HISTORICAL EVOLUTION OF ROMAN INFANTRY ARMS AND ARMOR

753 BC - 476 AD

An Interactive Qualifying Project Report
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Abstract

During its time, the Roman Empire gained a formidable reputation as a result of its discipline and organization. The Roman Empire has made a lasting impact on the world due to its culture, political structure, and military might. The purpose of this project was to examine how the materials and processes used to create the weapons and armour helped to contribute to the rise and fall of the Roman Empire. This was done by analyzing how the Empire was able to successfully integrate new technologies and strategies from the regions the Empire conquered. The focus of this project is on the Empire's military, including the organization of the army, and the tactics and weapons used. To better understand the technology and innovations during this time the Roman long sword, spatha, was replicated and analyzed.

Acknowledgments

The team would like to thank Professor Diana A. Lados and Professor Luca Capogna for this unique experience. The team would also like to thank Anthony Spangenberger for his guidance and time throughout the microstructure analysis. Lastly, this project could not have been done without Joshua Swalec, who offered his workshop, tools, and expertise throughout the manufacturing process

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1. Introduction

This project is an addition to the Historical Evolution of Arms and Armors Interactive Qualifying Project. The purpose of this project was to examine how the Roman Empire was able to dominate in wars and conquer a vast territory around the Mediterranean Sea. This was done by analyzing the culture of Rome, the organization of the military, and the technology behind the weapons and armor used by the Roman army. The Roman spatha, was chosen to be the weapon of focus for this project. The Spatha was replicated using similar methods used by armourers in the Roman Empire to better understand the technology and innovations the Empire used during its time.

The report first focuses on the history of Rome until the fall of the Roman Empire in 476 AD. This background explains how Rome became an empire and why the Roman army was able to conquer the territories around the Mediterranean Sea. The fall of the Roman Republic led to many changes within Rome's government and military. These changes were able to stabilize Rome as an Empire. However, as the Empire's constant expansion caused the Empire to lose its stability leading to its downfall. The Roman army was formidable, and is praised in modern times for its discipline and organization, while having the ability to adapt their strategies, tactics, and equipment.

The second part of this report discusses how the replicated spatha was constructed. The process and materials used are documented, and compared to the process and methods used in the Empire. The third part of this report examines the properties of the replicated spatha. This analysis was used to suggest what the properties of the Roman Spatha were like.

2. Historical Background

This section focuses on the historical background of the Empire from when the Empire began and fell. This includes how the culture of Rome drove the Empire to continuously expand in size, the military tactics used, major conflicts, the arms and armour used, and the mining and production of iron.

2.1 Timeline

Rome started as a monarchy in a small town in 753 BC, transformed into a Republic in 509 BC, and evolved into a formidable Empire in 27 BC [1, 2]. Throughout these eras there were many conflicts both internally and externally due to political and territorial disputes. Rome fluctuated between peace and war resulting in periods of prosperity as well as instability. To faces these changes, Rome continuously evolved its government, economy, and military, until the fall of the Empire in 476 AD [1, 3].

2.1.1 Roman Monarchy (753 BC – 509 BC)

Rome began as a small town on the Tiber River. According to legend, Rome was founded in 753 BC by Romulus. Romulus and his twin, Remus, were said to have been the sons of the war god, Mars. They had been ordered to drown in the Tiber River by a nearby king, but were rescued and then raised by a she-wolf. The twins eventually killed the king that had tried to drown them. Romulus then killed his brother, and became the first king of Rome [1, 2].

While Romulus ruled, he had established the Senate of Rome. The Senate was composed of 300 of the most noble or wealthy of men. The king selected who would serve in the Senate, but there would be 100 men representing each of the three tribes of Rome. During the monarchy, the Senate held little power, as the king held the most and could execute authority without the Senate's consent. The Senate was to serve mainly as the king's advisor, and veto or accept a new legislation [4].

Figure 2.1. Start of Rome [75].

The Roman Monarchy ended when the seventh king, Lucius Tarquinius Superbus was overthrown in 509 BC. Lucius was cruel and violent, which led to an uprising against the monarchy, and resulted in Rome becoming a republic [1, 2]. Figure 2.1 shows the expansion of Rome during the Monarchy.

2.1.2 Republic of Rome (509 BC – 44 BC)

After the fall of the monarchy, Rome became a republic to give power to the people. The Senate of Rome remained, but instead of a king there was now a government position called "consul". Each year two men elected by the people to be consuls for one-year terms. The two consuls served as commander in chief, and would alternate in who held the military power each month. During the beginning of the Republic, the consuls had executive and judicial power, and each had the power to veto the other [2, 4, 5].

Figure 2.2. The Roman Senate [76].

The consuls would also appoint members to the Senate, instead of letting the members be elected by the people. The power of the Senate also balanced the power given to the consuls, as the Senate directed the consuls in matters such as military conflicts. The Senate was in charge of the administration of civil government and day-to-day life, such as collecting money and managing state finances. The Senate also had the power to elect a dictator, who would assume control of the military for a six month term [2, 4, 5].

The Senate was still composed of the wealthy or those considered to be nobility. A depiction of what the Senate may have looked like can be seen in Figure 2.2. This lead to a power struggle, as the plebeians felt unrepresented, leading to disputes between the classes. As the Republic continued to conquer more territories, the gap between the rich and the poor grew, leading to the fall of the Republic [2, 5].

2.1.3 Fall of Republic

The Roman Republic fell as a result of civil war. Julius Caesar had gained the favor of the common people by serving as the general the Gallic War and advocating for reforms. The Senate demanded Caesar to step down from his command and return to Rome. Caesar refused fearing he would be prosecuted, and instead crossed the Rubicon with his army. This was an illegal act, and caused Pompey Magnus and majority of the Senate to flee Rome [2].

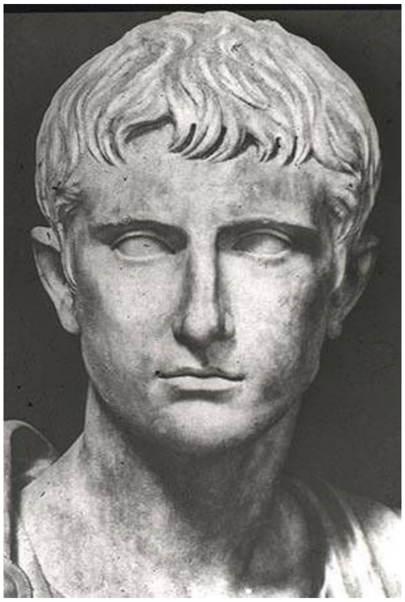


Figure 2.3. Augustus, First Emperor of Rome [77].

Caesar defeated Pompey in the Battle of Pharsalus, and then defeated Pompey's sons in the Battle of Munda. Fearing Caesar's power, several senators successfully plotted Caesar's assassination. Caesar's heir, Octavian along with Mark Antony and Marcus Lepidus led another civil war against Caesar's murderers. Antony late formed an alliance with Queen Cleopatra in Egypt, leading to the final civil war against Octavian. Octavian, shown in Figure 2.3, was victorious and became Rome's first Emperor under the name Augustus [2].
By now, Rome has expanded its territories around the Mediterranean Sea, as seen in Figure 2.4.

Figure 2.4. Roman Republic Territories (Orange Represents Rome Territories in 201 BC, Green Represents Additional Rome Territories by 100 BC) [2].

2.1.4 First and Second Century AD

The first two centuries of the Roman Empire are known as the Pax Romana which means "Roman Peace" [3, 7]. This is because from 27 BC to 180 AD, Rome was not involved with any large scale conflict [3]. After the fall of the Republic, Octavian was renamed Augustus. The Senate granted him powers for life, making him the first Roman Emperor Augustus used his powers to rebuild and establish order within Rome under his rule, by reforming systems like taxation, and creating official services such as a courier system, standing army, and police [6, 3]. Augustus also enlarged the Empire into Africa and Germania. However, he was able to stay out of large-scale conflicts by making peace with the Parthian Empire, and keeping a region of states around the Empire to protect Rome from an attack [6]. While not all of Augustus's successors followed his example, the Empire's stability and order continued, allowing the Empire to peak in 117 AD. At this time, the population was estimated to be 70 million people, almost 20% of the world's population [3, 7]. As seen in Figure 2.5, the Empire now occupied a vast territory surrounding the Mediterranean Sea.

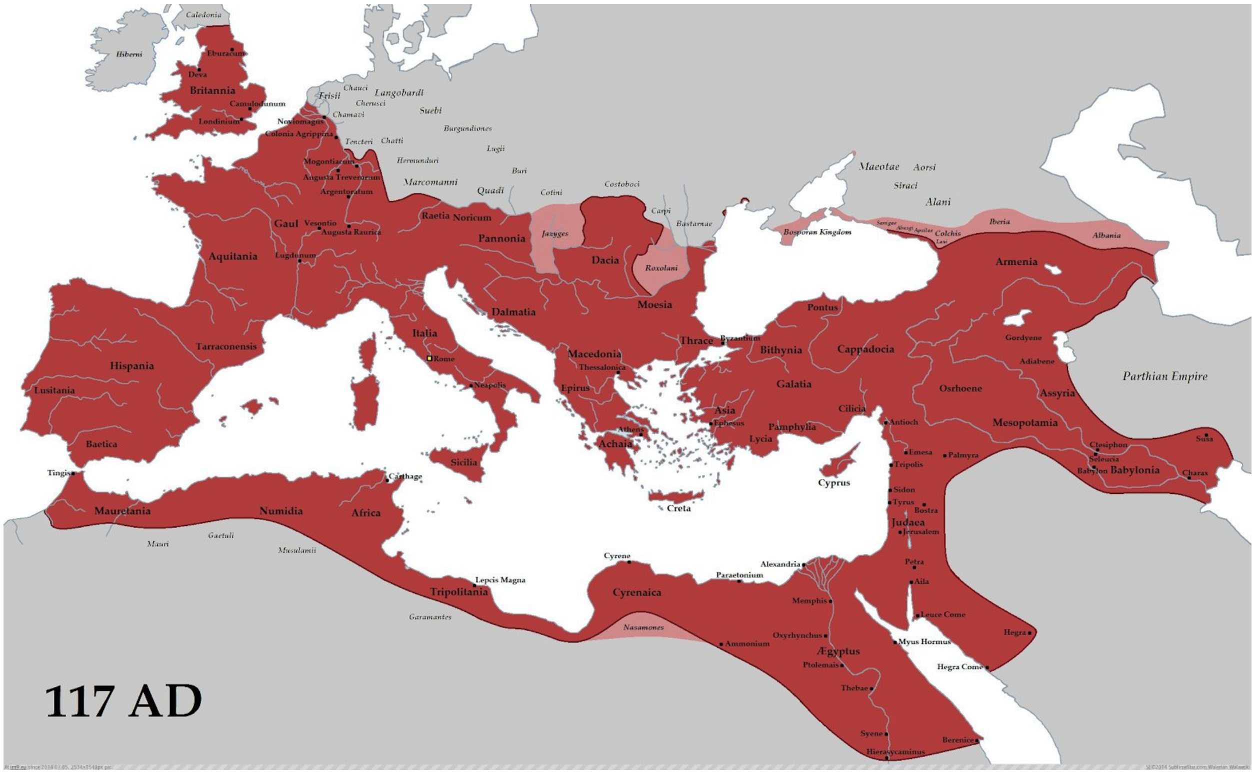


Figure 2.5. Roman Territory During Empire's Peak 117 AD [78].

The Pax Romana ended during the Nerva-Antonine dynasty. The Nerva-Antonine dynasty contained seven emperors, and lasted from 96 AD to 192 AD. Five of the seven emperors, Nerva, Trajan, Hadrian, Antoninus Pius, and Marcus Aurelius, were known as Five Good Emperors and ruled from 96 AD to 180 AD. Under their reign, the Empire grew stronger and was able to expand while maintaining order. The last of the Nerva-Antonine dynasty was Pertinax, who died in 192 AD [3].

The Severan Dynasty began in 93 AD. The end was marked by the assassination of Emperor Alexander Severus in 235 AD. This led the Empire into the Crisis of the Third Century [3].

2.1.5 Third Century AD

The Crisis of the Third Century, also known as the Imperial Crisis, lasted from 235 AD to 284 AD. The Empire was losing its stability due to civil wars, devaluation of Roman currency, and its large size causing the Empire to divide into three regions [3], as seen in Figure 2.6.

Figure 2.6. Roman Empire Division During Imperial Crisis [3].

Aurelian, Emperor from 270 AD to 275 AD, reunited the empire. Diocletian, Emperor from 284 AD to 305 AD, ended the crisis with reforms such as establishing the Tetrarchy. Tetrarchy, or the rule of four, split rome into four regions, with each region ruled by an emperor. Furthermore, in 285 AD, Diocletian divided Rome in half, creating the Western Roman Empire and Eastern Roman Empire (later known as the Byzantine Empire). This division can be seen looking at Figure 2.7. With reforms such as these, Diocletian was able to bring economical and military stability to the Empire [3].

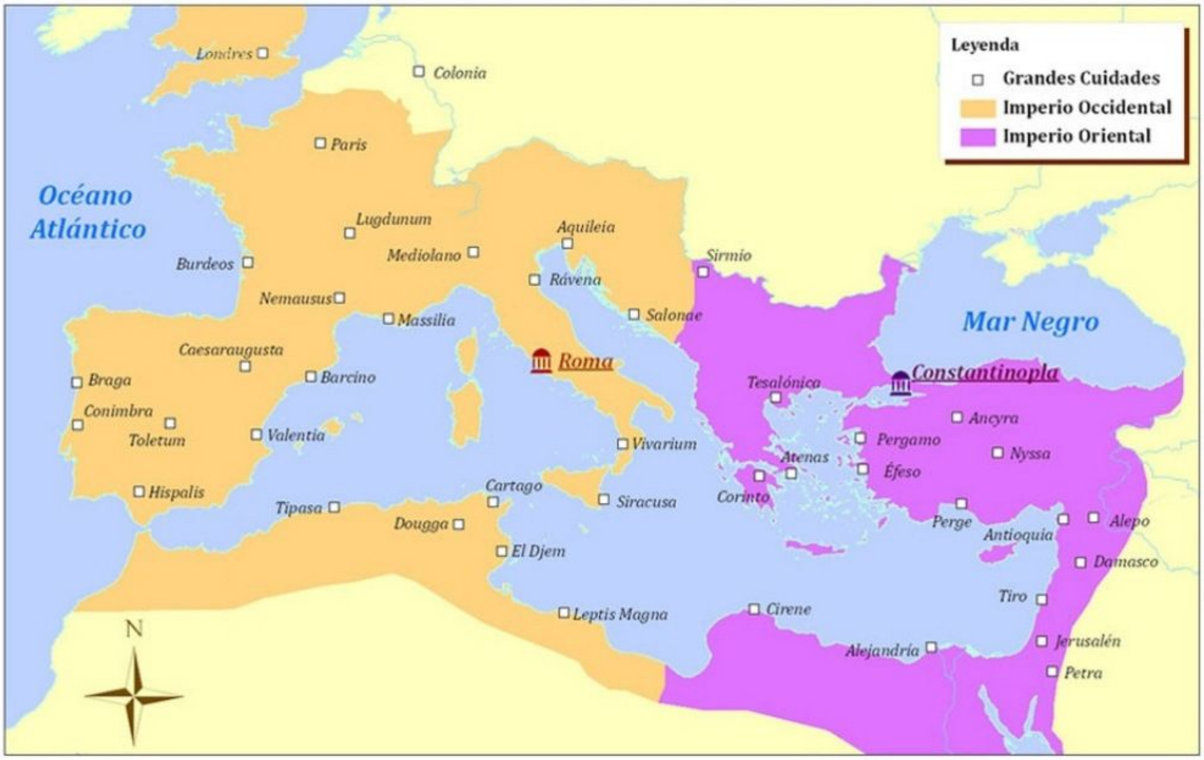


Figure 2.7. Roman Empire Split into the Western Roman Empire and Eastern Roman Empire [79].

2.1.6 Fall of Rome

The Western Empire, ruled by Maxentius, and the Eastern Empire, ruled by Constantine, engaged in civil war. Constantine defeated Maxentius in 312 AD in the Battle of the Milvian Bridge. In 330 AD, Constantine founded Byzantium (later called Constantinople), which led to the Eastern Empire's new name: Byzantine Empire. Constantine's influence spread tolerance for religion throughout the Empire, and chose a faith in Christianity. Science, technology, and philosophy flourished, and had efficient tax and administrative systems that supported the Empire until its fall in 1453 AD [3].

Many factors lead to the fall of the Western Empire. After losing to the Eastern Empire, the Western Empire was severely weakened by the Gothic Wars in 376 to 382 AD. The Germanic tribes continued to grow in strength and constantly attacked Rome. This continuously weakened the Empire as the military could no longer efficiently guard the borders, and the government could no longer collect taxes in the provinces. The people also began to accept the faith of Christianity. This lead to the people to undermine the old Roman laws which were based on adhering to the old Roman religion and beliefs.

This lead to the Empire's economic and military instability. The last Western Emperor was Romulus Augustus. Romulus abdicated in 476 AD, when King Odoacer invaded and gained control of the city of Rome [3].

2.2. Culture

The Roman culture was continuously changing due to the constant assimilation of new territories and people. The culture of Rome was one of the driving forces that gave the Empire's military its might. The beliefs of the people and the need for slaves and food led the Empire to expand and conquer for these resources.

2.2.1 Geography

Rome original boundaries were around around Palatine Hills [14], and a had mild climate which aided in farming. The city was built on seven hills which were easy to defend because of its strategic location. Rome's trade routes lay close to the Tiber River which gave them easy trade access and protection. Rome later conquered parts of the Italian peninsula which was surrounded by water on three sides and had mountains on the other side to protect it [14, 15].

In beginning of the Empire, Rome, not only had a good location for easy trade access and protection, but also were surrounded by two great civilizations. To the north were the Etruscans and on the south were the Greeks. The Etruscans had established themselves as great engineers and great writers. The Greeks were well known for their architecturing and creators of different form of governments such as Democracy. Rome was able to adopt and refine some the great ideas from the two surrounding civilizations to create a powerful empire .

2.2.2 Government

The Roman Republic had established the Senate to represent the will of the people. At the head of the Senate were two consuls who were elected by the Senate annually, and held the highest position in Rome [2]. The rise of the Emperors changed this hierarchy, as Emperors were known as princeps or the First Citizen. Emperor or Imperator was a title given to someone who was recognized by the Senate and whose power depended on their control of the Roman army. The Emperors were given lifelong powers. Many times succession was hereditary as seen with many of the Roman dynasties, but the was not an automatic inheritance [3, 8].

As the the Empire grew, it became harder to maintain control over such a vast territory. Diocletian's establishment of Tetrarchy was necessary to stabilize Rome due to its vast size. Tetrarchy divided Rome into four regions, with each region ruled by an Emperor. This did not last as the Emperors fought for dominance against each other. However, Diocletian was successful in dividing the Empire in two, resulting in the Western Roman Empire and the Eastern Empire. The two Empires were ruled by separate Emperors, unless a strong ruler could unite them [3].

2.2.3 Society and Religion

The construction of the Roman Civilization was only possible due to the Roman slaves. Slaves were usually people captured in battle, children of slaves, or Roman children that were sold for money. It is estimated that 20% of the Roman population were slaves [9, 10]. Slaves were enslaved for life unless given their freedom by their owners, or if they bought their freedom. Slavery was justified by the Romans by believing freedom was not a right but a privilege given to the winners. This is similar to how the Roman God Jupiter won his right to be free by overthrowing Saturn [9].

During the Republic, only citizens were allowed to vote. However, citizenship did not mean equality, as there was a divide in status and rights between those considered patricians and those considered plebeians. There were also conflicting views on how to grant citizenship to the people in conquered territories [2]. However, with the rise of the Empire, the Emperor took over many of the duties of the Senate reducing. This drastically decreased the power of the people and made voting rights and citizenship irrelevant [11]. The difference in social classes is depicted in Figure 2.8.

Figure 2.8. Roman Social Classes (left to right: Patricians, Slaves, Plebeians) [80].

2.2.4 Economy

The economy of the Empire was not complex. The main goal of the Empire was to feed its citizens and legionnaires, resulting in the economy to be based on agriculture and trade. Farmers could choose to donate surplus crops instead of paying taxes, which allowed the military to provide food for its legions. Staple crops were grains, olives, and grapes, and olive oil and wine were some of the Empire's largest exports [12]. Rome imported marble from Greece to make buildings, lead and tin from England to make weapons, and luxury goods such as silk, jewelry, pottery, and glass from Spain, France, the Middle East and North Africa. The transportation of these goods overland led to the establishment of a network of roads. These roads not only helped trade, but also allowed the fast mobilization of the Roman Army [12, 13].

The Empire's economy did not have a central bank system to monitor the cash flow and also had no control over the economic conditions which caused economic instability. Absence of the banks, created fiat currency because, transfer of large sum of money was allowed by the empire without the physical transfer of coins. An example of what the coins looked like is shown in Figure 2.9. When bankers received the money they kept the money for fixed or indefinite term, which was than lent to the third parties. The senatorial elites also lended money from their personal wealth on power of their social connections. The banks kept less in their reserves than what the total sum of the customer's deposits, this did not ensure the return of customers money in the case of a bank run. This caused more fiat currency and caused the money supply to fluctuate constantly [17, 18].

Figure 2.9. Augustus Coin [80].

Rome traded with places as far as India and China through sea routes that covered the Mediterranean Sea and Black Sea and many other land routes through roads built by the Romans. Rome mainly exported wine, olive oil, pottery and papyrus with their main trading partners like Spain, France, Middle East and Northern Africa [16]. Figure 2.10 shows the common trade routes during the Empire.

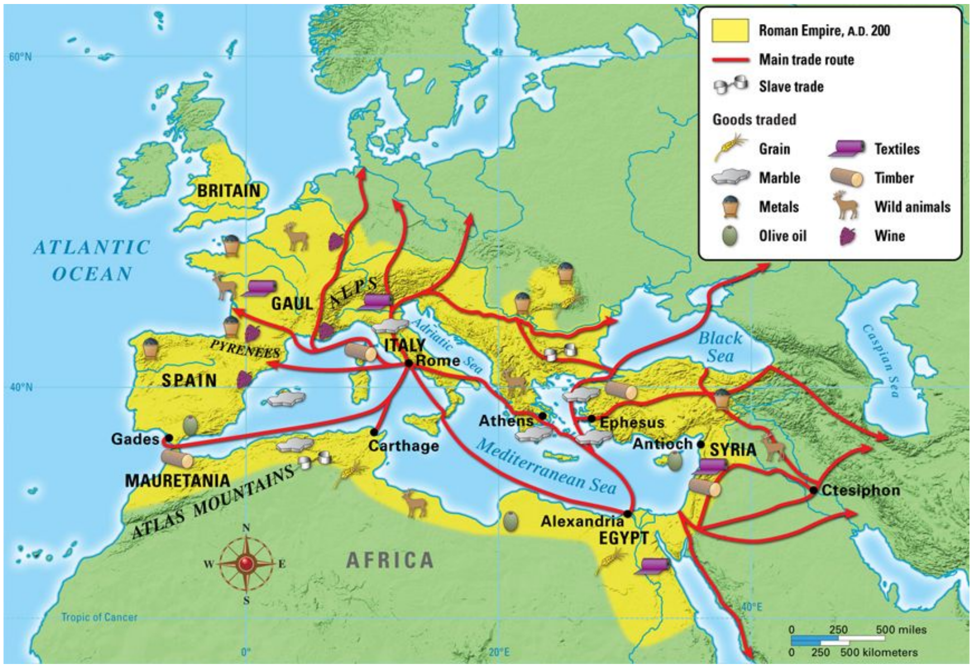


Figure 2.10. Roman Common Trade Routes [81].

2.3. Tactics and Reforms

Mighty. Brutal. Feared. The Roman army is known as one of the most disciplined and deadly force of the ancient world. Even though history remembers the names of emperors and generals, it was the ordinary men of the Roman military that carved out and kept the Empire. They trained, fought and marched thousands of miles on roads that they built. However, it took centuries to develop the feared professional army Empire was known for.

2.3.1 Battle Tactics

The Roman military is as old as Rome itself. The military itself has gone through many changes, having used a total of three uniquely different styles of conducting warfare: the phalanx, the maniple, and the cohort.

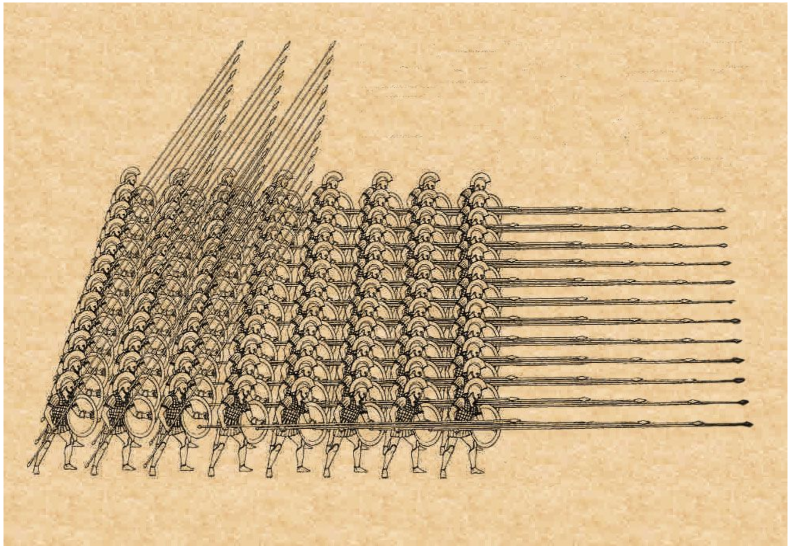


Figure 2.11. Phalanx Formation [83].

In the early days of the Roman Republic, the Roman army was made up of citizen soldiers. During the campaign season, landowning male citizens gathered and formed the formal Roman army. At the time, the men armed themselves using their own money. The richest recruits were able to afford helmets and body armour, and armed themselves with a sword or spear. The poorest had little more than rags to clothe them and rocks to throw.

The first style the army fought in a phalanx formation, similar to the greeks before them. A depiction of what the phalanx formation may have looked like can be seen in Figure 2.11. A phalanx was a group of tightly packed spearmen who move and fight as one. This formation worked very well against unorganized armys who ran head first into opposing armies. Using this formation the army seemed almost invincible from the front. However, this made the army very slow, and extremely vulnerable to flanking maneuvers or disruptive terrain. The phalanx worked very well for the Romans early on, but as they began expanding into central Italy, the presence of rough terrain disrupted the phalanx formation, making it must less effective in battle. The inhabitants of the mountainous central Italy used this advantage and by using techniques to even further disrupt the slow and awkward phalanx formation. After suffering a few costly defeats, the Romans changed their fighting style and to adapt to this new form of warfare.

The Maniple system was a perfect answer to the phalanx's inflexibility [19]. A Maniple was made up of multiple smaller, stand alone units. This allowed the units to fight in isolation, easily move to a more advantageous position, or to turn around and fight in a different direction than the unit next to them. This solved the "only fight from the front" problem that the phalanx had. Secondly, they could move much more fluently than a phalanx formation. Instead of being in one large battle line, maniples were arranged in a checkerboard pattern, with spaces in between units, as seen in Figure 2.12. Unlike the phalanx, the maniple could flex or bend to move over rough terrain and still stay in formation. In addition to this, the Maniple allowed for two significant advantages: troop replacement and troop reinforcement.

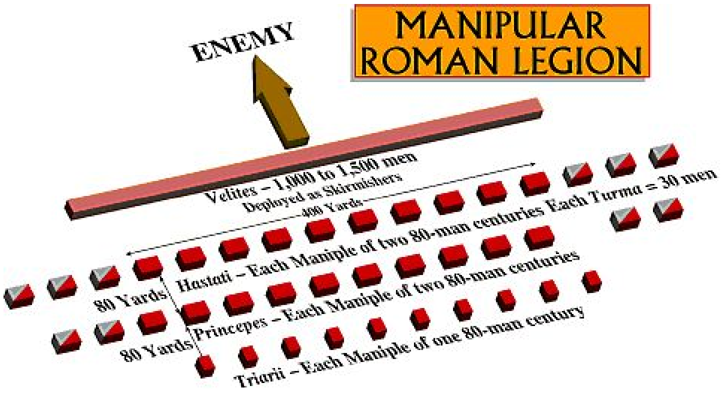


Figure 2.12. Roman Manipular Formation [84].

A common issue during ancient warfare was fatigue. When wearing so much armour, it takes up a lot of energy to fight. Often, pitched battles would last less than an hour as men would be too exhausted to fight any longer. The Roman maniple system worked perfectly to solve this issue. As the front line of troops began to tire from fighting, they could tactically retreat to the line behind them. This essentially replaced the front battle line with fresh troops and allowed the tired men to rest for future fighting. The front line troops were called the Hastati. They were the young and inexperienced men of the army, and were equipped with the sword, shield, and javelin [20]. The second line of troops was called the Principes, and were older and more experienced troops. They were also equipped with a sword and shield. In normal circumstances, the Hastati and Principes would alternate fighting for the duration of the battle. However if the battle was at a tipping point, then the Principes and Hastati would fall back to the third line of troops, the Triarii. The Triarii were the most experienced and elite troops, equipped with spears but more loosely packed than a phalanx. This method of troop replacement offered a significant edge over other battle strategies.

Not only could the checkerboard pattern be used for to allow fatigued units to retreat, but it also allowed for easy reinforcement and movement of troops behind the main battle line. With a significant portion of the army not on the direct front, the commander in charge was left with a lot of flexibility to move units to reinforce weak areas in the formation.

At the front of the manipular system were the poorest Roman soldiers, the Velites. These men could not afford armour or weapons, so many were armed with javelins or meer rocks. Despite being poorly equipped, these men acted as skirmishers for the main Hastati front line, soaking up enemy projectiles and whittling down opposing forces before the main battle line charged. After this they would quickly disperse and form up behind the safety of the Triarii.

The Romans stuck with the maniple system for a long time. During this time, they rose from a regional Italian power to the dominant force in the Mediterranean. However, as Rome grew, it began to face larger and more organized armies. The maniple system was created to fight against the Italian hill tribes Rome fought in its early days as a Republic. This system worked, but was not optimal for the large scale organized battles that were fought from 200 BC to 100 BC. The flexibility of the maniple no longer mattered when the units themselves were too small. When the Romans fought the hill tribes, reinforcing with one maniple here or there could make a difference, but when fighting other larger powers, these units were simply too small. Things had changed, and Rome needed to reorganize their army. With the Marius reforms in 107 BC (see section 2.1.4), Rome did just that.

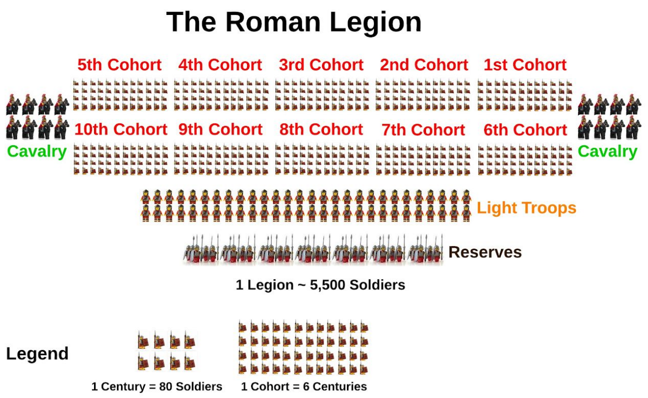


Figure 2.13. Roman Battle Formation with Cohorts [85].

The solution they came up with was called the cohort system, which can be seen in Figure 2.13. Fistly, legions no longer had 40 maniples and instead had ten cohorts. But, these cohorts were not simply large Maniples, they were more or less one large, equally skilled unit. In this system, units were no longer separated based on experience and weaponry. Also, in new Roman cohorts, each soldier carried around their own weapons and equipment. Each cohort could make a camp, build a bridge, clear a forest, and even build roads. Many roads that the legionaries built still stand to this day [49]. The cohorts were designed to be entirely self sufficient. When legions were stationed thousands of miles away from Rome, this type of training and autonomy was crucial. It was almost as if each legion was made up of ten smaller armies; this kind of logistical simplification is what made it possible to fight multiple campaigns far from the homeland [20]. It is important to emphasize how each cohort was essentially the same. This meant any individual unit could step in to replace another. This way, to make a larger legion, more cohorts were added without the any administrative or logistical hassle. Generals did not have to worry about composition of troops. Every unit was the same, so there could never be too many Hastati or too many Principes. Overall, the cohort system reflected the evolution of Rome from regional to global power. Units were now larger, uniform, and easy to manage, all essential for a large empire.

2.3.2 Marius Reforms

Gaius Marius was a Roman general who was promoted to Junior Consul due to his courage in battle. As Junior Consul, he was in charge of concluding the war with Jugurtha. However, he quickly realized that he had no army to fight with. All eligible Roman citizens were either dead, or already recruited into other armies [41]. Looking for a solution, Marius enacted three major reforms that dramatically changed the Roman army in a way that would stick until the fall of Rome.

The first thing Marius changed was the eligibility requirements for those being recruited into the army. Previously, only landholding men could become soldiers. The old belief was that if men had land back home, then they would have a reason to fight in the army and as such would not desert or show cowardice. Marius abolished this requirement, opening up recruitment to the masses of landless peasants. Along with the requirement for holding land, it was a common practice for Roman soldiers to provide their own arms and armour. The new peasants that would be recruited would not be able to do this, so Marius arranged for the state to provide the equipment. The common masses saw the army as a place to gain glory and riches, so naturally they flocked into Marius's armies [41].

Marius's second reform was on the organization of the army itself. Rome would now have a standing army, which no longer needed to be re-recruited and trained every year. Also,the structure of the army itself was changed into the cohort system, discussed earlier. A cohort was made up of six centuries, each containing 100 men: 80 infantry and 20 non-combatants. Each man was responsible for carrying his own equipment and rations for several days. This greatly cut down on the baggage train and increased the mobility of the entire force. With the combination of Marius's earlier reform of the state providing equipment, the new Marius cohort based legions were much more standardized, organized, and mobile.

Marius's final reform was that of incentivising men to become career soldiers. Pensions for retired soldiers were to be paid out after 20 years of service. In addition, a plot of land was guaranteed to retired men from conquered lands. The final icing on the cake was that after an agreed upon period of service, non-citizens of the Empire could become Roman citizens. The army became the path to moving up in class, and offered many long term benefits for staying a solider year round.

Not only did Marius's reforms create a system that allowed Rome to expand into the great Empire that it became, but it also brought about the beginning of the end of the Republic [40]. With the new emphasis on career soldiers coupled with the fact that soldiers were paid by their commanding general, the Roman army's loyalty shifted from Rome itself to that of its generals. Before the reforms, Roman soldiers were recruited for a campaign, and then disbanded after. After the reforms, these soldiers would remain in the army for 15-20 years. For this long period of time, they would have constant contact with their general, breeding fierce loyalty. Starting with Caesar, Roman legions would be used as a tool to gain political power. In effect, Roman legions became the personal armies of the generals that led them.

2.4 Major Conflicts

Throughout Rome's history, there have been many conflicts. This section covers the the major wars Rome was apart of. While Rome was victorious in most of the wars, Rome had its fair share of losses due to poor tactics and internal political conflicts. Most of these conflicts resulted resulted in Rome gaining new territories, and establishing military dominance around the Mediterranean. Even when Rome did lose, the army was able to learn from their failures and adopt new strategies and tactics to become victorious during the next conflict.

2.4.1 Samnite Wars (343 BC – 290 BC)

The first of Rome's wars with the Samnites began when the Oscan tribe attacked the Campanians who desperately asked Rome for aid, despite Rome holding a treaty with the Samnites. The Romans attempted to negotiate, but eventually declared war when the Samnites insisted on destroying Campania. Many of the battles fought were costly for both sides, with the Romans narrowly taking victories in last-ditch efforts. The Romans were a powerful fighting force, but the Samnites exposed many weaknesses in their phalanx formations, using the awkward terrain and a hail of spears to throw off the prized Roman coordination. The Roman army would eventually draw inspiration from these battles when the added the Pilum to their arsenal. The fighting died off around 341 BC, but hostilities remained high for the next 50 years, with war stopping and starting a number of times [58, 59].

2.4.2 Punic Wars (264 BC – 146 BC)

The First Punic War (264 BC – 241 BC) began as a territorial conflict in Sicily between the Mamertines and the Syracuse. A map of the Mediterranean territories before the war can be seen in Figure 2.14. This conflict escalated into war when the Romans and Carthaginians stepped in to aid their respective allies. The Romans began the fighting with a decisive land victory. After the Carthaginians began taking advantage with their large navy. The Romans had no established navy and could not compete with their enemy at sea. The Carthaginians would use their ships to attack the Roman army from sea, in the direction the Roman's once considered a natural defense. The Carthaginians would then retreat to where the Romans could not follow. In response, the Romans rapidly expanded their fleet, building over one hundred ships in a two month span. Because they were not used to naval combat, the Romans instead designed their ships to attach to opposing craft with grappling hooks and sharp spikes. This allowed the Romans to turn sea battles into their specialty: hand-to-hand combat. After routing Carthage's advantage, Rome won battle after battle, eventually forcing their enemy to surrender and evacuate Sicily [60, 61].

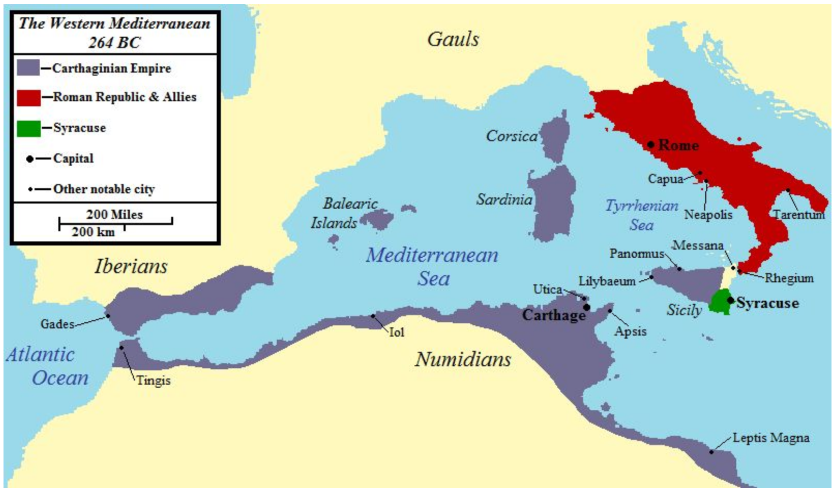


Figure 2.14. Rome and Carthage Pre-War [85].

The Second Punic War (218 BC – 201 BC) took place after Hannibal rose to power in Carthage and marched his army across the Alps to attack Rome. Although he took the Romans by surprise and won many battles, the freezing mountains had a lasting toll on his troops and supplies. Losing his siege engines and most of his elephants before even engaging in battle, he lacked the brute force necessary to take major cities. He was also unable to sway Rome's allies to turn on them in an attempt to cut off food and other supplies. Hannibal’s own troops, however, received very little aid from his allies back in Carthage, and despite their deadly effectiveness in battle, his army slowly ran out of supplies. Eventually, he attempted to retreat his army, but was finally defeated at the Battle of Zama [60].

Due to rising resentment over the next 50 years from Hispania and Greece, the Romans began the Third Punic War (149 BC – 146 BC), a brief campaign that would end in the destruction of Carthage and its people. Before declaring war, Rome began making increasingly difficult demands of the enemy nation, forcing them to bend to Rome’s will. Failing to meet their demands, Carthage was burned and destroyed, and its surviving people enslaved. The remaining Carthaginian territories were annexed into Rome, completing Rome’s victory over North African nation [60].

2.4.3 Gallic Wars (58 BC – 51 BC)

When the Helvetii, a group of five Gallic tribes, planned to migrate through (and likely raid) a Roman ally and a Roman province, Aedui and Transalpine Gaul respectively, Julius Caesar took the opportunity to further cement his political and military position. When the Helvetii sent emissaries to negotiate a peaceful passage, Caesar delayed them, giving his forces time to get in position. When the Helvetii tried to pass, Caesar’s legion in Transalpine Gaul stopped them. Unable to easily force their way through, the Helvetii turned back to negotiate a different route. They managed to beat Caesar by passing through Sequani into Aedui, where they began raiding. The weaker tribe asked Caesar for help. Having just taken command of three legions from Cisalpine Gaul, Caesar accepted. He ambushed the Helvetii as they crossed the river Arar, defeating and scattering the raiders. Caesar pursued the remaining Helvetii until his troops ran low on supplies. As they headed to a nearby town, the Helvetii turned around and began attacking the legion’s rear with their cavalry. The Romans then made their stand at the Battle of Bibracte, defeating the Helvetii again [62].

The Aedui again requested Caesar’s assistance with the Suebi tribe, who had forced their way onto Sequani land and posed a threat to all Roman and Roman ally land in the area. At first, Caesar was unable to take direct action because of the Senate. However, when he learned that the Suebi King, Ariovistus, intended to take over a large portion of Sequani land called Vesontio, he gathered his legions and began marching to confront the Suebi. The following conflict showed off the power of Caesar’s Germanic allies, in the form of an elite cavalry force that turned the tide of the battle. These Germanii, from the Usipetes and Tencteri tribes, were a powerful tool that Caesar often held in reserve, but were very effective when sent to fight. Caesar emerged victorious again, routing the Suebi from the Rhine.

Soon after, in 57 BC, Caesar again engaged Rome's Gallic enemies. While marching to confront the Belgae for attacking a Roman ally, Caesar's legions were ambushed by the Nervii, a warring tribe that prided themselves in the strength in battle. Caesar's men were nearly wiped out by the fierce strike, only being saved by timely reinforcements. After regaining the upper hand, Caesar was able to use his hired help to great effect. Knowing of the Nervii's strength and aggression, he had hired archers and peltasts to counter the Nervii shield wall and mass attack strategies. These troops, along with the pilum volleys of the Roman legions, inflicted massive casualties on the Nervii, who refused to surrender and all died on the battlefield. The defeat of the Nervii and then the Belgae gave Rome control over most of the Gaul, the Celtic land in modern-day Belgium [62, 63].

Over the years, resentment grew among the Gaul tribes, and after a failed uprising in 53 BC, Vercingetorix was able to unite the tribes against Rome. Avoiding a direct confrontation with the Roman army, Vercingetorix began destroying key Roman supply routes. Caesar led his forces to Alesia, where Vercingetorix was stationed. He successfully defeated the Gallic rebellion, as well as their relief force, leaving only small pockets of resistance that were wiped out by 51 BC [62]. A depiction of Vercingetorix surrendering can be seen in Figure 2.15.

Figure 2.15. Vercingetorix Surrenders to Caesar, Ending the Rebellion [86].

2.4.4 Cantabrian Wars (29 BC – 19 BC)

The Cantabrian Wars were the first major conflicts the Romans fought following their civil war and change from republic to empire. It was a long bloody war waged against the last independent nations of Hispania, the Cantabri and later the Astures. The Romans had had encounters with the Cantabri in the past, as early as the Second Punic Wars when they fought for Hannibal as mercenaries. One such encounter resulted in the loss of a Roman standard. This great dishonor, along with Hispania's natural resources (notably gold and iron), were likely causes of the war. The Cantabri proved formidable opponents, making use of their knowledge of the terrain to successfully use guerrilla warfare against the Roman army. It took the Romans eight full cohorts (about 30,000 soldiers) and auxiliary troops (about 20,000 reinforcements), as well as a flank by the Roman Navy, to finally subdue the enemy. Even then, local rebellions continued until 16 BC, forcing the Romans to station two legions in Hispania to control the area [64].

The Cantabri, as noted by Dio Cassius (a Roman historian) and the Cantabrian Stelae (historic and religious documentation carved in stone), were skilled with light arms, making them effective guerrilla fighters. They used their spears and short swords to make quick strikes at the marching Roman lines, and charged on horses when engaged in a head-to-head battle. As the Romans developed their own cavalry, they took inspiration from the Cantabri's mounted formations and shield-breaching tactics. The Cantabri were also fierce warriors who seemed to not fear death. They would rather end their own lives, often using a poison derived from yew tree seeds, than submit to Roman slavery [64].

2.4.5 Germanic Wars (113 BC – 596 AD)

The Germanic Wars cover a series of wars fought between Rome and the Germanic tribes, including dozens of major battles leading all the way up to the fall of the Western Roman Empire [65].

Drusus Campaign (11 BC)

In an effort to better secure Rome's borders, Augustus sent his stepson Drusus on a campaign to pacify the region surrounding the Rhine. Drusus confronted and defeated the Sicambri at the Lupia River, allowing him to cross the Rhine and advance into Germanii territory. He also ordered the construction of several strongholds in the area, as well as a bridge to span the river. On the return march, Drusus's army was ambushed in a narrow pass called Arbalo. The Roman's discipline outmatched the wild Germanii attack, and Drusus was victorious, completing his campaign to secure the Rhine [66, 67].

Battle of the Teutoburg Forest (9 AD)

The Roman march through the Germania saw success early on, with the subjugation of tribes such as the Cananefates and the Bructeri by Roman general Tiberius. Around 6 AD, a revolt broke out in the Balkans which demanded the attention of the Roman army. To quell to uprising, nearly half of the active Roman legions deployed to the Balkans, led by Tiberius and Quaestor Germanicus. This mass-campaign left Publius Quinctilius Varus only three legions available for the continued conquest of Germania.

While moving to put down a local uprising, Varus and his forces were surrounded by Germanic warriors. They had been marching out of formation at the time, and thus took heavy casualties before forming a defensive position. The attacking Germanii knew how to counter the Roman's tactics because they were led by Arminius, Varus's friend and advisor who had formed a secret alliance with the Germanii. As part of his betrayal, Arminius had planted false rumors of rebellion to lure Varus into his ambush. The location of the attack was perfect, with the landscape providing natural cover for the Germanii. It was also heavily raining, rendering the Roman bows useless and shields waterlogged and unwieldy. The three Roman legions, six auxilia, and three cavalry squads were entirely wiped out, totaling upwards of 15,000 men. Following their overwhelming victory, the Germanii swept through the Roman land east of the Rhine, with their advance being stopped just short of crossing the Rhine into Gaul [68, 69]. The land taken by the Germanii is shown in Figure 2.16.

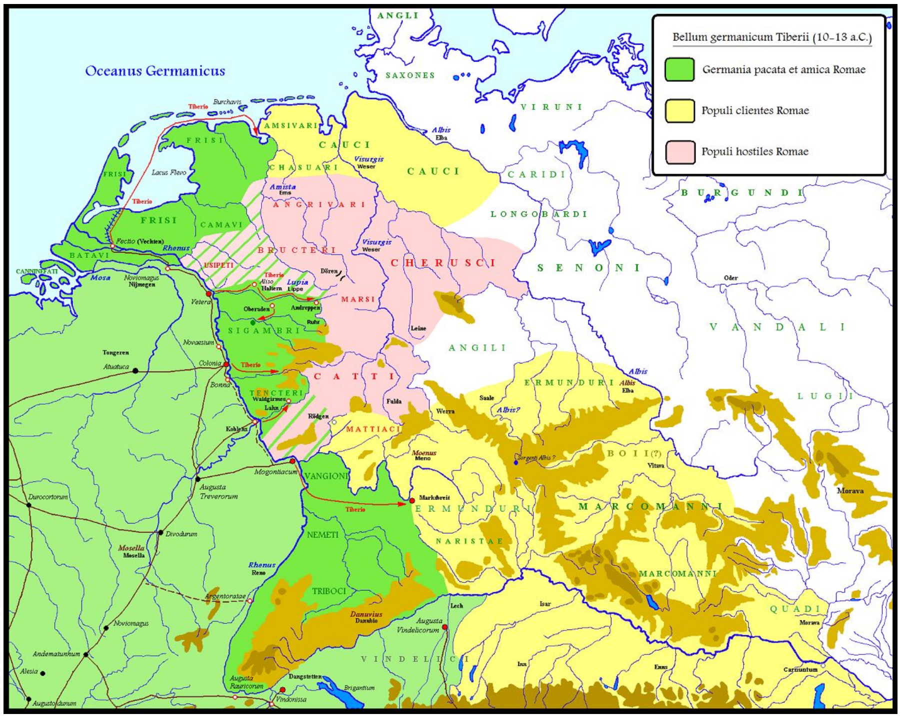


Figure 2.16. Land Arminius Claimed for Germania (Highlighted Pink) [87].

Fall of the Emperor/Crisis of the Third Century (235 AD – 284 AD)

Prior to his murder in 235 AD, Emperor Severus Alexander personally led troops against the Germanic tribes, which ended in the Emperor resorting to paying tribute to the Germanii. The Roman troops took this action as an insult, who felt the need to punish the tribes for crossing Roman borders.

This blow to their honor, as well as his failure to avenge the many Roman legions that had been defeated by the Germanii in the past, turned many of Severus's men against him, leading them to turn on and kill him [70].

Following the Emperor's assassination, Rome faced a period of disarray when many the Roman army's generals fought for his position, seeing 26 claims to the title in twice as many years. More focused on politics than defending the nation, the army failed to stop increased attacks from tribes like the Caspians, Goths, and Alamanni from across the Rhine. Adding to the chaos, the Plague of Cyprian spread through Rome around 250 AD, further weakening the nation. By 260 AD, Rome began to split into three separate states, forming the Gallic Empire to the west and the Palmyrene Empire to the east, leaving the remains of the Roman Empire in the middle [70].

2.4.6 Dacian Wars (101 AD – 106 AD)

The two Roman wars against Dacia sparked over the enemy nation's threat to Moesia, a Roman province. Emperor Trajan led his army in a series of battles, eventually defeating the Dacian army in the Battle of Tapae (101 AD). Dacian King Decebalus negotiated surrender with Trajan, but began rebuilding his forces to attack Rome again in the following years, leading to a second outbreak of war in 105 AD. The brief period of peace saw the construction of Trajan's Bridge in Drobeta, the largest bridge of its time. The Roman army was particularly effective because of the nation's roads and bridges that connected each part to everywhere else. This allowed legions to travel swiftly and efficiently, as shown when the second Dacian War broke out. The Roman army quickly forced the Dacian king back to his capital city, where they eventually forced Decebalus to flee. He killed himself rather than be captured by pursuing cavalry-men, officially ending the Dacian Wars [71].

2.4.7 Marcomannic Wars (166 AD – 180 AD)

In 166 AD, Roman troops returning from Parthia contracted the Antonine Plague. This disease killed nearly five million people, and multiple surrounding tribes and nations took advantage of Rome's sudden weakness. In the early days of conflict the Marcomannic king Ballomar helped negotiate a temporary truce between Roman Pannonia and the surrounding Germanic tribes. This treaty was broken soon after, forcing Rome to send a campaign to Pannonia. By this time, Ballomar had formed a coalition with the Germanic tribes, and they beat the Roman forces, pushing them back and into Italy. Rome fought hard to beat back the Marcomannic advance, reforming their land and sea passages into Italy.

Once the threat to Italy was dealt with, the Romans marched on Marcomanni, defeating them and their allies [72].

Following the Marcomanni's defeat, Rome turned to march on the Quadi, a tribe who had signed a treaty with Rome but broke it to aid the warring Germanic tribes. Led by Marcus Aurelius, Rome defeated the tribe and their ruler was replaced. However, the Quadi quickly dethroned their new king, forcing Rome to return and fully subjugate the rebels. In 177 AD, the Quadi rebelled again, this time compelling the Marcomanni to follow suit. Again, Aurelius led his troops north to confront the uprising. Despite being victorious yet again, the constant uprisings to the north showed how little hold the Empire had over the farther reach of their territory. Rome attempted to resolve this by stationing nearly half their standing army along their northern land, following the Danube and the Rhine Rivers [72].

2.5 Armor of the Roman Infantry

This section covers the armor used by the Romans during the Empire. While the armor quality and design changed throughout the span of the Empire, this section focus on the equipment used during the first and second century AD, when the Empire was at its peak.

2.5.1 Helmets

Roman soldiers typically wore helmets to protect themselves in battle. Although the designs improved over the centuries, they tended to follow a basic pattern: hemispherical top, with optional cheek and neck protection [52]. Interior padding was not a primary design concern, and was typically any cloth scraps that were available to the soldiers [52].

During the Republican Era, the most common form of helmet was known as the "Montefortino," a Celtic design that originated in the 4th century BC. This helmet was made out of a flat bronze plate, which was then beaten into shape with a hammer [57]. These helmets were not heavily stylized, and usually only had a crest or a plume. This design also saw use during the first century AD, typically with a larger neck guard than during the Republican Era. During this time, a significant number of additional other helmet designs came into use. The "Coolus" was a derivative of the Montefortino, significantly shorter and lacking the signature "arrow" on the top of the older design, as seen in Figure 2.17.

Figure 2.17. A Coolus Helmet [88].

Imperial-Gallic helmets, as seen in Figure 2.18, were another design that emerged during this time. These helmets also had Celtic origins, but were not directly derived from the Montefortino [57]. Imperial-Gallic helmets were the most heavily-stylised of all the designs, typically covered in elaborate bosses. Imperial-Italic helmets typically had similar designs to the Imperial-Gallic helmets, but the build quality was typically much worse. Both designs featured large neck guards and cheek guards, compared to the Montefortino and Coolus designs [52].

Figure 2.18. Reproduction of an Imperial-Gallic Helmet [89].

All helmet designs during the first century AD were made with either a copper alloy, or iron [57]. Iron helmets were beaten out of a plate, like the Republic's bronze helmets, but the new copper-alloy helmets were spun, which was a faster and more consistent process. The second century AD featured the Imperial-Gallic and the Imperial-Italic helmets, which gained additional cross-bracing, and larger neck and cheek guards [57]. The other helmet designs appear to have died out.

None of the previous designs appear to have survived to the third century AD, although that time period's designs did take some inspiration from the previous centuries. The most notable change was the addition of a much longer neck protector, which now extended down to shoulder level, before flaring out [57]. Older designs, like the Imperial-Gallic, flared out immediately below the helmet-bowl. The fourth and fifth centuries AD featured rapid deviation from all previous helmet designs. Now, helmet-bowls were designed out of two or more different pieces of iron, allowing for increased rigidity and a simplified manufacturing process [57].

2.5.2 Shields

The Scutum was the standard shield used by Roman infantry in battle. These shields appeared rectangular from the front, and were curved to better protect from the side [56]. The design had its origins in the early days of the Roman Republic, and the same basic design continued to be used until the third century AD, after which it was replaced by oval & circular shields [57].

The shield was typically constructed from wood and canvas or hide. Typically, the shield would be constructed with three different layers of strips of wood. The outer layers' strips were oriented horizontally, the inner layer vertically [56]. Once glued together, this arrangement prevented any weaknesses due to the direction of the wood grain. Then, the shield would be covered in either canvas or hide [57]. Other supporting structural elements were added, along with a boss, to protect the soldier's hand. In the Republican times, this boss was made out of wood, but the switch to an iron boss was made sometime during the first century AD, as it offered better protection [57]. Typically, this shield was 100-130 cm in height, and 60-80 cm in width [56].

The Scutum offered much better protection than other shield designs, but was much heavier. Because of this, they were more likely to be used by legionaries (Roman troops), while auxiliaries (non-Romans fighting alongside) tended to use smaller flat shields, such as the Parma [56]. An example of a Scutum can be seen in Figure 2.19.

Figure 2.19. A Well-Preserved Scutum [90].

The Parma was a flat, round shield that had its origins in the Republican days of Rome. Troops that did not use the Scutum tended to use flat oval shields that were cheaper to make, and were much lighter [57]. These two features caused the design to remain popular with auxiliaries, standard bearers, and other non-frontline troops. The parma as it's classically seen emerged during the first century AD, and remained in use through the second century AD, after which it was replaced by more modern designs [57].

2.5.3 Lorica Segmentata

The Lorica Segmentata was first designed in the first century AD, and survived through the second century AD. This type of armor is the most widely-recognized form of Roman armor. This design gained its name due to the multiple different plates (segments) that were used [57]. The chest was made out of upwards of six bands of two semi-circular strips. The shoulders were made out of several wide strips that gradually got shorter as they extended down the arms. The metal strips were typically either iron or low carbon-content steel, depending on when the armor was made [54]. Leather strips were used to hold the metal bands together, and a combination of brass fittings and leather ties were used to properly fit the armor to each soldier. Because the brass fittings were particularly thin, they would frequently break, and would have to be replaced [57]. By the second century AD, the design had been significantly refined. The armor was made out of a fewer number of plates, and the fittings were more robust. The reduced complexity of the armor ensured that it would last longer, and withstand heavier blows, without needing to be fixed as often [57].

Figure 2.20. Reenactors Wearing a Reproduction of the Lorica Segmentata [91].

2.5.4 Lorica Hamata

The Lorica Hamata was the Roman form of mail armor, and first saw use during the Republican times. This design was invented by the Celtics, but the Romans copied the design after seeing its effectiveness [57]. As seen in Figure 2.21, this armor was a shirt made out of tightly-linked brass rings, typically worn over other clothing, for comfort. Mail armor was very effective at stopping blades from cutting into soldiers, but it did little to soften the blow of a weapon's impact. Because of this, it faded out of common use by the first century AD, eventually only being used by auxiliaries and standard bearers [53], and only returned to widespread use briefly during the fourth century AD. [57] It was replaced by the Segmentata as the main infantry armor during the first century AD.

Figure 2.21. A Close-Up of Replica Mail Armor [92].

2.5.5 Lorica Squamata

Lorica Squamata was the third type of armor, originating in Republican times, that was typically used by auxiliaries and standard bearers in the Roman army [55]. Instead of large bands of metal, like the Segmentata had, the Squamata used smaller “scales,” usually linked together with leather strips, and a heavy linen undershirt [57], as seen in Figure 2.22. Squamata acted as a hybrid between plate armor and mail armor, combining the advantages of both. The multiple layers of iron or brass prevented swords and spears from easily penetrating the armor, while the small plates reduced the weight and increased a soldier’s mobility [57]. However, the armor was typically weak to upward thrusts of a weapon, because the scales are placed on top of one-another and allowed to hang [55].

During the first century AD, the design of the Squamata was improved by replacing the linen backing with a chainmail backing, vastly improving the strength of the armor. However, this design improvement also vastly increased the cost of the armor, as it was essentially a full shirt of chainmail plus a shirt of scale armor [55]. As a result, this design (called the Plumata), was not widely-used. However, it was popular among officers due to its improved strength [55].

Figure 2.22. A Preserved Piece of Lorica Squamata [93].

2.6 Weapons of Roman infantry

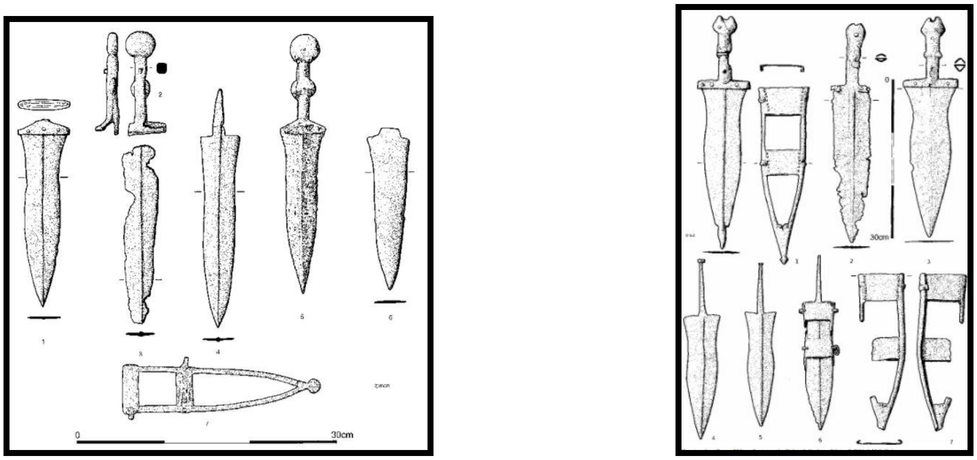
This section will discuss the main weapons of the Roman military. In addition to the weapons in this section the Roman army also relied on projectile weapons such as the bow and arrow and the crossbow as well as other close combat weapons.

2.6.1 Pugio (Dagger)

The Roman Pugio was the sidearm weapon for the Roman infantry soldier. The early Pugio had a blade ranging between 15-20 cm in length and featured a wide leaf shaped blade with a flat tang, as seen in Figures 2.23 and 2.24(a). The design intended that it was meant for fast stabs or thrusts rather than slashing. The origin of the Pugio is debatable due to the lack of information available. It was never mentioned in any ancient sources, but there was archaeological evidence that Hispania was the source of the weapon [40]. The fact that it was never mentioned in Polybios *Histories* indicates that it was not largely used in the Roman military during this time [21].


Figure. 2.23. Replica Roman Pugio [33].

More information about the Pugio is discovered in the late centuries. New styles emerged in the second century AD consisting of a slimmer blade with a central groove and a rod tang as seen in Figure 2.24(b). In the early third century AD, the Pugio blades were much larger than their predecessor. The blades could be up to 28cm in length and 9.2cm in width. The sheaths were made using different configurations of metal, wood and leather. Throughout the centuries of the Roman Empire soldiers commonly had decorations added to the front face of their Pugio's sheath. These personal touches to the sheath made the Pugio a showpiece as well as a weapon and was considered a "status symbol" for the soldiers [22].



(a) (b)

Figure 2.24. (a) Republic and First Century Pugio and (b) Second and Third Century Pugio [21].

2.6.2 Pilum (Javelin)

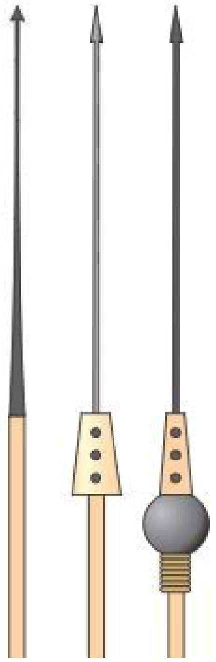


Figure 2.25. (From Left to Right), Socket Pilum, Tang Pilum, and Weighted Pilum [32].

The Roman *Pilum* (Plural *Pila*) was a heavy javelin consisting of a long iron shank with a sharp pointed end. This shank was connected to a long wooden shaft with a socket in the iron shank or by a tang on the shank inserted into the wooden shaft and secured with rivets. The socket Pilum and the Tang Pilum are shown in Figure 2.25. Its weight was used to provide the penetrating power on impact, eliminating the need for high velocities. It has been said that the Pilum was designed to bend upon impact, therefore disabling the weapon. This would guarantee that the enemy could not potentially use it against the Roman soldiers by throwing it back. Although a known fact that the Pilum shanks did bend, it could be considered a fallout of its design. The iron shank was designed to be able to penetrate the enemy's shield and then continue into the enemy soldier [21]. To accomplish this task, the iron shank needed to be of a long length to provide the reach that was needed to penetrate the opponent's shield then continue to strike and disable the opponent. A combination of the iron shaft being long, thin and a lack of tempering led to easy bending upon impact. A possible design flaw that turned out to be beneficial for the Romans. The Roman blacksmiths were familiar with the science behind tempering steel at this time so the choice of forgoing tempering could be due to the benefits of the shank bending upon impact.

Two version of the Pilum existed, the heavy and the light. The heavy Pilum had a length around 2m, and the light was slightly shorter. However, as time passed the heavy Pilum started to get smaller and the light started to grow until they were about equal in size. One problem with shrinking the length of the heavy Pilum was that it's mass also was depleted. This problem was solved by adding a bronze weight to the lower part of the shank. Most of this added weight was in the shape of a sphere that was connecting to the socket. The evolution of the Pilum can be seen in Figure 2.26, with early century Pila at the top continuing into late century Pila at the bottom of the image. The heavy Pilum was mainly constructed with a tang and rivets, while the light version was socketed. However, socketed heavy Pilums were also known to be made [21]. The use of the Pilum decreased during the third century AD because the main enemies of the Romans were cavalry soldiers. A shorter spear (*Hasta*) was adopted and provided more efficiency in fighting this type of opponent.

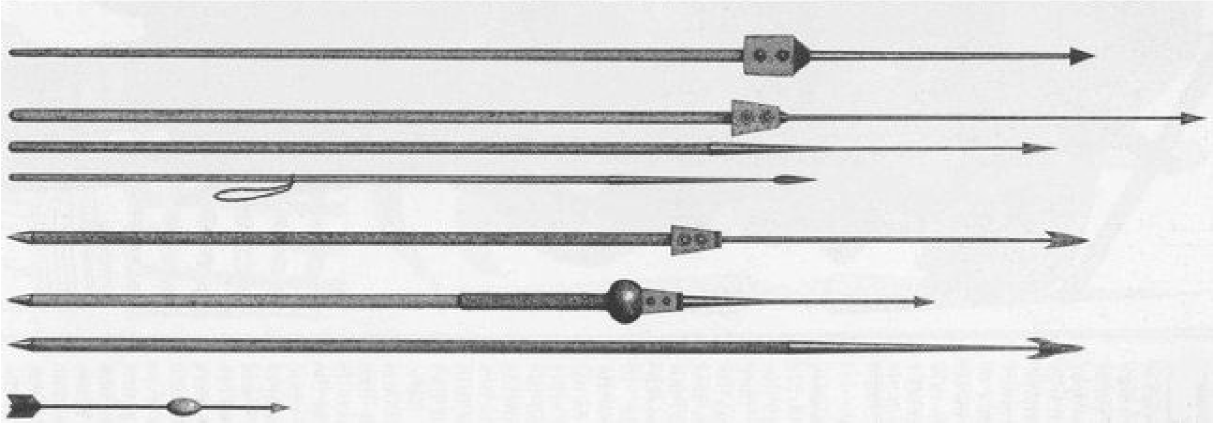


Figure 2.26. Roman Pilum Evolution [25].

2.6.3 Hasta (Spear)

Figure 2.27. Hasti used Against Cavalry [38].

The Hasta was an original weapon of the Roman army back when the phalanx formation was used. The weapon fell out of use with the switch to the sword, when the Pilum replaced the Hasta as the main Roman spear. It began to regain popularity with the Roman infantry during the third century. The Hasta was used differently than the Pilum. It was held and thrusted towards the enemy rather than thrown, like depicted in Figure 2.27. One major reason for the adaptation of the Hasta and the demise of the the Pilum was due to it being better suited for the large number of cavalrymen the Romans were experiencing during the third century. The weapons thicker shaft and heavy iron point, as opposed to the Pila soft point, let the weapon survive a thrust. The 2m shaft gave infantry troops range between both enemy footmen mounted cavalry [73].

2.6.4 Gladius (Sword)

The Gladius, as depicted in Figure 2.28, is considered an iconic weapon for the Roman infantry. This short double edged pointed sword led the Romans to win battles. The Gladius was designed to primarily be for stabbing, but it could also be used for slashing and cutting. The Gladius is a Spanish derived sword. When the Roman army first observed the weapon they admired it so much they chose to use it themselves. Although they adopted the sword it does not mean they adopted the extensive manufacturing processes that were used in its current production. The Spanish and Roman Gladius would only be alike in form [21].

The Gladius was an excellent close quarter combat weapon, especially when used in combination with a shield. The Roman infantry soldier would use his large shield for protection while delivering quick stabs to his enemy. Speed was the key for this weapon. The opponents of the Romans were mostly using long swords that required to be raised high to get a powerful downward strike. When the enemy's sword was raised, a Roman soldier could disable the opponent before the sword was lowered by quickly delivering several stabs to sensitive areas such as the arteries, throat, and groin [25].

Figure 2.28. Roman Soldier with Gladius Sword [26].

The word Gladius is a Latin word for sword, and could refer to any sword. However, it is commonly used to represent the short sword of the Roman infantry soldiers. The Roman Gladius went through several changes during its use creating four types over the Roman timeline. The types of Gladii are commonly categorized into two types called, the ‘Mainz’ and the ‘Pompeii’, with each containing two different sword types. These swords can be seen in Figure 2.29.

The first Gladius was the *Gladius Hispaniensis* ,or Spanish Sword, which had a leaf shaped blade around 5cm in width and a length ranging between 75-85cm. The Hispaniensis had the longest blade as well as a long triangular tip. The Hispaniensis type of Gladius was use up to the end of the Roman Republic (27 BC) and was transformed into the “Mainz” type Gladius. The Mainz gladius was slightly shorter (65cm-70cm) but larger in width (7mm) than its predecessor. This sword had a distinctive curvature along the length of the blade, tapering in towards the middle of the blade.

The Gladius sword underwent significant changes during the middle of the first century AD. The result was a transition from the Mainz type to the Pompeii type. The major difference is due to the parallel edges and a shorter tip. The Gladius also kept shrinking in length and width throughout the centuries with the Pompeii averaging between 60-65cm in length and 5-6cm in width. Another notable version of the Gladius is the Fulham Gladius. It could be considered a mix of the Mainz and pompeii types, consisting of the parallel edges of the Pompeii and the long tapering tip of the Mainz.

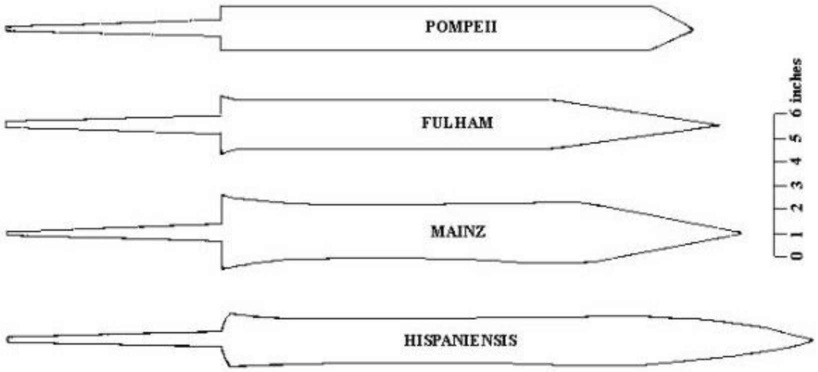


Figure 2.29. Roman Gladii Types [26].

2.6.5 Spatha (Long Sword)

The Spatha, shown in Figure 2.30, was a Roman cavalry sword that was derived from the Celtic long sword. Its length gave the cavalry men the reach they needed to attack the opposing soldiers. The blades ranged between 65-95 cm in length with a double edge. The swords could had triangular tips or rounded tips to reduce the potential of injury to the soldier legs and feet or to his horse. Evidence from first century AD tombstones showed that the calvary men wore the Spatha on their right side of their body, however later tombstones showed the men wearing their Spatha on their left side [27].

Two types of Spatha were in use during the Roman Empire. There was the *Straubing-Nydam* which was long and thin and the *Lauriacum-Hromowka* which was wide and heavy, shown in Figure 2.31. The weight and size of the Lauriacum Spatha implied it was meant for slashing while the Straubing Spatha could be a thrusting or slashing weapon.

In the first and second century AD, the Spatha was primarily used by the cavalry while the infantry soldiers relied on the shorter Gladius. In late second or early third century AD, the Spatha became more popular among the infantry soldiers [33]. The change to the Spatha suggested major changes in the battles the Roman infantry soldiers were facing. A possible explanation is this is the result of an increase in encounters between Roman infantry and enemy cavalry soldiers. This makes the identification of the sword's owner hard to tell because the Spatha seemed to be used evenly between the cavalry and infantry.

Figure 2.30. Replica Roman Spatha [33].

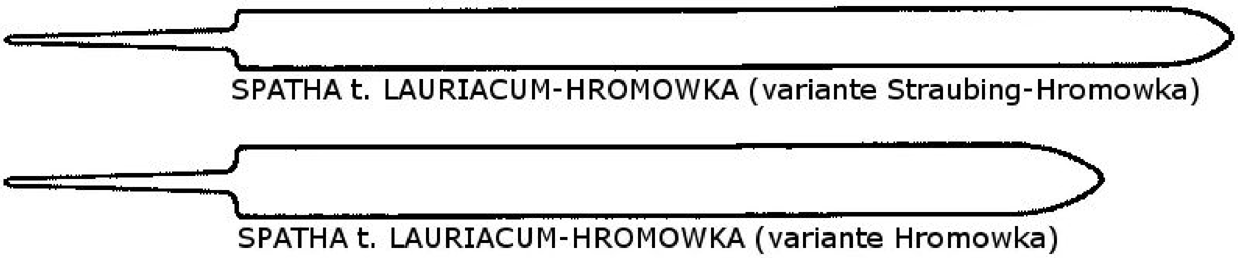


Figure 2.31. Straubing and Lauriacum Spatha [74].

The archaeological evidence of Roman Swords is by no means in abundance, but several swords have been found allowing research into the metallurgy of the swords. Of the swords discovered only a small number have been Spathas and the majority of these Spathas date back to the second and third century AD [28]. An example of an early century Spatha (first to second century AD) was found in Augst [29]. An analysis was conducted on this sword, which displayed laminations of iron and steel plates that were forge welded together. The metallurgy of the Roman Spatha will be discussed in detail in Chapter 3.

Another example of two Roman spathas belonging to two Roman cavalry soldiers can be seen in Figure 2.32. These swords date back to the second century AD and are located at the Canterbury Museum in England. These swords were found at the grave site of two Roman cavalry men in Canterbury England. This discovery is actual unique due to the fact that the cause of death of the soldiers is unknown and the burial did not follow the typical Roman burial techniques. The fact that the soldiers were buried with their swords was unusual and was uncommon of the Roman army. The Roman army had a strict policy of returning weapons to the armory upon the death of a soldier [39].

Figure 2.32. Spatha Swords from Canterbury Museum [35].

Of the Spathas found, the best preserved was discovered in Cologne Germany. This was a late century sword (fourth Century) and had a length of 90.5cm. The Ivory hilt and a silver reinforcement on the Scabbard tip was also well preserved. Figure 2.33 shows the blade and ivory hilt of the Spatha from Cologne [27].

Figure 2.33. Fourth Century Roman Spatha from Cologne Germany [27].

2.7 Roman Weapon Materials and Technology

This section discusses how the Romans produced their iron. This includes discussing technology and knowledge behind the Roman mining process, all the way to extracting the iron from the ore with the Roman iron blooms.

2.7.1 Roman Mining

The Romans mined everywhere in their vast empire. Tin, copper, lead, gold, silver, and the ever important iron were all critical to the success of the war machine and cultural center that was the Roman Empire. However, without access to power tools or any electrical lighting, the Romans had a limited ways to mine these ever important metals. There were three ways, each increasing in difficulty and complexity.

The first and simplest way was more or less a form of gold panning, where the metal was exposed on the surface in places like streambeds. Streams would erode away the ore, and the heavier metal would then settle to the bottom of the stream, allowing quick and easy collecting.

The second technique was a form of surface mining. When the Romans found deposits of ore in the ground or rocks, they could follow these veins into the surface by strip-mining [41]. What is even more interesting is a technique the Romans sometimes used to find these veins of ore. Using a system of aqueducts, they would fill up a large amount of water into tanks and then release it to break away the surrounding dirt and debris. This technique was known as “hussing” [42].

The last and most complicated technique was deep-vein mining and was only used for highly valuable metals like silver and gold. After a suitable site was found, tunnels were excavated in the rock to remove the ore. Narrow vertical shafts were driven through the rock, widening out to horizontal galleries where the ore was found, as depicted in Figure 2.34. Sometimes, horizontal adits from a hillside were driven as well. Working below ground, the miners had to deal with the need for lighting, the dangers of poor ventilation, and the presence of water in the tunnels [43].

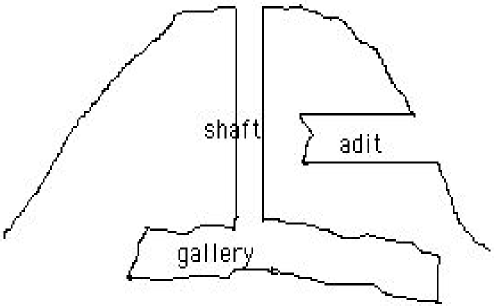


Figure 2.34. Mining Diagram [49].

2.7.2 Tools

The main mining tools used by Roman miners were made of iron, but stone tools have been found in some locations [44]. When mining hard rock, iron hammer and chisels would be used. When mining softer rock, 20cm long iron picks were used. Once the ore was mined it would be placed in buckets or baskets for easy transport.

When deep shaft mining, ventilation and lighting were also a problem. In terms of ventilation, when digging deep into the earth, toxic fumes released from the removed ore and rocks could be deadly to miners. Not only that, but inside the mines was hot. Every 30m below the surface increased the temperature by about 1℃. In order to fix this problem, the Romans build horizontal ventilation shafts to allow the warm and toxic gas from the mines to rise and be replaced by fresh air from the outside [45]. For lighting, miners used oil lamps just like those found in Roman homes. Torches could also have been used, but they would have just added to the already bad ventilation problem of the mines.

2.7.3 Iron Production

During the Roman empire the production of iron was spreading throughout Europe [23]. Figure 2.35 shows a map of iron productions across europe in the 3rd century. Iron had a broad range of applications in the Roman society. These applications include used in construction like beams and nails, tools used for metal, wood and stone working, and surgical instrument [23]. The largest application would be weapons and armor for the Roman military.

According to Pliny's Natural History, the Romans imported irons such as Seric Iron and Parthian Iron. The Iron ore that was collected from the various location of europe was not identical. The ore collected from some sources produced brittle iron that could only be used in low stress applications while others produced iron that would rust rapidly [23]. High quality ores could be found at locations such as Noricum. This ore produced some of the highest quality Roman steel and will be discussed further in chapter three. The main ores used in the Roman iron industry included iron oxides (hematite, goethite, limonite, magnetite), carbonates (siderite) and, less commonly, weathered hydrated silicates and sulfide ores [23]. According to Janet Lang (2017) the "Romans utilized low carbon or plain iron (C0.1%, with slag and oxide inconclusive), phosphoric iron (variable compositions, typically 0.5% P or less)" [23].

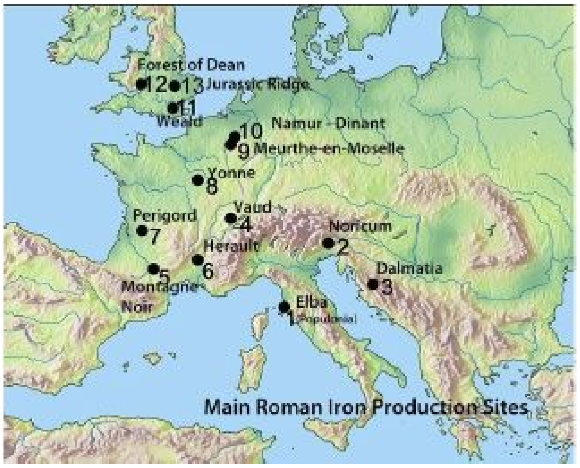
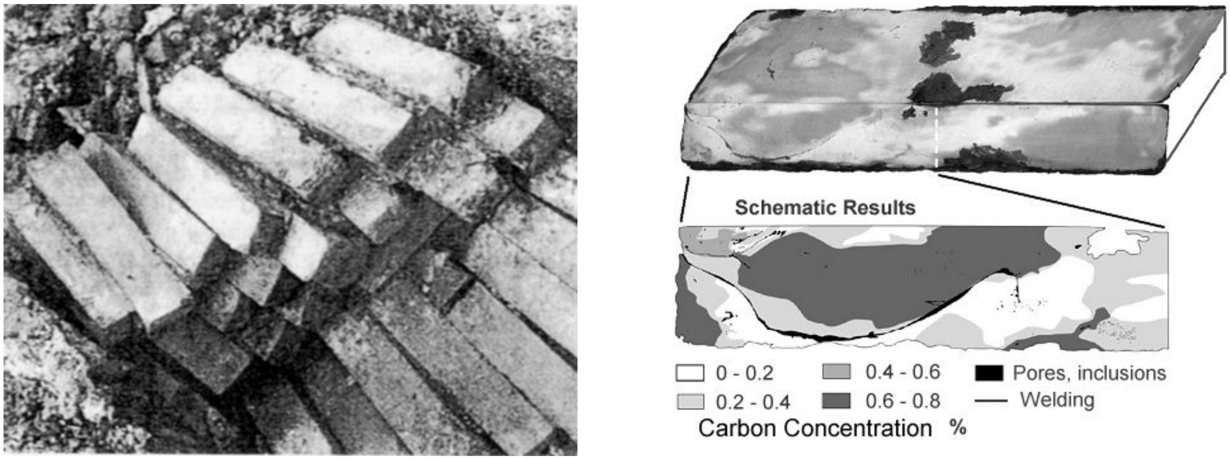


Figure 2.35. Iron Production Map [23].

Around 250 AD there was a boom in the iron industry, likely due to the well organized Roman iron industry. A common trait in Roman society was the use of standardization. The Romans would manufacture their iron into standardized rectangular bars of various sizes. A small amount of these bars have dug up while the majority have have been found from shipwrecks. Figures 2.36(a, b) shows iron bars found in a shipwreck in the Mediterranean. Bars from 27 BC - 96 AD bars have been analyzed and surprisingly the results would not make you appreciate the quality of Roman iron. The results displayed a heterogeneous mixture of Carbon and Phosphorous as well as many pores and weak welds [37].



(a) (b)

Figure 2.36. (a) Standardized Iron Bars from Shipwreck and (b) Iron Bar Analysis [50].

2.7.4 Roman Bloomeries

A bloomery is an ancient furnace and was the primary method of iron smelting in the Roman Empire. It produced a combination of iron, charcoal and slag, called “bloom”, which was further refined into wrought iron. The bloomery was later replaced by the blast furnace in the high middle ages. An example of what a bloomery looked like be seen in Figure 2.37.

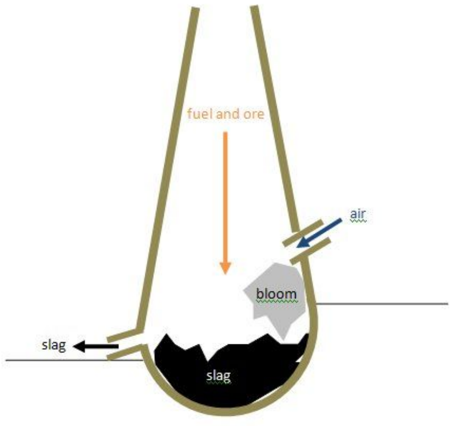


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Figure 2.37. Drawing of Roman Style Bloomery [94].

Figure 2.38. Bad Roman Bloom [51].

In a bloomery furnace, iron mixed with charcoal is placed on a bed of red-hot charcoal. It was common for the iron ore to be broken up (into 5-20 mm diameter pieces) and then roasted to remove water, carbon dioxide and to increase permeability. Once in the furnace the ore would be chemically reduced, but because ancient furnaces could not reach hot enough temperatures (reaching about 1300°C while needing 1500°C for the full process) the ore would remain in a solid state. As the ore was further reduced impurities would separate and create slag. The slag was produced by gangue, a worthless material that surrounds the ore mainly consisting of silica, lime and alumina. Around a temperature of 1100°C and 1300°C the slag would become molten and flow to the bottom of the furnace into the unreduced iron ore [27]. This mixture iron ore, charcoal and slag together produced the “bloom” as mentioned above [45]. Roman smiths would take this bloom and repeat the reheating process, being sure to hot hammer in between heatings. This difficult and tiring process removed most of the slag and produced wrought iron which was used for manufacturing weapons. Figure 2.38 shows an example of bad Roman bloom that was found in Hüttenberg, Austria [51].

3. Roman Manufacturing Processes and Materials

This chapter discusses the properties of the iron and steel used in the manufacturing of weapons and armor during the Roman Republic and Empire. This section also highlights the many processes and techniques used in the Ancient Roman blacksmithing.

3.1 Difference Between Iron and Steel

This section examines the difference between iron and steel. Both materials come in many forms with various important properties. Because of these properties, steel and iron were widely used in the ancient world for many different purposes.

3.1.1 Iron

Iron is a shiny, greyish metal which reacts with oxygen. By some estimates, iron had been used as early as 3200 BC. In today's world iron is the most widely used metal because of its low cost and abundance. Nearly 5.6% of the Earth is iron, which can be found primarily in minerals like hematite ($Fe_2O_{.3}$) and magnetite (Fe_3O_4), and also in sources such as limonite (FeO (OH) nH_2O) and siderite ($FeCO_3$). Ninety percent of all refined metal today is iron, mostly used in applications of civil engineering and manufacturing. Iron is used in a wide variety of fields because its properties can be changed by adding other elements to it such as chromium, vanadium, carbon, tungsten, and manganese [106].

3.1.2 Carburizing

Carburizing is a heat treating process in which iron absorbs carbon from a source, such as charcoal. Adding carbon atoms to the iron makes the metal harder. Carbon contents vary depending on the amount of time and the temperature during the process. When the metal is carburized at higher temperature for long time, the carbon atoms diffuse in metal inner depth. However, when the steel is cooled fast by quenching, this does does not give carbon atoms enough time to reach metal's inner depth. Rapidly cooling the metal leaves higher carbon content on the outer surface, and lower carbon content in its core [107].

3.1.3 Steel

There are many different alloys that can be created by adding different elements to iron. The most common alloy added is carbon, which produces steel. Steel is used in many different applications such as infrastructure, automobile, tools, appliances, etc. because of its low-cost and a good balance of toughness and ductility. When the iron contains less than 0.08% of carbon content it is called wrought iron. Wrought iron crystal structure have really small resistance between the iron atoms which make wrought iron soft and quiet ductile. When more than 0.1% of carbon is added to the iron it becomes an alloy commonly known as steel. Steel offers both toughness and ductility, and cast iron on the other hand consists of more than 2% carbon which make it tougher than steel, but it reduces the iron's ductility and makes it brittle. This makes steel the most commonly used alloy [108].

3.1.4 Various Steels

Most of the steel produced today is called carbon steel, which contains only small amounts of carbon. Carbon steel are just basic steel which contains less than one percent carbon and the steel that contains carbon between one to two percent are called high carbon steel. Increasing the carbon content in steel makes the steel harder because the carbon atoms prevent the iron atoms from moving apart each other, but this also make the metal lose its ductility. A wide variety of objects are made from carbon steel such as automobile, engine parts, etc [108].

Alloy steels are stronger, tougher, and more durable than the normal carbon steel. Adding elements such as chromium, copper, manganese, nickel, vanadium, or silicon, to iron and carbon, makes it an alloy steel. These elements add new and improved properties to the metal [108].

Tool steel are used in tools, and machine parts which requires it properties of extra hardness and the resistance to wear. This can be achieved by a process adding elements like nickel, molybdenum, or tungsten. More toughness is also added to the tools steel called tempering, which requires heating up the steel and then cooling it slowly [108].

Stainless steel is made by adding high quantity of chromium, and nickel. This makes the steel resistant to corrosion which allows it to be used in applications such as home appliances and medical equipments [108].

3.2 Roman Spatha Manufacturing

Before we begin the construction of our own spatha, we must understand how the Roman Spatha was made. There has not been many Roman Spatha (or Gladii) found, but of the Roman swords found and analyzed, there is general uniformity in the materials and processes used to make them. However, every sword is unique and it is clear that each smith put in their own personal touch [24].

3.2.1 Blacksmithing Process

The Romans had an adequate knowledge of the properties of iron and steel, but it is unclear how accurately these properties were used or produced. As stated in Section 2.7.3, the Romans knew the iron ore from different regions would yield steel and iron with different properties. The Romans also knew how to carburise the iron into steel, and produce steel with varying carbon content. This was very beneficial as the ideal swords would consist of a high carbon edge and a low carbon body. The high carbon edge would allow the sword to cut through harder objects and retain its sharp edge, while the low carbon body would allow the sword to bend without breaking. To create such a sword, the Romans would identify and weld together steel of various carbon. The Romans used forge welding, and after third century AD, used pattern welding, which will be explained in the next sections [30].

The thickness of the swords' cutting edges were then reduced with two techniques. One technique was to forge the sword to be thinner, conserving the metal of the blade. The other techniques was to grind away the edges using a whetstone and oil. The swords could then be hardened by quenching. Quenching is when a hot object is immersed into a quenching medium to be cooled rapidly. It was feared that quenching with water would make the metal brittle, so the iron was usually quenched with oil. Tempering or slack quenching was also used to reduce the hardness or brittleness of the metal. While the Romans clearly possessed knowledge of these processes and desired outcomes, they were not consistently used. The usage of these processes varied not only across different centuries, but also during the same century. More on this will be discussed in Section 3.3.

3.2.2 Forge Welding

The history of joining metals goes back to the Bronze age, where bronzes of different hardness were often joined by casting-in. This method consisted of placing a solid piece into a molten metal contained in a mold and allowing it to solidify without actually melting both metals, such as the blade of a sword into a handle or the tang of an arrowhead into the tip. As discussed in Section 2.7.4, ancient people smelted iron by first using bloomeries to make it into sponge iron, and then hammered it to work out the impurities to create wrought iron. The problem with this was that it was impossible to make large iron works from one piece of iron because of the heat and work required to produce even a small piece. To overcome this problem, forge welding was used to combine many small pieces of iron together into one large piece. As the process improved over time through trial and error, people began combining other kinds of metals and alloys with forge welding, creating alloys that were stronger and more durable than were possible before.

Welding is generally separated into two different categories: diffusion and fusion. Diffusion is the process used in forge welding. You heat the entire metal and the weld occurs directly between the weld interface. This includes cold welding, explosion welding, and forge welding. Forge welding is a preferable method to cold welding in many ways because it can be used on harder metals and alloys. Fusion welding is a more modern style that wasn't possible with ancient or medieval technology. However, it is much faster and localized than diffusion. Fusion is localized welding at a single point, usually involving temperatures significantly higher than the melting point of the metal in order to heat it up before it diffuses. Often a filler metal is used so that the weld doesn't segregate [97].

3.2.3 Pattern Welding

Pattern welding is the process of welding different pieces of iron or steel are welded in a way for an *intended* pattern to appear on the the surface [98]. Pattern welding first appeared around 200 AD and is mostly attributed to Celtic blades. However, the Romans possessed knowledge of pattern welding as it can be seen in many of their blades from 100 AD to 500 AD.

Pattern welding.does not seem to have any positive effect on the quality of the iron, except for the visual appeal. It is speculated that pattern welding was developed to make steel or iron pieces long enough for a long sword when only small pieces or iron or steel could be produced by the furnaces [29]. Knowledge of iron and steel with significantly different carbon content would allow the Romans to produce longer, aesthetically pleasing blades, such as the spatha, using pattern welding.

Examples of old, pattern welded blades that have been found can be seen in Figure 3.1. Due to the decomposition of the blades from the Empire's time, it is impossible to determine exactly how the blades looked at the time. Nonetheless, the surface effect of pattern welding can be seen looking at modern pattern welded blades. Figure 3.2 is an example of pattern welding on a (modern) spearhead.

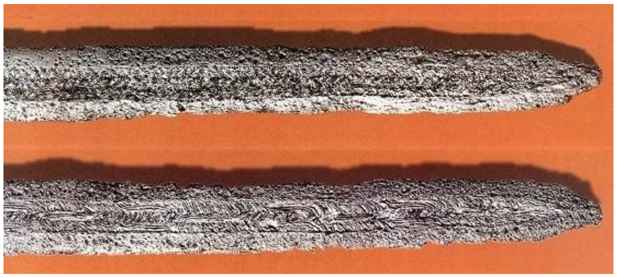


Figure 3.1. Old Pattern Welded Spatha [98].

Figure 3.2. Modern Pattern Welded Spearhead [99].

Both the pattern welding done now and during the Empire's time involves forging contrasting layers of metals together and then twisting the layers into rods as seen in Figures 3.3 and 3.4.

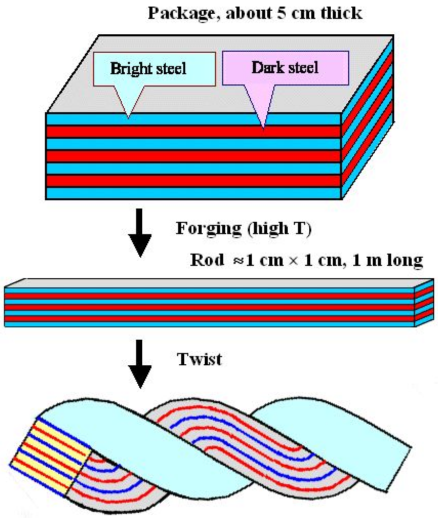


Figure 3.3. Pattern Welding Layering and Twisting of Metal [98].

Figure 3.4. Twisted Rods for Modern Pattern Welding [99].

The rods are then forged together usually along with other non-pattern welded metal as seen in Figure 3.5 [98].

Figure 3.5. Arrangement of Rods For Welding [98].

The finished surface pattern depends on multiple factors. The pattern that becomes exposed is dependent on much is grinded off the twisted striped rods, as well as the number of layers used to make the rods. The number of rods used and the direction of the twist during when arranging the rods also influence the finished pattern [98].

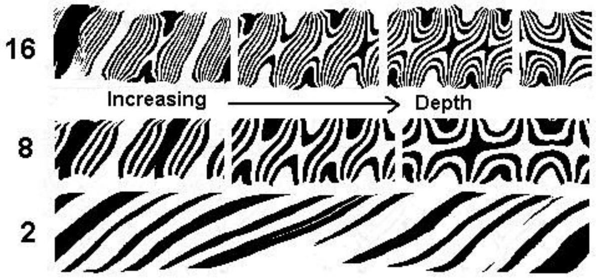


Figure 3.6. Pattern Result of Varying Amount of Layers and Ground off Depth [98].

Figure 3.7. Herringbone Pattern Result from Twists Running in Alternate Directions [98].

Figure 3.8. Interrupted Twist [99].

3.2.4 Hilt Material and Attachment

The Spatha hilt was made of wood, bone, or ivory, and a thin brass plate was usually set into the bottom of the hand guard. A couple hilt parts were found to be made of maple [27], but otherwise very few wood handles have survived the test of time. Bone and ivory grips were typically grooved and were usually hexagonal or octagonal in section. Pommels were generally spherical, a flattened "spheroid" shape, or even egg-shaped, though some were flat discs. They could be made of bone or steel, but were primarily wood matching the handle. The guards were similarly round or oval in plan, being made primarily from wood. A metal insert of bronze, or on occasion steel, was set into the guard's face to provide more protection for the hand.

The Spatha's tang ran all the way through all three parts of the hilt, and was peened over a washer or small brass finial at the end of the pommel. This process is identical to that used on the Gladius, and was the general standard of the time for sword hilts [101]. An example of a Roman sword hilt can be seen in Figure 3.9.

Figure 3.9. Roman Sword Hilt [100].

3.3 Analysis of Roman Swords

There are two main methods to learn about the technology and construction used in the arms and armor of any past military organization. One is through the analysis of the equipment, and the other is through the writings from historians of that time. This is no easy task as there may be insufficient archaeological evidence. When there are artifacts found, there is a high risk for damage of the pieces when analyzing, which is not ideal because the artifacts are the rare and possibly priceless. This would be the case when studying the arms and armor of the iconic Roman military. Despite the extensive duration of the Roman Republic and Empire, limited evidence has been found [29].

One reason for this could have been due to the regulation of the weapons by the Roman military. During the Empire, the equipment were owned by the military organization, not the soldiers. Because of this, the weapons and armor were expected to be given back upon the soldier's retirement. This is uncommon compared to other military organizations. For example, in many other military organizations the soldiers would be buried with their swords. When these grave sites were eventually found the weapons were also found. Unfortunately this would not be the case for the Roman soldiers, which ultimately lead to a small percentage of weapons found.

Although there is a small amount of archeological evidence, there has been enough analysis conducted on ancient Roman equipment to provide a foundation of knowledge on the techniques and construction practiced by the Roman military. A few Roman swords, including the Spatha, that have been found and analyzed, which will be discussed below.

A large amount of information about the metallography of Roman Era swords can be seen in Janet Lang’s Study of the Metallography of Some Roman Swords [30]. Her study consisted of six Roman swords, five from the British Museum and one from the Chichester Museum. A list of the swords is shown in Table 3.1 and can be seen in Figure 3.10.

Table 3.1. Time and Location of Swords in Janet Lang's Study [30]

Description	**Time**	**Location**
The Sword of Tiberius	First half of the first century AD	British Museum
The Fulham Sword	First half of the first century AD	British Museum
Sword found in the Thames	First to second century AD	British Museum
Sword found near the Mansion House	Late first century AD	British Museum
Sword from Hod Hill	Mid to late first Century AD	British Museum
Sword From Chichester	First half of the first century	Chichester Museum

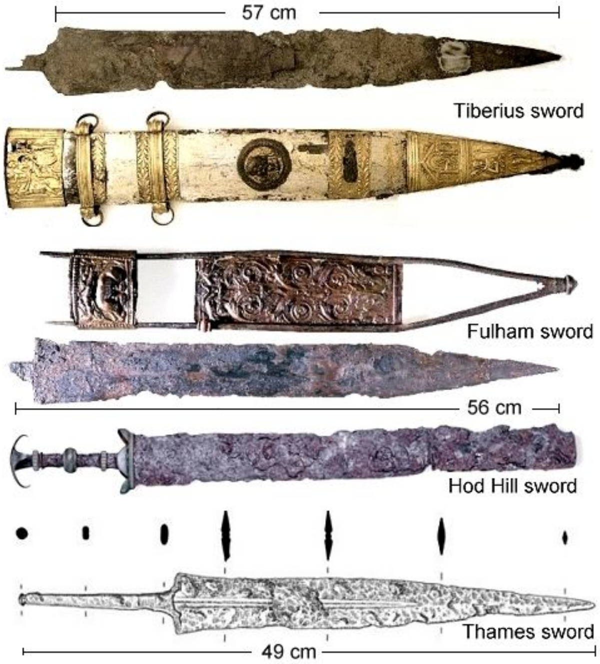


Figure 3.10. Swords from Janet Lang's Study [24].

All of these swords were identified as Gladii. The Sword of Tiberius, the Fulham Sword, the sword found in the Thames and the sword from Chichester were classified as the Mainz type. The sword found near the Mansion House had dimensions similar to a Pompeii type Gladius. Janet Lang tested each sword by taking wedge shaped samples from the cutting edge of the blade, as seen in Figure 3.11. These samples were examined using the same process our team will be using to examine our replica spatha. This process includes inspecting the samples under a microscope after setting the samples into epoxy resin, and then grinding and polishing the faces.

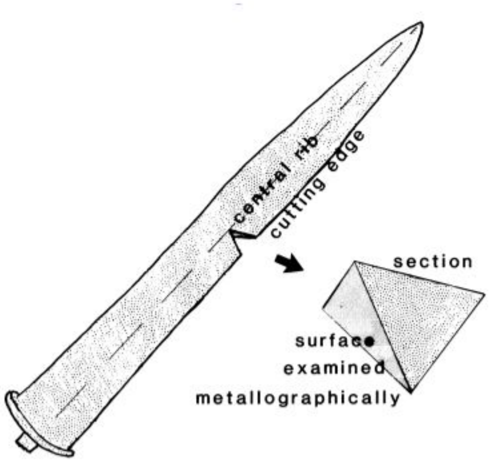
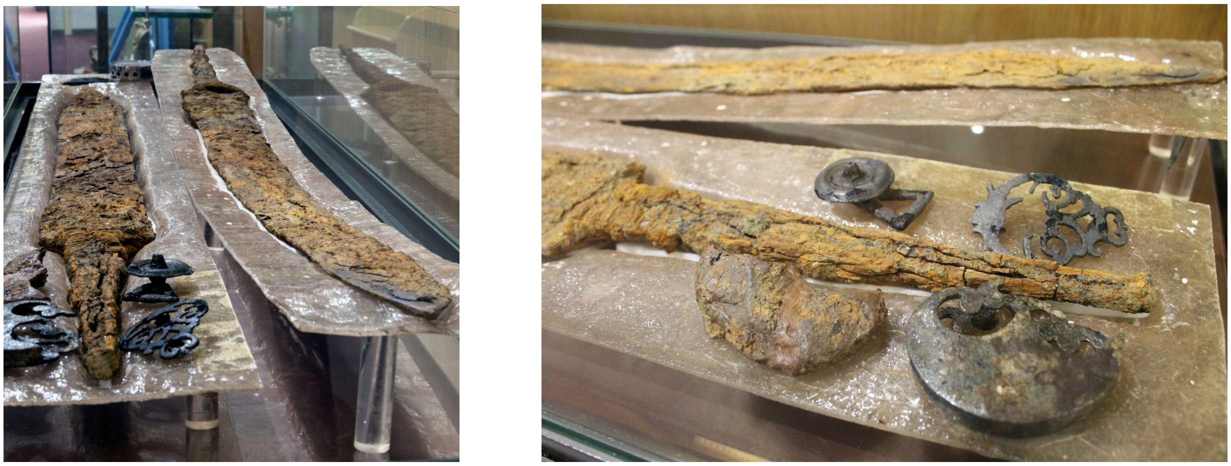


Figure 3.11. Sample Removed from Sword Edge [30].

The construction of the blades ranged from a single piece of iron to long strips of various carbon concentrations oriented in different lamination configurations. The edges of the swords were different as well. Some of the blades had the edges created by reducing the thickness of the blade toward the edges during the forging process, while others had their edges created by grinding material away. One important discovery this analysis showed was the Roman smiths knew about heat treatment processes. Quenching was used to improve the hardness of the edges. The quick cooling of high carbon blades would allow martensite to form, which would provide the hard cutting edge. However, martensite is also very brittle and could lead to problems with breakage. To counteract this brittleness the stress would need to be relieved by another heat treatment process such as tempering. Another method to counteract brittleness would be to slack quench. This is when the blade would be quenched in the liquid, but then removed before it was fully cooled. Therefore, the metal would experience a rapid cooling while quenching, and then continuing to cool at a slower rate, to the air temperature. This two stage cooling process would result in an incomplete hardening and would form other transformation products, such as pearlite and martensite. According to Lang's study it is difficult to determine whether this was carried out deliberately or accidentally [30].

Another analysis was conducted on two Roman Spathas that were found in Canterbury. The story behind these swords was discussed in Section 2.6.6, and can be seen in Figures 3.12 (a, b). X-rays were taken of the two blades. The results showed the swords were constructed using different techniques. One of the swords was constructed with four layers of iron that were forge welded together. The second sword had been constructed using a more advanced method. This sword consisted of a central iron bar that had been twisted along its length and then forge welded to another strip of iron [39]. This method was the pattern welding technique that was discussed in Section 3.2.3. Since these swords date back to the second or early third century AD, they help show the advancement of the blacksmithing technologies during the Roman Empire.



(a) (b)

Figure 3.12. (a) Spathas from Canterbury [39] and (b) Tang of Spathas from Canterbury [102].

A Spatha from Augst was analyzed and documented as well. This first or second century AD sword was constructed by forge welding a high carbon strip of steel between two strips of iron. The analysis of the blade showed the center section consisting of a 0.6% Carbon concentration and also shows phase transformations [29]. These transformation, specifically the formation of martensite, proves that this sword went through a rapid cooling process which improved the hardness of the blades edges. Figure 3.13 shows the microstructure transformations that took place.

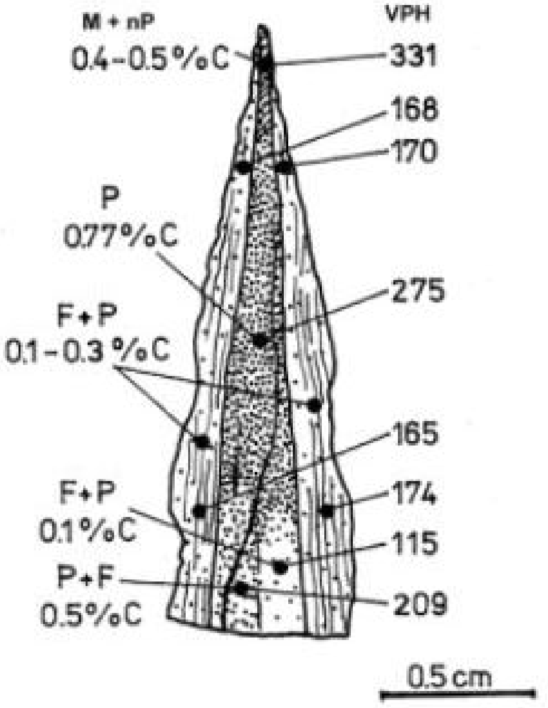


Figure 3.13. Spatha from Augst [29].

4. Material Analysis

This chapter will document the steps taken to create a Spatha sword similar to the Spathas made during Roman times. The sword chosen to be recreated is from late second to third century AD. This was the *Lauriacum-Hromowka* type described in Section 2.6.6. During the third century AD, the Roman spatha swords started to be created using more advanced techniques. Many late third century AD swords were constructed using steels of different carbon concentrations and were pattern welded together. After a discussion with Joshua Swalec, our group decided to construct our blade using a simpler, forge welding technique that was used by the Romans during first and second century AD. This simpler method was chosen due to the time frame and because of the difficulty of creating pattern welded blades.

4.1 Phase Diagrams

Phase diagrams are graphical representations of different physical states of a material under varying conditions. These diagrams help engineers to design and controls heat-treating procedures. A good understanding of alloy phase diagrams is important because of the strong association between the alloy microstructure and its mechanical properties. Also, the development of microstructures in an alloy is related to the characteristic of its phase diagram. Microstructures are characterized by the number of phases present, their proportions, and the manner in which they are distributed or arranged. This organization is directly observed using an optical or electron microscope. The heat treatment of the alloy, the alloying elements present, and the alloy concentration all affect the microstructure of the alloy. There are two main types of phase diagrams, one-component phase diagram, and binary phase diagram [103].

4.1.1 One-Component Phase Diagram

In one-component phase diagrams, the composition of the material is held constant, and the temperature and pressure are the dependent variables. This type of diagram is represented as a two dimensional pressure vs time plot. These diagrams are determined experimentally, which have solid, liquid, and vapor phase regions [103].

4.1.2 Binary Phase Diagram

In binary phase diagrams, pressure is held as a constant (usually at 1 atm), and the temperature and composition are the dependent variables. Binary phase diagrams also represent the quantities of phases at equilibrium, which affect the microsture of an alloy. Microstructures develop from phase transformation, changes that take place when temperature is changed. Binary phase diagrams help in predicting the phase transformation, and the resulting microstructures [103].

4.1.3 Iron-Iron Carbide Phase Diagram

Pure iron experiences two changes before it melts upon heating. When iron is at room temperature, it is present in a stable form, called ferrite, which has a body-centered cubic crystalline structure. When the iron is heated up to approximately 912°C (1674°F), ferrite changes phase into austenite, which has a face-centered cubic crystalline structure. If the iron is heated more than 1394°C (2541°F), it reverts back to ferrite, BCC phase, before it finally melts 1538°C (2800°F) [103].

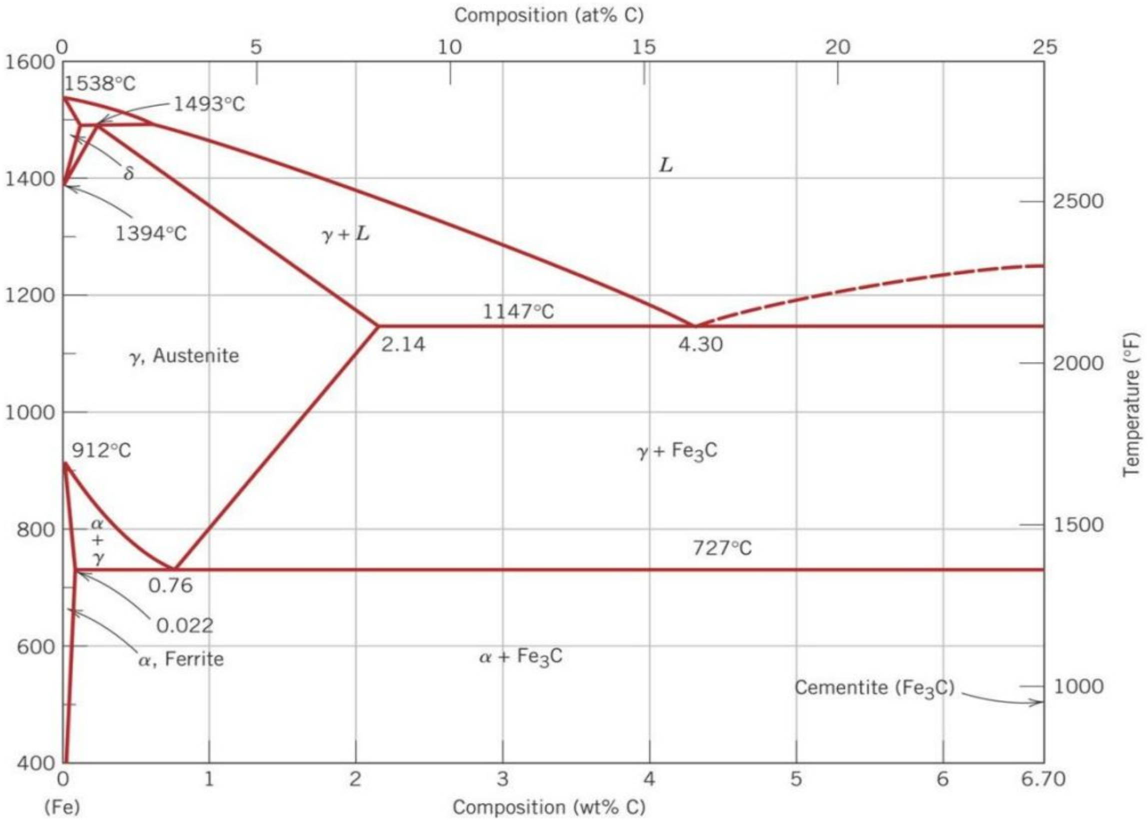
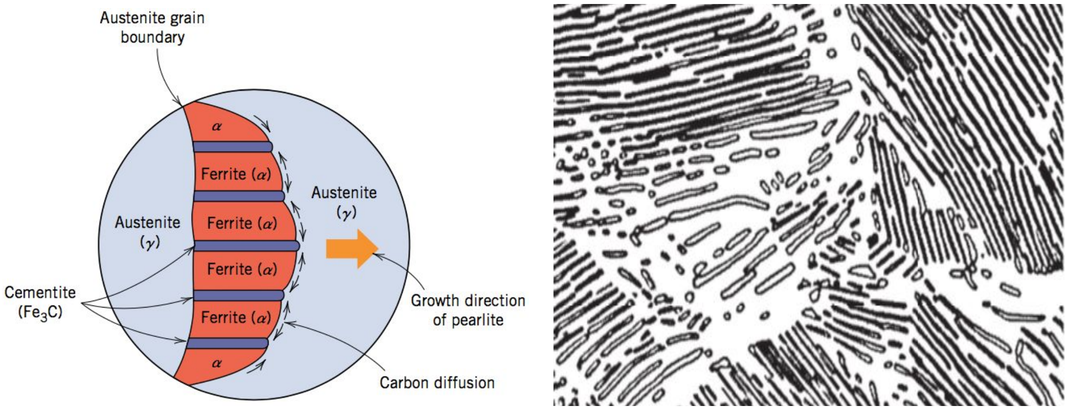


Figure 4.1. Iron-Iron Carbide Phase Diagram [103].

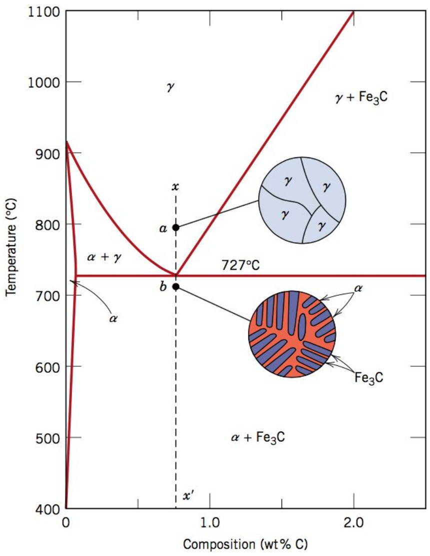
4.1.4 Microstructure Development in Iron-Carbon Alloy

Microstructures are a small scale structure of a material. A material's physical properties, such as strength, toughness, ductility, hardness, corrosion resistance, high and low temperature behaviours or wear resistance, is influenced by its microstructure. Microstructures of an alloy depend on its carbon content and its heat treatment [103].

Microstructure of eutectoid steel, which has a composition of 0.76 wt% of carbon distribution, forms perlite when cooled slowly. Perlite is a layered structure of two phases containing $\alpha - ferrite\ and\ cementite\ (Fe_3C)$. Redistribution of carbon atoms between ferrite and cementite by atomic distribution causes the layers of alternating phases in perlite, and layered structure of eutectic Perlite has properties intermediate to soft, ductile ferrite and hard, brittle cementite [103]. The microstructure and phase diagram of eutectic steel can be seen in Figures 4.2 (a, b) respectively.



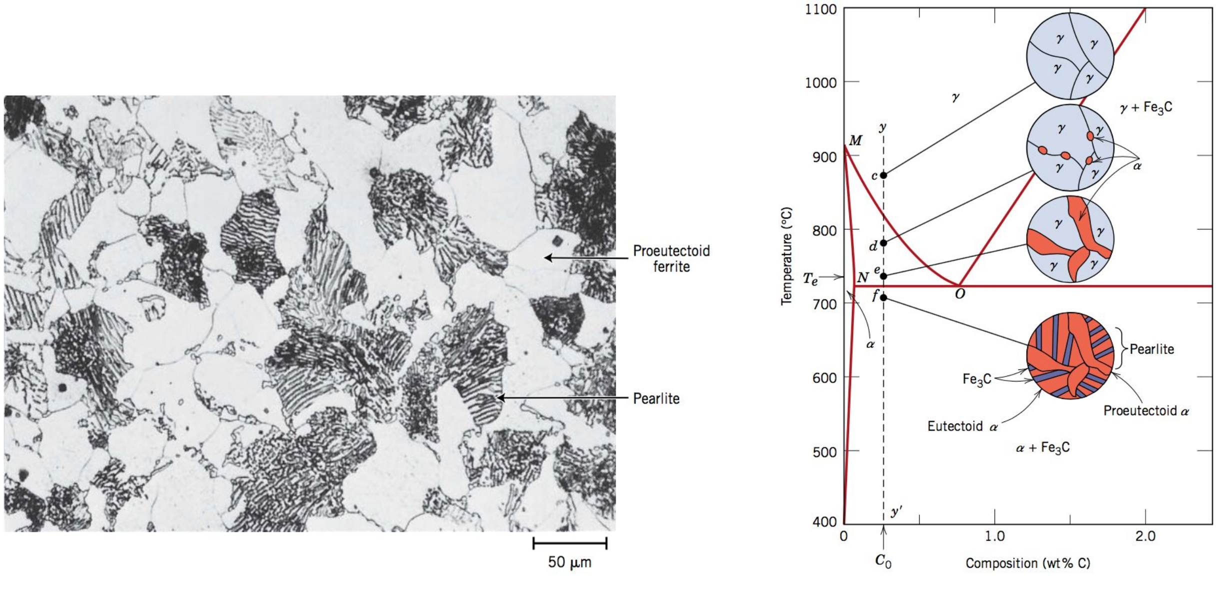
(a)



(b)

Figure 4.2. (a) Microstructure of Eutectoid Steel and (b) Phase Diagram of Eutectoid Steel [103].

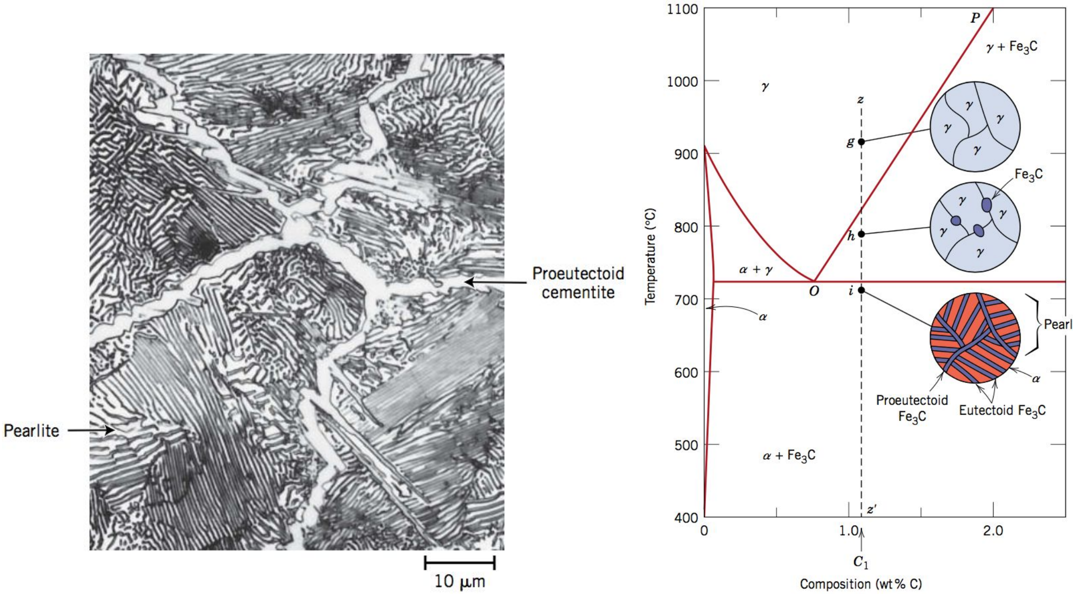
Hypoeutectoid steels have carbon composition of 0.022 - 0.76 wt% and the alloy also contains proeutectoid ferrite (which are formed above the eutectoid temperature), in addition to eutectoide perlite. The microstructure and phase diagram of hypoeutectoid steel containing proeutectoid ferrite can be seen in Figures 4.3 (a, b) [103].



(a) (b)

Figure 4.3. (a) Microstructure of Hypoeutectoid Steel and (b) Phase Diagram of Hypoeutectoid Steel Containing Proeutectoid Ferrite [103].

As shown in Figure 4.4, hypereutectoid alloys have carbon composition to right of eutectoid with composition of 0.76 - 2.14 wt% C. These alloys also contain proeutectoid cementite, which is also formed above the eutectoid temperature, in addition to pearlite [103].



(a) (b)

Figure 4.4. (a) Microstructure and (b) Diagram of Hypereutectoid Steel Containing Proeutectoid Cementite [103].

4.1.5 Isothermal Transformation Phase Diagrams and Heat Treatment

Isothermal transformation phase diagrams also known as time-temperature transformation (TTT) diagrams, or temperature vs time graphs. An example of which can be seen in Figure 4.5. TTT diagrams help understand the transformation of an alloy steel at elevated temperatures. These diagrams are only reasonable for one specific composition of the material. The temperature during the transformation is held constant, then rapidly cooled to a given temperature [103].

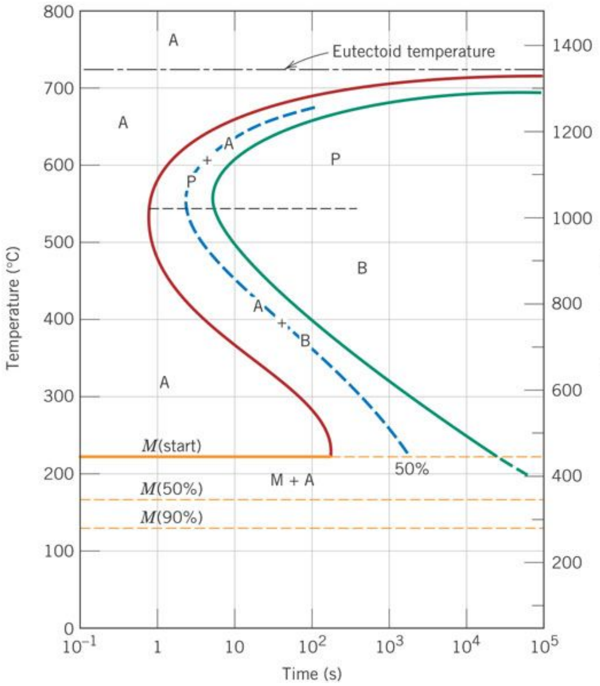


Figure 4.5. Isothermal Transformation Diagram [103].

An isothermal transformation curve is strongly correlated with the steels mechanical properties, microstructure, and the carbon steel heat treatment. The curve (ABCD) in Figure 4.6, is an actual isothermal heat treatment curve superimposed in the TTT diagram for an eutectoid iron-carbon alloy. The line AB represents the rapid cooling of austenite to a given temperature of approximately 615°C. The isothermal treatment at this temperature is represented by line BCD. As shown in the graph, the transformation of austenite to pearlite begins at point C and reaches completion to point D, in approximately 15 seconds [103].

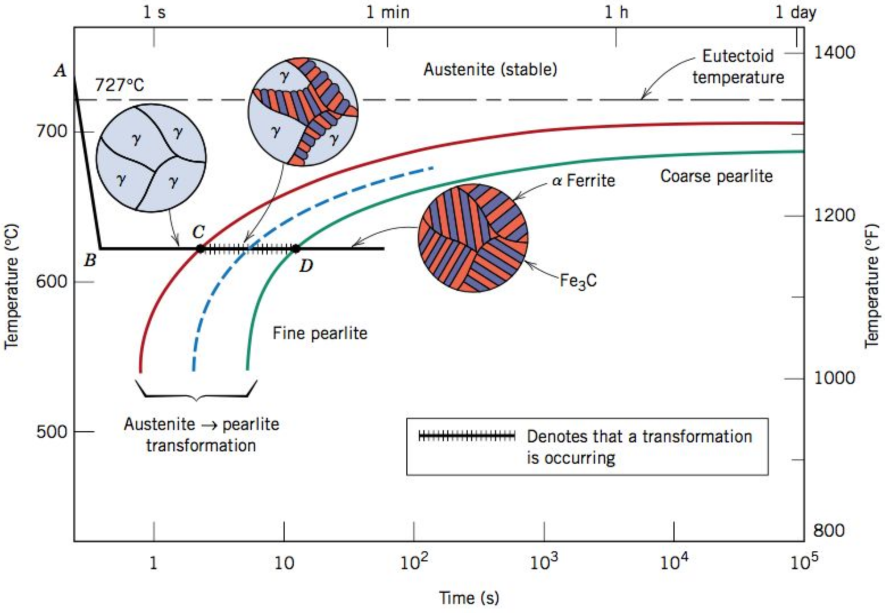


Figure 4.6. Isothermal Transformation Diagram with Superimposed Heat Treatment [103].

Thickness ratio of the ferrite and cementite layers in pearlite is approximately 8 to 1. The absolute layer thickness depends on the temperature at which the transformation occurs. Thick layers of both ferrite and Fe_3C form at temperature just below the eutectoid. These microstructures are called coarse pearlite. The diffusion rate of carbon is relative high at these temperatures, which allows them to diffuse for long distances, resulting in the formation of lamellae. On the other hand, fine pearlite is produced when thin-layered structures form at temperatures around 540°C. This is because as the temperature decreases, the rate of diffusion also decreases causing the layer to become progressively thinner [103].

Bainite, is a plate-like microstructure, which forms in iron-carbon alloys in temperatures ranging from 250°C to 550°C depending on the alloy content. Bainite is commonly composed of $\alpha - ferrite\ and\ cementite$. Ferrite, which is present in bainite, is harder than usual ferrite because of the high concentration of dislocations. If bainite is formed during continuous cooling, the cooling rate to form bainite would be faster than the cooling rate to form pearlite, but slower than the cooling rate to form martensite [103].

Spheroidite forms when steel is heated to about 700°C for 18-24 hours. This diffusion controlled process, so spheroidites can also be formed at lower temperature, but would require more time. In this microstructure, the Fe_3C phase appears as sphere like particles embedded in a continuous $\alpha - phase$ matrix, instead of alternating ferrite and cementite lamellae. This happens by further carbon distribution without having any change in the composition. This process softens higher carbon steels and allows for more formability. This is the softest and most ductile form of steel [103].

Martensite forms by rapidly cooling of austenite at a high rate, which does not give the carbon atoms enough time to diffuse out of the crystalline structure and form cementite. Quenching transforms FCC austenite to a highly strained BCC tetragonal form, which is called martensite. Martensite is supersaturated with carbon with shear deformations that result in large number of dislocations [103].

4.2 Materials

Our group chose to use two different types of steel for the Spatha blade: steel with a low carbon concentration and steel with a high carbon concentration. Tables 4.1 and 4.2 show the dimensions and chemical compositions of the materials purchased respectively. Both steels used for the sword were cold rolled. This is a manufacturing process where the steel is sent through rollers at room temperature which compressed the steel into flat sheets or bars. Being rolled at room temperature helps work harden, also known as strain hardening, the material and improves the mechanical properties.

Table 4.1. Original Material Dimensions for Replica Spatha

Property	**1018 Steel**	**1075 Steel**
Shape	Rectangular Plate	Rectangular Plate
Thickness	0.635cm	0.635cm
Length	91.44cm	91.44cm
Width	3.81cm	5.08cm
Yield Strength	53700 *psi*	58,000 *psi*
Hardness (*Brinell*)	175HB	189HB
Construction	Cold rolled	Cold rolled

Table 4.2. Chemical Component of Replica Spatha Materials

Element	**1018 Steel**	**1075 Steel**
Carbon (C)	0.152 %	0.7%
Silicon (Si)	0.210 %	0.2%
Manganese (Mn)	0.797 %	0.63%
Phosphorus (P)	0.014 %	0.01%
Sulfur (S)	0.013 %	0.005%
Chromium (Cr)	0.143 %	0.15%
Molybdenum (Mo)	0.051 %	0.02%
Nickel (Ni)	0.185 %	0.06%
Aluminium (AL)	0.017 %	0.033%

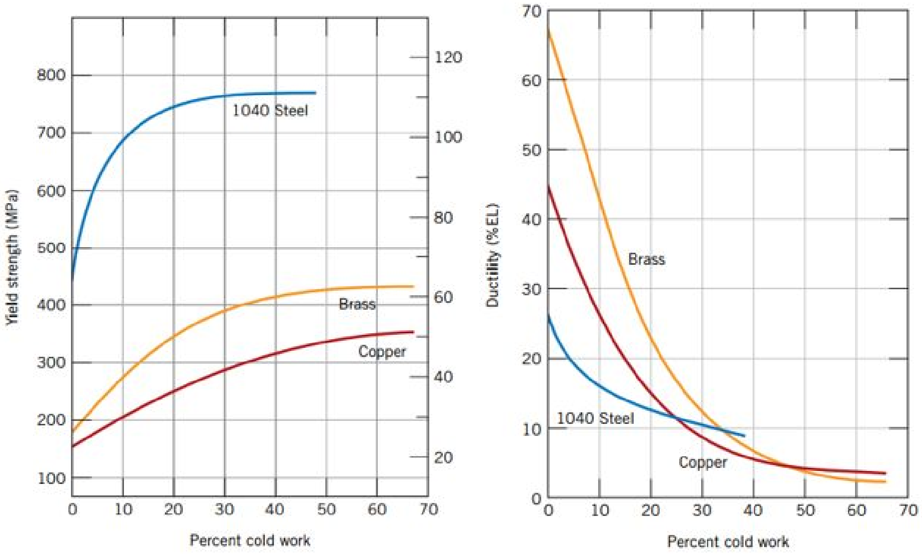
The amount of plastic deformation can be displayed as *percent cold work* rather than strain [103]. The percent cold work (%CW) is defined as,

$$\%CW = ((A_0 - A_d)/A_0) * 100$$

where, A_0 = Original area of the cross section that experiences deformation

A_d = Area after deformation

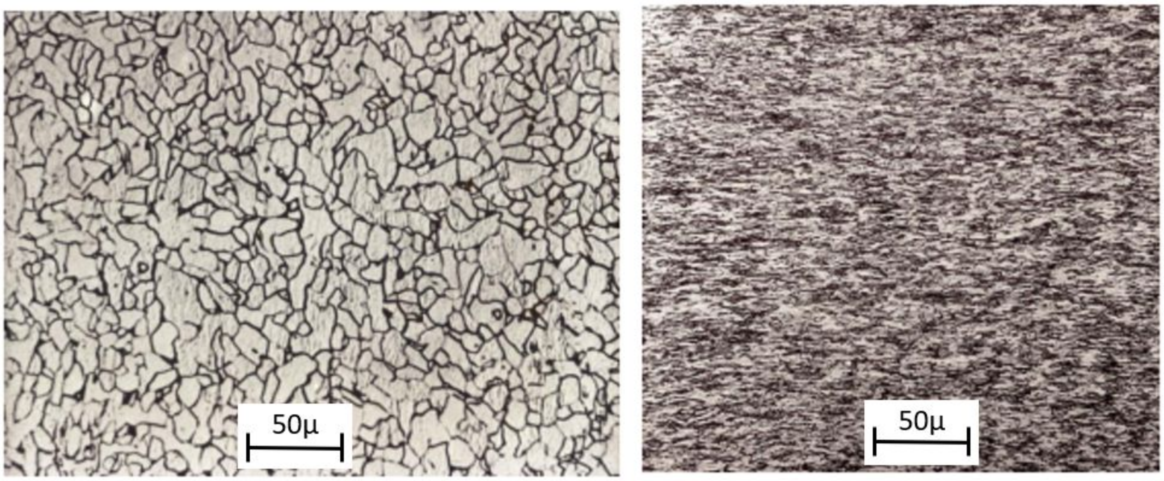
Figure 4.7(a) displays the increase in yield strength due to percent cold work. Figure 4.7(b) displays how that increase in strength causes a decrease in the materials ductility for steel, brass and copper.



(a) (b)

Figure 4.7. (a) Percent Cold Work vs. Yield Strength and (b) Percent Cold Work vs. Ductility [103].

Cold rolling also causes significant changes in the materials microstructure. When steel is cold rolled the grains of the ferrite are deformed and elongated along the rolling direction. This leads to a high dislocation density, a large amount of stored deformation energy, and anisotropic characteristics [105]. Anisotropy is defined as the directionality dependence of properties [103]. In other words, it implies the material has different properties in different directions. This is the opposite of isotropy, which properties are independent of direction. This characteristic of cold rolled steel is important to know because it means the steel will need to be examined in multiple orientations to determine the microstructures. Figure 4.8 (a, b) show the resulting microstructures of steel when hot rolled and cold rolled respectively. Knowing this information allows us to predict what the structure of the 1018 and 1075 steels will look like under the microscope. The grains should be elongated on the top and side faces but appear uniform on the front face.



(a) (b)

Figure 4.8. (a) Hot Rolled Steel Microstructure. (b) Cold Rolled Steel Microstructure [112].

The forge we will be using is fueled by propane and can reach temperatures between 1093°C-1371°C (2000°F-2500°F). Knowing the carbon concentration of our materials and the forge temperature makes it is possible to find the development of microstructure while forging and while cooling. As seen in Table 4.2, the carbon concentration of the 1018 and 1075 steels are 0.152 wt% C and 0.7 wt% C respectively. This data was collected from the specifications documents that were requested from the manufacture during the purchasing of the materials.

Figure 4.9 shows a section of the iron carbon phase diagram that includes our two materials. The green vertical lines show the carbon composition weights of our materials. The dashed horizontal blue lines show the arbitrary temperatures that will be discussed. These blue lines can also be used to find how much of each microstructure is evident in that regions.

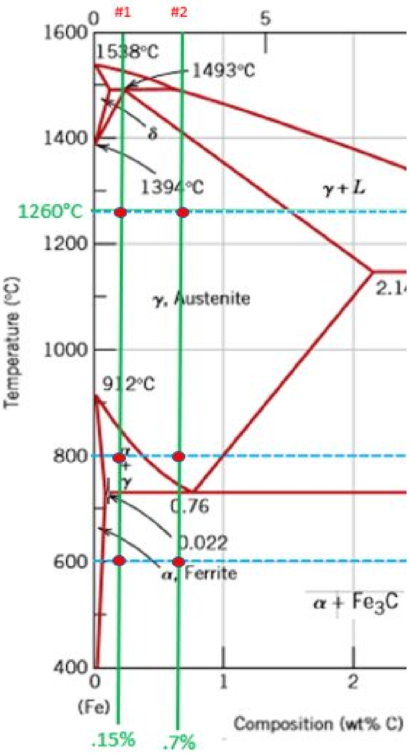


Figure 4.9. Iron-Carbon Phase Diagram for 1018 (#1) and 1075 (#2) Steel [103].

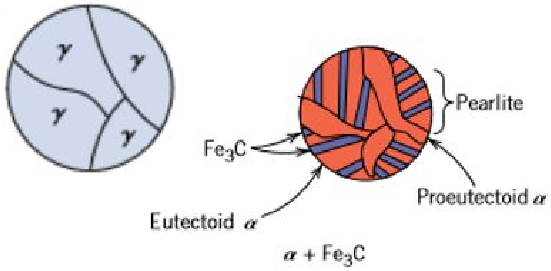


Figure 4.10 Austenite and Pearlite Microstructure [103].

When the steel is heated to the max temperature of the forge (1260°C), both steels transform into a fully austenite microstructure, as seen by the red dots along the tie line in Figure 4.10. As the temperature of the steel cools, the microstructures begins to transform. At 800°C, 1018 is comprised of austenite and ferrite, but the 1075 is still comprised of only austenite. After further cooling, both materials are located below the eutectoid temperature and are comprised of ferrite and cementite (Fe_3C). The ferrite-cementite mixture is also referred to as pearlite, seen in Figure 4.10.

The composition of any multi-phase region can be found using the lever rule. For example, let's use Figure 4.9 for the 1018 steel to find the composition of pearlite and proeutectoid ferrite for our materials, as well as the total ferrite (eutectoid and proeutectoid) and cementite. The blue line at 600°C is a tie line that extends the entirety of the ferrite - cementite phase region, from 0.022 wt% C to 6.70 wt% C. This tie line is used to find fractions for total ferrite and cementite. To find the fractions of pearlite and proeutectoid ferrite, the tie line extends only to the eutectoid composition, 0.76 wt% C. The calculations can be seen below in parts a and b.

$$W_{\propto} = \frac{6.7-0.15}{6.7-0.022} = 0.981*100 \approx 98\%$$

and

$$W_{Fe_3C} = \frac{0.15-0.022}{6.7-0.022} = 0.0192*100 \approx 1.9\%$$

(a) The fractions of total ferrite and cementite phases of 1018 steel

$$W_{p} = \frac{0.15-0.022}{0.76-0.022} = 0.173*100 \approx 17\%$$

and

$$W_{\propto'} = \frac{0.76-0.15}{0.76-0.022} = 0.827*100 \approx 83\%$$

(b) The fractions of the proeutectoid ferrite and pearlite of 1018 steel

5. Construction of the Replica Spatha

This chapter documents the creation of the replicated Spatha. This includes the initial design plan and actual construction of the blade.

5.1 Design Plan

The Spatha sword we will be constructing will be made using methods similar to the Roman blacksmiths during second century AD. Although the construction will be similar to the construction during the Roman times, the tools we will be using to create the sword will be of modern technology due to the short time frame. The replica Spatha is based the the *Lauriacum-Hromowka* sword which is a straight bladed sword with a small triangular tip. The dimensions used for the replica are from a Spatha found, from late second to third century AD [104]. Figure 5.1 shows a Solidworks CAD drawing for the replica Spatha blade, and Figure 5.2 shows the CAD model for the replica blade.

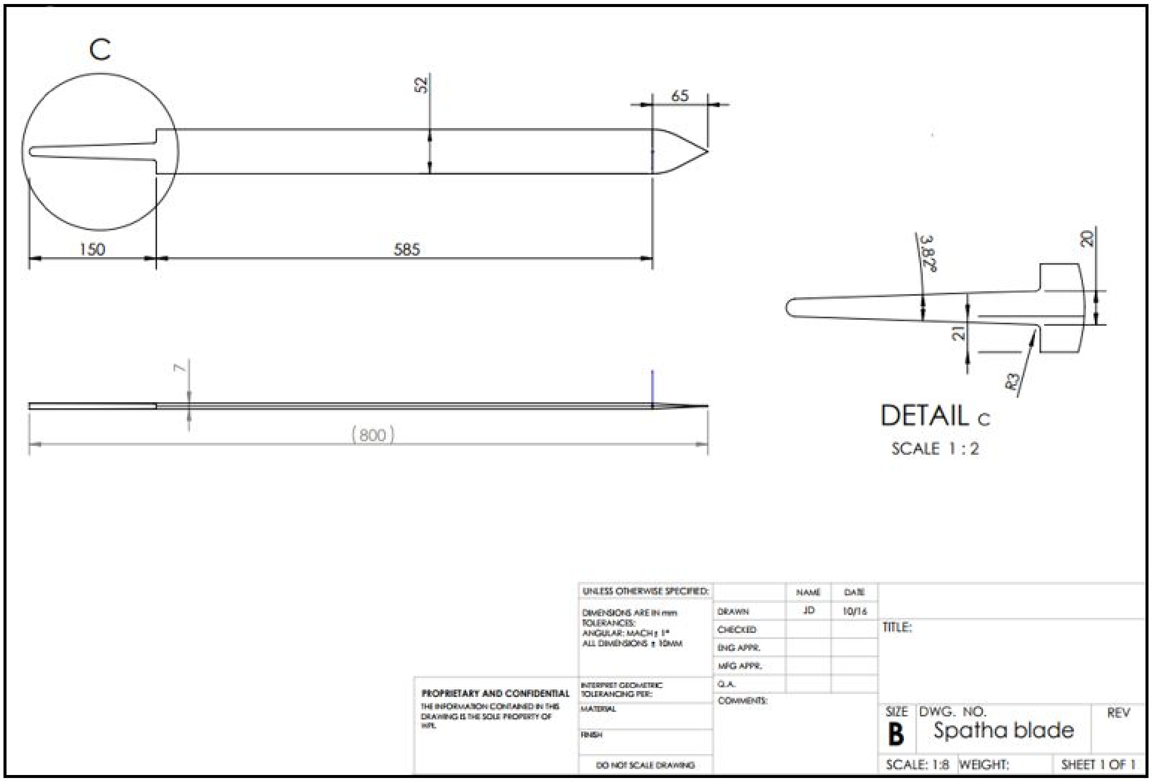


Figure 5.1. CAD Drawing of Replica Sword.

Figure 5.2. CAD Model of Replica Sword.

The replica Spatha will be created similarly to the Spatha of Augst. The blade will consist of three metal plated stacked or laminated together. The outer plates will be made from low carbon 1018 steel, classed with iron, and the center plate will be of high carbon 1075 steel. The order of the plates can be seen in Figure 5.3, with the light colored plates representing the iron (1018 steel) and the darker plate representing the high carbon steel (1075 steel).

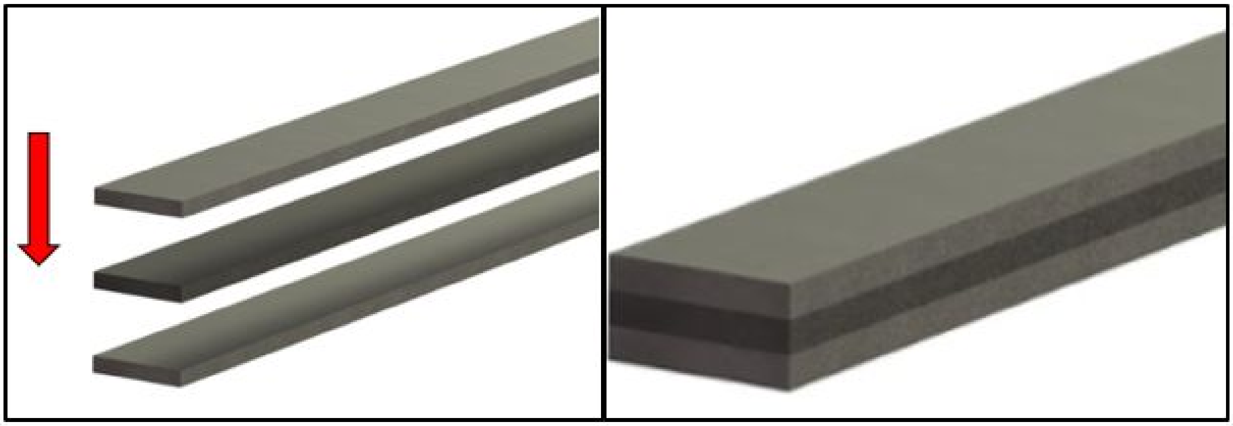


Figure 5.3. Order of Steel Laminations.

The use of the different plates allows the blade to have hard sharp edges, but still have the toughness needed upon impact. Toughness is defined as the ability of a material to absorb energy and plastically deformed without fracturing. The high carbon steel in the center of the blade is what will provide the hard edges of the blade and the iron will provide the toughness. If the entire blade was made from high carbon steel, the blade would be brittle and therefore be likely to break during use.

After the plates are stacked, or laminated, they will be forge welded them together. The entire stack would then be placed into the forge and heated to the proper temperature. Once removed from the forge, the steel stack will be pressed together by hammering, or by a hydraulic press to speed up the process.

Looking at Figure 5.4, there is a predicted difference between the dimensions of the plates and the dimensions of the final blade. This is because the plates were ordered with a smaller width, but a larger thickness than the desired width and length of the blade. It is expected when the stack of plates is compressed together, the thickness will decrease, and the width and length will increase.

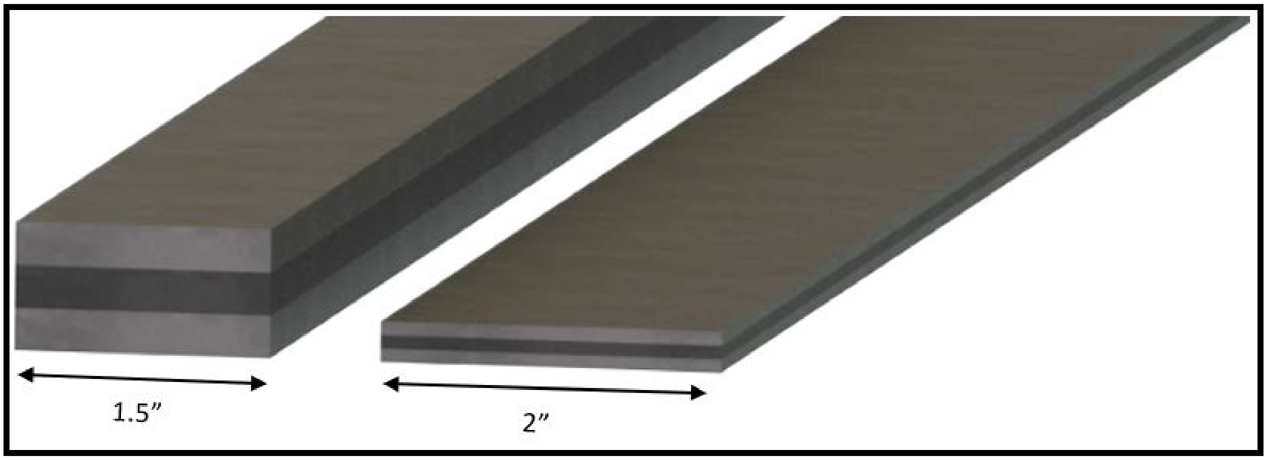


Figure 5.4. Steel Laminations Diagram.

Once the different layers iron and steel are forge welded together, the blade can be ground into the final shape. As the blade edges are ground away, the iron will be removed first leaving the high carbon steel at the edges of the blade, as seen in Figure 5.5.

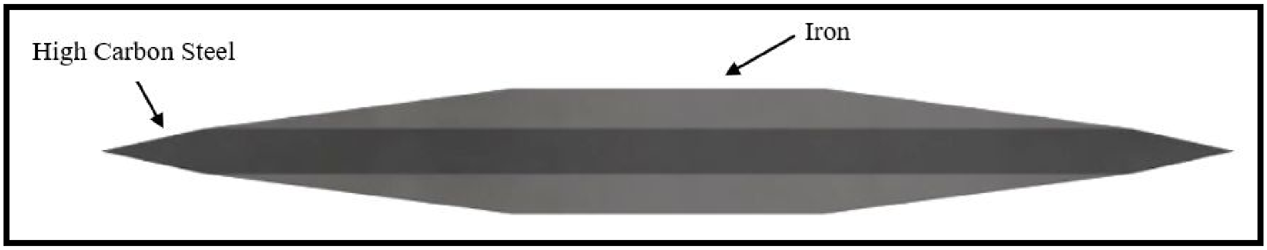


Figure 5.5. Steel Edge Diagram.

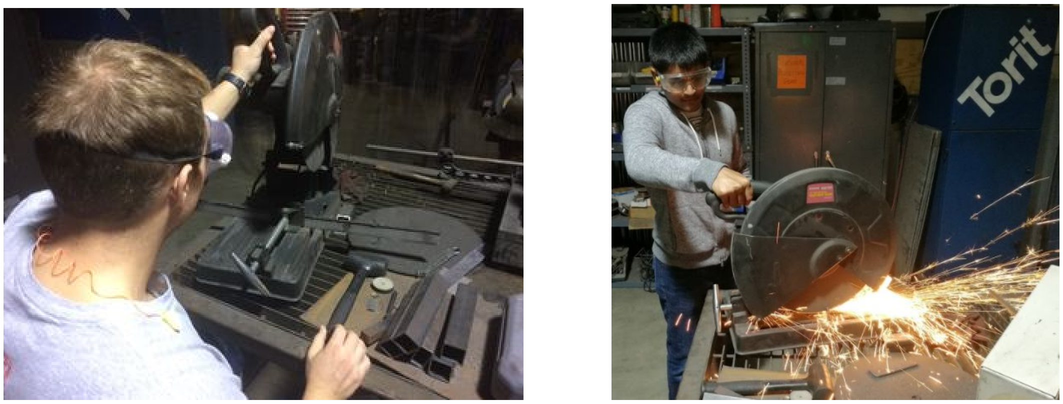
5.2 Blade Construction

Before any hammering could take place, we needed to turn the three separate plates of metal into one, properly sized piece. The starting width of the plates needed to be around 3.75cm (1.5in) wide. Only the 1018 steel was available at this width. The 1075 steel that was purchased was about 5cm (2in) wide and needed to be cut down to match the size of the 1018. This could have been done using a saw, but the high carbon concentration of the 1075 steel makes it very hard to cut. One option would be to use a specialized bandsaw blade made for high carbon steel. Unfortunately, the manufacturing labs at WPI did not have this type of blade. Instead, a plasma cutter was used to make quick work of cutting the steel. Plasma cutters are able to cut through electrically conductive materials by directing an accelerated jet of hot plasma into the material. The 5cm wide 1075 steel was clamped to the work surface with the 1018 steel on top acting as a guide, insuring a straight cut. This procedure can be seen in Figures 5.6 (a, b).

(a) (b)

Figure 5.6. (a) Original Plate of 1075 Steel and (b) Plasma Cutting the 1075 to the Proper Width.

After the different plates were at the same widths, they had to be cut to the same lengths. The process used to cut each plate into about 30cm (12in) long pieces using a chop saw, as seen in Figure 5.7. We noticed that our two metals, the 1018 and the 1075, threw off different spark patterns. These differences, as first noted by Max Bermann in 1909 [95], can be used to identify traits about the each metal, such as its carbon or alloy content.



(a) (b)

Figure 5.7. (a) Aligning Metal to be Cut and (b) Cutting Metals to the Proper Lengths.

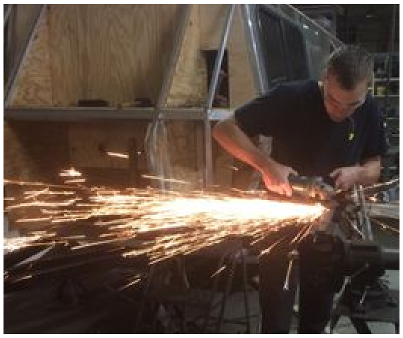


Figure 5.8. Hand Grinding.

In addition to cutting the steel into 30cm plates, we also used the saw to cut small blocks off of the raw stock. We cut one piece from one of the 1018 plates, and another from the 1075 plate. We brought these two pieces back to Washburn, where we removed a chunk of the 1075 that had been affected by the plasma cutting process. We then used the bandsaw to cut the 1018 sample and the remainder of the 1075 sample into three different pieces each, exposing all three faces of the samples. Finally, we ground down the edges & faces of the samples to remove any burrs and sharp edges that were present. These were samples of the original materials which were reserved for later analysis.

Once the metal for the actual blade was the right size, we used a hand-grinder to smooth off the faces of all three pieces. This process, as seen below in Figure 5.8, is important for the binding of the metals when we start heating them up. Scratches or bumps on the faces would result inbubbles or warping when the metal was heated and bound to each other.

Once all three were cleaned off, we welded them together so that they would stay aligned with each other when it came time to heat. We also welded on a long steel rod to one end of our stack, as seen in Figure 5.9. This provided us a grip with which to handle the metal while it heated in the furnace.

Figure 5.9. Three Sheets Welded Together and Attached to Steel Handle.

Our metal was now ready to work, so we fired up our furnace. For historical accuracy, we could have built and used a bloomery as described in Section 2.7.4, but we decided to use a propane furnace, as seen in Figure 5.10, was much more straightforward. Once the metal started to glow, we sprinkled borax powder over it as seen in Figure 5.11. This process was repeated a few times, giving the borax a chance to melt and adhere to the metal before adding more. The purpose of the borax is to help flux the metals. This prevents oxidation as the different metals are forged together [96].

Figure 5.10. Propane Furnace.

Figure 5.11. Adding Flux to the Hot Metal.

With the metal properly heated and fluxed, we began pressing and stretching the metal into the dimensions we needed. For the majority of this process, we utilized a powerful hydraulic press to compress the metal, as seen in Figure 5.12. Most of the pressing involved putting the metal in the machine flat, but because pressing elongates both the metal's length and width, we also pressed the thin side to prevent it from surpassing our desired width. We also used a hammer and anvil to reshape the metal as shown in Figure 5.13. This was mostly for straightening the metal when it got oddly bent, or just because it better represented how the Romans constructed their swords.

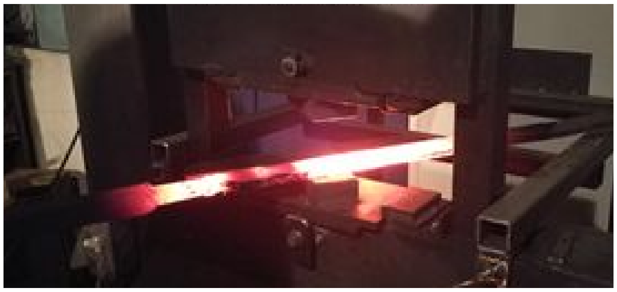


Figure 5.12. Stretching Metal on Pneumatic Press.

Figure 5.13. Hammering Sword on Anvil.

After we finished pressing our metal, it had been stretched from 3.75cm by 30cm (1.5in by 12in), and 2cm (0.75in) thick, to 5cm by 68.5cm (2in by 27in) and 0.6cm (0.25in) thick. From there, we hammered out the sword's tip by resting the hot metal at an angle on the anvil and striking the end, as depicted in Figure 5.14. It is also possible to for the tip by stretching the metal even longer and grinding down a point, but we decided that would take too long, as grinding is such a slow process. Once the point was made, we began to develop the edges of the blade. By angling the blade and hammering inward, we sloped the sides of the metal. Doing this on both sides created the blade of the word, creating the hexagonal shape of the sword that you can see in Figure 5.5 and 5.15.

With the body of the blade stretched and shaped to our liking, we began work on the tang. This is the short metal bit that extends from the base of the sword which will be surrounded by the handle. We removed the handle that we had welded on to help with forging. After, we marked off about 5cm from the base of the blade. From there, we use the clamp-like tool seen in Figure 5.16, to hold down the metal at the marked off length. The tool was then hammered to create dents in the blade at the point we had marked. The metal had to be very hot to prevent the sword from splitting, so we could only do a few hits at a time before reheating. Eventually, the dents were big enough that we could begin hammering them into the tang. Using both hammers and the press, we flattened out the tang to complete the forging of our sword, as seen in Figure 5.17.

Figure 5.14. Hammering the Point.

Figure 5.15. Sword After Hammering Edges.

Figure 5.16. Creating the Tang.

Figure 5.17. Forging Process Complete.

After the sword had cooled off, we began the final grinding phase. We first used the handheld 11.43cm (4.5in) angle grinder from the beginning of the project to go over the metal and remove all the scale (iron oxide), as seen in Figure 5.18(a, b). It was important to clear off these patches of scale, because they would cause premature wear of the belt sander belts. However, the hand grinder was not as consistent as the belt sander and it would have been much more difficult to grind the sword's edges down to a blade. After the rough edges had been removed, we moved on to belt grinding.

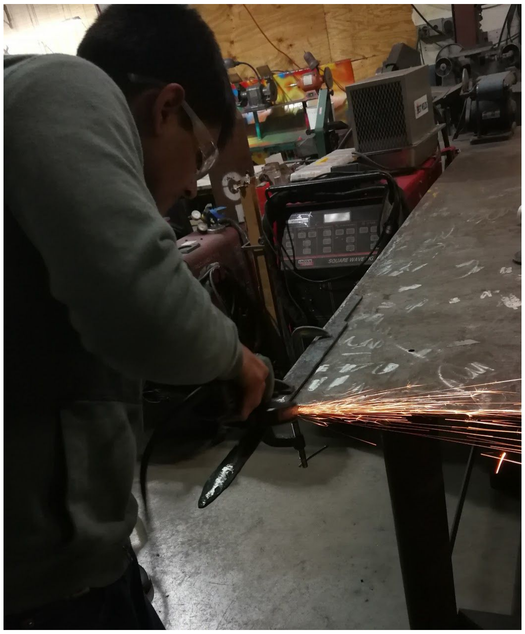


Figure 5.18(a) Grinding Off Iron Oxide.

Figure 5.18 (b) Cleaned Blade.

Using the belt grinder, we were able to smooth down the sword's edges and shape the rough forged blade into the smooth final blade shape. The sander's belts are available in many different "grit" values, which refers to the size of the particles of abrading materials embedded in the sandpaper. The lower the grit number the more abrasive the sandpaper is. Knowing that that several grits of paper would be needed a sanding belt assortment kit, consisting of a P36, P40, P60, P80, P120 and P150 grit, was purchased. The belts can be seen in Figure 5.19. These belts helped us quickly shape the blade with the lower grits and then remove the deep scratches by working our way up to the the higher grits. The belt sander had an attachment that held the belt flat against a metal backing plate. This allowed the edge of the sword to be straightened along its length, seen in Figure 5.20. The flat section of the belt was also used to flatten the sides of the blade and create the bevels. Once the rough outline of the final shape was created the top section of the belt sander was used to round the surface to the edges of the blade, seen in Figure 5.21. This was done along the entire length of the blade, starting from the lower grits all the way to the higher grits.

Figure 5.19. Sanding Belt Assortment.

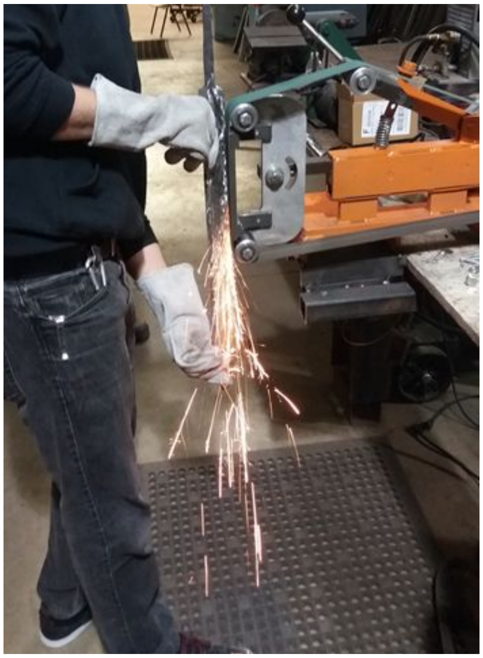


Figure 5.20. Straightening Blade Edge.

Figure 5.21. Final Profiling of Blade.

After the grinding and sanding was completed, we wanted to see if the high carbon edge of the blade was exposed. The blade was dipped in a ferric chloride ($FeCl_3$) solution to show the difference between the 1018 steel and the 1075 steel. As showed previously in the CAD models, the low carbon 1018 steel was to be removed on the edges leaving only the high carbon 1075 steel. This can be seen in Figure 5.22.

The last step that needed to be done to the blade was to shape the tang. This was done to provide a flat and square surface for the guard to sit against. A file guide was clamped on to the blade to help with the filling accuracy, seen Figure 5.23. Once the material above the guide was removed the swords blade was complete.

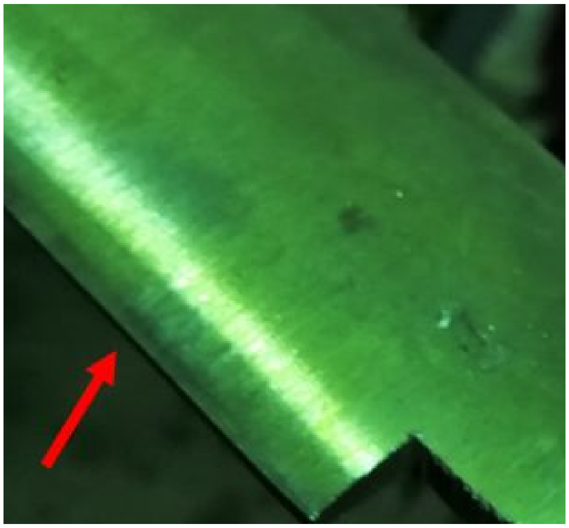


Figure 5.22. Etched Blade.

Figure 5.23. Filing Tang Using File Guide.

5.3 Handle Construction

The next task of the sword was to create a handle or hilt. The Roman Spatha hilt was comprised of a guard plate, a guard, a grip and a pommel. As discussed previously in Section 3.3.2, these pieces could be made from several different materials. The guard plates were mostly made from a copper alloy and the hilt components were made from wood or bone.

The design for our replica Spatha was created using similar dimensions to several Roman swords that were found. The guard plate would be manufactured out of brass and the hilt components out of hard maple wood. The hilt components were created in a CAD software before attempting to manufacture them. This helped during the cutting and shaping of the wood because the drawings could be used as templates. The hilt CAD model of the guard, grip, and pommel can be seen in Figures 5.24(a, b, c) respectively.

(a) (b) (c)

Figure 5.24. (a) CAD Model of Guard, (b) Grip, and (c) Pommel.

The hard maple wood for the hilt was purchased as a 7.62cm x 7.62cm x 30.48cm (3in x 3in x 12in, width x height x length) block, seen in Figure 5.25. The block was cut into several piece to make it easier for the individual parts to be made, see Figure 5.26. Using the CAD drawings as templates the individual parts were carefully crafted using many different power tools like the a bandsaw, a belt sander, a wood lathe and a router. Many of these power tools were inaccessible to WPI students, but with the help of the WPI carpentry department we were able to create the hilt pieces according to plan. In addition to the power tools, much of the hilt was made by hand using non-powered tools like files, chisels, and sandpaper.

Figure 5.25. Hard Maple Wood Block.

Figure 5.26. Individual Hilt Components.

As seen in Figure 5.27, the hilts grip had to be split down the middle in order to carve the channel for the blades tang. This was a rectangular channel and would have been difficult to produce due to the length of the grip. Once the channel is cut the handle can be glued back together and the final shape can be created.

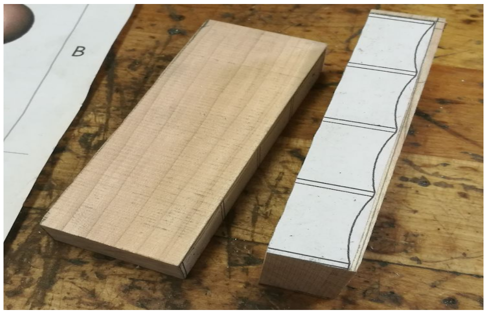


Figure 2.57. Grip Cut Down Center.

After the grip and pommel were turned to their final shape on the wood lathe, as seen in Figure 5.28(a), they needed the channels for the tang. The channel through the guard and pommel were cut using a mortising chisel, which is able to drill a square hole. Each half of the grip had the channel cut using a milling machine. After this process the two grip halves were glued together to make one solid piece, seen in Figure 5.28(b). Lastly, the guard was sanded into its final shape using a belt sander to create the rough profile and then hand sanding to clean and smooth the edges. The test fitting of the hilt components can be seen in Figure 5.28(c).


(a) (b) (c)

Figure 5.28. (a) Grip and Pommel Shape, (b) Grip Halves Glued Together, (c) Test Fitting Hilt Components.

The last components of the hilt to be created were the brass guard plate and the pommel washer, see Figure 5.29. Using the CAD model drawings as templates the dimensions were transferred to a 0.127cm (0.05in) thick sheet of brass. A hand saw was used to cut the rough profile because of the small size. Although more time consuming, removing the majority of the material with the hand saw and then finishing the final shape with files and sandpaper ultimately provided a more accurate result. The rectangular tang hole through the center of the plate and washer was made by drilling three small holes, side by side, and then finishing using small metal files. All of the completed hilt components can be seen in Figure 5.30.

Figure 5.29. Brass Guard and Pommel Washer.

Figure 5.30. Completed Hilt Components.

5.4 Handle Assembly

Figure 5.31. Stained Hilt Components.

Before assembling the hilt for our Spatha replica, the wood components were stained and then sealed using polyurethane, as seen in Figure 5.31. This will help the wood stay preserved as well as provide a appealing surface finish.

The proper assembly of the hilt components uses the tension of the peened tang to hold the components together. Due to a large amount of tolerance in the channels, the guard, grip and pommel had a loose fit between these components and the blade's tang. To solve this issue a two part epoxy was used to fill the gap, as seen in Figure 5.32. This ultimately provided a more secure assembly and eliminated the chance of the hilt becoming loose. The installation of the guard and grip can be seen in Figure 5.33.

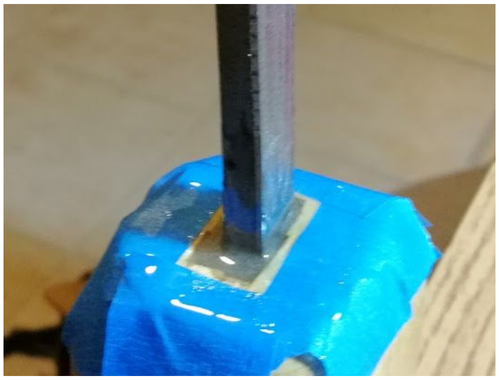


Figure 5.32. Securing Guard with Epoxy.

Figure 5.33. Installing Grip.

The final step needed to complete the sword was to install the pommel washer and peen the tang. As mentioned before in Section 3.3.2, this is how the hilt components are held together. By leaving the tang slightly longer than all the components, it is able to protrude through the brass washer. This small amount of steel is then struck many times to displace the material over the washer. The before and after peening of the tang can be seen in Figure 5.34(a, b) respectively. The completed sword can be seen in Figure 5.35.

Figure 5.34(a) Tang Before Peening and (b) Tang After Peening.

Figure 5.35. Finished Replica Roman Spatha Sword.

6. Metallographic Analysis

This section discusses how the samples for the metallographic analysis were prepared, analyzed, and any conclusions made from the analysis. We made eight different samples for microstructure analysis over the course of the project. Six of the samples were from the raw material we used to make the sword, and two samples were from the finished sword tip. One of the samples from the sword tip was heat treated (explained in Section 6.2.3), and the other was left untreated.

6.1 Preparation of Metallographic Samples

The samples were cut from our steel using a process detailed in Section 5.2. Of the six raw samples we have, three are for 1018 steel, and three are for 1075 steel. This allows us to view all three faces of the steel (xy, yz, and xz cross sections shown in Figure 6.1). Ordinarily, all three faces would be the same, due to the cooling process. However, our steel is cold-rolled, so the microstructure should look different in different directions, due to the stress applied to the steel. Because of the layering process we used while building our sword, one of the three faces (xz cross section) wouldn't be useful for analysis, because the material composition would change at different depths. The two remaining faces (xy and yz cross section) will show all three layers of steel, and the transitions between them.

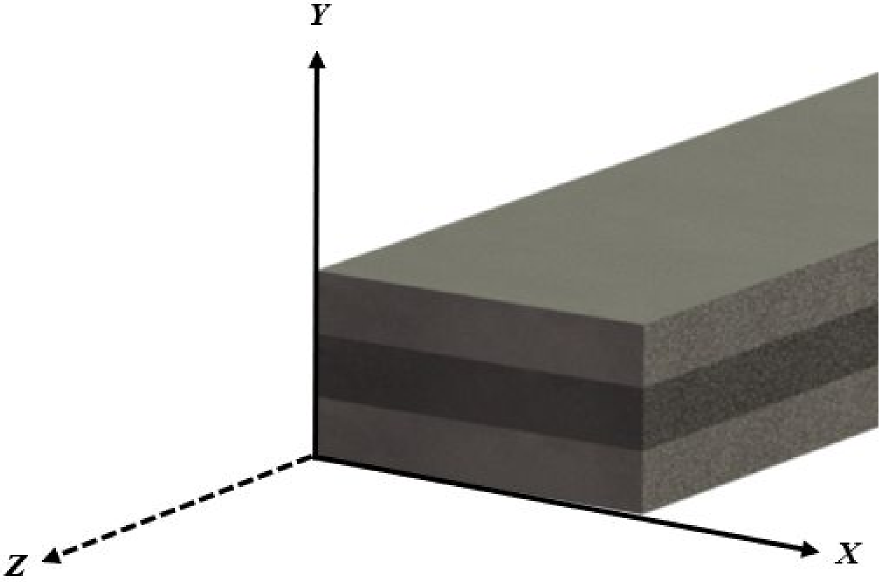


Figure 6.1. Sword Sample Orientation Reference.

6.1.1 Mounting

Once the samples were all cut, we mounted the samples using a SimpliMet 3000 mounting press, as seen in Figure 6.2. The press was used to add a phenolic resin around the sample. The resin would make the samples easier to handle when grinding and analyzing.

The face of the sample we wanted to analyze was placed face down and lowered into the press. The resin, in powder form, was then added over the sample. The top cap of press was then locked into position and the appropriate cycle for the press was selected. After the cycle was completed and the resin had solidified into a puck-like shape, the sample was raised back up and removed from the machine.

Figure 6.2. Mounting Press.

6.1.2 Grinding

After all the samples were mounted, we used a EcoMet 300 Pro Grinder-Polisher to grind the samples, as seen in Figure 6.3. This process erodes the oxidation and other contaminants that may exist on the surface of the metal to expose the microstructure of the steel, as well as level the surface to be analyzed. This is done by using a rotating disk of abrasive paper to remove the surface layer of the samples. A liquid coolant is also used to remove any heat from friction, as well as remove the debris worn away. To grind our sample, the grinder was set up with a 600 grit grinding paper and water to act as the coolant. The samples were held to the grinding surface for about three minutes. During this time, constant pressure was used to hold the samples in place to ensure the finished surface of the sample was smooth without facets. This stage was successfully completed when the samples had a flat surface, and small scratches (expected from the procedure) all in the same direction. An example what the sample looks like before grinding can be seen in Figure 6.4(a).

Figure 6.3. Grinding Sample.

(a) (b)

Figure 6.4. (a) Sample Before Grinding and Polishing and (b) After Grinding and Polishing.

6.1.3 Polishing

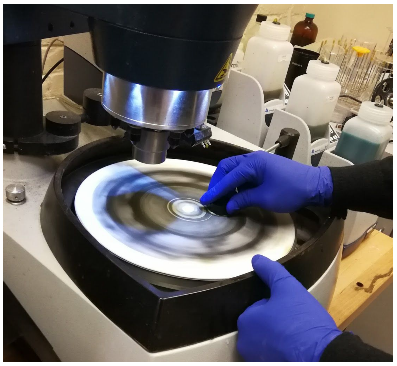


Figure 6.5. Polishing Sample.

The samples were then polished using the EcoMet, as seen in Figure 6.5. Polishing is done to remove any scratching from the grinding stage. The procedure is similar to grinding, but the polishing discs are used instead of grinding paper. Polishing discs are a soft cloth, with a grinding liquid added. The liquids we used contained 6 and 3 micron diamond particles suspended inside them. The samples were held to the polishing discs for about two minutes. The final polished surfaces were shiny and reflective. An example of one of our samples after polishing can be seen in Figure 6.4(b).

6.1.4 Etching

The next step was to etch the samples. This was done using a nital solution, consisting of 5% nitric acid (HNO_3) and 95% ethanol (C_2H_6O). Using a concentration greater than 5% nitric acid would have been risky, as a concentration of at least 10% would likely explode. The nital solution was applied to the samples about 5 seconds, and then immediately washed with water to stop the etching process. If the nital solution is applied for too long, over-etching may occur. A few of our samples were over etched as it was hard to determine how long the nital solution needed to be applied for, especially because the samples had different carbon compositions. When this happened, the samples had to be ground and polished again before re-etching.

6.1.5 Optical Microscopy

Once the samples were successfully prepared, a digital microscope was used to observe the microstructures of the steel. The magnifications used were 200x, 500x, and 1000x. The surface of the samples were scanned for a suitable location to analyze. Ideally, this location would be unscratched, an accurate representation of sample composition, and not over-etched. When such a location was found, the microscope was focused appropriately depending on the magnification being used. A picture was then taken of the surface and a scale was added to the picture.

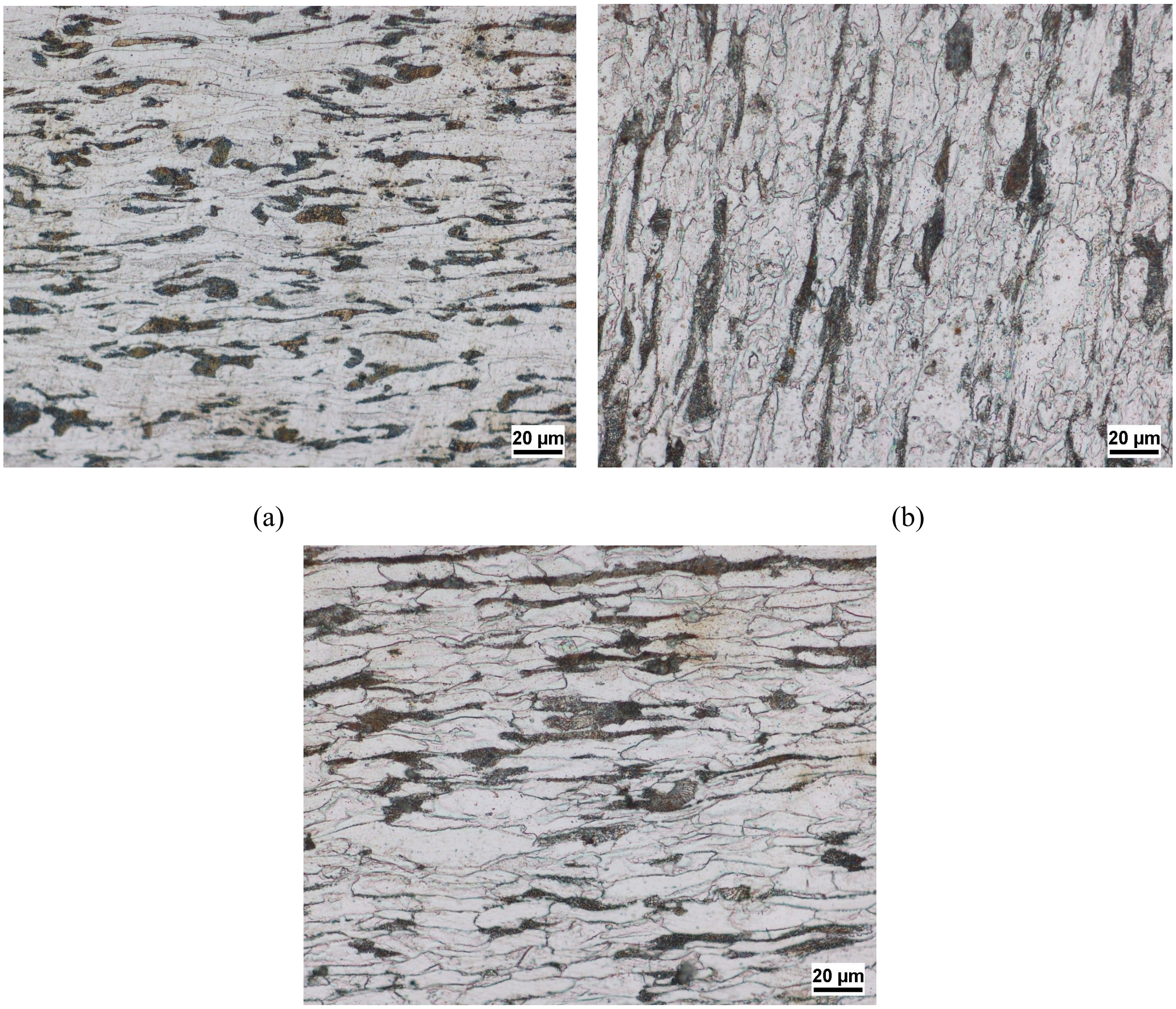
6.2 Microstructure Analysis

This section will discuss the microstructures for both metals (1018 and 1075), before and after the forging processes. Using the images captured with the optical microscope we are able to analyse the microstructures of the materials as well as see any transformations that happened during the forging or heat treating processes.

6.2.1 Raw Material Analysis

As mentioned in Section 4.2, both types of steels used were cold rolled. It was predicted that this process would cause deformation and elongation of the grains along the rolling direction, which could be seen looking at the xz and yz cross sections. Looking at Figures 6.6(a-c), all three faces of the 1018 steel show that this prediction was correct.

The images of the 1018 steel also showed a ferrite (lighter areas) and pearlite (the darker phase with lamellar structure of ferrite and carbide) structure. The pearlite would be classified as fine pearlite which forms at a temperature above the eutectoid temperature rather than coarse pearlite which forms just below the eutectoid temperature [103]. This transformation occured when the metal was originally heated to the austenite phase and then allowed to slowly cool during its production.

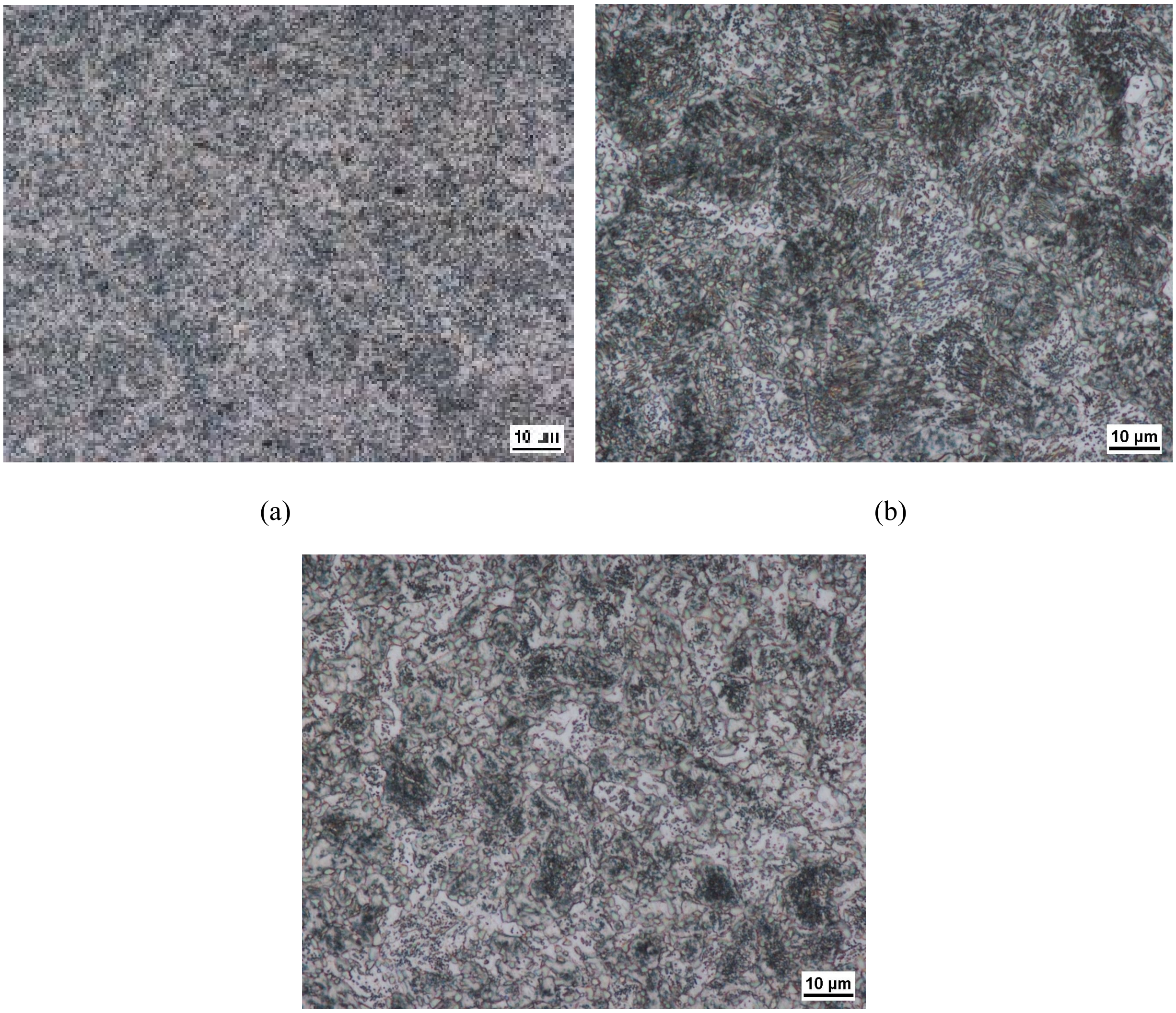


(a) (b)

(c)

Figure 6.6. Initial 1018 Steel 500x Magnification of (a) XY (b) YZ and (c) XZ Cross Section.

However, this was not the case with the 1075 steel. Even though the 1075 steel also underwent the cold rolling process, there was no elongation of the grains on either the top or side faces. Each face of the 1075 steel plate can be seen in Figure 6.7 (a-c). After inspecting the material document that came from the supplier of the 1075 steel, it was found that this material was annealed post cold rolling.



(a) (b)

(c)

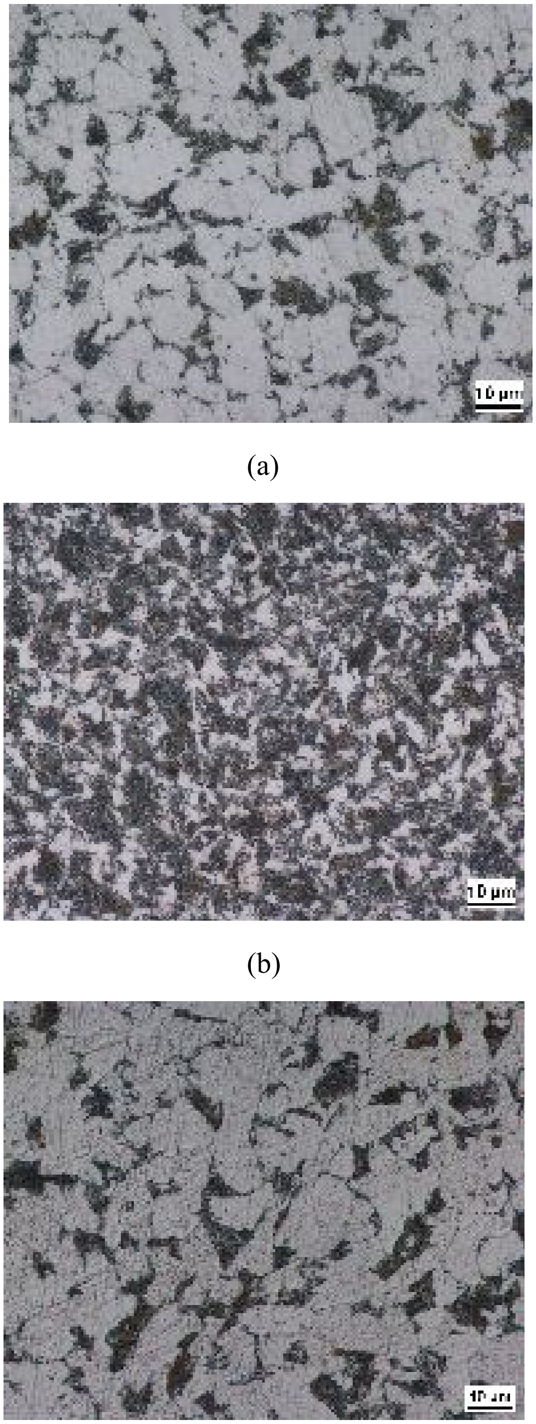
Figure 6.7. Initial 1075 Steel 1000x Magnification of (a) XY (b) YZ and (c) XZ Cross Section

The specifications of this treatment would have been helpful to know, but were not available from the manufacturer. Even without the specification of the process, just knowing that the material underwent this process allowed the group to understand a possible reason why the results did not match our predictions. At the beginning of the construction of the sword the 1075 steel plate had to be cut down its length using the plasma cutter. The plasma cutter produces a large amount of heat when cutting. Worrying how this heat would affect our sample, the area farthest away from where the steel was cut was chosen. These were the xz and yz cross sections of the plate, opposite of the plasma cut. These sides of the material should have shown the elongation of the grains, but do not. This may be contributed to the fact that the 1075 steel images show the cross sections of the *surface* of the material instead of the cross sections of the *center* of the material. It could be hypothesized that the annealing process caused a more isotropic grain orientation instead of elongation, and affected the surface of the material more than the center. If a sample was taken from the center of the material, it is possible we would have seen a grain orientation that matched our predictions.

The images also shows the structure of the 1075 consists of ferrite and fine pearlite, but also the transformation of spheroidized cementite can be seen. The spheroidite microstructure develops when the material is held at a temperature below the eutectoid temperature for a long period of time [103]. This result is reasonable considering the material was annealed by the manufacturer. The manufacturer did this treatment to soften the material and make it easier to work.

6.2.2 Sword Analysis (After Forging)

Looking at the different materials after forging the sword shows the transformations the material underwent during the forging process. During the construction of the blade, the laminations of the 1018 and 1075 steel were first welded together then pressed and hammered into the final shape. Before every time the material was worked, it needed to be placed into the forge and heated. The temperature of the forge was around 1260°C (2300F) which is within the austenite phase for both materials. When the forging was complete, the material was allowed to cool slowly. This process allows the formation of ferrite and pearlite as the materials cool below the eutectoid temperature of 723°C, as shown previously in Section 4.2. The ferrite and pearlite formations can be seen in Figures 6.8 (a-c).



(a)

(b)

(c)

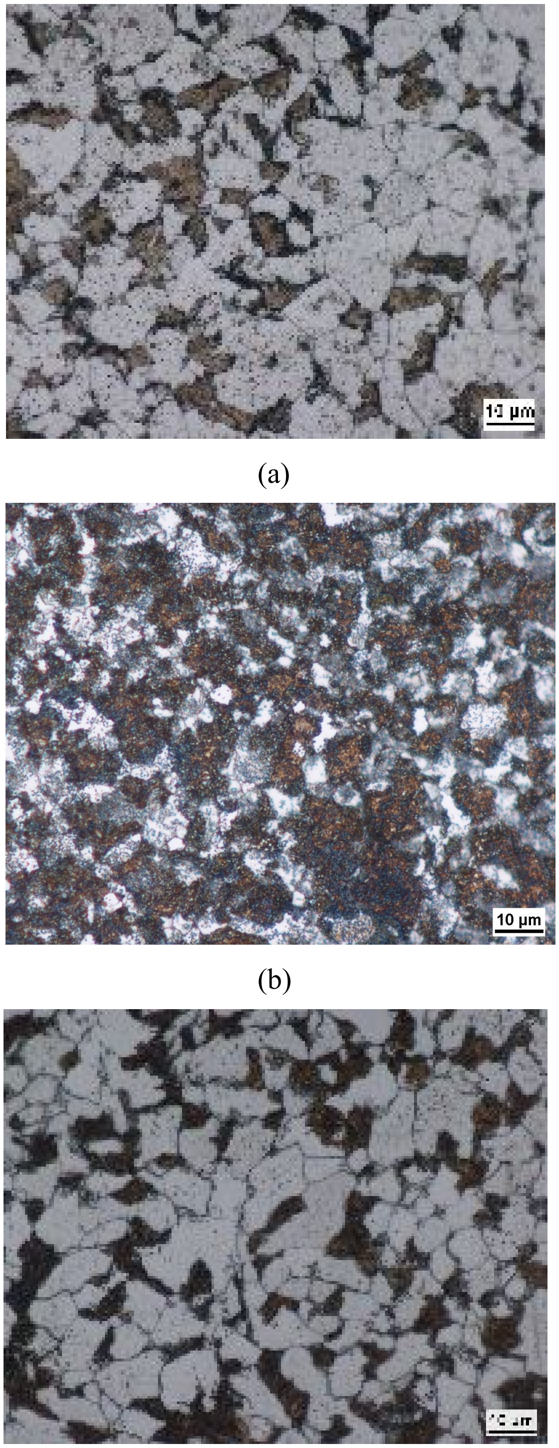
Figure 6.8. (a) First Layer of 1018 Steel, (b) 1075 Steel, and (c) Second Layer of 1018 Steel, all After Forging.

The high temperature of forge was also well above the normalizing temperature, about 55 °C (100 °F) above the upper critical line of the iron carbide phase diagram [110]. By using the Fe-Fe3C phase diagram we can see the result of this high temperature allows the formation of a fully homogeneous austenite phase. Comparing the forged 1018 sample to the original sample shows the transformation of the deformed and elongated grain orientation, from cold rolling, to a homogeneous orientation.

6.2.3 Sword Analysis (After Heat Treatment)

After the sword was forged a small section the the tip was removed for analysis. The team choose that it would be safer to forgo the heat treatment on the actual blade due to lack of the proper equipment and due to the risk of damage associated with the hardening process. The heat treating furnace located on the campus was not large enough for the blade so the forge at the blacksmith shop would have been used. The blade was about twice as long as the forge so the blade would need to be moved back and forth to be heated evenly. This could cause variations in temperature along the length of the blade and could potentially crack or break the blade during quenching.

The actual hardening process was done to two samples of the sword. The first method was done at the blacksmithing shop using a torch to heat the sample above the eutectoid temperature before it was quenched. The only indication of reaching this temperature was to check when the material lost its magnetic properties. The temperature at which certain materials lose their permanent magnetic properties is called the Curie temperature. The Curie temperature for steel is 770°C (1390°F), which is above the eutectoid temperature of the materials. However, after analyzing these samples it could be seen that these samples did not get entirely above the eutectoid temperature therefore did not reach the austenite phase. This resulted in only a partial formation of a martensite structure, as seen in Figure 6.9.



(a)

(b)

(c)

Figure 6.9. 1000x Magnification of XY Cross Sections of (a) First Layer of 1018 Steel, (b) 1075 Steel, and (c) Second Layer of 1018 Steel, After First Attempt of Heat Treatment.

The second attempt at the heat treatment was more successful. Using a digital furnace in the metallurgy lab made it able to accurately bring the sample into the austenite phase. Figure 6.10 shows the TTT diagram for steel during non-equilibrium cooling. The dashed purple line in the TTT diagram shows what is desired for our sample to form martensite. If the material is heated above the eutectoid temperature and then cooled rapidly, fast enough to miss the nose of the curve, martensite will be formed. Unlike the sample of the sword before the heat treatment no pearlite is expected to form. This is because pearlite is formed by solid state diffusion of the carbon from the austenite to form Fe3C. When the material is rapidly quenched it prevents this diffusion from occurring and instead yields a metastable martensite [103]. The TTT or Time-Temperature-Transformation includes temperature along the

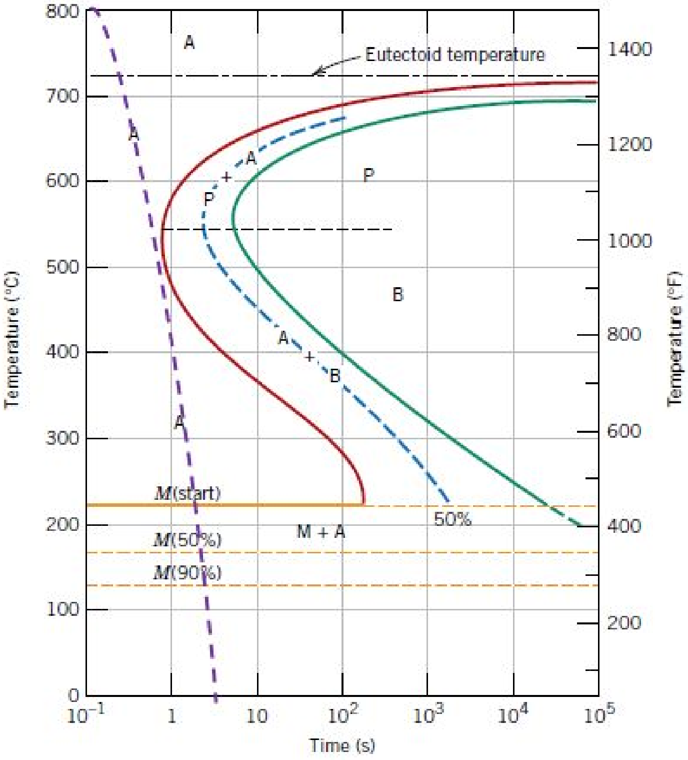


Figure 6.10. TTT Diagram Showing Sample Cooling Path [103].

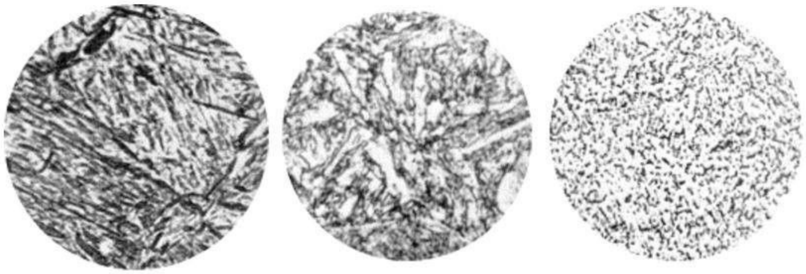
y-axis and time along the x-axis. Since time is a factor of the transformation it is important cool the sample in a very short amount of time. By only heat treating a small sample made it more likely to fulfill this requirement. Heat treating the entire blade would take a longer time to cool and can also cool the surface of the blade faster than the inner core.

The second sample was placed into the furnace and heated to around 915°C, seen in Figure 6.10(a). This temperature was the normalizing temperature of the 1018 steel and would bring both materials into the austenite phase [110]. After reaching this temperature the sample was quickly removed from the furnace and quenched in room temperature water, shown in Figure 6.101(b). This process would form martensite, a hard and brittle structure.

(a) (b)

Figure 6.11 (a) Furnace and (b) Quenching Tank Used for Heat Treatment.

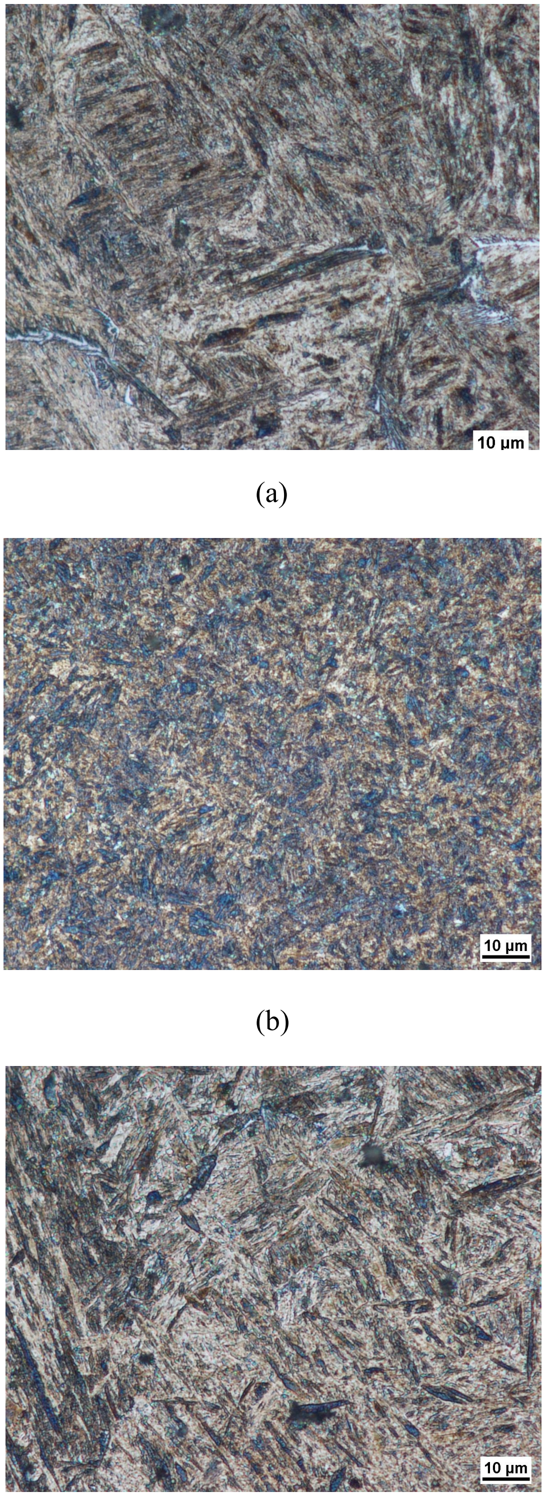
After quenching, the iron lattice is strained by the carbon atoms, producing the high hardness of the quenched steel. Tempering usually decrease the hardness, tensile strength, and yield strength, but under certain conditions, hardness may remain unaffected or may even be increased as a result [110]. Tempering the sample at a low temperature can cause no change in hardness, but can increase its yield strength, ductility and toughness. The tempering procedure was found in the ASM handbook [110]. A temperature of 204.4°C (400°F) was chosen for the sample and would need to be held at this temperature for two hours. This process will cause the formation of ferrite, very small spheroidal iron carbides, and will lower the carbon content of the martensite [103]. The transformation of martensite to tempered martensite to heavily tempered martensite can be seen in Figures 6.12(a-c).



(a) (b) (c)

Figure 6.12 (a) Martensite, (b) Tempered Martensite, (c) Heavily Tempered Martensite [111].

The results of hardening and tempering procedure, on the 1018 and 1075 steel, can be seen in Figure 6.13(a-c). The comparison of these images to the tempered martensite in Figures 6.12(a-c) shows that the second sample, unlike the first sample, fully transformed into martensite. This microstructure would provide the hardness the edge of the blade needs to stay sharp and the tempering process will increase the ductility of the blade, therefore producing a quality final result.



(a)

(b)

(c)

Figure 6.13. (a) First Layer of 1018 Steel, (b) 1075 Steel After Hardening and Tempering, (c) Second Layer of 1018 Steel.

7. Conclusion

The Ancient Roman civilization was constantly evolving. Rome started as a Monarchy before becoming a Republic, and eventually the Empire. Its people were driven by war and the expansion of Rome, forcing Rome to adapt new ways to organize their armies, battle tactics and fighting styles. With each new territory conquered, Rome assimilated new knowledge and processes. Rome became known for taking other societies' technologies and integrating them into their own culture, such as the use of weapons originating from other societies.

To better understand what Rome was able to accomplish, the Roman Spatha was studied in depth. The Spatha was derived from the Celtic long sword. The Roman cavalry began to use the Spatha during the first and second century AD, before it became more popular among the infantry soldiers in the second or early third century AD, replacing the Gladius. This adaptation was possibly a result of an increase in encounters between Roman infantry and enemy cavalry soldiers.

However, due to the Roman army's strict policy to return equipment of fallen or retired soldiers back to the armory, evidence of all roman military equipment, including the Spatha, is scarce. Of the Roman swords found and analyzed, it is apparent that the Roman blacksmiths of this time knew about heat treatment processes such as quenching and slack quenching. The analysis of the swords also revealed how the swords were constructed by either simply forge welding the steel, or by pattern welding which is a more complicated technique. The swords that were forge welded were from first and second century, while the pattern welded swords were from the second or early third century AD. This shows the advancement of the blacksmithing technologies during the Roman Empire.

Due to the time constraints for this project and lack of experience, our group decided to construct our Spatha using the simpler forge welding technique, even though it is an earlier technique. The sword consisted of a two outer plates made of a low carbon steel, and a center plate of high carbon steel. Using a propane forge, modern machinery like a hydraulic press and belt grinder, as well as simple tools like a hammer and anvil, the sword blade was constructed. The handle was then designed from hard maple and brass, and attached to the sword, completing it.

The measured microstructures of our sword were mostly consistent with our predictions. The raw 1018 steel had the flattened structure we expected from cold-rolled steel. Even though we incorrectly predicted that the 1075 would have the same flattened structure, that was only because we didn't know that the material was annealed before it was delivered. Our non-heat treated tip sample had exactly the structure we expected, with both ferrite and pearlite. The 1018 steel also lost its flattened structure during the forging process. Our initial attempt at heat-treating didn't reach a high enough temperature to completely transform the microstructure, leaving a large amount of ferrite untouched. Our second attempt at heat-treating did reach the correct temperature, and completely transformed both the 1018 and 1075 steel into martensite, as we predicted.

Over the course of the project, we managed to identify the tools and techniques the Romans used to manufacture a Spatha, and use those techniques to make an authentic replica. We also were able to make mostly correct predictions about the microstructure of the sword before, during, and after the forging process, both with and without heat-treatment. Finally, we were able to describe the reasons the Romans used this weapon, and the way they developed it themselves.

Appendix A

This is the material the team added to the website. It includes a summary of the replica's construction which encompasses the design of the sword, the creation, shaping, grinding of the blade, and handle creation and assembly. Information on Roman equipment such as the Gladius, Pugio, Pilum, shields, and armor were also added to the website.

Replica Construction

Design

The Spatha sword we constructed was made using methods similar to the Roman blacksmiths during second century AD. Although the construction was similar to the construction during the Roman times, the tools we used to create the sword are of modern technology due to our short time frame. The replica Spatha is based on the *Lauriacum-Hromowka* sword which is a straight bladed sword with a small triangular tip. The dimensions used for the replica are from a Spatha found, from late second to third century AD [104]. Figure A.1 shows a Solidworks CAD drawing for the replica Spatha blade.

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Figure A.1. CAD Model of Replica Sword.

The blade will consist of three metal plated stacked or laminated together. The outer plates will be made from low carbon 1018 steel, classed with iron, and the center plate will be of high carbon 1075 steel. The order of the plates can be seen in Figure A.2, with the light colored plates representing the iron (1018 steel) and the darker plate representing the high carbon steel (1075 steel).

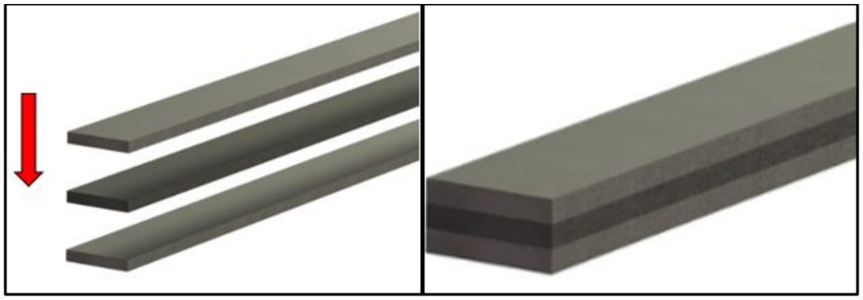


Figure A.2. Order of Steel Laminations.

The use of the different plates allows the blade to have hard sharp edges, but still have the toughness needed upon impact. The high carbon steel in the center of the blade is what will provide the hard edges of the blade and the iron will provide the toughness. If the entire blade was made from high carbon steel, the blade would be brittle and therefore be likely to break during use.

Creation of Blade

Before any hammering could take place, we needed to turn the three separate plates of metal into one, properly sized piece. The starting width of the plates needed to be around 3.75cm (1.5in) wide. Only the 1018 steel was available at this width. The 1075 steel that was purchased was about 5cm (2in) wide and needed to be cut down to match the size of the 1018. This could have been done using a saw, but the high carbon concentration of the 1075 steel makes it very hard to cut. One option would be to use a specialized bandsaw blade made for high carbon steel. Unfortunately, the manufacturing labs at WPI did not have this type of blade. Instead, a plasma cutter was used to make quick work of cutting the steel. Plasma cutters are able to cut through electrically conductive materials by directing an accelerated jet of hot plasma into the material. The 5cm wide 1075 steel was clamped to the work surface with the 1018 steel on top acting as a guide, insuring a straight cut. This procedure can be seen in Figures A.5 (a) and (b).

(a) (b)

Figure A.3. (a) Original Plate of 1075 Steel and (b) Plasma Cutting the 1075 to the Proper Width.

After the different plates were at the same widths, they had to be cut to the same lengths. The process used to cut each plate into about 30cm (12in) long pieces using a chop saw, as seen in Figure A.6.

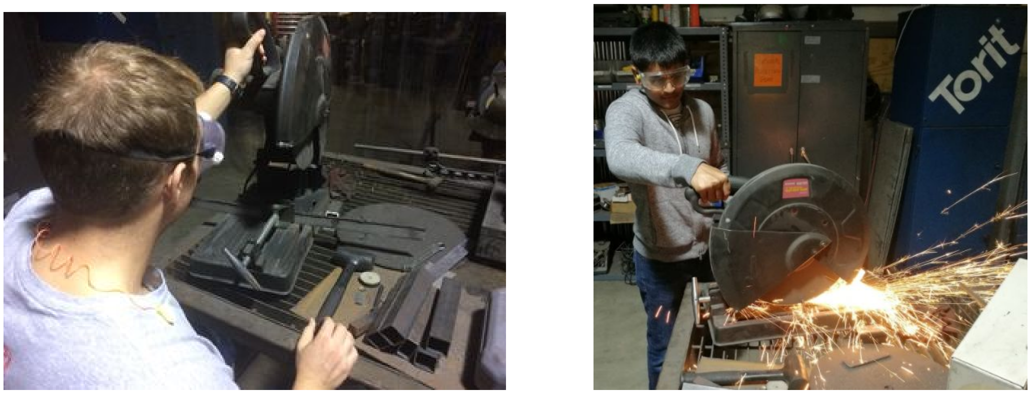

(a) (b)

Figure A.4. (a) Aligning Metal to be Cut and (b) Cutting Metals to the Proper Lengths.

In addition to cutting the steel into 30cm plates, we also used the saw to cut small blocks off of the raw stock. We cut one piece from one of the 1018 plates, and another from the 1075 plate. We brought these two pieces back to Washburn, where we removed a chunk of the 1075 that had been affected by the plasma cutting process. We then used the bandsaw to cut the 1018 sample and the remainder of the 1075 sample into three different pieces each, exposing all three faces of the samples. Finally, we ground down the edges & faces of the samples to remove any burrs and sharp edges that were present. These were samples of the original materials which were reserved for later analysis.

Once the metal for the actual blade was the right size, we used a hand-grinder to smooth off the faces of all three pieces. This process, as seen below in Figure A.5, is important for the binding of the metals when we start heating them up. Scratches or bumps on the faces would result in bubbles or warping when the metal was heated and bound to each other.

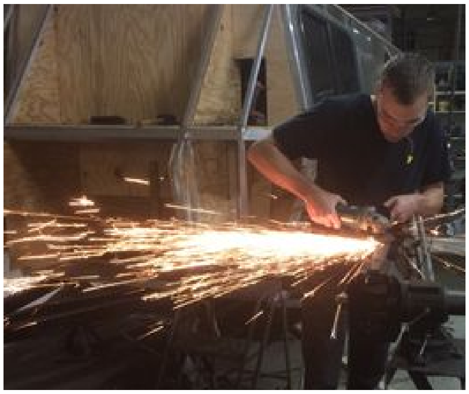


Figure A.5. Hand Grinding of The Sheets.

Once all three were cleaned off, we welded them together so that they would stay aligned with each other when it came time to heat. We also welded on a long steel rod to one end of our stack, as seen in Figure A.6. This provided us a grip with which to handle the metal while it heated in the furnace.

Figure A.6. Three Sheets Welded Together and Attached to Temporary Steel Handle.

Our metal was now ready to work, so we fired up our furnace. We could have created a historicly accurate blast furnace, but we decided to use a propane furnace, as seen in Figure A.7, which was much more straightforward. Once the metal started to glow, we sprinkled borax powder over it as seen in Figure A.8. This process was repeated a few times, giving the borax a chance to melt and adhere to the metal before adding more. The purpose of the borax is to help flux the metals. This prevents oxidation as the different metals are forged together.

Figure A.7. Propane Furnace.

Figure A.8. Adding Flux to the Hot Metal.

Shaping

With the metal properly heated and fluxed, we began pressing and stretching the metal into the dimensions we needed. For the majority of this process, we utilized a powerful hydraulic press to compress the metal, as seen in Figure A.9. Most of the pressing involved putting the metal in the machine flat, but because pressing elongates both the metal's length and width, we also pressed the thin side to prevent it from surpassing our desired width. We also used a hammer and anvil to reshape the metal as shown in Figure A.10. This was mostly for straightening the metal when it got oddly bent, but also so that we could get a taste of how it would be done in ancient times.

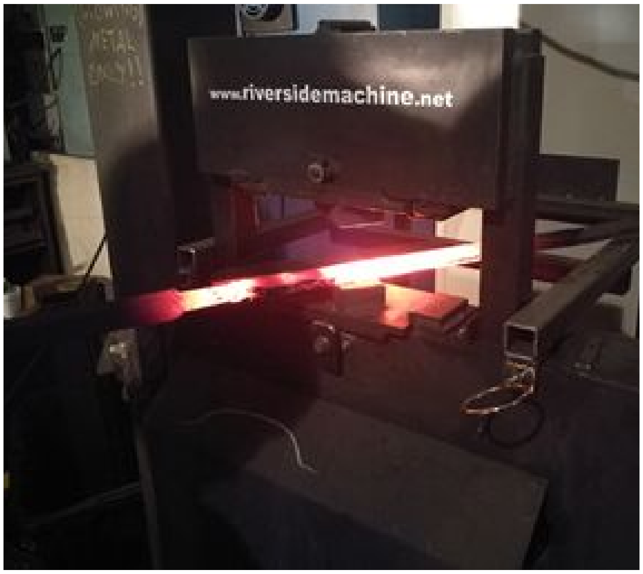


Figure A.9. Pneumatic Press Used for Stretching Metal.

Figure A.10. Hammering Sword on Anvil.

After we finished pressing our metal, it had been stretched from 3.75cm by 30cm (1.5in by 12in), and 2cm (0.75in) thick, to 5cm by 68.5cm (2in by 27in) and 0.6cm (0.25in) thick. From there, we hammered out the sword's tip by resting the hot metal at an angle on the anvil and striking the end, as depicted in Figure A.11. It is also possible to for the tip by stretching the metal even longer and grinding down a point, but we decided that would take too long, as grinding is such a slow process. Once the point was made, we began to develop the edges of the blade. By angling the blade and hammering inward, we sloped the sides of the metal. Doing this on both sides created the blade of the word, creating the hexagonal shape of the sword that you can see in Figure A.12.

Figure A.11. Hammering the Point.

Figure A.12. Sword After Hammering Edges

With the body of the blade stretched and shaped to our liking, we began work on the tang. This is the short metal bit that extends from the base of the sword which will be surrounded by the handle. We removed the handle that we had welded on to help with forging. After, we marked off about 5cm from the base of the blade. From there, we use the clamp-like tool seen in Figure 13, to hold down the metal at the marked off length.

Figure A.13. Creating the Tang.

The tool was then hammered to create dents in the blade at the point we had marked. The metal had to be very hot to prevent the sword from splitting, so we could only do a few hits at a time before reheating. Eventually, the dents were big enough that we could begin hammering them into the tang. Using both hammers and the press, we flattened out the tang to complete the forging of our sword, as seen in Figure A.14.

Figure A.14. Forging Process Complete.

Grinding

After the sword had cooled off, we began the final grinding phase. We first used the handheld 4.5” angle grinder from the beginning of the project to go over the metal and remove all the scale (iron oxide), as seen in Figure A.. It was important to clear off these patches of scale, because they would cause premature wear of the belt sander belts. However, the hand grinder was not as consistent as the belt sander and it would have been much more difficult to grind the sword’s edges down to a blade. After the rough edges had been removed, we moved on to belt grinding.

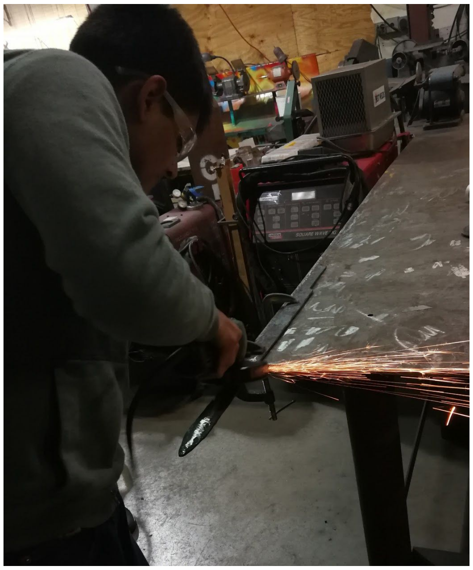


Figure A..15. Grinding off Iron Oxide.

Using the Belt grinder we were able to smooth down the edges of the sword. We used lower grits to quickly shape the blade and then worked our way up in grit to get a nice smooth finish. The belt sander had an attachment that held the belt flat against a metal backing plate. This allowed the edge of the sword to be straightened along its length, seen in Figure A.16a. The flat section of the belt was also used to flatten the sides of the blade and create the bevels. Once the rough outline of the final shape was created the top section of the belt sander was used to round the surface to the edges of the blade, seen in Figure A.16b.

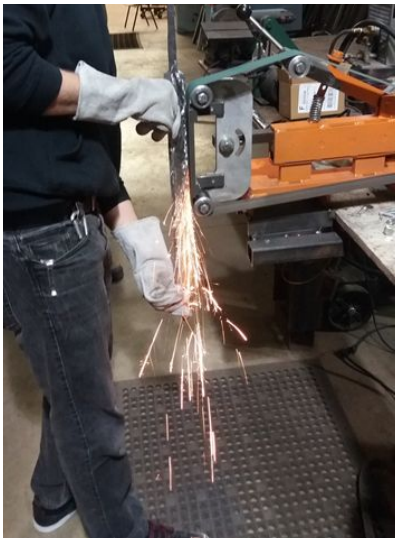


Figure A.16a. Straightening Blade Edge.

Figure A.16b. Final Profiling of Blade

The last step that needed to be done to the blade was to shape the tang. This was done to provide a flat and square surface for the guard to sit against. A file guide was clamped on to the blade to help with the filling accuracy, seen in Figure A.17. Once the material above the guide was removed the swords blade was complete.

Figure A.17. Filing Tang using File Guide

Handle Creation

Next up was to create the handle. The Roman Spatha hilt was comprised of a guard plate, a guard, a grip and a pommell. The design for our replica Spatha was created using similar dimensions to several roman swords that have been found. The guard plate would be manufactured out of Brass and the hilt components out of Hard Maple wood. The Hilt components were created in a CAD software before attempting to manufacture(Figure A.18).

Figure A.18. Handle CAD Model.

The hard Maple wood for the Hilt was purchased as a 3” x 3” x 12” (width x height x length) block. We used power tools to cut our block of wood into 3 separate pieces.

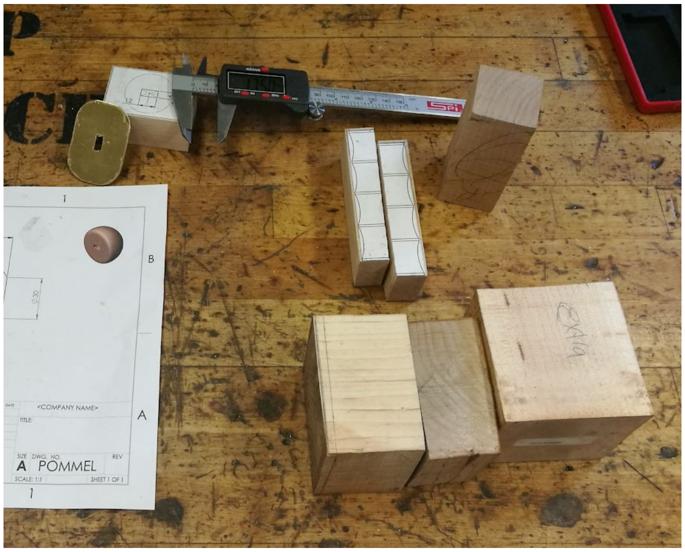


Figure A.19. Individual Hilt Components Cut

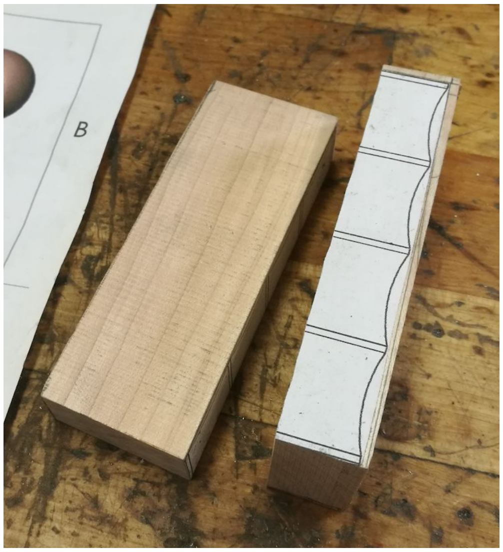


Figure A.20. Grip cut down center

We used chisels and grinders to shape down the blocks of wood to their rough shapes, and then drilled a hole through them with a milling machine to make room for the sword tang. The handle had to be cut in half in order to get a good hole through the middle because it was too long to cut a full hole through with the milling machine. We used glue to put the pieces back together, seen in Figure A.22. Lastly, the guard was sanded into its final shape using a belt sander to create the rough profile and then hand sanding to clean and smooth the edges. The test fitting of the Hilt components can be seen in figure A.23.

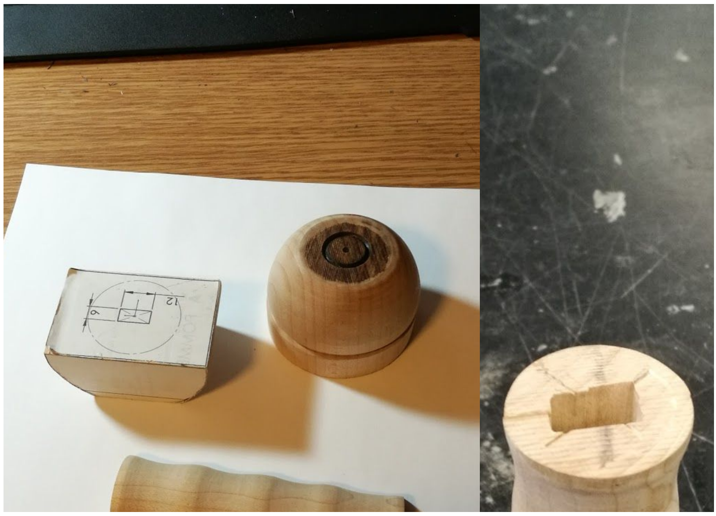


Figure A.22. Handle, Pommel and Guard Post Sanding

Figure A.23. Test Fitting of Hilt Components

The last components of the Hilt to be created was the Brass guard plate and the pommel washer, see Figure A.24a. Using the CAD model drawings as templates the dimensions were transferred to a 0.05in thick sheet of Brass. A hand saw was used to cut the rough profile because of the small size. After most of the material was removed, we used sandpaper to smooth down the outside of the guard to a nice final form. The rectangular tang hole through the center of the plate and washer was made by drilling three small holes, side by side, and then finishing using small metal files. All of the completed Hilt components can be seen in figure A.24b.

Figure A.24a. Pommel and Guard Washer

Figure A.24b. Finished Hilt Components

Handle Assembly

Before assembling the Hilt for our Spatha replica the wood was stained and then sealed using polyurethane. The stained and sealed Hilt components can be seen in Figure A.25.

Figure A.25. Stained Hilt Parts

The proper assembly of the hilt components uses the tension of the peened tang to hold the components together. Due to a large amount of tolerance in the channels the Grip and Pommel had a loose fit between these components and the blades tang. To solve this issue a two part epoxy was used to fill the gap, Figure A.26a.

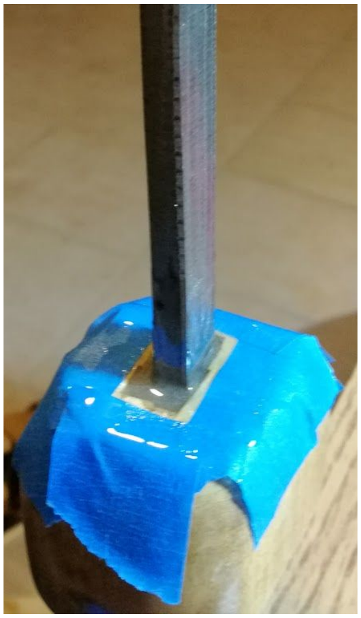


Figure A.26a. Securing Guard with Epoxy

Figure A.26b. Installing Grip.

The final step needed to complete the sword is to install the pommell washer and peen the tang. By leaving the tang slightly longer than all the components it is allowed to protrude through the brass washer. This small amount of steel is then struck many times to displace the material over the washer. The before and after peening of the tang can be seen in Figure A.27(a and b) and the completed sword in Figure A.28.

Figure A.27a. Tang Before Peening.

Figure A.27b. Tang After Peening

Figure A.28. Finished Replica Roman Spatha Sword.

Roman Equipment

Spatha

The Spatha was a Roman cavalry sword that was derived from the Celtic long sword. Its length gave the cavalry men the reach they needed to attack the opposing soldiers. The blades ranged between 65-95 cm in length with a double edge. The swords could had triangular tips or rounded tips to reduce the potential of injury to the soldier legs and feet or to his horse. In the late second or early third century AD, the Spatha became more popular among the infantry soldiers than the gladius [33], likely because of an increase in encounters between Roman infantry and enemy cavalry soldiers.

Figure A.28. Fourth Century Roman Spatha from Cologne Germany [27].

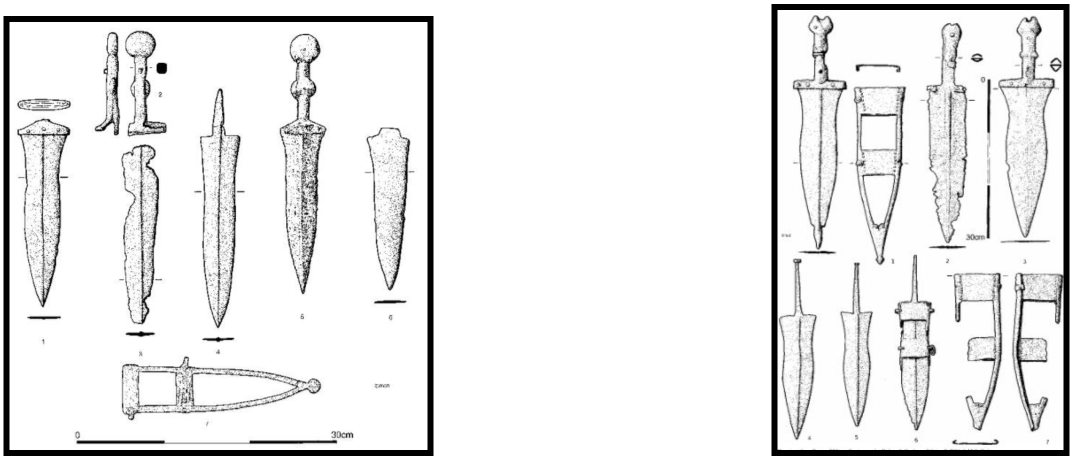
Gladius

The Gladius is considered an iconic weapon for the Roman infantry. This short double edged sword was designed to primarily be for stabbing, but it could also be used for slashing and cutting. The Gladius was an excellent close quarter combat weapon, especially when used in combination with a shield. The Roman infantry soldier would use his large shield for protection while delivering quick stabs to his enemy. Speed was the key for this weapon. The opponents of the Romans were mostly using long swords that required to be raised high to get a powerful downward strike. When the enemy's sword was raised, a Roman soldier could disable the opponent before the strike by quickly delivering several stabs to sensitive areas such as the arteries, throat, and groin [25].

Figure A.29. Roman Soldier with Gladius Sword [26].

Pugio

The Roman Pugio was the sidearm weapon for the Roman infantry soldier. The early Pugio had a blade ranging 15-20 cm in length and featured a wide leaf shaped blade with a flat tang. The design suggests the blade was intended for fast stabs or thrusts rather than slashing. The origin of the Pugio is debatable due to the lack of information available. It was never mentioned in any ancient sources, but there is archaeological evidence that the weapon may have originated in Hispania [40]. The fact that it was never mentioned in *Polybius Histories* indicates that it was not largely used in the Roman military during this time [21].



(a)
(b)

Figure A.30. (a) Republic and First Century Pugio and (b) Second and Third Century Pugio [21].

Pilum

The Roman Pilum was a heavy javelin consisting of a long iron shank with a sharp pointed end. This shank was connected to a long wooden shaft with a socket in the iron shank or by a tang on the shank inserted into the wooden shaft and secured with rivets. Its weight was used to provide the penetrating power on impact, eliminating the need for high velocities. The soft metal of the Pilum was designed to bend upon impact, disabling the weapon after use. This would prevent the enemy from potentially using the spear against the Roman soldiers by throwing it back. The length of the iron shank allowed it to penetrate an enemy's shield and continue into the enemy soldier [21].

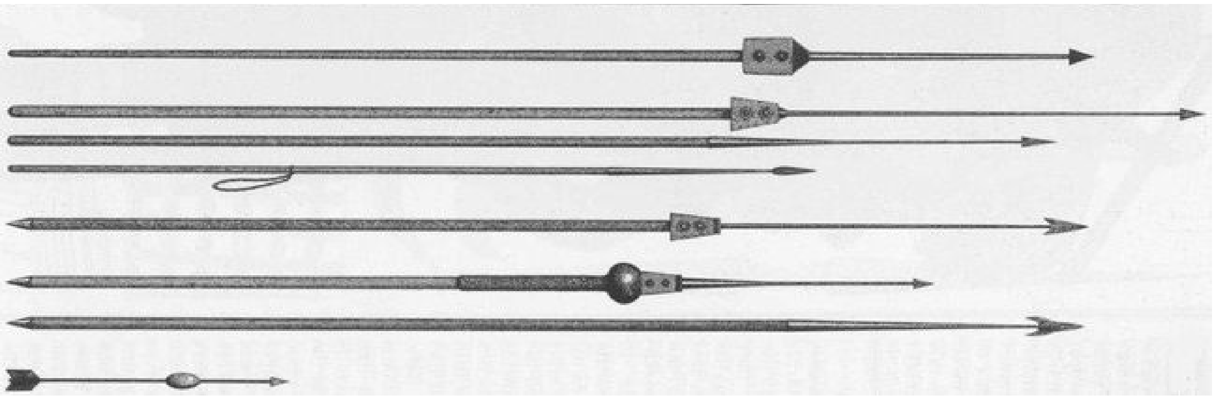


Figure A.31. Roman Pilum Evolution [25].

Shields

The Scutum was the standard shield used by Roman infantry in battle. These shields appeared rectangular from the front, and were curved to better protect from the side [56]. They were constructed with layered wood strips, with the grain going in different directions to prevent weakness [57]. Their size, up to 130 by 80 cm [56], made the Scutum heavier than most shields, so they were primarily used by legionaries, who fought on foot. Soldiers in a cohort (smaller sections of the overall legion) fought close together, so their shields overlapped and made sure every man was guarded from all sides.

Figure A.32. Roman Soldiers in formation with Scutum Shields [].

Armor

Early Roman troops wore a form of mail armor called “Lorica Hamata”, a chain-link suit that was effective at stopping blades. However, its weakness to blunt force led to the “Lorica Segmentata” and the “Lorica Squamata”. Segmentata was a type of plate armor, made up of iron or low-carbon steel sheets held together with leather and brass fittings. Squamata acted as a hybrid of plate and chain armor. It was made up of smaller metal scales linked together with chain, so the armor had both the heavy protection of plate armor and the blade protection and flexibility of chain-mail.

Roman helmets evolved over time, but they maintained a basic design; a hemispherical top rested on the head, with cheek and neck guards extending downwards [52]. Early models, like the “Montefortino” and the “Coolus” were made from bronze [57]. By the first century AD, helmets were made from iron or copper alloy. As time passed, both the cheek and neck guards grew larger and stronger, and techniques like cross-bracing and using multiple types of metal increased the overall strength and rigidity of helmets.

Figure A.32. Reproduction of the Lorica Segmentata [91].

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