُقاومة التغبيرا ٢- الجُزء الأوسط من المُنحَنى: حيث أنه ومع زيادة مَعرفةٍ الإنسان وخبراتِه يَتَسَرِّب الضوء إلى عَقله وقَلبه وتَقِلّ ثِقَتُه...ويزداد لديه الشَّك في آرائه ومدى قدرته على الإحاطة ا بموضوع ما الى الحَدّ الأدنى لها...فتتولد لديه تدريجياً ثقة حقيقية نابعة من عِلمٍ وإدراك حقيقى؛ ويتبدّد بَعدَها الوَهم تىاعاً! ٣- الجانب الأيمن من المُنحنى: لاحظوا أن الإنسان المُكتَملُ. المعرفة والتجربة (بموضوع ما)؛ لن تَتعدّى ثِقَتْه بنفسه نسبة (70%)…إذ يَظلُّ العالِمُ والخبير مدركاً بأنَّ شيئاً ما لازال غائباً عنه...وكذلك يَستَشعِر ضَعفَه تجاه الإدراك الكامل لماهتة الأمور والاحاطة الشاملة! وهو ما تجده في تَوَاضُع كَثير من العُلَماء والخُبرَاء الحقيقيين!

Dunning-Kruger Effect



Subatomic structure

Bohr model

BOHR ATOM



ELECTRON DESCRIPTION: FIXED POSITION FIXED ENERGY DISCRETE ORBITS

Nucleus: Z = # protons = 1 for hydrogen to 94 for plutonium N = # neutrons

Atomic mass $A \approx Z + N$

What's wrong with Bohr's model of the atom?

Chemistry > Bohr Model of the atom

2 Answers



The main problem with Bohr's model is that it works very well for atoms with only one electron, like H or He+, but not at all for multi-electron atoms. Bohr was able to predict the difference in energy between each energy level, allowing us to predict the energies of each line in the emission spectrum of hydrogen, and understand why electron energies are quantized.

Bohr's model breaks down when applied to multielectron atoms. It does not account for sublevels (s,p,d,f), orbitals or elecrtron spin. Bohr's model allows classical behavior of an electron (orbiting the nucleus at discrete distances from the nucleus.

The application of Schrodinger's equation to atoms is able to explain the nature of electrons in atoms more accurately.



Defects of the Bohr's model are as follows -

1) According the the uncertainty principle, the exact position and momentum of an electron is indeterminate and hence the concept of definite paths (as given by Bohr's model) is out if question. Thus the concept of orbitals is thrown out.

2) It couldn't be extended to multi-electron systems. Systems that could work would be $H, He^{+1}, Li^{+2}, Be^{+3}$ etc.

Also, the Bohr's theory couldn't explain the fine structure of hydrogen spectrum and splitting of spectral lines due to an external electric field (Stark effect) or magnetic field (Zeeman effect).

It couldn't explain why some lines on the spectra where brighter than the others, i.e., why are some transitions in the atom more favourable than the others.

Wave-mechanical model

ELECTRON ENERGY STATES

Electron Description

POSITION: PROBABILITY DISTRIBUTION

- have discrete energy states
- tend to occupy lowest available energy state.

OCCUPIRD ENERGY STATE (CONFIGURATION): ACCORDING TO QUANTUM NUBERS & ENERGY STATE

QUANTUM NUMBERS:

PRINCIPAL NUMBER
 SECONDARY NUMBER
 MAGNETIC NUMBER
 SPIN NUMBER



STABLE ELECTRON CONFIGURATIONS

Stable electron configurations...

have complete s and p subshells
tend to be unreactive.

Ζ	Element	Configuration
2	He	1s ²
10	Ne	$1s^{2}2s^{2}p^{6}$
18	Ar	1s ² 2s ² 2p ⁶ 3s ² 3p ⁶
36	Kr	1s ² 2s ² 2p ⁶ 3s ² 3p ⁶ 3d ¹⁰ 4s ² 4p ⁶

Not STABLE ELECTRON CONFIGURATIONS

• Most elements: Electron configuration not stable.

Element	Atomic #	Electron configuration
Hydrogen	1	1s ¹
Helium	2	1s ² (stable)
Lithium	3	1s ² 2s ¹
Beryllium	4	1s ² 2s ²
Boron	5	1s ² 2s ² 2p ¹
Carbon	6	1s ² 2s ² 2p ²
•••		•••
Neon	10	1s ² 2s ² 2p ⁶ (stable)
Sodium	11	1s ² 2s ² 2p ⁶ 3s ¹
Magnesium	12	1s ² 2s ² 2p ⁶ 3s ²
Aluminum	13	1s ² 2s ² 2p ⁶ 3s ² 3p ¹
		•••
Argon	18	1s ² 2s ² 2p ⁶ 3s ² 3p ⁶ (stable)
•••		•••
Krypton	36	1s ² 2s ² 2p ⁶ 3s ² 3p ⁶ 3d ¹⁰ 4s ² 4 ⁶ (stable)

• Why? Valence (outer) shell usually not filled completely.

Atomic Bonds



 Primary bonds -Metallic -lonic -Covalent Secondary bonds -Vander waals forces (London Forces) Mixed bonds

Primary bond for metals and their alloys

METALLIC BONDING

• Arises from a sea of donated valence electrons (1, 2, or 3 from each atom).



IONIC BONDING

- Occurs between + and ions.
- Requires electron transfer.
- Large difference in electronegativity required.
- Example: NaCl



COVALENT BONDING

- Requires shared electrons
- Example: CH4
 - C: has 4 valence e, needs 4 more
 - H: has 1 valence e, needs 1 more
 - Electronegativities are comparable.



SECONDARY BONDING

Arises from interaction between dipoles

• Fluctuating dipoles



Permanent dipoles-molecule induced



SUMMARY: BONDING

Type	Bond Energy	Comments
Ionic	Large!	Nondirectional (ceramics)
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Metallic	Variable large-Tungsten small-Mercury	Nondirectional (metals)
Secondary	smallest	Directional inter-chain (polymer) inter-molecular





Crystal structure

METALLIC CRYSTALS

- **1. SIMPLE CUBIC CRYSTAL STRUCTURE**
- 2. BODY CENTERED CUBIC CRYSTAL STRUCTURE (BCC)
- 3. FACE CENTERED CUBIC STRUCTURE (FCC)
- 4. HEXAGONAL CLOSE-PACKED CRYSTAL STRUCTURE (HCP)
- 5. TRICLINIC
- 6. MONOCLINIC
- 7. ORTHORHOMBIC
- 8. RHOMBOHEDRAL
- **9. TETRAGONAL**
 - Simple

- Body centered tetragonal (BCT)

SIMPLE CUBIC STRUCTURE (SC)

Rare due to poor packing

• Close-packed directions are cube edges.





• Coordination # = 6 (# nearest neighbors)







• APF for a simple cubic structure = 0.52

BODY CENTERED CUBIC STRUCTURE (BCC)

--Note: All atoms are identical; the center atom is shaded differently only for ease of viewing.



• Coordination # = 8





= 2 atoms/unit cell

Close-packed directions: length = 4R = $\sqrt{3}$ a

Close packed directions are cube diagonals.



• APF for a body-centered cubic structure = 0.68

FACE CENTERED CUBIC STRUCTURE (FCC)

--Note: All atoms are identical; the face-centered atoms are shaded differently only for ease of viewing.

• Coordination # = 12







Unit cell contains: 6 x 1/2 + 8 x 1/8 = 4 atoms/unit cell

Close packed directions are face diagonals.

Close-packed directions: length = 4R = $\sqrt{2}$ a



• APF for a body-centered cubic structure = 0.74

FCC STACKING SEQUENCE

- ABCABC... Stacking Sequence
- 2D Projection

B

A

C

A

B

A





A

B

A

A

A

B

A

A

B

A

B

A

C



• FCC Unit Cell



HEXAGONAL CLOSE-PACKED STRUCTURE (HCP)

ABAB... Stacking Sequence





• Coordination # = 12

• APF = 0.74

Microsturucture

AREA DEFECTS: GRAIN BOUNDARIES

Grain boundaries:

- are boundaries between crystals.
- are produced by the solidification process, for example.
- have a change in crystal orientation across them.
- impede dislocation motion.



Schematic



Metal Ingot



Grain size calculation methods

- Mean linear intercept method
- ASTM Method

 $N = 2^{n-1}$

- N = 1- 5 coarse grained structure
- *N* = 5 8 *Fine grained structure*
- 70% falls in the range

Crystalline changes during heating

• <u>Allotropy (Iron)</u>



Standards and Specifications of metals and alloys

Classification of materials and alloys is very important as it is:

- 1. Necessary not to repeat the conduction of experiments every time to explore the properties of the same alloy
- 2. Necessary for material selection for a certain applications.
- 3. Necessary to ease the communication among scientists and researchers
- 4. Necessary to ease the communications between companies and dealers.
- 5. Necessary to group materials and alloys that have the same behavior.

Methods of steel classification

The main methods of steel classification are:

- 1. By analysis
- 2. By mechanical properties
- 3. By use.

The widely used method of classification is by analysis.

Commonly used standard

Commonly used standards are:

- 1. British standard (BS)
- 2. American society for testing and materials (ASTM)
- 3. American iron and steel institute (AISI)
- 4. Society of automotive engineers (SAE)
- 5. German standard (DIN)
- 6. Former soviet union (commicon) standard (GOST)
- 7. Unified numbering system (UNS)

BS as an example

```
@ Each "En" designation detailed analysis
                                              range,
mechanical range, conditions, and other necessary
information
Example: BS970:060A52
060- percent of manganese
A – the requirements that the steel supplied to
     (A- analysis, M-mechanical properties, H-
     hardenability)
52- percent of carbon
If the first three digits are 200-240 it is free cutting
                Sulphur content
manganese steel.
```

Examples: Table 12.2 Higgins book

		Comp	position (%)				Typical Me	chanical p	roperties	
Туре	BS970.	С	Mn	Heat-treatment	Ruling Section (mm)	Tensile strength (N/mm ²)	Yield strength (N/mm ²)	Elongation Izod (%) (J)		Hardness (Brinell)
Low	015A03	0.03	0.15	Not heat-treatable—used where	-	-	-	-	-	-
car	050A1. 060A17	0.12	0.50 0.60	ductility and formability are required	2	-	-	-	=	=
	'20' - 070M20 carbon	0.20	0.70	Normalised at 880–910°C. Water-guenched 880–910°C:	150	430	215	21	-	150
				tempered 550-660°C.	20	620	355	20	41	180
h	'30' 080M30 carbon	0.30	0.80	Normalised at 860–890°C. Water quenched 860–890°C;	150	495	250	20	-	165
teels				lempered 550-660°C.	20	695	415	16	34	205
onal si	'40' 080M40 carbon	0.40	0.80	Normalised at 830–860°C. Water quenched 830–860°C; tempered 550–660°C.	150	540	280	16	20	180
uctic					20	770	465	16	34	230
115112	'50' 080M50 carbon	0.50	0.80	Normalised at 810-840°C. Oil guenched 810-840°C; tempered	150	620	310	14	-	205
				550-660°C.	12.7	925	570	12	-	275
	'55' 070M55 carbon	0.55	0.70	Normalised at 810–840°C. Oil quenched 810–840°C; tempered 550–660°C.	63.5	695	355	12	-	230
					20	930	575	12	-	275
	080A62	0.62	0.80	Heat-treated to give required		_				
oon	080A72	0.72	0.80	combination of hardness and		-	_			
	080A83	0.83	0.80	toughness-generally used as tool		-				
	060A86	0.86	0.60	steels		-				
	060A99	1.00	0.60	and the second second second second		-			The second second	

(Compositions for some of the carbon-manganese free-cutting steels will be found in Table 6.2) For typical uses of steels in the above Table refer to Table 7.1 and Fig. 7.7.

AISI and SAE

There is a minor variation between AISI and SAE standards.

AISI is a four digit system for plain carbon steel (Example: - - -). First two digits describe the steel and the remained is the percent of carbon. Examples:

10xx – plain carbon steel

1050 - plain carbon steel with .0.5% carbon

11xx – free machining plain carbon steel with sulphure addition


SAE three digits:

Example:

Stainless steel

2xx is achromium-nickel manganese steel non hardenable, austenitic

3xx....

4xx.....

Sometimes letter and two digits (Mxx)

M-molebdinum steel

T- tungesten steel

H- hot worked steel

O- oil hardened steel

Unified numbering system (UNS)

@ UNS provides a designation system for all present and future metals and alloys. The system was published by the SAE in 1975. SAE and ASTM are now using this system and it is proposed to the ISO.

@ UNS establishes 15 series of numbers for metals and alloys. Each UNS number consists of a single letter prefix followed by five digits. The letter is suggestive of the family of metals identified. Example: A- for aluminum, P- for precious materials

And whenever feasible, identification numbers are from existing systems. Example:

Plain carbon steel AISI1020

(becomes) G1 1020

Cont

D00001 D93599	Specified mechanical property
E 00001 - F92929	Cast inens, Corray, malleable, peurli
•	ducije (nodular), carbon SI
	Low alloy Steel casting
C-00001-6-95915	AISE-SAE Curbon & allow St
1 0 2 0 0 1 - H 935 53	AISE H Steels
	tool Sheel
K00001 - K93559	Miscellaneous steels & Ferrars
50000 - 598359	Stainless Steels
T0000193499	Tool Steels
non-terrors merculs	
A00001 - A99999	alumin & glumining
C 00001 - C 49999	Copper & Copper alloys
E _ E 94 ~ .	Rane earth and rare e
	Low meleing mergls
NA M >3593	prisce laneous meral
	Nickel & is allows
$-\rho$ $-\rho$	Precion alloys
	refraction & reaction



Individual work

Metallurgical Processes

By

Professor Issam S. Jalham

Industrial Engineering Department School of Engineering University of Jordan Amman - Jordan

Isothermal Transformation (I-T) Diagrams:

Isothermal Transformation (I-T) Diagrams:

Once it was discovered that the time and temperature of austenite transformation had a profound influence on the transformation products, a new kind of graph or diagram was needed. The ironcarbon diagram would not do, because it represents equilibrium or slow cooling and austenite transformation takes place under non-equilibrium conditions with various cooling rates. Austenite is unstable below the A1 line on the iron-carbon diagram and almost immediately begins to transform to some product such as pearlite or bainite. An I-T diagram shows this process very well.

Isothermal Transformation (I-T) Diagrams:

It is the heat treatment process that uses the Temperature – Time - Transformation (TTT) curves. (I-T diagrams are also called the Bain S-Curve or T-T-T (time-temperature-transformation) diagrams)

TTT Curve: It is a graphical representation of the cooling of the specimen that relates the microstructure to temperature and time.

<u>Purpose</u>: this process assumes that the temperature of the piece is held constant for a period of time before cooling.

Construction of the TTT Diagram

When plotting an I-T diagram, three facts should be kept in mind:

1. When austenite is cooled below the A1 line to a particular temperature and held at that temperature, it will begin to transform in a given time and will complete the transformation after a given time peculiar to that steel.

2. Martensite is formed only at relatively low temperatures and almost instantaneously.

3. If austenite transforms at any point in the transformation to a structure that is stable at room temperature, rapid cooling will not change the product already transformed, but the remaining untransformed austenite will form martensite.

Construction of the TTT Diagram

- X Data for isothermal transformation diagrams are obtained by heating large numbers of small steel specimens of a specific kind of steel to the austenitization temperature (Figure below). They are then abruptly transferred to furnaces or molten salt baths that have been heated to predetermined temperatures below the critical line A1.
- * To study the transformation at 1200°F (649°C), a set of specimens is held at 1200°F (649°C) constant temperature (isothermal). At regular time intervals a specimen is removed and rapidly quenched in iced brine. Microscopic examination will then show martensite if transformation has not yet started, but will show martensite and pearlite (in this case) if transformation has started, and only pearlite if transformation is complete. A mark is placed on the graph, indicating the time and temperature.

Construction of the TTT Diagram

This procedure is repeated at other temperatures until the entire graph is plotted for that particular steel (Figure 3). The vertical scale on the left represents temperature and the horizontal scale on the bottom represents time. It is plotted on a log scale that corresponds to 1 minute, 1 hour, 1 day, and 1 week. The letters Ms can be found at a specific temperature for each kind of steel. Ms represents the temperature at which austenite begins to transform to martensite during cooling. The Mf temperature is the point at which the transformation of austenite to martensite is completed or near 100 percent during cooling. This is sometimes replaced by a percentage of transformation.



FIGURE 3. Method of plotting I-T diagram. Austenitized specimens are placed in a furnace or salt bath and held at a specific temperature. They are removed at specific time intervals and quenched in brine. Each specimen, having been marked for its time period, is then prepared and checked with a microscope for its lack of transformation products (it would be fully martensite in that case) or its percentage of transformation and at what time interval transformation began and ended. Probably many more specimens would be used for a single temperature plot than this diagram shows.

PROCESSING OPTIONS



What About Cooling Rates?

- Faster cooling gives "non-equilibrium microconstituents"...
 - -Bainite
 - -Martensite
 - -And more!
- To know what microconstituents are present, you must look at cooling curve diagrams

Microconstituents vs. Cooling Rate

- Spheroidite: Spherical "globs" of Fe3C in Ferrite
- Pearlite: Layers of α ferrite and Fe3C
 - Course Pearlite
 - -Fine Pearlite
- Bainite: 200 500 °C Transformation

• Martensite: Rapid Cooling

Spheroidite

- If tempered for a long time, Fe3C forms "spheres" and grows inside Ferrite.
- Very soft, easy to machine



Bainite

Upper (550-350°C) - Rods of Fe3C Lower (350-250°C) - Fe3C Precipitates in Plates of Ferrite It is still Ferrite and Cementite! It's just acicular.



Martensite

X Diffusionless transformation of FCC to BCT (more volume!) X Lenticular structure × Very hard & very brittle.



General Demonstration: Isothermal Diagrams

ISOTHERMAL TRANSFORMATION DIAGRAMS

- Fe-C system, Co = 0.77wt%C
- Transformation at T = 675C.



COOLING HISTORY Fe-C SYSTEM

- Eutectoid composition, Co = 0.77wt%C
- Begin at T > 727C
- Rapidly cool to 625C and hold isothermally.



NON-EQUIL TRANSFORMATION PRODUCTS: Fe-C



OTHER PRODUCTS: Fe-C SYSTEM (1)



OTHER PRODUCTS: Fe-C SYSTEM (2)

Martensite: --γ(FCC) to Martensite (BCT)



Isothermal Transf. Diagram





Martentite needles
Austenite

- γ to M transformation..
 - -- is rapid!
 - -- % transf. depends on T only.

Critical cooling rates

Different alloys can affect the shape of the I-T diagrams:

- 1. An increase in carbon content moves the S-curve to the right (increases the time before transformation takes place).
- 2. Grain size also has an effect on hardenability (the property that determines the depth and distribution of hardness induced by quenching a ferrous alloy). Largergrain carbon steels also take more time to transform. This also moves the S-curve to the right.
- 3. The addition of alloy to the steel also moves the S-curve to the right.

A plain low carbon steel cannot be hardened for practical purposes because the nose of the diagram is at or falls short of the zero time line, and it would be impossible to avoid cutting into it with the quenching or cooling curve (shown before).



Cooling rate that passes through the star (nose) is called the critical cooling rate



FIGURE 5. The Ms temperature is a function of the carbon content and will be further lowered when alloying elements are added. After finding the Ms temperature for steel containing a particular carbon content, subtract the following: 70 times the percentage of chromlum, 70 times the percentage of manganese, 50 times the percentage of molybdenum, and 35 times the percentage of nickel (based on Fahrenheit temperatures).





Examples of isothermal heat treatment:

- 1. Eutectoid alloy of carbon steel
- 2. Hyper eutectoid alloy of carbon steel
- 3. Hypo eutectoid
- 4. Low carbon steel







Hypo eutectoid alloy

TTT diagram for a hypoeutectoid composition (0.5 wt % C) com--Fe₃C phase diagram. Microstructural development for the slow cool-

ing of this alloy was shown in Figure 5.5-5. By comparing Figures 6.2-6, 6.2-9, and 6.2-10, one will note that the martensitic transformation occurs at decreasing temperatures with increasing carbon content in the region of the eutectoid composition. (ITT diagram after Atlas of Isothermal Transformation and Cooling Transformation Diagrams, American Society for Metals, Metals Park, Ohio, 1977.)



FIGURE 7. Brine quench cooling curve for SAE 1008 carbon steel. (United States Steel Corporation)

A plain low carbon steel cannot

be hardened for practical purposes because the nose of the diagram is at or falls short of the zero time line, and it would be impossible to avoid cutting into it with the quenching or cooling curve.



FIGURE 8. Brine quench cooling curve for 1034 modified Mn steal. (United States Steel Corporation)

Isothermal heat treatment methods

Isothermal heat treatment methods similar to those of the conventional methods:

- **1. Isothermal annealing**
- 2. Austempering
- 3. Martempering
- 4. Spherodizing

Isothermal heat treatment methods

1. Isothermal annealing is done by quenching from above the critical range to the desired annealing temperature in the upper portion of the I-T diagram and holding at the anneal temperature for a length of time sufficient to produce complete transformation. This method produces a more uniform microstructure than conventional annealing, in which the steel is very slowly cooled.



FIGURE 9. Isothermal annealing. (Bethlehem Steel Corporation)

2. Another method of hardening and tempering is a form of isothermal quenching called austempering , in which a part is austenitized and quenched into a lead or salt bath held at a temperature of approximately 600°F (316°C) to produce a desired micro-structure of lower bainite. It is held at this temperature for several hours until a complete transformation has taken place.



FIGURE 7. Austempering. (Bethlehem Steel Corporation)

3. Martempering

the austenitized part is brought to slightly over the Ms temperature and held for a few minutes in order to equalize the interior and exterior temperatures to avoid stresses. Then the quench is continued to the Mf temperature, followed by conventional tempering.


4. Spherodizing

Spheroidite:

 --α crystals with spherical Fe₃C
 -diffusion dependent.
 -heat bainite or pearlite for long times
 -reduces interfacial area (driving force)

Isothermal Transf. Diagram





Heat treatment equipment:

HEAT TREATMENT FURNACES

Definition

Heat treating furnaces are essentially heating chambers, i.e., a refractory vessel which holds the steel stock as well the heat. The furnace chamber is heated with some source of heat. The supply of heat must be regulated depending on the requirement. More heat is needed during the heating period, but almost a constant heat is required when the furnace has attained the required temperature and is to be maintained at that temperature.

The heat has to be supplied to the whole of the properly designed furnace in a way that the temperature is constant everywhere, or at the places where the charge is being kept otherwise some parts may get under heated, or overheated. The doors, or openings are kept as small sized as possible to reduce the heat losses.

Tempering and low temperature furnaces may require provisions for forced air or atmosphere circulation. The carburized parts may be quenched inside the furnace itself. **General Requirements for Furnaces**

- 1. Heating source.
- 2. Conservation of heat generated.
- 3. Constant temperature inside it.
- 4. Openings.
- 5. Controlled atmosphere (necessary).
- 6. Structure of the furnace must withstand high temperatures and hard conditions.

Sizes: small to very large

Auxiliary parts: Temperature controller, Temperature cording system

Important factors: soaking time & soaking temp

Sizes: small to very large



CONSIDERATIONS FOR CHOOSING FURNACES

- 1. The purpose for which type of material needs to be heated.
- 2. Source of heat and the Nature of heat transfer to the material.
- 3. Heating by batch or continuously and the method of handling materials.
- 4. Type of heat recovery (an energy recovery system that recovers normally wasted heat; it can have great savings on energy bills).
- 5. Other types of furnace classifications.

For further detailed information about Heat Treatment furnaces you can refer to literature Here, we will give some useful information that may help in understanding what may happen during the process of heat treatment.

Disadvantages of small electric furnaces:

Oxidation at high temperature which leads to the decarburization of the surface of the metal.

Overcoming this problem:

- **1.** Inert gas environment
- 2. Wrapping the metal in stainless steel foil
- 3. Packing In cast iron chips
- 4. Wrapping with a paste of boric acid and water

Problems in heat treatment

- **1.** Overheating (coarse grains and poor quality)
- 2. Extreme overheating (damage of the grain boundaries)
- 3. Shape of the part (hole and sharp shoulders leads to a crack development)
- 4. Quench cracks

Characteristics of quench cracks:

- 1. In general, the fractures run from the surface towards the center in a relatively straight line. The crack tends to spread open
- 2. Since quench cracking occurs at relatively low temperatures, the crack will not show any decarburization or oxidation.
- **3.** The fracture surfaces will exhibit a fine crystalline structure when tempered after quenching

- 1. Overheating during the austenizing cycle (fine grains become coarse)
- 2. Improper selection of the quenching medium (using water or brine instead of oil for an oil hardening steels)
- **3. Improper selection of steel**
- 4. Time delay between quenching and tempering
- 5. Improper design (sharp edges, holes,...etc)
- 6. Improper angle of the work into the quenching medium.

Safety

When heat treating, always wear a face shield, leather, gloves, and long sleeves. There is a definite hazard to the face and eys when cooling the tool steel by quenching, that is, submerging it in oil. The oil, hot from the steel, tends to fly upward, so you should stand to one side of the oil tank and not lean over it.

Always work in pairs during heat treatment. One person can open and close the furnace door while the other handles the hot part. The heat-treated part should be positioned in the furnace so it can be conveniently removed. This will prevent the heat treater from dropping hot parts and help to ensure successful heat treatment. Atmospheric furnaces should never be opened until the gas supply is turned off. Failure to do so could result in an explosion.

Safety Note. Very toxic fumes are present when parts are being carburized with compounds containing potassium cyanide. These cyanogen compounds are highly poisonous and every precaution should be taken when using them. Kasenite[®], a trade name for a carburizing compound that is not toxic, is often found in school shops and machine shops.

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Casting process and metallurgy

Casting:

Molten metals are cast into molds and allowed to solidify for the purpose of producing the desired product by using different techniques(Processes).

Casting Processes:

- **1.** Sand casting
- 2. Shell molding
- 3. Plaster mold casting
- 4. Ceramic-mold casting
- 5. Evaporated pattern casting (lost-foam process)
- 6. Investment casting (lost wax process)

Casting Processes (cont.):

- **7. Permanent mold casting**
- Pressure casting
- Die casting
- Vacuum casting
- Slush casting
- 8. Centrifugal casting
- 9. Squeeze casting & semisolid metal forming
- **10. Composite mold casting operations**

Introduction:

1. The traditional method of casting metals is in sand molds and has been used for a thousand-year period. Sand casting is still the most prevalent form of casting; in the United States alone, about 15 million tons of metal are cast by this method each year. Typical applications of sand casting include machine bases, large turbine impellers, propellers, plumbing fixtures, and numerous component for agricultural and railroad equipment. 2. Types of Sands: Most sand- casting operations use silica sand (SiO2) as mold material. Sand is not expensive and is suitable as mold material because of its high- temperature characteristics and high melting point. There are <u>two general types of sand</u>: naturally bonded (bank sand) and synthetic (lake sand). Because its composition can be controlled more accurately, synthetic sand is preferred by most foundries. For proper functioning, mold sand must be clean and preferably new.

3. Sand Selection: Several <u>factors</u> are important in the selection of sand for molds, and it involves certain tradeoffs with respect to properties. Sand having fine, round grains can be packed closely and, thus, forms a smooth mold surface. Although fine-grained sand enhances mold strength, the fine grains also lower mold permeability (penetrating through pores). Good permeability of molds and cores allows gases and steam evolved during the casting to escape easily. Resistance to high temperature and cost are also factors that are taken into consideration.

4. Composition:

Sand 90% , clay 7%, and water 3%.

Sand molds

Sand molds are characterized by the types of sand that comprise them and by the methods used to produce them. There are three basic types of sand molds: green-sand, cold-box, and nobale molds. The most common mold material is green molding sand, which is a mixture of sand, clay, and water.

The term "green" refers to the fact that the sand in the mold is moist or damp while the metal is being poured into it. Green-sand molding is the least expensive method of making molds, and the sand is recycled easily for the subsequent use. In the skin-dried method, the mold surfaces are dried, either by storing the mold in air or by drying it with torches. Because of their higher strength, these molds generally are used for large castings.

Sand mold design:



The main parts of the mold:

- 1. Gating and
 - **Risering systems**
- 2. Mold cavity

The mold design parts & terms

- 1- the flask, which supports the mold itself. Twopieces molds consist of a cope on top and a drag on the bottom; the seam between them is the parting line. when more than two pieces are used in a sand mold, the additional parts are called cheeks.
- 2- a pouring basin or pouring cup, into which the molten metal is poured.
- 3- a sprue, through which the molten metal flows downward.
- 4- the runner system, which has channels that carry the molten metal from the sprue to the mold cavity. Gates are the inlets into the mold cavity.
- 5- risers, which supply additional molten metal to the casting as it shrinks during solidification. Two types of risers, a blind riser and an open riser

6- Cores, which are inserts made from sand. They are placed in the mold to form hollow regions or otherwise define the interior surface of the casting. Cores also are used on the outside of the casting to form features such as lettering on the surface of a casting or deep external pockets.

7- vents, which are placed in molds to carry off gases produced when the molten metal comes into contact with the sand in the mold and the core. Vents also exhaust air from the mold cavity as the molten metal flows into the mold. 8- Parting line (proper placement of parting *line facilitates gating & eliminate porosity)* 9- Draft (Tapering of sand mold). **10- Corners and angles should be avoided** 11. Allowances for shrinkage and machining should be added

Gating system design

The elements of gating system are :

- pouring basin, sprue and sprue base.
- runners, runner extension and ingates.
- Riser .

Pouring basin The main function of a pouring basin is to reduce the momentum of the liquid flowing into the mold by settling first into it



Pouring Basin



Crucible Mold Interface (Pouring Target)

Sprue and sprue base

It creates hydraulic pressure head, which will force the metal through the rest of the gating system and into the casting.





Ingate

The ingate can be considered as a weir with no reduction in cross section of the stream at the gate .

Ingate should not be located near a protruding part of the mould to avoid the striking of vertical mould walls by molten metal stream.

Ingates should be preferably be placed along the longitudinal axis of the mould wall.

It should not be placed near a core print or a chill.

Ingate cross sectional area should preferably be smaller than the smallest thickness of the casting so that the ingates solidify first and isolate the casting from the gating system.

Runner

The function of the runner is to change the direction of the flow of metal from vertical to horizontal.



Design theoretical basic principles :

- Bernoulli's theorem
- Law of mass continuity
- Pouring Time
- Reynold's Number
- Chvorinov's Rule

Are used to calculate velocity in ideal fluid system

$(V_{12} \div 2g) + (P_1 \div \rho) + h_1 = (V_{22} \div 2g) + (P_2 \div \rho) + h_2$

where :

V1 & V2 : metal velocity at two different points 1 & 2, in ft/sec.

- g : acceleration due to gravity.
- P & P : static pressure in the liquid at P1 P2 points 1 & 2 in lb/sq,in.
- h1 & h2 : height of liquid at points 1 & 2 in ft.
- **ρ** : density of liquid in lb/ cu.ft.

The law of continuity states that the flow rate must be the same at a given time in all portions of a fluid system. It may be written as:-

 $\mathbf{Q} = \mathbf{A}_1 \mathbf{V}_1 = \mathbf{A}_2 \mathbf{V}_2$

where

Q : metal flow rate in cu.ft/sec

A1 & A2 : cross-sectional area of flow channel at two different points 1 & 2 in sq.ft.

V1 & V2 : metal velocity at points 1 & 2 in ft/sec.

Reynold's Number

-Pouring time is the time to complete filling of a mold .

-Nature of flow in the gating system can be established by calculating Reynold's number

$$R_{N} = \frac{V \mathcal{D} \rho}{\mu}$$

- $R_N = Reynold's number$
- V = Mean Velocity of flow
- D = diameter of tubular flow
- m = Kinematics Viscosity = Dynamic viscosity / Density
 - · = Fluid density

• relates the solidification time for a simple casting to the volume and surface area of the casting.

$$t = B\left(\frac{V}{A}\right)^n$$

• Where t is the solidification time, V is the volume of the casting, A is the surface area of the casting that contacts the mold, n is a constant, and B is the mold constant.

Risering system design

- <u>Riser</u> is a part of gating system that forms the reservoir of molten metal necessary to compensate for losses due to shrinkage as the metal solidifies.
- **<u>Risers</u>** are only effective if three conditions are met:
- 1. The riser cools after the casting
- 2. The riser has enough material compensate for the casting shrinkage
- **3.** The casting <u>directionally solidifies</u> towards the riser

In order for the riser to cool after the casting the riser must cool more slowly than the casting. *Chvorinov's* **rule** briefly states that the slowest cooling time is achieved with the greatest volume and the least surface area; geometrically speaking, this is a sphere. So, ideally, a riser should be a sphere, but this isn't a very practical shape to insert into a mold, so a cylinder is used instead. The height to diameter ratio of the cylinder varies depending on the material, location of the riser, size of the flask, etc.

The shrinkage must be calculated for the casting to confirm that there is enough material in the riser to compensate for the shrinkage. If it appears there is not enough material then the size of the riser must be increased. This requirement is more important for plate-like shapes, while the first requirement is more important for chunky shapes.

The casting must be designed to produce directional solidification, which sweeps from the extremities of the mold cavity toward the riser(s). In this way, the riser can feed molten metal continuously to part of the casting that is solidifying One part of achieving this end is by placing the riser near the thickest and largest part of the casting, as that part of the casting will naturally want to solidify last. If this type of solidification is not possible, multiple risers that feed various sections of the casting or chills may be necessary

The efficiency of a casting is defined as the weight of the casting divided by the weight of the total amount of metal poured.

Risers can add a lot to the total weight being poured, so it is important to optimize their size and shape. Because risers exist only to ensure the integrity of the casting, they are removed after the part has cooled, and their metal is remelted to be used again. As a result, riser size, number, and placement should be carefully planned to reduce waste while filling all the shrinkage in the casting.

Method 1 :

To calculate the minimum size of a riser is to use Chvorinov's rule by setting the solidification time for the riser to be longer than that of the casting. Any time can be chosen but 25% longer is usually a safe choice, which is written as follows:

$$\left(\frac{V}{A}\right)_{\text{riser}}^{n} = 1.25 \left(\frac{V}{A}\right)_{\text{casting}}^{n}$$

Method 2 :

* Since risers are typically of a cylindrical shape, their important dimensions are the riser

- * diameter, DR, and the riser height, H.
- * For top risers, the riser height should be at least equal to the riser diameter, H = DR.
- * For side risers, H = 1.5DR is often used. A riser height exceeding 1.5 times the riser diameter is uneconomical and does not improve the feeding ability of the riser; in fact, it can lead to secondary shrinkage cavities inside the riser.
- *Some castings require one or more risers, depending on the feeding distances and the riser diameters. To calculate the riser size, one must know :
- 1. the shape factor, SF = (L +W)/T,
- 2. the volume, VC = L × W × T, of that part of the section that is fed by the riser.
- 3. Calculate the riser volume, VR the following expression : V = 2.51*VC*SF

Individual work

For detailed information as the determination of the number of risers, using the chart method, riserless design,etc, see the related literature.




Shell molding

Shell molding first was developed in the 1940s and has grown significantly because it can produce many types of castings with close dimensional tolerances and a good surface finish at low cost. Shell-molding applications include small mechanical parts requiring high precision, such as gear housings, cylinder heads, and connecting rods. The process also is used widely in producing high-precision molding cores.

In this process, a mounted pattern made of a ferrous metal or aluminum is (a) heated to a range of 175° to 370°C, (b) coated with a parting agent (such as silicone), and (c) clamped to a box or chamber. The box contains fine sand, mixed with 2.5 to 4% of a thermosetting resin binder (such as phenol-formaldehyde) that coats the sand particles. Either the box is rotated upside down (Fig.) or the sand mixture is blown over the pattern, allowing it to coat the pattern.



FIGURE The shell-molding process, also called the *dump-box* technique.

The assembly then is placed in an oven for a short period of time to complete the curing of the resin. In most shell-molding machines, the oven consists of a metal box with gas-fired burners that swing over the shell mold to cure it. The shell hardens around the pattern and is removed from the pattern using built-in ejector pins. Two half-shells are made in this manner and are bonded or clamped together to form a mold.

The thickness of the shell can be determined accurately by controlling the time that the pattern is in contact with the mold. In this way, the shell can be formed with the required strength and rigidity to hold the weight of the molten liquid. The shells are light and thin (usually 5 to 10 mm), and consequently, their thermal characteristics are different from those for thicker molds. Shell sand has a much lower permeability than the sand used for green-sand molding, because a sand of much smaller grain size is used for shell molding. The decomposition of the shell-sand binder also produces a high volume of gas. Consequently, unless the molds are vented properly, trapped air and gas can cause serious problems in the shell molding of ferrous castings. The high quality of the finished casting can reduce cleaning, machining, and other finishing costs significantly. Complex shapes can be produced with less labor, and the process can be automated fairly easily.

investment casting

Since the 1960s, investment-cast super-alloys have been replacing wrought counter-parts in high-performance gas turbines. Much development has been taking place in producing superalloys (nickel-based and cobalt-based). cleaner Improvements have been made in melting and casting techniques, such as vacuum-induction melting and using microprocessor controls. Impurity and inclusion levels have continually been reduced, improving the strength and ductility of these components. Such control is essential, because these parts operate at a temperature only about 50 C (90 F) below the solidus temperature of the alloy.

The microstructure of an integrally investment-cast, gasturbine rotor is shown. Note the fine, uniform, equiaxed grains throughout the rotor cross-section. The procedures include the use of a nucleate addition to the molten metal, as well as close control of its superheat, pouring techniques, and control of cooling rate of the casting. In contrast, note the coarse- grain structure in the lower half of the figure showing the same type of rotor cast conventionally. This rotor has inferior properties compared with the fine-grained rotor. Due to developments in these processes, the proportion of cast parts to other parts in aircraft engines has increased from 20% to about 45% by weight.



Schematic illustration of the investment casting (lost-wax) process. Castings produced by this method can be made with very fine detail and from a variety of metals. *Source*: Courtesy of Steel Founders' Society of America.

DIE-CASTING

The *die casting* process, developed in the early 1900s, is a further example of permanent-mold casting. Typical parts made by die casting are motor housings, engine blocks, business-machine and appliance components, hand tools, and toys. The weight of most castings ranges from less than 90 g to about 25 kg. Equipment costs, particularly the cost of dies, are somewhat high, but labor costs are generally low, because the process is now semi- or fully automated. Die casting is economical for large production runs.

In this process, the molten metal is forced into the die cavity at pressures ranging from 0.7 to 700 MPa.

The hot-chamber process (Fig.) involves the use of a piston, which traps a certain volume of molten metal and forces it into the die cavity through a gooseneck and nozzle. Pressures range up to 35 MPa with an average of about 15 MPa. The metal is held under pressure until it solidifies in the die. To improve die life and to aid in rapid metal cooling (thereby reducing cycle time) dies usually are cooled by circulating water or oil through various passageways in the die block. Low-meltingpoint alloys (such as zinc, magnesium, tin, and lead) commonly are cast using this process. Cycle times usually range from 200 to 300 shots (individual injections) per hour for zinc, although very small components such as zipper teeth can be cast at rates of 18,000 shots per hour.

In the cold-chamber process (Fig.), molten metal is poured into the injection cylinder (*shot chamber*). The chamber is not heated, hence the term *cold chamber*. The metal is forced into the die cavity at pressures usually ranging from 20 to 70 MPa, although they may be as high as 150 MPa.

The machines may be horizontal (as in the figure) or vertical, in which case the shot chamber is vertical. High-melting-point alloys of aluminum, magnesium, and copper normally are cast using this method, although other metals (including ferrous metals) also can be cast. Molten-metal temperatures start at about 600°C for aluminum and some magnesium alloys, and increase considerably for copper-based and iron-based alloys.



Schematic illustration of the hot-chamber die-casting process.

Schematic illustration of the cold-chamber die-casting process. These machines are large compared to the size of the casting, because high forces are required to keep the two halves of the dies closed under pressure. **Process capabilities and machine selection.** Die casting has the capability for rapid production of strong, high-quality parts with complex shapes, especially with aluminum, brass, magnesium, and zinc (Table). It also produces good dimensional accuracy and surface details, so that parts require little or no subsequent machining or finishing operations (net-shape forming). Because of the high pressures involved, walls as thin as 0.38 mm are produced, which are thinner than those obtained by other casting methods. However, ejector marks remain, as may small amounts of flash (thin material squeezed out between the dies) at the die parting line.

TΔ	R	T 1	F
10			ú

Alloy		Ultimate tensile strength (MPa)	Yield strength (MPa)	Elongation in 50 mm (%)	Applications
Alumin	um 380 (3.5 Cu-8.5 Si)	320	160	2.5	Appliances, automotive components, electrical motor frames and housings
	13 (12 Si)	300	150	2.5	Complex shapes with thin walls, part requiring strength at elevated temperatures
Brass 85	58 (60 Cu)	380	200	15	Plumbing fixtures, lock hardware, bushings ornamental castings
Magnes	ium AZ91 B (9 Al-0.7 Zn)	230	160	3	Power tools, automotive parts, sporting goods
Zinc	No. 3 (4 Al)	280		10	Automotive parts, office equipment, household utensils, building hardware, toys
	No. 5 (4 Al-1 Cu)	320	_	7	Appliances, automotive parts, building hardware, business equipment

Source: American Die Casting Institute.

Centrifugal casting

As its name implies, the *centrifugal-casting* process utilizes inertial forces (caused by rotation) to distribute the molten metal into the mold cavities—a method that was first suggested in the early 1800s. There are three types of centrifugal casting: true centrifugal casting, semicentrifugal casting, and centrifuging.

True centrifugal casting. In *true centrifugal casting*, hollow cylindrical parts (such as pipes, gun barrels, bushings, engine-cylinder liners, bearing rings with or without flanges, and streetlamp posts) are produced by the technique shown in Fig. 11.20. In this process, molten metal is poured into a rotating mold. The axis of rotation is usually horizontal but can be vertical for short workpieces. Molds are made of steel, iron, or graphite and may be coated with a refractory lining to increase mold life. The mold surfaces can be shaped so that pipes with various external designs can be cast. The inner surface of the casting remains cylindrical, because the molten metal is distributed uniformly by the centrifugal forces. However, because of density differences, lighter elements (such as dross, impurities, and pieces of the refractory lining) tend to collect on the inner surface of the casting. Consequently, the properties of the casting can vary throughout its thickness.

Cylindrical parts ranging from 13 mm to 3 m in diameter and 16 m long can be cast centrifugally with wall thicknesses ranging from 6 to 125 mm. The pressure generated by the centrifugal force is high (as much as 150 g); such high pressure is necessary for casting thick-walled parts. Castings with good quality, dimensional accuracy, and external surface detail are produced by this process.

Semicentrifugal casting. An example of *semicentrifugal casting* is shown in Fig. 11.21a. This method is used to cast parts with rotational symmetry, such as a wheel with spokes.

Centrifuging. In *centrifuging* (also called *centrifuge casting*), mold cavities of any shape are placed at a certain distance from the axis of rotation. The molten metal is poured from the center and is forced into the mold by centrifugal forces . The properties of the castings can vary by distance from the axis of rotation, as in true centrifugal casting.



(a) Schematic illustration of the semicentrifugal casting process. Wheels with spokes can be cast by this process. (b) Schematic illustration of casting by centrifuging. The molds are placed at the periphery of the machine, and the molten metal is forced into the molds by centrifugal force.

Casting Metallurgy



Types of castings

- A. Ferrous casting alloys
- **B.** Non ferrous casting alloys

A. Ferrous casting alloys:0.0-0.02 % carbon -Ferrite0.02-2.0% carbon -Steel2.0-4.3 carbon -Cast iron

Cast iron contains 2.0-4.3 % carbon Si = 2.3-3% added to increase fluidity

In this course, we will focus on ferrous alloys

Main Ferrous casting alloys

- 1. Gray cast iron
- 2. Ductile cast iron
- 3. White cast iron
- 4. Malleable
- 5. Compacted graphite iron (between flake graphite and nodular graphite cast iron)
- 6. Cast steels
- 7. Cast stainless steel

Gray cast iron

Main properties:

- Gray color
- Hard
- Weak in tension
- Graphite exists in the form of flakes

 $(500 \times)$.

- Microstructure: graphite flakes, pearlite, and ferrite



Microstructure: graphite flakes, pearlite, and ferrite

Ductile cast iron

- Ductile cast iron is known by *several names*: nodular iron, ductile iron, and spheroidal graphite iron. It gets the names from the balllike form of the graphite in the metal and the very ductile property it exhibits. Nodular cast iron combines many of the advantages of cast iron and steel. *Its advantages include* good castability, toughness, machinability, good shock and wear resistance, weld-ability, low melting point, corrosion resistance, and hardenability.
- The formation of the graphite into a ball form is accomplished by adding certain elements such as magnesium and cerium to the melt just prior to casting. The vigorous mixing reaction caused by adding these elements results in a homogenous spheroidal or ball-like structure of the graphite in the cast iron. The iron matrix or background material can be heat treated to form any one of the microstructures associated with steels, such as ferrite, bainite (as in austempered ductile iron), pearlite, or martensite

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shows the microstructure of the NCI without Niobium. Typical dark, spheroidal nodules of graphite are observed, embedded in ferrite regions (light areas) and a pearlite matrix (dark areas).



Figure 1. Microstructure of the NCI without Niobium (A=Ferrite, B = Graphite, C = Pearlite - optical microscopy).



Figure 3. Typical microstructure of a NCI with Niobium (SEM; EDS analysis at points 1 and 2).

displays the variation of the volume fraction of pearlite, ferrite, graphite and carbides of the samples with the Niobium content. The graphite fraction includes nodules associated with oxides, sulfides, micro-shrinkages and other inclusions, since it was impossible to separate these various features. The addition of Niobium promotes an increase in the amount of pearlite in NCIs up to about 0.7% Niobium, followed by a decrease for 0.8% Niobium. The volume fraction of ferrite varies in the inverse proportion to that of pearlite.



Figure 2. Variation of the volume fractions of pearlite, ferrite, carbides and graphite in NCIs for various Niobium contents.

White cast iron

- White cast iron is very hard, brittle, and virtually non machinable. In some cases it is used where there is a need for resistance to abrasion. White cast iron is often found in combination with other cast iron, such as gray cast iron, to improve the hardness and wear-resistant properties.
- There are basically two ways of obtaining white cast iron
- 1. by lowering the iron's silicon content;
- 2. by rapid cooling, which in this case yields what is called chilled cast iron. When cooled at a rapid rate, the excess carbon forms iron carbide and not graphite, thus making white cast iron.



Many times it is advantageous to have a hard, wear-resistant surface on the part, such as a bearing surface or outer rim. This is easily accomplished by putting chill plates in the mold so that the molten iron will cool faster in these localized areas, creating white cast iron.

The microstructure of white cast iron



Malleable cast iron

Malleable cast iron is noted for its strength, toughness, ductility, castability, and machinability. In the process of making malleable cast iron, it is first necessary to begin with white cast iron.

The white cast iron is then heat treated as follows:

1. Heat to about 1700°F (927°C).

- 2. Hold at this temperature for about 15 hours. This breaks down the iron carbide to austenite and graphite.
- 3. Slow cool to about 1300°F (704°C).
- 4. Hold at this temperature for approximately 15 hours.
- **5. Air cool to room temperature.**

This process breaks down the iron carbide into additional austenite and graphite. Upon cooling, the graphite will form into clusters or balls. The austenite will take on any one of the transformation products, depending on the cooling rate Malleable iron starts as a white iron casting that is then <u>heat treated</u> for a day or two at about 950 °C (1,740 °F) and then cooled over a day or two. As a result, the carbon in iron carbide transforms into graphite and ferrite plus carbon (austenite). The slow process allows the <u>surface tension</u> to form the graphite into spheroidal particles rather than flakes. Due to their lower <u>aspect ratio</u>, the spheroids are relatively short and far from one another, and have a lower <u>cross section</u> vis-a-vis a propagating crack or <u>phonon</u>. They also have blunt boundaries, as opposed to flakes, which alleviates the stress concentration problems found in grey cast iron. In general, the properties of malleable cast iron are more like those of <u>mild steel</u>. There is a limit to how large a part can be cast in malleable iron, as it is made from white cast iron.

Uses include electrical fittings, hand tools, pipe fittings, washers, brackets, fence fittings, power line hardware, farm equipment, mining hardware, and machine parts

Malleable iron is cast as <u>white iron</u>. The structure of Malleable cast iron is a metastable carbide in a pearlitic matrix. Through an <u>annealing</u> heat treatment, the brittle structure as first cast is transformed into the malleable form. Carbon agglomerates into small roughly spherical aggregates of graphite leaving a matrix of ferrite or pearlite according to the exact heat treatment used.

Three basic types of malleable iron are recognized within the casting industry: *blackheart* malleable iron, *whiteheart* malleable iron and *pearlitic* malleable



Compacted graphite iron

Compacted graphite iron (CGI), also known as **vermicular graphite iron** especially in non-English speaking countries, is a <u>metal</u> which is gaining popularity in applications that require either greater strength, or lower weight than <u>cast iron</u>.

R.D. Schelleng obtained a patent for the production of compacted graphite iron in 1965

The <u>graphite</u> in compacted graphite iron differs in structure from that in <u>gray iron</u> because the graphite particles are shorter and thicker



The first commercial application for compacted graphite iron was for the brake discs for high-speed rail <u>trains</u>. More recently compacted graphite iron has been used for <u>diesel</u> engine <u>blocks</u>. It has proven to be useful in the manufacture of V topology diesel engines where the loading on the block is very high between the cylinder banks, and for heavy goods vehicles which use diesel engines with high combustion pressures.

It is also used for turbo housings and exhaust manifolds, in the latter case to reduce corrosion.

Non ferrous casting alloys

- **1.** Al-base alloys
- 2. Mg-base alloys
- 3. Cu-base alloys
- 4. Zn-base alloys
- 5. High temperature base alloys such as Ti.....etc.

Phase Diagram



The Development of the Microstructure

Casting: Molten metals are cast into molds and allowed to solidify for the purpose of producing the desired product by using different techniques(Processes)

- 1. When a pure metal solidifies, each crystal begins to form independently from a nucleus or 'centre of crystallisation'.
- 2. The nucleus will be a simple unit of the appropriate crystal lattice, and from this the crystal will grow.
- The crystal develops by the addition of atoms according to 3. the lattice pattern it will follow, and rapidly begins to assume visible proportions in what is called a 'dendrite' (Gk 'dendron', a tree). This is a sort of crystal skeleton, rather like a backbone from which the arms begin to grow in other directions, depending upon the lattice pattern. From these secondary arms, tertiary arms begin to sprout, somewhat similar to the branches and twigs of a fir-tree. In the metallic dendrite, however, these branches and twigs conform to a rigid geometrical pattern. A metallic crystal grows in this way because heat is dissipated more quickly from a point, so that it will be there that the temperature falls most quickly leading to the formation of a rather elongated skeleton (Fig. 3.10).



Fig. 3.10 The early stages in the growth of a metallic dendrite.



Plate 3.1 Dendritic growth.

This iron dendrite grow from a nucleus at 'n' in a molten mixture of iron and copper. After all the available iron had been used up the dendrite ceased to grow, and the molten copper solidified as the matrix in which the iron dendrite remains embedded. (In fact the iron dendrite will contain a little dissolved copper—in 'solid solution'—whilst the copper matrix will contain a very small amount of dissolved iron). × 300..

- Several locations will show the same behavior
- Dendrite grows and thickens and the outer arms begin to contact with neighbouring dendrites
- Lattices will meet at different angles
- Once solidification complete:
- If the metal we have been considering is pure we shall see no evidence whatever of dendritic growth, since all atoms are identical.
- Dissolved impurities, however, will often tend to remain in the molten portion of the metal as long as possible, so that they are present in that part of the metal which ultimately solidifies in the spaces between the dendrite arms. Since their presence will often cause a slight alteration in the colour of the parent metal, the dendritic structure will be revealed on microscopical examination. The areas containing impurity will appear as patches between the dendrite arms (Fig. below)



Fig. 3.11 The dendritic growth of metallic crystals from the liquid state.

A solid pure metal (D) gives no hint of its dendritic origin since all atoms are identical, but an impure metal (E) carries the impurities between the dendritic arms, thus revealing the initial sketeton.

Large Ingots

In a large ingot the crystal size may vary considerably from the outside surface to the centre (Fig. 3.13). This is due to the variation which exists in the temperature gradient as the ingot solidifies and heat is transferred from the metal to the mould. When metal first makes contact with the mould the latter is cold, and this has a chilling effect which results in the formation of small crystals at the surface of the ingot. As the mould warms up, its chilling effect is reduced, so that the formation of nuclei will be retarded as solidification proceeds. Thus crystals towards the centre of the ingot will be larger. In an intermediate position the rate of cooling is favourable to the formation of elongated columnar crystals, so that we are frequently able to distinguish three separate zones in the crystal structure of an ingot, as shown in Fig. 3.13. More recent research into rapid solidification processes (RSP) has been carried out with the object of obtaining metals and alloys with extremely tiny crystals, and in some cases retaining the amorphous structure of the original liquid at ambient temperatures.



Fig. 3.13 The crystal structure in a section of a large ingot.

Correcting the microstructure of castings

Main correcting methods: 1.Annealing of castings 2.Normalizing of castings

Annealing of castings

- The most suitable treatment for a large casting involves heating it slowly up to a temperature about 40°C above its upper critical (thus the annealing temperature depends upon the carbon content of the steel), holding it at that temperature only just long enough for a uniform temperature to be attained throughout the casting and then allowing it to cool slowly in the furnace. This treatment not only introduces the improvements in mechanical properties associated with fine grain but also removes mechanical strains set up during solidification.
- As the lower critical temperature (723°C) is reached on heating, the patches of pearlite transform to austenite but these new crystals of austenite are very small since each patch of pearlite gives rise to many new austenite crystals. It is upon this fact that the complete success of this type of annealing process depends. As the temperature rises, the Widmanstatten-type plates of ferrite are dissolved by the austenite until, when the upper critical temperature is reached, the structure consists entirely of finegrained austenite. Cooling causes reprecipitation of the ferrite, but, since the new austenite crystals are small, the precipitated ferrite will also be distributed as small particles. Finally, as the lower critical temperature is reached, the remaining small patches of austenite will transform to pearlite. The structural changes taking place during annealing are illustrated dia-grammatically in Fig. 11.9.



Fig. 11.9 Structural changes occurring during the annealing of a steel casting (approx 0.35% carbon). The as-cast Widmanstätten structure is reheated to some temperature above its upper critical and then allowed to cool in the furnace.

Normalizing of castings

Normalising resembles the 'full' annealing of castings in that the maximum temperature attained is similar. It is in the method of cooling that the processes differ. Whilst, in annealing, cooling is retarded, in normalising the steel is removed from the furnace and allowed to cool in still air. This relatively rapid method of cooling limits grain growth in normalising, whilst the ferrite/cementite lamellae in pearl-ite will also be much finer. For both reasons the mechanical properties are somewhat better than in an annealed component. Moreover, the surface finish of a normalised article is often superior to that of an annealed one when machined, since the high ductility of the latter often gives rise to local tearing of the surface.

The type of structure obtained by normalising will depend largely upon the thickness of cross-section. Thin sections will give a much finer grain than thick sections, the latter differing little in structure from an annealed section.

Defects in castings

- 1. Blow-holes and porosity
- 2. Shrinkage
- 3. Segregation of impurities (the presence of low melting segregates along grain boundaries increase the tendency for hot tearing)
- 4. Incomplete casting
- 5. Line and point defects

Porosity

If the metal is cooled too rapidly during solidification, molten metal is often unable to 'feed' effectively into the spaces which form between the dendrites due to the shrinkage which accompanies freezing. These spaces then remain as cavities following the outline of the solid dendrite. Such shrinkage cavities can usually be distinguished from blow-holes formed by dissolved gas.

The former are of distinctive shape and occur at the crystal boundaries, whilst the latter are quite often irregular in form and occur at any point in the crystal structure (Fig. 3.12).





Shrinkage cavities (A) tend to follow the shape of the dendritic arms and occur at the crystal boundaries, whilst gas porosity (B) is usually of irregular snape and occurs at almost any point in the structure.



Plate 3.2B Shrinkage cavities (black areas) in cast tin bronze. These roughly follow the shape of the original dendrites and occur in that part of the alloy to solidify last. \times 200. Etched in ammonia-hydrogen peroxide.
Blow-holes

These are caused by:

- **1. furnace gases which have dissolved in the metal during melting:**
- Gas which has dissolved freely in the molten metal will be much less soluble in the solid metal. Therefore, as the metal solidifies, gas will be forced out of solution. Since dendrites have already formed, the bubbles of expelled gas become trapped by the dendrite arms and are prevented from rising to the surface. Most aluminium alloys and some of the copper alloys are susceptible to 'gassing' of this type, caused mainly by hydrogen dissolved from the furnace atmosphere. The difficulty can be overcome only by making sure that there is no dissolved gas in the melt prior to casting

2. by chemical reactions which have taken place in the melt.

Any iron oxide (present as oxygen ions) in the molten steel will tend to be reduced by carbon according to the following equation:

FeO + C = Fe + CO

This is what is commonly called a reversible reaction and the direction in which the resultant reaction proceeds depends largely upon the relative concentrations of the reactants and also upon the temperature. When carbon (in the form of anthracite for example) is added to the molten steel the reaction proceeds strongly to the right and since carbon monoxide, a gas, is lost to the system the reaction continues until very little FeO remains in equilibrium with the relatively large amount of carbon present. As the ingot begins to solidify, it is almost pure iron of which the initial dendrites are composed. This causes an increase in the concentration of carbon and the oxide, FeO, in the remaining molten metal, thus upsetting chemical equilibrium so that the above reaction will commence again. The bubbles of carbon monoxide formed are trapped by the growing dendrites, producing blow-holes. The formation of blow-holes of this type is prevented by adequate 'killing' of the steel before it is cast—that is, by adding a sufficiency of a deoxidising agent such as ferromanganese. This removes residual FeO and prevents the FeO-C reaction from occurring during subsequent solidification. In some cases the FeO-C reaction is utilised as in the production of 'rimmed' ingots

Shrinkage

The crystalline structure of most metals of engineering importance represent a close packing of atoms. Consequently solid metals occupy less space than they do as liquids and shrinkage takes place during solidification as a result of this decrease in volume. If the mould is of a design such that isolated pockets of liquid remain when the outside surface of the casting is solid, shrinkage cavities will form. Hence the mould must be so designed that there is always a 'head' of molten metal which solidifies last and can therefore 'feed' into the main body of the casting as it solidifies and shrinks. Shrinkage is also responsible for the effect known as 'piping' in cast ingots. Consider the ingot mould (Fig. 3.14A) filled instantaneously with molten steel. That metal which is adjacent to the mould surface solidifies almost immediately, and as it does so it shrinks. This causes the level of the remaining metal to fall slightly, and as further solidification takes place the process is repeated, the level of the remaining liquid falling still further. This sequence of events continues to be repeated until the metal is com pletely solid and a conical cavity or 'pipe' remains in the top portion of the ingot. With an ingot shaped as shown it is likely that a secondary pipe would be formed due to the shrinkage of trapped molten metal when it solidifies. It is usually necessary to shape large ingots in the way shown in Fig. 3.14A, that is, small end upwards, so that the mould can be lifted from the solidified ingot. Therefore various methods of minimising the pipe must be used (2.21—Part II). One of the most important of these methods is to pour the metal into the mould so that solidification almost keeps pace with pouring. In this way molten metal feeds into the pipe formed by the solidification and consequent shrinkage of the metal. Smaller ingots can be cast into moulds which taper in the opposite direction to that shown in Fig. 3.14A, ie large end upwards (Fig. 3.14B), since these can be trunnion-mounted to make ejection of the ingot possible.



Fig. 3.14 The influence of the shape of the mould on the extent of piping in a steel ingot.

Casting Design Modifications

Trial version of Okdo Pdf to Ppt Converter. http://www.okdosoft.com



Casting Cross-Sections

Trial version of Okdo Pdf to Ppt Converter. http://www.okdosoft.com



Avoiding Shrinkage Cavities

Trial version of Okdo Pdf to Ppt Converter. http://www.okdosoft.com





Normal Shrinkage Allowance for Some Metals Cast in Sand Molds

Trial version of Okdo Pdf to Ppt Converter. http://www.okdosoft.com

Metal	Percent
Gray cast iron	0.83-1.3
White cast iron	2.1
Malleable cast iron	0.78-1.0
Aluminum alloys	1.3
Magnesium alloys	1.3
Yellow brass	1.3-1.6
Phosphor bronze	1.0-1.6
Aluminum bronze	2.1
High-manganese steel	2.6

Page 12-6

Segregation of impurities

- There is a tendency for dissolved impurities to remain in that portion of the metal which solidifies last. The actual mechanism of this type of solidification will be dealt with later (8.23), and it will be sufficient here to consider its results.
- The dendrites which form first are of almost pure metal, and this will mean that the impurities become progressively more concentrated in the liquid which remains. Hence the metal which freezes last at the crystal boundaries contains the bulk of the impurities which were dissolved in the original molten metal. This local effect is known as minor segregation (Fig. 3.15A).
- As the columnar crystals begin to grow inwards, they will push in front of them some of the impurities which were dissolved in the molten metal from which they themselves solidified. In this way there is a tendency for much of the impurities in the original melt to become concentrated in the central pipe. If a vertical section of an ingot is polished and etched, these impurities show as V-shaped markings in the area of the pipe (Fig. 3.15B). The effect is called major segregation.
- With very large ingots the temperature gradient may become very slight towards the end of the solidification process, and it is common for the band of metal which has become highly charged with impurities, just in front of the advancing columnar crystals, to solidify last. Some impurities, when dissolved in a metal, will depress its freezing point considerably (similarly when lead is added to tin a low melting point solder is produced).

Segregation of impurities (cont.)

- Hence the thin band of impure metal just in advance of the growing columnar crystals has a much lower freezing point than the relatively pure molten metal at the centre. Since the temperature gradient is slight, this metal at the centre may begin to solidify in the form of equi-axed crystals, so that the impure molten metal is trapped in an intermediate position. This impure metal therefore solidifies last, causing inverted V-shaped markings to appear in the etched section of such an ingot. It is known as 'inverse-vee' segregation (Fig. 3.15C). Rimming steels contain no heavilysegregated areas because of the mechanical stirring action introduced by the evolution of carbon monoxide during the FeO/C reaction (3.21). Of these three types of segregation, minor segregation is probably the most deleterious in its effect, since it will cause overall brittleness of the castings and, depending upon the nature of the impurity, make an ingot hot- or cold-short, that is, liable to crumble during hot- or cold-working processes.
- From the foregoing remarks it will be evident that a casting, suffering as it may from so many different types of defect, is one of the more variable and least predictable of metallurgical structures. In some cases we can detect the presence of blow-holes and other cavities by the use of X-rays, but other defects may manifest themselves only during subsequent service. Such difficulties are largely overcome when we apply some mechanical working process during which such defects, if serious, will become apparent by the splitting or crumbling of the material undergoing treatment. At the same time a mechanical working process will give a product of greater uniformity in so far as structure and mechanical properties are concerned. Thus, all other things being equal, a forging is likely to be more reliable in service than a casting. Sometimes, however, such factors as intricate shape and cost of production dictate the choice of a casting. We must then ensure that it is of the best possible quality



Fig. 3.15 Types of segregation which may be encountered in steel ingots.

Line and point defects

In the foregoing sections we have been dealing with such defects as are likely to occur in cast metals. These defects may be so large that a microscope is not necessary to examine them. Others are small yet still within the range of a simple optical microscope. On the atomic scale however metallic structures which would be regarded as being of very high quality in the industrial sense nevertheless consist of crystals which contain numerous 'line' and 'points' defects scattered throughout the crystal lattice. These defects (Fig. 3.16) occur in wrought as well as in cast metals and though small in dimensions have considerable influence on mechanical properties.



Fig. 3.16 The imperfect nature of a metallic crystal.

Joining processes

Observations:

- 1. Products made of one component such as paper clips, nails, steel ball
- 2. Products made of two components such as kitchen knives, cooking spots,etc.
- 3. Products made of more than two components such as computers, cars, ...etc

Reasons behind assembly operations:

- 1. Product may be impossible to manufacture as a single piece
- 2. More economic to manufacture the product as individual parts
- 3. Different properties may be desirable (automotive brake shoes-surface and bulk)
- 4. For maintenance purposes
- 5. For transportation purposes

Joining processes fall into three major categories:

Welding
Adhesive bonding
Mechanical fastening

Our focus is welding

Welding processes fall into the following three categories:

- Fusion welding coalescence is accomplished by melting the two parts to be joined, in some cases adding filler metal to the joint. Examples: arc welding, resistance spot welding, oxyfuel gas welding
- 2. Solid state welding heat and/or pressure are used to achieve coalescence, but no melting of base metals occurs and no filler metal is added. Examples: forge welding, diffusion welding, friction welding
- 3. Brazing and soldering (uses fillers)

Examples of WELDING PROCESSES

Arc Welding (AW)

- A fusion welding process in which coalescence of the metals is achieved by the heat from an electric arc between an electrode and the work
- Electric energy from the arc produces temperatures ~ 10,000 F (5500 C), hot enough to melt any metal
- Most AW processes add filler metal to increase volume and strength of weld joint

What is an Electric Arc?

An electric arc is a discharge of electric current across a gap in a circuit

- It is sustained by an ionized column of gas (plasma) through which the current flows
- To initiate the arc in AW, electrode is brought into contact with work and then quickly separated from it by a short distance

Arc Welding

A pool of molten metal is formed near electrode tip, and as electrode is moved along joint, molten weld pool solidifies in its wake



Figure 31.1 Basic configuration of an arc welding process.

Two Basic Types of AW Electrodes

• Consumable – consumed during welding process • Source of filler metal in arc welding • Nonconsumable – not consumed during welding process Filler metal must be added separately

Forms of consumable electrodes

Welding rods (a.k.a. sticks) are 9 to 18 inches and 3/8 inch or less in diameter and must be changed frequently

Weld wire can be continuously fed from spools with long lengths of wire, avoiding frequent interruptions

In both rod and wire forms, electrode is consumed by arc and added to weld joint as filler metal

Nonconsumable Electrodes

- Made of tungsten which resists melting
- Gradually depleted during welding (vaporization is principal mechanism)
- Any filler metal must be supplied by a separate wire fed into weld pool

At high temperatures in AW, metals are chemically reactive to oxygen, nitrogen, and hydrogen in air *Mechanical properties of joint can be seriously degraded by these reactions *To protect operation, arc must be shielded from surrounding air in AW processes Arc shielding is accomplished by: *Shielding gases, e.g., argon, helium, CO₂ *Flux

Flux

A substance that prevents formation of oxides and other contaminants in welding, or dissolves them and facilitates removal

- Provides protective atmosphere for welding
- Stabilizes arc

• Reduces spattering

Various Flux Application Methods

- Pouring granular flux onto welding operation
- Stick electrode coated with flux material that melts during welding to cover operation
- Tubular electrodes in which flux is contained in the core and released as electrode is consumed

Power Source in Arc Welding

- Direct current (DC) vs. Alternating current (AC)
 - AC machines less expensive to purchase and operate, but generally restricted to ferrous metals
 - DC equipment can be used on all metals and is generally noted for better arc control

Other Fusion Welding Processes

FW processes that cannot be classified as arc, resistance, or oxyfuel welding use unique technologies to develop heat for melting

Applications are typically unique Processes which include:

Electron beam welding Laser beam welding Electroslag welding Thermit welding Coalescence of part surfaces is achieved by: *Pressure alone, or Heat and pressure *If both heat and pressure are used, heat is not enough to melt work surfaces *For some SSW processes, time is also a factor *No filler metal is added

*Each SSW process has its own way of creating a bond at the faying surfaces

Solid State Welding Processes

- Forge welding
- Cold welding
- Roll welding
- Hot pressure welding
- Diffusion welding
- Explosion welding
- Friction welding
- Ultrasonic welding

Weldability:

- It is the Capacity to be welded into a specific structure that has certain properties and characteristics and will satisfactorily meet service requirements. Thorough knowledge of the phase diagram is essential Factors affect weldability are:
- 1. composition (carbon content, alloying elements, microstructure)
- 2. Properties such as strength, toughness, ductility, notch sensitivity, elastic modulus, specific heat, melting point, thermal expansion, surface tension characteristics of the molten metal, corrosion resistance.
- *3. Preparation of surface affects the nature of oxide-films and adsorbed gases*
- 4. Shielding gases, fluxes, moisture, coating on electrodes, welding speed, cooling rate
- 5. Ost welding techniques such as stress relieving and heat treating.

Weldability of ferrous alloys

1.	Plain carbon steel	good	
2.	Medium carbon stee	l Fair	
<i>3.</i>	High carbon steel	poor	
4.	Low alloy steel	Fair	
<i>5.</i>	High alloy steel	good	
		(under controlled conditions)	
1.	Stainless steel	weldable	
2.	Cast iron	Varied weldability	

Weldability of non ferrous alloys

Type of the alloy	weldability	conditions
Al – alloys	weldable	High rate of heat input,Inert gas, lack of moisture,Zink and Copper not contained in it
Cu – alloys	weldable	High rate of heat input,Inert gas, lack of moisture
Ni – alloys	Weldable	Lack of sulfur content
Ti – alloys	Weldable	Proper use of shielding gases
Molybdenum and Tungesten	Weldable	Under controlled conditions
Niobium	Good	
Mg – alloys	Weldable	Use of protective shielding and fluxes

Defects in welds

Defect	Figure
Porosity	Caused by gases released during melting of the weld area but trapped during solidification, chemical reactions, Contaminants
Slag inclusions	<i>Compounds such as oxides ,fluxes, and electrode- coating materials that are trapped in the weld Zone</i>
Incomplete fusion & penetration	(a) Weld Incomplete fusion in fillet welds. B is often termed 'bridging' (b) Weld Incomplete fusion from oxide or dross at the center of a joint, especially in aluminum (c) Weld Incomplete fusion from oxide or dross at the center of a joint, especially in aluminum Incomplete fusion in a groove weld
Weld profile	(a) Underfill Inclusions Crack Incomplete penetration (b) Porosity Overlap Lack of penetration
Cracks	

Residual stresses

Testing of welds

Destructive testing:

- 1. Tension test
- 2. Bend test
- 3. Fracture toughness test
- 4. Corrosion and creep test

Non destructive testing:

- 1. Visual
- 2. Radigraphic (x-ray)
- 3. Magnetic particle
- 4. Liquid penetrant
- 5. Ultrasonic
Welding Metallurgy

Three welding distinct zones:



- Solidification in the weld zone is similar to that of casting
- The properties and the microstructure of HAZ depend on:
- 1. The rate of heating and the rate of cooling
- 2. The temperature to which this zone was raised
- *3. Metallurgical factors such as original grain size and degree of cold working.*
- Changes in Structure Resulting in Changes in Properties & Cold Cracking Due to Hydrogen

Steel Alloys With Allotropic Transformation









Fig : Grain structure in (a) a deep weld (b) a shallow weld. Note that the grains in the solidified weld metal are perpendicular to the surface of the base metal. In a good weld, the solidification line at the center in the deep weld shown in (a) has grain migration, which develops uniform strength in the weld bead.

Useful information

- 1. A single pass weld generally produces a coarse columnar structure in the weld zone, coarse grains in HAZ, and no change in the structure in the base metal zone.
- 2. A two-pass weld will recrystallize the HAZ of the first pass, thus stress relieving the first pass weld zone. Because of its finer grain size, the weld zone is usually stronger than the base metal.
- 3. If the cooling rate is slow, the grains in the weld are larger and those in the HAZ tend to become quiet large

4. If the cooling rate is rapid, the coarsening effect is minimal.

5. If the weld consists of several passes, the heating effect of later passes will normalize the previously solidified structure, leading to a refinement of the grains since each pass reheats part of the previous weld pass to above the critical temperature

- 6. Various metallurgical structures are formed in the weld zone as cooling or heating is taking place:
- Low carbon steel welding rods (0.08-0.15 %C) deposit ferrite grains with some pearlite and donot harden appreciably unless carbon is picked up from the base metal or from carbon-containing contaminants such as oil or grease.
- The formation of martensite in the heat-affected zone results in many failures in welds because of the brittleness of martensite.

Avoidance of the welding problems:

- 1. By preheating which prevents the formation of martensite by inducing slower cooling to the base metal
- 2. By postheating : tempering or annealing which eliminates brittle martensite that has already formed. Hardening may be needed also
- 3. Ferrite structures in weld areas may require stress relief if the structure is stressed during welding (heating to a temperature 510-649C for a short period of time which recrystallizes the ferrite grains).
- 4. Peening of the welds

peening is used to relief tensile stresses caused by welding by inducing compressive stresses

peening strengthens the weld metal but lowers its ductility

peening is done by hand with a hammer or by shot peening.

Why Preheat?

Preheat reduces the temperature differential between the weld region and the base metal

*Reduces the cooling rate, which reduces the chance of forming martensite in steels *Reduces distortion and shrinkage stress *Reduces the danger of weld cracking *Allows hydrogen to escape

Using Preheat to Avoid Hydrogen Cracking

If the base material is preheated, heat flows more slowly out of the weld region *Slower cooling rates avoid martensite formation *Preheat allows hydrogen to diffuse from the metal



Cooling rate
$$\propto$$
 (T - T_{base})³



Cooling rate
$$\propto$$
 (T - T_{base})²

Interaction of Preheat and Composition

CE = %C + %Mn/6 + %(Cr+Mo+V)/5 + %(Si+Ni+Cu)/15

Carbon equivalent (CE) measures ability to form martensite, which is necessary for hydrogen cracking no preheat *CE < 0.35* Or heat postweld treatment 0.35 < CE < 0.55 preheat 0.55 < CEpreheat and postweld heat treatment Preheat temp. as CE and plate thickness

Why Post-Weld Heat Treat?

The fast cooling rates associated with welding often produce martensite. During postweld heat treatment, martensite is tempered (transforms to ferrite and carbides). This leads to:

- 1. Reduction in hardness
- 2. Reduction in strength
- 3. Increasing in ductility
- 4. Increasing in toughness
- 5. Residual stress is also reduced by the postweld heat treatment

Multipass Welds

- Exhibit a range of microstructures
- Variation of mechanical properties across joint
- Postweld heat treatment tempers the structure
 - *Reduces* property variations across the joint



Knife-Line Attack in the HAZ



- Cr₂₃C₆ precipitate in HAZ
 - Band where peak temperature is 800-1600°F
- Can occur even in stabilized grades
 - *Peak temperature dissolves titanium carbides*
 - Cooling rate doesn't allow them to form again