Metallurgy and Coiled Tubing

Why does steel break? Why do some kinds rust quickly and others slowly? Why are some types of steel flexible like coat hangers, and others are brittle like high quality chef's knives? Why do welds and joints tend to fail more quickly than uninterrupted stretches of metal? From the outside, all steel looks like a uniform surface but under high magnification it has a lot of features which help to explain these, and many other properties of steels. Metallurgy and the behavior of metals is a huge topic, but today we will focus on only one of them: How can you bend a piece of steel repeatedly and still use it, and what happens to the metal as a result?

A coiled tubing unit. A single piece of round steel pipe is stored on the drum in the middle of the picture, unwrapped and put in a well, and returned to the drum when the work is finished. Then the steel tube is unwound and used again and again over the course of months or even years before it finally wears out and must be replaced. How is this possible? Why doesn't it break immediately? There are 3 key factors:

- Crystal Structure
- Grain Structure
- Work Hardening

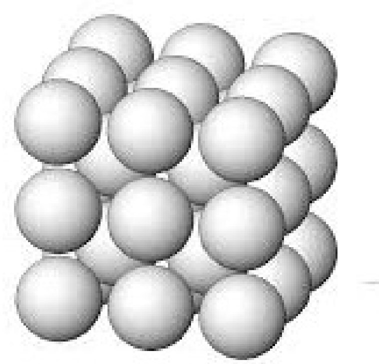
What is Steel made of?

Steel is basically iron, the element known as Fe in the periodic table of elements (Fe is for ferrum, the Latin name for iron) But it's not 100% Fe. Like many other metals, the properties of a block of iron can be changed by mixing it with other metals and elements. Specifically, to turn iron into steel you have to add some carbon to it. Other things are added to many types of steels to alter their properties in ways that are intended: nickel, chrome, molybdenum, and manganese are all common alloying elements that are added to steels. Sometimes things get into steel which are NOT intended – commonly this includes phosphorus, silicon, and sulfur.

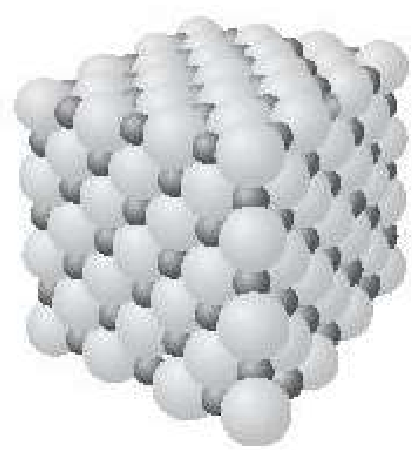
Crystal Structure

An item like a tube or a car door is made into whatever shape it is that is necessary for it to do the job it was made for. But on the atomic and molecular scale the steel has also been shaped and formed into the 'right' structure for the use that it will have.

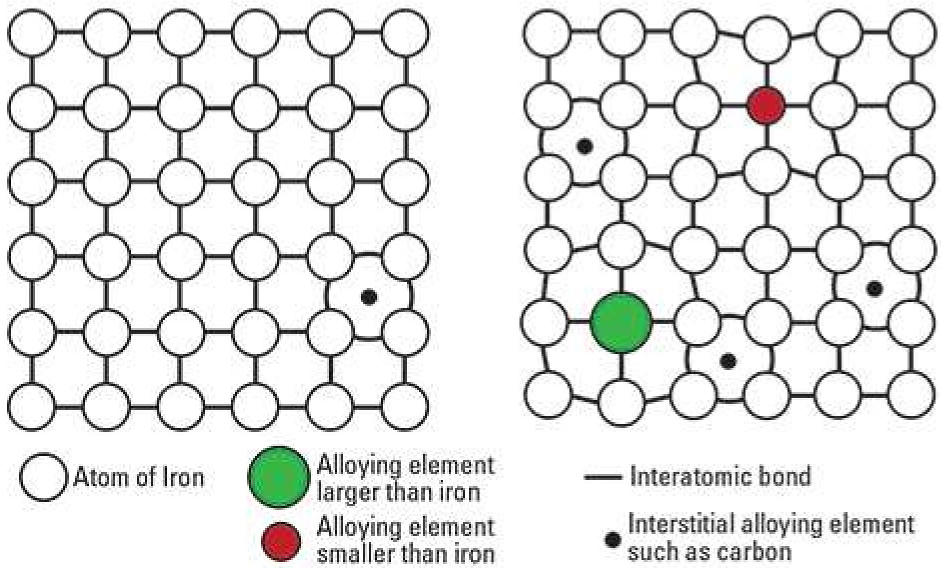
Pure iron: (only Fe) molecules stack together in a neat form that thematically looks like this, with each ball representing one iron atom. This structure isn't actually all that strong, but it IS pretty flexible and if it's very pure, it doesn't rust badly either. Wrought Iron is the most common example of this in everyday life. It's not very strong, but it's very flexible (called ductile), so much so that it's used as artistically twisted and bent things like gates, fences and light fixtures. You can reasonably bend pieces the size of your finger in diameter with your hands, and if you do this by accident you can bend them back again.



Cast Iron: Atoms of carbon are smaller than atoms of iron, so when carbon is added to iron to make steel it fits into the gaps in between the molecules to form a structure that looks more like this, where the small black points represent the carbon, and the grey ones are the iron. When every single gap is filled, as is shown in this picture, the result is cast iron. Strong, but not very flexible (not ductile). Don't try to bend the handles on your cast iron pots and pans at home – you probably won't be able to do it, and if you are strong enough to succeed, you will snap the handle off. Strong but brittle.



Steel represents an intermediate between the two, and usually has some other stuff in it. We will switch to a two-dimensional representation because it gets too complex to easily see in three dimensions on a two-dimensional screen or sheet of paper.



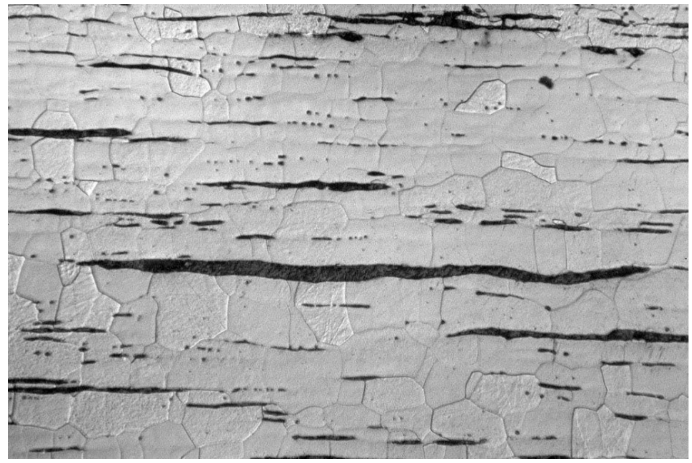
By having some carbon (but not too much) you get a nice balance between strength and flexibility. Adding other elements which are slightly different in size or electrical bonding strength from iron, but which replace it in the alloy produce properties like rust resistance, or smoother and easier bending than pure iron would have without sacrificing strength. Sulfur is the biggest enemy of good strong steels, because it is a big fat molecule which forces its way in between the iron atoms to try and get into the space where the carbon atoms might usually reside. It is so big that it breaks the bonds between the iron atoms around it making the whole structure weaker, and particularly likely to crack if it gets bent. And it causes corrosion too! Not a fun element if you like strong long-lasting steel.

Steels for a service like coiled tubing need to be as flexible as you can make them without sacrificing too much strength, since it's going to be seeing a lot of physical loads in addition to being bent a lot. Any elements like sulfur which can cause cracking are a big no-no because bending the steel around all over the place is just begging for cracks to start to form, which leads us to the next critical structure that has to be assembled correctly.

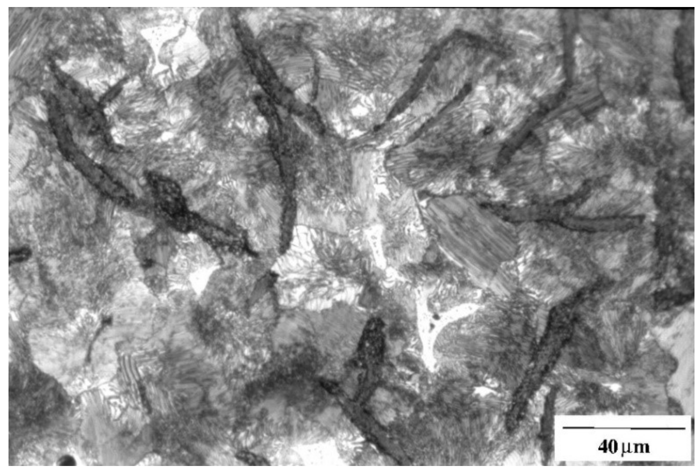
Grain Structure

A piece of steel large enough to be used by people is not one giant crystal – not only would that be undesirable, but it can't be done on a large scale. Instead a bunch of tiny crystals form in different places in the molten steel while it cools. As it gradually changes from a liquid to a solid the crystals grow together and join up into a solid mass. Some of them with similar composition and orientation form grains. Small groups of atoms that form crystals are too small to see by eye, but a good microscope, special lighting and a process called etching can be used to see the grain structure of steel in a microscope. Grains in steel can be understood to some degree like grain in wood. Unlike wood where the grain has a direction, the grains in steel are often arranged more randomly (although not always) Also unlike wood, the grain structure can be changed, and this is important. The similarities though are everything else. Grains can be fine or coarse, there can be 'knots' or gaps in the grain caused by various contaminants or by the way the grains grew and different steels and woods have different general structures that make them better at different tasks.

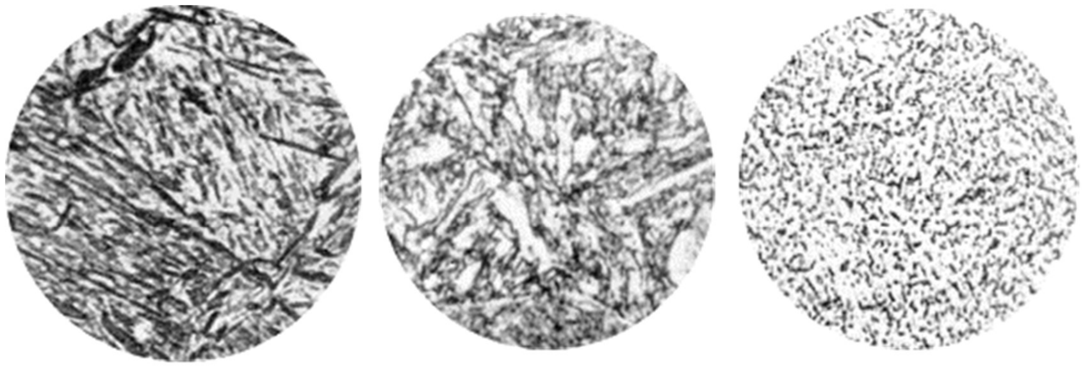
Wrought iron has a smooth structure with a mixture of nearly pure iron and iron with a little bit of carbon in it. It is smooth and straited looking, and it's easy to imagine the layers on the upper parts sliding over the layers on the lower parts – it's ductile – it should look that way!



Cast iron has a rocky looking structure with big fat grains of steel separated by small amounts of excess carbon. The large chunky grains cannot slide past each other and make for a very stiff (non-ductile) structure.



Steels can have a lot of different looking structures, but the one we want to look at in detail is martensite. It is a structure where all the different materials in the metal are blended together in such a way that you cannot easily find/see where carbon is, or where iron is, or where the other alloying materials are either.



Martensite Tempered Martensite Heavily Tempered

The grains can be sharp on the edges, but they butt directly up against other grains with the same structure they have, merely in different directions. With martensite, the speed at which the grains form affects their final sizes and orientation. If the grains form slowly during gradual cooling from molten steel to solid steel, they tend to be large as shown on the left hand side of the comparisons because the grains have a lot of opportunity to organize themselves into reasonably large structures. If the steel is later warmed up and then cooled quickly (Tempering), then smaller grains are 'forced' to be created. By making small grains, we get some of the best of both worlds between the smooth wrought iron structure and the rocky cast iron structure. Because the grains have rough sharp edges, they tend to resist being bent and form a strong structure for the steel. However because they are small, if you do manage to get them moving, they will tend to move reasonably well and then more or less fit back together again wherever they happen to stop at any one part of the internal structure of the steel looks pretty much like any other part and they can stick themselves back together again.

This is the structure you want for steel which will be bent a lot, but which still must be reasonably strong. It takes a lot of work to make it, and then keep it. The catch is that while the structure is formed by having the right elements in the steel, and by controlled cycles of heating and cooling, it can be taken apart again.

How it works

The reason that you cannot bend steel like this forever is that when it does move, every once in a while, the grains of steel will align perfectly and form new larger grains. Over time the structure of the steel gradually starts to move from small randomly oriented grains towards large grains. In addition the original structure is never 'perfect' it was a random collection of grains and inevitably somewhere in there are flaws of one sort or another caused by contaminants or cooling and heating irregularities or new ones are introduced, for example when somebody accidently whacks it with a hammer or clips a concrete corner or a rock while driving down the road. These flaws cause cracks to grow. Eventually either the steel cracks apart when the flaws and cracks get big enough, or the grains gradually get more and more well aligned until the steel either cracks on it's own, or weakens enough that it comes apart under stresses that it could have withstood with it's starting microstructure.

Conclusions

The exact study of failures and their mechanisms is a topic for another day, but the good news is that the growth of cracks and the creation of points of vulnerability as a result of grain alignment are both reasonably predictable if the starting properties of the steel are well known. As a result the eventual failure of steel under dramatic deformation like that of coiled tubing can be predicted. Until you try to account for corrosion, which is yet another metallurgical topic.