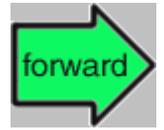




Overview of Major Steels

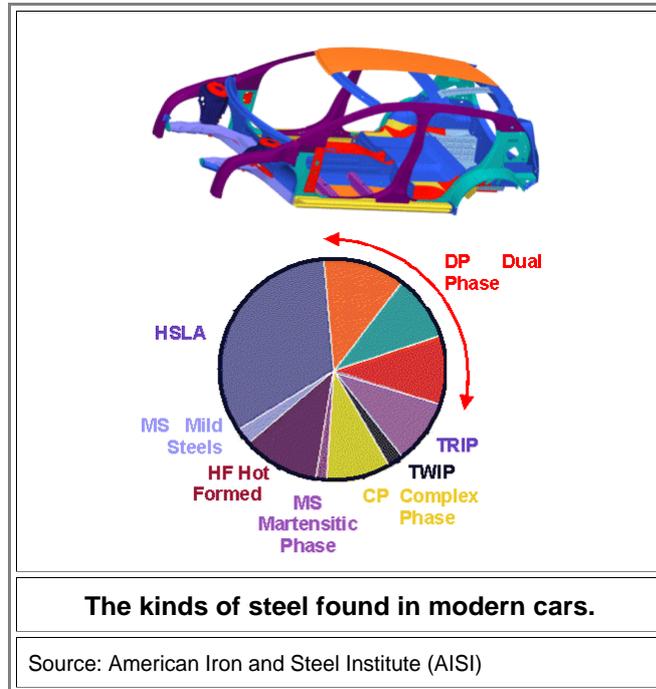


2. Some Common Steels

General Remarks

Advanced

I guess it is fair to say that the kinds of steel you find in regular cars would classify as *common* steels. Here is a simple figure showing what kinds of steel you might find in your car:

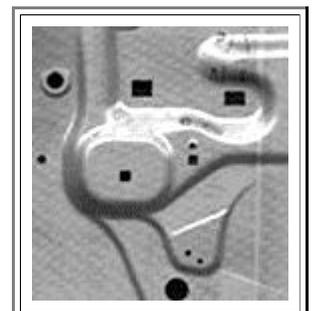


- Quite amazing, huh? Your car is a rolling exhibition of many kinds of steel, not to mention other metals and stuff. Of course, all cars are not created equal. There are good ones, and there are non-German ones that are made from few, simple and cheap steels. But apart from a bit of national chauvinism, all modern cars, and especially the cars of the near future, do make use of many different kinds of steel, including rather recent and advanced kinds, indeed. The reasons are clear. You want to have the best compromise between ease of making, safety in a crash, fuel economy and performance (both tied to weight), and of course costs. Ease of recycling, corrosion resistance, ease of painting, and so on and so forth, are also parameters that need to be considered when selecting a steel.

- Let's go on. It is perhaps also fair to say that steels used for oil and gas pipelines are *common* steels. Pipelines are not quite as visible as cars but wherever there are cars, there are also plenty of pipelines, and a lot of steel is used for their making.

We also use a lot of "structural steel" for buildings, or railway steel for - you guessed it! All rather common and yet very special, too.

- A common property that all these steels should have is weldability. Steels with appreciable amounts of cementite usually do not meet that criterion. If you want weldability *and* high strength, simple carbon steels are now out. However, if you need to form your steel into a complex shape like the inside of a car door you many want low-strength steel with large ductility that is easy to form and can be "drawn out" a lot. The picture on the right shows the inner part of a car door; note that there is substantial strain especially at the "bends". If you can harden the steel *after* forming that part - great! The list of wanted properties can easily be extended to almost infinity. The answer to such a list is an almost infinite number of available steel grades. In what follows I will cursorily look at a few generic ones, in particular *High-Strength Low-Alloy* (HSLA) and *Dual Phase* (DP) steels plus some relatives. The first kind I discussed already in the backbone to some extent.



What you don't find much in cars, pipelines, construction, and so on is *stainless steel*. Nevertheless, members of the stainless steel family are a common sight, just look around in your kitchen. I will deal with stainless steels in the remainder of this module.

High-Strength Low-Alloy Steel

High Strength Low Alloy (HSLA) steels, the paradigm of **MicroAlloy** (*MA*) steels, explore the simple idea that carbon, maybe, is not necessarily the best alloying element for making good steel. Even if you use it, you may not employ it to make just the iron carbide that we called cementite, but also for making carbides with the other metals supplied by alloying. The common denominator is only that most carbides tend to be very hard, and that small carbide precipitates thus are good obstacles for [impeding dislocation movement](#).

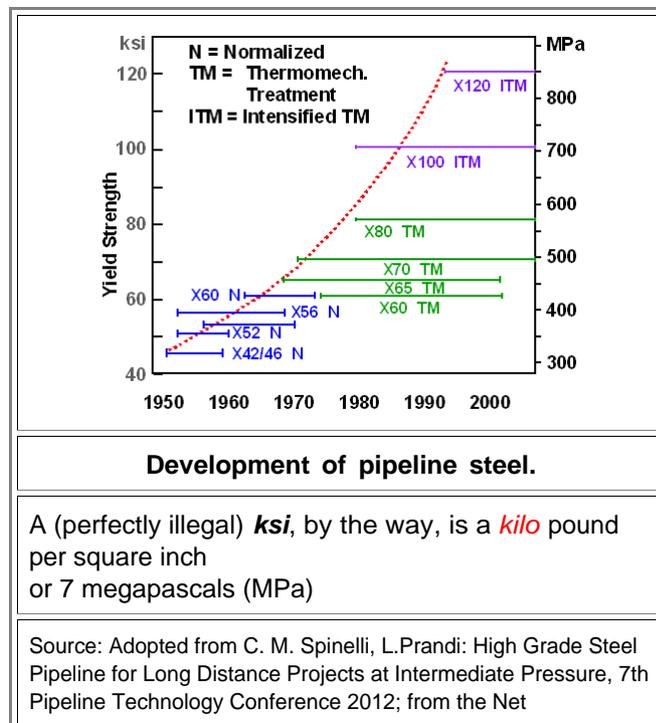
This idea comes up almost unavoidably as soon as you need a steel with a rather large yield strength (or hardness, same thing) that can be [\(liquid\) welded](#). You simply cannot get that from carbon steel since cementite in appreciable amounts will not [allow welding](#). If we look at costs, high-alloy steels are out too; not to mention that they are mostly not so easy to weld either.

There are many kinds of steels that fall into the HSLA group, and there is no clear-cut definition. You may consider *Dual-phase steels* or *weathering steels* as subgroups of HSLA steel or as categories in their own own right; it's just a matter of taste. I will treat them separately here.

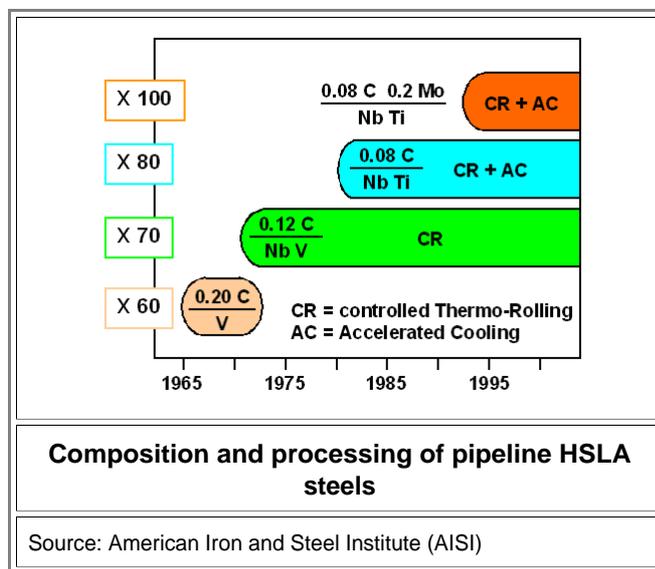
HSLA or micro-alloyed steels are produced by subjecting the proper mix to *controlled* rolling right from continuous solidification. They combine relatively low cost, moderate to high strengths, and very good toughness and fatigue strength, together with their ability to be readily welded. They have pretty much eliminated quenched and tempered carbons steels in all more demanding applications. HSLA steels have market share of about 12 % around 2012, which is quite lot - roughly 170 million tons per year.

HSLA steels, besides being used for cars and many other products, are the steels of choice for all pipelines. You simply need good weldability *and* high strength for obvious reasons. Ductility is not all that important because you deal with a rather simple shape.

The figure below illustrates what is going on in the development of pipeline steel. A tremendous amount of R&D work hides in this figure, not to mention major investments for production facilities. A major possible return on investment is the motivation for doing that. For example, the use of X80 steel in the construction of the first Ruhrgas pipeline led to a material saving of about 20,000 t, compared with X70 pipes, through a reduction of the wall thickness from 20.8 mm for X70 to 18.3 mm for X80. This resulted also in a reduction of the pipe laying costs, because of reduced pipe transportation costs and greatly reduced welding costs, as thinner walls meant reduced welding times.



The dotted red curve gives an idea about progress as time proceeds. Yield strengths have trebled, progress is accelerating, and it will be fascinating to see how it goes on. The next figure gives an idea of what is behind these steels. Ever more sophisticated mixtures and increasingly complex processing provided for progress.



● "Controlled thermo-rolling" plus "accelerated cooling" means that the rolling process that reduces the thickness of the sheet is done in two separate steps at different temperatures, followed after the last rolling step by defined cooling that is faster than natural cooling in air.

▸ Just one example for compositions. The X70 steel comes in several variants with compositions of, e.g.:

- Older version: Carbon (C): 0.07 %, Manganese (Mn): 1.5 %, Niobium (Nb), Vanadium (V), Titanium (Ti) combined: 0.095 % - 0.105 %, and Nitrogen (N): 50ppm (= 0.005 %).
- Newer version: Carbon (C): < 0.07 %, Manganese (Mn): 1.5 %, Niobium (Nb), Vanadium (V), Titanium (Ti) combined: 0.095 % - 0.105 % *plus* Copper (Cu), Nickel (Ni), Molybdenum (Mo) combined: up to 0.7 %

▸ It is illuminating to take a quick look at the history of HSLA steels. Early high-strength low-alloy steels came into being around 1930 because reducing the weight of railway cars, especially freight cars, became urgent. The approach was more or less empirical. That changed when in 1950+, **Norman Petch** and **Eric Hall** independently discovered that [smaller grains make stronger crystals](#). My students certainly learn about the Hall-Petch equation in this context. Of course, knowing that small grains are good is one thing, making small grains and keeping them from growing is an entirely different thing. It should be no surprise that you do it by [alloying](#); aluminum (together with a little bit of nitrogen, N), boron or other suitable elements might just do the job.

● Around that time we had some idea of what we want to do. Add some vanadium (V) and/or niobium (Nb) to iron with a small and well-defined concentration of carbon (and manganese plus Si for the by now well-known reasons) in such a way that small carbides result. The yield strength will go up accordingly, while you still can weld the steel since there is no cementite.

What I want to emphasize is that in the fifties of the 20th century we started to *design engineer* (we certainly don't want to be mixed up with those "designers" that make, for example, "designer eye wear"), steels, using the science behind yield strength and all the other parameters on a qualitative and semi-quantitative base.

Today, the common microalloying elements used in HSLA steels are molybdenum, vanadium, niobium and titanium. Processing has become rather complex but can be done fully automated.

▸ Time to stop. There is certainly far more to HSLA steels than what I've given you so far. But I will now move on to *dual phase* steels.

Dual Phase Steel

▸ Plain old carbon steel was a mix of the true phases iron (ferrite) and iron carbide (cementite), and thus a *two phase* material. When you quench it, you even get martensite as a kind of third metastable phase into the mix. So what is new about *dual* phase steel compared to good old *two*-phase carbon steel, possibly quenched?

● The first new thing is that we have what I like to call a "(proto)-science steel". First you think about what your product should be, then you engineer it. The thinking part, by the way, is why I don't call it "designer" steel. Let's think together. We want:

- Medium hard steel but no cementite because of weldability.
- A simple steel because of costs, meaning no difficult compositions and no costly alloying elements.
- For making cars, we want a very large ductility so we can form complex parts out of planar sheets by plastic deformation in a molding press.
- Ideally, the sheet should be relatively soft for easy forming but harden considerably during or after the forming process.

That calls for [contiguous soft grains](#) that work-harden during deformation and some hard particles / grains that supply basic yield strength or hardness. Most everything should be iron for weldability.

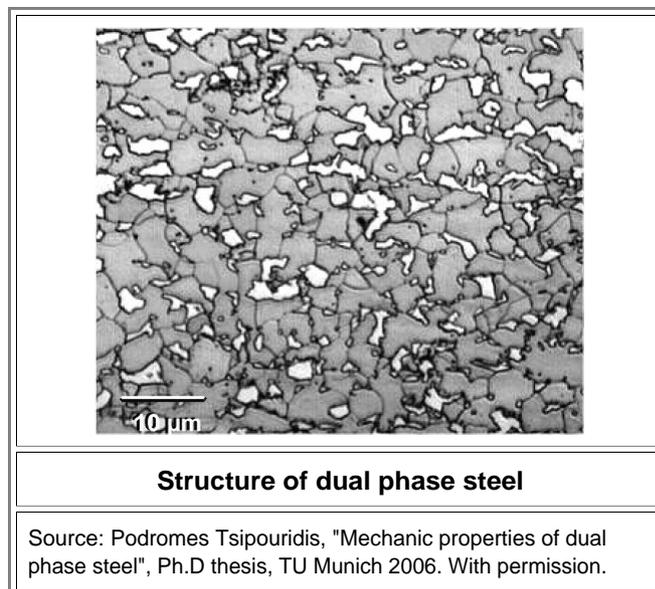
Now *think*. You know that martensite makes steel hard but also brittle. You also know that martensite results from carbon containing austenite if you cool rapidly, and that it is essentially iron. So let's go for a structure that contains contiguous "soft" ferrite grains with some hard martensite particles (about 20 % of volume) in between. That should do the job. Now let's make that.

If you *think* about it long enough (plus doing a few calculations), you realize that you can achieve that by holding a low-concentration carbon steel in the $\alpha + \gamma$ two-phase field for a while, i.e. below the [A₃](#) and above the [A₁](#) temperature. This process is called **intercritical annealing** and will get the steel close to equilibrium. You will have large ferrite grains and small interspersed austenite grains. Now cool down rather fast. Nothing much happens to the practically carbon-free ferrite but the austenite will transform almost completely to martensite if your thermal processing is right.

This way of thinking first produced DP steel in the 70ties of the 20th century. The name "*dual phase*" goes back to a paper by Hayami and Furukawa in 1975, and the steel community adopted it ever since. "*It refers to the two phases, ferrite and martensite, in the microstructure, although small amounts of bainite, pearlite and retained austenite may also be present*", says [Podromes Tsipouridis](#) in his Ph.D. thesis.

Of course, *you* know that martensite, bainite and pearlite are not real phases and now wonder if Mr. Tsipouridis should have gotten a Ph.D degree. Well, rest assured that he knows that too, just like all the other guys who, from the viewpoint of purists, write a bit sloppily about phases. Treating bainite, pearlite, and so on as [\(pseudo\)phases](#) makes writing and reading so much easier. Just try to state what is contained in the sentence above correctly, and you will understand.

Here is what the microstructure of a DP steel can look like. The white stuff is martensite, the rest consists of ferrite grains.



Dual-phase steels thus produced will have some special properties:

- Middling yield strengths, because the stress and strain produced when the martensite forms, produces a lot of dislocations in the ferrite, that are ready to move. So the soft ferrite "gives" early (around 300 MPa).
- No "upper" and "lower" yield point with accompanying inhomogeneous deformation ("[Lüders bands](#)") since dislocations are there and do not need to be nucleated first. They also can move right away since they were created at the low temperature of the martensite formation and therefore not encased and partially immobilized in a "[Cottrell-Bilby cloud](#)" of carbon interstitials since those are stuck in the martensite.
- A remarkable work hardening because upon deformation the ferrite will get "stuffed up" with dislocations and the yield stress in the final product can around 500 MPa -700 MPa, as high as in HSLA steels.
- A large ductility (around 30 %) because the contiguous ferrite can be drawn out quite a bit.

There are two problems with the simple process, however.

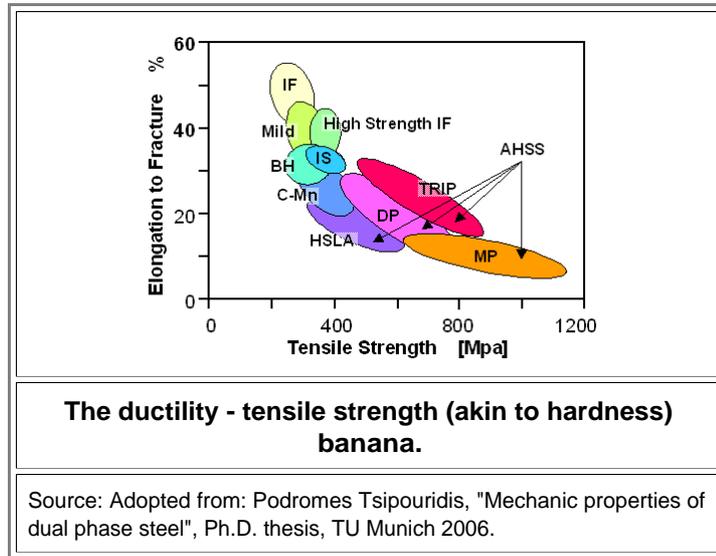
1. For the necessary intercritical annealing you must keep the steel at high temperatures for quite a while (say 3 hours) - and that is a costly process.
2. Transforming the austenite completely to martensite needs a large cooling rate, and that is not so easy to achieve, especially if the sheet is relatively thick.

The solution, by now trivial, is to do some alloying and to use water for cooling the stuff. Then you may even get the desired structure without annealing right from the primary casting process. Simple DP steels may contain (0.08 % - 0.2 %) C and (0.5 %-1.5 %) Mn with small additions of, e.g., Si (0,15 %), Cr (0.5 %) and Mo (0.2 % - 0.4%).

By now we have many different kinds of DP steels, and a lot of knowledge about optimizing properties for certain applications. They are expected to account for about 3/4 of the steels used in the car of the (near) future.

Other Steels You Might Find in Your Car

If we look on one of those diagrams showing tensile strength vs. ductility, we may find a graph as shown below for the kinds of steels used in the car industry (and for many other applications). We have the typical "banana" shape. With increasing yield strength the ductility comes down. How to escape from the banana is shown in the [last part](#) of this module series.



Let me first go through all the abbreviations and names and then discuss briefly the more interesting steels not yet discussed elsewhere.

- Mild = *Mild steel*.
- IF = *Interstitial Free steel*.
- BH = *Bake Hardening steel*.
- IS = *Isotropic Steel*
- C-Mn = carbon - manganese steel (whatever that means)
- HSLA = High Strength Low Alloy steel.
- DP = Dual Phase steel
- TRIP = [Transformation Induced Plasticity steel](#).
- MP = Multi Phase steel.
- AHSS = Advanced High Strength Steels; a family of steels as indicated.

Mild steel used to be the most common variety, containing carbon at low levels (and the ubiquitous Si and Mn). Not strong but cheap, weldable and easily deformed, which is good for forming car parts but not so good in a crash.

Car bodies of old were made from mild steel but that necessitates a hefty thickness of the steel that added considerable weight. That is not a problem as long as carbon dioxide emissions, the price of gasoline, and safety are not serious issues. It is a problem now in the more civilized countries.

Interstitial-free steel, as the name implies, has no or very little interstitially dissolved carbon and nitrogen, at most 0.003 % or so. That allows for large deformations or extreme ["drawability"](#). IF steel is also rather "soft" but that can be helped to some extent by alloying with small amounts of, e.g., titanium (Ti) or niobium (Nb), elements that form small carbide or nitride precipitates with the few of remaining "interstitials".

Deformation is very uniform and that keeps the surface rather flat since no "bumps" or ridges, related to [inhomogeneous deformation](#) (and known as "**Lüders bands**") will form.

In the last 20 years or so, IF grade steel became popular in the car industry. They are used for critical *drawing* applications for the last few decades. IF steels offer a very high degree of formability and good strain hardening features. Car components with immense intricacy, e.g. fenders, bonnet hoods, door insides, or spare wheel wells, can be made in one part by "drawing", meaning pressing a planar sheet into a mould. With "normal" mild steel, several pieces needed to be made and then welded together.

To provide for some hardness beyond what you get by the carbides / nitrides already there, solution hardening is best for keeping high ductility or formability. Since you cannot use the "best" solutes - interstitial carbon or nitrogen - for that purpose, you are now going to give much maligned **phosphorous** (P) a second chance. It's a great solution hardener, as one look at the [relevant data](#) will tell you.

Keeping grains small also helps a lot, and if you need "**high strength**" IF, you might "micro" alloy a bit more of titanium (Ti) plus Niobium (Nb) or vanadium (V). Unavoidably, however, when you increase hardness, you are going to lose some ductility.

By now it should have become rather clear that you better know what you are doing when you work with IF steel. We might take it as one of the first scientific steels.

- Of course, the [first law of economics](#), as always, cannot be beaten. You need to start with rather pure stuff, and you must keep the concentrations of whatever you alloy tightly controlled. That costs money and IF steels will be more expensive than mild carbon steels.

▶ **Bake-Hardening steels** combine relatively low yield strength and thus ease of forming with an appreciable increase in strength after a (low temperature) paint-"baking" process.

- Since you need to cure the paint of your car parts at temperatures around 200 °C (390 °F) in any case, the idea is to get the painted steel to increase its hardness for free during that unavoidable temperature treatment. If you have read up to this point, you are now solidly aware of the fact that increasing hardness always means to make dislocation movement more difficult. You also know that solution hardening works because suitable single atoms, like interstitial carbon, impede the movement of dislocations. So all you have to do is to allow those atoms to gather in a kind of cloud around dislocation lines. This should work if some diffusion can take place, and if some interstitial carbon is still there (and not completely tied up in cementite) since those interstitials like to hang out around dislocations because of the friendly stress and strain fields there - just like the [vacancies during dislocations climb](#). Nitrogen, by the way, would also work but causes too many problems because it [diffuses already at room temperature](#) by an appreciable amount.

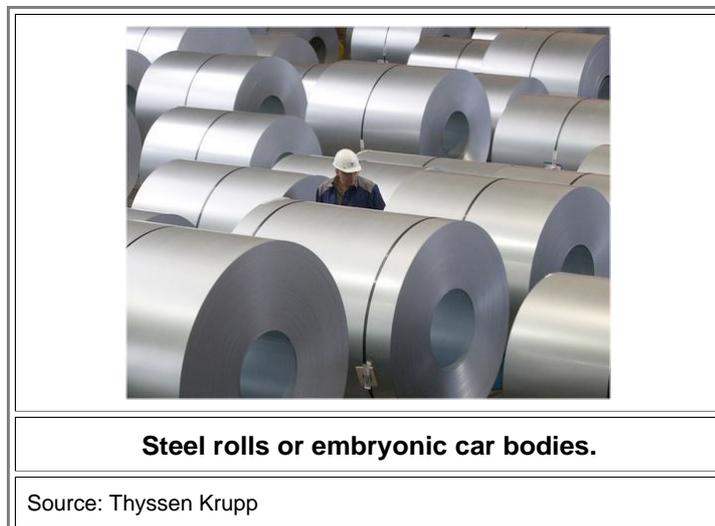
The trick then is to have a small reservoir of atomically dissolved carbon atoms in the ferrite at room temperature. If you can do this, your steel will show some bake-hardening, no matter what kind you have. It works with DP steels and so on.

It also [works at room temperature](#), just more slowly, if you're not careful. Terms like "[strain-ageing](#)" or "shelf-life" come up in this context.

- Bake-hardening steels are obviously of great and increasing importance to the car industry. They are of course optimized for their precise task and therefore addressed as entities in their own right and not just as variants of some other kind.

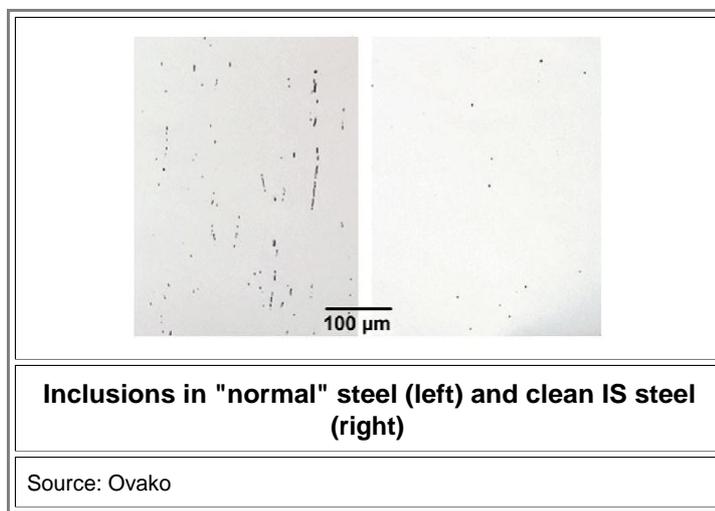
▶ **Isotropic steel (IS)** deforms the same way in all directions. That may come as a bit of a surprise because it indicates that other steels do not. That is indeed the case. Steels for drawing all kinds of parts from a sheet come in huge rolls made by running thicker sheets made by continuous casting through rolling presses. This implies that grains (and inclusions, precipitates, ...) are elongated in the rolling direction. In addition you might get a somewhat mysterious pattern formation called [banding](#) (more or less the same thing that causes the "water" pattern on [wootz blades](#))

- If you do tensile tests with specimens that were cut with the long axis in rolling direction or at right angles to it, respectively, the results will be different - the steel is *not* isotropic. That might be a problem if you need to deform heavily and precisely. Even worse, properties like fatigue resistance might also be worse in some direction.



▶ A major reason for this unwelcome anisotropy of behavior is that [inclusions](#) are crushed and elongated in the steel's rolling direction. So we should avoid that.

- The logical way to do that is to avoid inclusions altogether - by making [clean steel](#). Since 100 % avoidance is costly, the next step is to avoid elongation of whatever is still in there. The pictures below show what can be done (by the company Ovako, one of the leaders in this business).



Multi Phase steel, also called **complex phase steel**, you guessed it, consist of hard islands of martensite, bainite, retained austenite, and God knows what else, dispersed in ductile ferrite. It belongs to the "Advanced High Strength Steel" family and marks the end of the banana - hard but not all that ductile.

- I won't go into this kind of steel because it is far more interesting to see how we can stop being bananas and make hard but super-ductile steel by finally making [scientific steels](#).

Stainless Steels

What we now call *stainless steels* started with the development of "**chromium steels**" in 1912 by Krupp and Mann in Germany. They alloyed 9 % – 12 % chromium (Cr), and the idea was not so much to make *stainless* steel but steel for steam turbine blades. In other words: steel that could take high temperatures.

Around the same time one Brearley in the U.K., while attempting to develop better steel for **gun barrels**, accidentally discovered that martensitic steels containing 13% Cr and 0.2% C did not only show less abrasive wear, but also did not rust.

One wonders who were the war-mongers here. But obviously the whole thing was "in the air" because Haynes in the USA and Strauss and Maurer in Germany also recognized the "stainless" characteristics of high-chromium steels around this time.

Those early high-chromium, and comparatively high-carbon and thus *martensitic* steels were hard. They were subsequently developed commercially for applications such as cutlery knives, as well as for razors, scalpels, heat-resisting tools and bearings - see below.

To quote an Internet source: "It was not until after the end of World War II that the *development in process metallurgy* lead to the growth and widespread use of the modern stainless steels". You just won't get too far just by trial and error. Science was needed.

All stainless steels belong in the [high-alloy steel](#) group; they are also covered to some extent in the [backbone](#). They are stainless, i.e. do not rust, because a thin (and invisible) layer of a chromium-rich oxide film covers their surface that is impenetrable to oxygen. It is the same protection mechanism that works for silicon, aluminum, chromium and many other elements.

Iron oxides will generally not do the job of protecting the iron /steel below it. That's why most steels rust. The exception is [weathering steel](#), also known as **Corten steel**, but we do not count this kind under the "stainless" category because they actually are stained in the sense of looking soiled and discolored.

- Stainless steels proper must contain *at least* 11 % **chromium** (Cr). This magical number can actually be [calculated nowadays](#). It also makes clear that all stainless steels share a major problem: Chromium is expensive! In 2006 you paid more than 6.000 \$ per ton; and right now it is still close to 3.000 \$ a ton. "Plain" steel is found somewhere between 500 \$ - 1000 \$ a ton. Besides Cr, other alloying elements are always added in order to optimize the two principal properties - corrosion resistance and mechanical behavior - plus plenty of others. And that doesn't make it cheaper.

Stainless steels come in several distinct families. The most important ones are:

- Ferritic stainless steels
- Austenitic stainless steels
- Duplex (ferritic-austenitic) stainless steels
- Martensitic stainless steels

I'll look at them briefly one after the other.

Ferritic Stainless Steels.

Chromium by itself, we have learned already, is a [ferrite stabilizer](#). With not too much carbon, austenite will hardly ever form.

- A typical *ferritic* stainless steel consists of **0.04 % C**, **0,45 % Mn** and **12 % - 17 % Cr**. It is not particularly hard, but then its mainly used for forks and spoons, and other household stuff where hardness is not required. It should be stainless but rather ductile because that makes for easy shaping from thin sheets by stamping. High-temperature mechanical properties are not so good - but still good enough for exhaust pipes in cars. [Low temperatures embrittlement](#) does occur but is no problem for the applications mentioned.

▲ **Austenitic Stainless Steels.**

Obviously we need to alloy substantial amounts of so-called [\$\gamma\$ stabilizers](#) like nickel (Ni) or manganese (Mn) that lower the $\gamma \Rightarrow \alpha$ temperature (**A₁**) and thus keep the austenite (meta)stable even at room temperature and in the presence of the always needed large amounts of chromium (Cr).

The most common austenitic steel is "**18/8**" with about **18 % Cr** and **8 % Ni**, **1 % Mn** and only **(0.05 - 0.1) % C**.

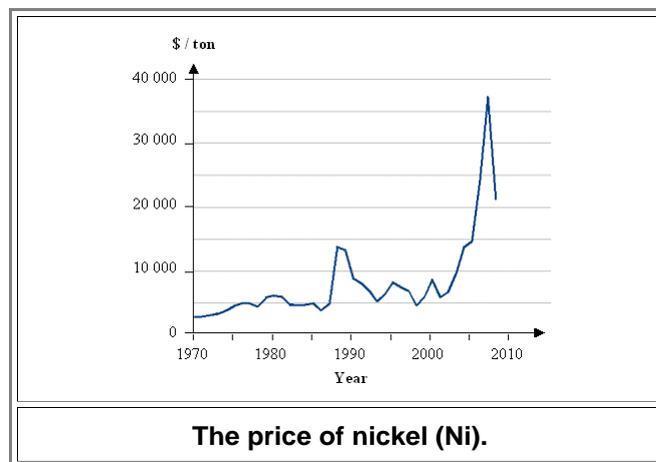
- **Ni** and **Mn** stabilize the austenite down to room temperature. What you get now is a [face-centered cubic crystal](#) (fcc), the austenite phase, and such a structure is completely different from the normal room temperature [body-centered cubic crystal](#) (bcc) or ferrite phase of iron / steel.

This is mainly a result of the nickel (Ni) addition. With increasing **Ni** concentration, the transformation temperature (**A₁**) decreases rapidly from the pure iron **914 °C** at **0 % Ni** via **720 °C** for **8% Ni** to **600 °C** for **15 % Ni**. That is already low enough to keep austenite (meta)stable at lower temperatures, too.

The major properties of **18/8 austenitic steel** are:

- [Like all fcc lattices](#), it tends to be more ductile than bcc lattices. That is also true for austenitic steel. It is comparatively ductile and can be cold worked. That will lead to considerable work-hardening (a direct consequence of the **fcc** structure with its dislocation geometry). This is great for cold-drawing or pressing kitchen sinks and bowls, not to mention the inside of your electron microscope and much piping in your nuclear power plant. It's not so good for machining, though.
- Like all fcc lattices, it is not given much to embrittlement by a [ductile-to-brittle \(DTB\) transition](#). Here is your steel for cold temperatures, e.g. for keeping and transporting liquid nitrogen. [Creep properties](#) are also quite good.
- It is relatively easy to weld.
- Fcc iron is not [magnetic](#). This is a big deal because regular iron and steel is always magnetic, and that might not be acceptable for some applications ike building submarines.

- One major catch is: **Nickel** is even more expensive than chromium! Look at this:



- A ton of austenitic steel contains about 100 kg of Nickel and thus must go for more than a couple of thousand Dollars at the minimum! For comparison: regular carbon steel is well below \$ 1.000 a ton.

▲ Of course, you can make austenitic steel without the chromium (it is then no longer stainless). A famous early austenitic steel is "**Hadfield's steel**". It was invented—you guessed it—by **Sir Robert Hadfield** in 1882 and thus rather early. It contained **13 % Mn** and **1.2 % C**.

- It combines maximum hardness with maximum strength. In its prime state, all the **Mn** and **C** is held in solid solution, but as soon as it is deformed, it will undergo a martensitic transformation nucleated by the deformation which leads to a hardening to about **(500 - 550) H_V**.

This is particularly important wherever wear resistance is the ultimate requirement - the heavily impacted surface areas harden while the bulk keeps its resilience. Examples for applications ranged from tank tracks, bulldozer blade edges, and cutting blades to WW I helmets.

In a way, Hadfield's steel may have been the first "**smart material**".

- Hadfield's steel was a more or less lucky discovery, of course, guided by experience and cunning, long before the scientific principles of steel and alloying were known.

[Article Link](#)

**Hadfield
steel**

▶ **Duplex Stainless Steels**

Duplex stainless contains ferrite and austenite phases, hence the name. Find a proper balance between ferrite stabilizing chromium and the austenite stabilizers nickel and manganese - and here you are! Of course it's not as simple as this but Duplex stainless steels do have a smaller nickel-content compared to the austenite steels. A ferrite : austenite = 50 : 50 structure produces high-strength duplex stainless that is good for demanding applications.

- Warm, humid and saline air plus sea spray, for example, call for particularly corrosion resistant steel, and that's why duplex steels are used in the desalinations or pulp and paper industry, or for tanks in the oil and gas industry.

▶ **Martensitic Stainless Steels**

Martensitic stainless steel contains mostly 11 % to 13% chromium and is both strong and hard with moderate corrosion resistance. You need some carbon and austenite for this, so a composition of. e.g., **0.3 % C, 13 % Cr, 0.4 % Mn** is used; always with some quenching in the processing, of course.

- Martensitic stainless steels are used for stainless knives or pairs of scissors, for example, but also for turbine blades.

▶ Back to [Overview of Major Steels](#)

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▶ On to

- [3. Some Special Steels](#)
- [4. Scientific Steels](#)