9.3.2 Maraging Steel

Using steel science, let's "design" high-tech steel once more to get a feeling for what can be done; we will stay with high-alloy steel. What we want to make now is a steel that is:

- easy to shape (meaning it is soft),
- extremely tough (meaning it is hard but still ductile),
- doesn't suffer from limited hardening depths.
- and can be welded.

That does sound like a big, fat contradiction in terms, doesn't it?

Well, yes, but there are ways. What we need is "obviously" a steel that we harden *after* we have worked it into the desired shape. Since we usually work steel around room temperature, the only option for a hardening process is now to *heat* the steel to some temperature, and keep it there for some time. Temperature profiling once more, just the "wrong" way around. So far we always softened a material by heating or tempering.
Or did we? Maybe you remember the example where an alloy got harder upon heating?
This yet-to-be-determined process also takes care of the uniformity of hardening. While you can never cool down quickly *and* uniformly, you can heat uniformly. Just heat up slowly. Since not much will happen before you reach the process temperature, all is well.

What we are about to do is to make "**maraging" steel**. The name is short for "**martensitic ageing**" and, while fully correct, leads you straight into wrong associations. So far, "*martensite*" was code for "distorted ferrite containing carbon and being extremely hard". While not wrong, it is a bit too special. I have pointed out before that martensite is only very hard if some carbon is stuck in there and distorted the crystal lattice. Undistorted martensite in iron would just be ferrite and that is rather soft. You might think that the term "undistorted martensite" is an oxymoron (a contradiction in terms) because it just means bcc ferrite. Well - you're wrong.
Nice clean bcc ferrite that resulted from the nice clean fcc austenite preceding it on the temperature scale by a sudden *martensitic transformation* is quite different from the bcc ferrite that is produced in the normal diffusion-driven way. It is small-grained and full of twin boundaries and dislocations! Why? Because carbon or no carbon - all the problems with fitting sheared parts of the crystal into the space available haven't changed.
What that means is that carbon-free martensite (= ferrite) is substantially harder then regular large-grained ferrite with not too many dislocations.

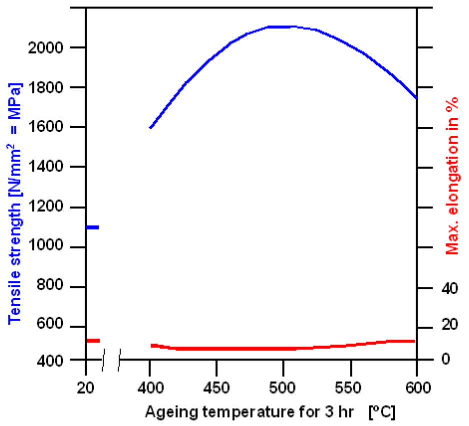
We want our maraging steel to be relatively soft when its in the martensite structure. That requires two things:

1. *No carbon*. But there is no martensite (= ferrite) formation by shear in pure iron, so we need
2. At least 19 % nickel (Ni).

Nickel, like manganese (Mn), cobalt (Co) and most of the nobler metals are known as **γ stabilizers**, they produce phase diagrams known as open γ-field systems (the link leads to the "alloy science module"). What all that means is that with increasing alloy element concentration the transition temperature austenite ⇒ ferrite (γ ⇒ α) comes down. That makes diffusive transitions more and more difficult and at some concentration they just can't happen at all any more. That's when martensitic transformation takes over. Even that can be suppressed for proper high-alloying and then leaves you with austenitic steel.
The γ ⇒ α transformation for Fe - 18% Ni steels starts at 600 ^{o}C (1112 ^{o}F), and that is just "too cold". These steels simply will not decompose peacefully into equilibrium austenite and ferrite, even if held for very long periods at lower temperatures. Instead, during cooling the Fe-Ni austenite transforms to hard but not extremely hard "martensite" with a bcc crystal structure.

That's already rather tricky but not doing you all that much good. The trick now is to alloy optimized amounts of elements like molybdenum (Mo), cobalt (Co) or titanium (Ti) that are capable of forming hard intermetallic compounds with nickel (Ni), things like Ni_3Mo or Ni_3Ti. Those alloy elements are not doing much during the cooling down necessary to form the iron-nickel martensite but will provide for a lot of added hardness when you now start the "ageing" bit, the annealing at the right temperature for the right time. It goes without saying that before you start hardening by ageing, you first shape you relatively soft material into the form you want it to be.

Of course, if you heat up to temperatures too high (roughly above 600 ^{o}C (1112 ^{o}F), you just form austenite again. But if you pick temperatures around 450 ^{o}C (842 ^{o}F), you might form a lot of tiny intermetallic precipitates faster than your martensite decomposes into austenite.
If everything is done just right, the precipitation hardening mechanism, on top of the hardening already there by the martensite, will easily double or even treble the hardness—without compromising ductility too much. This is what you see in the figure below:



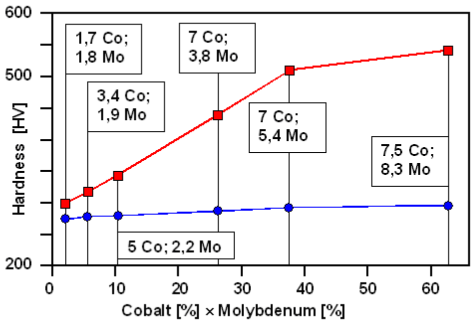
Yield strength (or hardness) development during the ageing of maraging steel.

Source: From a data sheet of "Böhler". A Ni 18.5 %, Co 9%, Mo 5%, Ti 0.7% steel

- A typical example of a good maraging steel is an iron alloy with 17 % - 19 % Ni, 7 % - 9 % Co, 4.5 % - 5 % Mo and 0.6 % - 0.9 % Ti. Tempering or "ageing" takes place around 490 ^{o}C, producing intermetallic precipitates. The term "ageing" was chosen in analogy to what we know from our old friend, the aluminum (Al) - copper (Cu) model system.

- The initial development of maraging steels is attributed largely to work by **C. G. Bieber**, in the late 1950s. This work resulted in the first two grades of maraging steel being introduced to the market. These steels contained 20 % and 25 % nickel, respectively, with small additions of aluminum (Al) from "killing" the steel, and titanium (Ti) and niobium (Nb) for forming precipitates. Since then many variants have been introduced.

- Maraging steel, while used for all kinds of especially demanding applications, is still under development and not all details are fully understood. In particular, adding substantial amounts of cobalt (Co) is rather helpful - see below - but what exactly cobalt does is not all that clear. Co may decrease the solubility of Ni_3Mo in the iron-nickel martensite but I'm not sure if that is the last word.



**Combined action of cobalt and molybdenum on the
hardness achievable hy ageing.**.

Source: Key to metals

- This is a rather curious diagram. It seems to indicate the hardening effect of proper "ageing", i.e. of forming optimal densities and sizes of certain precipitates seems to increase linearly with the *product* of the molybdenum and cobalt concentration. This means that it is proportional to each concentration by itself. This is now one of those many little puzzles posed by experiments that theory needs to solve.
  This link leads to a 1999 research paper, more or less selected at random, that nicely illustrates some of the problems, including "banding", something that will exercise us quite a lot as soon as I get to wootz swords; "dead heats" not amenable to "corrective healing actions"; and "elimination of the research staff" in order to save money and make the problems go away because nobody talks about them anymore.

- Maraging steel with yield strengths of 1500 MPa or more are possible (corresponding to a Vickers hardness up to 800 *everywhere*, not just in the "case"!) at a ductility of 6 % - 8 %!

- There is your material for your ultimate sword blade! Indeed, in modern fencing, three kinds of blades are used: the foil, the épée and the sabre / saber. The all look quite similar to the layman and often are made from maraging steel; this might even be required by international rules.
  However, production, import, and export of maraging steel is also monitored by international authorities because it is particularly suited for use in gas centrifuges for uranium enrichment. Lack of maraging steel significantly hampers this process; ask your friendly Iranian politician.

What Modern Steel Making Tells Us About Sword Making in the Old Times

- To summarize once more: Modern steels like the HSLA and maraging steels introduced here resulted from scientific insights into structures and hardening mechanisms. They are many more steels like that; the link will provide a lot of reading. Steel research and development is not yet finished but an ongoing and important enterprise. The decisive factors for progress were the scientific revolution in the early 20th century and the insights into what crystals are and how they deform around the middle of the 20th century.
  In the 3000 plus years of iron and steel technology before that, our forebears did not have the slightest chance to come up with something like micro-alloyed, stainless, or maraging steels.
  - You just can't get far in designing and testing steels if you don't know what happens, can't see your precipitates, and can't measure key properties in order to get quantitative data. In other words, with no knowledge about deformation mechanisms, impeding dislocation movement by obstacles, and at best optical microscopes instead of the whole bag of sophisticated micro-analytical tools we have today, you are simple "blind".
    If you want to make a better sword blade relative to the state-of-the-art, you can *only* go by trial and error. This will only get your that far. So if your technique, based on centuries of experience gained by your forebears, allows to make good blades most if not all the time, you eventually stop experimenting at all and cling slavishly to the recipes that work.

    Link Hub

    Major Steels

    Japanese sword blades, for example, are just plainly amazing giving the "blindness" of their forgers to what they were doing. The same thing, of course, is true for Celtic / Roman / Alemannic pattern welded swords and oriental wootz blades.
- The down side of this is that no more progress will be made after your blade-making process was declared perfect and canonized; e.g. in 16th century Japan. Is that bad?
  - Well, let's look at an example from a different but related sphere of human enterprise: art. Painting in the West was pretty good in the 16th century, just like sword making in Japan. **Botticelli**, **Cranach**, **Dürer**, **Leonardo**, **Raphael**, **Tizian**, and many others come easily to mind (I did grant you a halfway decent education)!
    Some may claim that the masterpieces from these painters have never been surpassed but I beg to differ. Painting in the West has evolved since then in a multitude of ways, and while I could do without certain works of art created since then, I would not like to miss the French impressionists, parts of art noveau, and many other art styles quite different from 16th century painting.
- In contrast, after apparent perfection was achieved, the art of steel as embodied in blade forging did not evolve further in Japan - and that's a pity. In other parts of the world it did; you only have to look the way the shape of swords changed and diversified.
  - Constant experimenting lead to progress in iron and steel technology, which in turn eventually lead to guns, submarines, fighter planes, nuclear bombs, and so on.
    You might consider that this does not constitute much progress with respect to armed conflicts. If the good or the bad guys win is still a matter of chance or taste; there are just a lot more dead innocent bystanders. I tend to agree.
    But better steel also gave us cars, railways, airplanes, boats, tractors, machinery of all kinds, radio and TV, computer tomography, painless drilling at the dentist, minimal invasive surgery (I got a taste treat of that and liked it very much!), and so on. All of that would be impossible without advanced steel.
    And don't tell me that there is hardly any steel in a computer or cell-phone! The factory where the microelectronic chips are made is full to the brim with machinery made from all kinds of steel!