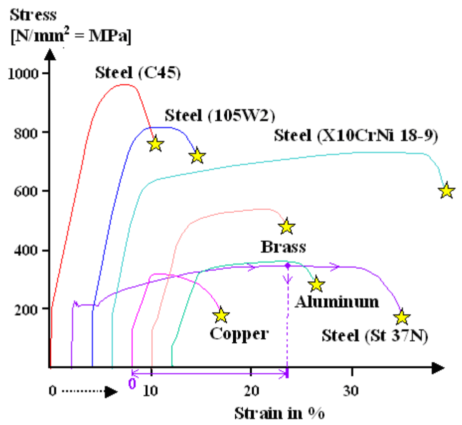
3.1.3 Just For You

- We still have to look at questions iv) and v) of your homework, the tensile testing of *soft* metals like copper (Cu) or gold (Au) and *hard* metals like steel. Did you come up with a result?
  - The figure below gives the answer in the form of *real* stress-strain diagrams for a bunch of different metals. To demonstrate a few points of tensile testing with respect to steel and sword making, I have done a number of tensile stress experiments just for you, the reader of this hyperscript.
  - That's a damned lie, of course, because it wasn't me but my able assistants who actually did the experiments - they wouldn't let me ruin their treasured (and expensive) testing equipment.



Stress - strain diagrams of various metals.

For clarity, the zero point for strain has been shifted somewhat for each curve.

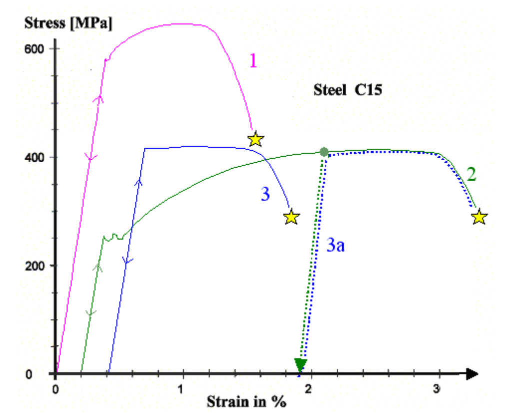
- The scale shows "Megapascals" (***MPa***) and, as promised, I give you another idea here of what that means.
  - Consider your weight. If you are a guy like me, we take it to be 100 kg (OK, just once: about 220 pounds). If you climb up a rope (I doubt that you can do this if you are a guy like me, but let's just assume you can), you are pulling at that rope with a force of 100 kg × 9,81 m/s^2 = 981 kgm/s^2 = 981 N. That's about the maximum force you can produce: pulling with all your weight.
    How thick should the rope be to take your weight?
  - If you don't use extremely strong monofilament, somewhat less than a square centimeter should be fine, let's say 0,3 cm^2 (= 3 · 10^{-5} m^2). That corresponds to a rope with a diameter of about 0,6 cm = 6 mm. Sort of like this: **O**
    The stress in the rope then would be 981 N / 3 · 10^{-5} m^2 = 32,7 MPa. So take note: The **maximum stress** you can produce pulling with all your weight on a 0,3 cm^2 cross-section is about **30 MPa**. There you have it. When real men produce *mechanical* stress by pulling at ropes, Mega Pascals are what you need to measure it with.
  - Of course, the *psychological* stress that professors like me can produce in undergraduates taking an oral exam will exceed that by far— but it's not measured in MPa. That's just another reminder that mere words are just mere words. Real ~~men~~ scientists need clear definitions and numbers if one is to know what is *really* talked about.
- Now let's focus on the major point: The **stress - strain curves** we get for **ductile materials** as shown above are *completely different* from the ones we had before for brittle materials

The stress -strain curves show plastic deformation

Plastic deformation is any deformation where the shape has permanently changed after releasing the stress

  - This is indicated for the steel ST 37N curve. Stop your machine at some point like the one indicated, release the stress and the strain will be permanent (about 15 % for the example shown). The specimen is now permanently longer. It has been *plastically deformed*.

- Now let's look at the other major features of those curves.
  - **1.** Eventually, after the specimen have been elongated to some final value indicated by the star, all specimen *fracture* as shown before. This is just an expression of the *first law of materials science* that we will encounter in full glory presently.
  - **2.** There are four kinds of steel in the figure. One (St 37N) is just as easily deformed as copper or aluminum, while the C45 type seems to be much *harder* in the sense that you have to apply far more stress to elongate it a few percent permanently or plastically.
    So, in pronounced contrast to their stiffness, all steels are *not* equal when it comes to their resistance to *plastic* deformation.
    You know, of course, that there are different kinds of steel with respect to *hardness* from what you know or have heard about swords. The question then is if there is some kind of relation between hardness and what we have here. There is. I'm coming to that. But first let's look at what else is of interest.
  - **3.** All curves run through a maximum stress shortly before they break. That means that if you elongated the materials up to that maximum, it now becomes easier to elongate them some more up to fracture. In other words: the ductile materials give you a *fair warning* that they are about to break, just like rubber. But in contrast to rubber, that becomes stiffer just before it breaks, ductile materials appear to become "weaker" (once more we lack a proper word) right before fracture.
  - **4.** Once more: if you release the stress at any one point to the right of the "perpendicular " part in the beginning, the strain does *not* go back to zero. The specimen stays elongated.
    The curves shown are thus the "upward curves", showing what happens if you *increase* the stress, strain and thus elongation. They are completely different from the "downward" curve. The downward curve simply goes almost straight down as indicated for the steel (ST 37N) curve at one point.
- Now let's look at the not-so-obvious features. As a little surprise for you, I had a few more tests done; look at the next figure:



Stress - strain curves of *one and the same kind of steel*.

For clarity, the zero point for strain has been shifted somewhat for each curve.

- What we see is that *one and the same kind of steel* shows rather different behavior in tensile testing.
  That's good. What that means is that you *can* change the properties of a given piece of steel by doing proper things to it like hammering it, or heating it, cooling it rapidly, and so on.
  Here we are at the very beginning of the *science* of making swords.
- So what was done to the steel in the figure above and what has changed?
  - Well, *curve 1* shows the properties of the steel "as bought". That's what you get when you buy C15 steel. The steel is pretty *hard* to deform. The machine needs to apply something like 700 MPa to elongate it just 1 %. It fractures after it was strained to about 1,5 %.
    If *you* would pull at the specimen with all your might, your measly 30 MPa or so applied to a wire of that steel would just elongate it by about 0,04 %. You wouldn't notice this.
  - *Curve 2* shows the steel after I **annealed** or **normalized** it. That simply means that the steel was kept at a temperature around 900 ^{o}C (1652 ^{o}F) for at least 30 minutes. "Annealing" means to do something by high temperatures, and "normalizing" means that you follow some prescribed recipes specifying how long you anneal at what temperature. More about the upcoming "*why*" questions to these procedures later.
    What you see is that after annealing / normalizing the steel, we need only *half* the stress from before to elongate it 1%. We can also strain the steel now to more than 3% before it breaks.
    It appears that keeping steel hot for some time tends to make it easier to deform or "*softer*".

  - *Curve 3* is exactly the same annealed steel as that in curve 2 but some devious person (might have been me) secretly strained it to about 2 % *before* giving it to the engineer in charge of the tensile test machine *without telling him*.

    Being smart, he might *see* that this piece of steel has been in a tensile test machine before (the big jaws of the machine leave traces), but being smart myself, I had removed all traces before I pass on the specimen.

    For my engineer (or anybody else), this specimen looks no different from the ones he tested before. There is no (easy) way of telling that it had been pre-stressed.

- We have a major point here. Somebody gives you a piece of metal for a tensile test, and there is just no (easy) way of knowing if somebody hasn't pulled at it, banged it with a hammer, or done God knows what to the specimen, changing its properties in a major way before it was given to you.

  In other words:

  The history of a piece of metal is important for its mechanical behavior.

- This *is* a major point. Consider the difference to brittle materials:

  - Somebody might have deformed a *brittle* material like glass (without breaking it, of course) in any conceivable way to his hearts contents. But when you come into possession of that glass, it behaves *exactly* as if all of that had not happened. It's history is *not* important at all.

    Ductile materials obviously have a kind of "memory" where information about what has happened in the past is stored. This is rather weird, think about it! The corresponding "*how?*" question is obvious and doesn't need to be spelled out in detail. The answer to it will contain much of what you need to know about the art of sword making. That will exercise us quite a lot in what follows.

- There are two more interesting points to be made about our three stress - strain curves from above:

  - **1.** If we move *curve 3* to the right, it matches perfectly with *curve 2* if we start it at around 2 % deformation.(*curve 3a*). In other words: if we stop the deformation of the sample represented by curve 2 at the circle and then release the stress, the strain would go down as shown by the green arrow. The sample is now permanently or plastically deformed, it is longer than it was before the test by about 1,9 %.

    If we take this sample and test it again, counting the strain from 0 %, we get *curve 3*.

    In essence we just continued where we left off. Our specimen "remembered" its past; its history is somehow stored in its structure. But if *you* don't know the history of your piece of steel, you would tend to see it as something different from the steel of *curve 2*. It is "harder" but less ductile, and it breaks earlier.

  - **2.** Looking once more at the stress- strain curves above for the C15 steel, we note another peculiarity: In the beginning - for about the first 0,1 % of elongation - all three specimen behave *exactly* the same way. The stress - strain curves are linear and have the same slope. When we looked a brittle material, we identified the slope of a stress - strain curve with its *Young's modulus*. Can we do the same thing here again?

    Yes, we can. In the straight parts of the diagrams above we just deform the steel *elastically*. Release the strain and the specimen goes right back to its original length as indicated by the arrows.

    So we can assign a *Young's modulus* modulus to ductile materials too, we just need to keep the stress /strain at a level low enough to have *only* elastic behavior. We are going to look at this more closely in the next sub-chapter.

    Now you know why I could discuss Young's modulus for all materials in the preceding sub-chapter.

    By the way, I also proved now *experimentally* the claim I made before: Three rather different kinds of steel have one and the same *Young's modulus* because the slope of all three curves is the same, indeed.

- What the experiment has given us is a first glimpse at **hardening mechanisms** and **softening mechanisms**.

  - There are several mechanism to *harden* metals. What we did to the C15 steel in the figure above is called **deformation hardening**, **strain hardening** or **work hardening**. Different words but meaning the same Work hardening is just one of several **hardening mechanisms** we will encounter.

  - Temperature treatments known as annealing or normalizing, meaning that you keep your steel hot for a while, seem to *soften* steel. Well, they do—but only if you do it *right* (furnace with controlled atmosphere and temperature, very slow cooling down, ...).

    If you just shove your steel it into a fire and take it out again, you might be in for a surprise. For example, if you cool your steel down *rapidly* after it was hot some time, it might not be softer but much harder—provided the temperature and the carbon content was high enough.

    In a fire, you also might either add a bit of carbon or remove some, depending how exactly you hold your steel into the fire or coals. What you take out of the fire then is a *different* material since a little bit of carbon, as you know of course, typically hardens steel.

- So working with iron and steel is tricky. *What* about the remaining 90 or so elements of the periodic table? Or just the 20 or so major metals? Can we also make them harder or softer like iron / steel?

  The answer to this *"what"* question is: yes, in principle.

  And now we are stuck with a lot of "why? and "how?" questions!