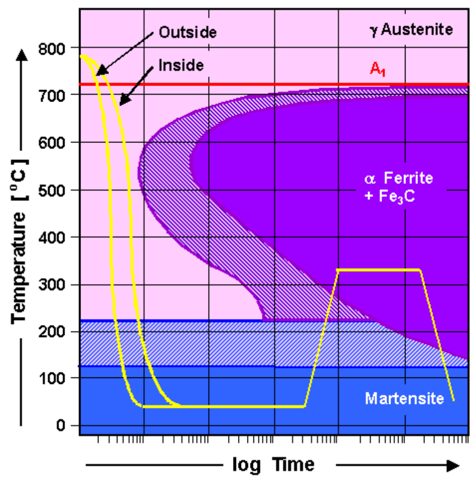
Science

3. Applications

Qualitative Uses of TTT Diagrams

As long as we stay *qualitative* , details don't matter. We might use TTT diagrams even for continuous cooling or for *any* temperature profile, even so they are not valid for this. It's like this old joke about a math professor who was criticized for always being so abstract. So he starts his next lecture about multi-dimensional geometry with: "Let's determine the volume of a generalized cow. As an easy first step, let's look at a spherical cow in 8 dimensions. A schematic picture of this cow looks like that (draws a circle)". Any closed line would have been just as good to get the point across, and, to be fair, he can't do much better with this topic.
It's about the same here. For illustrative purposes, only trying to get qualitative points across, the exact structure of the diagram doesn't really matter all that much.
The pictures below show how one can use TTT diagrams to illustrate quite nicely the differences between technologies for making hard steel.

- The first example shows how to make old-fashioned **tempered steel**. What the English called "tempered steel" was the ultimate for quite a while in Victorian England, let's say the last quarter of the 19th century to the beginning of the 20th century. Hat pins or umbrella spines of tempered steel were crucial to the well-being of an English Lady; they also served as tools or weapons, as everybody knows who is acquainted to **Amelia Peabody**. Tempered steel was also the ultimate steel for swords and anything else not too bulky.
This is how it goes:



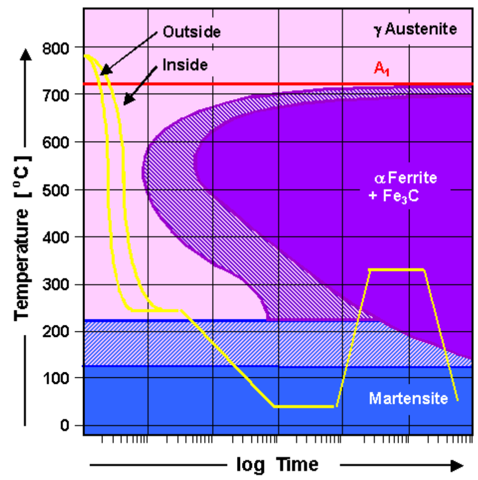
TTT diagram showing how to make *tempered steel*

- It's easy. First you quench rapidly enough to turn the outside and the inside (shown by two different cooling curves) into pure martensite. Then you wait a bit and heat up to a temperature that brings you into the ferrite + cementite region (preferably low down, where you can expect to get bainite). There you hold it for a while, then cool down to room temperature.
Bingo! You haver produced tempered steel.
It is clear what is going to happen. During the final tempering step, the carbon in the martensite, hating it there, will begin to diffuse around, generating small ferrite grains and small cementite particles in the process. By controlling temperature and annealing time, you can determine to what extent that takes place. The longer or hotter you temper, the more ductility is restored (and hardness lost) and the the brittleness of pure martensite gets "tempered". You will loose hardness yes, but gain ductility, and by optimizing the process you can get the best compromise for your needs.
You have some questions? Something here appears a bit fishy? Hold it. You are right and I will get to this in due time.
- First I give you a figure that gives some data to tempered steel.

Comparison between normalized and quenched and tempered plain carbon steel

- σ_{TS} and σ_Y give the (ultimate) tensile strength and the yield strength (= hardness), respectively; ϵ_f as a measure of ductility denotes the maximum strain at fracture.
- We compare plain carbon steel (as far as that is possible) that has been normalized , i.e. kept at high temperatures for a while and cooled down rather slowly, to quenched and tempered steel. The steel samples were small enough to allow heavy martensite formation for the quenched steel in all of the volume. After quenching the steel was tempered, i.e. held at a temperature between **(300 - 600) °C** ((572 - 1112) °C) for some time. Of course, what you get depends a lot on exactly how you do the tempering after quenching. Too long at too high temperatures and you are back to normalized steel properties. What is shown here is about the best you can do.
  Note that the ductility is about the same for both case while it would be practically zero for the "quenched only" samples.
  Tempered steel, in other words, can have *twice* the hardness of "normal" steel without compromising ductility! That is quite an achievement.

Tempering steel this way had a few disadvantages, however (besides the fishy stuff I will get to later). Even if everything goes as described above, the outside of your specimen has already turned to martensite when the inside is still austenite - as you can clearly *see in the TTT picture* above. That produces a lot of stress, leading to plastic deformation or even fracture, and that is not good.
So steel people came up with an improved process, called "**martempering** ". Here is how it goes:

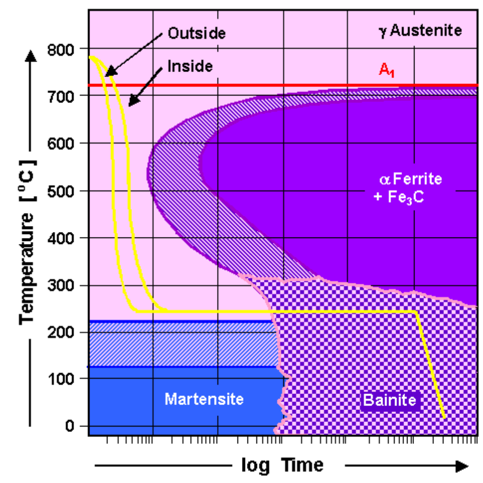


TTT diagram showing how to make
martempered steel

- You quench to a temperature just above the temperature where the transformation to martensite begins. At that temperature you hold the specimen until the inside has caught up with the outside. The thermal stresses still there can be relieved by plastically deforming the austenite.
  Then you cool slowly to room temperature, with essentially the same rate for the inside and the outside. This generates martensite uniformly in the specimen and you do not have large stress gradients, destroying your sample during the martensite production part. After that, you temper as in tempered steel.
  "Martempering", I suppose, is short for "tempering in the martensite region".

Of course, if you know about TTT diagrams and everything else I have covered so far, its's now easy to come up with the next big idea. All you need to know is that tempering or martempering essentially produces some kind of bainite. After all, the tempering process allows the martensite to decompose into cementite and ferrite, typically on a sub-micron scale. Depending on temper temperature and time, some left-over martensite and austenite might be around, too. That kind of mess we call bainite for lack of a better name.

- So how about producing some bainite right away by a process called "**austempering**", probably short for "tempering in the austenite region"? The TTT diagram below tells it all:



TTT diagram showing how to make
austempered steel

- All we need to do is to stop the cooling process just above the temperature where the transformation to martensite begins. At that temperature you hold the specimen *for a while*. The red part of the sentence is the only difference to what you do in martempering. The TTT diagram shows what happens. If you "austemper" your specimen long enough to dive into the α ferrite and cementite nose, you are going to form bainite since this is what you will get at the relatively low temperature; I have actually drawn it into the diagram.

This is great because you now get something very similar (but not identical) to tempered or martempered steel in an easier and cheaper way.

- All of that looks fairly obvious *as illustrated*. Well, yes - but it wasn't obvious at all in times when there where no TTT diagrams and very little knowledge about martensite, cementite, ferrite austenite, bainite and so on. It was rather a bit on the miraculous side. You could make the good stuff in various ways but only if you followed the working recipe closely.

I won't get deeper into this because now it is time to look at the "fishy" aspects of what I just did.

Why Does This Smell a Bit Fishy?

Let me guide you through the questions you were about to ask all this time.

First question: All those pictures above only appear to make some sense because you omitted to put numbers on the time scale. If you do this, it is evident that you have less than about 0.1 seconds to get by the nose. You just can't cool down a complete sword blade that fast! Never ever!

- Yes, you are right. However:

  1. Sword blades are not all you make from steel. The making of (thin) steel wire, for example, was and is far more important. For pianos, say, or for elevators, ships, suspension bridges, cranes and God knows what else. And thin wire you *can* cool down real fast. No thin steel wires - no thick steel cables - no elevators. No elevators - no buildings with more then 5 stories. And so on.
  2. There is no such thing as plain carbon steel - remember? Proper alloying can move the "nose" somewhat down the time scale, giving you more time to cool down without hitting it.

Second question: In the tempering and martempering TTT diagrams it looks like you start the tempering step at some *specific* time after you cooled to room temperature. This looks like BS. Nothing happens anymore at room temperature, and that means that I can do the tempering whenever I feel like it. Right after room temperature was reached - or 5 weeks or years later.

- Well, what can I say?

  1. Indeed - you are (almost) right. I apologize for the inconvenience. And now, pray, tell me how I should draw that into a TTT kind of diagram? I could draw in some interruptions of the time scale, of course, but that would just make the picture more complex without changing it very much. So I let it be.
  2. At least in the austempering case, it is essential to have the uninterrupted time scale.
  3. It is not really true that nothing at all happens anymore at room temperature. Martensite formation, for example, is only finished in finite time if you go to temperatures below room temperature. It may not be a good idea to wait too long before you do the tempering step.

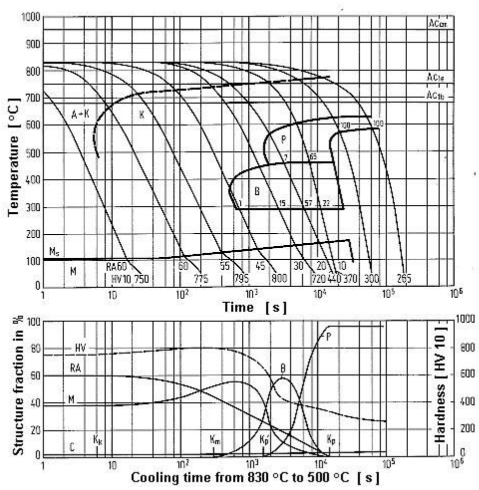
Third question: Shouldn't the TTT diagram for the tempering be different from the one for the cooling? I think the one for the cooling should be a CCT diagram with a starting point in austenite, and the one for the tempering at isothermal conditions should be a TTT diagram with a starting point of martensite. Right or wrong?

- Right. Absolutely and unconditionally. Now draw these two different diagrams. What do they look like? Aha - more or less like the one I used. Without numbers on the scales all those diagrams look more or less the same.

So let's keep things simple. One diagram fits (almost) all as long as we look at the *qualitative* side of things only!
If you, like most of humankind, were puzzled about all those empirically discovered different ways of making good steel some 100 years ago, the kind of diagrams shown above went a long way, indeed, of explaining what was going on. Even better, they didn't give away any of your trade secrets, like the precise tempering times, the tempering temperatures, in what kinds of liquids you quenched, and so on.

Quantitative Uses of TTT Diagrams

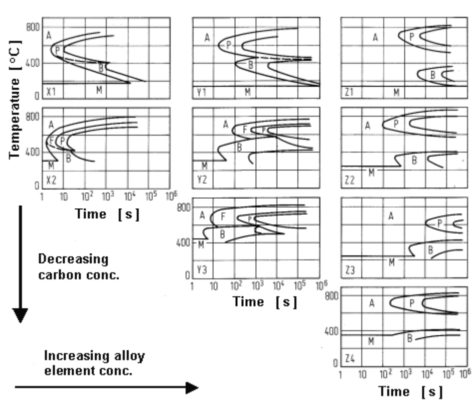
I have shown already two simple *quantitative* diagrams; the link takes you there. Here, just for illustrative purposes, I will give you two more randomly chosen examples.



Quantitative TTT diagram of nickel chromium steel

- This is a quantitative TTT or better CCT diagram for a Nickel Chromium steel (14 NiCr 14) with 1.03 % carbon. In addition to the CCT diagram we have a diagram that shows how much percent of martensite (M), Bainite (B), Pearlite (P) or remaining austenite (RA) you will find, together with the Vickers hardness (HV). Note also that the "noses" appear rather late in time
I won't explain all the numbers and details, suffice it to say that these curves contain a hell of a lot of useful information (including the final hardness HV) for the practitioners of the art. There are big books full of curves like this for all kinds of steel.

The second example, while fully quantitative, also contains some qualitative aspects.



Quantitative TTT diagram

- We have steels containing the alloy elements Mn, Cr, Mo, V, Ni, W and Si in a total concentration from about 1.7 % to beyond 10 %, and carbon in concentrations from 0.2 % to 0.75 %. The (strongly simplified) TTT diagrams show not only what you will get, but also that by alloying one can indeed move the pearlite / bainite noses to the right, i.e. to larger times as claimed above.

These curves once more, contain a hell of a lot of extremely useful information. They are complex - yes! But so is a detailed map of some area. Consider to run around in some unknown region without a map an you know how you would feel in the steel business without TTT diagrams.

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TTT Diagrams

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