Riveting, Soldering and Welding

Plus Gluing and Screwing

Joining in General

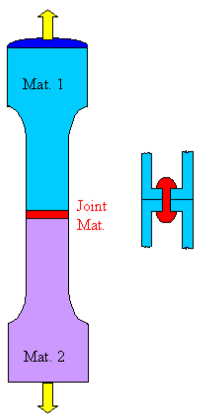
Illustration

So you have all kinds of steel pieces but not yet the object you want to make from that steel. Forging and casting can do a lot, but you can neither forge a big ship or a mechanical watch from a piece of steel, nor can you cast it.
You must **join** your pieces, and ***joining*** is a major part of Materials Engineering. It is also a difficult part of Materials Engineering, even if we do not consider joined systems with moveable parts like gear wheels.
If you think about it for a second, without joining you can't get very far. Even your flintstone arrow tip or axe head needed to be joined to the arrow shaft or some handle. While joining is obviously quite important for making all kinds of products, it is not clamorous and never easy.
Non-metals you can join by simple means like sowing, tying with thread or twine or nailing. The ancient Egyptians actually sowed their large wooden boats together. But with wood you can also use nails (if you know how to make them) and the not-so-ancient Vikings indeed nailed their boats together.
You use mortar for joining bricks and stones. This would be a huge topic by itself and I just mention it to point out that there are many ways for joining materials *in general*.

So let's get a bit less general. In what follows I restrict myself mainly to the joining of *metals*. The major techniques available for joining are:

- Screwing (the metal)
- Riveting
- Welding
- Soldering
- Gluing

Before I go onto details, let's ask ourselves a general question: What kind of *mechanical properties* can we expect from joined materials?
To get a first idea, we simply imagine doing a tensile test on an "ideal" joined specimen like this



Tensile Test for Joints

The two joined metals might be of the same kind or of a different kind. We can imagine making a "classical" specimen as shown, or some special contraption suited for the purpose as shown for testing riveted pieces of metal.
It is clear that the stress-strain curve will be a "mixture" of the stress-strain curves of the individual materials. It is equally clear that the "weakest" material determines all parameters like Young's modulus, yield strength or fracture behavior.
In addition, the two interfaces may "fracture" long before the materials would. Just imagine the red stuff to be adhesive tape between two steel pieces. Fracture will occur at the "seams" and not in the materials.

Idealized tensile test for joints

For gluing and soldering it is clear what I mean with "joint material". In the case of riveting it is also clear enough, but what about welding?

When you do *liquid* welding of two identical materials, you liquefy parts of your materials plus some material you flow into the joint. Even if the composition of all materials concerned is exactly the same, the microstructure of the weld seam will be quite different from that of the undisturbed material. The liquid parts will cool down rather rapidly and there is not much you can do about that. It would be rather unexpected if the microstructure of the liquefied part would be the same as that of the solid parts. Since the microstructure determines properties to a large extent, properties of the joint material will be different from that of the bulk material.
Moreover, the material next to the weld will not liquefy but nevertheless experience a "heat treatment" and thus change its microstructure. These **heat-affected zones** therefore also differ in properties from the unaffected bulk.
If the metals to be welded together had been exposed to special temperature treatments to bring out the best possible properties, the weld, obviously, can only be worse than the rest.

- I'm confident that I need not explain that the welding zone between two *different* materials is indeed a material quite different from the others. I'm also confident that it is clear to you that welding two different metals is a far more trickier business than to weld identical metals. And pondering the little bit I have stated so far, it may even become obvious that there are a lot of materials - including all kinds of steel - that simply *cannot* be welded without compromising properties at an unacceptable level.

Now let's get the two less important joining methods out of the way:

Gluing

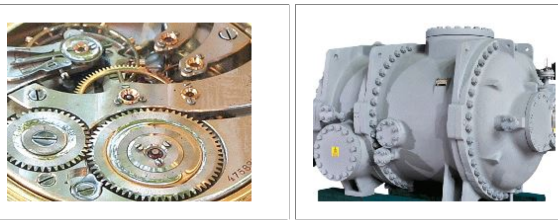
Gluing means that a thin layer of some *polymer*, some organic stuff, holds the two pieces together. The first condition thus is that the semi-liquid glue sticks to both pieces to be joined. Then it must mutate from some viscous or semi-liquid goo to a hard and strong solid after you applied it.

- Polymers typically don't stick very well to metals. They are also not all that great with respect to yield strength, Young's modulus or fracture strength.
  Joining metals by gluing thus seems ridiculous. Well, yes, but gluing plastics to metals is actually done and finding more and more enthusiasts. If you want to join fibre re-enforced stuff used for airplane parts to metal, gluing is essential. Find out for yourself what it is going on in this field.
- However, if you are a warrior, I do not recommend to repair your broken sword blade by gluing the parts together. So I won't go any deeper into the sticky stuff here except to say that gluing is a very old technique. Stone age man and woman glued their stuff together by using birch sap, for example.

Screwing

Screwing is also a very old technique - sorry, that's the other kind. Screwing things together is what you need to do when you intend to take things apart again. You also do it when you need to fix a small or thin piece of metal to something bulky

- You screw on the cylinder head to the bulk of your car engine because you may need to take it off one day. Even if you assume that this won't be necessary, riveting would require very deep holes and long rivets, making the process costly and awkward, and welding is simply impossible at the level of precision needed. I won't even mention gluing.
- So the big advantage of using screws for joining metals (or wood, or whatever) is that you can take it apart again. The big *dis* advantage of screws is also that you can take it apart again. As we (men) all know, from tending our kid's bicycles and innumerable other odd jobs, screws magically tend to get loose all by themselves if you don't pay a lot of attention.
  And as we (men) also know, high-quality screwing typically doesn't come all that cheap, either.



Tiny and big screws in common products

- Let's not forget that for screwing you need screws *and* threaded holes in the bulk of some material or threaded nuts (plus washers, clamp rings, retainers, ...). Making a screw wasn't so easy when you had to make them by hand with a hammer and a file; making nuts was worse. Screwing thus only could become a major joining technique after it became possible to cut precise threads with tools like a lathe.

Other big advantages of screwing are:

- Screwing doesn't compromise the properties of the metals screwed together.
- With screwing you can join different metals or generally different materials without too many problems.

- Of course, the properties of the joint now depend very much on the properties of the screws (and how many you have per area). So use extremely high quality steel screws, and since no heating is required, the joint property is known and not subject to more or less uncontrolled microstructural changes occurring during the cooling of molten parts in welding.
- High quality joining thus is generally possible, and that's why you find a hell of a lot of extremely high-quality screws in, for examples, air craft engines.

Riveting

There are plenty of large metal constructions that you do not want to take apart again and that better stay together solidly for a long time. Bridges, buildings, ships, airplanes - you can continue this list yourself. Screwing then is not necessary and simply too expensive. Welding would be the answer but welding is often not possible, even today, and it wasn't possible at all before 1920 or so for large steel constructions designed to be able to withstand large forces. Riveting was the answer, and to some extent still is.

- Here is a part of a riveted boiler vessel. It was used for something dear to the heart of real, sword-yielding men: brewing **beer**. The boiler performed flawlessly for many years and helped to keep the Copenhagen population happy for a long time. That was not always so. Around 1800, without reliable riveted together steel things, the quantity and quality of the beer brewed in Copenhagen was often compromised and one consumer complained bitterly: "In my small household, beer is often lacking for 8 to 14 days.... at these times my children must either go to the water pump, if the water is drinkable, or I must with sadness see them become weak on tea water". The Danish, by the way, are supposed to be among the most happy people on this planet.

Riveted boiler vessel in the Carlsberg brewery, Copenhagen, Denmark.

- The next picture shows a heavily riveted steel girder, made around 1890, that is still on duty in the Dresden / Germany central train station. A few parts are screwed together and it is easy to see why.

Riveted steel girder on the Dresden main station from around 1890
The link leads to a large scale picture

- Riveting isn't easy. You have to hold the two (typically very heavy) pieces firmly together, drill a (big) hole through the structure, insert a rivet (usually red-hot), hold it firmly against the structure on one side and bang it hard on the other side to flatten its head.
  - You needed a team of at least three people to set rivets. A ship like the Titanic had about 3 million rivets, and building a vessel like that was not only costly but also rather time consuming.
  - The properties of a riveted compound are tricky for two reasons: holes in the main part always weaken the structure and might act as sources of cracks. The strength of the whole contraption, as the figure above makes clear, depends to a large part on the properties of the rivets.
    There is one advantage, however: Cracks running through the bulk of a plate stop at the riveted joints and can not run into the other plate like at welded joints. The Liberty ship disaster bears witness to this.
    In the Internet you can find heated discussions about the "real" reasons why the Titanic took a dive. Was it the poor quality of the steel or of (some) rivets?
- Welding has replaced riveting in most mass-produced steel constructions. However, there are still plenty of steels that can't be welded because the weld joint would compromise the properties too much.
  - Welding aluminum alloys, for example, is still mostly not possible. Your "aluminum" bicycle" typically will have a welded frame, but your aluminum-alloy airliner will still be riveted together in many places (discreetly, the rivet heads don't stick out). Look at that next time you take a flight.

Soldering

- Soldering is absolutely essential to electronics, plumbing, and many other technologies, e.g. making a bicycle frame. Soldering, generally speaking, is a process for joining two pieces of metals (not necessarily of the same kind) by flowing a liquid filler metal - the solder - into the joint. The two metals to be joined never melt. They usually shouldn't even get very hot, so the solder must have a low melting point
  - For a long time, solder mostly meant tin/lead compounds either at or not too far from the eutectic composition (63 % tin /37 % Pb) with a melting point of 183 °C (361 °F). "Hard solders", melting at higher temperatures, are used, for example, in jewelry; they usually contain some silver. The process then is called "**brazing** ".
  - However, solder containing lead is forbidden since 2006 on the grounds that lead is a hazardous material (it is). The electronic industry spend humongous amounts of money to convert to new solders, typically a ternary Sn-Ag-Cu alloy. That was fine with me.
    However, when I saw builders putting tons of pure lead sheet on rooftops while my colleagues struggled like hell to keep a few grams out of some electronic product; I started to wonder a bit. Hunters, of course, still use lead for their shot gun ammunition. Now you have an interesting topic for discussions.
- Soldering retains electrical conductivity, and that is all-important for electronics. Direct soldering, however, is pretty bad for mechanical strength; the idea of soldering a broken sword blade together would be ludicrous. If you need mechanical strength, for example when you need to keep the tubes of a bicycle frame together, you either weld, and if that is not possible, connect the tubes by brazing them into sockets called "lugs".
- Soldering is an old technique. Many artifacts found in Sumer, ancient Egypt and so on are reported to have employed some kind of soldering or brazing - but so far I couldn't find any good pictures for that.

Liquid Welding

- First I need to make a disclaimer. *Most* people associate welding only with what I call *liquid* welding here. Some guy in a mask makes a lot of noise and an extremely bright light by liquefying some metal with a blow torch or some electric contraption.
  By contrast, *you* now know that the term "welding" also includes the joining of two identical pieces of iron or steel at temperatures well *below* the melting point by hammering them together at some elevated temperature. I have called that "hammer-welding" but is is also referred to as **pressure welding**, **fire welding**, **forge welding** or **contact welding**. This kind of welding can also be achieved with other metals.
  - There are even more (modern) methods for welding or bonding without melting. Describing "wire bonding", i.e. the technique of attaching tiny wires to contact patches on silicon chips, would fill many pages. Look up yourself key words like ultrasonic welding, explosion welding, friction stir welding, electromagnetic pulse welding, co-extrusion welding, cold welding, diffusion welding, exothermic welding, high frequency welding, hot pressure welding, induction welding, or roll welding.

- The modern word "**welding** ", in the sense of joining by welding, is from around 1830, it might derive from "to well" = to boil, rise, or from "to wield".
  In German, welding is called "schweissen", a word that contains "eisen" = iron and is related to "schwitzen" = sweating, swelter, exuding liquid. A "Schmied" (smith) "schweisst" (welds) the "eisen" (iron) by putting two pieces at "schweisshitze" (sweating heat), where the iron sweats because it starts to react with carbon and oxygen. It's all related, in other words, and non-liquid welding always was an integral part of iron technology.

Here I only take a very cursory view on *liquid* welding. Not because it wouldn't merit an in-depth description but because I don't know much about it. Whatever little I do know can be found in the science module.
The first thing to know is that without liquid welding of steel, the world would be a very different place. You wouldn't be driving a car, for example.

Science Link
Welding

- For *liquid* welding you must melt the materials to be welded. For iron that means that you need to exceed about 1500 ^{0}C (2732 ^{0}F) right at the (small) spot where you want to weld. This is not an easy undertaking; I have harped on this topic many times in this hyperscript and even written a special module. So how, when, and where was iron first joint by using *liquid welding*? I don't really know but can illustrate this point by referring to the Liberty Ship disaster.
  During WW II, welding on a large scale was done to produce "Liberty Ships", mostly because that allowed to build such a vessel in about 50 days, instead of 250 days required for riveting. That nicely illustrates the huge potential advantage of welding in comparison to riveting; what happened to those ships illustrates the dangers.
- If you look at older structures it becomes clear that welding on a large scale came into its own around 1930, give or take some 10 years.

The three essential points to note are:

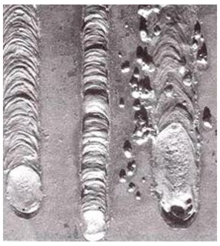
1. Achieving local melting.
2. Keeping the molten stuff from reacting with air or hydrogen that is around.
3. Achieving some kind of integrity of the finished weld.

So let's look at how one could achieve local melting. Omitting the more exotic methods like using explosives (sounds like fun, though), we have essentially two options:

1. Electricity (in the form of an electric arc).
2. A very hot flame from a blow torch.

- **1.** Electricity can transport enormous amount of energy through thin wires and thus is able to deliver a lot of energy into a small space. If you just want to heat some (conducting) object like steel, all it needs is to draw an arc, an electric discharge, from a point on your object to an electrode. The power delivered equals current ***I*** times voltage ***U***. If you run a bit more than 4 A at 230 V, easily delivered by a standard outlet, you can concentrate a power of 1 kW or 1 kJ/s on a few square millimeter. It takes about 1 kJ to melt 1 g of iron, so within seconds you start liquefying small amounts of the stuff. Real arc welders deliver far more power (typically at lower voltage and higher currents), of course.
  Historically, it was the Russian scientist Vasily Petrov who "discovered" the electrical arc in 1802, just a few years after Volta "discovered" electricity. W.E. Staite, an English subject, obtained a patent for arc melting in 1849. However, it took until 1881 before arc welding started to be really used, and the credit for that goes to the Russian Nikolai Nikolaijewitsch. Of course, without Werner v. Siemens invention of the electrodynamic generator in 1867, all of that would have been moot for lack of efficient power sources.
  Electric arc welding developed ever since and was used for a multitude of applications on a smaller scale. Being able to build large-scale objects like ships, train stations, or bridges by welding took some more years.
- **2.** You cannot get an energy of kJ in a small area by regular fires or flames. You must burn something, i.e. react it with oxygen, that produces a lot of energy in the reaction and you must burn a lot. So use pure oxygen (O_2) instead of air plus a highly combustible gas like propane (C_3H_8) or acetylene (C_2H_2) and you get (roughly) temperatures of 2.500 °C (4.530 °F) for propane and 3.500 °C (6.330 °F) for acetylene. If you burn propane just with air, you're stuck at 2.000 °C (3,630 °F). Acetylene thus makes the hottest flame but needs to be handled with care.
  The key was the bulk production of acetylene by reacting calcium carbide (CaC_2) with water; a simple but dangerous undertaking. First, of course, one needed to make calcium carbide, and for that one needed electricity and the ground-breaking inventions of Werner von Siemens and his brethren that allowed to "make" plenty of electrical energy.
  Blow torch welding (and cutting) was pioneered by the French engineers Edmond Fouché and Charles Picard around 1903.
  A modern blow torch is still a fearsome thing. It can be used for welding but is more useful nowadays for just *cutting*. After all, sooner or later we must cut down the big ships, tanks, and whatever else we welded together many years before.

- The second point - protecting the melt from reactions with air and so on - can often be done in a simple way by employing some "flux" material that protects the weld area from oxidation and contamination by producing carbon dioxide (CO_2) gas during the welding process. Your welding electrode is typically covered with the flux material and delivers it while you weld.
  - Otherwise you resort to "gas metal arc welding". In essence, you blow a stream of inert or semi-inert gas like argon or helium along your electrode, keeping the air off the liquid parts. Even better, you weld submerged in some liquid flux material.
    It is not getting cheaper this way, and the more complex it gets the more you need fully automated equipment.
- It remains to look at how one achieves some kind of integrity of the finished weld. In other words: there are good welds and there are bad welds, depending on how it was done. Look at the welds of cheap and expensive bicycles with welded frames and you see the difference between a uniform and very good weld, and a bumpy and clumsy but still good weld. I hope you don't see a really bad weld.

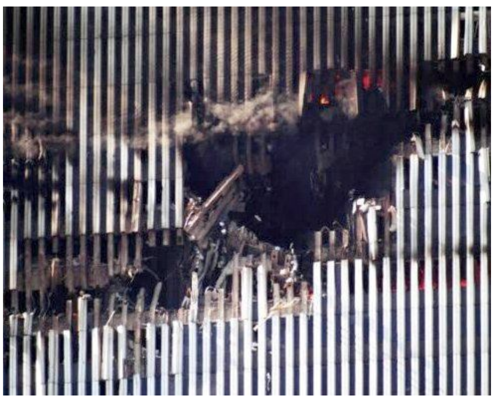


In the words of the "Welders Universe" (the source here) , what you see here is "The Good, the Bad and the Ugly".
It goes without saying that the properties follow this judgement.

On the right the ugly, dangerous and fraudulent (badly welded guardrail in Sicily; should have been screwed; was expensive; EU payed for it).

Welding quality

  - The point is: Welding is a demanding technology and the quality of what you get depends on the quality of who is doing it. As a colleague from the ship yard across the road tells me, only a few of their welders are allowed to do particular difficult welds, and even those experts need to have a good day to succeed.
- Can one join a broken sword blade by fusion welding? Rather not. Even if you manage to get a good weld, it looks ugly no matter how well you grind and polish it, and the blade will suffer in the process and loose quality.
  - Keep in mind: even the best possible weld seam will have mechanical properties different to those of the material welded. That was drastically demonstrated in 2001 as shown below.



World Trade Center 9/11 in 2001
The steel girders typically sheared off at the weld seams.