Fire Welding

The Problem

Illustration

Fire welding; also called **hammer welding**, **forge welding**, pressure welding or contact welding, is the most important technology in iron and steel working as long as you cannot melt the stuff. It is first used when a bloom is compacted, and after that in forging pretty much everything that was ever made from solid iron or steel. Until about 1000 AD, swords or other large iron / steel articles were almost always made by piling, i.e. by fire welding several pieces of iron / steel. After about 1000 AD swords might have been made from one billet of steel but that piece had been fagotted and thus was exposed to extensive fire welding, too. We do not know much about that, though.

I gave you already a whole module about "Welding with Hammer and Fire". It described what happens rather clearly, I think. So why do I have problems with fire or hammer welding *now*, remarking on it already here or there?

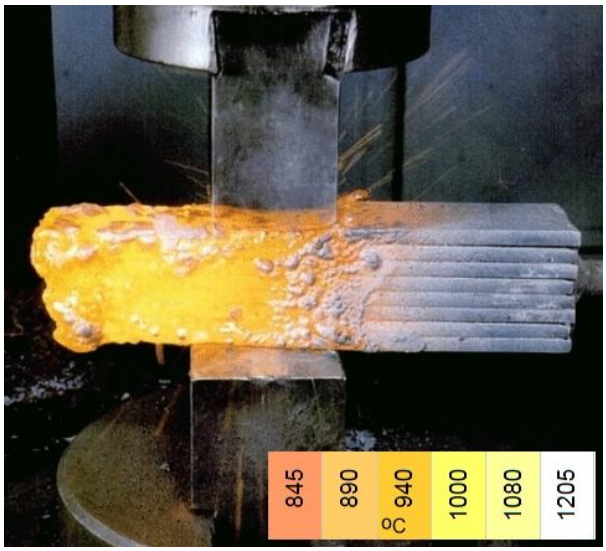
My present problem, or "the" problem is rather simple: too many questions come up as soon as one looks more closely at fire welding. In essence, they all concern how to get rid of the oxides that cover the surfaces to be welded. Typically, this is supposed to happen either via the reduction of the oxides in a reducing atmosphere at high temperatures and / or by liquefying the oxide by forming liquid fayalite (Fe_2SiO_4) or some other slag via the addition of "sand", meaning essentially SiO_2. Fayalite liquefaction requires temperatures of at least 1200 ^oC (2192 °F).

I concede that some left-over oxide might not be a big problem since the banging with a hammer will break it up into small parts. But these small particles then will be found in the vicinity of the weld seam, and you can't have too many without compromising the quality of the product.

Considering that fire welding took place all the time in iron and steel technology, it is obviously not all that difficult to do. Slag, oxide and "flux" particles are indeed found in weld seams quite frequently as one could expect. So where is the problem?

The problem is that there are too many questions that do not have clear and convincing answers. One or two open questions - OK. Don't worry, be happy. You may not know the answers but somebody else probably does and it will become clear sooner or later. Now look at my long list:

1. Sprinkling (quartz; SiO_2) sand on the hot surfaces to be welded to liquefy the oxide or scale by forming liquid slag (fayalite) would only work at temperatures of at least 1200 ^oC (2192 ^oF) - too high for normal smithing in antiquity. Early smiths could not routinely reach 1200 ^oC in their primitive hole-in-the-ground hearths. 1200 ^oC is already a high temperature in a good smelter, after all, and smelters are always much hotter than an open hearth.
2. A lot of fire welding was done *without* SiO_2 or anything else as "flux" material. Compacting a bloom is a first example. You may squeeze out the slag from cavities, but you still need to weld the surface together.
3. A lot of fire welding is done without a *reducing* atmosphere everywhere. Compacting a bloom... and so on. What's more, making just one rod for a pattern welded sword starts from a stack of plates like that shown below. I doubt very much that an ancient smith could have kept a packet like that always in the reducing part of his fire *and* at 1200 ^oC. Not to mention that having 1200 ^oC in the reducing part would require that the oxidizing part of the fire is *much hotter*! In case of doubt look at the smelting modules, e.g. here, to recall why.
4. A lot of fire welding was done well below 1200 ^oC (2192 °F). Compacting a bloom can serve as an example once more, and so can the picture below.
5. I don't see how sprinkling SiO_2 on the surface of a package as shown below could possibly produce liquid fayalite deep inside the structure.
6. Even if it does, I don't see how all the liquid could be completely "squeezed out" from in between flat and parallel sheets by banging as shown below.
7. Other "fluxes" like Borax (something like $Na_2B_4O_7{\cdot}10H_2O$) seem to make fire welding easier, too, especially it they contain iron powder. I don't doubt that this works, I just don't know how.
8. Hypereutectoid steel, e.g. wootz steel cannot be fire welded as stated by some writers on occasion. Is that true? And if yes, why? The Moravian swords described here do have fire welded high-carbon parts, it seems, and so do Japanese nihontos.
   In the same vein, it is often stated that only iron / steel can be fire welded but not, for example (alloyed) copper or gold. Is that true? And if yes, why? I would know no reason why this should not be possible if done "right".
9. How does a bit of carbon, phosphorus or other impurities change fire weldability? The welding temperature, for example, comes down with increasing carbon concentration, as many smiths report. Phosphorous also has a decisive influence. And so on. Why?
10. There are certain phenomenae observed with weld seams that are not so clear (see below)



Modern fire welding (with a temperature - color scale)

Source: Hein Denig: Alte Schmiedekunst / Damaszenerstahl. Inst. für Pfälzische Geschichte und Volkskunde; 2008

- The picture shows modern fire welding of eight sizeable flat sheets with a snug fit. How solid or even liquid stuff can get between the plates is not clear to me. Yes, I know that capillary action might suck it in - but the same capillary action then would make the getting out part rather difficult.
  It is also quite unlikely that the work piece is at a 1200 ^{o}C temperature. While one needs to be careful with the reproduction of colors on screens, it is certainly not fully white as required at that temperature. There is also no reducing atmosphere, of course. Nevertheless - the process works.

What Do We Know?

Let's dig a bit deeper by looking at some of what has been written about fire welding in the context of the questions above. A good way to start is Buchwald's momentous book: Iron and steel in ancient times.

Vagn Buchwald dedicates several pages of his book to "the art of hammer welding". He essentially follows the logic outlined above but with slight contradictions: hammer welding needs temperatures at "1100 - 1250 ^{o}C" or requires "heating to about 1100 ^{o}C in a reducing atmosphere". The oxide formation on hot iron is discussed in some detail, and Buchwald points out that "they (the oxides) easily reach a thickness of 0.2 mm in a matter of minutes at high temperatures". It appears that Buchwald assumes that some wüstite is unavoidable and that all welding seams must contain some of the stuff. Several pictures illustrate this by showing weld seams with inclusions of oxide (wüstite, FeO) or even SiO_2 grains on occasion. However, there are plenty of pictures elsewhere that show perfectly clean weld seams with no or very few oxide inclusions,

- On a more detailed level Buchwald argues that the oxidation process would result in a carbon denuded and phosphorous enriched surface layer and thus in a weld seam with impurity concentrations different from that of the bulk. That might well be the case and has been observed - but it doesn't necessarily follow from the arguments provided.
  The action of the SiO_2 "flux" is twofold. First, the fayalite "slag" formed by reaction with the oxide protects the iron /steel from the oxygen in the air and thus hinders further oxidation. Second, the liquefied stuff can be "squeezed out" or made to run away by tapping the work piece, providing clean surfaces.
  Buchwald mentions that Borax also works as "flux" but does not say how.
- He also adds a new point: "as a curiosity, sand/quartz will not react with the surface oxides on hot-forged iron unless the iron is surrounded by a reducing atmosphere, so that the surface oxide is FeO". That might well be true. We just get a new problem: if you sprinkle sand on the iron, it is rather hard to do this in a reducing atmosphere since during the sprinkling it is obviously exposed to the air. You can sprinkle on the sand and then bring iron plus sand back into the reducing part of your hearth (i.e. "under" the coals), of course, and hope for the best.

- Everything Buchwald writes makes sense - but doesn't really answer my questions from above. So let's look at how modern practitioners describe the fire welding process.
  - I checked several "manuals" for aspiring smiths' about how to fire weld. They all agreed that you should put some "flux" on the surfaces to be welded: "When the bars reach a bright orange, with the bars remaining in the fire, take your fire rake and make a hole in the fire over the scarves (pieces to be welded) so flux may be sprinkled on the face of the scarves".
    It is also recommended to make the two surfaces to be joined slightly convex. Then they only touch at the center and you can weld with the hammer from the center to the outside, allowing the liquid slag / flux to move away as you proceed.
  - There is also a general agreement about the following points:

    - You should keep oxygen "out", i.e. keep your workpieces in the reducing part of the fire.
    - The liquid forming by applying flux - whichever one - should envelop the workpiece, preventing further oxidation. This is important because when you take the pieces out of the fire to do the required hammering, they will be exposed to oxygen.
    - The welding temperature should be high - a "yellow-white appearance in color" is typically referred to. A "white heat" corresponding to the theoretically required 1200 ^{o}C is rather seen as dangerous and too high. "Care must be taken to avoid overheating the metal to the point that it gives off sparks from rapid oxidation (burning)".
- That is all fine and the recipes given obviously work. But I stick to my guns and claim that most of my question above have not been really answered. And don't forget that the situation now is different from that 2000 years ago. A modern smith can easily go up to 1200 ^{o}C, possibly even in the reducing part of his fire, by just cranking up the power of his air (or possibly oxygen) blower. An ancient smith would have had far more problems in doing that, if he could do it at all.
- As far as point 10 of my questions list is concerned, I simply, refer you to some modern writings - in this link. In addition I just point out that there is some suspicion that the Romans used a iron -arsenic alloy, i.e. a variant of "**speiss**", with a low melting point as "flux" for joining iron / steel. That means that they actually did not perform fire or hammer welding but soldered or **brazed** the pieces together. The arsenic will diffuse out of the "solder" into the iron and the final result is an iron -iron joint surrounded by a region high in arsenic (As). and low in carbon.

- Let's stop here. There are plenty of possible comments and elucidations to my questions from above. I could go on for quite some time but we just won't get anywhere.
  The facts are that fire welding is quite tricky and not easily done by beginners in smithing. It is not a particularly difficult job for an experienced smith, though. There is no doubt that in general terms fire welding proceeds more or less as described, but there is also no doubt in my mind that it is somewhat easier than it should be according to theory (a good thing!,) and that the details of what is going on are not yet fully understood.

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1) G. Becker: "Niedrig schmelzende Eisen-Arsen-Legierungen als Hilfsmittel für den Verbund römischer Schwertklingen." Arch. Eisenhüttenwes. 32, (1961) pp 661 - 665.