Technology and Armor in the Middle Ages

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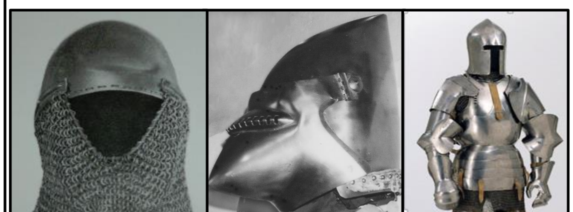
I: Introduction

From the Roman era[1] through most of the 13th century, European armor is typified[i] by multiple iron[2] plates joined to make a pieced article, such as the spangenhelm and great helm (Fig. 1), with body armor consisting of chainmail and (after 1250) small plates attached to a garment (i.e. coat of plates). In the

Figure 1: Examples of pieced armor [ii]

Spangenhelm[3] 7th C. | Great Helm[4] Mid 13th C. | Kettlehat[5] Late 13th C.

Figure 2: Examples of shaped armor



Cervelliere[6] 1340 | Bascinet[7] 1385 | Full Plate[8] Armor 1440-5

14th C. we begin to see more items shaped from larger single plates, such as the cervelliere and bascinet (Fig. 2).[iii] Body armor added more armor to arms and legs, and breast plates formed of fewer and larger plates, and eventually became full shaped plate armor in the mid 15th C.[9] The question to be examined is:

> **What changes enabled European armor to evolve from pieced construction (ca 12th C. AD) to large shaped items in the 14th to 15th centuries?**

European armor in the Middle Ages was typically made of *steel*[iv], defined as iron that contains carbon in any amount up to about 1.7 percent. Iron purified and worked in a charcoal-fueled fire is bound to have some carbon content however small, therefore in a medieval context the terms iron and steel will be used interchangeably.[10] Sections II and III will establish a basis to understand the technologies and limitations of iron working in medieval times, including the bloomery furnace that was used for production of raw iron from the early Iron Age through the Middle Ages.

Bloomery iron through the mid 13th C. was a heterogeneous material, with varying carbon content,

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[i] There are early examples of shaped one-piece iron armor, most notably the 10th C. conical helmet of St. Wenceslas in Prague. While the Duke of Bohemia may have had access to the best that period technology could provide, the iron helmet pieced from two, four or more plates was far more common. A photo may be viewed at: Berend, N.: http://christianization.hist.cam.ac.uk/images/html/prague-helmet-image.html

[ii] Please refer to Appendix A for more information on the illustrations in Figures.

[iii] The following discussion will use the words <u>pieced</u> and <u>shaped</u> to indicate the two styles of armor construction.

[iv] Please see the glossary, Appendix B.

hardness, and impurities within the product of a single production run. Impurities (slag) made the metal brittle, certainly an undesirable feature for armor worn in battle. Bloomeries were also limited in the quantity of metal produced. With natural air circulation, or even hand-pumped bellows, the output was typically less than 10 kg. With a limited supply of relatively poor quality material, the most common form of helmet through the early 1300s was pieced.[11]

Knowing these limitations it is natural for one to jump forward to the iconic 15th C. suits of polished plate armor that we see in museums, many of which are identified as *hardened steel*.[v] Surely this is the answer - that some great improvement in the working of steel led to the ability to shape these works of art. Surprisingly, this is not the answer. It is certain that techniques for hardening steel were known and did create metal with superior toughness, but the process of hardening steel occurs after the finished piece is shaped. The earliest known piece of fully hardened steel armor is a bascinet dated to 1330/40[12], yet one-piece helmets of unhardened steel are common from the same time period and later. Williams (2003)[13] lists 19 items of 14th C. German armor identified as “Bascinets and other one-piece items,” of which only one is hardened. The rest were produced from bloomery-quality steel, not substantially different from the steel seen in earlier armor. Even into the 15th C. unhardened armor was the norm, with the more costly hardened pieces going to those who could pay for the additional processing. It is interesting to note that after 1510, even the high end Italian armor suits were made of unhardened steel, as the aristocratic elite chose decoration over toughness.[14]

The pivotal invention that enabled production of larger steel plates, and subsequently pieces of shaped armor, was the water-powered ironworks that used a hydraulic *cam* to drive hammers and bellows. The cam, which converts the rotary power of the water wheel into intermittent or reciprocal power for hammers and bellows, was likely known to the ancient Romans, but it was not utilized in post-Roman Europe until the 13th C.[15] Water-powered trip hammers increased production rates and the consistency of worked metal, while the increased and more consistent airflow provided by water-powered bellows provided larger quantities of iron. By the end of the 13th C., the technology was spreading across Europe.

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[v]For more detail on the process for hardening steel, please refer to Dupras (2012) and Price (2000).

As the water-powered bellows became more widespread, armorers had access to larger plates of metal, and could begin producing shaped helms and body armor defenses for arms and legs.

One final advancement that propelled the medieval iron industry into even greater production was the discovery that the cooled product of molten iron could be reheated and made workable, which is referred to as *(re)fining*, and done in a *finery*. Earlier bloomery operators would avoid melting iron because the resulting metal (pig iron or cast iron) was hard and brittle so as to be useless for most applications. The finery process, however, removed excess carbon from the cast iron, to regenerate steel of lower carbon content that was pliable and useful[16]. With this knowledge, bloomery furnaces could be enlarged into blast furnaces that were much more efficient and with continuous operation produced molten iron in large quantities (measured in tons rather than kilograms), and the product reheated in the finery to produce malleable steel. Discovery of the finery process has been described as "… one of those subtle economic currents destined to have the widest bearing upon civilization."[17]

II: The basics: the chemistry of iron and steel, sources of iron ore, and source of carbon

A chemistry primer: Separation of iron from its ore is achieved by heating the ore in the presence of carbon. This was known since ancient times. The carbon in the smelting process performs three functions. First carbon, in the form of charcoal, was the fuel used to heat the iron ore. Second, iron oxides in the ore were reduced to pure metallic iron and the carbon oxidized, escaping as a gas:

$$FeO_x + C \rightarrow_{\text{heat, oxygen}} \rightarrow Fe + CO_x$$ [vi]

This allowed the iron to be separated from the non-ferrous rock, and to be collected as a lump of metal. The third function of carbon in the smelting operation comes from the fact that at elevated temperatures, carbon is absorbed into the crystal matrix of the metallic iron. The alloy of iron and (up to 1.7%) carbon is called *steel* (Appendix B). As carbon content increases, steel becomes both harder and more brittle. Analysis of medieval armor shows that the period armorer typically worked with steel of 0.02% to 0.8% carbon.[18] If the iron ore and carbon are heated to above the melting point of iron, the molten iron will

[vi] My apologies to any chemists who may be reading. The reactions taking place are much more complex, but let this simple explanation suffice. The purist may be satisfied by reading: Thiele, À. (2010).

rapidly absorb 2% to 4.3% carbon by weight.[19] Once cooled, the resulting metal (variously referred to as *pig iron* or *cast iron*) is both extremely hard and very brittle, making it very difficult to work and of little use to the period armorer. The 12th century blacksmith generally avoided heating iron ore to melting. In fact, the solidified cast iron was considered a waste product and discarded (referred to as *furnace rubbish* by archeologists[20]). Rubbish from archeological digs can be analyzed to gauge the efficiency of the smelting process being used at different locations.[21]

Source of iron ore: Pre-industrial smiths used two major sources of iron ore. In acidic ground water with high concentrations of dissolved iron, microorganisms filter iron out of the water and secrete it in the form of nodules of iron hydroxide (goethite), known as *bog iron*.[22] From the Iron Age through the 18th century, bog iron was an important source of iron ore all across Europe and in the American colonies. One disadvantage was that bog iron tends to be rich in phosphorus, which will increase the hardness of iron, but in high concentrations can make the resulting metal brittle.[23] Bog iron was easily obtained from shallow pits, and will actually regenerate over time.[24] In the 16th C., Biringuccio[25] tells of a "marvelous thing" about the iron ore found on the island of Elba: "…it is the opinion of many that within a certain time the ore is regenerated anew in that soil which has already been mined. If, indeed, this were true, it would be a great thing and would demonstrate a great provision of Nature or a great power of the heavens."

There are also references to the medieval mining of rock ore which is usually an iron carbonate such as siderite.[26] Deep mining was limited during medieval times as there was no efficient way to drain water from deep mine shafts.[27] Fortuitously, iron ore deposits are often found on hilltops and ridges[28], so deposits could yield ore for a long time before deep mining was required. Rock ore had the disadvantage of being accompanied by a large amount of other rock material, predominantly silica, which is an impurity that must be removed from smelted iron (see below).

Whichever source was used, the ore would then be roasted (to convert iron hydroxides and carbonates to a common starting material: iron oxide), then crushed[29] which through most of the medieval period would have been done manually.

Source of carbon: Charcoal was the fuel of choice for iron smelting since ancient times. Charcoal provides a relatively clean fire of constant temperature (as compared to raw wood), and can easily achieve the temperatures necessary to extract iron.[30] The charcoal fuel also provides the carbon for converting iron ore to metallic iron and/or steel. Charcoal production was a major industry in the medieval world, as shown by the rents, licenses and fines recorded by various Forest Courts.[31]

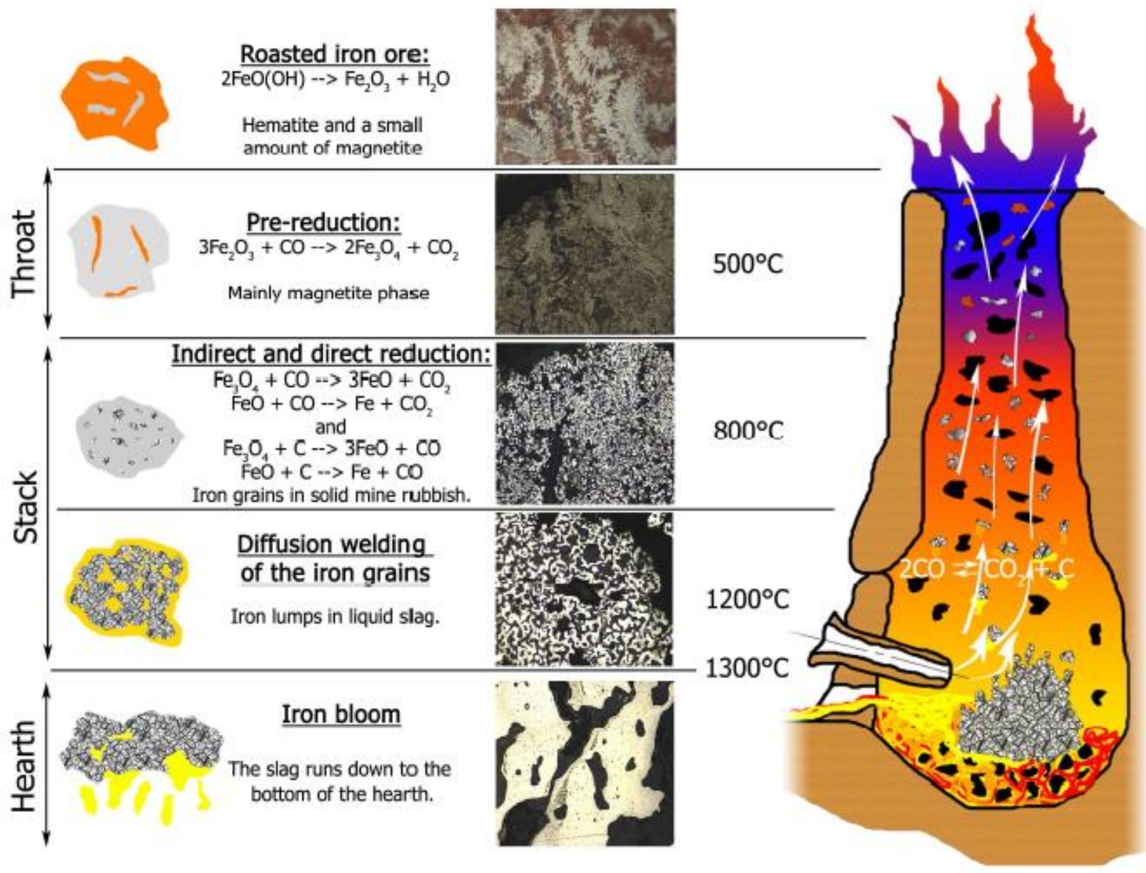
III: Smelting and forging wrought iron in the 12th and early 13th centuries

Smelting in the Medieval Bloomery: Charcoal and crushed iron ore were mixed (the charge) and burned in a bottle-shaped hearth, which drew in air from the bottom to provide oxygen directly into the charge (Fig. 3). Originally the hearth relied on natural air circulation but later used hand-operated bellows to force air into the bottom of the charge.[32] The basic approach was little changed from ancient times through the 14th century. At temperatures above 800^{o}C the iron oxides react with carbon to form free metallic iron and carbon dioxide (which escapes as a gas). 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*. This type of iron smelter is called a *bloomery*. The efficiency of separating iron from its ore is dependent upon many factors (ratio of ore to charcoal, air flow, time, temperature, and furnace dimensions), all of which needed to be understood and managed by the bloomery operator.[33]

The hot iron bloom also absorbs carbon (varying from 0.03% to 2%[34]) and becomes steel. Raising the temperature to the melting point of iron (1300 to 1500 ^{o}C depending on the carbon content) would produce waste, so these higher temperatures were avoided. At bloomery temperatures, much of the non-ferrous impurity (mainly silica from the native rock) would melt and coalesce as slag. After sufficient time had passed the bloom was removed and allowed to air cool. The resulting porous lump of metal contained a range of carbon content and crystallized solid slag (Fig. 4). Separation of bloom and slag, (as described below) was necessary for a quality product.

The bloomery is very inefficient in use of manpower and materials. First, it is a batch process, because when the bloom is removed to cool, the fire is extinguished and a new charge must be prepared

Figure 3: The metallurgy of the bloomery.[35]



before the process can be repeated. This cycle may take about 12 to 24 hours per run[36]. Second, when natural draft or even a manual bellows provided oxygen to the charge, a single bloomery run would provide a very poor yield from the original raw material due to the insufficient supply of oxygen.[37] (Table 1, p. 8) Third, obtaining a larger bloom is not simply a matter of building a bigger hearth. By the nature of the process, the bigger the hearth the more fuel one adds to the fire and the less heat is lost by outward radiation, resulting in a hotter fire. A hotter fire means the potential of melting the iron and producing waste.[38] Thus bloomery furnaces were by necessity limited in size simply to control heating of the charge.

Forging: The iron bloom would be reheated and hammer-forged to (1) consolidate the porous metal, (2) equilibrate the iron quality throughout the piece, and (3) drive out inclusions of slag. Slag within a steel plate disrupts the iron crystalline structure and causes points of brittleness, and so needs to

Figure 4. Iron Blooms excavated in Scandinavia[vii]

1kg bloom that has not been forged[39]

1kg bloom that has been slightly forged. White inner layer is iron & slag, dark outer layer is slag.[40]

be driven out. Modern micrographic analysis of period artifacts shows that slag was always still present to some degree in bloomery iron.[41] The hand forging process was very labor intensive and inefficient, requiring as much as 17 hours to produce 1 kg of consolidated iron.[42] The finished metal routinely contained enough slag to cause weak points. The slag content was a significant factor in limiting the size of any single piece of metal, as larger pieces would be more likely to shatter when stressed.[43]

Efficiency of wrought iron production: The output of the bloomery/forging process is referred to as *wrought iron*. A single bloom would be worked (wrought) into an iron bar which would then be shaped to fashion an object. In order to make larger plates, multiple bars (from multiple blooms) needed to be forge-welded together. This extra working of the iron, however, comes at a price. In the extreme heat of the bloomery furnace, iron oxides give up their oxygen to elemental carbon, which itself is oxidized leaving behind elemental iron. But in the forge the elemental iron is no longer protected by elemental carbon, so the heat will cause the iron to oxidize. Oxidized iron comes off in flakes (scale)[44] which at best drop off in the forge, or at worst are incorporated into the iron as additional slag. Losses due to oxidation in the forge can amount to 1/2 to 3/4 of the mass of iron during processing of the bloom into a finished item[45] (Table 1, p. 8), making it economically unfeasible to create larger plates this way. Analysis of period armor does not reveal weld lines where separate plates have been forge-welded together, so there is no evidence that this was practiced.[46] In addition, repeated heating of the metal causes loss of carbon as it is oxidized and released as carbon dioxide gas.[47] Repeated working of the iron is undesirable as it causes both loss of material, and a reduction in the hardness of the steel.

Blooms from archeological sites dating from the 8th to mid 14th century range from 0.1 to 12 kg,

vii Please refer to Appendix A for more information on the illustrations in Figures.

but average less than 10 kg.[48] Modern experimentation with a medieval-style bloomery produced blooms of 3.8 to 6.5 kg.[49] Size of the bloom would be determined by the size of the furnace (which was limited as we have seen earlier), by the iron content of the ore, and by the efficiency of extracting iron from the ore (Table 1).

Table 1 Efficiency of the various processes involved in iron production[50]

Process	Yield (%)
Extraction of bloom from ore (assuming high grade ore)	20%
Forging to consolidate bloom	50%[viii]
Forging to shape the bar	64%
Forge artifact	90%
Overall yield from raw ore: 0.2*0.5*0.64*0.9 =	6.4%
Overall yield of iron artifacts from one bloom 0.5*0.64*0.9 =	32%

Williams (2003) and Sim (2012)[51] cite other sources that estimate only 25% yield of finished product from an average bloom, based on experimental production of bloomery iron. For the sake of discussion, we will assume an average yield of 28%; that is a 10 kg bloom could produce a 2.8kg piece of armor. A one-piece helmet weighs 1.3 to 1.8 kg, and a breastplate from 2.6 to 4.5 kg.[52] Thus, blooms of 4.6 to 6.4 kg would be needed to create a one-piece helmet, or 9.3 to 16 kg for a one-piece breastplate. So a one-piece helmet might have been within the technological capabilities of the medieval smith if he had a superior smelter that could produce large blooms of good quality.

But even this is an optimistic estimate. The bloom recovered from the smelting process was a very heterogeneous mass, with carbon content (i.e. hardness) varying throughout, and large amounts of slag.[53] The smith could even out the quality by working the piece of metal (and accepting the losses), but slag inclusions were always present in the final product with resulting brittleness.[54] Thus with less than top quality raw material, the armorer would not attempt to stretch a single plate too far, lest it shatter in his hands, or worse yet, in battle. So while a one-piece helmet may have been within their technological capabilities, it is likely that the finished product would not have been able to withstand the punishment of combat unless it was made by the best smith from the largest, best quality bloom available.[55]

[viii] Different authors estimate 40 to 70% efficiency at this stage. 50% used as an average.

IV: Armor in the 13th and 14th Centuries

From the middle of the 13th century one sees increasing use of metal plates as armor in addition to chainmail. This included the coat of plates, followed by shaped pieces covering knees, shins, and later arms, worn over chainmail.[56] By 1330 it is rare to see period depictions of knights wearing only chainmail[57], and in the 1340 Milanese price decree, pieces of plate armor replace chainmail as the top selling items.[58] The first existing one-piece breast plate has been dated at 1390 to 1400 (Fig 5)[59].

Figure 5: Early Plate Armor[ix]

Coat of Plates[60] 1250 | Schynbald & Cervelliere[61] 1315-1325 | Poleyns & Couters[62] 1300-1325 | One-piece Breast Plate[63] 1390-1400

From around 1220 and into the 14th C. the cervelliere (Fig. 2. p. 1) became increasingly common.[64] This was a steel skull cap weighing about 1.4 kg, formed from a single piece of metal. It was worn by knights under the (riveted) Great Helm, and also increasingly was made available for common footsoldiers.[65] Late 13th C. records from Florence show large numbers being ordered and produced. In 1297 one armorer in Cascia pledged to produce 500 skullcaps at a rate of 7.3 per day.[66] In the early 1300s, the cervelliere evolved into the bascinet (Fig. 2, p. 1), now providing coverage to the sides and back of the neck. In 1313 there are records of 1200 bascinets being produced in Cascia.[67] Thus we return to the original question:

What changes enabled European armor to evolve from pieced construction (ca 12th C. AD) to shaped items in the 14th to 15th centuries?

V. Technological advances in the 13th and 14th Centuries

The answer to our question may be found in advances in industrial technology that began in the 13th century and together revolutionized the medieval steel industry. The most important of these

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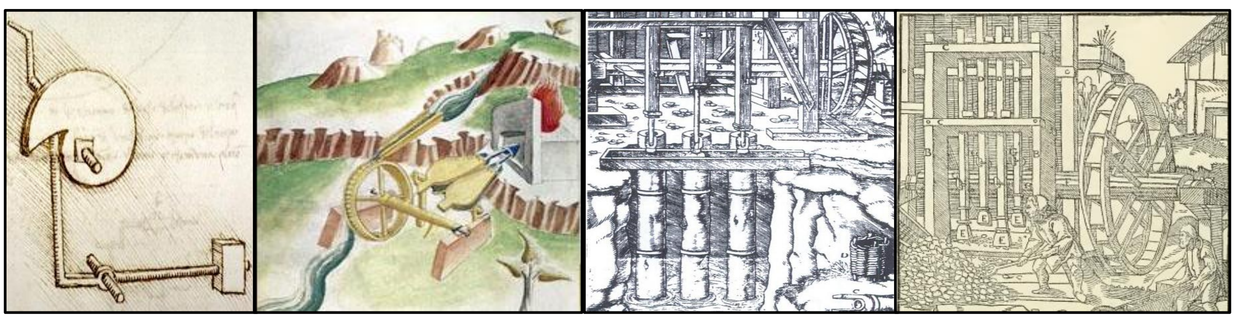
[ix] Please refer to Appendix A for more information on the illustrations in Figures.

innovations used water-powered machinery.[68] Water mills had been used to grind grain since ancient times and were commonplace in the medieval European landscape. Grain mills drive a simple wheel that steadily turns as long as power is applied. The critical invention that enabled water power to be used to drive discontinuous or reciprocating motion is the *cam*, which delivers power to lift and drop a hammer or to pump bellows. This invention enabled a number of separate innovations that affected the iron industry, the most important of which are (in chronological order) the trip hammer, the water-powered bellows and the blast furnace/finery process.

The trip hammer: A water wheel is connected to a huge hammer by way of a cam shaft (Fig. 6, p. 11). The turning wheel will lift the hammer, then drop it as the cam trips and the stored kinetic energy is released. Hydraulic hammers powered in this way are referred to as *trip hammers*.[69] Evidence exists that hydraulic hammers were used to forge iron by 1st century Romans[70] so this technology may have been lost as the Roman Empire receded. The earliest confirmed examples of hydraulic-powered hammers in medieval Europe are dated at 1200 (Kirkstall & Bordesley, England), 1202 (Evereux, France) and 1224 (Toaker, Sweden).[71] Hydraulic hammers were used to forge iron blooms into wrought iron, allowing the smith to work larger blooms when they became available. Trip hammers were also used to shape final pieces more quickly and efficiently than was possible when done by hand. Less time at the forge means less overall loss of metal to re-oxidation, and less slag introduced from scale. The smiths of Cascia who produced 7.3 cervellieres per day in 1297 used hydraulic trip hammers to achieve this feat.[72] By the beginning of the 14th C., hydraulic hammer mills had spread throughout central and eastern Europe.[73]

The water-powered bellows: An even more significant innovation was the water-powered bellows, also using the cam to drive the alternating motion to draw and pump air. As mentioned earlier, the bloomery furnace with hand powered bellows produced a yield of 20% extraction of metallic iron from the ore. This is largely due to the weak pulsating air stream and inefficient delivery of oxygen to the charge.[74] The earliest evidence of a furnace with hydraulic powered bellows appears at Trent, Italy, dated to around 1214,[75] however they did not become common until after 1300. This innovation blasts oxygen into the charge, making the reduction of iron oxide to metallic iron much more efficient.[76] Often two bellows were arranged to alternately pump and draw, such that one or the other was always pumping air into the charge, maintaining a continuous blast of oxygen (Fig. 6, below). The adaptation of water power to drive bellows, with no significant change to the bloomery itself, would have increased output from the bloomery furnace, enabling larger blooms of good quality. From the middle of the 14th C. we begin to see a rapid increase in the size of blooms, from 20kg to over 100 kg.[77] However, the bloomery operator needed to be careful that increased temperatures, brought about by increased airflow, did not melt the iron and generate waste. More importantly, the invention of the powered bellows is an essential precursor to the development of the blast furnace/finery process, to be described below. By the end of the 14th century water-powered ironworks were common across Europe and iron production sites without access to water power were closed down.[78] Reynolds[79] identifies the water-powered bellows as "…probably the single most important step in the transition from a technology based on wood to one based on metal."

Figure 6: Period illustrations of machinery used in the iron industry[x]



Cam actuated Trip-hammer[80]	Water-powered bellows with cam shaft[81]	Piston pumps to lift water from deep mines[82]	Water-powered stamps for crushing ore[83]

Other applications of water power to the medieval iron/armor industry: Increased demand for iron products required deeper mines. Even into the 18th century, the main limitation on the depth of mines was the removal of water. The ancients knew the use of mills and the Archimedian Screw, but this method was not powerful enough to bring up water from great depths. The first known reference to water-powered pumps in medieval mining is in a 1315 manuscript from Moravia.[84] The piston pump design shown in Fig. 6, introduced in 1540, was called by Agricola "…ingenious, durable and useful, and

[x] Please refer to Appendix A for more information on the illustrations in Figures.

not even costly."[85] With the ability to dig deeper mine shafts came the necessity for more powerful means to ventilate and service them. Designs for water-powered air pumps and hoisting machinery are described by Agricola.[86] Water power was also applied to the crushing of ore, again using a camshaft to lift and drop vertical stamps (Fig. 6). The first known application of this mechanism occurred in Germany, 1314. Another way that water power aided armorers directly was its application to the polishing of steel armor. Polishing a high end piece of plate armor in the late Middle Ages might incur as much as 80% of the total cost of an armor. For this reason, most armor was not highly polished, and those that were projected wealth and importance.[87] Water power was used to drive polishing wheels to make this possible.[88]

The medieval blast furnace: The third major innovation of the 13th century was the use of the blast furnace and finery. A blast furnace (Fig. 7) is operated much like a bloomery, but on a larger scale. As we have seen earlier, larger size means higher temperatures,[89] so the blast furnace was designed to produce molten iron. Larger size also required forceful input of air (i.e. oxygen) into the system, for which the water-powered bellows was essential in order to make it a consistent and reliable process.[90]

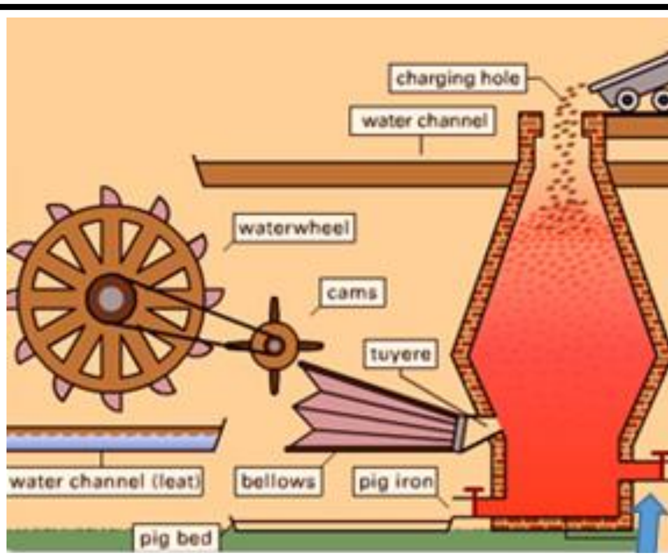


Figure 7 Medieval Blast Furnace[91] [xi]

This allows for several advantages. (1) Silicates in the ore also melt as slag in the blast furnace, but slag is less dense than the iron so it floats on the surface and can be poured off while still in liquid form. The molten slag also absorbs many impurities which can then be easily removed. The resulting iron product is much cleaner and more uniform than was obtainable in the bloomery process.[92] (2) The blast furnace is operated continuously, not batch-wise.

[xi] Please refer to Appendix A for more information on the illustrations in Figures.

In the bloomery, iron ore and charcoal are mixed and burned. When the batch is done the solid bloom is removed and the fire extinguished. In a blast furnace, iron ore mixed with charcoal is continuously fed into the top of the furnace. Iron oxides in the ore are reduced, 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.[93] With raw material fed in from the top and the end product drained from the bottom, the blast furnace may be operated continuously, providing much greater efficiency and quantities than were possible with the bloomery. The molten pig iron was shaped into ingots (*pigs*) or used in casting of final products (cast iron). (3) Pig iron has a high and uniform carbon content. Molten iron absorbs carbon rapidly, easily obtaining a carbon content of 4 to 6% throughout. Thus consistency and uniformity of the product was greatly improved.[94] (4) Removal of iron from the ore was much more efficient, which reduced the cost of raw material and increased output.[95]

It is clear that the ability to produce pig iron was known since antiquity[96], and most bloomeries were capable of melting iron if not properly controlled. Therefore creation of the blast furnace itself was not remarkable. The real innovation was coupling the blast furnace with the finery to transform pig iron into malleable steel (known as the *indirect process*. [97])

The medieval finery: We have already touched on the concepts exploited by the finery:

a: Molten iron in the presence of elemental carbon absorbs up to 4.3% carbon.

b: Reheating iron in the absence of elemental carbon releases oxidized carbon to the atmosphere.

In a finery the pig iron was reheated in an open hearth, not packed in charcoal as in the bloomery. In the extreme heat, the available carbon was oxidized and escaped as gas. The hot iron was then forged and beaten into bars. As mentioned before, reheating and forging causes loss of iron mass due to oxidation, and the finery process is no exception. Estimates of finery yields indicate that 30% to 50% of the mass of the original pig iron is lost during processing.[98] When pig iron was being produced by the ton in a blast furnace, the losses were tolerable.

There is much confusion as to the date(s) when the first blast furnace/finery site(s) appeared in medieval Europe, as the distinction between a true blast furnace and a large bloomery with water-powered bellows can be difficult to discern from archeological remains.[99] The first written evidence comes in the form of charters granted to ironworkers in Sweden (1340-54) and Belgium (1345-7).[100] The indirect process for smelting iron may have developed from the lead industry, as the two processes have similar requirements and existing records show that many14^{th} C. furnaces may have produced both iron and lead.[101] The indirect process spread throughout Europe during the second half of the 14^{th} C., bringing a great increase in the quantity and quality of iron available for all purposes. Cast iron cannonballs began to appear in the mid 1400s[102]. A 1460 description of a blast furnace in Northern Italy documented production of 200 pounds (90 kg) of cast iron per day[103], a vast improvement over bloomery production. As the mass of metal was not dependent upon the amount of ore packed into a bloomery, it was possible to make individual bars of any size, including bars large enough to produce plate armor, and the materials available to armorers improved dramatically[xii].

Table 2: Timeline

Items used		Technology
Chainmail & small pieced helmets	pre-1200	Bloomery Manual forging Manual bellows
	1200	Water-powered **Trip hammer**
Great Helm, Cervelliere	**1220**	
Coat of plates	**1250**	
Poleyns, Couters, Schynbalds, Bascinet	**1300**	Water-powered **Bellows**
	1314	**Ore Stamps**
	1315	**Pumps**
	1350	**Blast Furnace/Finery**
One-piece Breastplate	**1400**	
Full plate armor	**1440**	
Cast Iron Cannon Balls	**1450**	

Dates cited as presented in this paper

VI: **Conclusion**

This research has uncovered several interesting and surprising points. The evolution of armor from the 13^{th} to the 15^{th} C. (Table 2) was not due to the whim of fashion or some discovery in the armorer's art, or even divine inspiration.[104]..Rather, it was a by-product of advances in industrial engineering that had far reaching effects on medieval life. These technologies would be key factors in the creation of our modern civilization.

[xii] Note that the finery produced iron of comparable hardness (i.e. carbon content) as compared to the bloomery. The major improvements to the metal itself were low slag content, and in the quantities produced.

The (re)invention of the water-powered trip hammer had a significant effect on the smith's ability to condense blooms and shape final pieces. Anyone doubting the impact (pun intended) of this single innovation should watch the video referenced in endnote #69. Iron blooms could be cleaned and consolidated much more easily, and final articles shaped with greater speed and consistency than was possible by hand. This technology alone played a role in the proliferation of smaller plate armor pieces that we see in the mid 13th and early 14th C.

The water-powered bellows greatly improved efficiency of the bloomery process, providing larger quantities (as well as larger individual pieces) of steel than had been available before. But in order for the smith to handle the larger blooms, and make larger sheets of metal, the previously invented trip hammer was indispensable. This combination gave the armorers access to better materials, and enabled them to experiment with even larger pieces of armor.

Then, discovery of the finery process, coupled with the water-powered bellows, enabled medieval iron workers to convert their bloomeries into blast furnaces and produce steel of high quality in great quantity. The new metal available to armorers was similar in hardness (i.e. carbon content) to the earlier bloomery iron, but it was cleaner, more homogenous, and much more plentiful.

This research has also led to some valuable insight into the realities of medieval life. Students of history know that much was lost from Europe when the Roman Empire receded, and that communication of medieval ideas was slow. But being immersed in the details, it has been remarkable to see just how much technology was lost and how slowly it crept back. The modern scientific mind expects that an important discovery should be known and widely practiced within a few years. Not so in the medieval world. We have seen that the hydraulic bellows first appeared in Europe around 1214, but was not common until after 1300. The ability to produce large amounts of cast iron was available around 1340, but the casting of so simple an object as a cannonball was not achieved until the mid 1400s. With the rapid changes we have seen in the modern times, it is difficult to comprehend a world where change is measured in centuries. This presents a conceptual challenge to the modern scholar attempting to piece together scattered remnants from the historical record.

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Cergol Forge, Maglio of Bienno: https://www.youtube.com/watch?v=NAv3hkOQZjg Accessed 1/ 8/15.

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Museo Galileo: Taccola, (1449) *De machinis*: Water-powered bellows http://brunelleschi.imss.fi.it/ifoto.asp?foto=http://vitruvio.imss.fi.it/foto/4615_1612_0816/4615_1612_0816-025rs.jpg

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Wyckoff, D. (1958). Albertus Magnus on Ore Deposits**.** *Isis*, 49(2), 109-122, p. 115.

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[1]Johnson, S. (1980). A Late Roman Helmet from Burgh Castle. *Britannia*, 11, 303-312.

[2] Snodgrass, A. M. (1999). *Arms and armor of the Greek*s, Baltimore, MD: Johns Hopkins University Press, p. 21, 50-1.

Brailsford , J. W. (1951). Roman Helmet from London. *The British Museum Quarterly,* 16(1), 17-19.

Williams, A. (2003). *The Knight and the Blast Furnace*, Leiden, The Netherlands: Brill, p. 8.

Single piece, shaped bronze armor was used in ancient times (Snodgrass, p. 21, 50-1) and into the Roman era (Brailsford). Bronze is very malleable, and properly worked it can be made to be harder than medieval steel, but at much greater cost. Iron ore was so plentiful and easily obtained, that iron became the metal of choice once the technologies of its manufacture became known. (Williams 2003, p.8).

[3] Grancsay, S. V. (1931). Arms and Armor at the Metropolitan. *The American Magazine of Art,* 23(4), 277-284. p. 278.

[4] Williams, A., & Edge, D. (2004). Great Helms and their development into helmets. *Gladius*, 24:123-34, p. 127.

[5] Mäll, J., (2011). A 13th-Century Kettlehat From Kodasoo, Estonia. *Gladius*, 31, 83-92, p. 84.

[6] Koch, H. W. (1978). *Medieval Warfare.* New York, NY: Barnes and Noble, p. 67, 256.

[7] Williams, A., & Edge, D. (2004), p. 130.

[8] Glasgow Museums. The Avant Armor, http://collections.glasgowmuseums.com/starobject.html?oid=395798

Williams, A. (2003), p. 79-87.

[9] Williams, A. (2003), p. 53-8.

[10] One encounters many different uses of the words *steel* and *iron*. Many authors do not provide their own definition, but their usage of the words will differ from other authors. *Iron* can refer to the pure metal, but is also commonly used as a general term for any ferrous metal. I have chosen to use the modern definition of *steel* presented here. Iron purified and worked in a charcoal-fueled fire is bound to have some carbon content however small, and as the paper presents, medieval bloomery iron routinely contained from 0.03% to 2% carbon, which qualifies it as steel by the modern definition. Therefore in the context of medieval armor and the present report, the terms iron and steel are equivalent and will (for the sake of simplicity) be used interchangeably.

[11] Blair, C. (1959). *European Armour; circa 1066 to circa 1700*. New York, NY: McMillan, p. 25-30.

[12] Price, B. R. (2000). *Techniques of Medieval Armour Reproduction*. Boulder, CO: Paladin Press, p. 113.

[13] Williams, A. (2003), p. 332-60.

[14] Ibid, p. 203-329. Beginning about 1490, the practice of *fire gild*ing armor became increasingly popular. Fire gilding involved painting a mixture of gold and mercury on the finished piece, then heating it to boil away the mercury. The heating in the gilding process reversed the effects of the hardening process. Thus the two processes were not done on the same armor. By around 1510, the great majority of high end suits of armor were gilded in this way, and modern analysis of these suits shows no sign of hardening.

[15] Lucas, A. R. (2005). Industrial Milling in the Ancient and Medieval Worlds. *Technology and Culture*, 46(1), 1-30, p. 8-9.

[16] Rehder, J. E. (2000). *The Mastery and Uses of Fire in Antiquity,* Montreal, Canada: McGill-Queen’s University Press, p. 128.

[17] Hoover, H. C., & Hoover, L. H. (1912). *Georgius Agricola De Re Metallica Translated from the first Latin edition of 1556,* London, England: The Mining Magazine, p. 420.

[18] Johnson, C. (1999). *Some Aspects of Metallurgy and Production of European Armor*. Retrieved from The Oakeshott Institute website: http://oakeshott.org/metal.html. , p. 3.

Rehder, JE. (2000), p. 133. A survey of typical bloomery iron products reports carbon content ranging from 0.001% to 0.9%.

[19] Ibid, p. 140.
[20] Ibid, p. 124.
[21] Godfrey, E. (2007). *The technology of ancient and medieval directly reduced phosphoric iron.* (Doctoral dissertation). Retrieved from EThOS database. (# 567828), p. 31-2.
[22] Crerar, D. A., Knox, G. W., & Means J. L. (1979)., Biogeochemistry of bog iron in the New Jersey Pine Barrens**,** *Chemical Geology*, 24(1–2), 111–135, p. 111.
[23] Gordon, R. B., & Reynolds,T. S. (1985). Medieval Iron in Society-Norberg, Sweden, May 6-10, 1985. *Technology and Culture*, 27(1), 110-117, p. 113.
Godfrey, E. (2007), p. 35-40.
Rehder, J. E. (2000), p. 134.
[24] Godfrey, E. (2007), p. 62-76.
[25] Smith, C. S., & Gnudi, M. T. (1990). *The Pirotechnia of Vannoccio Biringuccio The Classic Sixteenth-Century Treatise on Metals and Metallurgy*, Toronto, Canada: General Publishing Company, p. 62. Retrieved from Google Books database.
[26] Wyckoff, D. (1958). Albertus Magnus on Ore Deposits**.** *Isis*, 49(2), 109-122, p. 115.
Godfrey, E. (2007), p. 75-6.
[27] Reynolds, T. S. (1983). *Stronger Than a Hundred Men; A History of the Vertical Water Wheel*, Baltimore, MD: Johns Hopkins University Press, p. 140-2.
[28] McKinstry, H. E. (1948). *Mining Geology*, Englewood Cliffs, NJ: Prentice-Hall, p. 224.
[29] Rehder, J. E. (2000), p. 124.
Thiele, À. (2010). Smelting experiments in the early medieval fajszi-type bloomery and the metallurgy of iron bloom. *Periodica Polytechnica*, 54(2), 99-104.
[30] Rehder, J. E. (2000), p. 34, 172-4.
Sim, D. (2012). *The Roman Iron Industry in Britain.* Stroud, England: History Press, p.39-40. Retrieved from Google Books database.
[31] The medieval iron industry was closely tied to the forests, as bog iron deposits were often found in low lying wooded areas, along with the fuel.
Birrell, J. R. (1980). The Medieval English Forest. *Journal of Forest History*, 24(2), 78-85 , p. 82-3.
Young, C. R. (1971). English Royal Forests under the Angevin Kings. *Journal of British Studies*, 12(1), 1-14, p. 12.
Birrell, J. R. (1969). Peasant Craftsmen in the Medieval Forest. *The Agricultural History Review*, 17(2), 91-97, p. 96.
Sim, D. (2012), presents a very good summary of period methods for charcoal production. While written specifically for the Roman era, the technology did not change into the Middle Ages. (p. 25-34)
[32] Rehder, J. E. (2000), p. 128.
[33] Ibid, p. 122-30.
[34] Ibid, p. 126.
[35] Thiele, À. (2010), Figure 5, p. 104.
[36] Sim, D. (2012), p. 47.
[37] Wheatley, H. B.(1913). Charcoal Ironworks. *Journal of the Royal Society of Arts*, 61, 977-83, p. 982-3. In the 16th C. ironworks were built to reprocess the furnace rubbish of earlier bloomery operations going back to Roman times. The author states "…Mr. Savery affirms that the Roman cinder-heaps of the Forest of Dean furnished half the iron produced for two hundred years after improved methods came to use."
Williams, A. (2003), p. 877, 890.
[38] Williams, A. (2003), p. 879.
[39] Buchwald V. F. (2005). *Iron and Steel in Ancient Times*. Copenhagen, Denmark: The Royal Danish Academy of Science and Letters, p. 101.
[40] Ibid, p. 101
[41] Williams, A. (2003), p. 891.
In fact, the amount and composition of the slag in furnace rubbish, or in finished steel objects can be used to identify the source of ore and the smelting process used to produce period steel:

Dillmann, P., & L'He´ritier, M. (2007). Slag inclusion analyses for studying ferrous alloys employed in French medieval buildings: supply of materials and diffusion of smelting processes. *Journal of Archaeological Science*, 34, 1810-23.
Buchwald V. F. (2005), p. 86-336.
[42] Sim, D. (2012), p 67.
[43] Williams, A. (2003), p. 891.
[44] Rehder, J. E. (2000), p. 136.
[45] Williams, A. (2003), p. 877-8.
[46] Ibid, p. 878.
[47] Rehder, J. E. (2000), p. 133.
[48] Tylecote, R. F. (1987). *The early history of metallurgy in Europe*, New York, NY: Longman House, p. 251.
Williams, A. (2003), p. 878.
[49] Williams, A. (2003), p. 877, 890.
[50] Sim, D. (2012), p 23. This work is based on Roman era technology, but is applicable to the medieval process as well. Sime gives separate values for "Smith billet"(80%) and "Forge Bar"(80%), I have combined these into one step: 0.8*0.8=64% efficiency.
[51] Williams, A. (2003), p. 877-8.
Sim, D. (2012), p 66.
[52] Williams, A. (2003), p, p. 55.
Muendel, J. (2002). The Manufacture of the Skullcap (Cervelliera) in the Florentine Countryside during the Age of Dante and the Problem of Identifying Michael Scot as Its Inventor. *Early Science and Medicine*, 7(2), 93-120, p. 99.
[53] Howe, H. M. (1916). *The Metallography of Steel and Cast Iron.* New York, NY: McGraw-Hill, p. 8. Retrieved from Google Books database.
[54] Williams, A. (2003), p. 879, 891, 939-40.
Williams, A. R. (1991). Slag inclusions in armour. *Historical Metallurgy*, 24, 69-80.
[55] I would suggest that this is how the 10^{th} C. Duke of Bohemia came to own a shaped one-piece conical helm. (refer to Footnote #i)
[56] Blair, C. (1959), p. 37-41.
[57] Ibid, p. 41.
[58] Pfaffenbichler, M. (1992). *Armourers*. London, England: British Museum Publications, p 9.
As another example of the expanding military industry, in 1295 one Frederic the Lombard fulfilled an order for Philip IV of France to deliver "2853 helmets, 6309 round shields, 4511 mail shirts, 751 pairs of gauntlets, 1374 gorgets and 5057 coats of plates." Pfaffenbichler (1992), p. 33.
[59] Williams, A. (2003), p. 73.
[60] Wikipedia, Cathedral of Magdeburg: http://en.wikipedia.org/wiki/Cathedral_of_Magdeburg, Accessed 1/3/15.
[61] Kennedy, M. (2010, November 11). King Arthur manuscript up for sale. *The Guardian*, Retrieved from: http://www.theguardian.com/artanddesign/gallery/2010/nov/11/heritage-history#img-7
[62] Web Gallery of Art, Ormesby Psalter: http://www.wga.hu/index1.html
[63] Williams, A. (2003), p. 73.
[64] Blair, C. (1959), p. 29.
[65] Muendel, J. (2002), p. 99.
Blair, C. (1959), p. 29-30, 51.
[66] Muendel, J. (2002), p. 99.
[67] Ibid, p. 104.
[68] Although windmills were known in medieval times, they do not seem to have played a significant role the iron industry. One might imagine a role for wind power in the mining industry, where the location of a mine is independent on a convenient source of water power, but the literature is mostly silent on the

subject. The period authors Agricola (Hoover and Hoover, 1912) and Biringuccio (Smith and Gnudi, 1990) do not mention the use of wind power in their books.

[69] Reynolds, T. S. (1983), p. 124-6. Various other names may be encountered: tilt-, helve-, drome-, martinet-, recumbent-, and drop hammer. Some of these terms identify specific designs, and some are simply different names for the same device. All are mechanically powered hammers used to pound iron.

Dupras, N. (2012). *Armourers and their workshops: the tools and techniques of late medieval armour production.* (Doctoral dissertation). Retrieved from EThOS database.(577382),p. 63.

Dupras (2012) cites a London assize of nuisance from 1377, where an armorer's neighbor complains "…blows of the sledge-hammers when the great pieces of iron… are being wrought into brestplates, quysers, jambers and other pieces of armour, shake the storie and earthen party-walls...and spoil the wine and ale in their cellar."

A video of a water-powered trip hammer in operation may be viewed at:

Cergol Forge, Maglio of Bienno: https://www.youtube.com/watch?v=NAv3hkOQZjg Accessed 1/8/15.

[70] Lucas, A. R. (2005), p. 8-9.

[71] Lucas, A. (2006). *Wind, Water, Work: Ancient and medieval milling technology,* Leiden, The Netherlands: Brill, p. 251, 254.

Lucas notes that the two English sites and the site at Toaker, Sweden, were Cistercian monasteries, and suggests that the Cistercians may have been leaders in reintroducing the technology in medieval Europe.

Reynolds, TS. (1983), p. 86.

[72] Muendel, J. (2002), p. 93-101.

[73] Lucas, A. (2006), p. 254, 266.

[74] Rehder, J. E. (2000), p. 73, 77-85.

[75] Reynolds, T. S. (1983), p. 53.

[76] Rehder, J. E. (2000), p. 127.

[77] Tylecote, R. F. (1987), p. 251.

Tylecote, R. F. (1990). *The prehistory of metallurgy in the British Isles*, London, England: The Institute of Metals, p. 211.

[78] Cortese, M. E., & Frankovich, R. (1995). Iron in medieval Tuscany. In *The importance of ironmaking. Technical Innovation and Social Change*, G. Magnusson (Ed.), Stockholm, Sweden: Jernkontorets, 211-231, p. 228.

[79] Reynolds, T. S. (1983), p. 87.

Godfrey, E. (2007), p. 11. states "…it was the replacement of man-power with water-power that proved crucial to the transition from bloomery to blast furnace technology in Europe and allowed for the development of larger scale iron production after the 15th century AD."

[80] Museo Galileo: Da Vinci, (1490-99) Madrid Manuscript, Cam actuated trip hammer http://brunelleschi.imss.fi.it/genscheda.asp?appl=LIR&xsl=paginamanoscritto&lingua=ENG&chiave=100914

[81]. Museo Galileo: Taccola, (1449) *De machinis*: Water-powered bellows.*:* http://brunelleschi.imss.fi.it/ifoto.asp?foto=http://vitruvio.imss.fi.it/foto/4615_1612_0816/4615_1612_0816-025rs.jpg

Reynolds, TS. (1983), p. 87.

[82] Macini, P & Mesini, E.(2003). The evolution of pumping systems through the early Renaissance. In *Henry P.G. Darcy and Other Pioneers in Hydraulics*. G. Brown, J. Garebrecht, & W. Hager, (Eds.), Reston, VA: American Society of Civil Engineers, 233-51, p. 244.

[83] Hoover, H. C., & Hoover, L. H. (1912), p. 284.

[84] Reynolds, T. S. (1983), p. 79.

[85] Macini, P & Mesini, E.(2003), p. 233-7, 242.

[86] Hoover, H. C., & Hoover, L. H. (1912), p. 208-10.

[87] Capwell, T. (2014) *Building Medieval Plate Armour: An Operator's Guide*. Dr. Tobias Capwell, Curator of Arms and Armour, The Wallace Collection, London. A public lecture presented in October 23, 2014, at Orange Coast College, Costa Mesa, CA. The lecture was recorded by Scott

Farrell, and may be accessed through the Chivalry Today website: http://chivalrytoday.com/building-medieval-plate-armor-operators-guide-dr-tobias-capwell/ This citation refers to time stamp 42:40 to 46:30 (minutes:seconds).

[88] Reynolds, T. S. (1983), p. 76.

[89] Williams, A. (2003), p. 879.

[90] Howe, H. M. (1916), p. 8.
Smith, C. S., & Gnudi, M. T. (1990), p. 147.

[91] British Broadcasting Corporation, Blast Furnace: http://www.bbc.co.uk/history/british/victorians/launch_ani_blast_furnace.shtml

[92] Dupras, N. (2012), p. 70.
Howe, H. M. (1916), p. 8.

[93] Howe, H. M. (1916), p. 23-24.

[94] Ibid, p. 23-24.

[95] Rehder, J. E. (2000), p. 128.

[96] Ibid, p. 127.

[97] Light, J. D. (2007). A Dictionary of Blacksmithing Terms. *Historical Archaeology*, 41(2), 84-157. p. 86.

The bloomery method is referred to as the *direct* process, where workable wrought iron is produced in one step. The combined blast furnace/finery process is referred to as the *indirect* process for steel production because the iron ore is first extracted into cast iron, then workable steel is produced by the secondary finery process. The indirect process is the basis for modern steelmaking.

[98] Dillmann, P., Perez, A., Vega, E., Arribet-Deroin, D., Aranda, R., L'He´ritier, M., Neff, D., & Bellot-Gurlet, L. (2012). Understanding the Walloon method of iron refining. *Historical Metallurgy*, 6(1), 19-31, p. 20.

[99] Gordon & Reynolds (1985) report a Swedish blast furnace operating ca. 1250, based on archeological evidence. While the authors seem firmly convinced that this site markes the earliest blast furnace in Europe, they do admit that "…*the conference was enlivened by lack of agreement*…" (p. 113). Many other authors cite this source as evidence of the birth of the modern steel industry. I prefer to rely on the written documentation to establish dates in this case.

[100] Awty, B. G. (2007). The Development and Dissemination of the Walloon Method of Ironworking. *Technology and Culture*, 48(4), 783-803, p. 786-8.

[101] Ibid, p. 789.
Awty, B. (1990). *The Blast Furnace in the Renaissance Period: Haut Foumeau or Fanderie?*. Read at the Science Museum, London. (No publishing information is given), 65-78, p. 68. Obtained on-line: http://pubs-newcomen.com/tfiles/61p065.pdf

[102] Tunis, E. (1999). *Weapons: A pictorial history*. Baltimore, MD: Johns Hopkins University Press, p. 77.

[103] Awty, B. (1990), p. 67.

[104] Boccaccio, G. (ca. 1440). Minerva instructing armourers. *De mulieribus claris.* British Library Royal 16 G V f. 11. Accessed from the British Library website: http://www.bl.uk/catalogues/illuminatedmanuscripts/ILLUMIN.ASP?Size=mid&IllID=43027.

Figure 1, left
7^{th} Century Frankish spangenhelm

Metropolitan Museum of Art, New York

This style consists of four separate bands that constitute a framework, riveted to four plates that fill in the spaces.

See Endnote 3.

Figure 1, middle
Mid 13th Century Great Helm

German Historical Museum, Berlin.

The first Great Helms appear around 1220.
(Blair (1959) p. 30)
This helm consists of five plates and a reinforcing strip across the eye slots, riveted together.

See endnote 4.

Figure 1, right
Late 13th Century Kettlehat

Estonian History Museum, Tallinn

This helmet consists of four pieces riveted together: brim, crest, and two side plates.

See Endnote 5.

Figure 2, left
1340 Cervelliere with chainmail aventail

Tower of London Armoury, London

The cervelliere is a simple skull cap shaped from a single sheet of metal

See Endnote 6.

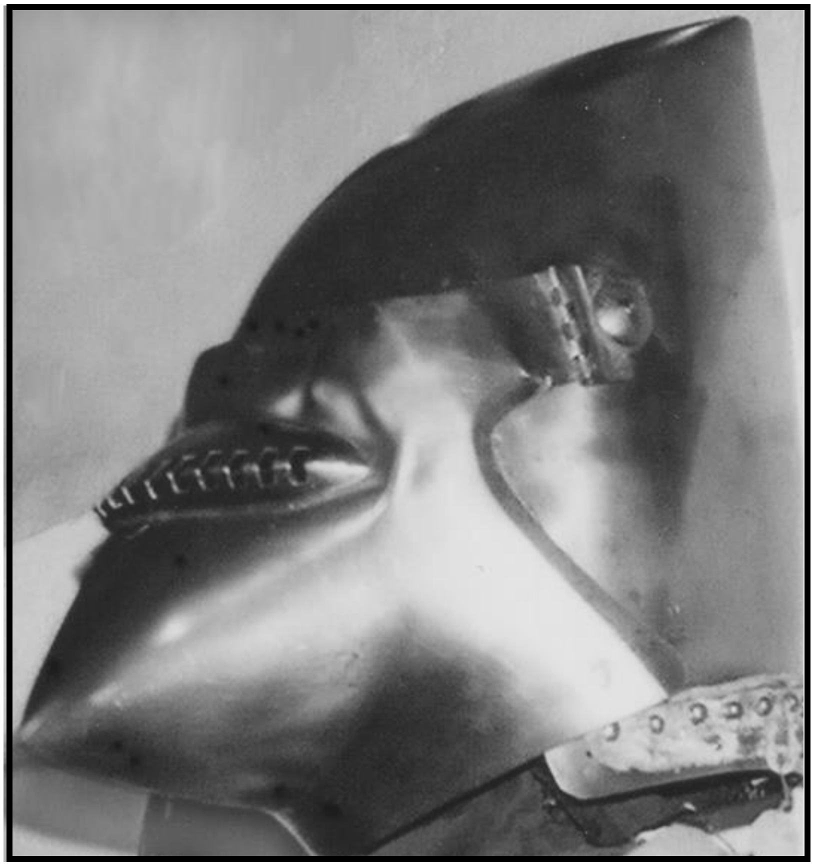

Figure 2, middle
1385 Bascinet with visor

Churburg Castle,
Schluderns, Italy

The bascinet is a larger helmet offering protection to the sides and back of the neck as well as the skull, but still shaped from a single sheet of metal. This example has attached a pivoting visor, also shaped from a single piece of steel.

See Endnote 7.

Figure 2, right
1440-5 The Avant Armor

Kelvingrove Art Gallery and
Museum, Glasgow, Scotland

One of the earliest extant complete suits of plate armor, manufactured in Italy. Named for the word *Avant* etched on the breastplate. Several pieces of the armor show evidence of hardening so this would have been a very high end item for its time.

See Endnote 8.

Figure 3, Left

Iron Age bloom of 1kg from Scandinavia

The bloom is unforged, and consists of iron mixed with slag.

See Endnote 37.

Figure 3, Right

Medieval bloom of 1kg from Scandinavia

The bloom is partially forged. Cutaway shows an inner core of iron (white) mixed with slag, surrounded by more slag.

See Endnote 38.

Figure 5, Left

Statue of St. Maurice,
Magdeburg Cathedral
ca. 1250

Earliest known depiction of a coat of plates. The 3rd century black African martyr is wearing 13th century armor.

See Endnote 57.

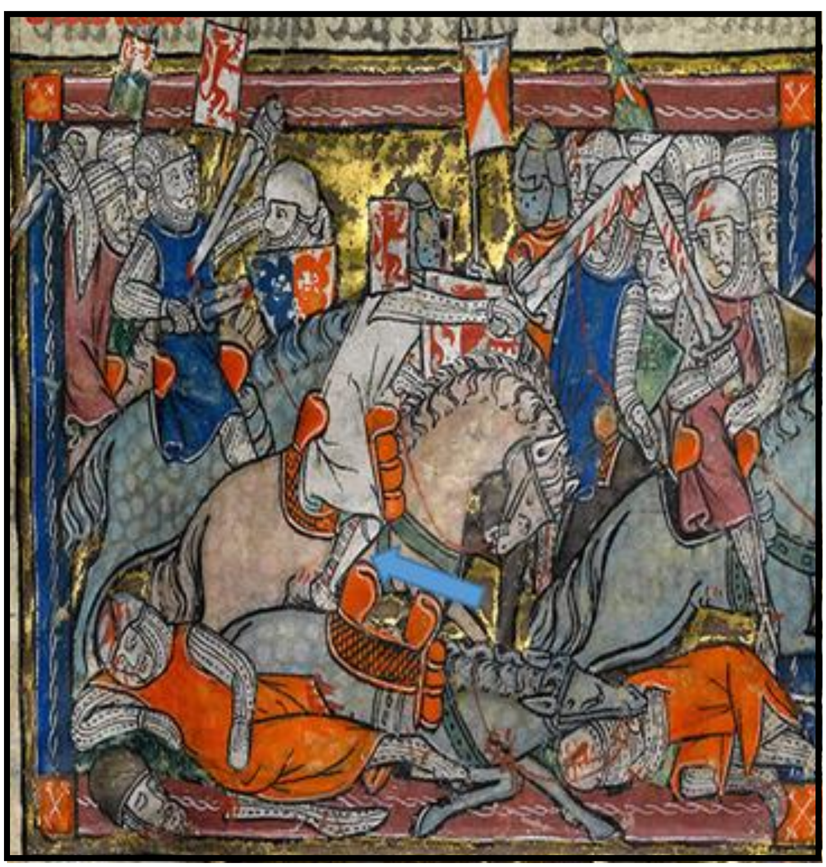

Figure 5, 2nd from Left

Rochefoucauld Grail
King Arthur slaying the Saxons
1315-1325

The central figure (Arthur?) is depicted with a pieced Great Helm, chainmail, and schynbalds (plate leg armor, blue arrow). Some figures are wearing pieced helmets, and some are wearing one-piece cervelliere with chain mail.

See Endnote 58.

Figure 5, 2nd from Right

Ormesby Psalter
1300-1325

Bodleian Library, Oxford

The warrior is wearing a pieced kettlehat, chainmail, couters (plate elbow armor, blue arrow), poleyns (plate knee armor, red arrow), and possibly plate demi-gauntlets (wrist and back of hand).

See Endnote 59.

Figure 5, Right

One-piece breastplate
Bavarian National Museum, Munich.

1390-1400

Rivets are securing a red velvet covering.

See Endnote 60.

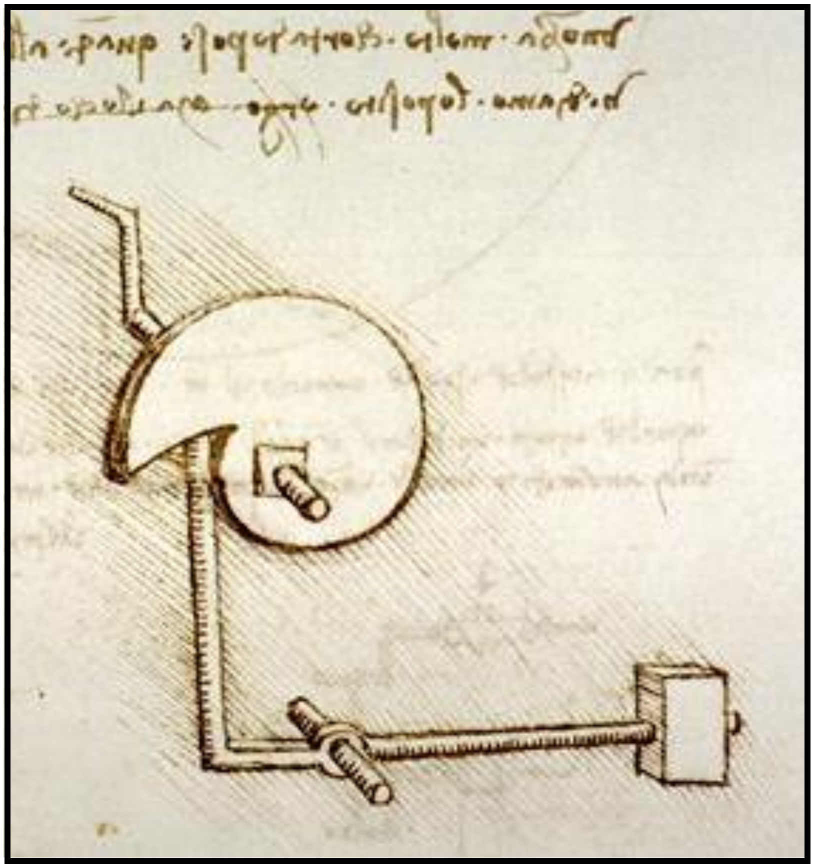

Figure 6, Left
Sketch by Leonardo Da Vinci
Madrid Manuscript
ca. 1490-99

National Library of Spain, Madrid

Hammer driven by eccentric cam.

See Endnote 77.

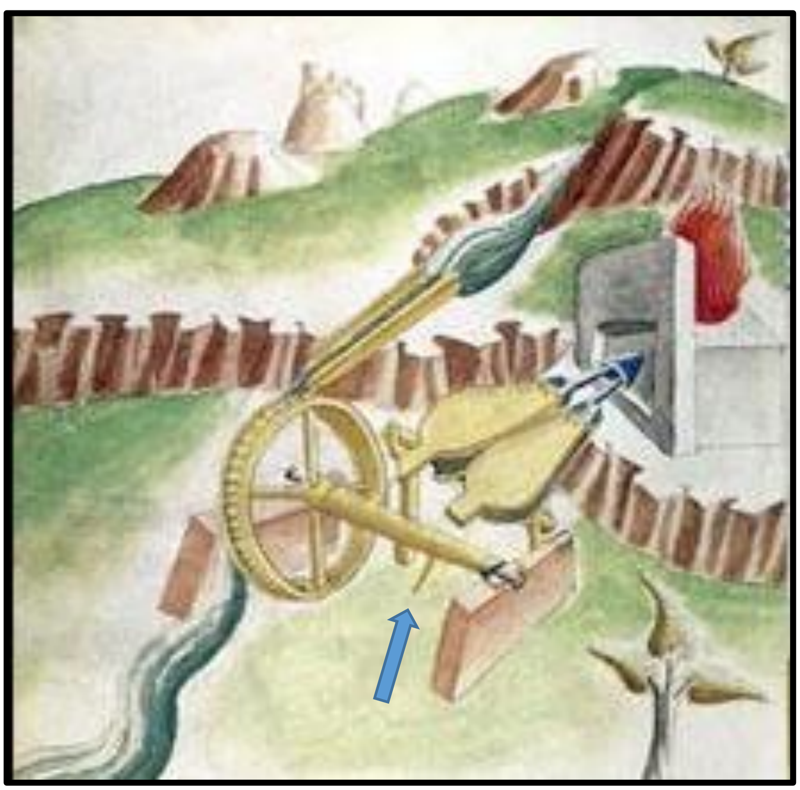

Figure 6, 2nd from Left

Illustration by Taccola, *De machinis*, ca 1449

Bavarian State Library, Munich

Hydraulic blowing plant with two camshaft-operated bellows. One tooth of the cam shaft is indicated by the blue arrow.

See Endnote 78.

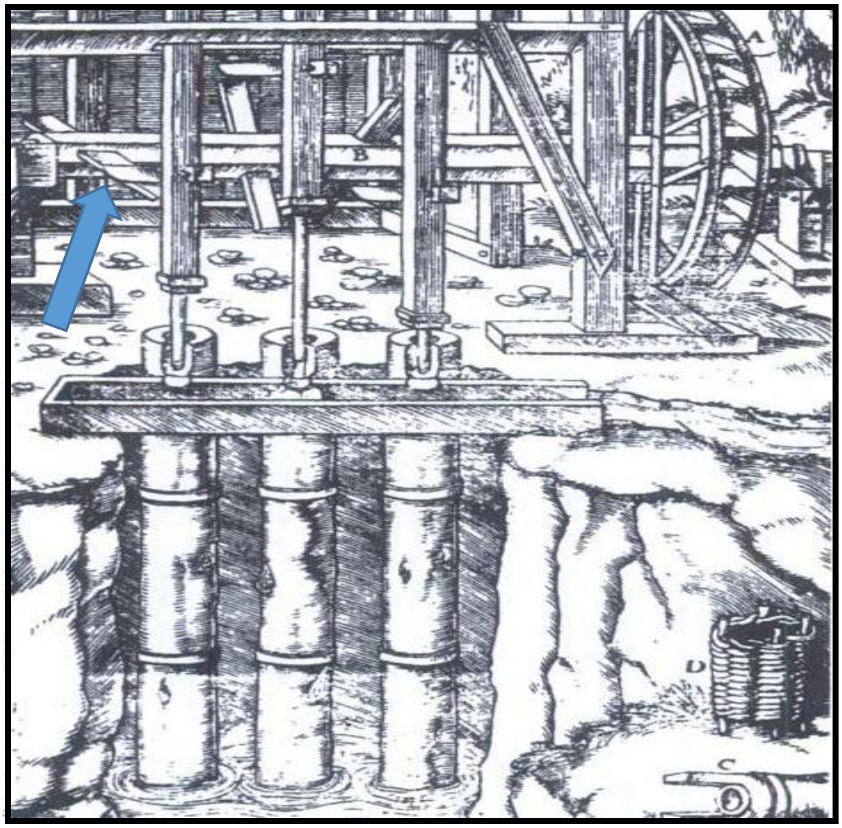

Figure 6, 2nd from Right

Illustration by Agricola, 1556
De re metallica

Cam-actuated piston pumps for removing water from deep mines (first introduced in 1540). The cam shaft is indicated by the blue arrow. This design "...is of enormous importance in the history of mining and pumping technology."
(Macini, P & Mesini, E.(2003). p. 242, 244.)

See Endnote 79.

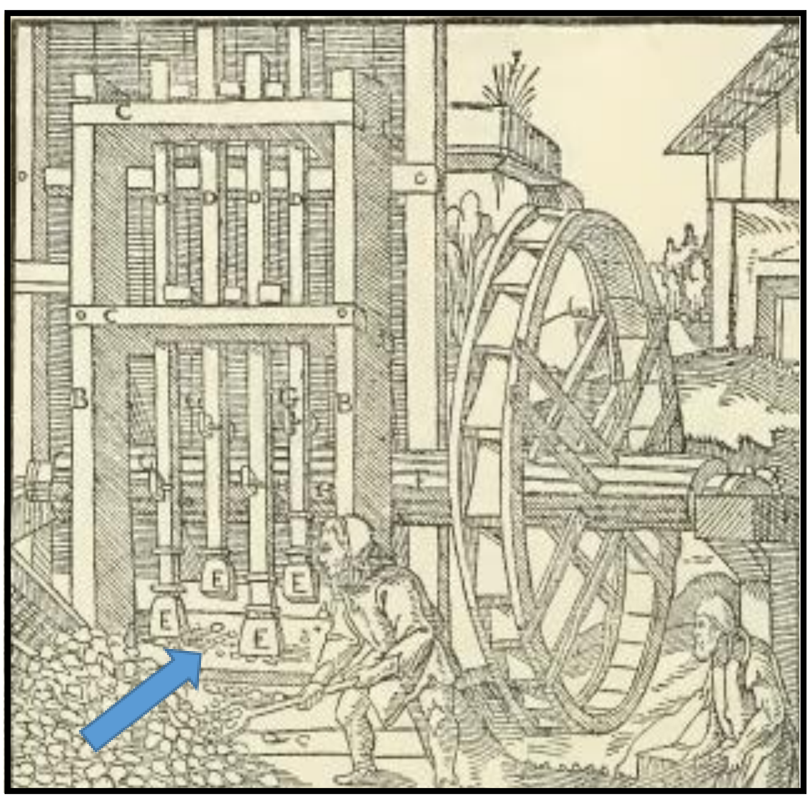

Figure 6, Right

Illustration by Agricola, 1556
De re metallica

Water-powered stamps used to crush ore. (first introduced in 1317)

Stamps are vertical posts, with heavy weighted heads. The stamps are alternately raised and dropped by a cam shaft driven by a water wheel. Stamp heads (labeled *E*) are indicated by the blue arrow.

See Endnote 80.

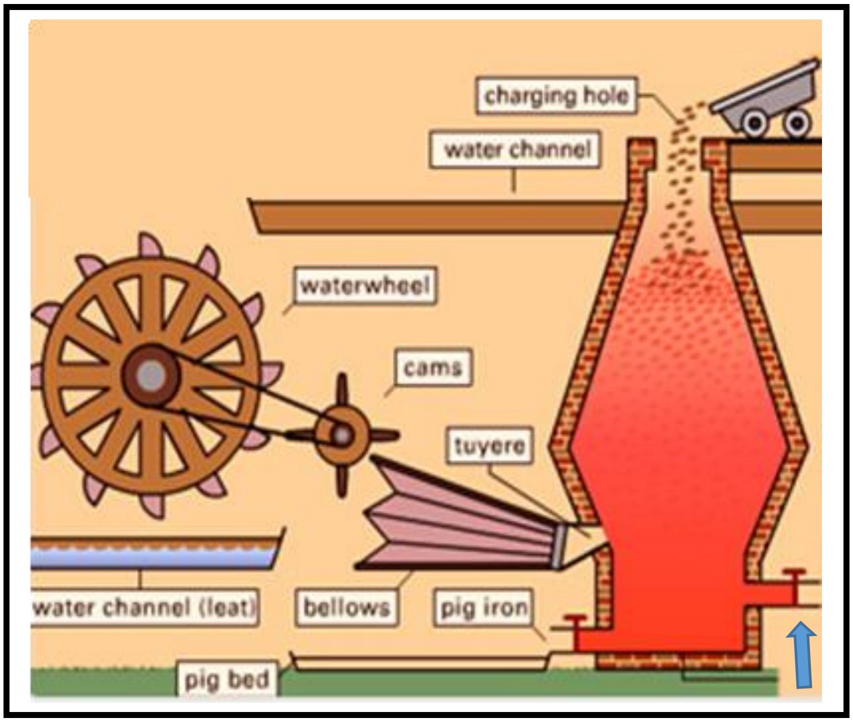

Figure 7

Modern illustration of a medieval blast furnace.

BBC Website

It is not labeled on the illustration, but the tap on the right side (blue arrow) would be used to drain off molten slag which floats on the surface of the molten iron. The tap on the lower left would be used to drain pig iron into molds.

See Endnote 90.

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, impure 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.

Cam:
A rotating or sliding piece (as an eccentric wheel or a cylinder with an irregular shape) in a mechanical linkage used especially in transforming rotary motion into linear motion.

Cast Iron
A name for the melted iron produced in a blast furnace, containing a large quantity of carbon (above 1.5%). It is typically called *cast iron* when the molten iron is poured into molds to form a finished product. In many references the terms *cast* and *pig* iron are used interchangeably. Pig iron and cast iron are very hard and brittle.

Forging
Heat-working a piece of metal to a predetermined shape, typically by hammering.

Hardened Steel

Quench Hardening
A process of hardening iron objects by heating below the melting point, 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 usually involves the formation of martensite, which greatly increases hardness of steel. To avoid brittleness the object would be reheated (tempered) to enable the crystalline structure to reform.

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 was achieved in period by embedding the object in powdered charcoal, then heating (but below the melting point of iron). The iron object will absorb additional carbon on its surface, producing a very thin layer of increased carbon content. When the hot object is rapidly cooled (quenched) the iron crystal lattice locks 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 confers exceptional hardness. The typical test for hardness 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. In its pure metallic form, iron is rather soft and easily deformed. *Iron* can refer to the pure metal, but is also commonly used as a general term for any ferrous metal. Special uses of the word include *cast iron* and *pig iron*, which specifically refer to a process where the metal is completely molten in the presence of carbon during its manufacture. Output from a bloomery, i.e. *bloomery iron*, was not molten in its manufacture.

Oxidation
The *loss* of electrons. In the context of iron smelting, elemental carbon (no charge) loses electrons (becomes more positively charged) and combines with oxygen ions (which are negatively charged) to form a neutral molecule: carbon monoxide or carbon dioxide. In the case of iron forging, elemental iron (no charge) loses electrons (becomes more positively charged) and combines with oxygen ions (which are negatively charged) to form a neutral molecule: iron oxide.

Pig Iron
A name for the melted iron produced in a blast furnace, containing a large quantity of carbon (above 1.5%). In many sources the terms *cast* and *pig* iron are used interchangeably. Named long ago when molten iron was poured through a trench in the ground to flow into shallow earthen holes, the arrangement looked like newborn pigs suckling. The central channel became known as the *sow*, and the molds were *pigs*.

American Iron and Steel Institute website:
http://www.steel.org/Making%20Steel/Glossary/Glossary%20P-T.aspx

Reduction (Reduced)
The *gain* of electrons. In the context of iron smelting, iron in its roasted ore (which is positively charged, as iron oxide) gains electrons to become metallic iron with neutral charge. In the case of iron forging, elemental iron (no charge) loses electrons (becomes more positively charged) and combines with oxygen ions (which are negatively charged) to form a neutral molecule: iron oxide.

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

American Iron and Steel Institute website:
http://www.steel.org/Making%20Steel/Glossary/Glossary%20A-E.aspx

Wrought Iron
Originally a term referring to the output from a bloomery, synonymous with *bloomery iron*. Once the blast furnace/finery process came into use, the output of the finery was also referred to as *wrought iron*, since it had very similar characteristics to the earlier bloomery iron, and it was also worked (*wrought*) in the finery during its manufacture. In Great Britain, wrought iron is commonly referred to as *malleable iron.*