The Evolution of Materials in Arms and Armors: Celtic Weaponry

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by

Justin Casilla
Patrick Fitzgerald
Shawn McCarthy
Adam White

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Professor Diana A. Lados
Mr. Tom H. Thomsen

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1. Abstract

The goal of this project is to investigate a specific ancient Celtic weapon known now as the falcata. Through careful research, investigate the connections between Celtic culture, geography, available technology, and the methods of manufacturing this weapon. Following the research, to share the process of recreating the falcata, and afterwards discuss the material analyses of the replica. Through reading this paper, the reader will develop a robust understanding of how this ancient Celtic weapon was made and used, as well as the similarities and differences to modern manufacturing techniques.

2. Introduction

The terms “Celt” and “Celtic” have been used in several manners: denoting people speaking Celtic languages; those people of prehistoric and early historic Europe whom shared traditions with the Hallstatt and La Tène cultures; or to distinguish these people from that of Roman or Greek descent.

The journey of the Celtic people can be traced back to 25 centuries ago over the vast lands of modern day Greece, Spain, Northern Italy, England, Wales, Scotland and Ireland. Due to their illiteracy, most of Celtic history and literature had been preserved through oral tradition. The only written records of the Celtic civilization are scriptures left by classical authors circa 500BCE. Despite how inaccurate these findings may be, they are fundamental for understanding Celtic cultural interactions, as well as their feuds with neighboring societies. The Celtic people were never united as a single civilization, but in their differences created groups such as the Gauls (originating in France) and Celtiberians (based in Iberia) [16].

The gradual expansion of the Roman Empire from the south, and the spread of Germanic tribes to the North and East eventually led to the downfall of the Celtic culture within most of Europe’s mainland, with the exception of Brittany alone who maintained Celtic tradition and linguistics, later bolstered by immigrants from the British Isles.

3. Background

Before discussing the manufacture or use of the falcata, it would be beneficial to first investigate the local environment in which this weapon was created and used. Components of this environment are the relative time period through which the Celts thrived, the culture that developed throughout this time, and the profile of Celtic war and weaponry therein.

3.1. Timeline

The Celtic timeline contains a collection of many events that vary through a wide range of dates and across vast geography. While there are still some discrepancies regarding the specifics of Celtic culture, the timeline of their culture will be represented here following the most agreed-upon theories of modern historians. Near the beginning of Celtic history, the Bronze age observes many different Indo-European tribes claiming new territories throughout Western Europe. These tribes include Greeks, Germans, Balts, Italics, and Celts. It was the coming of the Iron Age that saw the Celts advancing their capabilities in metalworking and weapon-crafting.

Figure 3.1.: Part of a Celtic ornamental bronze belt [26].

During as early as 600BCE, there are examples of metallic Celtic creations that incorporate complex swirling decorative lines, as shown in Figure 3.1. These specific examples were found in Hallstatt, an Austrian village. A recreation of a village similar to Hallstatt is shown in Figure 3.2. Many more examples of the advancement of Celtic metalworking can be found including that which is related to arms and armors, which will be further explored in this paper. By 500BCE, the Celts moved West, settling in Northern Spain and France. From here, they will stage many of their conquests throughout Britain and Rome.

Much conflict happened between the Celts and Romans, as the Roman empire was rapidly expanding throughout the 50sBCE and beyond. By 55BCE, the Romans made the first of their two invasions in Celtic Britain. Defeat was not one-sided, however, because the Celts fought back hard, defeating Julius Caesar's forces in 52 BCE. By 51BCE, however, the siege of Uxellodunum ends the Gallic War by Caesar's forces [26].

3.2. Culture

Similar to most cultures, the Celtic culture can be decomposed into a handful of aspects which together constitute the culture as a whole. For the Celts, their language comprised a significant portion of their culture, along with the religion that guided them, and the societal standards and expectations that held them together. However, *unlike* most other cultures, *war* also played a consistent and significant role in much of Celtic life.

3.2.1. Texts, Linguistics and Archeology

There are three types of evidence uncovered by archeologists and scholars from the Iron Age through the Roman period on Celtic history. First, there are documentary sources and texts. Classical records are the only means of understanding concepts such as language, and cultural identity, since they in themselves have no physical manifestation. Another is linguistics, modeled after Celtic names and words reference in historic texts, while some were place-names.

Figure 3.2.: Reenactment of Celtic village in Iron Age [18].

Ogham is the first known Irish method of writing, belonging to the fourth century, CE Unique to Ireland, the ogham alphabet, as historians have suggested, was a by-product of contact with the Latin American numerals. Scholars regard ogham as a beautiful language, which lies in its usefulness and simplicity. Characters would read from edge to edge, in direct comparison to carving along the edge of a stone monument. Though scholars know that the majority of scripture were authored on wood for conventional use, the only writings to have survived to modern day are tombstones or various stone markers constructed in the fifth and seventh centuries CE These stone markers were uncovered among ancient Irish settlements in Southern Ireland and the West coast of Britain [16]. Looking closer at the ogham, scholars were able to understand that each letters in the alphabet is based upon the common name of a species of tree.

The Celts began their civilization under a single unified language, that of Old Celtic. Philologists throughout time have uncovered that old Celtic was a descendent of Indo-European language tradition, and actually can be traced to the closest cousin of Italic, the usher to Latin. Initially the very first wave of Celtic immigrants upon the British Isles are referred to as the q-Celts, while establishing their native Goidelic. The exact date has not been precisely recorded, but Philologists date the window between 2000 to 1200BCE. Their title is born from the assimilation of the Old Celtic and Italic languages. One noted difference between these, is that Old Celtic lacked a “P” and replaced the Italic “O” with an “A”. Later in their timeline, came an additional wave of immigrants, whom were called p-Celts, speaking Brythonic. Goidelic then came to the creation of three Gaelic languages, spoken primarily in Ireland, Man and then Scotland. Like Goidelic, Brythonic branched into two British Isles languages, Welsh and Cornish, continuing to remain spoken in Brittany in the form of Breton [13]. Upon this, there may have hundreds of independent dialects resembling these forms of Celtic language, many serving as an aid to diplomacy and trade. These ancient languages eventually gave rise to the Scots Gaelic, Welsh and Manx, Celtic languages of Scotland, Wales and the Isle of Man respectively. These societies stemming from Celtic origin, as written by Felix Muller of the Historisches Museum in Berne in his book Art of the Celts: 700BCE to 700CE, with the size of the language area, people identified by Greeks or Romans as Celts would most likely not be able to associate with one another in a similar language [27].

Archaeological digs at the La Tène site located in Western France have revolutionized the way Celtic art and technology are perceived by scholars throughout the modern world. Initially archaeologists believed Celtic civilization, so lacking in linguistic documentation (ogham coming as a later Celtic tradition), would be incapable of making such leaps in geometrically and technologically complex pieces of art that were crafted by the Greeks or Romans. However, at La Tène, archaeologists were able to uncover sophisticated knot works, metal-workings, pottery, glass, and a geometric mosaic of nature. "Simple geometric elements such as parallel lines, concentric circles, and chevrons later are merged with compass construction techniques to create complicated geometric patterns" [16]. A sword constructed from the discovery of over seventy pieces in Kirkburn (East Yorkshire), which can be shown in Figure 3.3, as well as, a worked-iron blade, studs, and scabbard plates attest to the intricate skill of Celtic craftsmen.

Figure 3.3.: Iron Age Kirkburn Sword [6].

Native craftspeople mastered the art of iron smelting and showcased their skills through exquisite metal work designs, often carrying over to their love for intricate decoration and design. The majority of Celtic commoners lived in highly populated farming villages, with economic and cultural activities held in larger towns joining smaller settlements.

Many ancient, abandoned Celtic settlements, dating back to prehistoric times, can be seen in Ireland. Formations of large earthworks, such as ring-forts, cover Ireland, and ae thought to have been built during the Iron Age. Ring-forts can be seen abundantly surrounding single-dwelling homes. Raths (earthwork), cashels (stonework), and duns (defending sites) often were constructed surrounding a central dwelling, more usually thatched with heaths and amassed by earth. Having a roughly circular shape, some of these fortifications remained intact long enough to prodigiously erect surrounding raths [16].

3.2.2. Religion

A significant component of the Celtic culture was comprised of their religious beliefs and practices. The cornerstone of their religious beliefs was a strong connection to nature and natural phenomena. This strong affiliation with nature was guided by the druids of the clan. These druids were the head of druidism, and this elite status of carried over into the social rings as well. These druids acted similarly to the shamans and medicine men of other cultures—they were the seers and the healers and interpreted natural events to guide their clan [27]. They were in charge of the organization of rituals, sacrifices, education, and inter-tribe relations, and imbued with the authority to act as arbiter in disputes.

Druidism is one of the most iconic qualities known about the ancient Celts today, but the full details of their religion and beliefs are almost exclusively derived from biased parties, be it the Romans ridiculing the savagery of their sacrifices or the Christian monks writing down information over a millennium old. However, there is archaeological evidence, from which useful information may be drawn—collections of perfectly good weapons or valuable goods or weapons or livestock have been found around many Celtic settlements. These useful goods being left alone has led historians to believe that a large component of the Celtic religion was based on offerings to the gods, and that the savage sacrifices from Roman records were a subset of the traditional offerings. Moreover, archaeological findings are largely unable to substantiate the prominence of human sacrifice, further detracting credibility from the Roman records [22].

The prominence of nature also manifested in how and where the Celts worshiped. Most worship took place in sacred oak groves or at sacred rivers or lakes, where an utmost respect was demanded. These locations were especially powerful to the Celtic faith due to their serene nature and their quality of being unsoiled by man and his creations. Many offerings and sacrifices of precious goods took place here, and it was a society-wide understanding that those locations and those offerings were not to be touched, not even by raiders.

One interesting aspect of the Celtic religion over time was its fluidity. Since the religion was essentially exclusively oral in its transfer—by way of druid teachings—it largely molded to the general beliefs and sentiments of the people following it. Along with the spread of goods due to Mediterranean trade flourishing came the spread of ideas and ideologies, first Greek and then transitioning into Roman. Over the centuries this flow of new beliefs slowly affected the sentiments of the Celtic tribes, and soon many of the deities aligned in all but their name to deities of Greek/Roman mythology. Little is known of the specifics of the religions followed preceding the Roman conquest, but historians gather there were somewhere between 200 and 270 different deities worshiped in all [22].

3.2.3. Society

Unlike many other societies, Celtic society was heterarchially structured, as opposed to hierarchically [22]. The distinction is that while individuals in hierarchical systems have a well defined order and placement with respect to the whole, those in heterarchical systems do not. Heterarchical systems make use of many underlying ranking systems, but no one system is more prominent. Furthermore, the heterarchical system is more ambiguous and more easily changed [25]. Celtic culture had a strong aversion to singular rulers, even at the scale of tribes or settlements, but there were often a select few that held greater power. These individuals could increase their prominence within their local groups by gaining 'achieved status,' which one earned through battle prowess, marriages, generosity, and successful raids.

It was by these means that powerful warriors gained a following of other Celts. These groups of people following an elite few acted as factions, working as a group to distribute goods and services. The followers would often be expected to pay taxes into the faction, and in turn protection was supplied in turn. Especially skilled craftsmen and metalworkers could also find a high status inside these factions. The status of the elite few or the artisans was hardly set in stone though, since factions would frequently reorganize, or members would begin following a different faction with more impressive leaders/opportunities.

Druids would often associate with a certain faction, and their services would be particularly geared towards helping that group of Celts. Druids would be exempt from the taxation, and had a unique social standing that was a bit more solidified than other members, but still they had no more significant power than other respected figures in the faction.

Another component of the factions was their coordinated raids. Groups of warriors would go raiding nearby land to benefit their faction, and successful raids were one of the many ways to bolster one's reputation. Even exploring off and creating fortified settlements to spread the faction's influence and domain. These fortified hillforts, called 'oppida,' as shown in Figure 3.4, were the primary home of faction leaders, and also housed the most skilled artisans, especially smiths who would provide the arms, armor, and tools for the faction [22]. The raiding and exploring that factions encouraged was one of the main reasons for the rapid expansion of the Celts over Europe.

Figure 3.4.: Dig Site of an Oppida Hillfort in Spain [27].

The majority of the Celtic population did not live in these hillforts, but instead worked as farmers nearby in farmsteads or hamlets, providing sustenance for their family and the faction as part of their taxes. The most common crops for the Celts of continental Europe were grains, oats, peas, and lentils. Breeding livestock such as horses, cattle, goats, sheep, and pigs was also common. Other occupations included artisans to craft needed goods such as jewelry or tools, and there was also the occupation of paid mercenary/soldiers, who would be hired by the factions to provide generalized protection.

Another impact of flourishing Mediterranean trade was the further blurring of social status. With the influx of goods and new technology the importance of different skills shifted, and with new ideologies came altered evaluations of leaders [22].

3.3. War

At both a societal and cultural level, combat was at the heart of the Celts. " 'The whole race...is madly fond of war, high-spirited and quick to battle' "[22]. Beyond an expectation of ability to fight, there was a deep societal expectation of fitness—physical condition was a paramount trait of any Celt. Being unfit or overweight was grounds for serious punishment and shame within social groups. In addition to physical expectations, the Celtic mindset was also quite important to their frequent success in battle—and consequently their reputation as warriors. One of the teachings of the druids was that the human soul was eternal, so the Celts were often known as being excessively fearless in battle. This combined with their level of fitness and the fact that they often fought naked made them quite intimidating opponents [27]. Beyond its cultural permeation, war constituted a major portion of the Celtic way of life, especially as seen from the points of view of other cultures.

3.3.1. Reputation

Celtic warriors were known throughout settled people of the Mediterranean as barbarians, for hundreds of years. They were seen as nightmarish to more civilized people at the time, such as the Romans and Greeks and exercised a well-known trait of unpredictability, which earned them renowned reputation as a formidable warrior and opponent. "Their attacks on the battlefield were fearless, wild, and savage, but they were also skilled and deadly"[10]. Their deadliness and skill can be attributed to the fact that they developed many different fighting styles through having conquered much of Europe during their height. Celtic warriors became master swordsmen, through having fought close-combat battles with short-swords in Spain, and developed excellent armor for battle in southern Gaul. This shows how the Celtic warrior was adaptable and proactive in preparing for different fights to maximize their own power and effectiveness [10].

3.3.2. Weaponry

Celtic warriors used a variety of ancient weapons. From a distance warriors were ready with javelins, harpoons, bows and slings. Riverbed stones were often used to supply the slings due to their formation from currents. Though tactics from afar are often advantageous, the common Celtic warrior, being fond of close-quarters combat, often carried throwing weapons as his primary weapon. Young warriors usually began training and fighting with primitive javelins, bows and slings, awhile champions wielded well-crafted pila and harpoon-type javelins. Celtic warriors from the Alps known as Gaesatae, were said to have poisoned the tips of their ranged weapons. Later in time, the Picts had developed and carried the light crossbow [2].

In terms of close-range weapons, Celtic warriors battled with spears, two-hand hammers, axes and swords. Despite the rarity, the force of heavy weapons such as these delivered a blunt force capable of installing fatal injuries upon victims by piercing chain mail armor. Some Celtic swords have been discovered in Europe, though their intricate design point toward ritualistic purposes, they may have had military employment. Celtic swords began short and later gained length as they adapted to fight along chariots. Though they were renowned for their craftsmanship, the quality of Celtic swords was inconsistent. Some swords, however, works of art, were reported by ancient writers to have blunted upon initially impact. These warriors manufactured shields of all sorts in order to accommodate roles on during an attack. Round shield were used by light infantrymen, while heavy infantry wielded long shields, usually square, oval or hexagonal, which can be seen in Figure 3.5a. Celts took pride in the construction of their shields, incorporating spirals, circles and animal motifs.

An example would be the Battersea Shield, dating back from 100BCE to 100CE and built using sheet bronze, this stunning shield concept showcases the artistic style of La Tène.

Despite the development of new arms and armors throughout the classical world, the Celts surprisingly did not wear protective garments until circa 300BCE, the estimated date of the configuration of chain mail. Chain mail originated with the Celts as examples of primitive prototypes can be seen buried in Celtic graves within the third century. "The concept of thousands of small, interlocking metal rings is a complex one, and its implementation required considerable skill on the part of the blacksmith" [16]. Due the chainmail's precise design, and expensiveness, senior warriors and individuals born to royalty were the only people to obtain such technology, until it became more commonplace as blacksmiths came to perfect and teach these techniques to their apprentices. Chain mail was later adopted by the Romans upon realizing the effectiveness of it on the field of battle.

(a) Battersea shield [6].

(b) Chainmail hauberk [34].

(c) Roman designed Montefortino helmet [30].

Figure 3.5.: A selection of Celtic and Roman armor.

After came leather armor, light bronze breast plates, chain shirts, as shown in Figure 3.5b, and scale armor. Celts then came to develop a technique in which layers of metal scaled were sewn to linen, which then was bonded to chain armor, called Ceannlann armor [2]. Helmets were uncommon at first, limiting use to nobles. Celtic craftsmen eventually created the Montefortino and Coolus helmets, which Roman would then imitate for their very own legionnaires. Celtic warriors often attached real or metal horns to their helmets in order to look dominant and intimidating on the battlefield.

3.3.3. The Montefortino Helmet

The helmet, as shown in Figure 3.5c, was found by historians in the Montefortino region of Italy in a Celtic burial site. This was a type of helmet used by the Celts and later adapted by the Romans. The design of the helmet was a hollow half-sphere that covered the top of the head. There is also a short bill on the front, as well as a raised knob in the center of the sphere. The original use, like most Celtic armors, was to show nobility or status. Later the helmets were adopted for use in battle. The Romans adapted this style of helmet, as well as the Coolus (similar in design) helmet for their legionnaires to use. The Romans later changed the design of the helmet to include metal flaps that dangled over the ears for added protection for the sides of the head as well as a neck-guards.

3.3.4. Falcata

Much of the inspiration for the falcata came primarily with the development of the makhaira, a similar recurved blade introduced around the sixth century BCE. It is difficult to ascertain that Alexander the Great once owned the blade from Tomb II due to a lack of sufficient evidence, nor whether it belonged to Philip Arrhidaeous—Alexander's elder half-brother, whom ascended to the throne of Macedon and campaigned beside him—all that can be concluded is that the type used by the Macedonian army greatly resembles the depiction of Alexander's blade in the Alexander mosaic.

This theory is supported by the writings of Xenophone, a soldier whom had been exposed to actual cavalry experience and who documented his horsemanship and cavalry experience in exacting detail. Born a mere generation before Alexander, his findings hold relevant to horsemen today; "to Alexander they would have been the grounding gospel of his equine education" [32]. Weapon design during this age was very much not standardized, resulting varying structural properties such as length, broadness or curvature. These sickle-shaped weapons often were interchangeable, thus the falcata came about from minor regional variations. Despite becoming the principal weapon for Hannibal's Celtiberian infantry and cavalry, it wasn't until the nineteenth century CE that it became referred to as the falcata by Spanish scholars.

4. Historical Falcata Design and Manufacturing

After now having sufficiently discussed the environment in which the Celtic life took place, and the scenario in which their need for weaponry developed, discussion of the particular details of these Celts worked their metal, and especially how they manufactured the falcata. This section will investigate these topics, while establishing a foundation of understanding for the metallurgical consequences of the historical methods of sword creation.

4.1. Manufacturing Processes

The Celts had a process considered unique for how they produced the falcata. Nothing about the process was more efficient than other smelting methods and the time spent to create the weapon was much longer than most others. However, the process did produce a weapon of a much higher quality than what could be made by most other procedures at the time. Before discussing the actual process, it is important to identify the metals that the smiths were using and gain an understanding of basic metallurgy.

4.1.1. The Definition of Iron versus Steel

Steel is defined as an alloy of elemental iron and carbon while including trace amounts of some other elements. Steel can range anywhere from trace amounts of carbon to up to 2.1wt% carbon by weight; most steels used for manufacturing are around 0.1wt% to 0.9wt% carbon. Despite the carbon only making up a small amount of the alloy, this amount allows for steel to be significantly stronger than elemental iron [17]. Iron was smelted as early as the Bronze Age, however, reaching its melting point proved near impossible for the technology available at that time. Therefore, the process to create steel was to heat up the iron to a point where it was ductile enough to be shaped and then it could be hammered to appropriate dimensions and the impurities could be squeezed out. The falcata was produced using this process and, therefore, the metal held significant advantages.

4.1.2. Falcata Design Advantages

There are many design aspects of the falcata that gave the Celtic infantry advantages as they raced toward battle. Celt-Iberian tribes were fortunate to be located with plentiful resources to build efficient, high quality arms and armors. The falcata was forged initially with a straight single edge for the first half of the blade, and gradually widens, creating a double edge which ran to a sharp point. The blade began with a thinner cross sectional area toward the middle, but was designed to progressively increase in area as it continued to the tip. This increased area, in turn, distributed the weight of the weapon near the tip, while allowing for increased momentum when swinging. The slender to thick concept of the falcata not only improved the brute delivered force of the blade, but was still light enough to be used for swift thrusts. The hilt was predominantly molded from the same sheet, or bar of metal that the blade was, and usually wrapped around to form a handle, as well as hand-guard. An L-shaped projection toward the beginning of the hilt substitutes as a pommel in order to mitigate slippage when wielded. Additionally, a chain usually attached from top of the L-shaped serif to the base of the hilt to further reduce slip. Aside from the ability of the versatile falcata to execute chops, thrusts and drawing cuts, the curves greatly enhance the blades structural strength. “Multiple fullers ground along the upper edge if the blade, where it is thickest, provided additional rigidity and fine-tuned the weight and balance” [32].

Throughout the 6th and 7th Centuries, pattern welding consisted of placing thin layers of patterned steel onto a soft iron core, improving flexibility and developing a more efficient elastic core that would strengthen the blades resistance to bend or fracture.To test the quality of the sword a soldier would put the blade flat on his head, then proceed to pull both the tip and handle back until they touched their shoulders. Immediately after letting go the blade would spring back into its original shape without any bend or break [33].

4.1.3. The Celts and Smelting

The Celts are recognized as the primary developers of the “metallurgical practice of iron” [17] throughout Europe from the 6th century BCE onward. The constant fighting between Celtic tribes was part of their culture, and therefore crafting superior weapons and armor was ideal. Iron obtained from the blooms had its oxides removed and these pieces were worked into ingots of different forms. These bars were considered unfinished product but were used as a currency. These bars were produced with the intention of turning them into weapons. Including the operation to create the bars, roughly fifty operations would take place in order to make a weapon.

In relation to the falcata, the whole trade system was not really relevant. However, the war culture is what had an influence in the creation of the sword. With the warlike culture of the Celts, a weapon with the falcata's design advantages was paramount. As a weapon that could function like two different weapons allowed for more functionality and control and gave it an edge over a standard sword or ax. The production of a weapon that had such advantages prompted enemies of Celtic tribes to create responses to the falcata in their own arsenal. Most famously the Roman Gladius, translated from Latin as "sword", was produced as a counter-weapon to the falcata, as shown in Figure 4.1.

Figure 4.1.: The Roman gladius [31].

The Gladius was considered to be a strong weapon of choice to use against the falcata because the Gladius allowed the Romans to utilize short thrusts as a battle tactic with the short sword to counter attack once the Celtic warriors had tried to slash at their shields with the falcata. In of itself, the falcata's design was strong for its time, it did however, evolve combat to favor weapons that allowed short thrusting rather than large hacking and slashing motions. The design of the falcata, and therefore its production, fell drastically following the rise of the Roman Empire. It is, however, important to note that the process for producing a weapon with this quality of metal is significant to the changes in warfare.

4.1.4. Falcata Manufacturing Process

The Iberian mercenaries used a very specific process for producing the falcata. The sword was made up of three laminas of steel. Lamina is defined as a thin layer or plate. These steel plates were buried in the ground for two to three years, which eliminated some of the carbon content from the steel and this process made the steel stronger. This process was included because the way that these people forged their metals was through a bloomery, an ancient smelting medium through which the Celts at this time forged their metals [5].

4.1.5. Bloomery Process

The bloomery was one of the most ancient designs of a smelter/furnace, typically a structure of clay roughly a couple of feet tall, as shown in Figure 4.2). These furnaces were also built on dry surfaces such as sand, gravel, or a pile of slag. This was done in order to keep the inside dry and avoid moisture from the earth. There is also a need to clear roughly an eight foot radius due to charcoal sparks flying out.

Figure 4.2.: Fully constructed bloomery [36].

A big problem is managing to keep the inside of the smelter really hot, while also allowing some heat to escape so as to not melt the clay [36]. Sauder also says that, eventually, the smelter will find a state of equilibrium where the inside will reach acceptable temperatures, while the clay will not melt, however, the problem is that the further away from the proper design of a bloomery you are, the more fuel and ore you'll end up wasting in attempt to meet these equilibrium conditions [36]. Inside the bloomery, there is a layer of ignited charcoal and this could reach temperatures of 1300°C (2372°F). The iron ore was added to this along with more charcoal. This was a process of chemically reducing the iron ore, however, since these primitive furnaces could not reach the melting temperature of iron (roughly 1500°C, or 2732°F), the product was an amalgamation of the iron and slag. The product was imperfect, but could be heated up and hammered to remove most of the slag from the product and then wrought iron could be forged from it.

Researchers have found that many of the early iron products made in the bloomeries have had a level of phosphorous ranging typically from 0-4wt% [12]. Many experts in the field of steel-making would agree that having these levels of phosphorous in the finished product would be bad for the structure of the finished product. Researcher J.A. Charles would disagree, however. His research has found that having a low percentage of phosphorous in the iron actually increased the yield stress, tensile stress, and hardness. The other advantage to having phosphoric iron, is that it can be easily hot-worked. Hot-working is a process where a metal is brought above its re-crystallization temperature and then deformed in a plastic manner to fit the worker's design intent. The re-crystallization temperature of most metals is given a general rule of thumb of roughly 60wt% of its melting point. Researchers have also found evidence that early iron-workers used mostly the 0-4wt% phosphorous content iron for most of the makeup of their weapons. While they would use the low phosphorous content iron for making the tip of the swords of an overall higher quality.

The heating up of the metal allowed a "local carburization" to be achieved [17]. mixing of the heated up iron along with the Carbon Monoxide produced near the charcoal. Also, some bloomeries did manage to partially melt the iron and produce a wrought iron which was typically discarded as it was "hard, brittle, and unworkable" [17]. The author believes that the wrought iron was achieved as an accidental by-product of the bloomery and happened due to improving designs and internal temperatures of the furnaces. There is also evidence of rudimentary bellows, devices used to emit air in a controlled fashion, made from animal hides being used to control the carburization of the metal. This smelting process was what the Celts used to produce the falcata.

4.1.6. The Bloomery and the Falcata

The unique process of burying these steel plates before putting them in the bloomery was a way to account for the imperfections produced by the bloomery, making a higher quality metal after being put in the bloomery. The process after digging up the plates was to take the three plates used to make the weapon and put them in the bloomery together in order to have them blend together. The metal could then be manipulated and reformed through the traditional heating and hammering processes. This was a long process, however, it proved worthwhile as the quality of metal produced was actually significant enough to make an impact on the quality of weapon produced. The weapon was formed by welding together laminated steel sheets.

4.1.7. Laminated Steel Sheets

There was a necessity to use the process of laminated steel sheets to produce weapons in ancient times due to the nature of the bloomery. The process of laminated steel sheets was to take sheets of steel with differing carbon contents and forge them together into one blade. This process accounted for the imperfections of the smelted steel produced by the bloomery by averaging out the carbon contents of the produced steel.This process was what the Celts used to make the falcata.

The Celts had a unique process for the laminated steel sheets. Where they would bury the sheets for two to three years, and then the sheets would corrode, producing sheets of differing carbon contents. Then weak steel was removed from the sheets and they were put in the bloomery where the metal would be heated up and could then be forged together once hot enough to be combined. Researchers learned these important factors in falcata manufacturing by analyzing swords found from burial sites.

4.2. Analyses of Original Celtic Swords

One of the best ways to learn about ancient Celtic swords would be to perform systematic, destructive metallographic analyses, but this is not a very common practice since destroying historical artifacts is often a costly endeavor. However, there was one extensive analysis done by Radomir Pleiner and his graduate students, which was published in the book "The Celtic Sword" in 1993. In his analysis, Pleiner destructively examines the metallurgical properties of 120 iron Celtic swords from the La Tène region of continental Europe during 400BCE to 200BCE [20]. The examinations primarily involved determining the carbon content distribution throughout each cross section, and determining the boundaries of each distinct piece of metal that was forge-welded together to make the sword. This information is particularly useful to the group in gauging the most historically-accurate means of layering the lamina of metal, and particularly which qualities of steel to use.

One of the first major results from Pleiner's study was that there was a large amount of variation between the 120 swords tested—both in steel qualities and pattern of lamination. This variation is understood to be associated with the inconsistency in steel quality of product created in the blooms of the time, and also the small scale of individual blooms which required more individually created batches to make needed material. There were an assortment of low quality steel swords (wrought iron), which had dismally low carbon content, and many more of mid-to-high quality steel with respectably functional levels of carbon content [21]. Figure 4.3 is drawn from similar set of swords analyzed from 500BCE to 250BCE:

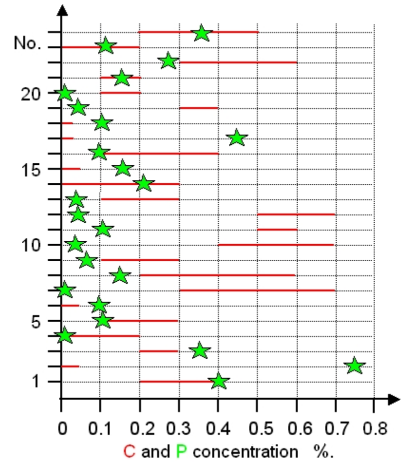
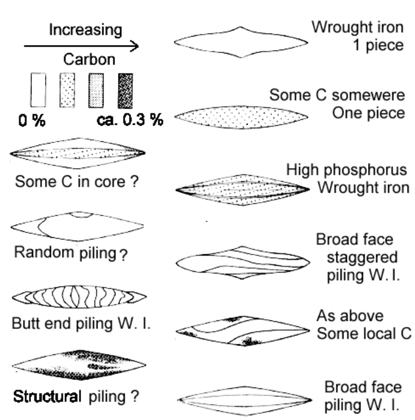


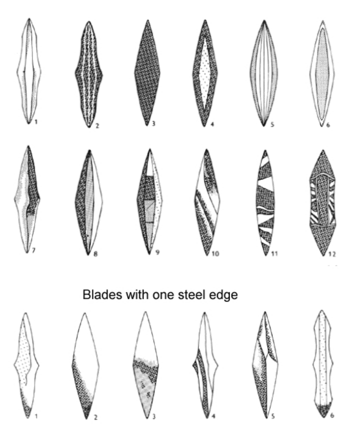
Figure 4.3.: Carbon and Phosphorus concentrations of ancient Celtic swords [20].

Based on the results depicted in Figure 4.3 and the results discussed in Pleiner's study, the carbon content of the swords ranged from basically zero carbon to 0.7wt% carbon by weight [20].

The second main result of Pleiner's study regarded the orientation of the plates used in the lamination process during forging, and the relative carbon contents of each piece of metal comprising the lamination. Primarily, it was found that harder (higher carbon) steels were used for the cutting edge, and softer steels were used on the faces of the blade which took less direct forces during use. This was certainly not a standardized procedure, and in some cases the locations of the soft and hard steels were reversed. This has led historians to believe that Celtic smiths at the time understood that laminations had the opportunity to improve sword quality, but did not always know what qualities of steel they were actually using.



(a) Low carbon steel swords.



(b) High carbon steel swords.

Figure 4.4.: Carbon distributions and lamination patterns of sword cross-sections [21].

Figures 4.4(a,b) demonstrate a selection of the lamination patterns used in the swords tested by Pleiner and his team. Darker regions of those images represent higher carbon content, relatively. From these images, it is not too difficult to see the commonality mentioned earlier about the most frequent lamination pattern used—a harder region for the edge, potentially all the way through the center of the blade, and softer regions around the faces of the blade where less hardness is needed.

4.3. The Manufactured Blade

In order to actually construct a decent replica, obtaining information describing the physical qualities and dimensions for the falcata was necessary. A portion of these qualitative goals were collected from other historians who have also recreated the falcata, Table 4.1 [8]. Figure 4.5 shows an example of such a replica [8].

Table 4.1.: Historical dimensions of the falcata [8]

Historical Falcata's Physical Qualities	
Weight	2 lbs 14 oz
Total Length	24 $\frac{3}{4}$ in
Blade Length	20 in
Handle Length	3 $\frac{1}{2}$ in
Max Blade Width	2 $\frac{5}{8}$ in
Min Blade Withd	1 $\frac{1}{2}$ in

The results found in Table 4.1 come from Greyson Brown's webpage where he created his own replica Falcata. Brown's design was the most reasonable for creating a replica blade. The team wanted to make a unique design, so the dimensions were the only resource used explicitly.

Figure 4.5.: Replica falcata [8].

There were conflicting designs on-line for certain aspects of the blade. The original swords found from burial sites were barely intact so certain things like the handle, groove, etc. were difficult to determine. Despite most replicas including a groove and a brass handle, as shown in Figure 4.5, the team decided to take a simpler approach and focus on the shape of the blade itself, which was determined from the digs, and keep the handle simple with wood.

5. The Design Plan

This section details the steps the team took in order to complete the replica falcata. There were some steps from the ancient process, such as burying the steel sheets in the ground, which were not feasible in order to complete the project within by the deadline. In addition to these differences, the team also had to use angle grinders, a power hammer, hydraulic press, etc. to help complete the project.

5.1. Overall Design Expectation

The actual goal for this project is to produce a falcata replica as close to the original as possible. It is difficult to perfectly follow the actual historic manufacturing process, but it is possible to mimic most of the steps that the Celts historically used in a modern setting. Given that there are three pieces of metal to work, the first idea is to make the pieces an equal width. There are two 1018 rectangular bars that have an average width of about one and one-quarter of an inch. The 1045 square bar, however, is roughly three-quarters of an inch. The idea is to flatten this square bar to roughly an equivalent width so that when the team combines the pieces together, the blade is uniform throughout. The plan is to then laminate these blades together once they have been worked to a relatively thin thickness.

Table 5.1 shows specific metal properties of the two types of metals acquired. Figure 5.1 shows an image of the three pieces of metal. Figures 5.2a, 5.2b, and 5.2c show the technical designs for the team's falcata design.

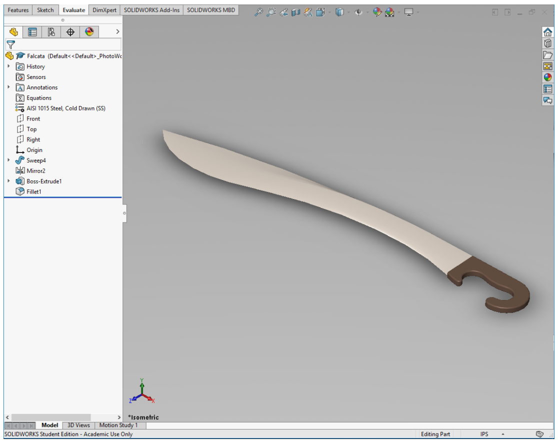
Table 5.1.: Properties of the two metals acquired for this project

Properties of Acquired Metals		
Property	1045 metal	1018 metal
Shape	Square Bar	Rectangular Bar
Finish	Unpolished	Unpolished
Length, ft	4.0	2.0
Thickness, in	0.750±0.004	0.250±0.006
Width, in	0.750±0.004	1.500±0.006
Yield Strength, psi	77,000	54,000
Hardness (Rockwell)	Medium (B88)	Medium (B70)
Construction	Cold Drawn	Cold Drawn
Carbon, wt%	0.43 - 0.50	0.13 - 0.20
Manganese, wt%	0.60 - 0.90	0.30 - 0.90
Silicon, wt%	0.15 - 0.30	0.15 - 0.30
Phosphorus, wt%	0.04 max	0.04 max
Sulfur, wt%	0.05 max	0.50 max
Iron, wt%	98.21 - 98.85	98.06 - 99.42
Density, lbs/in^3	0.284	0.238

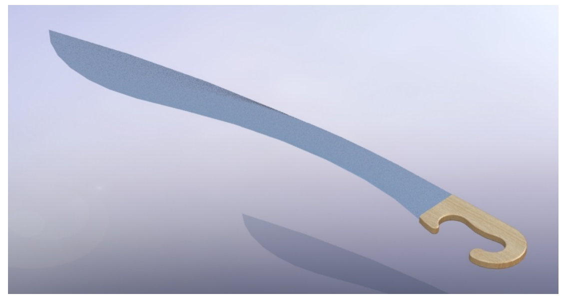
The material properties as shown in Table 5.1 display the carbon content for the steel. The carbon content is ideally supposed to be 0.45wt% carbon for the 1045 steel and 0.18wt% for the 1018 steel. Both of the types of steel were cold drawn, which is a process for manufacturing steel where the steel is formed so that it can fit through a die, which can then shape the steel. The steel passes through multiple die at room temperature in order to reach the desired shape [11].

Figure 5.1.: Raw materials.

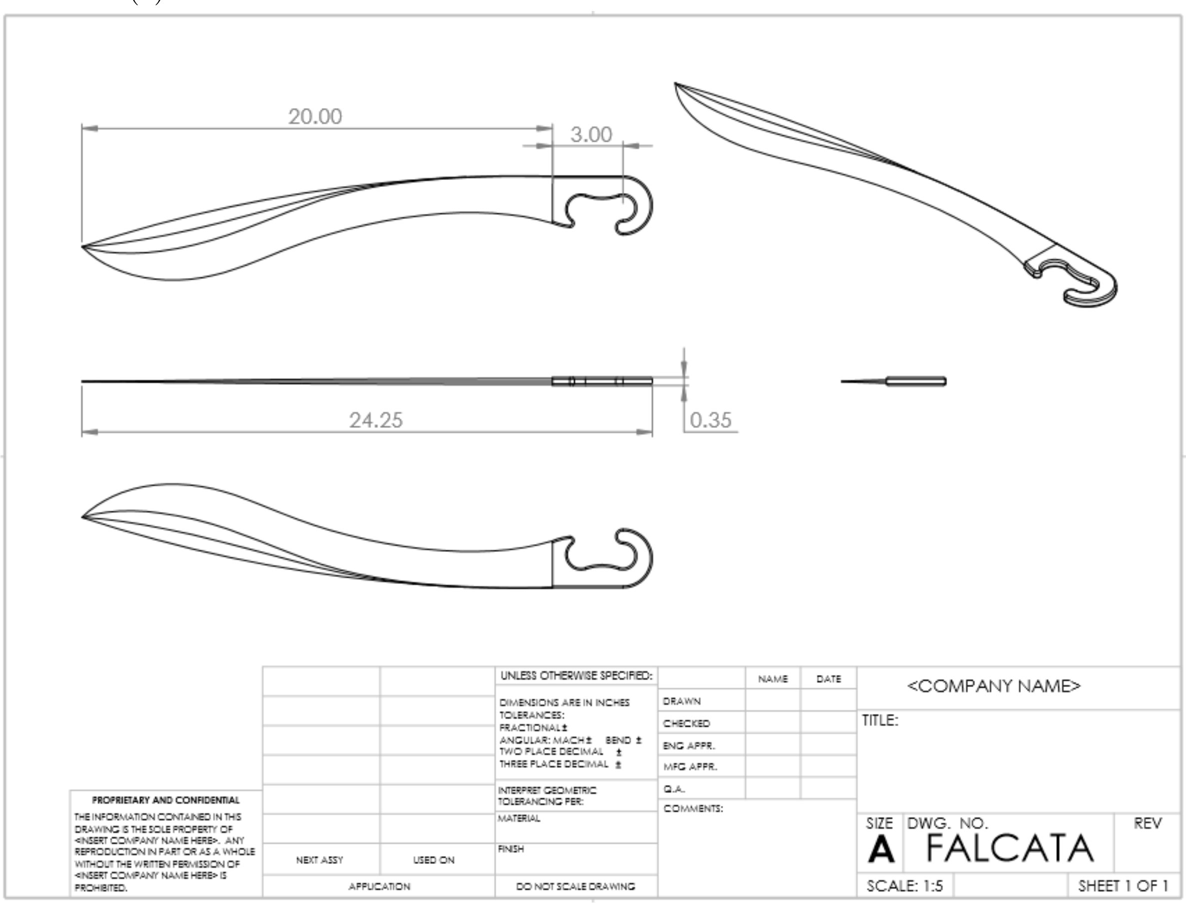
Figure 5.1 shows the raw materials that the team started with. The 1045 square bar, depicted left, was flattened to fit the width of the two 1018 rectangular bars, depicted right, so that the team could obtain a strong weld with uniform welding surfaces. The first step in the process was to obtain the desired dimensions for the 1045 bar.



(a) Falcata CAD model.



(b) Falcata render.



(c) Falcata drawing.

Figure 5.2.: The technical plan for the falcata design.

The CAD models and renders for the falcata reflect the team's ideal specifications for creating the blade. The actual blade created was not quite to the specifications of the CAD render but proportions were kept in mind, so equal percentages of the blade were shaped the same way. For example, the length of the stretched part of the blade is shorter but it takes up an equal percentage of the blade's length to keep the structure proportional.

5.2. Basic Forging Process

Most of the team was inexperienced when it came to actually using the forge and the tools in the forge to produce the falcata. The forge at the shop is roughly a few feet long and is powered by propane gas.

The tubing that attaches the propane tank to the forge is how the gas is transferred to the forge. There is a valve on the end of the propane tank that allows the gas to flow from the tank through the tubing. On the forge itself, there is another valve where the tubing connects that supplies the gas to the forge. Once both valves are on, a match or a lighter is required to contact the gas to start heating the forge. In addition to this, Josh, the team's mentor, also put in a small piece of paper that had been lit on fire.

After the forge is heated up enough, the metal pieces can be heated and then worked. The metal takes five to ten minutes to heat up the first time to a reasonable temperature, about 1200°C (2192°F), to begin working. The visual cue to indicate that a metal is hot enough to be worked reliably is an orange and yellow mix of color on the end of the metal, as shown in Figure 5.5. To remove the work-piece from the forge, tongs that are properly sized to the width of the material are used. Tongs must be always carefully fitted to the work, when properly fitted the jaws should touch the work throughout the entire length as shown in the bottom drawing in Figure 5.3 [28].

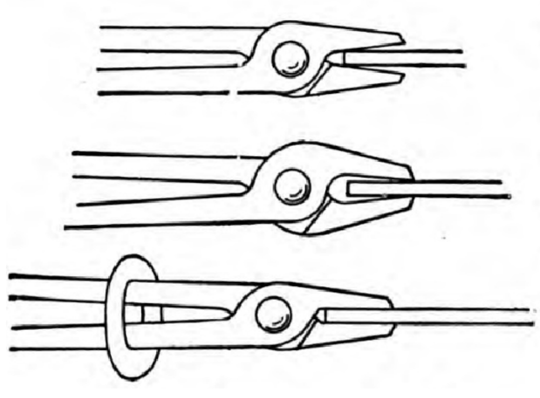


Figure 5.3.: Fitting tongs to work-piece [28].

If the work-piece is not fitted properly, as shown in the top two drawings in Figure 5.3, working on the metal can be considered quite dangerous, especially if the jaws are too close together. There are ways to perfectly fit the tongs to the work-piece which is to heat the jaws up in the forge and then clamp down on the work-piece and hammer the tongs to form fit the piece [28]. However, Josh has a wide range of tongs for the team to use as the practice of form fitting the tongs is rather outdated and there are now have industry standard widths and thicknesses of metals so that manufacturers can produce tongs with different dimensions, in a way similar to wrenches. Therefore, it is not of major concern, however, it is still important to have proper tools to grasp the metal with. After having proper tools to hold the metal, the smith can use an anvil, power hammer, etc. to shape the metal.

5.3. Flattening the 1045 Square Bar

Before the lamination of the three pieces of metal, the 1045 square bar needed to be flattened. The bar was ordered as a square because a rectangular shape steel with a similar carbon content could not be obtained with close dimensions to those of the 1018 steel. Josh had obtained a hydraulic press, though, which made flattening the piece a much quicker process than hammering the metal by hand.

The good thing about modern technologies and standards is that the metal obtained is shaped ideally; in ancient times the whole process of shaping the metal is just another step that comes with the process, for the team, it was an inconvenience that had to be dealt with. Most metal would not be shaped or sized how the blacksmith would want it and they would have to hammer out and fit most pieces to the size that they wanted. In addition, however, the blacksmiths had this as their main job, and therefore hammering out all pieces of metal individually was an aspect of the job and not an inconvenience as they had much more time to shape the metal. The process of using the hydraulic press to flatten the metal was significantly shorter, however, to the time that it would have taken to flatten a bar by hand. The time spent, in total, may have only been a third of the time spent to hammer it but the team could only meet once a week to work on the project for roughly two hours, and the flattening process took about two weeks, which then would have taken about six weeks to hammer it which was about half of the time allotted to work on the forging project.

The reason for flattening the bar is based on the structure the team wanted to obtain. The falcata is essentially a sandwich of metal. The 1018 steel is the outside while the 1045 is the inside. The team wanted equivalent or roughly equivalent representation of the metal on the piece. So that meant flattening the 1045 bar to roughly the same width as the

1018 bars, for when lamination happened. The goal was to get the width of the 1045 from three-quarters of an inch to roughly one and one half of an inch in width.

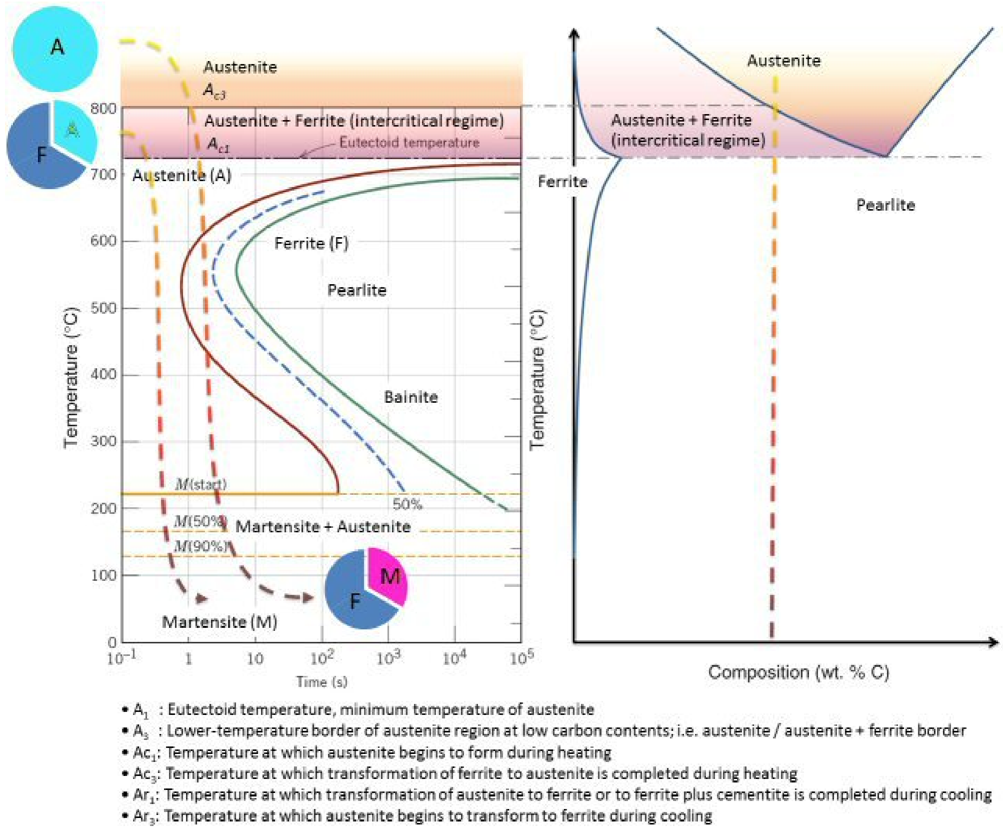


Figure 5.4.: Resulting microstructures in steel for different cooling rates.

The hydraulic press, shown in Figure 5.5, was used in order to flatten the 1045 square bar, but the team still needed to heat it up to the same temperature as if to hammer it down to size. The bar was heated to roughly 1200°C (2192°F) in order to work the piece. Forging temperatures of steel are represented in Figure 5.4. The details of phase diagrams for steel are discussed at length in Section 6.1. One issue that the team ran into was that multiple sessions were necessary in order to flatten the bar to its proper width, but the ancient process for manufacturing the sword did not involve quenching, which was necessary in order to cool the metal piece down in a timely fashion. The team discovered that if the bar was quenched at roughly 482°C (900°F), then the structural properties of the metal would remain unchanged and the team was able to identify that temperature by looking at the metal and seeing that the color was dark enough to safely assume to begin quenching the bar.

Figure 5.5.: The hydraulic press used for major flattening processes.

At first the flattening was effective as a flat, rectangular die on the hydraulic press to make the square bar more rectangular. The consistency of the width was not totally uniform, but it was good enough to serve the purpose. The team found out, though, that eventually the press seemed to not flatten the bar as much, and there was a simple physics solution.

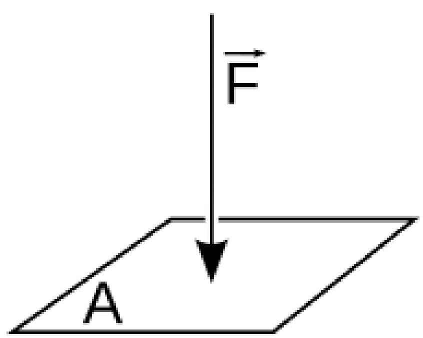


Figure 5.6.: Pressure is equal to the force applied to a cross-sectional area [35].

The relationship between force and area, as shown in Figure 5.6, was used to make the press more effective. As the piece used was rectangular, switching the orientation which the bar was put into the press made for a smaller cross-sectional area. In order to apply the same pressure, more force was put down on the work-piece and therefore the press was able to flatten the bar more effectively. The process to flatten the bar took a large portion of time, roughly three hours in total, but it was, however, a necessary process for making a uniform blade.

5.4. Cutting, Grinding, and Welding

Out of all the tools that were available at the shop, the team decided that a large band-saw would be most effective at cutting the metal bars. The desired lengths had to be determined, in order to be able to hammer them into the desirable shape and thickness. After consulting with Josh, the team all agreed that ten inches would be ideal for the actual sword, and an additional four inches would serve as a buffer and, more importantly, for the smaller sample created. The bars were marked, clamped them down, and cut.

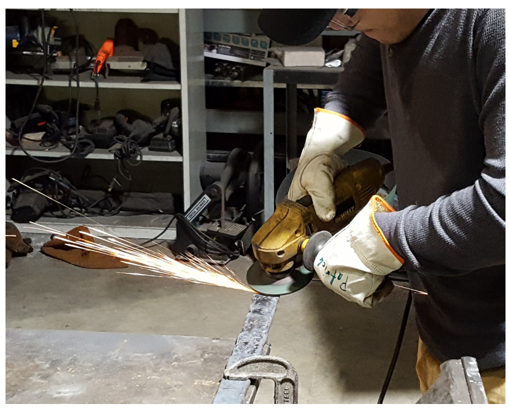


Figure 5.7.: Cleaning the welding surfaces before lamination.

Before proper lamination can be done, it is very important to thoroughly clean the surfaces of the metal bars that will be fused together. Figure 5.7 shows the approach to cleaning the weld surfaces. This process is important because it ensures that pollutants such as oxidized metal scaling, which is structurally very weak, does not get between the metals being joined. Also, grinding the metal surfaces gives them a coarse texture, which can aid in their joining. The team used a hand-held power tool called an angle-grinder. With this, they were able to clamp the bars steady and, one by one, grind down the entire surface of the bar that needed to be cleaned. The surfaces that needed to be processed this way were both sides of the 1045 bar and one side each of the two 1018 bars.

Figure 5.8.: Josh tack welding the bars together.

At this stage, the desired cuts were made the applicable surfaces were ground down. Before laminating through forge welding, the team needed to do something to keep the three bars solidly in place with one another. To do this, Josh tack welded them, as shown in Figure 5.8, on both sides while the bars were clamped together. Figure 5.9 shows the results from Josh's tack weld. This ensures that, when heating and hammering, the metal would not loosely move around. Later, the material from the tack welding can be removed.

Figure 5.9.: The results from the tack weld.

In terms of cutting, the old process may have been as simple as sizing the metal to desired dimensions, as the team ordered from a manufacturer with standard sizes, the old blacksmiths shaped the metals themselves. If they did want to make changes to the length of the metal, it would not involve using a band-saw, instead they could just heat the metal to a forging temperature and then use the pointed end of a hammer and separate the unwanted length away. The ancient process of forging a falcata did not involve the grinding of the weld surfaces with an angle-grinder, as the technology was not available and the insight into the chemistry was also not as well known. The intention of the grinding was to remove the possibility of oxidized metal scaling, but as the team discovered from the ancient process, the quality of metal produced from a bloomery was not anywhere near the quality of metal that around today, and the potential for oxidization of welding surfaces was not as well known. This process was used to protect the quality of the blade. In addition to this, tack-welding is a modern approach to a problem of keeping the metals fixed together so they can be compressed consistently. The ancient method may have required that much more of a dexterous work of the blacksmith to keep the bars from sliding out of place relative to each other.

5.5. Laminating the Metals Together

Once the team tack-welded the bars together, the process seemed to repeat itself. Josh told the team to heat up the stacked metal bars to roughly 2000°F. Every time the metal was put back into the forge the team were coated each side with borax (chemical formula: $Na_2B_4O_7 \cdot 10H_2O$). The method of pouring Borax over the piece is shown in Figure 5.10.

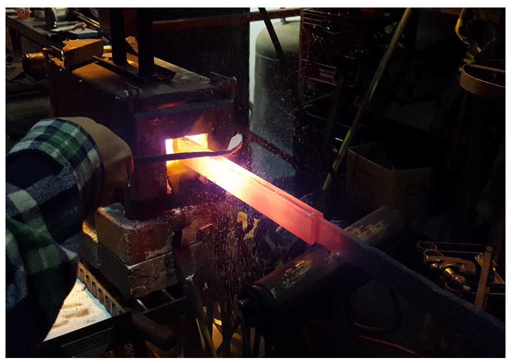


Figure 5.10.: Borax, used as the forging flux.

There is an importance to using borax as flux for the forging, as the surfaces must be clean or the metals will not properly join together. A flux is necessary to keep the welding surfaces from oxidizing as well as to remove other impurities from the metal. Adding a flux allows oxides to flow out of the metal when pressure is applied, and borax is the flux generally used for modern forging. As far as ancient flux in welding, referring to the section on the bloomery process, the ancient forging process had no such flux available or was, at least, not significant enough to be mentioned. There has been discussion, however, that ancient smiths used silica sand, found on beach shores, as flux for forge welding. In addition to this, the quality of metal produced was of such a poor quality and the surfaces were generally oxidized and poorly welded, which indicates a flux was most likely not used, or at least one not nearly as effective as borax.

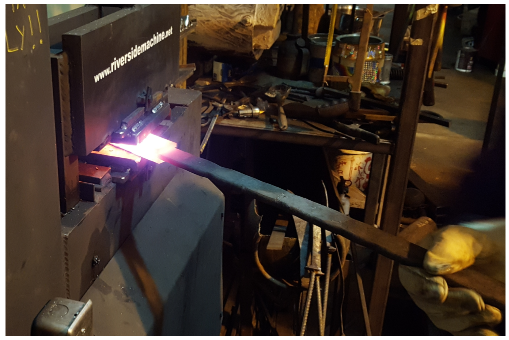


Figure 5.11.: The hydraulic press, used to start lamination.

The hydraulic press was used to try and squish the metals together as Figure 5.11 shows. The press seemed ineffective at first with the flat die. The team switched to a smaller, rectangular cross-section area die. The press still seemed to be ineffective, however, after the fourth or fifth pass, the metal just seemed to give way and compress. The team was then given a recommendation to use the power hammer to finish the flattening process, as the press seemed to make sections inconsistent in width. To give a more accurate description of what the press would do, the die on the press would push down in a rectangular cross section, however, the consistency of how far out the metal stretched tended to taper towards the far ends of the press. The press would generally leave the metal in multiple oval or elliptical looking sections, which could be pressed themselves to make the area more consistent but the power hammer offered much more consistency and control. In addition to that issue, the press would bend the metal and almost buckle it at certain sections. The team would be unable to press the metal down as much as desired the metal had to be hot enough to hammer out the inconsistencies and make the metal more straight.

Figure 5.12.: The power hammer used to efficiently laminate the metals.

The team was shown how to use the power hammer early on in the process as an alternative method to flatten the 1045 bar, but the team thought that the press would be faster. When given a strong recommendation to use the power hammer, the team took it and managed to flatten the bar significantly faster than with the press and much more consistently. The power hammer is represented in Figure 5.12. The other neat thing about using the power hammer, in addition to its consistency, is the amount of control it giver to the user. There are two surfaces that the metal can be placed on that will sandwich the metal with the power hammer. One is a flat surface and the other is curved to allow intricate more intricate designs. To use the hammer, the end point of the piece had to be hammered and then the bar had to be pushed through the hammer. Then the process reversed, moving back to where the hammering started. The power hammer helped the process of lengthening the metal from 20 inches to roughly 24 inches. The results are shown in Figure 5.13.

Figure 5.13.: The result after lamination.

When considering options for flattening, squishing, laminating, etc. metals together, the options that were available were to either hammer the metals by hand, use the hydraulic press, or use the power hammer. The team was more comfortable using the press at first, but when it proved ineffective at pressing the metal consistently, the team switched to to power hammer. The ancient process was definitely restricted to using the hammering process by hand, as this type of sword was not manufactured anywhere near the time when mechanized hammers became a forging option. As far as changing the actual material properties, the process only differs in the quality of metal that used as well as the flux. Which, in turn, produces a higher quality of metal and weld than the ancient process, but the overall size and weight of the sword come out the same. The team only used modern technology to expedite the ancient process instead of make a whole new weapon altogether.

5.6. Further Grinding and Cutting

Once the sword was flattened to a desirable thickness and length, Josh told the team to grind the edges of the metal to make sure that there were no cracks where the blade was forged together. An angle grinder was used to clean off the edges and this process is shown in Figure 5.14. The divisions between the 1045 and 1018 layers were not present on the entire piece, but only in a few, select spots. Some of these divisions were deeper than others but all were ground out without shearing off too much of the metal.

Figure 5.14.: Grinding the edges to see the weld quality.

After the grinding process, since there was a uniformly welded metal piece, the team was ready to cut off the excess metal to make a smaller scale sample of the weapon. From this smaller piece the team would also retrieve a cube of metal to analyze the resultant phase diagram. Six samples were needed before processing, one for each plane and three for each type of metal. Now only two samples were needed since the top down plane view would only show 1018 metal.

Figure 5.15.: The cut on the end to make an angle and get a piece for the sample.

Figure 5.15 shows the cut made to the metal piece in order to have a sample ready. An angle grinder with a cutting blade was used to make this cut. The metal was given some durability tests as well when the team was cutting it; when there was only a small piece still connecting the sample and the actual weapon, the team tried rotating the smaller piece to see if it would snap off but the connection between the two pieces was solid. The team was also instructed to cut the metal at an angle because it would remove an annoying step in the process of shaping. Since it was cut at an angle, the team did not need to hammer the end of the blade from a square into a curved elliptical pattern.

5.7. Beginning to Form the Sword: Counteractive Bending

After the material preparation was completed, the forming of the sword from the laminated bar began. With the final product in mind, the team knew the most stretching and work would take place at the last eight-or-so inches at the end of the blade. This region needed to be widened significantly to match the iconic contours of the falcata.

The team began by creating a bend in the aforementioned region, in the opposite direction desired for the blade's curvature to go. The reason for this was to counteract the bending expected to occur when the team started tapering. The act of tapering causes the original thick material to squish laterally, which in addition to relocating material outward which makes the face of the blade wider, there would be a degree of growth along the length in the thinner region. Since the thinning would be more significant at the blade's edge, the length-wise expansion in that region would also be higher, thereby causing a bending action. The tricky part of this bending-counteraction is that it is a predictive measure. For a knowledgeable and experienced smith to undergo this action on a blade is simple work, since they likely have a good feel for how much bending they will need. The team, on the other hand, has little experience with such estimates, so it was just stretched to a degree that seemed reasonable.

In order to achieve this bending, the team needed to first decide which side of the bar would become the edge of the blade. This was decided based on the location of the obtuse part of the angle-cut just before. This angle was made to make the job easier at this end, and in order to get the most aid out of it, the team decided to use the side opposite to the obtuse angle as the blade's edge, so that this straight region would become the stretched out curve needed for the edge. Had the other side been picked, the team would have had to deal with an angle being present on the edge, and would have had to smooth it out afterwards in order to have a smooth (differentiable) blade edge. Consequently, this made the side *with* the obtuse angle the side planned as the spine. Even with this choice, the team still set themselves up for needing to undergo these 'smoothing' processes for the spine, but felt that this scenario was slightly more beneficial, due to the spine's higher thickness compared to the edge, there would be a lot more material (and therefore less to worry about) when the team got to the grinding stages after the smithing process. This in turn would make grinding down any angle still persisting after the hammering an easier job.

Figure 5.16.: The counteractive bend (with a scale).

The exact 'how' of this bending process was simply heating the piece in the same fashion as had been done, and then have the end of the bar hang off the far end of the anvil, and have someone hit it downward. Since further down the bar was supported directly by the anvil, but the end being hit was not, this forced the bar to undergo a torque to counteract the hammer's forces. This internal torque was the main mechanism that caused the bending. The result of this bending can be seen in Figure 5.16; the inside of the curve has a radius of approximately 11 inches, but this level of specificity is by no means an exact science, nor was this necessarily the best curvature for the needs.

5.8. Stretching to Create Width

The forward curve of the sword is where the blade is at its widest. The bar after forge-welding ended up being about 1-5/8" wide and the forward section of the sword was expected to be nearly three inches wide. Before hammering this section, the team did not know just how much width could be gained from stretching the metal. The best way to control in what direction the metal stretches upon being hammered is by using a cross-peen hammer rather than the typical flat faced hammer. The peen allows for a more concentrated application of pressure in a specific dimension. Since the team wanted to stretch the sword across its width, they carefully hammered the peen parallel with the side of the sword,as shown in Figure 5.17.

Figure 5.17.: Using the cross-peen hammer to stretch out the width of the blade.

There is a limit to just how thin the metal could get before the integrity of the sword is compromised. Because of this, the team needed to pay special attention to how much the blade stretched in order to get it as close to the target width as possible. The team did not want the blade edge of the stretched portion of the sword to become less than a 1/16" thick before grinding. Keeping this in mind, the blade was hammered as much as possible to stretch the sword as wide as possible.

Throughout this process, and counteracting the bending that occurred from it, some geometry took shape that was not desired. Due to the fact that the team needed counteract the bending of the forward section of the sword which happened because of the stretching, a region of material accumulated at the very end of the sword in the form of an up-swept curve. This needed to be removed later on in order to achieve the correct shape. At first, the team tried correcting this region by hammering it back into place, but it ended up compromising the shape of the forward section too much and it was a better decision just to leave it there and deal with it after hammering was done. Figure 5.18 shows the result after the stretching.

Figure 5.18.: The end of the sword after the majority of the stretching was completed.

5.9. Creating the Overall Contours

After the greatest width manageable was reached for the far end of the blade, the team needed to get the rest of the sword into the desired shape. The tasks necessary to complete in this phase were: ensure continuity over the widths and thicknesses of the blade; reduce the width of the center region of the blade; and ensure the spine had the desired curves. In determining how to shape the sword further, the team made sure to overlook the excess material at the tip of the blade, since it would not contribute to the overall contour of the blade after it was cut.

The team first tackled the issue of continuity in width along the edge of the blade. In the widening process, the team only focused on stretching out the desired region thicker, and consequently, there was a noticeable bump between the stretched region and the rest of the blade. In order to correct this, identical methods as done for the rest of the stretching were used, but a lot less material than before was moved. In doing so, the widened region was extended slightly, and created a gradual slope and continuous curve over the entirety of the blade's edge. After this process, the discontinuities in thicknesses were also handled using the flat end of a hammer so as to primarily make contact with the blade at just the thick bumps.

In order to accentuate the characteristic shape of the falcata planned on, the team decided to also reduce the width of the region of the blade between the heavily-widened part and the handle. The team did not want to change the contour of the spine through this activity, so this reduction in width was done only from the edge inwards. In order to achieve this, the spine was laid flat against the anvil so the blade's edge was pointing straight up. With the heated blade sitting in this position, the team hit the edge straight on with a hammer with a somewhat round head. By pushing the edge into the bulk of the material, the blade became thicker in that region. Around once per heat cycle, the sword was rotated to be flat on one of its faces and hammer down with a flat hammer onto the newly formed bumps around the edge. This re-widened the blade slightly, but it still yielded a net decrease in the region's width. This process was repeated until a desired minimum width was reached, roughly two thirds of the widest width on the blade. Throughout this process, the team also ensured to maintain the continuity of the blade's thickness and width everywhere.

At this point, the thicknesses varied wildly across the blade. The spine was roughly the same thickness across its length, but the blade's edge ranged from only slightly thinner than the spine to very thin (just greater than the 1/16 inch limit decided on). The edge thickness was a direct function of how much stretching was done in that region—the more that was stretched in that region to increase the width, the less thickness it had left. This was a direct result of carefully pushing the metal towards the edge to create width, which by conservation of volume yielded an equivalent process of thinning. The region between the spine and the edge tapered uniformly from the edge to the spine, making the blade's faces locally flat. The high thickness regions were not ideal, since they needed to be ground down heavily. This would not be very historically accurate, since power tools were out of the question and other grinding methods would have been very tedious. The team left the very thick regions in place because blade's width could be ruined in the region if the thickness were reduced, which was not desired. Historically this problem would have been avoided largely with proper experience and more knowledgeable preparation in the earlier steps, so that only as much material would be in each region as needed. Since the team lacked this level of expertise, they decided to make up for it the smart way (power tools) since this decision would not change the material properties of the sword, nor the final result.

The final step of the contouring was to finalize the overall contours that would be most explicitly visible on the blade. These would be the final details of the blade that would be forged. This involved bending the entirety of the sword slightly in places in order to change the spine's curve, and the final contours of the edge would also fall into place since the widths in each region were already finalized. Based on the design drawing in Figure 5.2c, the team wanted to have the spine bend forward, increasing with distance away from the handle. When the team decided about which points on the spine to create a minor bend, the sword was placed spine-down on the horn of the anvil, and the edge on the far end of the sword was carefully hit downwards. By hitting the sword in a region the anvil did not directly support it, the team induced a temporary torque inside the sword, which resulted in the desired bending. Since the horn of the anvil was rounded, this enabled the team to loosely control the radius of the curve created, to the extent that abrupt corners were not created.

The final results of this detailed but quick set of continuity-oriented adjustments can be seen in Figure 5.19.

Figure 5.19.: The shape of the sword after most of the forging on the blade.

5.10. Forming the Tang

With all of the details of the blade's contours being nearly finalized, the team was ready to wrap up the forging part of the process with one last phase. All that was left on the sword was the handle region, which at this point was still rectangular as it had been since the lamination process. Before the sword was heated up, the team decided to cut off both the excess tip of the blade and the long temporary handle attached just below the blade's tang, which was had been becoming unwieldy due to its excessive length. To do this cutting, just as before, a hand-held grinding tool fitted with a cutting wheel was used. The long temporary handle was cut straight off, adding no bizarre angles or deformations to the end of the tang. The excess on the tip was cut off with a bit more care, since the contour it left behind would be of equal importance to that of the rest of the sword. The team made sure to start the cut in this region so that it was tangent to the region of the spine that led into it, and made sure that it cut off all the material they wished to be removed. Figure 5.20 shows the result of this cut.

Figure 5.20.: The shape of the sword after cutting off extra material on both ends.

With the cutting complete, the team heated up the blade's newly reachable tang in the handle region, and set to work. The team wanted to move most of the tang's material outside the center of the handle where the wielder's hand would rest, while simultaneously making the handle longer so larger hands could be accommodated, and also make the handle region thinner. All three of these tasks were well aligned with each other, since doing one helped with achieving the others (unlike earlier processes where hitting along one dimension inevitably created deformation along another dimension in an undesirable way).

During each heat cycle, with the sword's spine flat against the anvil, the tang was hammered down to create the hand-recess, and then the sword was rotated so as to hit the bulge in thickness that repeated to form from the reduction in width. The team did the hammering process differently for this phase differently than had been done for the rest of the sword, since the team was a bit more familiar with working the metal. While Adam held the blade of the sword and kept it in place, Patrick held a special tool for controlling where to hit on the hot metal, and Shawn used a large sledge hammer to deliver heavy blows through the tool Patrick held over the tang. Figure 5.21 shows a depiction of this process. The tool Patrick held was not a hammer in the sense that it was not meant to be swung, but served as a rounded tool to redirect and transfer the force of a hammer hit on top of it. This special redirection tool allowed Patrick to take full control of the careful detail of where and how the tang should be hit, and removed most of the delicacy needed of Shawn swinging the large hammer, since he could hit the top of the special tool much less precisely. This process worked much more rapidly than the previous methods.

Figure 5.21.: The 3-person layout used to shape the tang more rapidly.

With the hand-recess set into the tang to a reasonable degree, the team wanted to do a last bit of elongating the tang as a whole, and consequently to make it slightly thinner. Previously a cross peen hammer had been used to most effectively draw material out to produce stretching. However, when the team started this process, they asked if there was a better way than the cross peen hammer. A special tool that emulated the cross peen hammer's tip was offered, but scaling its region of effect by placing four or five of those same tips in an array. Placing the heated tang inside this custom-made tool produced the same effect as if it was hit with the equivalent hammer, but it worked much faster. Again, since this tool served as an interface between the sword and the hammer, the team used the sledge hammer again to make best use of time.

As this was to be the last use of the forge, the team decided to reheat the entire blade over again and make sure it was as straight as possible and that the shape was as close to perfect as could be achieved before the extensive grinding process. This involved looking down the sword in a bunch of different ways to determine where slight misalignments existed, and then gently hitting it with a hammer to counteract the misalignment. This did not take very long, since the team had already been pretty pleased with its contours, and only minor changes were made. After these tweaks, the team was *very* pleased with the overall straightness that the sword had, and had decided to move on from the forge to the final stages of the sword's creation, the grinding and the handle-mounting. Figure 5.22 shows an image of the blade after this last forging procedure, where the tang is fully shaped.

Figure 5.22.: The end of the forging process, with the fully shaped tang.

5.11. Fine-Tuning the Contours

In order to achieve the desired contours within a reasonable time, an angle grinder with a grinding wheel, as shown in Figure 5.23, was used. The use of this tool for this purpose can be seen in Figure 5.24. This allowed for the team to shave off any excess material and quickly dig out the scale from the surface of the blade. The team ground at the blade edge of the sword starting at a 45° angle and progressively made upward sweeping motions to create a gradual increase in thickness from blade edge to spine.

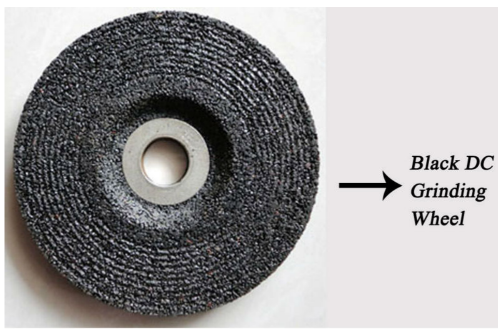


Figure 5.23.: A grinding wheel used to remove excess material quickly from surfaces [24].

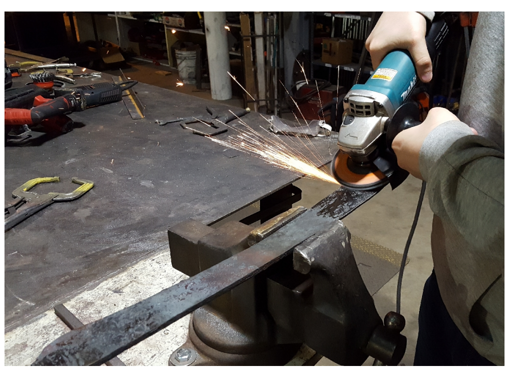


Figure 5.24.: Using the grinding wheel to remove scale.

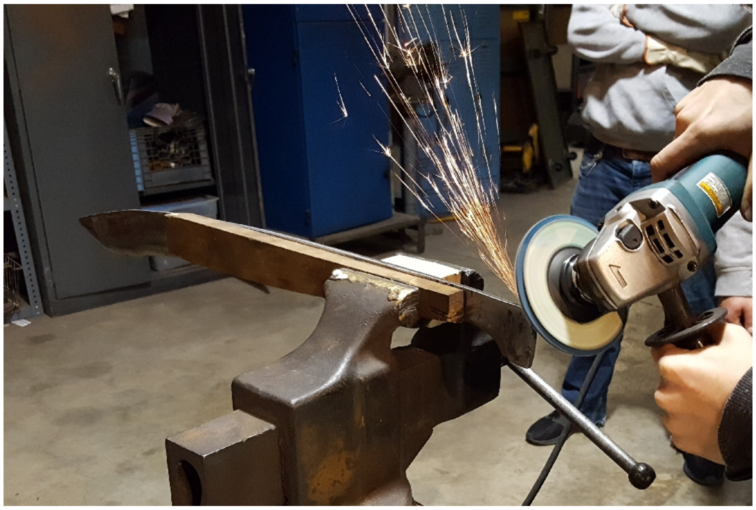


Figure 5.25.: Smoothing out the edges and thin parts of the blade.

Once all the desired material had been removed, the team switched to a sanding wheel, as shown in Figure 5.26. The sanding wheels are generally less abrasive than the grinding wheels which means that much less material is removed. Another good use of the sanding wheel is that it allows for much smoother transitions between the ground parts. For example, when the team did the gradual material removal from the blade edge to the spine, the individual passes from the angle grinder left the areas between the passes segmented. Figure 5.25 shows the process of contouring the edges. The angle of each pass was not close enough to the previous pass which is what caused the jaggedness in the metal. The sanding wheel was much less abrasive and allowed smooth passes, which contributed to making a smooth curve from the blade edge to the spine.

Figure 5.26.: Sanding wheels, used to remove materials from surfaces slowly [3].

The team then turned to grinding the tang. The plan for the tang was to have it as flat as possible on both faces so that the handle scales would contact each face as much as possible. The team used the grinding wheel as the tang was supposed to be reasonably thin, since the wood would take up a significant portion of the handle as well. This size reduction in the tang was to ensure that once the scales were attached, one could easily grasp their hands around the handle. The tang was apparently forged harder than the rest of the blade because, after many passes, the team ground through the 1018 steel and found the 1045 steel. This was not particularly problematic, though it was still no ideal as the tang was desired to contain the same composite as the blade. The team then carefully used a sanding wheel to pass over the faces a few times to ensure flatness and then moved on to fixing the handle. A near-finished state of this grinding and smoothing of the blade's faces can be seen in Figure 5.27.

Figure 5.27.: The blade with most of the scale cleaned off. The wooden pieces and the pins of the handle are on the upper left.

5.12. Finalizing the Handle

While the grinding process was underway, half of the group worked on preparing a piece of wood to be the attached to the tang to serve as the handle. These wooden pieces that sandwich the tang are called 'scales' (different from the scale on the metal, which is oxidization of the steel). The raw material was a chunk of maple. This preparation involved cutting rectangular prisms of wood out of the cylindrical half-log. Figure 5.28 depicts these prisms of wood. To do this, the team used a large ban saw and progressively cut off slices until a size that seemed to have enough material for the handle without being too much, which would otherwise necessitate excessive sanding later, was reached. One interesting note about the thin scrap slices of the maple was how incredibly rigid the material was!

Figure 5.28.: The raw cut maple prisms that would become the handle.

After the scales had been cut into roughly 5/8 inch thick pieces (two of them) the team traced out the shape of the handle from the tang's shape, and used a smaller ban saw to make a similar hand-recess into the wood. By doing this, excessive material could be removed to save time later. With the two scales clamped together, the group began approaching the lines traced with many shallow cuts with the ban saw's blade perpendicular to the actual line that had been planned to be cut as shown in Figure 5.29. After these were in place, the team was able to follow the actual traced line around directly with the ban saw blade, and the many other cuts allowed small chips to fall off the wood, preventing them from pinching on the ban saw's blade or affecting the motion of the cut as shown in Figure 5.30.

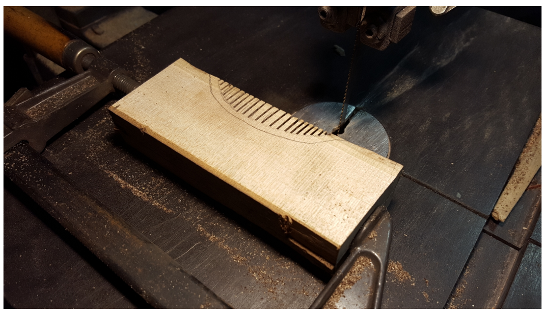


Figure 5.29.: The perpendicular pre-cuts.

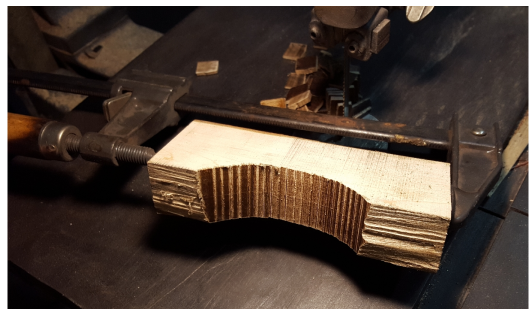


Figure 5.30.: The curved cut.

With the large chunk of material removed from where the hand-curve would be, the team then did some minor sanding to round off the edges of the scales that would need to be rounded off more later anyway. For this sanding process, and those to follow, made use of two different belt sanders. The first of which was a large planar sander mounted vertically, which was useful for making flat faces and sanding very quickly. The second was a thinner belt that offered a curved sanding region, which enabled sanding inside the hand-curve. The result of this edge smoothing is shown in Figure 5.31. It was important to not sand the scales down to a size that was smaller than the tang was at any given point, since sanding down the wood would be easier than grinding down the metal later.

Figure 5.31.: The rounded/smoothed handle scales.

After this pre-shaping was finished, and the rest of the blade had been ground down sufficiently, the team was ready to drill holes and set pins. The team decided to use 1/8" diameter brass pins, which were cut longer than the width of the two scales and the tang between them. To drill the metal, the team went about 1/16" larger than that so as to not bind when pushing the pins through, but for the wood, chose a drill bit 1/16" smaller instead, so it would have a tight fit on the pin. Figure 5.32 shows the drilling setup, using the drill sizes indicated on the drill press. Note that before the finalized decision of using a smaller drill bit in the wood, which could possibly split the wood, a prototype was made that mocked up the relevant positions and procedures. This test showed promising rigidity in the hold between the pin and the wood, and confirmed that the chosen drill bit size did not present a risk of splitting.

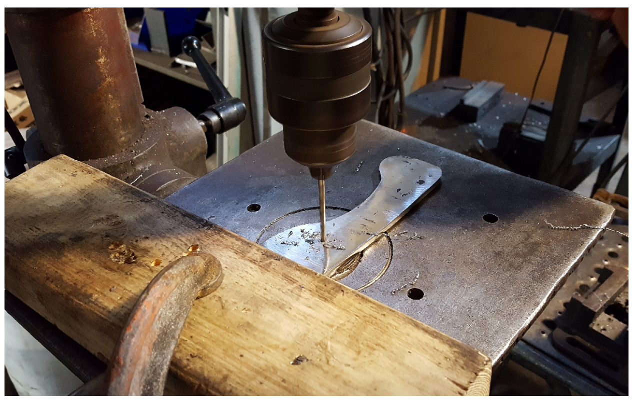


Figure 5.32.: Drilling through the tang for the pins.

The team decided to drill the metal first in three locations spaced out over the tang, and then drill the wood afterwards to fit those holes for best alignment. The group chose the hole-positions so there was one on either end of the handle and one in the middle, and each of them was around the middle of the width of the handle so that after sanding and rounding, the pins would sit in the bulkiest part of the wood. After the metal had been drilled, the team placed one of the scales underneath the tang and used the holes in the tang to guide the drilling into the wood (See Figure 5.33). It was made sure that the wood holes were staggered with respect to the metal holes, so that the pin would be forced to sit tightly against a side of the tang's hole and cause some minor internal stress. This stress would aid the handle in holding together without glue. After one scale was finished, the team turned everything around and placed other scale on top and aligned properly. The group then used the hole in the top piece of wood to drill down into the lower one, being careful to not damage or widen the hole being used as a guide.

Figure 5.33.: Drilling the wood using the other holes as guides.

The pins were cut to the rough size that would allow them to go through the two scales and the tang with excess left over, and the team also sharpened one end on each to a point so as to minimize the chance of it getting stuck inside the wood or against the metal. These pins can be seen in the top left corner of Figure 5.27. The group carefully and slowly hammered these through the wood-metal-wood sandwich, ensuring it was still well aligned whenever the pin got close to transitioning to a new layer. This went very smoothly. The results of this pinning process can be seen in Figure 5.34. The handle was very snuggly attached to the rest of the sword, which suggests that the choice in drill bit sizes and planned hole misalignment worked well.

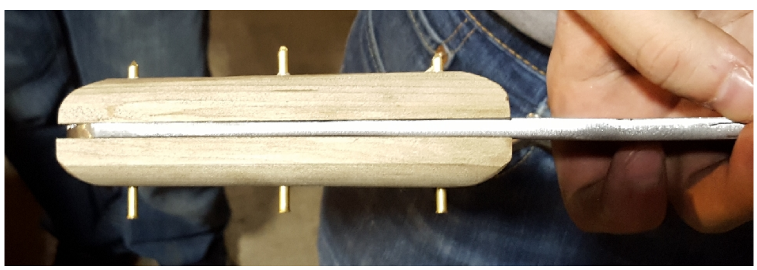


Figure 5.34.: The handle assembled before trimming pins.

After cutting the excess pin material off of each side with a cutting wheel, the team was ready for the final shaping using the belt sanders again. Since the tang was smaller than the wood at all locations, the group used the tang as a guide to sand down the wood to. First the overall silhouette of the wood was matched to that of the metal, and then the rounding and smoothing and more complicated contouring was done using less static methods. Throughout the sanding processes, the team ensured that the same shape was created on each side so that it was symmetrical. No extra care was needed when sanding the ends of the pins. This was the finishing touch on the blade, and the results of these steps on the handle can be seen in Figures 5.35 and 5.36.

Figure 5.35.: The finished handle from above.

Figure 5.36.: The finished handle from below.

5.13. The Final Sword

Upon properly shaping the blade, the sword appeared to have an abundance of valleys and bumps along the surface of the blade. In order to mitigate these deformations, the team continued to grind along the length of the blade. Using the angle grinder, the group swept across the surface back and forth gradually on the sides of the valleys until the blade seemed to appear smooth. After this process was completed, the team realized that the spine of the blade still appeared to have a rough texture, so it was decided to grind the spine of the blade in a similar fashion, revealing a somewhat reflective luster. The spine of the blade still resembled a sharp edge, so after additional filing and grinding, the spine eventually became blunted with a rather small fillet. After further blunting of the tip of the sword with the angle grinder, and rounding of the handle with the sand wheel to suit the final needs, the sword then seemed to depict the ideal finished blade (Figure 5.37).

Figure 5.37.: Final falcata replica, from a few slightly different angles.

5.14. Final Discussions on the Manufacturing of the Replica

The team believes that the replica has many successes when compared with the results to the historical models reviewed. The overall shape is to satisfaction though some of the ancient models did have a larger metallic curve on the front part of the blade edge. The team also replicated the little bit of metal that hangs off the handle guard quite well. The handle is also composed of reasonable material; wood was accessible and an economically viable option for creating sword handles from the period of the sword's origin. The group also believes that the power tools, which were used during the process of creating the sword, is justified as to replicate the results of the process to ideal standards. The team also had a deadline to meet, therefore flattening an entire 1045 bar by hand, forge welding by hand, and using an old grind wheel to achieve the results would have been too time consuming.

Despite the modern technology, there are some areas which could have been done more accurately. The overall shape is good but the blade is not as wide as desired, as it came up between a quarter of an inch and a half of an inch too thin. Based on most models reviewed, and evidence from the Celtic sites themselves, it is determined that most of the handles are made of brass. The team used wood to save time as there were not ways to make a brass cast at the shop readily available. In addition to that, the pins are not accurate either. The team used brass pins and some models used pins as well, but the evidence from the burial sites does not support that. The group also did not follow the lengthy process of burying the steel plates in the ground for two or more years as, again, there was a deadline to meet.

6. Materials Analysis

Materials science is the field of examining a material for its large-scale physical and mechanical properties, its atomic-scale properties, and the interdependence between them. Material analysis is the process of determining those properties, either predictively or experimentally, to understand the effects of different physical processes the material had undergone. This section will first share some background information concerning the regular procedures used to analyze steels, then will apply that information to predict what qualities are expected in the replica falcata, and finally will discuss the experimental results.

6.1. Background on Microstructure

A phase diagram is a way of representing the limits of stability of the various phases in a chemical system. It takes into account things such as the composition and temperature of the system. In metallurgy, a phase refers to a physically homogeneous state of matter, where the phase has a certain chemical composition, and a distinct type of atomic bonding and arrangement of elements. Phase diagrams help understand and predict microstructures depending on the phase transformations of an alloy at equilibrium as one of the parameters of the system is changed. The properties of an alloy not only depend on proportions of the phases, but also their microscopic structural arrangements. Microstructures are specified by the number of phases, their proportions and their arrangement in space. Phase diagrams will be used in this project in order to obtain a greater understanding of the chemical properties of the metals used both before and after worked. The team will take samples of the material all throughout the process of working with the metal and compare the changes in the phase diagram states to the specific process(es) done.

For microstructural analysis a sample must be prepared. This involves cutting a small piece off of the sword and modifying it to be of certain dimensions. The sample piece needs to be able to fit inside of a petri-dish-like tray. Then, phenolic powder is poured into the remaining space in the tray and baked into a solidified compound. The sample, now securely mounted and the sample surface can be polished and etched in order to obtain microstructural images.

6.1.1. Classification of Steels by Carbon Content

Upon alloying, iron with the addition of carbon yields the metastable iron-iron carbide phase diagram represented by Figure 6.1.

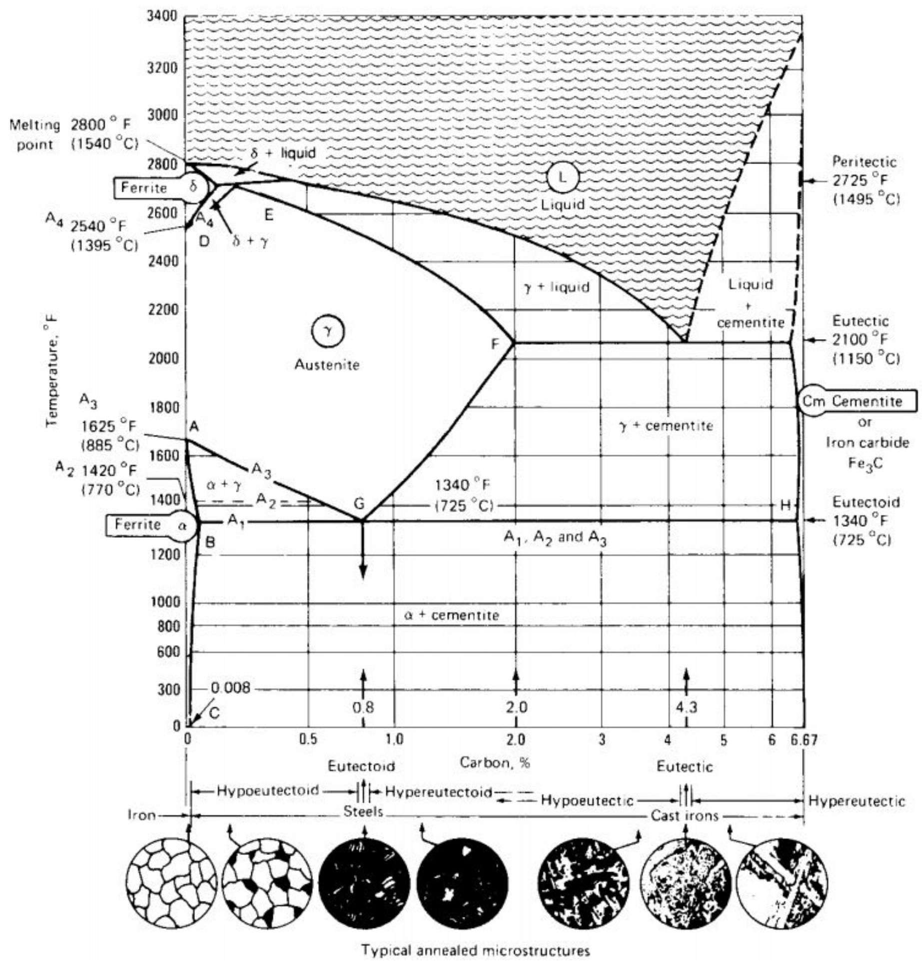


Figure 6.1.: Iron-Cementite phase diagram [4].

It is important to recognize that though there are merely three phases in steels, they may occupy a variety of structures.

Hypoeutectoid steels, with less than approximately 0.80wt% carbon, are indicated by the area bound by AGB in Figure 6.1. Here ferrite and austenite exist together despite their differences in carbon content. For example, assume a 0.40wt% carbon steel is heated slowly until it reaches a uniform temperature of 870°C (1600°F), creating a fully austenitic structure. As it slowly cools, ferrite starts to form from austenite when the temperature breaks line AG, into the AGB, with additional amount of ferrite forming decreases. Typically, with slow cooling condition, ferrite transforms from austenite by the time the temperature of the alloyed steel reaches line BG (A1) at 725°C (1340°F). These austenite islands, remaining at

725°C (1340°F), now contain the same amount of carbon as this eutectoid steel, or within the region 77% and 80%. Below 725°C (1340°F) pearlite forms. Further cooling to room temperature does not affect the microstructure, thus having a microstructure of ferrite grains with pearlite islands [4].

A typical microstructure of a 0.40wt% carbon steel is illustrated in Figure 6.2 (a). The purest white areas are islands of ferrite grains. Grains appearing white, but contain dark platelets are usually lamellar pearlite. These platelets are cementite or carbide interspersed through ferrite, depicted below the BH line in Figure 6.1, conforming to a two-phase structure.

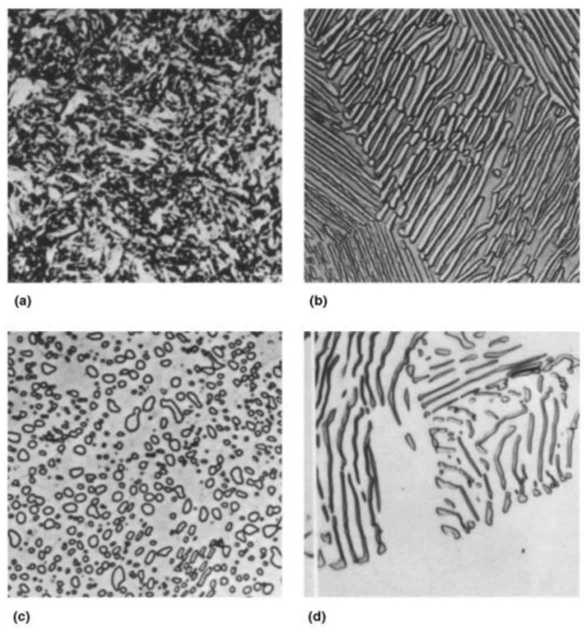


Figure 6.2.: Four different alloy microstructures showing different carbon contents [4].

Eutectoid steels containing about 0.77wt% carbon content become a solid solution at all temperatures between 725 and 1370°C (1340 and 2500°F). All carbon is dissolved in austenite. As the solid solution is slowly cooled several changes occur at the initial temperature 725°C (1340°F). This temperature is known as the transformation or critical temperature of the iron-cementite system. At this critical temperature, carbon steels within the range of 0.77wt% and 0.85wt% transform from a single homogeneous solid solution into two distinct new solid phases. These changes occur through constant temperature and the evolution of heat through time. These new phases are ferrite and cementite, but only occur simultaneously within this range, point G in Figure 6.1.

The microstructure of the typical eutectoid steel is shown in Figure 6.2(b). The white matrix is alpha ferrite, while the dark platelets are cementite. All the grains are pearlite, without the presence of surrounding free ferrite grains. Under specific cooling conditions, particle of cemenitite become spheroidal instead of elongated platelets, illustrated in Figure 6.2(b). Figure 6.2(c) indicates spheroidite, the two-phase structure resulting from slow cooling of a eutectoid steel below A_1. Here, notice the dispersion of cementite particles in alpha ferrite. There are no clear indications of grain boundaries. The spheroidized structure is usually preferred over pearlitic structures due to better machinability and formability.

Steels containing carbon contents of approximately 0.80 to 2.0wt% are referred to as hypereutectoid. Assume a steel containing between 1.0wt% and 2.0wt% has been heated to temperatures greater than those indicated by line GF in Figure 6.1, ensuring a structure containing 100wt% austenite. Upon cooling temperatures below line GF, cementite solubility, or A_{cm}, is reached. Simultaneously cementite begins to form from the austenite, while increasing amounts of cementite form as the temperature decreases. At temperatures below 725°C (1340°F), all remaining austenite transforms into pearlite. No additional changes occur as it eventually cools to room temperature, consisting of just pearlite and cementite. Figure 6.2(d) illustrates a microstructure containing cementite and pearlite [4].

6.1.2. Isothermal Reactions in Steel Alloys

There are three isothermal reactions that are apparent in these alloys. First, is the eutectic reaction, occurring at the eutectic temperature, 1147°C (Liquid $\Rightarrow$ austenite + Fe_3C) [4]. The eutectic point is indicated by a weight composition of 4.30wt% carbon, at this temperature. Throughout this reaction liquid alloy combined with a high carbon content yields austenite with 2.11wt% carbon and Fe_3C of 6.69wt% carbon. As the eutectic point has a 4.30wt% carbon, any alloy with a lesser percentage carbon will have an excess of austenite, which forms as the alloys cools from liquidus to eutectic temperature. In the same manner, an alloy with a greater wt% carbon will result in cementite (Fe_3C).

The second isothermal reaction occurs at 727°C for any alloys within the 0.0022 and 6.70wt% carbon, and the reaction is presented as: (austenite $\Rightarrow$ alpha-iron + Fe_3C). This reaction is similar to the eutectic reaction, but instead the reactant remains a solid opposed to a liquid. The eutectoid composition occurs at 0.76wt% carbon. An alloy with less than 0.76wt% cools from the pure austenite phase to that of the alpha-ferrite and austenite two phase section. This eutectoid reaction leads to alternating layers of alpha-ferrite and cementite, known as pearlite. This can be visualized in the optical microscope using an etching solution. This layered formation can be seen photographically and schematically below.

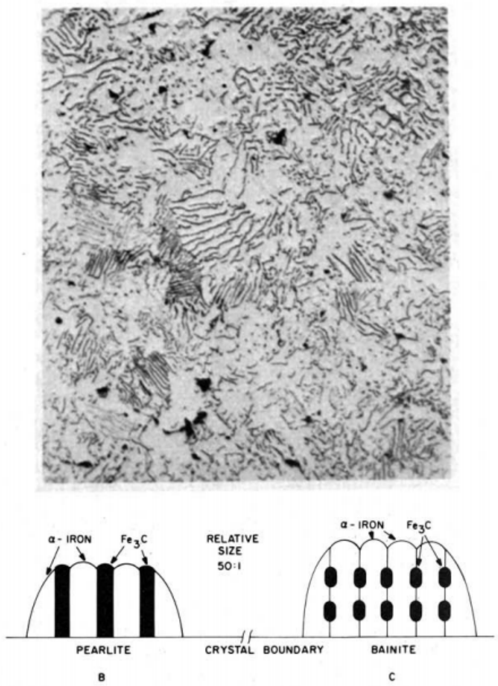


Figure 6.3.: A photomicrograph (500x) steel with 0.60at% carbon and showing in (A) the appearance of pearlite (lamellar structure) and Fe_3C, in (B) a schematic representation of alpha-iron and Fe_3C layers in pearlite, and in (C) the same in bainite [4].

The thickness of these alternating layers can in pearlite is determined by the cooling rate of the allow through the eutectoid temperature. Thus, the faster the cooling rate the thinner the layers. The ratio of these products in pearlite is fixed at 7.91 due to the eutectic composition.

The third isothermal reaction, is the peritectic reaction, which happens at 1493°C between 0.09 and 0.53wt% carbon: (gamma-iron + liquid alloy ⇒ austenite). The peritectic composition is 0.17wt% carbon, and the reaction contains both solid and liquid reactants, yielding a solid product. Alloys below the peritectic composition have excess gamma-iron as the peritectic reaction goes to completion. As gamma-iron is subsequently cooled, it is transformed to austenite. Alloys with a wt% carbon between 0.17 and 0.53 leave excess liquid upon completion of the peritectic reaction, and then solidifies as austenite with additional cooling [4].

The most frequently used groups of alloys are both steel and cast iron. Steel can be used as cast steel or wrought steel. The preferred carbon-content is tailored around the final use of these steels. Cast iron, a high carbon content alloy, is shaped by casting. Rapid cooling of cast iron during solification maintains the carbon in cementite, yielding a hard and brittle alloy known as white cast iron. Slower cooling allows the Fe_3C to decompose into graphite and alpha-iron yielding gray cast iron. Added lubrication properties of graphite might make gray cast iron easy to machine.

Name	Weight Percent Carbon Range	Temperature Range, °C	Crystalline Structure	Description
α-Iron or α-Ferrite	0–0.022	<912°	BCC	Ferromagnetic below 770°C, the Curie point. This temperature is independent of carbon content. (soft, ductile)
Austenite or γ-Iron	0–2.11	727–1495°	FCC	High temperature paramagnetic form of iron. (soft, ductile)
δ-Iron	0–0.09	1394–1538°	BCC	Paramagnetic
Cementite, Fe_3C	6.69	<1227°	Orthorhombic	Intermetallic ferromagnetic compound
Pearlite	0.022–2.11	<727°	BCC and Orthorhombic	Eutectoid mixture of α-iron and cementite resulting from the decomposition of austenite by diffusion (see Fig. 7). (strong, hard, moderately ductile)
Martensite	~0.2–2.11	metastable	Body-Centered Tetragonal	Formed through a shear mechanism by rapid quenching of austenite. (hard, strong, brittle)
Bainite	~0.2–2.11	metastable	BCC and Orthorhombic	A mixture of pearlite and cementite in which the cementite crystals are discontinuous (see Fig. 7). A very fine structure only observed after an isothermal transformation. (hard, strong, ductile)
Steel	~0.022–2.11	—	[a]	Pearlite or a pearlite–α-iron or pearlite-cementite mixture depending on carbon content and cooling rate.
Cast iron	2.11–6.69	—	[a]	A mixture of pearlite and cementite in white cast iron. A mixture of varying amounts of pearlite and α-iron plus graphite in gray cast iron. Similar to pig iron.
Wrought iron	<0.022	<912°	BCC	A mixture of α-iron with small amounts of iron-silicates.

Figure 6.4.: Iron-Cementite Terminology [4].

6.1.3. Heat Treatment of Steel

The above discussion details the properties of iron-carbon alloys under equilibrium conditions. From a practical standpoint, it is rather unlikely that these equilibrium condition will be achieved, except at elevated temperatures. In most cases, these nonequilibirum crystalline structures have desirable properties. For instance if a small piece of steel with 0.8wt% carbon is heated above 727°C, it then becomes austenite, and is then quenched in water, martensite rather than pearlite will be formed. The difference lies in the fact that pearlite is formed by solid state diffusion of carbon from austenite to form Fe_3C. Rapid quenching actually prevents this diffusion from occurring and instead yields a metastable mertensite. This austenite transformation to martensite does not depend on diffusion but on a shear mechanism. Within this shear mechanism, neighboring atoms are displaced relative to each other and form a body-centered tetragonal crytalline structure.

Naturally steels that are prepared for heat treatment are between 0.25 and 1.5wt% carbon. Below 0.25wt% carbon, the cooling rate required to obtain martensite is extremely high and rather difficult to reach. The resulting property improvement due to this alternative is negligible also. Steels containing more than 1.5wt% carbon show no property improvement when heat treated. Within the optimal range, 0.25 – 1.5wt% carbon, heat treatment is the most important factor to consider when attempting to improve their mechanical properties.

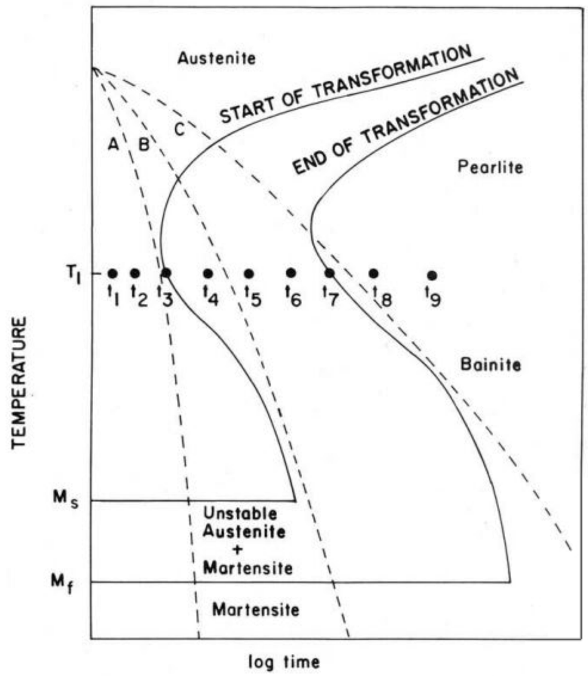


Figure 6.5.: The time-temperature-transformation diagram for austenite of a fixed composition [4].

A very useful method for studying the austenite transformation in regard to cooling is to use the time-temperature transformation diagram represented by Figure 6.5.

The results acquired from using this diagram are obtained by initially heating thin specimens of steel of a particular composition until they reach equilibrium in the austenite temperature range. These specimens are then quenched at an intermediate temperature, like T_1, in a molten salt-bath for various periods of time. These time intervals are represented by t_1, t_2, t_3, $\ldots t_n$ at temperature T_1 in Figure 6.5.

After these times the specimen is brought to room temperature. For specimens held at T_1 for less than t_3, not enough time has elapsed to promote pearlite formation. Times between t_3 and t_7 contain increasing amounts of pearlite. Any specimen held at temperature T_1 for t_7 or longer is completely transformed into pearlite. This process can be repeated for varying temperature, either greater or lesser than that of T_1. Both curves on the figure indicate the start and end of transformation for austenite to totally pearlite. Lower temperatures will produce fine pearlite structure, while higher temperatures will show a coarse structure. At still lower temperature bainite if formed with a finer grain structure. If any thin specimen of austenite is cooled from its temperature region along path A (Figure 6.5), it will start to transform to martensite at temperature M_s. Martensite is a metastable phase, with a body-centered tetragonal structure and is supersaturated with carbon. Cooling to the temperature M_f will result in a completely irreversible transformation. Any samples cooled between temperatures M_s and M_f have varying amounts of martensite. The overall amount of martensite formed increases with decreasing temperature [4].

To this point the discussion has been based around the assumption that these small thin specimens with small amounts of heat and have large surface to volume ratios are getting heat treated. Quenching a thicker piece of steel by water will result in rapid cooling with slow cooling toward the center of the piece. The curved line labeled A in Figure 6.5 is the cooling rate upon the surface of the piece. Accordingly, the curves labeled B and C represent cooling rates from increasing distances from the surface of the metal. If the cooling rate is fast enough, as in a small specimen, enough to avoid the very "nose" of the curve, then martensite will begin to form. If the cooling rate is slow enough, as in at greater depths or larger sample specimen, the sample will contain a mixture of both pearlite and martensite. If the cooling rate is so slow (line C) that the crosses the second (end of the transformation) curve, then pearlite will be the only phase to appear. In accordance, many pieces of steel only contain martensite on the surface and a mixture containing pearlite and martensite at increasing depths. Large pieces could contain pearlite only in the center. In order to encourage greater martensite at greater depths from the surface, the quenching rate must be increased or alloying elements, such as chromium, nickel, silicon, molybdenum, vanadium, or manganese, must be added to the steel. These additional alloying elements cause a shift of the transformation curve in Figure 6.5 to longer time spans, and allow for slower cooling rates.

Martensite is a stronger material, but it has low ductility (brittle). However, with subsequent reheating to intermediate temperatures, such as tempering, which decreases the hardness and strength, but increases its ductility. The decision of time and temperature of tempering depends on the final material properties of the steel. Tempering is the kinetic process that depends on both time and temperature. Initially, the first stage comes about when the tetragonal lattice of the martensite crystal transforms into a cubic lattice (see Figure 6.5). Then, Fe_3C starts to form as the carbon precipitates from this supersaturated lattice. With increasing tempering time and temperature, the size of Fe_3C particles increase, whilst the number of particles decreases [4]. This decrease in strength and hardness gives way to an increase in ductility. The tempering is often done to quench pieces to increase ductility.

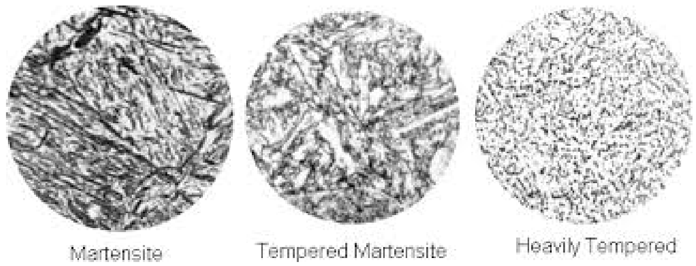


Figure 6.6.: Stages of Martensite tempering [23].

6.1.4. The Effects of Varying Cooling Rates

Most dramatic effects of cooling rates on the microstructure of steel alloys occurs at high cooling rates produced by rapid solidification processing and high density welding. Inherent difference in cooling rate for varying solidification processes are detailed in Figure 6.7 and are shown to cover nine orders of magnitude.

Process	Cooling Rate (K/s)
Directional solidification	10^{-1} to 10^{1}
Casting	10^{0} to 10^{2}
Arc welding	10^{1} to 10^{3}
EB welding	10^{2} to 10^{4}
LB welding	10^{2} to 10^{6}
Rapid solidification processing	10^{3} to 10^{7}
EB or LB surface modification	10^{5} to 10^{7}
Single laser pulse	10^{7} to 10^{8}

Figure 6.7.: Estimated cooling rate ranges for various solidification processes [14].

Lowest cooling rates (10^{-1} to 10^{1} K/s) occur under directional solidification or in large ingots. Minor changes in microstructure occur with variations in the cooling rate within this region. Cooling-rate variations over the range of 2-40 K/s will result in changed in the ferrite content from 13wt% to 16wt% while primary austenite-solidified compositions will decrease from 1.5wt% to 1.0wt%. Cooling rate increase in the range of 10 to 10^{3} favors the primary formation of ferrite.

Relatively moderate cooling rates (10 to 10^{3} K/s), produced during arc welds, showcase only small variations in the microstructure as the cooling rate is increased. Gradual decreases in ferrite content are apparent as weld travel speed increases, and increases in travel speed (in turn, increasing the cooling rate) favors the primary formation of austenite for dendritic solidification. Stainless steel welds and castings have the ability to modify the amount of ferrite in regard to microstructure, but this effect is only a minor consideration.

High cooling rates which occur in electron and laser beam welds have a significant impact on microstructure. Welding processes low cooling rates are reported to contain 10wt% of ferrite, while high cooling rate welding processes give a ferrite content of less than 1wt%. Reasons may include changes in the primary solidification mode from ferrite to austenite [4].

6.2. The Predictions for Resulting Microstructures in the Falcata

Since the team is working with separate regions of metal with 0.45wt% and 0.18wt% carbon content, these are the two scenarios that must be considered. The team plans to cool them from about 1000°C down to room temperature very slowly since there was no historical findings of quenching, so there will not be any rapid cooling. This leaves the group with very simple lever rule calculations. The two lines that will be traced as the temperature decreases are shown in Figure 6.8 as the blue vertical lines A and B. Line A corresponds to the 0.18wt% carbon metal, and the line B corresponds to the 0.45wt% carbon metal.

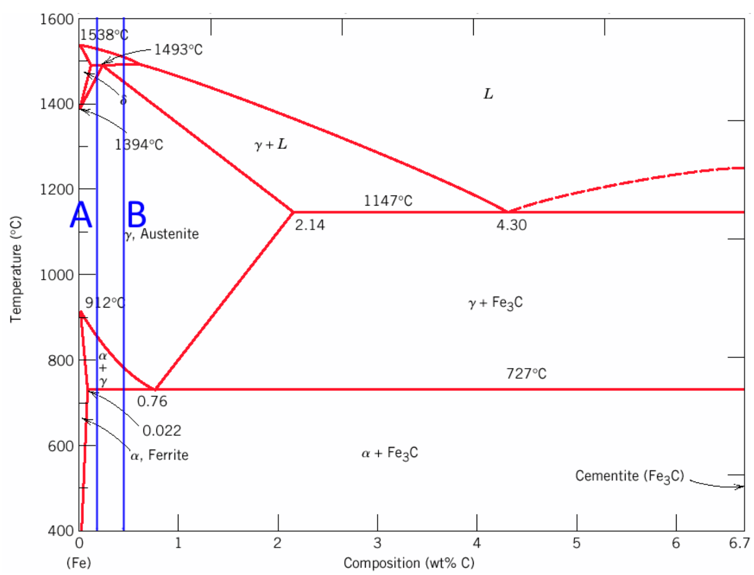


Figure 6.8.: The Fe-C phase diagram with blue lines A at 0.18wt% and B at 0.45wt% [9].

Since both are starting from 1000°C, they are both starting in the gamma phase (austenite), and there are no other forms of iron/carbon mixed in. Following the blue vertical lines down, it is found that the 1018 metal will reach its first phase transition at around 850°C, and the 1045 metal will reach its first phase transition at around 770°C. Since both of these transitions are from gamma to gamma + alpha, they can be handled at the same time, since they will follow the same sorts of procedures. As the two metals pass through this phase transition, some of the gamma begins transforming into alpha, initiating at the boundaries of gamma grains, since that is where the chemical structure is most vulnerable to change.

Employing the lever rule leads to the following relative concentrations of the different phases of the Fe-C solid solution, after the first phase transition that occurs. This specific transition only creates proeutectoid alpha, meaning there are only two different components at this point. The two end points to be used for the lever rule here are 0.022wt% carbon and 0.76wt% carbon (the eutectoid point).

1018 metal:

$$ProeutectoidAlpha\% = (0.76 - 0.18)/(0.76 - 0.022) = 79wt\%$$

$$Gamma\% = (0.18 - 0.022)/(0.76 - 0.022) = 21wt\%$$

1045 metal:

$$ProeutectoidAlpha\% = (0.76 - 0.45)/(0.76 - 0.022) = 42wt\%$$

$$Gamma\% = (0.45 - 0.022)/(0.76 - 0.022) = 58wt\%$$

The second phase transition each metal arrives at is passing below the eutectoid temperature, 723°C. Below this transition, the proeutectoid alpha changes by a negligible amount and for the group's purposes is assumed to remain constant. While more alpha will be formed after this transition, the grain structure will be significantly different, so they can be treated as separate compounds. Since the proeutectoid alpha is remaining unchanged, this amount of alpha will be removed from the total amount of alpha calculated by the lever rule just below 723°C. The gamma region will transform into a lamellar grouping of eutectoid alpha and cementite—the relative proportions of each is again dictated by the lever rule. The two end points to be used for the lever rule here are the 0.022wt% carbon again, and the 6.7wt% carbon, which is the point at which pure cementite forms.

1018 metal:

$$Alpha\% = (6.7 - .18)/(6.7 - 0.022) = 98wt\%$$

$$Cementite\% = (0.18 - 0.022)/(6.7 - 0.022) = 2wt\%$$

1045 metal:

$$EutectoidAlpha\% = (6.7 - .45)/(6.7 - 0.022) = 94wt\%$$

$$Cementite\% = (0.45 - 0.022)/(6.7 - 0.022) = 6wt\%$$

Since this is the last transition the metal will see on its path to room temperature, and the lever rule will have the relative proportions remain almost exactly the same, these numbers are the final percentages. The final proportion of alpha may be broken up into the components that were formed before the eutectoid point, and the material that was formed after. In order to do this, the total alpha should be subtracted by the proeutectoid alpha proportion (79wt% and 42wt% for 1018 and 1045, respectively).

1018 metal:

$$EutectoidAlpha\% = .98 - .79 = 19wt\%$$

1045 metal:

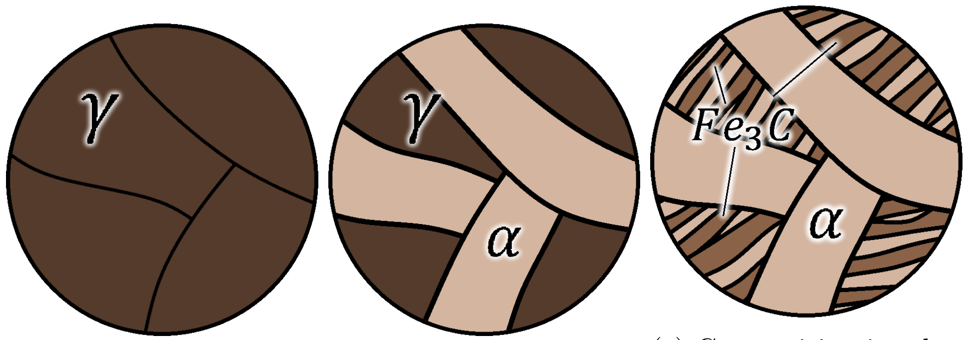
$$EutectoidAlpha\% = .94 - .42 = 52wt\%$$

Refer to Table 6.1 for a summary of these final results. Within this table, the total amount of alpha is only represented as the sum of the proeutectoid alpha and the eutectoid alpha proportions, but is not represented in total. The reason for separating them is that each type of alpha will have formed in different patterns, may be uniquely distinguished in microstructure images.

Table 6.1.: Proportion predictions for the different phases expected.

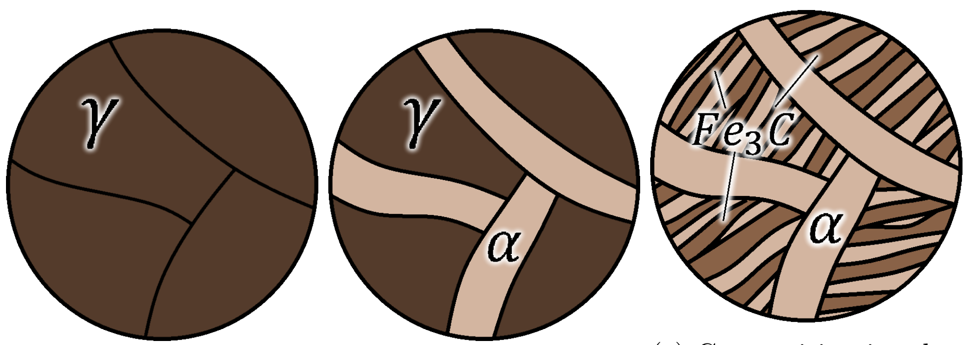
Component:	1018 metal	1045 metal
Proeutectoid Alpha	79wt%	42wt%
Eutectoid Alpha	19wt%	52wt%
Cementite	2wt%	6wt%

Another interesting feature possible to predict is the microstructure of the different metals at different points along the path of gradually changing temperature. Following the same steps as described above, and taking into account the proportion of each phase present, one can produce graphical representations of what these metals would look like under a microscope. The team will eventually compare the final state of this microstructure to the observed results. These graphical predictions are presented in Figures 6.9 and 6.10. As previously described, these take the process of forming proeutectoid alpha around the boundaries of the gamma when inside the alpha + gamma region of the phase diagram, and then transforming the remaining gamma into eutectoid alpha and cementite in a lamellar (layered, striped) pattern below the eutectoid temperature.



(a) Starting composition at 1000°C.
(b) Composition just below 850°C.
(c) Composition just below 723°C (final predictions).

Figure 6.9.: Predicted microstructures at various points for slow cooling of 1018 metal.



(a) Starting composition at 1000°C.
(b) Composition just below 770°C.
(c) Composition just below 723°C (final predictions).

Figure 6.10.: Predicted microstructures at various points for slow cooling of 1045 metal.

Importantly, since the temperatures at which the stock metal was worked and the time conditions under which they cooled are likely very similar to the metal will be worked, there is no expectation of any significant difference between the proportion of components in the final samples and the initial samples. The major change expected is a significant stretching of the microstructure, specifically the most stretching along the length of the sword, a slightly lesser degree of stretching along the width of the sword, and a slight degree of compression along the last dimension.

6.3. Preparing Samples for Microsturctural Analysis

In order to analyze the phase diagrams of the metals, the team needed to cut off three samples from each type of metal in a cube-shape. Since there was 1018 and 1045 steel, the group cut off six in total, and each sample would be oriented in a different plane. Therefore, there are x-y, y-z, and x-z plane oriented samples for both types of steel. The team then had to take the cubes and follow a process with multiple steps in order to analyze the phase diagrams. The axes used throughout the later analyses are: x-axis is along the full length of the sword; the y-axis is along the face of the blade perpendicular to the x-axis; and the z-axis is perpendicular to both x- and y-axes and is oriented as a line from one face of the blade to the face on the opposite side (through the sword).

6.3.1. Mounting the Samples

Figure 6.11 shows the machine that facilitated the mounting process. The important first step to mounting the samples with this machine was to open the water valve in the cabinet below the machine which allows the machine to cool the sample after it is done, since the machine brings the temperature of the sample up to at least 300 degrees Fahrenheit.

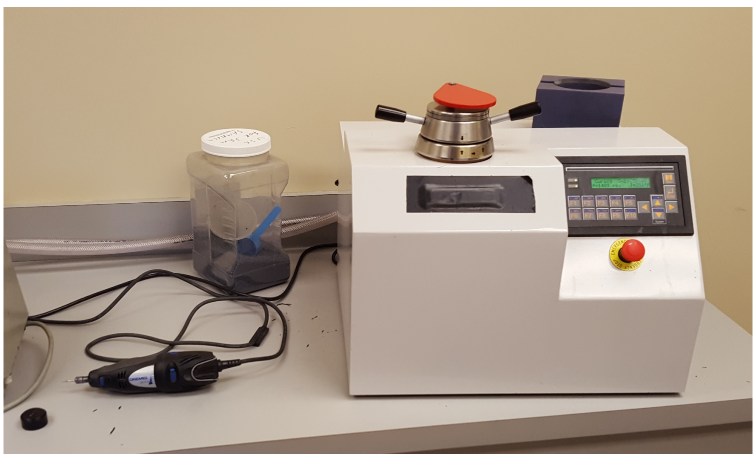


Figure 6.11.: The machine used to mount the steel samples.

Once the water is turned on and the machine is plugged in, the red cap on the top of the machine must be rotated and the silver cap with the two arms on it must also be rotated to an unlocked position, indicated by the arrows on the machine, and then removed from the machine. The operator can then press the up arrow key on the machine control panel to bring the plate in the cylindrical tube up to the top of the machine. The face of the metal sample which is to be analyzed must be put face down on the circular tray in the machine so that the when the powder solidifies, the face is still exposed. Figure 6.12 shows the proper positioning for a sample to be mounted in this particular machine.

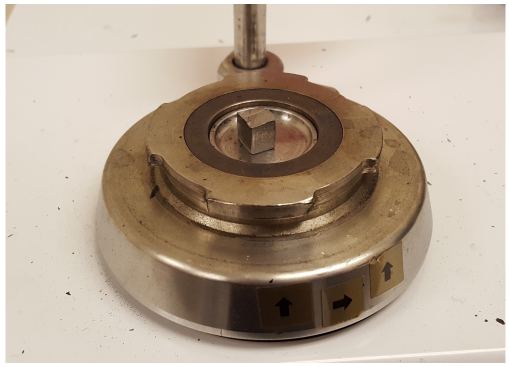


Figure 6.12.: The tray used to mount samples, as well as the proper positioning for a sample.

The face one wishes to analyze must be face down on the tray. Once the sample is placed, one can use the arrow key controls on the machine to lower the sample in the column. Figure 6.13 shows the material used for the mounting, as well as roughly how much one needs for this particular machine. About one scoop of the material with the device is needed to surround the metal sample. The proper way to deliver the material uniformly down the column is to use a funnel as seen in figure 6.13. This ensures that no powder spills.

Figure 6.13.: Amount of material needed for mounting the metal sample, as well as proper delivery techniques.

Figure 6.14.: The sample as it leaves the mounting press.

The entire process takes about 15 minutes per sample, as the machine can only process one metal sample at any given time. Once the powder is funneled into the column, the silver cap can be placed by aligning the arrows on the cap and the machine and rotating the cap left to line up with the other arrow, indicating that it is locked. The red cap is swung over the cap in order to provide an extra safety precaution in case the cap blows off if not properly fixed. Then, according to the steps, the team pressed function one on the machine, which set the pressure and temperature to a standard amount, and then ran the machine. Figure 6.14 shows the sample after the machine has run its course.

Figure 6.15.: Process used to mark/scribe the samples post-mounting.

Figure 6.15 shows the process used to identify the samples after they are mounted. Once the samples cooled, the team used the hand drill to scratch in the type of steel as well as the orientation of the face that observable. This was a strategy used so that the team could tell the samples apart for actual analysis.

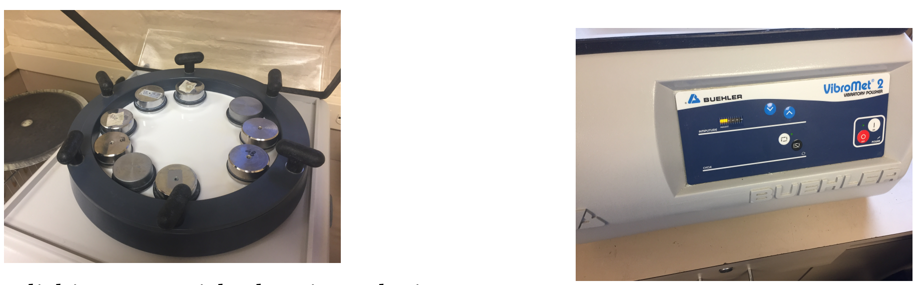
6.3.2. Grinding and Polishing Steel Samples

Microscopic imaging of the phases can only be seen after proper grinding and polishing processes have been completed. Initially, the Buehler EcoMet 300 Pro Grinder-Polisher is setup with magnetic grinding coarse paper, while the mounted orientations of the 1018 and 1045 steel are assembled in the mounting rack after lowering the rotating rack coincidental with the grinding paper. After this is complete the settings of the grinder must be set to display a singular force type with 15 Newtons of force; head speed 30 rpm and platen speed 150 rpm; smart dispenser off and water on (in order to serve as an appropriate lubricant given the surface's high coefficient of friction). To ensure the samples are properly ground, use cycles of three minutes to accurately gauge the surface of the sample, and mitigate over-grinding. Once samples project a smooth reflective surface, the molds are now prepared for proper polishing. Figure 6.16 displays this preparation.

Figure 6.16.: Grinding method using Buehler EcoMet 300 Pro Grinder-Polisher.

6.3.3. Overnight Polishing

After grinding away at the surface of the metal sample and doing some preliminary polishing, the team put the samples in a vibratory polisher overnight, ideally the night before the etching and microstructure analysis. The team was instructed to place the samples in these metal discs while placing the sample face down on a tool that kept the sample flat. Then tighten a small screw on the side of the metal disc that locked the sample in place so it could be placed in the vibratory polisher and receive uniform polishing on the metallic surface. Once the samples were locked in, the chemical compound, the white liquid in Figure 6.17(a), could be added to the polisher and then could close the clear lid and turn on the machine.



(a) The polishing tray with abrasive solution and samples.

(b) The control panel.

Figure 6.17.: The Buehler Vibromet 2 Vibratory Polisher.

The control panel for the polisher in Figure 6.17(a) is shown in Figure 6.17(b); the settings were recommended by a lab technician. He recommended to put the amplitude of the machine at 35-40% for the samples. The higher the amplitude, the more the polisher vibrates. The other commands were just to select the path of the vibration, change the amplitude of the vibration, and to turn the machine on. Ideally, after the steel samples go through a pass in this machine, the result leaves a polished sample ready to be etched.

6.3.4. Optical Microscopy

After the samples were correctly polished and etched, it was then time to bring them to the digital microscope to view the results. This microscope used a camera that connected directly to a computer, which allowed the team to view and edit the images quickly and efficiently. There were five different magnifications available on this microscope. The team chose just the 10x and 20x magnifications to capture all the information desired to document, as well as the 5x once. Each sample had a picture taken at 10x and 20x. The last two samples, after forge-welding, each had four pictures taken of them. 10x and 20x of a 1018 layer as well as 10x and 20x of the middle 1045 layer. One also had a fifth picture taken at 5x to show the boundary line transition between layers. These scales give a great view of the microstructure of the samples.

6.4. Microstructural Analysis Results

Section 6.3 highlighted the process of obtaining the pictures of the micro-structures using mounting, grinding, polishing, etching, and microscopic analysis. The team obtained the pictures and can then analyze the phases present in the microstructures. Before presenting or comparing the microstructural results, the group will present information gathered separately about the element-wise composition of each metal, which turned out to have rather interesting and unexpected results.

6.4.1. Chemical Composition of Metals

After having seen some odd features of the microstructures, it was decided that the team would do a different sort of measurement to confirm whether the assumptions about the metals' compositions were correct in the first place. Separate large samples were prepared for these tests, which made use of an electric spark test to derive information about compositions of the metal on a per-element basis. Tables 6.2 and 6.3 display the results of those tests for the 1045 bar and the 1018 bars, respectively.

Table 6.2.: The measured proportion of select elements of the 1045 alloy (wt%)

%C	%Si	%Mn	%P	%S	%Cr	%Ni	%Mo
0.209	0.192	0.81	<0.0005	0.0065	0.132	0.050	0.014
%Al	%Cu	%Co	%Ti	%Nb	%V	%W	%Pb
0.027	0.104	0.0064	<0.0005	<0.0040	0.003	0.009	0.017
%Mg	%B	%Sb	%Sn	%Zn	%As	%Bi	%Ta
<0.0005	0.0005	0.018	0.0080	0.0041	0.013	<0.0015	0.036
%Ca	%Ce	%Zr	%La	%Se	%N	%Fe	
0.0014	<0.0020	0.0017	<0.0005	0.014	0.0041	98.3	

Table 6.3.: The measured proportion of select elements of the 1018 alloy (wt%)

%C	%Si	%Mn	%P	%S	%Cr	%Ni	%Mo
0.152	0.188	0.66	<0.0005	0.0055	0.111	0.067	0.016
%Al	%Cu	%Co	%Ti	%Nb	%V	%W	%Pb
0.015	0.201	0.0071	<0.0005	<0.0040	0.0022	0.009	0.017
%Mg	%B	%Sb	%Sn	%Zn	%As	%Bi	%Ta
<0.0005	0.0004	0.018	0.015	0.0043	0.012	<0.0015	0.027
%Ca	%Ce	%Zr	%La	%Se	%N	%Fe	
0.0007	<0.0020	<0.0015	<0.0005	0.0123	0.0059	98.5	

Most of the values can be compared to those shared by the metals' producer upon purchase (Table 5.1) agree well with the ranges they provided. However, critically, there is one significant difference—the 1045 metal, which technically should have a carbon content of 0.45wt%, has well under half that, as shown in Table 6.2, being 0.21wt% carbon. Due to the fact that the main consideration in steel is its carbon content which, while very small compared to the amount of iron, still has drastic effects on the metal's properties. The carbon content of the 1018 metal, 0.15wt% was closer to the desired value of 0.18wt%, and was within the carbon range provided by the supplier.

The 1018 metal's predictions would roughly be the same as stated earlier, only needing a minor adjustment in the proportions of ferrite and cementite, but the overall structure would remain the same. The adjustment needed for the 1045 metal would be slightly more drastic, but still not especially so. The predictions for the 1045 metal would become very similar to what the 1018 was originally predicted to be. Overall, these two metals should be quite similar to each other, and should roughly follow the microstructural and technical predictions shown in Section 6.2.

6.4.2. Microstructure Images

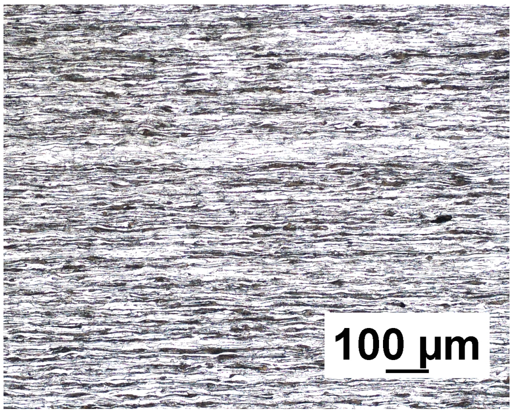
The microstructures for both metals (1018 and 1045)—before and after the forging processes—will be presented and discussed. This section presents a collection of optical images revealing the phases present, captured using the digital microscope, which serve as samples of the microstructures present in each of the metals before and after the manufacture of the sword.

The first set of microstructures correspond to the 1018 and are taken from the original samples before any processing. At this point, according to the supplier, this metal was cold drawn in order to create its shape. These images can be seen in Figures 6.18(a-f). Two levels of magnification are shown for each of three orientations observed (the X-Y, X-Z, and Y-Z cross-sections).

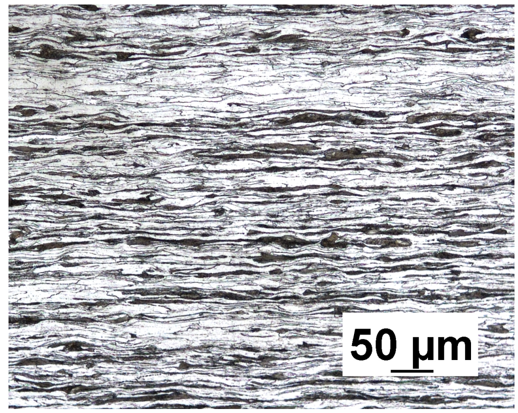
The most easily observed details in Figures 6.18(a-f) are the patterns of anisotropy. The directionality of the microstructure can be explained by the process this metal underwent. Since the cold drawing process was the main process that created the shape of the 1018 bar, it was the cause for the elongation and compressing that happened differently along each dimension of the bar. Due to the shape of the bar (which was very thin along the z-axis, moderately thin along the y-axis, and long along the x-axis) it makes sense that the most visually apparent elongation occurs in the Figure 6.18(a) along a cross section of the bar along which the most deformation would have taken place. The other two dimensions show lesser directionality, but are still consistent with resultant shape of the bar.

Additionally, Figures 6.18(b,d,f) visually display information about the proportions of the different phases present in the 1018 metal before undergoing the forging procedures. If the more common color—white—is interpreted as the phase expected to be more common for this metal—the ferrite (thus making the dark phase represent the cementite)—then the proportions of ferrite and cementite predicted for this metal are as expected. However, aside from the directionality largely caused by the elongation and compression during cold drawing, the predicted structure of ferrite and cementite is not especially apparent. This could suggest a more complex set of processes that the metal underwent before being acquired for this project, such as rapid cooling before the cold drawing, or some other heating pattern not mentioned by the producer.

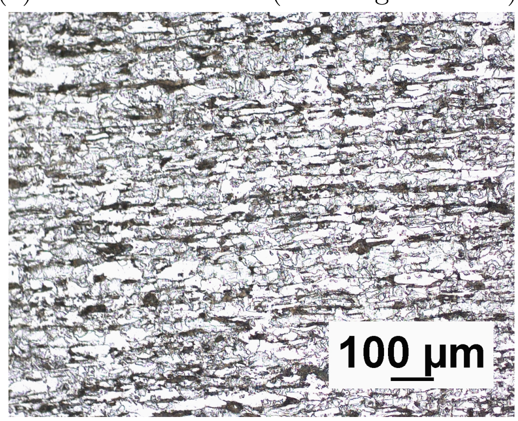
Next are the microstructures for the 1018 metal after it had undergone the manufacturing steps described in Chapter 5. As far as the microstructure should be concerned, those manufacturing steps involved the lamination and forge-welding, and then the stretching procedures used to actually create the overall shape of the sword. More importantly, the heating and cooling processes experienced by the metal was made as uniform and slow as possible. The most rapid cooling the metal would have experienced would be being hit with the hammer, which still was negligibly slow compared to cooling rates discussed in Section 6.1.4. In summary, the only major treatments the sword underwent were being heated and cooled slowly, which should make the assumptions made in the microstructural predictions valid.



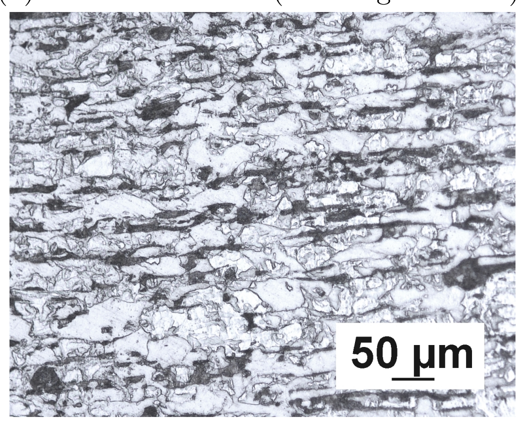
(a) Y-Z cross section (10x magnification).



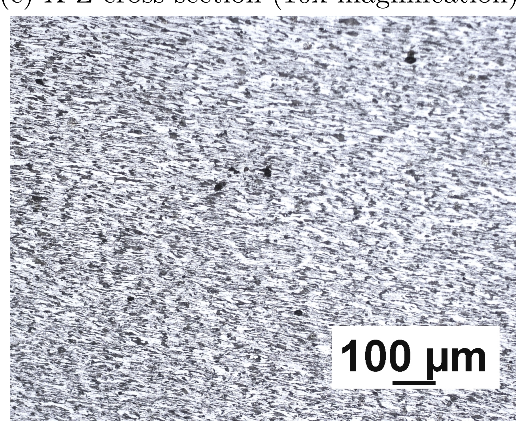
(b) Y-Z cross section (20x magnification).



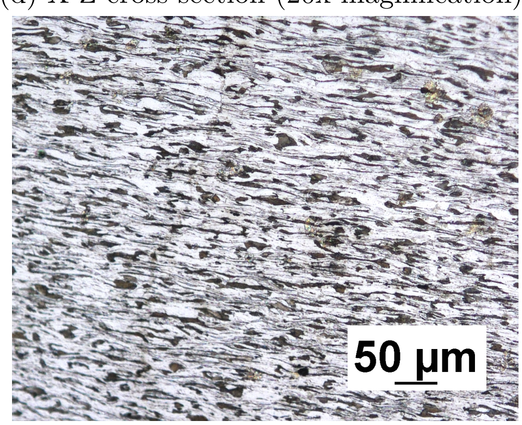
(c) X-Z cross section (10x magnification).



(d) X-Z cross section (20x magnification).



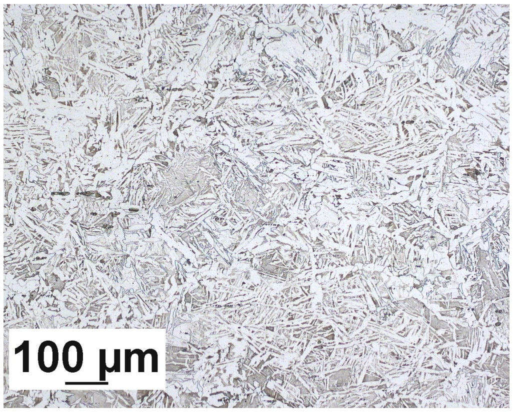
(e) X-Y cross section (10x magnification).



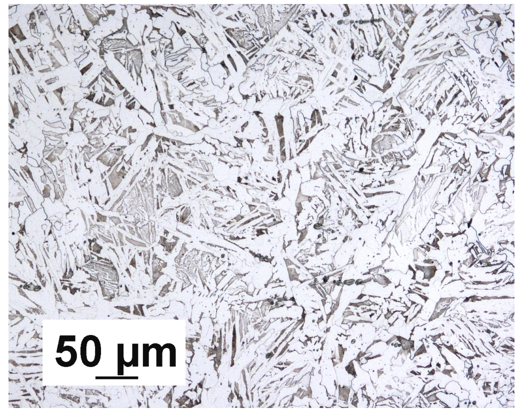
(f) X-Y cross section (20x magnification).

Figure 6.18.: The microstructures observed for the 1018 metal before forging.

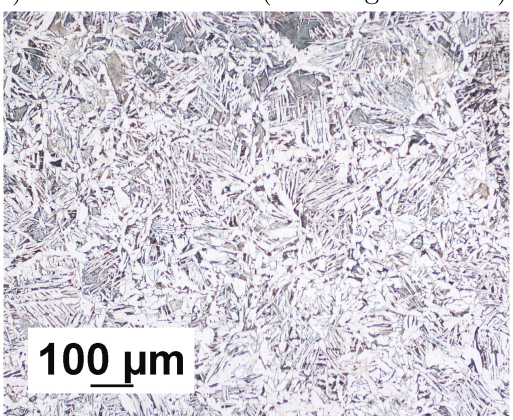
Since after the whole forging process the 1018 metal was laminated with the 1045 metal, the team had no feasible way to sample along all three dimensions, so the group settled on two dimensions instead. Microstructures of the 1018 metal along these two dimensions, and two levels of magnification corresponding to each, are shown in Figures 6.19(a-d).



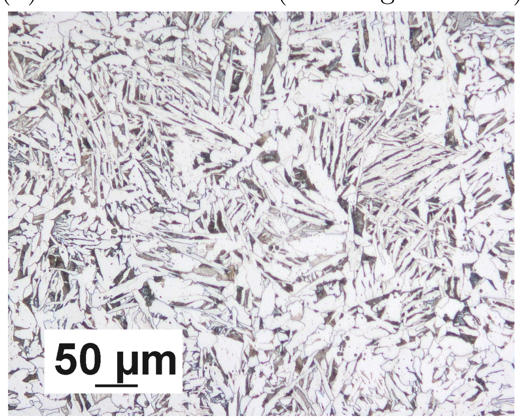
(a) X-Z cross section (10x magnification).



(b) X-Z cross section (20x magnification).



(c) Y-Z cross section (10x magnification).



(d) Y-Z cross section (20x magnification).

Figure 6.19.: The microstructures observed for the 1018 metal after forging.

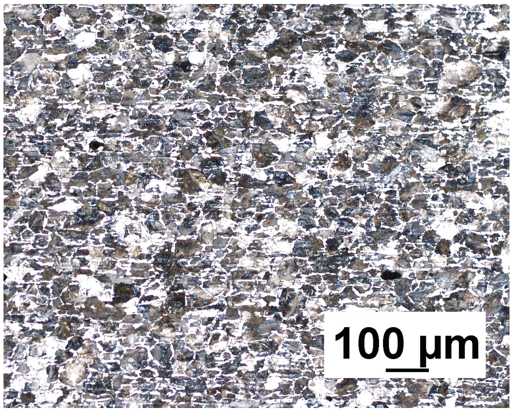
The images shown in Figures 6.19(a-d) are in closer agreement with the microstructural predictions and the present patterns. Assuming the same color correspondence mentioned earlier where white is ferrite and the darker regions are cementite, the predicted microstructure in Section 6.2 for the 1018 metal is seen. Figures 6.19(b,d) quite clearly show larger domains of white color, and in between those large patches, there are color patterns indicative of laminar structure of ferrite and cementite. Additionally, the overall more-white pattern agrees with the prediction that there would be a larger proportion of ferrite in the metal. The large ferritic patches and smaller lamellar patches of ferrite and cementite are reasonable results considering the assumptions made about negligible cooling effects.

However, there is a detail of these images that suggest a phenomenon had been overlooked when generating the predictions. Unlike the images in Figure 6.18, Figures 6.19(a-d) do not display any significant or obvious overall distortion which would correspond to the stretching or compression of the metal. While compression was predicted to create directionality in the microstructure, this was not observed. Having observed this fact, it seems clear this would result from the metal being heated up and cooled down slowly and frequently. The microstructures after forging correspond with the original predictions—the pre-processed microstructures were transformed into ferrite and cementite, resulting from this slow cooling .

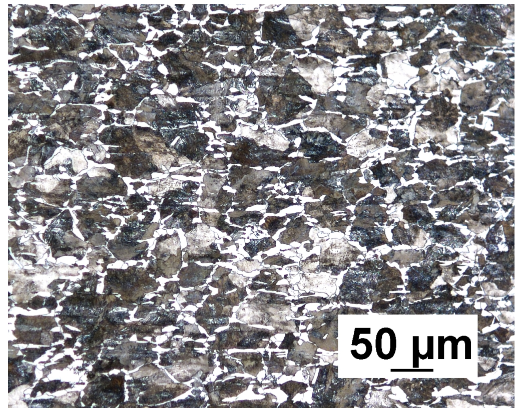
Next are the microscope results of for the microstructure of the 1045 metal. This metal was stated to have undergone the same cold drawing process as the 1018, although the dimensions of its bar are different, so the forces and stresses could have a slightly different effect on the microstructure. The 1045 microstructures are shown in Figures 6.20(a-f), using the same three dimensions and same two magnification levels used in Figure 6.18.

In Figures 6.20(a,c) a minor anisotropy is visible on two directions that experience stretching. The face shown in Figure 6.20(e) shows little to no directional striation and appears largely isotropic. These observations agree with the shape of the 1045 bar created by the cold drawing, considering it was a long, square bar, and along the first two mentioned dimensions there would be stretching visible in equal magnitudes, and along the third mentioned dimension (a cross section of the square part of the bar) would see no stretching along a single direction, as it would be uniformly scaled along that face to its new smaller square size. The striations in Figure 6.20(c) appear to be along an oblique angle, but it is likely that the sample was sitting on the microscope in an orientation where the axes of the metal misaligned slightly from the microscope. Other than this detail, the overall shape and large-scale patterns agree with the physical processes the team had expected the bar to have undergone.

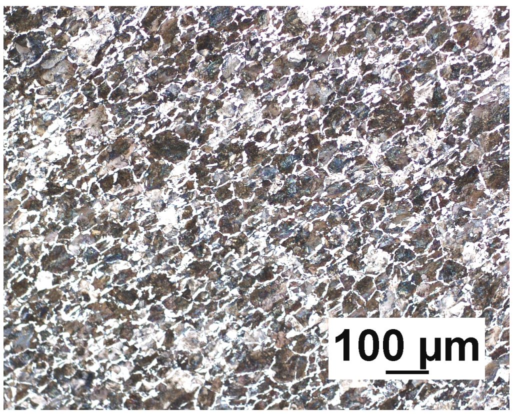
While the large-scale stretching is in good agreement, there are other details that are different from the predicted structures. The close up images shown in Figures 6.20(b,d,f) are different from the predictions corresponding to the assumption of slow cooling with the steel having 0.21wt% carbon. The fact that there are such large dark areas surrounded by white phases decorating the boundary, indicates a high proportion of pearlite, which would agree better with the microstructure of a hypereutectoid steel, instead of a hypoeutectoid one.



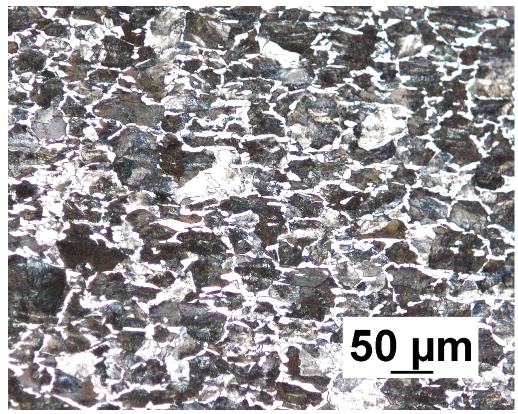
(a) Y-Z cross section (10x magnification).



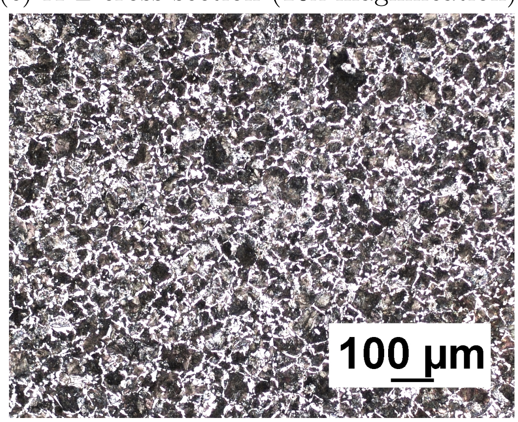
(b) Y-Z cross section (20x magnification).



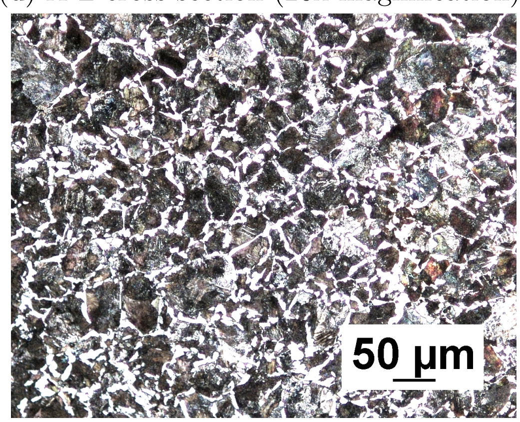
(c) X-Z cross section (10x magnification).



(d) X-Z cross section (20x magnification).



(e) X-Y cross section (10x magnification).

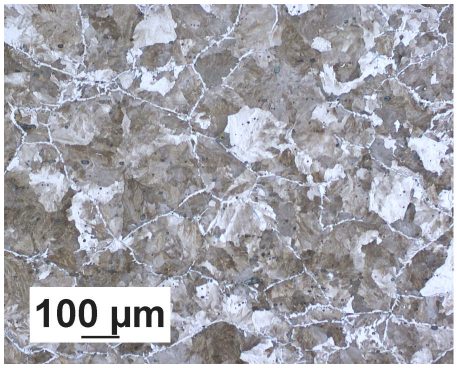


(f) X-Y cross section (20x magnification).

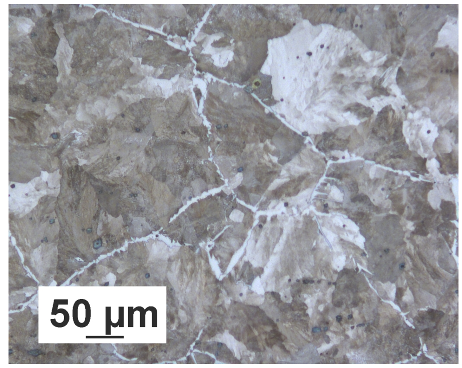
Figure 6.20.: The microstructures observed for the 1045 metal before forging.

Moving onto the last of the main microstructure images, this section will present and discuss the microscope results for the 1045 metal after manufacturing. These manufacturing steps were the same as the 1018 metal, since for most of the processes they were bonded together. The only other detail of the procedure that differs for the 1045 metal is that it was stretched out and flattened a bit before the forge welding. These post-process views of the

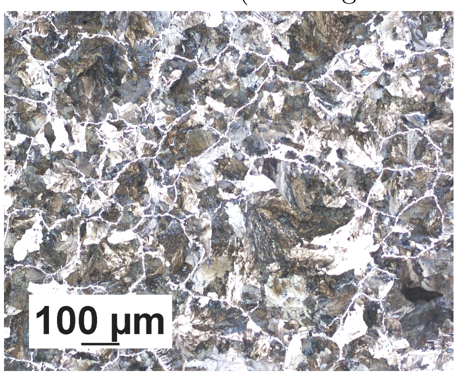
1045 metal's microstructures can be seen in Figures 6.21(a-d). These images are organized the same as those in Figure 6.19, with all the phases viewed at the same magnification.



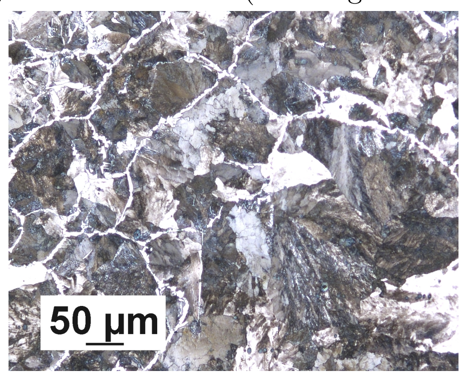
(a) X-Z cross section (10x magnification).



(b) X-Z cross section (20x magnification).



(c) Y-Z cross section (10x magnification).



(d) Y-Z cross section (20x magnification).

Figure 6.21.: The microstructures observed for the 1045 metal after forging.

The first thing that becomes apparent after comparing these images to the other microstructure images is that the phase domains here are significantly larger by a factor of 5 as compared to the initial 1045 metal images. Due to the large grain sizes, it is very difficult to discern whether there exists any anisotropy or visible stretching along a given direction, so no observations or conclusions can be drawn from that (although the 1018 metal's anisotropy displayed in Figure 6.19 would suggest there would be no directionality here either). Despite this drastic change in characteristic scale—which can be explained by the gentle heating and cooling processes—the structure appears to essentially be the same as it was, with large dark domains of pearlite surrounded by white regions of ferrite.

The overall structure displayed in Figure 6.21 has noticeable differences from what it was predicted to be, still showing patterns more common in hypereutectoid steels. These prediction-vs-measurement differences could possibly be due to corresponding differences in the original processes the 1045 bar underwent compared to the producer's specifications.

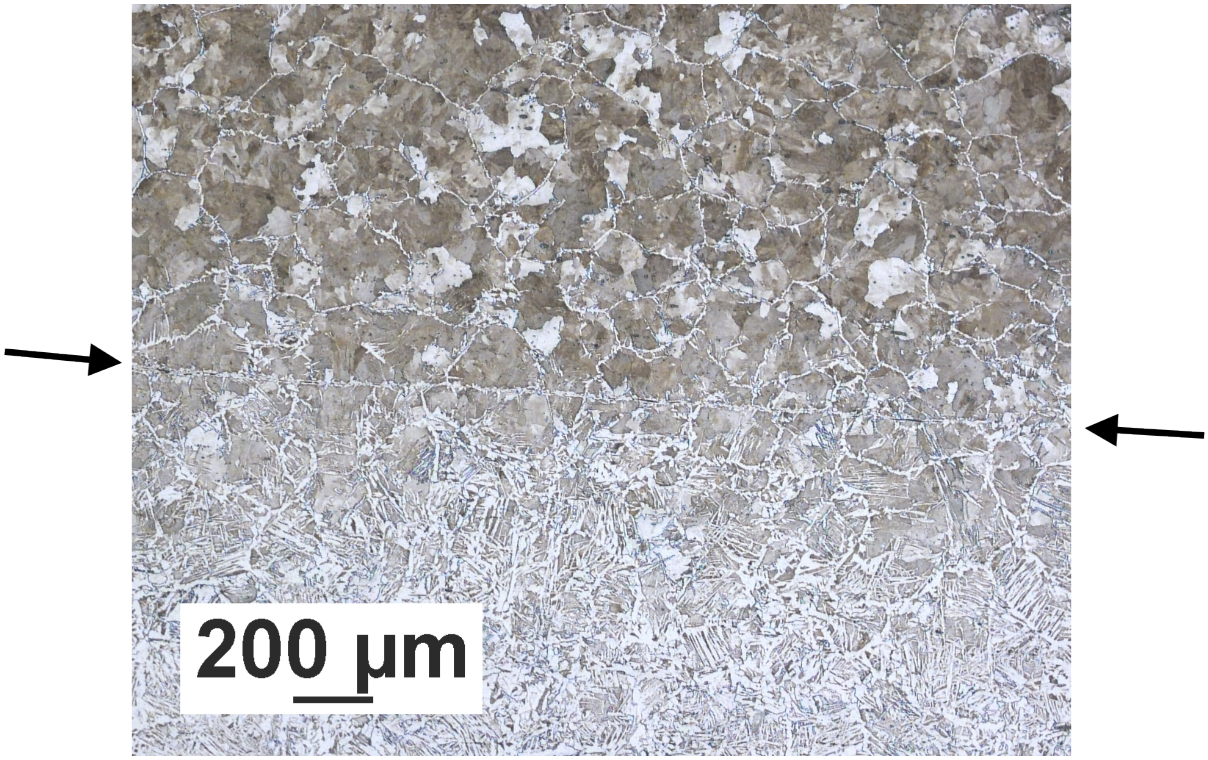


Figure 6.22.: Forge-weld boundary with the 1045 above the 1018 (5x magnification).

The final microstructure image is presented less for technical analysis and more to present an interesting feature of the forge welding process. Figure 6.22 shows the boundary between where the 1045 and the 1018 metals were laminated together. This boundary can be seen as a thin continuous line of white crossing the image horizontally near the center of the image (the ends of the boundary line are emphasized with two black arrows collinear to the line). This is a valuable perspective for two reasons. The first detail to observe is how successful the forge weld was at bonding the two layers of metal together—the boundary between those layers is on the same size scale as the grain boundaries throughout the bulk metals—meaning that the team was able to bond the metals together as well as if it had been the same piece from the beginning. The second feature worth pointing out is the diffusion of carbon that very clearly took place around the boundary. Due to the difference in carbon saturation in each of the metals, the diffusion of carbon from higher to lower carbon steel is displayed prominently through the gradual change in the microstructure around the boundary. The characteristic features of the 1018 alloy can also be seen slightly above the boundary line, while the large pearlitic grain structure of the 1045 can be observed also below the boundary.

7. Conclusions

The team investigated the background of the people who created the falcata. It was started by looking at the timeline of the Celts. The Celts became prominent weapon and metal workers at the onset of the Iron Age. The weapons and decoratively smithed items they made were quite advanced, often having high levels of manufactural and metallurgical complexity, even if the processes used were not entirely understood. A big part of their culture, however, was war. Complementing their advanced iron working, the Celts needed to produce high quality weapons and armor at a fast pace.

The Celts produced the falcata by a unique process of burying steel plates in the ground for two or three years to purify the weak metal from the sheet. The weak steel came from the process used to smelt it, the bloomery, which was not quite able to melt the iron and produced mostly slag. Burying the steel plates reduced the imperfections in the iron created in the bloomery, allowing for a higher quality metal. The sheets could then be laminated together by heating and applying force to the layers of metal, diffusing them in a solid state. The team found that a historical analysis of many ancient Celtic swords showed that the middle layer in lamination was generally steel of a higher carbon content, while the outside layers were generally lower in carbon content. The group then followed these standards in purchasing the metals for production of the replica.

Using the tools and workshop generously shared with us by Joshua Swalec, the metal was prepared for lamination, and the cleaned metal bars were forge-welded together in the historic soft-hard-soft pattern. The sword was then forged into shape using compressing and elongating procedures to approximate the desired design. After shaping and contouring the blade using a grind wheel and affixing a maple handle, the replica falcata was completed. While many of the processes were very technologically advanced as compared to those employed by the ancient Celts, special care was given to creating the sword so that the sword's physical properties were as accurate as possible to the ancient falcata which was being replicated.

Optical microstructure images were gathered from polished metal samples from before and after the forging process on the two types of steel. The microstructure phases present in those images were analyzed and compared to previously made predictions.

Overall, the project offered a window to the past through the research and replication of the falcata, and also offered a bridge to the present using the modern techniques of microstructure analysis to better understand the physical effects of the historical manufacturing procedures on the internal microstructures and properties of the sword.

A. Website Material

A.1. Making of a Falcata Replica

In order to obtain the necessary strength for our sword, we obtained both a 2ft mild and 4ft high carbon steel bars.

Figure A.1.: Raw materials.

To properly plan our forging strategy, it was essential that we develop a render utilizing CAD software to visualize our sword with suitable dimensions.

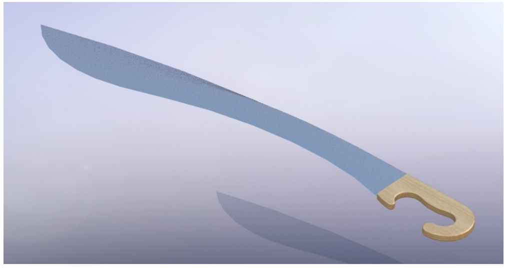


Figure A.2.: Falcata render.

Before we could laminate the two bars together, it was essential that we use a hydraulic press to prepare the bars in efficiently. This process was typically done by hand, but using the hydraulic press along with the available power hammer we were able to flatten the bars roughly equivalent in width through heat treating the blade until it was bright yellow in a propane supplied furnace.

Figure A.3.: The hydraulic press used for major flattening processes.

Prior to lamination it was important to mitigate pollutants such as oxidized metal scaling to ensure that after grinding them to a coarse texture, we could promote proper joining of the bars. Then the two bars were welded together for later hydraulic pressing. Using the large band saw we could properly trim the sword to our desired dimensions, awhile maintaining a consistent length.

Figure A.4.: The results from the tack weld.

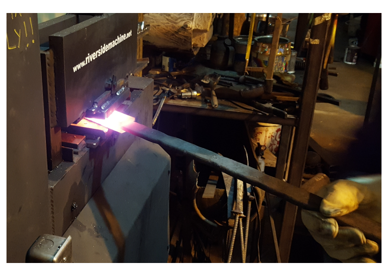


Figure A.5.: The hydraulic press, used to attempt lamination.

With the implementation of borax, we were able to keep the welding surfaces from oxidizing, and removing any other impurities from the surface of the metal. After utilizing a smaller, cross section area die we were able to flatten the bar to the necessary width.

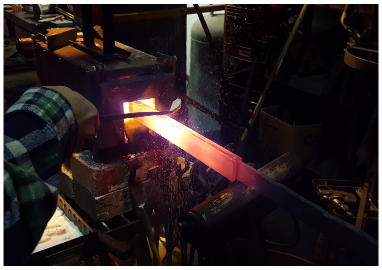


Figure A.6.: Borax, used as the forging flux.

To reduce the amount of present divisions along the laminated layers we grinded down selected deeper spots to ensure the layers seemed uniform along the width of the laminated bar. The bar was then cut to relieve any excess material. In order to create the proper contour, we decided to make the spine the side with the obtuse angle, while the blade edge would be would be along the length of the sword with an angled cut to make the smooth contour of the sword easier to shape. The blade was then heat treated and bended over an anvil until the radius approximately resembled the curvature needed.

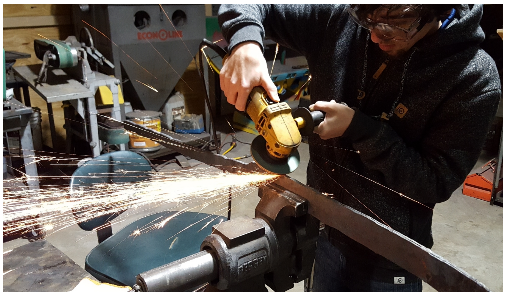


Figure A.7.: Grinding the edges to see the weld quality.

Figure A.8.: The cut on the end to make an angle and get a piece for the sample.

A.1.1. Counteractive Bending

Figure A.9.: The counteractive bend (with a scale).

Using a cross peen hammer rather than a typical flat faced hammer we were able to stretch the sword along its width, until a point just before the integrity of the sword was compromised, while developing optimal width.

Figure A.10.: The end of the forging process, with the fully shaped tang.

After the sword had been forged into the rough shape, it was then ground with a disc grinder to form the final shape.

Figure A.11.: The blade with most of the scale cleaned off. The rough pieces of the handles and the pins are on the upper left.

A.1.2. Handle

Since the end of the blade where the handle was to be formed was still rather rectangular, we traced the regions where metal was to be removed. We then grinded the handle to form the hand-recess, and thinned out the blade again using another the peen hammer process. Using the hammer to counteract any misalignments, we achieved our proper tang shape.

Figure A.12.: The 3-person layout used to shape the tang more rapidly.

Figure A.13.: Smoothing out the edges and thin parts of the blade.

Utilizing a piece of maple previously cut, we shaped the handle using a ban saw and progressively cut off pieces, making the hand nearly flush to the hand-recess, then continued to utilize a sanding machine to sand the edges for a rounded appearance for handling.

Figure A.14.: The perpendicular pre-cuts.

Figure A.15.: The rounded/smoothed handle scales.

Using the drill press we were able to properly align three holes equally along the newly grinded tang, and drill holes through with a tolerance slightly greater than that of the holes along the maple handle scales. Drilling holes with a tolerance slightly smaller allowed us to utilize compressive and tensile forces to wedge the maple flush to the tang. Brass pins were then hammered through the layers of maple and sword to finally form the proper handle.

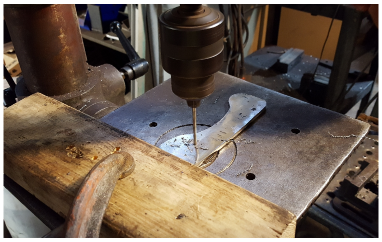


Figure A.16.: Drilling through the tang for the pins.

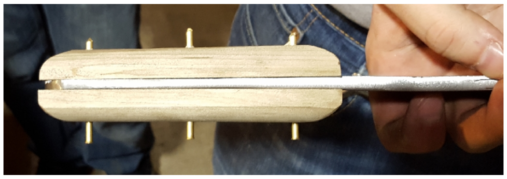


Figure A.17.: The handle assembled before trimming pins.

For the purpose of developing a suitable handle the brass pins were then sanded down finely to the surface of the maple, creating a flush appearance about the blade. Additional grinding was then beneficial to expose the proper luster of the metal.

Figure A.18.: The finished handle from below.

Final Blade:

Figure A.19.: Final falcata replica

A.2. Historic Synopsis

Celtic warriors used a variety of weapons during throughout their timeline. Covering large distances these warriors would utilize javelins, harpoons, bows and slings. Though tactics from afar were often advantageous, the common Celtic warrior was equipped with some form of throwing weapon. Young warriors would begin training and fighting with primitive javelins, bows and slings. These warriors battled with close-range weapons such as spears, two hand hammers, axes and swords. Swords were short and gradually became longer in order to be more efficiently used while riding chariots. The Celtic people were renowned for their craftsmanship, but often developed swords with rather inconsistent quality. The Celtics surprisingly did not develop protection garments until circa 300 BCE, where individuals born to royalty were the primary people to first utilize this technology, until it later became more commonplace after blacksmiths were able to teach these techniques to their apprentices. After came leather armor, light bronze breast plates, chain shirts and scale armor. They later developed a technique in which layers of metal scales were sewn to linen to then be bonded to chain armor called Ceannlann armor. Helmets were rather uncommon at first until Celtic craftsmen created the Montefortino and Coolus helmets. Celtic warriors often attached real or metal horns to their helmets to look dominant and intimidating on the battlefield.

A.3. Helmets

- Name: Coolus Helmet
- Origin: 3rd Century BC – 1st Century AD
- Material used: Bronze or copper alloy
- The Coolus pattern helmet had a rounded shape with a pronounced projecting neck guard and a large angular cheek piece. Most had a simple spike as a plug-in plume or crest holder.

Figure A.20.: Coolus Helmet

- Name: Montefortino Helmet
- Origin: 4th Century BC – 1st Century BC
- Material used: Brass
- This helmet had a hollow conical shape and a small extension at the back as a neck guard. Normally they had a plug-in plume holder on the crown of the helmet.

Figure A.21.: Roman designed Montefortino helmet [30].

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