6.2 Things Get Complicated

6.2.1 Creamy or Chunky?

Many materials consist of hard and soft phases, for example chunky chocolate ice-cream, peanut butter, nacre ("mother of pearl") or steel. Hard particles —chocolate chips, peanuts, calcium phosphate or cementite—are embedded in the soft smooth background of ice cream, butter, proteins or ferrite, respectively.

- So let me ask you: As far as steel for *your* sword blade is concerned: do *you* want it creamy or chunky? Do you want a lot of very small particles or rather a few large ones in your ice-cream, excuse me, ferrite?
  Since you only have a certain amount of the hard stuff, you can turn it into a lot of little particles, into just a few big ones, a mixture of big and small ones, or anything in between.

What's the best?

- This is an extremely far-going question, that's why it's emphasized.
  The answer is clear, of course: It's a matter of *taste* as far as chocolate ice cream or peanut butter is concerned. As far as nacre or steel is concerned, it's also a matter of taste with regard to the *properties* you want.
  As far as steel is concerned, the general agreement is that you want it *hard* but *ductile* .
  Hardness , as we have learned before, is simply a measure of the yield stress, the force per area at which dislocations begin to move. Hard but still ductile steel means that it's difficult but not impossible for the dislocations to move. If dislocation movement is impossible (like in cementite) you have a brittle material, and that's not what we want.
  The long and short of this is that we must allow the dislocations to move around a bit. Movement shouldn't be easy, however, and we want to be in full control.
  It's a bit like keeping teenagers under control. If you ground them completely, things break. You must let them roam around a bit but it is wise to slow them down, e.g. by keeping in control of car keys and money.
  For slowing down dislocations in steel, we use our hard cementite particles.

Let's generalize this insight into the next epiphany:

Hardening steel (or any other metal for that matter) means to put obstacles in the way of its dislocations.

Let's review the tools we have for this. There are essentially five major types of obstacles that make dislocation movement difficult but not impossible:

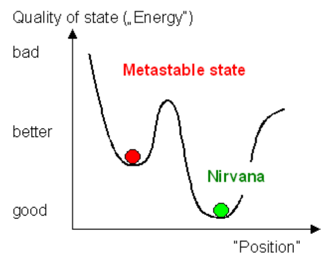
1. Extrinsic point defects or foreign atoms dissolved in the matrix.
2. Precipitates, made from the foreign atoms we have inside the steel.
3. Grain boundaries.
4. Other dislocations.
5. A *metastable* fourth phase of iron called "**martensite**".

- Martensite (whatever that is), our fifth tool, is rather unusual and specific to steel (and some other crystals). It is especially tricky but provides for the ultimate in steel hardness (and increased brittleness).
  I you want to use **martensite hardening** you really must torture the crystal. You must force it to make something it really, really hates: martensite!

Now what is a **metastable phase**? It cannot be part of a real nirvana state because the system, by definition, could do better.

- A metastable phase is a phase that is not really stable at the given temperature but bound to decay into the really stable phase, meaning a phase that is part of a nirvana state.
  A metastable phase is often just a *transient structure* encountered on the way from one clean and desired phase to another one. In other words, it's something like a teenager—no longer a child but not yet an adult.

A **diamond**, by the way, is a metastable phase of carbon. So you teenagers out there can stay cool and refrain from sending me hate mail. Metastable states can be quite valuable and they can last a long time. In this case we treat them like a stable phase and use them even in phase diagrams.
Nevertheless, they are *not* the nirvana states or the best of all possible states. You might perceive them in terms of an extremely simple diagram:



Stable and Metastable States

- The diagram shows the free energy; the lower the better. The black curve shows what is possible. Moving to the right towards nirvana, you might get stuck in a side valley that does not have the lowest possible free energy. If it is difficult to get out of there, you are stuck in a *metastable* state.
Words like "position" and "way" do not exclusively refer to common space but might be metaphors for more abstract entities.
- A system of atoms as seen by the second law can behave just like a "mass point", a ball, or *you* in a mountain range. You want to be as far down as possible. Gravity pulls us down, and the nirvana state we try to achieve is way down.
However, you might get stuck in a side valley that does not have the lowest possible free energy. If it is difficult to get out of there, you are stuck in a *metastable* state. You only get out of it and over to the deepest point by first *worsening* your situation again. You must first go *up* to be able to get *down* to nirvvana.
If you don't have the energy any more to do this you are now trapped in the metastable state until you can get it up again. That might take quite a while, depending on circumstances.

  If we now look at a diamond crystal instead of you, it is pretty much the same thing. The fcc diamond lattice is not what the carbon atoms would like to have. They would much prefer the hexagonal graphite structure. But to get "there", a lot of reshuffling of atomic arrangements is required and at room temperature the energy for doing that is just not available. Diamond is thus a metastable structure of carbon. And, as women know, diamonds are girl's best friends. And that's because they last forever. Well, if kept around room temperature, they last at least as long as the girl and that is good enough. Heat it up sufficiently (= supplying energy) and they will turn into graphite.
Cementite in iron, by the way, is also only metastable. The stable state of carbon in iron would be graphite. Cementite is, however, stable enough not to do anything in your and my and our offsprings lifetime, so we do not need to worry about this.

I will come to martensite in more detail shortly when I discuss hardening mechanisms in detail. Since hardening steel is a major part of the smith's art, I will dedicate a whole chapter to the basics of hardening mechanisms in steel or just about any crystal

- But before I do that, I'll answer that pressing question that must have been on the back of your mind all this time:

What happens when we go from the liquid phase to a two-phase region?