11.2.2 Metallurgy of Celtic Swords

What to Look For

What do we know about Celtic swords from a Materials Science and Engineering point of view? Quite a bit - and not enough!
We already have some idea about the production of Celtic iron and steel in bloomeries and the kind of quality they could achieve. I gave you three examples:

1. The "Ferrum Noricum". While the term is usually associated with the Roman iron production around 0 AD, the Celts or proto-Celts were there earlier. The place is not all that far from Halstatt, after all.
2. Snowdonia, a place in Wales, where the local strain of Celts made iron and steel.
3. Wetzlar, as an example of an area where iron production in bloomeries was done from about 800 BC to 1200 AD by the Celts and whatever other culture happened to be around within this time span.

- We know from these examples that iron making in early bloomeries - during the Halstatt and early La Tène period, say - was a tricky affair, producing small blooms of uncertain quality. We know even more. We can be certain that only a tiny percentage of the sites where the old Celts ran bloomeries has been discovered by now. We can also be certain that the way the bloomeries were run and the bloom was processed differed from place to place and from time to time.
  You and I know even more then most archaeologists who worked on Celts. We know that we don't have to ask ourselves how the old Celts made steel because *we* know that their bloomeries produced (wrought) iron *and* steel and not just exclusively wrought iron as all and sundry believed not that long ago (some still believe that today). That means that we do not have to worry about how the old smiths "carburized" their wrought iron. We know that that was not the way they made (bulk) steel for the simple reason that it can't be done.
  What we do have to worry about is how the old smiths picked different grades of iron from a given bloom.

One can't discuss Celtic swords without mentioning the special ones. Besides the "Knollenknaufschwerter " already mentioned, we have the ones with an "anthropoid" or human-like (bronze) hilt (see below) and the "antenna hilt" type. Those are very distinctive hilts but the blades seem to be no different from the more usual ones.

Anthropoid bronze hilts on iron Celtic swords / daggers (late La Tène)
Far more

Source: Left: Photographed in the British museum. Right: North Grimstone / Yorkshire sword

We also know that iron / steel was traded. The Celtic double pyramid or bipyramidal iron bars go back to at least 450 BC. The so-called "currency bars" or "sword bars" (much better German name) go back to at least 200 BC. They consisted of rather inhomogeneous iron / steel, just like the Roman standard iron bars centuries later.
A Celtic sword smith thus definitely had access to iron / steel. He either bought some of the standard stuff from travelling salesmen, from the local iron monger, or he made it himself. Then he made a good-looking sword. We know that he could do that because we have them, see also the examples above.

- Now we have to ask a tough question: Was it just a good-looking sword or also a good sword? There is a difference, just think of (insert name of your choice).

So let's assume you got hold of an old Celtic sword. Let's also assume you have a metallurgical lab at your disposal that allows you to analyze your sword to your hearts content. So what are you going to do?

- If you are new in the business you would tend to run samples through all the equipment you have got. I see that a lot when I referee science papers from countries that are rather new in the R&D business. They have a piece of silicon with some trimming (maybe its porous on one side) and run it through all they have. Lo and behold, X-ray diffraction shows unambiguously that this piece of silicon actually consists of silicon, and scanning electron microscopy leaves no doubt that on the polished surface nothing can be seen. I kid you not.

Back to swords or to doing material analysis proper. The kind of analytical method you want to use depends on the questions you want to find answers for. So consider your questions. Then consider that not all questions are equal. Some questions are just nonsense, some have only wrong answers. You want examples? OK - here goes: is an electron only green whenever it is not red? Should your wife wear item 1 or item 2 for whatever function you are going to? With respect to swords a not-so-smart question would be: is Polybius right? Can you find an answer to that question by analyzing your sword? No you can't. You might find that your sword is easy to bend but that does not prove that the swords Polybius saw in action bend easily, too. If you analyze a lot of Celtic swords, and they all bend easily, than you might say that there is a strong probability that Polybius was right. In other words: if you only have results from one specimen (or from just one location on the specimen), it is dangerous to generalize.
A good and interesting question could be: What is the *average* carbon, phosphorous, and so on, concentration in the blade? That is a question you can answer. The price, however, is the complete destruction of the blade. This is usually not permissible so you need to compromise.

- If you now think long and hard you will eventually come to the conclusion that the best compromise between destroying as little as possible while getting the best possible results for answering relevant questions (I come to that) is

  - Look at the structure of etched cross-sections.
  - Do micro-hardness tests on these cross-sections.
  - Determine the concentration of some critical elements like phosphorous and manganese from a few small samples.

  You want to do that for a sizeable number of swords that represent a certain age and culture in order to get some feeling for what is typical.
  It needs only some quick thinking now to figure out the serious drawback to this approach: It's a lot of work! It will take years of skilled *and* hard work. You can only attempt this if you are a professor who can command cheap skilled labor also known as **graduate students**, people who love to do stuff like this as we have figured out before.

I sure hope that **Radomír Pleiner** had plenty of graduate students helping him to do his rather long and involved work as described above. Pleiner analyzed about 120 La Tène iron swords from 400 BC - 200 BC in great detail and described the results in his book. In what follows I will try to summarize his results.

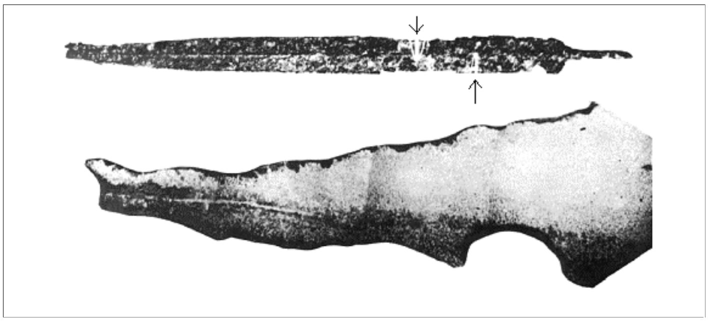
- But first let's consider the questions we would like to get answers for. They are not so different from the questions we have asked with respect to the Luristani swords:

  1. Are the swords made from one piece or by "piling", i.e. by fire welding several pieces?
  2. Was the material first homogenized by "folding"?
  3. Did the smith conscientiously use different grades of iron / steel if fire welding was used?
  4. Was the smith aware of the "phosphorous issue"?
  5. Was the smith aware of surface carburizing or, far more important, de-carburizing during forging?
  6. Did the smith know about hardening by quenching?
  7. Capability of the smith? His infrastructure? Stone hammer and stone anvil on the floor or dedicated special equipment in a forge with a hearth?

A First Result of Pleiner

Let's start by looking at one result of Pleiner's work and then take it from there.

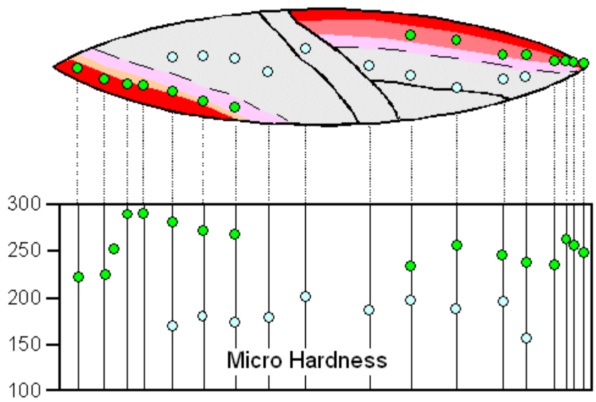
- Here is a picture of the sword "Tuchomysl 6.13, NW Bohemia". The two places where a half cross-section has been cut out are marked by arrows. Below is a low-magnification view of the etched cross-section. The greyishness roughly marks the carbon concentration; it increases from light to dark.



Celtic sword and half of the etched cross-section

Source

What you can see quite clearly is that you can't see much. You need to look at many pictures at high magnification if you want to get an idea of what is there. But you can't publish that; editors do not enjoy square-meter sized photographs for science journals or books. You must render your results publishable by making schematic drawings like this one:



The schematic structure of the cross-section of the sword above
The carbon concentration decreases from red to grey.

Source. Adopted from Pleiner

- The black lines mark weld seams (not always clearly discernible), the colors the rough carbon concentration. In addition, micro-hardness values are given for the positions indicated.

What we can conclude, being ever so careful [1], is:

At least one Celtic smith used piling conscientiously. And he did not harden by water-quenching

Not bad. But then Pleiner looked at many swords and now we must take note that the sword above was about "The Best". Before I go deeper into this, let's look at a much earlier "analysis" of Celtic swords found at Marix (wherever that might be), assigned to one Colonel Verchère de Reffye. In a 1866 book [2] he is quoted as follows:

- ""We may remark,' he says, ' that the cutting edges of these swords are not of the same iron as the body of the blade. The workman, after having forged this part out of very *tough iron* (tres-nerveux, very fibrous iron), drawn out lengthwise, welded on each side little strips of *soft iron* to form the cutting edges; this iron was afterwards beaten to an edge by the hammer. The soldier could thus after the fight repair with the hammer the damage done to his sword, just as a reaper sharpens his scythe when it is notched."
- Could that be true? Celts made swords with a hard core and soft edges? Yes, indeed. Some Celtic swords had soft edges, and, as we shall see, some pattern-welded blades made 700 or so years later were built the same way. I knew about this phenomena before I knew about the Colonel's explanation for this. His explanation was one of the two that had occurred to me, too. The other one is that the smith was drunk.

It's time for making a statement that might come as a surprise for some:

Swords of the same kind are typically very different in their composition and construction

- This is true for the Celtic La Tène swords I'm looking at here, for pattern-welded swords, Viking swords, and so on. After a PhD student I'm advising dug out a medieval smithy (800 AD - 1200 AD), he analyzed about 10 remains of knives and found everything! Perfectly constructed blades with a hard edge and a soft inside, blades banged together randomly from up to 5 kinds of iron / steel, and anything imaginable in between these extremes.
The statement is probably also true for many other kinds of old swords (e.g. "wootz" blades) but one needs to analyze a large number of swords of the same kind to be able to prove or disprove that statement, and that has mostly not been done.
What that signifies is not really clear. One might assume that some smiths were very good, some very bad, and the rest in between, but that does neither help much nor can it be concluded from the still far too few data.

Celtic Swords According to Pleiner

Pleiner gives very detailed statistical data that I need to simplify to make them digestible. They are also slightly garbled on occasion, like percentages not adding up to 100 %. The numbers in what follows are therefore always just approximations or order of magnitudes.
I will run through the major findings by answering questions.

1. Were swords forged from a *single* piece of iron / steel, e.g. from a currency bar or a part of a bi-pyramidal piece?

Yes! Some but not many of the swords investigated were made from one piece as far as one can tell. In this case the material was typically wrought iron to mild steel.
Pleiner also employed a smith and with his help figured out a few points about the making of swords. For example, they proved that it is possible, indeed, to forge a blade from one piece of iron just with a hammer. Possible but not easy.

2. How about the material? *Wrought iron or steel*?

About 40 % of the swords investigated were made from wrought iron or mild steel **-** and characterized by Pleiner as "inferior". The "single-piece" swords are part of this group. The rest contains some steel. The wrought iron group, however, includes iron with appreciable concentrations of phosphorous, and the blades may be harder than expected for pure wrought iron.

3. What about fire-welding pieces together? That is a tough questions for several reasons. Before I address it, I need to get the vocabulary clear:

- "**Piling**" is the general word used for the process of making a bigger piece of iron / steel by fire-welding several smaller pieces.
- "**Folding**" is the term used when you weld one piece of iron / steel to itself by, well, folding it.
- "**Faggoting**" is the term used for making a piece of iron / steel more uniform by folding and stretching several times. The word does not address the process but the intended result. The link goes deeper

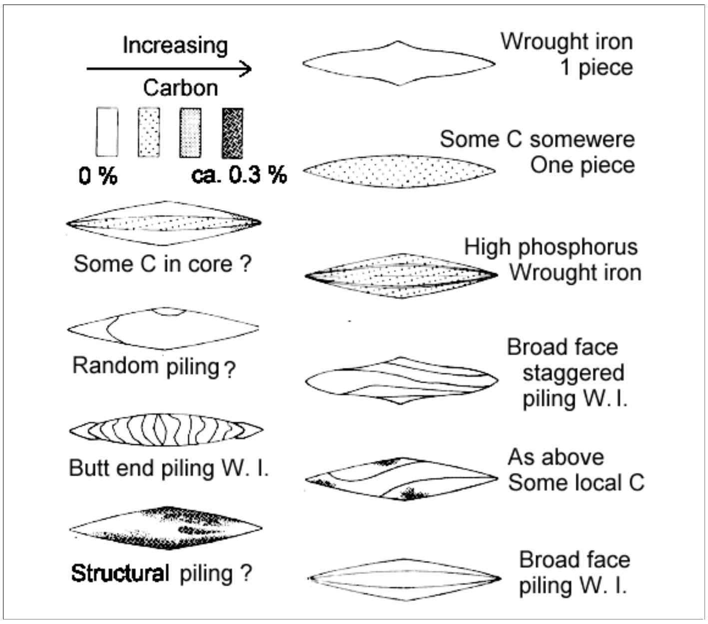
Piling itself can be done in many ways. I list them here in increasing order of sophistication:

- "**Random structural** piling" means that the shape of the pieces welded together didn't matter.
- "**Random compositional** piling" means that no discernible strategy was followed in choosing the carbon / phosphorous content of the of iron /steel welded together. Random *structural* piling is mostly random as to *composition*, too.
- "**Structural piling**" means the opposite. The pieces to be welded have defined geometric shapes. It still could be random compositional piling, though.
- "**Compositional piling**" tries to establish special compositions in selected parts of the object, e.g. hard edges / soft core for a sword. It is then automatically also structural piling.
- "**Pattern welding"** is a sub-group of compositional and structural piling or welding. The different pieces of iron / steel are welded in such a way that an *intended* pattern becomes visible on the surface after some suitable etching or other treatment.

This is essentially a list of options for the smith. It is rather clear, and a smith might go for any of the five possibilities (and mix everything a bit, too). There is *no problem* for the *smith*.

There *is a problem*, however, for the *archaeometallurgist* looking a the product much later. He might find one of those swords with a hard inside and soft edges made by "face welding" (see below) a soft iron piece on both faces of a hard core piece. While this indicates structural piling it is not clear if the smith also attempted compositional piling. That would mean that the smith, for reasons of his own, *wanted* to make a soft-hard-soft structure and knew exactly what he was doing. But the smith just as well might have taken pieces at random and the soft-hard-soft result is purely accidental. The same question comes up for all those swords where just *one* edge consists of hard steel.
In the same vein, random compositional piling might produce a blade that develops a pattern on its surface after some suitable treatment. It is not pattern welding, however, since that pattern was not intended.
One last problem needs to be addressed. If a smith piled pieces of the same kind of iron in whatever way, we may not be able to see that. Well-done welding seams in this case are not easy to recognize after a few high-temperature treatments. What looks, for example, like a uniform piece of wrought iron might well have been made by piling. The opposite might be found as well: clearly recognizable welding seams even so no piling by the smith took place. In this case we look at welding seams that go back to the consolidation of the bloom and the forging of the half-products like the bipyramidal bar.

Now you are prepared to appreciate the magnificent work Pleiner has done in the face of all these vagaries.
Look at the picture below that shows how old Celtic smiths made not-so-hot swords by structural piling but with not much regard to compositional piling. They just piled thin wrought iron / mild steel bars in order to get a blade:



The various (random) piling geometries of wrought iron (W.I.) swords

Source. Adopted from Pleiner

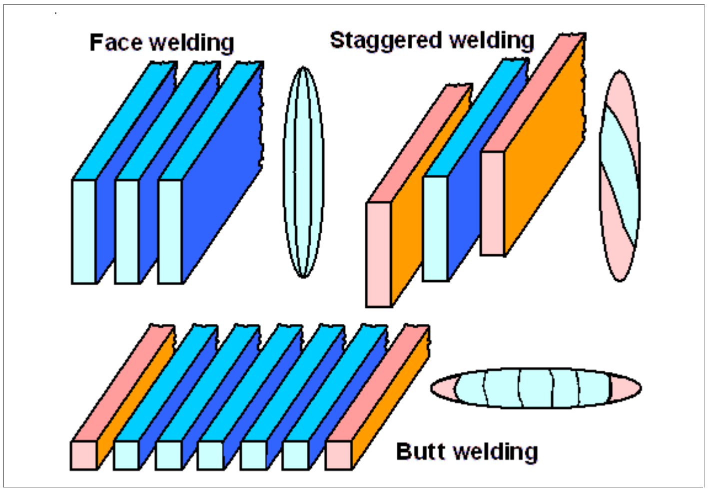
Note that one or two cross-sections are not necessarily representative for the whole length of a blade. But what becomes clear in any case is that Celtic smiths used many different ways to construct sword blades by fire or hammer welding wrought iron or mild steel bars. Some piling might have been random, in other cases the smith might have made an attempt at structural piling but essentially failed.
This looks a bit stupid on a first glance. If you fire weld a few pieces of wrought iron, the result is one piece of wrought iron. So why bother?

- Here are some possible reasons.

  1. The smith must first have made the relatively small wrought iron bars needed for welding. And he could have made them by cutting off small pieces from a bipyramidal bar that he stretched out to a long bar with some *folding* in between. In other words: he was fagotting his pieces. It is most likely easier to fagott or homogenize several small pieces than one large piece by folding. Fire welding the smaller pieces than produces a more uniform large piece than working with the raw material directly.
  2. Phosphorous was employed to harden the wrought iron ferrite. We have already seen that this "works" to some extent. Of course the smith had no idea about phosphorous but knew perhaps that welding pieces from different suppliers (with different phosphorous content) gives good results. Or he had other reasons. It is impossible to fully assess phosphorous issues from one cross-section but it is possible to determine that phosphorous played a role and that might have been an inducement to piling.
  3. The smith knew what he was doing but we don't. His reason might have been good or just plain BS and superstition; we simply don't know.

- Whatever these smiths thought they were doing, and however skilled they forged their iron, their blades were not very good. They were rather on the soft side everywhere. However, all the piling might have made them somewhat more resistant to fracture.

Before I go on to better blades made by structural piling, I need to outline the three basic geometries used for structural piling:

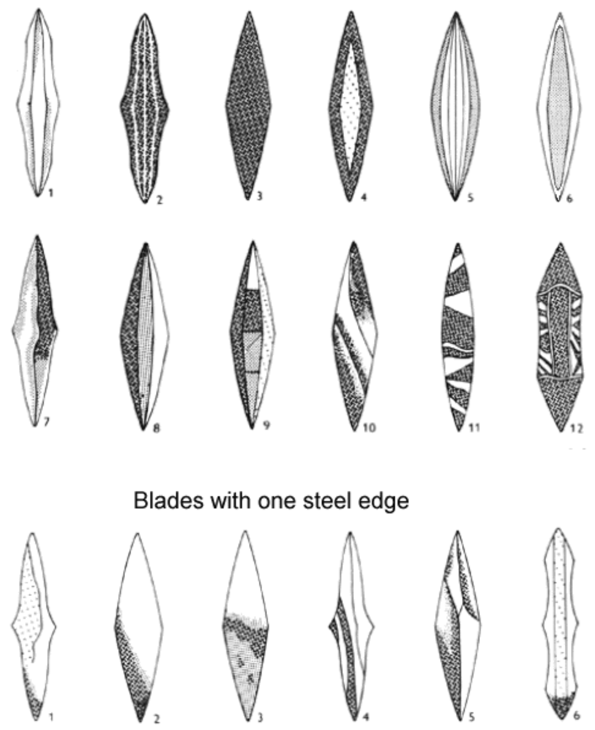


The three essential welding geometries

Source. Adopted from [Pleiner]

The picture is sufficiently clear and needs no long explanation. If you imagine more than two colors for different iron / steel grades, you see that a lot of different structures could result. If you go for **face welding** or staggered welding you need to start from a few thin and wide bars or sheets, if you go for **butt welding** you need a number of long rods with more or less square cross-sections. Butt welding is obviously more involved than face welding.
The question of course is: which way of piling is the best? The answer, as always, is simple: it depends! On all kinds of things but also on how well the smith can fire-weld. I'll come back to this.

It's time to look a the more interesting swords that Pleiner found in his investigation, the swords that contain medium to high carbon steel. Here are the types of cross-sectional structures found:



**Cross-sections of Celtic La Tène blades showing piling structures
and carbon concentration (scaling with greyishness)**

Source. Adopted from Pleiner

I'm not going into details because that would take forever. Even so it becomes quite clear from the picture that:

- Some Celtic smiths were able to to produce good swords with hard edges by doing compositional piling, sometimes in a rather complex way.
- Some Celtic smiths produced swords with soft edges (e.g. No. 6 above), quite likely by compositional piling. Why they did that we don't know.
- Some smiths made complex asymmetric structures, at least to some extent by compositional piling. Again we do not know why.
- There are several blades with just one hard steel edge. This might be accidental but it seem just as likely that this was done intentionally by compositional piling in various ways.
- A few blades get close to pattern welding. However, the iron / steel rods were usually not twisted and it does not appear that the smith wanted to produce a pattern. There is only *one exception* (No. 12) where twisted rods appear to have been used. This sword looks rather like one from the 2nd or 3rd century AD. However, there are Celtic swords not investigated by Pleiner that show definite pattern welding utilizing "striped rods". Here is an example
- There is no clear indication of hardening by quenching.

Based on Pleiner's insights as outlined above, we can now attempt to answer all the questions from above. Note that whenever I say, for example, "Celtic smith" I actually mean[1)] "at least one Celtic smith at some place in the larger Celtic regions and at some specific time between 500 BC and 100 BC". From investigating some few 100 artifacts, found all over Europe and from a time span covering several 100 years, one just can't generalize too much and all numbers should be seen with error margins of at least 10 %. But using all the necessary disclaimers all the time makes the text unreadable.
First let's look at a summary of Pleiner's results (with subdivisions only for the "full cross-sections" part):

Group	**Full cross-section**	**Half cross-section; parts**
A Wrought Iron swords	**40 % (25 Swords)**	**60 % (20 Swords)**
A1 No weld	11%	
A2 Face welded	16 %	
A3 Butt welded	13 %	
B Hard edge swords	**60 % (37 Swords)**	**40 % (13 Swords)**
B1 Two hard edges	40 %	
B2 Single hard edge	20 %	

Pleiner defines 6 sub groups for the B1 type swords but that brings us close to the edge of the statistics abyss. You can't do a meaningful statistical analysis anymore when the number of objects you try to classify is not much larger than the number of classes you need. In other words: every one of the swords analyzed is rather unique. I already needed to show how 18 different kinds of compositional cross-sections to classify about 100 swords!

Here are our old questions once more. Some I have already answered but let's go through all of them anyway; it doesn't hurt to see it twice. The answers are *my* answers:

1. *Question:* Are the swords made from one piece or by "piling", i.e. fire welding several pieces?
   Answer: Both. But piling is more prominent than one-piece forging; see the table above.
2. Was the material homogenized by faggoting?
   Answer: It is quite likely that fagotting was done. But one can't be absolutely sure. You simply can't tell from just one cross-section. The picture in this link, however, might illustrate some faggoting of a Celtic swrod.
3. *Question:* Did the smith conscientiously use different grades of iron / steel if fire welding was used?
   Answer: Yes. Definitely. However, he might have gotten it wrong.
4. *Question:* Was the smith aware of the "phosphorous issue"?
   Answer: Hard to tell. It is noteworthy in this context that about 1/3 of the wrought iron blades had relatively hard edges due to phosphorous. It does appear that some smiths conscientiously picked phosphorous iron for the edge parts.
5. *Question:* Was the smith aware of carburizing or, far more important, de-carburizing during forging?
   Answer: No. There is no clear indication for this.
6. *Question:* Did the smith know about hardening by quenching?
   Answer: No. A very few blades appear to have been rapidly cooled but that is neither certain nor does it seem to have been done intentionally.
7. *Question:* Capability of the smith? His infrastructure? Stone hammer and stone anvil on the floor or dedicated special equipment in a forge with a hearth?
   Answer: The smiths were rather good. Just to shape a decent sword from a lump of iron is rather skilled work; fire welding is even more tricky. Some of the fire welded constructions could only have been done by real masters. There were probably no anvils as we know; forging most likely happened on stones. The set of tools was primitive but not much different from what you would have found in a 19th century smithy. In the hands of a master they were very effective. But we hardly know anything about the smiths.

It follows that Celtic La Tène swords look about the same from the outside but the insides could be rather different. Some bad or mediocre swords were made because the smiths apparently couldn't do better. Alternatively, maybe, you just got what you could pay for. Some bad or mediocre swords, however, were made with plenty of skill and cunning. Why a smith conscientiously should have made a sword with a hard core and soft edges we don't know. Then we have well-constructed swords and some quite elaborate ones, leading up to the pattern welding that reached its full bloom around 400 BC, 600 - 800 years later.

Did you notice that a new big question is lurking in all the questions and answers above? No? Well, you must have noticed that a lot of fire welding (also called hammer welding, forge welding, ...) was going on. Big deal you might think, that's what happens already during the compacting of the raw bloom, no to mention the forging of bipyramidal bars or any other form of trade iron. Yes, but making a sword by fire welding several strips of iron in one of the many ways shown above is a different story. The Celtic smiths could do it - but with varying quality. There are blades with very good welds and bad welds next to each other.
OK - but what is the **question**? Here it is:

How come ancient Celtic smiths could do fire welding while modern Materials Scientist cannot?

As I have outlined before, you only can join iron to iron if you remove the oxide (FeO) first. This is supposedly done by sprinkling some sand (quartz; SiO_2) on the hot surfaces to be welded, liquefying the oxide or scale. The liquid stuff is then squeezrd out under the hammer. That's what I have told you way back.
In the meantime, however, we have learned that this is a more complicated process. What really happens when you sprinkle sand on the surface is that you produce fayalite (Fe_2 SiO_4), the main component of slag. Fayalite is liquid, indeed - but only around 1200 ^oC (2192 ^oF), a temperature rather too high for normal smithing. I have alluded to this mystery before and I shall get back to it. Meanwhile the advanced module gives some more information about the topic.

Advanced Link

Fire Welding

But now it is time to answer the big question. Was Polybius right? Pleiner devotes several pages to this question, coming up with: "the metallographic evidence shows that Polybius was right up to a point". Then he goes on to show that the "point" Polybius comes up to is actually rather low. So *my* statement is:

Polybius was wrong - up to a point

My reasons are:

1. More than 60 % of the swords investigated by Pleiner would have been definitely good steel swords, not given to heavy bending on the first blow.
2. From the remaining 40 % wrought iron swords a noticeable percentage would have been hardened by phosphorous and these swords would not have been given to easy bending either.
3. Pleiner had two wrought iron swords made that were "soft" iron throughout and tested them by hitting all kinds of things. While deep notches were produced, no heavy bending occurred. The swords would have caused major injuries not only on the first strike but also on many following ones, no matter how heavily notched or slightly bend they were.

Of course, it is possible that Polybius or his source witnessed a bunch of Celts with particularly bad swords. It is just as possible that Polybius reported unsubstantiated rumors he had heard, that he exaggerated a bit, or that he was befuddled because heavily bend Celtic swords do exist, indeed - in the graves of the warriors. These swords were ritually "killed" by bending and possibly even by notching.
Nevertheless, some Celtic swords might not have made a big impression on Roman legionaries. A badly made wrought iron blade, possibly with some major internal inhomogeneities like large slag inclusion or bad welds, either from the stock material or from forging, might do strange things after the first blow - in particular if the guy wielding the sword wasn't so hot either.

A "killed" La Tène typ sword; 100 BC

Source: From burials near Tudvad, Denmark. National Museum Copenhagen.

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1) A mathematician, a physicist, and an engineer are riding a train through Scotland. The engineer looks out the window, sees a black sheep, and exclaims, "Hey! They've got black sheep in Scotland!" The physicist looks out the window and corrects the engineer: "strictly speaking, all we can say is that there's at least one black sheep in Scotland." The mathematician looks out the window and corrects the physicist: "strictly speaking, all we know is that there is at least one sheep in Scotland that is black on one side."

2) Ferdinand Keller: The lake Dwellings of Switzerland and other parts of Europe" (1866), translated