Lecture 8

Pearlite

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Introduction

Pearlite is probably the most familiar microstructural feature in the whole science of metallography. It was discovered by Sorby in 1886, who correctly assumed it to be a lamellar mixture of iron and iron carbide ($\text{Fe}_3\text{C}$).

Pearlitic transformation is clearly classified as reconstructive. Pearlite nuclei occur on austenite grain boundaries, but it can also be associated with both pro-eutectoid ferrite and cementite in off-eutectoid steels. Pearlite nodules can also nucleate on inclusions.

The idealized view of pearlite:
a semispherical nodule of pearlite nucleated at an austenite grain boundary, and growing gradually into one austenite grain

Colonies and Nodules of Pearlite

Any large volume of pearlite is observed to be composed of a number of structural units in which the lamellae are parallel or largely parallel, and in which the ferrite and cementite in lamellae exhibit a common crystallographic orientation; these units of structure are known as *pearlite colonies*.

A *nodule* of pearlite may consist of multiple colonies. Everywhere within a nodule of pearlite, ferrite maintains almost the same crystallographic orientation (small misorientations possible).

*A pearlite nodule, in this case consisting of three pearlite colonies*
Cooperative Growth of Pearlite

Growth direction of pearlite

Carbon diffusion pattern in austenite

\[ \alpha \]

\[ \theta \]

\[ \gamma \]
Interlamellar Spacing

**Apparent** interlamellar spacing

The *spacing variations* of the lamellae in different areas may be partly due to differences in angles that they make with the plane of polish.

**True** interlamellar spacing

\[ \lambda_0 = \lambda \sin \theta \]

Interlamellar Spacing

The interlamellar spacing in a given steel is controlled by the amount of undercooling:

\[ \lambda = \frac{4Y_{\alpha/Fe_3C}T_E}{\Delta H_v \Delta T} \]

- **Interfacial energy per unit area of \( \alpha/Fe_3C \) boundary**
- **Equilibrium temperature in degrees Kelvin (\( Ae_1 \), 723 °C or 996 K in Fe-C steels)**
- **Undercooling below \( Ae_1 \)**
- **Difference in enthalpy per unit volume between austenite and a mixture of ferrite and cementite**

**Interlamellar Spacing**
Average true interlamellar spacing of pearlite as a function of undercooling below the \(Ae_1\) temperature for some carbon and low alloy steels.
Nucleation and Crystallography

Kurdjumov-Sachs (K-S) O.R.: \((111)_\gamma_2 // (110)\alpha\)  
\([1\bar{1}0]_\gamma_2 // [1\bar{1}1]_\alpha\)

**B and C: pro-eutectoid ferrite**

**A: pearlitic ferrite**

**K-S or similar O.R. between \(\gamma_2\) and \(\alpha\)**

**Bainite**

**Martensite**

**WS ferrite**

**observed**

**Austenite grain boundary**

**not observed**

Nucleation and Crystallography

When pearlite nucleates on clean austenite grain boundaries:

- Pearlitic ferrite and cementite are not orientation related to the austenite grain in which they grow (\( \gamma_2 \) in the schematic below), therefore the pearlite/austenite interface is incoherent.

- There is always a well-defined crystallographic orientation relationship and habit planes (small-scale steps even though interfaces might appear curved in low magnification micrographs) between the cementite and ferrite lamellae within a pearlite colony. The most important relationships are:

  **Isaichev relationship**
  
  \[
  [010]_\theta // [111]_\alpha, \\
  (103)_{\theta} // (01-1)_{\alpha}
  \]

  **Pitsch/Petch relationship**
  
  \[
  (001)_{\theta} // (-2-15)_{\alpha}, \\
  [010]_{\theta} 2.6^\circ \text{ from } [131]_\alpha, \\
  [100]_{\theta} 2.6^\circ \text{ from } [-31-1]_{\alpha}
  \]

  **Bagaryatski relationship**
  
  \[
  [100]_{\theta} // [1-10]_\alpha, \\
  [010]_{\theta} // [111]_\alpha, \\
  (001)_{\theta} // (11-2)_{\alpha}
  \]

\[\gamma\] grain boundary

Incoherent interface


Mehl and co-workers took the view that pearlite lamellae formed by a **sidewise nucleation** and **edgewise growth** mechanism. In this way, the rapid increase in the number of lamellae in a colony could be explained.

*Sidewise nucleation and edgewise growth mechanism*

*(repeated nucleation of alternate layers of ferrite and cementite by sidewise compositional fluctuations in austenite)*

Lamellae Multiplication

Hillert concludes that the increase in the number of lamellae could equally well result from the branching of lamellae during the growth of pearlite.

SEM micrograph of a deeply etched Fe-0.46C-0.65Mn-0.28Si hypo-eutectoid steel (ferrite dissolved in an etchant) illustrating branching of the cementite lamellae

Parallel and Radial Lamellae

**Transformation temperature**

- **High**
  - Parallel pearlite colonies

- **Intermediate**
  - Mixed parallel and radial pearlite colonies

- **Low**
  - Radial pearlite colonies

Microscopy of Pearlite

Light optical micrographs

0.3\%C

0.5\%C

0.7\%C

Microscopy of Pearlite

*Light optical micrograph*

Fe-1.5%C

- Cementite network on prior austenite grain boundaries
- Widmanstätten cementite

Scale: 0.2 mm
**Microscopy of Pearlite**

**Scanning electron micrograph**

Fe–3.50Mn–2.46C (at.%)


**Transmission electron micrograph**

Fe–0.76C–0.91Mn

Microscopy of Pearlite

High resolution TEM image of pearlitic cementite showing the maintenance of the atomic habit plane by microsteps during lamellar curvature. The macroscopic habit plane and the \((001)_{\text{Fe}_3\text{C}}\) planes are clearly not parallel.
Equilibrium Pearlite Fraction in Fe-C Steels

Values based on the lever rule

Fraction of Pearlite

wt% Carbon

Fully Pearlitic Off-Eutectoid Steels

Required condition to obtain a fully pearlitic microstructure in off-eutectoid alloys: simultaneous supersaturation of $\gamma$ with respect to both $\alpha$ and Fe$_3$C (rapid cooling to the hatched region)

Fully Pearlitic Off-Eutectoid Steels

**Eutectoid temperature**

Arrows indicate where common tangents touch the free energy curves. In the concentration range highlighted in green, austenite is simultaneously unstable with respect to both ferrite and cementite. Therefore, if the formation of pro-eutectoid phases is inhibited at higher temperatures, off-eutectoid steel compositions in the range highlighted in green may transform to 100% pearlite.
Nucleation and Growth Rates

Both the nucleation and growth rates of pearlite in a eutectoid carbon steel increase as the transformation temperature decreases. This causes accelerated pearlitic transformation at lower temperatures.

\[ \text{Rate of nucleation (nuclei/mm}^3/\text{sec)} \]

\[ \text{Rate of growth (mm/sec)} \]

\[ \text{Temperature, °C} \]

Fe-0.78%C-0.63%Mn

Steady-State Growth of Pearlite

The interlamellar spacing remains constant for a fixed transformation temperature. This is indeed valid for binary Fe-C steels and leads to a constant growth rate for pearlite (steady state).

Fe-1.02%C-0.31%Si-0.26%Mn
680 °C

Effect of Grain Size on Pearlite Formation Kinetics

Effect of Alloying Elements on Pearlite Reaction

In contrast to most alloying elements, Co accelerates the pearlite formation.

Effect of Manganese on Pearlite Reaction

Hyper-eutectoid steels with indicated Mn contents after full austenitization and cooling to room temperature at a rate of 0.5 °C/s

Mn addition clearly decelerates the formation of pearlite
Non-Steady-State Growth of Pearlite

When substitutional solutes are present, they may partition between the coexisting phases so that the austenite may become enriched or depleted with respect to such elements as the transformation proceeds. As the composition of austenite approaches an equilibrium composition different from the bulk composition, the driving force for the transformation decreases which causes a gradual increase in the interlamellar spacing as the pearlite grows, a phenomenon known as **divergent pearlite**. The above process decelerates the growth rate of pearlite.

*Optical micrographs of divergent pearlite colonies formed in a Fe–0.55%C–5.42%Mn steel after heat treatment at 625 °C for 384 h in the (γ + α + M₃C) phase field.*

Partitioning of Mn

Atom probe tomography (APT) showing austenite/pearlite interface in an Fe-9.66Mn-2.98C (at.%) steel after aging at 600 °C for 6 h.

Full Annealing, Normalizing, Spheroidizing

Fe-C equilibrium phase diagram showing approximate temperature ranges for some common heat treatment practices

Temperature, °C
C, mass-%

Full Annealing, Normalizing, Spheroidizing

Full Annealing and Normalizing Heat Treatments

Full Annealing Heat Treatment

**Heat Treatment:** heating just above the $A_c_3$ temperature for low- and medium-carbon steels and just above the $A_c_1$ temperature for hyper-eutectoid steels followed by slow furnace cooling

**Microstructure:** coarse-grained allotriomorphic ferrite and pearlite with coarse interlamellar spacing. In the case of hyper-eutectoid steels, the pro-eutectoid ferrite is replaced with the pro-eutectoid cementite.

**Purpose:** obtaining a relatively soft microstructure with good machinability
Normalizing Heat Treatment

**Heat Treatment:** austenitizing at approximately 50 °C above $A_c_3$ temperature for low- and medium-carbon steels and above or below $A_c_{cm}$ temperature for hyper-eutectoid steels (when austenitizing above $A_c_{cm}$, the continuous network of pro-eutectoid cementite which subsequently forms may cause cracking in the case of high hardenability steels) followed by **air cooling**. The higher austenitizing temperatures compared to full annealing ensure that most carbides are dissolved, and the more rapid air cooling produces a finer microstructure, thereby a higher strength.

**Microstructure:** uniform, fine-grained allotriomorphic ferrite and pearlite with fine interlamellar spacing. In the case of hyper-eutectoid steels, the pro-eutectoid ferrite is replaced with the pro-eutectoid cementite.

**Purpose:** normalizing is often applied to hot-formed (rolled, forged, etc.) carbon and alloy steels. For instance, forging of bars to complex shapes is accomplished at high temperatures in the austenite phase field. As a result of high forging temperatures, austenite grain sizes are coarse, and in view of different deformation in forgings of complex shape, austenite grain size might be quite non-uniform which leads to coarse, non-uniform ferrite/pearlite microstructures on cooling. Reheating during normalizing causes uniform nucleation of new austenite grains, and because normalizing temperatures are kept below grain-coarsening temperatures, austenite grain size remains fine, and the austenite transforms to uniform, fine ferrite/pearlite microstructures during air cooling. The normalized microstructures provide excellent starting microstructures for subsequent hardening heat treatments.

Spheroidizing Heat Treatment

The **softest condition** of any steel is the one obtained with a microstructure consisting of spherical carbide particles uniformly dispersed in a ferritic matrix. The **thermodynamic driving force** for spheroidization is the reduction of ferrite/carbide interface energy.

*Fe-1%Mn-0.66%C steel formed by annealing martensite at 700 °C for 24 hours.*
Strengthening of Pearlite by Wire Drawing

UTS vs. C content of steel wire after 95-99% cold reduction.

Patenting consists of heating to austenite and continuous cooling or isothermal holding to produce a uniform fine pearlite microstructure. Bainitic microstructures are susceptible to delamination after drawing. Fine pearlite obtained by patenting has been found to be the most suitable starting microstructure for wire drawing.
Divorced Pearlite in Hyper-Eutectoid Steels

**Lamellar Pearlite**
- Cooling from the γ field
- Ferrite and cementite grow from γ in a cooperative manner
- Not as machinable as spheroidized cementite

**Divorced Pearlite**
- Cooling from the intercritical range (between \(Ae_1\) and \(Ae_{cm}\))
- \(\alpha\) and \(\theta\) grow from γ in a non-cooperative manner (existing undissolved \(\theta\) particles grow and absorb the excess C in γ)
- Readily machinable (a more economical method of softening pearlite compared to the conventional spheroidizing below \(Ae_1\))

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Conditions for Divorced Pearlite Formation

Factors favoring divorced pearlite formation:

- Presence of closely-spaced cementite particles in austenite
- Reaction at small undercoolings

![Graph showing conditions for divorced pearlite formation](image)
