Chapters 13 & 14

Metals & Alloys

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Why Iron & Steel/Ferrous Alloy?

Material	Elastic Modulus (GPa)	Yield Strength (MPa)	Tensile Strength (MPa)	Ductility (% EL)	Fracture Toughness ($MPam^{0.5}$)	Hardness (HB)	Cost ($/ton)
Low C steel	**~200**	**~250**	**~400-550**	**~20-30%**	**~55-220**	**~150**	**~900**
High C steel	**~200**	**~400-2000**	**~800-3000**	**~5-10%**	**~20-50**	**~200**	**~1100**
7075-T6 Al alloy	~70	~450	~570-700	~9%	~25-40	~60	~3500
Ti-6Al-4V alloy	~110	~900	~1000	~11%	~55-100	~330	~20,000
Inconel 718 super alloy	~205	~1100	~1300	~20%	~55-115	~340	~30,000

- **Broad range of properties at very low price (comparing with all other metals)**

Features in Fe-C Phase Diagram

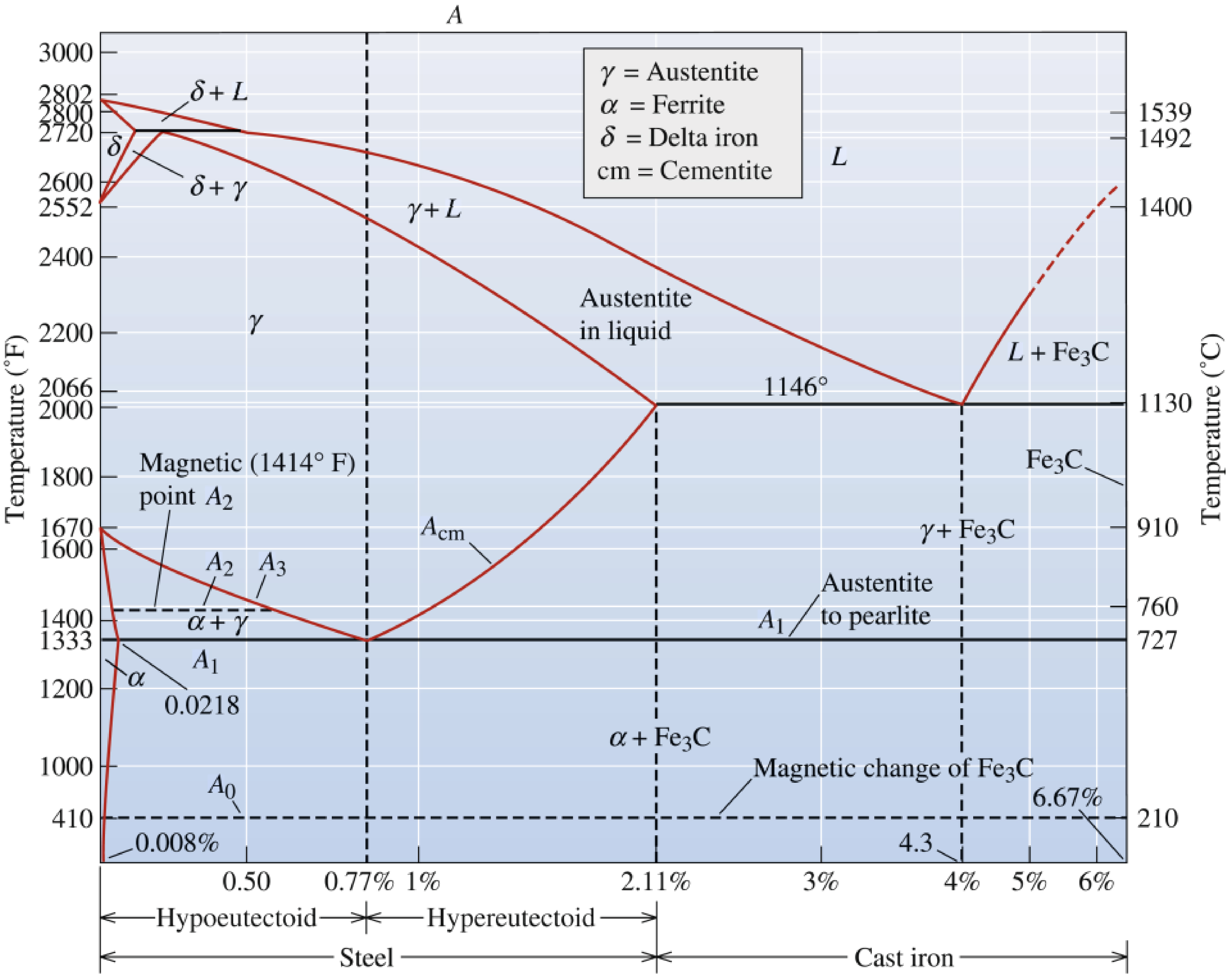
- **T_m for pure Fe** 1538ºC
- **Eutectic reaction**

  $T_{eutectic}$ = 1146ºC

  $L = \gamma + Fe_3C$
- **Eutectoid reaction**

  $T_{eutectoid}$ = 727ºC

  $\gamma = \alpha + Fe_3C$
- Solubility of C in α-Fe: 0.0218 wt.% C @ 727ºC
- Solubility of C in γ -Fe: 2.11 wt.% C @ 1146ºC



Classification of Ferrous Alloy

Ferrous alloy

Alloys based on iron (Fe)

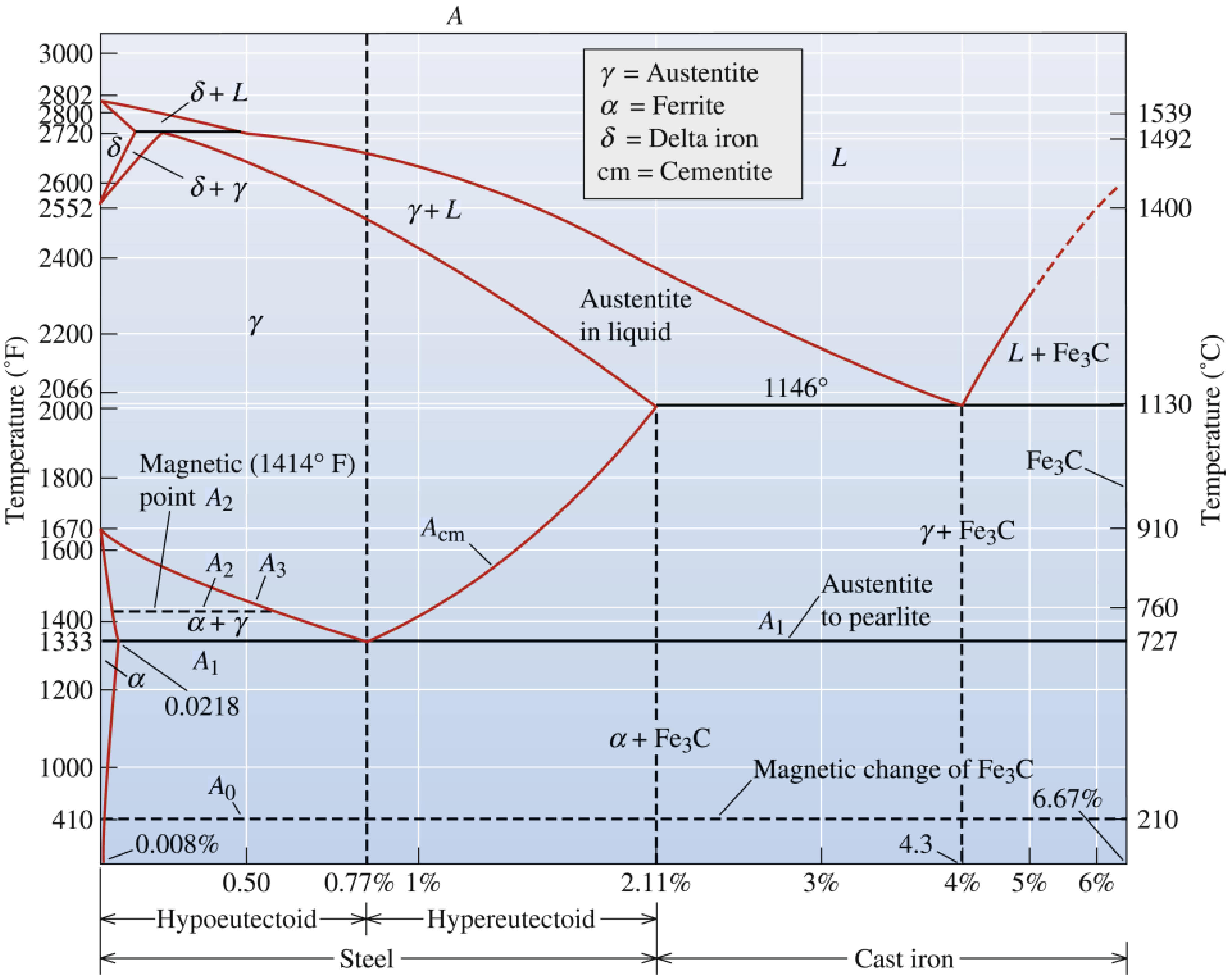
<u>Cast Iron</u>

- Ferrous alloy w/ ~2.11-4.3 wt.% C
- “castable” due to low melting point

<u>(Carbon) steel</u>

Ferrous alloy w/ <~2.11 wt.% C

- Low C steel: <~0.3%
- Medium C steel: ~0.3-0.6%
- High C steel: ~0.6-2% C



Numbering for Steels by Society Automotive Engineers (SAE)

4 digit naming system:

1yxx Carbon steels
… …
4yxx Molybdenum steels
5yxx Chromium steels
… …

- y Additional info, e.g., major alloying element (concentration)
- xx wt.% C $\times$ 100

Examples:

1060 Plain C steel with 0.60 wt% C (< 1 wt% Mn)
1140 C steel with 0.40 wt% C and ~1 wt.% Mn

Low Carbon Steel

- C content: ~0-0.3 wt.%
- Cannot be heat treated to form very hard, martensite phase
- Properties:
  - Relatively soft and lower strength
  - More ductile
  - Machinable and weldable
  - Lowest cost
- Applications
  - Pipelines
  - Metal cans (often tin plated)
  - Steel parts in buildings (I-beam, rebar)

https://en.wikipedia.org/wiki/Tin_can
http://www.ansonsteels.com/Low-carbon-steel-from-anson-steel.html
http://www.wisegeek.com/what-are-the-different-uses-of-low-carbon-steel.htm

High Strength Low Alloy (HSLA) Steel

- Carbon content: 0-0.3wt%
- With alloying elements (Cu, Ni, V, Mo, etc.) to strengthen
- Can be heat treated to improve mechanical strength
- Properties
  - More corrosion resistant than low carbon steel
  - Applications
    - ✓ Bridges
    - ✓ Buildings
    - ✓ Pressure vessels

https://s.marketwatch.com/public/resources/images/MW-FC855_bridge_ZH_20161229230700.jpg

http://www.hsla-v.org/hsla_video_blast.php

http://www.imoa.info/molybdenum-uses/molybdenum-grade-alloy-steels-irons/high-strength-low-alloy-steel.php

Medium Carbon Steel

- Carbon content: ~0.3-0.60 wt% C
- Can be heat treated (from Austenite to Martensite phase) to improve strength and hardness
- Can be alloyed to further improve heat treatment property (i.e., to control microstructure)
- Properties
  - Higher strength and harder than low carbon steel
  - Good wear resistance
  - Lower ductility than low C steel, but adequate
- Applications
  - Railway wheels and tracks
  - Crank and shafts

http://yu-jei.com.tw/ARCW.html
https://www.uline.com/Product/Detail/H-6410/Hand-Tools/

High Carbon Steel

- Carbon content: ~0.60-2.0 wt% C
- Can be heat treated (from Austenite to martensite phase)
- Can be alloyed to further improve hardness etc.
- Properties
  - Strongest and hardest
  - Good wear resistance
  - Low ductility
- Applications
  - Cutting and machining tools: knives, razors, saw blades
  - Crankshafts

http://www.dx.com/p/high-carbon-steel-round-shank-woodworking-lip-spur-drill-bit-set-silver-black-369121#.WNAs1k2rOcw

http://www.echefknife.com/blog/high-carbon-steel-white-blue-super/

http://www.tatasteeleurope.com/en/products-and-services/flat/narrow-strip/carbon/carbon

Stainless Steel

- Primary alloying element Cr: at least 11 wt.%, together with other alloying elements (e.g., Ni, W, etc.)
- Properties
  - Significantly improved corrosion resistance over carbon steel
  - Wide range of mechanical properties
- Applications
  - Pipes/tubings
  - Chemical production reaction vessels
  - Marine applications
  - Jet engine parts

Stainless steel	Cr (wt.%)	Ni (wt.%)	Mo (wt.%)	Mn (wt%)	C (wt%)
304	~19	~9	/	<2	<0.08
316	~17	~12	~2.5	<2	<0.08
410	~12.5	/	/	<1	<0.15

https://www.unifiedalloys.com/blog/stainless-steel-marine-applications

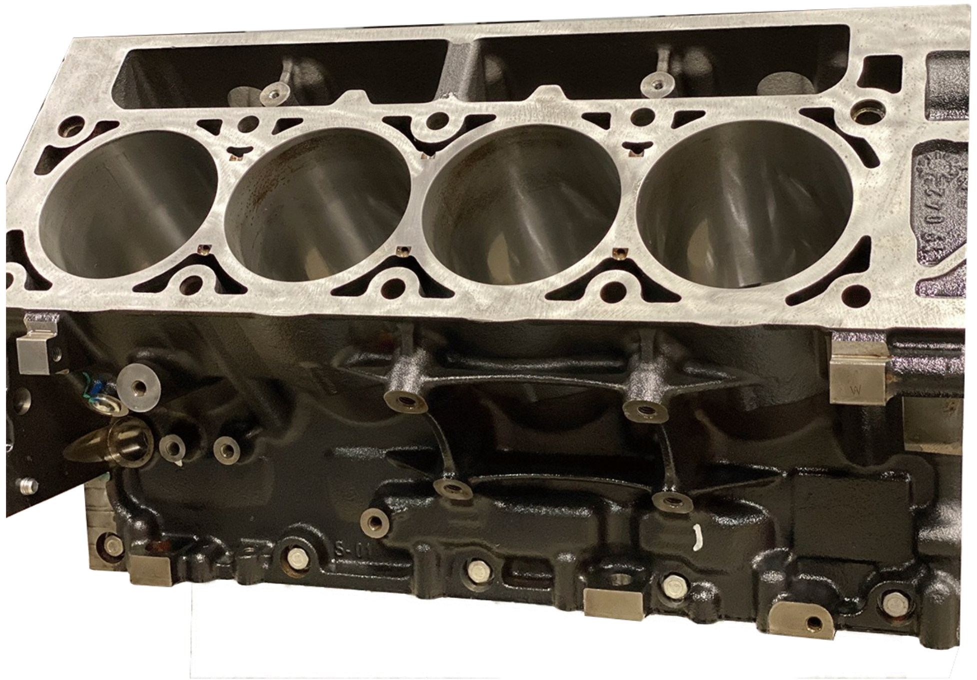
https://www.excelmetal.net/stainless-steel-316-tube-fittings.html

https://www.foodandwine.com/lifestyle/kitchen/best-stainless-steel-cookware-sets

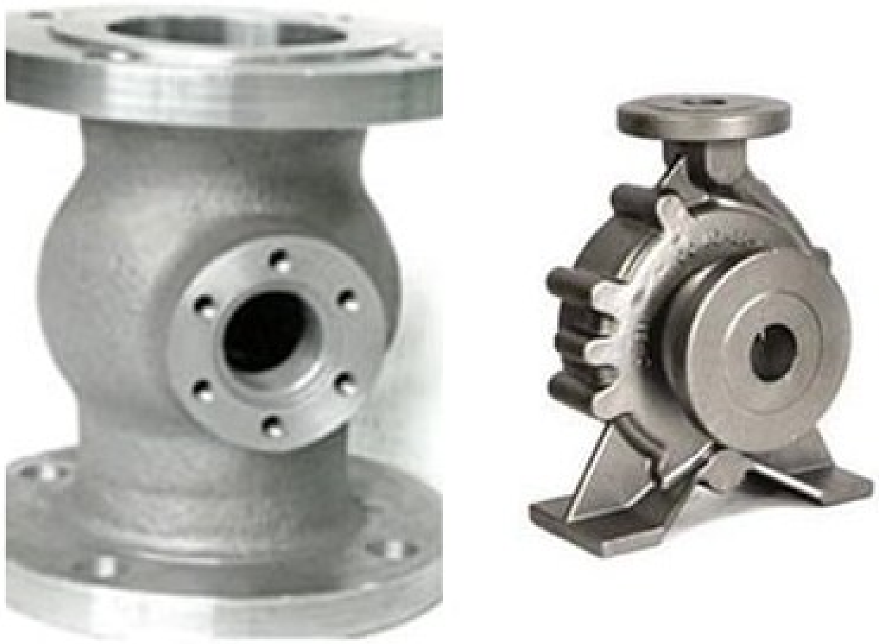
Cast Iron

- Ferrous alloys with > ~2.1 wt.% C, often ~3 - 4.5 wt.% C
- Low melting (T_L~1130-1200^{o}C) – easy to cast (via liquid)
- Generally low cost, for various applications (pots, engine block, valves,)
- Mechanical property varies

https://en.wikipedia.org/wiki/Cast-iron_cookware



https://www.mastmotorsports.com/products/gm-gen-v-cast-iron-bare-block-l8t-6-6-truck-block



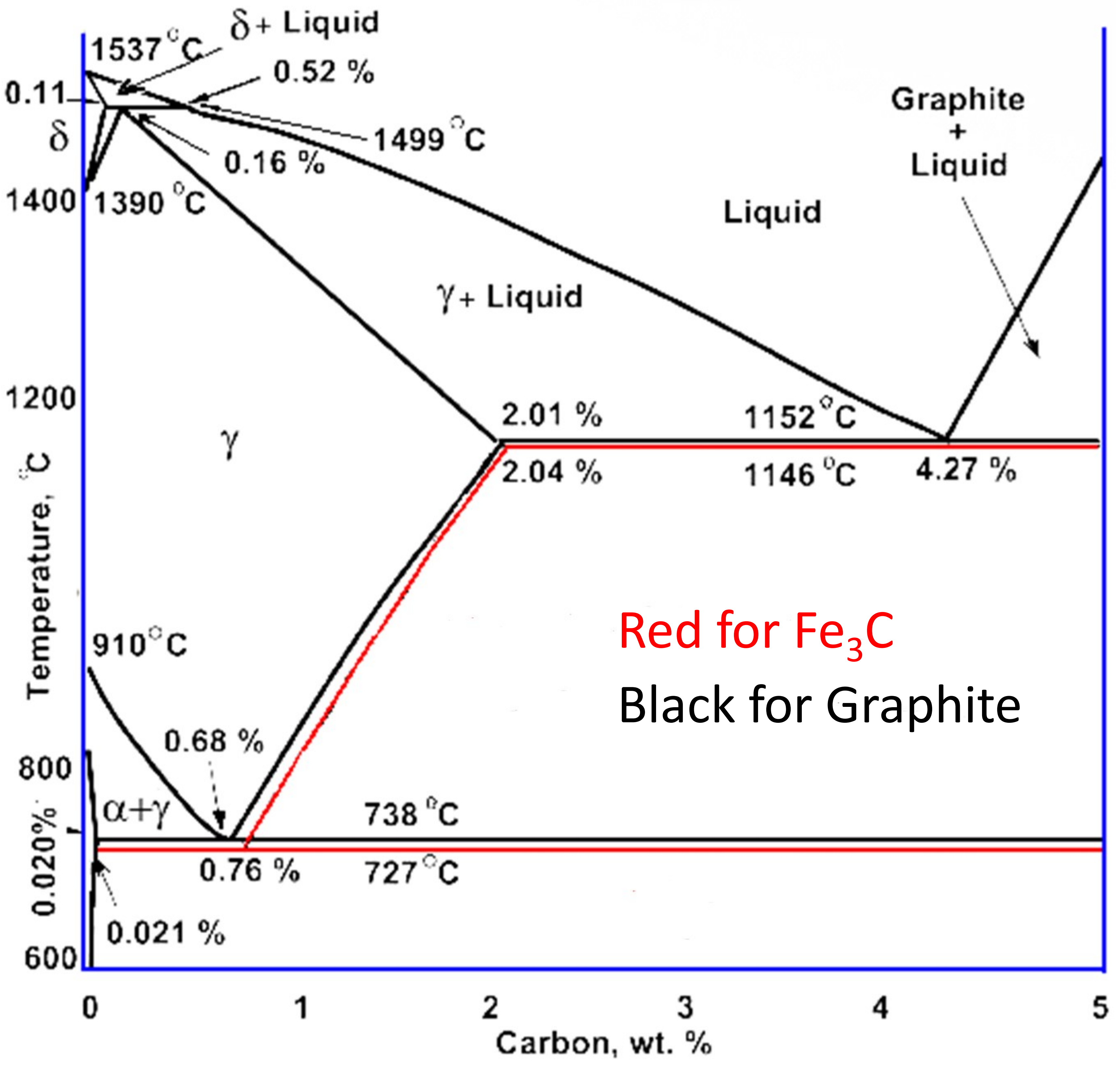
https://www.investmentcastingpci.com/pump-castings/

Formation of Graphite from Fe_3C in Cast Iron

- Cementite Fe_3C is NOT a phase under equilibrium - not the lowest energy or not stable

- Given time, at elevated T, Fe_3C decomposes:
  $Fe_3C \rightarrow 3\ Fe\ (\alpha) + C\ (Graphite)$

- Graphite formation promoted by:
  - Slow cooling
  - Adding Si (> 1 wt.%)



https://www.tf.uni-kiel.de/matwis/amat/iss/kap_6/illustr/s6_1_2.html

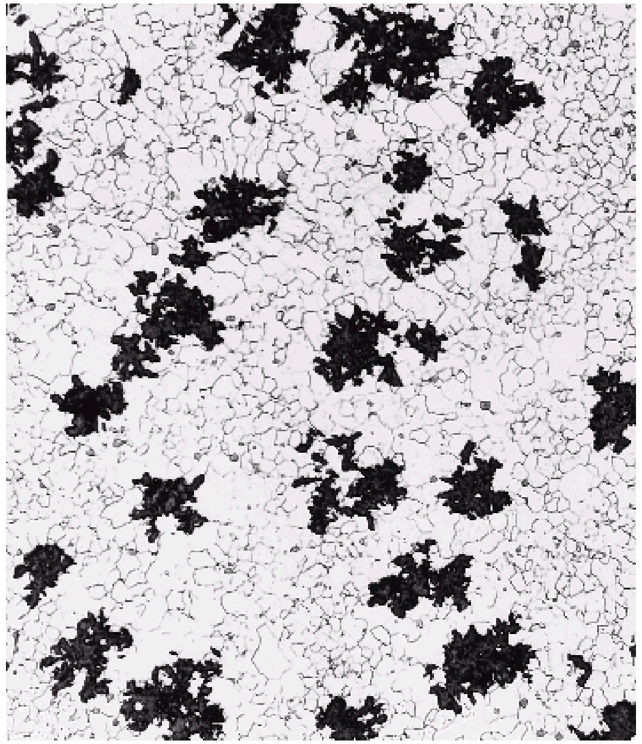
Types of Cast Iron (1)

White iron

- < 1 wt% Si and/or fast cooling
- Carbon exists as cementite (Fe_3C)
- Hard and brittle
- Only as **intermediate** in processing

Malleable iron

- Heat treat white iron at 800-900ºC
- Graphite in clusters
- Reasonably strong and ductile



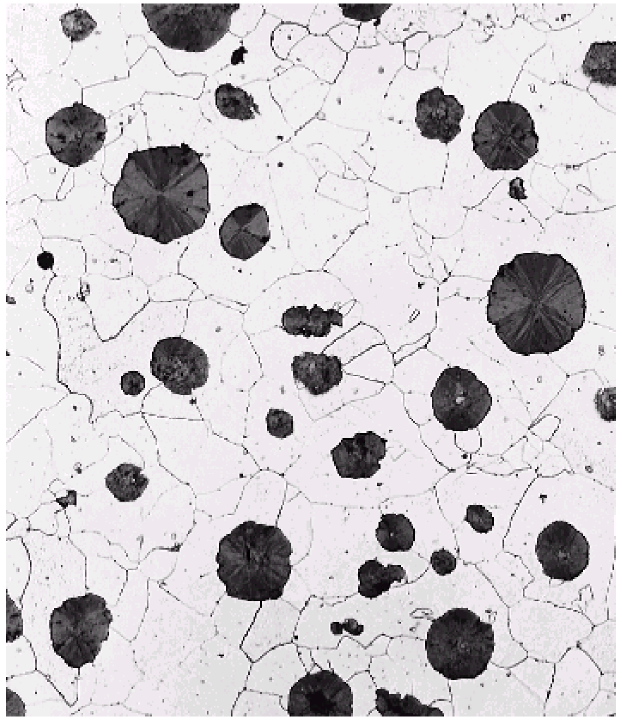
Types of Cast Iron (2)

Gray iron

- Graphite in flake shape
- Weak & brittle in tension due to sharp tips of graphite phase associated with **many micro-cracks**
- Excellent vibrational **dampening**
- Use for heavy equipment base
- Very low cost

Ductile (or Nodular) iron

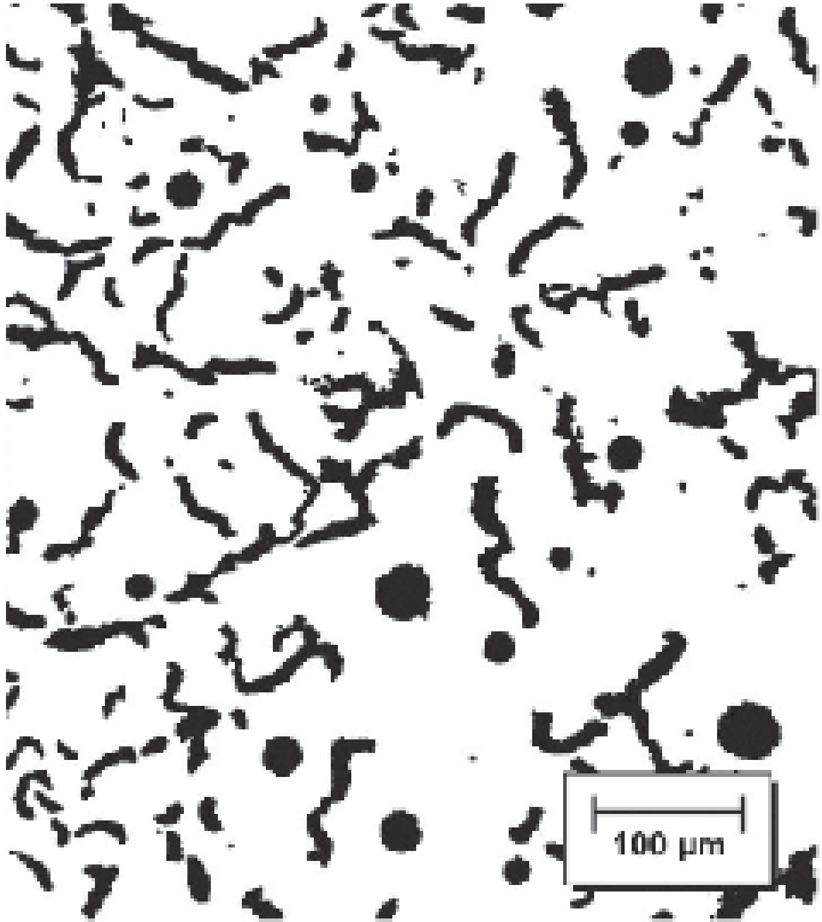
- Add Mg and/or Ce
- Graphite in nodule/spherical shape
- Matrix often stronger
- Use for valves, pump bodies …



Types of Cast Iron (3)

Compacted graphite iron

- Relatively high thermal conductivity
- Good resistance to thermal shock
- Lower oxidation at elevated temperatures
- Use for diesel engine blocks, exhaust manifolds, etc.



Take-home Message

For iron/steel, even for the same composition, different processing leads to different microstructures (e.g., cementite or graphite shape and distribution), which then strongly influences mechanical properties and their application.

Major Limitation for Iron & Steel

- High densities (~7.8 g/cc)
  - NOT for applications where weight concern is paramount: tennis racket baseball bat

- Relatively low electrical conductivities
  - NOT for carrying electricity

- Generally poor corrosion resistance
  - For stainless steel, significant Cr (>10 at.%) and other elements such as Ni, W, etc. added to improve corrosion resistance

Aluminum Alloys

- Al based alloys w/ other elements, e.g., Cu, Li, Mg, Si, Zn etc.
- May go through cold-working & heat treatment for enhanced properties

	σ_y (MPa)	σ_U (MPa)	Ductility %EL
Pure Al	17	45	60
Cold-worked Al	150	165	15
Solid-solution strengthened Al (<solubility limit)	41	110	35
Dispersion-strengthened Al (e.g., Al-Si eutectic)	150	290	35
Age hardened Al	500	570	11

- When low density (~2.7 g/cm^3), decent corrosion resistance & strength are needed






Limitations w/ Aluminum Alloys

- Low melting point
  - Activation oxidation at ~400^{o}C
  - Mechanical degrades significantly at ~180^{o}C!
- Active corrosion in strongly acid/base environment or connecting with more noble metals (e.g., Cu, Fe, Ni)
- Much lower modulus than steel (~1/3)
  - Same stress: ~2 times more elastic deformation
- Much lower toughness than steel (~1/3)
- Low fatigue endurance limit
- Cost: more expensive than steel (>3 times per unit weight, >30% per unit volume)

Copper Alloy

- Brass: Cu-Zn alloy
- Bronze: Cu-Sn or other Cu alloys
- Properties determined by composition (alloying) , heat treatment, and cold-working
- For applications where decent corrosion resistance & strength are required, while weight/density (~8.5 g/cm^3) is not a concern

Limitations with Copper Alloys

- Low melting point
  - Active oxidation at ~250^{o}C
  - Mechanical property degradation >~300^{o}C
- Active corrosion in oxidizing acid/base environment
- Much lower toughness than steel (~1/3)
- Higher density (8.5 g/cm^{3}) than steel
- Cost: >10 times more expensive than steel!
- Not often for structural applications, but do get used in external structures

Titanium Alloy

- Low density: ~4.5 g/cm^3
- Excellent corrosion resistance at ambient condition, including for marine use
- Excellent strength & hardness

Limitations

- Active oxidation >~400^oC
- (Very) Difficult to machine (work hardening)
- >~30 times more expensive than steel!
- Use when weight, strength, & corrosion resistance are critical, while cost is not

Other Alloys

- **Mg** alloys
  - Very low density (~1.7 g/cm^3)
  - Low melting point & active oxidation >~200^{o}C
  - Very limited use when weight concern is paramount: race car, body armor base

- **Refractory** alloys (W, Mo, Nb, Ta, etc.)
  - Extremely high temperature application
  - Very high density (>10 g/cm^3) and high cost

- **Noble** metal alloys (Ag, Au, Pt, Rh, etc.)
  - Almost oxidation/corrosion proof
  - For special chemical/electronic applications

Production of Selected Raw Metals

- Steel:

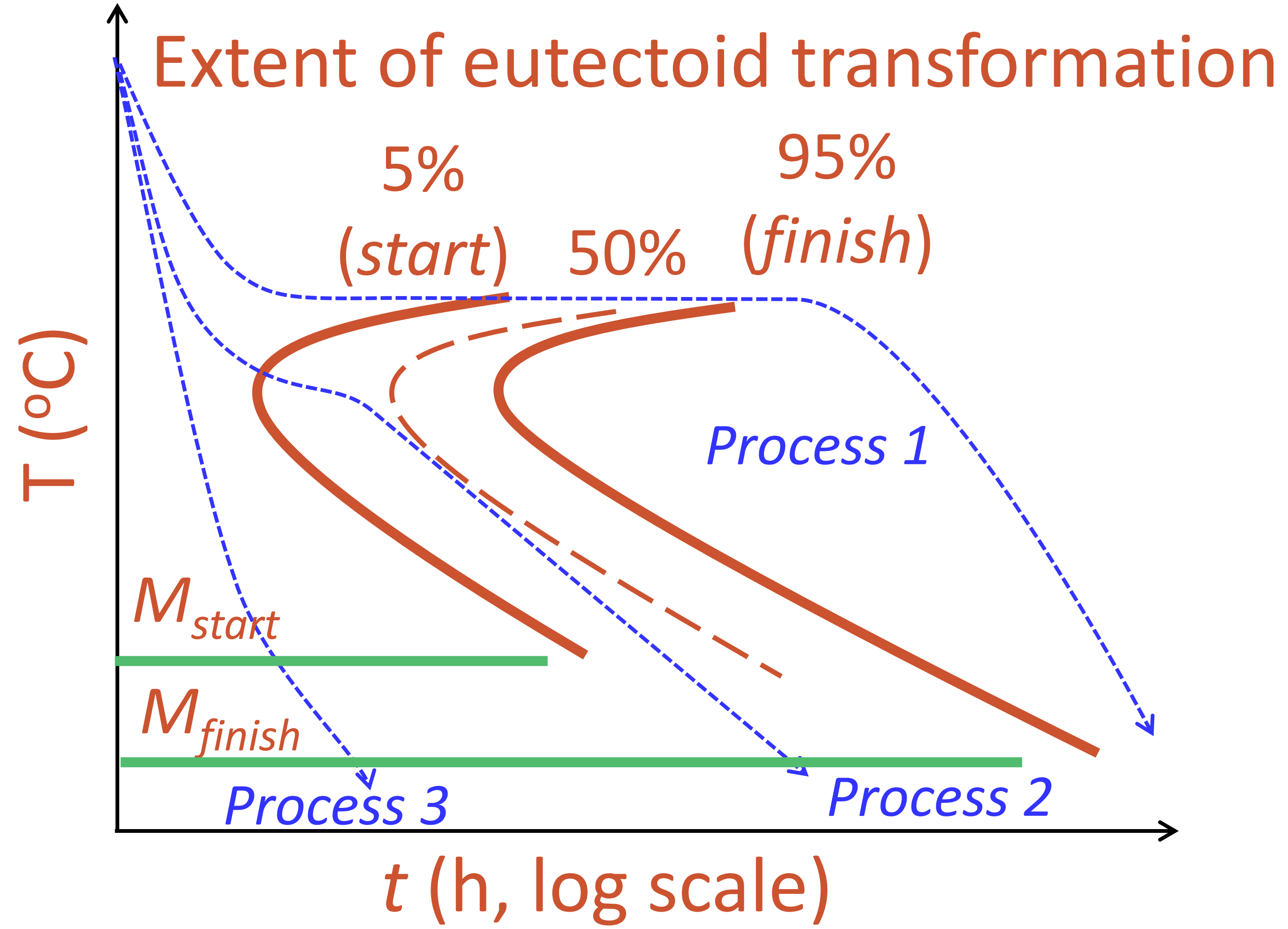
  Reduction of Fe_2O_3 by coke (C) **$3C + Fe_2O_3 = 2Fe + 3CO$**

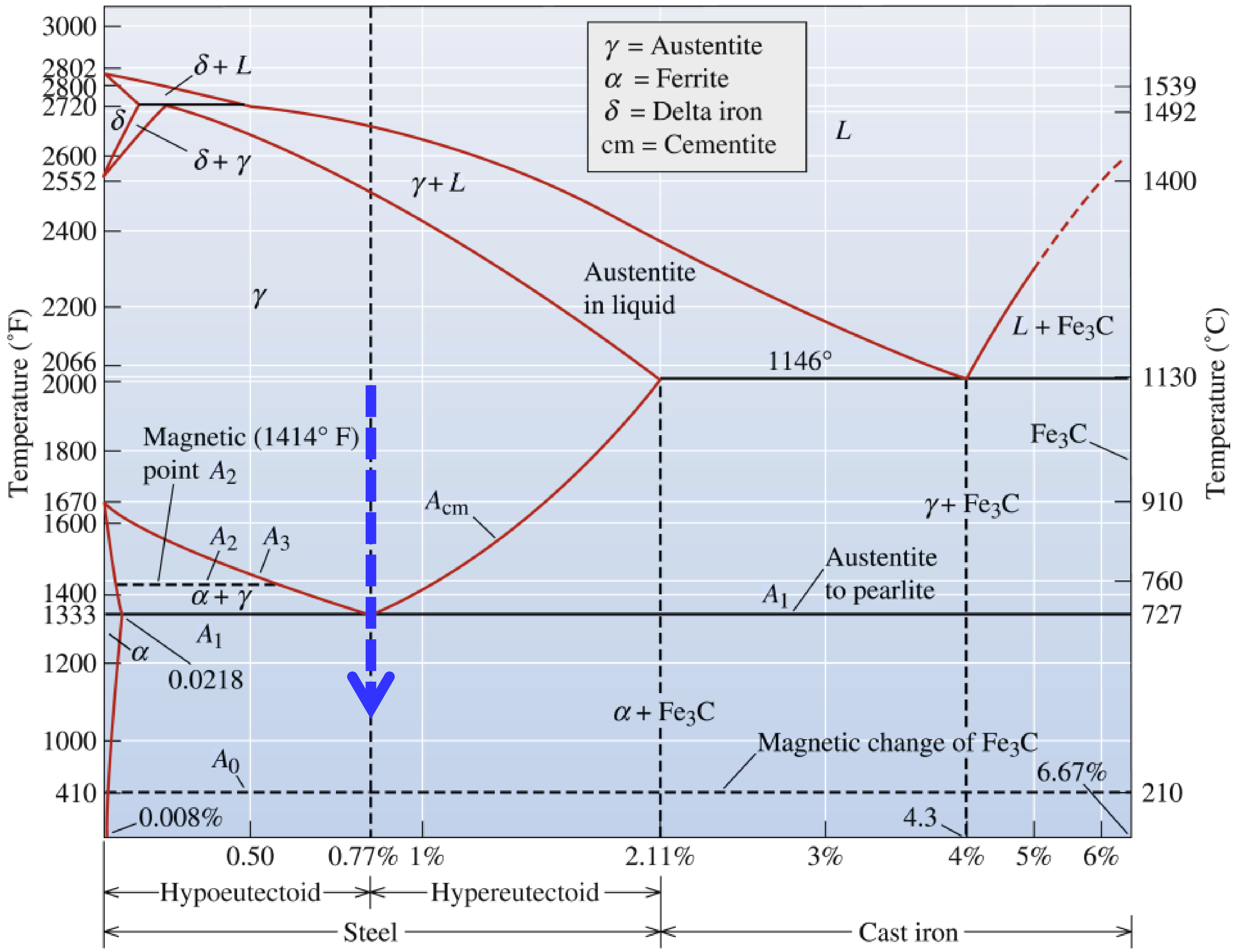
- Aluminum

  Electrolysis of Al_2O_3 in molten salt: **$2Al_2O_3 + 3C = 4Al + 3CO_2$**

Temperature - Time - Transformation (TTT) Diagram

Curves (e.g., in brown below) describing, qualitatively, extent (%) of phase transformation (e.g., γ-Fe eutectoid transf), vs. temperature & time

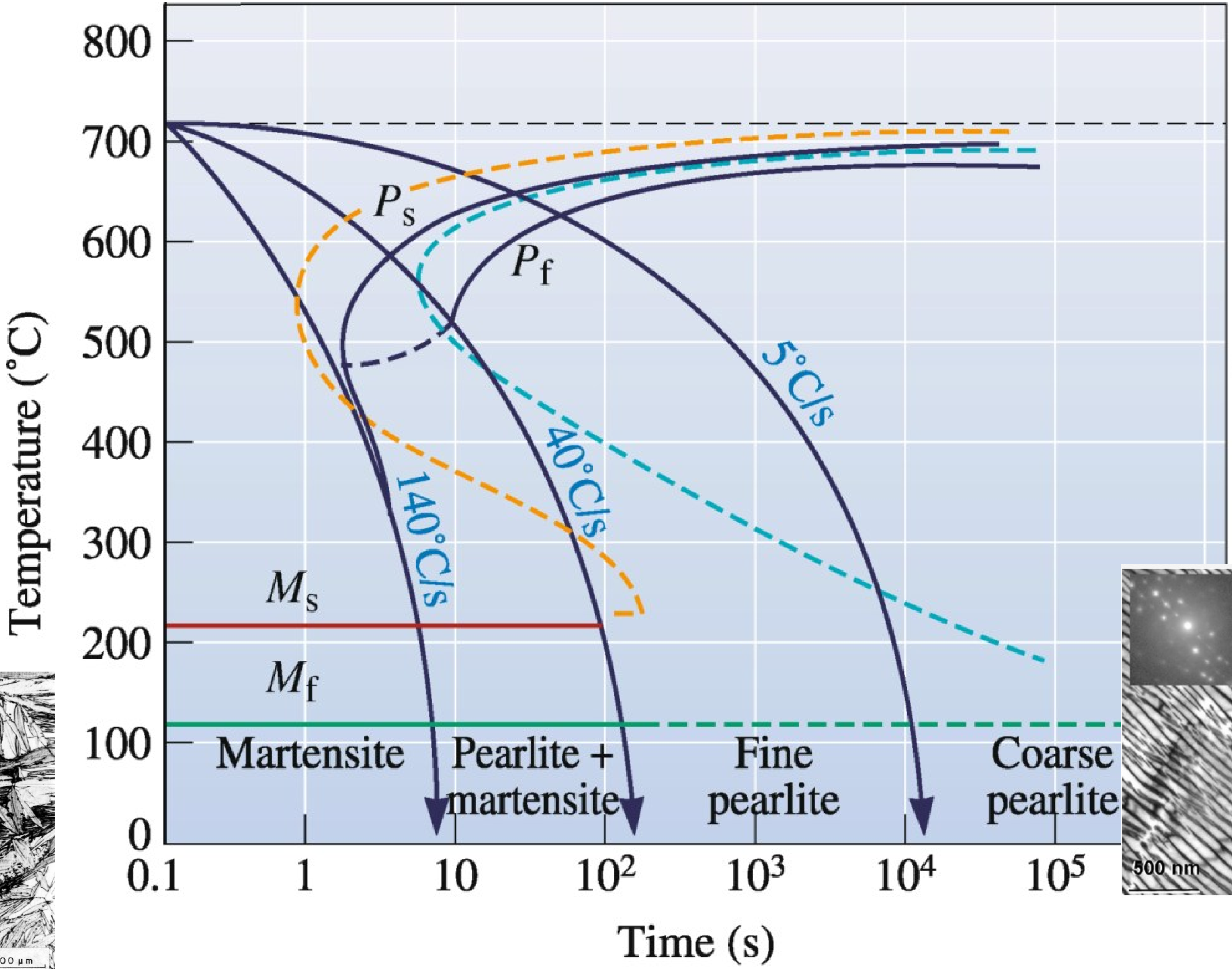


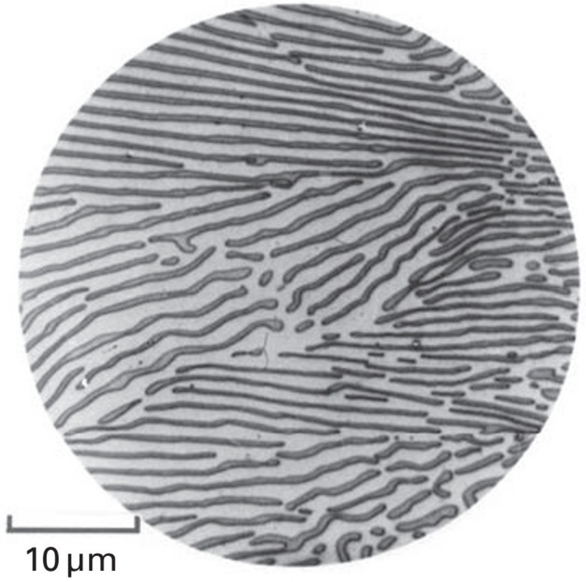


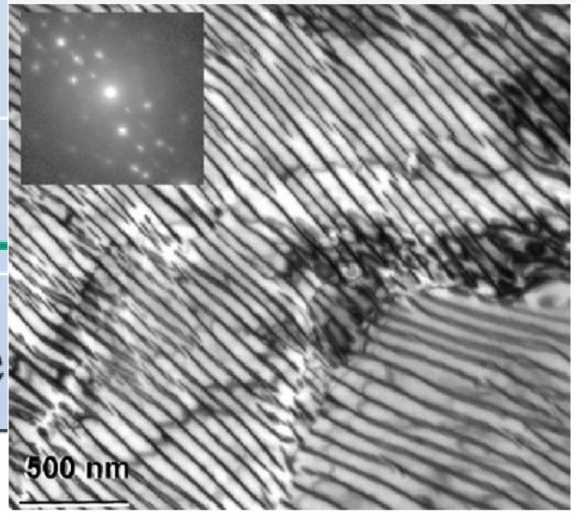
Heat treatments (e.g., cooling via quenching) may have many different T vs. t profiles, e.g., Process 1 vs. Process 2 vs. Process 3
→ Leading to different microstructures and, as a result, (mechanical & other) properties

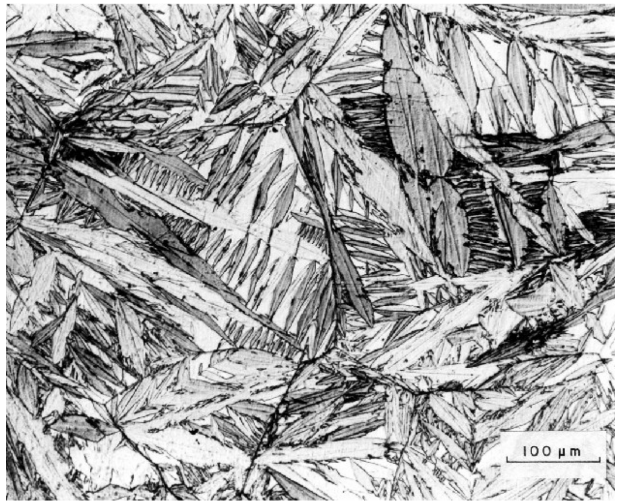
Temperature - Time -Transformation (TTT) Diagram

Different processing leading to different micro-structures and properties









Metal Manufacturing/Processing

- Casting
- Hot-working
  - Forging
  - Hot-rolling
- Cold-working
  - Cold-rolling
  - Stamping
- Heat treatments
  - Normal cooling vs. quench
  - Reheat: anneal, age…
- Additional processing
  - Lathing
  - Polishing/grinding
  - Coating…









END

Homework 0

Carefully review chapter 13 and 14 lecture slides and, if interested, read textbook sections of Askeland 13 and 14 and give an honor statement confirming the reading