8.4.3 Feeling Stressed?

We are now *almost* done with the easy stuff. We only need to look at one last thing that happens when we cool down some steel:

Cooling down produces a lot of stress in the steel.

- What does that mean? Imagine some small volume somewhere inside your blade. If there is stress acting on that little piece of your steel, it means that mechanical forces are acting on it; pushing, pulling or shearing, trying to change its shape.
- Why should there be stress during cooling? There are two main reasons:

  1. The different phases of steel have different **specific volumes**. That's a general and well-known thing. The liquid phase of any *metal* always occupies a larger volume than the solid phase, so why should austenite and ferrite occupy the same volume for the same number of iron atoms involved?
     When the phase changes from ferrite to austenite or vice verse, the concomitant volume changes will simply generate **phase change stress**.
  2. The inside always cools down more slowly than the outside. In other words: different parts of your blade have different temperatures during cooling. We say there is a **temperature gradient**. When things get hotter, their volume expands; we named that thermal expansion. When things get colder, their volume must shrink accordingly. During cooling the outside is always colder then the inside and thus has shrunken more than the hot inside part. The cold outside then presses on the inside like a vice trying to compress it, the hot inside tries to pull the dole outside apart. In other words: During cooling your blade (or microchip) will experience compressive stress in the inside and tensile stress on the outside. The faster you cool, the bigger the temperature gradients, the bigger the **temperature gradient stress**.

So there is unavoidable stress during cooling down. What does it mean? You should be able to answer that question yourself. The answer is:

- Look at the stress -strain diagram for the kind of steel you have!
  If the yield strength is surpassed locally, the steel will deform plastically, generating a lot of dislocations in the process. Too much stress and it will simply fracture. You get more local stress if you cool down quickly, of course.
  The effects for you, the ancient smith, are clear. Upon (fast) cooling your steel or blade may:

  - *Bend*, i.e. deform plastically. Only if the unavoidable plastic deformation is exactly symmetrical (the left part wants to bend to the left, the right part to the right; the effects then cancel if they are of equal but opposite strength), you won't notice that.
    Katanas do bend during quenching, If you did everything right, they bend the way you like.
  - *Shatter*, i.e. fracture into two or more pieces. Not good for blade making but good for testing the steel you have.
  - *Fracture* only *internally* . In other words, you have cracks crisscrossing the steel, but the whole thing still sticks together. If those cracks are only in the inside where you can't see them, you are now about to produce an inferior blade that probably will kill its owner in a fight because it breaks on heavy impact.

- You realize, of course, that the occurrence of stress during cooling is not limited to iron and steel. The reasons given for **thermal stress** are extremely general; the second one applies to *any* material. Cool a brittle material like glass too fast and it will not only fracture, it will explode. Cool silicon too fast and it either fractures or, as long as the average temperature is still high, it deforms plastically. In both cases the silicon is now worthless for the product you had in mind.

Science Link
Thermal stress

The End is Near!

At this point we are completely done with the *easy* stuff. I will now move on to the tricky stuff, hoping that you see that as a promise and not as a threat.
The first step in doing this is to admit that:

There is no such thing as plain carbon steel!

- If you believe that some piece of steel is plain carbon steel, you are wrong.
You *always* have some "dirt" or impurities in your "plain" carbon steel besides the alloying element carbon. Since even minute amounts (like 0,001 %) of something *might* make a big difference to what you get when forging a sword blade, you just have to live with some uncertainty. Mostly, however, small amounts of impurities are not a big problem.
Then it might be far worse. Unbeknownst to you, the ancient smith, you may *not* have (dirty) carbon steel but something quite different: *phosphorous* steel. A lot of old sword blades in (northern) Europe were actually made from **phosphorous steel** and not from carbon steel. Or from phosphorous, arsenic and carbon steel. This opens a whole new can of worms and I will have to get back to this later.
You, the ancient smith, didn't know anything about that. You just left us with blades of breathtaking complexity and beauty. Nobody knows your name anymore.
The ancient famous philosophers knew just as little as you, the smith, about iron, steel or most everything else from the world of materials. But in contrast to you, they didn't *make* anything but just thought about it and then wrote down their guesses and opinions (mostly wrong) in excessive length. Their names are still known and revered by some.
- So I want *you*, the reader, to do the following:

Next time you look at an ancient blade from some unknown smith or a copy of an old book from, say, Aristotle, consider who did more for the development of mankind.

It's time for a getting-philosophical-break during which we consider this thesis (or theorem?): **E Pluribus Unum**.
In particular, I want you to give some thought also to the *anti*thesis. Even if Latin is Greek to you, the sentence should be vaguely familiar to you if you happen to live in the USA[1)].
(Hint: It's easier to have deep thoughts while taking deep drafts from a suitable beverage. With luck, you won't even remember your deep thoughts on the next day).

- A beak, wings, two feet - and look how many birds you get, including some that are not even flying around out there. Iron atoms and carbon atoms - and look how many steels you get!
  - Actually, if you did your contemplating right, you realized that there are far more birds in the picture, not to mention out there, than the species of carbon steel I have mentioned so far.
    To answer your implicit question: Yes - I did keep a few more things concerning carbon steel from you. Besides the "*bainite*" and *Widmanstätten ferrite* " alluded to not that long ago, we have a lot of stuff that goes under headings like "**cast-iron**", with a subculture of its own, distinguishing, for example, between "white" and "gray" cast iron. We have phases called **ledeburite** (after **Adolf Ledebur**; 1837-1916) or **graphite**, and so on.
    There are also strange new animals like **stacking faults**, **split dislocations**, **partial dislocations** . **grain boundary dislocations** that live inside the phases—you get the drift. There are more birds and interesting parts of birds, indeed, and I could go on for a while, elaborating carbon steel.
- **Surprise!**

Even if you are eager to go on, I give up - as far as the Backbone is concerned **If you don't want to give up,** **switch to the Science part**

- I will now simply go on to the next chapter entitled "Real Steel" and move from mere birds to all animals, including beloved ones like cats and dogs but also slimeworms and university administrators.
  In the case of animals, this needs more ingredients than just beaks, wings and clawed feet (e.g. tails, slime and being narrow minded). In the case of steel, we will now add more than one alloying element.
  If the resulting structure at room temperature is good or problematic for the applications you had in mind will depend on the mix you started with and the conditions you provided.
  - So far, we only scratched the surface of steel science and technology. If you really want to go a *lot* farther, you should become a material scientist in general and a steel expert in particular. That means studying full time for only 5 - 7 years plus spending some time in a smithy or steel mill.
    If you only want to go a bit farther, check the "Science" and "Miscellaneous" modules.
- Why do I forsake you at this point? Because it just doesn't make much sense to introduce and discuss things like TTT-diagrams *without equations*. Not that I couldn't do that, I just don't feel like it.
  I promise, however, to keep those science modules relatively simple. So if you want to give it a shot, here are all the links.

Science Module **Bainite**	**Science Module** **Widmann-stätten**	**Science Modules** **TTT Diagrams**	**Science Module** **Thermal stress**

---

1) *E pluribus unum* is Latin and translates as "Out of many, one" or "One from many". The antithesis would be: Many from one, e.g. many *kinds of steel* out of one (or few) *ingredients* or an universe with all its many manifestations out of one equation.
E pluribus unum is the phrase found on the Seal of the United States, along with "Annuit cœptis" (He [God] has favored our undertakings) and "Novus ordo seclorum" (New Order of the Ages) on the backside, together with the truncated pyramid with the Eye on top.
E pluribus unum was considered a de facto motto of the United States until 1956 when the United States Congress passed an act adopting "In God We Trust" as the official motto but leaving open which God.