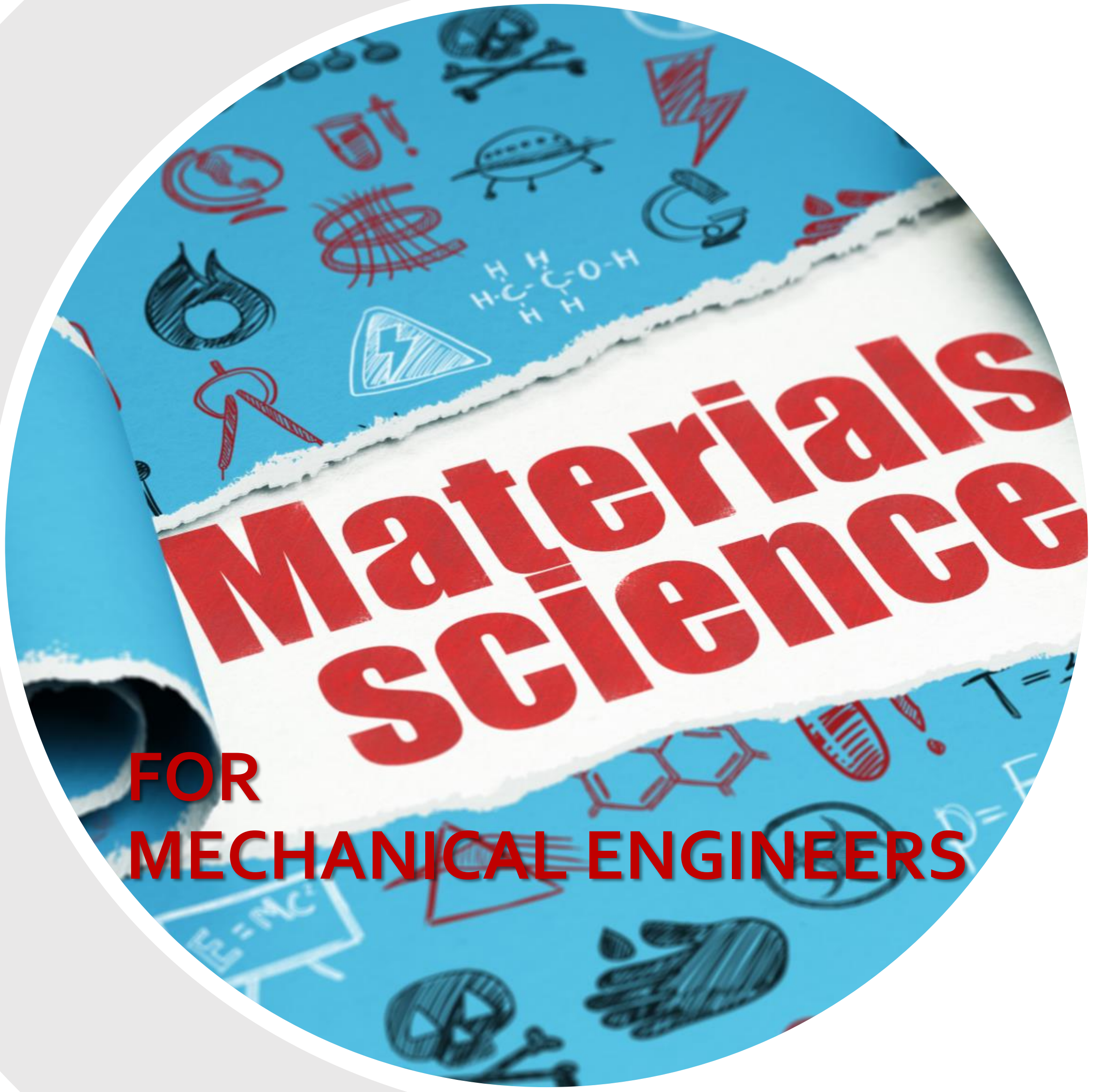


FOR
MECHANICAL ENGINEERS

Phase transformations

SPRING 2022-2023

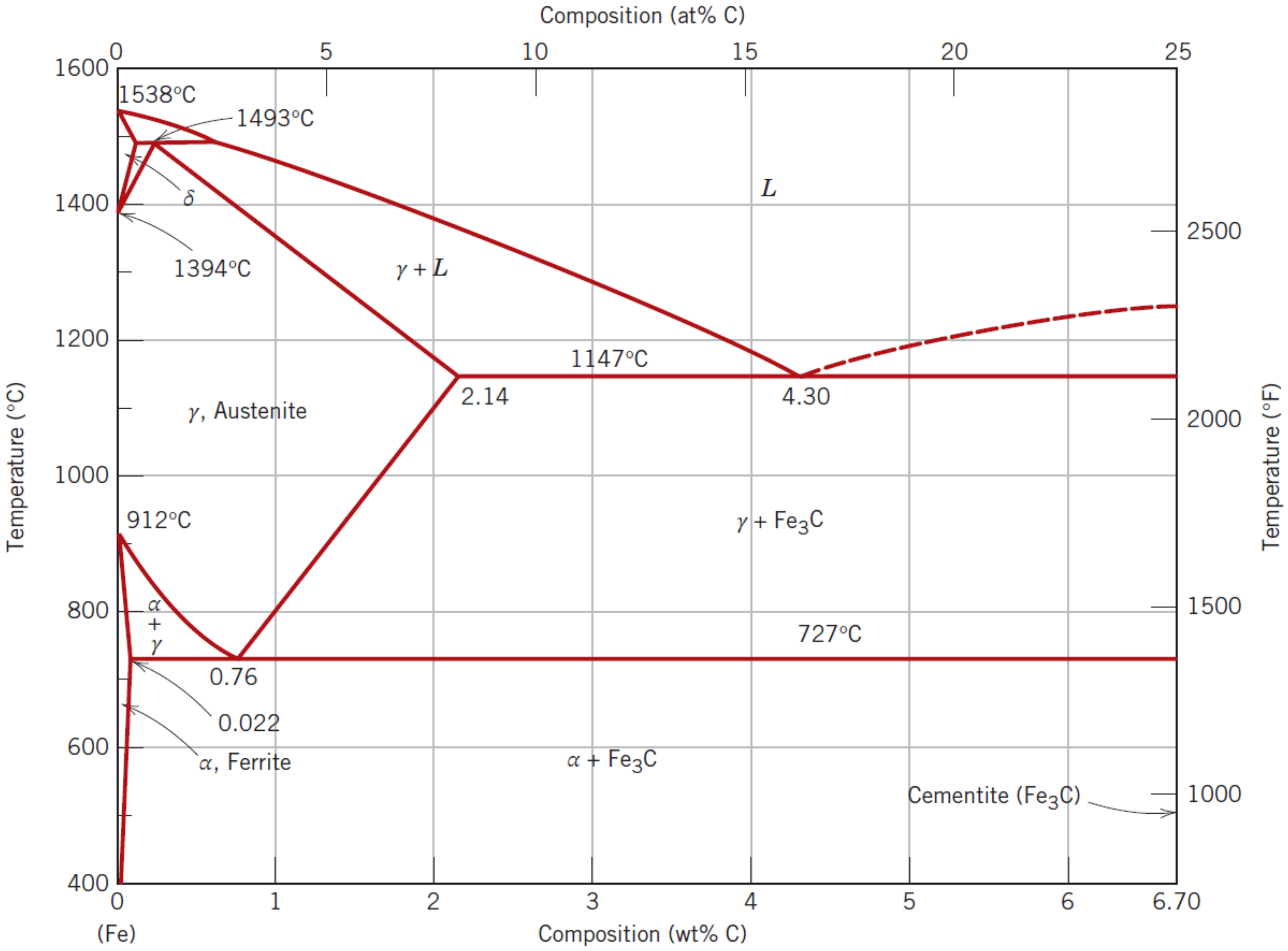
INTRODUCTION

The development of a set of desirable mechanical characteristics for a material often results from a phase transformation that is created by a heat treatment.

The time and temperature dependencies of some phase transformations are conveniently represented on modified phase diagrams.

It is important to know how to use these diagrams in order to design a heat treatment for some alloy that will yield the desired room-temperature mechanical properties.

For example, the tensile strength of an iron–carbon alloy of eutectoid composition (0.76 wt% C) can be varied between approximately 700 MPa (100,000 psi) and 2000 MPa (300,000 psi) depending on the heat treatment employed.



INTRODUCTION

With phase transformations, normally at least one new phase is formed that has different physical/chemical characteristics and/or a different structure than the parent phase.

Furthermore, most phase transformations do not occur instantaneously. Rather, they begin by the formation of numerous small particles of the new phase(s), which increase in size until the transformation has reached completion.

The progress of a phase transformation may be broken down into two distinct stages: **nucleation** and **growth.**

Nucleation involves the appearance of very small particles, or nuclei of the new phase (often consisting of only a few hundred atoms), which are capable of growing.

During the growth stage, these nuclei increase in size, which results in the disappearance of some (or all) of the parent phase.

The transformation reaches completion if the growth of these new-phase particles is allowed to proceed until the equilibrium fraction is attained.

NUCLEATION

Nucleation: localized formation of a distinct thermodynamic phase.

Nucleation can occur in a gas, liquid or solid phase. Some examples of phases that may form via nucleation include:

1) in gas: Creation of liquid droplets in saturated vapor;
2) in liquid: formation of gaseous bubbles, crystals (e.g., ice formation from water), or glassy regions;
3) in solid: Nucleation of crystalline, amorphous, and even vacancy clusters in solid materials. Such solid state nucleation is important, for example, to the semiconductor industry.

- Most nucleation processes are physical, rather than chemical.

- There are two types of nucleation: *homogeneous* and *heterogeneous*. The distinction between them is made according to the site at which nucleating events occur.

- Nucleation normally occurs at nucleation sites on surfaces contacting the liquid or vapor. Suspended particles or minute bubbles also provide nucleation sites. This is called heterogeneous nucleation

- For the homogeneous type, nuclei of the new phase form uniformly throughout the parent phase, whereas for the heterogeneous type, nuclei form preferentially at structural inhomogeneities, such as container surfaces, insoluble impurities, grain boundaries, and dislocations.

NUCLEATION

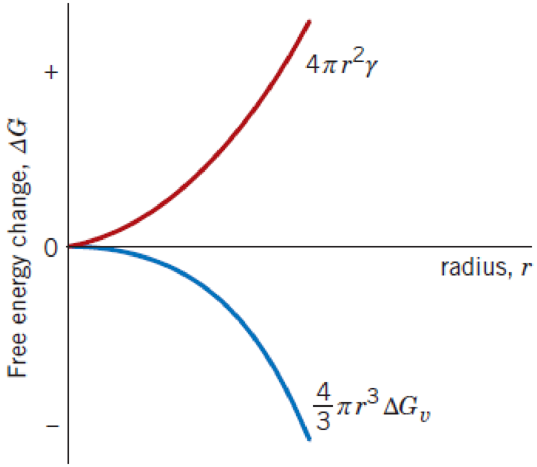
- Nucleation without preferential nucleation sites is homogeneous nucleation, It occurs spontaneously and randomly, but it requires superheating or supercooling of the medium.

- Compared to the heterogeneous nucleation (which starts at nucleation sites on surfaces), Homogeneous nucleation occurs with much more difficulty in the interior of a uniform substance. The creation of a nucleus implies the formation of an interface at the boundaries of a new phase.

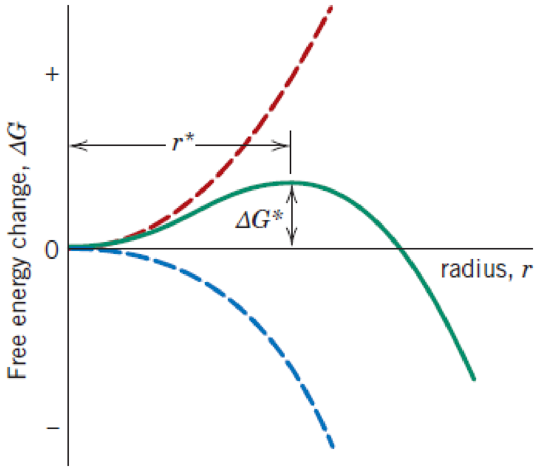
GROWTH

Growth

The growth step in a phase transformation begins once an embryo has exceeded the critical size, r^*, and becomes a stable nucleus.



Schematic curves for volume free energy and surface free energy contributions to the total free energy change attending the formation of a spherical embryo/nucleus during solidification.



Schematic plot of free energy versus embryo/nucleus radius, on which is shown the critical free energy change (ΔG^*) and the critical nucleus radius (r^*).

Note that nucleation will continue to occur simultaneously with growth of the new-phase particles; of course, nucleation cannot occur in regions that have already transformed into the new phase.

Furthermore, the growth process will cease in any region where particles of the new phase meet because here the transformation will have reached completion.

Particle growth occurs by long-range atomic diffusion, which normally involves several steps—for example, diffusion through the parent phase, across a phase boundary, and then into the nucleus. Consequently, the growth rate $G \cdot$ is determined by the rate of diffusion, and its temperature dependence is the same as for the diffusion coefficient.

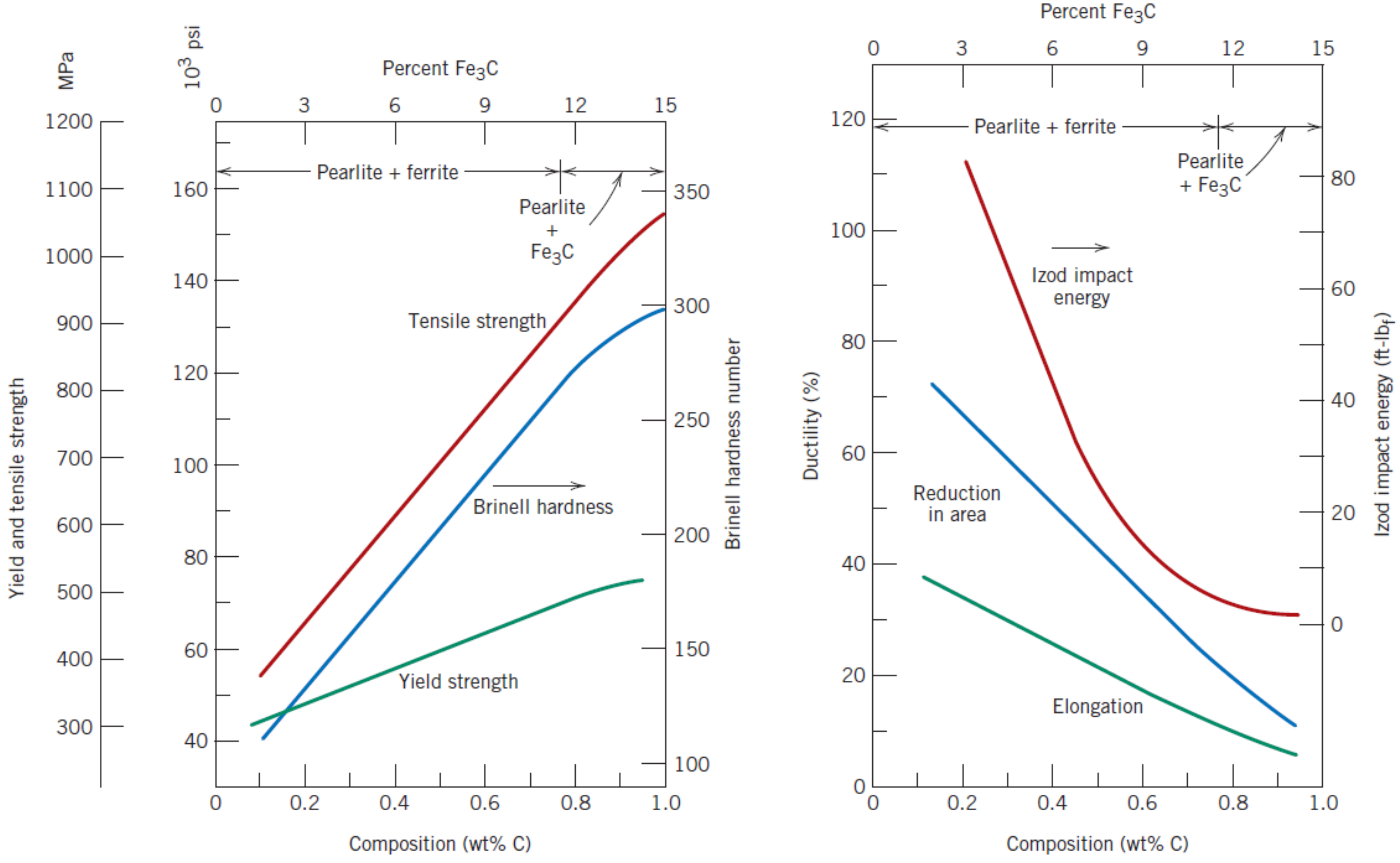
MECHANICAL BEHAVIOR OF IRON–CARBON ALLOYS

Pearlite

Cementite is much harder but more brittle than ferrite. Thus, increasing the fraction of Fe_3C in a steel alloy while holding other microstructural elements constant will result in a harder and stronger material.

Tensile and yield strengths and the Brinell hardness number are plotted as a function of the weight percent carbon (or equivalently as the percentage of Fe_3C) for steels that are composed of *fine pearlite*.

All three parameters increase with increasing carbon concentration. Inasmuch as cementite is more brittle, increasing its content results in a decrease in both ductility and toughness (or impact energy).



MECHANICAL BEHAVIOR OF IRON–CARBON ALLOYS

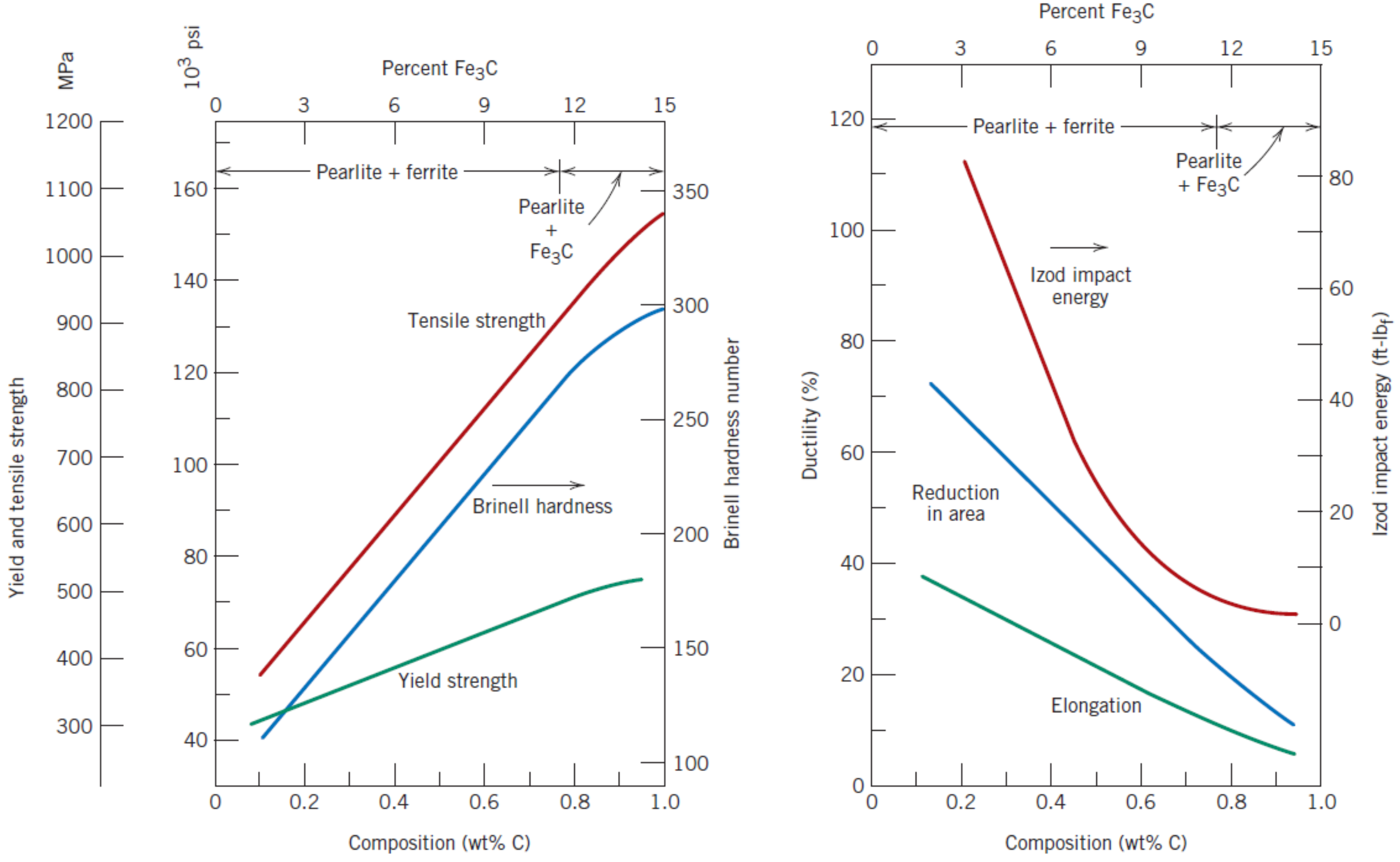
The layer thickness of each of the ferrite and cementite phases in the microstructure also influences the mechanical behaviour of the material.

Fine pearlite is harder and stronger than coarse pearlite, as demonstrated by the upper two curves, which plots hardness versus the carbon concentration.

The reasons for this behaviour relate to phenomena that occur at the α–Fe_3C phase boundaries.

First, there is a large degree of adherence between the two phases across a boundary.

Therefore, the strong and rigid cementite phase severely restricts deformation of the softer ferrite phase in the regions adjacent to the boundary; thus the cementite maybe said to reinforce the ferrite.



MECHANICAL BEHAVIOR OF IRON–CARBON ALLOYS

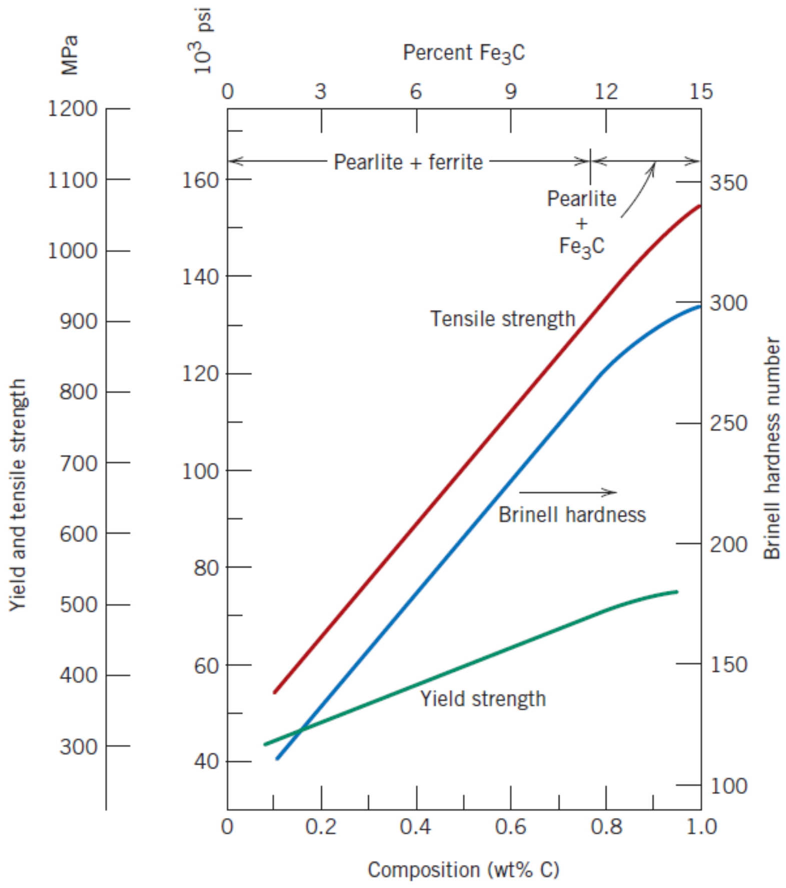
The degree of this reinforcement is substantially higher in fine pearlite because of the greater phase boundary area per unit volume of material.

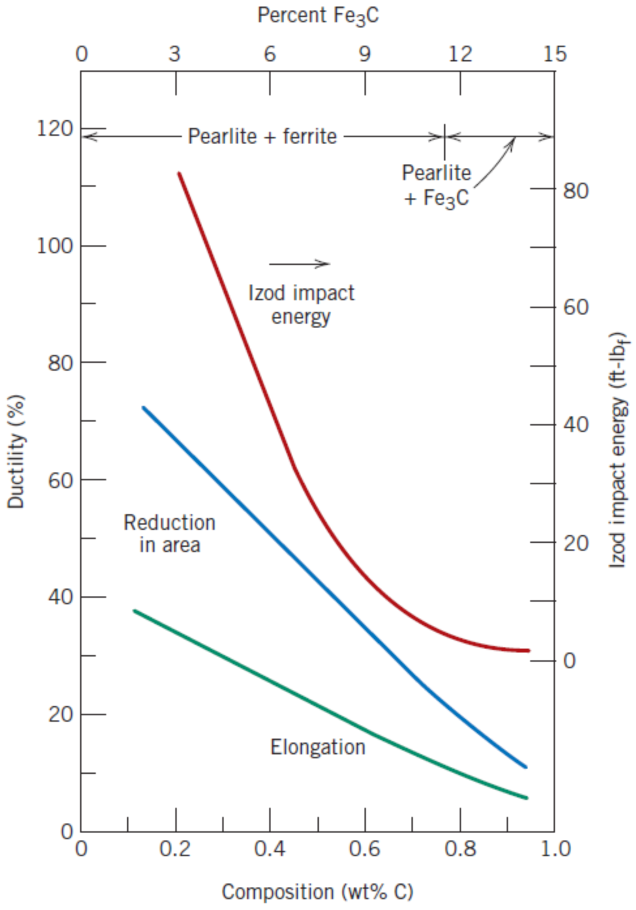
In addition, phase boundaries serve as barriers to dislocation motion in much the same way as grain boundaries.

For fine pearlite there are more boundaries through which a dislocation must pass during plastic deformation.

Thus, the greater reinforcement and restriction of dislocation motion in fine pearlite account for its greater hardness and strength.

Coarse pearlite is more ductile than fine pearlite, as illustrated, which plots percentage reduction in area versus carbon concentration for both microstructure types.





MECHANICAL BEHAVIOR OF IRON–CARBON ALLOYS

This behaviour results from the greater restriction to plastic deformation of the fine pearlite.

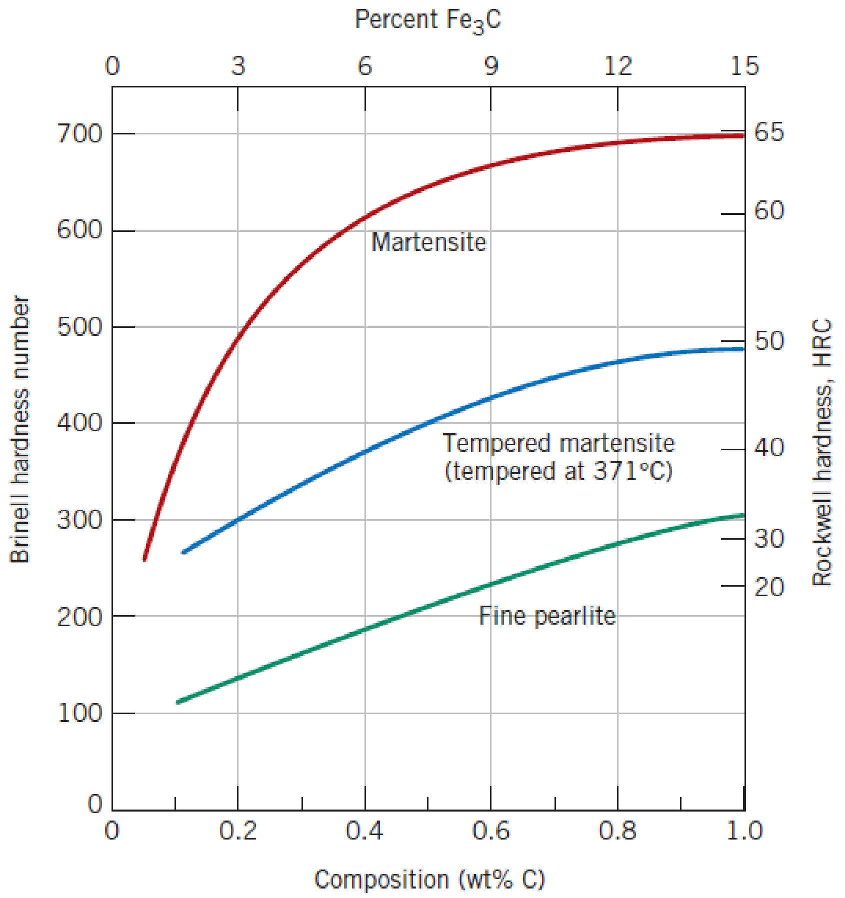
Martensite

Of the various microstructures that may be produced for a given steel alloy, martensite is the hardest and strongest and, in addition, the most brittle; it has, in fact, negligible ductility.

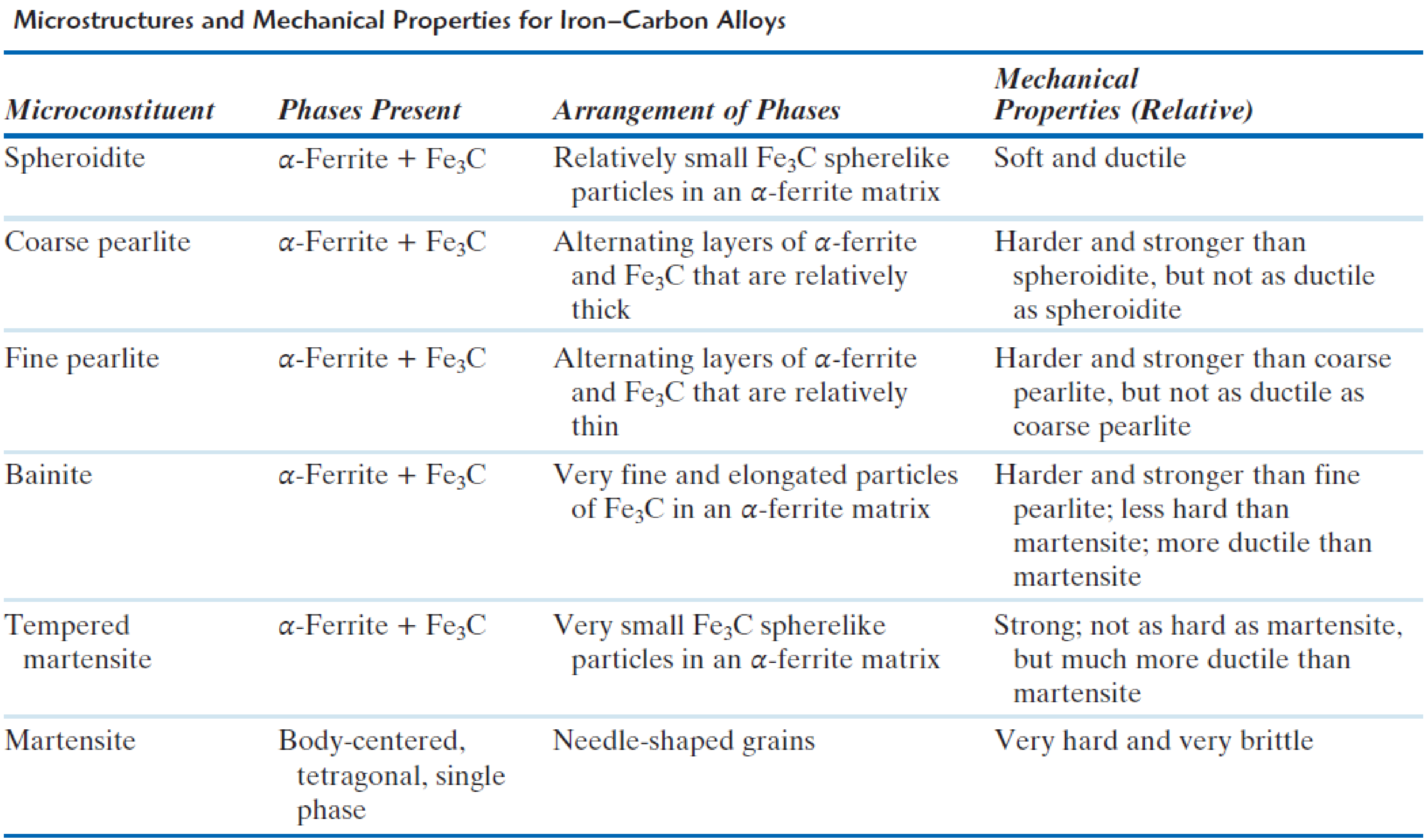
Its hardness is dependent on the carbon content, up to about 0.6 wt% as demonstrated, showing the hardness of martensite and fine pearlite as a function of weight percent carbon.

In contrast to pearlitic steels, the strength and hardness of martensite are not thought to be related to microstructure.

Rather, these properties are attributed to the effectiveness of the interstitial carbon atoms in hindering dislocation motion, and to the relatively few slip systems (along which dislocations move) for the BCT structure.



MECHANICAL BEHAVIOR OF IRON–CARBON ALLOYS*



Microstructures and Mechanical Properties for Iron–Carbon Alloys

Microconstituent	*Phases Present*	*Arrangement of Phases*	*Mechanical Properties (Relative)*
Spheroidite	α-Ferrite + Fe_3C	Relatively small Fe_3C spherelike particles in an α-ferrite matrix	Soft and ductile
Coarse pearlite	α-Ferrite + Fe_3C	Alternating layers of α-ferrite and Fe_3C that are relatively thick	Harder and stronger than spheroidite, but not as ductile as spheroidite
Fine pearlite	α-Ferrite + Fe_3C	Alternating layers of α-ferrite and Fe_3C that are relatively thin	Harder and stronger than coarse pearlite, but not as ductile as coarse pearlite
Bainite	α-Ferrite + Fe_3C	Very fine and elongated particles of Fe_3C in an α-ferrite matrix	Harder and stronger than fine pearlite; less hard than martensite; more ductile than martensite
Tempered martensite	α-Ferrite + Fe_3C	Very small Fe_3C spherelike particles in an α-ferrite matrix	Strong; not as hard as martensite, but much more ductile than martensite
Martensite	Body-centered, tetragonal, single phase	Needle-shaped grains	Very hard and very brittle

See photomicrographs at: https://callumjodwyer.wixsite.com/beng-project/mech-properties-of-iron-carbon-alloys

*Check the file labelled “Iron-Carbon Alloys” on MS Teams for more information

SHAPE-MEMORY ALLOYS