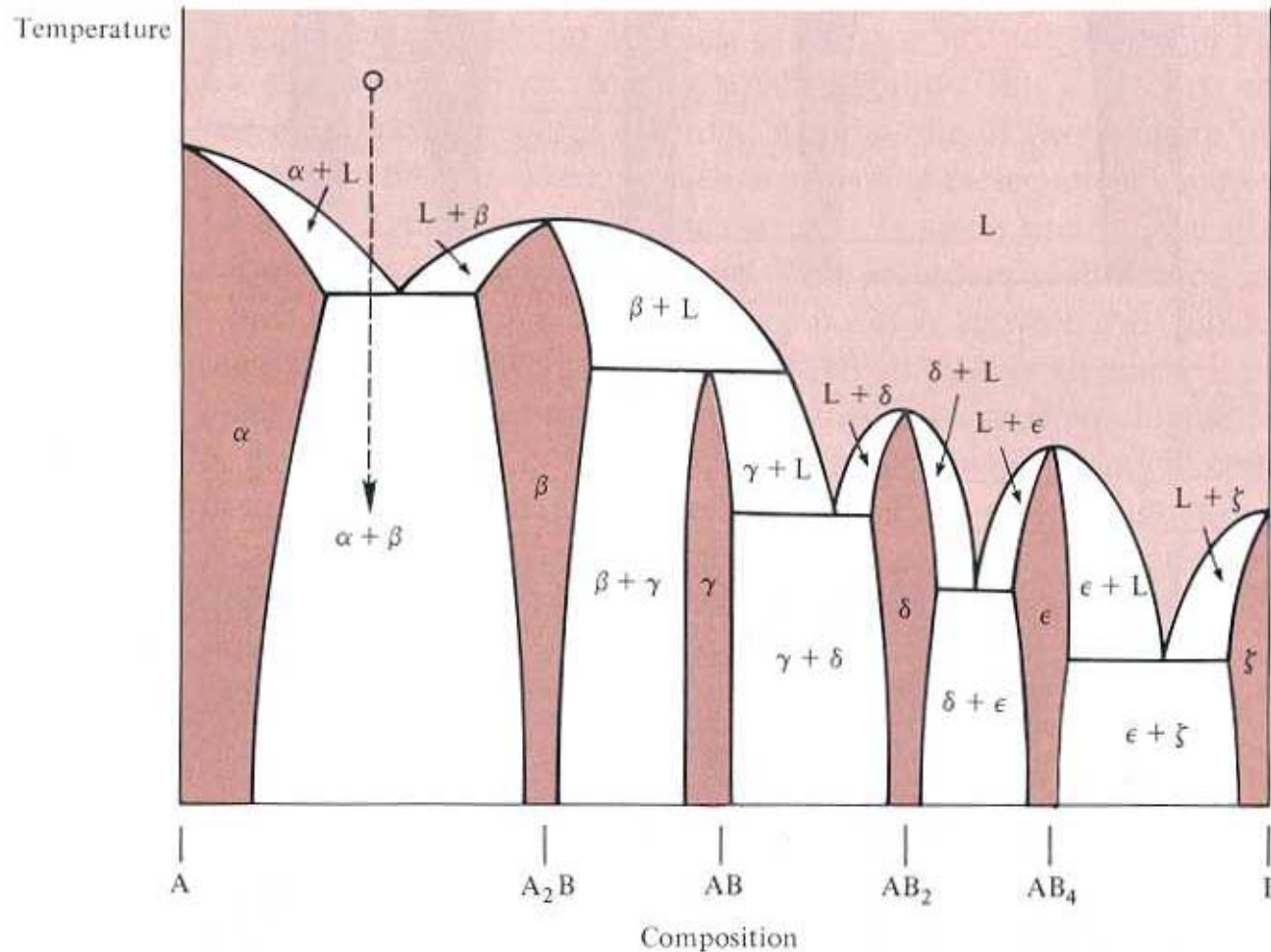


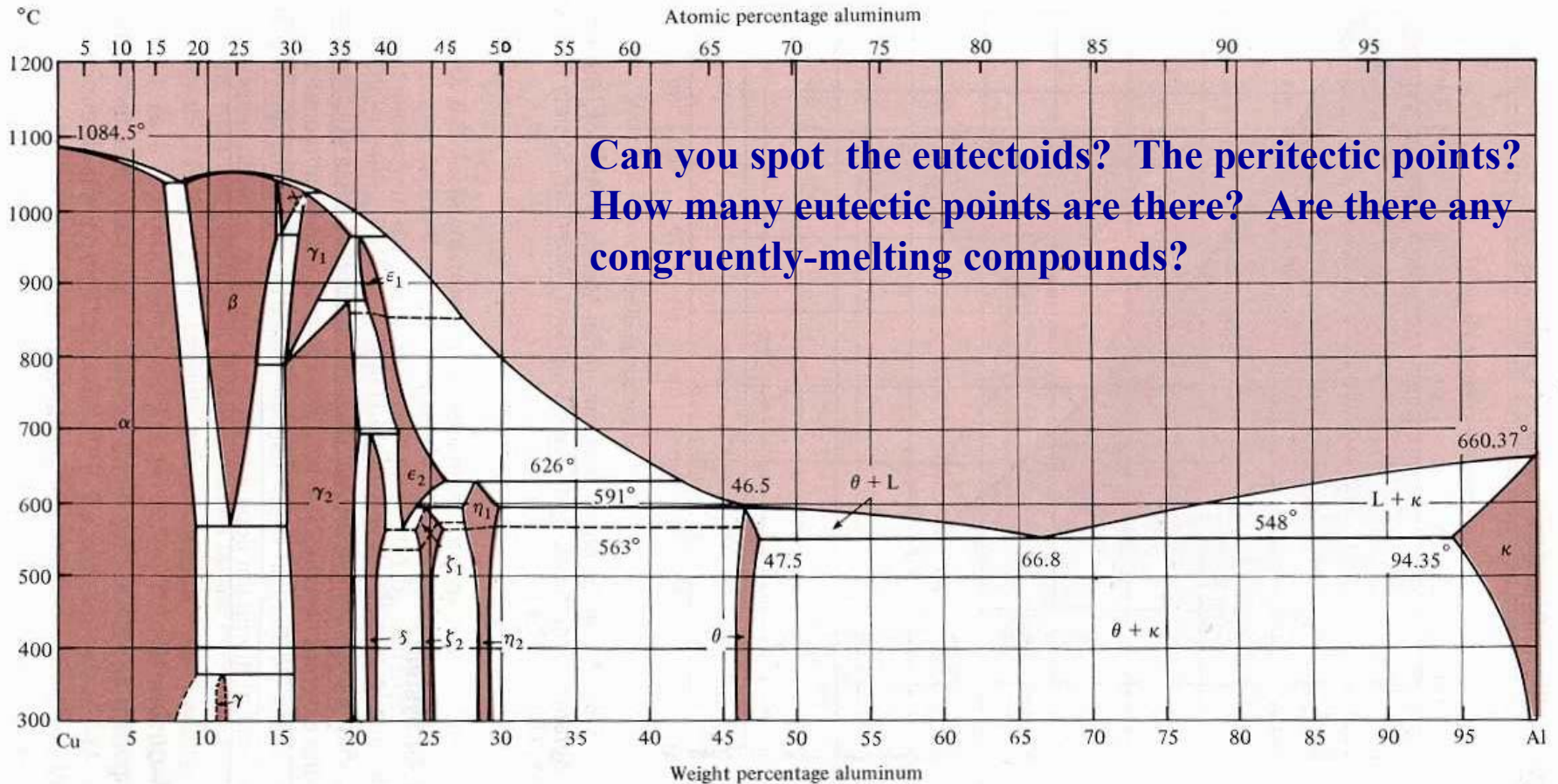
Binary Phase Diagrams - II



Note the alternating one phase / two phase pattern at any given temperature

Time-Temperature-Transformation Diagrams

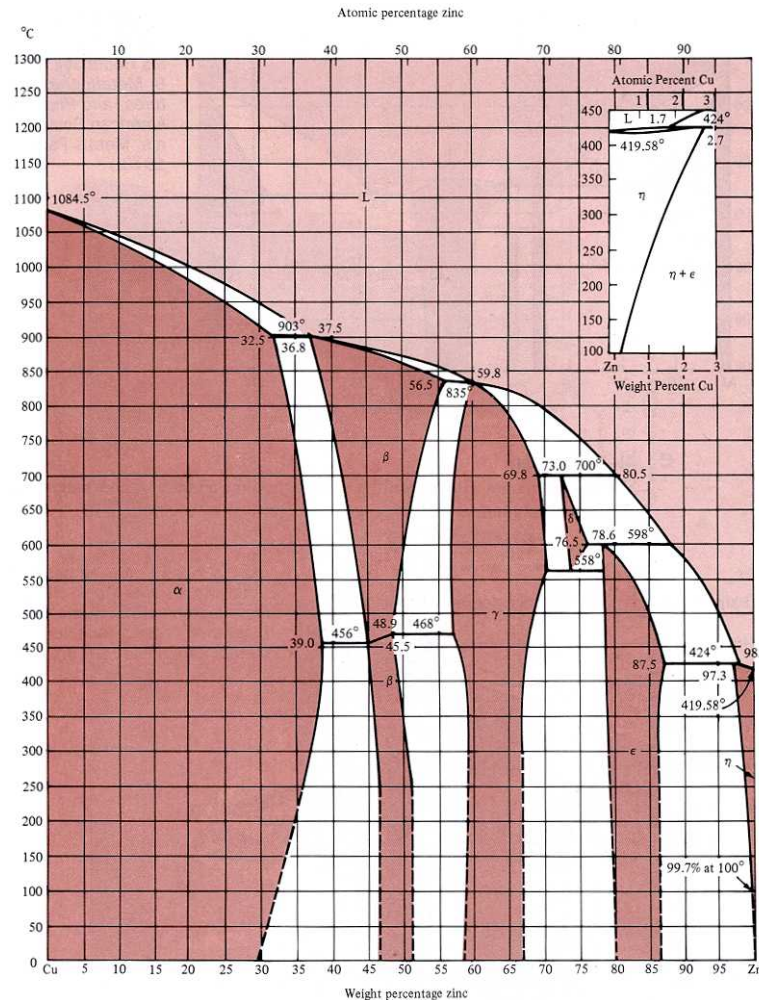
Binary Phase Diagrams - Cu-Al



Note the alternating one phase / two phase pattern at any given temperature

Time-Temperature-Transformation Diagrams

Binary Phase Diagrams - Cu-Zn



How many single phase regions are there in this phase diagram?

The answer is 7

Note the alternating one phase / two phase pattern at any given temperature

Time-Temperature-Transformation Diagrams

Definitions

Iron:

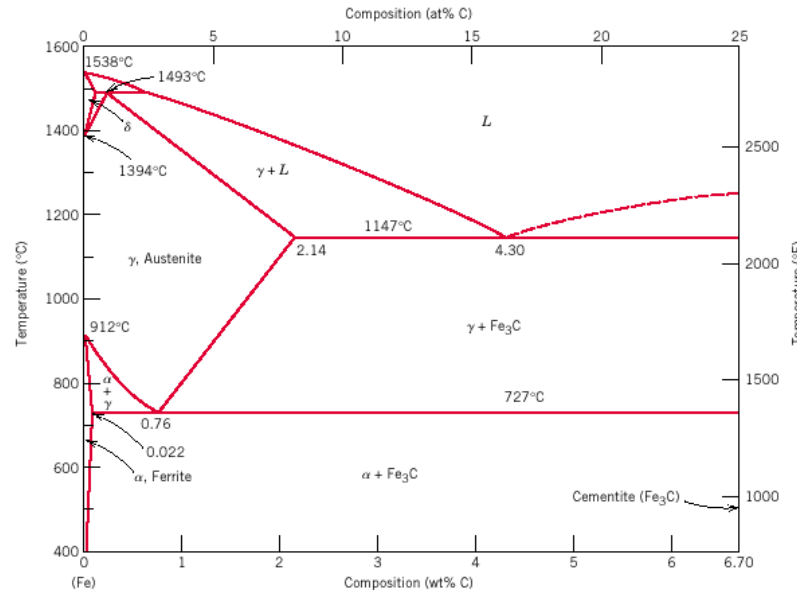
As an alloy, typically containing up to 0.008 wt. % C.

Steel:

Iron with a carefully controlled quantity of interstitial carbon, typically between 0.008 wt. % C to ~ 2.14 wt. % C. The microstructure generally consists of ferrite + cementite.

Cast Iron:

A form of impure iron containing between 2.5 wt. % and 4.5 wt. % C. The high carbon content makes it relatively hard and brittle and it tends to crack under tension.



‘Dead-mild’ steel:

Fe containing up to 0.15 % C. Used where high ductility is necessary during forming (auto bodies, tin cans, nails, and wire).

Mild steel:

Fe containing 0.15 to 0.3 wt. % C. Wrought forms are used for many structural members, shafting, levers, and forging.

Medium-carbon steel:

Fe containing 0.4 to 0.6 wt. % C. Widely used for axles, connecting rods, gears, rails, etc.

Tool steels:

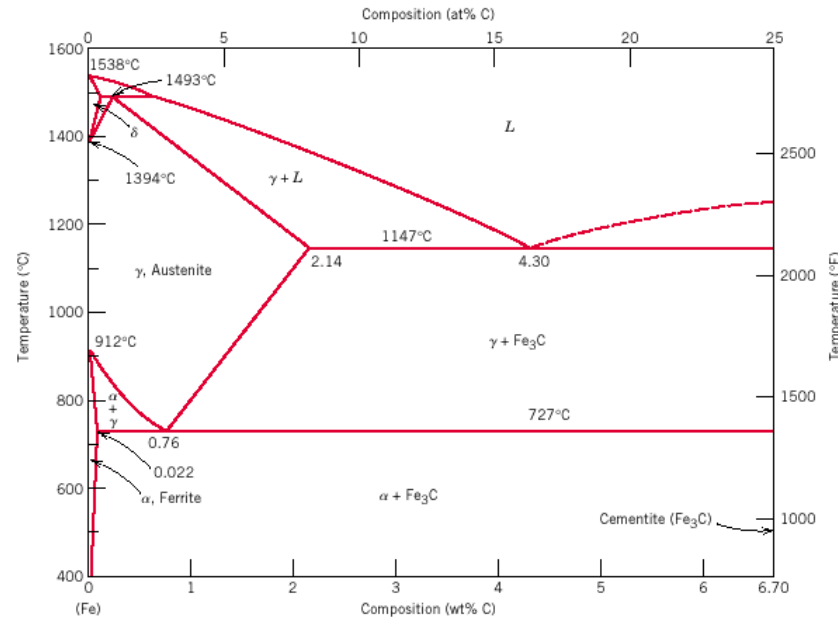
Fe containing 0.6 to 1.5 wt. % C. Can be hardened for use in machining and forming

Time-Temperature-Transformation Diagrams

More definitions

Ferrite (α):

Ferrite (or alpha-iron, α) is the low temperature, BCC phase of iron, in which up to 0.022 wt. % C is soluble. α is one product of transformation of austenite upon cooling through the eutectoid temperature (727°C). α transforms to FCC above 912°C.



Austenite (γ):

Austenite (γ) is a high temperature, FCC phase of iron, in which up to 2.14 wt. % C is soluble (at 1147°C). Austenite is nonmagnetic and has a high ductility. γ can be retained in microstructures by rapid cooling.

Cementite, Fe_3C :

Cementite is the name given to Fe_3C , corresponding to Fe-6.7 wt. % C. It is one product of the transformation of austenite upon cooling through 727°C. Cementite is a hard and brittle compound.

Pearlite:

Pearlite is a two-phase mixture of ferrite (α) + cementite (Fe_3C) resulting from cooling of γ below the eutectoid temperature. Note: this is NOT A PHASE, but a mixture of two phases.

Phase Transformations in Metals

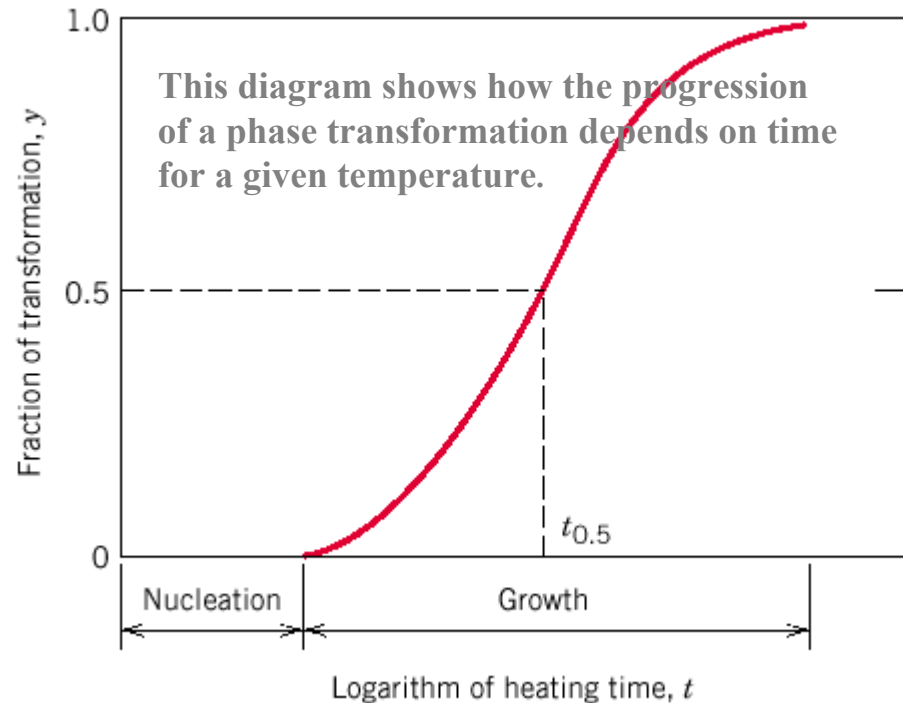
Examples:

A cup of water, if placed outside on a cold winter day, does not solidify immediately; rather, it may take a few minutes for the process to complete. As it becomes progressively colder outside, the time required for the water to completely solidify decreases.

Similarly, if an ice cube is placed in an oven, it does not melt instantly, but does so gradually, over the span of a few seconds to a few minutes. As the temperature of the oven is increased, the time required for the ice cube to melt decreases.

Central concept:

The examples illustrate the fact that a finite amount of time is required for phase transformations to occur, and that the length of time for this to occur depends on temperature



Phase transformations in solids do not occur instantaneously, but are time dependent!

Phase Transformations in Metals

Types of phase transformations:

I. Diffusion-dependent with no change in composition:

solidification (or melting) of pure metals

allotropic transformations (BCC Fe $\rightarrow$ FCC Fe)

recrystallization and grain growth

II. Diffusion-dependent with change in phase composition

non-equilibrium freezing of a two (or more) component alloy

eutectic and eutectoid reactions

III. Diffusionless

martensitic transformations, metastable phases (to be discussed)

Time-Temperature-Transformation Diagrams

Phase Transformations in Metals

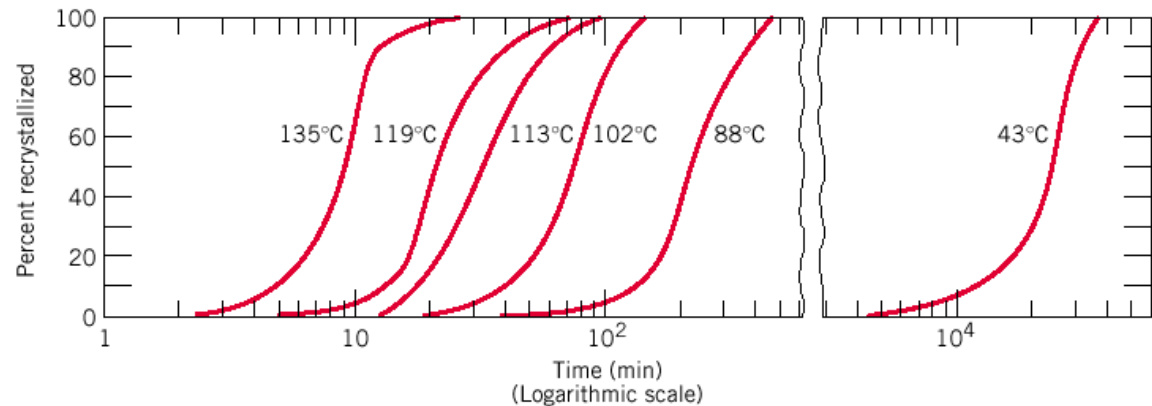
Example:

A good example of the effect of temperature on the time required for phase transformation completion is provided by the recrystallization of copper.

Significance:

In all phase transformations, growth of the new phase is always preceded by nucleation. Most nucleation is heterogeneous, that is, induced by the presence of impurity atoms, voids, cracks, or other defects in the container walls, etc. Once nuclei form, growth of the new phase is described by *kinetics*, or the rate of transformation.

Recrystallization of copper as a function of time at various temperatures



Notice how the time required for this particular phase transformation increases as the temperature is lowered; taking three orders of magnitude longer at 43 deg. C than at 135 deg. C

In other transformations, the time required for completion increases with increasing temperature. One example is freezing (solidification). (It takes longer for water to solidify at 31 deg. F than it does at -25 deg. F)

Phase Transformations in Fe-C Metals

Theory:

The relationship between fraction of transformation, y , and time, t , is given by: $y = 1 - \exp(-kt^n)$

where k and n are constants. This is known as the **Avrami equation**.

Rate constant:

“rate of transformation,” r , is defined as

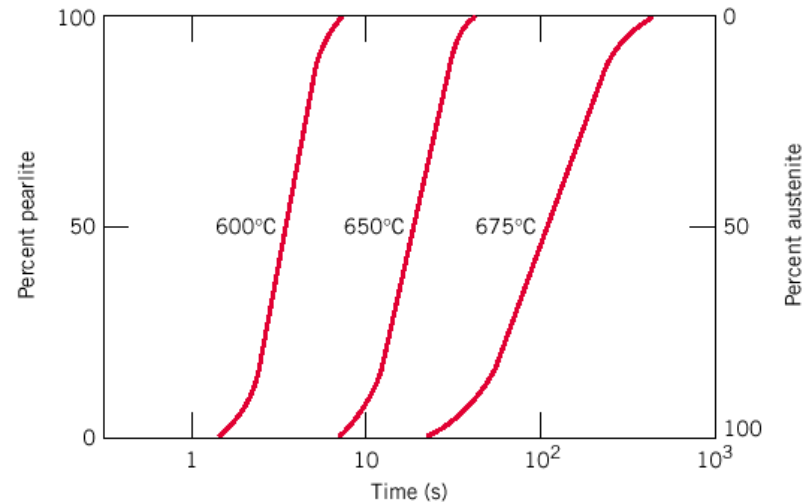
$$r = \frac{1}{t_{0.5}}$$

where $t_{0.5}$ is the time for the transformation to reach 50% of completion.

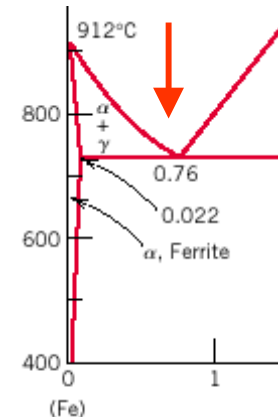
Most reactions are “thermally activated,” that is, are described by an equation of the form

$$r = A \exp(-Q/RT)$$

Note that higher temperatures result in slower transformation kinetics of austenite to pearlite



Austenite to pearlite transformation curves for Fe-C alloys of the eutectoid composition (0.76 wt. % C) at various isothermal temperatures.



Time-Temperature-Transformation Diagrams

Phase Transformations in Fe-C Metals

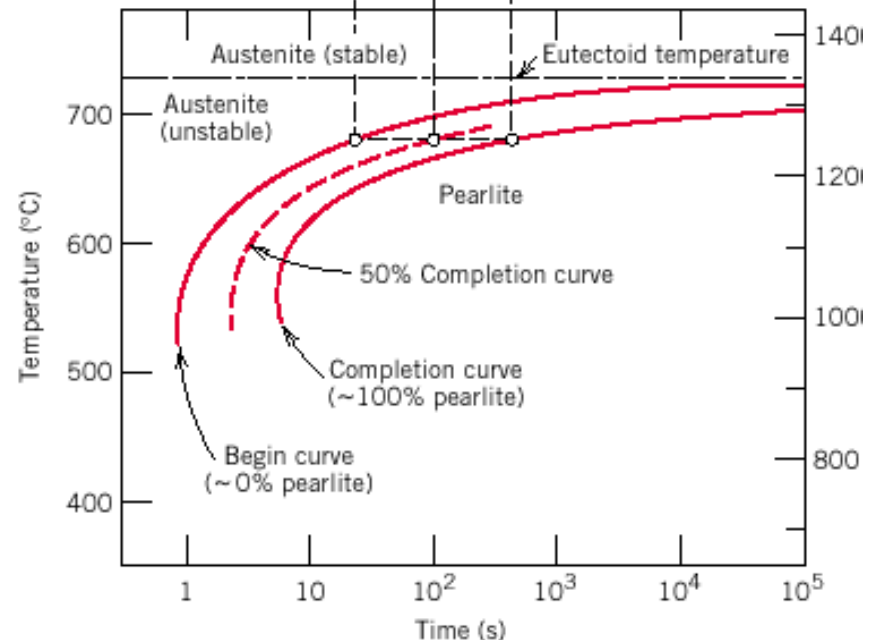
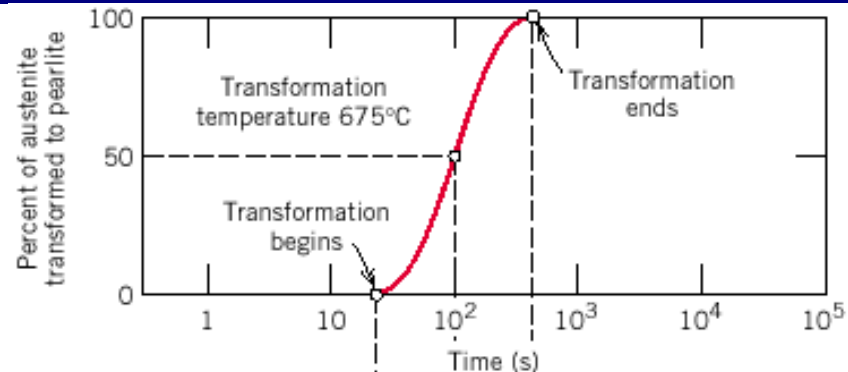
Motivation:

Recall what the previous transformation curves looked like. →

We would like to display this information for all temperatures in a more concise and compact manner.

TTT diagrams:

This diagram, called a time-temperature-transformation (or TTT) diagram, shows the time required to start, reach the halfway point, and complete the transformation from austenite (γ) to pearlite for temperatures above 500°C. (Obviously there will be no transformation above the eutectoid temperature because austenite is the stable phase above this point.)



Time-Temperature-Transformation Diagrams

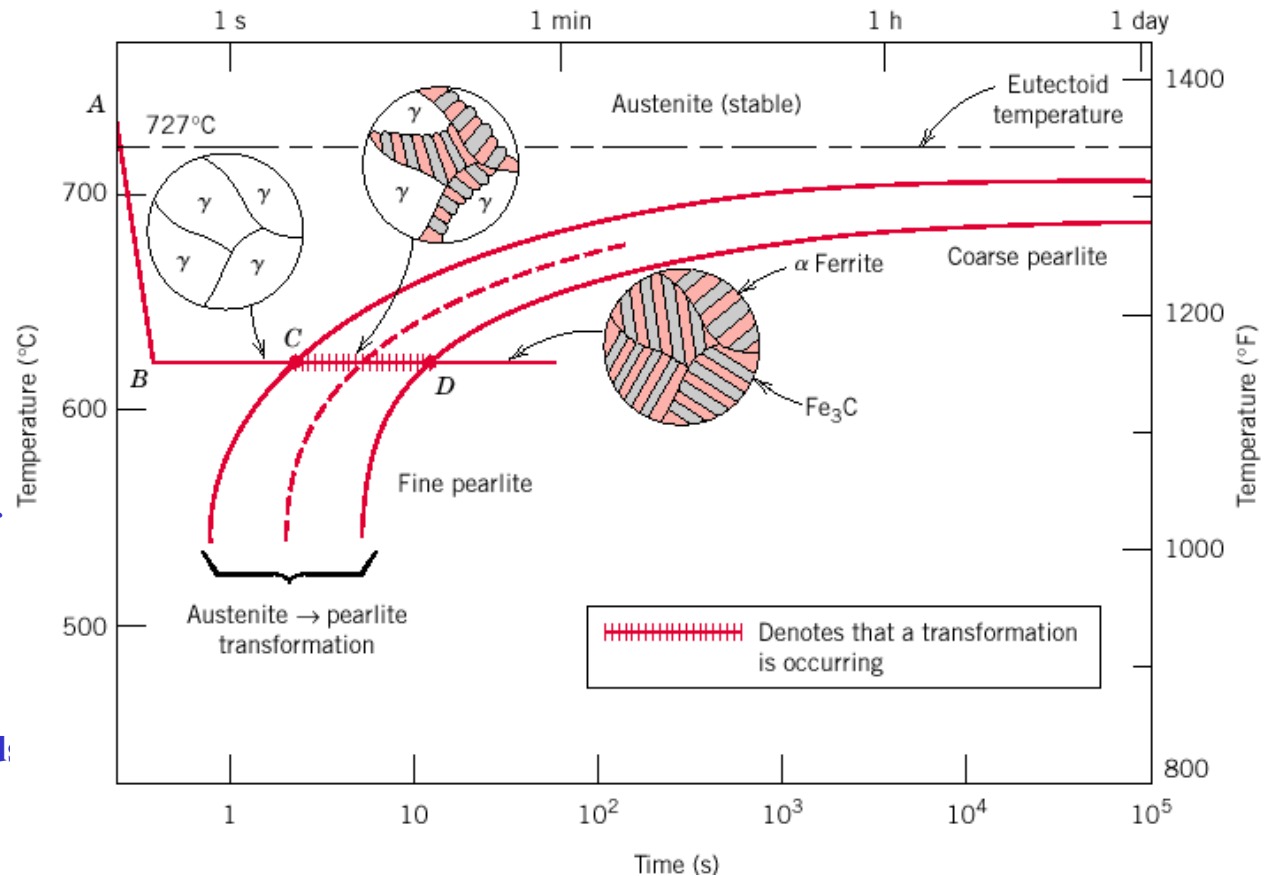
Phase Transformations in Fe-C Metals

Example:

Let's take a closer look at how the TTT diagram works for one particular situation; we quickly cool γ to 620°C and then hold the temperature constant.

Interpretation:

After reaching the desired temperature, it takes a couple of seconds before transformation begins. Pearlite begins to nucleate from the γ grain boundaries. The transformation is 50% complete after ~ 7 seconds and 100% after ~ 20 seconds. Note: time is plotted on a log scale.



Note the distinction between “coarse pearlite” and “fine pearlite”...

Phase Transformations in Fe-C Metals

pearlite spacing:

Spacing of the alternate layers of a eutectic or eutectoid microstructure depends on the temperature. For temperatures just below the eutectoid, the spacing is coarse. At temperatures significantly below the eutectoid, the spacing is noticeably more fine.

Theory:

Eutectoid (or eutectic) lamellae require diffusion in each of the solid bands or layers. At lower temperatures, diffusion rates decrease which mean atoms cannot travel as far over a certain time interval. Consequently, we see only relatively small distances between successive bands.



“High” temp / large spacing
“coarse pearlite”



“Low” temp / fine spacing
“fine pearlite”

Time-Temperature-Transformation Diagrams

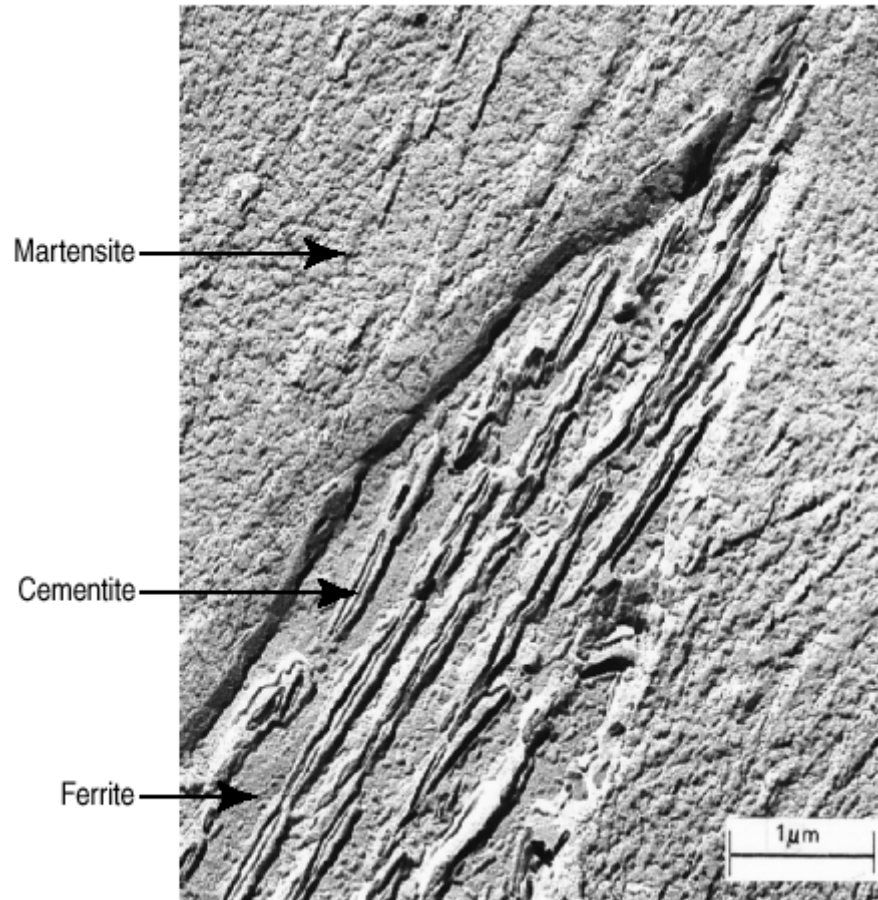
Phase Transformations in Fe-C Metals

Bainite:

Suppose we cool austenite to a temperature below $\sim 540^{\circ}\text{C}$. Rather than producing ever-finer pearlite, we now see a different arrangement of the ferrite and cementite phases. “Bainite” is a name associated with a particular arrangement of ferrite and cementite resulting from cooling eutectoid γ at 200°C to $\sim 540^{\circ}\text{C}$.

Upper Bainite:

If cool eutectoid γ between 300°C and 540°C , we have UPPER BAINITE. This consists of thin strips (laths, or needles) of α , separated by elongated cementite. The laths are very small, ~ 1 micron. The matrix is martensite (TBD)



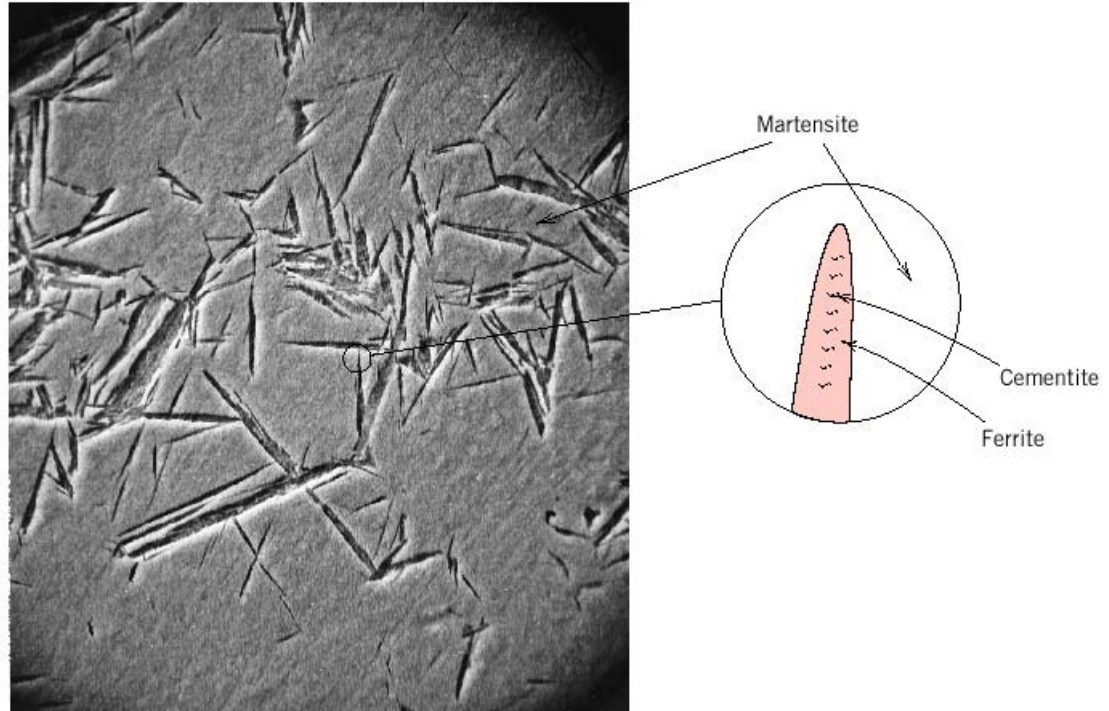
Phase Transformations in Fe-C Metals

Lower Bainite:

If cool eutectoid γ between 200°C and 300°C, we have LOWER BAINITE.

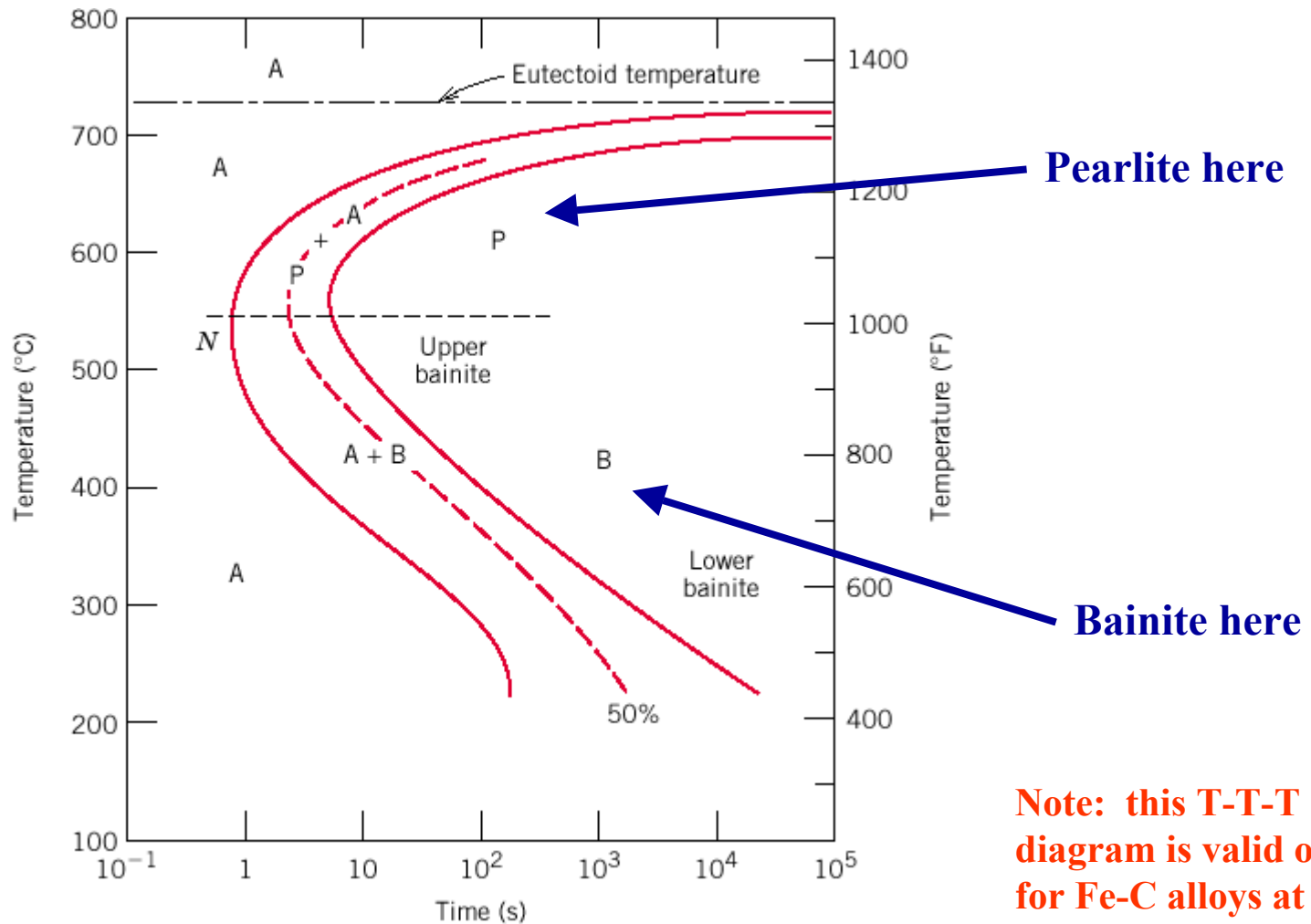
Lower Bainite consists of thin plates of α , containing very fine rods or blades of cementite, as shown in the diagram. Unlike upper bainite, the cementite is contained entirely within the plates of ferrite. The cementite is too small to see without the aid of an electron microscope.

The matrix is martensite (TBD)



The nucleation and growth of upper and lower bainite can be shown on a T-T-T diagram:

Phase Transformations in Fe-C Metals



Note: this T-T-T diagram is valid only for Fe-C alloys at the eutectoid composition!