ANCIENT REGIONAL STEEL QUALITY: HISTORICAL METHODS OF STEEL PRODUCTION AROUND THE WORLD

An Interactive Qualifying Project Report

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Samuel Young

1. Abstract

The purpose of this paper is to compare the iron production techniques of three regions of the world: Northern Europe, India, and Japan, in order to better understand the material characteristics of the end product and how this shaped the development of weapons and armor of the region. We are seeking, in our research, to draw the links between resources, production and technology at play in regards to iron in antiquity. In this paper, we will describe our methods of research, our methods of reproduction, testing methods and, conclusions.

To best understand the labor and material requirements of ancient iron making we constructed a historically accurate bloomery from the Viking era to test our research and learn more about the process. This paper will discuss our research of all three regions, compare and contrast each region, and discuss our own conclusions after producing iron.

2. Introduction

Many people can view movies or go to a museum and immediately tell that a certain set of armor or a distinctive weapon is very clearly from a specific region. For example, they can recognize a Japanese Katana, a European Breast plate, or an elegantly curving Indian sword. All of these serve the function of carrying out warfare with the greatest possible advantage and yet each region has markedly different patterns of weapon and armor.

Why do these differences exist? Our research finds these differences can largely be traced back to contemporaneous materials available to these cultures. The goal of this IQP is to study the materials and methods available in three regions for the production of steel during the early to high middle ages, and to examine how the quality or quantity of the steel produced had an effect on the regional culture. We will research and discuss the historical sources of iron ore and methods used to produce usable material from it. Lastly, in order to better understand the methods employed to create medieval steel and the quality of steel that could be obtained using those methods, we will construct a European bloomery furnace and attempt to smelt our own steel. Once we have obtained our own iron blooms, we will examine them to determine their quality and compare our observations of microstructure and material quality to our own predictions and archaeological records of medieval steel.

3. European Smelting

3.1 Background

Steel production is a key part of history in many regions. In Europe specifically, the production of steel was an integral part of society and colonization, as it was used to build “modern” tools, weapons, and armor. Evidence that Europeans had the raw material to produce iron is supported by the large amount of iron ore found in bogs, however, based on archeological evidence, the capability to smelt it was not fully developed until around 870 – 1000 AD. In this section, we will examine the methods and materials used to produce steel in Europe, with a focus on northern Europe, specifically the Nordic countries from which the Vikings hailed.

A lot of the Viking's ability to establish colonies around the North Atlantic was derived from a combination of their ability to find supplies of ore as well as their ability to effectively smelt it (Kevin P Smith 184). The Norse placed high importance on the smelting of iron as well as locating testing sources, in bogs, for example. The ability to utilize new agricultural tools such as “scythes, sickles and pack saddles”, as well as “household tools, ships' parts, household fittings and weapons” put the Norse miles ahead of other colonies (Smith 184).

There is significant documentation on the importance of smelting ore into usable iron across L'Anse aux Meadows and Newfoundland due to the heavy presence of foundries and other smelting facilities. (Smith 185). In L’anse aux Meadows, much of the steel which was forged was “rich in silicate impurities, which formed a glass surface on the iron” (William R Short). This “stronger” forged steel was readily used for ships and tools, which allowed the Norse to rise to power; sailing throughout the North Atlantic reaping and pillaging with their more advanced technology.

Although there is substantial documentation of iron being a critical resource in medieval Icelandic society in terms of colonization, there is little documentation on its role in the economy and trade (Smith).

3.2 The Bloomery Furnace

Creating the furnace was the hardest part of the smelting process. It in the medieval era, it took hundreds of pounds of clay, sand, and hay or horse manure to construct a bloomery furnace capable of smelting the iron ore into usable steel billets.

The process of building the furnace while extensive, was primarily labor intensive and did not require much technical skill. The base of the furnace, also known as the plinth, helped keep ground moisture away, as well as provided convenient access to the bottom of the furnace for bloom removal (Sauder, 3). While brick was not prevalent during this time period, a foundation would have been created which was similar to this using stones which could be shaped together, or using no foundation at all:

FIGURE 1. THE BASE OF THE FURNACE.

(HTTP://WWW.LEESAUDER.COM/PDFS/FURNACE%20CONSTRUCTION.PDF)

The next step in producing the furnace is to prepare the clay. The Norse mixed clay with sand, water, and a source of fiber, usually horse manure (Sauder, 2). They then built the furnace around a wooden pillar to give it shape. This pillar was removed after the clay was somewhat dried. The clay from the furnace would then be fired, to dry it out further and hold the structure.

Due to the nature of clay, the steps necessary to heat up the furnace were complicated and rigorously tested. In order to avoid thermal shock, and destroying the furnace, the furnace would have to be slowly heated up using a “natural draft" (hurstwic.org). Once the furnace was warmed, however, a tuyere, an air intake pipe at the base of the furnace used to provide oxygen to the fire, was used to blast air into the furnace using bellows.

Once the furnace was fully heated, the smelting process could begin. The ore and charcoal were added to the furnace at a roughly 1:1 ratio, by weight, and melted down. According to William R. Short, “Inside the furnace, the temperature reached 1100-1300ºC (2000-2400ºF) at the bottom of the furnace near the iron. A reducing atmosphere was created, rich in carbon monoxide. The gas scavenged the oxygen from the iron compounds in the ore, converting them to elemental iron:

$$Fe_2O_3 + 3CO \rightarrow 2Fe + 3CO_2$$

The actual production of steel via smelting was a fairly simple process. Lee Sauder and Skip Williams break the process down into five stages. These stages are pre-heating, smelting, recycling, the burn down, and the extraction (Sauder, 124-126). While the specifics of these steps could change from furnace to furnace and from smith to smith, all smelts done with a bloomery furnace will go through these stages.

In the first stage, pre-heating, the bloomery furnace is brought up to temperature before the smelting begins in order to keep the clay from heating too fast and cracking. A small fire is lit inside the furnace, starting with dry wood with a layer of charcoal on top. At the beginning of the heat, there is no forced air from bellows or other blowing devices, as this would cause the furnace to heat up too quickly. Once the fire has begun to burn down, more charcoal can be added and the temperature can be increased using a light draft from the bellows (Sauder, 124).

The second stage is the smelting, the longest and most labor intensive step. Ore and charcoal are added to the furnace periodically and allowed to burn down. It is during this stage that the ore becomes a liquid, the slag begins to run out of the furnace, and carbon from the charcoal begins to enter the iron. Sauder and Williams use a ratio of 1:1 charcoal to ore, adding four pounds of ore and four pounds of charcoal every ten minutes or so. Eventually as slag build up in the bottom of the furnace, the third stage, recycling, can begin. In this stage the slag arch of the furnace is tapped to remove some of the slag, which at this point should be a black color. The slag is cooled, broken up, and re-added to the furnace along with more charcoal. This is done because the slag, while it contains many impurities, also contains reduced iron, which did not stick to the bloom on its first run through the furnace. Eventually, the slag coming out will develop a green coloration and become more viscous, indicating that it has a lower iron content. This is the signal for the next stage (Sauder, 125) (Sauder, 3).

The fourth stage is the burn-down, in which no further ore is added. Once the furnace has reached its limit and the bloom is at its largest practical size, more charcoal is added and it is allowed to burn down to the level of the tuyere. According to Sauder, this final charge of charcoal has a decarburizing effect on the steel, decreasing the carbon content of the metal.

Once the charcoal has burned down, the furnace can be left to cool until it is time for the extraction (Sauder, 126).

FIGURE 2. AN EXAMPLE OF AN IRON BLOOM.

(JEFF PRINGLE HTTP://WWW.HURSTWIC.ORG/HISTORY/ARTICLES/MANUFACTURING/TEXT/BOG_IRON.HTM)

Once the furnace has cooled down, the bloom can be extracted from it. It will appear as a solid spongy looking mass of iron. Any remaining slag can at this point be knocked off and the remaining material is almost ready to use. The last step is to reheat the bloom in a blacksmith's forge, and hammer it into a bar or billet.

The steel obtained from this process was impure and would be comparable to raw iron by today's standards, but at the time this was a much stronger material which was useful for tools, ship making and weapons. Sauder and Williams were able to produce steel comparable to a modern mild steel, but that was with an intimate knowledge of the chemical processes and several hundred years of metallurgical research that would not have been available to early European smiths (Sauder, 126). It should be noted that the experiments done by Sauder and

Williams were modern experiments using modern tools and equipment. As such they do not align directly with the specific practices of medieval smiths, but they provide proof of concept for the use of the bloomery furnace and are a benchmark that can be used to evaluate the most likely methods employed by historical smiths.

3.3 The Cultural Impact of Steel in Europe

3.3.1 Steel and Religion

The production of steel was a process of incredible importance in Northern Europe, and this importance is reflected in the mythology of the people who lived there. In the mythology of the Nordic countries, skilled smiths could be regarded with a wonder that elevated them to mythic status. In many myths, the process of creating objects from metal was often indistinguishable from magic. Finnish mythology, as chronicled in the Kalevala, has a poem depicting the creation of the first iron by the God Ilmarinen which corresponds almost perfectly to the process laid out by Sauder and Williams for the operation of a bloomery furnace. One excerpt reads:

"Ere arose the star of evening,
Iron ore had left the marshes,
From the water-beds had risen,
Had been carried to the furnace,
In the fire the smith had laid it,
Laid it in his smelting furnace.
Ilmarinen starts the bellows,
Gives three motions of the handle,
And the iron flows in streamlets
From the forge of the magician,
Soon becomes like baker's leaven,
Soft as dough for bread of barley.
Then out-screamed the metal, Iron:
'Wondrous blacksmith, Ilmarinen,
Take, O take me from thy furnace,
From this fire and cruel torture.'"
(Kalevala, IX, 11)

The first three lines of this verse describe the gathering of the bog iron from the marshes. The poet then mentions the pre-heating stage of the smelting. While it is not explicitly explained, the fire is already in the furnace, which implies a knowledge of the fact that the furnace had to be hot before adding the ore. Once the ore is added, Ilmarinen begins to pump the bellows, signaling the start of the high heat smelting stage. The poet then describes the flow of slag from the furnace, and the formation of the bloom “like a bakers leaven, soft as dough,” an accurate if stylized description of the iron bloom. Once the iron has formed it “out-screamed,” signaling to the smith that it is ready to be removed. While the iron certainly would not have screamed outside of myths, the furnace did have ways of signaling to the smith that it was ready for the burn down, namely the change in color and viscosity of the slag, or the increasing difficulty to maintain temperature and keep the truyere clear, both phenomena documented by Sauder.

Magic items, especially weapons, pervade Nordic mythology. Some of these weapons are the sort of magic weapons we can recognize in the popular mythology of today, e.g. the flaming sword of the fire giant Surt (The Poetic Edda,Voluspa, 51). Many of the qualities possessed by these magic weapons, however, are not “magical” in the way we look at magic in popular culture today. Rather, the weapons seen as magical in Norse mythology have qualities like being indestructible or incredibly sharp, as is the case with the sword Gram forged by Reginn. It is worth noting as well, that many of the old stories were written not as myths, but as histories, and the people, as well as the weapons they wielded, were believed to have existed. The Story of the Volsungs was meant to be a history, not a myth. Reginn, Sigurd, and the sword Gram were all taken to exist. This, then, begs the question, what could have inspired these magical weapons? In sections 3.3.2 Social Hierarchy of Steel and 3.3.3 Steel and Trade we will examine two possible explanations for the “magical” weapons of European myth.

3.3.2 Social Hierarchy of Steel

The importance of metalsmiths in Europe cannot be overstated. As discussed in section 3.3.1, particularly skillful metalworking was indistinguishable from magic to many who saw it. In his Prose Edda, Snorri Sturluson tells of the creation of incredible magic items by the Svartálfum, or the Dwarves/Black Elves. The following verses are an excerpt from the tale, and a glimpse into the level to which metalworking and magic were entwined in the old stories.

Hví er gull kallat haddr Sifjar? Loki Laufeyjarson hafði þat gert til lævísi at klippa hár allt af Sif. En er Þórr varð þess varr, tók hann Loka ok myndi lemja hvert bein í honum, áðr hann svarði þess, at hann skal fá af Svartálfum, at þeir skulu gera af gulli Sifju hadd þann, er svá skal vaxa sem annat hár. Eftir þat fór Loki til þeira dverga, er heita Ívaldasynir, ok gerðu þeir haddinn ok Skíðblaðni ok geirinn, er Óðinn átti, er Gungnir heitir.

XXXV. "Why is gold called Sif's Hair? Loki Laufeyarson, for mischief's sake, cut off all Sif's hair. But when Thor learned of this, he seized Loki, and would have broken every bone in him, had he not sworn to get the Black Elves to make Sif hair of gold, such that it would grow like other hair. After that, Loki went to those dwarves who are called Ívaldi's Sons; and they made the hair, and Skídbladnir also, and the spear which became Odin's possession, and was called Gungnir.

Skaldskarparmal, XXXV

This was the power of the smith in the mythos of northern Europe. Tales of magical smithing are not limited to the Gods, however, and there are numerous instances of human smiths whose skill with the forge gives them almost magical seeming powers. The Saga of the Volsungs gives an account of the smith Reginn, who forges Gram, a sword with seemingly magical properties.

"Now Reginn made a sword. And when he brought it out of the forge, it seemed to the apprentices as if flames were leaping from its edges. He told Sigurd to take the sword and said he was no swordsmith if this one broke. Sigurd hewed at the anvil and split it to its base. The blade did not shatter or break. He praised the sword highly and went to the river with a tuft of wool, which he threw in against the current. The sword cut the wool in two when the tuft ran against the blade" (The Saga of the Volsungs, 60)

This is not the only mention of the smith Reginn in Norse mythology, but it is likely the most well-known, and it showcases another common mythological phenomenon from the Eddas and the oral traditions of Europe, magic weapons seeming to possess unmatched strength and thought to be unbreakable.

While they were not in the same social class as the nobility, evidence uncovered from burial sites in Norway attest to the importance of metalworkers. Graves filled with both cremated remains as well as tools and personal belongings indicate that smiths in Norse society enjoyed a position of high importance, near the upper reaches of their social class (Nordahl, 1).

These stories of legendary smiths serve to show the importance of metalsmiths in the society. Europe, from the dark ages through the Middle Ages was a society of warriors, from Vikings to knights, and these men lived and died by their weapons and armor. From swords to simple farm tools, there was no shortage of work for metalworkers in European society and their status reflected that importance.

3.3.3 Steel and Trade

One explanation for the presence of seemingly "magic" weapons in European mythology can be explained by analyzing trade routes from Europe to the Middle East and India which allowed high quality steel to make its way into Europe. These trade routes ran from Northern Europe down the Volga River, to the Middle East and Constantinople. Figure 3 shows the most popular of these trade routes. Evidence from the Ibn Fadlan, Emissary from the Abbassid Caliphate to the Vlga Bulgars, proves that Viking traders from northern Europe had contact with traders from the Middle East. One particularly stirring episode from his writing recounts a ship burial, which he witnessed.

"The dead chieftain was put in a temporary grave which was covered for ten days until they had sewn new clothes for him. One of his thrall women volunteered to join him in the afterlife and she was guarded day and night, being given a great amount of intoxicating drinks while she sang happily. When the time had arrived for cremation, they pulled his longship ashore and put it on a platform of wood, and they made a bed for the dead chieftain on the ship."

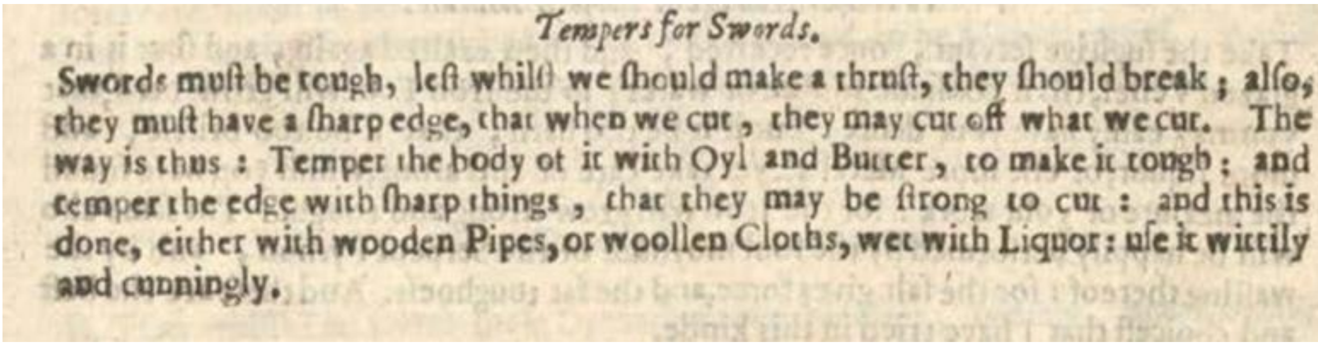
(Frye, 68)

FIGURE 3. VOLGA AND BYZANTINE TRADE ROUTES IN THE 11TH CENTURY.

The quality of steel that was imported from the Middle East was a much higher quality than could be found in Europe at the time. A further discussion of Damascus steel will be explored in Section 3, but the most important things to note are the incredible toughness and flexibility of Damascus steel compared to European steels at the time (NOVA, Secrets of the Viking Sword). Blades made of Damascus steel could hold a sharper edge and were more ductile than blades made of European steel, as a result of the poor quality of European steel. This gave blades made of Damascus steel an almost magical appearance in nature, being able to flex and bend without breaking, and keep a much sharper edge for longer than swords made of inferior European steel.

3.3.4 Weapons and Armor in Europe

The production of steel in Europe is an interesting phenomenon, because while the quantity of steel produced was significant, the quality of the steel was often quite poor. Studies have shown that medieval bloomery iron, due to large slag inclusions, was in fact quite brittle, and was neither tough nor ductile by today's standards (Thiele, 38). Sauder and Williams, however, have shown that it is possible, though it require substantial skill and knowledge, to produce steel similar to modern mild steel (Sauder, 126). While mild steel is fairly low in carbon and as a result quite soft, the steel can be hardened by quenching it in oil, or another substance that can impart substantial carbon content to the surface of the metal. This process, called case hardening, gives the metal a hard outer shell but a soft core, making it resistant to wear due to the hard outer shell, but still able to bear stress without fracturing due to the soft core (Liu, 1). This process is often used today to make gears or automotive parts. While the smiths of the middle ages would not have known the complicated chemical reactions that cause case hardening, they certainly found a variety of different heat treating and hardening methods, and though their explanations of the mechanisms behind these methods of strengthening steel may have been erroneous, the results were still a higher quality steel than they would have had they not treated it. An excerpt from John Baptiste Porta's "Natural Magick" from 1645 describes one such method of treating steel.



Tempers for Swords.

Swords muſt be tough, leſt whilſt we ſhould make a thruſt, they ſhould break; alſo, they muſt have a ſharp edge, that when we cut, they may cut off what we cut. The way is thus: Temper the body of it with Oyl and Butter, to make it tough; and temper the edge with ſharp things, that they may be ſtrong to cut: and this is done, either with wooden Pipes, or woollen Cloths, wet with Liquor: uſe it wittily and cunningly.

FIGURE 4. EXCERPT FROM "NATURAL MAGICK".

By tempering the steel in oil, Porta does exactly what the text says. The quench in oil would have carburized the outer few millimeters of the steel, creating a hard outer casing around a softer interior core which would have made the edge hard enough to allow sharpening, but the sword as a whole would stay tough enough to bend rather than fracture on a thrust. While this excerpt is about six hundred years after the Viking age, the idea that certain smiths had accidentally discovered mechanisms such as case hardening is a reasonable explanation for the tales of legendary smiths such as Reginn, and "magic" swords like Gram, the magic being the superior quality of the steel leading to its perceived indestructibility, especially compared to lower quality steels which were more likely to fracture under stress, or too soft to keep a sharp edge.

While the quality of steel produced in Europe was poor, the quantity was quite substantial, which allowed metalsmithing in Europe to flourish and led to numerous and rapid advances in the technology of arms and armor. From the Dark ages through the high middle ages, European armor evolved from leather armor, to chainmail, and by 1200 Europe saw the production of the first full plate armor (Shlager and Lauer, 363). By 1250, plate armor featured individually jointed plates in gauntlets and around joints, allowing knights to enter battle completely encased in full plate without unnecessarily hampering their ability to wield weapons.

FIGURE 5. GAUNTLETS OF EMPEROR MAXIMILIAN I.

Weaponry in Europe was able to follow a similar trend, evolving from early spears, axes, and swords to elaborate polearms and weapons like the war pick or the war hammer, weapons specifically designed to get around the protections afforded by full plate armor. This evolution is proof that although European steel was inferior in quality to that found in India or the Middle East, the sheer quantity available allowed for impressive technological innovation.

FIGURE 6. POLISH WAR PICKS.

4. Steel Production in India

4.1 Background

As early as 6000BC, southern India has been creating wootz (crucible) steel. Wootz steel is a remarkable type of steel that has been highly sought after for thousands of years because of its amazing properties of being both strong and ductile at room temperatures. The word wootz is actually an "English corruption" of the southern Indian word *ukku* that actually means steel (Srinivasan and Ranganathan, 69). Damascus steel, the processed steel from the wootz ingots, was once the premium steel on the planet although modern steels now outshine the steel from years past. Damascus steel was created when wootz ingots from India were traded with the city of Damascus. Wootz steel is typically very recognizable because of the wonderful carbon patterns that are visible on the surface of the finished steel. The higher the quality of the wootz steel, the more prominent the carbide patterns appear. The patterns are apparent in Figure 7.

FIGURE 7. CARBIDE PATTERNS IN DAMASCUS STEEL.

The exact locations of the early wootz steel production were at Mysore, Malabar, and Golconda (Srinivasan and Ranganathan, 69). Later on, manufacturing centers started forming all over India. All the way up to the nineteenth century, weapons made of wootz steel were being created in Lahore, Amritsar, Agar, Jaipur, Gwalior, Tanjore, Mysore and Golconda (Srinivasan and Ranganathan, 69). Sadly, none of these sites survive to this day. Artifacts of crucibles and weapons have been found in the Indian area that date back to 3000-4000BCE (Feuerbach, 49).

4.2 The Production of Crucible Steel

Unfortunately, as stated many times, the process of actually creating Damascus steel from wootz ingots has been essentially lost for reasons that are not completely understood. From what historians and scientists have uncovered, one-time use crucibles were created to smelt the wootz steel ingots surrounded by a huge amount of charcoal (Secrets of the Viking Sword). The furnace is made of clay bricks with soft clay holding it together and there is just an opening on the bottom for the flame and to take in air. The furnace gets to a temperature of around 3000F and is able to turn the metal into a liquid entirely. The carbon from the charcoal is infused into the steel, giving it the carbon needed to strengthen the material. In this picture, the furnace is on display along with the airhole:

FIGURE 8. A MODERN REPRODUCTION OF AN INDIAN OR MIDDLE EASTERN FURNACE. (HTTPS://WWW.YOUTUBE.COM/WATCH?V=J6WOYCXQZA0)

Based on observations from a microscope, the composition of the damascus steel breaks down as follows: 65% SiO_2, 24% Al_2O_3, 4% K_2O and 0.5% CaO (Feuerbach, 50). Although scientists have not been able to study Damascus steel perfectly, because of the loss of its creation methods, scientists have looked at similar materials at an extremely close proximity and they have been able to learn quite a bit.

One study delved into the microstructures of Ultra High Carbon Steels (UHCS) and took fantastic close-up pictures of the grain structures of the materials.

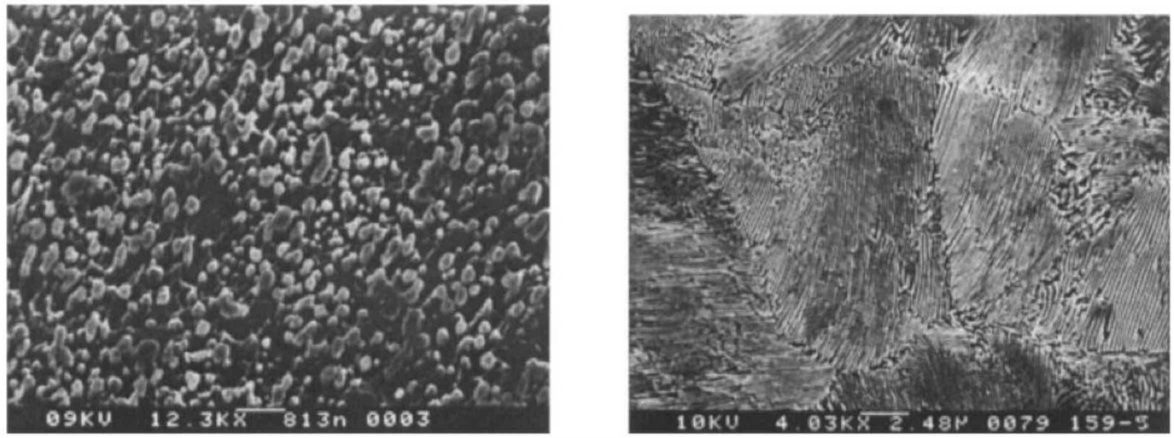


FIGURE 9. GRAIN STRUCTURE OF ULTRA HIGH CARBON STEEL (UHCS).

(http://ac.els-cdn.com/S0924013601007944/1-s2.0-S0924013601007944-main.pdf?_tid=f40a6ad0-7217-11e5-bfc6-00000aab0f02&acdnat=1444788471_d0333aba7f8fe056db84509dbb21002e)

As material science progressed and the chemistry behind the elements became clearer, phase diagrams for many combinations were created. For wootz steel, the important phase diagram needed was the Iron-Carbon diagram. For blacksmiths, the phase diagram was of upmost importance to ensure that the steel was created with the best quality.

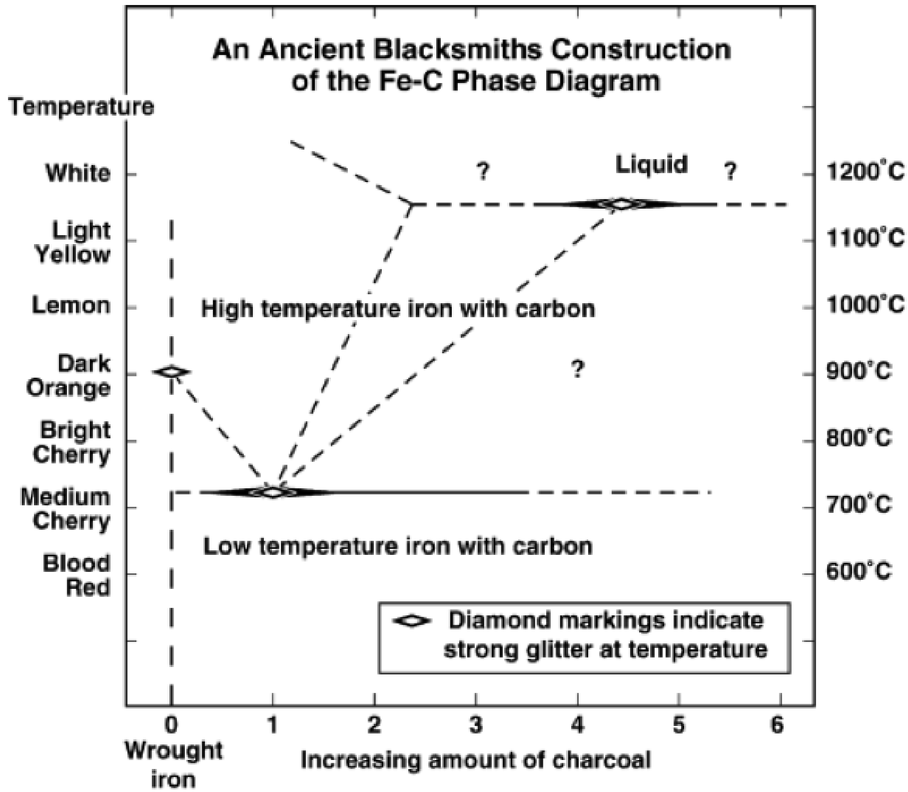


FIGURE 10. A HISTORICAL BLACKSMITH FE3C PHASE DIAGRAM

(HTTP://WWW.SANSKRITIMAGAZINE.COM/HISTORY/TALE-CRUCIBLE-WOOTZ-STEEL-ANCIENT-INDIA/)

As seen, the exact processes and specifics about the material properties were not necessarily known, but they had the general principles on how to get the steel molded into the form that they wanted. In Figure 11, the modern-age Iron-Carbon phase diagram is seen:

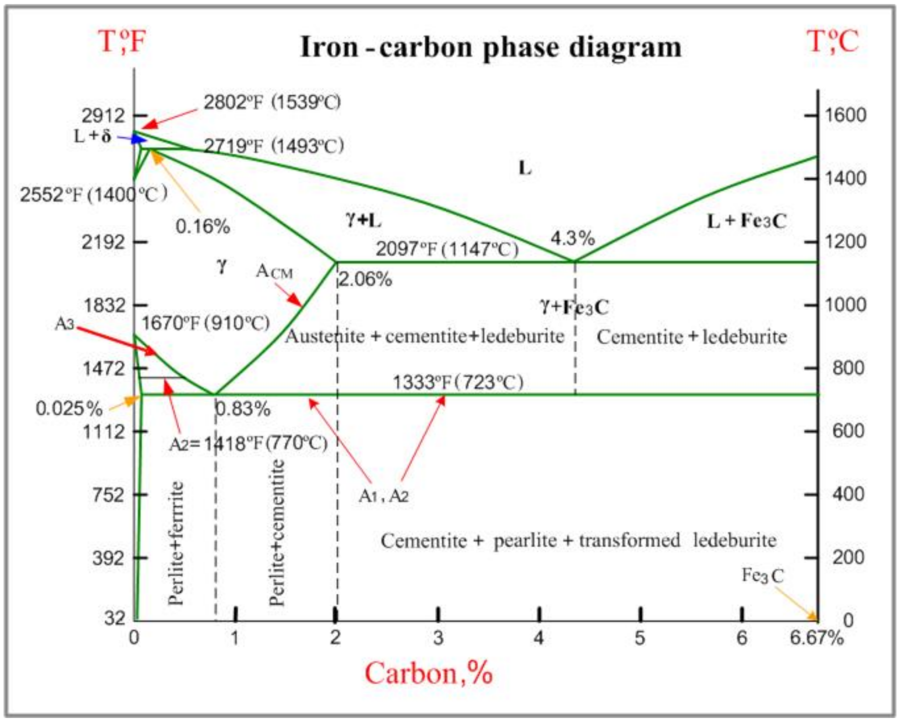


FIGURE 11. A MODERN FE3C PHASE DIAGRAM
(HTTP://STEELGURU.COM/UPLOADS/REPORTS/FA1-29-03-2010.PNG)

Clearly, there is much more detail to the diagram with the actual processes, percentages, and temperatures needed for creating the steel is much more known.

A Swedish scientist by the name of Tobern Bergman realized that steel itself, and wootz steel in particular, is an alloy consisting of iron and carbon, and that Wootz steel has a very high carbon content (1-2%) in comparison to other steels (Srinivasan and Ranganathan, 73). It was originally believed that steel was just another metal element such as copper, iron, and silver. Because of the high carbon content, the wootz steel exhibits a crystalline structure outwardly. Interestingly, Damascus steel can be defined in two different ways: the creation of steel from smelting the high carbon alloy or by just welding iron and steel together to make the etching on the surface. The original Damascus steel is, of course, the first type mentioned. Classic

Damascus steel has very unique markings on the outer edge of the final item that is entirely natural, unlikely the pattern welded steel of modern times. The second type of "Damascus steel" is now popular because of the high difficulty in recreating authentic Damascus steel but is created much differently through a process called pattern welding. The general method of creating the Modern Damascus is by smelting different types of steel together, drawing out the billet, then folding it back onto itself, which creates the sought-after layers (Casheenblades.com). Because the final product has the classic bands and patterns, it is widely accepted as just "Modern Damascus steel."

In India, as in Damascus, many of their weapons and armor were made from the wootz steel that they manufactured. Because of the steel's resilient properties, along with being so pure, weapons were able to be thinner and more curved. Damascus steel has an incredible ability to be flexed without breaking. The ancient Indian Tulwar is an excellent example of the curved blades of Damascus steel. This curve is accomplished by striking the iron, rather than using a "form." That can only be accomplished with malleable metal and the nature of this iron allows this malleability.

FIGURE 12. INDIAN TULWAR.

(HTTP://WWW.ORIENTAL-ARMS.CO.IL/PHOTOS/ITEMS/57/002757/PH-0.JPG)

Along with the composition of Damascus steel, the way the steel is created or treated is incredibly important. Depending on the way that it is treated, the hardness can vary wildly. Treatments such as case hardening, discussed in our earlier section in regards to European swords, is one example of the way the quenching of metal can cause dramatic changes in its microstructure and ability to bear stress.

Many recent experiments have attempted to recreate the original, ancient Damascus steel, however, most attempts at perfectly recreating the unique patterns of years past have not been successful. Even Michael Faraday, one of the world's greatest scientists and the father of electricity, tried but was incapable of recreating wootz steel (Srinivasan and Ranganathan, 70). He is still considered a great master of metal alloys, despite this fault. There are, however, a few documented cases of properly recreating Damascus steel and one account came from Russia in the early 1800s but there is not very much information regarding the way they carried out the process.

As stated earlier, the processes that actually created the Damascus steel was lost over the years, essentially ceasing entirely around 1750 AD. Historians do not know for sure why the methods for creating Damascus steel suddenly vanished, but they certainly have their own theories. The primary theory is that the demand for Damascus weapons was consistently decreasing for years with the invention of new weapons and steel-making techniques and this definitely contributed to the total loss of the creation process. Along with the new technology, historians also believe that there were many other historical reasons for the decline of Damascus steel. These include the possibility of deteriorating trade routes, loss of technical knowledge derived from loss of communication and secrecy, and also from the fact that their British rulers discouraged Indian trade of the wootz steel ingots (Burton, 111).

4.3 Cultural Impact of Steel in India

4.3.1 Steel and Religion

The ties from religion to the art of blacksmithing were deep and pervasive through society. Smiths were placed in the class of artisans along with carpenters, bronze-workers, and sculptors; all of which were regarded as originating from the God *Viśwákarma*, that is the God of Architecture and Engineering (Jaikishan & Balsubramaniam, 482). Along with the God of Architecture, blacksmiths also heavily worshipped *Mammayi*, the Goddess of Metal-Work. At the beginning of each Telegu New Year, blacksmiths take their tools and put them aside for nine days to offer prayers to *Mammayi* (Jaikishan & Balsubramaniam, 485).

4.3.2 Social Hierarchy of Steel

Culturally, the mining, creation and trading of steel had massive impacts in all of the areas where steel production dominated. Social hierarchies were created and producing wootz steel was not just an export, but a way of life. Typically, the way communities were set up was by having one community set up with the basis of extracting the iron ore, building the furnaces, and doing the smelting of the material while another did the actual working of the iron (Jaikishan & Balsubramaniam, 482). In addition to the extracting and iron working communities, there was also trading communities that actually took the material and traded with trading companies and surrounding villages. Blacksmiths were looked upon as high-ranking members of the social hierarchy because of the importance of their work and were generally accepted as higher in the hierarchy than the members of the iron extracting community. One major reason that blacksmiths were regarded highly was because they had strong ties with the ruling class because of their ability to create weapons that were needed for war.

4.3.3 Steel and Trade

Wootz steel was a major country export as the world progressed into the imperial age. Based off records from the Dutch East India Company, there was a significant trade route that took wootz steel out of the region (Jaikishan & Balsubramaniam, 489). Much of the steel exports went to ports along the Red Sea and then inland to areas such as Damascus (Chandra, 112).

There are a few accounts from the reign of Alexander the Great that he was presented with 100 fine Indian weapons around 300BC (Srinivasan and Ranganathan, 68). The Greeks and Romans noted the huge amount of steel export from southern India.

Later on, Arabs took blocks of wootz steel to Damascus to manufacture their own steel, thus giving the name of Damascus steel. This established a trade route between southern India and Damascus where the Indians shipped out ingots of their wootz steel that eventually turned into the famed Damascus steel. This trade route continued for centuries. Although Damascus steel was the famed name, in the 12th century the Arab Edrisi said that the Indians were still the best manufacturers of wootz steel (Srinivasan and Ranganathan, 68). When the Europeans started visiting Asia, they were often quoted as saying that Indian wootz steel was far superior to European steel. Unfortunately there are not too many documents that share how the wootz steel was created, however, the strongest accounts of the crucible steel manufacturing came from travelling European traders from the early to mid-1800s (Srinivasan and Ranganathan, 69). They say that the manufacturing process was so efficient that huge shipments of tens of thousands of items were sent from the area, which is incredibly industrial for the time.

4.3.4 Weapons and Armor of India

One typical weapon that was created from the Damascus steel was Persian scimitars. It clearly exhibits the typical characteristics of Damascus steel with the thin, curved blade.

FIGURE 13. PERSIAN SCIMITAR.

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5. Japanese Smelting

5.1 Background

Due to the expertise required to produce, and the usefulness of the resulting tools, development of metal processing is a major step for any emerging culture. The more isolated and relatively metal free an area was, the more steel and iron tools were revered by the local population during their initial introduction. Japan's natural metal reserves are low, and the Japanese Islands were once extremely isolated. These two factors combined to create an historical culture which considered iron and steel tools to be nearly mythical in nature during the early 300s BC.

Before an import trade route was established, Japan's primary source of iron ore came from a sand called ironsand. Ironsand is a byproduct of the erosion of granite. In some areas such as New Zealand, ironsand can be found as in beaches and other coastal features where the sea has abraded the shoreline. In Japan however, it is found almost exclusively in mountainous regions.

Ironsand is considered to be highly impure, since it contains much more sand than useable ore. The best ironsand found in Japan has an iron content of only 2.5%. This necessitated that an ancient smith either transport tens of tons of raw material or that they assemble their smithy near a large source of ironsand. Since there were limited sources of ironsand and therefore a limited number of active metal workers, the cultural respect for these workshops was enormous.

5.2 The Tatara Furnace

Once collected, the ironsand is shoveled by assistants through a specialized furnace. Shown in Figure 14, the traditional Japanese furnace that was called a "Tatara".

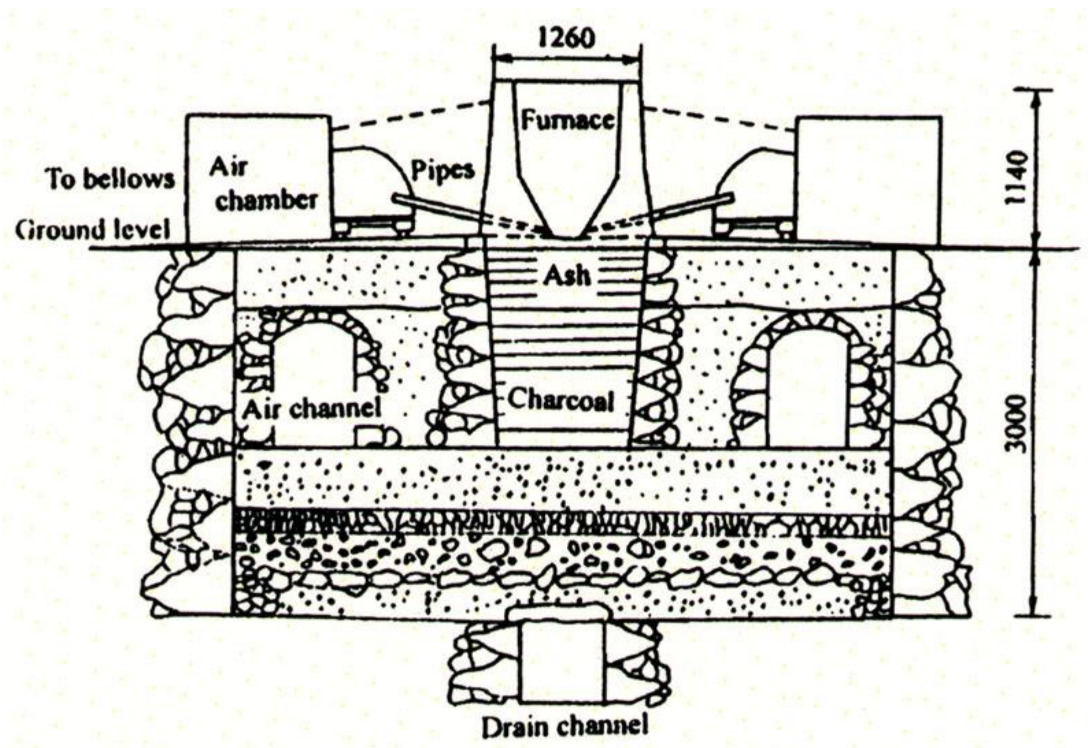


FIGURE 14. A TATARA FURNACE (INOUE, 194).

The tatara furnace, shown in Figure 14, functions similarly to the norther European furnace discussed in section 3. The key differences in the Japanese method stem from the longer time needed to complete a smelting of ironsand. A tatara furnace was often run for days or even weeks. This necessitated the construction of a shelter and an underground air system in case of inclement weather.

Heat for the tatara furnace was generated though the burning of charcoal. Air channels, pipes, and bellows transmit high flowrate atmosphere through the tatara, increasing the temperature at which the fuel combusts. Yoshindo Yoshihara writes “The furnace, which consists of a rectangular box constructed from clay, incorporates an elaborate underground structure to prevent heat radiation and moisture absorption.” (The Art of the Japanese Sword, 112)

The Operations of a tatara requires several assistants as well as at least one smith. The bellows must be run nearly constantly to maintain the necessary temperatures, and ironsand and charcoal must be poured into the open top of the furnace at regular intervals. The workers often form pairs to operate the large bellows on either side of the combustion area, alternating their efforts to avoid exhaustion. The underground drain channel allows the molten slag and metal to run out through the bottom of the furnace, creating additional space for new materials to be added to the forge. The run-off which escapes through the drain channel then cools and solidifies, where it can be sorted into useful material and useless slag. Iron generated in this fashion is sometimes put back into the fire in order to further purify the metal.

Because the charcoal burned is high in carbon and other trace elements, the “iron” refined from this process absorbs impurities. These impurities allowed ancient smiths to produce a metal which although no match for modern steels was certainly much more durable than a virgin or un-enriched iron.

	TiFe	FeO	Fe_2O_3	SiO_2	P	S	CaO	MgO	V_2O_5	Al_2O_3	TiO_2
Virgin	3.46	0.91	3.99	68.32	0.026	0.002	22.26	0.86	0.03	17.26	0.42
Enriched	60.43	22.03	6.19	7.68	0.080	0.021	0.90	0.37	0.30	2.38	0.93

(wt%)

FIGURE 15. IMPURITIES IN TATARA STEEL (INOUE, 196).

Figure 15 describes the compositional differences between a sample of virgin iron and a sample of enriched iron. As may be seen, trace impurities have been inherited by the iron during the stages of smelting. Despite most of these impurities being present only in small percentages, the trace elements in a steel alloy have a significant effect on the metals properties.

To an ancient Japanese smith, the most relevant of these properties would have been those which effected the forging and application of weapons. Insufficient hardenability would render a steel too soft for violent applications, while too much embrittlement or insufficient impact resistance would create a weapon prone to shattering. Figure 16 shows how increasing or decreasing concentrations of trace elements effects the hardenability, strength, ductility, impact resistance, and temper embrittlement of steel and iron alloys. Not included in the Figure is Carbon, the addition of which increases the overall toughness of the steel.

Property	Cu	Ni	Cr	Mo	Sn	Sb
Hardenability	+	+	+	+	+, 0	+, 0
Strength/hardness	+	+	+ / -	+	+	+
Ductility	+	+ / -	+ / -	-	-	
Impact resistance	+	+	0	-	0, -	
Temper embrittlement					+	+

FIGURE 16. EFFECTS OF TRADE ELEMENTS ON ALLOYS (INDUSTRIAL HEATING RSS, 2).

In order to ensure that the most slag possible was removed from the ironsand during smelting, the process was carefully regulated. The ancient Japanese smiths divided the procedure into four main stages or phases of refining. Figures 16 and 17 show the lengths of time and the heights of flame, which are needed for the first two stages.

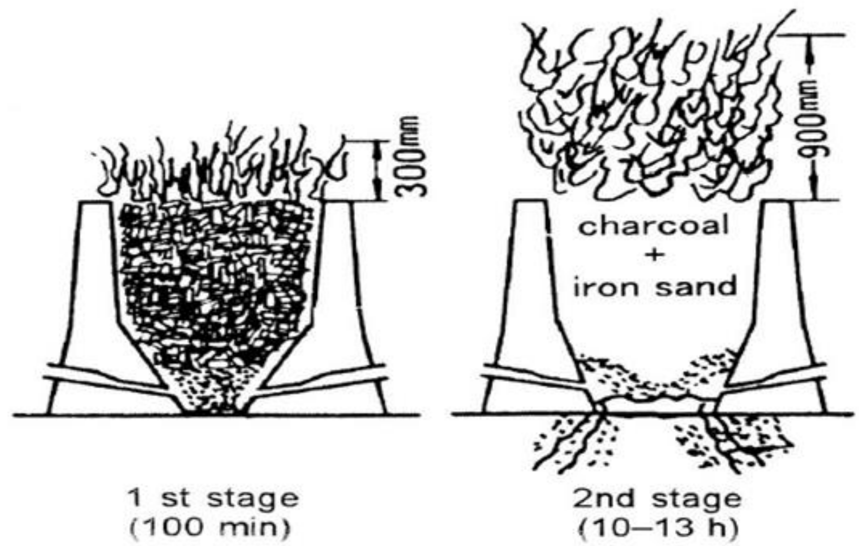


FIGURE 17. TATARA FURNACE STAGES 1 AND 2 (KITAMURA, 278).

During the initial stages, called the 1st and 2nd stages, the ironsand is undergoing its initial heating and settling. This is the time when the most readily removed slag runs off through the drain channel, leaving a hot and condensed core. What results is a material which is a mixture of molten and heated iron and the toughest elements of slag. The next two phases combined will take over three times as long as the first two. A visual guide to steps three and four may be seen in Figure 17.

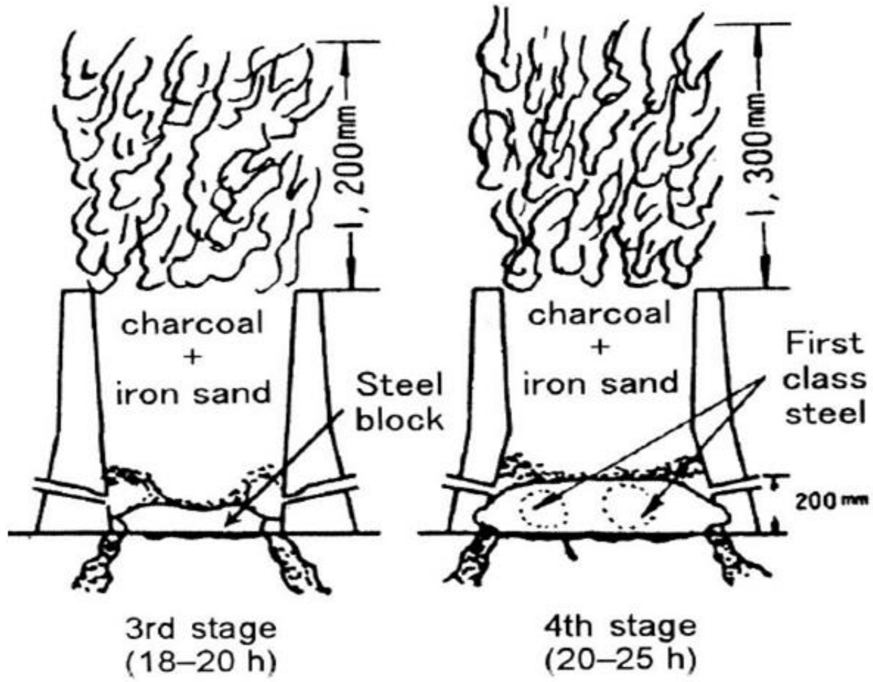


FIGURE 18. TATARA FURNACE STAGES 3 AND 4 (KITAMURA, 278).

The next two, longer, stages, attempt the difficult removal of the most durable slag and are referred to as the 3rd and 4th stages. These phases also melt all the remaining iron together, concluding the first steps needed in producing ore.

The metal which this method produces has enough impurities to make it comparatively superior for ancient applications to a more pure iron. For this reason, one may refer to the harvested material as steel once it has left the oven. This steel is traditionally known as "Tamahagane". A comparison of trace elements between modern forged steel, core steel, and traditionally recreated Tamahagane is shown in Figure 19.

	C	Si	Mn	P	S	Ni	Cr	Cu	Ti
Tamahagane	1.05	0.01	0.01	0.029	0.002	Nil	Tr	<0.01	0.003
Forged steel	0.54	0.03	<0.01	0.029	0.005	0.001	<0.01	0.01	0.008
Core steel	0.28	0.02	0.02	0.029	0.007	0.001	0.01	0.01	0.008

(wt%)

FIGURE 19. IMPURITIES IN TAMAHAGANE STEEL (INOUE, 196).

The data in Figure 19. Impurities in Tamahagane steel (Inoue, 196). shows the inadequacies of Tamahagane. The ancient metal's high carbon content made it brittle and difficult to work with, often necessitating complex differential heat treatment procedures in order to make tools which would be relatively simple for smiths from other cultures to manufacture using better quality metals. Almost completely lacking in chromium, Tamahagane has very little corrosion or weather resistance, making it extremely prone to oxidation. Despite these failings, Tamahagane was among the finest metals ever made by traditional Japanese methods.

5.3 The Cultural Impact of Steel in Japan

5.3.1 Steel and Religion

World religious beliefs can vary widely, sometimes to the extreme. This uniqueness is often especially true for historical religions, which developed on isolated or nearly isolated islands. One example of such diversity is Shintoism, a religion initially developed in Japan. According to William Deal, author of "Handbook to Life in Medieval and Early Modern Japan," the oldest written work from Japan is known as the Kojiki. This work is also one of the oldest religious artifacts of Shintoism, and provides an explanation of the Japanese religious context of metals, as summarized below.

The Kojiki recounts a Japanese creation story. The tale relates the Sun Goddess Amaterasu to the royal family, claiming that the emperor and his family are descended directly from the mythical creators of the islands. This belief system is known as Shinto, and is believed to be the indigenous religion of Japan.

Shinto belief also holds that the Imperial family may be identified by their objects of authority, as in many western religions. William Deal recounts his findings on this subject from the Kojiki.

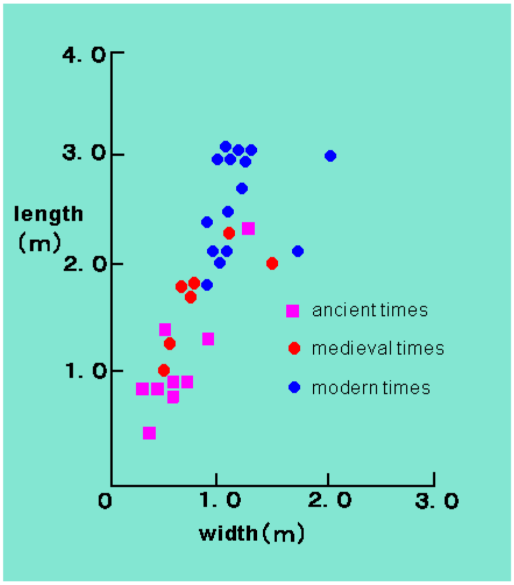
"All Japanese emperors are said to descend from this sacred beginning with Amaterasu. The Three regalia-mirror, sword, and jewel-the symbols of imperial ruling authority, are said to have originated with Amaterasu who started the tradition of passing these symbols to each subsequent ruler." (Handbook to Life in Medieval and Early Modern Japan, 191)

As two out of Shinto's three symbols of power are metal, and these objects are said to come directly from the creators of the land, as are their owners, this passage shows the importance of metals in Shinto beliefs. Further analysis may be made according to the nature of the metals these symbols are made from. Poorly refined materials would have been nearly impossible to polish into a mirror using the technology of the day. A usable sword capable of holding an edge would also have been a nearly impossible task, as can be seen from the methodology section of this report.

With a source such as the Kojiki claiming such divine properties for steel and its owners, it can be said that steel and its rarity in Japan played a formative role in the regional religious beliefs and traditions of the time.

5.3.2 Social Hierarchy of Steel

The cultural ramifications of this extreme steel rarity were significant. One of the most visible results was that smiths in Japanese society were treated with growing respect. In fact, as Japanese metalworking technology developed, the ancient smiths were able to build larger and more efficient Tatara, improving their societal position even further.



Changes in Furnace Length and Width

FIGURE 20. VARIATIONS IN SIZE OF THE TATARA FURNACE ("ABOUT TATARA", 1).

Figure 20 shows this growth effect extremely well. This graph makes it apparent that the forges have become even wider and longer as times have passed from ancient to medieval to modern.

One of these modern tatami was made by Tatsuo Inoue, a registered sword smith who uses these ancient techniques to make weapons and tools in the traditional Japanese manner. He writes:

"Almost all Japanese swords with some exceptions are made of Tamahagane steel, or noble steel, specially prepared by the tatara system by use of iron sand, but not by normal ore as seen in the old painting (see Figure 21.)" (Inoue, 193)

The old painting which this quotation references, shown in Figure 21, is of another tatara being used. This system is refining normal Ore, and Inoue is attempting to point out the rarity of this event, saying that the vast majority of the time smiths in Japan would have to use the natural ironsand reserves found on the islands.

FIGURE 21. IRONSAND READY FOR THE TATARA (INOUE, 194).

This excerpt serves to reinforce the difficulty of producing steel in Japan, but Inoue's main effort with the above phrases was to make it clear that nearly all swords were made of steel provided by this method.

This fact further reveals the high degree of cultural respect which was and still is felt for smiths in Japan. To be an ancient Japanese smith was to be one of a very few providers of swords in an area with a war strewn history. In fact, because swords were in such a high demand in Japan, nearly all steel manufactured was used for building these weapons. Because of this, the development of the traditional Japanese sword or "Katana" is an excellent way to show the advancement and societal impact of steel in ancient arms and armors.

In the Japanese tradition, it was believed that a portion of the blade smith's soul entered and resided in the blade, making its home there upon the final quenching of the blade. Accordingly, the preparation for the final quench involved prayer, meditation and ritual to prepare the blade smith, since the state of his soul at the time of the quench would live on in the finished blade. This belief in the spirit residing in the blade went so far that when Tokugawwa Ieyasu became Shogun in 1603, the use and carry of blades made by the swordsmith Muramasa was banned, since the Shogun had been the target of assassins who had borne blades made by Muramasa. Muramasa was later vilified in the Japanese tradition, and his blades gained a reputation for being particularly evil or bloodthirsty. It was even claimed that he quenched his swords in blood, so that once drawn they could not be put away until they had spilled blood again.

5.3.3 Steel and Trade in Japan

The Katana's development was also strongly affected by the influences of other Asiatic cultures during the early 300s BC. This may be seen in the relatively sudden advancements in Japanese smelting techniques, as well as in the addition of higher quality materials from areas such as China and Korea. The opening of these international trade routes also brought about the adoption of rice cultivation techniques, including metal tools for agriculture. These adaptations marked the beginning of the Yayoi period of Japan's history, which is currently considered to be from 900 BC to 250 AD. Before the Yayoi period, the islands inhabitants were known as the

Jomon people. Martin Colcutt wrote about these ages and cultures in an article for the Japan Society:

"The Yayoi period also saw the extensive use of metal. Practical iron tools from Korea (such as axes and knives) have been found in the oldest Yayoi sites in the western part of Japan and even in a Jomon site from the same period in the northern island of Hokkaido. Ritual bronze objects such as mirrors, swords and spears also came from China and Korea. Eventually the Yayoi people learned to mine, smelt and produce these items on their own. One example of this local manufacture was the bronze, bell shaped objects known as dotaku. The idea for these objects may have come from the continent, but they quickly developed into a uniquely Japanese style. They appear to have symbolized divine spirits, and hence to have been used for religious fertility symbols." (Colcutt, 1)

Colcutt's quotation serves to highlight Japan's adoption of Chinese and Korean metal work, as well as mentioning the stylistic adaptations made by the Jomon people. The use of bronze in fertility symbols is of special interest, since the scarcity of refined metals prior to the Yayoi period would have made such decorative uses of metals extremely rare. Charles Higham gives further information on the cultural changes wrought by the new techniques and materials.

"The establishment of Chinese provinces in the northern Korean Peninsula conveyed knowledge of bronze and iron closer to the Japanese islands, and with Yayoi bronze spears, halberds, swords, mirrors, and bells appeared. In each case, the imported items were transformed by local bronze casters into forms more suited to local tastes and requirements. Thus the weapons were enlarged and broadened. The mirrors became smaller, and the bells greatly enlarged. The Yayoi bell is a notable achievement of bronze casting, with its decorative scenes and, in the largest example, a height of 1.35 meters. Much if not all the metal cast in Japan appears to have originated in imported items that were recycled or copper ingots. Earlier bronzes employed Korean metals; later smiths preferred Chinese sources. The same applies to iron. There are rich iron-ore sources in southern Korea, and finished products were traded south into Kyushu and western Honshu. Iron tools and weapons are regularly found in Yayoi sites, but not in great quantities, and local smelting does not appear to have been commonplace until after the end of the Yayoi period." (Higham, 404)

Since the ancient Japanese were largely seeking to import metals, there was very little export in steels or other refined materials leaving Japan. Instead, Japan as a whole tended to trade away goods, which required relatively few resources but a high degree of skill to manufacture. Art of all kinds was especially successful as a trade good, since the Japanese craftsmen of the time had, as mentioned in Higham's writing, unique stylistic preferences which made their work both interesting and highly limited in availability.

As a whole, Japan's pre-modern trade with other nations served to export goods specific to the islands culture while importing materials which were rare or difficult to produce locally.

5.3.4 Japanese Arms and Armor

In addition to making smiths legendary figures of society, the scarcity and relatively poor quality of Japanese steel had its greatest effect on the forging and form of the Japanese katana and armor. In the case of the katana, this effect was to make it comparatively extremely difficult to make swords. Because of the steels aforementioned brittle qualities, longer weapons required a specially softened core to avoid shattering or sheering during impact. This quality was especially necessary in weapons wielded from horseback, since the forces involved are much greater than those found in non-mounted combat. The inherent problem with this soft-core approach is that a sword must also be hard enough to hold an edge through repeated uses during a battle. The Japanese smiths were able to circumvent this problem by covering the spine of a weapon with clay prior to heat treatment. This extra insulation of the Yamahagane created a brittle edge while leaving a soft spine during the forging of a blade.

Before the Tamahagane can be used in a sword however, it must first be hammered into a plate, crushed, and reformed into a flat plate or block with a protruding tang for handling. This plate, traditionally called a "Tekoita" is then repeatedly notched, folded, and reformed until the steel is malleable and ductile enough to be formed into the shape of the blade. The diagram in Figure 22. Forging tamahagane steel (Inoue, 195). details the steps of the procedure.

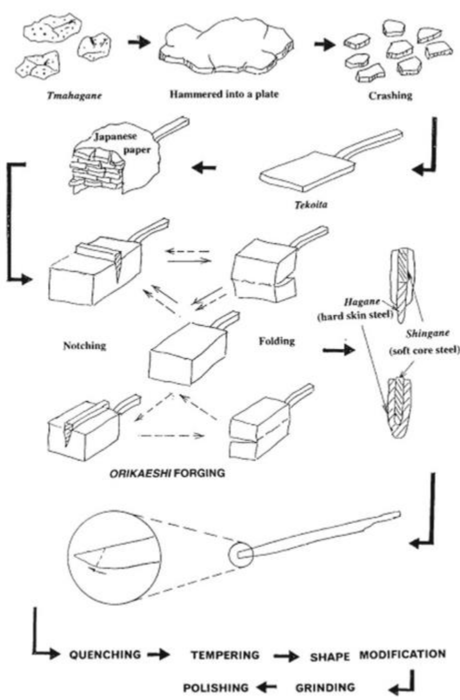


FIGURE 22. FORGING TAMAHAGANE STEEL (INOUE, 195).

Once the blade is in shape, heat treatment is applied only to the edge of the blade, so that the spine of the blade will remain flexible and durable. This is done by covering the spine of the blade heavily with clay to protect it from the heat which is then applied to the edge. Once finished, the Katana displays properties, which although impressive for the resources available to the Japanese, would none the less have compared poorly with swords from Europe or India.

Since steel was such a rarity, handles and guards on katana were often made of wood, woven rope or cloth, or other more available materials. This trend is also displayed in the second major effect of Japan's steel scarcity. Because every possible scrap of metal was needed for making actual swords, there was little to none left over for armor. The images below show the ingenious solution which the Japanese were forced to adopt.

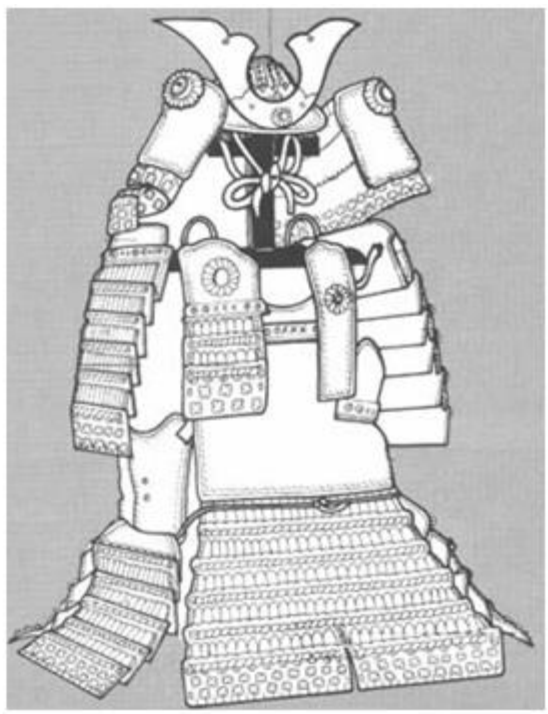


FIGURE 23. SAMURAI ARMOR (MILITARY PROTECTION IN JAPAN, 1).

This lack of metals led to the Japanese development of an armor called "lamellar armor". This was a protective layer made from many pieces of bamboo or wood. The pieces were strung together through holes in the plates into the desired shapes.

Figure 24 shows a photo of lamellar plates before they are added to a suit of armor. These plates are not strong, and even with several layers they provided only marginal protection against a blade.

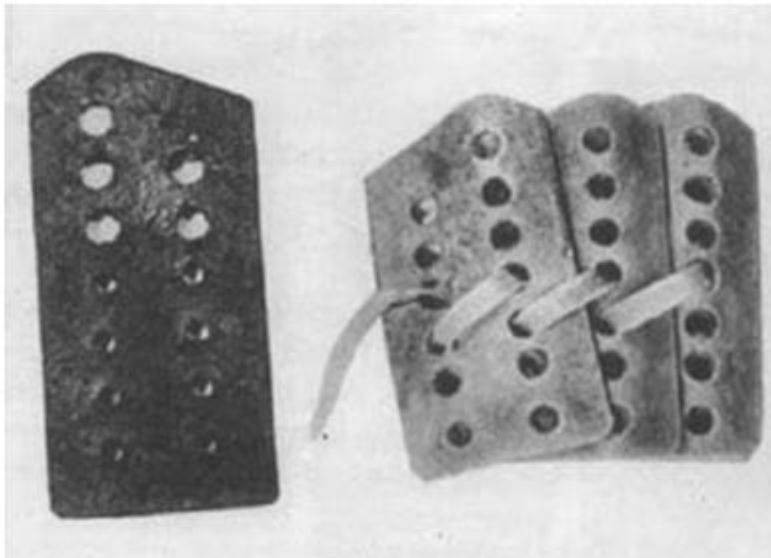


FIGURE 24. LAMELLAR PLATES (MILITARY PROTECTION IN JAPAN, 1).

6. Comparison of All Three Regions

A comparison of our selected regions of the world show the way that the availability and quality of steel in a region can have profound effects on each region's culture, and the volume and type of materials produced in the region. While all of the cultures discussed developed steel production independent of each other, the similarities between them show the importance of good steel as a resource for both military and civilian applications. In order to explore the similarities and differences between these regions, we will compare each region in the context of the areas discussed previously, specifically: religion, trade, and the actual objects produced by each region.

6.1 Religious Comparisons

Steel and metalworking find a place in the religious traditions of all of the cultures we have discussed. As noted, all three regions had indigenous religions with dedicated deities of smithing. These deities tend to be associated with the very primal forces of creation, and produce many incredible items. Examples include Ilmarinen creating the Sampo, a magical mill that produced grain or salt, the dwarves of Norse mythology creating the hammer Mjolnir and the spear Gungnir, the Japanese Goddess Inari helping to create the sword *Kogitsune-maru*, and the creation of Lord Shivas golden palace by Vishvakarman.

A distinction can be drawn between northern European and Japanese weapons in regards to the spiritual significance of swords. Magic swords, as we have already discussed, are abundant Norse and Japanese tradition. An important difference between the two, however, is that in the Norse tradition, magic swords were the exceptional case, rather than the rule. These swords, imbued with special powers or properties, were the swords of legendary heroes or powerful kings or nobles. Whereas in Japan, the soul of the smith resided in the blade, therefore, there was a culture of spiritual significance around all swords. The Dainsleif blade, made by the Dwarves, was cursed so that once drawn, it could not be put away until it had killed a man. Compare this to the ban on all blades made by the smith Muramasa, whose swords were said to have similar bloodlust. In the Norse tradition, the Dainsleif is an exception, a singular magical sword from myth. In the Japanese tradition, an entire generation of blades from a real swordsmith was banned.

This difference between Norse and Japanese tradition can be accounted for as a result of the scarcity of steel in the given regions. In Japan, steel was quite difficult to make, and that which was made was of poor quality. The relatively small number of swords made were expensive and rare to the degree that the sword was a status symbol of the imperial house. In Northern Europe, steel was comparatively plentiful and of relatively better quality. While a sword was still an expensive status symbol, steel in general was more prolific in society, so while a sword was expensive, it was not as incredible an object as in the Japanese culture. Warriors in the Norse culture would be buried or burned with their swords, where in Japan the blades would have been passed down family lines as artifacts or heirlooms, since a sword in Japan was a much more significant expenditure of resources.

6.2 Trade and War Comparisons

Steel, whether in the form of weapons or raw material, had a significant impact on the development of trade routes, influencing both the waging of war and by more peaceful means. India, by virtue of its sizeable steel industry, was able to build a trade network reaching from India, through the Middle East, all the way to Europe, with Damascus steel ending up in the hands of the Vikings. The large quantity of steel that India was able to produce, coupled with the superior quality of the steel, made it a valued trading item from antiquity through the 1800s, when the secret of making Damascus steel was unfortunately lost. The quantity and quality of steel produced exceeded that of either Europe or Japan, which allowed for a booming trade which was not constrained by the need to use all of their steel to arm and produce tools for their own people.

The Vikings of northern Europe bear consideration for the complexity and reach of both their trade routes and their raids. As recorded by Ibn Fadlan, Viking trade routes down the Volga River stretched far enough to interact with traders from India and the Middle East. This allowed the flow of Damascus steel, while not in large quantities, all the way back to Northern Europe. Viking raids were able to terrorize Western Europe, including France and England, and colonies were established in England, Ireland, and as far as Nova Scotia. This culture of war was made possible by an industry of iron and steel production that allowed this warrior culture to thrive. While the Viking lands of Norway and Sweden were poor in arable farmland, bog iron production allowed the Vikings to arm and equip the men necessary for colonization and territorial expansion in search of better farmland.

6.3 Quantity and Quality of Materials Produced

The quantity and quality of good produced is the easiest and most telling comparison between the regions we have examined, since the goods produced are a direct reflection of the material available to produce them. The most striking difference to be seen is that between the development of arms and armor in Japan versus Europe. Looking specifically at armor, in Europe we can trace the evolution of metal armor from chain and scale mail all the way to advanced full plate armor that could cover an individual from head to toe in steel. Japan saw no such development in armor, even members of the nobility and rich, powerful samurai depended on lamellar armor made of lacquered bamboo or wood for protection. This distinction is due to the staggering difference in quantity of steel available in the two regions. A suit of European full plate could weigh as much as 50 kg, the approximate weight of 50 Japanese katanas. If steel was in such short supply that the katana was valuable enough to have its own soul, then how huge a price would a suit of full plate fetch in Feudal Japan?

7. Material Properties

7.1 Material Science Background

54Apart from the history of ancient arms and armor, it's exceedingly important to understand the science of the particular materials that our team is using. Since we do not know the exact composition of our material, it is needed to some experiments to better understand what the material is.

As seen earlier, the primary elements going into the creation of this material is Iron and Carbon (Fe_3C). When brought together, these two elements can form many different materials that are dependent on the percentage of Carbon, cooling processes, etc. Looking at a Fe_3C diagram, it is much easier to visualize.

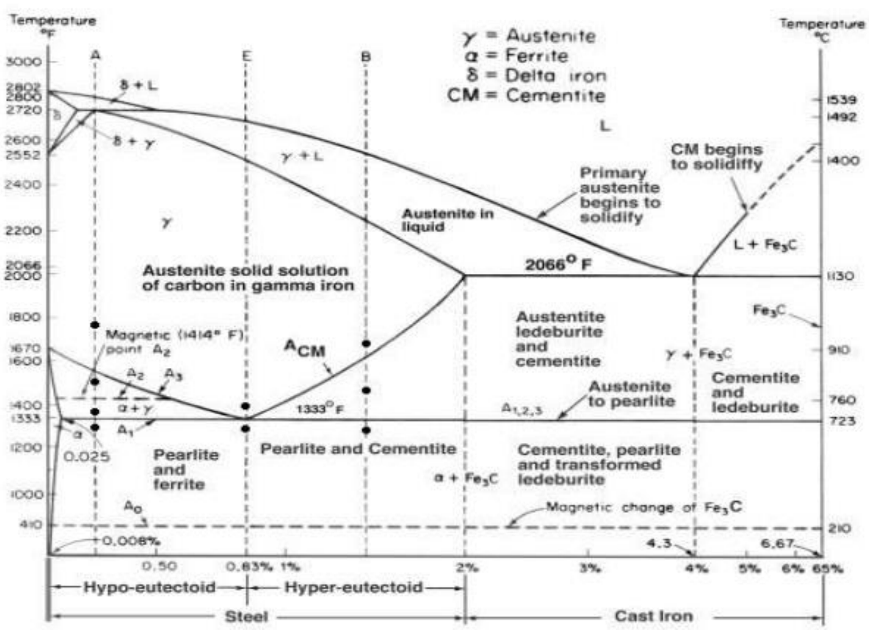


FIGURE 25. FE-FE3C PHASE DIAGRAM.

(HTTP://GLADIUS.REVISTAS.CSIC.ES/INDEX.PHP/GLADIUS/ARTICLE/VIEWFILE/218/222)

When looking at each of the steels seen on the Fe_3C Diagram, they all have different microstructural properties that give them very different properties that allow for various applications. On the chart, there is pearlite, austenite, cementite, and ferrite.

Before speaking about the microstructures of these individual steels, knowing what is used to classify these materials is imperative. Typical descriptions of material include hardness, carbon percentage, and crystal structure. Looking at the research done by Alan Williams, we can now delve deeper into the different steels that are created by Iron and Carbon.

Pearlite is a mix of iron and iron carbide with a maximum carbon percentage of .8% and a hardness of 250-300 VPH. Conversely, martensite microstructure has tendencies to have triangle symmetry with hardness varying between 200 and 800 VPH depending on the carbon content. Cementite is purely iron carbide (Fe_3C) and is frequently found with pearlite in both hypereutectoid and cast iron materials. Crystals of ferrite is entirely pure iron and has a hardness of 80-120 VPH. This pure iron is not made harder by quenching. Based off this same research, the carbon content of several ancient European steel weapons were seen to vary from .2% to .75%, which allows for many different types of steel (Williams, 123). This lack of consistency in metallurgy aligns with the lack of written records and many sites of metal creation.

7.2 Predicted Material Properties

Prior to examining the microstructure of our finished billet, we predicted what form it would take. Preliminary testing done by Professor Lados showed that the steel had a carbon content of 1.5 wt%, so we were able to use that information along with information about our method of cooling the billet to make our predictions about the microstructure of the steel. The 1.5 wt% Carbon makes our steel hypereutectoid, meaning that if it cools slowly from a high heat, it should begin to form pro-eutectoid cementite, followed by eutectoid ferrite and cementite, which is called pearlite. According to our calculations using the lever rule, and the iron-carbon phase diagram, our billet should show a microstructure containing approximately 11.5% pro-eutectoid cementite and 88.5% eutectoid pearlite. Since we allowed our billet to cool over a long time at room temperature and did not quench it, it should follow the phase diagram reasonably closely, and we should not see the formation of any martensite.

7.2.1 Material Cooling Rate

Following the smelting of the steel, the team hammered and folded the billet at a very hot temperature of 2200ºF. Once the slag inclusions and impurities were beaten out, the team began its cool down process. Our temperature estimates are based on the color of the material as it was heated and cooled.

In our process, we allowed the sample to air dry starting at around 2200ºF (1200ºC) that after 30 minutes cooled to about 1000ºF (540ºC). Josh needed to close the shop at this time so the team quenched the hot billet into water, bringing it to room temperature. The process is shown in Figure 26. .

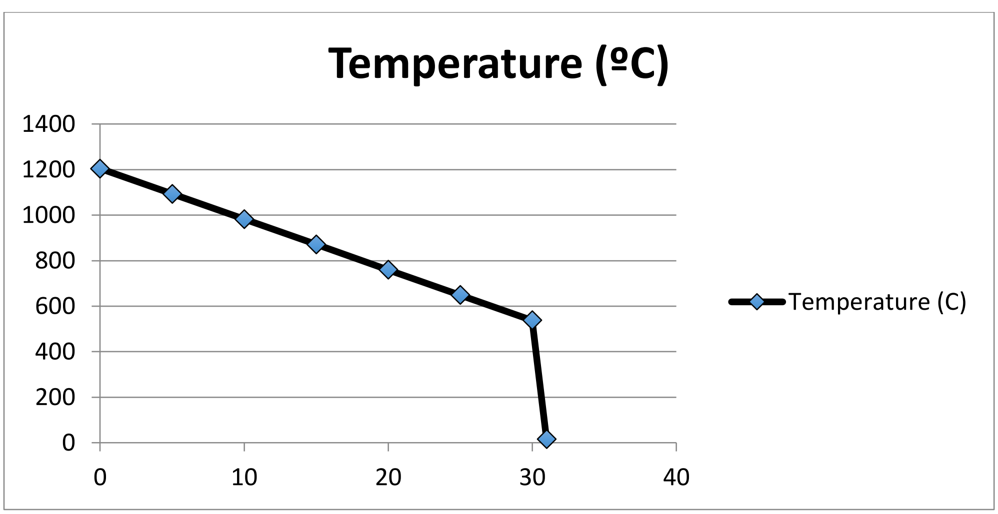


FIGURE 26. TEMPERATURE VS. TIME.

7.2.2 Phase Calculations Using the Lever Rule

Even though it is hard to tell what the sample's material properties are, we looked at the Fe_3C diagram and used the lever rule to create some predictions.

We chose a carbon percent of 1.5% as a prediction on where we believed the sample would fall after a carbon test. Because the sample cooled slowly enough, the calculated microstructures should be intact.

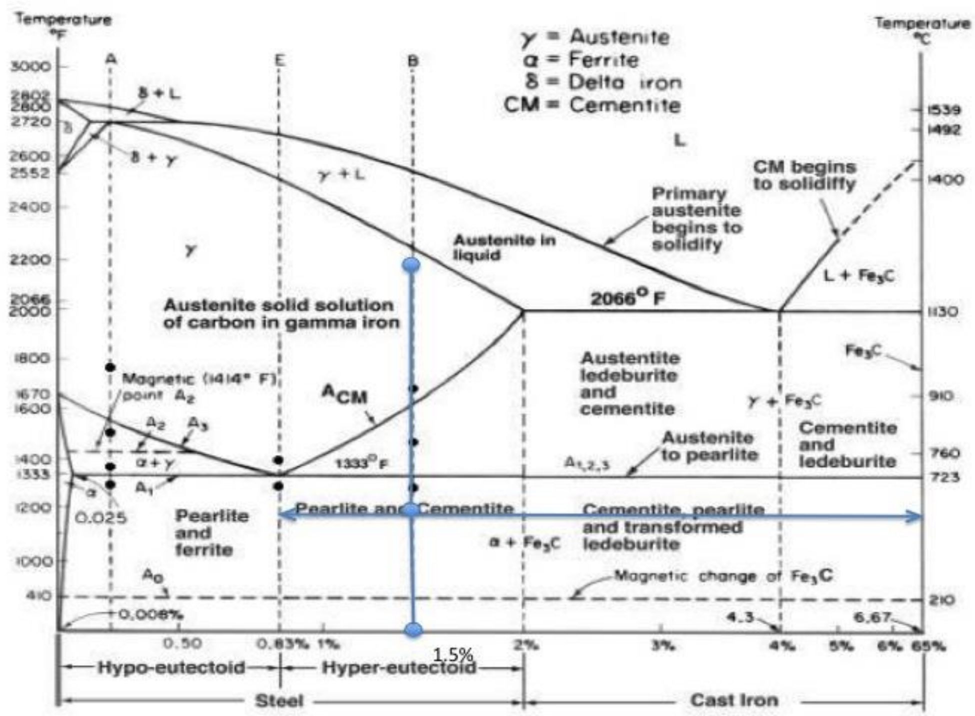


FIGURE 27. FE3C PHASE DIAGRAM WITH CALCULATIONS.

Calculations / Predictions:

Following the lever rule from the phase diagram in Figure 27, our predicted microstructural predictions are discussed next.

W_fPearlite = $\frac{6.67-1.5}{6.67-0.83} = 88.5\%$

$W_f Fe_3C$ = $\frac{1.5-0.83}{6.67-0.83} = 11.5\%$

7.3 Microstructural Characterization

Microstructures are the structures that are observed when a material is observed with a microscope. Understanding microstructures is another extremely important facet of discerning the material properties of our specimen because knowing the microstructure leads to the hardness, toughness, ductility and much more.

In the context of this project, looking into the microstructure of the materials on the Fe_3C diagram is vital. In these next figures, the microstructures of these materials will be evident. We will first look at Martensite.

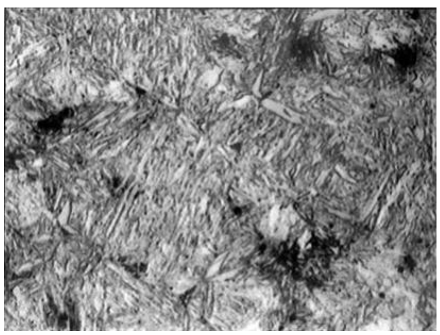


FIGURE 28. MARTENSITE MICROSTRUCTURE.

(HTTPS://UPLOAD.WIKIMEDIA.ORG/WIKIPEDIA/COMMONS/F/FA/STEEL_035_WATER_QUENCHED.PNG)

With the martensite microstructure, it can be seen how the crystals were not given time to settle as the structures are hastily organized and in no particular pattern.

The next microstructure that needs to be looked at is pearlite. Pearlite is a material that has a mix of ferrite and cementite that is typically used in insulating materials.

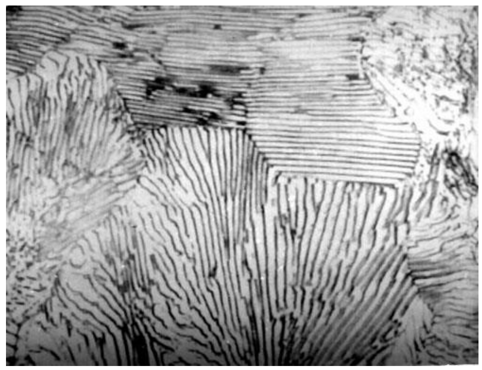


FIGURE 29. PEARLITE MICROSTRUCTURE.
(HTTP://HSC.CSU.EDU.AU/ENGINEERING_STUDIES/APPLICATION/CIVIL/1-1/PEARLITE.JPG)

The pearlite is more organized with bands of the ferrite and cementite with clearly distinct boundaries between the two. Pearlite is made by cooling the hot metal slowly, unlike quenching the material for fast cooling.

Another possible material from Iron and Carbon is austenite. Austenite is used for stainless steel and many other applications.

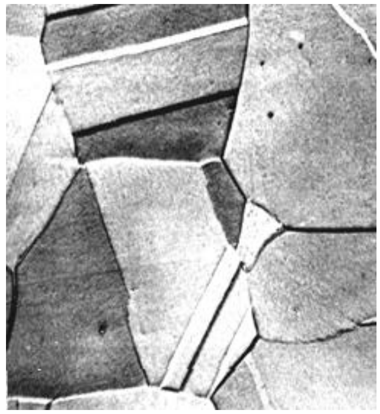


FIGURE 30. AUSTENITE MICROSTRUCTURE.

(HTTP://WWW.SV.VT.EDU/CLASSES/MSE2094_NOTEBOOK/96CLASSPROJ/EXPERIMENTAL/AUSTENITE.GIF)

Austenite has clear grain boundaries and out of the three microstructures displayed thus far, it has the most organization.

Another microstructure of interest is ferrite. Ferrite is a material that gives iron and steels their magnetic properties. Ferrite has a very low carbon content.

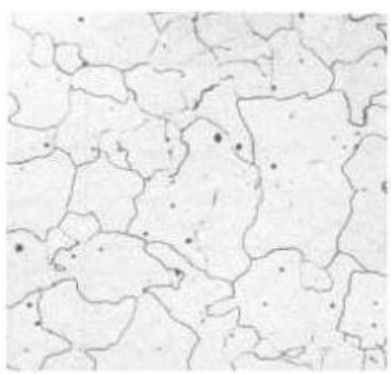


FIGURE 31. FERRITE MICROSTRUCTURE.

(HTTP://PRACTICALMAINTENANCE.NET/WP-CONTENT/UPLOADS/MICROSTRUCTURE-OF-FERRITE.JPG)

With ferrite, there are clearly defined boundaries but not as sharp as austenite's boundaries.

The final microstructure of note is cementite. Cementite is a crystal of Fe_3C, containing 6.67 % carbon (Callister & Rethswich, 335). It is hard and brittle, lending strength but not ductility to steels in which is it present. Cementite is one of the two crystal structures formed within pearlite, but it can also form on its own in the form of pro-eutectoid cementite when a hypereutectoid steel, one with greater than .76 wt% carbon, is heated above the eutectoid point and cooled slowly. Figure 28 shows an example of pro-eutectoid cementite.

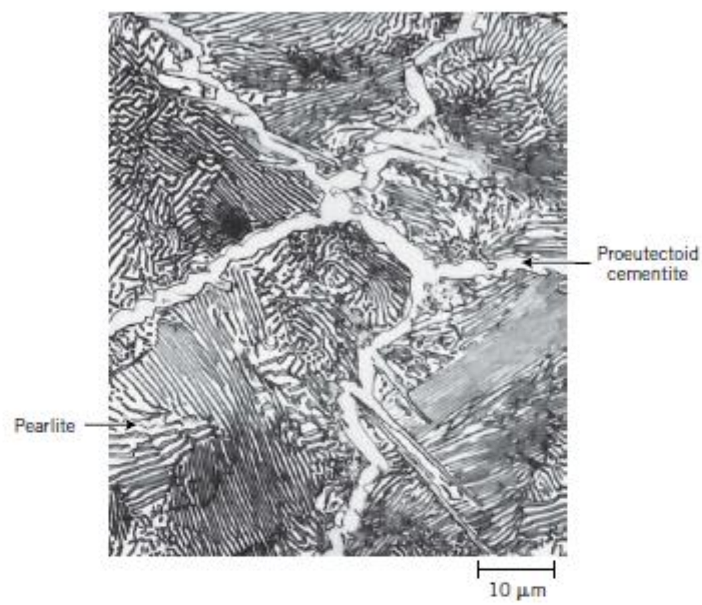


FIGURE 32. PRO-EUTECTOID CEMENTITE AND PEARLITE. (CALLISTER & RETHSWICH, 343)

Looking at these microstructures and understanding the material properties that correspond to them is extremely important in the creation of steel that has the properties that is needed for a particular application.

8. Our Research

8.1 Acquiring the materials

In our efforts to understand the labor and technology required in ancient iron production we decided to create and operate our own bloomery. This will provide us with hands on experience with the subject matter as well as providing us with historically accurate material to analyze. Of course we will only get these things if we replicate as close as possible what our research indicates was the historic method and materials. Our research grants us the method and a materials list, but the materials themselves need to be tracked down. And due to the anachronistic nature of our work finding what we need in sufficient quantities at reasonable prices was a small challenge in itself.

Firstly we need what lies at the very core of iron production, iron ore. For simplicities sake we had decided to create a European style bloomery furnace, as they are the most straight-forward in design. This means that the iron ore we would be seeking ought to be bog iron. Fortunately for our work bog iron is a reasonably common occurrence in northern climates. Unfortunately for our work it was the only local source of iron in New England and so was mined from colonization to the civil war, and to the best of our searching we could find no one selling bog iron ore. So we set out to find it ourselves.

The first step was finding an area to search. We already know that it can occur in bogs but there is only a chance that it will. The Bacteria that gather the iron together into clumps only occur in very specific conditions that are not entirely understood. Therefore to find locations to search in we turned to historic sources. There were a fair number of bog iron sources all across the region however we found that Brookfield, MA was a center of bog iron harvesting and refining in its time (Robert Wilder). We were lucky enough to have a group member with a home in the area with access to some promising bogs.

But a bog is a large area and there may be no iron there, we must look for signs of its presence and to determine if iron is in the area and to narrow down where to search in the bog. The signs include an orange sludge found at the edges or bottom of a bog pool, and a sheen on the surface of the water similar to that of an oil patch but with sharp edges that break apart when disturbed. Your odds are also increased if you search after a place where the flow of the bog goes downhill and tumbles over the rocks. (Wareham Forge) as this will oxidize more of the iron that has been leeched out of the rocks, meaning that when the bacteria inadvertently bring it in with their water they will quickly store it away to get rid of it.

We began to canvas the bog. Going out with sounding rods to jab down through the organic layer to see if we hit iron every 10 feet or so. We noticed promising signs of iron, seeing both the orange pudding and the iron based oil slick effect. Combined with our knowledge of this being a historical bog iron region we were certain there was iron about. However despite hours of searching we were unable to find bog iron. All we got for our trouble was black mud up to our biceps and water in our boots. The physical labor demanded of this process as well as the trial and error nature of the search confirm the very high value of iron in the Viking Age.

Fortunately for our search we got lucky in the sandy hummocks surrounding our search area, there had been a blowout revealing a seam of iron in the hill itself.

FIGURE 33. BOG IRON IN HILLSIDE.

It formed a horizontal layer about 3 inches thick of rust colored sand and rock. We collected a great deal of this for use in smelting. Though we were unsure as to its actual iron content at the time it must contain a fair amount as many rocks had enough rocks in them that they could be broken by hand.

FIGURE 34. ROCK WITH IRON CONTENT.

The next materials we needed were those for the construction of the furnace. And that means clay. Specifically clay mixed with sand and peat moss. For our clay we needed two kinds for our furnace. One which was highly fire resistant, and another which was a very sticky, binding, clay to hold things together. For this we used Foundry Hill Cream clay. The peat moss is mixed in as a binding material, it offers fiber to act as a lattice for the clay to attach to. It was a readily available material to people in northern climates, especially considering that the iron was already being gathered in bogs. The clay was purchased from Amherst Pottery Supply, and the sand and peat moss were purchased from a hardware store.

8.2 Constructing the furnace

With our materials in hand it was time to construct the furnace. The first step in construction is mixing our materials. With the clay and sand we are essentially creating a fire resistant cement which like all cement must be mixed and dried. We mixed our materials in the following amounts, 50 pounds of sand, 5 pounds of cream hill clay, the sticky bonding variety, 25 pounds of EPK Kaolin, and 1 pound of peat moss. After adding water and mixing our material came out to a heavy grey smooth mixture. In total we used 100 pounds of EPK kaolin, 300 pounds of all-purpose masonry sand, 50lb of peat moss, 50 pounds of foundry hill cream, and 48 firebricks.

FIGURE 35. MIXING CLAY.

At the same time as we were mixing the clay we constructed the plinth out of firebricks.

FIGURE 36. BASE FIREBRICKS FOR FURNACE.

This provides a base for the structure to be built on and by leaving several bricks un-mortared it provides a way of opening a larger hole to pull out the slag and bloom.

The next step was prepping the mixed clay for use. To do this we scooped up and compacted bricks out of the material and laid them on a tarp to dry.

FIGURE 37. CLAY BALLS FOR FURNACE SIDINGS.

The clay balls needed to dry since the water content was too high, meaning they were very soft. Had we tried to stack them to form the bloomer, they would have collapsed under their own weight. Separating them into bricks helps to speed the drying process by increasing the surface to volume ratio.

While the balls dried we constructed the frame that we would build the bloomery around. For this we used a concrete setting tube to provide a circular center, around which we placed loose wooden staves.

FIGURE 38 FURNACE STRUCTURAL SUPPORT TUBES.

The wooden staves' purpose is threefold. First, they expand the inner diameter to 18 inches, which is the design we were making. Second, they provide a fuel that will be right against the walls for when we fire harden the structure. Third, because they are loose they can be removed during the fire hardening of the outside of the bloomery. This is important because the hardening process causes the clay to contract and if it is not allowed to do so it will crack, so taking out staves as the fire burns negates this.

With the air dried clay we could now begin molding the clay around the frame. The walls needed to be fairly thick, both for strength and to withstand the heat. We built it to be 2.5 inches thick. Though the base was intentionally built thicker more to handle more load.

FIGURE 39. LAYERING CLAY ONTO FURNACE SIDES.

As we built up about every 3 or 4 inches we would wrap a loop of twine around the clay to help resist the clays urge to bulge out as weight is added on top.

FIGURE 40. SEMI-BUILT FURNACE.

We planned to construct the entire bloomery in 1 day however the weather was not cooperative, and the more recent bricks of our clay mix were not drying quickly enough. We covered the bricks with a tarp and left it overnight. When we arrived the next morning they were of near perfect consistency.

We then continued to build up the walls of the bloomery until they were three feet tall. The height of the furnace is a very important part of the process as it allows the ore to fall a distance through a thick layer of extremely hot charcoal, exposing it to a great deal of carbon monoxide. At high temperatures the oxygen bound to the iron in our ore will now bond to the carbon monoxide, freeing the iron particles and allowing them to freely filter down into the slag bath at the base where they can collate into the bloom.

With our furnace built to the proper height it was time to harden it. To do this we built up a fire around the outside. We do this before lighting the fire on the interior of the bloomery so that as the outer clay contracts with fire hardening the inner clay is still soft and able to shift. We made sure to remove some of the inner wooden supports for the same reason. Once the exterior had hardened to a tough leather like consistency the furnace was strong enough that we could cut out an arch about 10 inches wide and 12 inches tall at the base. This is our tap arch. The tap arch remains covered during most of the smelting process however as slag builds up from multiple charges of ore it may threaten to block the airflow. So from time to time the slag needs to be "tapped" and with the arch there with a few strokes of an iron rod you can make a channel for the molten slap go flow out of. The Tap arch also provides a way of removing the bloom without destroying the furnace. Immediately after carving out the tap arch the tuyere hole is cut. This is the hole through which we will place our airflow pipe. It is raised up a distance from the base so as not to immediately be drowned by slag, and angled downwards.

Lastly we light the fire on the inside of the furnace to harden the clay completely. Once this is done the bloomery is finished and ready to begin smelting iron ore.

8.3 Smelting the Iron

Before we can actually melt down our ore we had to do some prep work with our materials. The charcoal needs to be broken up into small chunks in order to get the largest surface area as possible to get the most efficient burn. At the same time the ore also needs to be broken up into small lumps and roasted over a wood fire. This step helps to dry out any remaining moisture from the rock and helps remove sulfur from the ore. Sulfur will weaken any iron that you produce, by roasting it the sulfur bonds with oxygen to form sulfur dioxide which is carried away by the atmosphere. Once this is done and the lighting fire is burning hot we can add our first charcoal. We added more charcoal slowly, allowing the fire to grow upwards through each layer we added. This brought the temperature up nice and steadily and we avoided any cracking. Next we began adding air to our fire. We had opted to concede to modern technology on this point. Rather than acquire or construct bellows we used an air blower with an air restrictor pipe. Knowing that a smelt takes many hours did not make us keep to wok a pump all day.

When we added the air a dull roar could be heard as the charcoal began to burn more fiercely. Smoke billowed out the top until the fire began burning at the top most layer, at which point the smoke combusted into a flame that rose 3 feet into the air out of the top of our smelter.

FIGURE 41. FURNACE IN OPERATION.

Now began the cycle of allowing the charcoal to burn down a distance before adding charges of equal mass of iron ore and charcoal and repeating. Our first smelt had fairly limited materials and so we added five 5lb charges of iron and charcoal. This is the ore that we had retrieved from the sandy blow out. After all charges were added we waited for the charcoal to burn down to about the tuyere hole. At this point we opened up out tap arch and began extracting the bloom. The heat was intense. Even with protective gloves, apron, and facemask the person working had to step away a number of times during the process to get out of the heat. We found significant deposits of slag stuck to the walls around the tuyere and pockets of it throughout the remaining charcoal. But we could not find the bloom. Some promising looking pieces were extracted and experimentally struck, but rather than compressing and deforming as hot iron they merely broke apart, indicating slag.

Once things cooled off a bit we ran a magnet over everything we raked out and examined what we collected. What we found were small round beads of iron. The largest the size a blueberry and the smallest scarcely a pin hole. We looked over our process and realized we had made two large mistakes. Firstly we had too little iron. It is difficult to tell the iron content of ore when it is found and what we gathered turned out to have a fairly low percentage. It occurred to us that perhaps there was a reason that people passed this deposit over and allowed the bogs to concentrate it for them. Secondly we simply did not use enough material overall. The ore has many impurities which become slag. As described in our section about the smelting process the slag allows the iron particles, freed from oxygen after going through the layers of charcoal, to float around and stick together. Without a large slag bath at the base of the bloomer, your iron will not have a medium to form together into a bloom. We speculate due to the large size of our bloomery, the amount of ore we put in was simply too small to create slag bath at the base, and so the iron that was purified wound up forming together and cooling in isolated patches.

We were not satisfied by this result. So we began our search for materials again. And this time decided to go with a more controlled approach. Since purchasing ore was difficult if searching for quantities of less than a few tons, and finding our own proved difficult, we decided to make our own ore. Ore is essentially just rust and silica. In our research we found (insert source) (dark ages recreation company) and they had conducted experiments on creating a synthetic ore to approximate the real thing for the same reason we needed to. This time we went and purchased pure FeO3, silica, and flour to serve as an organic binding agent that also simulates the organic material often found in ores.

We then mixed them as 80% FeO3 10% silica and 10% flour by weight and added water to make a paste. This we formed into balls that we baked until hard. This would approximate a high quality bog iron and leave no doubt as to the availability of FeO3 in our ore. We were also taking no chances with quantity this time, mixing up a batch of 50lbs.

FIGURE 42. IRON ORE SUBSTITUTE.

FIGURE 43. BAKING THE ORE.

Armed with supplies we set to our second smelt. The preparations from before were repeated. Breaking up materials, preheating the bloomery, filling with charcoal and adding air. The Process was the same as well for the most part. We added charges equal by mass at approximately 12 minute intervals until we were out of material. However, this time we had our slag bath. We had enough that it had to be tapped to allow the excess to flow out. This excess matched the description that Sauder put forward as being good to add again from the top, so we collected what came out of our first tapping, broke it up and added it back to the top of our bloomery.

FIGURE 44. TAPPING SLAG FROM FURNACE.

We allowed our charcoal to burn down again, and opened up the tap arch to rake out the coals. This time as we extracted several approximately fist sized very dense chunks that when struck while glowing hot compressed rather than broke apart. Once these cooled we tested them with a magnet and found them to be composed mostly of iron. We had our blooms.

FIGURE 45. COOLED SLAG.

FIGURE 46. PART OF THE COOLED BLOOM.

While doing this we also observed that our tuyere, which we made out of an iron pipe, was missing. Everything that had extended past the tuyere hole in the side of our foundry was gone. We immediately realized that we had been running our bloomery with too much air, letting it get too hot. However we were unsure how much of it had melted, and joined with the iron from our ore, and how much had burned off with the masses of iron sparks we had noticed coming out the top of our bloomery. None of our blooms seemed noticeably different in composition from one another and all generally matched the historical descriptions and modern images of porous iron and slag stuck together, so if the tuyere pipe had joined our bloom it was indistinguishable from the rest.

These chunks were what we took to the forge to join together and refine.

8.4 Preparing Samples of the Iron Bloom

After acquiring the steel from the furnace it was brought to the anvil to be refined. This step is very important to the bloomery furnace method of iron production, for when a bloom forms it is porous and sponge-like, this means that slag will be trapped within it in small pockets. Slag, being essentially glass must be removed to create a good working material. The way to do this is by repeatedly heating the bloom, hammering it, and folding it. This will work out the slag inclusions and force the iron into a more homogenous bar.

However we had to perform an additional step in order to obtain an iron billet large enough to be theoretically made into a weapon. Our bloomery failed to create one large bloom, rather it create a number of smaller ones. These needed to be consolidated together through a technique known as forge welding. This involves bringing the two pieces of steel to be joined nearly to melting point and then hammering them together. It is labor intensive and if the steel is left in for too long it will melt and become very difficult to reclaim. We simplified the process somewhat by using modern welding to weakly hold our pieces together in a stack while they are heated so that all could be forge welded at once. However if not for this it would have been a painstaking two at a time process. It is no wonder that items made of many smaller pieces of iron were cheaper than a large work made from a single piece.

After producing our billet the team moved its focus to examination and analysis of the material. To view and confirm the microstructure, we needed to take pictures of the three different directions (x, y, and z) of the material. To accomplish this, the billet of steel needed to be polished and mounted correctly.

8.4.1 Mounting and polishing

The billet was first cut into three cubes approximately 1cm cubed in size. These cubes were loaded into a PhenoCure pre mold machine to be mounted. The Phenocure mold melts a premold plastic around the sample piece inside, creating a cylindrical sample with one face showing on the top. This sample can then be ground down and polished until it is ready to be viewed under the microscope. We placed our three samples into the machine one at a time, each showcasing a different face. Once the molds were made, we polished them up to 600 grit in preparation for our final polish.

8.4.2 Final Polishing

Following the mounting and initial polishing processes, Professor Boquan Li showed the team into his lab to do the final mirror polishing.

Professor Li showed the team three table polishers with grits of 1 micron, .3 micron, and .05 micron with particular solutions for each that had suspended particles to assist in the polishing of each piece.

Following, the tutorials from Professor Li, the group went to work on the three mounted pieces. Sam manned the 1 micron grit sander while Matt manned the .3 micron and Chris worked with the final .05 micron sized sander. Sam started the sander at a good speed then sprayed the first solution on the sanding wheel and also carefully put a small amount on the mounted sample. Following this, he put the sample on the sander and applied moderate pressure while turning the sample 45 degrees every minute or so. After several minutes, he passed off the first sample and got started on the second. Matt and Chris followed the same process and by the end, the team had three mounted and fully polished samples of the material.

FIGURE 47. POLISHING THE SAMPLES.

8.4.3 Etching

The final step before looking at the sample's microstructure was to etch the surface with an acid to better see the steel's surface as best as possible. We acquired Nital as our etchant and following our weekly IQP team meeting, the team went with a graduate assistant to complete the etching on the three mounted samples.

Because of the dangerous chemical we were using, the entire team put on heavy duty gloves to protect our hands and forearms. Next up, we diluted the acid by adding 98mL of ethanol to a beaker and 2mL of the Nital. We did this step carefully and precisely.

For the final step of the etching, one team member picked up each mounted sample with a pair of tongs and placed it on the surface of the acidic solution with the steel facing outwards. The sample was lightly stirred in the solution for 10 to 15 seconds and then pulled out and rinsed with water.

Now that the surface was a mirror surface that now displayed its microstructure, the team could move onto taking pictures of their microstructure.

8.5 Microstructural Analysis of the Iron Bloom

Once the samples had been prepared, we used an optical microscope to examine and take pictures of our samples. The microscope showed that we were correct in our predication, and we had produced hypereutectoid steel which had cooled slowly, allowing the formation of pro-eutectoid cementite and pearlite.

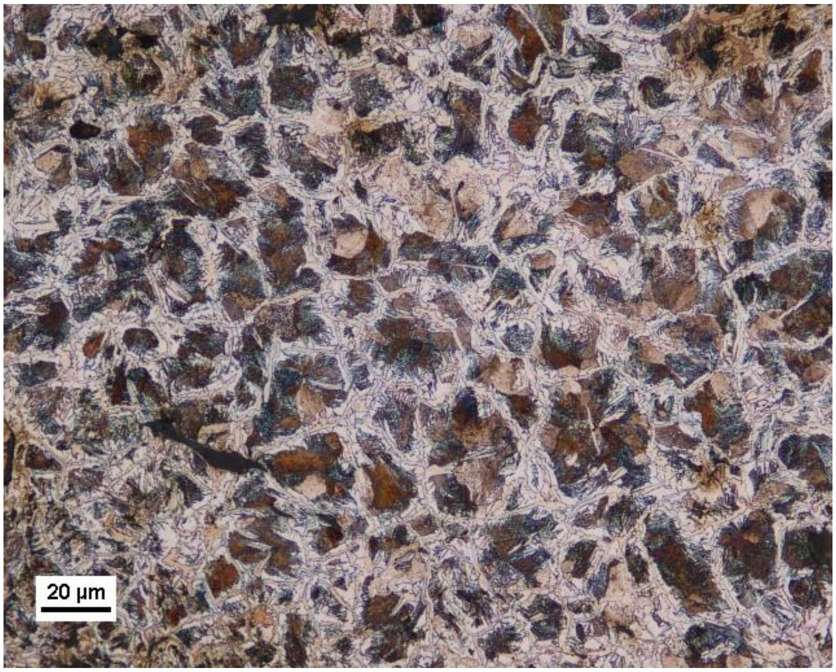


FIGURE 48. Y AXIS OF SAMPLE AT 20X.

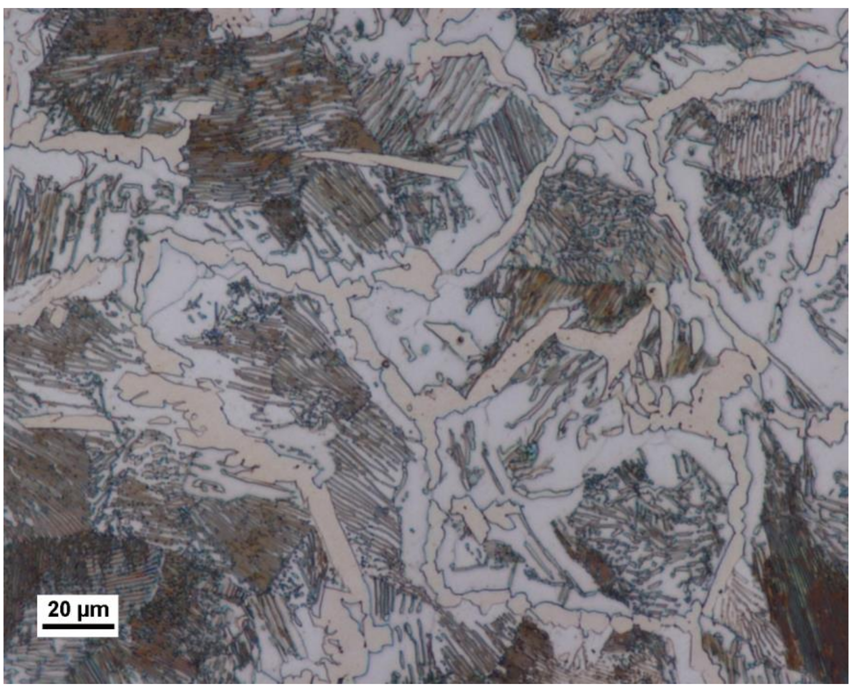


FIGURE 49. Y AXIS OF SAMPLE AT 100X.

Figure 48 and Figure 49 are images of the sample showing the Y axis face of our piece. This image clearly shows the formation of pro-eutectoid cementite and pearlite, meaning our initial calculations about composition were correct. In order to confirm the accuracy of our predictions in terms of the amount of cementite formed, we used the binary threshold on the microscope to isolate the areas of pro-eutectoid cementite, and then take their area. From our pictures of the microstructure, the area was found to be 10.2% pro-eutectoid cementite, less than 1.5% difference from our initial calculation of 11.5%.

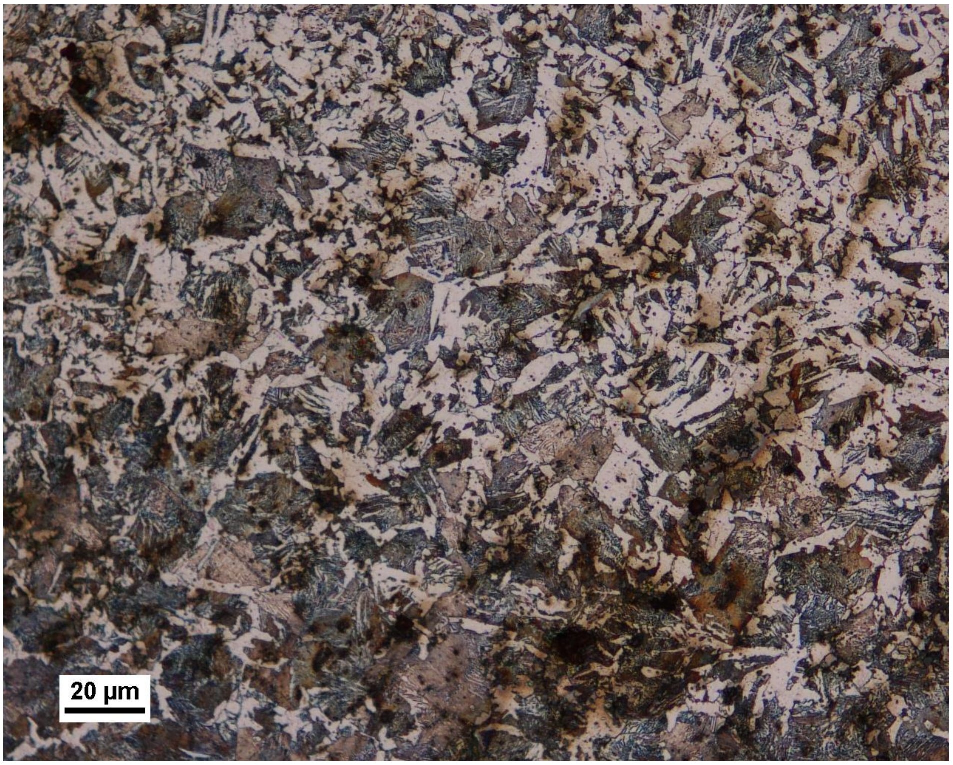


FIGURE 50. X AXIS OF SAMPLE AT 20X.

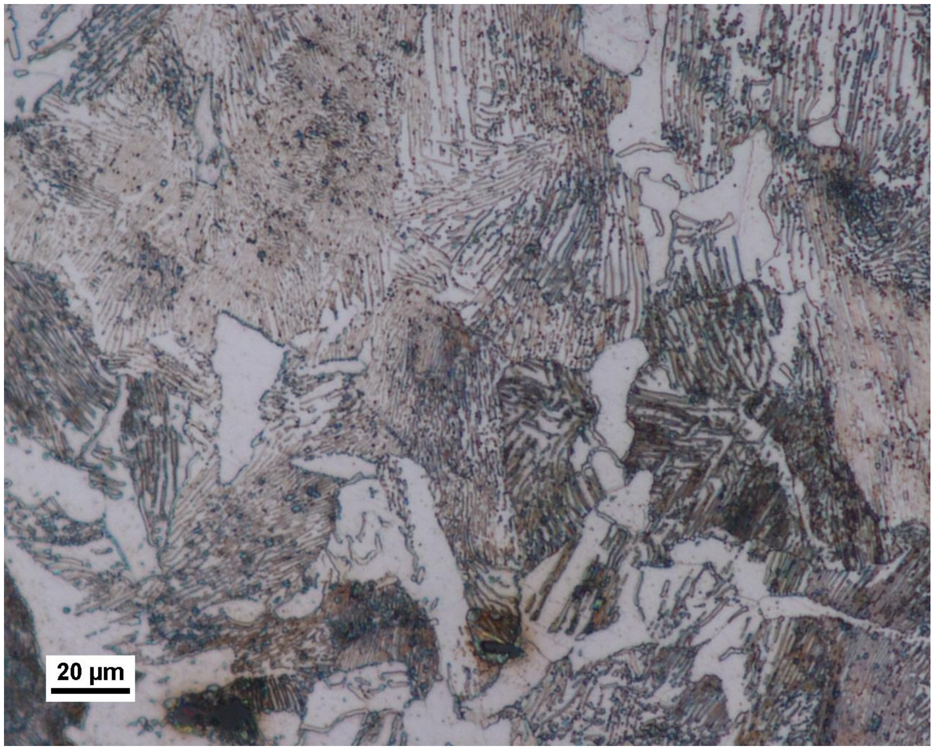


FIGURE 51. X AXIS OF SAMPLE AT 100X.

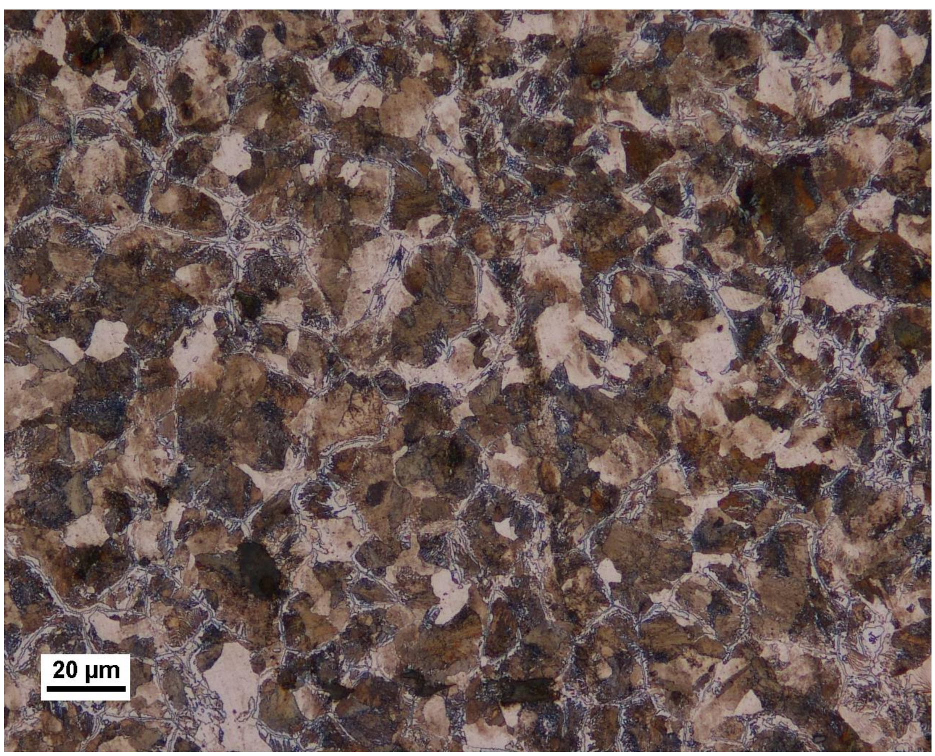


FIGURE 52. Z AXIS OF SAMPLE AT 20X.

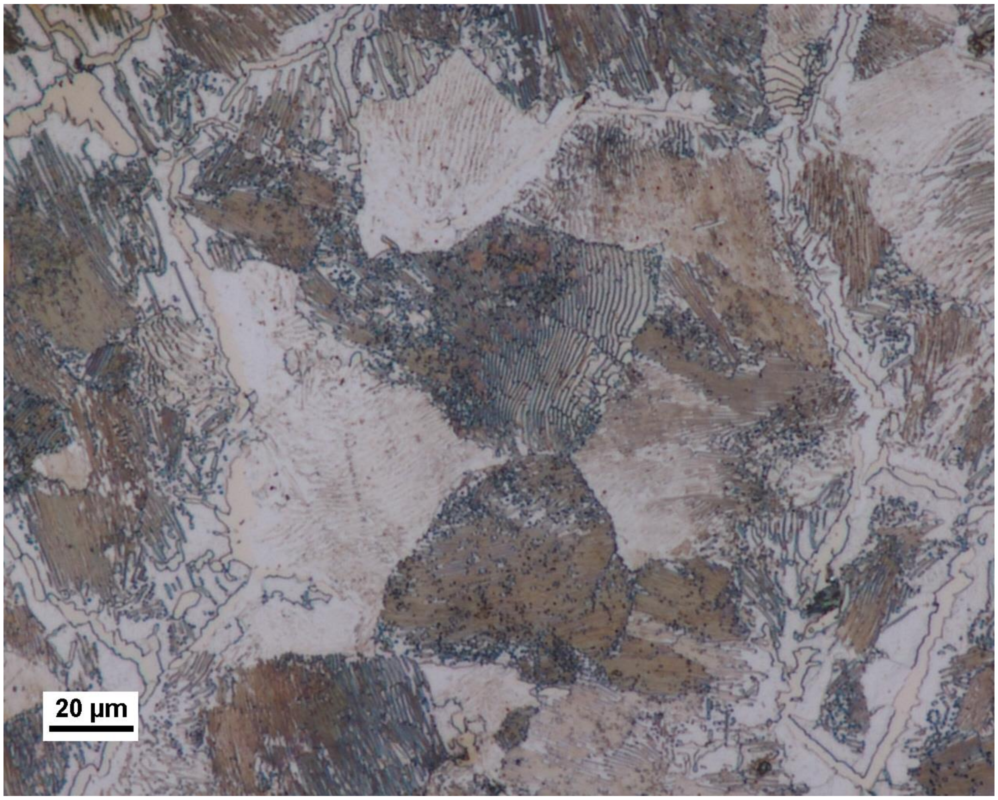


Figure 53. Z Axis of Sample at 100x.

A final aspect of the microstructure to note is the presence of slag inclusions in the steel. The black shape circled in Figure 54 is one such slag inclusion. The method of steel production that we utilized, being historically accurate, allowed for the presence of slag inclusions in the finished steel. The pieces of slag could be any impurity introduced in the process. Prior to the Bessemer process, the way to remove these impurities from the steel was to repeatedly heat and fold the steel, slowly working out the impurities. While we did this, much like our historical counterparts, we were not able to remove all of the impurities from the steel. As a result, our steel shows the same slag inclusions common in historical steels made prior to the Bessemer process.

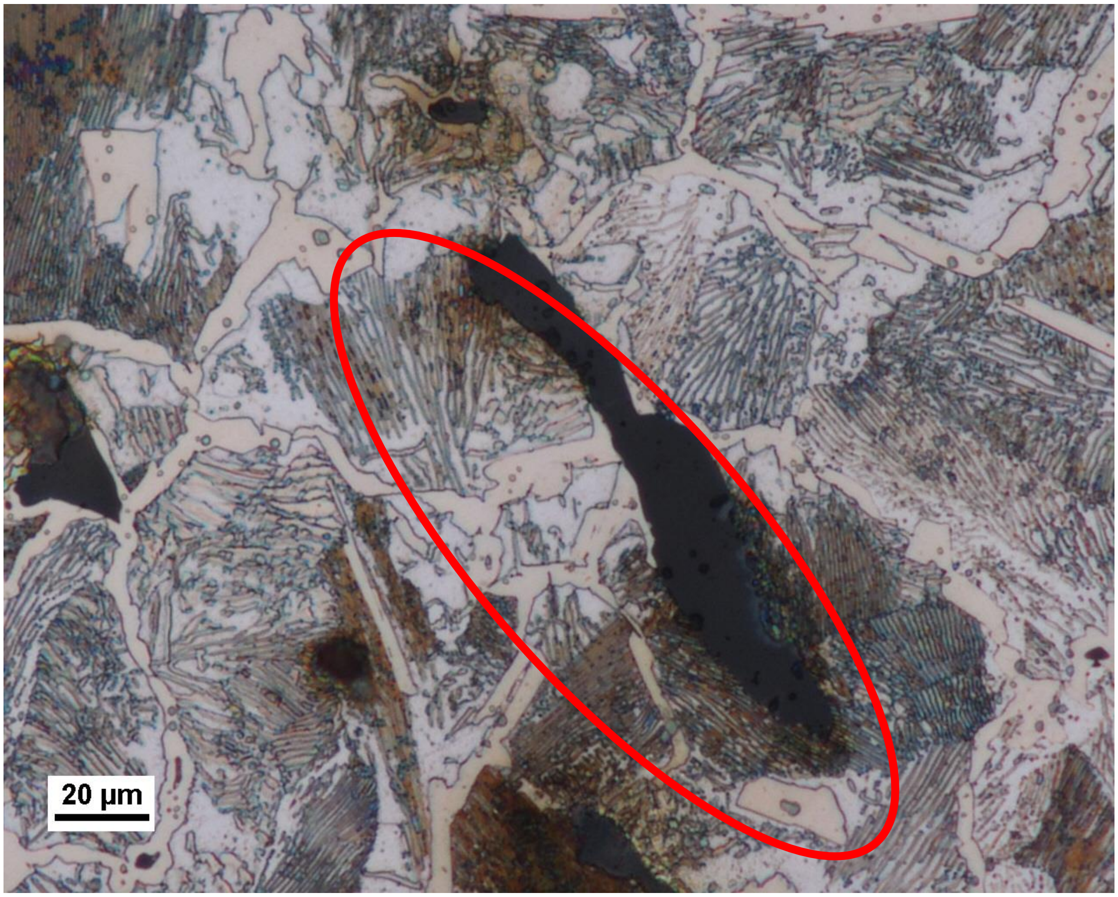


FIGURE 54. SLAG INCLUSION IN THE Y FACE.

9. Conclusion

Changes in industrial materials are a powerful force on a civilization, so much so we define ages by the dominant use of a certain material, stone, bronze, iron, etc. But it is not merely the type of material that shapes a culture, but its availability. The Bessemer process was not a change in material but a change in production, cheapening steel with vast quantity, allowing for its use in countless applications where it previously would have been prohibitively expensive. It fueled the rise of the modern era. So in the ancient world did availability and quality largely define the limits of what could be done?

Our work in reproducing iron in a historically accurate fashion proved at every step of the process why iron and steel were held in such high regard, and why by extension it would be a valuable trade good. Though exact technique varied region to region, across all, iron production remains a very labor intensive process.

Europe with its poor, but available iron, developed heavier armor and weaponry. Though limited by the size and varied nature of the blooms from the smelters, enough could be pieced together to make larger pieces.

India with its excellent steel traded it far and wide, and could make swords lighter and stronger than any other available at the time

Japan, lacking good sources of iron of its own compensated by working what they produced expertly and reserving iron for where it was absolutely needed in all weapons and armor. Giving rise to the form of the katana as we know it today, and forcing Japanese armor to be composed of nonmetallic components.

The varieties of ore and processing techniques account for a wide range of differences in arms and armor design no matter where you go. To gain a deeper understanding of historical weapon design our project delved into the very roots of weapon design by understanding what people had to work with at the time

Following the microstructure and carbon analysis, the sample closely aligned to our theoretical predictions. The piece ended up being in a usable range, although the carbon content was still high.

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"HJRK A 56 - Gauntlets of Maximilian I, c. 1485" by Lorenz Helmschmied, 1485 - Photograph by Sandstein. Licensed under CC BY 3.0 via Commons - https://commons.wikimedia.org/wiki/File:HJRK_A_56_-_Gauntlets_of_Maximilian_I,_c._1485.jpg#/media/File:HJRK_A_56_-_Gauntlets_of_Maximilian_I,_c._1485.jpg

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APPENDIX A

Making our own steel

The creation of our steel can be divided into two phases. First, we had to construct or bloomer furnace. Once constructed, the next step was to prepare and smelt our ore. The construction of the actual furnace took two days total, and a smelt could be done in one day. This appendix details those steps.

Phase 1: Constructing the furnace

The first step in construction of our furnace was mixing our materials. With the clay and sand we were essentially creating a fire resistant cement which like all cement must be mixed and dried. We mixed our materials in the following amounts, 50 pounds of sand, 5 pounds of cream hill clay, the sticky bonding variety, 25 pounds of EPK Kaolin, and 1 pound of peat moss. After adding water and mixing our material came out to a heavy grey smooth mixture. In total we used 100 pounds of EPK kaolin, 300 pounds of all-purpose masonry sand, 50lb of peat moss, 50 pounds of foundry hill cream, and 48 firebricks.

FIGURE 1. MIXING CLAY.

At the same time as we were mixing the clay we constructed the plinth out of firebricks.

FIGURE 2. BASE FIREBRICKS FOR FURNACE.

This provides a base for the structure to be built on and by leaving several bricks un-mortared it provides a way of opening a larger hole to pull out the slag and bloom.

The next step was prepping the mixed clay for use. To do this we scooped up and compacted bricks out of the material and laid them on a tarp to dry.

Figure 3. Clay Balls for Furnace Sidings.

The clay balls needed to dry since the water content was too high, meaning they were very soft. Had we tried to stack them to form the bloomer, they would have collapsed under their own weight. The separating into bricks helps to speed the drying process by increasing the surface to volume ratio.

While the balls dried we constructed the frame that we would build the bloomery around. For this we used a concrete setting tube to provide a circular center, around which we placed loose wooden staves.

FIGURE 4. FURNACE STRUCTURAL SUPPORT TUBES.

The wooden staves' purpose is threefold. First, they expand the inner diameter to 18 inches, which is the design we were making. Second, they provide a fuel that will be right against the walls for when we fire harden the structure. Third, because they are loose they can be removed during the fire hardening of the outside of the bloomery. This is important because the hardening process causes the clay to contract and if it isn't allowed to do so it will crack, so taking out staves as the fire burns negates this.

With the air dried clay we could now begin molding the clay around the frame. The walls needed to be fairly thick, both for strength and to withstand the heat. We built it to be 2.5 inches thick. Though the base was intentionally built thicker more to handle more load.

FIGURE 5. LAYERING CLAY ONTO FURNACE SIDES.

As we built up about every 3 or 4 inches we would wrap a loop of twine around the clay to help resist the clays urge to bulge out as weight is added on top.

FIGURE 6. SEMI-BUILT FURNACE.

We then continued to build up the walls of the bloomery until they were three feet tall. The height of the furnace is a very important part of the process as it allows the ore to fall a distance through a thick layer of extremely hot charcoal, exposing it to a great deal of carbon monoxide. At high temperatures the oxygen bound to the iron in our ore will now bond to the carbon monoxide, freeing the iron particles and allowing them to freely filter down into the slag bath at the base where they can collate into the bloom.

With our furnace built to the proper height it was time to harden it. To do this we built up a fire around the outside. We do this before lighting the fire on the interior of the bloomery so that as the outer clay contracts with fire hardening the inner clay is still soft and able to shift.

FIGURE 7. STARTING THE OUTSIDE FIRE.

We made sure to remove some of the inner wooden supports for the same reason. Once the exterior had hardened to a tough leather like consistency the furnace was strong enough that we could cut out an arch about 10 inches wide and 12 inches tall at the base. This is our tap arch. The tap arch remains covered during most of the smelting process however as slag builds up from multiple charges of ore it may threaten to block the airflow. So from time to time the slag needs to be "tapped" and with the arch there with a few strokes of an iron rod you can make a channel for the molten slap go flow out of. The Tap arch also provides a way of removing the bloom without destroying the furnace.

FIGURE 8. CUTTING THE TAP ARCH

Immediately after carving out the tap arch, the tuyere hole is cut. This is the hole through which we will place our airflow pipe. It is raised up a distance from the base and angled downwards, so as not to immediately be drowned by slag.

Lastly, we light the fire on the inside of the furnace to harden the clay completely. Once this is done the bloomery is finished and ready to begin smelting iron ore.

FIGURE 9. FIRING THE FURNACE.

Phase 2: Smelting the ore

The next step was the preparation and smelting of the ore. Since we made our own analogue instead of naturally occurring ore, we first had to mix together the ingredients in our ore. We mixed 80% FeO3, 10% silica, and 10% flour by weight and added water to make a paste. This we formed into balls that we baked until hard. This would approximate a high quality bog iron and leave no doubt as to the availability of FeO3 in our ore. We mixed up a batch of 50 pounds.

FIGURE 10. IRON ORE SUBSTITUTE.

FIGURE 11. BAKING THE ORE.

Once the ore was baked into a crumbly, clay-like consistency, we broke it up into small chunks for feeding into the furnace. We also broke up our charcoal into small chunks approximately 2 cubic inches in size. We then separated the 50 pounds of ore and the charcoal into five charges of equal weight, ten pounds of charcoal and ten pounds of ore. We added the charges at approximately 12 minute intervals until we were out of material. By charge four we had enough slag that it could be tapped to allow the excess to flow out. This excess matched the description that Sauder put forward as being good to add again from the top, so we collected what came out of our first tapping, broke it up and added it back to the top of our bloomer as a sixth charge.

FIGURE 12. TAPPING SLAG FROM FURNACE.

We allowed our charcoal to burn down again, and opened up the tap arch to rake out the coals. We extracted several approximately fist sized very dense chunks that when struck while glowing hot compressed rather than broke apart. Once these cooled we tested them with a magnet and found them to be composed mostly of iron. While we did not have one large bloom, we had several smaller blooms that we could forge weld together.

FIGURE 13. COOLED SLAG.

FIGURE 14. PART OF THE COOLED BLOOM.

APPENDIX B

Website Changes

<u>IQP Report Page</u>
Added “2015-2016” with finalized report.

<u>IQP Teams Page</u>
Added “2015-2016” with team name.

<u>Replica Construction Page</u>
Added “2015-2016” with picture of our replica.
Added APPENDIX A procedure of replicating furnace and billet.

<u>Europe World Map Page</u>
Added in Norse History (In Medieval Area) into the Scandinavian Section

<u>East Asia World Map Page</u>
Added more weapons under Japan from Japanese background section.
Added history of Japenese Steel in regards to religion.