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Overview of Major Steels

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Science

3. Some Special Steels

General Remarks

There is nothing really special about the steels below except that the all go to some extremes for just one "special" property. As far as "commonness" is concerned, they might be all around you. That doesn't mean that you and about everybody else out there are aware of that.
Here is the list of what follows:

- **High Purity Steels**; allowing unprecedented precision in microalloying
- **Weathering Steels** that do not rust - but do not look like that.
- **Machining Steels** for easy turning on a lathe.
- **Tool Steels** for doing the turning on a lathe.
- **Spring Steels**. You guessed it.
- **Transformer steels**; all around you but well hidden.

High Purity Steels

High purity steels are not steels to be directly used for products. The term just denotes a starting condition. You also could just call it "iron" in a chemical sense, always meaning that the stuff in question is clean. High purity steel, also called **clean steel**, thus is steel with a very low concentration of impurity elements such as phosphorus (P), sulfur (S), oxygen (O), nitrogen, (N), hydrogen (H), and particularly carbon (C). Just as important: there are also *no inclusions* or other non-steel objects in the steel.

A somewhat more precise nomenclature suggested on occasion is:

- *High purity steels*: Steels with low levels of solutes.
- *Low residual steels*: Steels with low levels of impurities that originate from re-melted scrap.
- *Clean steels*: Steels with a low frequency of defects that can be related to the presence of oxides.

Whatever that means. Essentially we are talking about not having anything in there except for the alloy elements that *you* wanted to add in order to turn high-purity iron into some steel. Note that you need no longer add manganese to counter evil effects of the impurity sulfur, and so on.

In order to get there, you need to fight on several battlefields:

1. Cleaning your pig iron; the stuff that comes out of your modern blast furnace. Everything that is not iron, in particular sulfur (S), phosphorous (P), and so on, must go out. For doing this you run oxygen through the melt and line the crucible with various ceramics that take out this and that. But that's routine for the making of any steel. So on top of that you add more processing, like de-gassing in vacuum, in order to get especially clean "raw" iron.
2. Now you need to "kill" you semi-clean or really clean iron because it still contains dissolved oxygen and various oxides. For doing that you add silicon, aluminum, calcium, or ?. You *must* do this. You cannot live with the oxygen in the stuff. The "killers" bind the oxygen by forming oxides like SiO_2, Al_2O_3, ...
3. There is no choice: You now must get your "killer-oxides" out of your melt, which otherwise will be incorporated as inclusions.
4. Now you are done and can start to put the alloying elements of your choice into the melt. However, you need to make sure that nothing *falls* into the melt when you handle it. After all, your crucibles, "ladles", lances for blasting oxygen, ... will be rather "crusty" from whatever solidifies during their use.

So it's not easy. Nor is it cheap. You do everything you do for regular cheap-and-dirty steel and then some - at additional costs. Nevertheless, "clean steel" is the way to go. All the unclean stuff compromises the properties, especially in the long run; here is a particular striking example. Customers are tightening the requirements. The table below gives you an idea about some present specifications, and you can be sure that with time they will be made even tighter.

Product	Max. Allowed Impurity Conc.	Max. allowed Inclusion Size
Car body sheets	[C] = 30 ppm, [N] = 40 ppm	100 µm
Beer cans	[C] = 30 ppm, [N] = 40 ppm, Total oxide = 20 ppm	20 µm
Tire cord	[H] = 2 ppm, [N] = 40 ppm, Total oxide = 15 ppm	100 µm
Note: 1 ppm = 0.0001%		

- The state of the art around 2010 are impurity concentrations of N+O+S+P < 50 ppm. Nevertheless, even with a sulfur (S) concentration as low as 10 ppm, you still get some MnS precipitates, which are undesired.

There is a slight irony in this. Whenever we look at *ancient* steel, inclusions of slag, residual charcoal, dirt, and God knows what else was encountered. That was a major problem and caused a lot of "innovations", e.g. all those complex ways of forging like folding or faggoting, pattern welding, piling, and so on. On top of that we had hardening by using carbon and / or phosphorus.
When we look at *modern* steel (e.g. by reading text books) we primarily discuss the various alloy elements used, processing parameters, and all kinds of special treatments. What we usually don't discuss all that much are **inclusions** because compared to ancient steel there isn't much.
That is no longer justified. In the case of *modern* steel we also have inclusions of oxides, sulfides, dirt, and God knows what else, just at a much lower level compared to ancient times. And these inclusion are becoming a bigger and bigger problem.

- You always will have some inclusions. You might even have a lot, look at this picture! If you are lucky, you will not notice them much, If you are unlucky, the one and only inclusion in a large batch of steel ends up in the wheel of your railway car or in your sword, leading to unexpected fracture, killing you swiftly and unexpectedly in the fullness of time.

Weathering Steels

Since the name "stainless" for non-rusting steel was assigned to "chromium steels" as early as 1912, a new kind of corrosion resistant steel coming up much later was termed "weathering steel". In contrast to stainless steels it does not rely on forming a protective *chromium* oxide layer but emulates the behavior of metals like aluminum in forming a protective *iron* oxide layer.

- Of course, as soon as steel science started in earnest, i.e. around 1900, the rust problem was looked into by many researchers and corporations. In the 1930s, U.S Steel Corporation discovered that steels containing certain amounts of Cu, P and other alloying elements showed a good resistance to atmospheric corrosion in industrial and rural environments. But the stuff did not form a completely protective oxide layer and still showed a high corrosion rate if chlorine ions (Cl^-) were present. Since "chlorine ions" is just a fancy way of saying "salt water" or ocean air, those steels were not much good.
- It took a lot more time and effort to figure out exactly how to alloy and process iron so that a steel results that forms a protective iorn oxide layer that is not only immune to chlorine ions but self-heals if cracks develop due to some mechanical loading, for example.

Weathering steel typically goes by the trade mark "**Corten steel** " and has been in use since about 1960. Typical compositions (in wt%) are

Grade	C	Si	Mn	P	S	Cr	Cu	Ni	V
Corten A	0.12	0.25 -0.75	0.20 -0.50	0.07 -0.15	0.03	0.50 -1.25	0.25 -0.55	0.65	-
Corten B	0.16	0.30 -0.50	0.80 -1.25	0.030	0.03	0.40 -0.65	0.25 -0.40	0.40	0.02 -0.10

- Nothing spectacular there; we have a low-alloy mix. However, the intentional use of **phosphorous** (P), **sulfur** (S) and copper (Cu) is unusual.
- What, exactly, causes the "rust-proof" properties? I don't know. Somebody knows, I assume, but it is not an obvious, easy-to-explain thing.

Weathering steels are great but have a severe **disadvantage**: They look rusty, very much so! Only rigid cultivation can enable a man to find truth in a lie, says Mark Twain, and as far as I'm concerned, the same principle applies to finding aesthetic beauty in rusted iron. Some artists and architects did take to the material but most people, I believe, find the buildings and whatever else Corten was used for, just plain ugly. Millennia of negative conditioning to the appearance of rusty swords, knives, and so on, are not erased all that easily.

Use of weathering steel in Copenhagen.

- There are also "real" problems with weathering steel - but as far as I'm concerned, they pale by comparison to the aesthetic one. Note that the Danish are famous for design. The architect of the building above, however, was obviously inspired by the aesthetics of the Corten steel used for the railroad in the foreground.

Machining Steels

Machining your steel means shaping it by mechanically removing parts of it. Think of carving the Venus de Milo with a hammer and a chisel from steel. Actually, just think of drilling a hole; even you can do that. In essence, something sharp and hopefully made from tool steel, must cut, abrade or break off parts of the material being machined. This is obviously more difficult to do to a hard steel than to a soft steel.

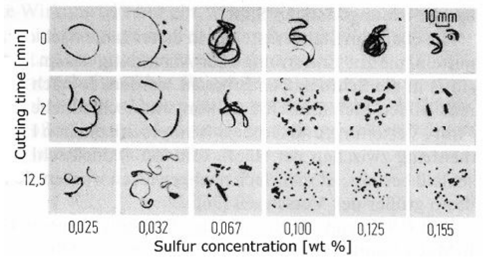
- Or is it? Try to drill a hole with precise dimensions through soft stuff like acrylic, cheddar cheese, or pudding - it ain't necessarily easy. For drilling brass, you actually blunt your drill bits. There is a simple message in this:

Machining materials is a science in its own right!

Of course, if you have all the time and money in the world, it is easy to machine your parts to perfection. Just go slow and take it easy. If money counts (and it sure does for most of us) things like cutting speed, dimension control, and life time of your cutting tools become extremely important.

- I can't go into this here in any depth and thus will only make one point: The shape of the bore chips or flakes coming off are important. The nice long spirals shown on the right are decorative but not good! You want the stuff to come of in little particles.
  In essence, everything that makes your steel tougher and less susceptible to embrittlement is bad for machining. Of course, completely brittle materials are hard to machine, too. Try to drill a hole into glass! It can be done - but never with nice glass spirals flaking off.
- You are left with two options:
  - Take you steel as it is and optimize the tool for machining it. This calls for sophisticated tool bits with very hard stuff including diamond at the "cutting edge".
  - Optimize the steel you want to machine. This calls for compromises.

Now I can make my point. Look at the next picture:



Steel Cutting flakes and Sulfur Concentration

Source: "Werkstoffkunde Stahl"; p. 625

- The more sulfur and the longer you cut, the better the results.
  So here is the exception to the iron rule that sulfur is always bad! You actually might add some sulfur (S) to machining steel or elements like lead (Pb), bismuth (Bi), selenium (Se) or tellurium (Te).
  In essence, the sulfide particles in there (mostly manganese sulfides) fracture easily and to some extent even "lubricate" the whole shmeer, in particular if the temperature goes up a bit. That's why things improve with increasing cutting time in the figure above.
- Of course, your steel is not as good as it could be without the sulfur. The finished product, however, will be much cheaper. Make your choice.

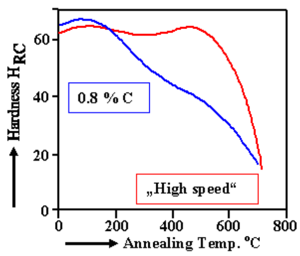
Tool Steels

Tool steels are needed for machining; see above. They must be very hard - after all you want them to cut regular steel on a lathe or with your power drill.

- Essentially you use high-carbon steel; the most common mixture is **1 % C** and **0.3 % Si**, **0.3 % Mn**. Properly quenched and tempered, at least the outer cutting part will be hard.
- However, if the tool becomes hot - and that happens whenever you try to cut metal - you may loose the hardness because you "run the temper", i.e. anneal the martensite. This restricts you to low cutting speeds and plenty of cutting fluid, needed for permanent cooling.

Economically this is not so good. So you turn to **high-speed steels** with a composition of, e.g., **1 % C**, **0.4 % Si**, **0.4 % Mn**, **4 % Cr**, **6 % Mo**, **6 % W**, **2 % V**, and **5 % Co**. Obviously we now have a high-alloy steel. And equally obviously, just knowing the composition doesn't tell you all that much about how it "works".

- First we nee to process that steel. We quench and temper as usual. We have a lot of carbon so some cementite must be expected, giving basic strength. Finely dispersed carbides forming with some of the metals provide additional solid solution hardening. But that is not the point yet.
  The point is what happens if the tool gets hot? Say **500 ^{o}C - 600 ^{o}C (932^{o}F - 1112^{o}F)**, more than enough to give you a good quick burn if you touch it.
  Then the **Fe_3C** cementite particles dissolve. The carbon they release is snatched up by the alloy metals and forms tiny and very hard precipitates of metal carbides like **Mo_2C**; **W_2C**, and **VC**. This is called **secondary hardening** and makes the steel even stronger than it has been with the original cementite. The effect is shown in the figure below.



Hardness of Tool Steel (red) as a function of temperature
0.8 % C, 18 % W, 4 % Cr, 2 % V tool steel; regular **0.8 %** carbon steel.

Of course, you now have a rich field for optimizing - which elements and how much of each; and there are many kinds of high speed steel. The picture, for example, shows a sample with a composition quite different from the composition given above.

Spring Steels

If you hear the word "spring", you probably think of the kind of things shown below. You're a nerd. I think of having (occasionally) sun again, birds singing, ~~girls willing~~ , the flowers, the bees, and so on.
But let's not get distracted. Let's think about making spring steel.

Springs

A spring is something that you want to be able to pull or squeeze a large amount, always being sure that it will turn right back to its old dimension when you let go. The point is not to get deceived by the spiral shape. It is the wound wire that needs to get longer if you pull. The winding just ensures that the strain, the relative length change of your spring, is far larger than that of the wire.
That means that even *straight* wires that you elongate or bend, in the hope that they will only deform *elastically* , are springs. **Piano wire**, for example.

- Now it is simple. Large purely elastic deformations call for large yield strengths or very hard materials. But they must not be brittle. The springs for the wheels of your car should be able to take hard impacts anywhere on their surface, e.g. by stones kicked up, without shattering. It's exactly like your sword. A nick or dent upon impact is preferable to outright fracture.
  We need a hard steel with some ductility left.
- There is plenty to choose from. Most popular alloys include high-carbon steels (e.g. for piano or guitar strings), martensitic low-carbon, chrome vanadium steel, or hard stainless steels.
  Having all this variety is a good thing. Because we forgot something. Many springs are lustily moving up and down, to and fro, many, many times, That's why we have many of them, after all. Forget about piano wires or the spring in your ball point writer in this context - there you worry about creep! What we need to worry about for the busy springs is **fatigue**! Fracture that suddenly occurs after a certain number of vibrational cycles.

Transformer steels

Transformer steels, also called **electrical steel**, needs to have very special *magnetic properties* and in addition should have a high specific electric resistance. Its uses are clear: It is put inside the coil of electrical transformers or electromagnets. In a transformer, it increases the magnetic field produced by some (AC) current running through a coil by a huge factor (called the "permeability" of the material), and "transports" that magnetic field to another coil, where it induces a current - but typically at another voltage. That's how a transformer transforms voltages from one value to another one.
In an electromagnet, typically found inside large generators, it does essentially the same thing, except that the other coil can rotate around the generator axis and is driven by the outside energy source. In an electrical motor we have the same thing once again - it is (as long as we are simple minded) just a generator driven in reverse.

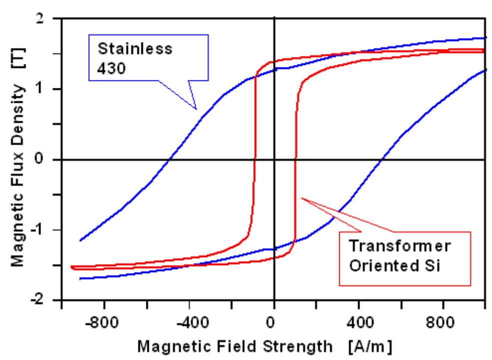
- Not all that long ago every electric household appliance - TV, radio, refrigerator, ... - contained a transformer with a core of "electrical steel". Electrical steel is of prime importance. Without it we wouldn't have affordable transformers / electromagnets / generators, and without those we simply would have no electricity, and therefore no culture and civilization where you and I would not be serves or slaves.
  So transformer steel is a "*special steel*" that should be of interest to us. About 10 Mio tons are produced every year.

So what are the "very special magnetic properties" we require? Very simple: high *permeability* and a hystereses loop that is as soft as possible. If words like *permeability* , *hystereses*, or *Tesla* don't mean anything to you, I do not only feel sorry for you but offer advice: Read up this module!
Ferritic steel is always ferromagnetic with a rather large permeability, so how about hystereses behavior? Knowing the least little bit about ferromagnetic materials and their hysteres curves tells you that you should keep you material as perfect as possible for soft hystereses curves. So let's take pure and large-grained iron?

- Well - no! Materials that are as perfect as possible also have the lowest possible electrical resistance - and we want that as high as possible! Why? Because alternating magnetic fields induce currents in conductors and these currents drain energy out of the system, heating the material. That's why we make transformer cores from thin painted sheets of steel that are piled on top of each other, with the paint layer providing for electrical insulation. But we can't make these sheets too thin, and still loose some energy due to the "**eddy" currents** induced inside the material. We want to keep those eddy currents small, and that calls for a high resistance.
We need to compromise - by alloying something suitable and by inducing anisotropy. Then we add a little of this and that (e.g. Mn, Al) to optimize whatever else we are after.

Science Link
Magnetism

- To make a long story short: We alloy mainly *silicon* (Si) at concentrations of up to 6 % but mostly around 3 %. The steel becomes brittle and hard to work with for the higher concentration. That increases the specific resistivity from about **10 µΩcm** for pure iron to around **45 µΩ cm**; nothing to be sneered at.
Then we remember that we need good magnetic properties mainly in the direction of the magnetic flux, but high resistivity in the direction perpendicular to that. If you don't remember that, you probably did not study Physics, Electrical Engineering, Materials Science or something similar for at least a few years. Well, don't feel (too) bad. Nobody is perfect after all, so just believe me. So we elongate grains in the right directions, making the material anisotropic. And so on.
What we might get in terms of magnetic properties is shown below. The red hystereses loop is not completely perfect but far better than the loop for some stainless steel or mot other steels.



Magnetic hystereses loops for transformer steel and some stainless steel for comparison.

All you need to know about these curves is that the area they inclose is a direct measure of the losses, the energy that is drained from the incoming electrical energy and just heats up the material. That is a serious issue and motivates a lot of R&D work to improve things a lot more. We might, for example, go for a new steel that does not just convert 99 % of the incoming energy to output energy, but a whopping 99.1 %!

- That's not worth the bother, you think? Let's see. The huge 370 MVA Transformer in your friendly neighborhood power plant takes off 1 % of the input power = 3.7 MVA = 3.7 MW (Megawatt). If it would only take off 0.9 %, you save 0.37 MW = 370 kW (kilowatt) of power. Your house, for comparison, runs nicely on just a few kW. With the energy saved you could power your whole neighbourhood.

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