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One problem and three solutions: The steel of the European, Indo-Persian and Japanese swords compared.

Part 1- The European swords of the seventeen and eighteen centuries

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This year, the Brazilians, who are Japanese descendents living in Brazil, are commemorating the first centenary of the arrival of the first ship with 800 of them from Japan. This series of articles is dedicated to this group, who, although few in numbers, have made an enormous contribution to their adopted society.

Ideally a sword should be very tough, and should cut very well; however, swords are made of steel that is a mixture of carbon and iron and, as we are going to see, there are compromises to be made between toughness and sharpness in their manufacture. Generally, if steel can sustain an extremely good cutting edge it is brittle; when is not very brittle, it is somewhat soft. The compromises to be made and the problems to be solved to make swords tough and sharp at the same time were met differently in different cultures. This series of articles examines and analyzes the compromises and solutions employed by the smiths of 17^{th} and 18^{th} century Europe to deal with the problems. Further these techniques are compared with those employed by both the Indo-Persian and Japanese smiths. As we know the Japanese solutions are the best and we hope to show why this is so in this series of articles.

Pure iron is soft. It does not hold a cutting edge well. It is known that steel, that is iron with a bit of carbon, is much harder. It is also known that too much carbon makes the steel very hard and at the same time brittle. AS a result, the first problem swordsmiths had to solve was to decide **how much carbon** their steel should have. The second problem is that it was also discovered that **heat treatment**, for instance heating the sword and then quenching it, could greatly alter the quality of the steel. The third problem is that **mechanical treatment**, that is forging, also improved the quality of the steel. Depending on the amount of carbon a special type of forging is necessary. These three factors were dealt differently in different cultures. The resulting swords were very different.

The first difference to be noted in a sword is its ability to cut. Unfortunately, this difference is difficult to test by collectors who do not want to risk damaging their swords. Unlike European swords, patterns in the surface known as watered steel, or Damascus steel in the occident and *hada* in Japanese swords is apparent. The European swords of the 17th and 18th centuries, the ones we are going to consider in this article, present no patterns in the steel, that is, the European sword steel shows no watered steel or *hada*. The Indo-Persian swords present very distinct marks. (The steel that makes these swords is known as *wootz* steel and the pattern seen in the steel surface is called Damascus.) The Japanese sword steel presents a pattern we call *hada.* One of our problems is to decide if the Damascus in Indo-Persian swords is the same pattern seen in the Japanese swords steel and known as *hada.*

This subject has been treated before in articles in the Newsletter of the Japanese Sword Society of the US. The most technical of them was an article by Jeffrey Wadsworth, Dong Wha Kum and Olegy D. Sherby [1, 2]. A sentence of this article, that we quote, was mis-interpreted by readers of this Newsletter. It says, "Two misconceptions are prevalent with respect to multiple folding [a forging technique] procedure…. the second is that multiple folding led to a pattern welded structure." Further down in the article we are told that " No visible pattern welded structure is obtained, not only because the individual layers, 0.2 mm [57 micro-in] are unresolved to the naked eye, but also because the carbon content of each layer is identical (carbon atoms traverse a distance of 1.4 mm [57 micro-in] in 30s at 1000 ^{o}C [1830 ^{o}F]." This sentence seems to deny the existence of *hada* that we can all see in our swords. In fact it does not deny it, but we surely need to know exactly what is being said before concluding that the article is wrong. It is also important to us to quote another sentence of this article that appears just before the sentence quoted above. It says, "(Incidentally it is sometimes possible to observe true watering on Japanese swords as a result of its high carbon content and processing history.)"

As a result we have a few problems to deal with. Why is it that the European steel presents no markings? Is the Damascus steel the same as the Japanese steel? We shall first deal with carbon in steel. This will allow for further discussion.

How steel was made before the modern age?

In order to understand how high carbon content steel was made we use the explanations given by Sherby and Wadsworth in another article in **Scientific American** [3], and the explanations given by Bloofield in an article in **Physics Today** [4].

The following picture describes a very primitive way of making steel. This is approximately what was done in India to produce steel with more than 1% carbon by mass. The resulting "cakes" are called wootz steel. (The making of steel before the industrial age is a fascinating subject that is treated very thoroughly in the book by Rostolker and Bronson [5]. The Japanese method is as we know to use the *tatara* (smelting furnace.)

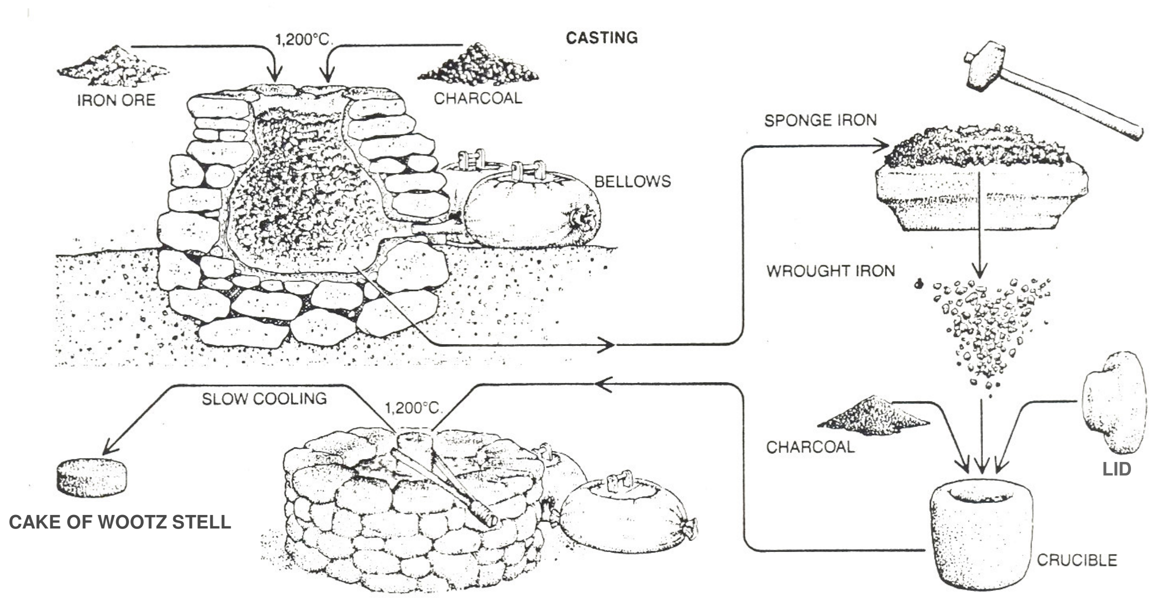

Figure 1

Figure 1 shows a primitive way of producing steel with a high content of carbon (adapted from [3])

The figure shows iron ore, which is usually found as an oxide. (In an oxide, iron combines with oxygen and forms rust. This is the reason for the famous colors of the Japanese sands used to make steel.) It is necessary first to remove the oxygen by reacting it with carbon (carbon is the charcoal) and this produces, depending on the amount of charcoal, either **wrought iron,** which have a very low content of carbon or **pig iron,** which has more than 4% by weight of carbon. The rest of the figure assumes that the first phase (shown in the top of the figure) has produced **wrought iron.** At room temperature, a chunk of iron is made of many crystalline grains of **ferrite.** A crystalline grain is a small crystal and as in every crystal the atoms are arranged regularly. In the case of **ferrite** the atoms are arranged in a structure called **body-centered cubic lattice** that is show in Figure 2 A.

Figure 2 Structures of iron crystals.

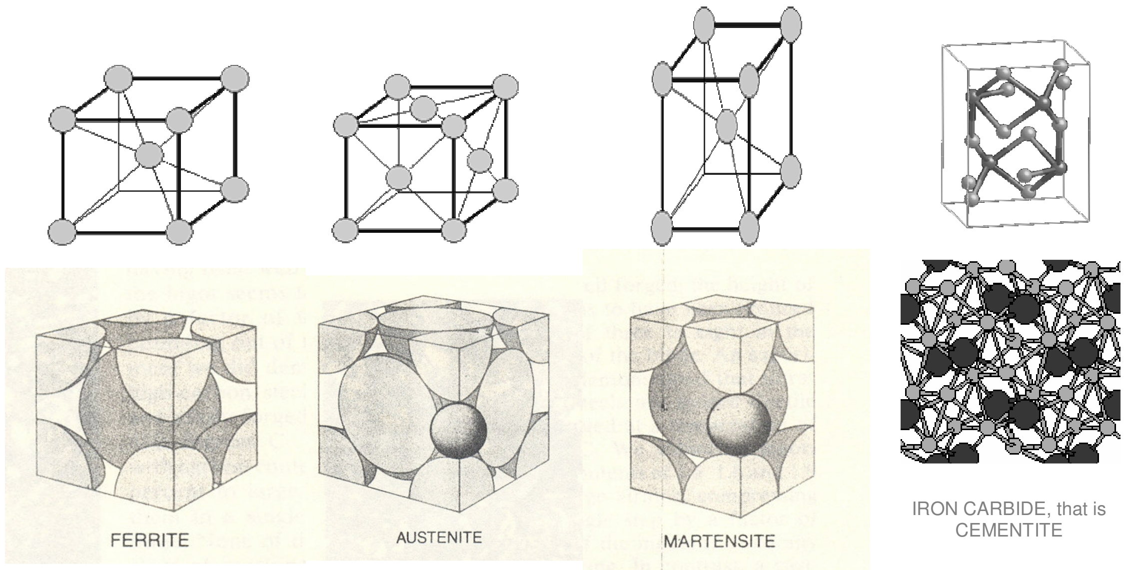

Figure A Figure B Figure C Figure D

FIGURE A - shows the body-centered lattice. This should be imagined repeating indefinitely in space. The atoms are at the corners, as shown in figure at the bottom. The spheres at the corners and at the center are iron atoms. Only 1/8 of an atom is shown at the corners.
FIGURE B - shows the face-centered lattice of *austenite*. The atoms are on the lattice points as shown in the figure at the bottom. The spheres are the iron atoms and note that there is room for the carbon to enter the structure occupying the middle of the sides as indicated by the small black sphere.
FIGURE C- shows a body-centered lattice distorted. A carbon atom is shown in the figure at the bottom which distorts it. This forms *martensite*. When the temperature goes down, the structure tries to return to the structure of *ferrite*; however, a carbon atom gets trapped and the structure of the crystal is deformed. The *martensite* is very hard but is not stable.
FIGURE D - shows the lattice of *cementite*. The atoms are arranged in it as shown in the figure at the bottom and the resulting structure is *iron carbide,* also called *cementite*. *Cementite* is formed when the *austenite* cools down. Some of it forms this special compound. *Cementite* is very hard but not as hard as *martensite*.

Carbon is nearly insoluble in **ferrite**; however, when the temperature increases, the structure of the iron changes from body-centered, shown in Figure 2A, to face-centered, shown in Figure 2B. Iron with this crystal structure is called **austenite** and it has room for carbon to penetrate. This is shown in the Figure 2B by the small black sphere representing carbon.

The transition from **ferrite** to **austenite** begins to occur above 727 ºC. If the temperature is further increased to above 912 ºC (see the phase diagram explained in the appendix) the steel, with less than 1% carbon, becomes pure **austenite** that, in spite of the carbon content, is soft and ductile. Because of this, the European swordsmiths preferred to make their swords at this temperature. (At this temperature the steel would be white hot.) Nevertheless, of course, we want the sword steel to be at room temperature. What happens when the temperature goes down? It depends on how fast the temperature goes down. If it goes down slowly (in the air) the resulting steel will be a mixture of **ferrite** and **cementite** (see the structure of **cementite** also known as **iron carbide** in figure 2D), known as **pearlite**. This steel, **pearlite,** is tough but it is not particularly hard and so it does not take a good edge. The first possible solution is to increase the carbon content but if this is increased too much it becomes too brittle. This is so because, if the content of carbon is high there is too much **cementite** mixed with **ferrite** in the **pearlite**. Why is it brittle? It is brittle because the **cementite,** which is very hard, forms a network inside the crystals that can break very easily. **Pearlite** is very useful if the content of carbon is not high and therefore **cemetite does not** form a continuous network throughout the **ferrite.** In this case, it does not break easily and, in fact, it is used to make extremely sturdy utensils. Unfortunately, as mentioned, it does not take a good cutting edge.

So the European swordsmiths worked with only a relatively small carbon content (0.4%-0. 5%) and quenched the resulting product in oil or water instead of letting the sword cool down slowly. Quenching in oil or water with low carbon content resulted, in **bainite,** instead of **pearlite. Bainite** is a mixture of **ferrite** and **cementite,** but has the **cementite** more finely dispersed within the **ferrite.** So it is much harder than **pearlite** and still tough.

This was the European solution to make good swords. Their swords are made manly of **bainite.** Moreover, **v**ery rapid quenching in water results in **martensite (**in addition to **bainite),** which is the hardest steel, ideal for edges. The crystal of **martensite** is shown in figure 2C. One can see in figure 2C that, because of the rapid cooling, the carbon atoms get trapped in the **ferrite** crystal and deforms it. **Martensite** is very hard but brittle and is not stable, so it is not shown in the phase diagram presented in the technical appendix. (The *nie* and *nioi* of the Japanese swords are made of **martensite.** Given a few millions of years the **martensite** of the *yakiba* of your Japanese sword will decay to **ferrite** or **cementite.**)

We should add that the European solution is not as simple as described above. This is because the rapid quenching results in stresses in the metal, which in combination with martensite (perhaps just a little due to the low carbon content) produced a sword that was still a little too brittle. As a result, the European swordsmiths tempered the steel. This process consists in heating the sword to few hundred degrees and letting it cool slowly. With this in mind, using low carbon content and by a clever combination of quenching and tempering, European sword makers could achieve reasonable results. The result was reasonably tough steel that could be used to make swords. The important point here is that the European swordsmiths found that increasing the carbon content resulted in a brittle blade. They gave up making swords with very high carbon content.

As we shall see, the Indo-Persians and the Japanese managed to work with much higher carbon content. As a result, their swords are much sharper than the European ones. We shall explain how they achieved this in a moment but first let's us examine two European swords to see what they look like and how they were used.

To understand European swords it is necessary to include a little historical background. The 17th and 18th centuries were not very peaceful in Europe. In Japan Tokugawa Ieyasu managed to finally unify the country and two centuries of peace (with incredible tyranny) prevailed. In Europe, incessant war was fought among kings (incredible tyrants) who represented countries. The swords used to fight wars were different from the swords used by civilians to fight duels.

The sword shown in Figure 3 is a *Hanger* (a sword to be used by the infantry). It was mass-produced in Germany around 1750 C.E. and, although it has a low content of carbon and was probably quenched in oil, it is quite good. It does not cut as well as Indo-Persian swords or Japanese swords and it is not as good looking. However, I would not like to receive a blow from it. It certainly did its job of killing or maiming the enemy very effectively. Its steel presents no texture like Damascus (also called watering) that is the texture that can be seen in the Indo-Persians swords. It does not display a somewhat different pattern we know as *hada* which can be seen in Japanese swords. (We shall study carefully the differences between Damascus and *hada* later on in this series of articles.)

The Figure 4 shows an eighteen-century civilian sword, known as a *Small Sword*. (A better name would be a *baroque rapier*.) It does not cut! It has a triangular "hollow ground" cross-section and is very stiff. Rapiers were meant only to thrust and they are deadly if used by a trained swordsman. The use of thrust-only swords by civilians was something that started in Italy in the end of the 16th century. The technique was brought to England and was resisted by the English master of arms [6, 7]. One of them, George Silver, wrote a book arguing that the very long thrusting swords (rapiers) could not be used in the battlefield. However, it is apparently easy to kill persons by just opening a small hole in their bodies and so the civilian continued to use the *rapier*, later shortened and called a *Small Sword*.

The figures 5 and 6 are drawings that show how those weapons were used (from reference [8]). In figure 5, we have a *Small Sword* being used against a *Small Sword*, and in figure 6 we have a *Small Sword* (used by a civilian) being used against the "*Broad Sword*" (used by a soldier). More pictures of European swords can be found in references [9] and [10]. I tend to agree with George Silver that it is very difficult if not impossible to use a *small sword* in the battlefield no matter how deadly it may be in duels.

Figure 3 -This show a European *hanger,* that is, a military sword circa 1750 C.E.

Figure 4 -This shows a French *Small Sword* for civilian use only, circa 1760 C.E.

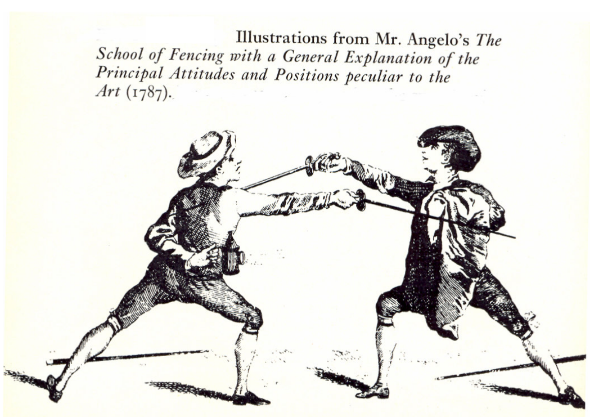

Figure 5

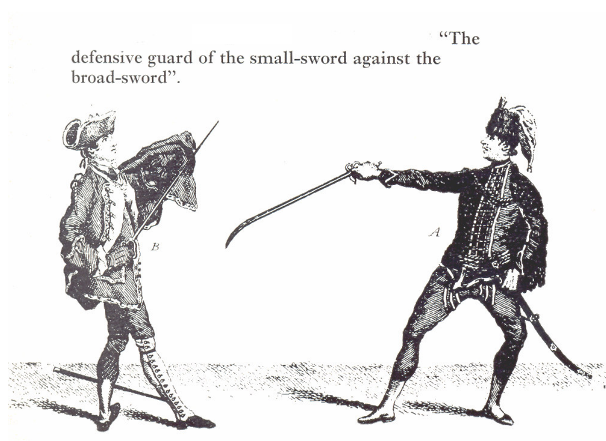

Figure 6

Conclusions concerning European swords

They were made with a relatively low carbon content (compared with Indo-Persian and Japanese swords). They were quenched in either water or oil and tempered. No surface patterns (watering or *hada)* can be seen in their surfaces, because the content of carbon is low and because no attempt to artificially make the markings occurred. (I shall have more to say about this in the next article of this series.) One should bear in mind that swords like this can be easily mass-produced, for a reasonable price, and that is just what Europe needed from the 17th to the 18th centuries.

The quenching method is important not only for swords but also for armor. An armor made of **pearlite** can sustain a bullet better than an armor made of **bainite**. On the other hand armor of **bainite** can deflect a sword or dagger point much better than armor made of **pearlite**. See the article by Anthony de Reuck [11] for a more detailed discussion.

There is another way of producing tough swords that was used much earlier than the process described above. This is to mix almost pure iron with high carbon steel and forge the sword with this material. The resulting blade has steel that is called laminated or welded Damascus. The book by C. S. Smith [12] shows the resulting surface markings in Merovingian (650-700 C.E.) blades and in more recent Keris. (Keris or Kris is the name given to the blades used in Indonesia and Malaysia). Also reference [1] has a photo of a Chinese sword made with this technique. In [1] it is said that Japanese sword are the most famous welded product. In fact, as we all know, Japanese swords are made of steels of different carbon contents. The core of the sword, for example, is almost pure iron. However the different steels are not mixed as in a welded-patterned Kris sword.

In the next article we shall concentrate on how the Indo-Persian swordsmiths could make swords with a high content of carbon (so very sharp) but at the same time very tough. Then we shall see how the Japanese could do even better.

TECHNICAL SUMMARY APPENDIX

The iron-carbon phase diagram is the focus of Figure [7]. Steel can be prepared with the specific carbon content at the specific temperature shown. That steel will be stable. Iron crystals in carbon steels can exist in the three forms shown. **Austenite** can exist only at a high temperature (see the phase diagram below). Carbon can penetrate the crystal of **austenite** (see the small black sphere in Figure 2B). When quenched **austenite** becomes **ferrite** and **cementite (iron carbide**) shown in figure 2D. We can also have **martensite**, which however is not stable and therefore does not appear in the phase diagram. Given a few million years the **martensite** of the *hamon* of your Japanese sword is likely to break down to a mixture of **ferrite** and **cementite,** but please do not worry too much about this.

Note that below 727 ºC we can have only **ferrite** and **iron carbide** (also known as **cementite**). A European swordsmith would work as follows: He would begin from point A (20 ^{o}C) in the phase diagram and raise the temperature until it reaches B. At B (1200 ^{o}C) he would have only **austenite,** which is easy to forge. He would then make the sword. The next step is crucial. He wants to drop the temperature back to point A. If he does it slowly the **ferrite** and **cementite** will arrange themselves in layers, that is, the steel will become **pearlite.** (The name comes from the layered structure of pearls.) If he does it fast enough, the **ferrite** and **cementite** will rearrange into **bainite** in which the **cementite** is finely mixed with the **ferrite** and so the resulting sword will be considerably harder and still very tough.

What happens when one increases the amount of carbon? As mentioned above, the **iron carbide (cementite)** becomes too abundant and forms a continuous network through the **ferrite** background. This makes the sword very hard, but brittle. Even so both Indo-Persian and Japanese swordsmiths solved this problem. Stay tuned to the next article in the series to learn how they did this.

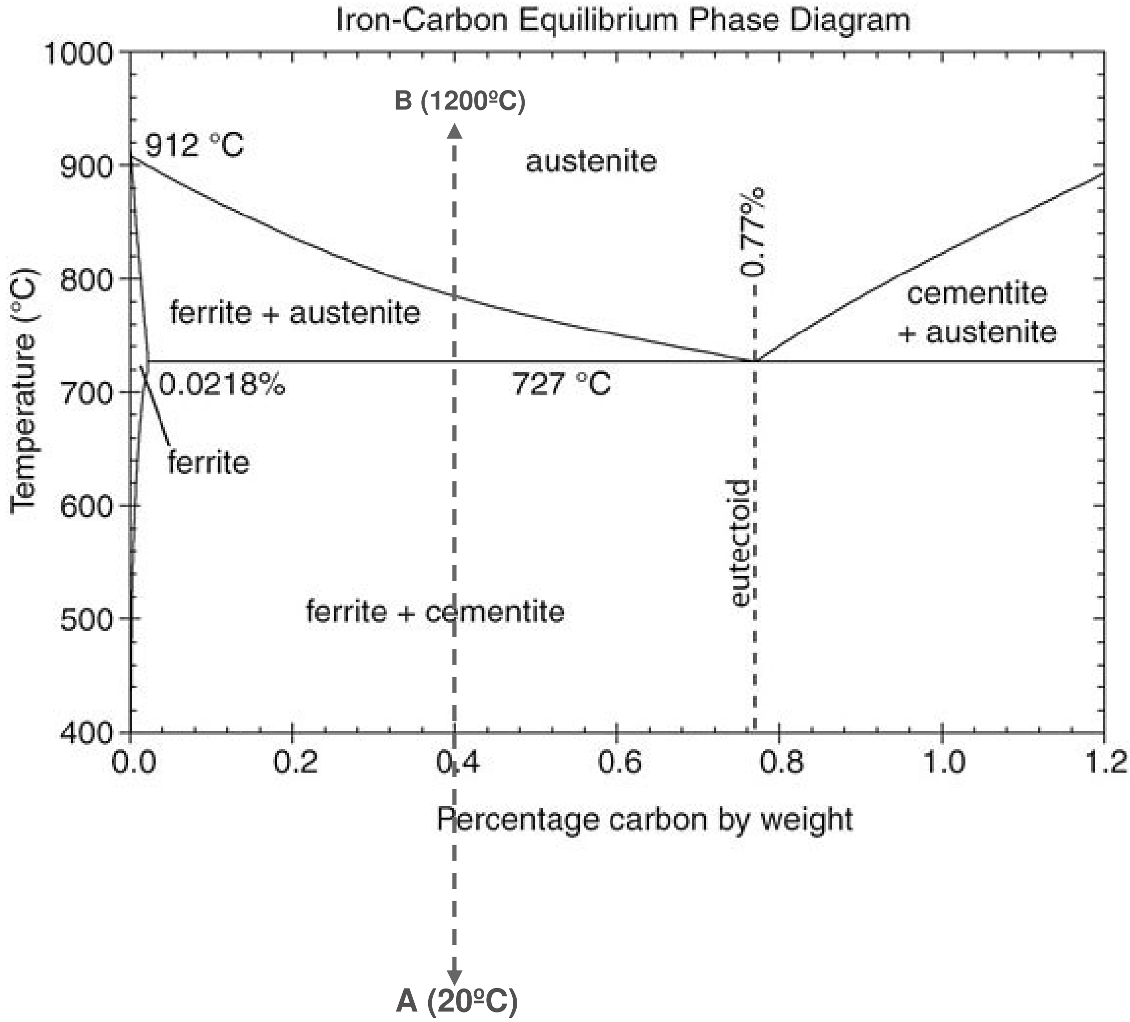

Figure 7

Figure 7 - shows the "phase diagram" of iron carbon compounds. The vertical axis shows temperatures in degrees Celsius. The horizontal axis shows the percent of carbon in the compound. The vertical line A to B shows the procedure used by an European swordsmith to heat treat a sword with 0.4% carbon starting from A at 20 ºC and going to B at 1200 ºC. The sword is forged at this high temperature and then rapidly quenched as explained in the text.

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