3.2.3 Fracture and Microcracks

You simply cannot descibe the fracture behavior of a material in just *one* number. When we nevertheless do just that, it is akin to bankers describing *you* in just one number like "net worth". The number is not necessarily wrong but does not do justice to all aspects of you (I hope).
If Materials Scientists describe fracture behavior in just one number, they do not use the easily measured *fracture energy* but a more sophisticated measure called "**fracture toughness**". The unit of fracture toughness is **Pam**$^{1/2}$ (Pascal times square root of meter) and now you know that you don't want to know more about that - yet.
However, if you are a reckless enterprising spirit, you find more about that in the science module "**Fracture Mechanics**".

Fracture mechanics belongs to one of the most difficult fields of Materials Science. It is supposed to be able to calculate under which kind of mechanical loading things break right away. That's tough enough but it also supposed to be able to calculate under which kind of conditions things, fail, i.e. break eventually.
Generalizing a bit, the really tough question for Material Science to answer, is: Why do things go kaput? Why does pretty much everything, including you, **fail** sooner or later? This is transcending just fracture mechanics since it includes topics like:

Science Link
Fracture Mechanics

- Why can you bend your sword a hundred times to some extend and at the hundred-and-first try it snaps?
- Why do tightly wound screws come loose after a while?
- Why do your computer chips die after some time of use? I'm talking hardware here, not software.
- Why does your light source eventually fail? And I'm not just considering the good old light bulb but *any* source, including modern ***LED***'s.
- Why do your cells stop to work properly as you get old?

I will give answers to some of "why" questions coming up in this context but not before we covered far more ground.
As far as fracture mechanics is concerned, I will go only *one* notch above of what I covered already. Looking at *serious* fracture mechanics would need several notches. I thus will *only* look at fracture that occurs *right away* under some conditions of overloading to *relatively* brittle materials. Relatively brittle materials are either really brittle materials like glass or ductile materials like iron that have been strained close to the breaking point.
The general experience is that some swords (or other objects) if hit hard will fracture while some other swords, made from virtually identical steel, do not. Virtually identical might mean, for example, that the yield strengths or hardnesses of the two steels are quite similar.

The major reason for this different behavior can be expressed as follows:

Fracture of all materials, including ductile metals, depends sensitively on the presence of what we will call nanocracks

Strange enough, **nanocracks** are generally called **microcracks** in serious literature about fracture. It is strange because nowadays many rather ordinary things that are *not* nano at all (meaning smaller than 100 nm) are called "nano this-or-that". But the cracks causing fracture, which are *truly* in the nanometer dimensions, we call "micro". How come? Simple. Back in the good old times, everything very small was called micro this-or-that. We scientists didn't have to invent new fancy names like nano this-or-that to get funding in those good old times.

A *nanocrack* is any small area inside your material where your material does not stick together properly; I'll get to that later in more detail. Nanocracks might be "true" cracks like the cracks propagating into glass whem it breaks, just much, much smaller, or an inclusion of something with not much strength, for example graphite in (cast) iron. Nanocracks thus are "defects" in the material and typically so small that you can't see them, not even in the most powerful optical microscopes at thousandfold magnification. Even if your microscope would be a hundred times better, magnifying things hundred-thousand times, you would have a hard time to see the nanocracks that make some steels more fracture prone than others.

Unfortunately, there are a *lot* of reasons why materials should contain or develop nanocracks with different if small sizes, shapes and densities (number per cubic centimeters). What that means is that there are a *lot* of reasons why identical materials might show different fracture behavior.

That it is always the *largest* nanocrack in the material that initiates fracture doesn't make things easier.
In other words: a steel that contains *one* largish (still invisible) nanocrack and a few smaller ones will break more easily than a steel that contains a *hell of a lot* of medium sized ones. One bad apple spoils the bunch, as the saying goes.

- It's time for a **epiphany**:

Minimizing nanocracks in your blade is done by folding and hammer-welding of your primary steel.

- *You*, the ancient smith, couldn't avoid the nanocracks and all kinds of other *defects* inside the steel pieces you picked from the smelter. Your nanocracks were actually not even so "nano", they were rather large. Your best bet was to **homogenize** your material and make sure that its properties were the same throughout. This needed a lot of heating, folding and banging, and that helped to erase nanocracks, or at least make them smaller.
  - *You*, the ancient smith, certainly did not know what kind of nanocracks your material contained.

    You didn't even know what your material *was* for God's sake. You just had a common *name* like "iron" for it. You did not have the *true name* of your material because that would have meant that you would have power over it. The word "nano", if you understood Greek, meant simply "dwarf" to you. "Steel" was another word for, perhaps, some kind of especially pure iron.

    Attention! I'm getting fundamental; veering off the topic!

  - *I*, a modern day materials scientist, *do* know what my material is. I know the **true name** of the object. In the old days that meant I held power over the object and could do magic. It means the same thing in the new days. We do hold incredible power!
- *You*, the ancient smith, had to deal with your material **empirically** since you did not know its true name. You gained knowledge by learning from your master and by trial and error of your own. With time you became experienced and developed a feeling of what could be done with the material at hand.
  - You never deviated from recipes that worked. If all of sudden they didn't work anymore (and that happened for sure; it still happens in "High Tech" work of today), you were puzzled and frightened. Your only recourse was to sacrifice to your Gods and hope for the best, like that your bosses wouldn't sacrifice you.
    In most cases some solution was found or imported from somewhere else. Empirical knowledge grew and eventually things like locomotives with many steel parts ran on some iron-related (more cast-iron than steel) rails. The early trains derailed and failed a lot—but the industrial revolution, based on steel, had begun. And it began on almost exclusively empirical knowledge that had accumulated through the millennia.
- In our modern times some magicians (also called scientists) do know the true names of things. That's why the can produce magic like cell phones. You don't believe that? Then prove to me that an i-phone and its brethren do *not* operate on magic! I bet you can't.

- What was the issue again? Right, nanocracks and fracture!
  I can do some magic here because in contrast to *you*, the ancient smith, *I* typically know my material and what kind of nanocracks it contains. Knowing that I can *calculate* the fracture behavior of my material.
  - If I don't know what kind of nanocracks my material contains, I look at it with a powerful electron microscope or other sophisticated apparatus and find out.
    But there is a catch. The catch is that I can only investigate *extremely small* regions this way. Worse, I *destroy* the specimen by investigating it. So I still don't know *with certainty* what kind of nanocracks the left-over piece of steel has that I did not investigate but use for forging a sword or a railroad wheel.
    However, looking at many specimen, doing statistics and all that, I will gain objective knowledge and a quantitative data base about what the material most *likely* can do.
    Most *likely*, however, does not mean: *for sure*. Some small uncertainty and residual risks remain.
    For example, one out of thousands of lots of a well-known steel did contain a critical nanocrack. That piece of steel ended up in a train wheel and killed 101 people in 1988, when a high-speed ICE train derailed because of the sudden failure (=fracture) of the wheel after many hours of use.
    Horrible accidents like this one seem to cast some doubt on our understanding of materials. Just the opposite is true. Since we can never completely test the materials we want to use, we need to know about them. In other words: we need theory.
- What I'm driving at here is the **second law of Materials Science and Engineering**:

There is nothing more practical than a good theory

- Theory tells you exactly if a piece of steel (or whatever) will fracture under some load, provided you know whatever it is you need to know for doing the calculations. Theory also tells you unambiguously that concerning fracture, you deal with something that has intrinsically a **statistical** component. You only can come up with *probabilities*.
  - If you now think that the theory of fracture mechanics is rather useless because it could not prevent the train accident mentioned above, you are utterly wrong.
    Consider how often something critical *could* break, and how often things actually *do* break. A railway car wheel, the wheels of your car or of any car. The steel cables of elevators, cranes, or suspension bridges. The steel beams of high rise buildings. The bricks and stones of pyramids, cathedrals or houses. Whatever.
    Failure of critical parts happens *almost* never for *two* reasons.

    1. The parts in question are so much oversized that they can easily bear the load they are subjected to. This was the time honored way of structural design for millennia. Pyramids, cathedrals, temples, houses, bridges and so on that could not take the stress have collapsed long ago. What we have left today are the survivors. The problem with "design by *trial and error* and large safety margins" is that you use more material and energy than you would have needed.
    2. For some time now we can calculate facture behavior well enough to allow for *intelligent* design. That's one of many reasons for the huge progress made in optimizing the weight - performance ratio. The crucial components of your car are much lighter now than 50 years ago but can take much more punishment. The ICE train where the disastrous wheel fracture occurred goes 300 km/h; the trains 50 years ago, running on much heavier wheels, were far slower. Jumbo jets actuall can *fly*, for God's sake!
  - Where does that leave you, the ancient smith? Caught between a rock and a hard place! You did not have scientific knowledge about assessing the properties of your steel and to work it to the best of its properties. You couldn't use the pyramid builders recipe of making it solid and heavy either. You could have made an unbreakable sword, it just would have been too heavy to use.
    That's why swords are such great objects for studying the history of metal technology. Swords were always at the cutting edge of technology. Sword makers couldn't play it safe like pyramid builders by using large safety margins.
- Let's look at little bit more on what *theory* is telling us about nanocracks and fracture.
  - When materials fail after years of flawless service, the small and harmless nanocracks they originally contained slowly grew bigger and bigger over the years. Eventually one of them reached critical size and —boooom!
    There are a number of mechanisms that make nanocracks grow and preventing that can be difficult. That's what happened in the train wheel.
- One way of looking at sudden fracture is therefore the "**critical size of nanocrack**" concept or what I like to call the "**Griffith**" concept, after its inventor.
- Looking at the **fracture toughness** of steel or anything else, to introduce the proper word right here, "simply" means to know under what kind of mechanical loading conditions nanocracks start to grow.
  - If they grow, fracture is unavoidable; it's just a matter of time. Now if you apply tremendous force or stress (pulling, pushing, banging, whatever) you can break anything quickly.
    Look at a car shredder for example. It simply breaks the metal parts of your car into little metal pieces almost instantaneously by brute force. In this case nanocracks grow with maximum speed, which is the speed of sound in the material or 5,12 km/s=3,81 miles/s in iron.
- If you dive deeply into Griffith theory and don't drown, you may emerge with a way to put a material-specific number on its *fracture toughness* as determined by the relative ease of nanocrack growth.
  - You will even find a way to measure that property, the *fracture toughness* from above. It gives you at least a good idea of what you can expect from given materials with flaws called nanocracks.
    Fracture toughness too is measured in units of energy; in this case it is the energy needed to enlarge a crack a certain amount. It is a number different from that of a Charpy impact test. It is also more useful for serious calculations
  - So what's the difference? The long and short of it is that the *fracture energy* from the Charpy test tells you how hard you have to hit your blade (or your opponents blade) so it fractures at the point of impact.
    The Griffith *fracture toughness* tells you if and where your blade will fracture if you bend it too much or apply random mechanical forces that are not just focused at a given "point".
- One last point. The energy of a mass of 1 kg falling down from a height of 2 m is about 20 J. As we know from the various fracture tests, this is enough to induce fracture in some not-so-good steels

- So, yes, King **Richard "Lion Heart"** could have fractured the iron handle of a mace with a cross section of at best a few cm^2 with his heavy (a few kg) sword swinging it down real hard.
  The "famous" meeting between him and Sultan **Saladin** (who cut through a falling silk scarf with his ultra-sharp "wootz" scimitar) is pure fiction, however. It comes from **Sir Walter Scott's** novel "**Talisman**" from 1825. It never took place in reality.