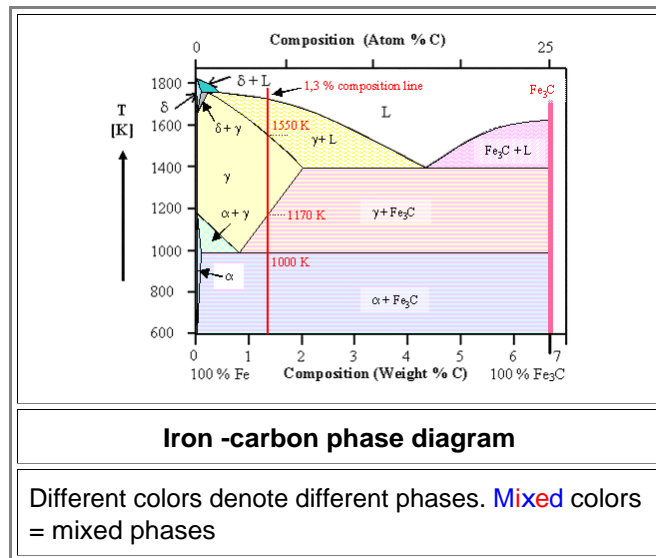


## 6.1.2 Reading Phase Diagrams: Single Phases and Boundaries

Now let's go to work. First I redraw the iron-carbon phase diagram in a way that will help you to better appreciate the different phases.



What we have now is a simple rule: **different** phases = **different** colors. **Mixed** colors = **mixed** phases. You remember, of course, what a phase is? Thanks; otherwise [go back to chapter 2.3.1](#).

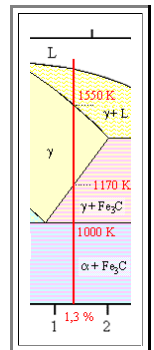
Let's start to "read" the iron-carbon phase diagram. First we pick some particular concentration of carbon, let's say **1,3 %**. I like that concentration because it is easy to draw into the phase diagram as a vertical line. The relevant part is shown on the right for immediate reference. Along the red line we have the same composition but different temperatures.

From 600 K (328 °C; 620 °F) and below (not shown) up to just about 1000 K (727 °C; 1341 °F) we have the **mixed** phase "blue and pink".

At 1000 K (727 °C; 1341 °F) there is a [phase transformation](#) to the mixed phase "pink and yellow".

This first phase transformation is the most important one for you, the ancient (or modern) smith. Most of the time when you stick your work piece into the hot coals on your hearth, you do it to induce this phase transformation. We will call the temperature of about 1000 K (727 °C; 1341 °F) where this phase transformation occurs "**the**" **transition temperature** (usually abbreviated **A<sub>1</sub>**) because it is the most important one.

If you keep going up with the temperature, another phase transformation occurs around 1170 K (897 °C; 1447 °F). The mixed phase "pink and yellow" now transforms to the pure phase "yellow". Then, around 1550 K (1277 °C; 2331 °F), we hit the mixed phase "yellow-white" and around 1730 K (1457 °C; 2655 °F), it's all white, meaning that the phase transformation at this temperature simply denotes complete **melting** because white is the **liquid phase**, always abbreviated "**L**".



It's time to look a bit more closely at what, exactly **defines a single phase**. What I offered you [long ago](#) in this respect is a bit too wishy-washy to suffice us here. So here goes.

**A phase is a region of space where all physical properties of a material (e.g. density, hardness, chemical composition) are essentially uniform.**

A phase therefore is a piece of material that is chemically uniform, physically distinct, and often (or at least in principle) mechanically separable from its environment.

Now we know what the **lines in a phase diagram** mean: They denote "where", i.e. at what compositions and temperature, **a phase transformation takes place**. They separate different phases or different mixtures of phases in composition - temperature "space".

If we do the same procedure for pure iron (all the way to the left for 0 % carbon), we run through three single phases (blue, yellow, bluish) as we go up with the temperature. The small part of the phase diagram on the right shows only the first two phases.

We know already what they signify: blue = bcc (body centered cubic) crystal, yellow = fcc (face centered cubic), bluish = bcc once more.

Of course, we can only have single phases in this case, and it's time to give them names. The ironclad rule is that solid phases are *always* assigned a Greek letter. For historical reasons, a phase might have a more or less fancy name *in addition*. Sometimes there are even two names, often involving dead white guys. What we have in the case of pure iron is:

- Blue =  $\alpha$  (**alpha**) phase = **ferrite** = bcc iron crystal .
- Yellow =  $\gamma$  (**gamma**) phase = **austenite** = fcc iron crystal .
- Bluish =  $\delta$  (**delta**) phase = bcc crystal once more; too unimportant to rate a name.

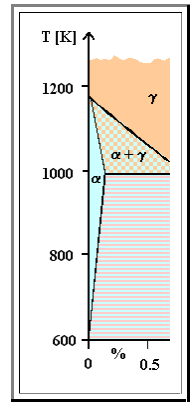
What we have in the case of iron plus some carbon is exactly the same. As long as you "are" within a one-phase region, shown here by one color, you have the phase going with that color. To make that perfectly clear, I repeat the list above for iron *plus* some carbon:

- Blue =  $\alpha$  (**alpha**) phase = **ferrite** = bcc iron crystal *with some dissolved carbon*.
- Yellow =  $\gamma$  (**gamma**) phase = **austenite** = fcc iron crystal *with some dissolved carbon*.
- Bluish =  $\delta$  (**delta**) phase = bcc crystal once more; too unimportant to rate a name, *with some dissolved carbon*

Names like *Ferrite* or *austenite* thus do not refer to *pure* iron but to iron with some *dissolved carbon* in it. How much carbon that could be at some given temperature is shown by the single-phase regions in the phase diagram. Generally speaking, the composition of *single phases* in binary alloys is always A (or B) with *dissolved* B (or A, respectively) in it.

This is important. We must allow single phases to contain two kinds of atoms as long as they are atomically "mixed". This is, after all, the **definition** of a phase as given above, if you think about it. Dissolved single atoms are distributed uniformly and cannot be separated.

Let's repeat:



**"Ferrite", "austenite" and so on does not mean *pure* iron with some specific crystal structure, but iron with some specific crystal structure *and* some dissolved carbon in it**

How much carbon can be *dissolved* in a phase is something that the phase diagram tells you.

**Dissolved** means that the foreign atoms are sitting as individuals in the crystal (interstitial places for carbon in iron) in some random distribution. In other words: they are extrinsic point defects. Any point inside the blue area in the phase diagram above (the  $\alpha$ -phase or ferrite phase) denotes an allowed combination of the **solid solution** of carbon concentration and temperature. The carbon then is definitely dissolved.

Note that if it is hot enough, the carbon atoms don't "sit" still but move around at random. They diffuse, as we called that process. We will also have vacancies moving around and thus the atoms don't sit perfectly still either.

Nevertheless, a snapshot would always look like our old figure with just the right number of carbon atoms showing. The composition, in other words doesn't change by all this moving about.

So any point within the slender blue region in the phase diagram denotes alpha phase or ferrite, and ferrite always has a **bcc** lattice and various but invariably *small* carbon concentrations (including zero) at some temperature.

Any point in the yellow region denotes the gamma phase or austenite, and austenite always has a **fcc** lattice and various carbon concentrations from zero to a maximum of about 2 % at some temperature.

The name *ferrite* derives from the Latin "ferrum" for iron. It is always a bcc crystal and the best it can do with respect to dissolving carbon is about 0.1 % around 1000 K (727 °C, 1341 °F). This we call the **solubility limit**.

Austenite was named after Sir William Chandler Roberts-Austen, a British metallurgist (1843-1902), who conducted extensive studies on the effects of impurities on the mechanical properties of pure metals. Austenite or the  $\gamma$  phase is always a fcc crystal. It can dissolve carbon much better than ferrite - almost 2 % around 1400 K (1127 °C, 2061 °F), and still about 0,7 % around 1000 K (727 °C, 1341 °F).

The difference in carbon dissolving "power" between austenite and ferrite is at the core of steel making and blade forging, and we will spend much time at unraveling the consequences.

Now let's look at the **melting point** of iron with some carbon in it. The line between the yellow-white and the white "L" region gives us that information. L = "Liquidus" always denotes the **liquid phase** (why use a simple word if there is a Latin one?). Of course the liquid phase can also contain carbon.

The line separating the liquid phase from the other phase "below" that line gives the melting point as a function of the impurity concentration = carbon concentration in our case here .

As I claimed [long ago](#) and explained to some extent [not so long ago](#), the melting point comes down indeed with increasing carbon content to a minimum of 1403 K (1130 °C, 2066 °F) for a carbon concentration just a bit above 4 wt%.

So an iron-carbon alloy with about 4 % carbon would be your **ideal composition** for **casting iron**. Why? There are actually *two* good reasons:

1. **First:** at that composition you have the *lowest* melting point you will ever find in the Fe - C system. Low melting points are good because it is [not so easy](#) to achieve temperatures above 1100 °C (2012 °F).
2. **Second:** this is an *eutectic composition*.

??? If this looks Greek to you, that's because it is.

Alright. I admit that even a decent general education in most countries does not include ancient Greek anymore. Even one of my daughters, who did time in a classical German "Gymnasium" and certainly learned ancient Greek (together with a lot of Latin and a bit of (ancient, of course) Hebrew), didn't know what "*eutectic*" meant. So you are definitely excused for not knowing that either.

I will get to it [soon](#). But first we look once more at what happens at the 1,3 % carbon concentration I marked with a red line in the phase diagram above.

For a composition of 1,3 wt% carbon in iron, the phase just below the line that defines the melting point is a *mixed phase*, denoted by  $\gamma + L$ . That can only mean a *mixture* of *solid*  $\gamma$  phase or austenite and the *liquid*.

That's not as strange as it might appear: At 0 °C (32 °F) you can keep a mixture of liquid water and ice (= solid water) stable as long as you like. Try it. You are allowed to use whisky instead of water.

Inside the ( $\gamma + L$ ) mixed phase you can keep a mixture of liquid steel and solid steel stable as long as you like (and can take the heat). If you go to different locations *inside* the mixed phase region, you only change the relative amounts of liquid and solid (lots of ice and a little whisky or lots of whisky and a little ice). But whatever you have is still a mixed phase.

When you, the smith, make a sword blade, you have steel with some defined carbon concentration that you subject to various temperatures while forging it. Assume for simplicities sake that the carbon concentration doesn't change during forging, all the heating and cooling simply means that you *move up and down* a vertical line in the phase diagram.

If you go above 1000 K (727 °C, 1341 °F) for carbon concentrations in the usual range (about 0,1 wt% - 2 wt%), your steel will run through at least one phase transformation. And you will go above that temperature for sure; doing that it is what forging is all about.

So here comes an epiphany in one line that you should read out loud:

**What you have on your anvil above about  
1000 K is a **completely different** material  
from what you have at room temperature.**

How different is "*completely different*"? Well, you will agree that a diamond is completely different from a lump of coal (at least your wife will), so why should it be otherwise with ferrite and austenite?

They are two *different* phases of the same material (iron + some carbon) and there is no reason whatsoever that their properties couldn't be just as different as those of graphite and diamond. Their electrical conductivities or the magnetic properties, for example are different, and so are their mechanical properties like hardness.

It's only because nobody has much use for a 1000 K hot iron wire or magnet that we don't care much about these differences and are not aware of them.

Nevertheless, the lattice type, the ability to dissolve carbon, and the mechanical "hardness" and the general deformation behavior are quite different in ferrite or austenite. Austenite is actually a bit harder than ferrite at high temperatures. Both phases, however, are far softer at high temperatures than ferrite at low temperature That is the major reason why you heat your steel when you want to shape it by forging.