Material Degradation of Nuclear Structures
Mitigation by Nondestructive Evaluation

17 MnMoV 6 4 (WB35): Stretched Zone
3. **Focus on Steel – Carbon Steels**

3.1. Basic Characteristics of Steel

3.2. Steel Qualities and Characterization Methods

3.3. Carbon Steel Microstructures

3.4. Microstructure Transformation

3.5. Transformation Diagrams

3.6. Localized Hardening

3.7. Steel Alloys
# Products of Austenitic Transformations

<table>
<thead>
<tr>
<th>Microconstituents</th>
<th>Description</th>
</tr>
</thead>
</table>
| Pearlite         | • Transformation rate increases with decreasing temperature  
                  • Coarse pearlite: alternating ferrite and cementite layers are relatively **thick**  
                  • Fine pearlite: alternating ferrite and cementite layers are relatively **thin**  
                  • Formed between 540 °C to 727 °C (above the nose) |
| Bainite          | • Forms at temperatures between those at which pearlite and martensite transformation occurs  
                  • Microstructure consists of α-ferrite and fine dispersion of cementite  
                  • Formed between 215 °C to 540 °C (below the nose) |
| Spheroidite      | • Steel alloy composed of either pearlitic or bainitic microstructures is heated and held at a temperature below the eutectoid point for a long time (example: ≈700 °C for 18 – 24 h)  
                  • Sphere-like particles |
| Martensite       | • A metastable iron phase supersaturated in carbon that is the product of a diffusionless transformation from austenite  
                  • Quenched to a relatively low temperature |
<table>
<thead>
<tr>
<th>Microconstituent</th>
<th>Phases Present</th>
<th>Arrangement of Phases</th>
<th>Mechanical Properties (Relative)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spheroidite</td>
<td>α Ferrite + Fe₃C</td>
<td>Relatively small Fe₃C sphere-like particles in an α-ferrite matrix</td>
<td>Soft and ductile</td>
</tr>
<tr>
<td>Coarse Pearlite</td>
<td>α Ferrite + Fe₃C</td>
<td>Alternating layers of α-ferrite and Fe₃C that are relatively thick</td>
<td>Harder and stronger than spheroidite, but not as ductile as spheroidite</td>
</tr>
<tr>
<td>Fine Pearlite</td>
<td>α Ferrite + Fe₃C</td>
<td>Alternating layers of α-ferrite and Fe₃C that are relatively thin</td>
<td>Harder and stronger than coarse pearlite, but not as ductile as coarse pearlite</td>
</tr>
<tr>
<td>Bainite</td>
<td>α Ferrite + Fe₃C</td>
<td>Very fine and elongated particles of Fe₃C in a α-ferrite matrix</td>
<td>Hardness and strength greater than fine pearlite; hardness less than martensite; ductility greater than martensite</td>
</tr>
<tr>
<td>Tempered Martensite</td>
<td>α Ferrite + Fe₃C</td>
<td>Very small Fe₃C sphere-like particles in an α-ferrite matrix</td>
<td>Strong; not as hard as martensite, but much more ductile than martensite</td>
</tr>
<tr>
<td>Martensite</td>
<td>Body-centered tetragonal, single phase</td>
<td>Needle-shaped grains</td>
<td>Very hard and very brittle</td>
</tr>
</tbody>
</table>
Heat Treatments
Transformation Diagrams

Transformation Diagrams help to understand transformations

There are two main types of transformation diagrams that are helpful in selecting the optimum steel and processing route to achieve a specified set of properties:

- **time-temperature transformation (TTT) diagram**
- **continuous cooling transformation (CCT) diagram**
Heat Treatments

**Time-temperature transformation (TTT) diagrams**
(isothermal diagrams: rate of transformation at a constant temperature)

A sample is:

- austenitized,
- then cooled rapidly to a specified lower temperature,
- then held at that temperature for a specified time

**Continuous cooling transformation (CCT) diagrams**
(extent of transformation during a continuously decreasing temperature)

A sample is:

- austenitized,
- then cooled at a predetermined rate

*(the rate and degree of transformation is measured by dilatometry, for example)*
Heat Treatments

For understanding:

Let us go to the roots, the

IRON CARBON DIAGRAM
Heat Treatments
A Short Review on the Iron-Carbon Phase Diagram

Iron-Iron Carbide (Fe–Fe₃C) Phase Diagram
(Steel Part up to 7% Carbon)
Heat Treatments - Microstructure

Eutectoid Steel

Hypoeutectoid Steel

\[ \gamma \rightarrow \alpha + \gamma \rightarrow \alpha + Fe_3C \]
Heat Treatments
Pearlite

Photomicrograph of Pearlite
(Dark bands: Cementite)
Pearlite

a laminated structure formed of alternate layers of ferrite and cementite.

It combines the hardness and strength of cementite with the ductility of ferrite. It is the key to the wide range of steel properties.

The laminar structure acts as a barrier to crack movement as in composites. This gives it toughness.
Heat Treatments – Hypoeutectic Alloys

$\text{Fe}_3\text{C}$

Eutectoid $\alpha$

Proeutectoid $\alpha$

Pearlite
Heat Treatments – Microstructure of Hypereutectic Steels

\[ \gamma \rightarrow \gamma + \text{Fe}_3\text{C} \rightarrow \alpha + \text{Fe}_3\text{C} \]
TTT Diagrams

TTT diagram stands for “time-temperature-transformation “ diagram

TTT diagrams give the kinetics of isothermal transformations

TTT diagrams measure the rate of transformation at a constant temperature:

A sample is austenitized and then cooled rapidly to a lower temperature and held at that temperature whilst the rate of transformation is measured. 

* for example by dilatometry.
Heat Treatments-Isothermal Transformation (TTT-) Diagram

At $T_1$:
- $t_2 = \text{incubation period}$
- $t_4 = \text{finish time}$

At $t_1$ ("nose"):
- minimum incubation period

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Time temperature transformation (schematic) diagram for plain carbon eutectoid steel
EXAMPLE: EUTECTOID STEEL

The S-shaped curves are shifted to longer times at higher T showing that the transformation is dominated by nucleation and not by diffusion.

Diffusion occurs faster at higher temperatures, nucleation rate increases with super-cooling.
The thickness ratio of the ferrite & cementite layers in pearlite is about 8:1.

The absolute layer thickness increases with temperature.
(Coarse) Pearlitic Microstructure under Optical Microscope

Heat Treatments - Isothermal Transformation (TTT-) Diagram
Colonies of Pearlite under Optical Microscope
(Courtesy of S.S. Babu www)
Heat Treatments-Isothermal Transformation (TTT-) Diagram

Transmission Electron Micrograph of extremely fine Pearlite
At the nose temperature, fine pearlite and upper bainite form simultaneously though the mechanisms of their formation are entirely different.

The nose is the result of superimposition of two transformation noses: one for pearlitic reaction other for bainitic reaction.
Heat Treatments TTT Diagram

SUMMARY

- S-shaped curves at different $T$ build up the TTT diagram
- The TTT diagram are for the isothermal transformations
- At low temperatures, nucleation rate is higher, and the transformation occurs sooner; furthermore, diffusion is slower and grain growth is reduced
- Slow diffusion leads to fine-grained microstructure with thin layered pearlite (fine pearlite)
- At higher temperatures, high diffusion rates allow for larger grain growth and the formation of thick layered pearlite (coarse pearlite)
- At compositions other than eutectoid, a proeutectoid phase (ferrite or cementite) coexists with pearlite
- Additional curves for proeutectoid transformation must be included on TTT diagrams
Heat Treatments – Formation of Bainite Microstructure

- For $T \sim 300-540^\circ C$, **upper bainite** consists of needles of ferrite separated by long cementite particles.
- For $T \sim 200-300^\circ C$, **lower bainite** consists of thin plates of ferrite containing very fine rods or blades of cementite.
- In the bainite region, transformation rate is controlled by microstructure growth (diffusion) rather than nucleation. Since diffusion is slow at low temperatures, this phase has a very fine (microscopic) microstructure.
- Pearlite and bainite transformations are competitive; transformation between pearlite and bainite not possible without first reheating to form austenite.
Heat Treatments – Formation of Bainite Microstructure

- Upper bainite
- Martensite
- Cementite
- Ferrite

- Lower bainite
- Martensite
- Cementite
- Ferrite

1 μm
Heat Treatments TTT Diagram

Factors affecting TTT diagram

- Composition of steel
  - (a) carbon wt%,
  - (b) alloying element wt%
- Grain size of austenite
- Heterogeneity of austenite
- Strain
Transformation Diagrams – Effect of Carbon Content

Carbon wt\% - (C\%) < 0.77 wt\%

\[ \text{C\%} \uparrow \quad \text{A}_3 \text{ and } \text{A}_{r3} \downarrow \]

during cooling (A_{r3})
during heating (A_{c3})
Equilibrium (A_{c3})

The incubation period for the austenite to pearlite increases:
  i.e. the C-curve of the diagram moves to right.

Carbon wt\% > 0.77 wt\%

\[ \text{C\%} \uparrow \quad \text{A}_{cm} \uparrow \]

Austenite becomes less stable with respect to cementite precipitation,
transformation to pearlite becomes faster. Therefore C curve moves towards left.

The critical cooling rate required to prevent diffusional transformation
is minimum for eutectoid steel.
Schematic TTT diagram for plain carbon hypoeutectoid steel

- $A_{e3}$
- $A_{e1}$
- $\gamma + \alpha$
- $\alpha + CP$
- $\alpha + P$
- $FP$
- $FP + UB$
- $UB$
- $Metastable \gamma$
- $M_S$
- $M_{50}$
- $M_F$
- $M$

Temperature

Log time

Hardness

Schematic TTT diagram for plain carbon hypoeutectoid steel

- $\gamma$=austenite
- $\alpha$=ferrite
- $CP$=coarse pearlite
- $P$=pearlite
- $FP$=fine pearlite
- $UB$=upper Bainite
- $LB$=lower Bainite
- $M$=martensite
- $M_S$=Martensite start temperature
- $M_{50}$=temperature for 50% martensite formation
- $M_F$=martensite finish temperature

Material Degradation of Nuclear Structures - Mitigation by Nondestructive Evaluation

TPU Lecture Course 2014

Michael Kröning
Transformation Diagrams – Effect of Carbon Content

Schematic TTT diagram for plain carbon hypereutectoid steel

Michael Kröning
Focus on Steel – Steel Qualities

Effects of carbon content on the microstructures of plain-carbon steels:

a) Hypoeutectoid steel (0.4% C) ferrite grains (white) and pearlite (gray streaks) in a white matrix. 1000.

(b) Eutectoid steel (0.77% C) (all pearlite grains). 2000.

c) Eutectoid steel (0.77% C) with all cementite in the spheroidal form. 1000.

(d) Hypereutectoid steel (1.0% C) pearlite with excess cementite bounding the grains. 1000.
Effect of Austenite Grain Size on
TTT Diagram of Plain Carbon Hypoeutectoid Steel

\[ T \] = Temperature
\[ \text{Log}(t, t) \] = Logarithm of time

\( A_e^3 \) = For finer austenite
\( A_e^1 \) = Transformation start temperature
\( \gamma + \alpha \) = Austenite + Ferrite
\( \alpha + CP \) = Ferrite + Coarse Pearlite
\( \alpha + P \) = Ferrite + Pearlite
\( \gamma + P \) = Austenite + Pearlite
50% FP + 50% UB = 50% Fine Pearlite + 50% Upper Bainite
UB = Upper Bainite
LB = Lower Bainite
M = Martensite
\( M_s \) = Martensite start temperature
\( M_{50} \) = Temperature for 50% martensite formation
\( M_F \) = Martensite finish temperature

\( \gamma \) = Austenite
\( \alpha \) = Ferrite
CP = Coarse Pearlite
P = Pearlite
FP = Fine Pearlite
UB = Upper Bainite
LB = Lower Bainite
M = Martensite
M_s = Martensite start temperature
M_{50} = Temperature for 50% martensite formation
M_F = Martensite finish temperature

Michael Kröning
Material Degradation of Nuclear Structures - Mitigation by Nondestructive Evaluation
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Morphology and Nucleation Site of Acicular Ferrite

*Within the bainitic transformation temperature range, large grain size promotes acicular ferrite formation under isothermal condition*
Transformation Diagrams – Effect of Austenite Grain Size

Acicular Ferrite

Michael Kröning
Material Degradation of Nuclear Structures - Mitigation by Nondestructive Evaluation
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Transformation Diagrams – Massive Alpha Ferrite (for comparison)
Heat Treatments TTT Diagram – Modification by Strain

Principles of dynamic strain induced transformation (DSIT) during deformation at constant temperature

Michael Kröning
Material Degradation of Nuclear Structures - Mitigation by Nondestructive Evaluation
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Heat treatments – TTT diagram

$M_s$: Martensitic Start Temperature

$M_{50}$: 50% Martensite

$M_{90}$: 90% Martensite

Time-Temperature Paths on Isothermal Transformation Diagram
Heat Treatments

Time Temperature Transformation (TTT) Diagram

Austenite converts completely to fine pearlite after eight seconds at 873 K. This phase is stable and will not be changed on holding for 100,000 seconds at 873 K.

The final structure, when cooled, is fine pearlite.

Time-Temperature Paths on Isothermal Transformation Diagram
Focus on Steel – Quenching and Tempering

ASTM A508 / A508M - 14

Standard Specification for Quenched and Tempered Vacuum-Treated Carbon and Alloy Steel Forgings for Pressure Vessels

Basic chemical composition of the steel, wt. (%)

<p>| | | | | | | | | |</p>
<table>
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<tr>
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<td>0.003</td>
<td>0.0029</td>
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</tr>
</tbody>
</table>
Focus on Steel – Quenching and Tempering

A508 Steel
Etched in Nital 2%

low carbon martensite, slightly decomposed in ferrite and carbides during the 350 °C tempering treatment. The large austenite grain size increased the steel hardenability and so favored both martensite transformation (at the expenses of the bainite) and austenite retaining, the latter as small acicular areas.
Focus on Steel – Quenching and Tempering

**Partial recrystallization during discontinuous cooling,**

*induced a heterogeneous distribution of austenitic grains.*

*The elevated austenitizing temperatures favored the formation of a coarse microstructure, as well as alloying segregation at the grain boundaries (intergranular fracture!).*

*The microstructure presents heavily spheroidized carbides as a result of the tempering treatment at 575 °C. The material's hardenability was reduced due to the recrystallization, grain homogenization and refinement cycles, sequentially applied to the material, which prevented austenite retaining and favored the formation of tempered bainite, at the expenses of the martensite.*
Focus on Steel – Quenching and Tempering

A508 Steel
Etched in Nital 2%

The microstructure exhibits a quite complex arrangement of different phases, in which it can be inferred retained austenite, martensite, bainite and a mixture of ferrite and carbides slightly coalesced during the 350 °C tempering process.
Focus on Steel – Quenching and Tempering

The microstructure maintain great morphologic similarity to the microstructure generated by partial recrystallization due to the likeness between their quenching and final tempering conditions. As a consequence of higher austenitizing soaking time and temperature applied, it rendered a coarser microstructure. This leads to a lower toughness value.
Focus on Steel – Quenching and Tempering

Very high austenitizing soaking times and temperatures result in grain coarseness. This condition also induces segregation at grain boundaries with the risk of intergranular crack propagation. It resembles the microstructure of “low carbon martensite” related to the very high hardenability caused by large austenitic grain size that gave rise to low carbon martensite, instead of bainite.
A continuous cooling transformation (CCT) phase diagram is used to represent which types of phase changes will occur in a material as it is cooled at different rates. These diagrams are often more useful than TTT diagrams because it is more convenient to cool materials at a certain rate than to cool quickly and hold at a certain temperature.

Types of Continuous Cooling Diagrams

There are two types of continuous cooling diagrams drawn for practical purposes. The diagrams plot transformation start, a specific transformation fraction, and transformation finish temperature for all products against:

- Type 1: transformation time on each cooling curve
- Type 2: cooling rate or bar diameter of the specimen for each type of cooling medium.
Heat treatments – continuous cooling transformation diagram

Illustration of a continuous cooling transformation (cct) diagram for steel
Heat treatments – continuous cooling transformation diagram

Schematic Cooling Curves

Any slope change indicates phase transformation. Fraction of transformation roughly can be estimated.
Steel EN S355 (ASTM A-572 Grade 50) warranted yield stress: 355 MPa for welding (fast cooling, linear scale)
Heat Treatments
Continuous Cooling Transformation (CCT) Diagram

An Example of Converting TTT to CCT: Graphic Method
(Grange & Kiefer 1941)

\[ T_3 = (T_1 + T_2) / 2 \]
and \[ t_3 = t_2 - t_1 \]
or \[ t_2 = (t_1 + t_3) / 2 \]
Continuous Cooling Transformation (CCT) Diagram & Microstructure

4340 Steel Alloy

Critical cooling rate

Eutectoid temperature

Bainite "nose"

Austenite → Bainite

Austenite → Martensite

M (start)

M

M + B

M + F + P + B

F + P

Time (s)
# Focus on Steel – Carbon Steels

## Typical Industrial Heat Treatment Service

<table>
<thead>
<tr>
<th>Spec</th>
<th>Grade</th>
<th>Remarks</th>
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<td>Post Weld Heat Treatment for Pressure Vessels Constructed of Low Alloy Steels</td>
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<td>Sec VIII DIV1 UNF-56</td>
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<td>Post Weld Heat Treatment of Nonferrous Materials</td>
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<td><strong>ASTM</strong></td>
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<tr>
<td>A671 Table 2</td>
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<td>Heat Treatment of EFW Steel Pipe for Atmospheric and Low Temperatures</td>
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<td>A672 Table 2</td>
<td></td>
<td>Heat Treatment of EFW Steel Pipe for High-pressure Service at Moderate Temperatures</td>
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<td>A691 Table 2</td>
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<td>Heat Treatment of Carbon &amp; Alloy Steel Pipe, EFW for High-Pressure Service at High Temperatures</td>
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<td><strong>Others</strong></td>
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<tr>
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<td>Normalized or Normalized and Tempered of Steel Structure</td>
</tr>
</tbody>
</table>
Focus on Steel – Carbon Steels

IT IS A MATTER OF CONTINUING RESEARCH & DEVELOPMENT:

For example, the group „mechanical properties of interfaces“ investigates homophase (grain boundaries, stacking faults) as well as heterophase (coatings, precipitates, lamellar alloys) interfaces, with a focus on metals and alloys.
Focus on Steel – Steel Qualities

Literature

1. web.utk.edu/~prack/MSE%20300/FeC.pdf
2. R. Manna, *Time Temperature Transformation (TTT) Diagrams*, Centre of Advanced Study, Department of Metallurgical Engineering, Institute of Technology, Banaras Hindu University, Varanasi-221 005, India; rmanna.met@itbhu.ac.in
3. Heat Treatment of Steel Terminology
   TPU Lectures 14-15\Heat Treatment Of Steel Terminology.docx
**STEEL CLASSIFICATION**

**BY PURPOSE:**

*DIN EN 10027-1*

<table>
<thead>
<tr>
<th>Code Nr.</th>
<th>Scope</th>
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<tbody>
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<td>Steels for cold working</td>
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<tr>
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<td>Engineering steels</td>
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<tr>
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<td>High-strength flat products</td>
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**S235JR+C**

*S*: steel for steel construction

235: SMYS 235 N/mm²

**JR** = 27J notch impact strength 20 °

**C** = cold rolled

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</table>

**C** cold working

**L** for low temperatures

**H** for semi profiles

**W** weatherproof
As carbon content increases beyond 0.8%, no more *pearlite* can be formed. The excess carbon forms *cementite* which is deposited in between the *pearlite* grains. This increases the hardness, but slightly reduces the strength. The ductility of all plain carbon steels over 0.8% carbon is very low.
Focus on Steel – Bainit Formation

Bainite Microstructure