Cast Iron (CI):

- **Types of Cast Iron:**
  - White CI (all C combined Fe3C).
  - Malleable CI (most C uncombined).
  - Gray CI (most C uncombined in form of Graphite flakes).
  - Chilled CI (White CI layer at surface + Gray Iron interior).
  - Nodular CI (the C uncombined in the form of compact spheroids).
  - Alloy CI.
Cast Iron (CI):

White CI:

- Hard + Wear resistance + Brittle
- They are used where resistance to wear is most important and the service does not require ductility (ex. Liner for Cement mixer, ball mills, drawing dies).
- White CI → Malleable CI.
- Mechanical Properties
  - $H_B$ (375 – 600).
  - T. S (20,000 – 70,000) psi.
  - C. S (200,000 – 250,000) psi.
  - $E$ (24 – 28) $\times 10^6$ psi.

Malleable CI:

- $Fe_3C$ (Metastable Phase) at:
  1- Elevated Temperature.
  2- Existence of solid non metallic impurities.
  3- Higher C content.
  4- Presence of element that cause decomposition of $Fe_3C$.

Fe$_3$C $\rightleftharpoons$ 3 Fe + C
**Cast Iron (CI):**

- **Malleable CI:**
  - The purpose of malleabilization is to convert all Fe₃C in (white CI) irregular (nodules of graphite + Ferrite) by two stages of annealing:

  - **1st stage** - white CI → Pearlite $\gamma$ dissolve
    - Slowly reheatd $(1650 - 1750)^\circ F$
  
  - $\text{Fe}_3\text{C}$ as it is heated to annealing Temperature $T^o$.
  
  - $\text{Fe}_3\text{C} \xleftarrow{3 \text{ Fe } + \text{ C}}$ graphitization starts at malleabilizing Temperature $T$.

---

- ترسيب نوى الكرافيت يستنزف كاربون السمنتايت.
- تحلل السمنتايت يستمر ويؤدي بدوره إلى ترسيب (C) أكثر على نوى الكرافيت.
- تنمو نوى الكرافيت بمعدلات متساوية في كل الإتجاهات وبالنهاية تظهر (nuclei) أو ما يشبه الكرات (nodules) أو ما يشبه الكرات (Temper Graphite) أو (Temper C)
- يتكون على السطح البيجي بين الكاربيد الإبتدائي وينمو حول النوى أثناء التفاعل الذي يتضمن تداخل (1st stage annealing) والأوستتايت المشبع خلال وتحلل الكاربيد.....
Cast Iron (CI):

- **Malleable CI:**
  - Nucleation + graphitization accelerated by the presence of (\(\text{Si} \& \text{C}\)) and it will be increased (\(\uparrow\)).
  - The rate of annealing depend on  
    - Chemical composition.
    - Nucleation tendency.
    - \(T^o\) of annealing \(\alpha\) (no. of temper \(\text{C}\) particles produced).
  - \(T^o\) of annealing \(\uparrow\) more graphite particle / unit area.
  - Annealing Temperature controlled between 1650 - 1750 °F.
  - Held at this temperature until all massive Carbide have been decomposed (30 – 72) hour.
  - The surface of 1\(^{st}\) stage (temper Carbon nodules distributed in matrix of Austenite \(\gamma\).
Cast Iron (CI):

Malleable CI:

2nd stage – (see fig. 24).
- C (dissolved in γ) → graphite.
- Reheating γ → α.

Fig. (24), The change in microstructure as a function of malleabilizing Cycle.
Cast Iron (CI):

**Gray CI:**
- Gray CI are hypoeutectic alloy (2.5 – 4)% C.
- Strength of Gray CI depend on the matrix in which the graphite is embedded.
  - If matrix is $\alpha$ -> Ferritic Gray CI (soft + weak).
  - If matrix is P -> Perlitic Gray CI.
  - If matrix is ($\alpha + P$) -> Ferritic & Perlitic Gray CI.

- Si -> increase fluidity of molten alloy + shift the eutectic composition to the left, it is a graphitizer.
- The highest tensile strength is obtained with (2.75% C + 1.5% Si) over 40,000 psi (see fig. 25).

*Fig. (25), Relation of Structure to C & Si content of CI.*
Gray CI:

- **S** is present in commercial Gray CI between (0.06 – 0.12)%, the effect of S is opposite to the effect of **Si**.

  \[
  \text{Fe} + \text{S} \rightarrow \text{FeS} \quad \text{(lower the melting point) ~ increase cracking at elevating Temperature} \quad T^\circ
  \]

- **Mn** Carbide stabilizer, increase the amount of combined **C**.

  \[
  \text{Mn} + \text{S} \rightarrow \text{MnS}
  \]

- **P** is present in Gray CI between (0.1 – 0.9)%

  \[
  \text{P} + 3\text{Fe} \rightarrow \text{Fe}_3\text{P}.
  \]

- **P** increases the fluidity.

- **P** increases the fluidity.

If we can control the contents (**S, Mn, Si, P**) of Gray CI, we can control its hardness through (Graphite Flakes) distribution, size, and shape.
1. **Stress Relief:**

- Residual stress in CI (Gray I) causes:
  - Reduce strength
  - Distortion
  - Cracking

- $T^\circ$ of stress relieving is $(1000 - 1050)^\circ f$ (below the transformation of range $P \rightarrow \gamma$).

- Holding 1 hr at this range $(75 - 85)\%$ of residual stress can be removed. (see fig. 26)

*Fig. (26), Effect of Time & Temp. on Residual Stress*
Heat Treatment of Gray Iron:

2. **Annealing:**
   - Heating to $T^o (1300 – 1400)$ °f:
     - $\text{Fe}_3\text{C} \rightarrow \alpha + \text{C}$
   - Holding at this $T^o$ for along time to allow the graphitizing process completion.

3. **Normalizing:**
   - Heating to $T^o (1625 – 1700)$ °f
     - $\text{Fe}_3\text{C} \rightarrow \alpha + \text{C}$
   - Holding at this $T^o$ for 1 hr/in of max. section thickness.
   - Cooled in still air to $R_{T^o}$. 
Heat Treatment of Gray Iron:

4. **Hardening:**

- Gray Iron like steel can be hardened when cooled rapidly (Quench).
- Gray Iron is furnace hardened from (1575 – 1600) °F, then reheating in the range from (300 – 1200) °F Increase toughness + Stress relief.
- Quenching medium (water, oil, hot salt, air) depend on composition + section size.

Quenching medium

Water

Used for quenching with flame or induction hardening

Very drastic cause cracking + distortion unless the casting are massive uniform cross section

Hot Oil or Hot Salt

minimize (Distortion + Quenching Cracking)
Nodular Cast Iron: (Ductile Iron, Spheroidal Graphite)

- CI in the graphite is present as tiny balls or spheroids because of the presence of alloying element (Mn, Ce, S < 0.015) this alloys described as (Desulfurized).

- Strength + Toughness > Gray Iron that is obtained as a solidification & doesn’t need heat treatment (H. T).

\[
\text{C}\% \text{ (Gray)} = \text{C}\% \text{ (Nodules)}
\]

- **Types of Nodular CI:**
  - **Ferritic**
    - (P) In matrix <10%
  - **Pearlitic**
    - (P) In matrix > 10%
    - Normalized by air cooling from (1600 – 1650) °F
  - **Quenched**
    - Obtained by quenching in oil or water from (1600 – 1650) °F
  - **Austentic**
    - (Highly alloying type)
    - High corrosive resistance + good Creep resistance

- Stronger, less ductile
Heat Treatment of Nudolar Iron:

- **Stress Relief**
  - **Purpose:** stress relief range (1000 – 1150 °F), time 1 hr/in of section

- **Ferritizing anneal**
  - Heat to 1650 °F
  - Cool to 1450 °F in 1 hr.
  - Cool to 1200 °F at 35 °F/hr.

- **Normalize**
  - **Purpose:** to obtain Pearlitic structure.
  - Heat to 1650 °F
  - Hold at a temp.
  - Cool to 1450 °F in Furnace.
  - Air Quench (may be temper).

- **Quench & Temper**
  - **Purpose:** higher Strength + hardness
  - Heat to 1600 – 1650 °F.
  - Oil Quench.
  - Tempered.

- **Surface hardening**
  - **Purpose:** wear resistance
  - **1 - Flame Hardening**
    - Hardness (C53 – C60) is obtained.
    - Care should be taken to relief residual stress prior to flame hardening to get rid of cracking in hardened case + stress relief after hardening is desirable (300 – 400) °F.
  - **2 - Induction hardening**
Heat Treatment of White Iron (WCI):

Heat Treatment to reduce high residual stress:
- Fairly high To may be employed for stress relief (1500 – 1600 °f):
  - As the To increased the time at To must be reduced to prevent Graphitization.
- Martensitic, Ni – Cr white iron → abrasion resistance.
  - High Tempering To → loss in abrasion resistance.
  - Tempering for 3 hr at 400 °f → stress relief without altering abrasion resistance.

Unalloyed
- Heat treated at relatively high To (18 hr at 1500 °f or 8 hr at 1600 °f).
  To accomplish re-solution of coarse primary carbide.
  Cooling to produce fine + uniform grain structure + small loss in hardness & wear resistance.

Martensitic (Ni – Cr)
- May have large amount of retained (γ) in matrix.
  Undesirable, most of (γ) may be eliminated by:
  - Tempering (5 hr at 800 °f) or (3 hr at 900 °f).
  - Exposure to subzero To (- 300 °f all γ → M) or (- 50 °f, 40% γ → M).

Heat Treatment for refinement of structure
**Cast Iron (CI):**

- **Alloy Cast Iron:** Cast Iron + added elements (except Si, S, P which are normally obtained from raw material).

  - Alloying element (Cr, Cu, Mo, Ni, V) will accelerate or retard graphitization.

  - **Cr:**
    - Cr + C → Combined C (more stable)
    - Cr increase → Strength, Hardness, Depth of chill, Resistance to wear + Heat
    - Cr decrease → machinability
Cast Iron (CI):

- The effect of Cr on microstructure illustrated as:

<table>
<thead>
<tr>
<th>Cr%</th>
<th>Structure</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>$\alpha$ + Coarse graphite (G)</td>
</tr>
<tr>
<td>0.3</td>
<td>$&lt; \alpha$ + less (P) + finer (G)</td>
</tr>
<tr>
<td>0.6</td>
<td>P (Pearlite) + fine (G)</td>
</tr>
<tr>
<td>1.0</td>
<td>P + fine (G) + small Carbide</td>
</tr>
<tr>
<td>3.0</td>
<td>Disappear of (G)</td>
</tr>
<tr>
<td>5.0</td>
<td>much Carbide</td>
</tr>
<tr>
<td>10 – 30</td>
<td>fine Carbide</td>
</tr>
</tbody>
</table>

- **Cu**: (0.25 – 2.5%)  
  Cu graphitizer = 1/5% Si  
  Cu break up Fe$_3$C + Strengthen the matrix.

- **Mo**: (0.25 – 1.25%)
  Mo improve

  - Fatigue
  - Tensile
  - Transverse
  - Hardness
  - Heat resistance + retards transformation of (γ)  
  - increase hardenability

  \{ \text{Strength} \}
Cast Iron (CI):

- **V**: (0.1 – 0.25%) added
  - Very powerful Carbide form.
  - Stabilizer Fe\(_3\)C.
  - Reduce graphitization.

  - V increase Tensile Strength
  - Transverse Strength
  - Hardness

- **Ni**: (0.5 – 6%)
  - Graphitizer (1/2 as effect as Si)
  - Retard \(\gamma\) transformation
  - Stabilizer.

  Ni + (1% Mo) → microstructure of matrix tends to be Bainite (BHN = 385)

  4% Ni + 1.5% Cr → excellent abrasion resistance to white CI because the
  primary dendrites + originally \(\gamma\) → Martensite (M).

  Combination of Fe\(_3\)C in Martensite → increases hardness to 600 – 700 BH.
  + Good strength toughness.

  (14 – 38)% Ni added to Gray Iron → heat resistance + Corrosion
  + expansivity.

  (Because of Ni transform the matrix \(\gamma\))
Cast Iron (CI):

Summary of Cast Iron microstructures and the phases existing at various temperatures.