



Making Steel in the Middle Ages



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Introduction

Historians plot the development of human civilization in terms of the hardness and durability of materials used to make tools. Copper was the first metal to be exploited by man, as it was plentiful and could be collected in its pure metallic form. The Copper Age ended when societies learned to combine copper and tin to make bronze. This was not an obvious step. Someone figured out that by combining two materials, a third emerged which was more than its component parts. Thus we see beginnings of the science of metallurgy.

The Iron Age began when men made another intuitive leap and found that a useful metal could be created from rock. From the early Iron Age through most of the medieval period the only method to extract iron from raw ore was the bloomery^a process which produced soft iron of low carbon content. It was not superior strength that caused iron to become the dominant metal. Early iron was not superior to bronze, only more plentiful. While copper was very common in early times, tin was in limited supply. Both iron and bronze were used by 3rd C Romans.¹

Iron becomes harder as its content of carbon increases and it becomes steel. In time, various technologies were developed to make iron into steel which could be far superior to bronze, with dramatic effects on human civilization. Some historians have proposed that the Iron Age should be followed by a Steel Age, following the link between civilization and technology.²

An earlier paper discussed medieval technologies for extracting metallic iron from its ore.³ The present work will explore how the products of the bloomery were transformed into steel for stronger and more durable tools, weapons and armor.

Iron Crystal Structure and Quenching

Metallic iron has a crystalline structure, which means that the iron atoms are arranged in a repeating three-dimensional grid or lattice. When heat is applied, the atoms vibrate. With

^a See the Glossary in Appendix 1.

increasing atomic motion the whole lattice structure expands as the atoms start to move away from each other. Carbon atoms are the right size to slip through this expanding lattice and sit inside the iron crystal. If the heat source is removed at this point and the iron allowed to cool slowly, the carbon atoms will remain trapped inside, and this makes the iron crystal harder.⁴

This is what we call *steel*. (see Table 1)

Like water, steel passes through the familiar phases of solid, liquid, and gas, but the situation is more complex in a very subtle but important way. Normal steel at room temperature exists in a specific crystalline structure called “ferrite.” At 723 to 912 degrees Centigrade (°C) the iron and carbon atoms shift into a different arrangement called “austenite”. The hot steel is still solid, the energized atoms are simply more stable in the new austenite configuration. If allowed to cool slowly, the atoms will shift back and the metal will revert to its original condition. But if hot steel in the austenite form is very rapidly cooled, the iron and carbon atoms don’t have time to shift back into their former places and instead are frozen somewhere between ferrite and austenite, forming a new crystal structure called “martensite”. Martensite is an extremely hard form of steel, much harder than would be predicted simply on the basis of carbon content alone.⁵ Steel must contain a minimum of around 0.4 percent (%) carbon to see an increase in hardness after heat treatment.⁶ This technique of rapidly cooling a red-hot piece of steel in water (called *quenching*) has been practiced since antiquity, as we see in Homer’s *Odyssey* (c. 800 BCE):

As when a smith, in forging axe or adze plunges, to temper it, the hissing blade into cold water, strengthening thus the steel, so hissed the eyeball of the Cyclops round that olive stake.⁷

Quenching was easy to do, but hard to control. Blacksmiths learned to recognize the colors of heated steel to determine the appropriate time to quench⁸. If the metal was too hot, or the change in temperature too fast, the object could crack.⁹ In medieval times the processes

learned over a lifetime of trial and error would have been closely guarded secrets. Even if it didn't crack, the process of rapid quenching would often cause a steel object to become brittle. Imagine a steel bar heated to the perfect temperature and thrust into water. The bar does not become one big orderly crystal of martensite, instead cooling will begin at many points on the surface of the bar. With crystal formation beginning at many points the growing crystals bump into other growing crystals, leaving a patchwork of disjointed edges. The interfaces between separate crystal structures will be weak spots which are easily broken, which imparts brittleness.

Preventing brittleness is why steel is “tempered” after quenching. In the tempering step the steel bar is reheated ... but not too much. If the bar is heated back to the formation of austenite (around 738°C) then the bar returns to its original form. This is called “normalizing”. Gentle heating (up to 600°C)¹⁰ allows the atoms at the crystal boundaries to move around into more stable positions, relaxing strain at the edges between neighboring crystals. Once cool, the bar becomes a more stable piece of interlocked martensite. Only in the 16th C do we begin to see records of both quenching and tempering being done in Europe. Prior to that, temper was what happened to steel when it was quenched¹¹ as in the quote above: “*plunges, to temper it*”

Giambattista della Porta (1589) provided the first European description of a tempering step (the author calls it a “return”) performed after quenching on a coat of chain mail:

Take soft Iron Armour ... and make a good Fire about it: then at the time fit ... quench the whole Harness, red hot, in the aforesaid water for so it becomes most hard ... But because it is most hard, lest the rings of a Coat of Male should be broken, and fly in pieces, there must be strength added to the hardness. Workmen call it a Return. ... {T}hen make red hot a plate of Iron. and lay part of the Coat of Male, or all of it upon the same ... cast it again into the water, and that hardness abated; and will it yield to the stroke more easily..¹²

One variation was the “partial” or “interrupted” quench, in which the hot steel was quickly immersed, and withdrawn before the piece had fully cooled. The heat retained in the

core of the object would radiate outward, and perform a bit of tempering on the martensite at the surface. This technique would be very difficult to control properly, particularly in a time without thermometers or timepieces, so consistent results were difficult to obtain. A more common method was to cool the hot steel slowly by quenching it in a dense liquid, such as oil. With a

Table 1 Relative hardness of metals	Hardness VPH units ¹³	
Pure Copper	50	14
Pure Iron	90	
Sterling Silver	100	15
Bronze	155 to 270	16
0.6% Carbon Steel, unhardened	260	17
" ,slack quench	400	
" ,water quench	800 or more	

slower rate of cooling the conversion to martensite was not as complete (some of the austenite would revert directly to ferrite), but the forming martensite crystals had some time to adjust their boundaries, similar to the tempering process, but all in one step

with the quench. This is called a “slack quench” and was documented in Roman times:

It is the custom to quench smaller iron forgings in oil, for fear that water might harden them and make them brittle. ¹⁸ (Pliny the Elder, c. 77 CE)

A German pamphlet published in 1532 (*Von Stahel und Eysen*, “On Steel and Iron”) gives these two-stage quenching recipes, featuring an initial slow step in oil, followed by a fast quench in water as the hot steel plunges further into the bath:

Take tallow, heat it and pour into a vessel that contains cold water. ... {G}ently thrust whatever you wish to harden through the tallow so that it is hardened first by the tallow and then water.

Take clarified honey, fresh urine from a he-goat, alum, borax, olive oil, salt; mix everything together and quench therein. ¹⁹

The quenching step was so critical yet poorly understood, that all manner of ingredients were tried in the search for that perfect quenching bath, e.g. blood, pigeon droppings, the urine of a small red haired boy, pomegranate, herbs, powdered horn, radish juice, morning dew, human excrement, earthworms, tadpoles, grubs and snails (“including their little spiral houses”).²⁰

The *Kunstabuch* and the Proper Use of Alchemy.

The Protestant Reformation had societal effects well beyond the method of worship and one's relationship to God. One of Martin Luther's reforms was to stress that each individual be able to read the Bible in his or her own language in order to interpret God's word for themselves, and to accomplish this everyone needed to be able to read. Thus in 16th C Germany we see a massive educational effort that did not discriminate between sex or social station. And to serve this growing literacy movement, the printing press came into its own. One item of great demand was the *Kunstabuch* (Art Book) that taught practical lessons in arts, crafts and household chores.

In 1535, publisher Christian Egenolff combined four *Kunstabuchen* into one volume called *Rechter Gebrauch d'Alchiemi* (*Proper Use of Alchemy*). To Egenolff, alchemy as practiced by mystics was “*smoke, ash, many words and infidelity*” and it was his intention to rectify the practice of alchemy by presenting its secrets “*for all skilled workmen*”. What followed was an early attempt to provide scientific information to the layman. Egenolff avoided the complex arcane terminology used by alchemists and instead broke everything down into simple German, even providing translations of alchemical symbols and terms.²¹ The first three parts of *Rechter Gebrauch* covered chemistry and techniques for goldsmiths, recipes for artists to make inks and colors, and instructions for use of chemicals in the dyeing and cleaning of clothes. The fourth part of *Rechter Gebrauch* was *Von Stahel und Eysen* (On Steel and Iron). This pamphlet was unique in its time for revealing the secrets of an art that must have in its own way seemed magical to the uninitiated. Some of the details might seem a bit far-fetched today (such as the use of urine, verbena juice and cockchafer grubs to quench steel) but as the rest of the pamphlet seems to come right from the blacksmith's workbench it may well be that these recipes are accurately reporting the state of the art as practiced in the 16th C..

From Roman times it was believed that the waters of certain rivers had superior quenching characteristics.²² It has been suggested²³ that attributing the quality of their steel to the local river may have been a shrewd way for smiths to disguise secret methods.

The Medieval European Definition of “Steel”

According to today’s iron and steel industry, the modern definition of steel is “iron that contains carbon in any amount up to about 1.7%”,²⁴ however this is not the definition being used in medieval sources or even the modern historical literature. Medieval merchants knew the different abundance and properties of iron and steel, and priced them accordingly. (Table 2) In medieval Europe, iron was metal that could not be hardened by heat treatment (known today as mild steel), while steel was metal that could be hardened.²⁵ This does not mean that steel *must* be hardened to gain that name, only that it *could be* hardened. This is an important point, the quench-hardening step comes after the steel is fashioned into an object, so international trade in raw steel and iron would have dealt with unhardened materials. Smiths and merchants needed to be able to recognize the different metals in their raw form. Given that steel was in high

Table 2 Price of iron and steel in medieval England ²⁶				
	Year			
	1300	1400	1500	1550
Iron	0.45 d	0.84 d	0.44 d	1.27 d
Steel	1.65 d	1.60 d	1.20 d	2.32 d
Average prices in pence (d) per pound				

demand but limited in quantity, metalworkers found other clever ways to make steel, or to make better use of what they had.

Case Hardening and Carburization

Imagine a bar of pure iron surrounded by carbon dust. As heat is applied, the iron atoms vibrate and the crystal lattice expands, allowing carbon atoms to diffuse into the lattice of iron atoms. The external surfaces of the iron bar are closest to the carbon, and so will absorb carbon first while the interior of the iron bar initially remains carbon-free. Time is required for the

carbon to diffuse from the outside to the inside of the iron bar. If allowed enough time, eventually the iron will absorb as much carbon as it can, and the resulting steel bar will be uniform throughout. If the heat source is removed before the process is complete, the carbon content will vary throughout the bar; highest at the surface, and lowest in the center. This process is called *case hardening* or *carburization* and was described by the Vedic physician Susruta c.700 BCE²⁷ for the hardening of surgical tools. Through Roman times this was accomplished by simply burying the iron object in hot coals²⁸, but the technique later evolved to encasing the object with carbon in a clay vessel.²⁹ After carburization, if the hot object is quenched, martensite will form at its surface. Theophilus (c. 1100) gives this advice for hardening the surface of a file:

*These are made from soft iron ... {C}ut with a hammer or a chisel or a small knife, smear them with old pig fat (a source of carbon) and wrap them around with leather strips cut from goat skin (more carbon) ... After this cover them individually with kneaded clay, leaving the tangs bare. When they are dried, put them into the fire, blow vigorously, and the goat skin will be burnt. Hastily extract them from the clay and quench them evenly in water.*³⁰

By controlling the time allowed for carbon to permeate the piece of iron, one can obtain a piece of metal that is both hard on the surface and flexible at its core. Depending on the heat of the forge, one must allow 6-10 hours to get 0.4% carbon to a depth of 0.05 inch, or over 24 hours to get 0.4% carbon to a depth of 0.125 inch.³¹

Medieval smiths had limited amounts of good steel to work with, so they would combine it with softer iron in the making of tools. For example, a strip of hardened steel would be forge-welded onto an iron body in order to give a tool or sword a hard edge. In the technique called “piling”, alternating strips of hard steel and softer iron would be forge-welded together to produce a tool or weapon that incorporated the hardness of expensive steel with cheaper soft

iron.³² A version of this technique has also been called “pattern-welding”³³. Pattern-welded blades are often marketed today as “Damascus steel”, and the curious reader may find numerous published references and websites where modern blade smiths claim to be reproducing authentic Damascus steel. This technique was used by Romans³⁴, ancient Celts, Vikings³⁵, and Merovingian Franks³⁶ to make swords, and in more recent times to make gun barrels.³⁷ While this method can produce an attractive damask pattern, and has the benefit of combining the flexibility of softer iron with the strength of harder steel, these are not true Damascus steel objects forged from a single cake of crucible steel (as will be described more fully below).

“Co-fusion” methods for making steel:

Pure iron melts at 1538 °C, but the presence of impurities will decrease its melting point. Iron with 0.5 % carbon melts at 1495 °C, and iron with 2 % carbon melts at 1154 °C. Once the iron crystal lattice melts, the liquid iron can rapidly absorb as much as 4.3% carbon, to become cast iron when it cools. Cast iron is hard and very brittle, and prior to the 14th C European smiths did not know how to turn cast iron into malleable steel. Thus the bloomery operator would avoid melting iron because cast iron was discarded as waste. The fact that the melting point decreases as the carbon content of steel increases illustrates one of the technical challenges to the bloomery operator. High carbon content is good, but high carbon content plus high temperature can spoil the batch. This also shows one of the advantages to the blast furnace and finery process that became common in the 14th C; just get everything hot enough so that it all melts. One doesn't have to finesse the line between steel and cast iron if one knows how to turn cast iron into a useable product.

While the medieval European smith avoided making cast iron, his Chinese counterparts made use of cast iron by combining it with soft iron to make steel. This approach to steel making has been called *co-fusion*.³⁸ There are records that this approach to making steel was

practiced in China as early as the 6th C³⁹, and there is one reference by al-Biruni suggesting that the method had migrated to medieval Islam by the year 1000⁴⁰ These sources show two ways in which co-fusion was practiced: 1) layering molten cast iron between bars of soft iron, and 2) spreading powdered cast iron between bars of soft iron before heating. In either process, the molten cast iron between two layers of soft iron will enable carbon to diffuse out of the cast iron and into the soft iron, making the cast iron softer and the soft iron harder. This approach does not appear in medieval Europe until Birignocio (1540, “*Pirotechnia*”) described the following process:

*Thus they keep it and turn it again and again so that all that solid iron may take into its pores those subtle substances that are found in the melted iron, by whose virtue the coarse substances that are in the bloom are consumed and expanded, and all of them become soft and pasty.*⁴¹

Trade Secrets and the 16th C Military Industrial Complex

Vannoccio Biringuccio (1480-1539) was a metalworker, and at times inspector and purchasing agent for the Florentine military.⁴² As such he would have been shown secret processes that would have been state of the art in his day. Such an official could also leak sensitive information to the competition, after all, he wrote a book on metallurgy from his experiences, and wrote “...my intention is only to tell you the method of making them, in order that what most masters hold as a very great secret may be manifest to you.”⁴³ It is quite possible that a government contractor might show him the factory, but not disclose the entire process. Modern practitioners have tried to duplicate the method as written down by Biringuccio but it doesn’t quite seem to work exactly as written.⁴⁴ Biringuccio’s accounts of metallurgy are remarkable for their time in being factual and evidence based, as opposed to the mysticism that pervaded alchemical treatises of the time. “*I have no knowledge other than that gained through my own eyes.*”⁴⁵ So while he may have faithfully recorded what he was told, it is possible that he wasn’t told everything.

The solid iron didn't melt because, as discussed above, low carbon iron would melt at a higher temperature than does high carbon cast iron. The solid iron bar absorbs carbon, and in time it becomes "*soft and pasty*" (i.e. with increasing carbon content it is approaching its melting point at the temperature of molten cast iron.)

Crucible Steel

The bloomery process produced iron and steel of varying carbon content, but mostly low carbon iron. Even bloomery steel is limited to at most 0.8% carbon, due to the low melting point of high carbon steels. Anything above 2% carbon is cast iron, hard, brittle and unworkable. Steel of 1% to 2% carbon would be very hard with some brittleness but still workable, however this range was mostly out of reach for early smiths. The limiting factor of the bloomery was the presence of an excess of carbon; if high carbon iron was allowed to melt it would rapidly absorb more carbon and become cast iron. The idea behind crucible steel is that soft iron is sealed in a container with a limited amount of carbon, then heated to melting. If an excess of carbon was present, this would produce cast iron. But if, for example, only 1% (by weight) of carbon were added to the crucible, then the molten iron could only absorb at most 1% carbon.⁴⁶

Another method to achieve the same end would be to mix pieces of soft iron and cast iron in a closed crucible.⁴⁷ If equal quantities of the two are combined and melted, then the resulting ingot will have carbon content half-way between the two. With either of these methods one could achieve a carbon content of 1% to 2%. Having the steel melt in the crucible provided another significant benefit. Bloomery iron always⁴⁸ contained bits of non-metallic rock left over from the smelting process (slag). Slag inclusions in iron artifacts would contribute to brittleness and breakage. In a crucible, molten steel will separate from molten slag (the slag floats on top), producing a clean homogenous metal. So crucible steel benefits by being both cleaner and higher carbon than the average bloomery product.

al-Kindi on iron and steel

Ya'qub ibn Ishaq al-Kindi (c. 800-870) was known in Europe as “The Philosopher of the Arabs”, quite an honor when one considers the other great minds who contributed to Islam’s Golden Age. One of the first scholars to lead Baghdad’s House of Wisdom (combination library, research institute and scriptorium), he made significant contributions to philosophy, theology, optics, geometry, astronomy, and medicine and wrote on a host of other topics, including the cause of thunder, lightning, snow and rain; pigeon breeding, bees, and the making of swords.⁴⁹ In two works produced during the reign of caliph Mu’tasim (c.840) we see a very detailed account of iron and steel metallurgy in the 9th C Islamic world.⁵⁰

Know that iron ... is divided into two primary categories: mined and unmined. The mined is itself divided into two categories: hard iron, which is male, hard, and able to be quenched during its forging; and soft iron which is female, soft, and cannot be quenched.

This designation of male and female iron was used in Islamic literature for centuries afterward. “Mined” iron is the metal as it comes from the bloomery, containing pieces of low carbon content, and some higher. We now identify female iron as having less than 0.4%, and male iron as having greater than 0.4% carbon. Steel is only produced as a secondary process, and so is “unmined”:

...unmined iron, it is steel. It is manufactured from mined iron by adding to it during the melting something which refines it and makes its softness strength so that it becomes firm and pliable.²³

What al-Kindi identifies as “steel” is what we call “crucible steel”. The “something” that is added to make mined iron strong is carbon.

The crucible steel process is currently believed to have originated in India, and may date from as early as 300 BCE⁵¹. Historical sources tell us that there were many types of crucible steel available. It is generally agreed that much of this crucible steel came from India in medieval times, although there is evidence that it was also produced in Central Asia⁵², Moorish Spain⁵³ and Iran (however the Iranian steel was deemed to be of poor quality and we are told that Indian steel was more desirable.)⁵⁴ The medieval Arabic word for steel referred only to crucible steel, and simple high carbon (male) iron from the bloomery was considered inferior:

*Swords may be forged from the male type, but they are dry swords that break quickly when they encounter adversity ... {S}o almost no one would forge from them except one ignorant or in need in a place where there is only male iron.*⁵⁵ (Al-Kindi, c. 860, “On Swords and Their Kinds”)

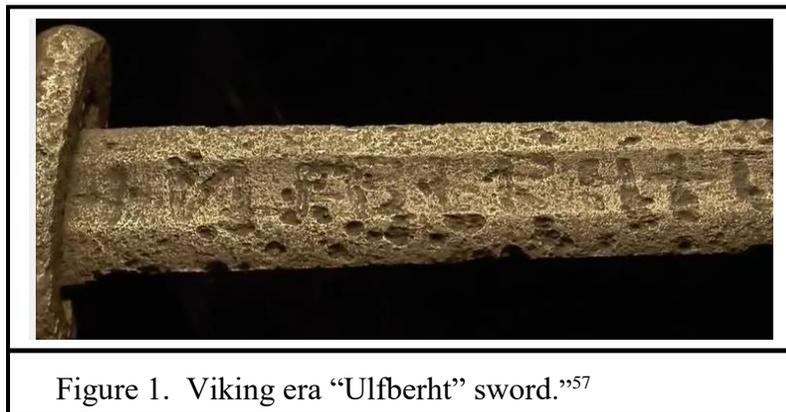


Figure 1. Viking era “Ulfberht” sword.”⁵⁷

Certain Viking swords have been found in Scandinavia that contain better quality steel than was commonly available elsewhere in the west⁵⁶. These swords (or the steel from

which they were made) were most likely crucible steel made in the East and shipped to Scandinavia. The technology for making crucible steel, however, didn’t catch on in the West until the 18th C.⁵⁸

Indian crucible steel is known today as “Damascus steel” or “Wootz.”⁵⁹, and is best known by the attractive wavy pattern it often shows. Islamic authors referred to the patterns as “water”, only found on a high quality Indian steel blade:

It has a water whose wavy streaks are glistening. It is like a pond over whose surface the wind is gliding. ⁶⁰ (Aws bin-Hadjar, c. 540.)

In the perfect weapon, the extreme of sharpness lay hid, like poison in the fangs of a serpent; and the water of the blade looked like ants creeping on the surface of a diamond.

⁶¹ (Hasan Nazaimi, c. 1200, “*The Crown of Exploits*”)

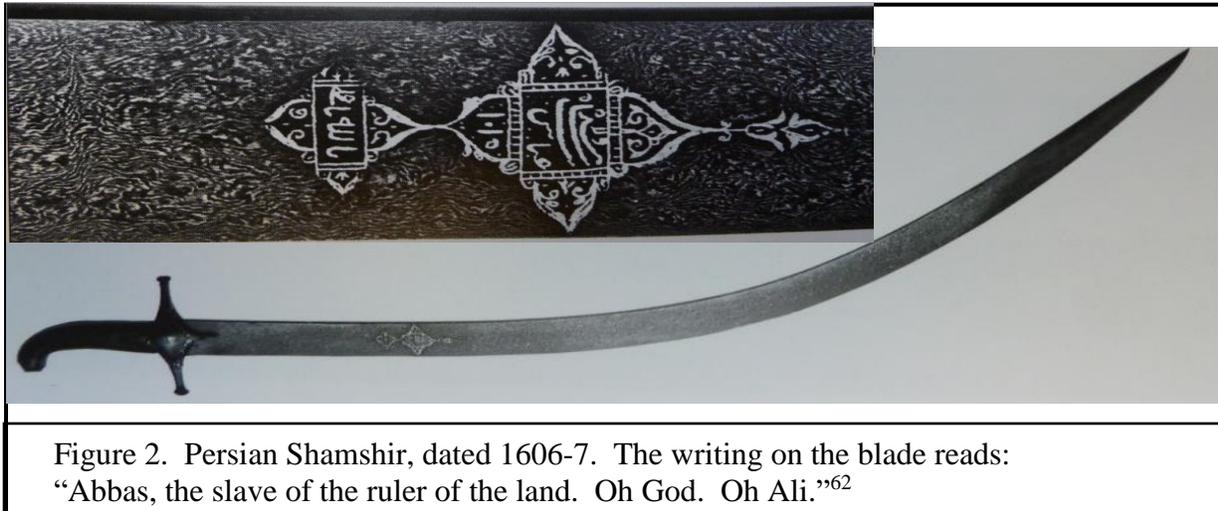


Figure 2. Persian Shamshir, dated 1606-7. The writing on the blade reads: “Abbas, the slave of the ruler of the land. Oh God. Oh Ali.”⁶²

Being an ultrahigh (1 to 2%) carbon crucible steel, Wootz/Damascus steel was very hard and able to hold a very sharp edge. This is documented in the quotes above, as well as by other contemporary Islamic authors and later western observers who praised its hardness and the sharpness of its blades, but who also recorded that Indian steel had a reputation for brittleness, also to be expected for ultrahigh carbon steel.

*Their swords are made crooked like a falchion, very sharp but for want of skill in those that temper them, will break rather than bend; and therefore we often sell our sword blades at high prices that will bow and become straight again.*⁶³ (Edward Terry, 1616)

Crucible steel was the highest quality steel available in the Middle Ages, and rightfully demanded a premium price. Although weapons get much of the attention, it is known that crucible steel was used in other applications as well, including wire for musical instruments⁶⁴, files, scissors⁶⁵, mirrors⁶⁶ and farm implements⁶⁷. Indian steel was certainly an important commodity in medieval times. However modern archeology is discovering evidence that medieval production and use of crucible steel was much greater than had previously been thought, and was not limited to Indian “Damascus” steel.

International trade in precious metals

India has been known as a major exporter of iron and steel since antiquity.

2nd C: Import fees from the reign of Marcus Aurelius show large amounts of *ferrum indicum* being imported by Rome⁶⁸. It is not known how much of this was soft iron, and how much was crucible steel, but the 2nd C alchemist Zosimos of Alexandria described the process of making crucible steel, and said that it had been invented in India.⁶⁹

6th. C The Byzantine Empire recorded Indian steel among its imports in 565 CE.⁷⁰

9th. C: Al-Kindi (ca. 840) documented that crucible steel in the Arabic world came from India (*al-Hind*, the land of the Hindus).⁷¹

10th. C: Li Shizhen, (Chinese physician and philosopher) wrote: “*Bin iron, which is produced by the Western Barbarians, is especially fine. It is so hard and sharp that it can cut gold and jade.*”⁷² “Bin” (also “Bin-tie”) was the Chinese word for crucible steel.

10th. C: There are references to “Indian steel” armor being used in Moorish Spain in 985 CE. By the early 13th C crucible steel was being manufactured in Seville by Islamic smiths, but after the city was retaken by Christians in 1248 the production of crucible steel ceased.⁷³ Christian Europe showed little interest in the technology for hundreds of years.

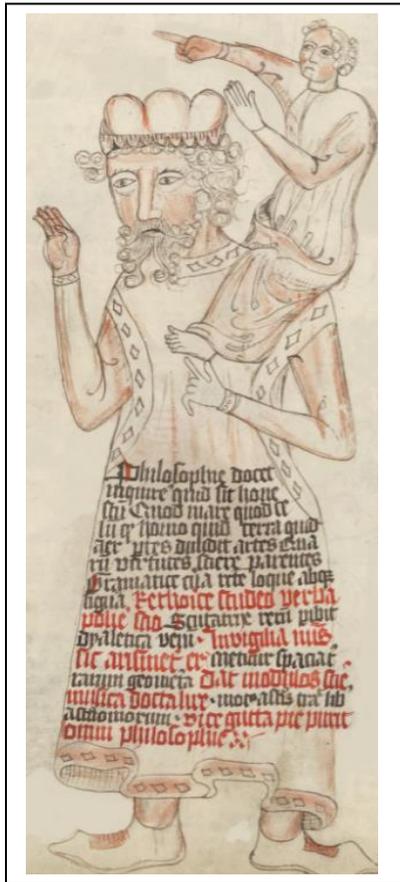
11th to 13th C: In a fascinating collection of business letters dated from 1080 to 1240, we learn that merchants supplying Indian iron and steel to the rest of the world identified five different products: “refurbished” (scrap iron), “regular iron” (wrought iron), “eggs” (crucible steel ingots), “shiny” (polished crucible steel, used for mirrors and jewelry) and “smooth” (crucible steel beaten into bars).⁷⁴

19th C: Egerton (1896) states that since the 15th C, the best Damascus steel swords were made in Persia, using steel imported from India.⁷⁵

Conclusion

The history of technology is the history of human civilization, from the use of sharpened sticks through the development of space age materials to take us farther and faster. The sophistication of steelmaking technology used in the Middle Ages is a testament to the creative ingenuity of our forbearers, particularly in light of the fact that they did not understand the molecular processes involved as we do today. It would indeed be a mistake to claim that modern man is in any way more clever or more intelligent than medieval craftsmen and scientists, or the philosophers of antiquity who preceded them. Communication and the written word allow us to share information across the millennia, so that our rapid technical advances today are firmly grounded in the work of those early pioneers. Sir Isaac Newton (1675) wrote:

*“if I have seen further, it is by standing on ye shoulders of giants.”*⁷⁶



Interestingly, even this quote has roots in an earlier age. The philosopher Bernard of Chartres (c. 1124) wrote over 500 years earlier:

*We are like dwarves perched on the shoulders of giants, and thus we are able to see more and farther than the latter. And this is not at all because of the acuteness of our sight or the stature of our body, but because we are carried aloft and elevated by the magnitude of the giants.*⁷⁷

Figure 3: *Encyclopedic manuscript containing allegorical and medical drawings, Germany, ca. 1410.*⁷⁸

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Blast Furnace

A furnace used to extract iron from its ore, not common in Europe until the 14th C. Iron ore mixed with charcoal is continuously fed into the top of the furnace. Iron oxides in the ore react with carbon to form free metallic iron and carbon dioxide, and the molten iron (and molten slag) flow downward to collect at the bottom of the furnace. Molten slag, floating on top of the iron, is tapped off, then the molten iron is drained. With raw material fed in from the top and the end product drained from the bottom, the blast furnace could be operated continuously, providing much greater efficiency and quantities than were possible with the *bloomery*. The cooled product of the blast furnace, called *cast iron*, was reheated in a secondary process called the *finery* to produce workable iron.

Bloom, Bloomery

The *bloomery* is an ancient type of furnace used to extract iron from its ore. Charcoal and crushed iron ore would be mixed and heated. Iron oxides in the ore react with carbon to form free metallic iron and carbon dioxide. The temperature of the furnace is maintained below the melting point of iron, which is semi-solid and coalesces into a loose spongy mass called a *bloom*. The *bloomery* was largely replaced in 14th C Europe by the *blast furnace*.

Brittleness

The tendency of an object to shatter when force is applied. Iron is made brittle by an inconsistent internal crystalline structure. Increasing carbon concentration in steel makes it harder, but more brittle. Brittleness can also occur if hot iron is cooled very quickly (*quenching*), where the crystals are locked in an irregular pattern and may fracture along the interfaces of the mismatched crystal lattices. Also, iron containing impurities from the original ore will tend to be brittle. The most resilient iron is that which has a consistent internal crystalline structure.

Cast Iron

A name for the product of molten iron produced in a bloomery or blast furnace, containing carbon above 2 percent. Cast iron is very hard and brittle, and could not be worked by medieval smiths until around the 14th C, with the discovery of the *finery* process. Prior to that, smiths would avoid producing cast iron, and when they did it was considered a waste product.

Crucible Steel

Soft iron is sealed in a container with a limited amount of carbon, then heated to its melting point. In this way the carbon content can be controlled to produce steel in the range of 1 to 2 percent carbon.

Finery

In a *finery*, cast iron produced by the *blast furnace* was reheated in an open hearth, exposed to the air. Excess carbon in the cast iron combined with oxygen in the air and escaped as gas. In this way, hard unworkable cast iron could be made malleable by decreasing its carbon content.

Forge-welding

Combining two pieces of metal by heating both and hammering to fuse the pieces together.

Hardened Steel**Quench Hardening**

A process of hardening steel objects by heating, followed by cooling to increase the hardness substantially. *Slack Quenching* used dense liquids (often oil) that allowed slow cooling, and better control of the process. *Full Quenching* was done by taking the glowing item out of the forge and immersing immediately in water for very rapid cooling. The process results in the formation of *martensite*, which greatly increases hardness of steel. To avoid brittleness the object would be *tempered*.

Case Hardening (aka Carburization)

A process by which low carbon steel has been further processed to increase the carbon content (and *hardness*) at the surface of the object. This is achieved by embedding the object in powdered charcoal, then heating below the melting point of iron. The iron object absorbs additional carbon on its surface, producing a very thin layer of increased carbon content. When the hot object is cooled rapidly (*quenched*) the iron crystal lattice freezes into a particularly favorable configuration known as *martensite*, which confers exceptional hardness.

Hardness

The ability of a metal to absorb force without deforming. Higher carbon content in iron confers increased hardness, and converting high carbon iron to *martensite* increases its hardness even further. The typical test for hardness (the Vickers Pyramid Hardness test: VPH) is to measure the indentation made by a weighted object dropped from a standard height. This property dictates the ability of a weapon (or tool) to take an edge, or a piece of armor to take blows without bending.

Iron

The most common metallic element in the earth's crust. *Iron* can refer to the pure metal, but is also commonly used as a general term for any ferrous metal. *Cast iron* specifically refers to iron which has melted in the presence of excess carbon during its manufacture. *Bloomery iron*, the product of the medieval *bloomery*, was not molten in its manufacture.

Medieval European definition: Product of the *bloomery* that cannot be hardened by *quenching*

Medieval Islamic definition: Any product of the *bloomery*.

Martensite

A particular crystalline structure of steel that is much harder than untreated steel. Martensite is created by heating untreated steel, then *quenching* in oil or water.

Slag

Impurities in the process of iron processing. Non-ferrous rock (mostly silica) is an impurity to be removed in the smelting process. The term is also used to refer to residual non-ferrous impurities in a finished iron object.

Steel

Modern definition: Iron that contains carbon in any amount up to about 1.7 percent.

Medieval European definition: Product of the *bloomery* that can be hardened by *quenching*

Medieval Islamic definition: What we call today *crucible steel*

Cover Page:

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