

Introduction to Gray Cast Iron Brake Rotor Metallurgy

Mark Ihm

TRW Automotive



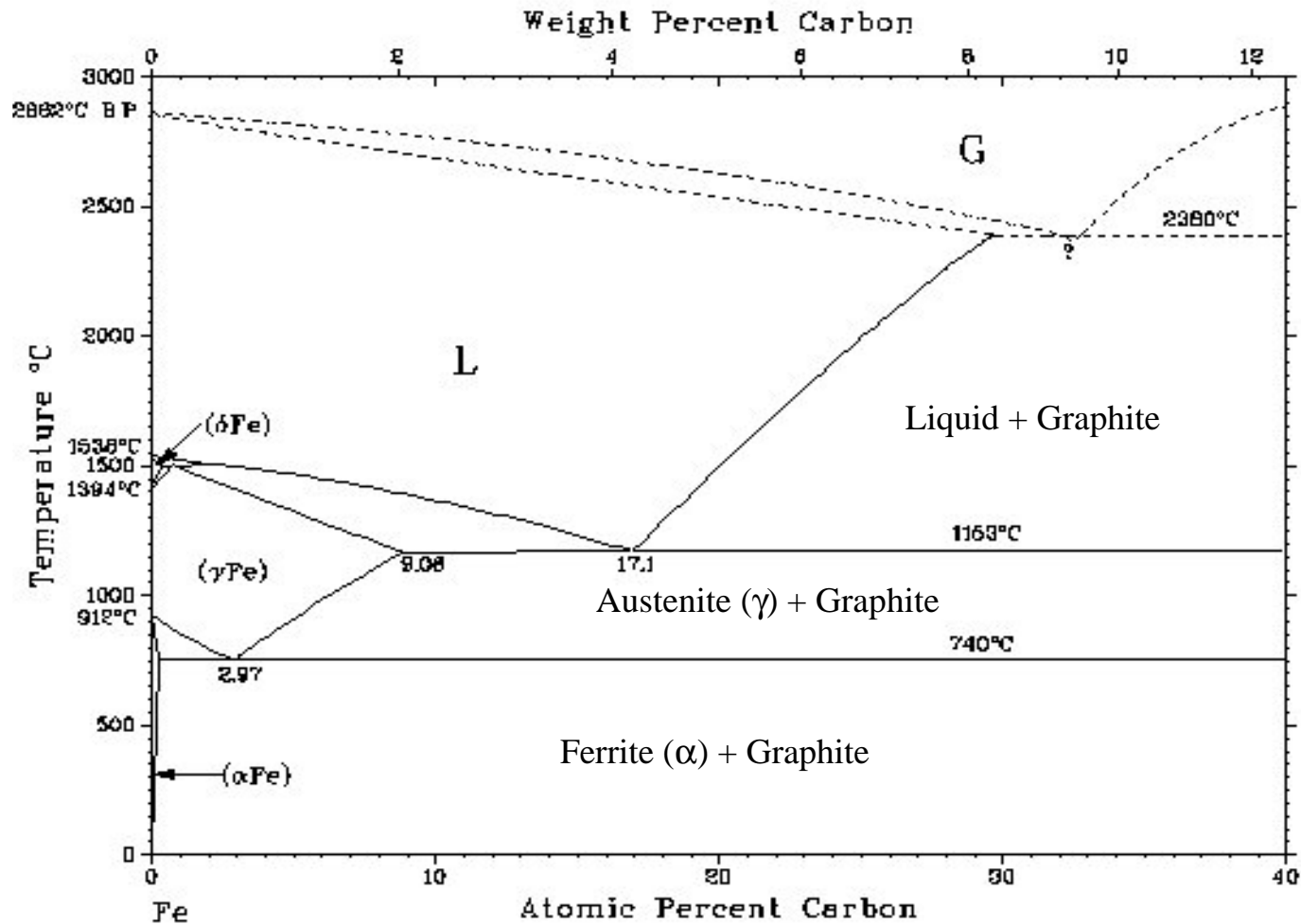
Tutorial Outline

- Introduction
- Microstructures of Cast Irons
- Properties of Gray Cast Irons
- Influence of Casting Processes
- Future of Gray Cast Iron Rotors

Introduction to Gray Cast Iron Brake Rotor Metallurgy

The properties of cast iron components are controlled by the microstructure of the material, which consequentially are determined by the chemistry and processing of the cast iron.

Equilibrium Iron-Carbon Binary Phase Diagram

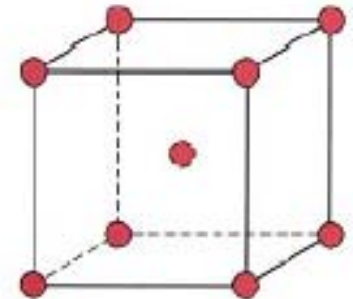
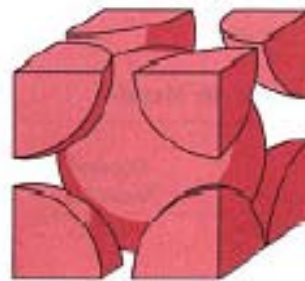


Equilibrium Solid Phases in the Binary Iron-Carbon System

- Ferrite (α -Fe)
- Austenite (γ -Fe)
- Delta Iron (δ -Fe)
- Graphite (C)

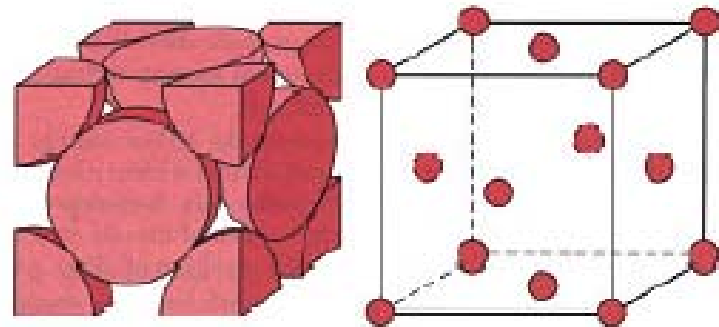
Ferrite Iron Phase

- Body-center cubic crystal structure
- Stable up to 912°C in Fe-C system
- Density: 7.86 grams/cm³ at 20°C
- Soft and very ductile phase



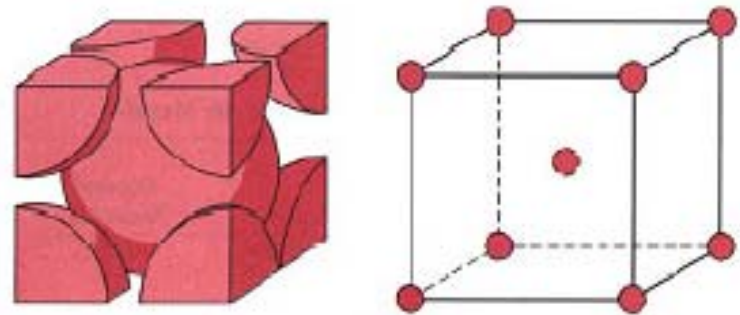
Austenite Iron Phase

- Face-center cubic crystal structure
- Stable from 740°C to 1493°C in Fe-C system
- Density: 7.84 grams/cm³ at 20°C
- Strong, hard and tough phase



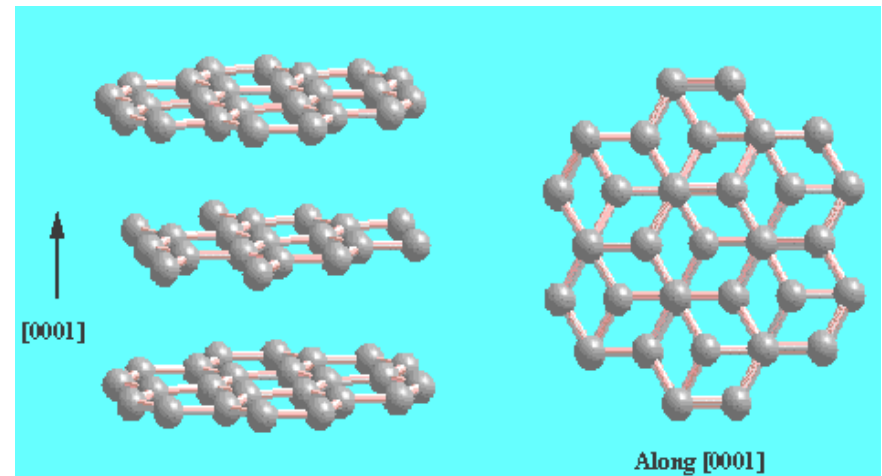
Delta Iron Phase

- Body-center cubic crystal structure
- Stable from 1394 °C to 1538°C
- Since temperature range is limited to very high temperatures, very little is published about mechanical and physical properties.



Graphite Carbon Phase

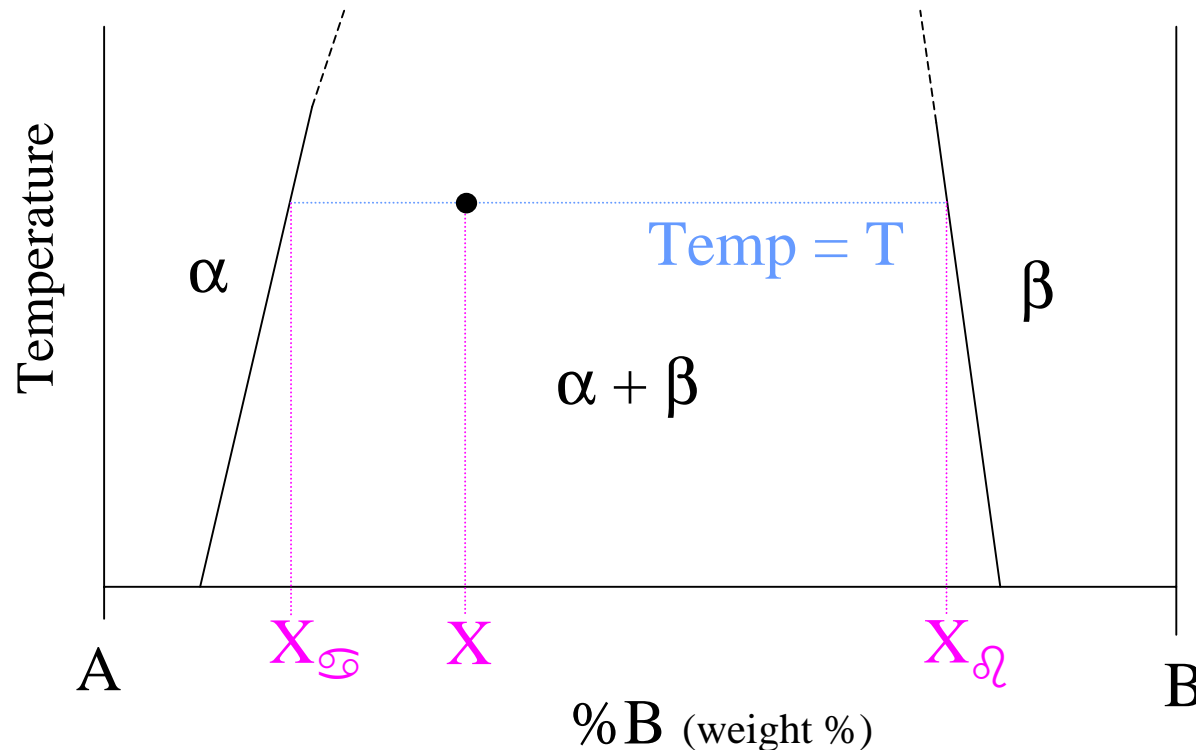
- Layered hexagonal structure with covalent bonding of atoms in each layer
- Density: 2.25 grams/cm³ at 20°C
- Layers easily slide against each other and make graphite a solid lubricant
- Soft and low strength



The “Lever Rule” in Equilibrium Binary Phase Diagram

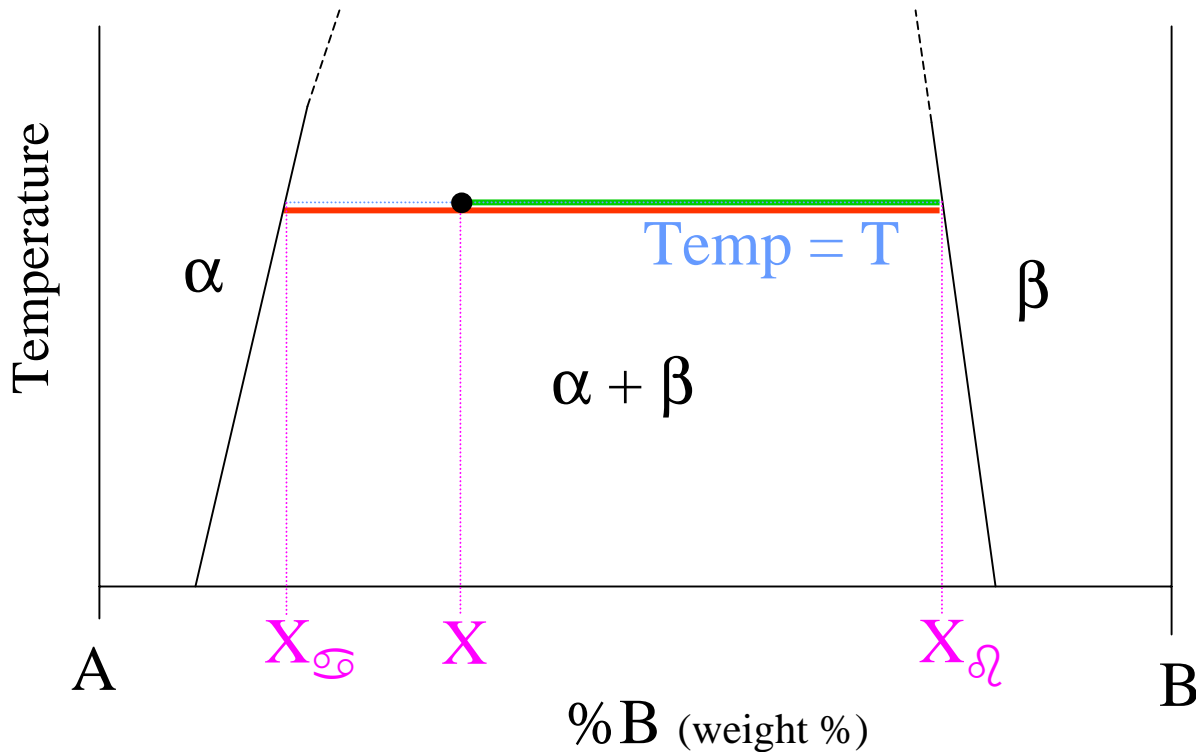
The LEVER RULE is used to determine the compositions of phases and the relative proportions of phases to each other in the two phase regions of binary phase diagrams. The LEVER RULE applies only to regions where two phases exist together and only under isothermal conditions.

The “Lever Rule”



For an overall composition “X” at temperature “T”, the composition of the α -phase is X_{α} and the composition of the β -phase is X_{β} .

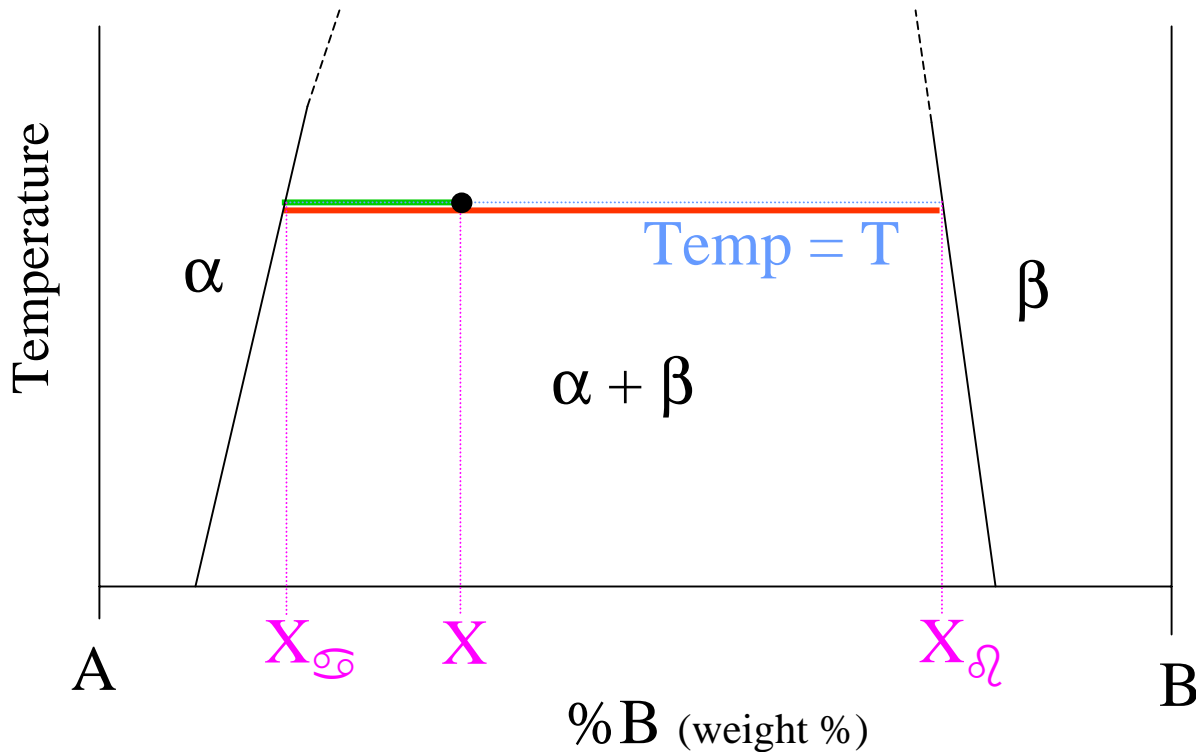
The “Lever Rule”



For an overall composition “X” at temperature “T” the weight fraction of the α -phase (F_{α}) is represented by the equation:

$$F_{\alpha} = (X_{\beta} - X)/(X_{\beta} - X_{\alpha})$$

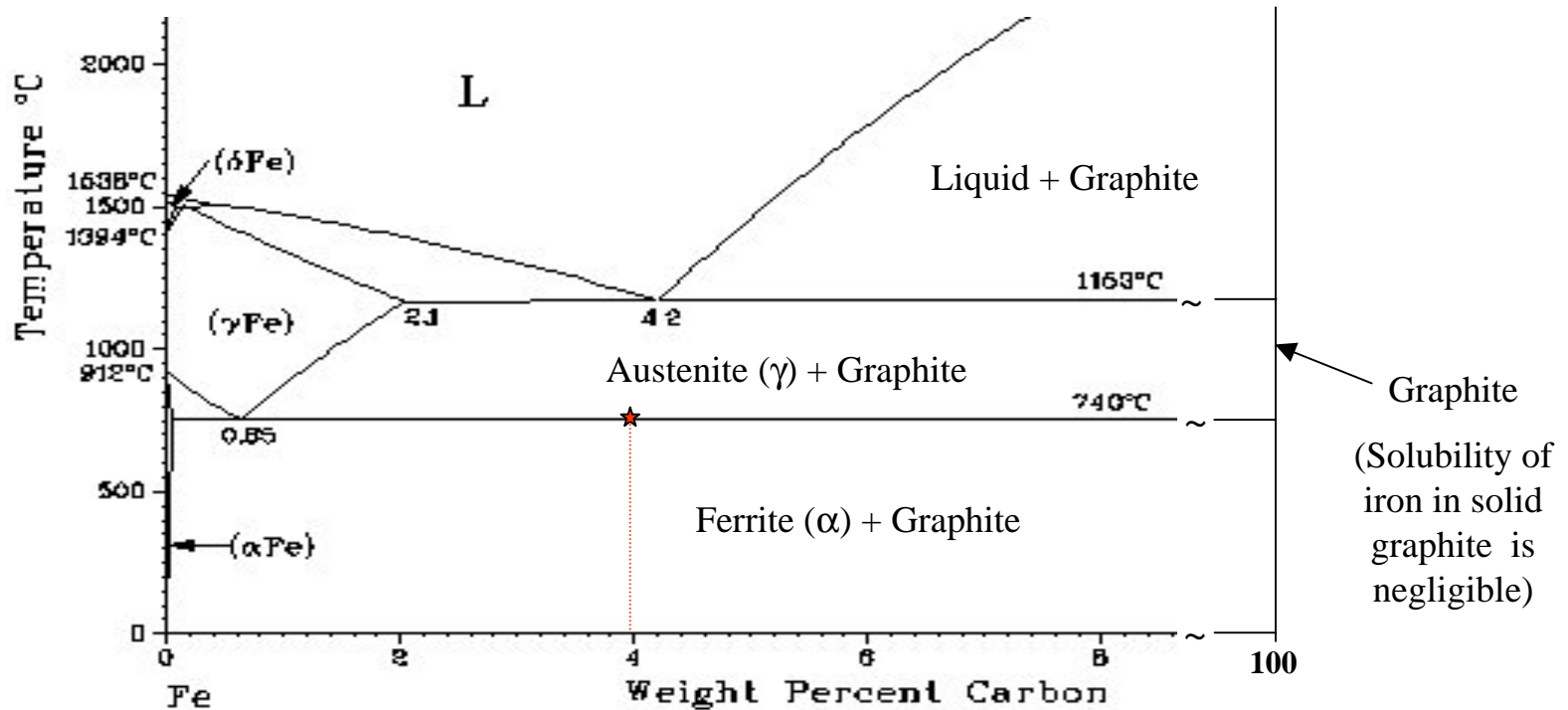
The “Lever Rule”



For an overall composition “X” at temperature “T” the weight fraction of the ω -phase (F_{ω}) is represented by the equation:

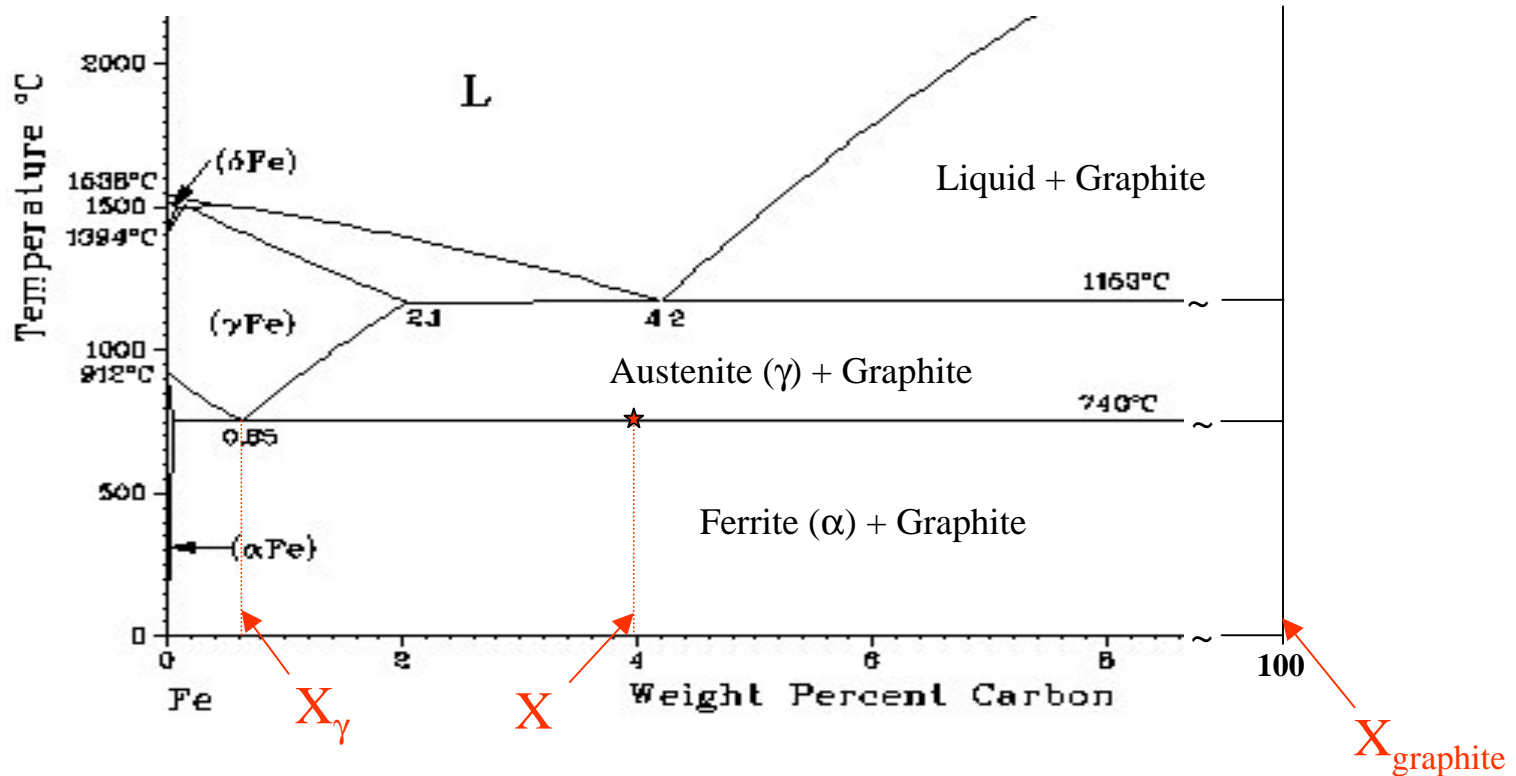
$$F_{\omega} = (X - X_{\alpha}) / (X_{\omega} - X_{\alpha})$$

Practice Problem #1



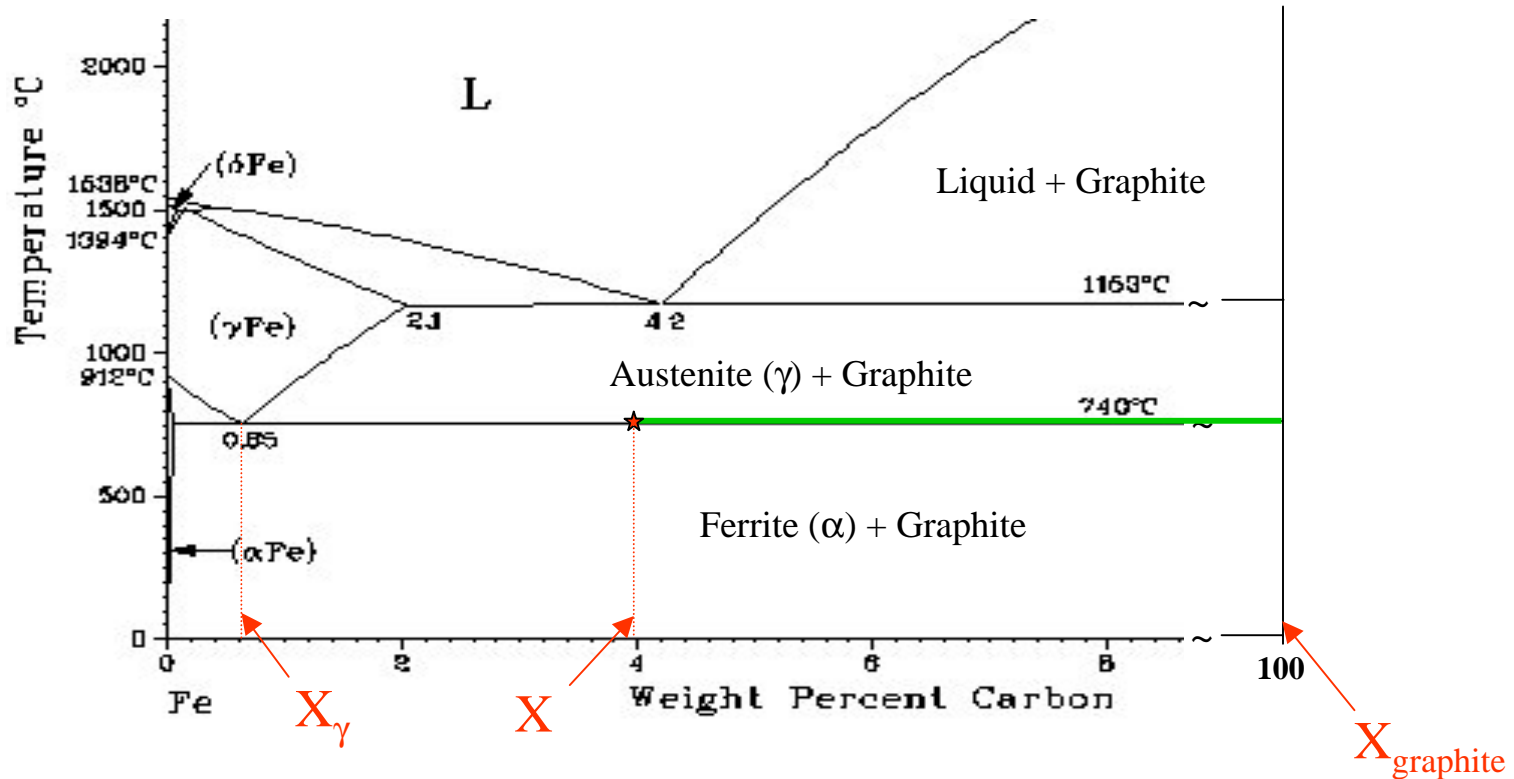
For an overall composition of iron with 4 % carbon held at 741°C, what are the compositions of the two phases and weight fractions of each phase?

Practice Problem #1



The austenite phase contains 0.85% carbon at 741°C, and the graphite phase contains 100% carbon.

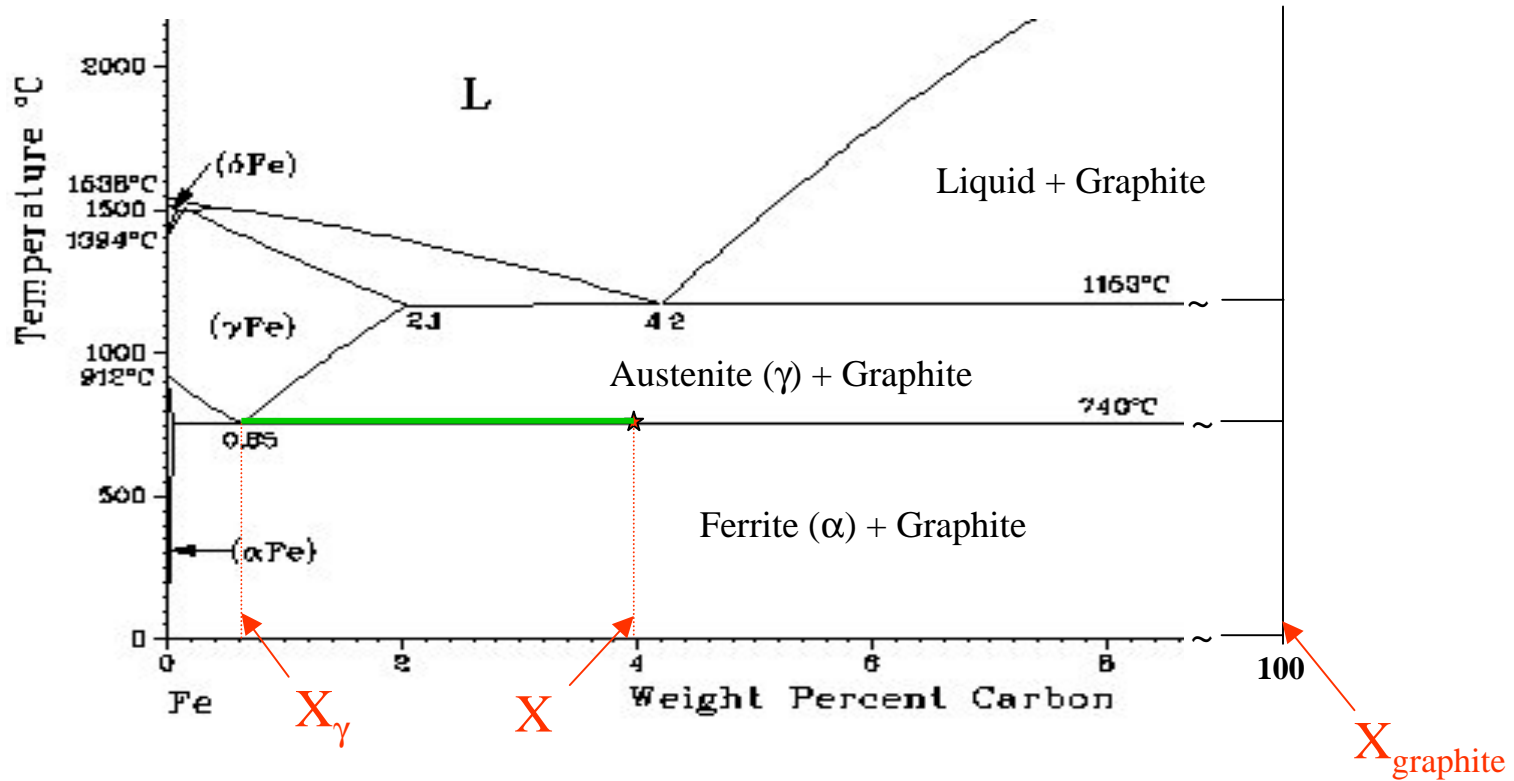
Practice Problem #1



The weight fraction of the austenite phase is calculated as:

$$F_{\gamma} = (X_{\text{graphite}} - X) / (X_{\text{graphite}} - X_{\gamma}) = (100 - 4) / (100 - 0.85) = 0.968 = 96.8\%$$

Practice Problem #1



The weight fraction of the graphite phase is calculated as:

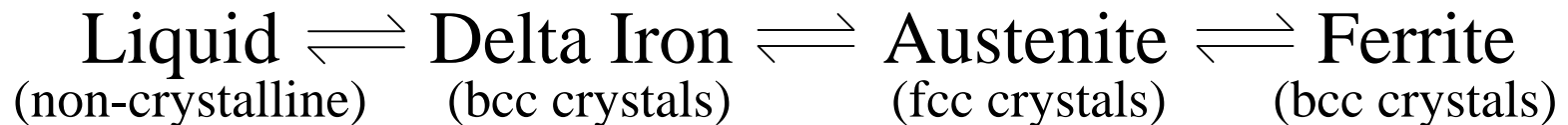
$$F_{\text{graphite}} = (X - X_{\gamma}) / (X_{\text{graphite}} - X_{\gamma}) = (4 - 0.85) / (100 - 0.85) = 0.032 = 3.2\%$$

Phase Transformations in Equilibrium Binary Phase Systems

Single Phase Transformations ($A \rightleftharpoons B$)

- Typically involve pure materials
- Compositions of phases are identical
- Do not involve diffusion of atoms
- Transformation occurs at a single temperature

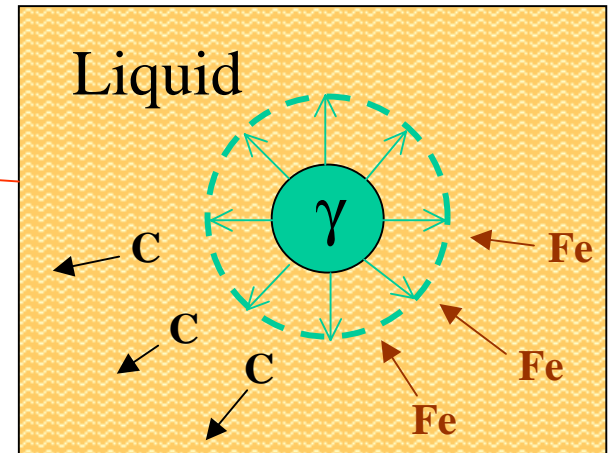
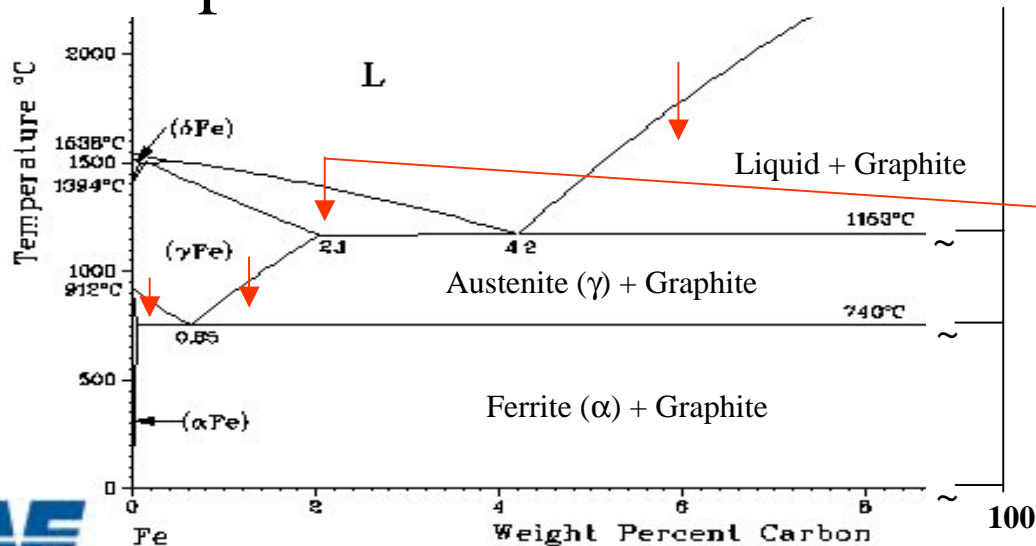
Single Phase Transformations for Pure Iron



Phase Transformations in Equilibrium Binary Phase Systems

2-Phase Transformations ($A \rightleftharpoons A + B$)

- Occur over a range of temperatures and compositions
- Second phase precipitates and grows in first phase
- First phase is still stable

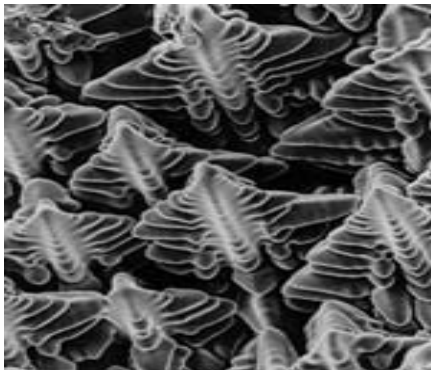


Phase Transformations in Equilibrium

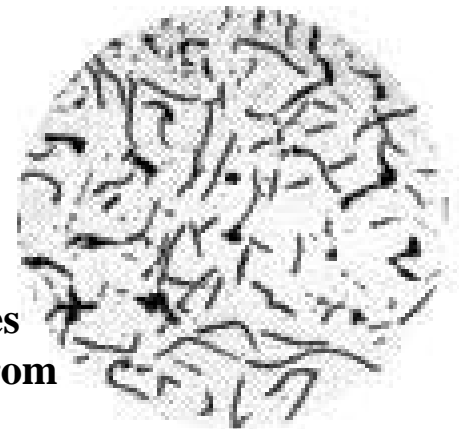
Binary Phase Systems

Second Phase Precipitate Microstructure

- The form of the second phase is dependent upon cooling rates and diffusion rates of solute atoms in solution.
- The form is also dependent upon availability of nucleation sites.
- The form may also be dependent upon the crystal structure of two phases.



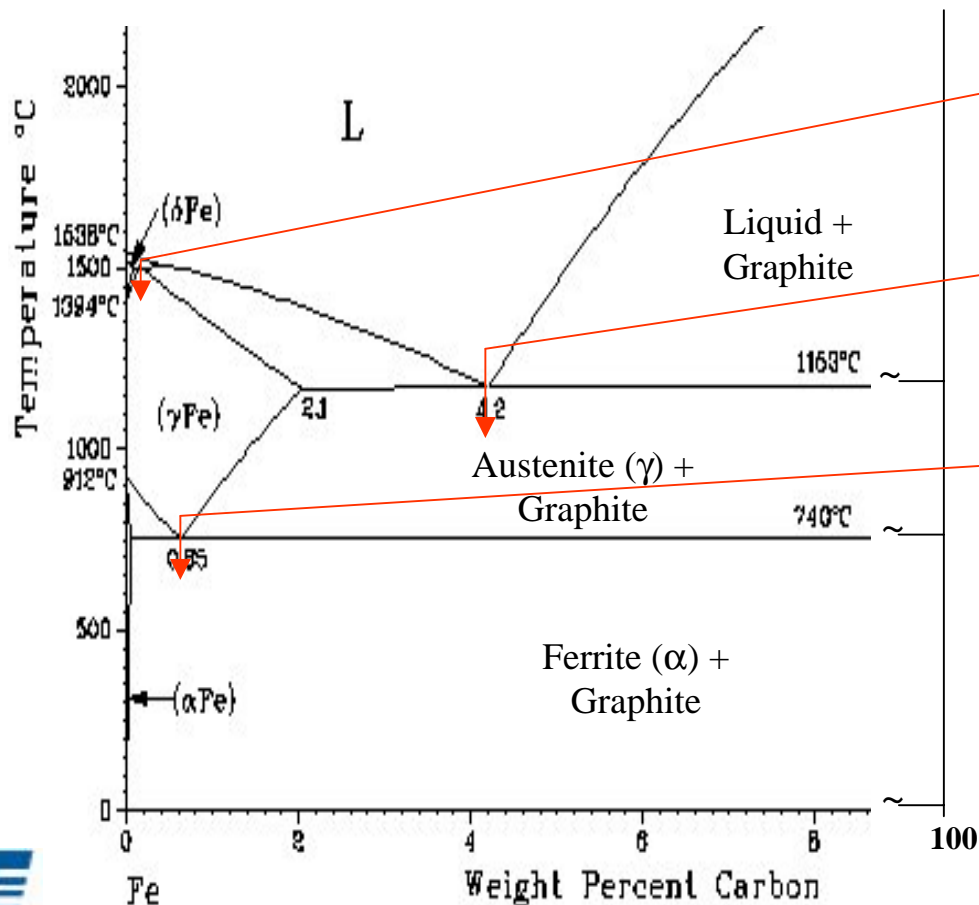
**Solid dendrites
growing from a
rapidly cooled liquid**



**Graphite flakes
precipitated from
liquid iron**

Phase Transformations in the Iron-Carbon Equilibrium Binary Phase Systems

3-Phase Transformations Iron-Carbon Alloys



Peritectic Transformation
(Liquid + Solid A \rightleftharpoons Solid B)

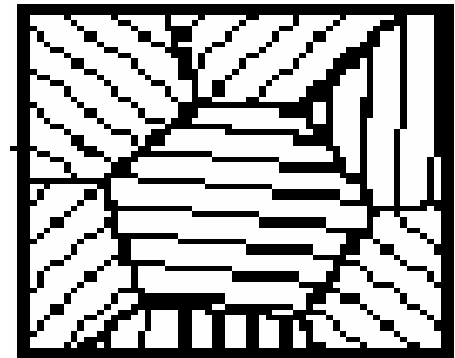
Eutectic Transformation
(Liquid \rightleftharpoons Solid A + Solid B)

Eutectoid Transformation
(Solid A \rightleftharpoons Solid B + Solid C)

Phase Transformations in Equilibrium

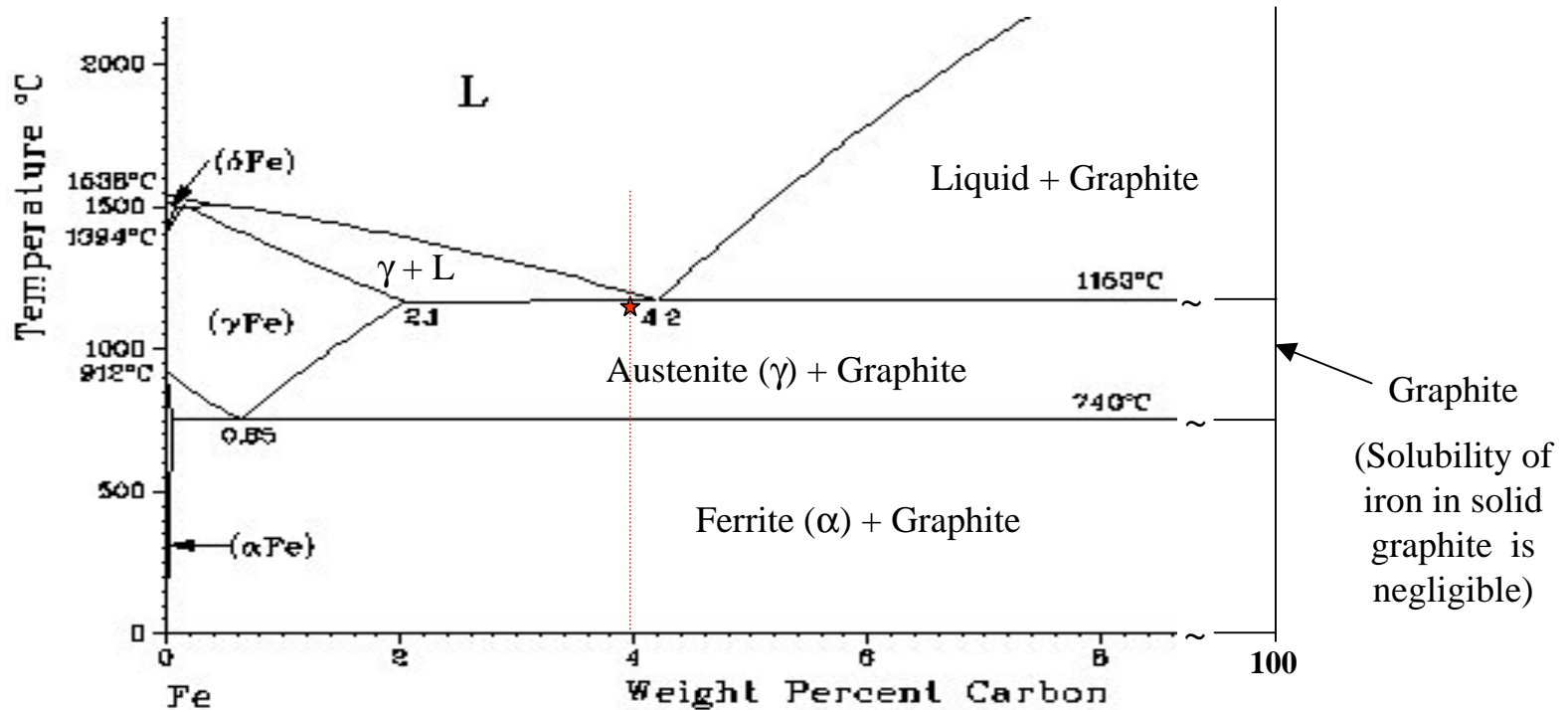
Binary Phase Systems

- 3-Phase Transformations ($A \rightleftharpoons B + C$)
 - 3-phase transformations occur at a single temperature and composition.
 - Eutectic and eutectoid transformations involve simultaneous nucleation and growth of two phases together.
 - Typical microstructure is a lamellar structure with alternating layers of the two phases.



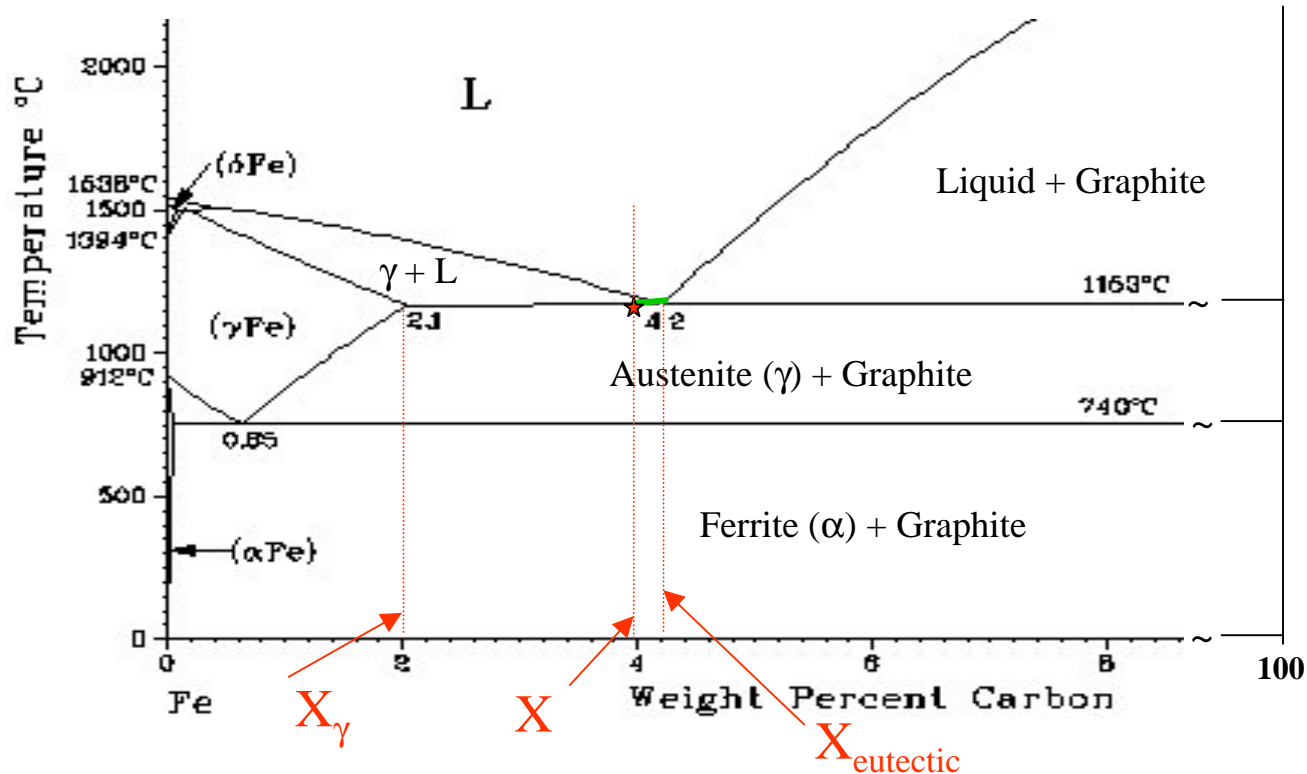
Typical lamellar microstructure from a eutectic transformation

Practice Problem #2



For an overall composition of iron with 4 % carbon slowly cooled from 1200°C to 1152°C, what are the weight fractions of primary austenite and the eutectic microstructures?

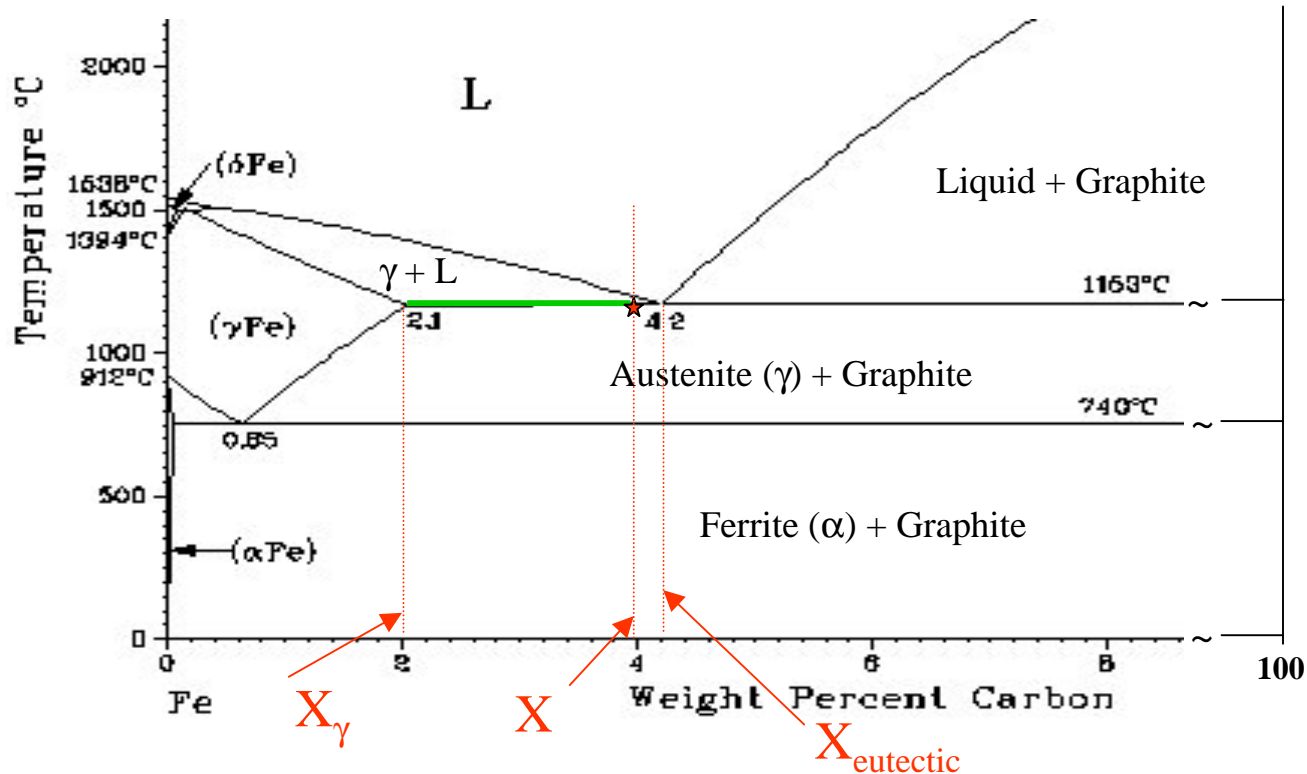
Practice Problem #2



The weight fraction of the primary austenite microstructure is calculated as:

$$F_\gamma = (X_{\text{eutectic}} - X) / (X_{\text{eutectic}} - X_\gamma) = (4.2 - 4) / (4.2 - 2.1) = 0.095 = 9.5\%$$

Practice Problem #2

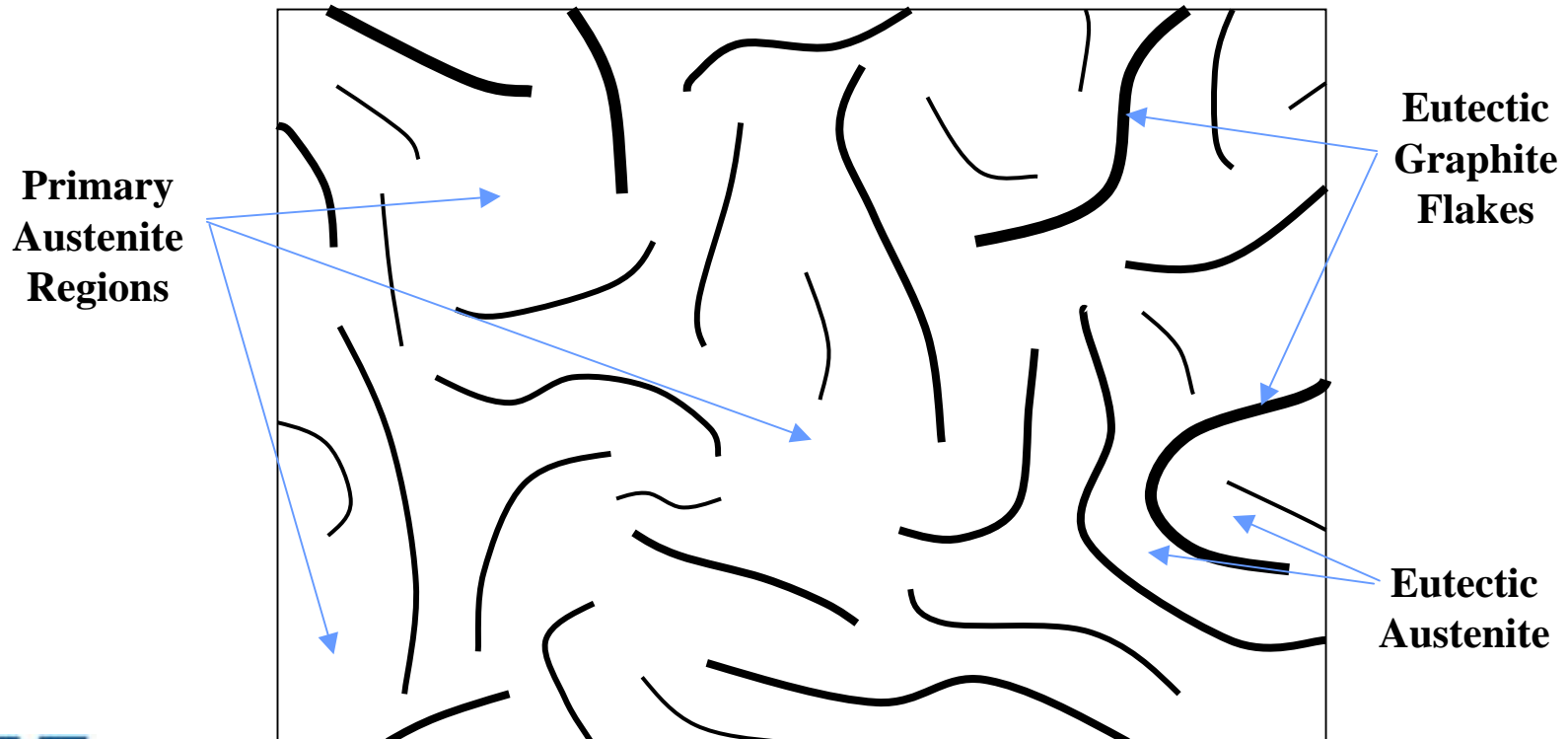


The weight fraction of the eutectic microstructure is calculated as:

$$F_{\text{eutectic}} = (X - X_\gamma) / (X_{\text{eutectic}} - X_\gamma) = (4 - 2.1) / (4.2 - 2.1) = 0.905 = 90.5\%$$

Practice Problem #2

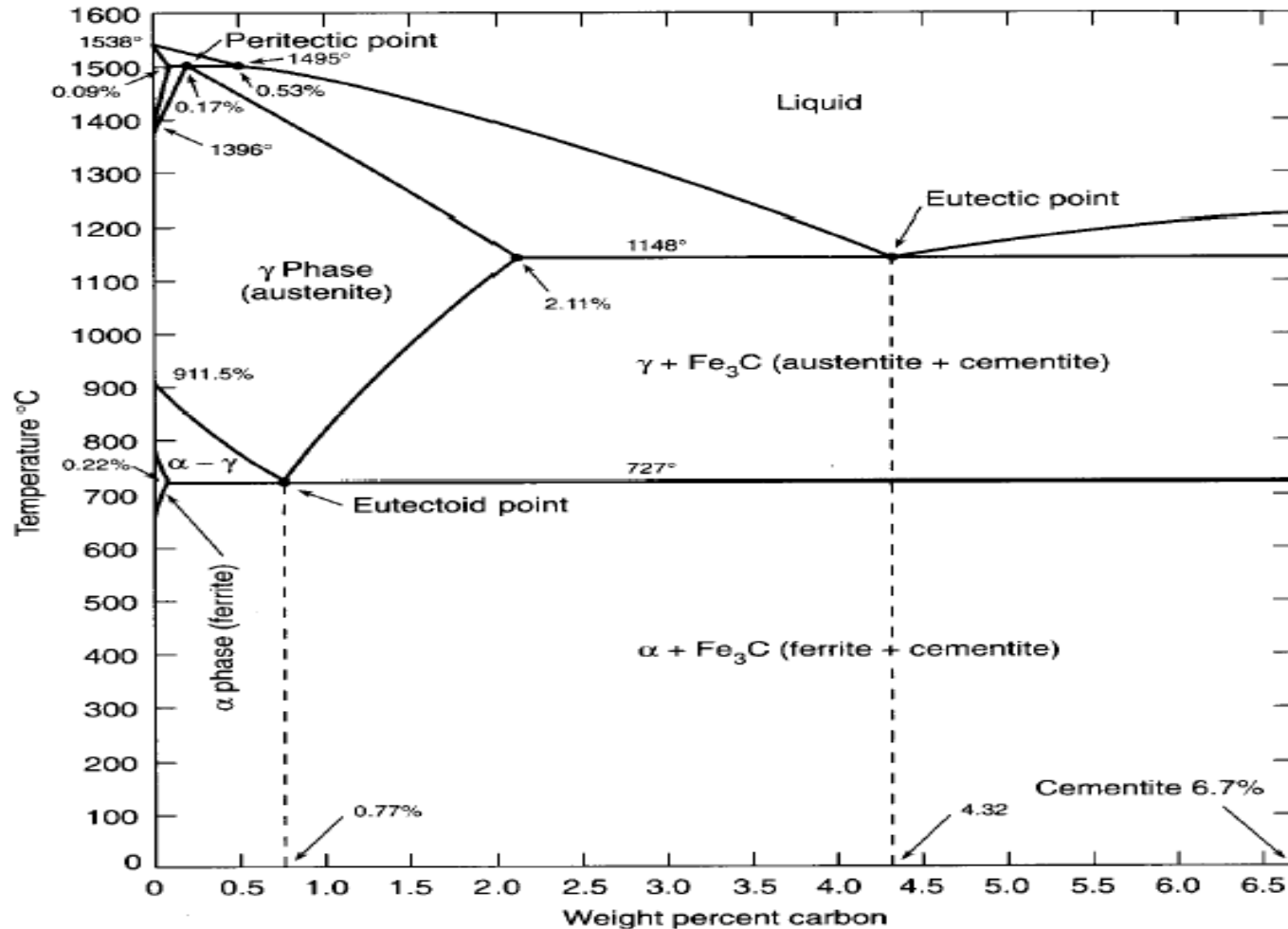
The microstructure consists of primary austenite and a eutectic mixture of austenite and graphite:



Meta-Stable Iron-Carbon System

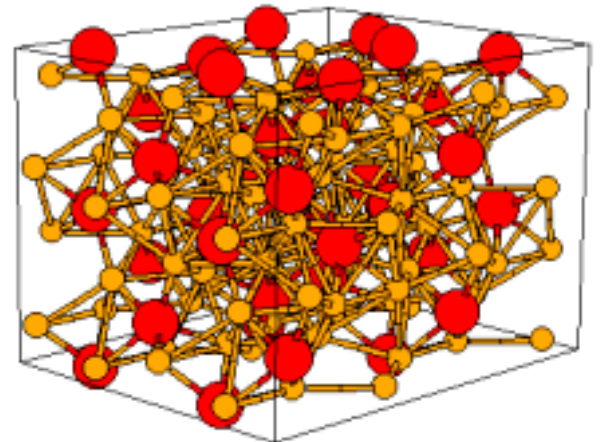
The formation of graphite in the equilibrium iron-carbon system is dependent upon the diffusion of carbon through the iron matrix to form the graphite precipitates. If the cooling rate is fast, then the carbon is not able to segregate, and iron carbide (Fe_3C) forms in place of graphite. This meta-stable system is commonly called the iron-iron carbide system.

Meta-Stable Iron-Iron Carbide Binary Phase Diagram

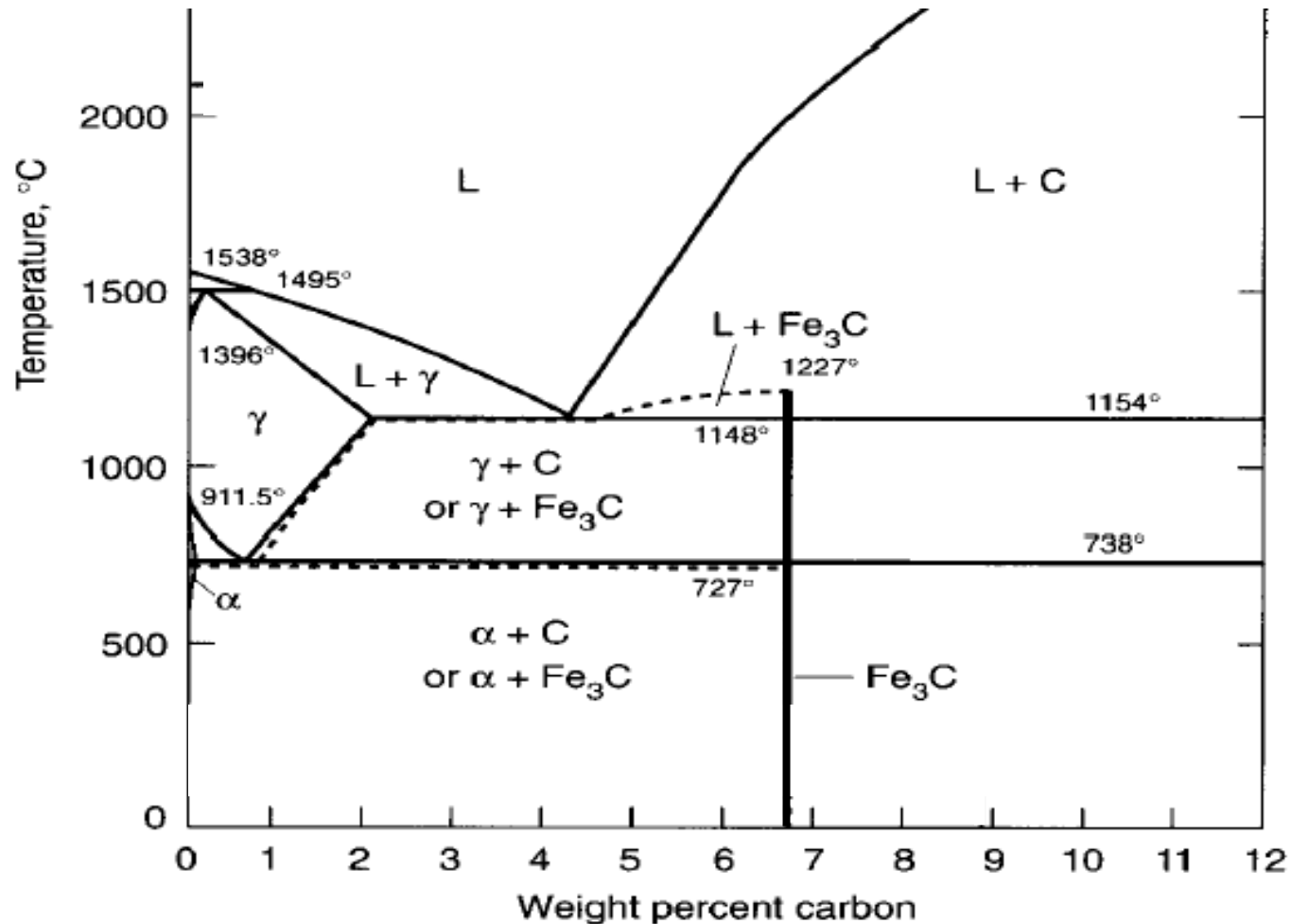


Iron Carbide Phase

- Fe_3C is the chemical composition, and it has orthorhombic crystal structure.
- Iron carbide breaks down to iron and graphite with sufficient time and temperature.
- For practical purposes it is considered stable below 450°C .
- Density: 7.66 grams/cm^3 at 20°C
- Very hard and brittle phase
- Commonly called “cementite”

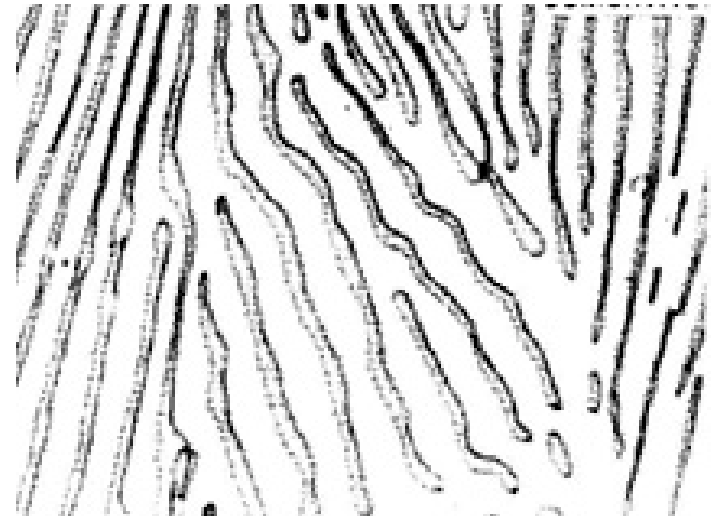


Combination of Equilibrium and Meta-Stable Phase Diagrams

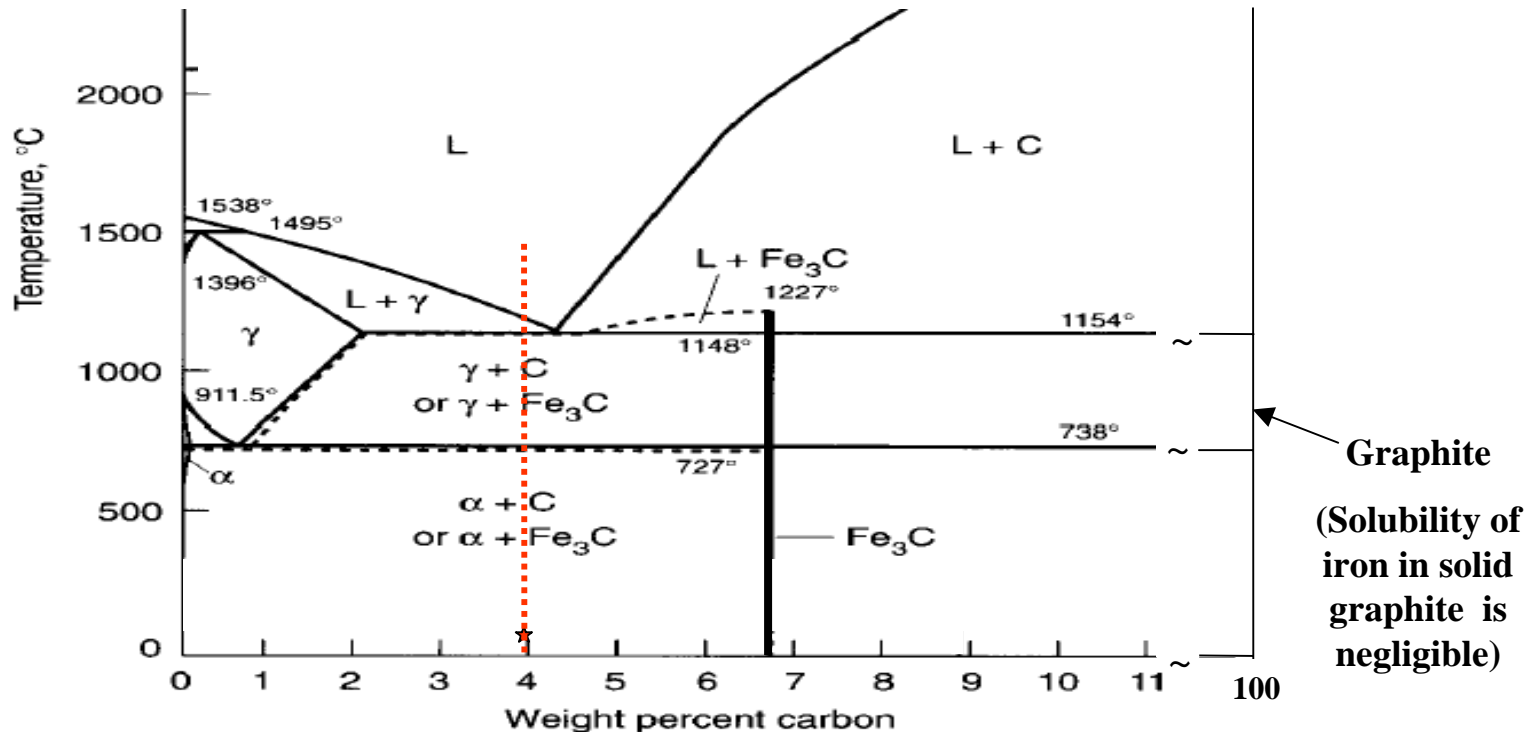


Eutectoid Transformations in the Iron-Carbon Binary Phase Systems

- The ferrite-graphite eutectoid transformation is extremely uncommon due to the very slow cooling required.
- The ferrite-iron carbide transformation is the predominant eutectoid transformation.
- The ferrite-iron carbide eutectic microstructure is commonly called “pearlite”.
- Pearlite has a lamellar microstructure.

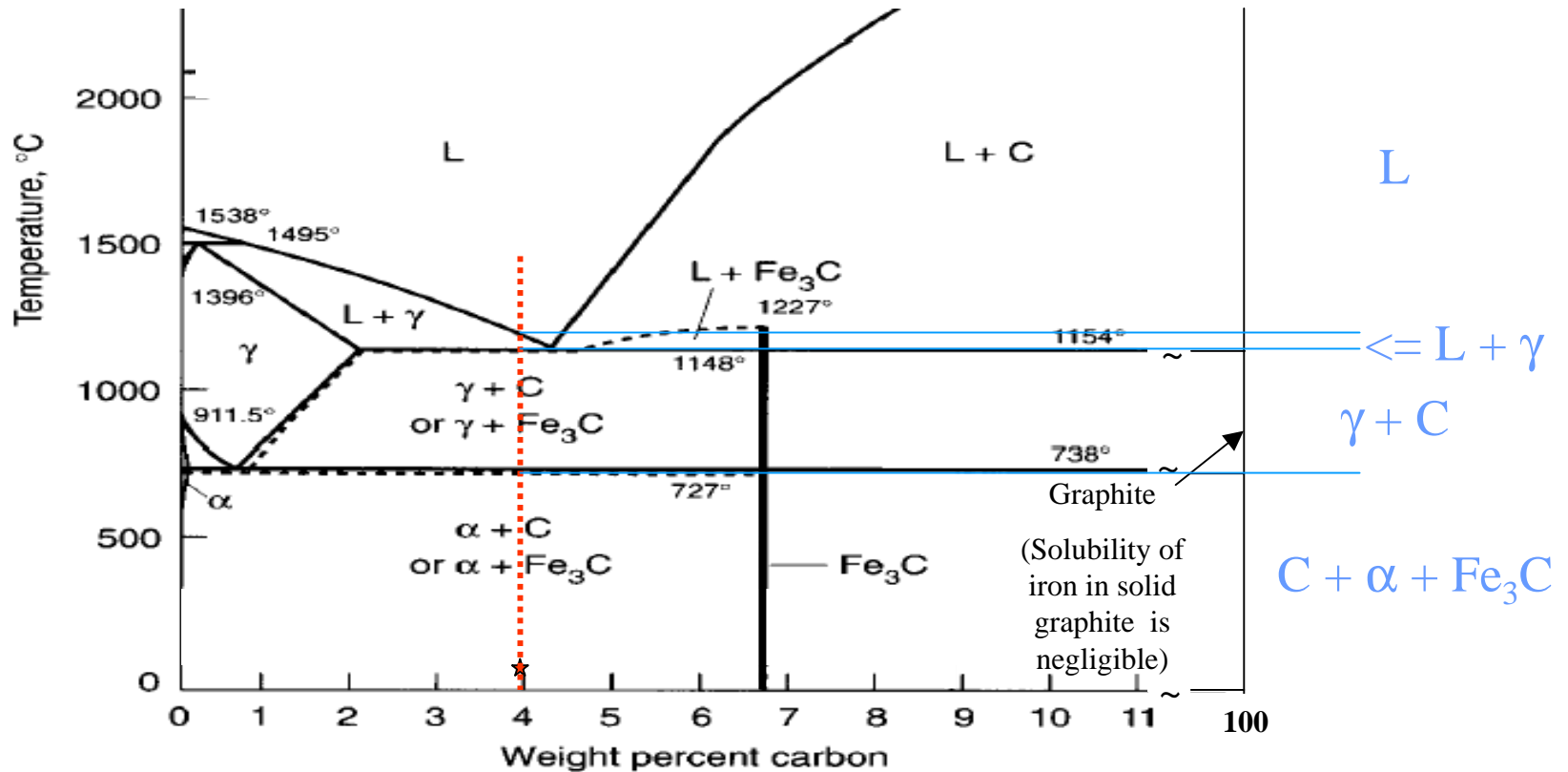


Practice Problem #3



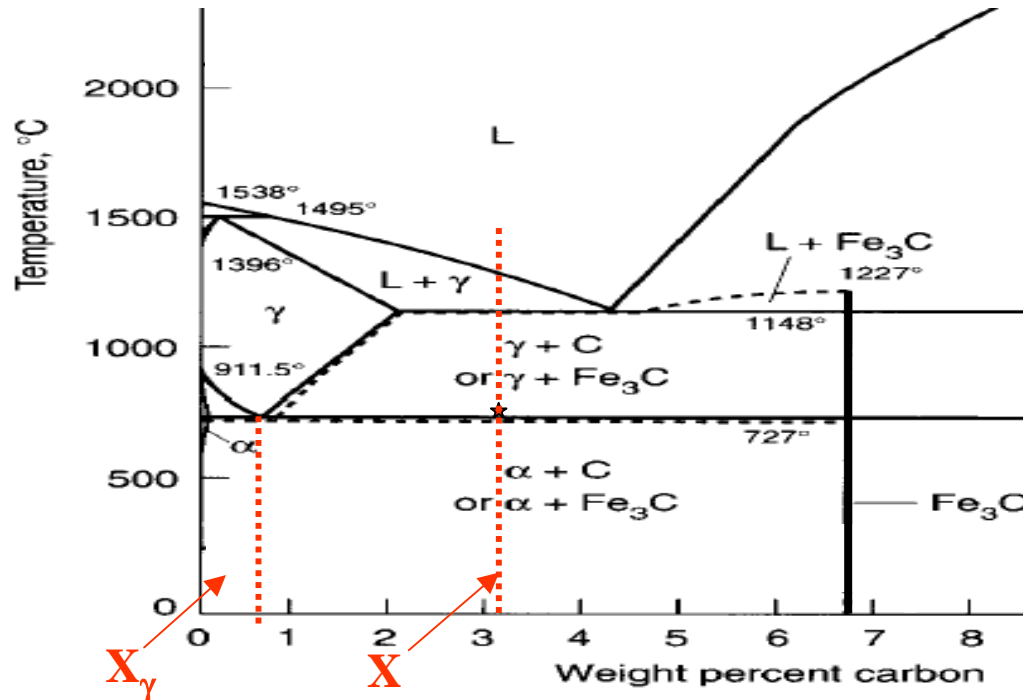
A cast iron with an overall composition of 4 % carbon is cooled slow enough through the eutectic transformation temperature to produce austenite and graphite, but not cooled slow enough through the eutectoid transformation temperature to produce ferrite and graphite. At room temperature, what are the phases and microconstituents present and their approximate weight fractions?

Practice Problem #3



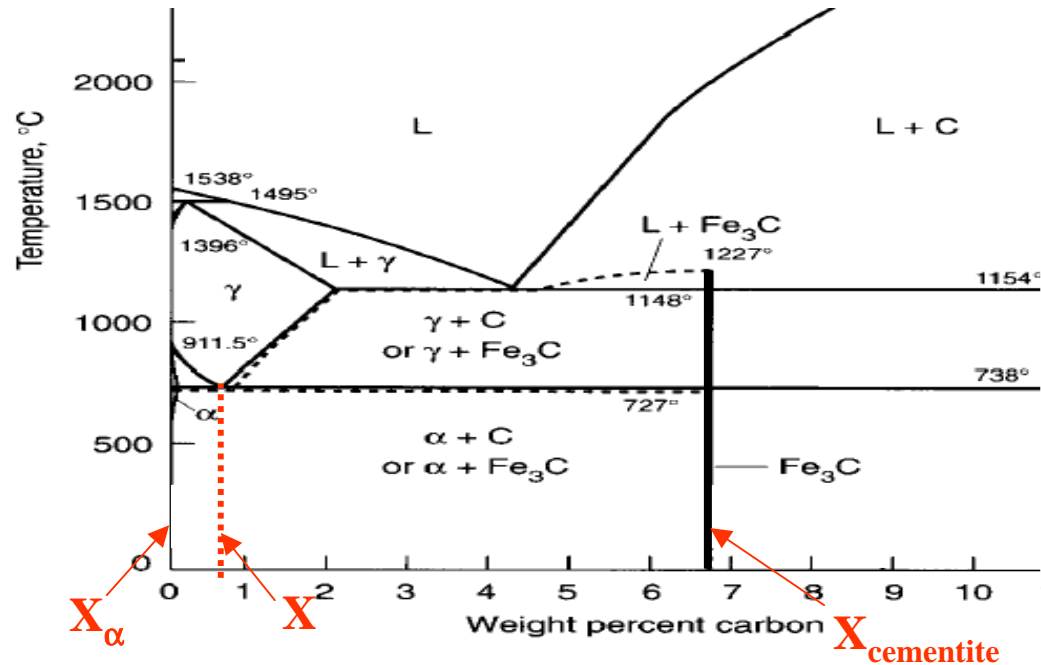
The phases present at room temperature will be graphite (C), ferrite (α) and cementite (Fe_3C).

Practice Problem #3



From problem #1 we saw that the material consisted of 96.8% austenite and 3.2% graphite by weight at a temperature just above the eutectoid transformation temperature. The existing graphite remains stable and the austenite will transform to pearlite (the eutectic mixture of ferrite and cementite) through this transformation.

Practice Problem #3



Using the LEVER RULE now with eutectoid austenite composition as X the weight fractions ferrite and cementite that transform from the austenite are calculated as follows:

$$F_{\alpha \text{ from } \gamma} = (X_{\text{cementite}} - X) / (X_{\text{cementite}} - X_{\alpha}) = (6.7 - 0.8) / (6.7 - 0.02) = 0.883 = 88.3\%$$

$$F_{\text{Fe}_3\text{C from } \gamma} = (X - X_{\alpha}) / (X_{\text{cementite}} - X_{\alpha}) = (0.8 - 0.02) / (6.7 - 0.02) = 0.117 = 11.7\%$$

Practice Problem #3

The overall volume fractions of the ferrite and the cementite in the total microstructure is calculated as follows:

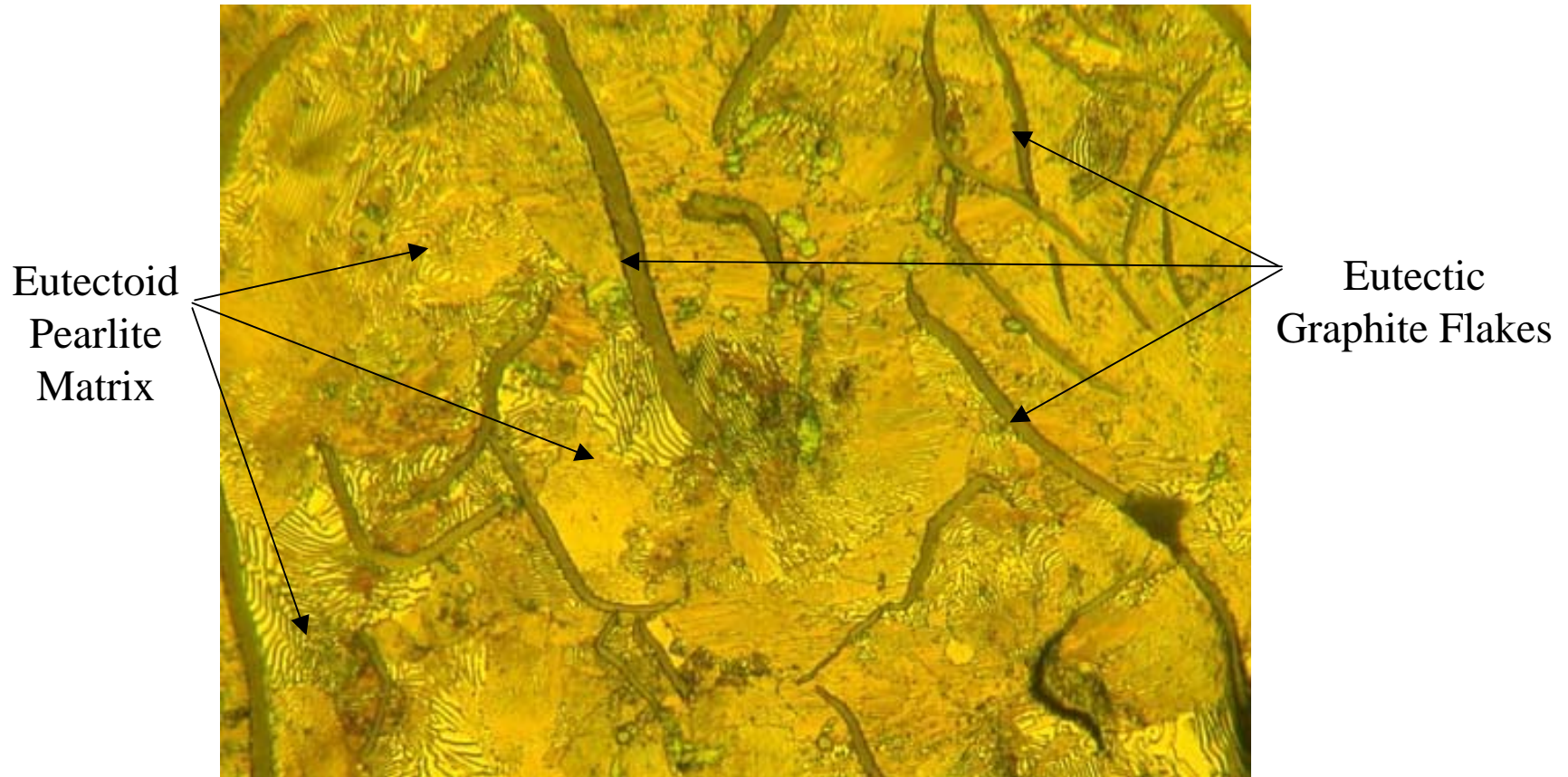
$$F_{\text{ferrite total}} = F_{\alpha \text{ from } \gamma} \times F_{\gamma} = 0.883 \times 0.968 = 0.855 = 85.5\%$$

$$F_{\text{cementite total}} = F_{\text{Fe}_3\text{C from } \gamma} \times F_{\gamma} = 0.117 \times 0.968 = 0.113 = 11.3\%$$

<u>Phases Weight Percentages</u>		<u>Microconstituents Weight Percentages</u>	
Ferrite	85.5%		
Cementite	11.3%	Pearlite	96.8%
Graphite	<u>3.2%</u>	Graphite Flakes	<u>3.2%</u>
	100.0%		100.0%

Practice Problem #3

Microstructure consists of graphite flakes in a matrix of pearlite:



Microstructure of Gray Cast Iron (200X and Nital Etch)

Other Microstructures in the Iron-Carbon Binary System

- Martensite is an unstable phase that can form when austenite is cooled below a critical temperature too quickly for carbon to diffuse and form iron carbide.
- Bainite is non-equilibrium microstructure of acicular ferrite and fine carbides.
- Both martensite and bainite will revert to ferrite and cementite particles with tempering at elevated temperatures (typically greater than 150°C).

Martensite Phase

- Martensite has a body centered tetragonal crystal structure
- Carbon content must typically be greater than 0.1%
- Breaks down to iron and cementite (Fe_3C) with sufficient time and temperature (considered semi-stable below 150°C)
- Density: 7.8 grams/cm^3 at 20°C
- Very hard and strong phase, but minimal ductility
- Martensite has a needle-like microstructure



Martensite with some retained austenite

"Needle like" Structure of martensite

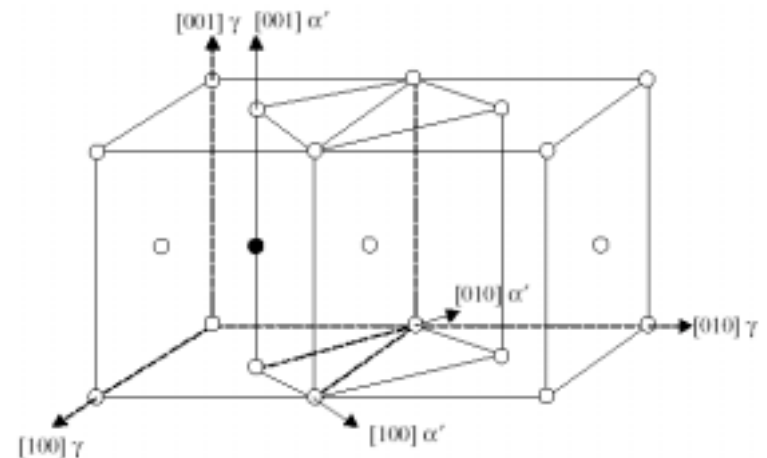


Fig. 6.3 The lattice correspondence for formation of martensite from austenite: tetragonal unit cell outlined in austenite

Bainite Microstructure

- Bainite consists of acicular (needle-like) ferrite with very small cementite particles dispersed throughout.
- The carbon content must typically be greater than 0.1%.
- Bainite transforms to iron and cementite with sufficient time and temperature (considered semi-stable below 150°C).
- Bainite is a very hard and tough microstructure.



Lower Bainite

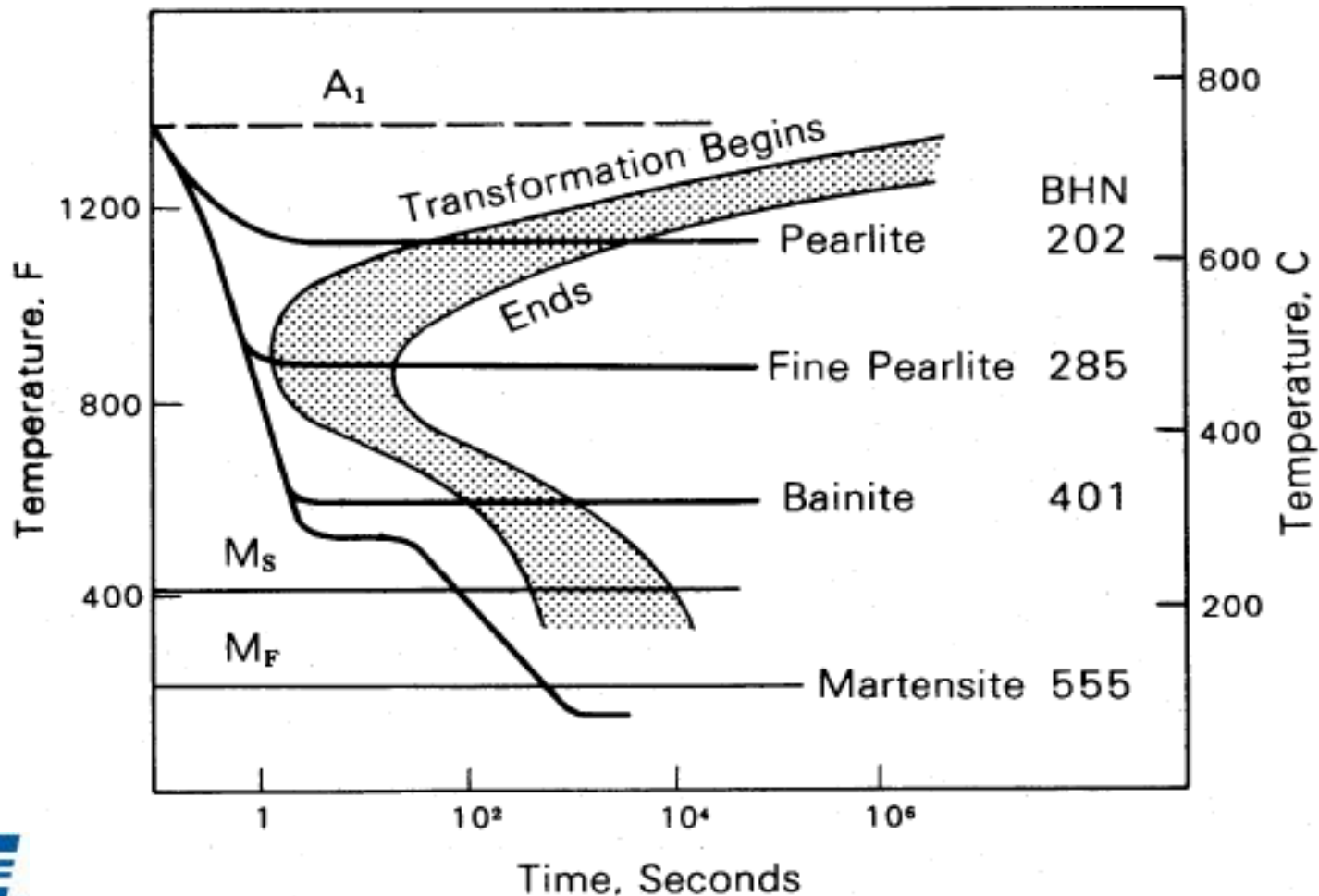


Upper Bainite

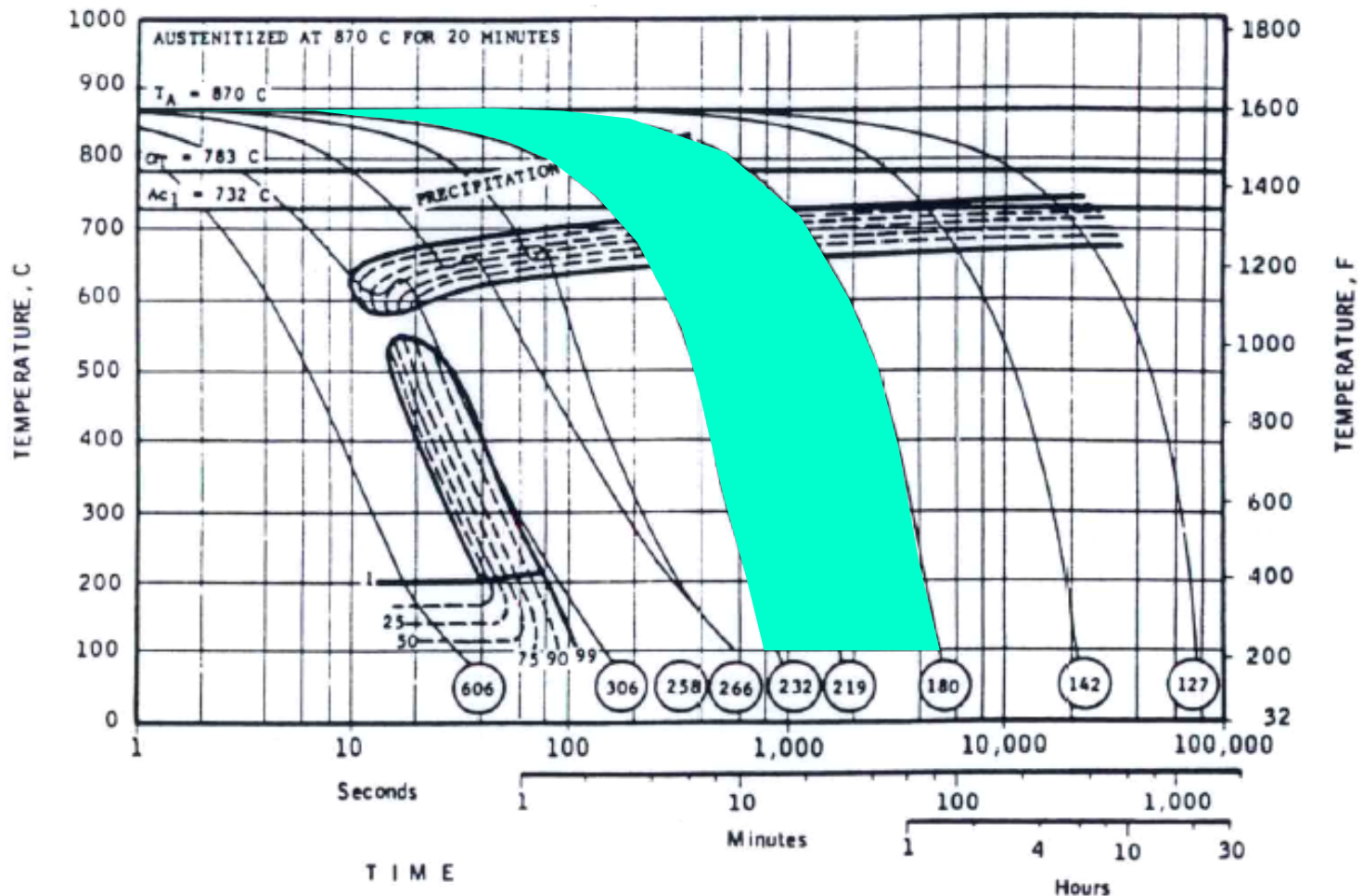
Austenite Transformation Diagrams

- Austenite transformation diagrams are used to predict the microstructures that will form from the austenite depending upon time, temperature and cooling rate.
- Time-temperature transformation (TTT) diagrams measure the extent of transformation with time at a constant temperature.
- Continuous cooling transformation (CCT) diagrams measure the extent of transformation as a function of time for a continuously decreasing temperature.

Time-Temperature Transformation Diagram for Cast Iron

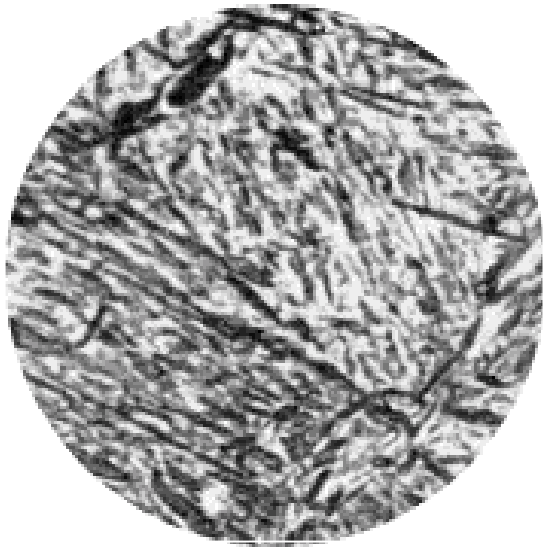


Continuous Cooling Transformation Diagram for Cast Iron

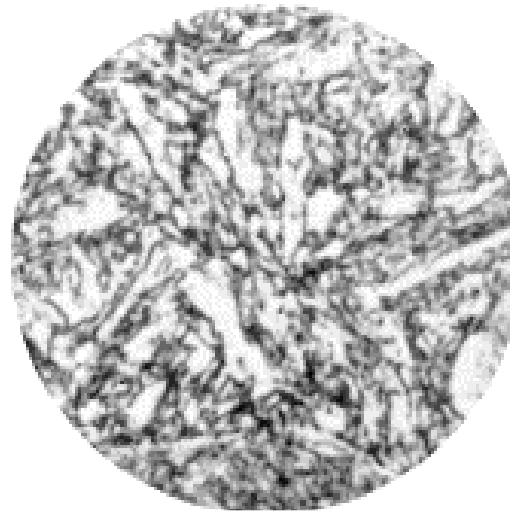


Tempering of Martensite and Bainite

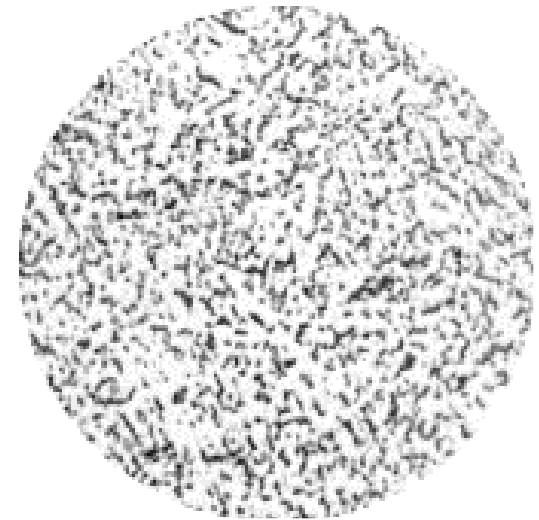
Martensite and bainite will temper at temperatures above 150 °C to form ferrite and spheroidal iron carbides.



Martensite



Tempered Martensite

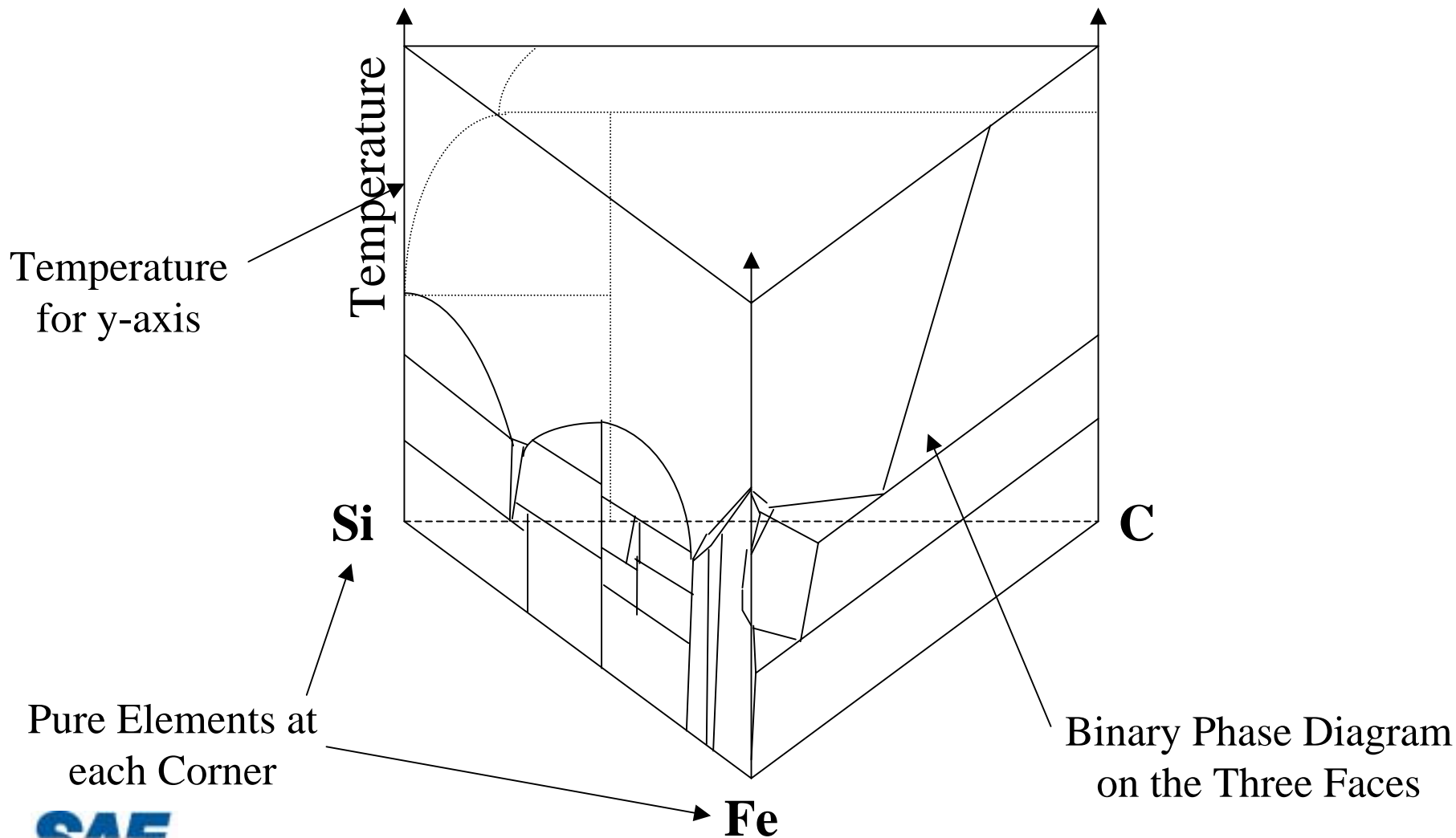


Heavily Tempered
Martensite

The Addition of Silicon to the Iron-Carbon System

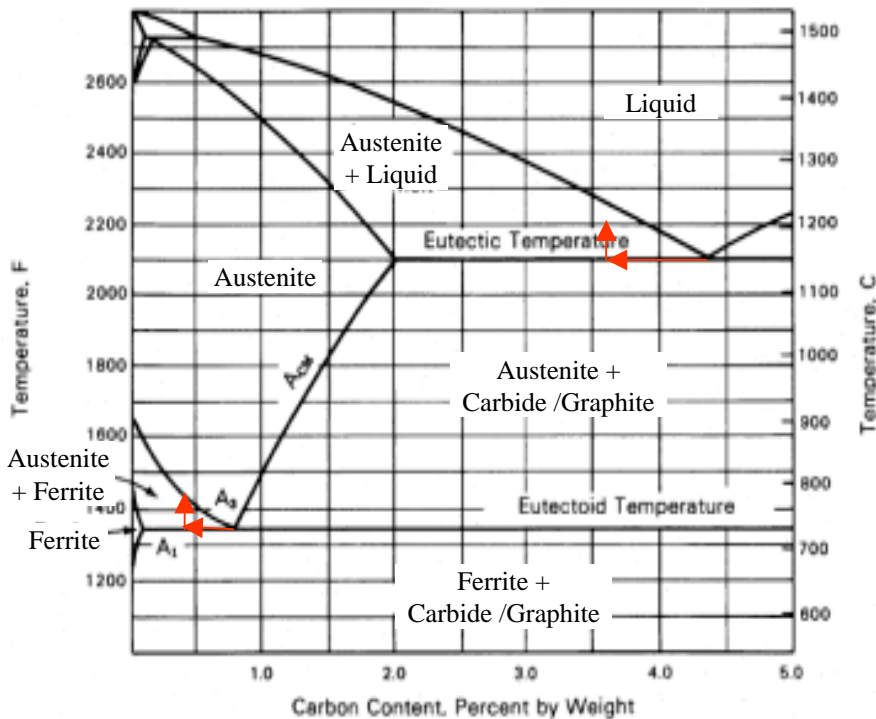
- Silicon is added to cast irons in the range of 1% to 4% in order to increase the amount of under-cooling required for the formation of cementite and promote the formation of graphite during solidification.
- The range of silicon added is sufficient that the iron-carbon binary phase diagram is insufficient to predict the phases and microstructures that form.
- The iron-carbon-silicon ternary phase diagram and/or sections of this diagram are needed to properly predict the phases and microstructures that form.

Iron-Carbon-Silicon Ternary Phase Diagram

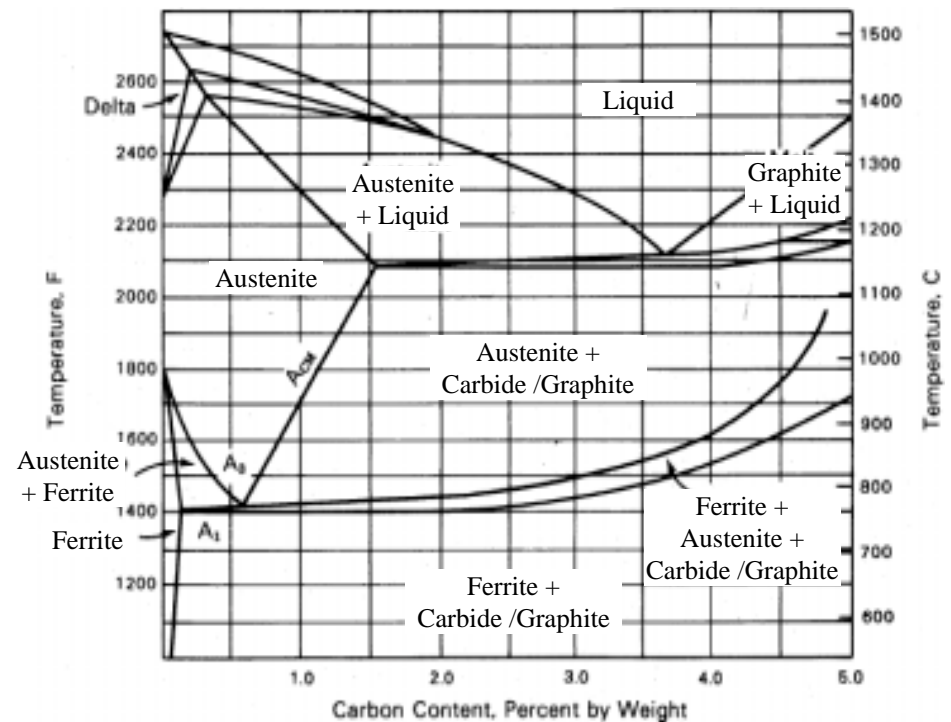


Effects of Silicon on the Eutectic and Eutectoid Transformations

Iron-Carbon Phase Diagram

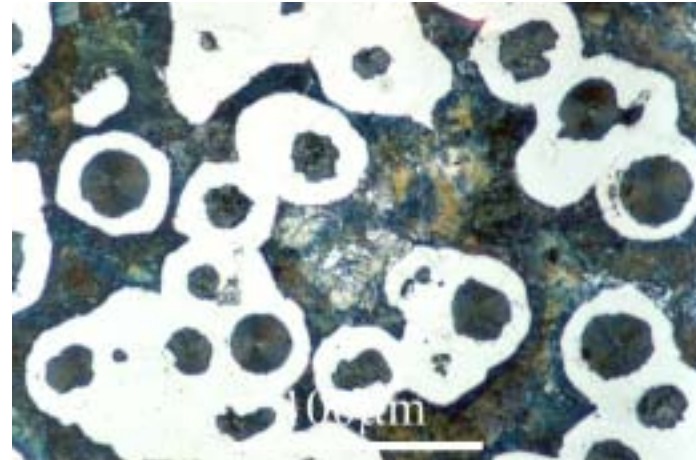


Iron-Carbon-Silicon(2%) Phase Diagram



Microstructural Effects of Silicon Additions in Cast Irons

- Silicon strongly reduces the potential for eutectic carbides during solidification and promotes the formation of primary graphite.
- Silicon promotes the precipitation of secondary graphite on the primary graphite during the eutectoid transformation, which results in large areas of ferrite (commonly called “free ferrite”) around the graphite particles.

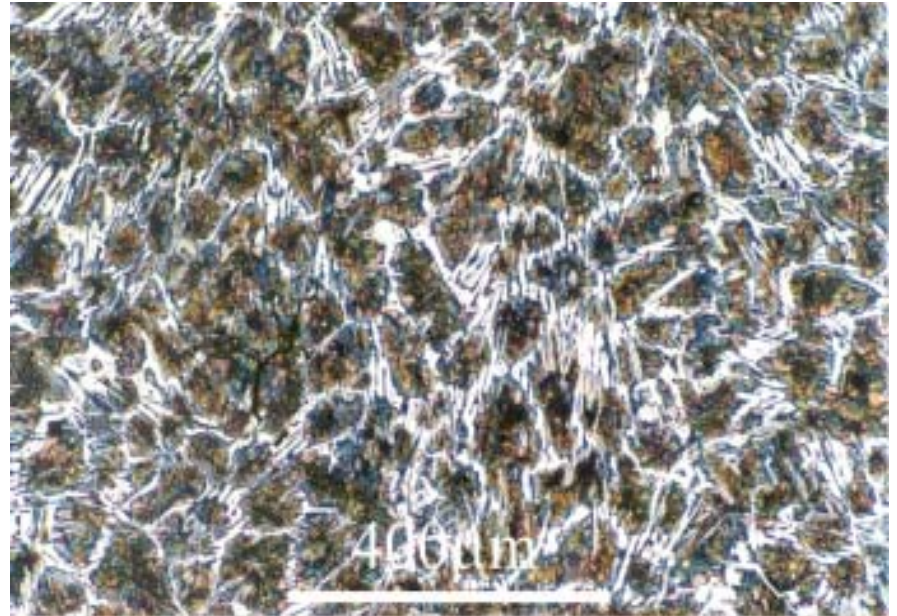


Classifications of Cast Irons

- Classifications are determined by the eutectic graphite/carbide forms present in the iron microstructure.
 - Classifications are controlled by alloying, solidification rates and heat treatment.
 - Classifications of cast irons
 - White Irons
 - Malleable Irons
 - Gray Irons
 - Ductile Irons
 - Compacted Graphite Irons
- } Graphitic Cast Irons

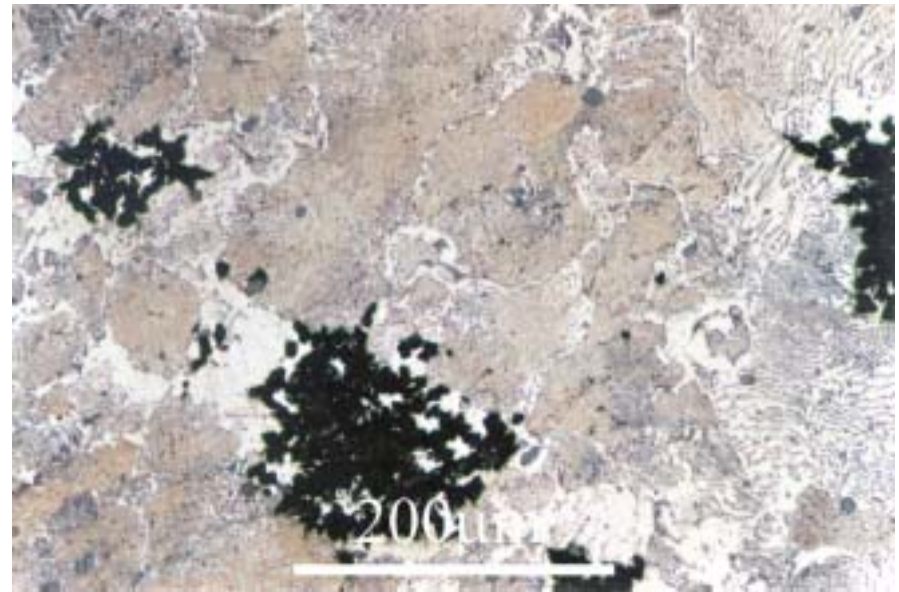
White Cast Irons

- White cast irons form eutectic cementite during solidification.
- The white iron microstructure is due to fast solidification rates and alloying that promotes eutectic carbide formation.
- White irons typically have low ductility, high hardness and great wear resistance.
- White irons get their name from the shininess of their crystalline fractures in comparison to the dull gray fractures of graphite irons.



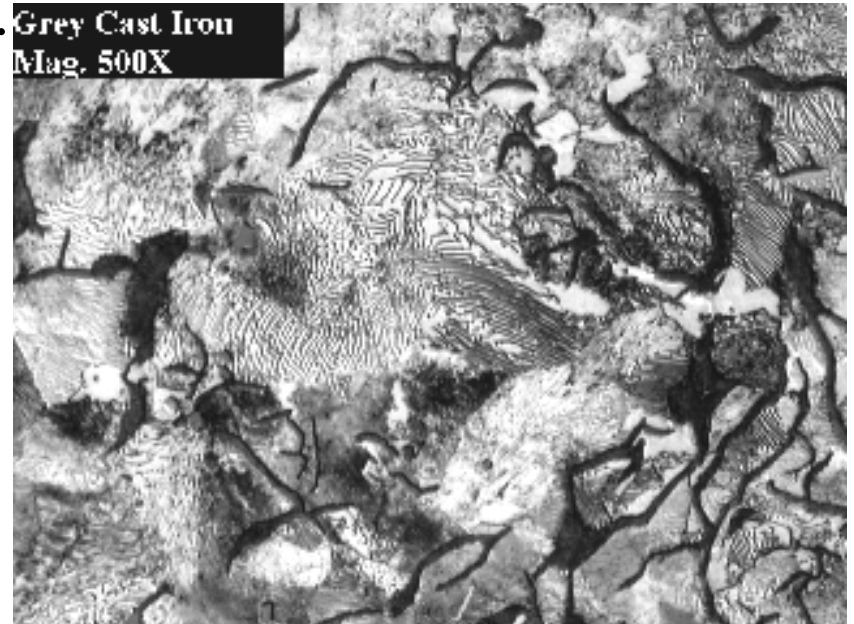
Malleable Cast Irons

- Malleable cast irons are formed by annealing white irons to transform the eutectic cementite to graphite.
- Malleable irons have good ductility and good strength.
- Matrix microstructure is dependent upon the cooling rate from the graphitization annealing.
- Before the discovery of nodular irons, malleable irons were the only ductile class of cast irons.



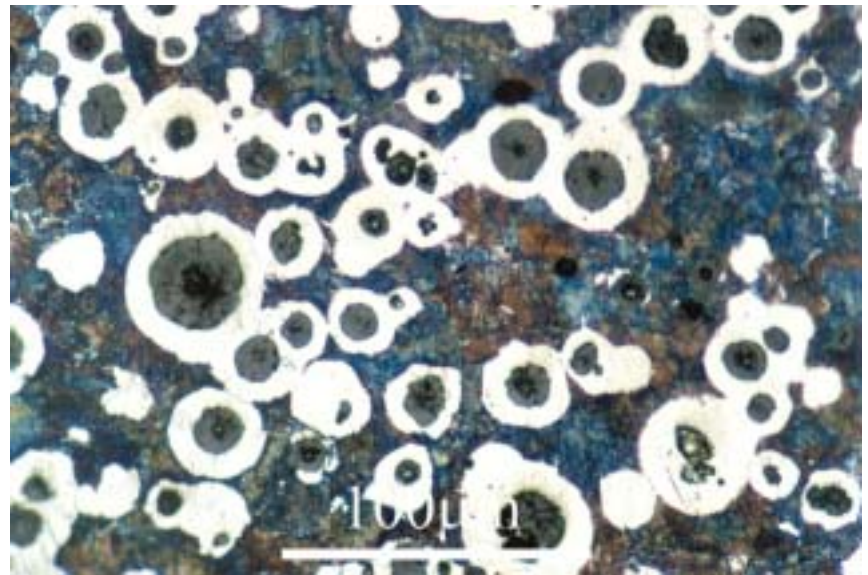
Gray Cast Irons

- Gray cast irons form graphite flakes during solidification.
- The gray iron microstructure is due to slow solidification rates and silicon alloying that promotes graphite formation.
- Gray irons typically have low ductility and moderate strength, but they have high thermal conductivity and excellent vibration damping properties.
- Gray irons get their name from their dull gray fracture features.



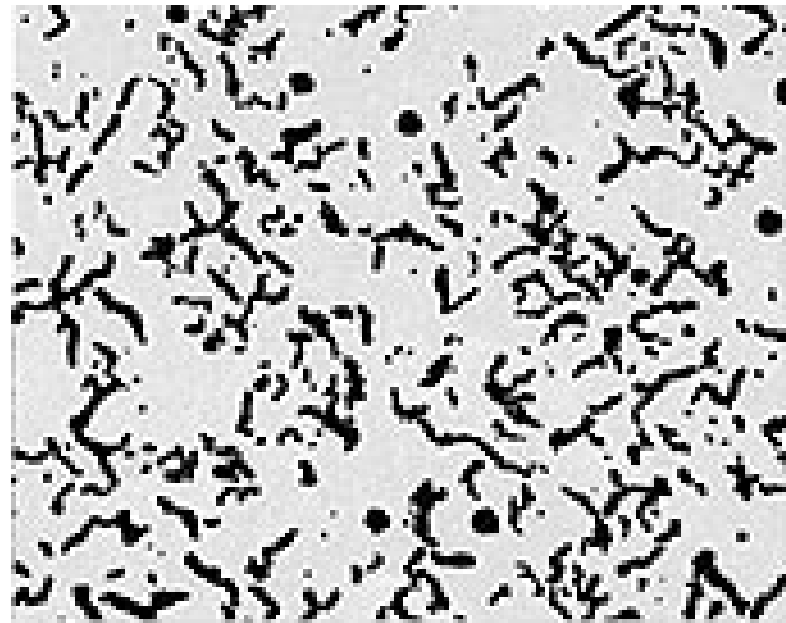
Nodular Cast Irons

- Nodular cast irons form graphite spheres during solidification.
- The nodular iron microstructure is due to slow solidification rates and magnesium or cerium alloying that promotes spherical graphite formation.
- Nodular irons typically have high ductility and strength.
- Nodular irons were first discovered in the 1940's.
- Nodular irons are also called “ductile irons” or “spheroidal graphite irons”.

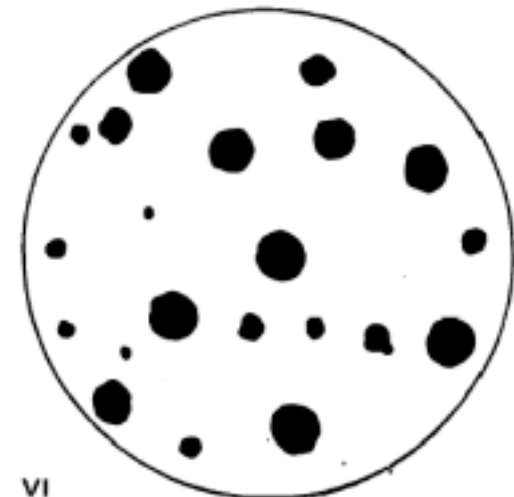
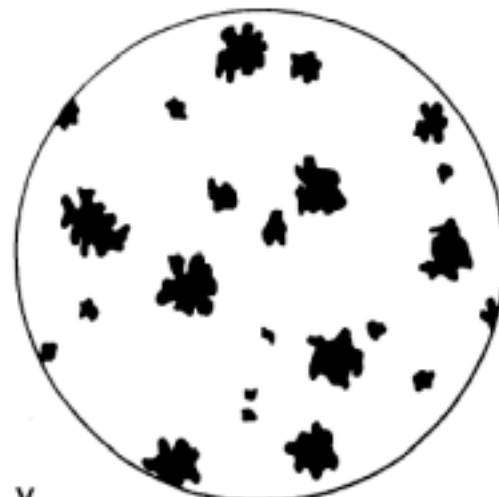


Compacted Graphite Cast Irons

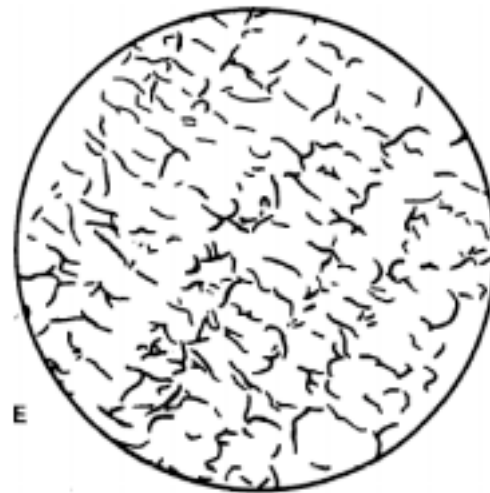
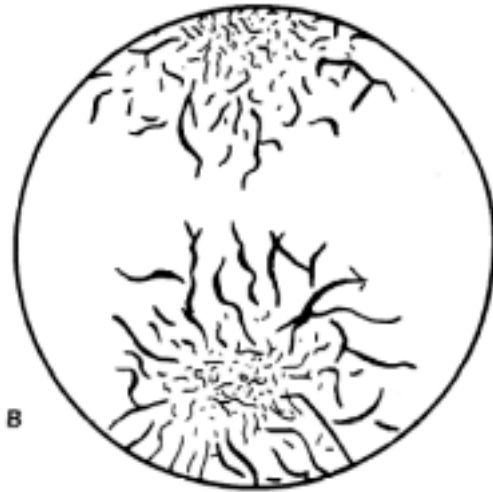
- Compacted graphite cast irons form graphite particles with a shape between graphite flakes of gray cast iron and graphite nodules of nodular cast iron.
- Compacted graphite cast irons have properties between those of gray cast iron and nodular cast iron.
- Compacted graphite irons require very tight control of the nodularizing alloying (magnesium or cerium).



Graphite Forms per ISO 945



Graphite Flake Distributions per ISO 945



Graphite Morphologies in Gray Cast Iron Castings

- Type A graphite flake structures are generally the preferred structures.
- Type B graphite flake structures may result when there is poor inoculation and nucleation.
- Type C graphite flake structures are typically found in hypereutectic gray irons where the graphite flakes are the first to precipitate from the melt.
- Types D and E graphite flake structures are typically found where undercooling of melt is the greatest (edges, parting lines, thin sections, etc...).

Graphite Morphology Variation in Gray Cast Iron Castings

- Graphite morphology variation is affected by the casting and/or mold design.
- Graphite morphology variation is increased with poor inoculation practices.
- First areas to solidify may have types D and E graphite morphologies if inoculation is insufficient.
- Types D and E graphite morphologies often have free ferrite associated with them, which can affect the machinability and other properties in the area affected.

Properties of Gray Cast Irons

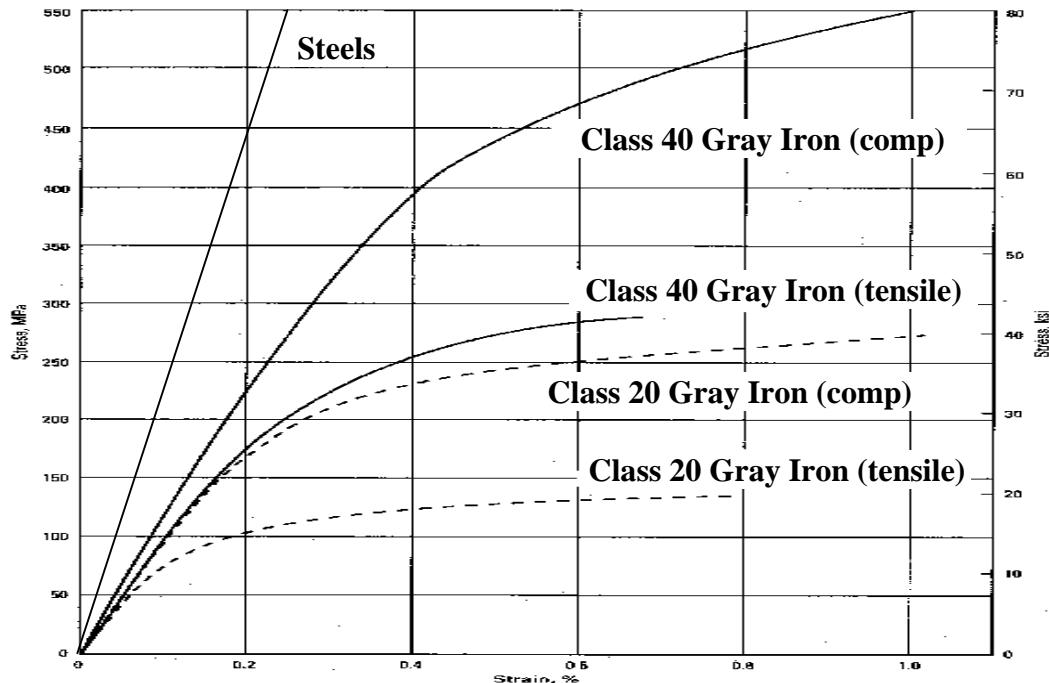
- Classifications and Mechanical Properties
- Elevated Temperature Properties
- Wear and Abrasion Resistance
- Heat Absorption Properties
- Thermal Conductivity
- Vibration Damping
- Corrosion Resistance
- Machinability

Gray Cast Iron Classifications and Mechanical Properties

Casting Grade SAE J431		Class per ASTM A48M	Typical Carbon Content (%)	Theoretical Minimum Tensile Strength (MPa)	Typical Brinell Hardness Range (BHN)
Current	Previous				
G7	G1800	20	3.50 - 3.70	124	163 – 223
G9	G2500	25	3.45 - 3.65	170	170 – 229
G10	G3000	30	3.35 - 3.60	198	187 – 241
G11	G3500	35	3.30 - 3.55	217	207 – 255
G12	G4000	40	3.25 - 3.50	272	217 – 259
G13	G4000	40	3.15 - 3.40	268	217 – 259

Mechanical Properties of Gray Cast Irons

Elastic modulus is lower than that of steels and nodular iron, and it is non-linear. Elastic modulus decreases with increasing graphite content.

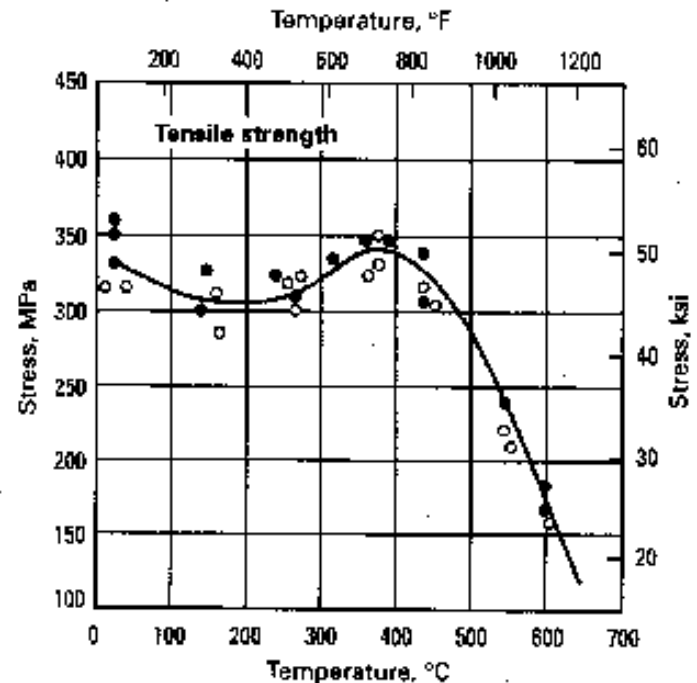
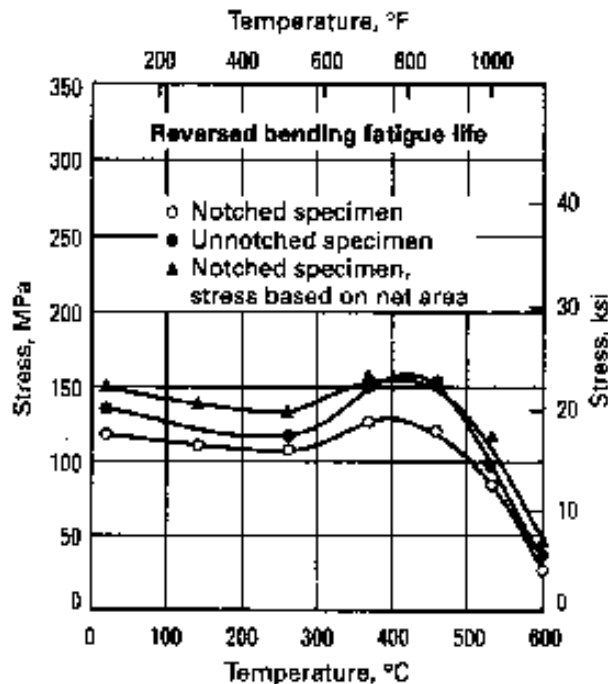


Mechanical Properties of Gray Cast Irons

- Gray cast irons exhibit very little ductility. Typical elongations in tensile testing are less than 0.5%.
- Impact strength and notch sensitivity are poor due to the graphite flakes acting as stress risers.
- Fatigue strengths of gray cast irons are low due to effects of the graphite flakes on crack initiation.

Elevated Temperature Mechanical Properties of Gray Cast Irons

Gray cast irons maintain their mechanical properties up to approximately 500°C. Above 500°C the mechanical properties drop quickly.



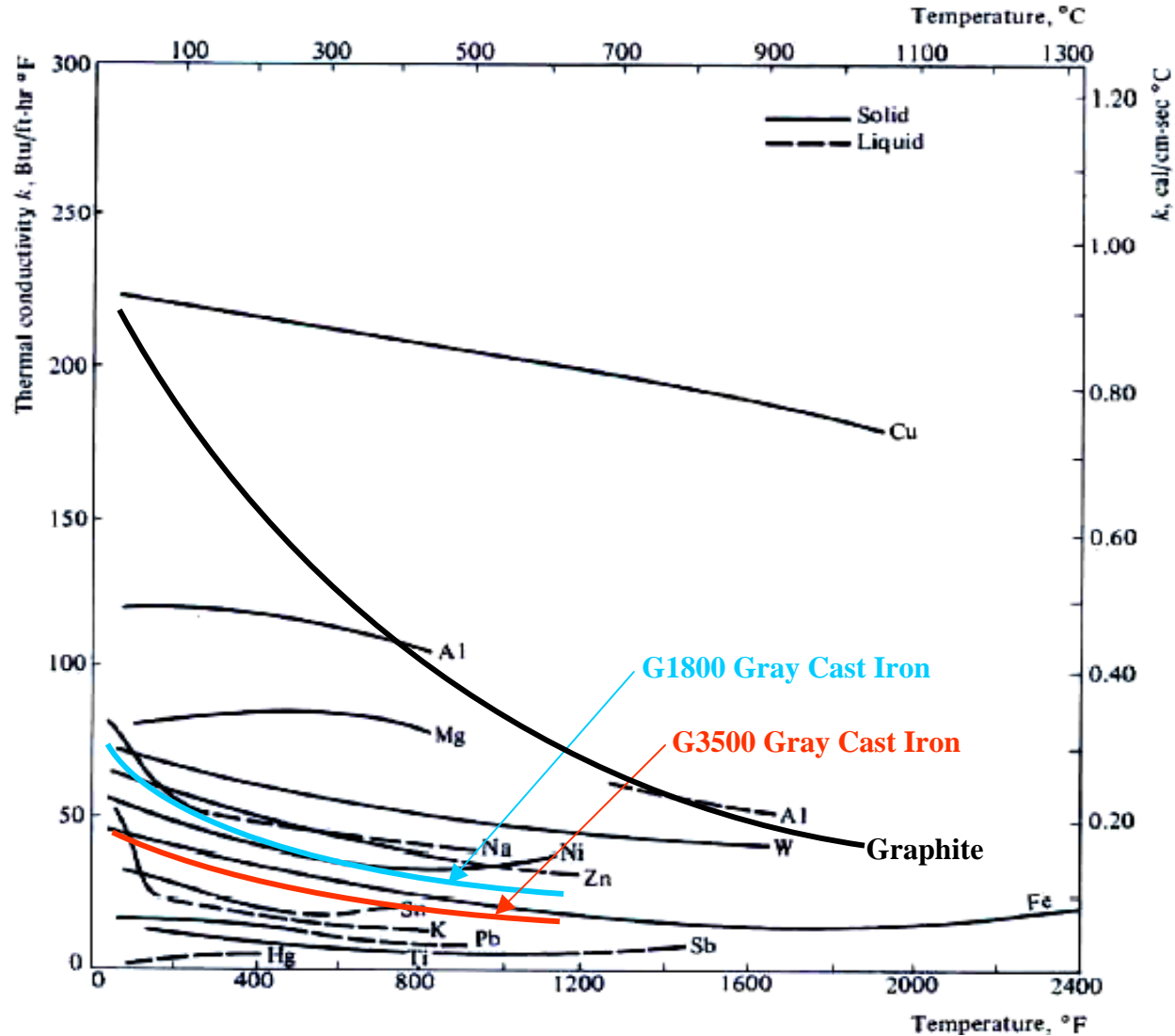
Wear and Abrasion Resistance of Gray Cast Irons

- The wear/abrasion resistance of gray cast irons are dependent upon the microstructures.
- Increasing amounts of graphite and free ferrite reduce wear/abrasion resistance.
- Increasing amounts of pearlite improves wear/abrasion resistance.
- The higher grades tend to have greater wear/abrasion resistance than lower grades.
- Gray cast irons have wear/abrasion resistance comparable to non-heat treated medium carbon steels.

Heat Absorption Properties of Gray Cast Irons

Material	Density (g/cm³)	Heat Capacity (J/kg °K)	Specific Heat (J/cm³ °K)	Melt Temperature (°C)
G1800 Gray Cast Iron	7.15	545	0.076	1150
G3000 Gray Cast Iron	7.2	545	0.076	1145
G4000 Gray Cast Iron	7.25	545	0.075	1145
1008 Plain Carbon Steel	7.86	481	0.061	1620
302 Austenitic Stainless Steel	7.93	500	0.063	1400
356 Cast Aluminum Alloy	2.69	963	0.358	675
Copper	8.94	494	0.055	1083
Brass	8.75	380	0.043	990
AZ63 Cast Magnesium	1.8	1005	0.558	455

Thermal Conductivity of Gray Cast Irons

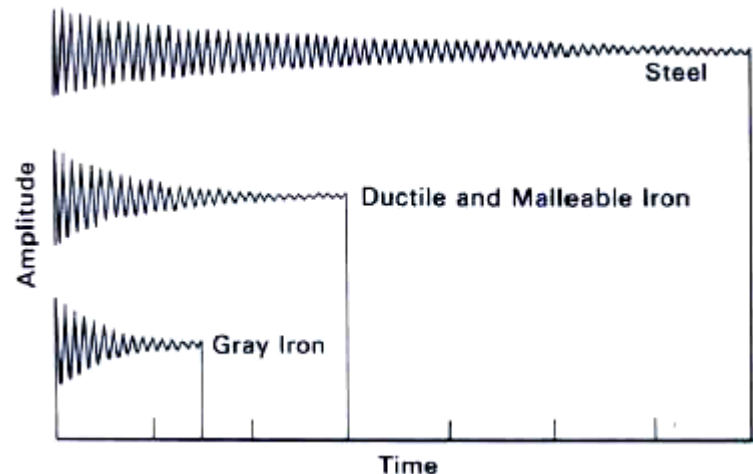


Vibration Damping Properties of Gray Cast Irons

The composite nature of gray cast irons (steel plus graphite flakes) along with crystal and bonding structure of graphite makes gray cast irons one of the best vibration damping metals.

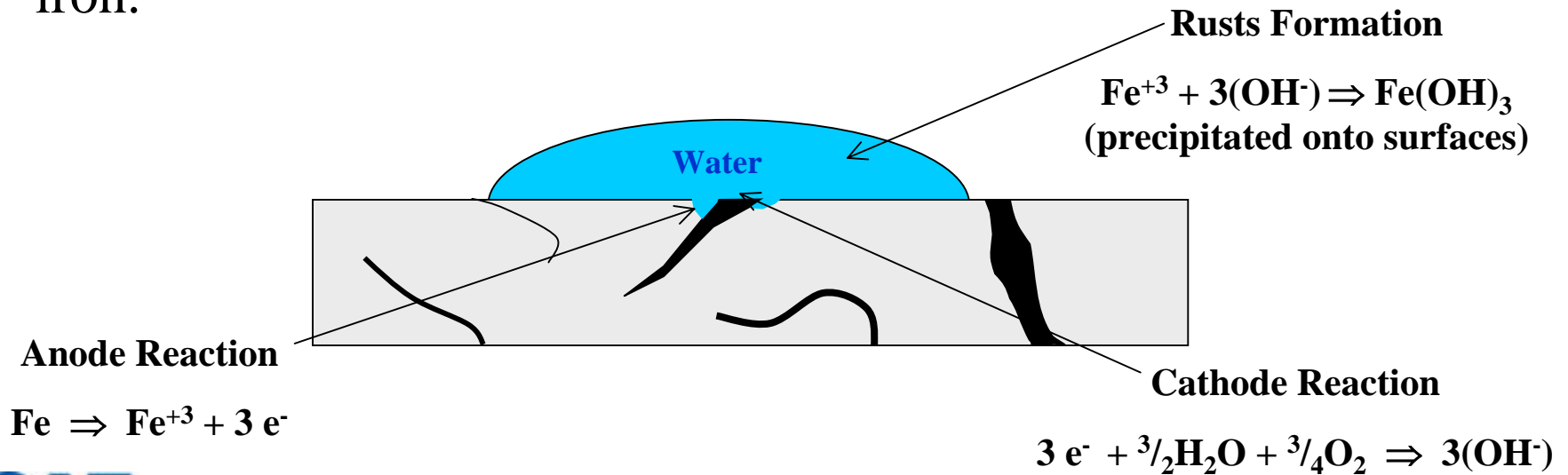
A Comparison of Damping Capacities

Type of Metal	Relative Decrease in Amplitude of Vibration per Cycle
Carbon Steel	1.0–2.0
Malleable Iron	3.3–6.3
Ductile Iron	3.0–9.4
50,000-psi Gray Iron	4.0–9.0
40,000-psi Gray Iron	8.5–12.0
30,000-psi Gray Iron	20–60
Hypoeutectic Gray Iron 3.2% C, 2.0% Si	40
Eutectic Gray Iron 3.9% C, 0.9% Si	105
Hypereutectic Gray Iron 3.7% C, 1.8% Si	126



Corrosion Resistance of Gray Cast Irons

The difference in electrode potentials between the ferrite/iron carbide matrix and the graphite flakes is very large. This results in mini-galvanic cells with graphite as the cathode and the ferrite/iron carbide matrix as the sacrificial anode, which is the primary cause of the very poor corrosion resistance of gray cast iron.



Manufacturability of Gray Cast Irons

- **Excellent Castability**
 - Low melting temperatures of near eutectic compositions minimize oxidation of the molten iron.
 - Small solidification temperature range of near eutectic compositions helps minimize shrinkage porosity.
 - Low density of graphite reduces the volumetric shrinkage during the solidification of the eutectic material.
- **Excellent Machinability**
 - Graphite flakes make gray cast irons chip well, which reduces stress on machining tools.
 - Graphite flakes also act as solid lubricants.
 - High thermal conductivity minimizes heat build-up in tool.

Properties Desired for Brake Rotors

- High strength and durability to sustain torque loads from braking
- Stable mechanical and frictional properties through range of expected service temperatures
- High wear resistance through range of expected service temperatures
- High heat absorption capability to absorb braking energy
- High thermal conductivity to transport frictional heat away from braking surfaces
- High vibration damping capacity to minimize NVH issues
- Minimal thermal expansion to minimize performance variability
- High degree of corrosion resistance
- Excellent machinability
- Inexpensive material and processing costs

Properties of Gray Cast Irons

Sample Questions

1. Which grade of gray cast iron (G7 or G10) would provide greater wear resistance for rotor applications?
2. Which grade of gray cast iron (G7 or G10) would provide greater resistance to thermal cracking for rotor applications?
3. Which grade of gray cast iron (G7 or G10) would provide reduced brake noise for rotor applications?

Properties of Gray Cast Irons

Sample Questions

1. Which grade of gray cast iron (G7 or G10) would provide greater wear resistance for rotor applications?

Answer: Grade G10 has a lower graphite content and greater pearlite content, and therefore, it has greater wear resistance.

2. Which grade of gray cast iron (G7 or G10) would provide greater resistance to thermal cracking for rotor applications?

Answer: Grade G7 has a higher graphite content and higher thermal conductivity, and therefore, it has greater thermal cracking resistance.

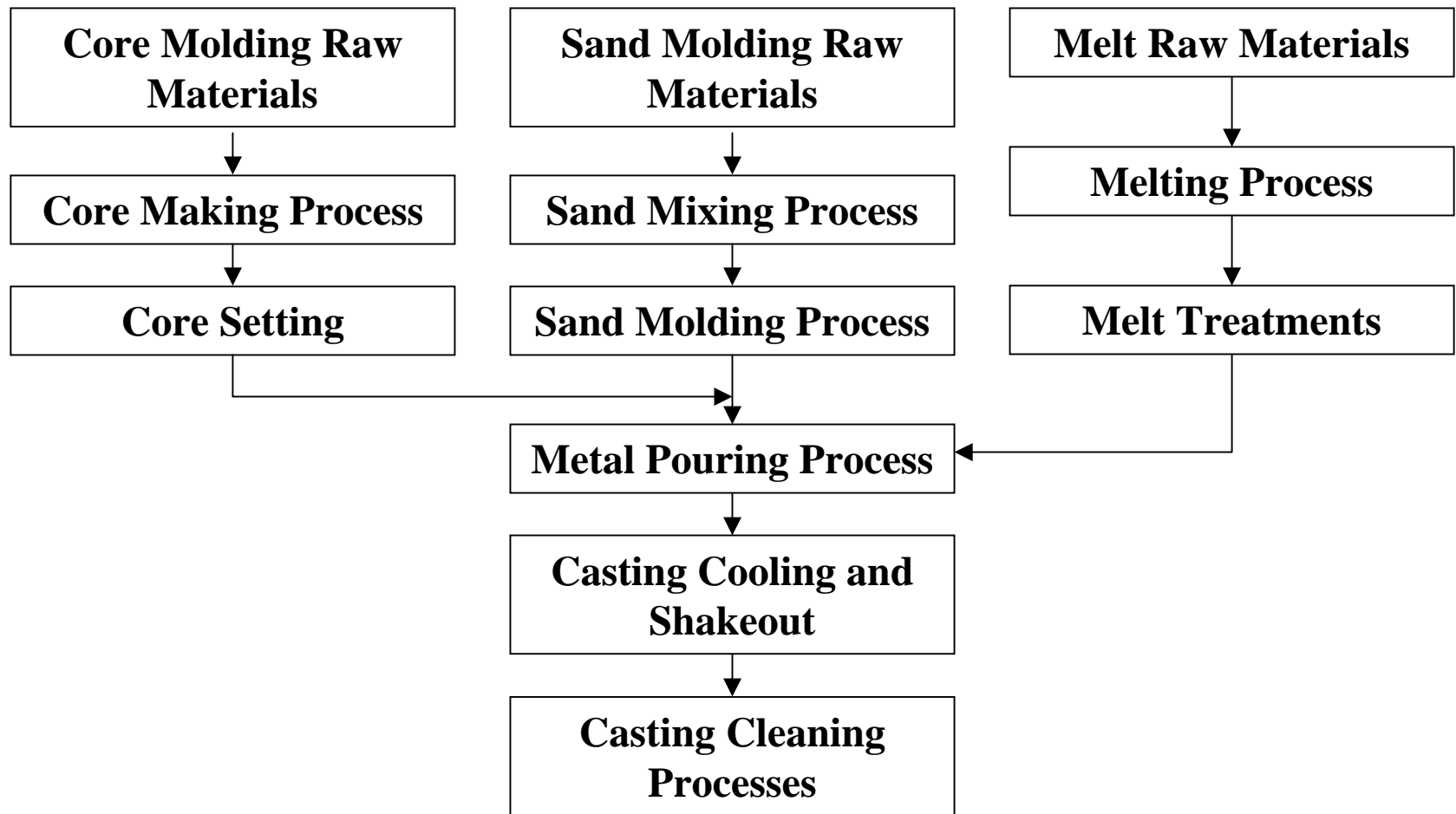
Properties of Gray Cast Irons

Sample Questions

1. Which grade of gray cast iron (G7 or G10) would provide reduced brake noise for rotor applications?

Answer: Neither grade will guarantee reduced brake noise. While Grade 7 has a higher graphite content and better damping properties than grade G11, the effects of the change in resonant frequencies and frictional behavior could actually increase brake noise. Brake noise analyses must take into account all of the effects that a material change can cause.

Typical Gray Cast Iron Rotor Casting Process



Melting Processes Used for Production of Gray Cast Iron Castings

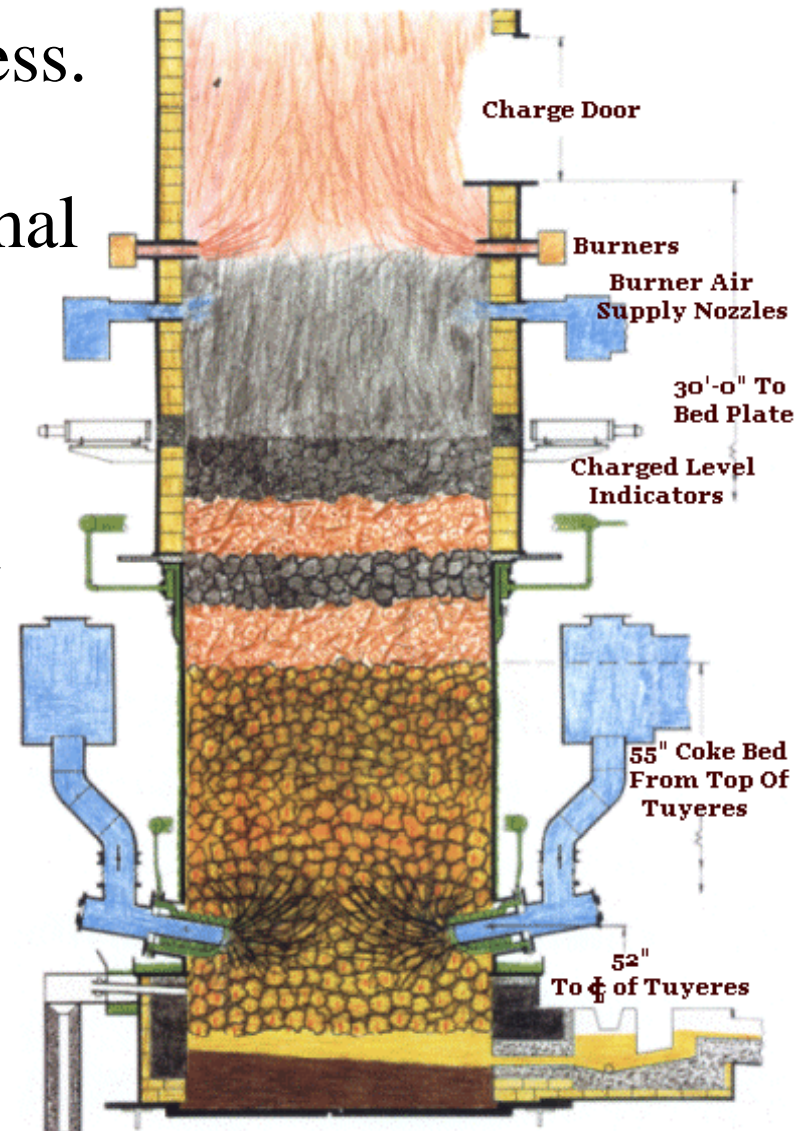
- Cupola Melting
- Electric Melting
 - Electric Induction Melting
 - Electric Arc Melting
- Combustion Fired Reverberatory Melting

Raw Materials Used in the Melting of Gray Cast Irons

- Iron Sources
 - Scrap Iron
 - Internal Returns
 - Machined Chip Briquettes
 - External Purchased Scrap
 - Scrap Steel
 - Pig Iron
- Coke
- Graphite and Silicon Carbide
- Ferro-silicon and Ferro-manganese

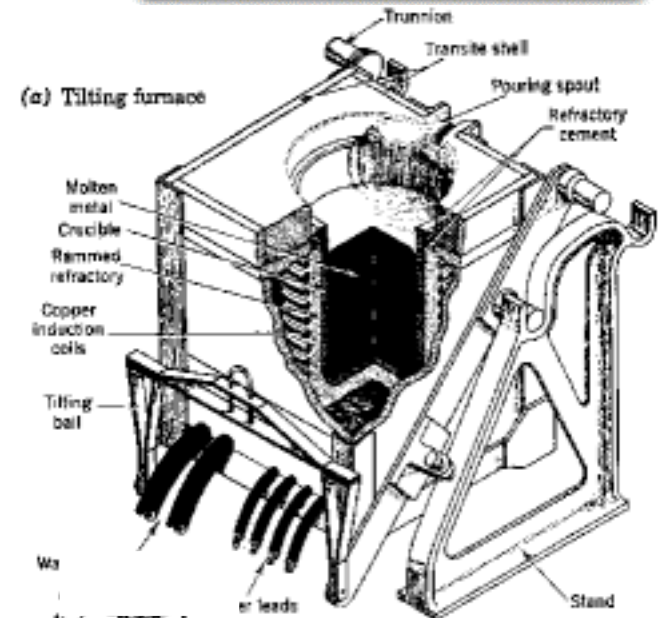
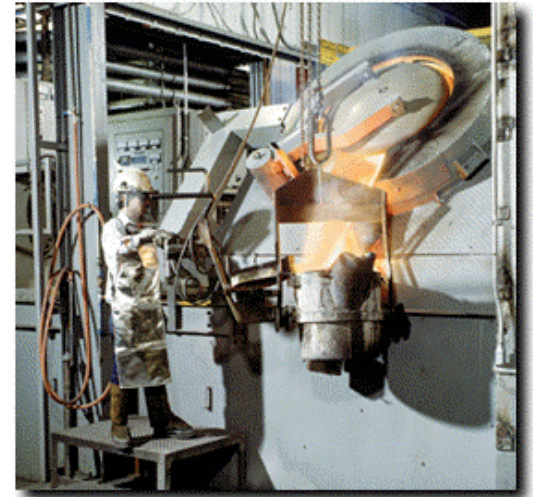
Cupola Melting of Gray Cast Iron

- It's a continuous melting process.
- Exothermic reaction between coke and air provides the thermal energy for melting.
- Coke and its reaction products provide the carbon in the melt.
- Uses greatest variety of charge materials.
- Varying melt content is very difficult.
- It is more difficult to meet environmental standards.



Electric Melting of Gray Cast Iron

- It's a batch melting process.
- Induced electric current in charge or electric arc provides the thermal energy for melting.
- Graphite and silicon carbide are added to provide carbon in the melt.
- Restricted to specific charge materials.
- Each batch can have a different target composition.
- Less environmental concerns.
- More sensitive to impurities.



Inoculation of Molten Gray Cast Iron

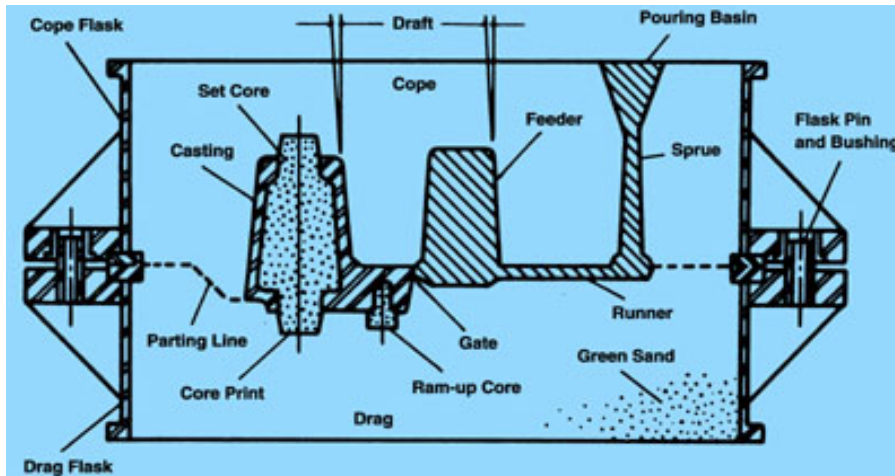
- Inoculant is added to the liquid metal to help prevent the formation of eutectic carbides and aid graphite nucleation.
- Inoculants are primarily ferro-silicon often with small amounts of varying elements to aid in nucleation.
- Inoculants are typically added in the pouring/transfer ladles and in-stream during pouring.
- Inoculation also helps to prevent dendritic graphite (types D and E per ISO 945).
- The effects of inoculation are reduced with time after they are introduced to the liquid metal. This is commonly called “inoculant fade.”

Molding Processes Used for Production of Gray Cast Iron Castings

- Permanent Mold Processes
- Investment Mold Processes
- Sand Mold Processes
 - Cope and Drag Sand Molding
 - Disamatic Flaskless Sand Molding
 - Lost Foam Sand Molding

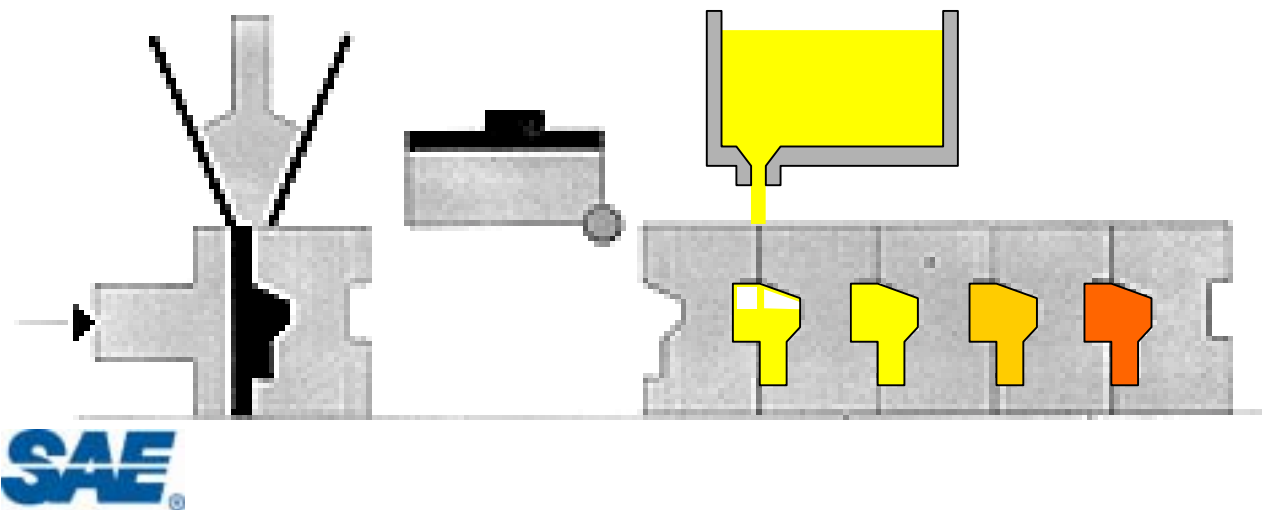
Cope & Drag Sand Molding Process

- Mold parting is horizontal.
- Molded sand and casting are contained in a steel flask.
- There are minimal casting size and weight limitations.
- There is greater flexibility for gating and riser design.
- In some cases this process can provide a more uniform casting microstructure and soundness.



Disamatic Flaskless Sand Molding Process

- Mold parting is vertical.
- All metal in gates, risers and casting cavities are contained within the flaskless sand molds.
- There are casting size and weight limitations due to the hydrostatic pressure built up within the mold.
- There is reduced flexibility for gating and risers.



Molding Sand Properties

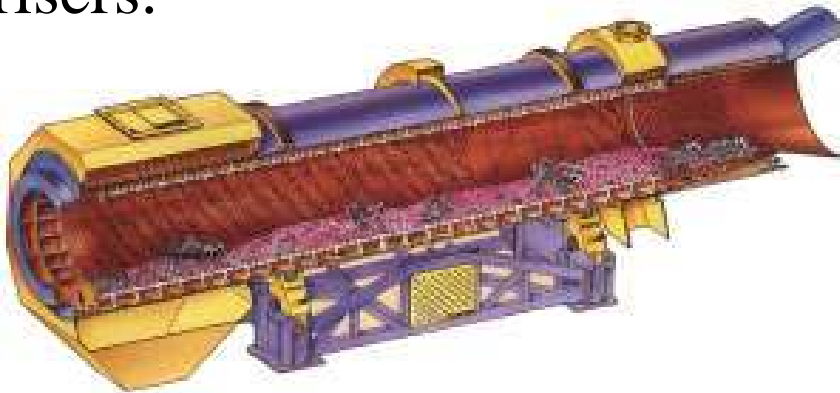
- The properties of green sand and core sand have a significant impact on the dimensional consistency and metallurgical quality of the castings.
- Typical green sand properties controlled in the mixing and molding process:
 - Green sand compactability
 - Green sand strength
 - Sand moisture
 - Sand temperature
 - Green Sand Permeability
 - Green Sand Plasticity
 - Wet tensile strength
 - Volatile material composition
 - Percent Active Clay
 - Weight Loss on Ignition
 - Green Sand Granularity

Casting Cooling in the Sand Mold

- The time the casting spends in the sand mold is typically 20 to 60 minutes. This time is often referred to as the “shake-out” time.
- The time the casting spends in the sand provides slow uniform cooling of the castings.
 - A long shake-out time can help minimize residual stresses that can lead to rotor warpage in service.
 - A long shake-out time could result in free ferrite formation and soften the castings. This is especially true for high carbon gray cast irons.
 - Too short of a shake-out time may lead to possible austenite transformations to martensite or bainite.

Removal of Castings from the Sand Molds

- In the Disamatic flaskless molding process the sand molds and castings are pushed off the end of the molding lines onto shaker tables.
- In the cope and drag molding process the sand molds and castings are pressed out of the flasks.
- Didion rotary drums and/or shaker tables are used to separate the sand from the castings and break off gates and risers.



Casting Cleaning

- Any remaining gates, risers or sprues still attached to the castings are manually hammered off.
- Castings are shot blasted to remove any remaining sand and clean off minor flash. Either tumble or rack blasting are used.
- Castings are ground (manually or semi-automatically) to removed excessive flash or gate material that may interfere with machining.

Heat-Treatment of Rotor Castings

Gray cast iron can be heat treated with many of the same processes that are used for steels and nodular cast irons.

Rotor Casting Heat-Treatments

- Stress Relieving Heat-Treatments
- Annealing Heat-Treatments
- Other Heat-Treatments

Stress Relieving Heat-Treatment of Gray Cast Iron Rotors

- Stress relieving of gray cast iron rotors can be performed to minimize rotor warpage that can occur under extreme service conditions.
- Stress relieving of semi-finished rotors is done in Europe for many rotors designed for high performance vehicles.
- Stress relieving is typically performed in the temperature range of 500°C and 650°C for periods up to 24 hours.
- Stress relieving has no significant effect on microstructure or mechanical properties.

Annealing Heat-Treatment of Gray Cast Iron Rotor Castings

- Annealing of gray cast iron rotor castings was performed in the past to soften hard castings.
- Annealing is typically performed in the temperature range of 600°C and 700°C for periods up to 24 hours.
- Annealing will reduce the hardness of the castings.
- Annealing will begin to spheroidize the iron carbide in the pearlite microstructure.
- Annealing may increase the amount of free ferrite through graphitization of the iron carbide in the pearlite matrix.
- Annealing is typically not allowed for gray cast iron rotors today.

Other Heat-Treatments Considered for Gray Cast Iron Rotor Castings

Many other heat treatments have been considered to improve specific properties of the gray cast iron, but the costs and/or the technical disadvantages have outweighed the benefits.

- Austempering Heat Treatments
- Induction Hardening Heat Treatments
- Carburizing and Nitrocarburizing Heat Treatments

Cast Iron Rotor Casting Process

Sample Questions

1. Which melting process (cupola or electric) would likely be best if you desired a slightly lower silicon content than is used in the standard gray cast iron grades?
2. Which molding process (cope and drag or Disamatic) would likely provide a more uniform casting integrity and balance for a integral hub and rotor design with a large offset?
3. Which sand separation process (Didion drum or shaker tables) would be more likely to cause damage to thin and/or sensitive sections of a casting?

Cast Iron Rotor Casting Process

Sample Questions

Which melting process (cupola or electric) would likely be best if you desired a slightly lower silicon content than is used in the standard gray cast iron grades?

Answer: It is difficult to adjust chemistries with a cupola melting process because of the continuous melting. Electric batch melting provides the ability to tailor chemistries specific to designs.

Cast Iron Rotor Casting Process

Sample Questions

Which molding process (cope and drag or Disamatic) would likely provide a more uniform casting integrity and casting balance for a integral hub and rotor design with a large offset?

Answer: The Disamatic molding process typically gates from the bottom and has risers at the top, which can result in varying degrees of shrinkage porosity with more complex casting designs. The cope and drag process can better utilize a riser and gating pattern that minimizes shrinkage porosity.

Cast Iron Rotor Casting Process

Sample Questions

Which sand separation process (Didion drum or shaker tables) would be more likely to cause damage to thin and/or sensitive sections of a casting?

Answer: The casting in a Didion drum can fall and strike other casting from distances as much as 2 to 3 feet. Therefore, shaker tables may provide less damage to castings with thin or sensitive sections than Didion drums.

Areas for Future Material Developments for Gray Cast Iron Rotors

- Coatings and surface treatments to prevent or minimize brake surface corrosion
- Alloying to improve thermal conductivity and/or wear resistance
- Alloying or heat treatments to modify the microstructure for improved vibration damping
- Composites of gray iron and other metals or ceramics

Alternative Materials to Gray Cast Iron for Brake Rotor Applications

- Aluminum Metal-Matrix Composite Materials
 - Operational brake surface temperatures are limited to approximately 450°C maximum.
 - Cost is approximately 2 to 3 times the cost of gray cast iron rotors.
- Graphite/Graphite and Graphite/SiC Composite Materials
 - Operational temperatures not limited by rotor material.
 - Frictional properties are better at higher temperatures.
 - Cost is nearly a hundred times the cost of gray cast iron rotors.

Concluding Remarks

Gray cast iron has nearly all the properties that are desired for brake rotor applications. This combined with the very low costs of materials and processing makes gray cast iron a potentially unbeatable material value in brake rotor applications.