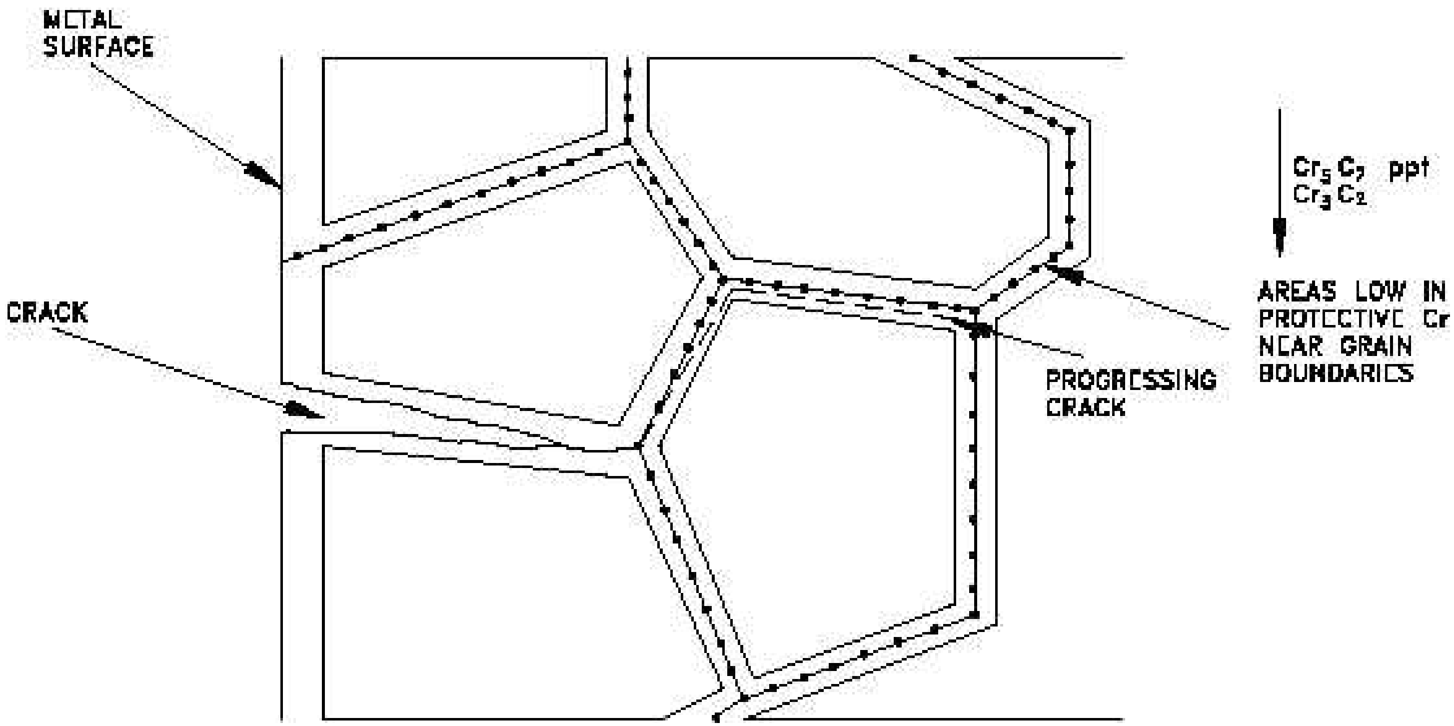
Intergranular corrosion

- This is also known as grain boundary attack and is characterized by attack of a narrow band of material along the grain boundary.
- Intergranular corrosion is caused by the precipitation of chromium carbides along the grain boundaries.
- If austenitic and duplex stainless steels are maintained in the temperature range of 550 – 800 °C, carbides of chromium and iron are formed along grain boundaries.
- Correpondingly, due to the low diffusion coefficient of chromium a narrow band of material close to the grain boundary gets depleted with chromium.

Intergranular corrosion



Intergranular corrosion

- The corrosion resistance of this chromium depleted region is less.
- If the material is exposed to an aggressive environment, this chromium depleted region is attacked and material along the grain boundaries will be corroded.
- As a result even individual grains may drop off from the material and the material may lose its strength and integrity
- Ferritic stainless steels are also susceptible to intergranular corroion, however for them the critical temperature region is in the range of 900 – 950 °C

This intergranular attack is also called sensitization

Intergranular corrosion

- Temperatures critical for sensitization are typically encountered during welding in an area 3–5 mm from the weld metal
- The risk for intergranular corrosion may be reduced by employing the following ways:
  - By decreasing the C-content
  - By aloying the steel with an element (like titanium or niobium) which forms a more stable carbide than chromium

Intergranular corrosion

- To avoid sensitization by reducing the C-content, the steel should have < 0.03 wt.% C
- These steels are classified as low carbon grades (i.e. L-Grades)
- By adding Ti and Nb in stainless steels, due to their greater tendency to form carbides than chromium, carbides of these elements are formed preferentially. No carbon is thus available to form carbide with chromium, which thus remains in solution and the steel maintains its resistance to intergranular attack.
- Addition of Nb and Ti in stainless steel to resist intergranular corroion is called stabilization.

Stainless steel mechanical properties

Room temperature properties of martensitic steels

- These steels are characterized by high strength and limited ductility.
- These steels are typically used in hardened and tempered condition and the strength increases with carbon content
- They possess excellent hardenability and even thick sections can be fully hardened.

Stainless steel mechanical properties

Room temperature properties of ferritic steels

- They have relatively low yield strength and work hardening is also limited ➔ rather flat stress-strain curve in the plastic region.
- Strength normally increases with increasing C-content
- Ductility normally decreases with increasing chromium content
- Good ductility requires very low C- and N-content

Stainless steel mechanical properties

Room temperature properties of duplex steels

- They have a relatively high yield strength
- Yield stress normally increases with increasing C- and N-levels.
- The strength of duplex steels increase with increasing ferrite content.
- They have good ductility and exhibit strong work hardening

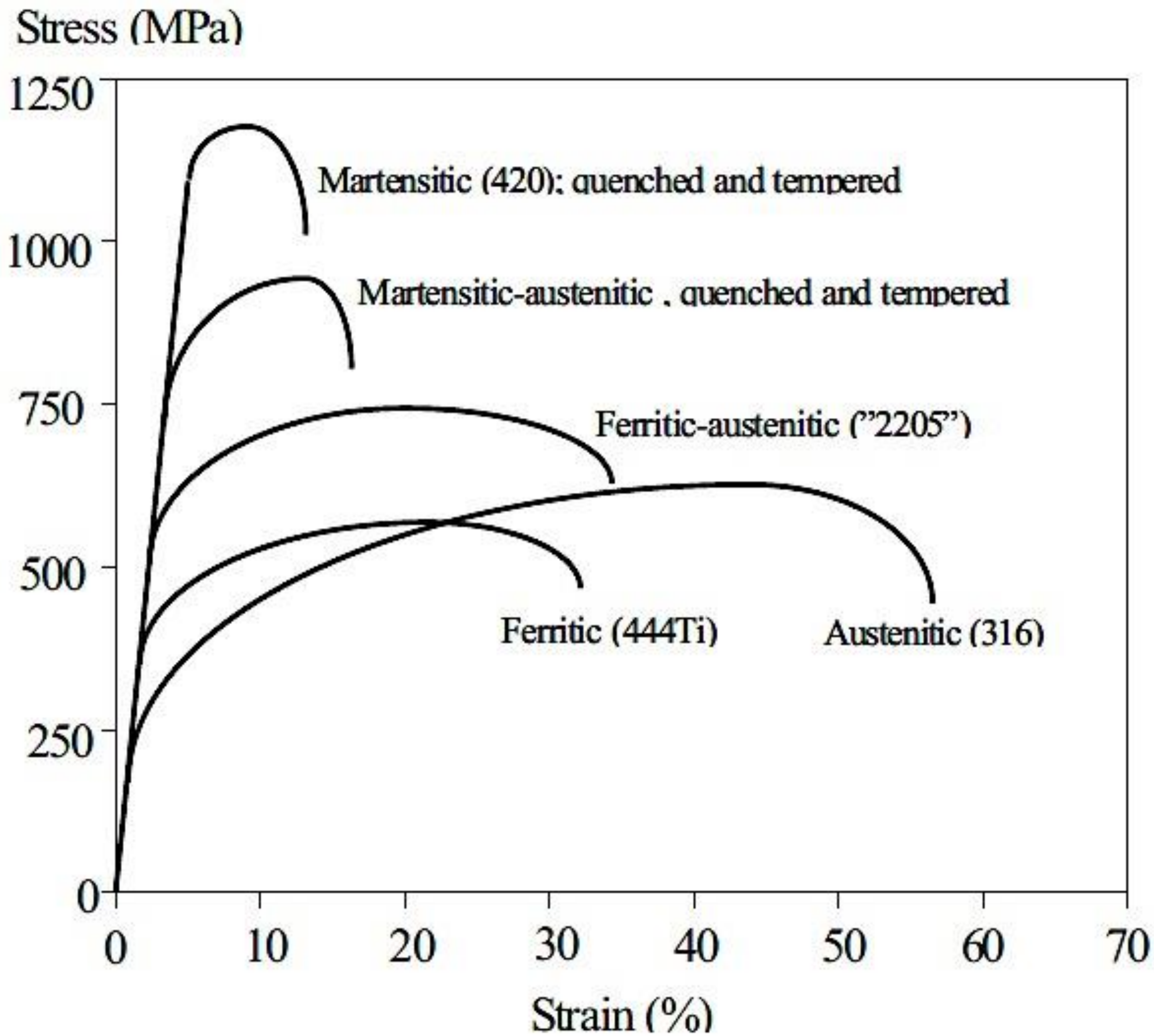
Stainless steel mechanical properties

Room temperature properties of austenitic steels

- They have a relatively low yield strength and are characterized by strong work hardening behavior
- Strength of these steels increases with increasing C-, N- and Mo-content
- However, increasing C-content to increase strength is not recommended as that deteriorates the corrosion resistance.
- Austenitic stainless steels have very high ductility and they are very tough

Stainless steel mechanical properties

Summary



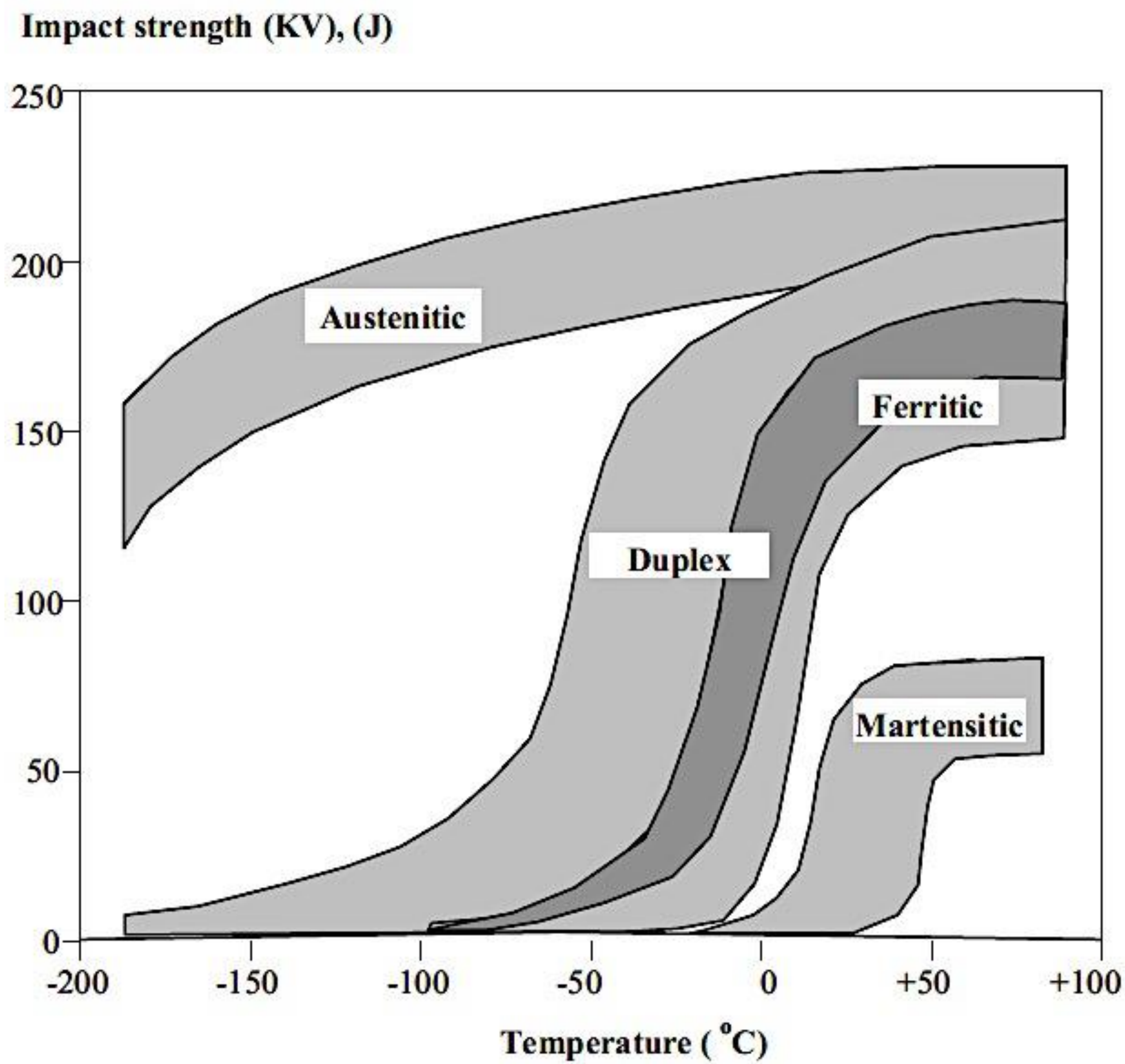
Toughness of stainless steel

- Toughness of the different types of stainless steels show considerable scatter
- Toughness is generally dependent on temperature and increases with temperature
- Martensitic, ferritic and duplex stainless steels are characterized by a ductile to brittle transition
- For ferritic steels the transition temperature increases with increasing C- and N-content
- With increasing ferrite content in duplex steels, the toughness decreases and the transition temperature increases

Toughness of stainless steel

- Austenitic stainless steels do not show any transition from ductile to brittle behavior
- They have high toughness at all temperatures ➔ they are the preferred material for low temperature applications
- For martensitic stainless steels the ductile to brittle transition occurs at slightly below room temperature
- This transition in ferritic and duplex steels occurs in the range of 0 to -60 °C, with ferritic steels covering the upper range.

Toughness of stainless steel



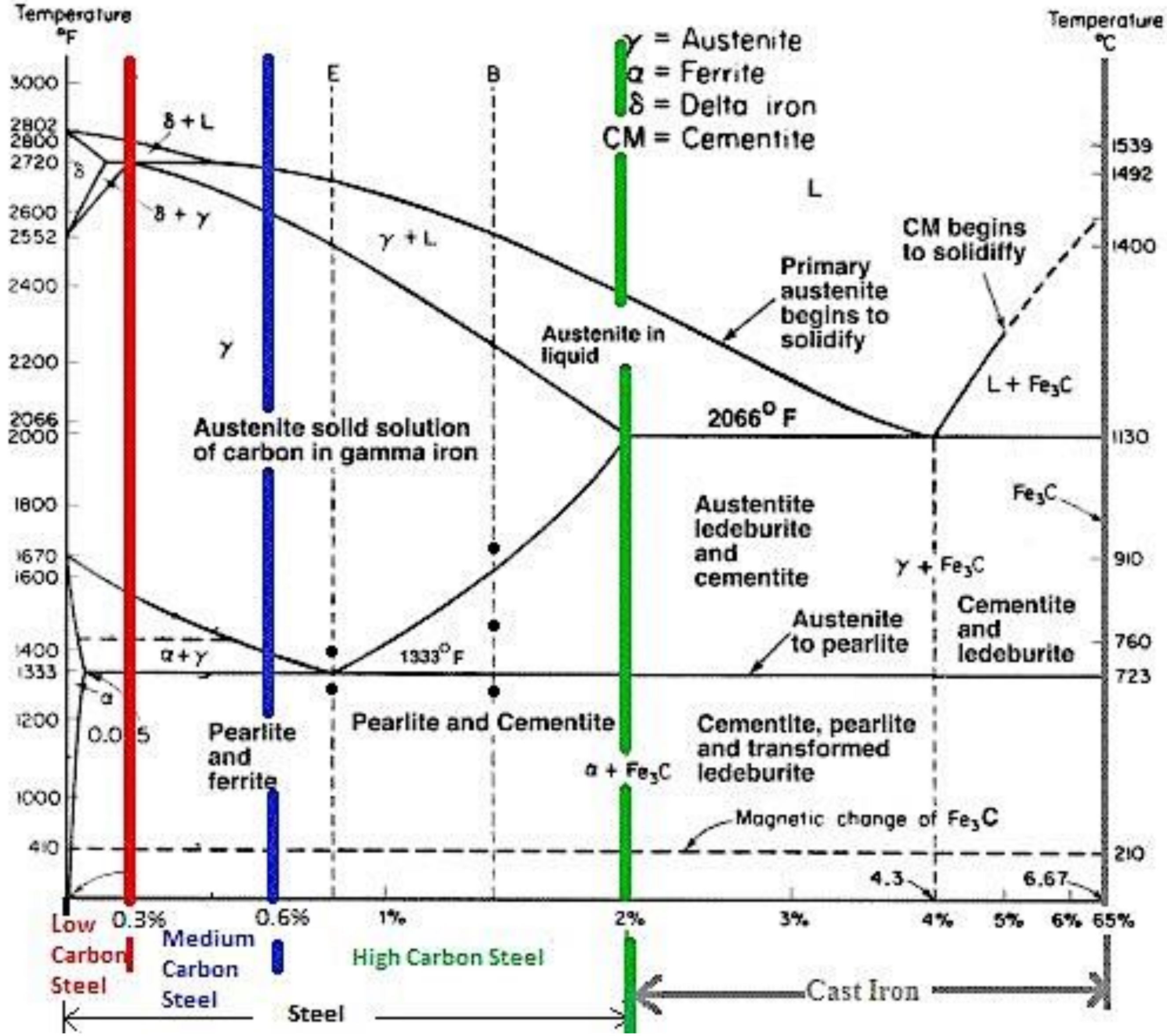
Lecture 3

Classification of ferrous alloys

Ferrous alloys are broadly classified into two groups:

- Iron carbon alloys containing < 2.1 wt.% C are called steels. In practice however steels rarely contain > 1.4 wt.% C
- Iron carbon alloys containing between 2.1 wt.% and 6.7 wt.% C are called cast irons. Commercial cast irons however normally contain max. 4.5 wt.% C

Cast iron



Temperature °F
Temperature °C
γ = Austenite
α = Ferrite
δ = Delta iron
CM = Cementite
E
B
δ + L
δ
δ + γ
γ + L
L
γ
CM begins to solidify
Primary austenite begins to solidify
Austenite in liquid
L + Fe3C
2066° F
Austenite solid solution of carbon in gamma iron
Austentite ledeburite and cementite
Fe3C
γ + Fe3C
Cementite and ledeburite
Austenite to pearlite
α + γ
1333° F
α
Pearlite and ferrite
Pearlite and Cementite
Cementite, pearlite and transformed ledeburite
α + Fe3C
Magnetic change of Fe3C
4.3
6.67
3000
2802
2800
2720
2600
2552
2400
2200
2066
2000
1800
1670
1600
1400
1333
1200
1000
410
1539
1492
1400
1130
910
760
723
210
0.3%
0.6%
1%
2%
3%
4%
5%
6%
6.5%
Low Carbon Steel
Medium Carbon Steel
High Carbon Steel
Steel
Cast Iron

Cast iron

- In practice most cast irons typically contaiy between 3.0 and 4.5 wt.% C and different alloying elements
- The $Fe\text{-}Fe_3C$ phase diagram shows that the alloys in this composition range typically melt in the temperature range of 1150 – 1300 °C
- This melting range of cast irons is significantly less than that for steels (typically > 1450 °C)
- Cast irons are therefore easily melted and very castable

Cast iron

- Cementite in steel is a metastable compound and under certain circumstances it dissociates to form ferrite and graphite

$$Fe_3C \Leftrightarrow 3Fe + C\left(graphite\right)$$

- Graphite formation (i.e. graphitization) is favored by a very slow cooling rate during solidification and presence of silicon as alloying element in the range of > 1 wt.%

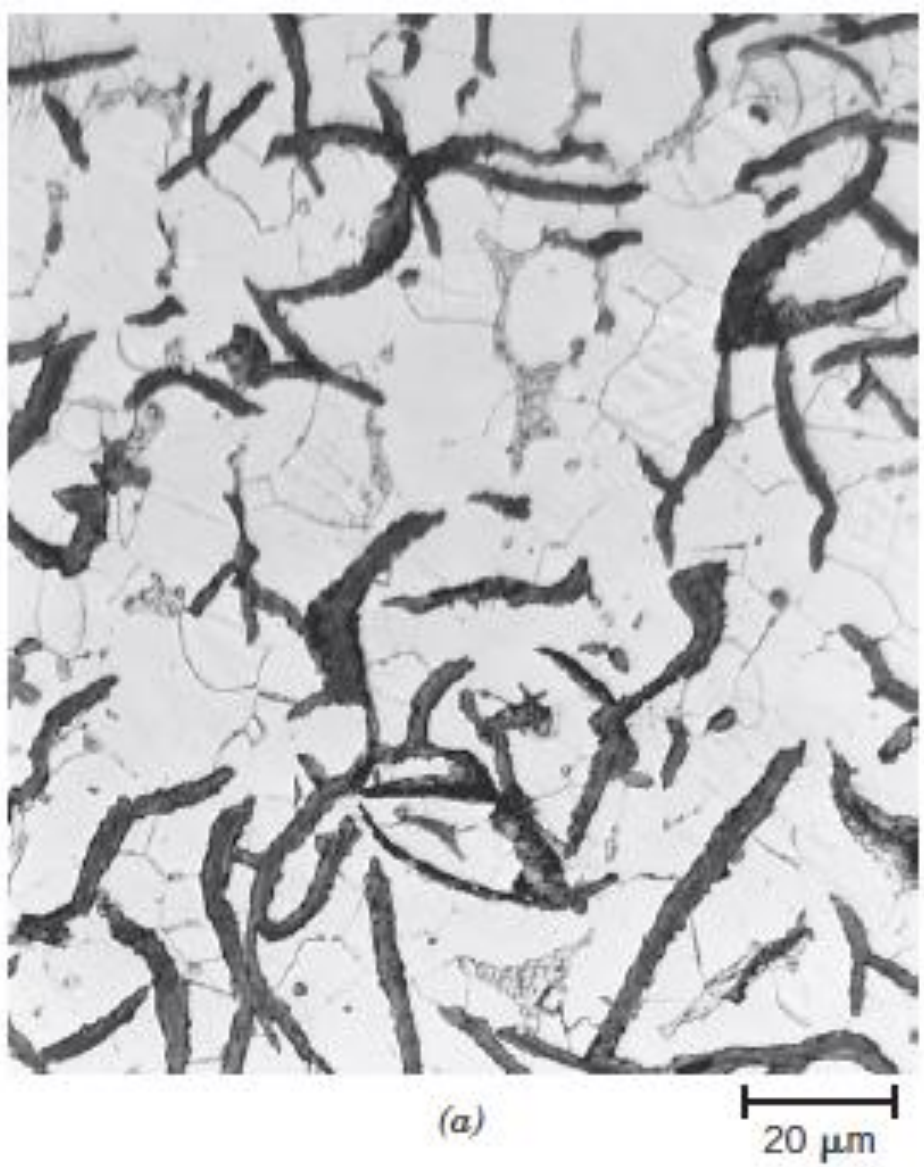
- In most cast irons carbon is present as graphite and it strongly contrinutes to the microstructure and mechanical properties of cast iron

- Most common cast iron types will be briefly discussed here

Gray cast iron

- Gray cast irons contain between 2.5 – 4.0 wt.% C and 1.0 – 3.0 wt.% Si
- The graphite in gray cast iron is mostly present in the form of flakes surrounded by α-ferrite or pearlitic matrix.
- The fracture surface of gray cast irons typically have a dull gray appearance and hence the name gray cast iron
- The tips of the graphite flakes are rather sharp and may serve as points of stress concentration under external tensile stress ➔ gray cast iron is rather weak and brittle in tension
- Much better mechanical properties are obtained under compression

Gray cast iron



Typical optical micrograph of gray cast iron

Gray cast iron

- Gray cast irons have several beneficial properties:
  - They are very effective in damping vibrational energy
  - Gray cast irons have very good wear resistance
  - In the molten state gray cast irons have high fluidity, hence for casting intricate shapes, gray cast irons give less casting defects and casting shrinkage is low
  - Gray cast iron is also very cheap material
- Lowering the silicon content or increasing the cooling rate may prevent the complete dissociation of cementite to form graphite ➔ microstructure consists of graphite flakes in a pearlitic matrix

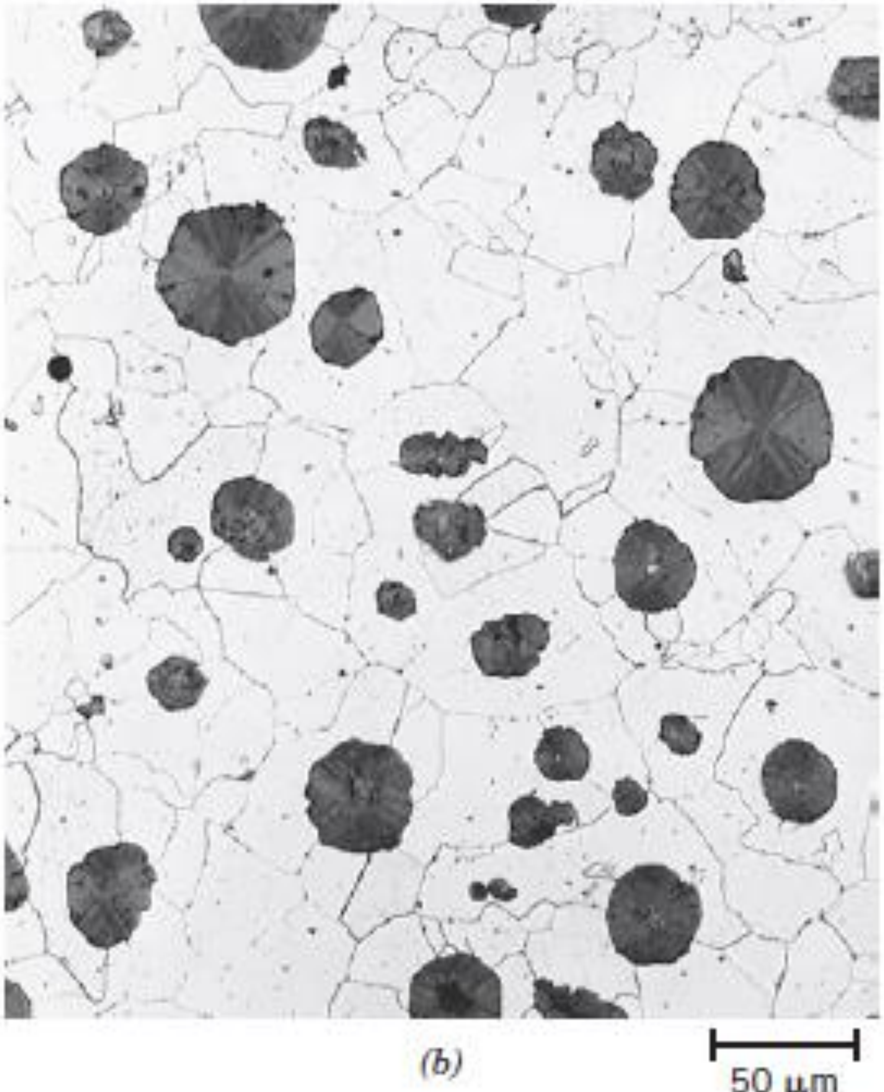
Gray cast iron properties

Grade	UNS Number	Composition (wt%)[a]	Matrix Structure	Mechanical Properties: Tensile Strength [MPa (ksi)]	Mechanical Properties: Yield Strength [MPa (ksi)]	Mechanical Properties: Ductility [%EL in 50 mm (2 in.)]
Gray Iron						
SAE G1800	F10004	3.40–3.7 C, 2.55 Si, 0.7 Mn	Ferrite + Pearlite	124 (18)	—	—
SAE G2500	F10005	3.2–3.5 C, 2.20 Si, 0.8 Mn	Ferrite + Pearlite	173 (25)	—	—
SAE G4000	F10008	3.0–3.3 C, 2.0 Si, 0.8 Mn	Pearlite	276 (40)	—	—

Ductile or nodular cast iron

- Addition of small amount of magnesium and/or cerium to gray cast iron before casting alters the microstructure
- The shapes of graphite change from flaky to nodules or sphere like
- The matrix surrounding the graphite nodules are either ferrite or pearlite depending upon the heat treatment
- Castings made of ductile cast iron are ductile and much more stronger than gray cast iron and mechanical properties even approach steel
- Typical applications: Valves, pump bodies, crankshafts, gears and several machine components

Ductile cast iron



(b)

Typical optical micrograph of ductile cast iron

Ductile cast iron properties

				Mechanical Properties		
Grade	*UNS Number*	*Composition (wt%)[a]*	*Matrix Structure*	*Tensile Strength [MPa (ksi)]*	*Yield Strength [MPa (ksi)]*	*Ductility [%EL in 50 mm (2 in.)]*
				Ductile (Nodular) Iron		
ASTM A536						
60–40–18	F32800	3.5–3.8 C, 2.0–2.8 Si, 0.05 Mg, <0.20 Ni, <0.10 Mo	Ferrite	414 (60)	276 (40)	18
100–70–03	F34800		Pearlite	689 (100)	483 (70)	3
120–90–02	F36200		Tempered martensite	827 (120)	621 (90)	2

White cast iron

- In cast irons containing < 1 wt.% Si cooled at a rapid rate, most of the carbon exists as cementite, instead of graphite
- The fracture surface of such an alloy has a white coloured appearance ➔ white cast iron
- Due to the presence of large amounts of cementite phase, white cast iron is extremely hard and brittle and almost unmachinable
- The use of white cast iron is limited to applications requiring a very hard and wear resistant surface , without a high degree of ductility; e.g. rollers in rolling mills

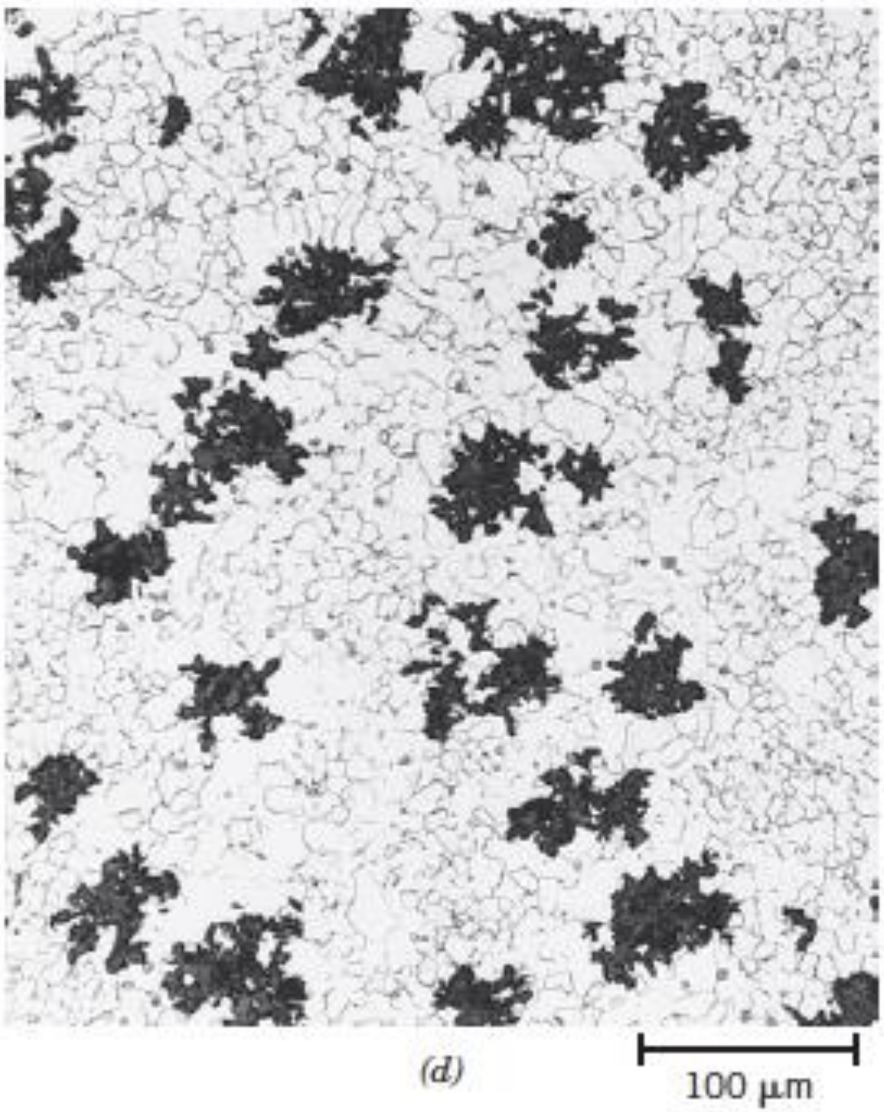
White cast iron

Typical optical micrograph of white cast iron

Malleable cast iron

- Malleable cast iron is produced by heating white cast iron at temperatures between 800-900 °C for a prolonged period in a neutral atmosphere
- This treatment decomposes the cementite, forming graphite existing in the form of clusters or rosettes surrounded by a ferrite or pearlite matrix
- Malleable cast irons possess relatively high strength and sufficient ductility or malleability
- Typical applications include connecting rods, transmission gears for the automotive industry, and also flanges, pipe fittings and valve parts for railroad, marine and other heavy-duty services

Malleable cast iron



Typical optical micrograph of malleable cast iron

Malleable cast iron properties

				Mechanical Properties		
Grade	***UNS Number***	***Composition (wt%)[a]***	***Matrix Structure***	***Tensile Strength [MPa (ksi)]***	***Yield Strength [MPa (ksi)]***	***Ductility [%EL in 50 mm (2 in.)]***
				Malleable Iron		
32510	F22200	2.3–2.7 C, 1.0–1.75 Si, <0.55 Mn	Ferrite	345 (50)	224 (32)	10
45006	F23131	2.4–2.7 C, 1.25–1.55 Si, <0.55 Mn	Ferrite + Pearlite	448 (65)	310 (45)	6

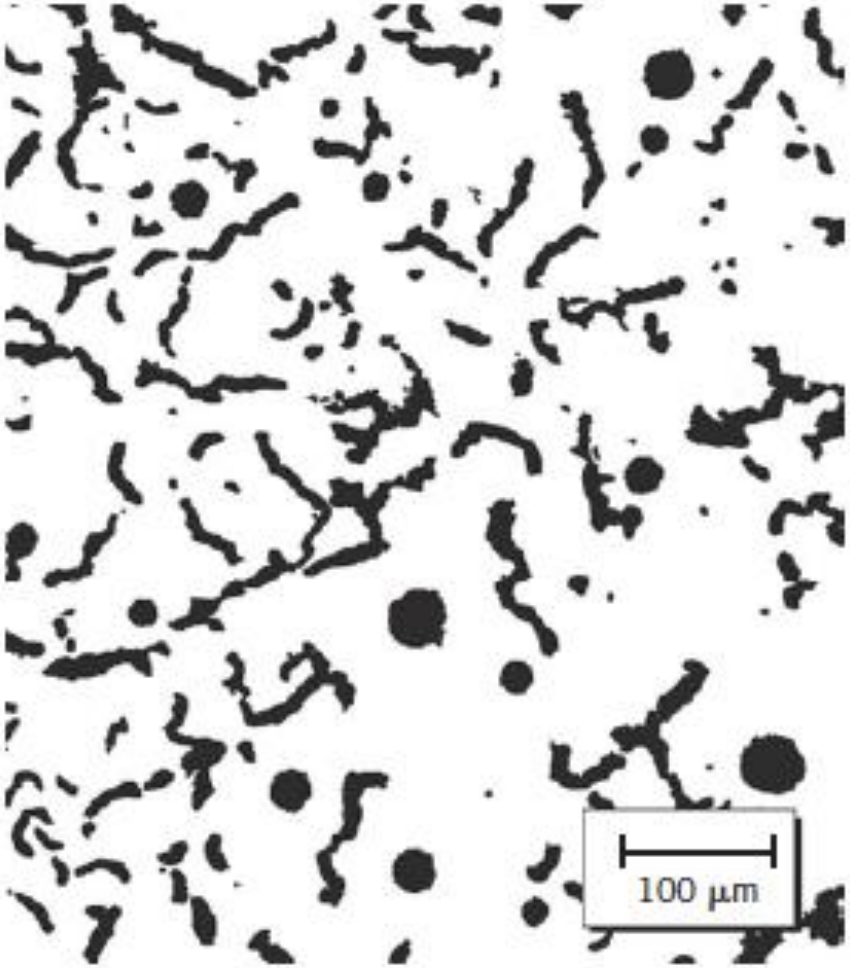
Compacted graphite cast iron

- They have a silicon content in the range of 1.7 – 3.0 wt.% and C-content between 3.1 – 4.0 wt.%
- Graphite in compacted graphite cast iron has a wormlike appearance and the microstructure of this cast iron is intermediate between gray and ductile cast iron
- Mg and Ce are also added to convert some graphite to nodular form, however their content is less than for ductile cast iron
- Depending upon the heat treatment the matrix phase is ferritic or pearlite

Compacted graphite cast iron

- The mechanical properties of compacted graphite cast iron is dependent upon the microstructure
- An increase in degree of nodularity increases both strength and ductility
- Compared to other cast irons, compacted graphite cast irons have some beneficial properties:
  - Higher thermal conductivity
  - Better resistance to thermal shock
  - Lower oxidation at elevated temperatures
- Typical applications include diesel engine blocks, engine manifolds, brake discs for high speed trains, flywheels etc.

Compacted graphite cast iron



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Typical optical micrograph of compacted graphite cast iron

Compacted graphite cast iron properties

Grade	UNS Number	Composition (wt%)[a]	Matrix Structure	Mechanical Properties: Tensile Strength [MPa (ksi)]	Yield Strength [MPa (ksi)]	Ductility [%EL in 50 mm (2 in.)]
				Compacted Graphite Iron		
ASTM A842						
Grade 250	—	3.1–4.0 C, 1.7–3.0 Si, 0.015–0.035 Mg, 0.06–0.13 Ti	Ferrite	250 (36)	175 (25)	3
Grade 450	—		Pearlite	450 (65)	315 (46)	1