

# Properties of Steel

Illustration

In what follows I only want to get you acquainted with steel properties *in general* - in contrast to the bulk of the hyperscript, where I go into details. In particular, I will look at all those properties that are not so interesting to Materials Scientists but get Materials Engineers very excited, e.g. machinability or weldability. And no - I will not discuss very much *how* and *why* properties change when you start making steel out of iron by alloying. This is, after all, to a large extent what the whole Hyperscript is about.

## Basic Properties of Pure Iron

It is a good idea to list some of the very basic properties of *pure* iron before I give you some ideas about steel properties and how those are affected by alloying.

If nothing else is stated, all numbers in what follows are for room temperature.

Let's start with the basics:

- The *crystal lattice* is bcc or fcc, depending on temperature. The *lattice constants*  $a$  are different and depend on temperature as given by the coefficient of thermal expansion  $\alpha_{Fe}$ . The temperatures give the transition temperature between the bcc / fcc phase.

The bcc lattice has two atoms per unit cell, the fcc lattice has 4. If one calculates the volume change bcc  $\rightleftharpoons$  fcc from the data, you have to compare half the volume of the fcc unit cell to that of the bcc unit cell at 911 °C (about 0.290 nm), i.e. 24.4 Å<sup>3</sup> (bcc)  $\rightleftharpoons$  24.31 Å<sup>3</sup> (fcc), corresponding to a **volume change** of about **0.4 %**. The second transformation at 1.390 °C changes the volume by about 0.18 %.

- The *density*  $\rho_{Fe}$  of iron at room temperature is rather large; iron is a "heavy" metal.

The density of the fcc phase is a bit (about 0.4 %) larger, it is the close-packed structure, after all.

In the liquid state, the density is 13 % smaller than that at room temperature, which makes for easy casting since the ingot contracts and thus comes free from the mould walls.

This is in contrast to water and silicon (Si), where the volume expands, leading to violent explosions of pipes / moulds!

- Basic *thermal properties*, beside the phase transformation temperatures given above, are:

Coefficient of thermal expansion  $\alpha_{Fe}$  at room temperature.

It tells you how the length / volume expands with increasing temperature. It is one of the major causes of thermal stress.

*Thermal conductivity*  $\kappa$

The (specific) thermal conductivity or heat conductivity measures how much heat power (energy per second, measured in Watt (W)) flows through 1 m<sup>2</sup> for a temperature difference of 1 K.

Do not confuse with

*Specific heat* or *heat capacity*  $c$ , the energy needed to increase the temperature by 1 K (or 1 °Celsius).

Specific heats are often given for either 1 mol or 1 kg of the material

(1 mol  $_{Fe}$  = 17.89 kg).

*Heat of fusion*  $E_{Fu}$  or the energy needed / released for the transformation solid  $\rightleftharpoons$  liquid.

*Heat of vaporization*  $E_{Va}$  or the energy needed / released for the transformation liquid  $\rightleftharpoons$  gas.

*Curie temperature*  $T_{Ci}$ ; the temperature below which iron becomes ferromagnetic.

- Turning to the basic *mechanical properties* we have:

$a_{bcc}(RT)$	= 0.287 nm
$a_{fcc}(911\text{ °C})$	= 0.365 nm
$a_{bcc}(1.394\text{ °C})$	= 0.293 nm
<b>Melting point</b>	
$T_M$	= 1538 °C
<b>Boiling point</b>	
$T_B$	= 2862 °C

$\rho_{bcc}(RT)$	= 7.874 g/cm <sup>3</sup> = 7874 kg/m <sup>3</sup>
$\rho_L$	= 6.98 g/cm <sup>3</sup> = 6980 kg/m <sup>3</sup>

$$\alpha_{Fe} = 11.8 \cdot 10^{-6} \text{ K}^{-1} = 11.8 \mu\text{m} / (\text{m} \cdot \text{K})$$

$$\kappa_{Fe} = 80.4 \text{ W} / (\text{m} \cdot \text{K})$$

$$X_{Fe} = 25.10 \text{ J} / (\text{mol} \cdot \text{K}) = 449 \text{ J} / (\text{kg} \cdot \text{K})$$

$$E_{Fu} = 13.8 \text{ kJ} / \text{mol} = 246.8 \text{ kJ} / \text{kg}$$

$$E_{Va} = 340 \text{ kJ} / \text{mol} = 6015 \text{ kJ} / \text{kg}$$

$$T_{Ci} = 770 \text{ °C}$$

- **Elastic moduli** or parameters like **Young's modulus Y**, **shear modulus G** or **Poisson's ratio  $\nu$** . You need two, then all others can be calculated.  
All these parameters measure or describe how hard it is to change the distance between the atoms by applying forces for some specific geometry.  
The property that goes with these parameters is often called **stiffness**. It's a somewhat misleading name, however, because stiffness is usually not seen as a *specific* property relative to a defined geometry, but as a product property. In this case the geometry of the object comes in, too. A thick wide blade is "stiffer" than a slender one, even so the *specific* "stiffness" values of the material are the same.

$$Y_{Fe} = 170 \text{ GPa}$$

$$G_{Fe} = 82 \text{ GPa}$$

$$\nu_{Fe} = 0.29$$

- The **speed of sound  $v_S$**  in iron is not all that important but counts as mechanical property that is good to know.

$$v_S = 5\,120 \text{ m/s}$$

Then there are a few miscellaneous properties:

- **Specific electric resistivity  $\rho_{el}$**  or **conductivity  $\sigma_{el}$** .  
The value of specific electric resistivity, in simple terms, gives the value of the resistance of a 1 cm sized cube of a material in  $\Omega$  (Ohm). The specific conductivity is the inverse;  $\sigma = 1/\rho$ .  
Values are for room temperature, the resistivity always increases with increasing temperatures.
- **Magnetic permeability  $\mu$**   
This, in extremely simple terms, indicates how much stronger" an electromagnet will get if you put iron inside the coil.  
The exact value depends on many things.

$$\sigma_{Fe} = 96.1 \text{ n}\Omega \cdot \text{m}$$

$$= 9.61 \text{ }\mu\Omega \cdot \text{cm}$$

$$\mu_{Fe} = 3000 - 10.000$$

## Properties of Low Alloy Steel Not Much Different From Iron

As long as we look at low alloy steel, we look at iron with just a few at% of something else in it. That means that most of the bonds between the atoms of the steel are iron-iron bonds. We must expect that properties that come directly from the bonds then deviate from the the properties of iron just "a few percent", too. We need to consider *atom* percent here, of course. We also call these properties: "*defect-insensitive*".

- Well, yes - but there are exceptions. The exceptions from the rule only occur if some iron-rich compound can be formed, e.g.  $\text{Fe}_3\text{C}$ . With 25 *at%* carbon (corresponding to 6.5 *wt%*) you get 100 at%  $\text{Fe}_3\text{C}$  or cementite, and *all* properties are now totally different from iron. With 1 wt % carbon you still can produce - roughly - 20 at % cementite and that is enough to change the properties noticeably. You now have a *composite material*.  
Here is a good example of what might happen with the property "Young's modulus" in bronze if a copper-rich intermetallic phase occurs. The way to deal with that is doing some averaging as demonstrated in the "composite materials" module.

Keeping this in mind, what we have in terms of properties not much changed by (low) alloying are:

- Parameters like *Young's modulus Y*, shear modulus **G** or Poisson's ratio  $\nu$ .
- The *coefficient of thermal expansion*  $\alpha_{Fe}$ .
- The thermal properties regarding energies resting with the atoms - *heat capacity*, *heat of fusion*, etc.
- *Electrical* and *thermal conductivity* might also be included in the list above but are already borderline. These properties are defect sensitive in the sense that 1 % of something can induce far larger changes - but not *extremely* large changes. Changes induced in these cases always go in only one direction: alloying makes the property worse! That's because in both cases scattering of electrons or "phonons" at defects decrease the transport of electricity or heat energy, respectively, and thus always turn up the resistance.
- Magnetic properties are also influenced by defects and thus may respond stronger than linearly to alloying. The effects, while not *extremely* pronounced, still make huge differences for applications .
- Transformation temperatures (including the melting point) and the kind of phases that are stable are quite sensitive to alloying. That's what phase diagrams are all about, after all.

## Properties Strongly Affected By Alloying

I'm now looking at all kinds of alloys, i.e. low and high alloy steels. The list will include properties that are not particularly interesting for pure iron (and thus may never have been characterized in detail). The properties affected by alloying we might subdivide into:

- Mechanical properties
- Processing properties
- Ageing properties
- Special stuff

I have not listed "structure" as a property affected by alloying because, as you know by now, it is *always* the influence of alloying elements on the *structure* that causes *all* property changes.

### Mechanical Properties

In essence, we have all the properties that describe the [tensile test](#) with numbers. This concerns in particular these quantities:.

- [Yield stress](#)  $R_P$  or [hardness](#). The yield stress denotes the onset of plastic deformation. It is determined in an elaborate and costly test. The much simpler [hardness test](#) measures essentially the same quantity but expresses it in different numbers.
- [Ultimate tensile strength](#)  $R_M$ . The maximum stress a material can bear. Exceed it, and fracture will be unavoidable.
- [Ductility](#) or maximum elongation  $\epsilon_{max}$ . [Typically](#), the higher the yield stress  $R_P$ , the smaller  $\epsilon_{max}$ ; "hard" materials tend to be more brittle.
- [Inhomogeneous deformation](#) or all the bad things associated with, e.g., "Lüders band formation". That's a typical "detail" to the science of plastic deformation that exercises the engineers no end!

Then we have some fracture parameters like the [fracture toughness](#)  $K_{Ic}$  and some more special parameters. Most important, we need to consider *all* these parameters as a function of temperature, to account for [ductile-to-brittle transitions](#) (DTB) or cold and hot shortness, in old-fashioned terms.

Of course, alloying affects all these properties in a major way. Steel was "invented", so to speak, because there was an overwhelming need to increase the hardness of wrought iron.

You know by now that if you want to increase hardness, the thing to do is to make dislocation movement in your alloy more difficult than in the pure material. This can be done by just having foreign atoms around, by producing precipitates like  $Fe_3C$  (cementite), by enabling martensite formation, by keeping grain sizes small, or, quite generally, by having a high density of [crystal defects](#) in an optimized distribution. All of that responds to alloying. There are many examples all over the Hyperscript, so I won't dwell on this anymore.

### Processing Properties

Processing includes making a piece of steel in the first place, and then doing something with it. If we exclude the basic making of steel from dirty iron and its first solidification in, e.g., continuous casting, key properties are:

- **Hardenability**
- **Critical cooling rates and hardness depth.**
- **Machinability**
- **Workability**
- **Weldability**
- **Surface quality**

Let's look at these topics one by one

#### Hardenability

The possibility to harden your material by quenching *after* you shaped it. "Plain" carbon steel was, after all, the only material with *hardenability* for millennia. Forge you blade, quench it in something cold - and the outside of it is now much harder. Try that with wrought iron, copper, bronze or about anything else readily available, and there is *no* such effect. Hardenability comes from martensite formation, and only (carbon) steel thus possesses the this property. Hardenability may be measured by the *hardness depth* achievable, see below.

Hardenability depends on forming metastable martensite directly from carbon-containing austenite instead of stable ferrite-cementite mixes. Hardenability thus gets better with increasing carbon concentration (as long as it is not too large) and with increasing stability of the austenite (i.e. decreasing  $A_1$  temperature) by alloying  [\$\gamma\$ -stabilizers](#). In both cases it gets more difficult to move the carbon out of the austenite during the available time, encouraging martensite formation. Of course, if the austenite is (meta)stable down to ambient temperatures, there is no more hardenability.

- However, we now can harden a lot of materials by other means than quenching and martensite formation, and we do that extensively, e.g. as [described for aluminum](#).

There are more and more steels too, that are hardened after shaping by *heating* and not by quenching, e.g. [maraging steels](#) or [bake-hardening steels](#). Nevertheless, the term "hardenability" in a strict sense refers only to hardening through more or less rapid cooling.

### Critical cooling rates and hardness depth.

If your steel has the basic property "hardenability", you need to know how fast you have to do the cooling. Generally you want to cool quickly as quickly as possible because time is money, but also without needing to do expensive tricks. You don't, for example, want to throw your steel into *dragons blood* as in the old times since this stuff comes dear. Whatever, you must cool faster than some *critical cooling rate* specified for your steel to get an appreciable effect

Since only surface-near parts can be cooled real fast, there is something called *hardness depth*. Below the hardness depth, cooling rates were not large enough to produce martensite and thus some hardening. This is all nicely illustrated by the [Jominy test](#).

- Simple carbon steels do not have a large hardness depth. Alloying the right way can decrease the critical cooling rate and thus increase the hardness depth [considerably](#).

Don't forget: If you cool *too fast*, all kinds of things can go wrong because the large [thermal gradients](#) produce large stress. Maybe your steel simply gets too hard, maybe it bends, twists or even fractures. Of course, alloying affects this in major ways too.

### Machinability

Many steel products need to be machined in some way before they are finished. You need to drill holes and possibly thread them, turn your piece on a lathe into some cylindrical geometry (possibly plus threads), or mill the surface to some required profile. You want to do that as quickly as possible (time is money!), as precisely as needed, and with tools (drill bits, cutting tools, ..) that should last very long before their edges get dull and they have to be sharpened or replaced.

It's hard to put a number on machinability, but you know it when you experience it. The machinability of pudding, acrylic or stainless steel is far worse than that of mild carbon steel, if for quite different reasons.

- If your steel is a given, you must gird your loins and machine it as best as you can. At least you can optimize the tools, e.g. by using [high-speed tool steel](#).

If you have some leeway, you may want to use a special steel optimized for machinability and called "[machine steel](#)". It has been alloyed in such a way (actually with a bit of the otherwise always very unwanted sulfur (S)) that it is particularly easy to machine.

### Workability is a term that describes, in essence, the ease of shaping some piece of steel by *plastic deformation*.

The terms **formability** and **drawability** are more or less synonymous. The term drawability goes back to the old technique of [wire drawing](#) through a die but now means "drawing" a sheet into a form or die to get a certain shape like a car fender.

- Of course, workability is tied to [ductility](#). If your material is barely ductile, you won't be able to change its shape very much by plastic deformation. Good drawability thus certainly needs good ductility - but that is not enough. The material should also deform homogeneously, isotropically, show little *springback*, and it should not develop ridges and bumps on the surface. There are several comparatively simple tests for drawability. Most easily understood is the "**deep drawing cup test**". Take a thin round piece of the metal to be tested and "draw" it into a cup. If it works, it looks as shown in the picture on the right. In this case it's an Al cup but that doesn't matter for the principle.

What you can see is:

- The deformation in the example is not isotropic. The presence of the "ears" proves that it is more difficult to draw the material in four perpendicular directions (related to the rolling direction of the sheet).
- The deformation is rather homogeneous. Apart from the anisotropy, it looks pretty much the same everywhere.
- How much you can draw the material - just keep at it until it starts to crack somewhere.
- The quality of the surface.

- **Springback** is an unavoidable nuisance whenever you "draw" a part by plastic deformation. There is no plastic deformation without some elastic deformation first - the harder the material the more! When you take off the stress applied for the plastic deformation you wanted, the elastic part of the deformation will relax - your material *springs back* to some extent.

You cannot prevent that, you only can try to live with it.

### Weldability

This means not only the possibility to join two pieces of the same metal by simple [liquid or torch welding](#), but to do so *without* compromising other properties, in particular mechanical strength, at the weld seams.



- When you do *liquid* or fusion welding, you liquefy the metal. Then it cools down "naturally" because there isn't much leeway to run all kinds of thermal profiles now. If your metal to be welded only contains low concentrations of alloying elements and cooled down naturally, chances are that the microstructure of the weld seam and the microstructure of the bulk metals are not too different. It follows that the properties should not be too different either.

In other words; you might expect that welding of pure metals should be possible without too many problems, and that this should still be true for mild steels and, hopefully, low-alloy steels with no particular "tricky" microstructure.

- Contrariwise, if you went through great pains to establish a complex microstructure with all kinds of very small precipitates and metastable stuff like martensite, you can forget about (liquid) welding. That, of course, means that most if not all "high tech" alloys cannot be easily welded.

And that's only the start of problems! Far more severe ones come from the violent nature of welding and the exposure of the liquid metal to the gases: nitrogen and oxygen of the air and the hydrogen produced during welding.

**We have a big problem!**

- Welding, however, is absolutely essential for our civilization. That's why there are lots of F+E people out there, trying to find some way to enable some kind of welding for hard-to-weld alloys. Major industries depend on that. You simply cannot make cheap cars, ships, railways, pipelines, scyscrapers, and so on, if you can't weld the steel together. You can't make cheap airplanes from non-weldable steel either, you actually cannot make airplanes from any steel - they would be too heavy.

That's why you make expensive airplanes from non-weldable "high-tech" high-strength [aluminum \(Al\) alloy](#) and [rivet / screw](#) the parts together.

And that is one of the reasons why you and I do not own a major airplane: we can't afford it - in contrast to our welded cars. As a little consolation I give you the special *welding science* module.

[Science  
Link](#)

**Welding**

### Ageing Properties

- Ageing means that (some) properties change in a negative way with time. Most everything ages that way. You age and that means that you tend to fail in more and more things. Sometimes this happens to aged steel. It can't perform anymore and ~~its wife~~ needs to be replaced.

In contrast to you, elementary particles don't age. They're always exactly the same. Even atoms, if left alone don't age. Steel, if not exposed to stress and unfriendly surroundings doesn't age either, or only so slowly that it doesn't matter much. The driving force for ageing is the desire to achieve nirvana. The greater your present distance to the nirvana state, the greater the tendency to age. Your personal first nirvana state, by the way, consists of some gases (hydrogen, oxygen, carbon dioxide), water and a bit of compost.

However, if you go through all the trouble of making a special steel, you usually won't have it just lying around leisurely but use it to the best of its abilities. The material then experiences some stress in the common sense of the word, the same kind of stress you experience when you are driven to your limits by your ~~spouse~~ employer. We may distinguish three types of stress that tend to age steel:

1. Mechanical stress leading to *age hardening*, *creep* or *fatigue*
2. Chemical stress in an unfriendly environment leading to *corrosion*.
3. Social stress through intimate contact with other materials, leading to *wear* and tear on the surface

Let's look at these ageing mechanism and the properties they entail one by one.

### Resistance to **Creep** and **Fatigue**

- **Creep** describes very slow plastic deformation under a constant stress that is below the nominal yield stress. It eventually will result in fracture. Its mechanism is tied to vacancy migration that enables, for example, dislocations to [climb](#) around obstacles like precipitates.

For steel used at ambient temperatures, creep is not a huge problem. However, if you want to use your steel at higher temperatures, e.g. in pressurized boilers, you should pay attention to its *creep resistance*. The basic theory of creep tells you that for achieving increased creep resistance it is a good idea to have many small precipitates, i.e. fine alloy carbides, in small grains plus some solution strengtheners. Beyond that level of design principles it gets more complicated than I care to discuss here.

● **Fatigue** describes sudden fracture occurring after many vibrations with strain amplitudes well below the yield strain. It's something to watch out for if your steel is stressed in an oscillatory manner. How does one improve the fatigue resistance of some steel? If I would know this, I would be a rich man. The detailed mechanisms of fatigue in complex alloy systems are not all that clear yet. But to the extent we do know, it is clear that it will not be easy to fight the problem at its roots. However, fatigue in the end means the growth of crack tips, and we do know quite a bit about that; refer to the "[welding science module](#)" to get a survey. So what we can do to increase fatigue resistance is:

- Remove stress concentration sites on the surface, e.g. by polishing your material. Keep the surface smooth, no sharp corners for example.
- Remove "nanocracks" = unsuitable internal defects in the steel by optimized alloying and processing (hahah!).
- Increase the stress needed to "open" surface-near cracks by treating (typically also hardening) the surface in such a way that it is under [residual compressive stress](#).

▶ **Age hardening** in this context means that your steel gets harder just lying around at ambient temperatures. [Here](#) is an example.

● What happens is relatively simple to explain. Interstitials like carbon or nitrogen atoms that happen to be still around (instead of being tied up in carbides and nitrides) are still sufficiently mobile at room temperature to roam around. They will eventually get caught around dislocations, forming so-called "[Cottrell-Bilby](#)" clouds, thereby making dislocation movement more difficult and thus increasing hardness.

A related effect is "[strain-ageing](#)".

The remedy is clear: Make "[interstitial-free](#)" (IS) steel or at least add some [nitrogen scavenger](#) like titanium to avoid the more dangerous loose nitrogen interstitials at room temperature.

Of course, when you use [bake-hardening steel](#) or [maraging steel](#), you essentially use an "ageing" mechanism to increase the strength of your material. You just do it at elevated temperatures to get results fast.

▶ **Corrosion resistance** as a steel property contains resistance to ordinary **rusting** but also resistance to corroding reactions in, well, corroding environments.

Just as your skin doesn't corrode much in water and air but rather quickly (and unpleasantly) in nitric acid or potassium hydroxide, so do some steels. If you want not just a generally all-round corrosion resistant steel but one that has this desirable property also at high temperature, you must have been an extremely good boy or girl before Santa Claus (disguised as Materials Scientist) will bow to your wish.

● [Stainless steel](#) does neither rust nor stain, while [Corten steel](#) doesn't rust but certainly stains. If you want to do better than that, you must apply the fine art of alloying and alloy the [right \(and often expensive\) elements](#).

As far as just ordinary rusting is concerned, basic information can be found [here](#).

▶ **Wear resistance** is the ability to resist the gradual wearing away of the surface by abrasion and friction.

It is certainly a very desirable property for a drill bit or the balls in ball bearings for obvious reasons. But even hard steel exposed to soft stuff like paper (e.g. the drums for off-set printing) will show wear with time.

Wear is also what makes your knives blunt.

● The harder the more wear resistant, of course. Yes, but that's only true *on average*. Why? Because hardness or yield strength is often an average or [composite property](#). A soft ferrite matrix with some extremely hard carbide particles will register as medium hard in a hardness test but, with its very hard particles, will scratch the hell out of a much harder steel that owns its hardness to solution hardening and therefore is uniformly hard

So you want to make the surface near regions *really* hard. If [case-hardening](#) works, fine. if not, you might use principles where the beginning of a surface-near deformation work-hardens the materials right where scratching would start - for example in [Hadfield's steel](#) or more modern versions of that.. If all else fails, coat your steel with something really hard like titanium nitride, TiN - the stuff that looks like gold and that you have seen on drill bits (or on your faked Rolex).

### Special Stuff

▶ Last. I will go into a few special properties that are not so common as the ones above but nevertheless of some or even prime importance for some applications.

▶ **Surface quality.** The beginning of a car body is a [huge roll of special steel](#). Great care was taken to have a rather perfect surface. Now you draw it into [some part of a car body](#). Is the surface still nearly perfect or did it develop ridges, bumps and God knows what else, on a small but visible scale? So well visible that you still see it after the car body was painted! Then you have a huge problem!

● Your problem is tied to inhomogeneous plastic deformation in general, and all kinds of annoying details in particular. [This module](#) gives a taste treat.

▶ **Magnetic and electric properties**

Extremely important properties if you treasure electricity in general.

● You will find everything of general interest relating to these properties [here](#).

▶ **Thermal properties**

Not very exciting. Except for [Invar steel](#).

## Color, reflectance

This is arguably the least important property of steel. If you agree, think about it. Together with the surface condition (polished, rough, ...) it actually determines what *you* see. Why steel looks like steel and you like .... yes? You might argue that while this is true in general, it's a boring truth for steel or metals because they all look alike: silvery grey, just like metals. Well, yes and no. Gold and copper are not silvery grey and different kinds of steel can look quite different, too.

Making a pattern-welded show-off sword from two different steels only makes sense if the surfaces of those steels look different so you can [see the pattern](#). Maybe it takes some etching before you see the two different steels but so what. Etching can only reveal differences that must come from different properties of different steels.

So why do things look the way they look?

I'm opening a rather large can of worms (or of science delights) here. I'm talking about the interaction of visible light and the surface of materials, here some steel (or metal). We want answers to question like:

1. Why is gold yellowish, copper red-brownish, and the rest of metals silverish?
2. Why are some steels bluish?
3. What determines the small but well-visible differences between the silverish appearance of metals?
4. Why, for example, appears steel containing a bit of phosphorus (P) somehow "whiter" than most other steels?

For answers, we need to consider three ingredients:

1. The topological condition of the surface. Is it [polished or rough](#) on some scale?
2. Are there layers of something transparent on the surface? I'm not talking about visible rust or paint but very thin layers of transparent featureless oxides, nitrides, phosphides, whatever.
3. The way the metals itself interacts with light. Gold will be golden in appearance, and silver will be silvery, no matter if polished, rough, matte or coated with something transparent and very thin.

This topic is not of prime importance for modern steel but was of some importance in the making of pattern welded swords.