Lecture on Materials Science - Alloy (3/3)

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Parts of the script are adopted from Prof. Dr.-Ing. Jürgen Häberle

Contents

Real Diagrams

Real Diagrams

- The diagrams discussed so far are ideal diagrams and do not represent reality.
- The Iron-Carbon Diagram (ICD) is the most important real diagram.
- The base metal is iron, forming steel or cast iron.
- The ICD is composed of ideal diagrams: peritectic, eutectic, and eutectoid sub-diagrams.

- Depending on the carbon appearance, we can distinguish between:
  - **Stable system Fe-C**: Carbon exists as graphite.
  - **Metastable system Fe-Fe_3C**: Carbon is bound in Fe_3C (intermediate phase cementite).
- Stable means the carbon in graphite form cannot decompose further, while Fe_3C decomposes into iron and temper carbon upon prolonged annealing.
- The metastable system represents a relative minimum of the system's total energy. For technical purposes, it is considered "sufficiently stable."

Iron-Carbon Diagram (ICD)

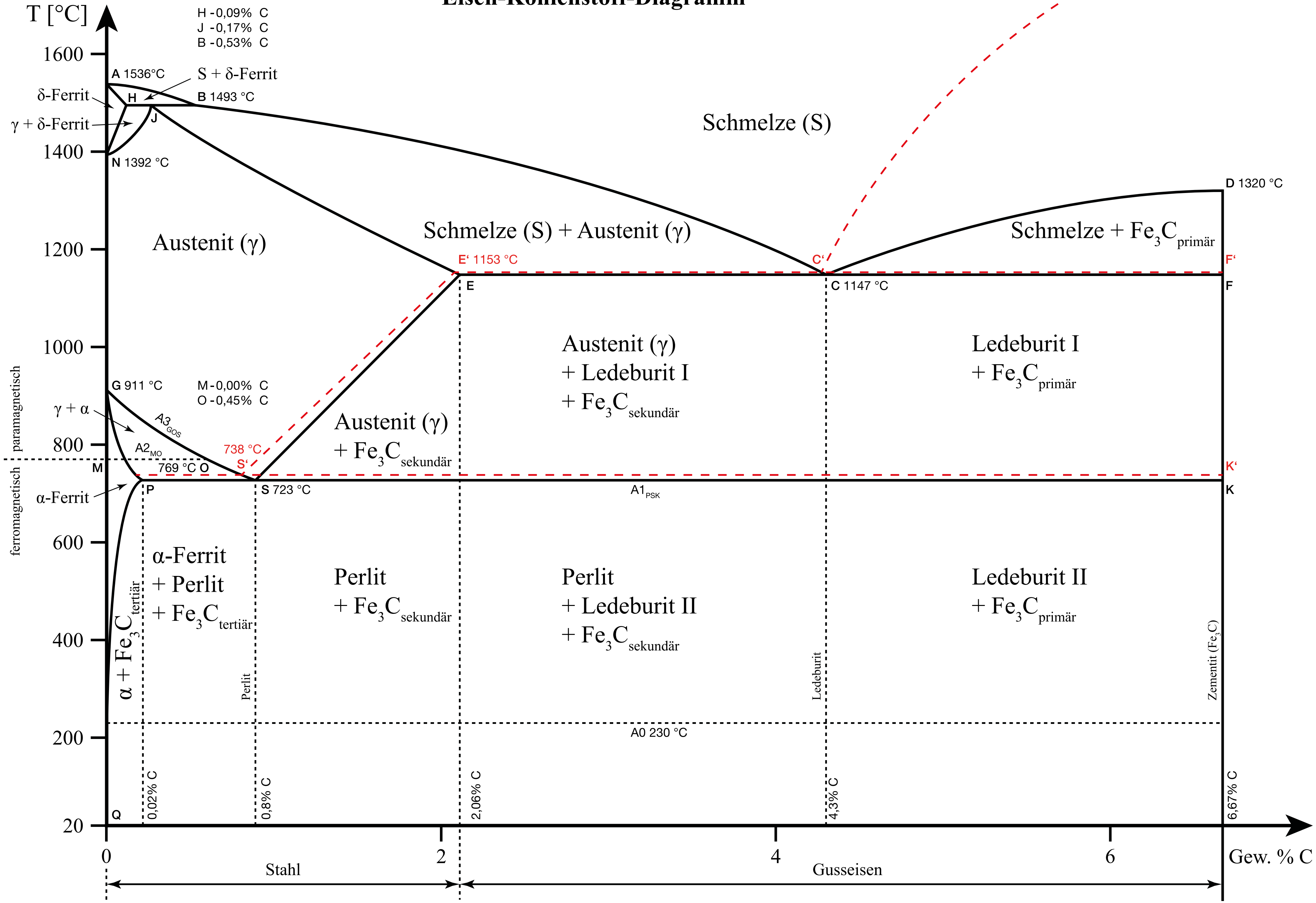
- Most important phase diagram.
- Iron is the key material in mechanical engineering.

Reasons:

- Low cost
- High strength and elastic stiffness
- Variety of possible alloys
- Availability
- Castability, weldability, etc.

Explanation video for the Iron-Carbon Diagram

Eisen-Kohlenstoff-Diagramm



Important Equilibrium Lines

ABCD - Liquidus line

AHIECF - Solidus line

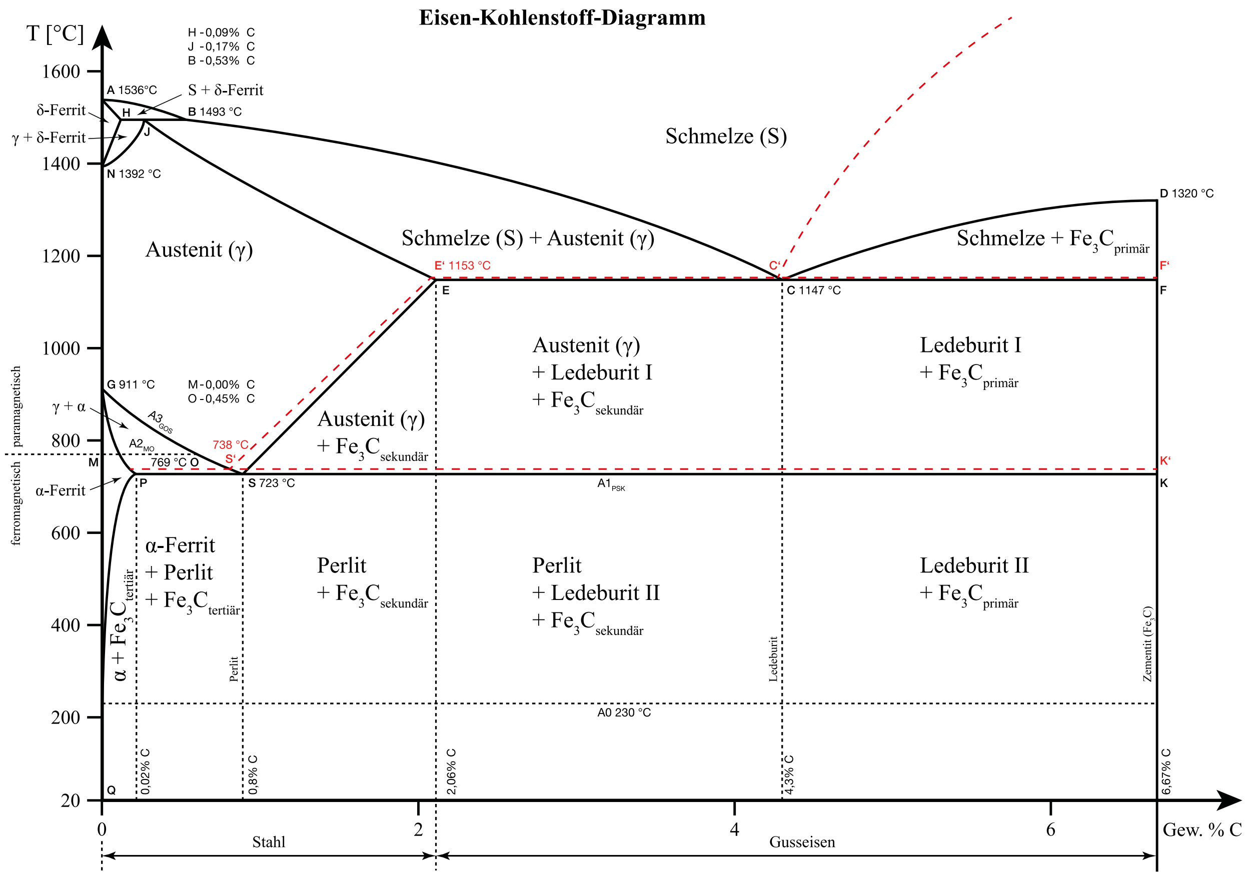
ECF - Eutectic line

PSK - Eutectoid line

ES, PQ - Saturation lines

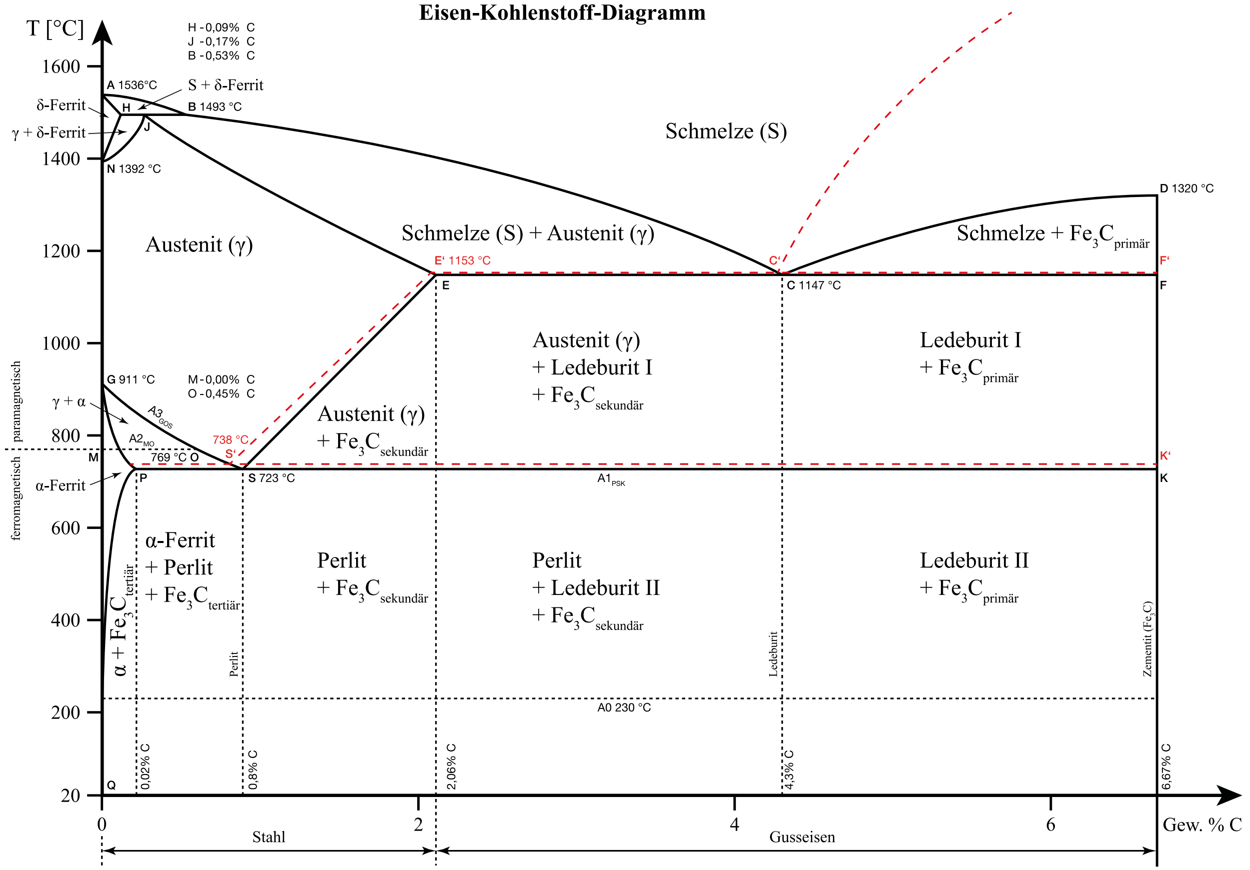
MOSK - Curie line

QPSECD - Formation/Dissolution of Fe_3C



Points in the Phase Diagram

- **S**: Eutectoid point
- **C**: Eutectic point
- **G**: α / γ - Transformation point of pure iron
- **E**: Maximum C-solubility in α-matrix
- **P**: Maximum C-solubility in γ-matrix



Critical Temperatures (Transformation Temperatures)

A arreter (stop)

r refroidir (cool)

c chauffer (heat)

e équilibre (equilibrium)

Ac_1 723°C

Ac_3 Dependent on C content

Grenzlinie im Fe-C-Diagramm	...begrenzt das Umwandlungs-geschehen	Bezeichnung der Grenzlinien-temperaturen, ermittelt im Gleichgewicht	beim Abkühlen	beim Erwärmen
PSK	$\alpha + Fe_3C \leftrightarrow \gamma$	A_{e1}	A_{r1}	A_{c1}
GS	$\alpha + \gamma \leftrightarrow \gamma$	A_{e3}	A_{r3}	A_{c3}
SE	$\gamma + Fe_3C \leftrightarrow \gamma$	$A_{e\ cm}$	$A_{r\ cm}$	$A_{c\ cm}$
NI	$\gamma + \delta \leftrightarrow \gamma$	A_{e4}	A_{r4}	A_{c4}

Phases and Microstructures in the Iron-Carbon System

Solid Solutions

Grenzlinie im Fe-C-Diagramm	...begrenzt das Umwandlungs-geschehen	Bezeichnung der Grenzlinien-temperaturen, ermittelt im Gleichgewicht	beim Abkühlen	beim Erwärmen
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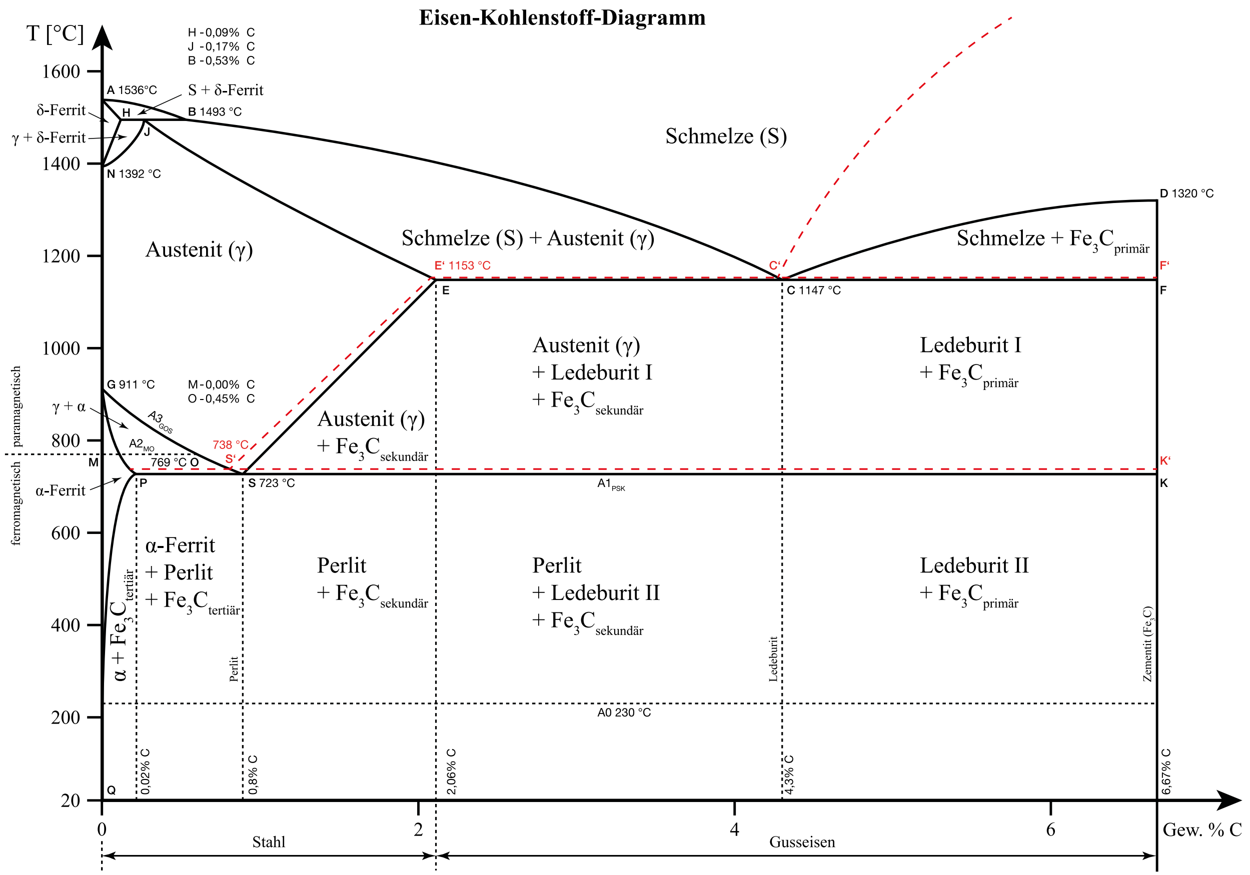
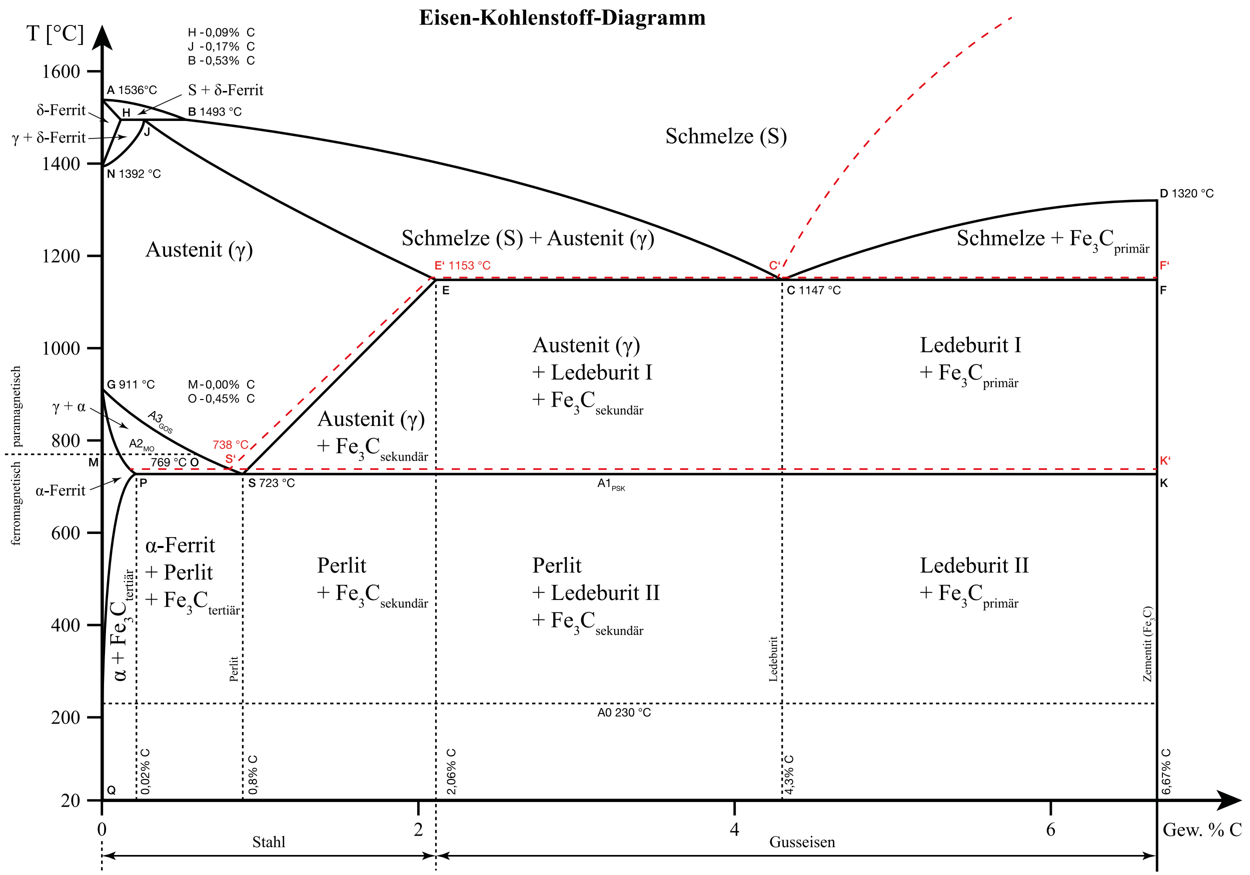
NI	$\gamma + \delta \leftrightarrow \gamma$	A_{e4}	A_{r4}	A_{c4}

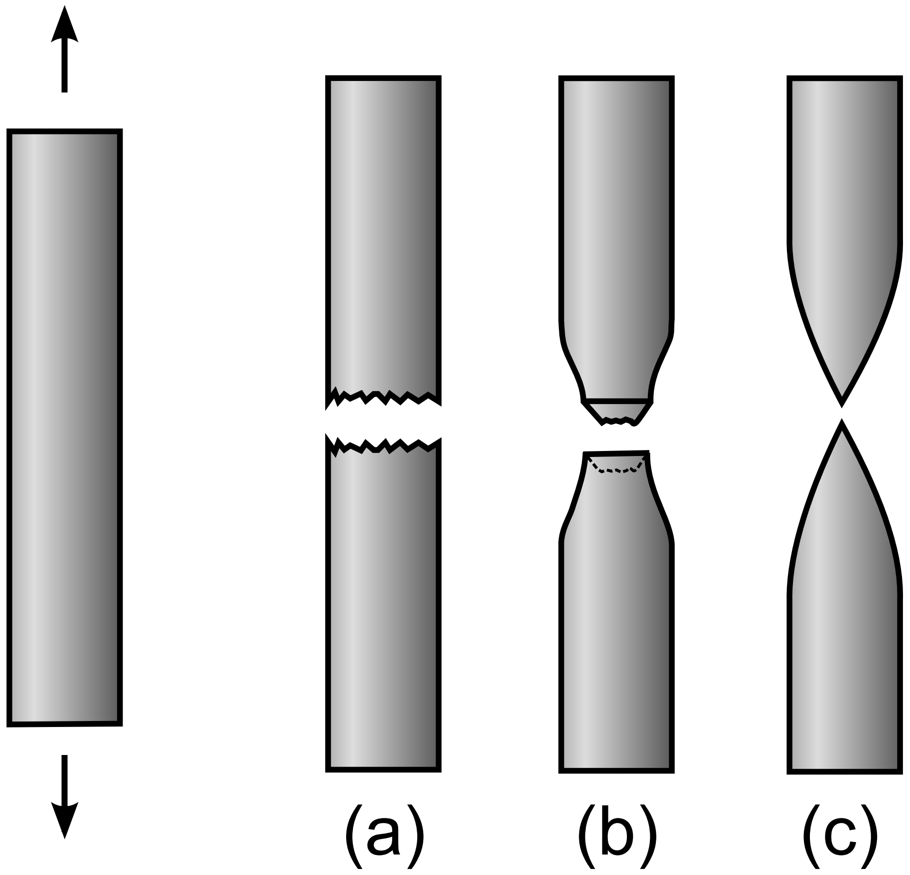


α-Solid Solution (BCC)

- Microstructure designation: Ferrite (α-Ferrite).
- Pure ferritic microstructure has low hardness/strength but high ductility.
- Maximum C solubility: 0.02%



- high ductility



Hardness / Strength

Strength

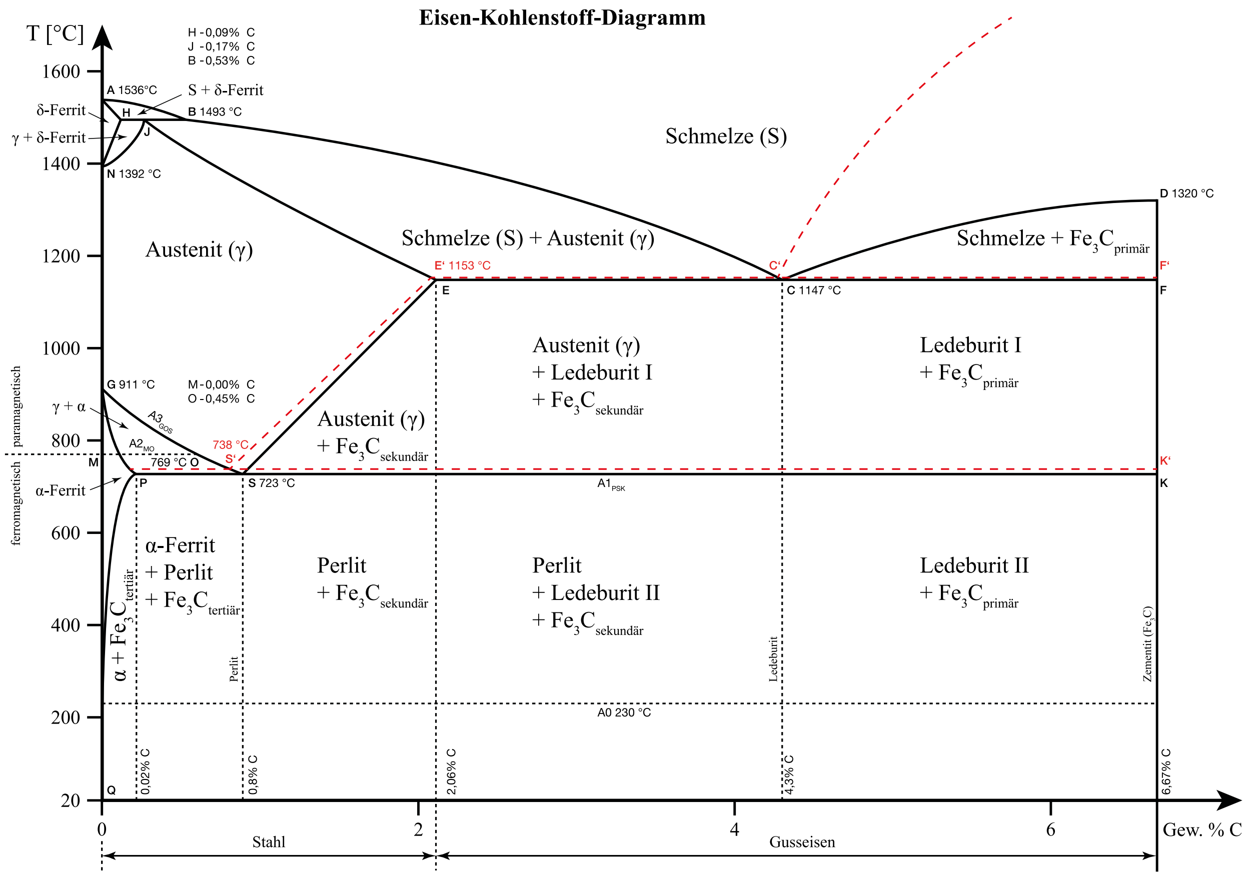
- Measure of maximum load-bearing capacity before failure.
- Force per cross-sectional area.

Hardness

- Mechanical resistance to penetration by another material.
- Measure of wear resistance.

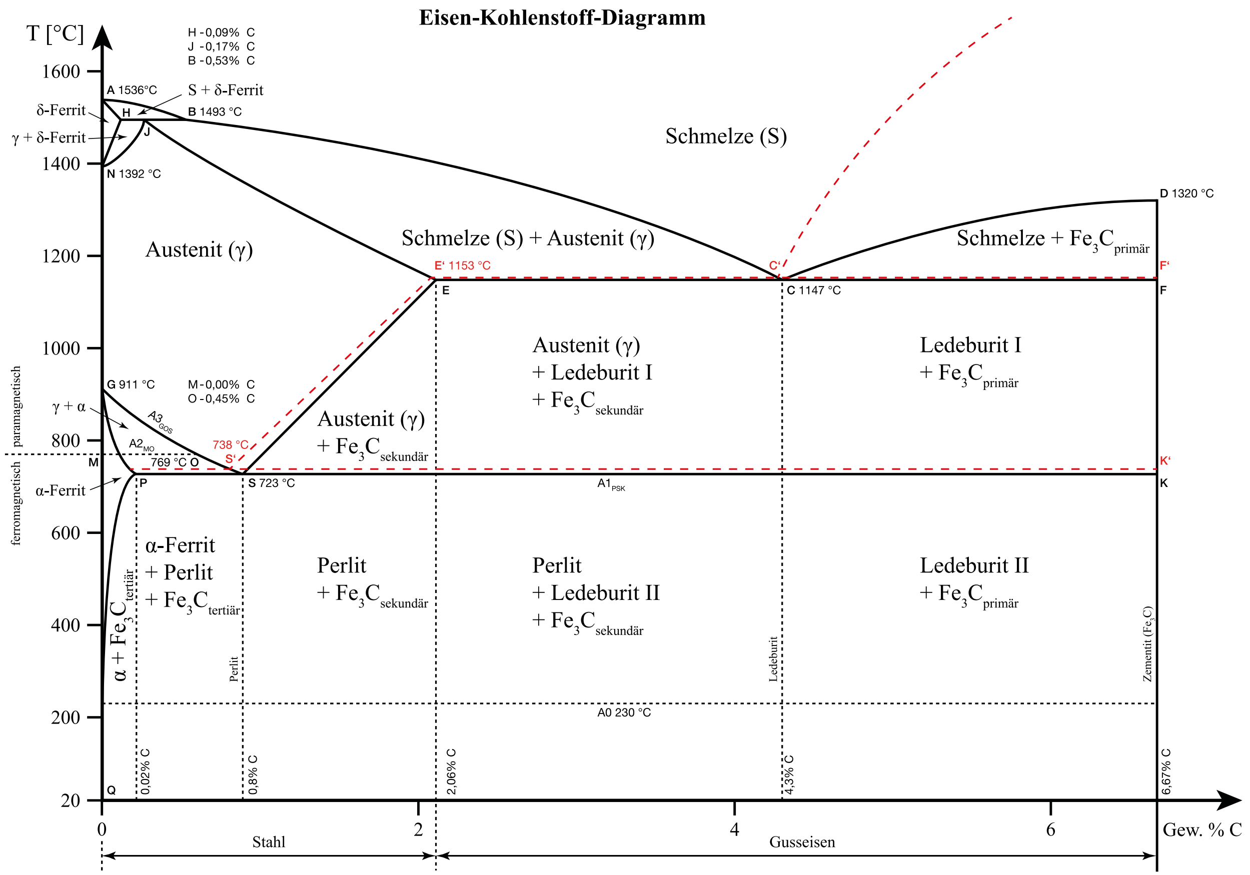
δ-Solid Solution (BCC)

- δ-Ferrite is stable only above 1392°C.
- Technically of minor importance.
- Maximum C solubility: 0.12%.

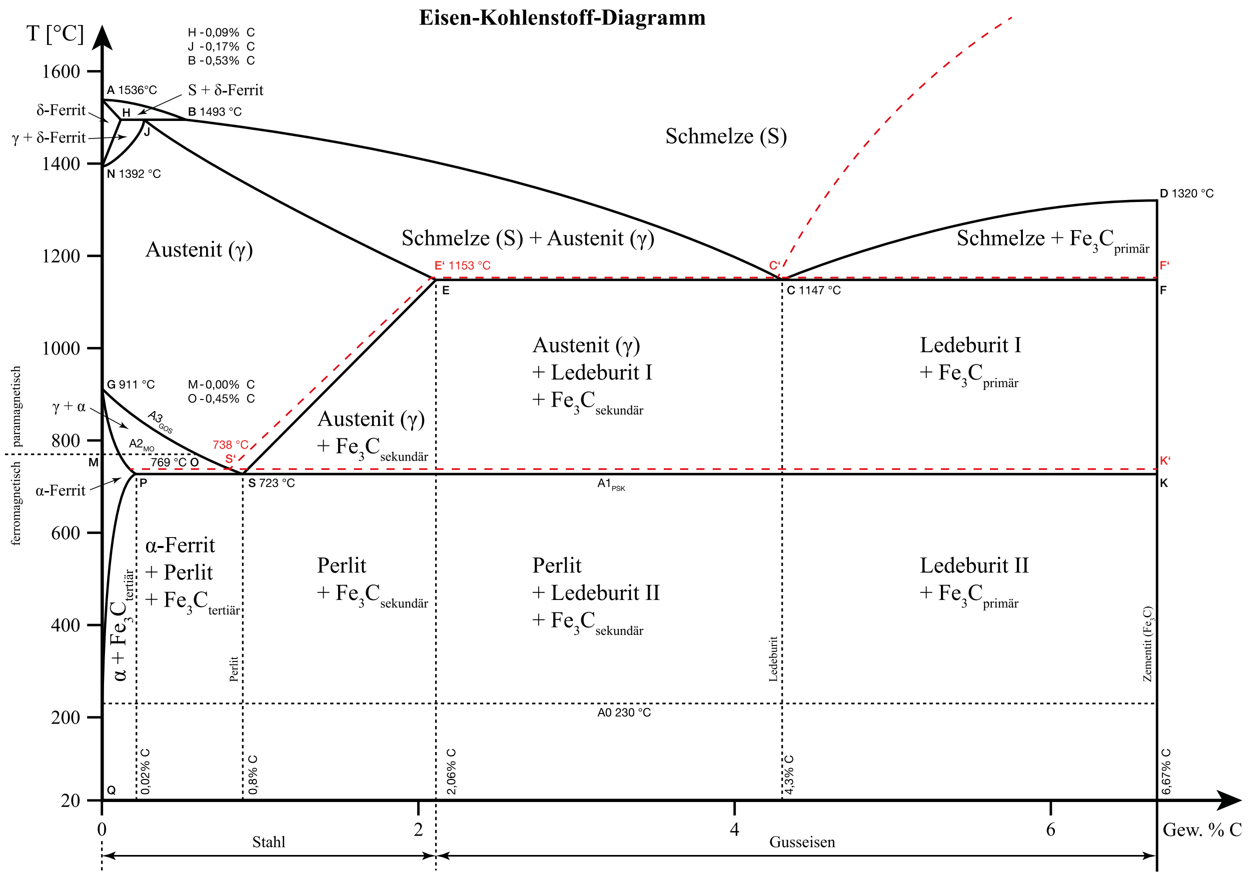


γ-Solid Solution (FCC)

- Microstructure designation: Austenite.
- Forms above the G-S-E line.
- Can remain stable at room temperature with alloying additions (e.g., Ni, Mn) and quenching (austenitic steels).



- Non-magnetic, tough, and hardenable through cold working (manganese, nickel, chromium-nickel steels).
- High heat resistance, good corrosion and oxidation resistance.
- Maximum C solubility: 2.06%.

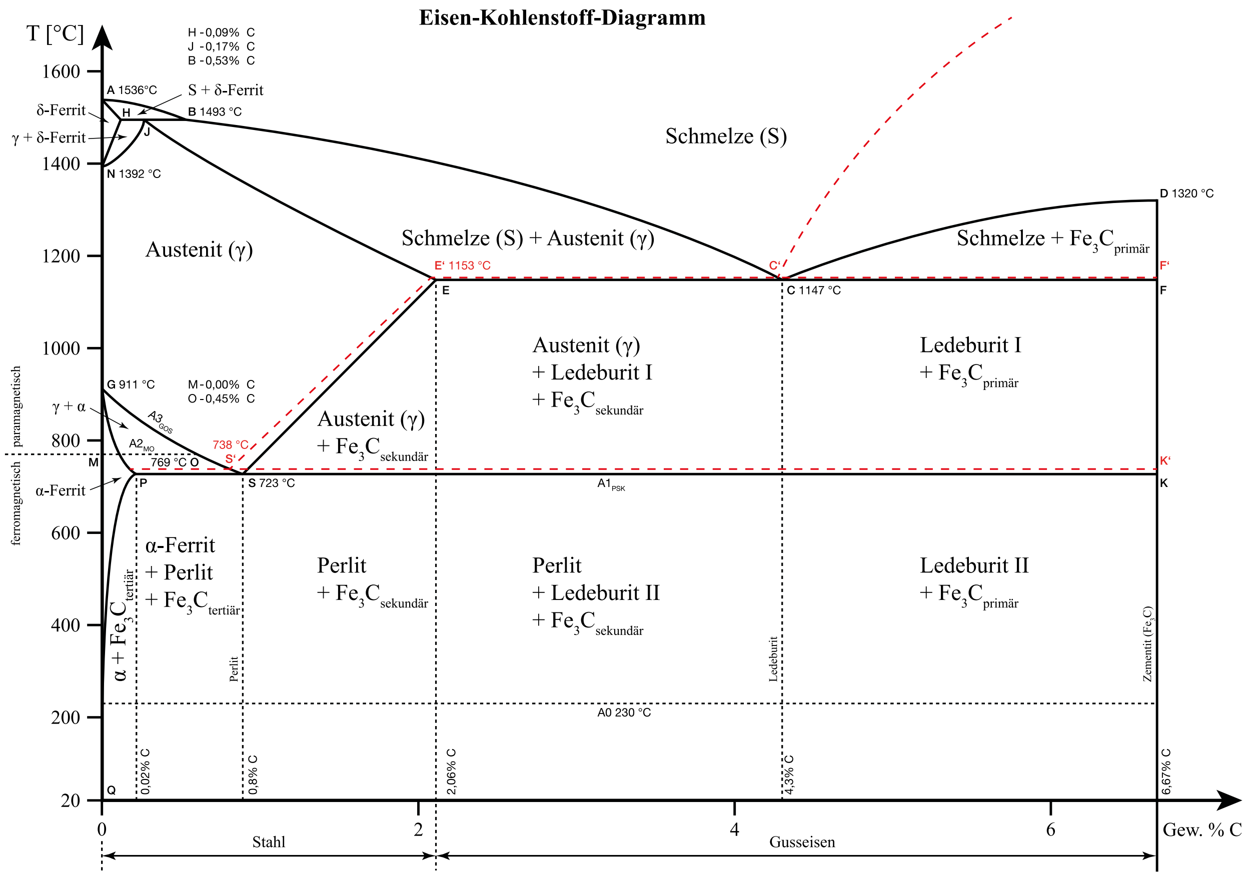


Austenite

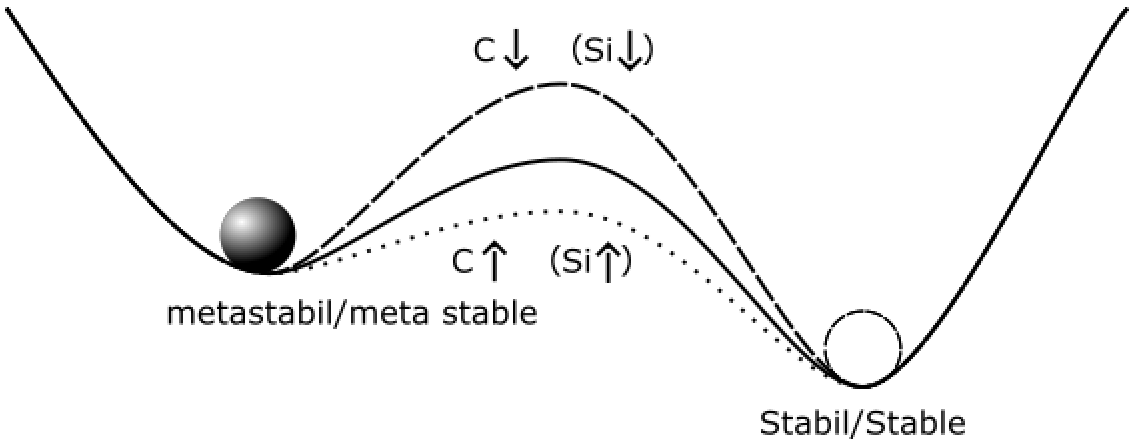
- Refers to the face-centered cubic (FCC) modification (phase) of pure iron and its solid solutions.
- Exhibits high solubility for carbon atoms.

Intermediate Phase: Cementite (Iron Carbide Fe_3C)

- C content: 6.67 wt%.

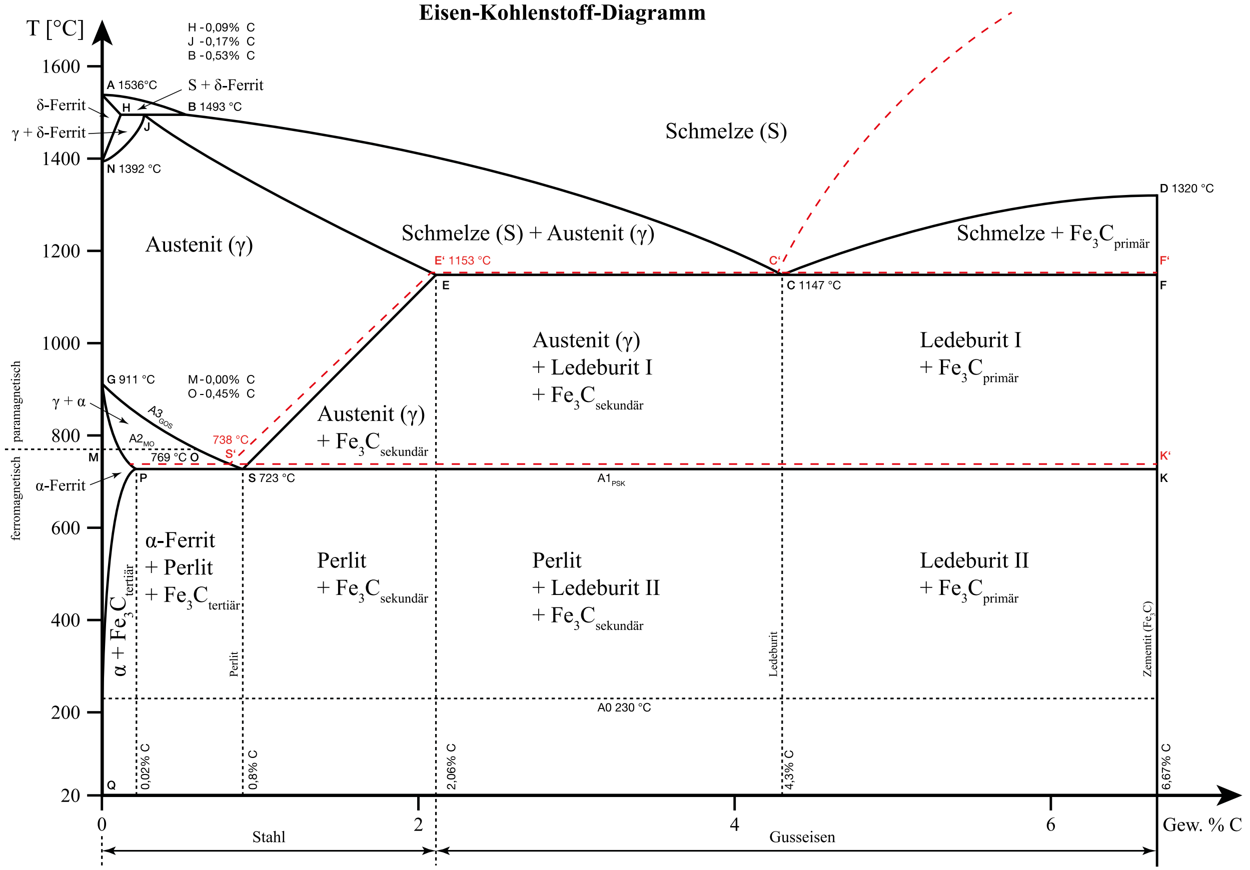


Meta stable systems



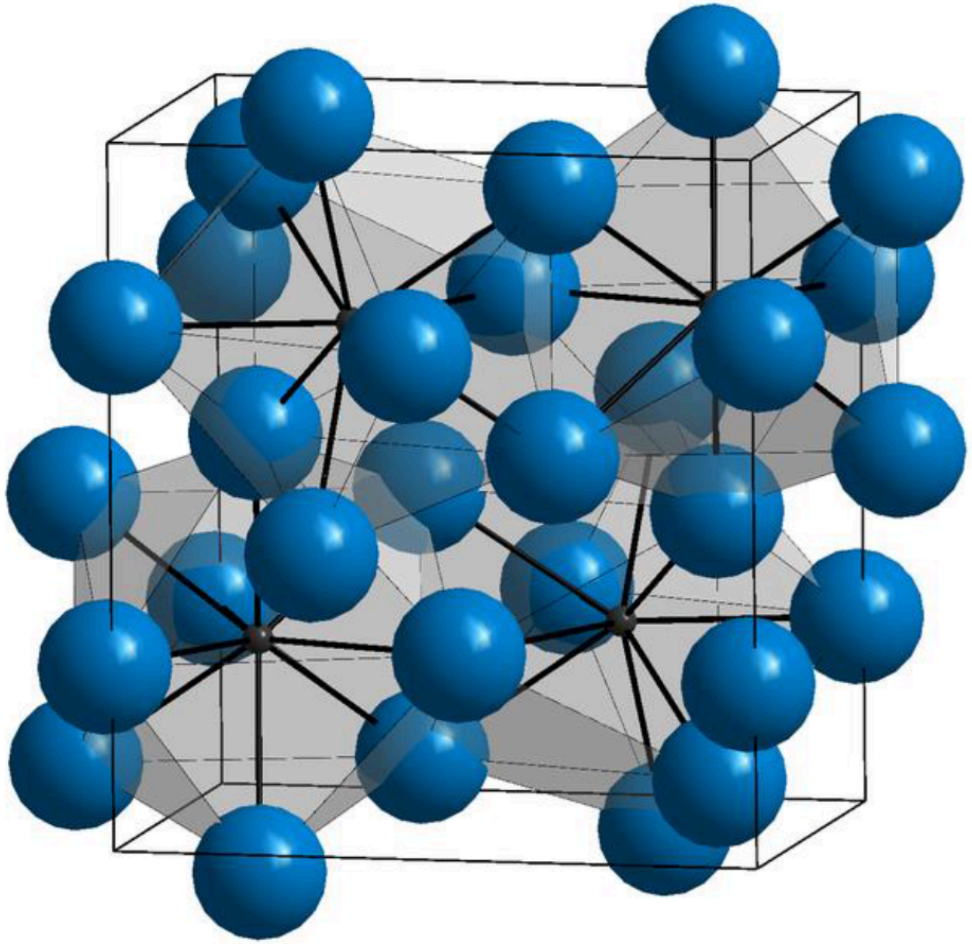
Types:

- **Primary Cementite:**
  - Crystallizes directly from the melt (line CD).
- **Secondary Cementite:**
  - Precipitates from austenite (line ES).
- **Tertiary Cementite:**
  - Precipitates from ferrite (line PQ).

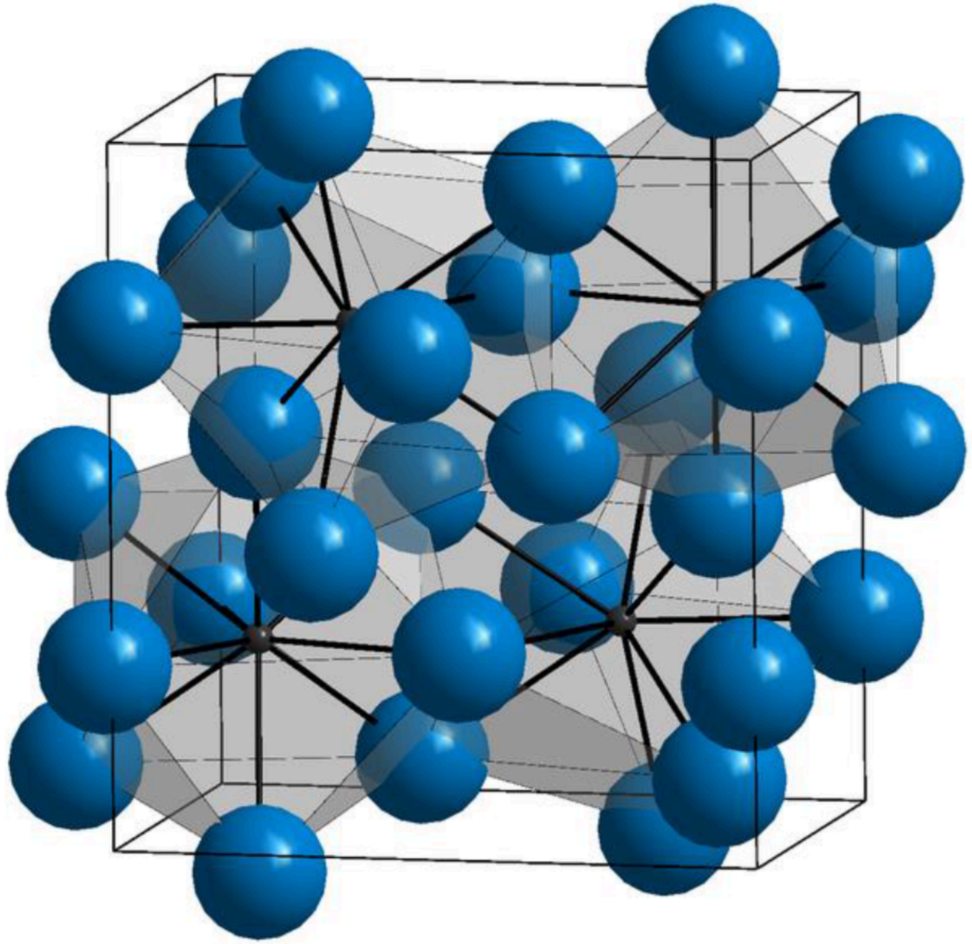


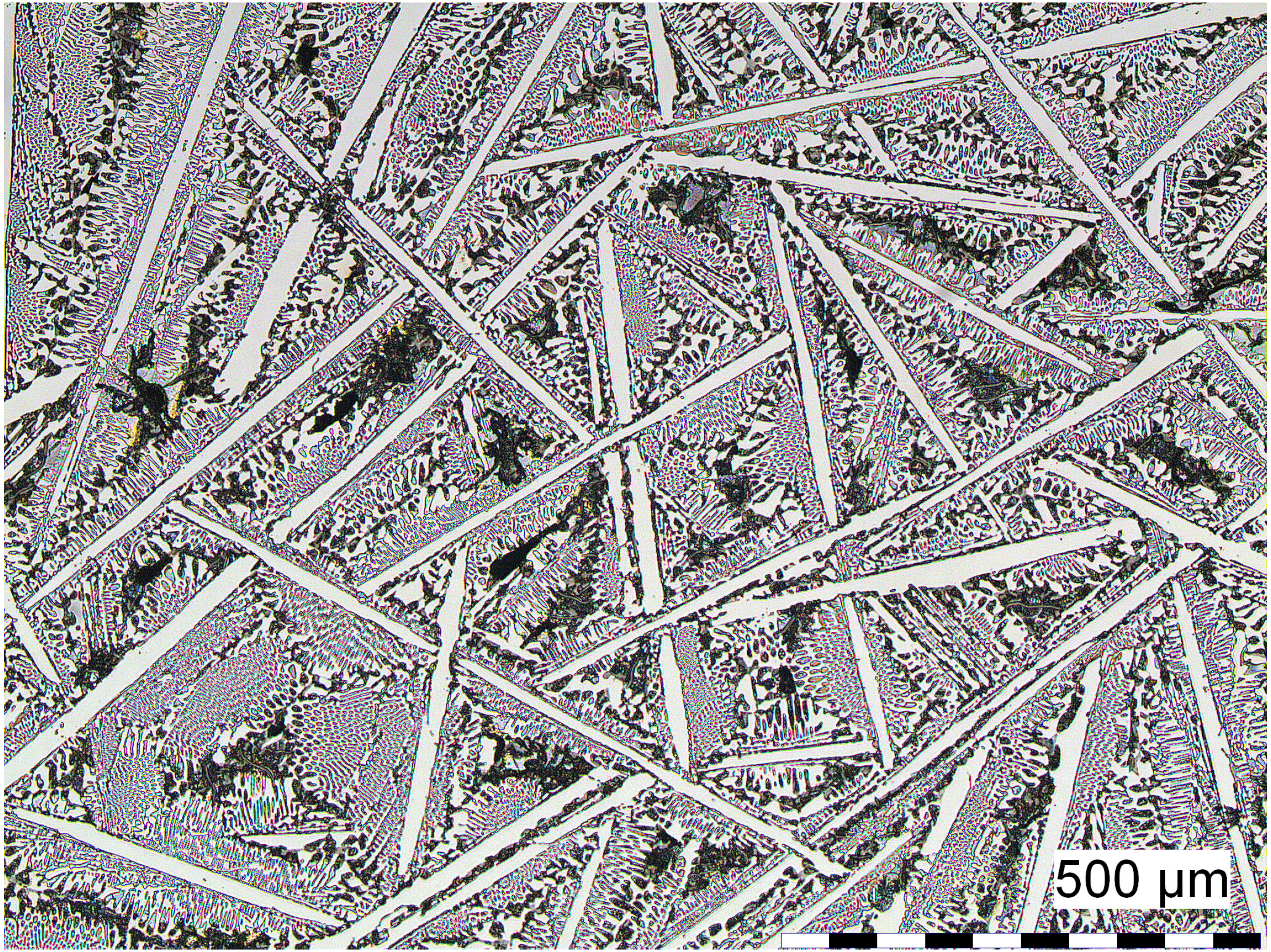
Crystal Structure

- Orthorhombic unit cell:
  - 12 iron and 4 carbon atoms.
  - Carbon atoms are irregularly surrounded by 8 iron atoms.



- Cementite is hard and brittle.
- Most technical iron-carbon alloys solidify with cementite formation.

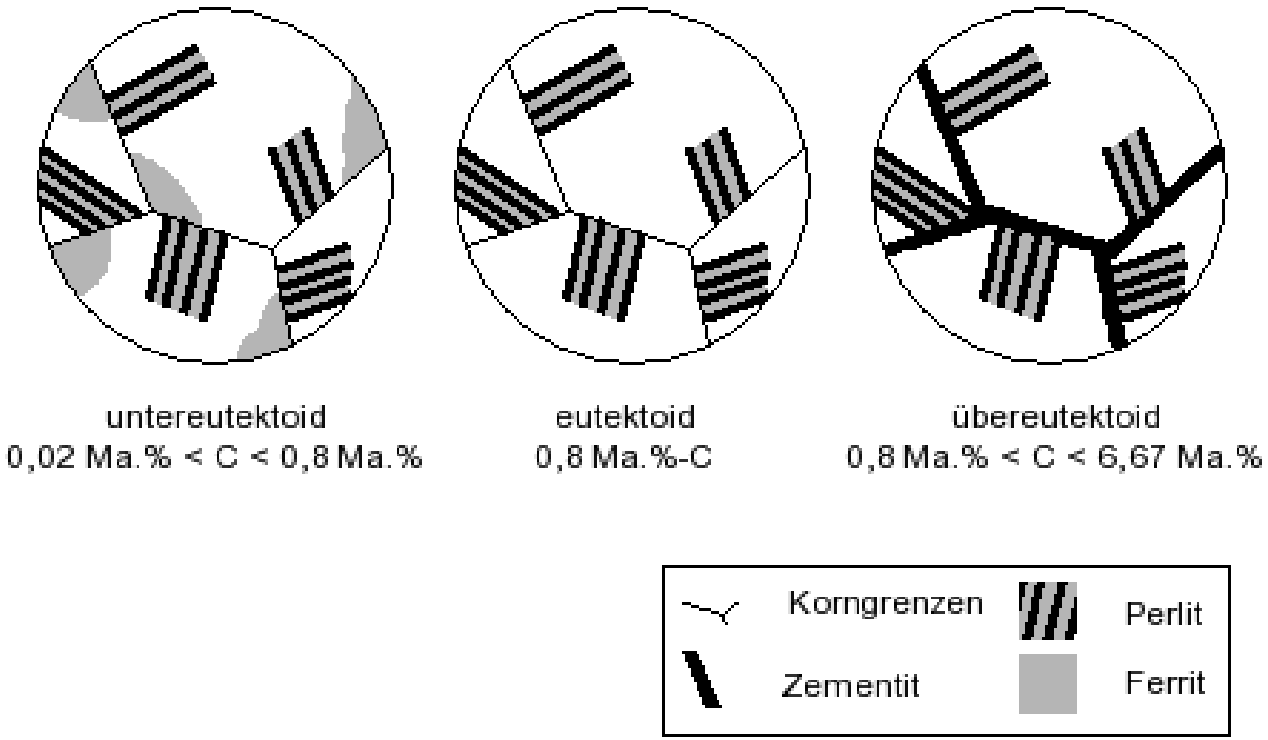



500 µm

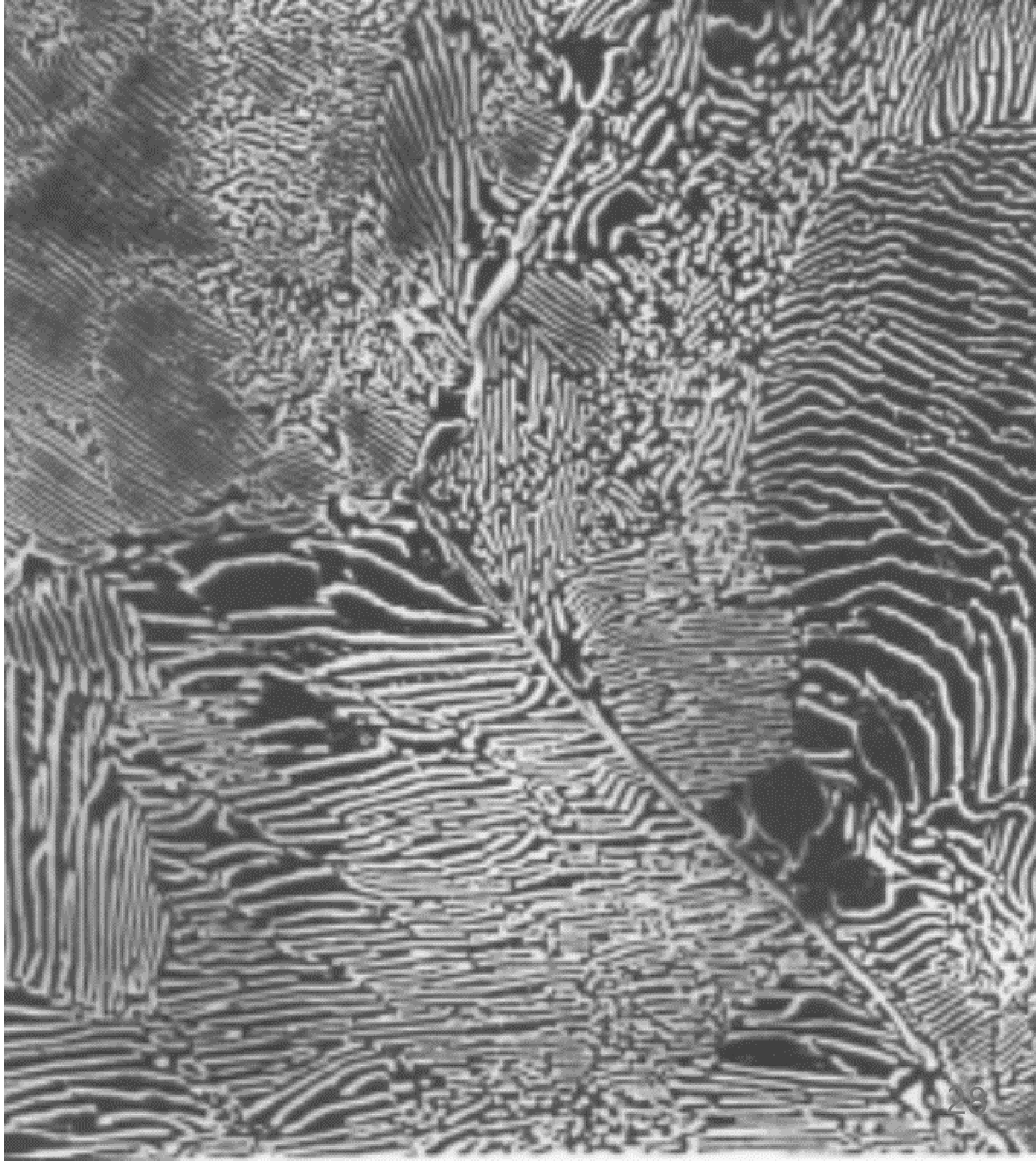
Phase Mixtures / Solid Solution Mixtures

Pearlite (Eutectoid)

- Microstructure of cementite and ferrite (= phase mixture).
- Forms through the "eutectoid" decomposition of austenite (γ-solid solution) with 0.8% C at 723°C.
- Point S: 100% pearlite.
- Relatively high hardness and strength, low ductility.

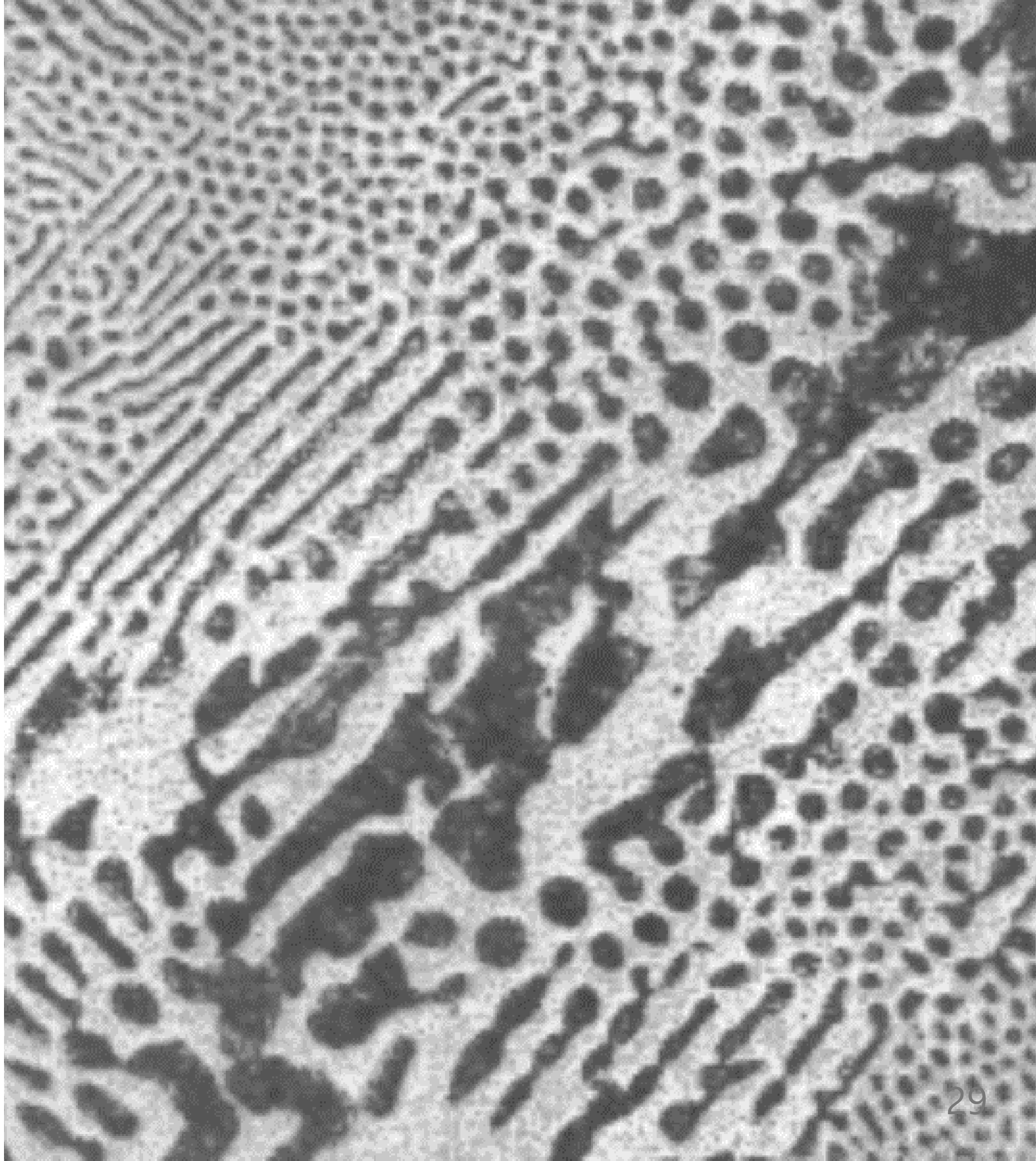


- Lamellar structure (layers of α-ferrite and Fe_3C crystals).
- Categorized into coarse, fine, and very fine pearlite based on lamellar spacing.



Ledeburite

- Microstructure of austenite and cementite or their decomposition products (pearlite and secondary cementite).
- C content: 4.3%, melting temperature: 1147°C.
- Point C: 100% ledeburite.



- **Ledeburite I**: Austenite and cementite (above 723°C).
- **Ledeburite II**: Pearlite, primary cementite, and secondary cementite (at room temperature).
- Faster cooling may form bainite or martensite instead.
- Properties: Very low ductility, characteristic "panther skin" pattern.

The properties of the alloy (e.g., steel, cast iron) depend on the involved phases, their relative amounts, and their distribution in the microstructure.

Phases and Microstructures in Non-Equilibrium States

- Equilibrium states are dominated by diffusion processes.
- Rapid temperature changes hinder the carbon diffusion required for the segregation of austenite.
- This leads to the formation of novel microstructural components that deviate from the equilibrium state.
- Results in "supersaturated" carbon.

NOT IN THE PHASE DIAGRAM!

Martensite

- Body-centered tetragonal (BCT) lattice structure ("strained ferritic lattice").
- Typically features a fine, needle-like, very hard, and brittle microstructure.
- The carbon, trapped in the BCC lattice of α-Fe, distorts and expands the lattice tetragonally through a "diffusionless transformation."

- is formed in carbon steels by the rapid cooling (quenching) of the austenite
- carbon atoms do not have time to diffuse out of the crystal structure in large enough quantities to form cementite (Fe3C).

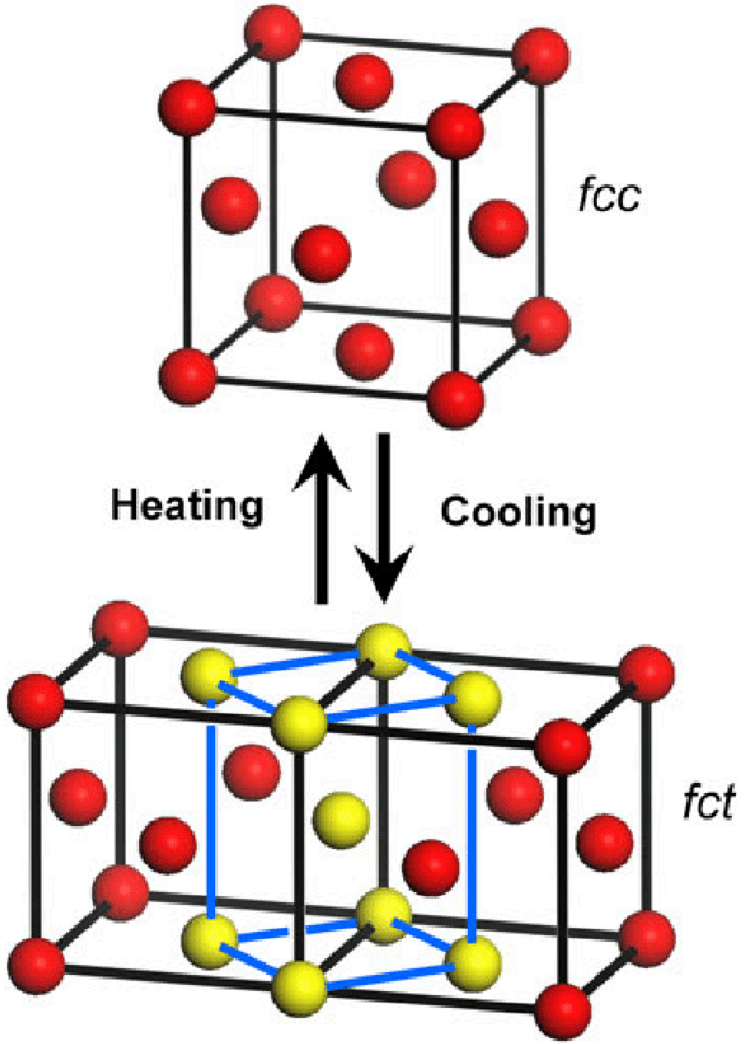


Image Reference

Bainite

- Unlike martensite formation, bainite involves both lattice transformations and diffusion processes.
- Forms in the temperature range between the pearlite and martensite stages during cooling at rates that are too slow for martensite and too fast for pearlite.

Bainite Formation

- Pure bainite can only be achieved through isothermal cooling, such as during austempering.
- Preferred in cases where quenching and tempering could lead to cracking risks.
- Offers excellent strength and toughness properties.

Iron-Carbon Alloy Designations

Carbon Content (mass-%)	Designation	Type
$0.02 < C < 0.8$	(Carbon) Steel	Hypoeutectoid Steel
$C = 0.8$	(Carbon) Steel	Eutectoid Steel
$0.8 < C < 2.06$	(Carbon) Steel	Hypereutectoid Steel
$2.06 < C < 4.3$	Cast Iron	Hypoeutectic Cast Iron
$C = 4.3$	Cast Iron	Eutectic Cast Iron
$4.3 < C < 6.67$	Cast Iron	Hypereutectic Cast Iron

Steel Properties

- Carbon content less than 2.06%.
- High tensile strength.
- More expensive than cast iron.
- More ductile and tougher than cast iron.
- Weldable.
- Higher melting point than cast iron.

Cast Iron

- Carbon content above 2.06%.
- Excellent castability (low melting point, good fluidity, etc.).
- Hard and brittle.
- Machinability depends on the specific type:
  - Grey cast iron with graphite lamellae is highly machinable.
- Strength is lower than steel, but damping properties are superior.
- Commonly contains silicon for improved castability and other alloying elements like manganese, chromium, or nickel.

Grey Cast Iron

- Carbon is present as graphite, giving it a gray fracture surface.
- Good thermal conductivity and damping properties.
- Brittle but self-lubricating due to exposed graphite.

Nodular Cast Iron

- Features better mechanical properties than grey cast iron.
- Exhibits ductile behavior due to spherical graphite inclusions.

Vermicular Cast Iron

- Intermediate properties between grey and nodular cast iron.
- Challenging production due to narrow processing tolerances.
- Higher strength, toughness, and reduced sensitivity to wall thickness compared to grey cast iron.

Comparison: Steel vs. Cast Iron

Property	Steel	Cast Iron
Density	$7.85 \frac{g}{cm^3}$	$7.2 \frac{g}{cm^3}$
Melting Point	High (approx. $1500^\circ C$)	Low ($1150^\circ C$)
Toughness	High	Low
Corrosion Resistance	Similar	Slightly better
Shrinkage Factor	Low	Very low (1%)

Comparison of Cast Iron Types

- **Grey Cast Iron**:
  - The most common and simplest type of cast iron.
  - Graphite is present in the form of thin, irregularly shaped lamellae.
  - The graphite lamellae act as notches under tensile stress, which significantly reduces the tensile strength.
  - However, it has high compressive strength and excellent damping properties.

- **Grey Cast Iron with Lamellar Graphite**
  - Ductility and toughness are lower compared to other types of cast iron, but the material exhibits excellent heat conductivity.
  - It has favorable self-lubricating properties when the graphite is exposed or when other lubricants are used in the cavities of the graphite.

Nodular Cast Iron

- **Nodular (Ductile) Cast Iron**:
  - This type features graphite in the form of spherical nodules, resulting in superior mechanical properties compared to grey cast iron.
  - It behaves in a ductile manner and has enhanced tensile strength and toughness.
  - This form of cast iron is also weldable and can be machined to a high degree.

Vermicular Cast Iron

- **Vermicular Cast Iron**:
  - Has properties between those of grey and nodular cast iron.
  - Production is more difficult due to the specific requirements for melt treatment and controlled solidification.
  - Benefits include higher strength and toughness, along with lower thermal expansion.

General Characteristics of Cast Iron Types:

Type	Characteristics	Benefits
Grey Cast Iron	Graphite in lamellar form; brittle	Good machinability, heat conductivity
Nodular Cast Iron	Graphite in spherical nodules; ductile	High tensile strength, impact resistance
Vermicular Cast Iron	Intermediate properties; controlled graphite structure	Higher toughness, better casting properties

Properties of Cast Iron and Steel

Property	Cast Iron	Steel
Damping Capacity	High	Low
Compressive Strength	High	Moderate
Tensile Strength	Low	High
Thermal Conductivity	Good	Lower than cast iron
Machinability	Good (in specific forms)	Excellent in most forms
Weldability	Limited (except in nodular types)	Excellent

Material Selection

- **Grey Cast Iron** is ideal for applications where damping capacity and castability are important, such as engine blocks and brake rotors.
- **Nodular Cast Iron** is used where higher mechanical properties and toughness are required, for example in automotive and industrial applications like crankshafts and gear wheels.
- **Vermicular Cast Iron** is often selected when a balance between strength and castability is necessary, often used in specific automotive and machinery components.

Stability of Carbon Systems in Iron Alloys

- **Stable Systems**: When the carbon is present in the form of graphite crystals, these systems are more likely to occur under the following conditions:
  - Higher carbon content.
  - Higher silicon content.
  - Slower cooling rates.
  - These systems typically occur in cast irons.
- **Metastable Systems**: These systems are characterized by cementite (Fe_3C) crystals, where the carbon is not in a free state and is instead chemically bound in the iron lattice.