11.6.4 Metallurgy of the Japanese Sword

Materials and Processes

Japanese smiths made Japanese swords or nihonotos exclusively from bloomery iron and steel. That business started around 1000 AD and was kept up with only small interruptions until the present day. Bloomery steel only! That is the first special point from a metallurgical point of view. Why? Well - consider:

- The Koreans and Chinese neighbors to the West, supposedly the people from whom the technology was borrowed, made their steel from cast iron already more than 1000 years before the Japanese started to make nihonotos. At least the Chinese did; about the Koreans I do not know anything.
- The Indians, even more to the West, made their swords from crucible steel also long before 1000 AD. The same can be said about parts of Central Asia.
- The Europeans did work with bloomery iron in 1000 AD but switched to blast furnaces and a cast iron based technology in 1300 and beyond.

The katana started to become prominent in the 15th century and at that time almost nobody besides the Japanese made swords still from bloomery iron and steel. That means that Japanese swords still contained inclusions of slag and whatever else trapped in a bloom. Moreover, a bloom is always rather inhomogeneous with respect to the carbon concentration (and anything else in there). Working with a bloom was always a problem, and keeping up with the advanced competition, however remote, then necessitates special measures:

1. Optimization of the bloomery process to minimize the "dirt" always encountered.
2. Optimization of the bloomery process to produce high-carbon steel, the difficult thing to produce with a bloomery.
3. Finding ways to asses and classify the needed steel grades (low, medium, high carbon).
4. Extensive faggoting to homogenize the always non-uniform bloomery steels. That, in turn, requires the ability to fire weld with near perfection.
5. Some luck.

Everything else needed for making a Japanese sword is more or less independent of the steel production process. The differential quenching technology with the clay coating and all, would be the same for a blade piled from cast steel, for example.

The first two points are covered by the "invention" of the tatara furnace. It obviously could do the job. There might have been better ways to deal with the first two points but the tatara worked. It was an expensive and not very efficient process but so what.

A tatara could and would produce cast iron [1)]. From what I read I would guess that it might have contained molten steel too on occasion and that would account for almost slag-free "tamahagane ". European smelters had also been able to produce high carbon steel in their bloomeries but we do not know all that much about these bloomeries and how they were run.

Point three applies to all smiths working with structural and compositional piling. What the Japanese smiths did to assess their steel is relatively clear, I have already dealt with that. A bit more about the "tricks" of the smiths can be found here.

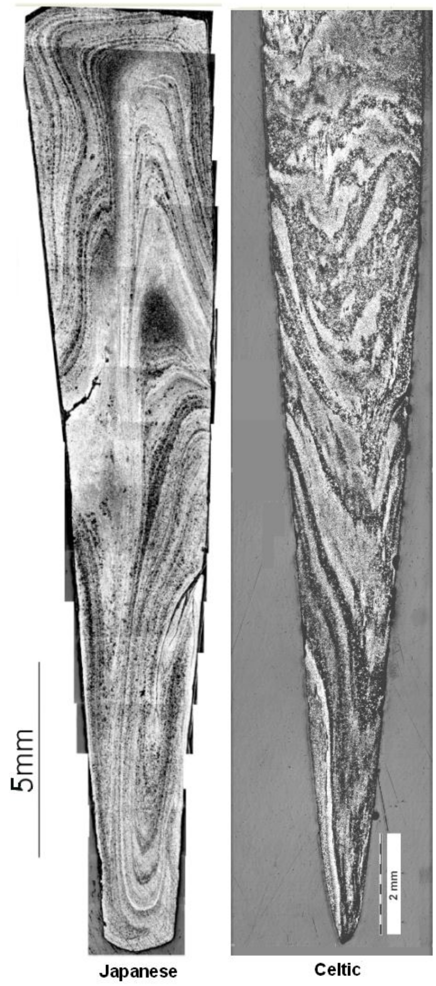
I'll deal with point 4, faggoting, below but before I do that let's look at point 6: some good luck is needed!

Being lucky is essential. On the one hand, the Japanese had tough luck since they do not own a whole mountain made from decent iron ore like the Austrians or Svedish. On the other hand, their "iron sands" are virtually free of phosphorous and sulfur. This is just good old dumb luck that compensates for the lack of iron ore mountains.

Let's have a quick look at the "West" for comparison. Large advances in bloomery techniques were made around 1000 AD, give or take century or two, and that allowed to replace the (expensive) pattern welded sword by the better and cheaper piled all-steel sword. While there may or may not have been some imports of high-carbon wootz steel to make the "true" +VLFBERH+T" types of Viking swords, self-made high-carbon bloomery steel was definitely around in Central Europe, witness the "Moravian" swords and many others. The trick seems to have been to run your bloomery at high temperatures while avoiding to produce cast iron. Details, however, still evade us (at least me).

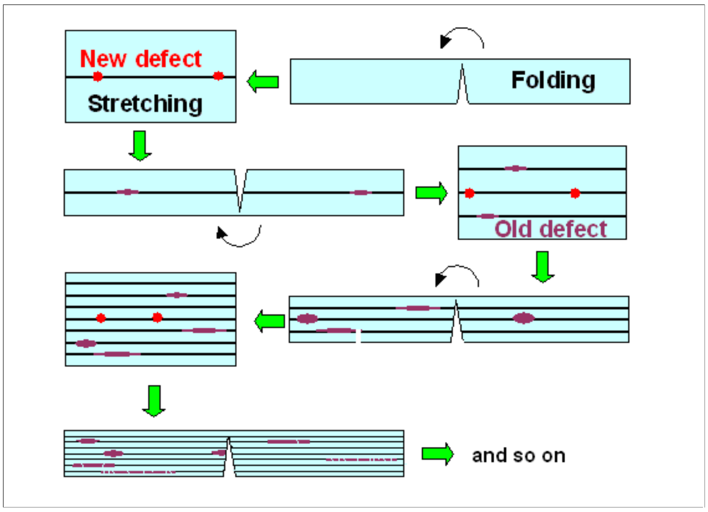
Faggoting was also know in the West. However, we hardly know anything about that since the number of old swords metallurgically examined to determine if and how faggoting was done is close to zero. I'm only aware of **Stefan Maeder's work** in this direction. I have (convincingly!) argued, however, that elaborate pattern welding simply makes no sense if you didn't faggot your steel before you used it.

The situation in Japan is as different as it can be. Assessing the quality of Japanese blades from 1000 AD onwards included looking at the "hada", the visible structure on the blade that results from faggoting. I have dealt with that already. It would be premature, however, to conclude that "the Japanese" were better at faggoting than everybody else. Here is a comparison:



Left: Japanese faggoted steel from the 20th century. Nital etch
Right: 300 BC Celtic Sword from La Tène. Japanese polishing

- You need to be aware of the fact that this is a completely random comparison! The Japanese sample comes from the 20th century Japanese sword smith Shimizu, who left it for analysis. It is not yet a finished blade but close to that stage. The investigation of this sample was done by Jang-Sik Park in 2004 [1)]. He used classical metallography, polishing followed by Nital etching, to reveal the structure.
  The Celtic sax was investigated by Stefan Maeder; I have used this picture before. In this case "Japanese polishing" was used to reveal the structure. Of course, these two samples cannot be seen as representative for untold number of swords forged during 1000 years or so. And yet! They do show that faggoting was used in both cases and that there are many similarities.
  There are simply not many other pictures like that. There might be a few around that I'm not aware of but there aren't many for sure.
  - What we see is that the steel is not even remotely homogeneous, despite faggoting. There is a layered structure and that means that something is distributed in a layered fashion. It might be the carbon concentration but with more folding and thus smaller and smaller thicknesses of the layers, the carbon concentration would eventually even out by diffusion. It thus stands to reason that we see weld defects, small particles and the like, that are in found in the weld seams. In fact, there are a lot of sharp dark "dots" visible that could not have resulted from a carbon concentration gradient.
- Faggoting means fire welding every time you fold. Doing that you cannot completely avoid getting some "dirt" like oxide inclusion into your weld seam, and you may have occasional other weld defects. Every folding increases the number of these defects, and every stretching draws them out. Drawn out defects like oxide or slag inclusions may break up into strings of small particles. Very schematically, things proceed like this:

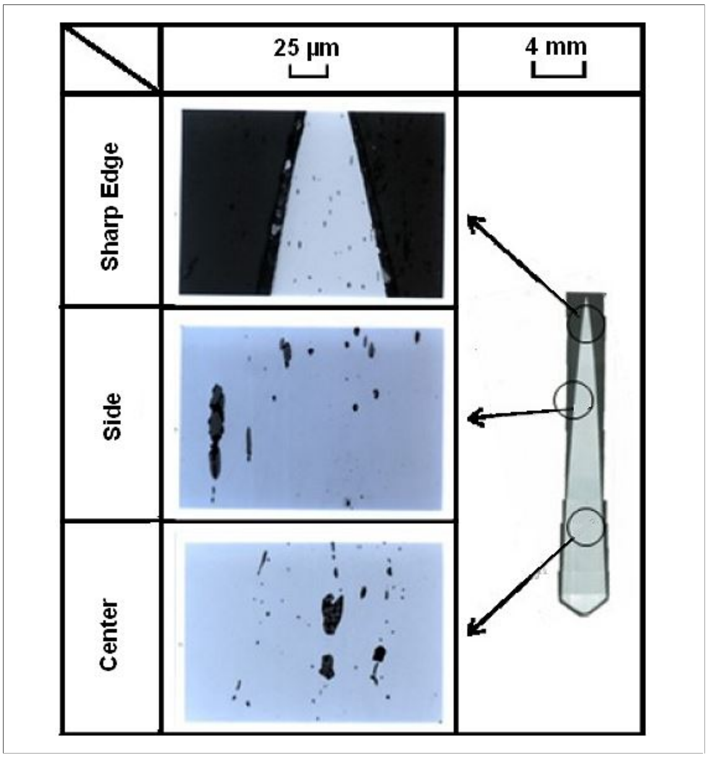


Folding, stretching and defects in the weld seam

- Faggoting with 10 foldings or even more then demands high welding standards; otherwise you defy the purpose. However, welding will never be perfect and the small defects in the seams will produce the faint pattern you actually see, the "hada" or whatever. In other words: The fact that you actually *see* something on a Japanese blade is a sign for a somewhat non-uniform, a somewhat imperfect material. A homogeneous and well-polished steel is simply free of any structure that you could see without a microscope. Nevertheless, Japanese smiths certainly had mastered fire welding as well as everybody else. I wonder how they solved the problems I have listed here.

Metallurgical Investigations

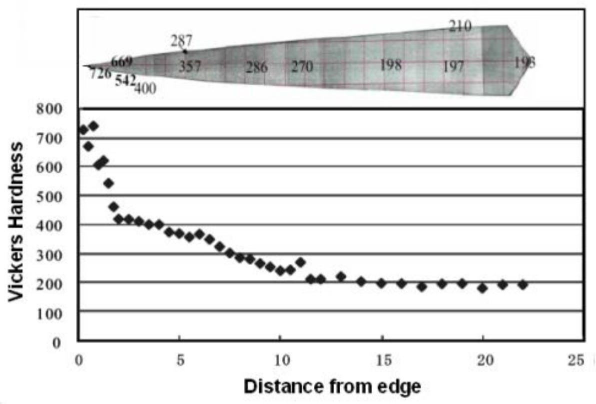
- "In contrast to the reputation of the Japanese sword, however, not much attention as been paid to the dynamic evolution of its microstructure on its way to be manufactured from the tatara ingot" writes Jang-Sik Park in 2004. "There are a few references written in English (to the metallography), unfortunately. Further, the precise metallurgical characteristics of Japanese sword have not been clear yet" writes M. Yaso et al. [2)]
  It certainly appears that they are right. I have yet to see cross-sections that clearly show one of the more complex constructions in the claimed variety of styles.
  - As far as the simple constructions are concerned - one piece (maru), soft core, hard jacket/edge (kobuse) and hard edge, soft spine, medium jacket (honsanmai) - what do you expect? Hard edge martensite will look like martensite, medium jacket steel will be pearlite, and soft core steel will go into the ferrite direction.
    Points of interest are rather:
    - How many inclusions of slag and other defects are observed. How did this develop from 900 AD to the present day?
    - How was faggoting done and how did it develop?
- Here is one pictures showing that a Japanese sword form around 1400 had plenty of inclusions:



Slag inclusion in a 2nd generation Muramasa sword from around 1400.

Source: M. Yasoa, et al..

- The specimen was taken from an old sword which was produced by the 2nd generation of Muramasa about 600 years ago. It had been hardened as demonstrated here:

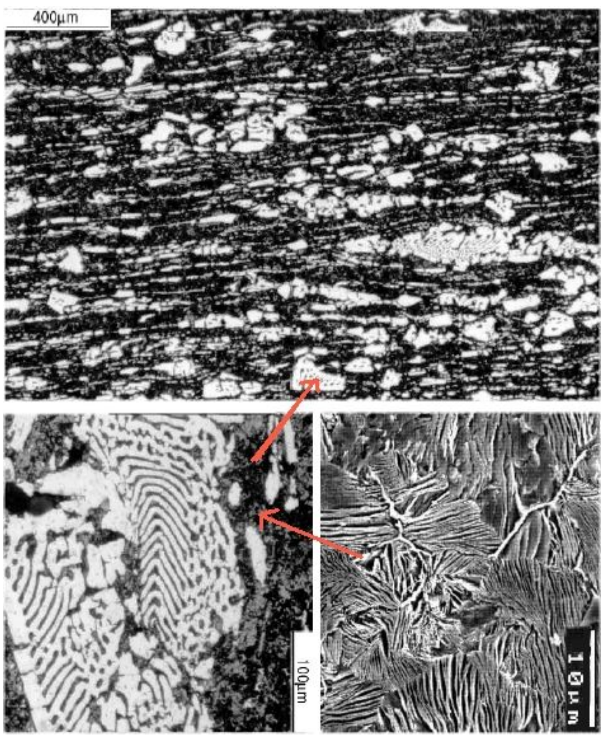


Hardness via distance from edge for 2nd generation Muramasa sword

Source: M. Yasoa, et al..

  - It is not clear, however, if hardening with a clay coating has been used; no mention of the hamon is made. It is also not clear if piling was used and what kind. The pictures given do not show faggoting. The authors refer to faggoting though, but in a nonsensical manner ("The grain size of sharp edge part is observed to be very fine, about 10-15 µm as a result of the effect of 10 several times-forgings in sword making process").
    The microstructural pictures provided in [2)] show essentially pearlite outside the martensitic regions. Since a hardness value of 800 can be reached with eutectoid or even somewhat hypoeutectoid steel, it is possible that this blade was actually made from one piece of (0.6 - 0.8) % carbon steel.
    I'm not saying that this is so. I'm saying that we have far to few studies and that the ones we have do not address, not to mention answer, some of the open questions.

- As far as fagoting goes, the picture above is one of the few I know of. From the same paper we have a few more pictures of some interest. They show that stage in the forging where the smith has fire welded a number of tamahagane pieces and possibly folded them over once:



Top: Broken up and banded cementite in a plate of tamahagane fire welded from a number of smaller pieces. **Bottom: The fine structure of the cementite particles and the pearlite in between. Note change of scale**
Source: M. Yasoa, et al..

- What you see is that all this hammering and flattening does not only make up the cementite as one would expect but lines up the fragments, producing a striated or banded structure. That is not necessarily what you would expect - except, perhaps, if you have read the little module about banding, written in the context of wootz swords.

That reminds us of the basic truth that is at the core of this Hyperscript:
The mind-boggling complications of iron and steel engineering gives us all these different swords, objects of supreme terror and beauty, embodying the powerful principles of learning by doing and mastering the manifold complexities of your trade. But all of this pales before the magnificence of a few simple principles of science, whose beauty and power far outshine any katana, shamshir or pattern welded spatha.

The End [3)]

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1) Jang-Sik Park: "Traditional Japanese Sword Making from a Tatara Ingot As Estimated from Microstructural Examinations", ISIJ International, Vol **44** No6 (**2004**) pp. 1040 - 1048

2) M. Yasoa, T. Takaiwa, Y. Minagi, K. Kubota, S. Morito, T. Ohba, A. K.Das: "Study of Microstructures on Cross Section of JAPANESE SWORD", Proc. ESOMAT 2009, 07018 (2009)

2) Sort of. It is the end of what I have to say about swords and *material science*. There is one more chapter, however, deailing with the *physics* of wielding a sword.
There also might be sequels. You might see that as a threat or a promise.