## Lecture 6

# Cast Irons

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# Fe-C Phase Diagram

**Solid lines:**
Fe-$Fe_3C$ diagram
***Metastable system***

**Dashed lines:**
Fe-Gr. diagram
***Stable system***

***Steels***

**Peritectic reaction**

$$\delta + Liq. \xrightarrow{1495\,°C\,,\,0.16\,wt\%C} \gamma$$

***Steels and cast irons***

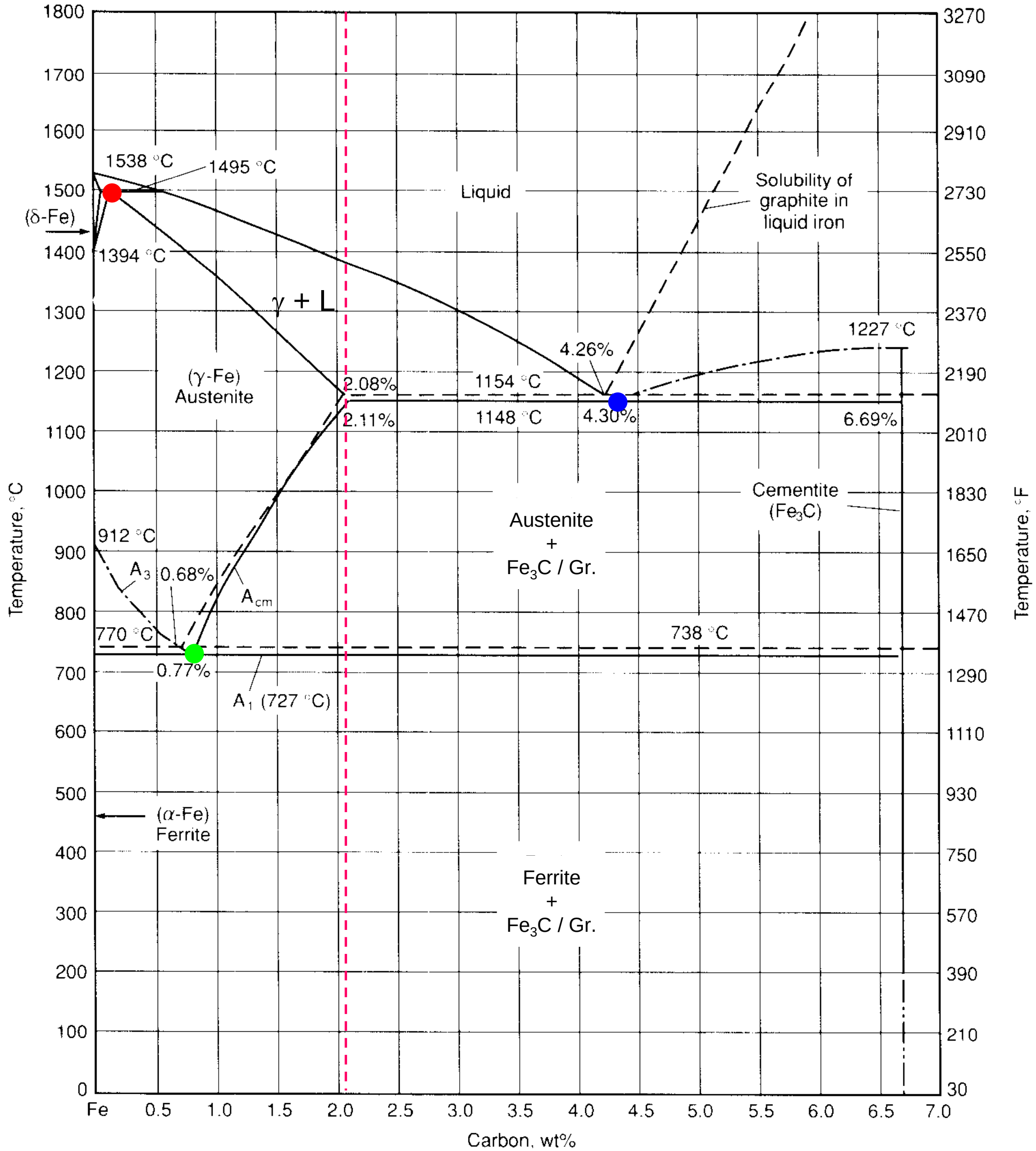
**Eutectoid reaction**

$$\gamma \rightarrow \alpha + \begin{cases} Fe_3C \\ Gr. \end{cases}$$

***Cast irons***

**Eutectic reaction**

$$Liq. \rightarrow \gamma + \begin{cases} Fe_3C \\ Gr. \end{cases}$$



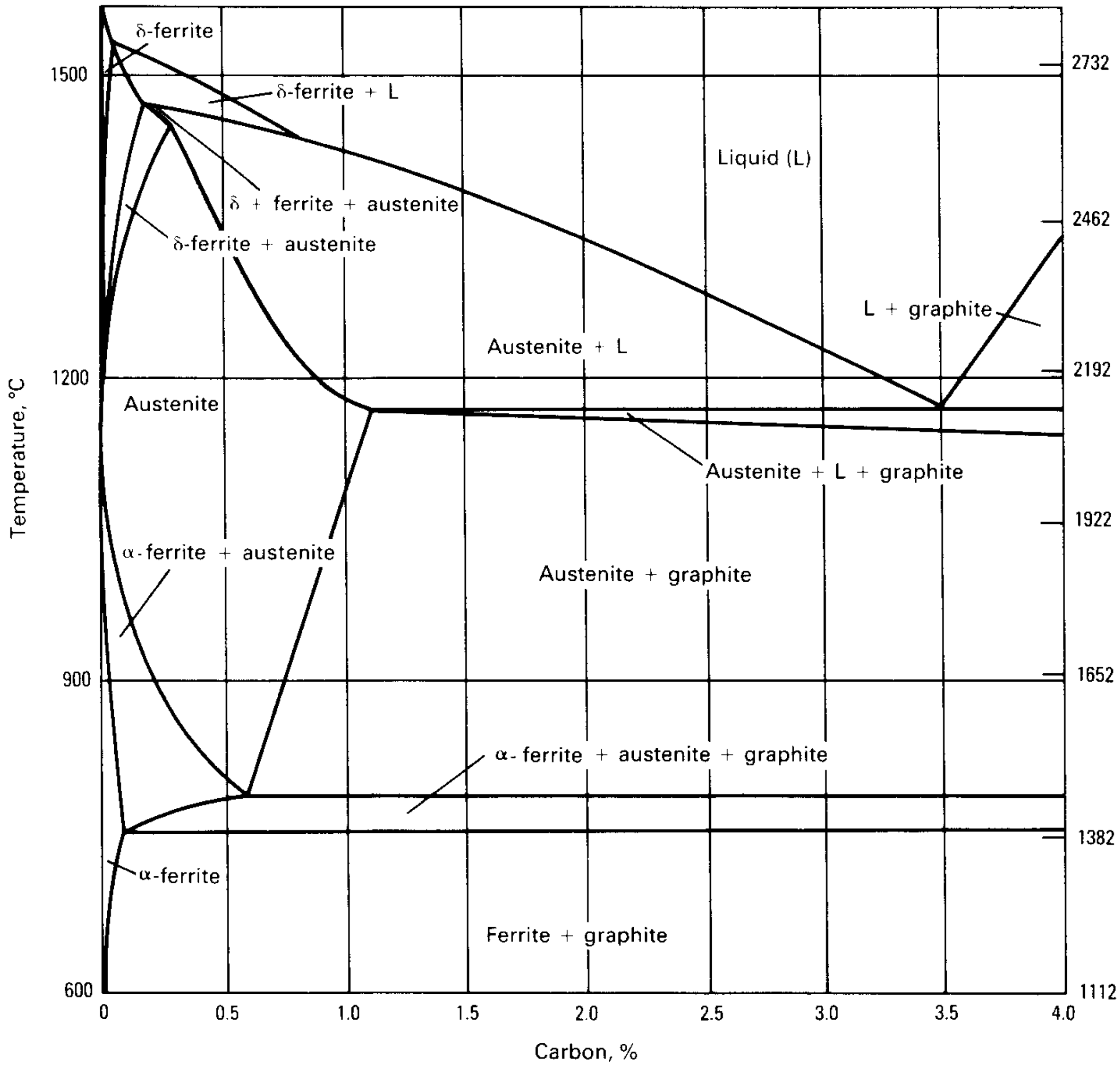

***Steel ⇦ ⇨ Cast Iron***

ASM Handbook: Volume 1: Properties and Selection: Irons, Steels, and High-Performance Alloys, ASM International, Materials Park, Ohio, 1992.

# Carbon Equivalent Concept

Si displaces the eutectic point to lower carbon concentrations. The Carbon Equivalent (CE) equation below takes into account the effect of Si and P on the displacement of the eutectic point. Eutectic composition is where the CE is equal to 4.3.

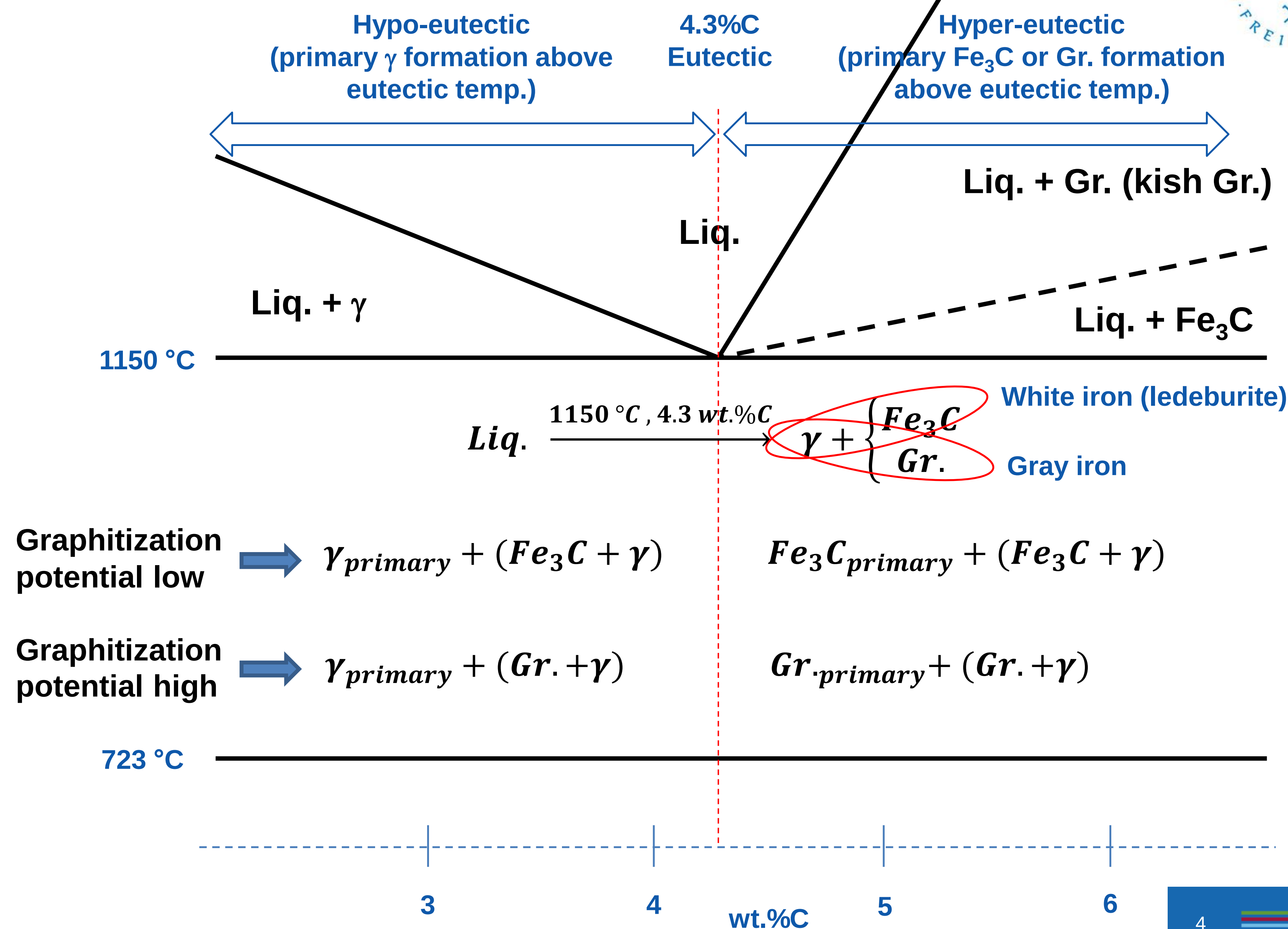
$$CE = \%C + \frac{(\%Si + \%P)}{3}$$



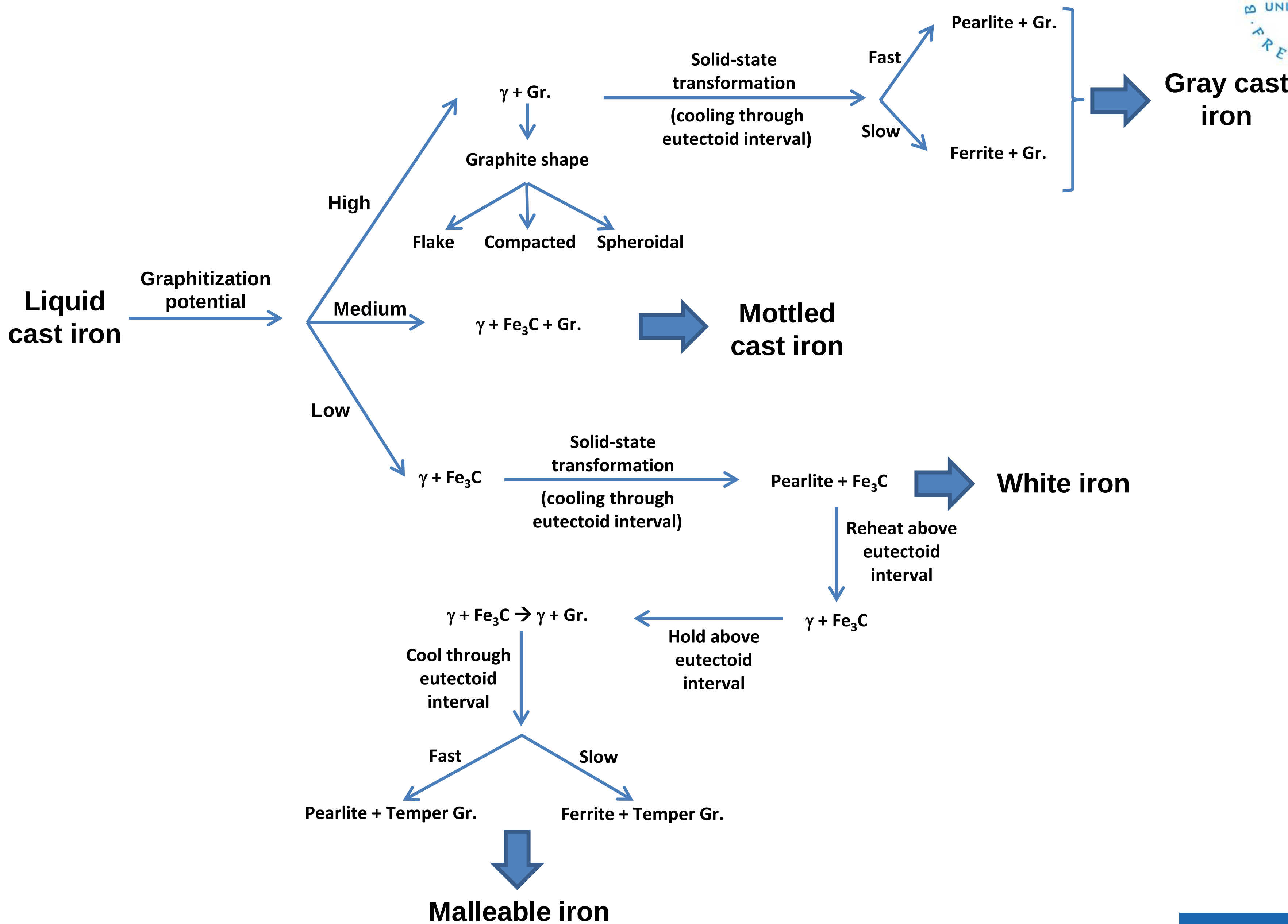

***Pseudo-binary Fe-2.5 wt.%Si-C Phase Diagram***

ASM Handbook: Volume 15: Casting, ASM International, Materials Park, Ohio, 1992.

# Constitution of Cast Irons



# Cast Irons: Overview




ASM Handbook: Volume 1: Properties and Selection: Irons, Steels, and High-Performance Alloys, ASM International, Materials Park, Ohio, 1992.

# Cast Iron: Applications


Not common but also possible with cast iron:

# Graphitization; Role of Alloying Elements

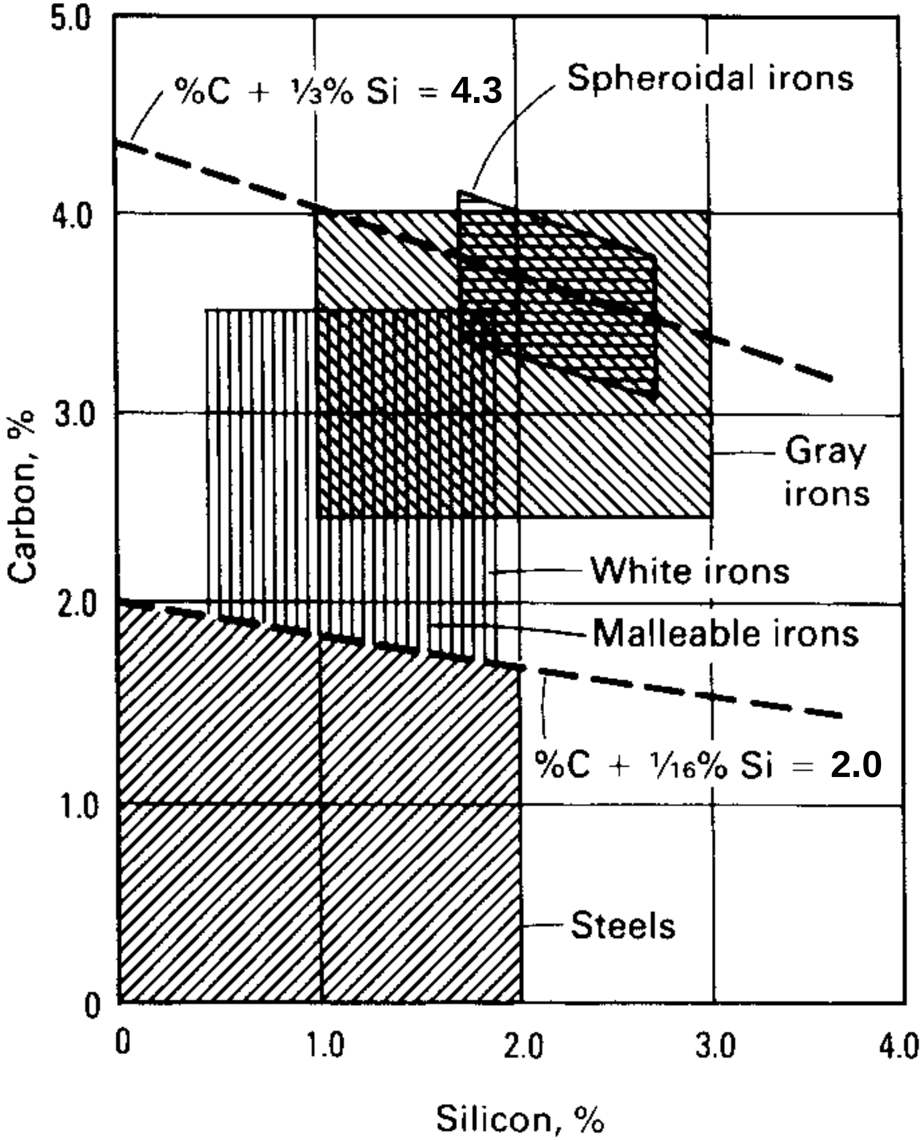
Decreasing graphitization potential ↓

| | |
|---|---|
| Carbon | **High graphitization potential** |
| Tin | |
| Phosphorous | |
| Silicon | |
| Aluminum | |
| Copper | |
| Nickel | |
| Iron | **Neutral** |
| Manganese | |
| Chromium | |
| Molybdenum | |
| Vanadium | **High negative graphitization potential** |

ASM Specialty Handbook: Cast Irons, ASM International, Materials Park, Ohio, 1996.

# Chemical Composition

**Carbon and silicon composition ranges of different classes of cast irons and steels.**




ASM Handbook: Volume 1: Properties and Selection: Irons, Steels, and High-Performance Alloys, ASM International, Materials Park, Ohio, 1992.

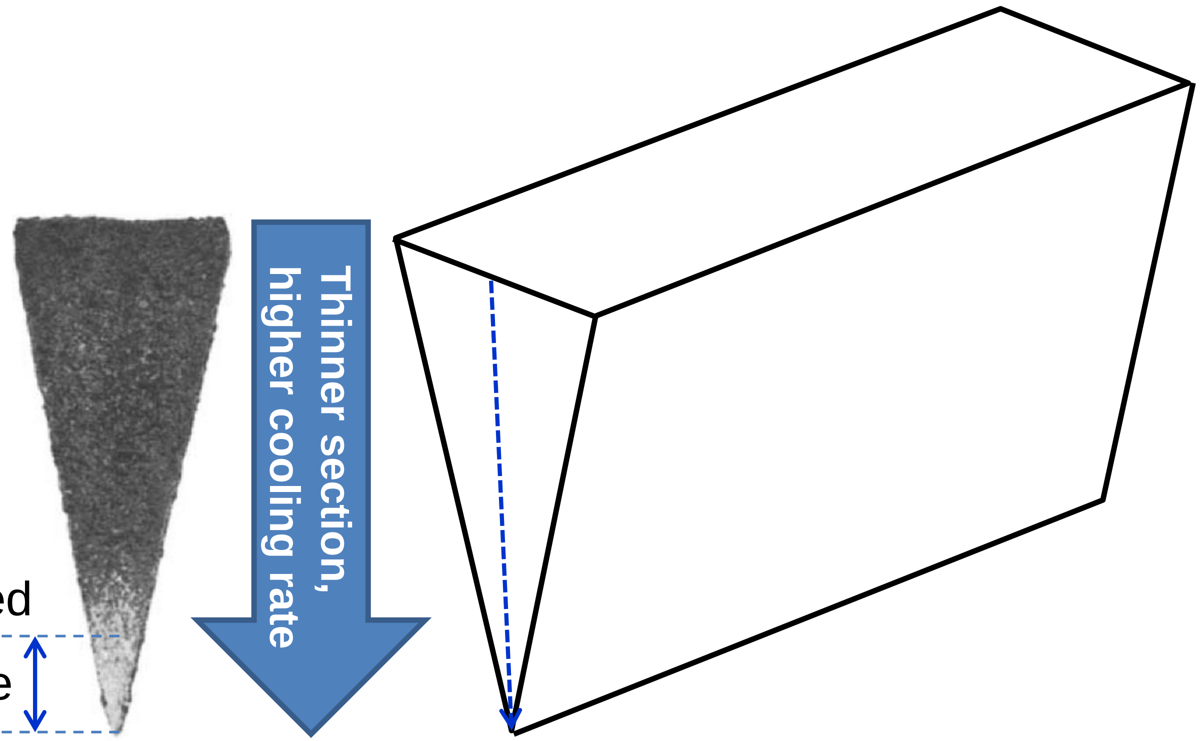
# Wedge Test

The tendency of an iron to solidify as white or gray iron may be evaluated by casting a wedge-shaped specimen. The fracture surface is then examined and the distance from the wedge tip to the end of the white zone is measured. The larger the white zone, the higher the tendency of the steel to solidify as white iron.

$\boldsymbol{Liq.} \rightarrow \boldsymbol{\gamma} + \boldsymbol{Gr.}$ Gray

$\boldsymbol{Liq.} \rightarrow \boldsymbol{\gamma} + \boldsymbol{Fe_3C} + \boldsymbol{Gr.}$ Mottled

$\boldsymbol{Liq.} \rightarrow \boldsymbol{\gamma} + \boldsymbol{Fe_3C}$ White

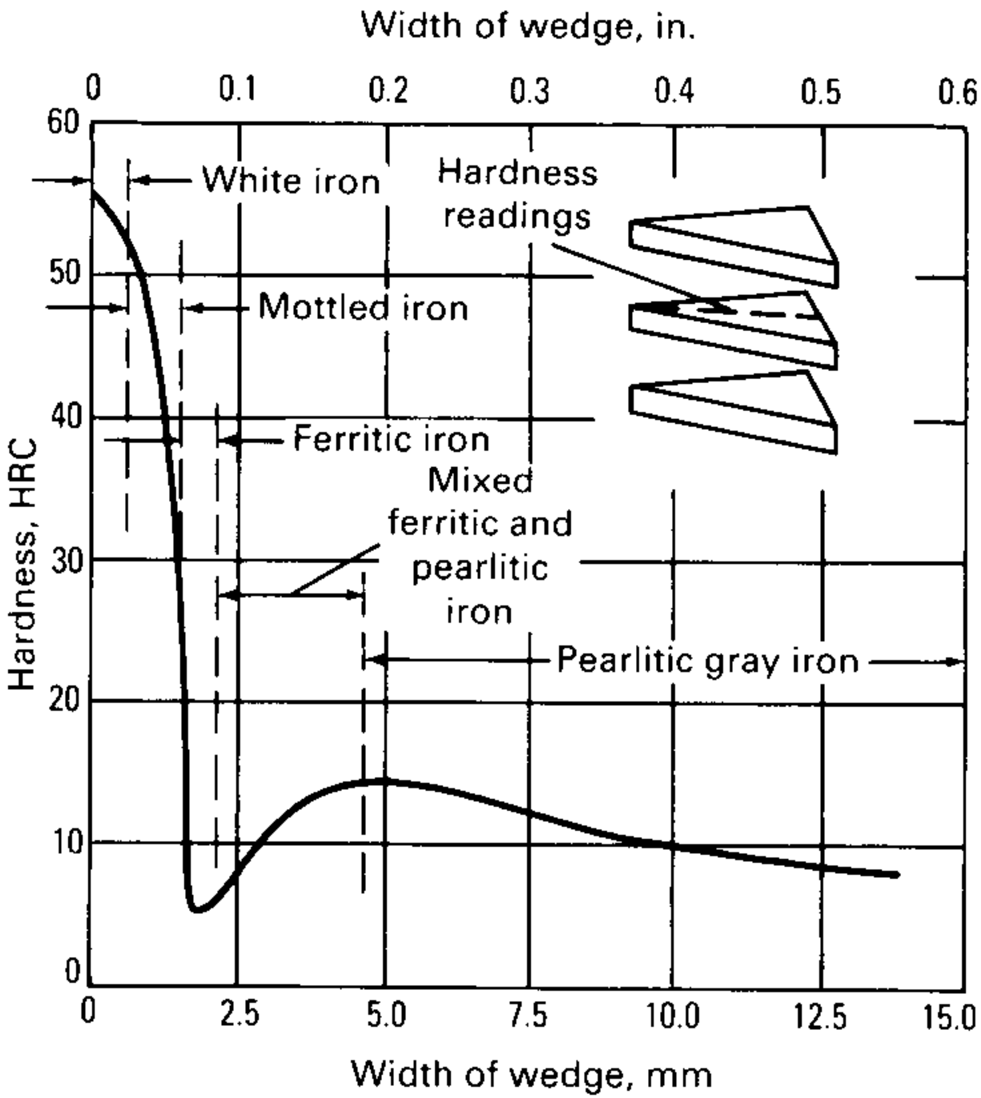



G.F. Vander Voort, Metallography, Principles and Practice, ASM International, 1984.

# Wedge Test

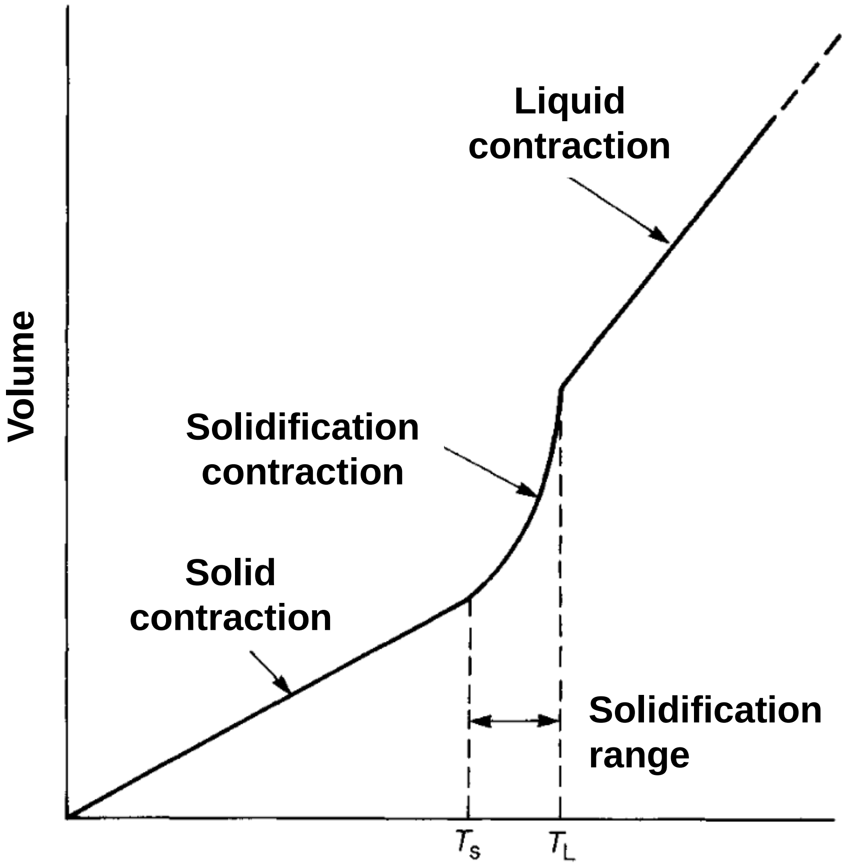
***Gray Iron***

*Fe-3.52 C-2.55 Si-1.01 Mn-0.215 P-0.086 S*

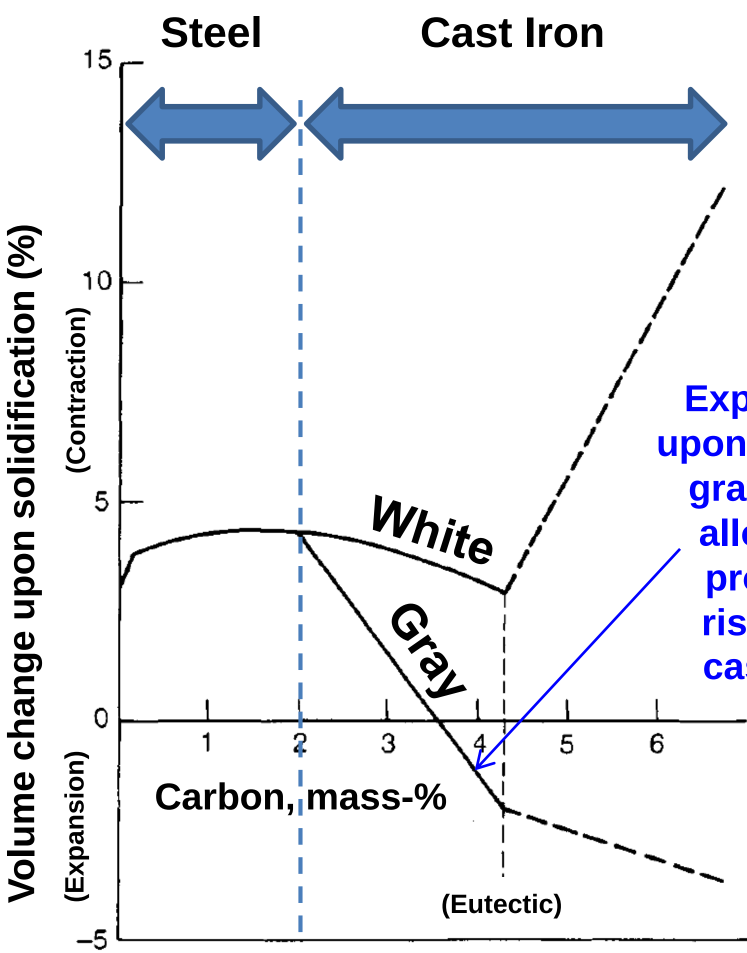



ASM Handbook: Volume 15: Casting, ASM International, Materials Park, Ohio, 1992.

# Expansion during Graphite Formation



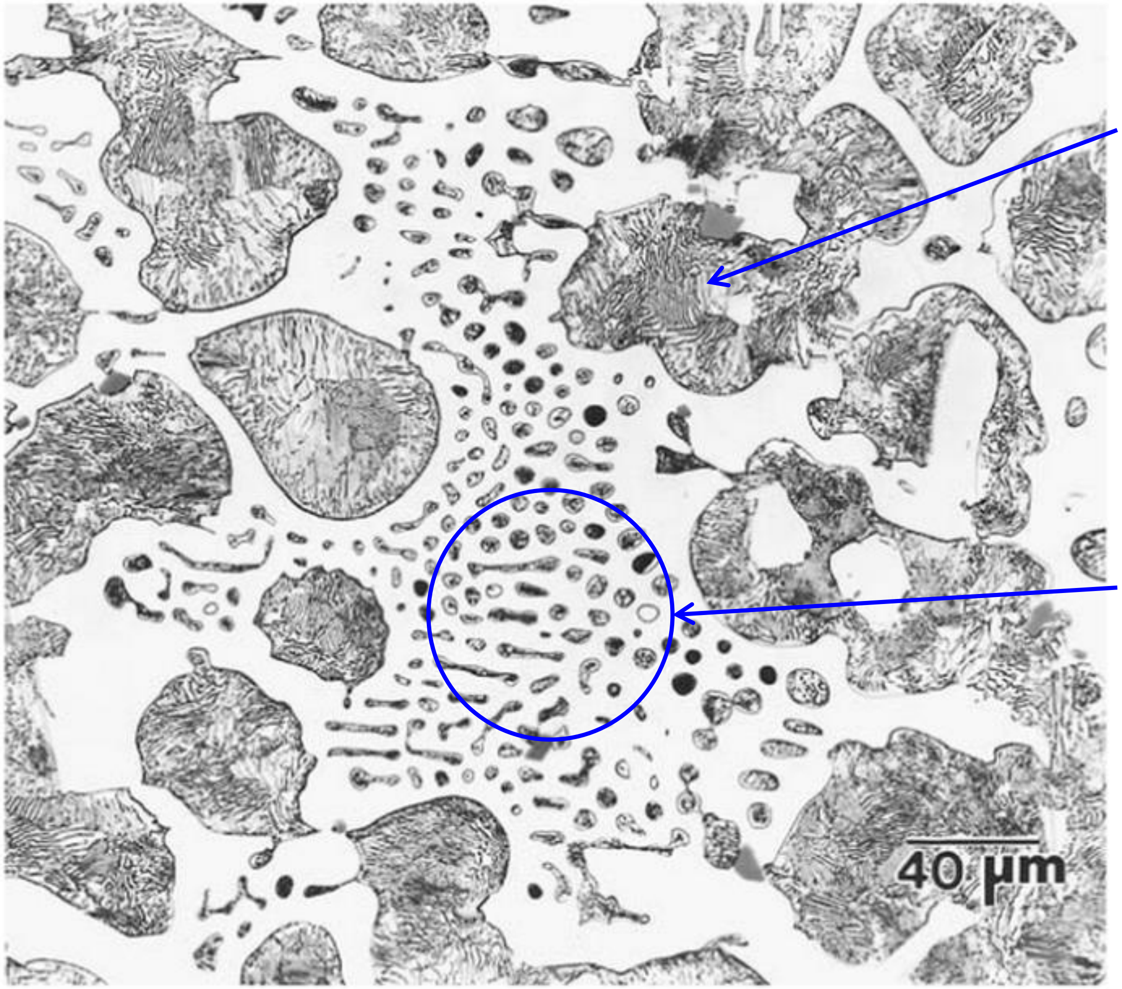

Schematic illustration of three shrinkage regimes in most alloys: in the liquid; during freezing; and in the solid state




The volume change on freezing of Fe-C alloys.

J. Campbell, Castings, Butterworth Heinemann, 2nd Edition, 2003.

# White Cast Iron




*Primary $\gamma$ above eutectoid temperature, pearlite ($\alpha$ + $Fe_3C$) below eutectoid temperature*

***Ledeburite***
*($\gamma$ + $Fe_3C$ right after eutectic solidification, pearlite + $Fe_3C$ below eutectoid temperature)*

# White Cast Iron

- High hardness and abrasion resistance
- Low Carbon Equivalents (CEs)
- Usually used after alloying with Cr (high-Cr white iron) or Ni+Cr (Ni-hard white iron) for higher hardnesses
- The high hardness originates from a ***hard martensitic matrix*** and the presence of a ***large fraction of hard alloy carbides*** such as $M_3C$ and $M_7C_3$ (M denotes Cr, Fe, …)

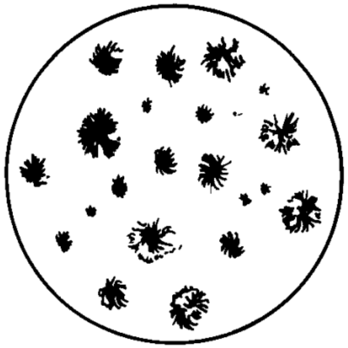
**Example compositions of high-alloy white irons**

| Type | Designation | C (wt.%) | Mn (wt.%) | Si (wt.%) | Ni (wt.%) | Cr (wt.%) | Mo (wt.%) |
|---|---|---|---|---|---|---|---|
| Ni-Cr (Ni-hard) | Ni-Cr-HC | 3.0-3.6 | 1.3 max | 0.8 max | 3.3-3.5 | 1.4-4 | 1.0 max |
| | Ni-Hi Cr | 2.5-3.6 | 1.3 max | 1.0-2.2 | 5.0-7.0 | 7.0-11.0 | 1.0 max |
| High-Cr | 12%Cr | 2.4-2.8 | 0.5-1.5 | 1.0 max | 0.5 max | 11.0-14.0 | 0.5-1.0 |
| | 20%Cr-Mo-LC | 2.0-2.6 | 0.5-1.5 | 1.0 max | 1.5 max | 18.0-23.0 | 1.5 max |
| | 25%Cr | 2.3-3.0 | 0.5-1.5 | 1.0 max | 1.5 max | 23.0-28.0 | 1.5 max |

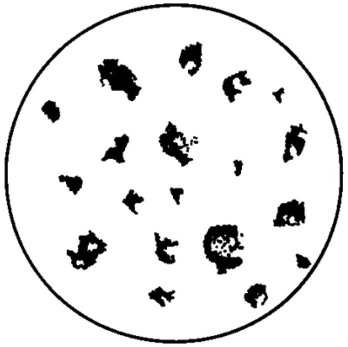
ASM Handbook: Volume 15: Casting, ASM International, Materials Park, Ohio, 1992.

# Gray Iron: Graphite Shapes

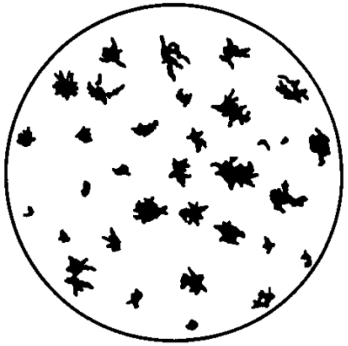
**Typical graphite shapes according to ASTM A247 standard.**



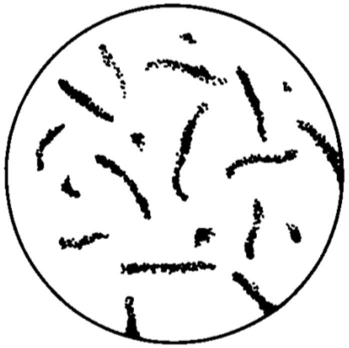
Spheroidal



Imperfect spheroidal

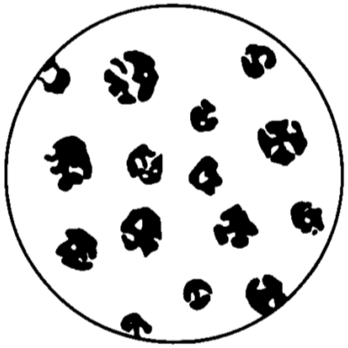


Temper



Compacted

Crab

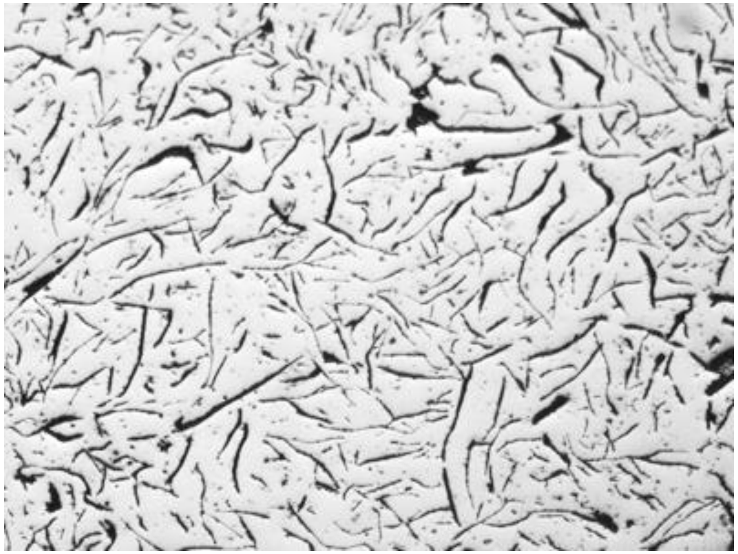


Exploded

Flake

ASM Handbook: Volume 1: Properties and Selection: Irons, Steels, and High-Performance Alloys, ASM International, Materials Park, Ohio, 1992.

# Gray Iron (Iron with Flake Graphite)



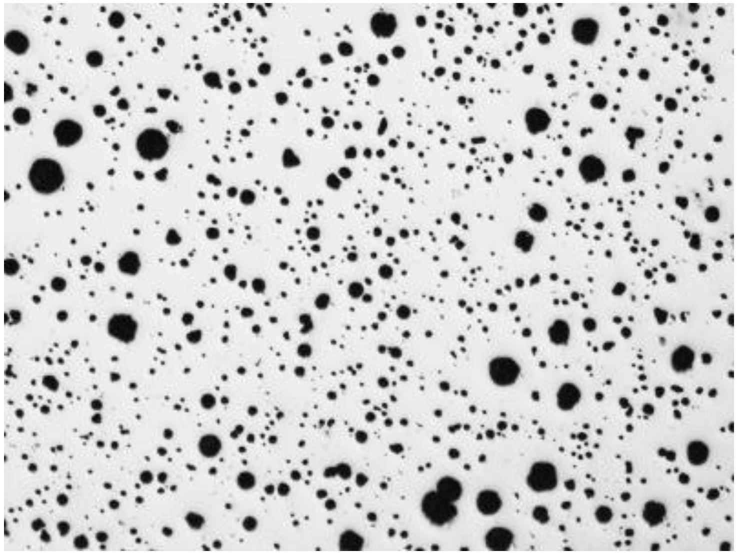
**Graphite flakes in a ferritic matrix**

- Graphite flakes in FG iron can take various shapes, sizes, and orientations depending on composition and casting conditions
- Excellent damping capacity
- Brittle
- Good machinability because of easy chip formation and cutting tool lubrication by graphite
- Good heat conduction due to interconnected graphite flakes
- The matrix microstructure depends on the cooling conditions through the eutectoid interval (usually pearlite or ferrite rather than martensite)
- Graphitization is aided by the inoculation process. Inoculation agent (usually ferrosilicon or graphite) which is added to the melt just before casting promotes the nucleation of graphite rather than cementite during solidification.

ASM Specialty Handbook: Cast Irons, ASM International, Materials Park, Ohio, 1996.

# Ductile Iron (Iron with Spheroidal Graphite)





**Graphite nodules in a ferritic matrix**

- Also known as spheroidal graphite (SG) iron or nodular iron
- Graphite is more or less spherical in shape
- The size and the number of graphite nodules per unit area influences mechanical properties
- Higher ductility than gray iron
- The matrix microstructure depends on the cooling conditions through the eutectoid interval (usually pearlite, ferrite or a mixture of both although martensite formation is also possible at high cooling rates)
- Spherical graphite is achieved by the addition of elements such as **Mg**. The process of Mg addition to the melt is challenging because of its ready evaporation.

ASM Specialty Handbook: Cast Irons, ASM International, Materials Park, Ohio, 1996.

# Ductile Iron

## Influence of minor elements on graphite shape

| Element category | Element |
|---|---|
| Spheroidizer: | Magnesium, calcium, rare earth elements (cerium, lanthanum, etc.), yttrium |
| Neutral: | Iron, carbon, alloying elements |
| Anti-spheroidizer: | Aluminum, arsenic, bismuth, tellurium, titanium, lead, sulfur, antimony |

The amount of Mg required to produce spheroidal graphite is 0.03-0.05 wt.%. In practice, however, more Mg is required to account for the recovery rate of the technique used for the Mg addition and to compensate for the Mg loss due to the MgS formation;

$$\mathbf{Mg}_{\mathbf{added}} = \frac{0.75\ \mathrm{S} + \text{net Mg level needed for spheroidization}}{\begin{array}{c}\text{Recovery of Mg in the Mg addition technique utilized} \\ \text{(fraction of Mg which actually enters the melt)}\end{array}}$$

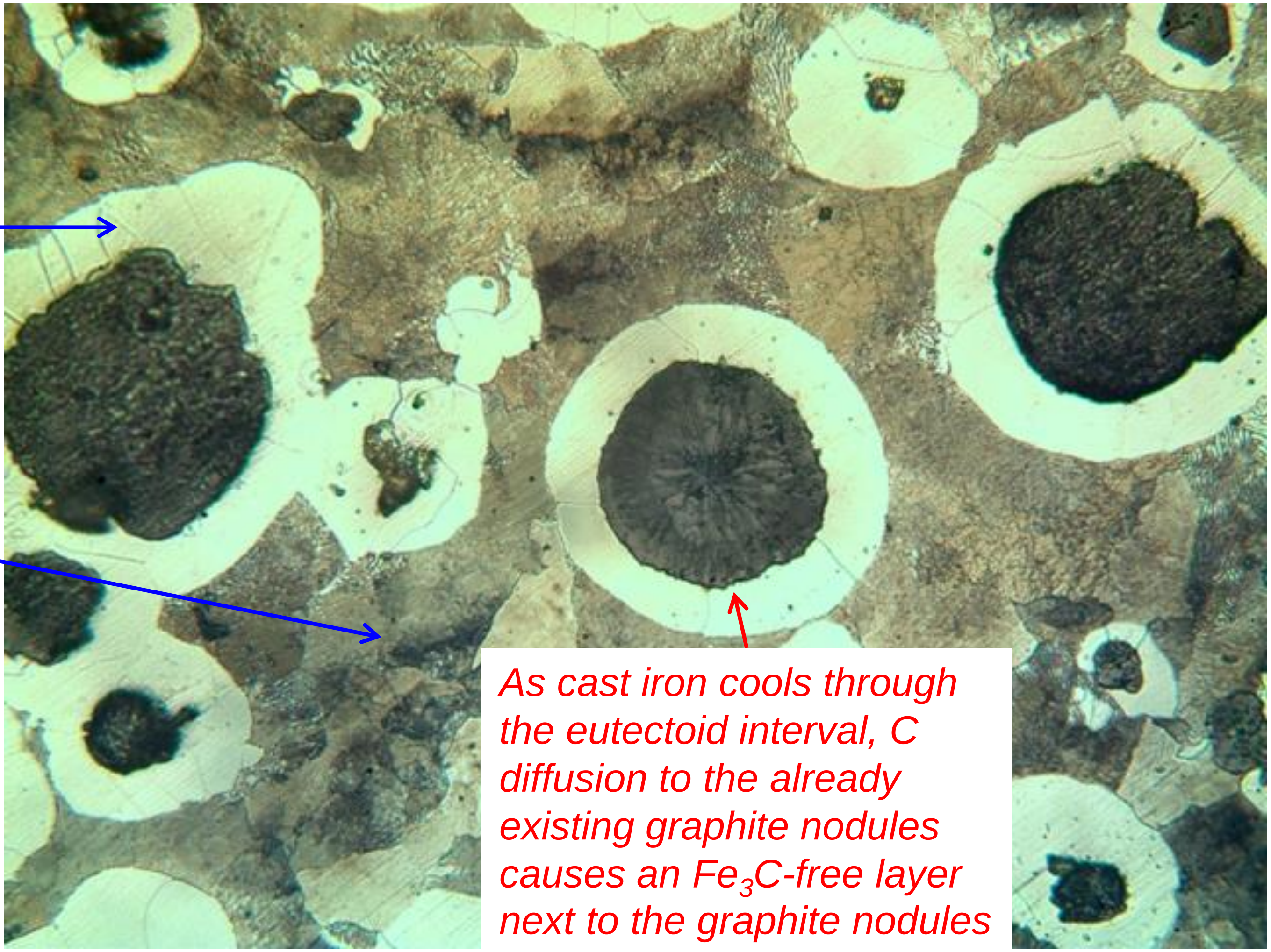
ASM Specialty Handbook: Cast Irons, ASM International, Materials Park, Ohio, 1996.

# Ductile Iron

## Bull's-eye microstructures in SG iron

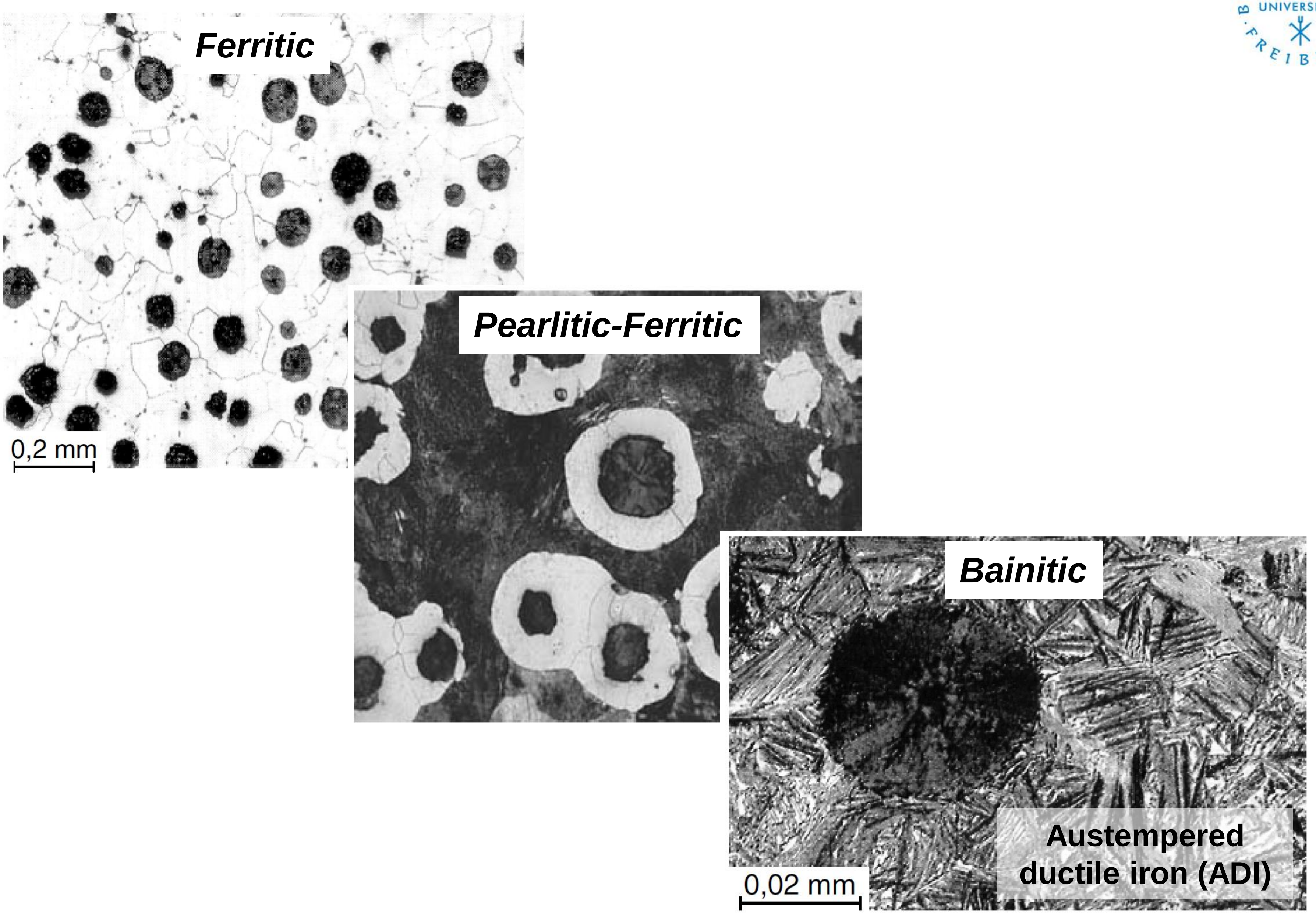
$Fe_3C$-free ferritic layer next to graphite nodules

Pearlitic matrix

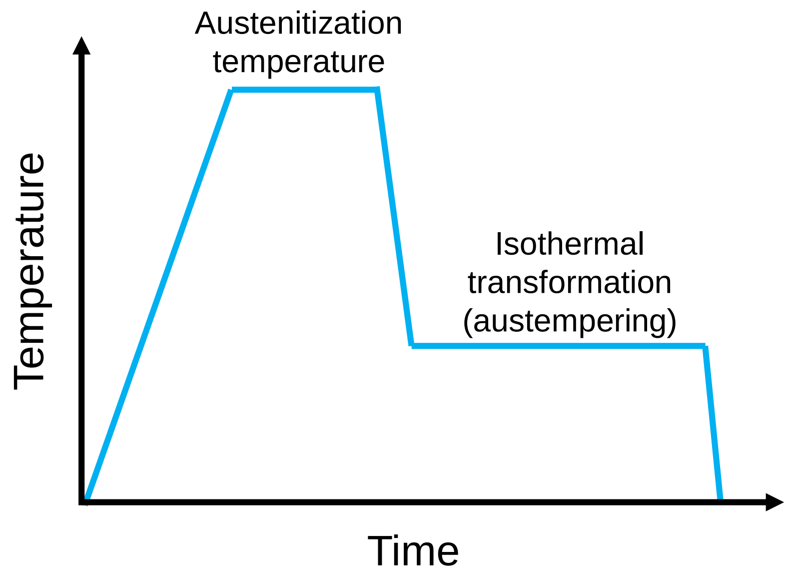


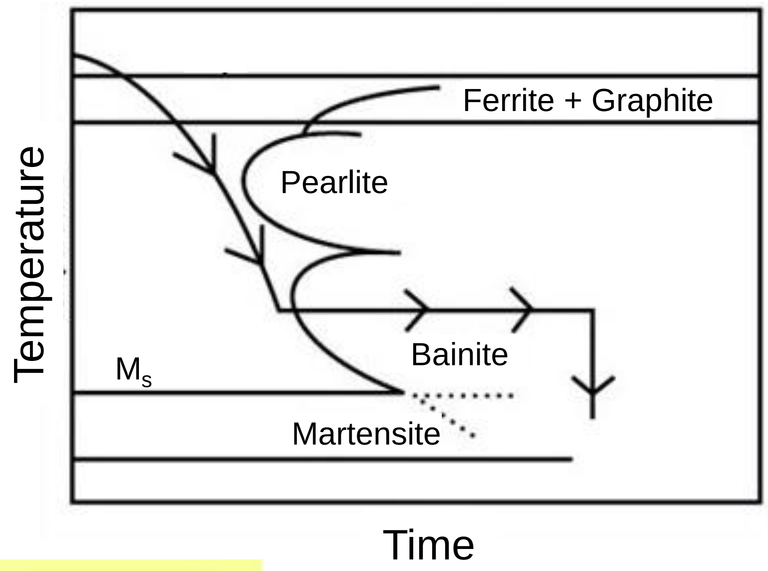
*As cast iron cools through the eutectoid interval, C diffusion to the already existing graphite nodules causes an $Fe_3C$-free layer next to the graphite nodules*

# Matrix Types

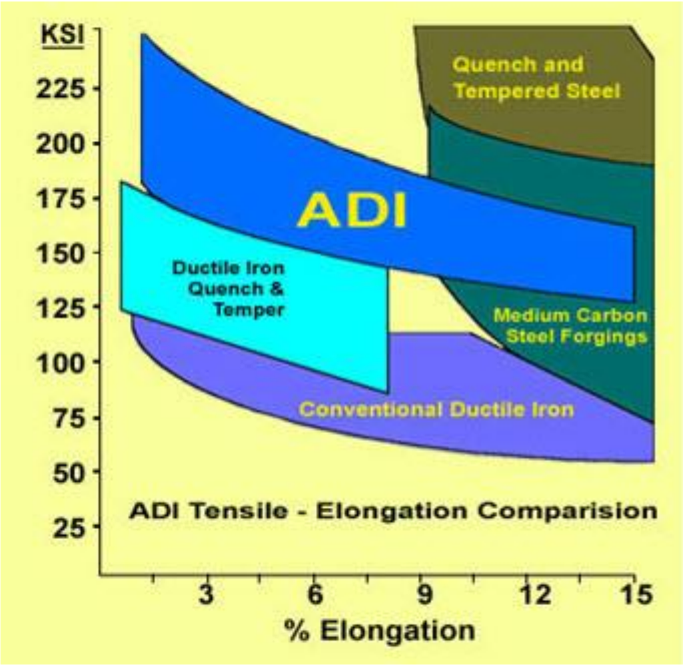


# Austempered Ductile Iron (ADI)



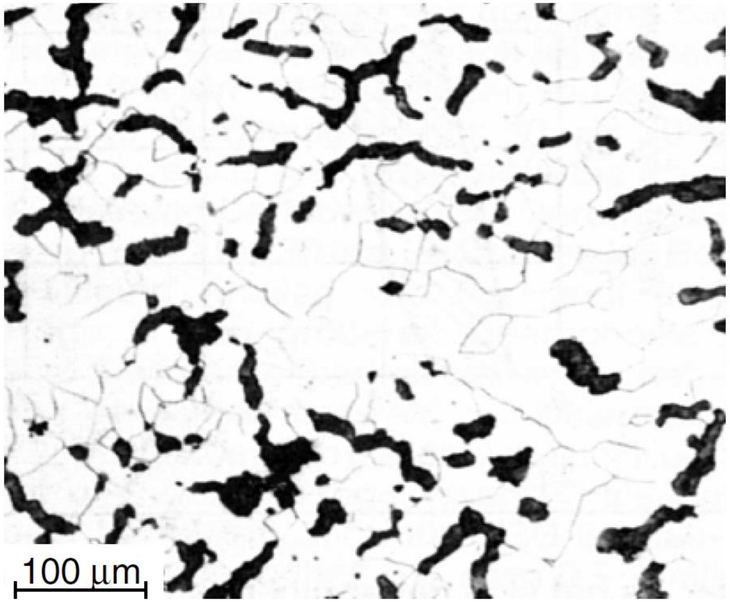




1 ksi ≈ 7 MPa




http://www.totalmateria.com/page.aspx?ID=CheckArticle&site=kts&NM=243

# Compacted Graphite Iron

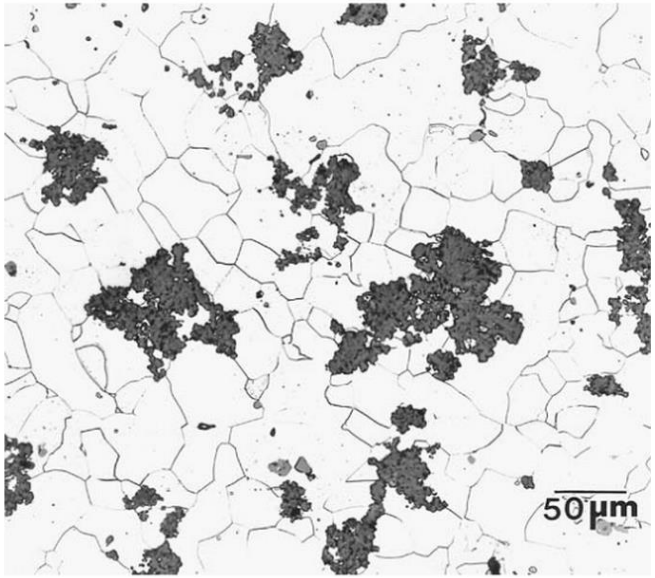



**Compacted graphite in a ferritic matrix**

- Also known as CG iron or vermicular graphite iron
- Graphite shape intermediate between spheroidal and flake
- Microstructure of CG iron is free of flake graphite and the amount of spheroidal graphite is less than 20%
- Properties intermediate between FG and SG
- Produced by the addition of Mg in amounts lower than needed to obtain SG or by combined addition of spheroidizing and anti-spheroidizing elements (for example Mg+Ti addition)

ASM Specialty Handbook: Cast Irons, ASM International, Materials Park, Ohio, 1996.

# Malleable Iron

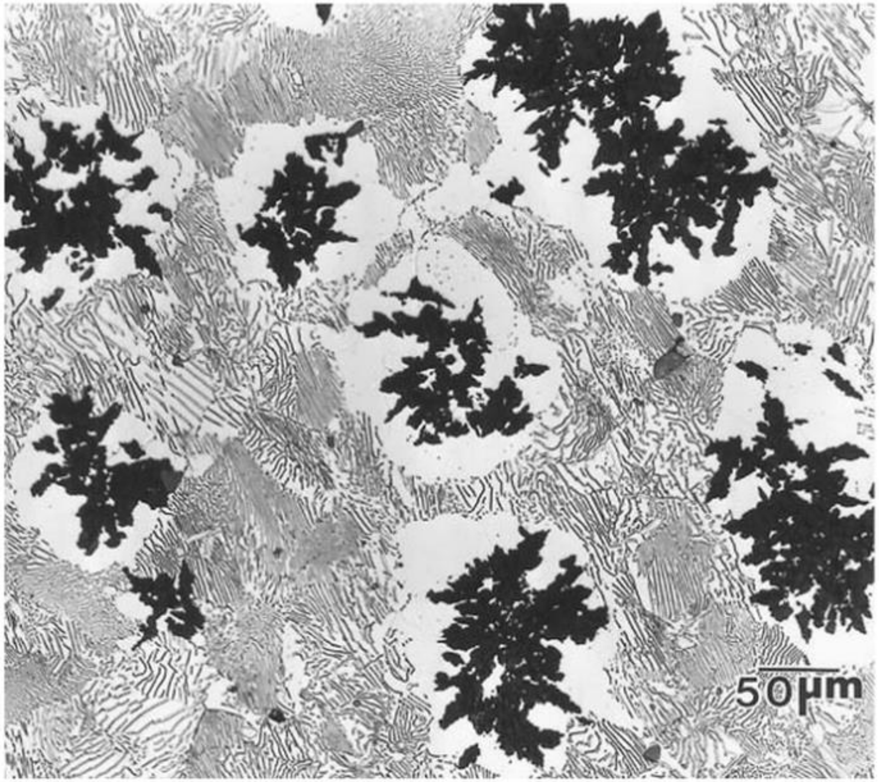



**Temper graphite in a ferritic matrix**

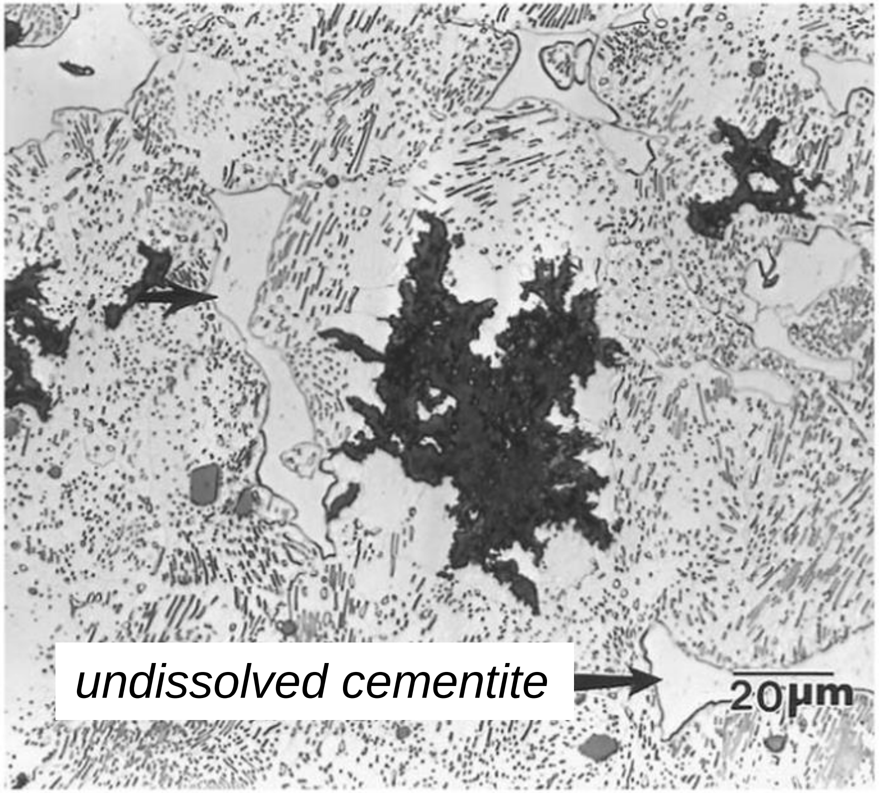
- Also known as temper graphite (TG) iron
- Production method:
  - Solidification as white iron (therefore not applicable to heavy sections)
  - Subsequent reheating and holding at temperatures between eutectoid and eutectic temperatures (typically 950 °C) for cementite decomposition to $\gamma$ + temper graphite ($1^{st}$ stage)
  - Controlled cooling to obtain the desirable matrix microstructure ($2^{nd}$ stage)
- Graphite morphology and mechanical properties similar to SG
- Applicable to thin sections where solidification as ductile iron is not possible
- Small amounts of elements such as Bi and Te are used to suppress graphite formation during solidification (0.01 wt.% Bi, 0.0005-0.001 wt.% Te)
- Elements such as B and Al are used to speed up the cementite decomposition during the $1^{st}$ heat treatment stage (0.001 wt.% B, 0.005 wt.% Al)

ASM Specialty Handbook: Cast Irons, ASM International, Materials Park, Ohio, 1996.

# Malleable Iron




*Temper carbon graphite surrounded by ferrite in a matrix of pearlite*




*Example of incomplete malleablization heat treatment.*

# Mealleable Iron: Automotive Applications

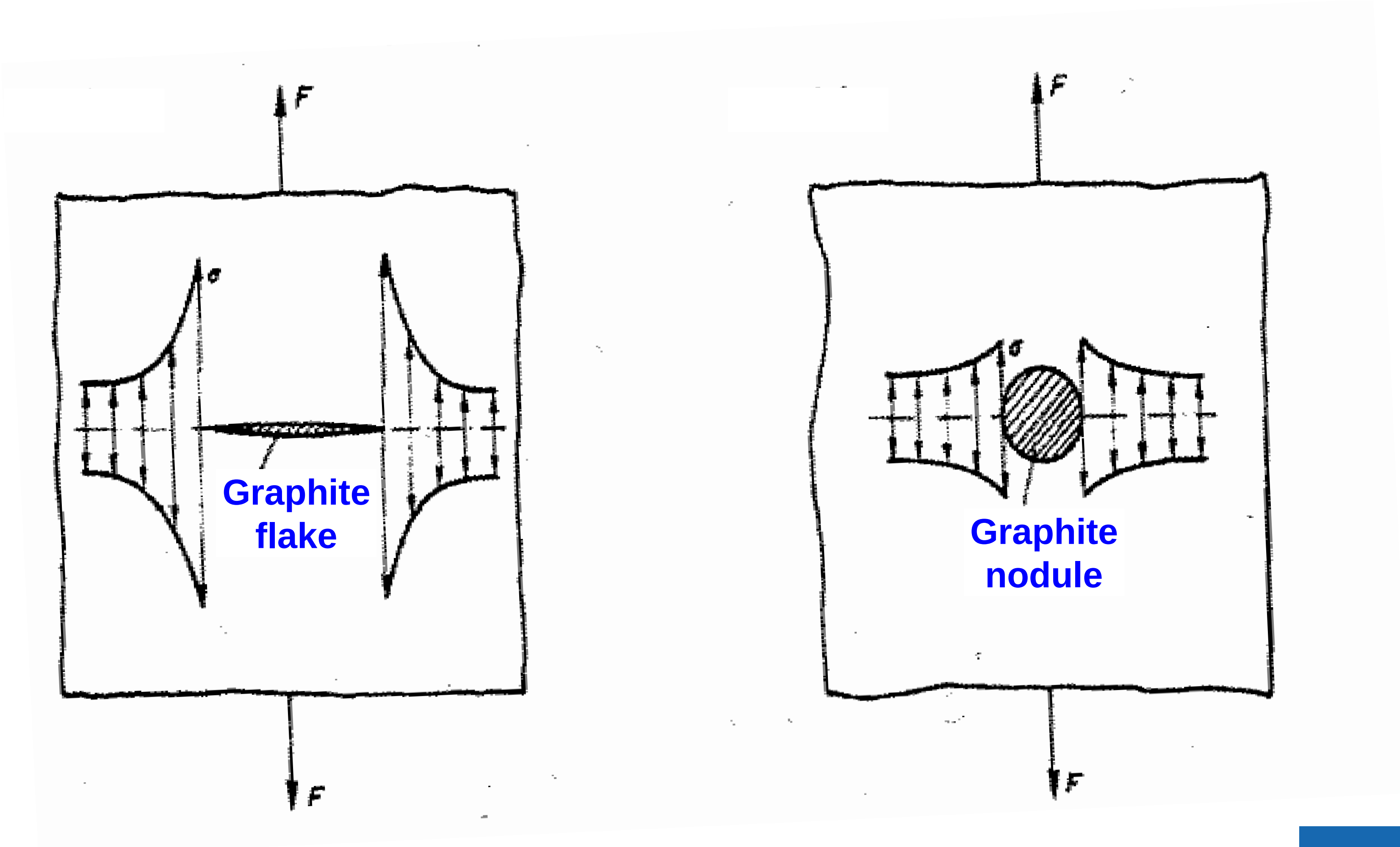



Steering gear housing

ASM Specialty Handbook: Cast Irons, ASM International, Materials Park, Ohio, 1996.

# Stress Concentration at Graphite Flakes

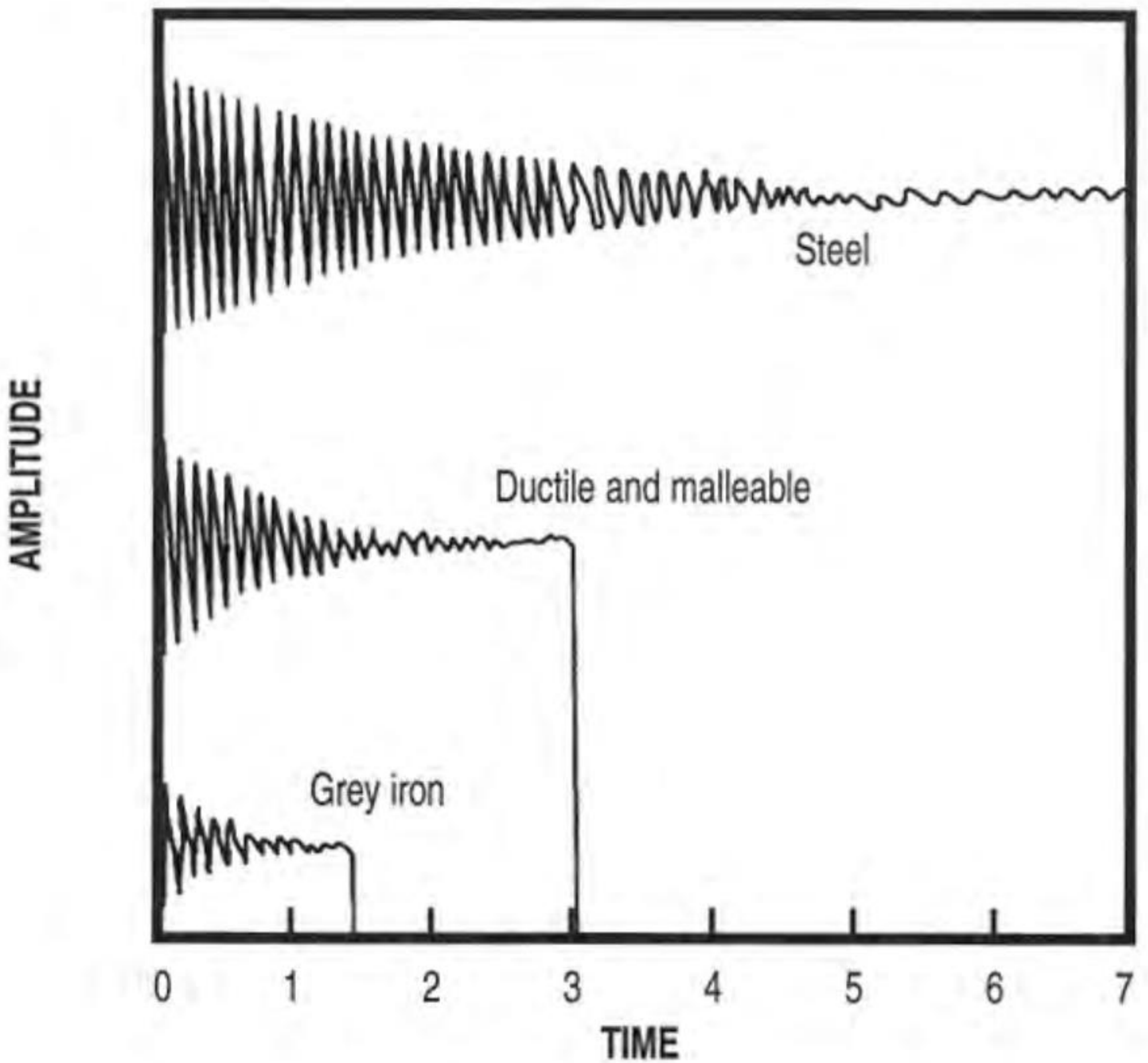
Graphite flakes act as internal defects and cause stress concentration. Stress concentration is especially pronounced in the case of flake graphite.




J. Peterseim, Lecture notes for Materials Engineering II (Werkstofftechnik II), FH Münster.

# Vibration Damping

Relative damping behaviors of steel, ductile & malleable irons and gray iron




http://www.petersonsteel.com/wp-content/uploads/2011/03/Reducing-Gear-Noise.pdf

# Steel vs. Cast Iron

## Rough comparison of the properties of steels and gray cast irons

| | Steel | Gray Cast Iron |
|---|---|---|
| **Carbon content** | less than about 2 wt.% | more than about 2 wt.% |
| **Eutectic solidification** | no | yes |
| **Formability** | high | low |
| **Castability** | low | high |
| **Consumption** | high | low |
| **Graphite in microstructure** | no | possible |
| **Machinability** | moderate | high |
| **Weldability** | high | low |