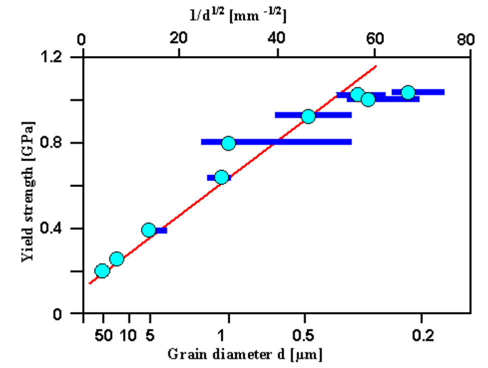
8.3.2 Size Matters

Grain size matters for hardness. If you want to increase hardness, small is beautiful.
Grain boundaries are very serious obstacles for moving dislocations. In our military analogy, they act like fortified borders between states. The smaller the grains, the more grain boundaries you have, the harder the material will be.

- Unimaginative, as *engineers* sometimes tend to be, we named this hardening mechanism "**grain size hardening**". But *scientists* are often quite imaginative when if comes to naming new things, not to mention using good scientific names for unscientific purposes. I'll give you examples in this link.
- Back to the boring stuff. If you make your grains four times smaller, hardness will go up two-fold. No equations. I promised. But you realize there is a square root in there somewhere. Below, you can "see" it



Yield strength (or hardness) vs. grain size for stainless steel

Source: Kawasaki Steel

- It's a 12.5 % Cr, 9.5 % Ni, 2 % Mo, 0.1 % N steel. The blue lines give error margins or scatter of results. Note that you get a linear relationship if you plot the data vs. one over the square root of the grain size (see how cunningly I avoid equations?). In carbon steel the numbers are different but the general relation is the same.
So grain size hardening can *quadruple* the hardness!

Great - but how do we make small grains? The crystal *hates* small grains, nirvana calls for huge ones. Once more we need to fight the second law. The problem is that no matter what you do during forging, grains will tend to get larger, never smaller.

- Banging with your hammer a low temperatures might help, but not all that much. If you run your steel through a roller mill, it will get much flatter and the grains will become elongated (see this picture) but their size as measured by their volume does not change much.
Kawasaki steel, presumably knowing what to do about steel, obviously had a hard time to get grain sizes below about 1 µm for making the measurements shown in the figure above as evidenced by the far larger error bars for the small grain sizes.

So let's forget about grain size hardening for forging swords. There may or may not be some improvement on grain size (meaning they get smaller) that is caused by what you do, but you have no good control and therefore you cannot use it systematically. Worse, chances are rather good that by what you do you will make the grains bigger.
Now for a new thought: "OK, agreed, I can't make the grains smaller - but, maybe, I can keep them from becoming bigger?"
Yes, you can!

- If grains grow, their grain boundaries and thus also atoms have to move. So make grain boundary movement difficult. Since you must heat up your steel during forging, unavoidably supplying vacancies and whatever else is needed for atoms to move, the prerequisite for grain boundaries to move are there and your options are limited:

  1. Minimize your "**thermal budget**", i.e. the weighted product of temperature times time. It must be a "weighted" budget because a few minutes at high temperature does more harm than hours at a somewhat lower temperature.
     Another way of putting that is: minimize the total diffusion length of the iron atoms.
  2. Add some impurities that make it difficult for grain boundaries to move. The trick, of course, is to identify suitable impurities, get them into the grain boundaries, and avoid negative effects on other properties.
     Not all that easy but possible.

If you happen to be a *modern* smith (nowadays called Material Scientist or Engineer), you do not work with plain carbon steel but with an iron alloy that contains more alloying elements than just carbon. Some of those elements might be in there to do the job mentioned above.
Of course, if you are a modern material Scientist, you might also know the tricks of **nano technology** and you might be able to come up with "nano grained" steel that is quite hard just from grain boundary hardening as shown above.

- Chances are pretty good, however, that you will fall into the "cost issue" trap. Your "nano" steel is too expensive and nobody will buy it. Except, of course, the Pentagon or some Arabian King.