Ferrous Metallurgy:

The Chemistry and Structure of Iron and Steel

Pure Iron

- Iron from which the residual carbon left over from smelting has been removed.
- In the pure state it is a very soft grey metal
- Of no commercial use

Wrought Iron

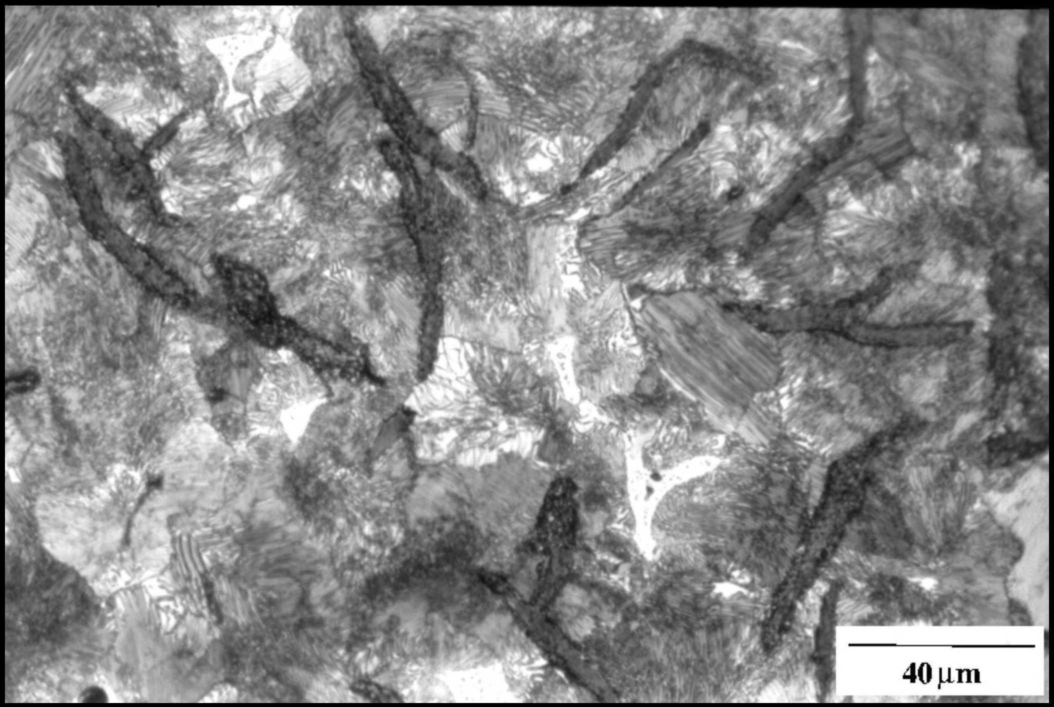
- Has approx 0.05% carbon
- Used since about 2000 BC
- Is stronger than most other pure metals.
- Made into weapons, armour, cooking pots and vessels
- Main limitation to wider uses due to processing (no way of making large items and no welding)

Abraham Darby's Ironbridge

Cast Iron

- Between 2% & 4% carbon content
- Standard grey cast iron very brittle due to carbon rosettes in the structure acting as stress-raisers
- Possible to use heat treatment to improve the structure, this gives materials such as ductile iron and malleable iron (black heart)

Ductile iron used in drain grids



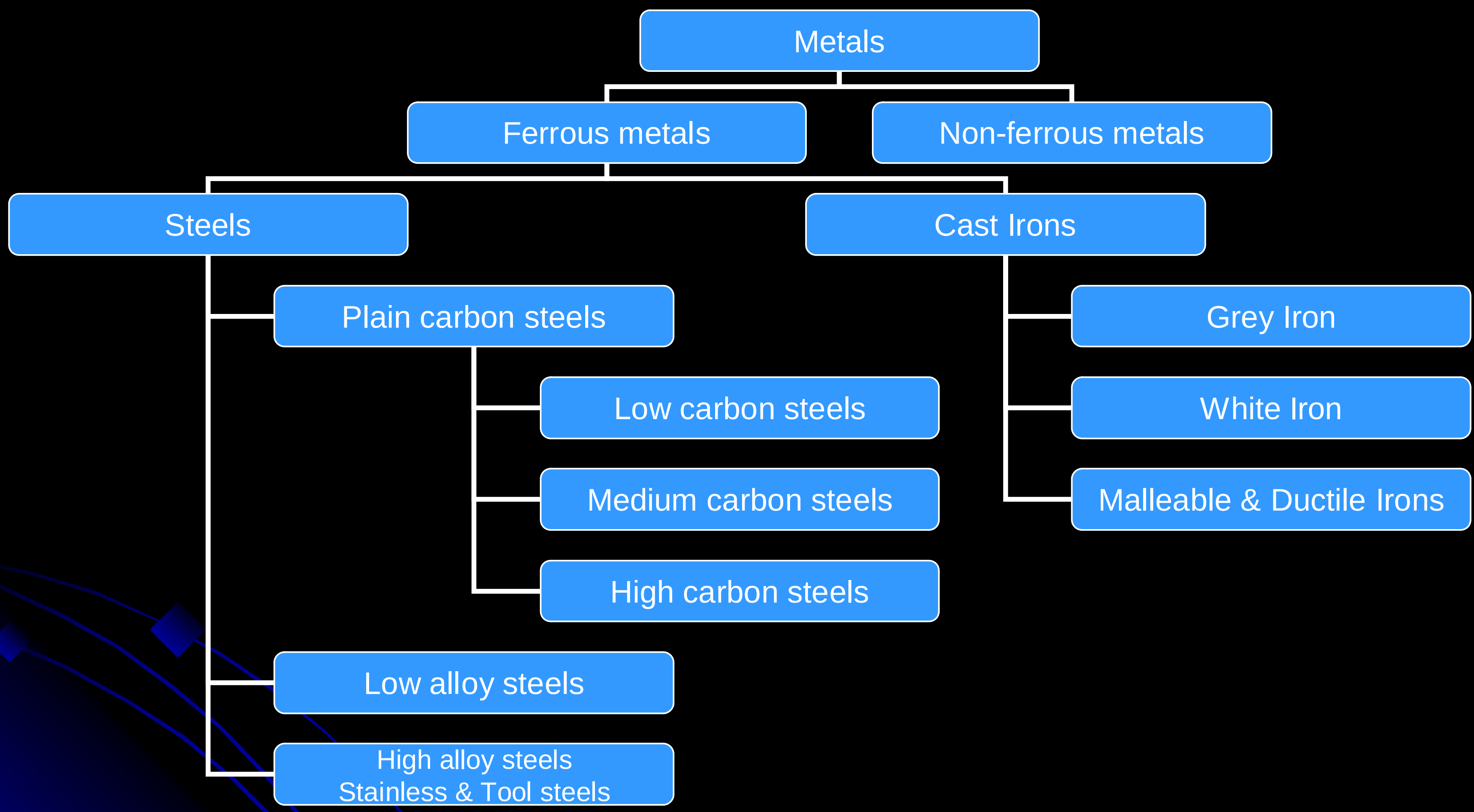
Grey cast iron showing the graphite flakes in a pearlite matrix

Steel

0.001% to 1.5% carbon

Wide range of properties due to:

- Variation in carbon content
- Cold working
- Heat treatment
- Addition of alloying elements


Metals
Ferrous metals
Non-ferrous metals
Steels
Cast Irons
Plain carbon steels
Low carbon steels
Medium carbon steels
High carbon steels
Low alloy steels
High alloy steels
Stainless & Tool steels
Grey Iron
White Iron
Malleable & Ductile Irons

Microstructure of Steel

Five main constituents:

- Ferrite
- Austenite
- Cementite
- Pearlite
- Martensite

Iron, Iron Alloys and Fe-C system

- Iron
  - Medium of first transition series: $Ar3d^6 4s2$
  - Earth Crust contains ~ 4% Fe
  - Tf =1540 C ; Th ~ 750 C
  - Useful Phase Transformations (bcc-fcc)
  - Ferromagnetic below 768 C

Iron, Iron Alloys and Fe-C system (contd)

- Interstitials:
  - H, B, C, N, O
- Substitutionals:
  - Mostly transition series left, right and below of Fe
- Fe-C system is the basis of steel metallurgy

Phases and Phase Diagrams

- **Phases**
  - **Ferrite (α: T < 906, δ: 1401 < T <1540 C)**
  - **Austenite (γ: 906 C < T < 1401 C)**
  - **Liquid (*l*: T > 1540 C)**
  - **Carbide, Nitride, Oxide Compounds**
- **Phase Diagrams**
  - **Graphic display of stable phases as function of temperature.**

Crystalline Structures, Microconstituents and Microstructures

- Crystalline Stuctures
  - Ferrite (Body Centered Cubic; BCC)
  - Austenite (Face Centered Cubic; FCC)
  - Carbides, Nitrides, Oxides (Complex)

Crystalline Structures, Microconstituents and Microstructures (contd)

- **Microconstituents**
  - **Ferrite**
  - **Austenite**
  - **Pearlite (Ferrite-Carbide Micro-Composite)**

Crystalline Structures, Microconstituents and Microstructures (contd)

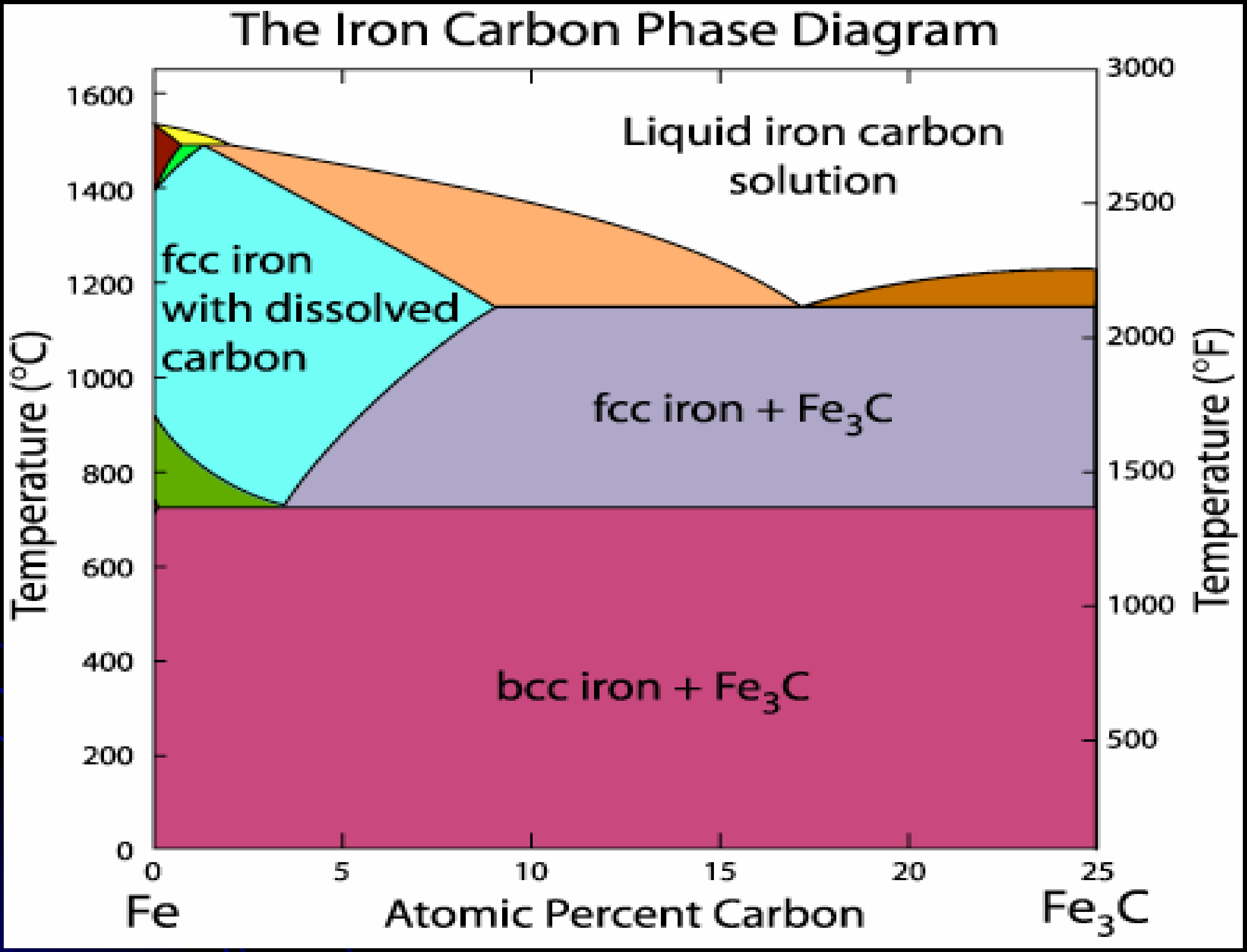
- **Microstructures**
  - **Ferrite (Grains, Allotriomorphs, Widmanstatten Side-Plates)**
  - **Austenite (Grains - Twinned)**
  - **Pearlite (Ferrite-Carbide Colonies)**

Additional Microconstituents

- Martensite
  - Body Centered Tetragonal; BCT
  - C-supersaturated Ferrite
  - Laths, Plates, Needles
- Bainite
  - BCC-BCT
  - Ferrite-Carbide Micro-Composite
  - Laths, Plates

Properties of Individual Microconstituents in Steel (contd)

- **Pearlite**
  - **Yield strength 200 - 800 MPa**
  - **Tensile strength 600 - 1200 MPa**
- **Bainite**
  - **Yield strength 800 - 1300 MPa**
  - **Tensile strength 1300 - 1400 MPa**
- **Martensite**
  - **Yield strength 500 - 1800 MPa**

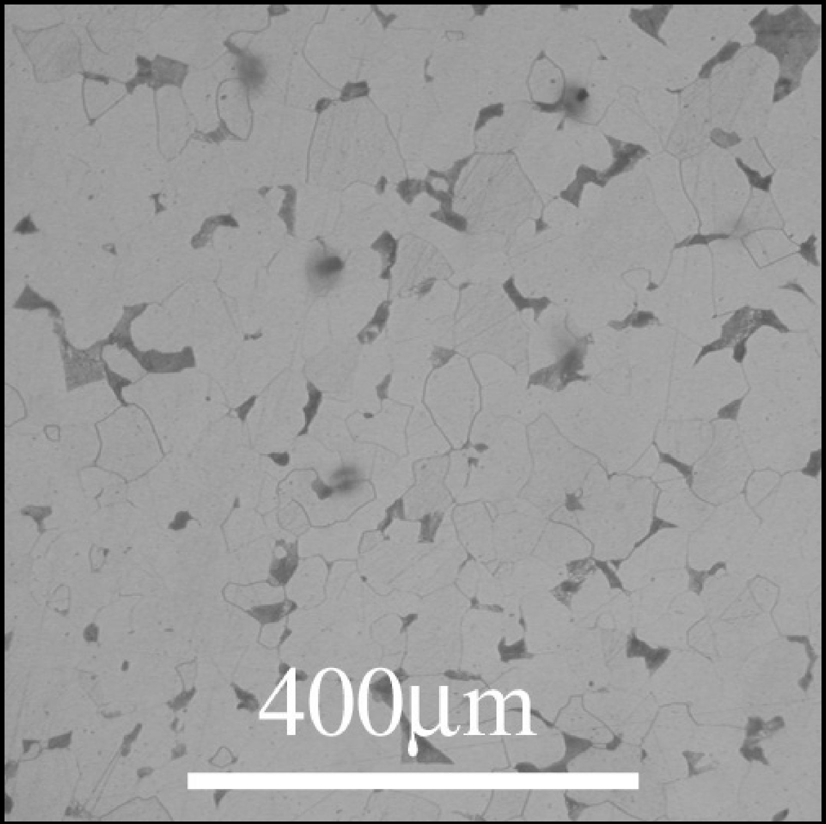

The Iron Carbon Phase Diagram
Liquid iron carbon solution
fcc iron with dissolved carbon
fcc iron + Fe_3C
bcc iron + Fe_3C
Temperature (°C)
Temperature (°F)
1600
1400
1200
1000
800
600
400
200
0
3000
2500
2000
1500
1000
500
0
5
10
15
20
25
Fe
Atomic Percent Carbon
Fe_3C

Ferrite

The structure of pure iron.

Has a body-centred cubic (BCC) crystal structure. It is soft and ductile and imparts these properties to the steel. Very little carbon (less than 0.01% carbon will dissolve in ferrite at room temperature). Often known as α iron.

A photomicrograph of 0.1% carbon steel (mild steel). The light areas are ferrite.



Austenite

This is the structure of iron at high temperatures (over 912 deg C).

Has a face-centre cubic (FCC) crystal structure.   This material is important in that it is the structure from which other structures are formed when the material cools from elevated temperatures. Often known as γ iron. Not present at room temperatures.

Cementite

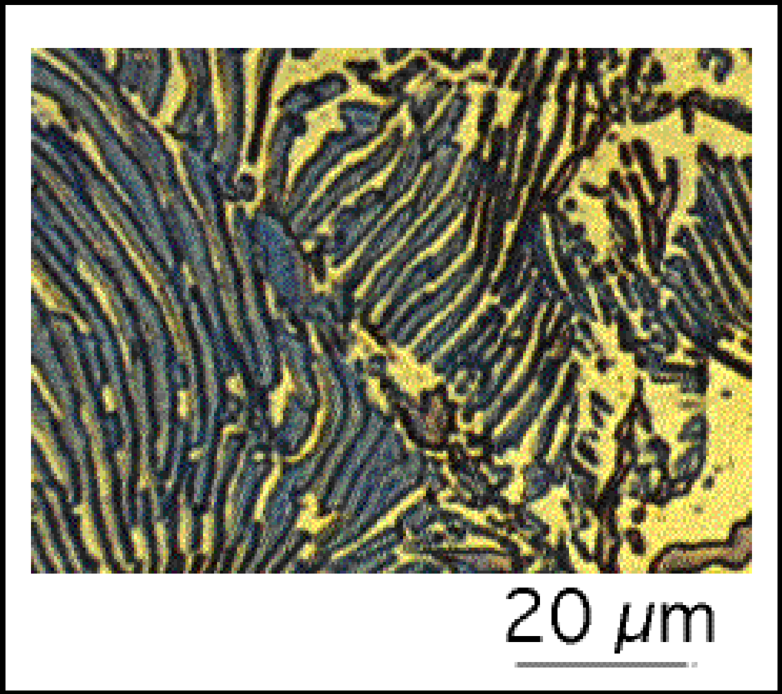
A compound of iron and carbon, iron carbide (Fe_3C).

It is hard and brittle and its presence in steels causes an increase in hardness and a reduction in ductility and toughness.

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 and is the key to the wide range of the properties of steels. The laminar structure also acts as a barrier to crack movement as in composites. This gives it toughness.



Two-dimensional view of pearlite, consisting of alternating layers of cementite and ferrite.

Three-dimensional analogy to the structure of pearlite, i.e. the cabbage represents a single crystal of pearlite, and the water in the bucket the single crystal of ferrite.

Martensite

A very hard needle-like structure of iron and carbon.

Only formed by very rapid cooling from the austenitic structure (i.e. above upper critical temperature). Needs to be modified by tempering before acceptable properties reached.

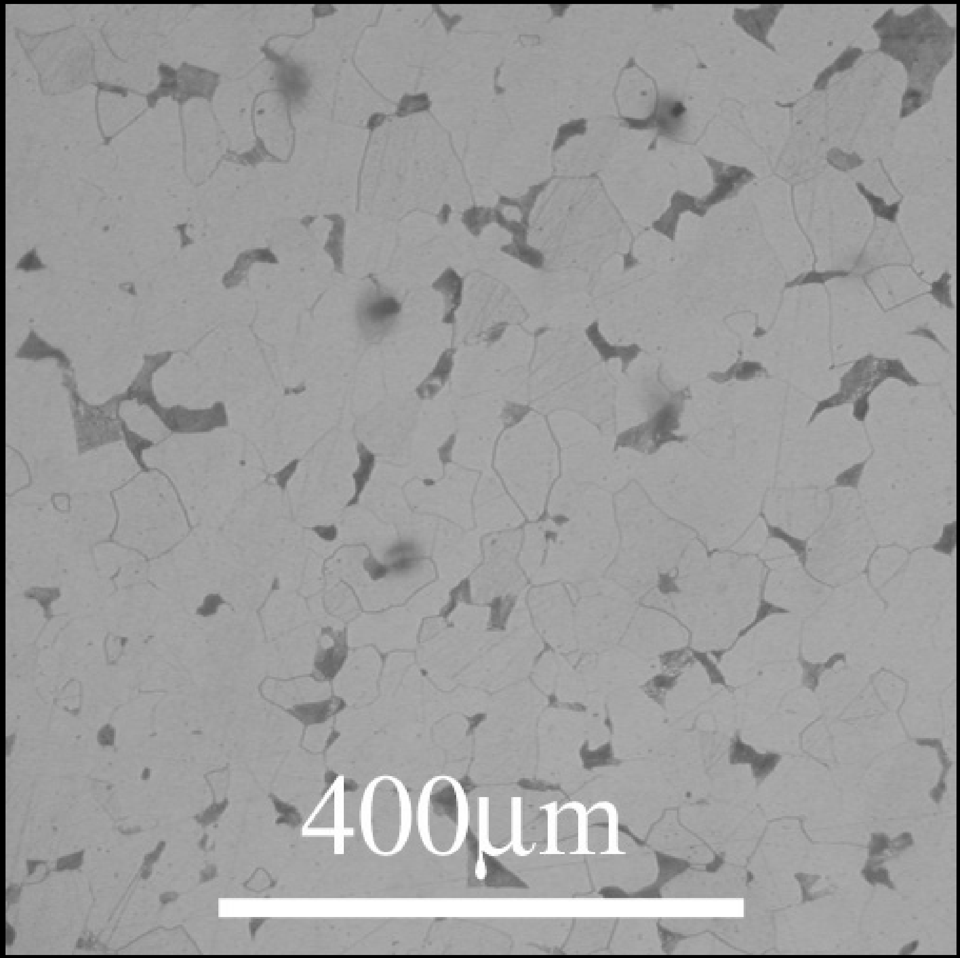
The needle-like structure of martensite, the white areas are retained austenite.

Carbon

In steels none of the carbon is present as free carbon. It is all dissolved in the iron as part of the previously described structures.

0.1% Carbon Steel

Note the small amount of pearlite in the structure



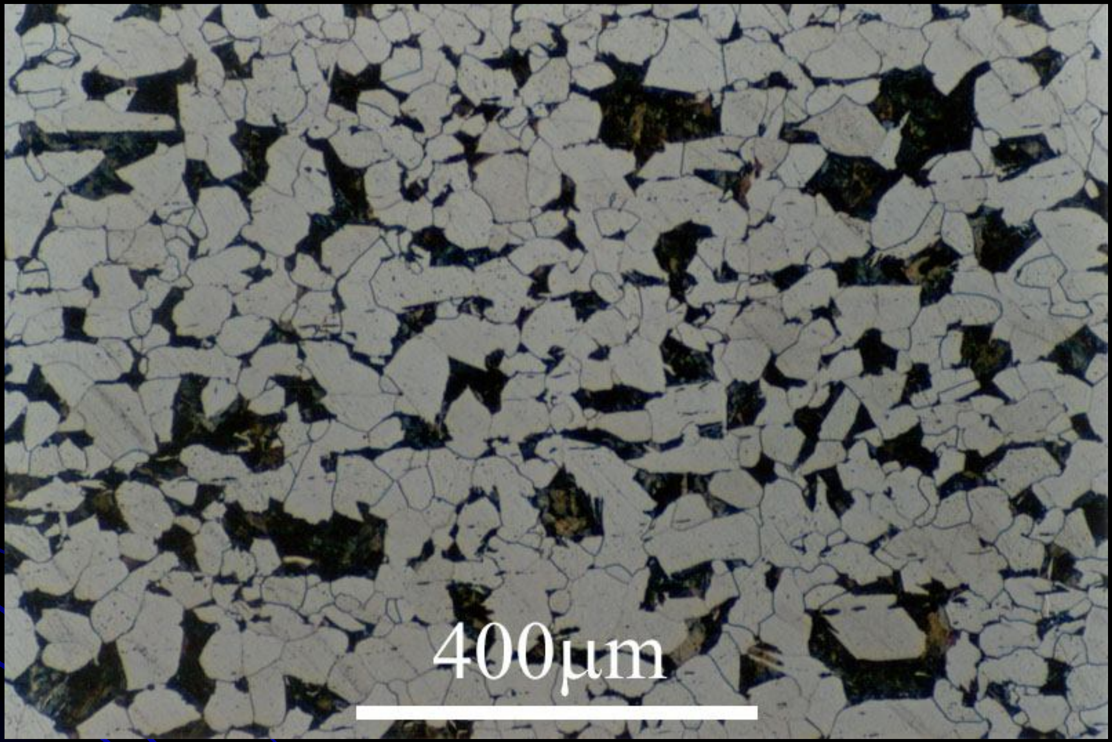
Applications

A typical application of low carbon steel in a car body.

Effect of Carbon Content

Increasing the carbon content decreases the amount of *ferrite* and increases the proportion of *pearlite* in the structure.

0.2% Carbon Steel



Note the increased amount of pearlite compared with the 0.1% ‘dead mild’ steel

Eutectic Structure

This leads to an increase in strength and hardness and a reduction in ductility.

This continues until there is 0.8% carbon at which point the structure is 100% *pearlite*. This is known as a ***eutectic*** structure.

Over 0.8% Carbon

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.

Properties of Carbon Steels

Carbon content wt %	Properties	Applications
0.01 - 0.1	Soft, ductile, no useful hardening by heat treatment except by normalizing, but can be work-hardened. Weldable.	Pressings where high formability required
0.1 - 0.25	Strong, ductile, no useful hardening by heat treatment except by normalizing, but can be work-hardened. Weldable. Ductile-brittle transition temperature is just below room temperature	General engineering uses for a mild steel
0.25 - 0.6	Very strong, heat treatable to produce a wide range of properties in quenched and tempered conditions. Difficult to weld. Can become brittle below room temperature.	Bars and forgings for a wide range of engineering components. Connecting rods, springs, hammers, axle shafts requiring strength and toughness.

Properties of Carbon Steels

Carbon content wt %	Properties	Applications
0.6 - 0.9	Strong, whether heat treated or not. Ductility lower when less carbon is present	Used where maximum strength rather than toughness is important. Tools, wear resisting components (piano wire and silver steels are in this group).
0.9 - 2.0	Wear resistant and can be made very hard at expense of toughness and ductility. Cannot be welded. Tend to be brittle if the structure is not carefully controlled	Cutting tools like wood chisels, files, saw blades.