# The Evolution of Materials in Arms and Armors: The Viking Seax Knife

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# 1. Abstract

For this IQP, our team seeks to research the historical evolution of the Viking Seax knife from its origins as a farming tool to its future use as a weapon, and to investigate the varying material properties of the blade through the various stages of forging that it would be subjected to. Our project will begin with a thorough examination of the background in which the knife was initially used, with supporting information including the culture of the Vikings, their influence on surrounding areas, the strategies they employed to survive and thrive up in their Scandinavian homeland, and a comparison of the various weapons they relied on coupled with the typical manufacturing methods employed by their blacksmiths. An introduction to the Seax knife will follow, and in this section we will begin to discuss the progression of this tool into a weapon exclusively used for combat. An integral part of this project is the creation of a Seax knife of our own through historically accurate methods. With this in mind, we will forge a blade of our own and fuse it to a wooden hilt which should ensure historical accuracy in our recreation of the Viking Seax knife, albeit with a ground down cutting edge. Through the smithing process, we will also take cut samples from a steel bar identical to the one that will be turned into the knife so that we will be able to examine the material properties of the blade without needing to cut samples out of it.

## 2. Introduction

The Vikings were a nomadic group, meaning they often traveled from place to place, fighting along the way. This leads to many developments in the process of making actual weaponry and also in the design of the weapons themselves. The Seax Knife was one of the most popular Viking weapons of the time.  It was often used as a secondary weapon however its reliability increased its popularity and use on the battlefield. As times went on the size of these blades also increased, starting with a basic sized knife, roughly 6-12 inches, too a much larger version that could often reach 24 inches. The paper will discuss why exactly the Vikings developed such a weapon, why it had certain characteristics, and how they produced them. As well as research in the blacksmithing of the Seax knife by the Vikings, the process of how we made the replicas will also be shown. There will be two replicas, one using some modern methods such as plasma cutting in order to speed the process up and make it simpler, and the other being done the same way the Vikings did just solely by heating and hammering.  This will provide some insight on what the Vikings had to go through in order to make a Seax knife as opposed to what we are capable of today. During the working of the replicas that we produced we studied the microstructures of the materials under microscopes in order to find out certain characteristics such as phases, grain sizes, imperfections, and how the material changes as it is worked by heating, hammering, and quenching.

# 3. Who Were the Vikings

## 3.1. Geography

The Vikings were people indigenous to what are now the countries of Sweden, Norway, and Denmark from the late 8th through late 11th centuries. They lived in an environment that was difficult to traverse on land, as a result of the mountainous characteristics of the region, instead opted to take to the sea for means of transportation. The cold climate and long winters made farming more difficult that it was further south, motivating the Vikings to rely heavily on fishing for food production in addition to farming. Due to the general shape of the Vikings Scandinavian homeland, it was much more advantageous to hone their ability as sea farers and improve the speed with which they could move through water, as trading and looting overseas was an enormous source of profit for the Vikings. The alternative route to Northern Europe would have been a land route that would have taken the Vikings along an extremely long round about trek through some of the northernmost locations on Earth, and the time and energy required to make the trek on foot would render it a complete impossibility where profitability would be concerned.

*Figure 1. Map of Scandinavia. [1].*

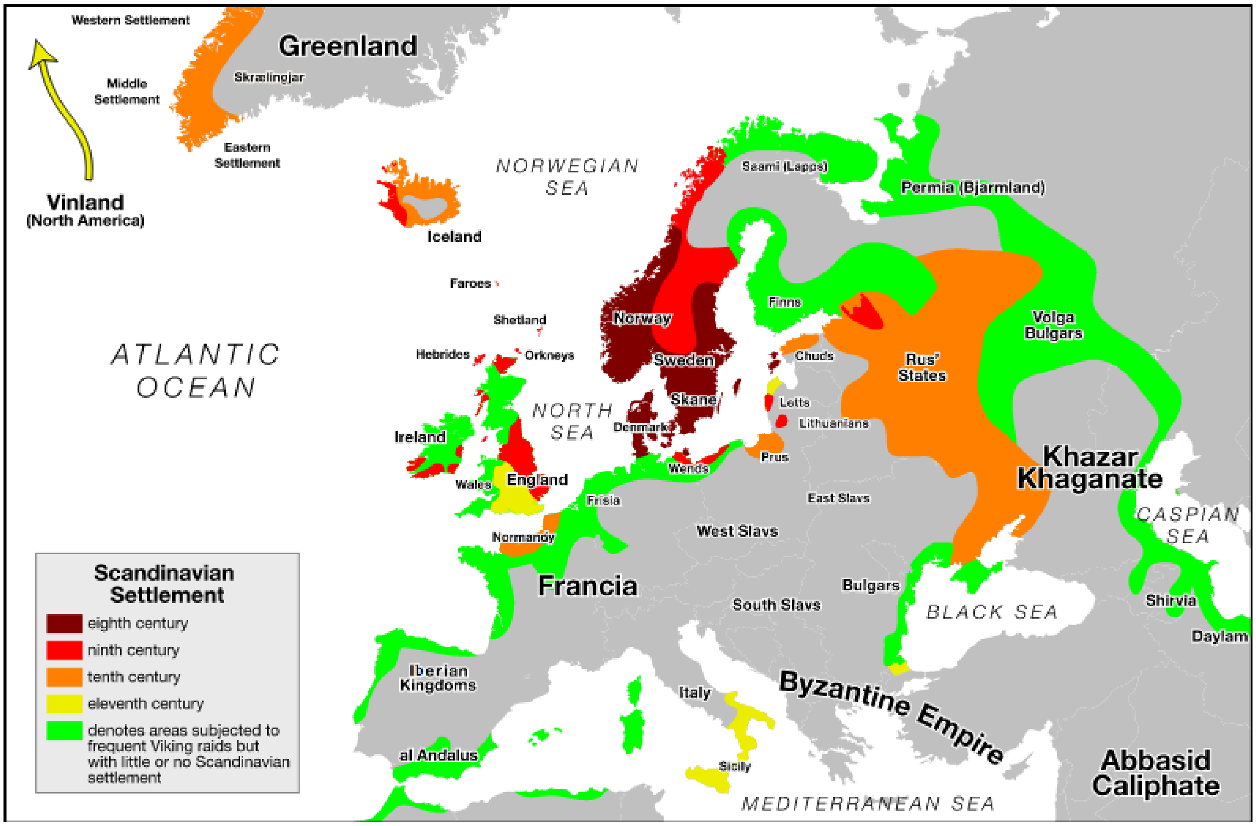


*Figure 2. Extent of Viking Expansion. [10].*

## 3.2. Farming

Although better known for their more exciting pursuits, the Vikings were a primarily agricultural society. Most Norsemen lived and worked on small farms, thickly settled in areas where the soil was particularly good and spread thin where it was not. These farms were usually run by a farmer and his family, who hired servants and farm hands and bought the occasional slave to tend to the crops and livestock. The people and animals usually lived in a fenced in group of buildings centered around a longhouse. Originally home to people and animals alike, the longhouse eventually became a devoted barn for the livestock as people and their workspaces were moved to other buildings. An ideal location for a longhouse and the other nearby farm buildings was a hill or other raised piece of ground with a good view, preferably with nearby running water for drinking.

Although most farmers both grew crops and raised livestock, their most important source of income and sustenance was their cattle. This dependency is expressed in the Norse language with the word “fé,” which translates to “cattle” as well as “money.” Like most agricultural societies, the Vikings had many uses for their cows. They were milked to produce fresh dairy and to allow the production of cheeses, butters, and curds (called skyr) which could be more easily stored for the winter. Oxen could be used to pull plows or sleighs. Wealthy farmers could also afford to slaughter some of the animals for beef. These animals were often allowed to roam about during the summer, but they had to be kept inside and fed with hay over the winter months. Other animals raised by Viking farmers included sheep, goats, and pigs. Although all of these animals were used for meat, sheep were especially valued for their wool and both sheep and goats were used for milking. Horses were not only raised by many farmers for meat and transport, but actively bread by some farmers to be used in horse fights, a common form of entertainment for the wealthier members of society.

All these animals required a substantial amount of hay to survive over the winter. Each cow would usually consume more than two tons of hay over the winter months. A large farm could have needed as much as 200 acres to produce a sufficient quantity of hay. The hayfields were protected from animals by walls constructed from stone and turf. The existence and upkeep of these walls were sufficiently important that laws were created to set minimum dimensions, “shoulder-height of a man and five feet thick at the base.”

In addition to hay for their prized livestock, farmers grew a wide variety of crops. Barley was the staple grain, but they also grew oats and rye, with some wheat in the southernmost areas. Vegetable crops included cabbage, peas, onions, and beans.

Farms needed to be self-sustaining and could not afford to depend on outsiders to provide important services like producing and maintaining tools. Maintaining the edges on scythes and other sharp implements was a constant struggle, and grinding them on a whetstone was not enough to deal with the wear and tear of daily use. For this reason, every Viking farmer had at least a basic blacksmith’s forge and understood how to use it. The farmers also had to rely on themselves for any carpentry work which needed to be done.

The places where the Vikings lived (modern day Norway, Denmark, Sweden, and Iceland, among others) were further north and much cooler than the rest of Europe. This made cultivation of very common crops like wheat far more difficult, even impossible in some places. However, there is evidence that the climate in the region has cooled since the Viking times. Examination of the Arjep Ruotesjekna glacier in Sweden unveiled fossilized moss beneath the glacier dating back to around the 12th century, proving "that the glacier was smaller during the Viking Age than it is today" [41]. Evidence from that area also suggests that the tree line was higher at that time.

## 3.3. Politics

The topographies of the different regions of Scandinavia resulted in low degrees of unity among Viking groups. In the more northern regions that are now Sweden and Norway, "mountainous terrain and fjords formed strong natural boundaries. Communities there remained independent of each other" [47]. This dissociation of the various Viking groups resulted in a multitude of kingdoms forming, without the generation of any organized, centralized government. For example, in northern Scandinavia "By 800, some 30 small kingdoms existed in Norway" [47]. As a result of geographic isolation, the communities of Vikings were not able to easily interact with each other, hence their inability to communicate with enough ease to form any sort of single Scandinavian kingdom. This sort of disunity was not unique to the Vikings, and is attributed to other groups in the same relative geographic region. According to an article published by the International World History Project, "Viking political organization resembled that of other early Germanic peoples: a society of warrior chiefs and loyal followers." [48], which presents almost a feudal outlook on the Viking political structure, where the individual kingdoms are led by a strong ruler who in turn protects those who serve him, in return for taxes, from which the chief or leader is able to maintain his position through his wealth and power. Despite the diffusion of power across the many minor kingdoms of Scandinavia, Norway, Sweden and Denmark ultimately each ended up unifying under a single king. In an article on the history of Sweden, "The first undisputed king of Sweden was Eric the Victorious, who lived around 970–994" [49], which dates the reign of the first Swedish King a few decades after the unification of Denmark under a single king, Gorm the Old, who "was the first historically recognized King of Denmark, reigning from c. 936 to his death c. 958 [50]. Prior to both of these kingships, and ancestor to the eventual king of England, Norway, Denmark, and parts of Sweden, Cnut the Great; was Harald

Fairhair, who “was remembered by medieval historians as the first King of Norway … he reigned from c. 872 to 930.” [51]. As the Viking Age waned, kings rose and fell until the late 11th century, where “In Scandinavia the Viking age is considered to have ended with the establishment of royal authority in the Scandinavian countries and the establishment of Christianity as the dominant religion” not as a result of all of the kings being deposed and replaced, but due to the fact that this deviation from traditional societal and religious roots ushered in a new era, the Middle Ages, one in which Scandinavians would no longer be called Vikings, though this is more due to the definition of what constitutes a Viking than anything else.

## 3.4. Longships

The Vikings were renowned for their superb boat building ability and seamanship. Boasting one of the best navies of the era, the Vikings were able to sail farther, faster, and in more variable situations than the majority of the other European nations. The Vikings relied on their signature longships for all means of sea faring, with various size vessels filling different niches in the Vikings maritime operations. Viking longships were “characterized as a graceful, long, narrow, light, wooden boat with a shallow-draft hull designed for speed” [2]. These ships were able to quickly change direction, even allowing the ship to reverse direction without requiring that the ship turn around, as a result of “the symmetrical bow and stern” [52]. Another crucial feature of the longships was their ability to sail in extremely shallow water, due to the fact that “The ship's shallow draft allowed navigation in waters only one metre deep and permitted beach landings” [52]. From this base model, the Vikings adapted the longship to suit whatever needs they had. Various types of longships included warships and merchant ships. Warships included the Snekke, the Drekkar, and the Skeid. These ships were all long (approximately 30 meters) and narrow and could accommodate 18 pairs of oarsmen in addition to a large square sail. The two main classes of merchant ships were the Knarr, which “was 16.5 meters long, built of pine and it could carry up to 40 tonnes of goods” [53], and the Byrding, which was much smaller and more maneuverable. Some of the overarching characteristics that set merchant ships apart from warships is that the Vikings had adapted them to be “broader in proportion to their length than the warships. They had a wider and deeper hull for cargo, and they were clearly much more dependent on the sail than the oars" [53]. These ships did not operate according to the same Modus Operandi as the warships, where speed if of the essence, instead relying more heavily on the sail for longer, slower journeys with less exciting destinations in store. Due to the reliance by the Vikings on waterways for transportation, the bulk of the Viking watercrafts were neither warships nor merchant vessels. "The vast majority of boats which were used during the Viking Age were neither warships nor merchant ships. They were small boats which were needed for day to day life ..., boats designed for fishing, transporting people, goods and local news from one settlement to another" [53]. Just as other countries used horses or oxen for transportation, the Vikings used ships.

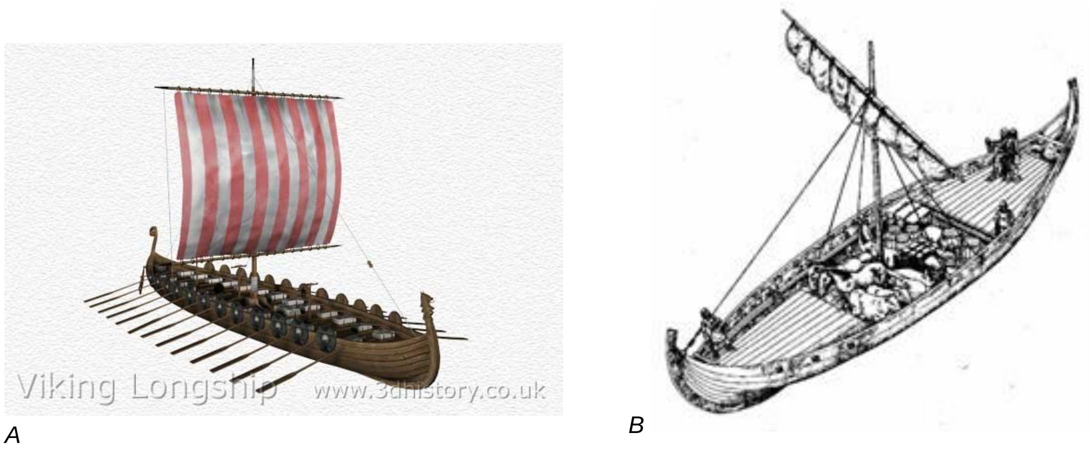


Figure 3. A.Viking Warship. [2]. B. Viking Merchant Ship. [3].

## 3.5. Pillaging and Raiding

While originally "The Old Norse feminine noun víking refers to an expedition overseas", it evolved over time to take on a new meaning, where "the phrase "to go on a viking" implie[d] participation in raiding activity or piracy and not simply seaborne missions of trade and commerce" [55]. The Vikings were defined by their lifestyle of exploration and raiding. Their raiding exploits were largely facilitated by their advanced longships, which allowed the Vikings to sail up shallow rivers, even lifting their crafts over obstacles, and attack and loot a target, then make a hasty escape without even needing to turn their ship around as it could be sailed in either direction, forwards or reverse. Common targets included coastal towns and cities, populations on riverbanks, and the treasure trove of all Viking raids, a wealthy church or monastery. The Vikings tended to opt for more poorly defended targets that they could raid and escape with their spoils before any sort of organized defense could begin to fight them off. The Vikings have also been reported as taking to blackmail to make a profit. Upon realizing the importance that the Christian Church placed upon holy books and manuscripts, the Vikings began to take these writings hostage and demanded a price for their safe return. A notable account of such a practice, and it's successful result for the Vikings, can be read in "Notes added to a page of the Codex Aureus, a magnificently decorated Gospel Book, [that] record how the Anglo-Saxon aristocrat Ealdorman Aelfred and his wife paid pure gold to the Vikings to ensure the book's safe return to Christchurch" [54]. One of the most well documented Viking raids is the looting of Lindisfarne, which "was the first major Viking attack recorded in England" [56]. The Vikings set a precedent with this raid that shocked England. The Vikings, as Pagans, had no qualms with attacking a monastery. They saw a poorly defended target that held great riches, within easy striking distance and with easy escape routes. The Vikings continued to pillage churches and monasteries, even burning them to the ground in cases, until the eventual conversion of Scandinavia to Christianity, a process that took centuries.

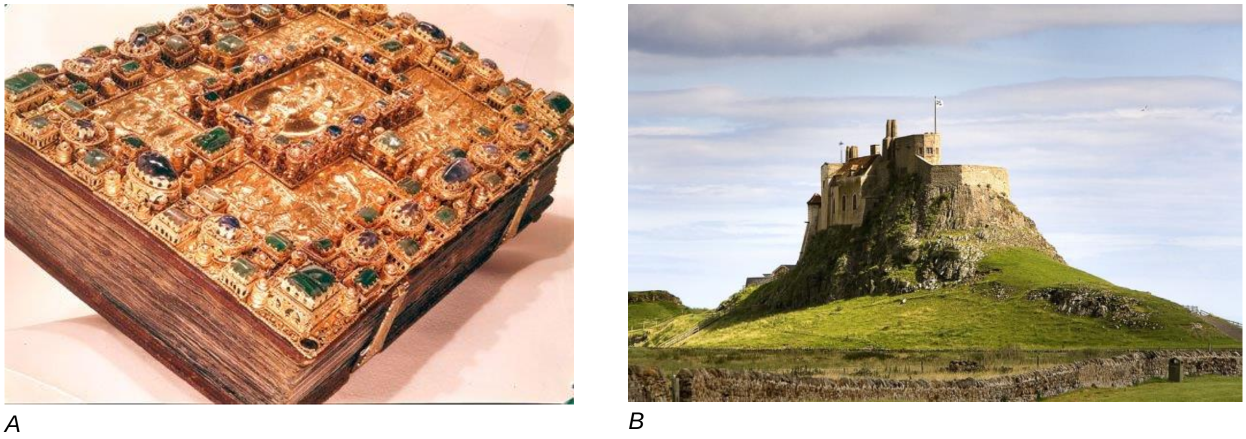


*Figure 4. A.Codex Aureus. [4]. B. Lindisfarne. [5].*

## 3.6. Society

The Vikings were a society that truly lived and died by the sword. While they did maintain farms to sustain themselves, the Vikings were notoriously successful raiders, where their signature flat bottomed longships were able to sail up rivers far too shallow for other vessels of such size, raiding commenced, and then a swift getaway was made. The extent of their raiding took the Vikings overseas in a multitude of directions, but a main focus for the Vikings was England and the European coast. Vikings have been known to raid monasteries in England, where they made off with incredible amounts of gold and other valuable objects. While the Vikings were often portrayed as cruel, or bullies for picking on those who couldn't defend themselves, the Vikings viewed the whole activity in a very different light. "In the mind of the Norse people, raiding was very distinct from theft. Theft was abhorrent. According to the Norse mythology as told in Snorra Edda, theft was one of the few acts that would condemn a man to a place of torment after his death. On the other hand, raiding was an honorable challenge to a fight, with the victor retaining all of the spoils" [36]. This coincides perfectly with the value placed by the Vikings on constantly being prepared and constantly staying armed. In their minds, if the people that they were raiding lived by the same societal code as they did, the inhabitants of the monasteries would be armed and able to repel the raiders. As a result of their negligence, they suffered the consequences, in the Vikings' opinion.

## 3.7. Weaponry

As a society largely shaped by warfare, all Vikings owned weapons, as per societal standards, and viewed weaponry and armor as a means by which the various social classes could be distinguished from one another. The Vikings deemed it necessary to carry their weapons with them everywhere which can be justified by an excerpt from the Hávamál, a collection of Norse poems believed to have been delivered to the Vikings from their God Odin as a set of moral and social codes, that states: "Let a man never stir on his road a step without his weapons of war; for unsure is the knowing when need shall arise of a spear on the way without" [37]. This quote is the Viking equivalent of the motto: "Always be Prepared," where weapons are advised to be carried at all times. The armament of a Viking was also indicative of his social status, where the nobility and warriors would be equipped with ornate armor and a multitude of weapons such as battle axes and spears, while a farmer or peasant might only own a spear or hand axe. Vikings placed enormous emphasis on their weapons, as these weapons provided them with a means of hunting, of waging war, and of protecting themselves from harm. Some of the more prominent weapons used by the Vikings included the bow and arrows, spears, halberds, knives, swords, and axes; to mention the offensive armaments.

### 3.7.1. Bow and Arrows

It was not uncommon for Vikings to bring hunting bows into battle when lacking a proper longbow, which were massive, some even necessitating a 130lbs draw weight, which is extremely high when compared to many of the typical bows used today. For instance, most recurve bows currently used for hunting have draw weights less than 50lbs. The typical maximum range of these bows was 800 feet, and this value was even used as a unit of length by the Vikings who aptly referred to this distance as a bowshot. The major benefits of fighting with the bow and arrows is the obvious range advantage, where squads of archers can take out a large number of infantry long before the foot soldiers reach the archers. A drawback of fighting with the bow is that once an enemy managed to bring the fight to close quarters, a bow would be worse than useless, leading to reliance upon melee weapons, which were the weapons of choice for the majority of the Viking soldiers.

*Figure 5.Viking Bow and Arrows. [6].*

### 3.7.2. Melee Weapons

Spears and halberds provided a range advantage over other hand weapons, while still allowing the person wielding it to fight at close quarters with relative ease. These weapons were particularly effective against charging infantry or cavalry, of which there were none of the latter group in Scandinavia. Axes and swords had an even shorter range of operation than spears and halberds, and these weapons were best suited to extremely close quarters fighting where spears and halberds could possibly be at a disadvantage due to their increased length. Axes in particular/ as well as spears, were the cheapest and most prominent weapons seen among the Viking ranks. The fact that these weapons were mostly wood with a relatively small cutting head made them cheaper to manufacture and therefore more easily accessible to the peasants and farmers who constituted the bulk of the Viking armies.

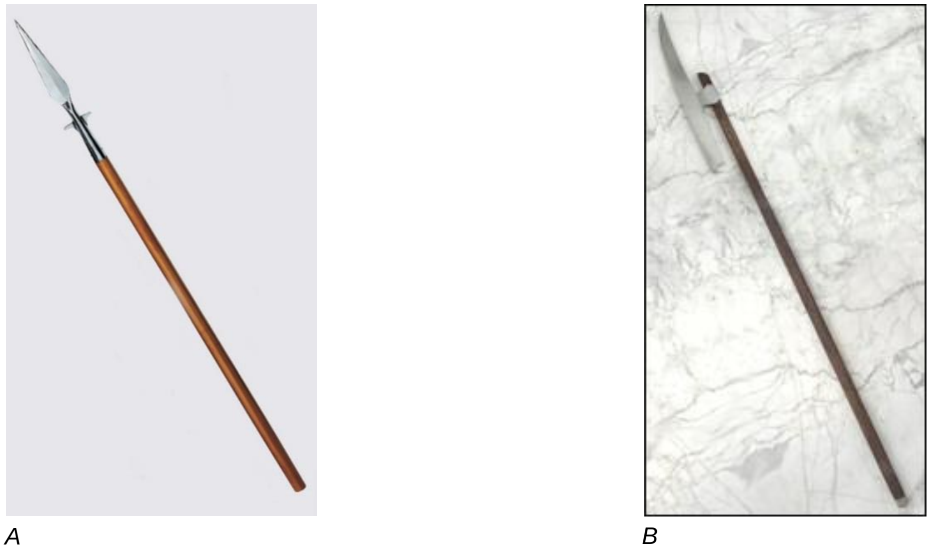


*Figure 6. A.Viking Spear. [7]. B.Viking Halberd. [8].*

### 3.7.3. Side Arms

Worn primarily as a side arm was the knife. This weapon was used more as a last resort than anything else, where if your sword or axe broke or an enemy entered the range at which a bow would be useless, the knife could be pulled out. The Seax knife was a large single bladed knife that was worn in a scabbard with the blade facing up, which would allow a soldier to draw the blade and continue upwards inflicting a cut on an enemy in one stroke without needing to turn the blade in midair.

*Figure 7. Viking Seax. [9].*

## 4. The Seax Knife

The usefulness of a heavy knife for farming and other aspects of daily life are obvious. Smaller Seax knives known as “hadSeaxs” could be used to skin animals, carve wood, eat food, and other mundane tasks. S.C. Hawkes [61] argues that the primary purpose of the Seax was for hunting, specifically ritual hunting of deer and distribution of the venison.

*Figure 8. Seax Knives with Sheaths.*

### 4.1. Evolution from Tool to Weapon

In most circumstances, knives in the Viking community were used as tools for various everyday tasks such as cutting food, chopping, cutting ropes, and other daily tasks. The Seax knife specifically served mainly for hacking due to its thicker back side (which could be as big as 3/8 in thick) and its heavier weight compared to other knives. Due to this, the Vikings began using the knife as a weapon in combat. The knife generally could be made rather crudely by the local blacksmith and still serve its purpose, and in most cases this was the method sought out to make these knives.  Since their benefits lie in the weight, the blade did not need to be fine craftsmanship.  This helped the widespread use of these knives in both everyday life and combat.  The Seax knives found in combat generally tended to be of greater length than those found in use for general uses, however both sufficed for either task due to the usefulness of the knife and its attributes.  The Vikings liked using the Seax knives in combat for various reasons, one of which being the weight of the blade.  The smaller sized Seax knife already was both thick, sturdy, and heavily as well as easy and quick to make, not requiring any large amount of craftsmanship to make an effective blade making it an attractive option for a secondary weapon in combat.  So taking these attributes, by simply making it longer they made the weapon heavier and have a longer range making it that much more useful in battle.

Almost all Vikings would be found with some version of these knifes in a horizontal hilt on their waists.  This served as an easy to reach weapon when in close range in combat, and in some cases the Vikings would even use it as a weapon of choice, replacing their one-handed swords.  Although on heavy padded or chain-mailed targets the knife may not make any visible damage such as lacerations, the sheer weight of the blow from the heavy knife could cause internal bleeding and break bones.  If the target was not wearing armor, the blade could easily cause lacerations and cut off limbs.  The other perk of these blades was that due to the slightly smaller size than most hand weapons, they were able to be concealed behind their shields making them excellent for surprising the target when in close range.  All these benefits factored into the increase and spread of the usage of the Seax knife in combat, they were not only effective but also easy to make, making them a common item of most Viking warriors.

## 4.2. Weapon Material

The primary material used in the manufacturing of the Vikings weaponry was iron. The Vikings knew how to mine, and mined to some extent throughout parts of

Scandinavia. However, their primary method of obtaining raw iron was through the use of bog iron. Bog iron is found in deposits of impure iron unsurprisingly found in bogs or swamps, locations where mountain streams ran through soft ground, carrying dissolved iron from the mountains. In a bog location, iron concentrates into deposits primarily through the environment itself and anaerobic bacteria. A bog is a highly acidic natural environment with low amounts of dissolved oxygen. In this environment, a chemical reaction forms insoluble iron compounds. Additionally, certain bacteria, Gallionella and Leptothrix, concentrate iron as part of their life process.

Another byproduct of this process is the oily film so often found on water surfaces in bogs. This is referred to as jarnbrak in Iceland, iron slick. This slick would make in very simple to find deposits of bog iron. The top layer of the bog, the peat, must be cut, exposing small balls of iron, no larger than a marble. They are mostly pure, though few in number.  Oddly enough, they are a renewable resource, and the bog can be harvested approximately ten to 20 years. Alternatively, in some regions where bog iron was not as plentiful, iron ore was used. Rather than mined, it was found as “red earth”, a rough powder. After the raw ore was accessed, it would be heated to remove moisture and make it more porous so the iron could be more easily smelted.

Smelting the iron ore made use of a bloomery furnace, shown in Figure 9, and were made of clay. The clay itself was actually made of sand, clay, water, and horse dung, the undigested hay in the dung providing structural support. The mixture was strong enough to contain the weight, as well as the correct insulating properties. Once the furnace was built, a fire was started with a natural draft, intended to prevent the rapid change in temperature from fracturing the furnace. Once partially heated, air was forced in with bellows, and it was filled with charcoal. As with any smithy or furnace, airflow was used to control the burn rate. Charcoal and ore were consistently added to the top at a one to one ratio. Temperatures near the base of the furnace approached 1100-1300 degrees Celsius. This creates a reduction atmosphere, with a high concentration of carbon dioxide. The environment shapes the ore into elemental iron, with the following formula:

$$\mathrm{Fe_2O_3 + 3CO \rightarrow 2Fe + 3CO_2}$$

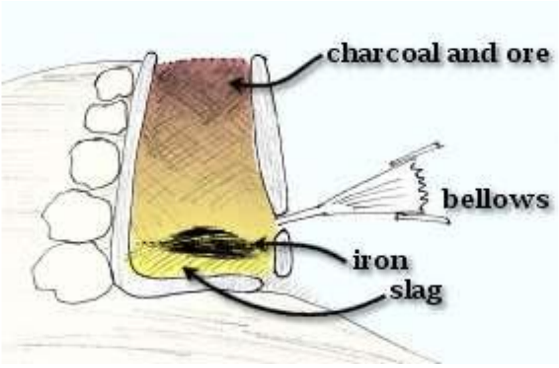


*Figure 9. Bloomery.*

During the process, more charcoal and ore would be added to the furnace and constantly attended to, adjusting fuel, iron ore, and air flow for the best results. Slag, the byproducts of any smelting process, was drained through the base of the furnace. When the smelting process was complete, the bottom section of the furnace was removed, and the bloom, a mixture of low-carbon iron, slag, slag and charcoal, was removed. The surface slag and charcoal would be knocked off, and then the bloom was refined through folding, removing impurities. The final end product of the smelting would be a malleable low-carbon steel, ready for the next step, forging. Despite consistent quality iron, a large amount was wasted in the slag. The amount of waste, combined with the time, skill, and energy necessary for smelting, made iron a very valuable commodity.

Once the relatively pure iron was obtained, a process for forging called pattern welding was used. The smith would weld multiple layers of metal together, iron in the case of the Vikings, then heated and hammered into a single composite mass. The process of composite welding allows smaller pieces of carburized iron to be worked at once, creating a stronger blade than would exist with only iron, the carburized iron plates having formed a thin layer of harder higher carbon steel on the surface. The multiple types of iron in the metal would create a blade that had the necessary strength and flexibility and the differing hardness of the respective metals formed intricate patterns.

The metal would be drawn out into a longer thinner bar, possibly multiple times, depending on the desired outcome. It would eventually be shaped completely into a blade shape, then allowed to cool and filed and ground to sharpness and finished polish.

*Figure 10. Varying Steel Compositions within Blade.*

## 4.3. Origins

It is difficult to track the origin of the Seax. It was clearly most well-known from the Saxons, who were named for their blades. However, it is unlikely they created the Seax. Burials sites, and the tools and weapons buried with the interned, allow for a basic historical outline and geographical spread of the blade. The earliest known findings put the beginning of the blade around the fifth century, though the earliest findings in Europe date approximately at the seventh century. The Saxons settled South-east Britain, bringing their weapons and tools with them. As creating a sword was prohibitively expensive at the time, a tool that was also useful as a weapon was used, becoming an essential tool, not merely bound to the men for war, but also useful for the women, for food and farming. As something so important, it spread with every aspect of their culture, and touched each culture they came in contact with in turn.

Seax of Beagnoth is a unique find that allowed historians some insight into the blades history and background. It was found in the Thames in 1857 and is estimated to have come from the ninth or tenth centuries. Part of what makes it unique is its inscriptions, a full set of Futhorc runes, the old runic alphabet.

# 5. Stock Material Used for Replicas

The original piece we ordered was a 1/4 inch by 1 ½ inch bar of cold rolled 1018 steel. “1018” is a numerical code which indicates the type and content of the metal. The initial “1” represents carbon steel, while the following “0” indicates that the metal contains no “major secondary elements” [15], as some types of steel have sulphur, lead, calcium, or other “impurities” added to make machining the replica easier. Finally, the last two digits indicate the carbon content. In this case, the “18” means that this piece of steel is approximately 0.18% carbon, although controlling the precise carbon content throughout the process is impossible and the “true” carbon content is somewhere between 0.15 and 0.20%. Our piece was purchased from MSC Industrial Supply Co., who bought it from Nessteel Inc., who bought it from an unspecified steel mill.

## 5.1. Manufacturing and Properties of the Steels Used in the Replicas

Steel is a carbon-iron alloy of which up to 2.14wt% consists of carbon. The usage of various other alloys such as manganese, vanadium or tungsten can alter the material properties of the metal. To use carbon as an example, carbon breaks up the clean body centered cubic crystal (BCC) structure of pure iron, strengthening it. This occurs as a result of the carbon fitting into holes in the structure, and preventing slippage. The end result is a stronger material, but one that is less ductile.

Steel had long existed, produced in bloomer forges, but experienced an increase in production once better and more efficient methods were found in the 17th century for blister steel and crucible steel. In the mid nineteenth century, the Bessemer process was invented, but were followed by Siemens-Martin process and then Gilchrist-Thomas process that refined the quality of steel. Basic Oxygen Steelmaking refined it even more, leading to today, with over 1.6 billion tons produced annually.

Pig iron is generally used in the production of steels. It has higher carbon content, usually 3.5-4.5% [59], making it far too brittle to use on its own, but ideal for the production of steels. Originally, pig iron would be melted and agitated, and a current of air directed over it, causing the impurities to be oxidized. The modern technique involves pouring molten pig iron into a furnace which is either electric arc, induction, or basic oxygen. The furnace burns off the impurities, and allows for adjustment of the composition.

When steel began bigger production, it began to replace many things normally made with iron. It is currently used in the construction of roads, rails, basic appliances, and buildings. Most tall buildings have a steel skeleton, and much concrete is supported by steel rebar. Many components of cars, despite aluminum and plastics are still made of steel. Screws, nails, silverware, ships, pipes, mining vehicles and devices, washing machines and heavy equipment, all made primarily of, or containing steel. Before the 17th century, and the Bessemer process, steel was highly costly, and used only when nothing else could be used, such as for knife blades, springs, and clocks and watches. Plastic is now replacing some steels and carbon fiber in cases where cost does not matter.

Long steel is used in steel rebar, rail tracks, structural steel in buildings and bridges, wires. Flat carbon steel is used in major appliances and magnetic cores, and inside and outside body of cars, trains, and ships. Stainless steel is used in cutlery, rulers, surgical instruments, watches, and guns.

As mentioned before, steel is stronger than pure iron, but less ductile. As carbon content increases, steel increases in strength, and decreases in ductility. At higher than 2.14wt%, it is considered cast iron.

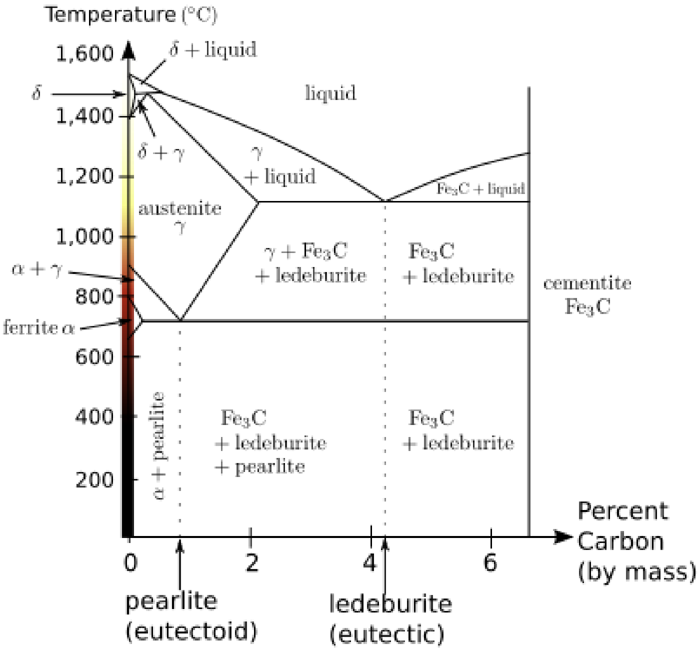


*Figure 11. A Graph only Going up to 6.67% Carbon.*

Mild steel, also known as low carbon or plain-carbon steel, is very common due to its relatively low cost while still gaining better material properties sufficient for most applications. It contains about .05% to .32% carbon and has a low tensile strength, but surface hardness can be increased via carburizing. Carburizing is a heat treatment where the treated metal is exposed to carbon, usually in the form of charcoal or carbon monoxide, to make it stronger. Longer time and higher temps can increase the depth. When quenched and cooled fast, the exterior becomes hard as the surface austenite turns to martensite, and the core is soft and tough as a ferritic or pearlite microstructure. This only works for low carbon steels, and has a case hardness maximum of .25 inches.

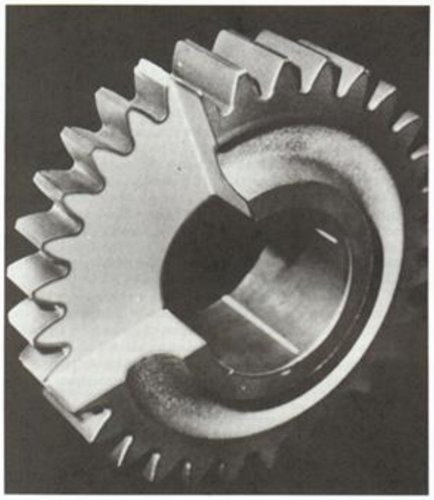


*Figure 12. Cross Section of a Carburized Steel Gear. [23].*

Figure 12 shows a cross section of a carburized steel gear. Mild carbon steel is used when a large amount is required. Useful in structural steel, cars, street furniture, etc.

Medium to high carbon steels contain .25-.6% and .9-2.5% carbon respectively. Medium carbon steel balances ductility, strength and has good wear resistance. It is used in large parts, forging, and car parts. High carbon steel is used for springs or high strength wires. At this level of carbon, other trace elements might be added to control the alloy properties. Manganese is added for better hardenability of lower carbon steels. Likewise, the addition of only 0.17% phosphorus increases both the yield and tensile strength of low-carbon sheet steel by about 62 MPa (9 ksi) while also improving the bake hardening response and deep drawability. Others components added might include sulfur, chromium, cobalt, molybdenum, nickel, niobium, titanium, tungsten, vanadium, and zirconium. Some traces of silicon, oxygen, nitrogen, and aluminum may also be included.

Ultra high carbon steel refers to steels containing 2.5-3.0% carbon. These are usually used for special instances, such as knifes, axles, or punches. Shaping of these steels is done with powder metallurgy. At this point, it is generally considered cast iron.

The naming convention for steels is given by four digits. The first two are the type of material, and the second are the amount of carbon given by Table 1.

*Table 1. AISI Material Grades [24]*

| | | |
|---|---|---|
| Carbon Steel | 10XX | Plain carbon steel , Mn 1.00% max |
| | 11XX | Resulfurized free cutting |
| | 12XX | Resulfurized - Rephosphorized free cutting |
| | 15XX | Plain carbon steel, Mn 1.00-1.65% |
| Manganese Steel | 13XX | Mn 1.75% |
| Nickel Steel | 23XX | Ni 3.50% |
| | 25XX | Ni 5.00% |
| Nickel Chromium Steel | 31XX | Ni 1.25%, Cr 0.65-0.80% |
| | 32XX | Ni 1.75%, Cr 1.07% |
| | 33XX | Ni 3.50%, Cr 1.50-1.57% |
| | 34XX | Ni 3.00%, Cr 0.77% |
| Molybdenum Steel | 40XX | Mo 0.20-0.25% |
| | 44XX | Mo 0.40-0.52% |
| Chromium Molybdenum Steel | 41XX | Cr 0.50-0.95%, Mo 0.12-0.30% |
| Nickel Chromium Molybdenum Steel | 43XX | Ni 1.82%, Cr 0.50-0.80%, Mo 0.25% |
| | 47XX | Ni 1.05%, Cr 0.45%, Mo 0.20-0.35% |
| Nickel Molybdenum Steel | 46XX | Ni 0.85-1.82%, Mo 0.20-0.25% |
| | 48XX | Ni 3.50%, Mo 0.25% |
| Chromium Steel | 50XX | Cr 0.27-0.65% |
| | 51XX | Cr 0.80-1.05% |
| | 50XXX | Cr 0.50%, C 1.00% min |
| | 51XXX | Cr 1.02%, C 1.00% min |
| | 52XXX | Cr 1.45%, C 1.00% min |
| Chromium Vanadium Steel | 61XX | Cr 0.60-0.95%, V 0.10-0.15% |
| Tungsten Chromium Steel | 72XX | W 1.75%, Cr 0.75% |
| Nickel Chromium Molybdenum Steel | 81XX | Ni 0.30%, Cr 0.40%, Mo 0.12% |
| | 86XX | Ni 0.55%, Cr 0.50%, Mo 0.20% |
| | 87XX | Ni 0.55%, Cr 0.50%, Mo 0.25% |
| | 88XX | Ni 0.55% Cr 0.50% Mo 0.35% |
| Silicon Manganese Steel | 92XX | Si 1.40-2.00%, Mn 0.65-0.85% Cr 0.65% |
| Nickel Chromium Molybdenum Steel | 93XX | Ni 3.25%, Cr 1.20%, Mo 0.12% |
| | 94XX | Ni 0.45%, Cr 0.40%, Mo 0.12% |
| | 97XX | Ni 0.55%, Cr 0.20%, Mo 0.20% |
| | 98XX | Ni 1.00%, Cr 0.80%, Mo 0.25% |

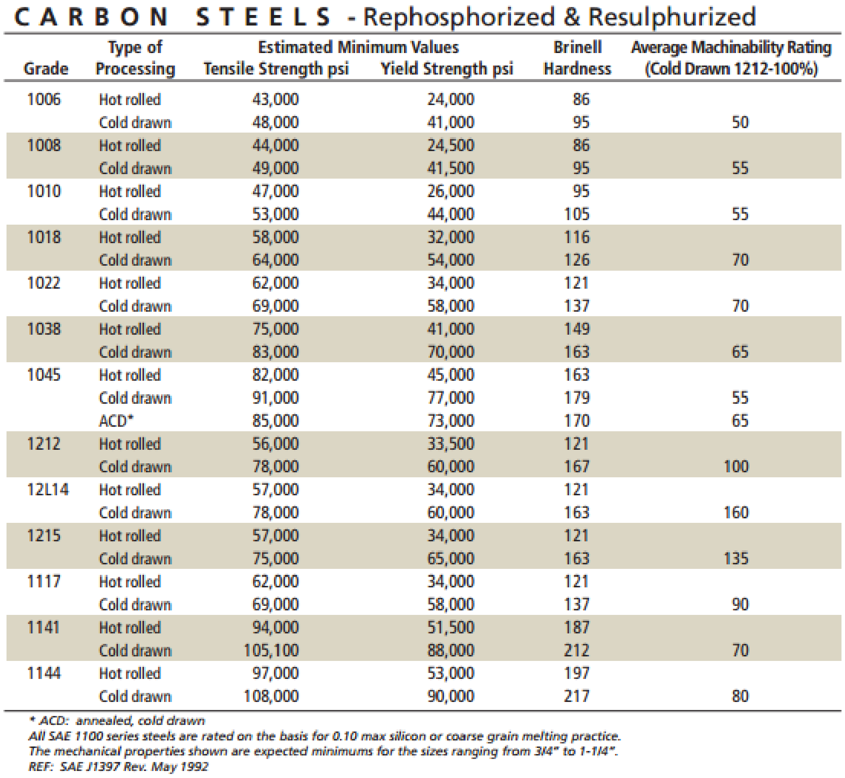
While carbon composes at a maximum of 3% of steels for practical uses, with alloy steel, additional elements can make up between 1 and 50% of the steel. The difference between low alloy and high alloy steels is somewhat arbitrary and not well agreed on. Smith and Hashemi use 4%, while Degarmo makes use of 8%. Generally, alloy steel still refers to low alloy steels. Alloys are created to improve any number of properties of steels above that of normal carbon steels, including, strength, toughness, hardness, wear resistance, corrosion resistance, hardenability, and hot hardness. Often this requires heat treating to achieve these properties. These are usually used in very specific scenarios such as jet engines, spacecraft, or reactors. Alloy steel is also often used for objects where magnetism matters, like electric motors or transformers.

Alloyed elements are added in small amounts for smaller things, like strength, hardenability, or higher for special things, like corrosion resistance or temperature stability, Table 2. Table 3 shows typical strength values for various types of steels.

*Table 2. Principal Effects of Major Alloying Elements for Steel [25]*

| **Principal effects of major alloying elements for steel** | | |
|---|---|---|
| **Element** | **Percentage** | **Primary function** |
| Aluminum | 0.95–1.30 | Alloying element in nitriding steels |
| Bismuth | - | Improves machinability |
| Boron | 0.001–0.003 | A powerful hardenability agent |
| Chromium | 0.5–2 | Increases hardenability |
| | 4–18 | Increases corrosion resistance |
| Copper | 0.1–0.4 | Corrosion resistance |
| Lead | - | Improved machinability |
| Manganese | 0.25–0.40 | Combines with sulfur and with phosphorus to reduce the brittleness. Also helps to remove excess oxygen from molten steel. |
| | >1 | Increases hardenability by lowering transformation points and causing transformations to be sluggish |
| Molybdenum | 0.2–5 | Stable carbides; inhibits grain growth. Increases the toughness of steel, thus making molybdenum a very valuable alloy metal for making the cutting parts of machine tools and also the turbine blades of turbojet engines. Also used in rocket motors. |
| Nickel | 2–5 | Toughener |
| | 12–20 | Increases corrosion resistance |
| Silicon | 0.2–0.7 | Increases strength |
| | 2.0 | Spring steels |
| | Higher percentages | Improves magnetic properties |
| Sulfur | 0.08–0.15 | Free-machining properties |
| Titanium | - | Fixes carbon in inert particles; reduces martensitic hardness in chromium steels |
| Tungsten | - | Also increases the melting point. |
| Vanadium | 0.15 | Stable carbides; increases strength while retaining ductility; promotes fine grain structure. Increases the toughness at high temperatures |

*Table 3. Mechanical Properties for Different Types of Steels [26]*



**CARBON STEELS - Rephosphorized & Resulphurized**

| Grade | Type of Processing | Estimated Minimum Values<br>Tensile Strength psi | Yield Strength psi | Brinell Hardness | Average Machinability Rating (Cold Drawn 1212-100%) |
|---|---|---|---|---|---|
| 1006 | Hot rolled | 43,000 | 24,000 | 86 | |
| | Cold drawn | 48,000 | 41,000 | 95 | 50 |
| 1008 | Hot rolled | 44,000 | 24,500 | 86 | |
| | Cold drawn | 49,000 | 41,500 | 95 | 55 |
| 1010 | Hot rolled | 47,000 | 26,000 | 95 | |
| | Cold drawn | 53,000 | 44,000 | 105 | 55 |
| 1018 | Hot rolled | 58,000 | 32,000 | 116 | |
| | Cold drawn | 64,000 | 54,000 | 126 | 70 |
| 1022 | Hot rolled | 62,000 | 34,000 | 121 | |
| | Cold drawn | 69,000 | 58,000 | 137 | 70 |
| 1038 | Hot rolled | 75,000 | 41,000 | 149 | |
| | Cold drawn | 83,000 | 70,000 | 163 | 65 |
| 1045 | Hot rolled | 82,000 | 45,000 | 163 | |
| | Cold drawn | 91,000 | 77,000 | 179 | 55 |
| | ACD* | 85,000 | 73,000 | 170 | 65 |
| 1212 | Hot rolled | 56,000 | 33,500 | 121 | |
| | Cold drawn | 78,000 | 60,000 | 167 | 100 |
| 12L14 | Hot rolled | 57,000 | 34,000 | 121 | |
| | Cold drawn | 78,000 | 60,000 | 163 | 160 |
| 1215 | Hot rolled | 57,000 | 34,000 | 121 | |
| | Cold drawn | 75,000 | 65,000 | 163 | 135 |
| 1117 | Hot rolled | 62,000 | 34,000 | 121 | |
| | Cold drawn | 69,000 | 58,000 | 137 | 90 |
| 1141 | Hot rolled | 94,000 | 51,500 | 187 | |
| | Cold drawn | 105,100 | 88,000 | 212 | 70 |
| 1144 | Hot rolled | 97,000 | 53,000 | 197 | |
| | Cold drawn | 108,000 | 90,000 | 217 | 80 |

** ACD: annealed, cold drawn*
*All SAE 1100 series steels are rated on the basis for 0.10 max silicon or coarse grain melting practice.*
*The mechanical properties shown are expected minimums for the sizes ranging from 3/4" to 1-1/4".*
*REF: SAE J1397 Rev. May 1992*

## 5.2. Steel Stock Fabrication

Steel is a key industry in the modern era, as the material is essential for production of a wide variety of products including cars, industrial machinery, buildings, and electronics. More than 1.6 billion tons of steel were produced worldwide in 2014 [18]. Although the basic principles remain the same, modern techniques for producing steel (including the bars we used for our knives) are considerably more advanced.

Unlike the Vikings (who relied primarily on “bog iron”) today’s steel is produced from iron ore, mined in roughly 50 countries across the world. Brazil and Australia are the largest contributors, each responsible for approximately one third of global ore exports. This iron ore is fed into a blast furnace along with coal coke, limestone, and heated air. The hot air allows the coke to combust, producing sufficient heat to melt the iron as well as additional carbon. The limestone acts as a “flux,” bonding with various impurities known as slag and floating to the surface to be skimmed off. In the past, this iron was usually poured into troughs and allowed to cool into bars of pig iron, but most modern steelmaking facilities are constructed to allow the molten iron to be moved to the next step while still in its liquid state.

There are several methods for converting this iron into steel, but the most popular is known as Basic Oxygen Steelmaking, or BOS. The molten steel is poured into a large container called a ladle, where it is mixed with a smaller amount of solid scrap steel which makes up roughly 25-30% of the metal mass. Maintaining the correct amount of scrap relative to the molten iron (called the charge balance) is essential because it absorbs additional thermal energy produced later on in the process. After the hot and cold metal has been added, fluxes (typically a mix of lime and dolomite) are poured into the ladle, and a water cooled copper “lance” is dipped into the mixture. The lance blows 99.5% pure oxygen into the molten metal at supersonic speeds, triggering several key chemical reactions. Oxidized silicon forms silica and reacts with the lime and dolomite fluxes, while carbon ignites and forms carbon monoxide and carbon dioxide. These combine to form a gaseous cloud of slag impurities. These reactions are exothermic, producing enough heat to raise the temperature to 1700 degrees Celsius and melting the scrap metal. After the blowing process is complete (it usually takes 15-20 minutes), the molten steel is poured into a new ladle to be cast into a bar, ingot, or other shape suitable for further work. The accumulated slag is removed separately and sold for use in asphalt production or as railroad ballast.

Another common method for producing steel is the Electric Arc Furnace, or EAF. It uses similar concepts as the BOS design, but the primary source of heat is a high voltage electric arc (hence the name). The EAF is gradually growing in popularity in the United States. Unlike the BOS method, the EAF is not autogenous, generating most of the necessary heat via electrical charges or burning natural gas instead of from reactions with purified oxygen. None the less, the general principles are the same: A carefully selected quantity of scrap must be mixed in with the hot metal, a quantity of oxygen must be blown through, and fluxes like lime must be added to convert unwanted elements like sulphur and phosphorus into slag so it can be more easily removed.

Our piece would have been taken to a manufacturing plant to be reheated to above its recrystallization temperature (typically 925 degrees Celsius) and fed between large rollers to reduce it to the desired shape and thickness. This is known as “hot rolling.” After this step, our steel was allowed to cool and then given further processing, rolling it again while below the recrystallization temperature. This is sometimes referred to as “cold rolling,” although “cold finishing” is considered to be the proper term for bar products like our piece.

Hot rolled steel is typically cheaper than cold rolled, but it is also less consistent in size, shape, and tolerance because the heated metal tends to shrink as it cools. On the other hand, cold rolled material is generally harder (due to a higher carbon content) and has a cleaner surface. This makes it more difficult to work in the forge, but should also produce a superior final product.

# 6. Our Blade Replica Design

To aid in the manufacturing process, our team generated Solidworks models of the Seax knife with accurate dimensions, as well as engineering drawings, Figures 13 and 14. The plan is to make a Seax with a 14 inch blade attached to a 5 inch long handle. This handle will begin with an elliptical piece of metal at the base of the blade that just barely circumscribes the blade profile at the base. The tang will protrude 4.5 inches from the ¼ inch thick metal ellipse, and the handle will have a ¼ elliptical pommel identical to the one at the base of the blade, albeit even more rounded. We will take a piece of ash wood and sand it down to the shape that we desire for our handle and then we will cut it in half and remove material from the inside of the elliptical prism so that the tang will fit inside. We will then seal the hilt onto the tang, most likely with glue, however if we are able to attach the hilt with a piece of metal pushed through both sides of the wood and passing through a hole in the blade, then we will attempt to do that first.

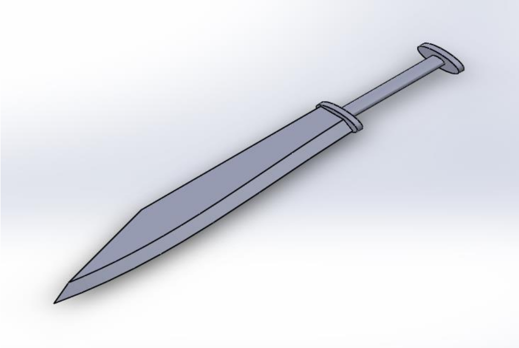


*Figure 13. Seax Knife Solidworks Model.*

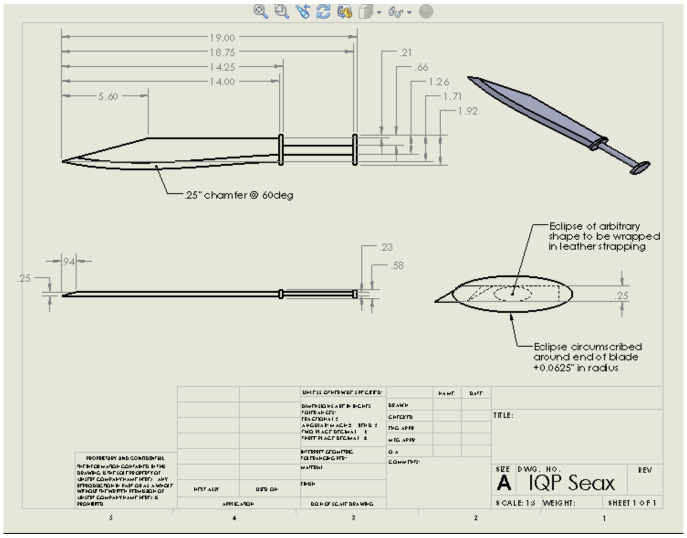


*Figure 14. Seax Knife Engineering Drawing.*

# 7. Manufacturing of the Blade

The materials process that will be used in order to create the Viking Seax knife will be forging, also called blacksmithing. We will be using a square bar of 1018 low carbon steel for our Seax knife. Through the basic process of heating and hammering we will slowly shape our workpiece into the desired shape. Throughout the process we will study the microstructure of the material we are using in order to view the changes that occur throughout the process.

## 7.1. Basics of Blacksmithing

Blacksmithing is, in the basic sense, the process of heating a metal up to make it soft, and then hammer it to form it in a desired shape. The first metals used for blacksmithing were bronze and iron, however iron was found to be more useful and easier to obtain. The refined skills of a blacksmith likely began in the Iron Age. Blacksmiths were generally the center of the towns, often holding high ranking positions. They would be sought out for to make tools, horseshoes, armor, weapons, and anything that was made from metal for the most part. The major event that brought about the rise of blacksmithing was the discovery of being able to make the coals burn hotter by the use of manually operated bellows. Once the demand for blacksmiths increased due to discovery of more things they could be used for, it quickly spread throughout Europe. As the ages went on the process of blacksmithing stayed relatively the same, aside from inventions of larger furnaces and using water power. The decline of blacksmithing began when the blast furnace was invented. That as well as advancements in the production of iron around 1700 lead to the decline of blacksmiths. These days, blacksmiths have become highly specialized in order to survive, making artisan pieces as well as replicas for various museums.

## 7.2. Blacksmithing Tools and Techniques

There are a number of tools which are required in order to manually smith a piece of steel into a finished product. To start out, some form of a forge is necessary to heat the metal hot enough to work. Typically the fuel of choice was coal, with charcoal as a possible alternative in places where wood was common but coal was scarce. Some modern smiths have also made use of propane fueled forges. A coal fired forge generally consists of a large flat hearth and a firepot. A chimney is also required to allow smoke and other gasses to escape. The firepot is located below and often behind the hearth, and is connected to a bellows or other form of mechanical pump designed for blowing air. When the forge is in use, this is the hottest part of the fire, containing a “ball” of combusting coal and coal coke, surrounded by heated but non-combusting coal and kept oxygenated by air forced in through the bellows. The extra oxygen is necessary to allow the coal to burn properly. The hearth generally contains a decent quantity of fresh coal, which is progressively moved closer to the fire as more coal is consumed and new coal is placed around the edges. This process allows the coal to heat up and gradually turn into coke, a superior fuel, before being burned in the fire or removed to be used later for a particularly fuel intensive process like welding.

Probably the most important hand tools for a blacksmith are the iconic hammer and anvil. The anvil is a large piece of metal with a roughly triangular shape, generally weighing several hundred pounds and attached to a large wooden stand. Anvil heights vary from person to person, but are usually designed to align with the height of the blacksmith’s knuckles when his arm is hanging at his side. The anvil is the surface on which the blacksmith shapes his work, and is therefore designed to be as hard and smooth as possible. There are also a wide variety of useful features on a typical anvil, each with a clear purpose. The flat top is obviously designed as a surface to hammer on, while the long rectangular shape and the sharp 90 degree edges are there to make it easier to form a “shoulder” in a bar of metal, and flatten one part while leaving the rest untouched. The rounded, conical “horn” on one side of the anvil is used to bend metal into even curves and circles. The two holes also have specific purposes: the roughly 1”x1” square “hardy hole,” for inserting tools like the “hardy” or “softy,” and the ½” circular hole used primarily for flattening the head of a nail without disrupting the tapered end. Finally, the small “ledge” on many anvils allows the blacksmith to keep a piece straight while hammering on one end, usually to start a bend or curve.

The blacksmith’s hammer is a very versatile tool when used in conjunction with his other implements. With it he can reshape a piece of metal to make it longer, shorter, thinner, or thicker on any axis. He can make simple bends and elaborate curves, draw out an end into a point. The hammer can also be used indirectly, applying the force which allows another tool to do its job. Some examples include the hardy, the punch, and the flatter.

A hardy is essentially a large, blocky chisel with a square base designed to fit into the hardy hole on the anvil. It is used to cut notches or grooves into a piece of metal, which is held on top of the edge and struck from above. Notches can be used to denote a specific point on a piece of metal (where the blade ends and the handle begins, for example), as a “guide” for the metal to bend into, or even to cut it into two pieces.

A punch is generally an elongated, conical shape of various lengths and widths, made from metal treated to be especially hard. They are sometimes connected to a handle for safety and ease of use. The purpose of a punch is fairly intuitive: it it positioned vertically above the work, narrow end down, and struck from above such that it either indents the material or punches through it, forming a hole.

A flatter is similar to a punch in operation, if completely opposite in effect. It closely resembles a hammer with an unusually broad and often square head. To use it, the flatter is placed on top of a piece and struck with a hammer, flattening out the work and reducing or removing indentations caused by normal hammering.

Tongs are another crucial blacksmithing tool. Although it is possible and often easier for a blacksmith to work long pieces or metal while holding the cool end in their hand, this is impossible for pieces small enough that both ends become too hot to safely hold. Tongs allow the blacksmith to grab onto and control any part of his work, no matter how hot it may be. The most basic set of tongs consists of two metal rods connected by a pin in the same way as the blades of a pair of scissors. The shorter ends of both rods are modified to hold on to pieces of specific shapes or sizes, from small, flat grips for narrow bars to matching semicircles several inches across, designed to hold half-brick size blocks. Due to the very specific use of each form, a typical blacksmiths workspace has a tremendously large number of differently shaped tongs available to be used.

Finally, a blacksmith requires a container of water, usually referred to as a “slack tub.” This is primarily used for quenching and cooling the work, but it also doubles as a valuable safety precaution in the event of burns caused by accidental exposure to hot coals, metal, or tools.

## 7.3. Fundamentals of Forging

Forging is one of, if not the, oldest metalworking processes. In the twelfth century, the introduction of the water wheel and water power made the use of a hand powered hammer and anvil impractical, but instigated the beginning of powered forging. In modern production, forging is done with massive presses and hammers powered by compressed air, electricity, hydraulics, or steam. These hammers have weights in the thousands of pounds, and smaller ones, 500 lbs or less, are often used in art smithies or small metalworking shops. Steam powered hammers still exist, though are uncommon as other power sources are more efficient.

Forging is useful as the parts created are much stronger than a similar cast or machined part. When shaped, the grain warps, leading to a continuous grain and improved strength characteristics. Steel and iron are usually forged hot, though some metals can be forged cold. Hot forging prevents the strain hardening that would result from cold working. Strain hardening refers to the process of deforming a metal to strengthen it. This makes it difficult to perform other operations on the metal. When strain hardening would be desired, in most instances it is more efficient and more controllable to heat treat the piece.

Forging in large amounts requires high expenditure in machinery, tooling, facilities, and personnel. For high temperature forging, a furnace is needed to heat ingots. Due to size and dangers, an entire building is usually required. For drop forging, vibration needs to be absorbed. Dies are very often used to shape the metal, which must be precisely machined, built, and treated to withstand the repeated high forces.

Though there are many forging processes, they can be grouped into three sections. Drawn out, where the length increases and the width decreases. Upset, where the length decreases, and the width increases. And squeezed in closed compression dies, which results in a multidirectional flow.

Forging processes are usually classified according to temperature, thought they can be done at multiple temperatures. Temperature classification refers to the crystallization temperature; if forging occurs above recrystallization temperature, it is called hot forging. If lower, but above 30%, it is called warm forging. If below 30%, in which the metal is generally worked at room temperature, it is called cold forging. Hot forging prevents work hardening as the effects are negated by the recrystallization process, whereas cold forging does result in work hardening.

Drop forging drops a hammer onto the piece to bludgeon it into the shape of the die. There are two types of die forging, open and closed. Open die does not fully enclose the piece, while closed die forging does.

Open die forging is also called smith forging, a modern and powered equivalent of a hammer and anvil. The hammer hits and deforms the metal which has been placed on an anvil. Open die forging is referred to as such because the dies, the surfaces in contact with the work piece do not surround it, allowing the metal to move.

“Advantages

- Reduced chance of voids
- Better fatigue resistance
- Improved microstructure
- Continuous grain flow
- Finer grain size
- Greater strength”

[29]

Closed die forging is also called impression die forging. The metal is placed into a two part mold, top and bottom, which the hammer then strikes. Excess metal is forced out of the sides, resulting in flash.

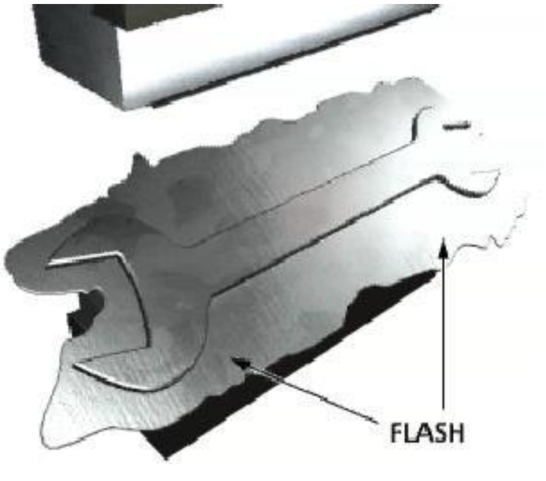


*Figure 15. Flash. [28].*

Flash cools more quickly than the rest of the piece, and as such is harder. This makes it more difficult for more flash to form, ensuring that the soft metal fully fills the die.

Flash is removed at the end of the process. Commercially, the work piece is put through several dies, starting with molding the metal into a general shape of the end goal, and getting closer with each step. Impression forging has become more effective in recent years with automation, allowing for induction heating, mechanical feeding, positioning and manipulation, and the direct heat treatment of parts after forging.

To get around the formation of flash, flashless forging, or true closed die forging may be used. The dies are completely closed, preventing flash as well as saving up to 20 – 40% of material, but the process is much more expensive due to more complex die designs and the required better lubrication and equipment.

The overall process of closed die forging has high manufacturing cost to begin with, but each recurring piece costs little extra.

Press forging refers to a similar process to normal drop forging, but it is a slow continuous process rather than quick and abrupt. This allows for the deformation of the entire work piece, versus drop forging which generally only deforms the exterior of the piece. It also allows for full knowledge and control of the strain rate, as well very high tolerances. The downsides are the time and amount of heat necessary to make it work.

Upset forging is the lengthwise compression of metals in order to increase diameter. It is generally used to create valves, couplings, bolts, and screws. Most often used for small parts, but can be used for round bars of up to 9.8 inches in diameter. There are three rules that must be followed for upset forging. [29], pp. 395–396.

- “The length of unsupported metal that can be upset in one blow without injurious buckling should be limited to three times the diameter of the bar.
- Lengths of stock greater than three times the diameter may be upset successfully, provided that the diameter of the upset is not more than 1.5 times the diameter of the stock.
- In an upset requiring stock length greater than three times the diameter of the stock, and where the diameter of the cavity is not more than 1.5 times the diameter of the stock, the length of unsupported metal beyond the face of the die must not exceed the diameter of the bar.”

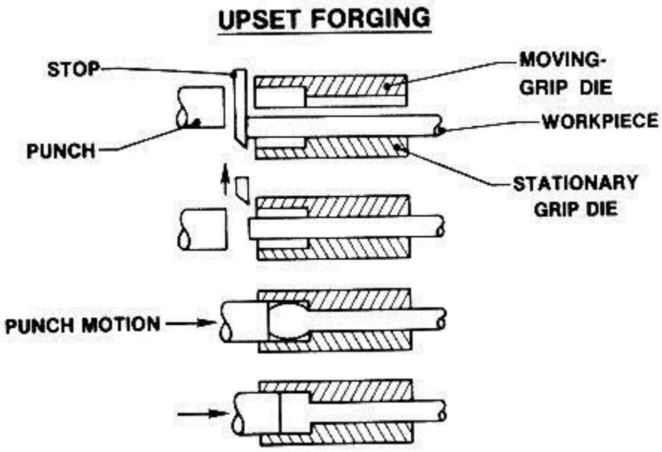


Figure 16. Motion of Upset Forging. [30].

Roll forging describes a process where round or flat bar stock is flattened between a set of two rollers to reduce thickness and increase the length. Roll forging can be used for simple shapes such as sheet metal, or more complex shapes, like leaf springs or railroad tracks.

## 7.4. Blade Forging

We shall begin by taking the piece of 1018 mild steel we purchased for the creation of our replica and studying the microstructure of it under a microscope.  We will look at the various grain structures in the replica and take note of what they look like before the process of forging takes place.  We will also take note of any flaws we may see in the structure of the material.  We may also do various hardness and impact tests in order to see the characteristics of the untreated metal.  The material will then be taken to Ferromorphics, a local blacksmith workshop, where the process of forging shall begin. We shall heat the steel up using the forge and then using a hammer, we shall hammer the workpiece into the shape of the Seax knife.

The first section of the knife to be worked on shall be the blade itself.  The steel will be hammered down to a smaller thickness as well as slightly wider due to the original stock being slightly thicker and narrower than the desired finish product.  This was done due to the process of hammering causing the metal to spread and thin out. After the blade has been thinned out and widened we shall hammer in the angle on the edge of the blade.  After blade itself is complete we will create the tang in order to put on the wooden handle of the blade.

After the piece of steel has been hammered into the shape of the knife we will then again study the microstructure of it in order to see and compare the differences from before it was forged to after. We may also draw the metal, which is the process of stretching and thinning out the metal, in order to achieve a certain length if we originally hammer it to be too small or simply want a longer piece. One method that is used to draw out a piece of metal in blacksmithing is by using a chisel to make notches in the blade. Then when the blade is hammered it spreads out and lengthens easier due to these notches, resulting in a longer and thinner replica.  If we do draw the metal out, we will once again study the structure.  Depending on which way we stretch the piece out, it can cause the grain structures to look different.

The last process in the creation of the blade, depending on the result of the blade after the forging, is case hardening. Case hardening is a process that makes the outer layer of the metal harder by first heating the metal red hot and then plunging it into a case hardening compound that is typically high in carbon content. After that you heat the metal once again and then plunge it into cold water.  This will leave the outside layer of the metal hard while the inside remains softer, hence the name case hardening.  This process will also change the microstructure of the metal and you will be able to see the differences between the hardened outside and the softer middle. Due to this we will once again study the microstructure of the replica in order to take another look at the changes that have occurred.

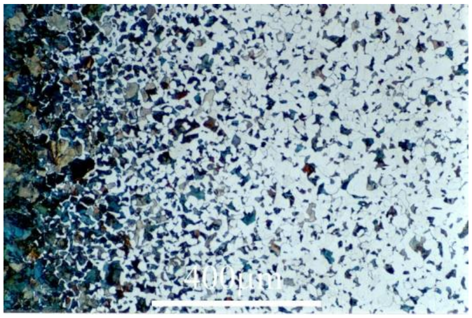


*Figure 17. Case Hardened Steel Microstructure. [60].*

## 7.5. Attaching the Grip

The last step to making the blade is to make the wooden handle to go over the tang, which is the tail end of the blade that is inserted into handles. For this we will be using untreated ash wood, and by means of sanding we will shape the wooden handle in the correct shape for the handle. The handle will be two replicas that will close over the tang and then either be glued of riveted on. After this is complete we may wrap the wooden handle in leather to give an additional authentic look. Depending on whether we go with the leather or not, we may also etch a design in the wood and blade in order to give a more artistic and professional appearance. Here is a theoretical example of what our knife could potentially look like, assuming we do not have any complications with the forging process and have the skill to make such a high quality knife.

## 8. Evolution of Blacksmithing Techniques

The Vikings were forced to make due with limited raw iron supplies and very rudimentary forges with which they smithed their weapons and armor. Far from an ideal furnace, bloomeries were constructed out of clay, and were used to heat the iron ore to suitable temperatures for metalworking.

*Figure 18. Clay and Horse Manure Bloomery.*

*Figure 19. Viking Iron Bloom.*

A common misconception is that Viking blacksmiths were able to melt down the iron ore and mold it into whatever shape they desired. The bloomeries that the Viking smiths had at their disposal were capable of melting iron down into a softer substance that still contained lots of impurities, however this was very much not a liquid. It was not until the “Fourteenth Century in Europe with the introduction of the blast furnace which used a much greater volume of air and layered the iron ore with charcoal” [10] that this was possible. The only technique available to Viking smiths to purify the iron bloom, which refers to the soft iron blob left in the base of the bloomery, was hammering, which “was the only way to get rid of the impurities that made bloom iron so brittle. Hammering closed up the pores in the iron bloom and welded them shut” [12]. Each time iron is heated and cooled down, approximately 1% of the mass of the metal is lost, and much of this loss is in the form of impurities. The Vikings were capable of making steel, by infusing iron with pure carbon, but doing so was very difficult and the capacity of their steel making operations were so limited that the Vikings elected to alternate strips of iron with steel along the cutting edge of a blade in an effort to make the small steel reserve last as long as possible. For example, “An expensive and very strong knife, sword or axe could be made by forging alternate layers of iron and steel together” and exclusively for “the cutting edges and points of iron tools and weapons” [11]. This technique of using the minimal amount of steel and iron to do the job is a common theme that can be observed in Viking weapons and armor, where weapons such as the spear and hand axe were among the most popular combat weapons, while requiring only a modest supply of metal to create the blade. Viking blacksmiths specialized in a very complex trade, and “carefully guard[ed] the secrets of their craft, revealing them only to their chosen apprentices, who would often be their own sons or other members of the family.” [11] This trend resulted in blacksmiths being renowned for their skill, understood by only a few people in a Viking settlement, as it was a skillset that was kept close to the chest, and was invaluable in that day and age. Smiths were so important that “Rulers and important noblemen would often have their own personal smith” [11] to craft them custom weapons and armor, as both weaponry and armor were prominent signs of class status, and the more ornate and expensive a noble’s armament appeared, the wealthier, and therefore more powerful he appeared as well. Stemming from the almost cult-like tendencies of smiths and their private circles, “The skills and processes of working metal (especially iron) were a mystery to most people in ancient and Viking times and were thought by superstitious people to be magical. 'Magical' iron and skilled smiths feature in the myths and legends of the Anglo-Saxon, Scandinavian and other Germanic peoples” [9]. As a result of this association with the supernatural, and with respect to superstition, “The iron horseshoe - one of the typical products of the smith - is still regarded as a 'magical' symbol today and is hung on walls and doors to bring good luck” [11].

*Figure 20. Viking Horseshoe.*

Viking blacksmiths were extremely skilled in their work, especially considering the sparse supply of metal from which to work, and the primitive design of their forges. They were held in high esteem for their talent, and valued immensely because of the invaluable service that they could offer their community.

# 9. Blacksmithing of the Replicas

The first step in the process of making our blade was ordering the material. For this blade we decided to use 1018 steel due to its low carbon content making it easier to forge. The bar was ¼ inches thick by 1 inch wide and would be hammered out to be thicker.

## 9.1. First Replica

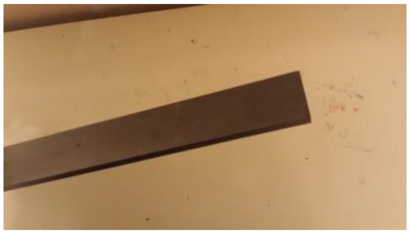


Figure 21. Original 1018 Steel Stock.

From the stock we cut roughly a 14 inches piece and began by plasma cutting a general shape of our replica. In the era of the Vikings of course they were not fortunate enough to have such technology, however we took this method as to speed up the process slightly and simplify things. After this was completed, we had to grind down the edges of the metal to make a more straight finish do to the cut not being very straight and consistent. This inconsistency was due to not moving the tip at a constant speed as well as cutting too much in on one section making a notch that had to be grinded out. During the grinding process we also smoothed out all the edges in order to make the replica not have sharp edges and slightly easier to handle during the forging process.

Figure 22. Grinding the First Replica into the Rough Shape.

After grinding the steel replica down to have a relatively straight edge in the general shape we wanted our replica we began the process of forging it. Using the forge at Ferromorphics, we would heat up the metal until it was a bright orange and then proceeding to hammer out one edge of the replica since the seax knife is a single sided blade. We had to be careful of overheating the metal, which we almost did a few times, or else the metal replica would essentially fall apart where the metal was white hot. In the process of making the blade edge thinner we began to notice that the blade was beginning to curve a considerable amount. We found that the process of stretching out just one side naturally curves the blade, so since the seax is a straight blade with a thick back side, we had to straighten the blade back out every 2 or so heats. This conveniently also made the sections that we made slightly too thin (due to later needing enough material to grind out the hammer marks) a bit thicker due to us hammering on the edge to make it straight again.

*Figure 23. Connor Hammering the Blade Edge of the Steel Replica.*

Another thing we also began to notice was that the blade was getting exceptionally longer than we originally expected, so much so that the 14’ replica we started with had become roughly 18’. We also noticed that by heating the tip up so many times and thinning it out to much that we effectively had “burnt” the metal leaving an undesirable finish. Since the replica had become too long anyways, we decide to cut the burnt tip off, which gave us the size we wanted. We did this by using a hot chisel insert in the anvil and hammering the undesirable section off. This method was used, although possibly not the most practical, due to time efficiency as well as no bandsaws being available for use at the time.  After the replica was shortened, we created the tip of the blade from the section that we cut off due to needing to repair it from the cut-off anyways.  After this was done we touched up on blade portion itself, extending it further down and trying to create more of a blade.

*Figure 24. Rough Blade Portion Finished, Tang Next to be Worked on.*

*Figure 25. Final Replica Without Handle.*

The next step we took in making the blade was creating the tang.  To create the tang we used a more modern method to show how modern methods have made things simpler.  We used an angle grinder with a cutoff wheel in order to cut down the stock we had remaining to a more narrow piece and general shape we wanted so we did not have to do as much hammering.  After this was done we heated the tang a few times and hammered it out to get the shape and length we wanted.  Next, we used the angle grinder once again, this time with a grinding wheel, in order to grind down the blade itself in order to try and smooth out the surface, give it a better finish, and try and get out a majority of the hammer marks. After this was done we went around the outside of the blade with a grinding wheel in order to chamfer and smooth out the edges so that they were not sharp (it being a replica, we did not want it to be capable of actually hurting someone.

The next process is the making of the handle itself. For this we decided to go with the method of wrapping the handle in leather due to time constraints. The leather was chosen in order to make the blade look authentic and of the time. The leather is cut into thin strips roughly half an inch to an inch thick in order to make the wrapping look good. One piece of leather is taken and wrapped and glued over the bottom of the tang to ensure no metal is showing. Once this was done an end of a leather strip is glued to the top of the tang and double wrapped in order to ensure it does not come loose, then the leather is wrapped in a spiral manner down the blade. Once at the bottom of the blade, the leather strip is once again glued in order to ensure it does not come undone. The final step if desired would be to buff out the blade in order to get a mirror finish.

## 9.2. Second Replica

Our second replica was started after the first, allowing us to learn from some earlier mistakes. Although the material we used was the same, we cut off a shorter piece to start out with because we knew the process of drawing out the blade would give us significantly more length than the original bar. We also decided on a fundamentally different approach, opting to use “traditional” blacksmith tools over modern machines like plasma cutters whenever possible.

Our first step was to hammer out the blade side of the Seax to form a noticeable (if still very dull) edge. Although this did produce very clear “sharp” and “dull” sides, our hammering also caused the blade to curve slightly. We corrected this by periodically hammering on the edges to straighten the replica, although this in turn had the effect of slightly dulling our “sharp” edge.

It should be noted that over the course of this process, we generally aimed to get our replica to a “bright orange” or “yellow” heat. Although this makes the material very soft and easy to work, it also increases the risk of burning the metal if it is allowed to heat for too long. Although we were able to avoid any catastrophic damage, we did manage to burn our blade several times. In addition to altering the macrostructure of the material, this also left us with a rather rough and inconsistent texture across most of our blade.

Once we had a clearly defined blade, we decided to draw out the point of the blade. This was an important step to create the shape we wanted, as we not only needed to form the sharp tip but also the distinct “corner” on the dull edge of the blade which identifies the knife as a “broken back” seax. We accomplished this by heating and hammering the “dull” edge very close to the end of the blade, pushing the excess material towards the tip and producing a very clear downward slope from the spot where we wanted the back to “break.” This did result in some minor warping which was easily corrected by hammering out the flat side. We wanted to make sure we didn’t leave a small tip to be inadvertently burn off while we were working on a different part of the replica, so we did not finish the tip all at once, instead leaving it roughly half an inch across and still squared off.

At this point, we decided it was important to clearly indicate where the tang ended and the blade began, so we used a hardy to notch both edges and went back to drawing out and realigning the blade. Once we were mostly satisfied with the length, width, and alignment, we began to work on the tang and the part of the blade adjacent to it. Due to an initial error of judgment, we decided to make the blade directly in front of the tang narrower than we actually wanted, although we were quickly able to correct the problem with no lasting damage done.

The tang end of our replica was roughly six inches long at this stage, more than twice as long as we wanted it to be. We decided to cut off about five inches in order to make the tank a more appropriate size. Although we considered cutting it using a hardy as a contemporary Viking blacksmith probably would have, we ultimately decided that using a grinder would be much easier and decided that taking advantage of living in the modern era to get a cleaner cut and save the time it would have taken to get the rather obstinate hardy back out of the anvil.

At this point, all we had to do to fix up the tang was to make it shorter and thicker than the blade side by hammering down the edges. Unfortunately, due to some irrational nonchalance and a touch of basic negligence, we managed to expedite the process considerably by burning away a quarter-sized chunk of the metal we had left over for the tang. Although the absence of this material made the rest of the metal much easier to hammer into the correct shape and the severely warped and bubbly texture should be safely concealed by the wood handle of the final product, this was indisputably a noteworthy and embarrassing mistake.

Very carefully, in order to avoid any risk of burning, we heated the tip to a mild orange color and hammered the back of the blade downward to form a distinct point, carefully re-aligning the blade every time it warped to one side or another. Once the point was finished, we moved on to cleaning up the blade by heating sections to a mild orange and smoothing them out with the flatter to eliminate as many dents and burn marks as we could. Once we were satisfied that the blade was straight and relatively smooth, we quenched it in water and used the grinder to produce a shiny, metallic finish and remove as many smaller imperfections along the blade as we could.

*Figure 26. Second Blade Being Hammered.*

*Figure 27. Second Replica Before Tang.*

## 10. Sample Preparation for Microstructure Analysis

For the making of the sample pieces that were to be studied under a microscope, a small piece about ½ inch by ½ inch was cut from the steel bar. It was then cut using a hacksaw on three different planes in order to be able to see the microstructure and grain from three different sides. Using a mounting press, the three pieces were set into a PhenoCure premold in order to be able to polish and use in the microscope more easily. This process was done by first taking the sample and putting it in the machine followed by the premold, after this was set the machine heats up the premold and sets the piece in it securely.

*Figure 28. Mounting Press.*

*Figure 29. Example of PhenoCure Premold with Sample.*

Once the mounting was finished, the samples were then polished using a grinding/polishing machine and sandpapers varying from 120 grade all the way to .03 microns.

*Figure 30. Grinding Machine Used in Polishing of Samples.*

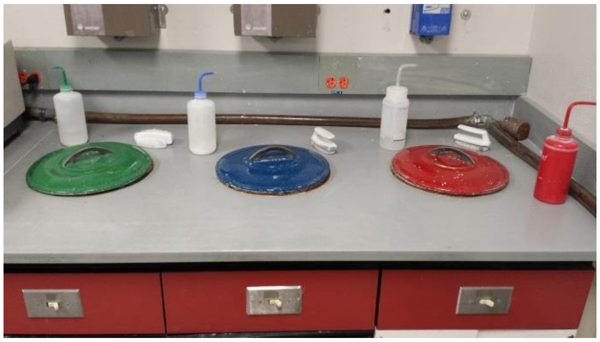


*Figure 31. Additional Polishing Machines Used.*

This produced a nice mirror finish on the samples which is required when viewing the pieces under a microscope because any scratches or imperfections would be noticeable and get in the way of observing the grain structure. One thing that was noticed due to the samples being steel, if they were allowed to be wet for too long they would began to show spots of presumably rust on them. This would seem to occur even sooner the finer the paper you used.

*Figure 32. Sample Pieces After Mounting and Polishing.*

# 11. Stock vs. Replicas

Throughout the course of this project, we will be smithing the 1018 steel from a bar stock into a blade, and will ultimately end up altering the microstructure and mechanical characteristics of our metal in the process. As a result of heating the steel to make it more malleable, we will be able to hammer down one edge into a keen cutting edge (to be ground down). When hammering the steel, the bar will begin to stretch horizontally which will yield the extra ¼ inches in width planned for in our design specifications. The steel has a BCC crystal structure at room temperature, however once it reaches 1300 deg F (704.44 deg C), this structure changes to FCC. This change makes the steel a lot more malleable, as BCC crystal structures only have 4 slip planes, while FCC crystal structures have 12. From the Fe-C phase diagram, we will first predict the expected microstructures based on the processing conditions that the alloy was subjected to, and then perform a microstructural analysis of the actual blade material for comparison.

## 11.1. Predicted Microstructures

The microstructure of a material refers to its structure as seen under the microscope when polished to a very flat face and etched. Crystal structure refers primarily to the 3D arrangement of the atoms, while microstructure represents the actual phases resulting from the processing of the material. The microstructure greatly influences material properties such as strength, ductility, toughness, corrosion resistance, wear resistance, and most others.

The microstructure of a given piece of steel will depend primarily on two things, temperature and carbon content. From the Fe-C phase diagram, and based on the relationship between the two, we can predict the microstructures of the steel: ferrite, cementite, pearlite, or other phases that are forming under non-equilibrium conditions (fast cooling rates) such as martensite or bainite.  Higher in ferrite alloys have lower carbon content, on the left side of the phase diagram. Cementite-rich alloys have higher carbon content, on the opposite side of the phase diagram (high-carbon steels and cast irons) up to 6.67wt% carbon.

Martensite and pearlite refer to different microstructures. Martensite exists in two forms, lath martensite in low carbons steels, and plate martensite in high-carbon steels. Martensite, Figure 33, is formed by rapid cooling of the steel, known as quenching, which does not allow enough time for carbon atoms to diffuse and form phases like ferrite or pearlite.

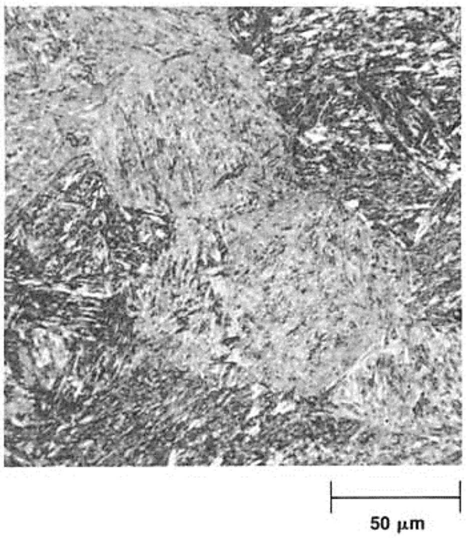


*Figure 33. Light Micrograph of Lath Martensite in 4340 steel. [32].*

Pearlite forms during a slow cooling eutectoid reaction, creating alternating parallel lamellae of ferrite and cementite, producing a two-phase structure. The cementite lamellae appear light and ferrite ones dark on the SEM photo in Figure 34.

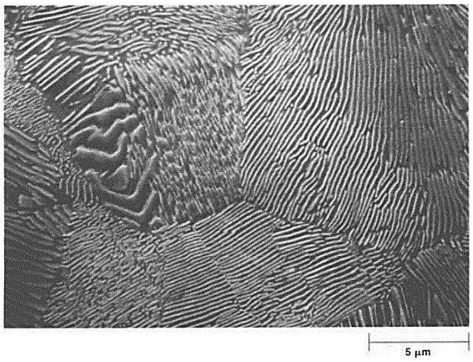


*Figure 34. Scanning Electron Micrograph Showing Pearlite in Rail Steel. [33].*

When pearlite forms, iron atoms must transfer between austenite and pearlite. At a critical low temperature, this becomes no longer possible, and the iron atoms change structure by shearing. This creates bainite. It forms elongated shapes, and the cementite is no longer continuous or lamellar.

The bainite forms at cooling rates higher than those for pearlite transformation, and it can be upper or lower bainite. In medium- and high-carbon steels, upper bainite typically consists of groups of ferrite spikes with coarse cementite particles between the spikes (and it has a more crystallographic appearance related to the prior austenite phase), Figure 35. The bainite that forms at lower temperatures is termed lower bainite and consists of large needlelike plates that contain high densities of very fine carbide particles, Figure 36.

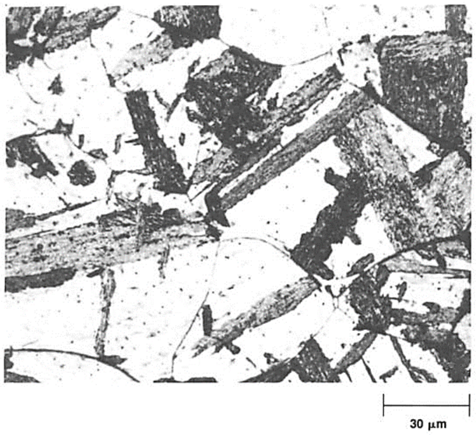


*Figure 35. Light Micrograph Showing Upper Bainite (Dark) Formed in 4150 steel. [33].*

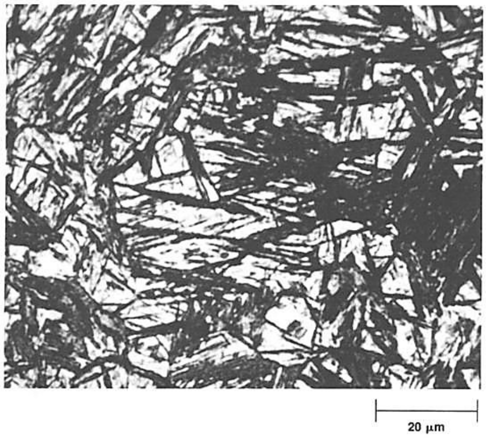


*Figure 36. Light Micrograph Showing Lower Bainite (Dark Plates) Formed in 4150 steel. [33].*

As previously mentioned the stock steel we used to make our piece was hot rolled to approximate size, allowed to cool naturally, and then cold rolled to the final dimensions, Figure 37. The grain elongation in the rolling direction can be observed. The slow cooling rate will make the structure of the steel consist of ferrite and pearlite, Figure 38. Based on our 0.18wt% carbon, the resulting ferrite will be ~79% and pearlite 11%, Figure 39 (level rule calculations).

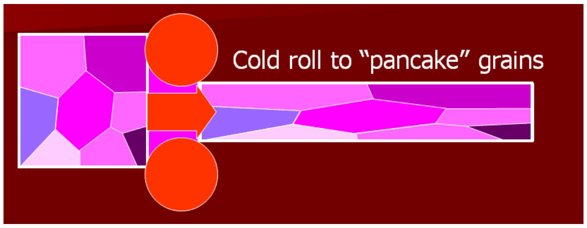


*Figure 37. Effects of Cold Rolling on Steel Grain Structure.*

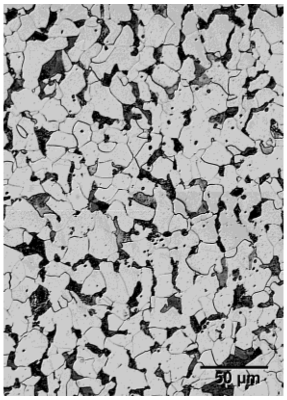


*Figure 38. Microstructure of 1018 Steel.*

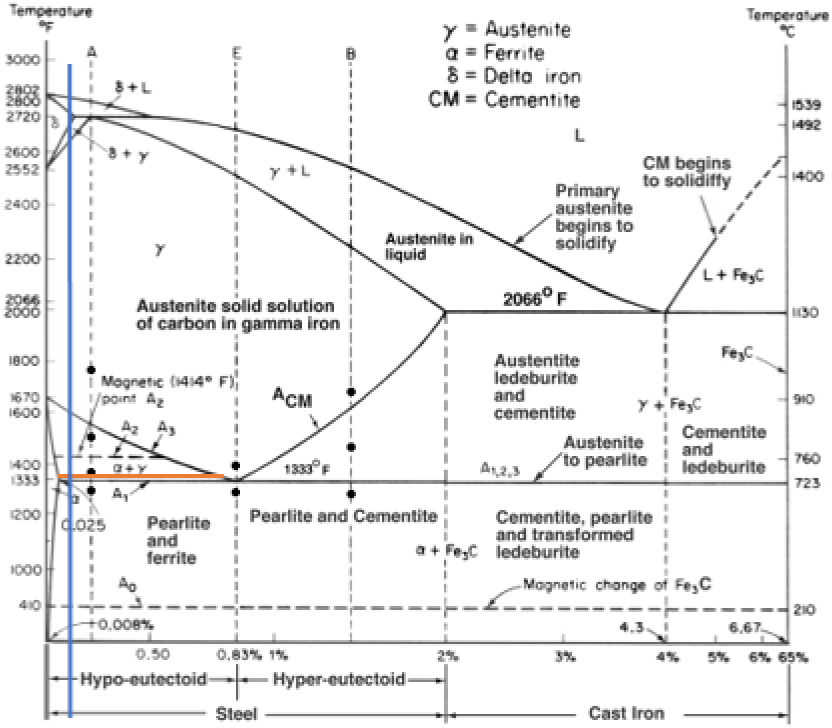


*Figure 39. Iron-Iron Carbide Phase Diagram. [58].*

We estimate that we heated our steel stock material to approximately 925 degrees Celsius during the actual forging operation, basing our estimation on the color coding for temperature given in Table 4.

*Table 4. Heat Chart for Blacksmithing [57]*

| Fahrenheit | The Color of the Steel |
|---|---|
| 2000° | Bright Yellow |
| 1900° | Dark Yellow |
| 1800° | Orange Yellow |
| 1700° | Orange |
| 1600° | Orange Red |
| 1500° | Bright Red |
| 1400° | Red |
| 1300° | Medium Red |
| 1200° | Dull Red |
| 1100° | Slight Red |
| 1000° | Very Slightly Red, Mostly Grey |
| 800° | Dark Grey |
| 575° | Blue |
| 540° | Dark Purple |
| 520° | Purple |
| 500° | Brown/Purple |
| 480° | Brown |
| 465° | Dark Straw |
| 445° | Light Straw |
| 390° | Faint Straw |

After heating the steel to the working temperature, it was removed from the forge and hammered (and air cooled) until it could no longer be worked (approximately 450 degrees Celsius), and then final quenched. As this temperature is below the eutectoid temperature, final quench would have no effect on the blade microstructure. Given the air cool during hammering, the microstructure will not be martensitic, and most likely bainitic with some ferrite.

In addition to the actual hammering and quenching work, the team also did a separate experiment when the stock material was quenched directly from the austenitizing temperature (925 degrees Celsius). Skipping the hammering step will help understand the microstructural difference caused by a faster cooling than that in the hammering (air cooling) followed by water quenching. The microstructure in this specimen is expected to be either martensitic or a finer upper bainite.

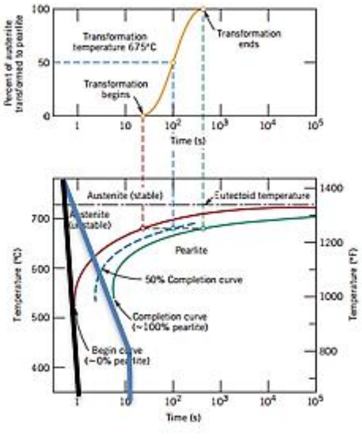


*Figure 40. Continuous Cooling Transformation Diagram.*

## 11.2. Actual Replica Microstructures

As previously discussed, before any treatment, our replica was fairly typical rolled stock 1018 steel.

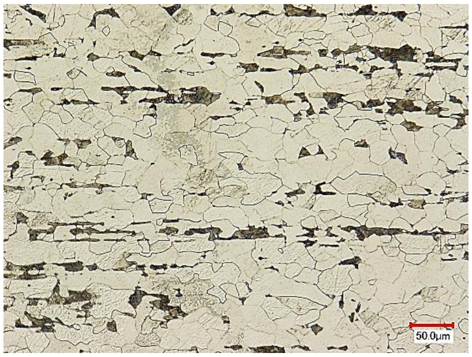


*Figure 41. Rolled 1018 Stock Steel 600x.*

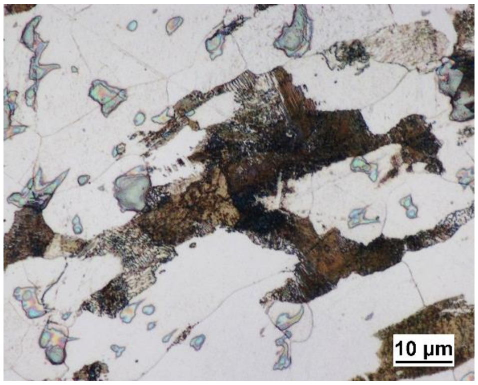


*Figure 42. Rolled 1018 Stock Steel 1000x.*

From these images we can see the microstructure was indeed constituted of ferrite (the white grains) and pearlite (the darker areas of lamellar ferrite and cementite). The pearlite is aligned at the boundaries of the ferritic grains, which are parallel to the rolling direction.

Regarding the two replicas, we have the following two resulting microstructures. For the first sample, the austenitized, hammered forged (while air cooled), and quenched steel, the microstructure consists of large and dispersed upper bainite areas with some remaining ferrite, Figures 43 and 44.

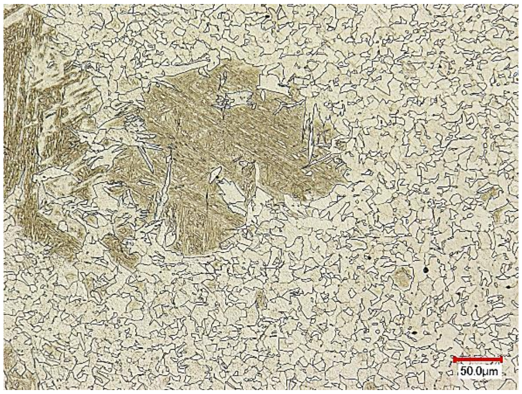


*Figure 43. 1018 Hammered Steel 600x.*

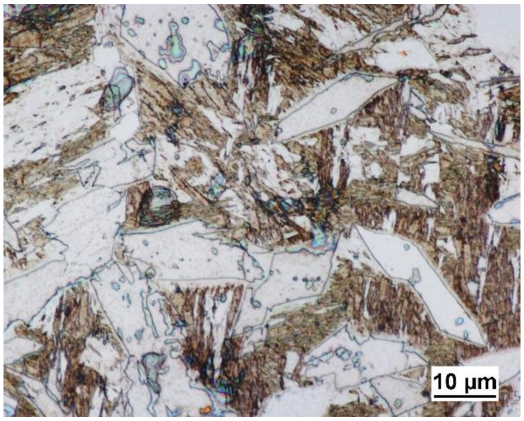


*Figure 44. 1018 Hammered Steel 1000x.*

For the second sample, the austenitized and directly quenched steel, the microstructure consists of finer and closely spaced upper bainite areas, also with some remaining ferrite, Figures 45 and 46.

*Figure 45. Quenched 1018 Steel x600.*

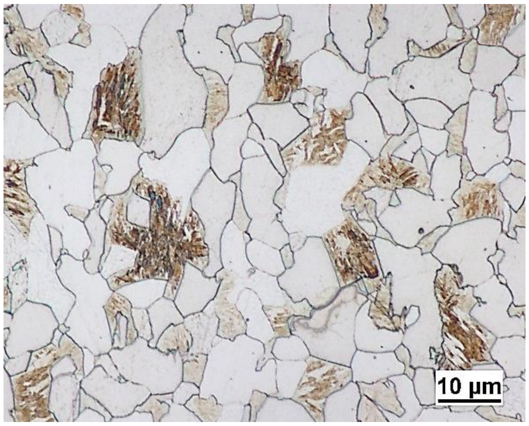


*Figure 46. Quenched 1018 Steel 1000x.*

The optical photos of the microstructures in Figures 43-46 show close resemblance with our predictions based on the phase diagram calculations and considerations of the cooling characteristics of the materials during various processing steps that we followed in preparing our blades.

## 12. Conclusions

In this project we looked at the history of the Vikings for background on our weapon, and saw the evolution of the Seax from simple farming and utility blade into a weapon of war. We studied forging and smelting techniques, both modern and antiquated to understand how blades were produced in the past and how they might be produced now. Our own experiments with forging allowed us to reproduce the subject of our project and examine its microstructure. We made our predictions, and while not all of them were accurate this is to be expected.

# 13. Appendix

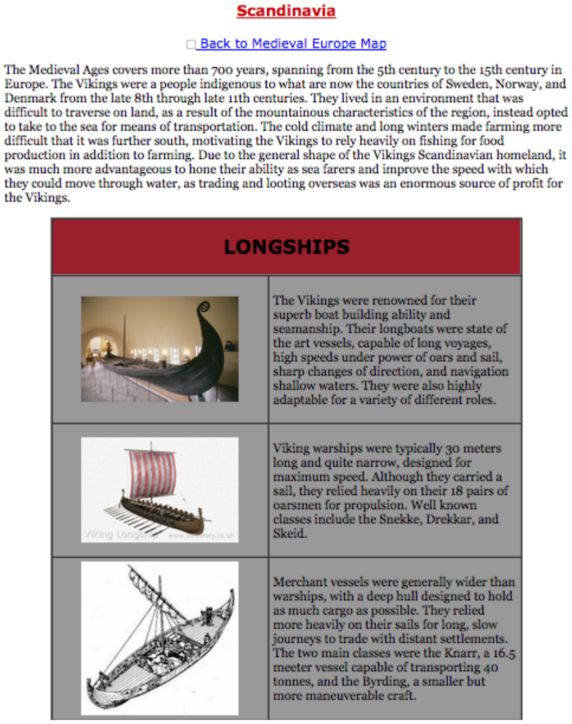
**Europe**

☐ Back to World Map

Click on the location you'd like to explore below, or pick a different time period.

Current Time Period:

Figure 47. Map of Medieval Europe



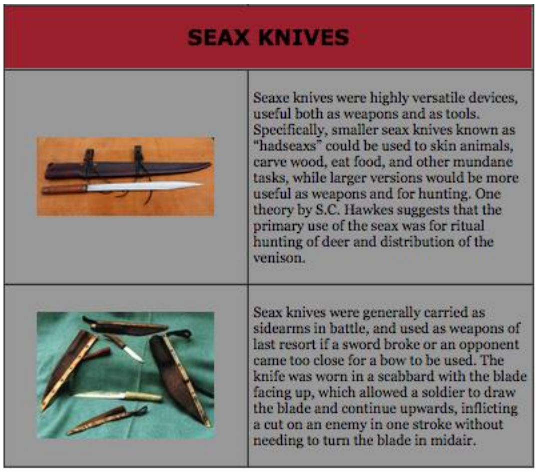
**Scandinavia**

☐ Back to Medieval Europe Map

The Medieval Ages covers more than 700 years, spanning from the 5th century to the 15th century in Europe. The Vikings were a people indigenous to what are now the countries of Sweden, Norway, and Denmark from the late 8th through late 11th centuries. They lived in an environment that was difficult to traverse on land, as a result of the mountainous characteristics of the region, instead opted to take to the sea for means of transportation. The cold climate and long winters made farming more difficult that it was further south, motivating the Vikings to rely heavily on fishing for food production in addition to farming. Due to the general shape of the Vikings Scandinavian homeland, it was much more advantageous to hone their ability as sea farers and improve the speed with which they could move through water, as trading and looting overseas was an enormous source of profit for the Vikings.

| LONGSHIPS | |
|---|---|
| | The Vikings were renowned for their superb boat building ability and seamanship. Their longboats were state of the art vessels, capable of long voyages, high speeds under power of oars and sail, sharp changes of direction, and navigation shallow waters. They were also highly adaptable for a variety of different roles. |
| | Viking warships were typically 30 meters long and quite narrow, designed for maximum speed. Although they carried a sail, they relied heavily on their 18 pairs of oarsmen for propulsion. Well known classes include the Snekke, Drekkar, and Skeid. |
| | Merchant vessels were generally wider than warships, with a deep hull designed to hold as much cargo as possible. They relied more heavily on their sails for long, slow journeys to trade with distant settlements. The two main classes were the Knarr, a 16.5 meeter vessel capable of transporting 40 tonnes, and the Byrding, a smaller but more maneuverable craft. |

Figure 48. Info Page Linked From the Map.



**SEAX KNIVES**

Seaxe knives were highly versatile devices, useful both as weapons and as tools. Specifically, smaller seax knives known as "hadseaxs" could be used to skin animals, carve wood, eat food, and other mundane tasks, while larger versions would be more useful as weapons and for hunting. One theory by S.C. Hawkes suggests that the primary use of the seax was for ritual hunting of deer and distribution of the venison.

Seax knives were generally carried as sidearms in battle, and used as weapons of last resort if a sword broke or an opponent came too close for a bow to be used. The knife was worn in a scabbard with the blade facing up, which allowed a soldier to draw the blade and continue upwards, inflicting a cut on an enemy in one stroke without needing to turn the blade in midair.

*Figure 49. Info Page Linked From the Map Cont.*

**2013-2014:**

Making of a Crossbow

Making of a Gladius

**2014-2015:**

Making of a Seax Knife
First Replica
Second Replica

Making of a Horseman's Axe

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*Figure 50. The Central Page with Links to Both Replicas.*

**IQP Reports:**

- ▶ 2010-2011:
- ▶ 2011-2012:
- ▶ 2012-2013:
- ▶ 2013-2014:
- ▼ 2014-2015:
  - History of the Viking Seax Knife
  - Battleaxe

*Figure 51. The Page Linking to the Final Report.*

**Project Teams:**

▶ 2010-2011:
▶ 2011-2012:
▶ 2012-2013:
▶ 2013-2014:
▼ 2013-2014:

Matt Ryder, Mechanical Engineering, Class of 2016
Connor Morette, Mechanical Engineering, Class of 2016
Luke Proctor, Mechanical Engineering, Class of 2016
Rick Wight, Computer Science, Class of 2016

*Figure 52. The Page Listing the Members of Each Team.*

## 14. References

[1] Digital image. Freeworldmaps.net, n.d. Web. 19 Oct. 2014.

[2] Viking Longship. Digital image. Www.3dhistory.co.uk. N.p., n.d. Web. 19 Oct. 2014.

[3] Ucla.edu, n.d. Web. 19 Oct. 2014.

[4] Tag Archives: Palaces. Digital image. A Corner of Tenth Century Europe. N.p., n.d. Web. 19 Oct. 2014.

[5] Lindisfarne. Digital image. Wikipedia. Wikimedia Foundation, 18 Oct. 2014. Web. 19 Oct. 2014.

[6] Digital image. Www.hurstwic.org, n.d. Web. 19 Oct. 2014.

[7] N.p., n.d. Web. <http://static.mijnwebwinkel.nl/winkel/celticwebmerchant/full27756273.jpg>.

[8] N.p., n.d. Web. 19 Oct. 2014. <http://rautaportti.fi/images/Images%20Other%20Weapons/600592%20VikingHalberd_05.jpg>.

[9] N.p., n.d. Web. 19 Oct. 2014. <http://www.owenbush.co.uk/wp-content/uploads/301-and-sheath.jpg>.

[10] "Viking Expansion." Wikipedia. Wikimedia Foundation, n.d. Web. 19 Dec. 2014.

[11] "Metalworking and the Smith." Ironworking and the Blacksmith. 14 Aug. 2004. Web. <http://viking.no/e/england/york/metal_working_and_the_smith.html>.

[12] "The Emergence of Iron Smelting and Blacksmithing: 900 B. C. to the Early Roman Empire." JaysRomanHistory.com. Web. <http://www.jaysromanhistory.com/romeweb/glossary/timeln/t10.htm>.

[13] "Difference Between Hot and Cold Rolled Steel | Metal Supermarkets."Difference Between Hot Rolled Steel and Cold Rolled Steel Comments. Metal Supermarkets, 11 Sept. 2014. Web. 22 Jan. 2015. <http://metalsupermarkets.com/blog/difference-between-hot-rolled-steel-and-cold-rolled-steel/>. Basic breakdown of hot rolled and cold rolled steel.
[14] "1018 Cold Roll Steel." Speedy Metals. Speedy Metals. Web. 22 Jan. 2015. <http://www.speedymetals.com/information/Material26.html>. Statistical breakdown of 1018 cold rolled steel.

[15] "Understanding The Carbon Steel Grade System." EPS Heat Treat Headlines RSS. Engineering Products Sales Corp., 19 June 2007. Web. 22 Jan. 2015.

<http://www.epsovens.com/heat-treat-headlines/understanding-the-carbon-steel-grade-system/4>. Explanation of the numbering system for different types of steel.

[16] "The Steel Making Industry." Primary Metals. Illinois Sustainable Technology Center. Web. 25 Jan. 2015. <http://www.istc.illinois.edu/info/library_docs/manuals/primmetals/chapter2.htm>. Breakdown of how steel is produced at a plant. Potentially out of date (mid to late 90s)

[17] "Cold Drawn Steel AISI 1018." Nessteel.com. NESSteel Inc. Web. 30 Jan. 2015. <http://nessteel.com/wp-content/uploads/2013/08/1018-Data-.pdf>. Breakdown of properties of 1018 steel from the company which produced our piece.

[18] Walters, Nicholas, and Soo Jung Kim. "World Crude Steel Output Increases by 1.2% in 2014." World Steel Association. World Steel Association, 22 Jan. 2015. Web. 31 Jan. 2015. <http://www.worldsteel.org/media-centre/press-releases/2015/World-crude-steel-output-increases-by-1.2--in-2014.html>. Steel production statistics for 2014.

[18] "Iron Ore Statistics and Information." USGS Minerals Information: Iron Ore. United States Geological Survey. Web. 31 Jan. 2015. <http://minerals.usgs.gov/minerals/pubs/commodity/iron_ore/>. Basic statistics on production of iron ore.

[19] Stubbles, John. "The Basic Oxygen Steelmaking (BOS) Process." Steel Works The Online Resource for Steel. Web. 31 Jan. 2015. <http://www.steel.org/Making%20Steel/How%20Its%20Made/Processes/Processes%20Info/The%20Basic%20Oxygen%20Steelmaking%20Process.aspx>. very detailed breakdown of how Basic Oxygen Steelmaking is done.

[20] Kudliński, Z., K. Janiszewski, and J. Pieprzyca. "Research the Impact of Steel Scrap Participation in the Metallic Charge for the Yield of Liquid Steel Casted in BOF Process." Archives of Material Science and Engineering. Archives of Material Science and Engineering, 12 Jan. 2012. Web. 3 Feb. 2015. <http://www.archivesmse.org/vol58_2/58218.pdf>. Paper examining how altering the quantity and composition of the steel scrap impacts the BOS process.

[21] "Common Uses for Slag." National Slag Association. 1 Jan. 2013. Web. 4 Feb. 2015. <http://www.nationalslag.org/common-uses-slag>. Industrial uses for slag.

[22] Jones, Jeremy A. T. "Electric Arc Furnace Steelmaking." Steel Works The Online Resource for Steel. Web. 4 Feb. 2015. <http://www.steel.org/Making%20Steel/How%20Its%20Made/Processes/Processes%20Info/Electric%20Arc%20Furnace%20Steelmaking.aspx>. Detailed breakdown of EAF Steelmaking.

[23] Kelly, Shawn. "Fatigue." Fatigue. 4 Mar. 1997. Web. 14 Feb. 2015. <http://www.sv.vt.edu/classes/MSE2094_NoteBook/97ClassProj/anal/kelly/fatigue.html>.

[24] "SAE/AISI Carbon Steel Naming Conventions." SAE/AISI Carbon Steel Naming Conventions. 11 July 2012. Web. 14 Feb. 2015. <http://www.azom.com/article.aspx?ArticleID=6151>.

[25] Degarmo, E. Paul; Black, J T.; Kohser, Ronald A. (2007), Materials and Processes in Manufacturing (10th ed.), Wiley, ISBN 978-0-470-05512-0.

[26] "Mechanical Properties of Steel." Web. 14 Feb. 2015. <http://www.pivotpins.com/pdf/mechanical_properties_of_steel.pdf>.

[27] "Great Lakes Forge." Forged Crankshafts. Web. 14 Feb. 2015. <http://www.glforge.com/crankshafts.html>.

[28] "Process Encyclopaedia." Process Encyclopaedia. Web. 14 Feb. 2015. <http://www-materials.eng.cam.ac.uk/mpsite/process_encyc/non-IE/forging.html>.

[29] Degarmo, E. Paul; Black, J T.; Kohser, Ronald A. (2007), Materials and Processes in Manufacturing (10th ed.), Wiley, ISBN 978-0-470-05512-0.

[30] "The Web's Where You Study In!" Upset Forging. 1 Jan. 2008. Web. 14 Feb. 2015. <http://www.ustudy.in/node/2890>.

[31] Krauss, G. "Microstructures, Processing, and Properties of Steels." ASM Handbooks Online. ASM Handbook Committee, 1 Jan. 1990. Web. <http://products.asminternational.org/hbk/do/section/content/V01/D02/A02/s0001256.htm?highlight=false>.

[32] Krauss, G. "Microstructures, Processing, and Properties of Steels." ASM Handbooks Online. ASM Handbook Committee, 1 Jan. 1990. Web. <http://products.asminternational.org/hbk/do/section/content/V01/D02/A02/s0001262.htm?highlight=false>.

[33] Krauss, G. "Microstructures, Processing, and Properties of Steels." ASM Handbooks Online. ASM Handbook Committee, 1 Jan. 1990. Web. <http://products.asminternational.org/hbk/do/section/content/V01/D02/A02/s0001258.htm?highlight=false>.

[34] Krauss, G. "Microstructures, Processing, and Properties of Steels." ASM Handbooks Online. ASM Handbook Committee, 1 Jan. 1990. Web.<http://products.asminternational.org/hbk/do/section/content/V01/D02/A02/s0001258.htm?highlight=false>.

[35] Krauss, G. "Microstructures, Processing, and Properties of Steels." ASM Handbooks Online. ASM Handbook Committee, 1 Jan. 1990. Web.

<http://products.asminternational.org/hbk/do/section/content/V01/D02/A02/s0001258.htm?highlight=false>.

[36] Short, William R. "Viking Raids." Hurstwic.org. Web. <http://www.hurstwic.org/history/articles/society/text/raids.htm>.

[37] Bray, Olive. "Hávamál - Words of Odin the High One." Pitt.edu. Ed. D. L. Hashman. 28 Mar. 2003. Web. <http://www.pitt.edu/~dash/havamal.html>.

[38] Grant-Jones, Simon. "History of the Blacksmith." History of the Blacksmith. Simongrant-jones.com. Web. 12 Oct. 2014. <http://www.simongrant-jones.com/history_of_the_blacksmith.html>.

[39] Roelofs, H., S. Hasler, L. Chabbi, U. Urlau, J. Chen, and H. K. D. H. Bhadeshia. "Multiphase Structures in Case Hardening Steels following Continuous Cooling." Swiss-Steel.com. University of Cambridge, Materials Science and Metallurgy, Cambridge CB2 3QZ, U. K., 1 May 2008. Web. 4 Feb. 2015. <http://www.swiss-steel.com/fileadmin/files/swiss-steel.com/documents/dokumente/9_Multiphase_structures.pdf>.

[40] Short, William R. "Farms and Villages in the Viking Age." Hurstwic.org. Web. 12 Oct. 2014. <http://www.hurstwic.org/history/articles/daily_living/text/Villages.htm>.

[41] Baranowski, StanisÅ‚aw, and Wibjörn Karlén. "Remnants of Viking Age Tundra in Spitsbergen and Northern Scandinavia. Vol. 58, No. 1/2 (1976) , Pp. 35-40." JSTOR. Wiley on Behalf of the Swedish Society for Anthropology and Geography, 1 Jan. 1976. Web. 13 Oct. 2014. <http://www.jstor.org/stable/520741>.

[42] Sykes, Naomi. "A Haunch for Hrothgar." Fallow Deer Project. The Journal of the British Deer Society, 1 Jan. 2010. Web. 10 Oct. 2014. <http://fallow-deer-project.net/img/upload/370/documents/Haunch for Hrothgar.PDF>.

[43] Kontny, Bartosz. "OUTSIDE INFLUENCE OR LOCAL DEVELOPMENT? SEAXES FROM THE CEMETERIES OF THE BALT TRIBES IN NORTHERN POLAND (THE ELBLĄG GROUP)." Mopv.uw.edu. University of Warsaw Institute of Archeology, 1 Jan. 2010. Web. 13 Oct. 2014. <http://www.mpov.uw.edu.pl/userfiles/pl/Badania/Publikacje/kontnyoutsideinfluenceorlocaldevelopment.pdf>.

[44] Levick, Ben, Roland Williamson, and Jay Boydon. "Pastimes of the Viking & Anglo-Saxon Age." Regia Anglorum. 1 Jan. 2009. Web. 14 Oct. 2014. <http://www.regia.org/pastimes.htm>.

[45] "Viking | People." Encyclopedia Britannica Online. Encyclopedia Britannica. Web. <http://www.britannica.com/EBchecked/topic/628781/Viking>.

[46] James, Edward. "Overview: The Vikings, 800 to 1066." BBC News. BBC, 29 Mar. 2011. Web. 1 Jan. 2014. <http://www.bbc.co.uk/history/ancient/vikings/overview_vikings_01.shtml>.

[47] "Viking Age." Wikipedia. Wikimedia Foundation, 16 Oct. 2014. Web. 18 Oct. 2014.

[48] VIKINGS. Rep. History World International, n.d. Web. 15 Oct. 2014.

[49] "History of Sweden (800-1521)." Wikipedia. Wikimedia Foundation, 20 Aug. 2014. Web. 16 Oct. 2014.

[50] "Gorm the Old." Wikipedia. Wikimedia Foundation, 19 July 2014. Web. 18 Oct. 2014.

[51] "Harald Fairhair." Wikipedia. Wikimedia Foundation, 12 Oct. 2014. Web. 18 Oct. 2014.

[52] "Longship." Wikipedia. Wikimedia Foundation, 1 Oct. 2014. Web. 19 Oct. 2014.

[53] "Types of Viking Ships." Types of Viking Ships. Danishnet.com, n.d. Web. 19 Oct. 2014.

[54] "Where Did They Come From?" Jorvik Where Did They Come from Comments. JORVIK Viking Centre, n.d. Web. 19 Oct. 2014.

[55] "Vikings." Wikipedia. Wikimedia Foundation, 18 Oct. 2014. Web. 19 Oct. 2014.

[56] "Vikings Looted Lindisfarne." Christianity.com. N.p., n.d. Web. 19 Oct. 2014.

[57] Kalif, Will. "Heat Chart for Blacksmithing." *Heat Chart for Blacksmithing*. Kalif Publishing, 1 Jan. 2001. Web. 3 Mar. 2015. <http://www.stormthecastle.com/blacksmithing/blacksmith-steel-heat-and-coloring-chart.htm>.

[58] Ballentine, Kim. "Iron-Iron Carbide Phase Diagram Example." *Iron-Iron Carbide Phase Diagram Example*. 28 Apr. 1996. Web. 3 Mar. 2015. <http://www.sv.vt.edu/classes/MSE2094_NoteBook/96ClassProj/examples/kimcon.html>.

[59] Camp, James McIntyre; Francis, Charles Blaine (1920). The Making, Shaping and Treating of Steel (2nd ed.). Pittsburgh: Carnegie Steel Co. p. 174. OCLC.

[60] Chorane, R. F. " Fe, C 0.2 (wt%) Steel, Case Hardened." CORE-Materials • Fe, C 0.2 (wt%) Steel, Case Hardened. N.p., 4 Sept. 2002. Web. 06 Mar. 2015.

[61] Hawkes, SC (1969) "Iron weaving sword", In Millard, L, Jarman, S, and Hawkes, SC (eds), 'Anglo-Saxon burials near the Lord of the Manor, Ramsgate', Archaeologia Cantiana 2.