EVOLUTION OF MATERIALS IN ARMS AND ARMORS: MEDIEVAL ERA BATTLE AXE

An Interactive Qualifying Project Report

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1. Abstract

The Medieval Era was known as an extremely violent time period due to the hunger for power and wealth. This desire for power caused wars and skirmishes and made arms and armors very prominent. The need for better weapons increased and caused significant change in medieval technology, architecture, and weaponry. The purpose of this project was to explore the historical background of Western Europe during the Middle Ages and research the evolution of weaponry based on the available materials and processing methods. As part of this project, a battle axe replica was constructed using the traditional methods. Furthermore, research on the material properties of 1045 steel was conducted, and samples of annealed and forged steel were taken and analyzed using modern inspection techniques. Lastly, information regarding medieval era weaponry was summarized and added to the WPI Historical Evolution in Materials of Arms and Armors website.

2. Acknowledgements

The project team would like to express great appreciation to Professor Diana Lados and Mr. Tom Thomsen for creating the Historical Evolution of Materials in Arms and Armor IQP series and for allowing this team to be a part of the wonderful experience and contribute to the on-going website.

This team would also like to acknowledge the help provided by Joshua Swalec and his team at Ferromorphics in Worcester, MA. Because of the time, effort, proper equipment, advice and expertise provided by those at Ferromorphics, this team was able to successfully create a replica of a Medieval Battle Axe using traditional forging methods.

Finally, this team would like to offer a special thanks to Dr. Boquan Li for instructing us on how to mount and polish the samples in his Materials Analysis Lab, and to Yi Pan and Anthony Spangenberger for taking the time and patiently helping the team with the process of etching, and the use of the Optical Microscope and analysis.

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6. Introduction

This project was a part of the Historical Evolution of Materials in Arms and Armor Interactive Qualifying Project (IQP) series. The purpose of this project was to examine the evolution of weapons, specifically the battle axe, during the medieval era in Western Europe, in terms of the design, materials, and manufacturing. Another main goal was to construct a replica of the medieval battle axe and analyze the material properties as well as the microstructures of the metal, to compare before with after. The last purpose of this project was to update the online website that was already created, with information concluded during this project.

The battle axe, one of the most used weapons during the Middle Ages, emerged first as an axe to help with labor. As armor became prominent, it was easily noticeable that an axe would be a very efficient way to wound a soldier, since wielding and using an axe required very little skill. To illustrate the evolution of weaponry, especially the battle axe, this report begins with a historical exploration of the Medieval Era in Western Europe, followed by the culture and types of roles during the time period, and ending the section with the different materials and manufacturing processes available.

Finally, the team's construction of the Medieval Battle Axe replica is recorded, along with the predicted and observed analysis of the material properties resulting from the before and after of the forging process. This is followed by condensing of the important information and updating the WPI Historical Evolution of Materials in Arms and Armors IQP website.

7. History of the Region – Medieval Period

The Medieval period, or middle ages, spanned the late 5th century to the early 15th. These years were times of great progress, struggle for power, advances in technology, expression of the arts, and general improvements in quality of life for most. These improvements assisted in increasing the overall population of Europe, but lead to trouble towards the end. Medieval France and England during the 1100's to 1400's were especially tough times as plague, famine and war spread across all of Europe (Bogart, 2009).

7.1 Important Events

7.1.1 English Rule

In England, our time period starts the Reign of King Henry I. King Henry ruled from 1100-1135 and was the youngest of his three brothers, William, Richard and Robert. His apparent death was due to eating too much fish. 1135-1154 marks the reign of King Stephen (nephew of Henry I). Steve was kind and generous, and desired by the people to rule, rather than a woman. The next in line was actually King Henry's wife Matilda. In 1118, the Knights Templar was founded to protect European pilgrims on their journey to Jerusalem, and to protect the city itself. The Knights Templar was also ordered to aid France and Germany, in 1147, with the Second Crusade. This time around, more troops were needed to reclaim the land lost originally claimed as the country of Edessa, in the first crusade (Ozment, 1980).

Next, after invading England, King Henry II (grandson of Henry I) removed King Steven from power. He was king from 1154-1189. After him was King Richard I (third son of Henry II) from 1189-1199. He was known as King Richard the Lionheart and was one of the 7 children of Henry II. In 1187, Saladin managed to unite the Muslim world and recapture Jerusalem. This sparked the start of the Third Crusade in 1190. King John (fifth son of Henry II) ruled from 1199-1216 after King Richard. After his return from the Third Crusade, Richard made John his heir to the throne. During his rule, the Fourth Crusade embarked in 1202 and Constantinople was captured. In 1214 Barons waged a revolt in attempt to gain rights. The conflict ended in 1215 with the signing of the Magna Carta (Ozment, 1980).

The reign of King Henry III (son of John) began in 1216 when he crowned king at the age of 9. Until 1227 regents waiting on Henry to come of age ruled England. In 1258, Provisions of Oxford were forced upon Henry III. These established a new form of government that gave power to 15 barons on council and limited regal authority. Henry III was king until his death in 1272. King Edward I (son of Henry III) began his reign in 1272. William Wallace emerged as the leader of the Scottish resistance to England in 1297. After numerous battles with the scots Edward attempted to invade Scotland, and died in 1307 en-route. In 1295, Marco Polo published his tales of China. 1307 marked the start of the reign of King Edward II (son of Edward I). Before being crowned king, Edward was the first English prince to hold the title of Prince of Wales. The Knights Templar were rounded up in 1307 and murdered by Philip the Fair of France, with the backing of the Pope (Ozment, 1980).

Following that, in an attempted abuse of power, Edward II went to war with the barons. In 1327 King Edward III (son of Edward II) ruled England and parts of France. Late that year, King Edward II was put to death and Edward III seized control of the English court. Edward had 12 children, 5 survived. The most recognized was the Black Prince, Edward, his oldest son. After defeating the scots, he claimed himself as king of France marking the start of the Hundred Years' War. During this time, England and France struggled for dominance of Western Europe. 1346 marks The Battle of Crecy where the English were defeated. The Black Death began to ravage

Europe for the first of many times in 1347. An estimated 20% - 40% of the population is thought to have died within the first year. With the help of the Black Prince, the English were victorious at the battle of Poitiers in 1357 (Ozment, 1980).

King Richard II (grandson of Edward III, son of the Black Prince) was next to rule starting in 1377 at 11 years old when Edward III died. In 1381 Peasants Revolted in England against the heavy taxes put on them that were needed to fight the French. King Richard met with, and dispersed, the armed mob. The king was then able to speak to every one of the concerned at the death of Wat Tyler. In 1382 John Wycliffe translated the Bible to English. King Richard II banished Henry Bolingbroke to France in 1399. Later that year, he returned with an army, courtesy of France, and forced Richard to step down. During his years as king, he got sick several times, in many instances his son Hal was forced to step in. Hal later succeed Henry IV as King Henry V in 1413 (Ozment, 1980).

As king, Henry V invaded Harfleur, France, and forced them to surrender. From there, he and his armies' invaded Agincourt in 1415, marking one of the greatest victories for the English in the Hundred Years' War. Later he was recognized as heir to the French throne under the Treaty of Troyes, and married Catherine of Valois to further validate the cause. He died in 1422, and his son took over as King Henry VI at 9 months old. In 1429 Joan of Arc lifted the siege of Orleans for the Dauphin of France. This enabled him to eventually be crowned at Reims. In 1430 Joan of Arc was captured, the later tried, and burned at the stake. King Henry took power in 1437 when his mother died but mental illness lead his role as king being questioned. Calais was the only English possession left on Continental Europe when in 1453 the Hundred Years War ended with struggles for power growing internally in England. In 1455 civil war broke out called the Wars of the Roses. This lead to the demise of King Henry VI, he was captured and imprisoned in London and died. By 1471, Edward IV had taken control of England as King and declares war on France again. Edward got sick in 1483 and named his brother Richard protector of his young sons, rightful heirs to the throne. That same year Edward died and neither of his sons was fit to rule at their young age. His brother Richard was pronounced King Richard III in 1483; young Richard and Edward were never seen again. King Richard’s defeat in 1485 by Henry Tudor marked the end of the Plantagenet dynasty and the Wars of the Roses. There started the Tudor dynasty (Ozment, 1980).

7.1.2 French Rule

Starting in 1100 France, an extensive architectural sculpture movement swept throughout the country. The earliest were capitals with narrative decoration that appeared in Chauvigny around 1080. In 1112, Saint Bernard joined the abbey of Cîteaux (founded in 1098), in an effort to restore a monarchy under Benedictine rule. Bernard founded the abbey of Clairvaux in 1115 and the Cistercian order flourished under his leadership. In 1146 Bernard called for the Second Crusade, it was supposed to be the last Crusade with assistance of the Knights Templar. He died in 1153. In July 1137, Eleanor of Aquitaine married King Louis VII of France. Their marriage was annulled in 1152, and Eleanor immediately married Henry Plantagenet, who became Henry II of England in 1154. This marriage brought Aquitaine, Normandy, and England under one rule, and marked the beginning of English presence in France. Eleanor's court at Poitiers became a great center for poetry and culture (Ozment, 1980).

From 1140–1150 Abbot Suger, advisor to Louis VI and Louis VII began to remodel the royal abbey church of Saint-Denis outside Paris. Paris flourished with a great community of scholars, including Peter Abelard, Peter Lombard, and John of Salisbury. The city became the leading center in Europe for the study of theology and liberal arts. The University of Paris was founded between 1150 and 1170. In 1180, Philip Augustus took power as king of France. As king, he transitioned the title of "the king of the Franks" to “the king of France”. Philip increased the royal treasury, reformed his political administration, and built defenses to secure Paris as the capital. In addition, in 1194 he established the court permanently in Paris and he extended his territorial influence in too much of what is modern-day France. In 1209 Pope Innocent III, with the help of Cistercian monks, launched the Albigensian Crusade in southern France. In an attempt to deal with the growing problem of heresy in the Toulouse area, the political struggle eventually lead to war between the independent southern territories, and lords from northern France (Thematic Essay, 2001).

By 1229, Count Raymond VII of Toulouse surrendered the territory to the King Philip’s control. In 1226 Louis IX took the throne. He exemplified the virtues of a Christian knight with his strong sense of responsibilities and works of charity. Louis IX made Paris a thriving cultural center by protecting the both of the university and the arts in the city. Louis IX commissioned the Sainte-Chapelle, his royal chapel on the Île de la Cité, as the safe haven for the Crown of Thorns, in 1237. While king, Paris became the center for the production of precious arts, including: manuscript illuminations, ivory carvings, and goldsmiths' work. Louis died in 1270 and was canonized in 1297. “In France the transition from feudal to monarchical state actually began with the Capetian kings and reached a decisive stage during the reign of Philip IV the Fair (1285-1314).” (Ozment, 1980) The Capetian kings had fostered national unity through the use of one language by 1274 (Ozment, 1980).

Around this same time, Primat, a monk, translated The Grandes Chroniques de France from Latin into French. The Grandes Chroniques de France was a manuscript celebrating the Capetian dynasty written at Saint-Denis. By 1300, France was recognized as the most powerful nation in

Europe with a population of 20 million. At the time, Germany fostered a population of 14 million and England around 4 million. In 1309, the French pope Clement V took up residence in Avignon due to political unrest in Italy. From there, 6 more popes lived in Avignon instead of Rome. Following such a rise, “Europeans suffered the worst famine of the Middle Ages between 1315 and 1317, and recurring poor harvests kept resistance to disease low when bubonic plague, following the trade routes from the east into and throughout Western Europe, struck in midcentury.” (Ozment, 1980) Endemic wars and the development of sea trade contributed to the decline of the annual fairs held in the county of Champagne east of Paris in the 1320s. Diverse wares such as Flemish cloth and tapestry work, Chinese silk, Egyptian satin, Eastern spices, furs from the North, and even wax from Russia had been available at these fairs. These rare goods had made the region a crucial center of international commerce and banking since the late eleventh century (Ozment, 1980).

Following the decline, Philip VI took over the French throne in 1328. He was the first French king from the Valois branch of the Capetian dynasty. By 1348 the Black Death had reached France. It is estimate that it killed a third of the population France alone. Towards the end of the time period, France and England fought in the Hundred Years’ War from 1337 to 1453. Although Philip VI had taken over the throne, King Edward III of England claimed the French throne for England. In need of funds to fight the English, the French also heavily taxed the commoners and poor. “Increased taxation and such restrictive legislation provoked peasant revolts in fourteenth-century Flanders, France (1358), England (1381), and in Germany during the fifteenth and first quarter of the sixteenth century.”(Ozment, 1980) The war ended when Charles VII of France regained Normandy and Aquitaine. By the end of the Hundred Years’ War, England was distracted with the War of the Roses, which allowed France to break free (Ozment, 1980).

7.2 Architecture and Art

7.2.1 Castles

In the Medieval era, castles were built everywhere across Europe. These magnificent structures housed the monarchs across decades and reflected the art, technology, changing styles and power within each kingdom of the time. Many still stand today after hundreds of years reflecting remarkable architecture for how limited tools and resources were during the time. In addition to a home, Castles expanded in size to accommodate: judicial buildings, courts, good storage, and acted as refuge in time of war. The first modern castles were built by the Normans in the mid-11th century and were specifically designed to withstand attacks mainly from one direction. Over time, castle construction evolved to included walls 12-15ft thick, higher walls and proper lookout locations. Like city centers today, towns would grow around castles and then more would be built around the town (English Castles, n.d).

Figure 1. Medieval Castle (National Geographic).

7.2.2 Cathedrals

Aside from castle construction, cathedrals were built as an expression of faith with less restrictions that castles had. Cathedrals were built by members of the community as a way to forgive sins. This provided an alternative option to going on crusades, allowing people to dedicate more effort into construction. Many of these people never lived to see the finished building, some cathedrals took centuries to complete such as the York Minster Cathedral, spanning 252 years. While some were disgusted by the excessive amounts of money spent in decoration of such buildings, most agreed it was money well spent allow a proper place of worship. Much of the money came from Cathedral chapters themselves, with some assistance from Bishops. Within each chapter, money was raised by donations and fines. In addition, chapters would take religious artifacts on tour and charge others to see them. In England and France, these reflect the growth of Christianity during the time. One of the most well-known from the time is Notre Dame Cathedral in Paris (Cathedral Building, n.d.).

Figure 2. Notre Dame Cathedral in Paris (Google Images).

7.2.3 Gothic Style

Gothic Architecture style contributed to the distinct features within the Cathedrals and Castles. These include: stained glass windows, gargoyles, pointed arches, tall spires and massive pieces of granite and marble. The different types of English Gothic Architecture styles are divided into three time periods. The first being early English Gothic Style (also called Lancet Gothic) spanned from 1200 to 1300. This was named from the lancet arch which was an acutely pointed Gothic arch, like a lance. Next from 1300 to 1400 was the Decorated Gothic Style, as cathedrals showed more elegant features and overall fluidity in the construction. Last was the Perpendicular Gothic Style, which ran from 1400 to 1500.

In this style, following the Black Death, the attitude towards arts and culture was far more pessimistic, focusing on death. Windows became larger but overall flamboyance was lost and the cathedrals became less detailed and flashy. In France, much of the early cathedrals adopted the English style. In 1144, the French styles appeared as minor alterations. "The Gothic architects started to apply ribbed vaulting and pointed arches to emphasize light and soaring spaces. The focus on vertical lines increased as did the ratio of glass to stone. The new French Style of architecture applied at first to churches and cathedrals in France soon spread to other structures." (Medieval Life, n.d).

7.2.4 Medieval Art

Medieval art evolved during the middle ages into beautiful depictions of religion. Much consists of Illuminated manuscripts, mosaics, and fresco paintings. Other forms include metal work, panel painting, gold and silver works, embroidery, ceramics, tesserae, sculptures, stained glass, and heraldry. Heraldry is the practice of designing badges and coats of arms. Their work spanned from use of parchment paper, painted wood, enamel, stone, glass and embroidery. Stained glass was used in churches and cathedrals. Small colored pieces of glass were bound together by lead strips and usually depicting religious figures or stories. Much of the sculpture work was an extension of roman style but modernized. Tesserae is a single tile in a mosaic. These pieces used flat glass with gold leaf in-between to illuminate the work. Mosaics consist of small tiles and pieces of glass arranged to form pictures, similar to stained glass artwork. Panel paintings were done on large pieces of wood, or many pieces of wood joined together. Fresco is the plaster work done on church ceilings. Last, Ceramics were hand shaped to make cook ware, jugs, jars and other kitchen equipment of the time (Thematic Essay, 2001).

8. Medieval Period Weaponry

The medieval era was known as an extremely violent period due to the hunger for power and wealth. Many different types of weapons were created, and they were made with the available technology and raw materials. A lot of castles were built as power bases, but there were frequent invasions, causing battles and wars. As the number of battles and invasions increased, the want for better weapons was high, and this caused significant change in medieval technology, architecture, and weaponry (Alchin, 2014).

8.1 Types of Weapons

The classifications for the different weapons in the medieval era were melee, and ranged, where within the ranged group is siege weapons and guns. Some of the example melee weapons were sword, battle axe, billhook, dagger, halberd, and mace. Since much of the medieval fighting was done in close quarters, melee weapons were very important and it was crucial to have the best melee weapon as well as soldiers. Some of the example ranged weapons were throwing axe, crossbow, longbow, catapult, and guns (Alchin, 2014). As time progressed, fighting at long range became important and the ranged and siege weapons were used to bring down castles. Apart from the classification of the weapons, they basically fell into three categories: weaponry used by foot soldiers and archers, weaponry used by lords and knights, and siege weapons and guns (Nimocks, 2011).

8.2 Types of Armed Men

In the early medieval era when mostly melee weapons were used, the main types of armed men were knights and then the foot soldiers. As the need for ranged increased, archers and soldiers that worked the siege weapons were added to the list. Most of the armed men held different weapons, and this was because of their rank in the Feudal System.

8.2.1 Knights

Knights, usually of the highest status in terms of soldiers, used the best and most expensive of weapons. They spent most of their lives gaining experience at using different weapons and enhancing skills with swords, lances, and axes. To gain the status of knighthood was a very long task; it wasn't just given out because a young man was a son of noble (Alchin, 2014).

8.2.1.1 Becoming a Knight

The process began at a very early age, after the age of seven, when young men were sent into care of some noblemen. The first seven years were spent as a Page where lots of games and exercises were conducted so as to learn skills such as horsemanship and learn to use weapons. The next seven years were spent as a Squire, where they were treated as men capable of fighting in battles. The training also became difficult, dangerous, and injuries were common. Not only did they learn to use weapons and protect lords, but they enhanced skills of bravery and the ability to cooperate.

Figure 3. Ceremony of Becoming a Knight (Ducksters, 2014).

8.2.1.2 Code of Chivalry

As knights, they were men who took an oath to protect their land, provide service to nobles, and enforce the law and deal with conduct caused by lower class. They were also expected to follow the Medieval Code of Chivalry. The ten commandments of the Code of Chivalry were as follows (Medieval Code of Chivalry, 2011):

1. Thou shalt believe all that the Church teaches, and shalt observe all its directions.
2. Thou shalt defend the Church.
3. Thou shalt respect all weaknesses, and shalt constitute thyself the defender of them.
4. Thou shalt love the country in which thou wast born.
5. Thou shalt not recoil before the enemy.
6. Thou shalt make war against the Infidel without cessation and without mercy.
7. Thou shalt perform scrupulously thy feudal duties, if they be not contrary to the laws of God.
8. Thou shalt never lie, and shalt remain faithful to thy pledged word.
9. Thou shalt be general and give largesse to everyone.

10. Thou shalt be everywhere and always the champion of the Right and the Good against Injustice and Evil.

The most sacred commandment for the knights was the first one. Church was and still is an important part of life, and just the thought of "God filled knights' heart" and how knight's service was because of the church, it meant a lot to them (Medieval Code of Chivalry, 2011).

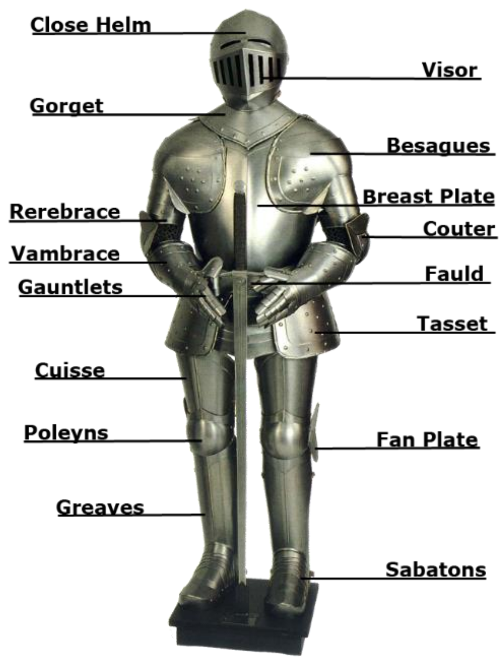


Figure 4. Parts of Armor of a Knight (Ravencroft, 2013).

8.2.1.3 Knight in Armor

Because they were the ones that trained their whole lives, knights were the main users of armors and the best of the weapons. With the money they earned or had, they were able to afford not only the best materials, but also the best blacksmith to produce and decorate their armor and weapons. For the knight, the armor was for protection and a source of his reputation, since usually the armor was stamped with the seal of the Lord family being served. Typical armor that knights usually wore were helmets, greaves – armor that protected lower legs, gauntlets – armor that protected hands and wrists, and sabatons – armor that protected the feet.

8.2.2 Soldiers

In terms of rank in the feudal system, below the knights were the peasants and commoners. During the early medieval times, the men were required to fight for the Lords. Most often, they were given no armor and fought with simple tools like axes or with a spear and shield. Usually they had to bring their own equipment, and other times, the Lord outfitted them with armor and weapons. As the times went on and the need for soldiers and range weapons increased, peasants and commoners who showed skill, discipline, and fighting ability started getting trained for being foot soldiers and those who showed skill and accuracy started getting trained for archery and siege weapons (Alchin, 2014).

8.2.3 Other Medieval Roles

Although most of the commoners were either brought to train to use weapons or employed as servants in the Lords' Manors, there were some that worked different jobs in the towns and on their own that related to medieval weaponry. One of the jobs was the armorer. The armorer had the important job of making sure the armor fit each individual perfectly so as to not be distracting during battle.

Figure 5. Blacksmith: Important job done by skilled commoner (Some Interesting Facts, 2014).

Another job was the atilliator or the bower, who was in the castle and in charge of making bows, arrows, and crossbows. Crossbows will be talked about later on, but basically they were short ranged range weapons and shot metal tipped arrows. A very important job was the blacksmith. He was the one who forged and sharpened weapons, and repaired armor. Finally, another important job was the carpenter. This occupation was a bit more varied but he built everything from furniture to siege weapons engines. A carpenter was considered highly skilled and could shape and make anything out of wood (Alchin, 2014).

8.3 Evolution of the Melee Weapon: Axe

Looking as far back as the Stone Age, the axe started out as a hand-axe which was just a rough lump of stone and was one of the earliest tools to be used by mankind. Some of the initial applications included very simple tasks such as uprooting, crushing, or pounding. Even though it wouldn't have been used at all as the axe we know now, slowly change started to occur as the needs increased. Later on, it was realized that without a handle, the striking power and efficiency of the tool would be very low (Coghlan, 1943). So with trial and error, there was an addition of a handle to the axe, which changed the major function of it to being able to cut timber. The axe is one of the oldest tools/weapons; made of stone, bronze, iron, and finally steel (Medieval Battle Axes, 2014).

8.3.1 The Axe

Comparing to how the early form of the axe was not even a weapon, but more of a tool to gather necessities such as wood, plants, and food, to the axe known during the medieval times, there were a lot of changes. By this time, it was made to be a weapon, used by foot soldiers and some knights. It was extremely inexpensive to produce and required limited skill so it was well suited as a weapon for peasants and commoners. The axe consists of two primary parts; the axe head and the haft, also known as the handle (Alchin, 2014).

Axes could be differentiated in many ways; size, shape, and the way it was used. The size of the axe varied from 1 foot up to 5 feet. It was sometimes mounted on long shafts, making it a longer weapon and allowing it to be less close combat. The shape of the axe is where a lot of creativity came into play, it could be single headed, double headed, or single headed with a pickaxe type of point on the other side. The blade was crescent shaped and it measured about 10 inches between the upper and lower points, but that was varied as well.

The axe was a very effective weapon for offensive attacks, but poor for defensive. It was a lethal weapon, designed and used to penetrate armor and shatter shields. Because of its offensive ability, the axe was a very common weapon used, not only by commoners and foot soldiers, but also by some knights. Of course the knights usually designed their own and hired the best blacksmiths to use the latest materials available, but the overall skill required was the same. As far as training was considered for the axe, skill in using the weapon and understanding the strategy of warfare was necessary. The training method usually was based on strength and accuracy of hitting a target at different power levels and target areas. The final way of differentiating an axe was the way it was used in combat and different types of axes required additional training and skill (Alchin, 2014).

8.3.1.1 Throwing Axe

The first type of axe, the medieval throwing axe, was used mostly by foot soldiers and as a ranged weapon. To achieve maximum penetration, it was often swung first around and over the head to obtain speed and momentum and then thrown at the enemy. Often, it was used in volleys, start of the war or invasion where tons of arrows are shot into the enemies, as this would throw off the enemy formation. Some of the throwing axes had light frames and heavy heads, so they were specifically designed for throwing. Being designed for this purpose, it was able to be hurled at fast speeds and could penetrate armor plates and shatter shields about 40 feet away (Alchin, 2014).

Figure 6. Medieval Throwing Axe (PJS, 2011).

8.3.1.2 Pole Axe

A different type of the axe was the pole axe and was often used by knights on horseback. The weapon consisted of a broad, but short axe blade on a wooden pole, and it was between 4 and 5 feet long. The name for this weapon came from the word pollaxe from an old English word, and this is because they were originally just an axe mounted on a pole. The pole axe was always evolving and changing to be a very good weapon and more effective against swords. As the pole length increased, it became a more effective fighting weapon, but severely lacked in the defensive capabilities. As a result, most of the soldiers who had a pole axe also brought along a dagger or a sword to be able to fight at very close range (Alchin, 2014).

Figure 7. Medieval Pole Axe (Weapons, 2009).

8.3.1.3 Battle Axe

The final type of axe was the battle axe and was used equally by both foot soldiers and knights. It was used a close combat melee weapon and required a lot less precision compared to the throwing knife, and was more effective than the pole axe. Before, an expensive, long, straight sword was the preferred weapon of the upper class knights, but as armor started covering all of the knight’s body, and anti-sword features were added, greater impact weapons had to be designed. A battle axe that struck with a lot of force applied significant damage and injury to a knight in armor. The battle axe became known as an armor-crushing weapon and sometimes worked better than a mace, since the single blow was concentrated in a smaller area. It was also used often as a cutting weapon and was very capable of cutting limbs off of an enemy in a swift stroke (Alchin, 2014).

Figure 8. Medieval Horseman's Battle Axe (Weapons, 2009).

8.4 Other Weapons

Even though the axe was a very important part of the medieval weaponry, not only for battle but also for other chores, there were other weapons in use as well. The big four categories of weapons used were melee, ranged, sieged, and gun.

8.4.1 Melee Weapons

Melee weapons were close combat weapons used in the medieval era, and were used most commonly by foot soldiers. Over the several hundred years of the medieval times, the melee weapons were continuously developing. This was due to the metal working skills of the blacksmiths and the need for better weaponry to overtake the improvement in armor (Kalif, 2012).

8.4.1.1 Dagger

Figure 9. Medieval Dagger (Jenny, 2014).

The dagger was a two-sided blade used by soldiers and sometimes knights. It was mostly used for close combat and as a secondary weapon, like if the primary weapon was a type of axe, or sword, and that either got taken, was lost, or broke. Even in the earlier times and during most of middle ages, daggers and knives were always considered as secondary or tertiary weapons. Most of the cultures mainly fought with long weapons such as pole weapons, swords, and axes. The dagger was especially necessary for archers and long range weapon wielders, such as crossbow, throwing axe, or other because if the enemy got into the close combat range, melee weapon would have the best chance of winning. With the increase of use of protective plate armor during the medieval ages, the dagger became an increasingly important weapon for stabbing through the gaps in the armor. Overall, the dagger was a common murder weapon and was used mostly by commoners or aristocrats who wished to remain anonymous (Weapons, 2009).

8.4.1.2 Sword

The sword was a double edged and came in many varieties, used by all armed men and as a primary form of a weapon. The intentions and physics of the swordsmanship have remained the same through the decades, but the techniques of forging and making vary among different cultures and periods of time, resulting in varieties of blade designs and purposes. Unlike the bow, spear, or axe, the sword is a pure weapon and is sometimes considered the symbol of warfare or state power (Weapons, 2009). As seen from the Figure 7, medieval era swords varied in size, shape, and the decoration (color, emblem).

Figure 10. The Medieval Sword (Knights Edge, 2008).

One of the most used type of sword was the Longsword, type of European sword used during the late medieval period. Some of the important features of the longsword was that it had grips of about 10 to 15 inches, allowing of room for both hands if required. The length of the swords are between 40 and 48 inches and weigh around 2.5 to 5 pounds. The longsword is usually held with both hands, but there are some that use it single-handed. The longsword was a quick, and effective weapon, capable of dealing dangerous thrusts, slices, cuts, and stabs (McDonald, 2010).

8.4.1.3 Mace

Figure 11. Medieval Era: Flail Mace (McDonald, 2010).

The mace was a large club with a normal or spiked ball at the end, and sometimes the ball was fixed to a chain. It was first used by the Nobles, but soon enough, everyone started because it was able to injure enemies wearing heavy armor such as chain mail. The mace was made of a strong, heavy, wooden but metal reinforced shaft with a head made of iron, or steel. The length of the maces usually vary but for the foot soldiers, it is about 2 or 3 feet, while those made for cavalrymen or knights were longer and better designed. Sometimes, there were also two-handed maces and the lengths of those could be even larger. The mace was a very important weapon because before that, during the middle ages, metal chain armor protected against blows of edged weapons and arrows and was very hard to counter. Now, the maces could inflict damage on well armored knights, causing damage with just the force without penetrating armor (McDonald, 2010).

8.4.2 Ranged Weapons

Ranged weapons were effective in combat in comparison to melee weapons, as they gave the wielder the opportunity to launch projectiles before a melee weapon armed enemy posed a threat with the distance. Important ranged weapons that came into play during the medieval period were bows. The way the bows worked was that as the bow was drawn, energy became stored as potential energy and transformed into kinetic energy as the string is released, and the string transfers it to the arrow. After the invention of gunpowder and development of firearms, ranged weapons started getting out of use (McDonald, 2010).

8.4.2.1 Longbow

A longbow was a type of bow that was tall, almost equal to the height of the person who used it, and this allowed the user a long draw. The longbow was not re-curved, the limbs were narrow so that they were circular. The traditional longbows were made from single pieces of wood, and were mostly used for hunting and warfare. Because the bow could be made from a single piece of wood, it could be crafted very quickly and easily. The longbows for warfare purposes tended to be very powerful and topped the power of 900 Newtons at the 32-inch draw mark. The longbow archers also participated in the ranged volleys at the beginning of the battle. Overall, a typical archer was provided between 60 and 72 arrows at time of battle, and so most archers used their ammunition sparingly, since running out of the arrows would be the worst (McDonald, 2010).

Figure 12. Medieval Longbow Practice (McDonald, 2010).

8.4.2.2 Crossbow

The crossbow is another ranged weapon that fires metal bolts with great force. The bow, also known as the prod or lath, of early crossbows was made of a single piece of wood, usually ash or yew. The arrow projectiles of the crossbow were called bolts. They were much shorter than normal arrows but because of the metal, they were several times heavier. Because the prod of the crossbow was very short compared to ordinary bows, resulting in shorter draw length, and required more draw weight to store the same amount of energy as a normal bow with normal draw length did.

Figure 13. Medieval Crossbow (McDonald, 2010).

The crossbow had a mechanism that held the drawn bow string and had a trigger system that retained the force of the cocked string and then released the nut which released the string to shoot the bolt. Some of the early designs for the trigger featured a slot into which the string was placed and then a vertical rod came up through the hole, forcing the string out and the bolt to fire. In European armies, the crossbow archers occupied a central position in the formations and they preceded the attacks of the knights. The more powerful gunpowder weapons eventually replaced crossbows, even though early on, guns had slower firing rates and terrible accuracy compared to crossbows (McDonald, 2010).

8.4.3 Siege Weapons

The middle ages saw the use of many new modes of warfare and an effective one was siege warfare. Siege weapons consisted of battering rams, catapults, trebuchets, and much more and was mostly used for either defense or breaking down walls and castles.

8.4.3.1 Trebuchet

The trebuchet or catapult were large devices that had a throwing arm, and their primary purpose was to throw large rocks at castles and the walls to knock them down. The trebuchet came from the ancient sling and had a short piece of wood to extend the arm and provide greater leverage. The trebuchet or catapult were often just created on the site from local wood and were custom made to fit the landscape and the target. There were many different types of trebuchets but the most used ones were the traction and counterweight trebuchets. The traction trebuchet had a hurling arm that was powered by a crew of men, pulling on ropes attached to a lever arm. The counterweight trebuchet was powered by a very heavy counterweight acting on the lever arm.

Figure 14. Medieval Trebuchet (McDonald, 2010).

The range of these trebuchets were between 2000 to well over 3000 feet when the traction hurled almost 750 pound weights while the counterweight flung 300 pound weights at very high speeds. Most of the trebuchets were designed to utilize between 15 and 45 men. Sometimes the men would be local citizens assisting with the siege or in order to stop the invasion on their town. Because of the time required to load the sling and raise the counterweight or pull ropes, the rate of fire was slow at about a couple of shots per hour. The payload of the trebuchet was usually a large rounded stone but armies started getting creative and projectiles started including dead animals, beehives, severed heads, fireball, and prisoners (McDonald, 2010).

8.4.4 Guns

Gunpowder was introduced to Europe in 1250, invented by China, and this powerful technology was starting to be better understood and eventually guns, bombs, and cannons started being built (Weapons, 2009).

8.4.4.1 Hand Cannon

The hand cannon was the early form of firearm during medieval times and was the simplest type of firearm. The hand cannon was a weapon, consisting of a barrel with a handle, but came in many different shapes and sizes. Not all cannons had metal in their construction, and in fact in China, they used bamboo tubes instead. For firing the hand cannon, it had to be head in two hands while another person applied the means for ignition, which was wood, coal, iron rods, or slow burning matches. The early hand cannons fired pebbles that were found on the group, but often, most fired ammunition such as balls of stone, or iron. Because the poor quality of powder and construction, they were not very effective and barely had power to punch through the light armor. As the technology was experimented with and was better understood, more weapons involving gunpowder starting surfacing (McDonald, 2010).

Figure 15. Medieval Hand Cannon (McDonald, 2010).

9. Evolution of Materials

9.1 The Stone Age

The Stone Age began with the creation of tools being created out of stone and ends with the implementation of bronze as a replacement. Though exact dates are tough to confirm, archeologists deemed that the earliest date to begin the Stone Age is about 2.5 million years ago in Africa and ends in the Near East around 3300 BCE. The Stone Age can be broken up into three different periods. These periods are the Paleolithic, Mesolithic and the Neolithic period.

The Paleolithic Era is the longest of the three periods, beginning approximately 2.5 million years ago and ending at the end of the last of the last Ice Age, about 9600 BCE. There are various stone industries that were spawned out of techniques that were learned and the quality of the tools created. Two such industries were the Oldowan and the Acheulean. The Oldowan were choppers that were simple in design from Africa from about 2.5 millions of years ago. The tool was created by hammering the stone so that sharper flakes are chipped out of the stone. The Acheulean was a stone that was symmetrical and complicated for the era in design. The edges of the Acheulean were sharp and were similar in shape to arrowheads. The Paleolithic Era also so the birth of something that shaped the history. Tribes begin to work together and develop, starting the idea of civilization. The end of the Paleolithic Era also saw the first of artistic expression.

Figure 16. Oldowan Sample (Wikipedia, 2014).

The Mesolithic Era began around the end of the last Ice Age and ends with the birth of agriculture. This period ends at various points for each region. For example, the Near East developed agriculture around 9000 BCE where Northern Europe started farming around 4000 BCE. This era saw little in terms of technological breakthroughs except for the advancement of tools from the previous era, making them more efficient and easier to use. The era also saw changes in geographical regions. Japan was disconnected from the main land Asia, same with the British Isles from Europe.

Finally, the Neolithic Era began with the advancement of agriculture and ends with the introduction of bronze as a tool material. The tools developed in this era where focused on improving the farming and herding process. Such developments include plows and irrigation systems. At the same time, people began to work with stoves and ovens which is the start of pottery as well as bricks for building. The end of the Neolithic Era saw the beginning of copper metallurgy. As copper is an ingredient in bronze, this began the fade of stone tools from common use.

Figure 17. Acheulean sample (Wikipedia, 2014).

9.2 The Bronze Age

Unlike the Stone Age, which was characterized by unorganized human settlements, Bronze Age civilizations developed into highly evolved societies. The Bronze Age produced the first early written material and saw huge changes in society and live in general. The Bronze Age began in Mesopotamia around 4500 BC, in eastern Asia around 300 BC, and in Europe around 1900 BC. The Near East civilizations are the oldest Bronze Age civilizations in Mesopotamia. They are not only the earliest societies to adopt religion and a formal political structure, but led in the invention of the wheel, boats, and ships. These innovations in transportation helped develop trade between regions and civilizations. This trade became an important aspect of Bronze Age civilization and fueled the first features of urbanization.

In Europe, far reaching trade networks were first established around 3200 BC to import tin and charcoal to Cyprus where extensive copper mines were located. These metals were combined and made into various objects that were then exported for a profit.

Figure 18. Bronze Age artifacts (Wikipedia, 2014).

The knowledge of navigation became an important skill to trade, but it was not refined until the formal method of determination of longitude was discovered around 1750 AD-well after the Bronze Age had ended. In the Catacomb cultures, corded pottery was integrated into the steppes and polished battle axes became a common weapon to help link their culture to the west. Large armies were organized and outfitted with bronze weapons. Before the implementation of bronze weapons, it had been extremely expensive to make weapons out of pure copper. These weapons were forged out of pure copper and were smaller items like daggers and axe heads.

Once it became more cost effective to make bronze weapons, organized armies became the foundation for power. Many empires rose up during this period, most notably the Egyptian, Hittite, and Syrian Empires.

Figure 19. Bronze Age dagger and bowl found in Egyptian coffin (Wikipedia, 2014).

These empires often went to war to fight over key natural resources or farming lands. War characterized the period and many cities rose and fell. Toward the end of the Bronze Age, the Hittite and Syrian empires fell. Archeologists are still uncertain what brought an end to these two empires and severely crippled Egypt's political system. Some believe that natural disasters such as earthquakes rocked the region while others believe that a peasant revolution occurred which destabilized these once powerful empires. Either way, these once powerful empires fell and provided a power vacuum where the man with the better equipped army would win. In other words, the man with the sharper sword would prevail.

9.3 The Iron Age

The Iron Age brought down the end of the Bronze Age. Iron allowed tools and weapons to be sharper and more durable than their copper and tin counterparts. Eventually, iron would be mixed with carbon and other elements to create an alloy that was stronger, lighter and sharper; steel. Iron had a downside. It was scarce in various regions and, if found, was more difficult than bronze to forge. The Chinese were the first to perfect the smelting of iron, due to the ovens that they used previously for ceramics. The Iron Age, like the Stone Age, is broken up into sections. These sections are Iron I and Iron II. This section will focus primarily in the regions of the Middle East and Europe.

Iron I, which begins around 1200 BCE, sees similarities and differences with the Bronze Age. As these two eras overlap, even within the same region, the process used to smelt and forge iron were at first similar to those of bronze. Since bronze tools were casted, so were the early iron tools. Early iron was far more durable and sharper than bronze but lacked the alloy properties of later iron and even steel. Iron brought improvements to war, allowing for fortifications to be supplemented with a harder material. Iron weaponry forced opposing sides to create new armors made out of iron, as swords would tear through leather and hammers would smash bronze. As more nations acquire iron and begin forging effectively, the Iron I era comes to an end around 1000 BCE with the great empires of Egypt and Assyria falling off and the rising of Israel and Judea.

Figure 20. Iron armor from the Middle East in the Early Iron Age (Wikipedia, 2014).

Iron II, starting around 1000 BCE, saw the most significant change in the forging process of iron. Instead of being casted, iron is now being open-air forged. Forging allows the iron to be more durable as the metal is actively being hammered, thus the metal will be more resistant to impact damage. It also takes out the need for alloys to be added (though eventually carbon will be added to create steel) to make the material tougher. With tougher weapons, expanding nations and empires, such as Judah and Rome. Rome conquered most of Europe and thus brought forging techniques to northern and western Europe.

Figure 21. Examples of Iron weapons (Wikipedia, 2014).

Though Iron II ends in the Middle East around 550 BCE, it continued on in Europe until about 50 BCE. The end of the Iron Age does not mean that Europe ceases in using iron as a material. It is more of the end of the technological revolution that was created out of the discovery of iron. Better weapons and armor were continued to be created as the years progressed, culminating in the alloy of steel that came about in the Medieval Era.

9.4 The Medieval Era

The Medieval Era is the tip of the iron and steel era. Blacksmiths have been working with iron for hundreds of years, since iron was used as a tool in the 1000's BCE. Eventually, blacksmiths began carburizing iron, the process of which adds between 0.5 percent and 2 percent of the element carbon into the iron, and quenching the iron in water creating the alloy of iron known simply as steel. Repeating the carburizing and quenching process to temper the iron or steel to increase to the toughness of the material by reducing the hardness, allowing the metal to become more ductile. Steel weapons and armor became some of the most desired items by kings and rulers. A poem by Rudyard Kipling called Cold Iron captured the importance of iron in the era. The first verse is as follows:

Gold is for the mistress -- silver for the maid --
Copper for the craftsman cunning at his trade."
"Good!" said the Baron, sitting in his hall,
"But Iron -- Cold Iron -- is master of them all."

Mr. Kipling, like the kings and lords of the Medieval Era, saw that he or she with the best iron, and eventually steel, would control the era.

During the Medieval Period, metals were becoming one of the most important materials. Towns were formed solely based around a mine that had discovered a large vein of copper, silver, gold, or iron. Iron soon became the most important of these because it was fairly common and could be worked into a variety of usable objects such as weapons or tools. Over time, these smaller mining operations developed into large scale efforts that attempted to maximize their production. Those who controlled the iron mines became wealthy and powerful. Iron was key to winning wars, and the control of these mines became of key importance to medieval political structures. Iron that was not used for the war effort could be exported and sold abroad to others who needed this precious metal to fund their war efforts.

Figure 22. Remnants of a Medieval mine (Wikipedia, 2014).

The quality of the iron ore was of utmost importance because medieval purification efforts had limited success. Iron can easily combine with many other elements making the possibility for impurities great. Large amounts of manpower were required to purify the iron ore; therefore, a high quality piece was highly dependent on the effort put into purification and ultimately the ore that was used. These sophisticated refining processes required large amounts of capital which only the wealthy could provide. Powerful kings and rulers often surrounded themselves with skilled blacksmiths who could equip their army with quality arms and armor. Thus the blacksmith's trade became highly respected and very profitable if you were willing to put in a large time and practice.

Blacksmiths in the Medieval Era were critical members of their respective communities. Blacksmithing went beyond just arms and armor. Small village blacksmiths focused primarily on household and farm tools such as plows, horseshoes and irrigation equipment. If a blacksmith was able to hone his skills, they could move into the cities where they could become members of a guild. Guilds provided protection for the blacksmiths allowed for ample trade opportunities. Monks in abbeys and monasteries also learned the blacksmith trade to produce any tools or equipment needed. The most sought after of all blacksmiths were those that could produce the finest weapons and armors. Kings and rulers often had their own personal blacksmith that worked within the castle grounds. Such blacksmiths were tasked with creating and maintaining the weapons, armor and equipment of the lords and knights that they served. Though there expertise or place of work may have varied from blacksmith to blacksmith, the general setup of a blacksmiths forge was the same.

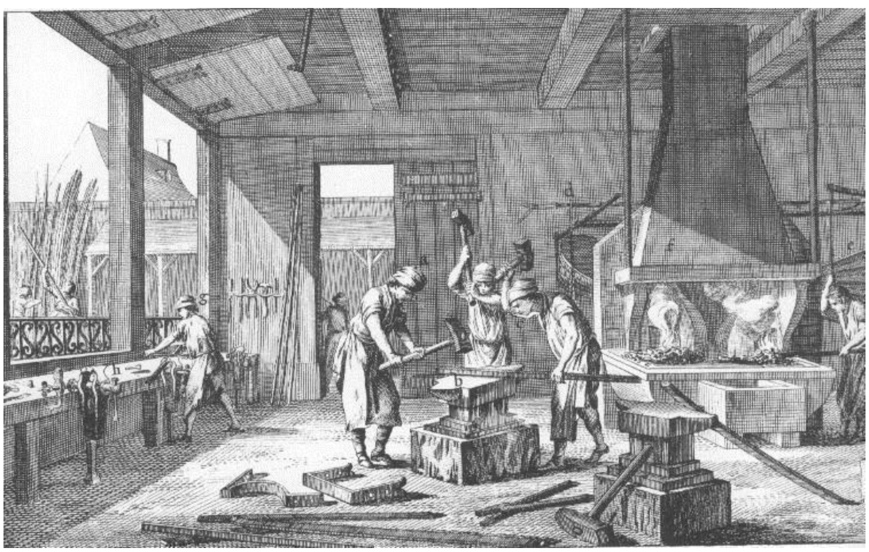


Figure 23. Portrayal of a Medieval blacksmith (Wikipedia, 2014).

The forges used by blacksmiths were also quite intricate. Forges were built around special hearths or fireplaces known as furnaces. The furnaces were used to heat the iron or steel to high temperatures so that the iron or steel could be molded on the anvil. As there was no way to accurately indicate the exact temperature of the metal in the furnace, blacksmiths used the color of the heated metal to dictate how they wish to form the material. Furnaces were mostly fueled with the local wood, charcoal, and coal. To protect themselves from the sparks and potential fires that resulted from hammering the metals, blacksmiths wore long leather aprons on top of woolen tunics. Bellows allowed the fires within the furnace to burn at greater temperatures, allowing for the iron to become malleable quicker and for steel to carburize more efficiently. Early bellows were operated by hand, usually by the blacksmith's apprentice. Larger forges were built along riversides. Using the power of the water allowed for larger furnaces and bellows. Such blacksmiths were able to produce large amount of tools, weapons and armor.

Other tools could be found in a typical forge include tongs, axes, chisels, bits, nails and molds. These tools were often created by the blacksmith himself. Finally, the cornerstone of all forges as the anvil. An anvil was large block of iron or steel, with a shaped cone on one side, the anvil was used as the hammering surface. Along with a good hammer, blacksmiths created some of the beautiful and destructive pieces of art in the Medieval Era. Hence why the image of most commonly associated with blacksmiths is the anvil.

Figure 24. Medieval armor (Wikipedia, 2014).

10. Methodology

10.1 Why Medieval Era Battle Axe Was Chosen?

After the fall of Rome, when the Roman civilization began to crumble, a new Medieval Era emerged. This time period was known as the Middle Ages and it stretched out for almost 700 years. The Middle Ages was one of the most significant times in human history, and consisted of three main sections; Early, High, and Late Middle Ages (Ward 2014).

The Early Ages was known as the Dark Ages since people were mainly concerned about survival and the amount of significant technological advances decreased. There were new Barbarian kingdoms that settled in such as Visigoths in Spain, Ostrogoths in Italy, Franks in France and the Anglo-Saxon kingdoms in Britain (Bogart 2009). The main factors of civilization during this period were the Christian Church and the manorial system. The church preserved a lot of knowledge and arts, especially in cathedrals and monastic houses. It continued to have strong leadership and organization throughout the entire dark period (Bogart 2009). A manorial system was basically an area of surrounding land with industrial, usually built around the wealthy and their manors.

The High Middle Ages started around 1000 AD and seemed like the highlight of medieval times. Great improvements were made in terms of health, trade, and innovation. The entire population increased by almost double in all of Europe, there was significant progress in farming technology, and there was an increase in medical technology. With this increase in health as well as population, it gave rise to Feudalism (Bogart 2009). Feudalism is where the king gave his land as grant to nobles in exchange for military service. Because of this system, powerful military force came about and caused The Crusades, which ended and brought it into the Later Middle Ages.

The Later Middle Ages was a difficult time in Europe, because there were a ton of wars, famine, and disease. There was the Great Famine, and following right after was the Black Plague, which was caused by poor hygiene. State governments came more into power because of the splitting of the Roman Catholic Church (Bogart 2009).

10.1.1 Selected Historical Period

We, as a group, chose the Medieval Era because this was a very influential time in Europe. There were a lot of advancements in technology, warfare, medicine, etc. There were many changes in power, going from Rome to kings to the Catholic Church. Finally, this was the best option because during these medieval times, there were a lot of weapons that were created that changed the course of warfare; melee weapons, ranged weapons, and siege weapons.

We were very interested in the melee weapons in Europe, and this is especially because looking at the IQP website, we noticed that all the items in the medieval era were pieces of armor and there were no arms. We wanted to make the page well rounded by adding arms and armors for all sections before moving on to new areas on the world map. We found out that battle axes were very popular during the medieval times and they went through several phases of evolution, so it seemed to be the best project piece for us to do.

10.1.2 Weapon Design

Our design below is what we would like the axe to look like. Depending on how far we are able to stretch the steel, we will attempt to draw out and curve the top and bottom portions, making it slightly longer on the top. The pointed hammer on the end will also be drawn out, shaped, and then ground to our liking.

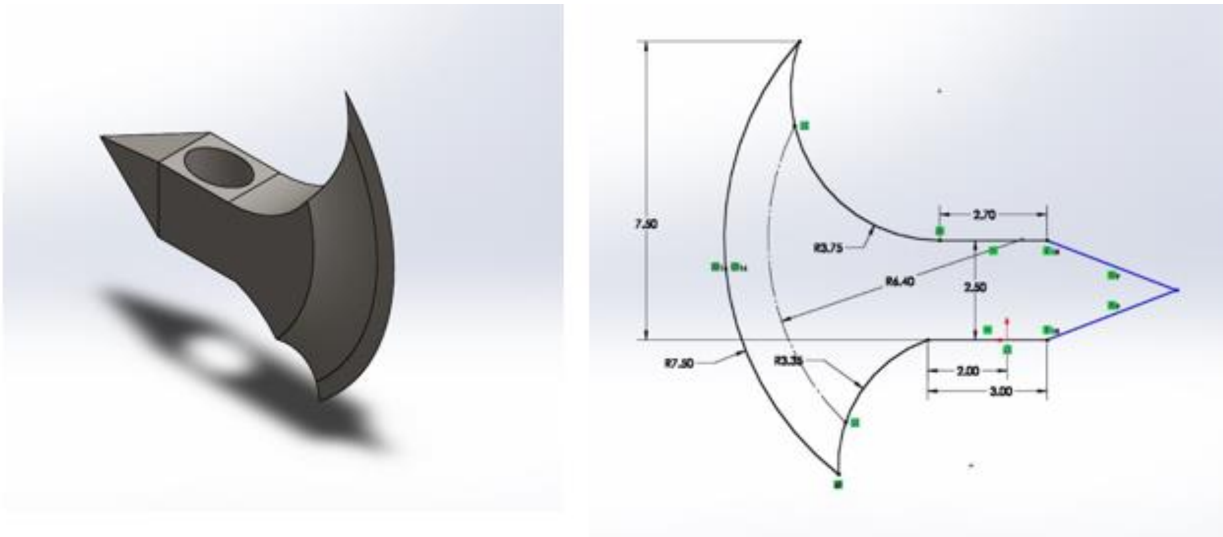


Figure 25. The axe head model (left) and the design of the head (right).

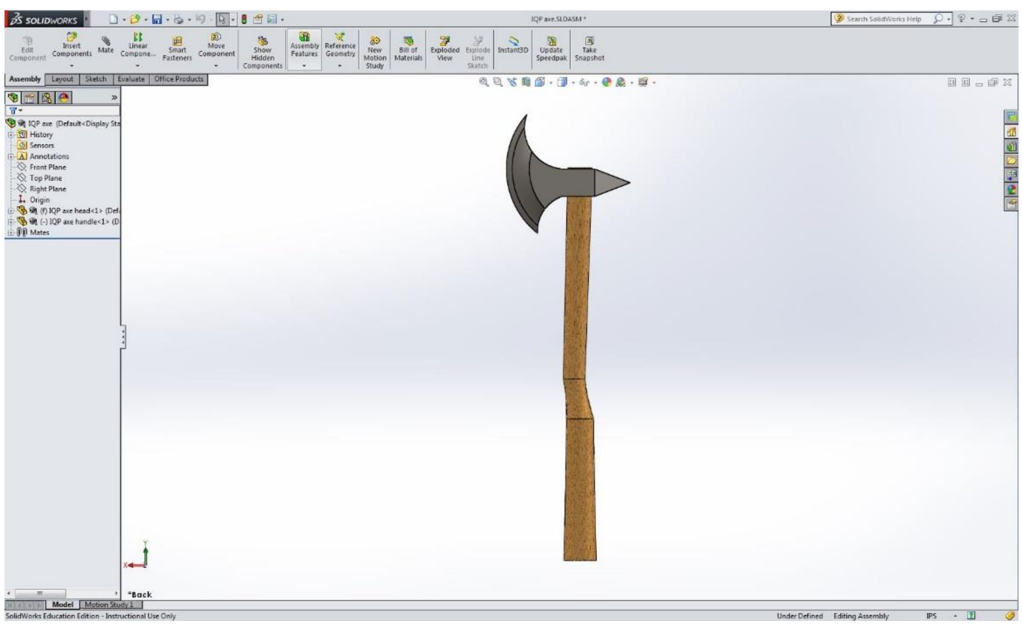


Figure 26. Overall battle axe design using Solidworks.

10.2 Material Selection and Characterization

10.2.1 Mechanical and Thermal Properties

When faced with the challenge as to which metal we were going to choose to make our replica Medieval Battle Axe, we consulted a variety of resources. First, we consulted with our research of the Medieval Era and found that a battle axe of that era would most likely have been made from some kind of medium to high carbon steel. After considering the literature, we decided that a high carbon 1060 steel would be similar to that used in the Medieval Era. We then decided to consult CES EduPack to compare some of the various properties of steels in that range as seen in Table 1.

Table 1. Different types of steels and their properties

Type of Steel	**1015**	**1030**	**1045**	**1060**
Density (lb/in^3)	0.285	0.285	0.285	0.285
Young's Modulus (psi)	31.2x10^6	31.3x10^6	31.3x10^6	31.3x10^6
Yield Strength (ksi)	50	55.1	66.7	77.6
Hardness (HV)	143	200	228	270
Tensile Strength (ksi)	67.4	88.5	100	131
Compressive Strength (ksi)	50	55.1	66.7	77.6
Melting Point (°F)	2780	2760	2740	2720
Maximum Service Temp (°F)	675	667	662	653
Thermal Expansion Coefficient (µstrain/°F)	7.22	6.94	6.67	6.67

After comparing some of the properties of the steels, we met with the blacksmith we were working with, Mr. Josh Swalec, to ask for his opinion. He recommended a medium carbon 1045 steel because it would be easier to forge into the specific shape we desired and would still have the strength we wanted. We decided that this would be the best choice for our replica given the time restraints we are working under. Also, according to the graph, 1045 steel is still relatively hard compared to the other choices but is much more workable than a high carbon steel.

After deciding on the type of steel, we had to decide what shape we wanted our stock steel to come in. After consulting with Josh Swalec, he recommended a 1.5in by 1.5in square rod because it would be easier to form the whole in the center of the axe head. He also suggested that we would need at least one foot in length to forge the axe from. As a group, we decided to get a three foot rod in order to have extra metal in case we do not successfully form the axe on the first try. We also wanted a little extra in order to perform microstructure analysis from. Below in Figure 27, you can see the rod as we received it from the supplier before any metalworking.

Figure 27. Our 1045 Steel rod before metalworking.

10.2.2 Fe – C Phase Diagram and Microstructure Analysis

1045 steel is a medium carbon steel with 0.45% carbon content. The 10 in the 1045 means that it is a standard iron carbon steel, and the 45 means that there is 0.45% carbon content. The amount of carbon in the steel is very important with respect to its respective properties. Generally speaking, adding more carbon to the steel increases its strength while making the metal more brittle. Therefore, engineers pay close attention to the carbon content in their steel in order to have the most suitable properties for whatever application the steel is being used for. We chose 1045 steel because it is not too hard to be hammered into shape but is still relatively hard.

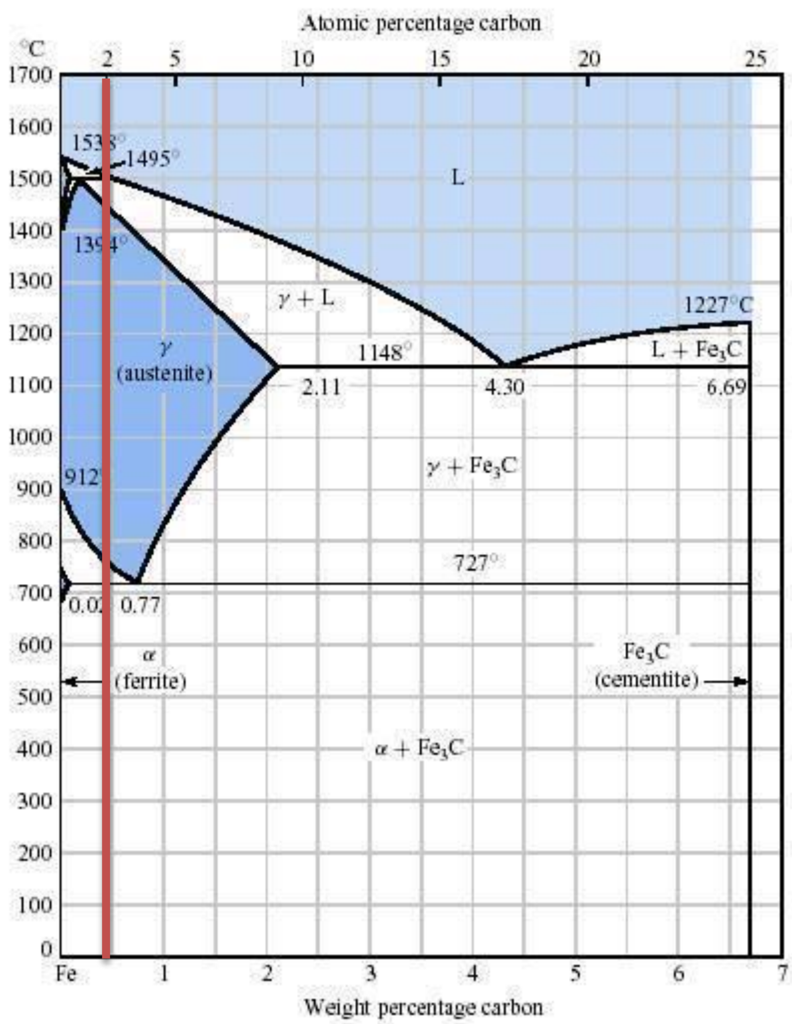


Figure 28. Fe – C Phase Diagram (Wikipedia, 2014).

Figure 28 shows the Iron-Carbon phase diagram with a vertical orange line marking 1045 carbon steel. The eutectic composition for carbon steels is 0.77% carbon. Since our composition is 0.45% carbon, this means that we are working with a composition before the eutectic composition which means that 1045 is a hypoeutectic steel. As you cool 1045 steel from a liquid, you begin forming austenite at the liquidous line which is about 1500°C. You continue to form more and more austenite until you hit the solidous line at 1430°C where all of the liquid has solidified into austenite. The next line you hit is the solvous line at 770°C. You then begin forming a solid solution with a small amount of ferrite. Once you pass below the eutectic temperature at 727° the remaining austenite that was not converted into primary ferrite instantly becomes pearlite. Perlite has the eutectic composition of ferrite and cementite. Ferrite is a material composed primarily of iron with a small amount of interstitial carbon atoms. These interstitial carbon atoms squeeze in between the lattice of iron. Ferrite, also known as Fe_3C, is a very hard and brittle intermetallic compound. This is where much of the strength in steel comes from. Once you decrease the temperature any further, there is no further changes in the material.

At equilibrium, the following calculations were made to determine the microstructure of our 1045 steel.

$$\frac{0.77-0.45}{0.77-0.02} * 100 = 42.7\%\ Proeutectoid\ Ferrite\ (\alpha)$$

$$\frac{0.45-0.02}{0.77-0.02} * 100 = 57.3\%\ Pearlite$$

$$\frac{6.67-0.77}{6.67-0.02} * 100 = 88.7\%\ Eutectoid\ Ferrite\ (\alpha)\ in\ Pearlite$$

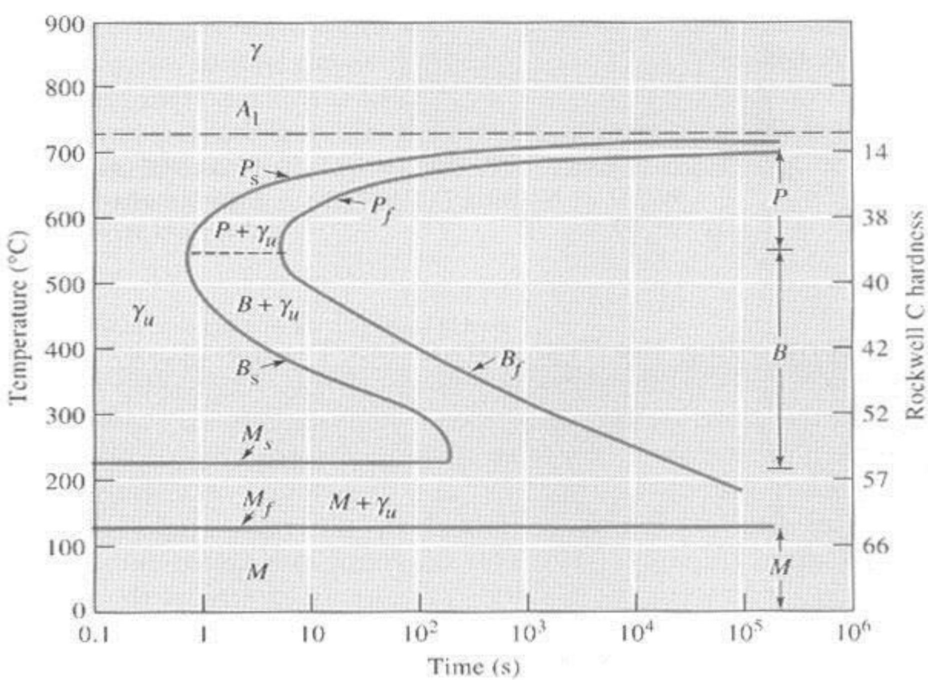
$$\frac{0.77-0.02}{6.67-0.02} * 100 = 11.3\%\ Eutectoid\ Cementite\ (Fe_3C)\ in\ Pearlite$$

$$57.3\%\ Pearlite * 88.7\%\ Eutectoid\ Ferrite\ in\ Pearlite = 50.8\ \%\ Eutectoid\ Ferrite\ (\alpha)$$

$$57.3\%\ Pearlite * 11.3\%\ Eutectoid\ Cementite = 6.5\ \%\ Eutectoid\ Cementite\ (Fe_3C)$$

From these calculations, it can be found that 42.7% proeutectoid ferrite forms prior to the eutectoid temperature. Once the temperature drops below the eutectoid temperature of 727°C, the remaining austenite is transformed into pearlite which is the eutectoid composition of steel. The calculations show that of the remaining 57.3% pearlite, 88.7% of it is eutectoid ferrite and 11.3% of it is eutectoid cementite. Multiplying these concentrations by the percent pearlite in our steel, you find that 50.8% of our microstructure should be eutectoid ferrite and 6.5% should be cementite. Overall, 93.5% of the microstructure is ferrite and 6.5% of it is cementite.

Besides the specific composition of carbon in the steel, the cooling rate of the metal is very important to the resulting properties. The faster you cool a material, the less time you give that material to form the respective equilibrium phases according to the phase diagram. Steels are especially susceptible to the effects of cooling rate. The time-temperature-transition diagram shows how cooling rate effects the resulting microstructure of the material. This diagram for eutectoid steel is shown in Figure 29. Eutectoid steel contains a carbon composition of 0.77%. Our steel contains 0.45% carbon; therefore, this diagram is not exact but will be similar to how our 1045 steel will form with respect to cooling rate.



(TTT) diagram for a eutectoid steel.

Figure 29. Time-Temperature-Transition Diagram for Eutectoid Steel (Wikipedia, 2014).

The TTT diagram is a useful tool to determine the resulting microstructure and hardness with respect to cooling scheme. The Rockwell hardness is also shown on the TTT diagram. This can be used to create a material with the desired hardness needed for a respective application. Three different structures form when you cool a material quickly. If you rapidly cool the steel from above 727°C to room temperature, you will form 100% martensite, which is very hard but brittle form of steel. If you cool it and hold the steel in a range marked by the B, bainite forms, which is a medium hardness and more ductile structure. If you cool rapidly then hold the steel at a temperature above 550°C, you will form the most ductile but least strong form of steel known as pearlite. Pearlite comes in two forms-fine and coarse. Fine pearlite is preferable because it is stronger with minimal losses in ductility. Fine pearlite forms in a temperature around 600-550°C as shown on the TTT diagram.

For our battle axe, we quenched the axe head in a bucket of water after forging. The cooling rate of our axe head could be calculated knowing the temperature we heated it to, final temperature (room temperature), and the time it took to get to the final temperature. The cooling time was estimated to be between 2-5 seconds.

$$Cooling\ Rate = \frac{\Delta T}{\Delta t} = \frac{850-40}{2\ seconds}\ to\ \frac{850-40}{5\ seconds}$$

$$Cooling\ Rate = 162\frac{℃}{s}\ to\ 405\frac{℃}{s}$$

Knowing our cooling rate, we can predict the microstructure of the steel after the quenching process. We draw a line at our particular cooling rates on the 1045 steel TTT diagram. We then read off what microstructure will be present in the metal based on the different steel phases on the TTT diagram.

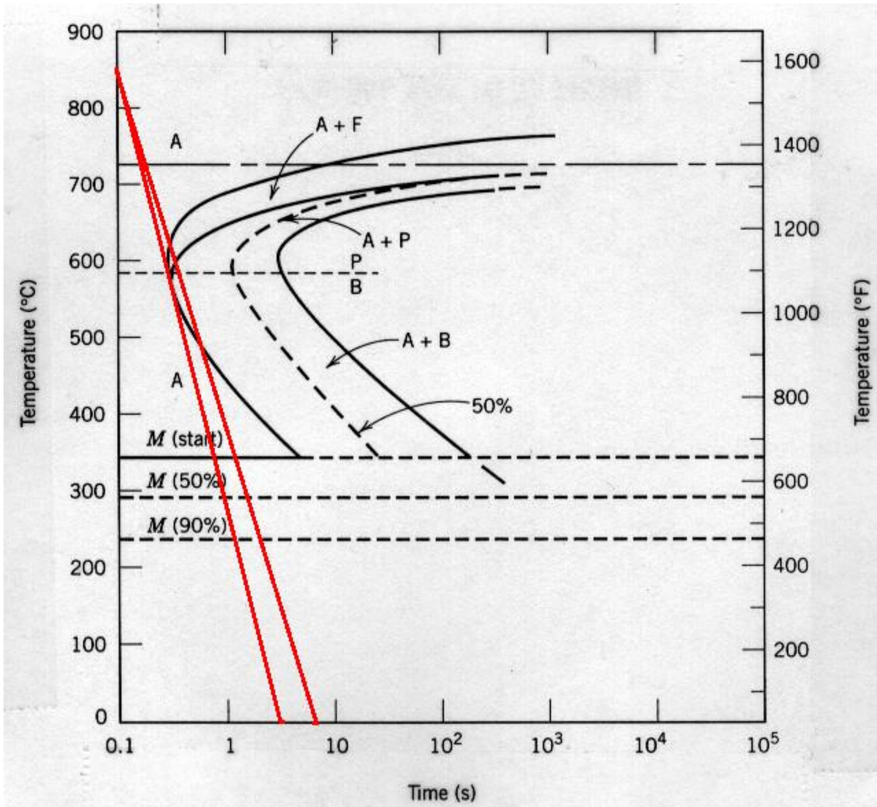


Figure 30. 1045 Steel TTT Diagram (Wikipedia, 2014).

Looking on the TTT diagram in Figure 30, we predict that there will be a small portion of bainite with a majority of martensite in our final microstructure. Martensite is a very hard and brittle phase that is formed when the steel is cooled at very high cooling rates. Bainite is a slightly more ductile phase with a still relatively high hardness. The small portion of bainite in our microstructure will provide the ductility needed to prevent the axe from shattering while still maintaining a very high hardness. This structure is ideal for a battle axe in order to maintain its sharpness during use and prevent chipping when striking hard pieces of armor.

10.3 Construction of a Medieval Battle Axe Replica

10.3.1 Forging

Forging is the process of shaping a metal using compressive forces. Our team decided to use hot forging, where a metal is heated to very high temperatures in a coal fired forge and then shaped using an anvil and a hammer. We decided to utilize resources close to Worcester by working on our project in Ferromorphics, a blacksmithing shop run by Joshua Swalec. Initially, a tour of the place was given and there was a lot of talk about what we were planning on making and what material would be best to use. We came to the conclusion, based on research and asking Josh because of his experience, that 1045 Medium Carbon Steel would be best for this project.

Figure 31. The forced air coal forged, located in Ferromorphics main shop.

10.3.1.1 Axe Barb

The point of the axe, also known as barb was the first objective in the forging process. We began with heating what was to be the rear of the axe head to a light orange color. After the piece reached the desired temperature, we held the piece with a set of tongs at a 45° on the anvil and hammered each side of the 1.5 in x 1.5 in square steel. The hammering started out where the person holding the metal hit with a small hammer, to control the area of attack, while another person used a large sledge hammer, to actually shape the metal. After many rounds of heating and hammering, a point was created.

A problem arose where the corners began folding over, where the point came together. If we continued in such a way, the barb would not be as strong with the air pocket inside. As a result, we cut back all four points using a band saw so that when we do finish the barb, there would not an air pocket. Once the metal was cut and the air pocket was removed, the process restarted of heating and hammering to finally create a very good point shown in Figure 32.

Figure 32. The axe head cooling after drawing out the point.

10.3.1.2 Axe Handle Hole

The slot which became the hole for our axe handle proved to be quite tricky. We started by drilling an initial small pilot hole with a drill press with our piece at room temperature. The size of the initial pilot hole was around ⅜ in. If we were to tap a pilot hole as what would have happened in the middle ages, it would have added countless hours on the build time because a sharp enough punch would be required and there would be no guarantee of it being straight. The pilot hole was a good guideline and eased the process of creating the axe handle hole.

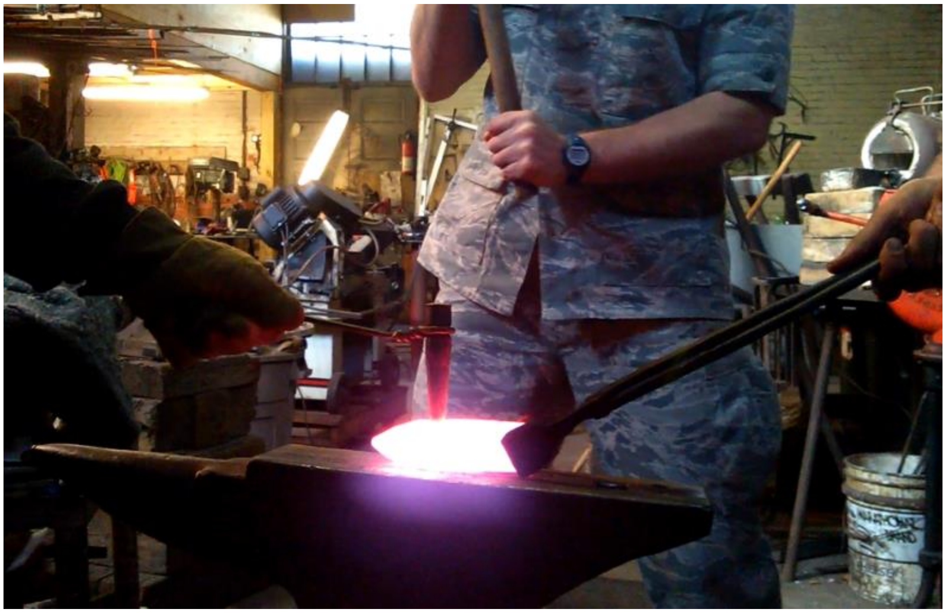


Figure 33. Hammering punch to create handle hole.

With the pilot hole drilled, we had to heat the entire piece in order to have even heating while we began expanding it with a skinny narrow punch, alternating between the top and bottom of the block. After many repeats, the narrow punch went through and through, and so a bigger punch was used to expand the hole even more. Increasing in size, we eventually reached a size we wanted, an ellipse shape approximately an inch in length. We later had to come back to the hole and retouch the hole with the largest punch for final touches.

Figure 34. Punched hole, slowly expanding.

10.3.1.3 Axe Blade

The blade was our final and most time consuming objective for our axe. We began heating the steel to a yellow color which is a very high temperature. Working with very high temperatures and trying to hold the piece while it was being hammered on was extremely hard, so we decided to weld a steel rod to our piece so then it would be easier to work with. Josh recommended that we use a peened sledgehammer at an angle to the blade to start and then alternating to the flat head of the sledgehammer. This back and forth between the peen and the flat head fanned the blade out. Though this added width to the blade, the top and bottom edges folded over on themselves. Like with the barb, this would cause some structural issues with the blade. Josh said that there was a chance the cracks could occur if left unchecked.

Figure 35. Wedge hammer to stretch metal horizontally.

We proceeded to grind these edges down with a power grinder as grinding them down with a file add additional hours to the project. The back and forth process continued until we reached a desired width. To achieve the downward taper, Josh showed us how use the horn of the anvil to curve the metal. This caused us to lose some of the desired width in the blade, forcing us to go between the horn for the curve and the flat top for the actual blade. We were forced to compromise some of the curve of the blade to keep our desired blade width and overall shape.

Figure 36. Axe blade side view.

10.3.1.4 Axe Handle

The axe handle was given to us by Josh from some of his old supplies lying around. It was an old woodcutting axe handle made out of hickory. It was cut to the desired size, notched and smoothed down to fit perfectly and very tightly into the hole in the axe head. The handle also had a very nice angle to it, making it easy to hold and possibly use for swinging.

Figure 37. Securing axe head to handle.

10.3.2 Finishing Processes

10.3.2.1 Different Finishes Possible

We had several options for how to finish the axe head after the shaping was done. One method is to quench the entire work piece in oil. While this would have helped harden the axe, we did not feel it was necessary. On the same point, completely quenching it in water was not a smart option. By rapidly cooling it in water, some parts would cool faster than others due to the thickness of the work piece. Last, quenching in salt water would have also worked but we would have risked the chance of bubbles forming and faster corrosion.

10.3.2.2 Choosing the Correct Finishes

To finish the axe head, we decided to only quench the blade edge and the point. After rapidly cooling these sections they became much harder, back in the day this would have been quite desirable as the sharpened edge would hold for longer and the pointed hammer would have been more resilient to fracture. After that, we let the part air cool until we could safely handle it.

The most authentic way to finish the head was to make it look useable. After filing and brushing off the top coat of metal, we oiled the head. This is an inexpensive method for preventing rust from forming on the raw metal surface. In addition, we coated the head in a rust preventative solution to ensure its use as a clean future example.

Figure 38. Quenching the blade.

10.4 Material Analysis

10.4.1 X Y Z Views

As with any three dimensional object, there are three sides that need to be observed. We cut the sample pieces that were eventually mounted so that the XY face (called X view), YZ face (Y view), and XZ face (Z view) could all be examined. Each view allowed us to look at the microstructure at different angles, which in turn allowed us to see any and all grain structures and boundaries. This also allows us to view the grain elongation that takes place during the forging process.

10.4.2 Mounting

Figure 39. Mounted samples ready for polishing.

In order to properly polish, etch, and view our samples under a microscope, they first needed to be mounted. Dr. Li showed us how to properly use the mounting press that was in the material science lab. We placed a sample with the face that was to be examined face down on the press and placed a 1.25 in diameter phenolic pre-formed mounting agent on top of it. The press heated the mounting agent, allowing it to mold around the sample on all sides except the one that was face down. For our Y view and Z view, which were quite thin, we placed in mounting clips so that they would be more stable before being placed in the mounting press. In total, six samples were mounted. Three samples were the 1045 carbon steel in factory conditions and the three samples were

10.4.3 Polishing

Polishing the samples for analysis was required so that there was a mirror like finish on the sample for ideal etching. Two different polishing wheels were used. The first was a Nano 2000T grinder-polisher. Starting with 120 grit paper, and decreasing to 220, 400 and 600 in order, we polished on the rotating wheel that was cooled with water to mitigate the effects of friction. The samples were rotated on during the process to eliminate scratches in the direction the wheel was spinning. The polisher had two spinning wheels, allowing us to have different grit paper on the wheels to work on different samples.

Figure 40. Samples being polished.

After polishing the 600 grit paper, we moved to the special silica grinding wheels. These wheels used an aluminum powder instead of water. The three wheels had various thickness of the grains of the silica, 1 micron, 0.8 micron and 0.05 micron. Again, the three wheels allowed us to work on three samples at a time. We later had to come back to the silica grinding wheels during the etching process to grind off a layer that was over etched and get back to the mirror finish that was desired.

10.4.4 Etching

The etching process allows us to look at the grain structure and boundaries underneath a microscope by tearing away a very small layer of the surface. We decided to etch with nital instead of picral as nital allows to view the grain boundary and structure where picral only shows the grain boundary. Nital is percent mixture of ethyl alcohol and nitric acid. We started by making a two percent nital solution, as to not waste nitric acid. We etched one sample by dipping the sample into the solution with tongs and viewed it under the microscope to see if two percent would suffice, and it did not. So we added more nitric acid to the solution so that it was five percent nital. Though this was suffice, some samples were left in the nital for too long and burned the surface. Burning the surface was a matter of leaving the sample in the nital solution was the difference of fractions of a second. Three of our samples ended up over-etched and required re-polishing and re-etching.

Figure 41. Testing the Nital solution.

10.4.5 Microscope Analysis

Professor Lados was kind enough to allow us to use her microscope. With the help of Anthony, one of the lab assistants, we took pictures of our six samples. Of the six, we cut, mounted and labeled three of these as X1, Y1, and Z1. Next, we cut samples of the worked metal and labeled them as X2, Y2, and Z2, making sure to stay consistent with the orientation of the piece. For each sample, we took two pictures, one at 200x zoom (50µm) and another at 500x zoom (20µm) allowing us to see the change in the grain structure after working the steel.

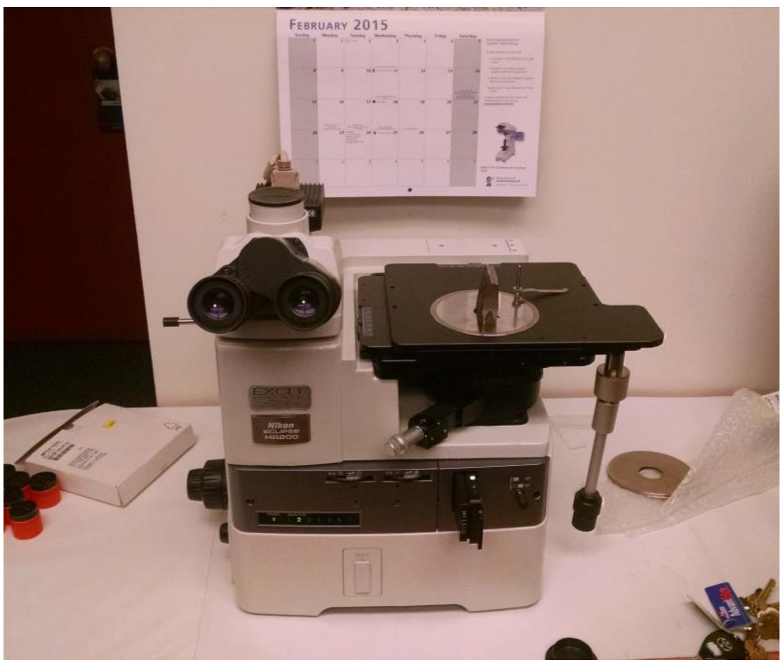


Figure 42. Optical microscope used for microstructure analysis.

10.5 Microstructure Predictions

10.5.1 Samples 1 – 3

After contacting the manufacturer of our 1045 steel bar, we were informed that the bar was initially cold rolled. The steel was then annealed in order to make the steel soft enough to cut and mold to shape. This was evident when we cut the material to shape using a bandsaw. The blade cut through the rod fairly easy considering we are using a medium carbon steel. Since the steel was annealed, there shouldn't be significant grain elongation in the length direction of the rod. Before the rod was annealed, there would be significant grain elongation in the direction that the metal was rolled. Figure 43 illustrates the difference between a cold rolled and annealed microstructure.

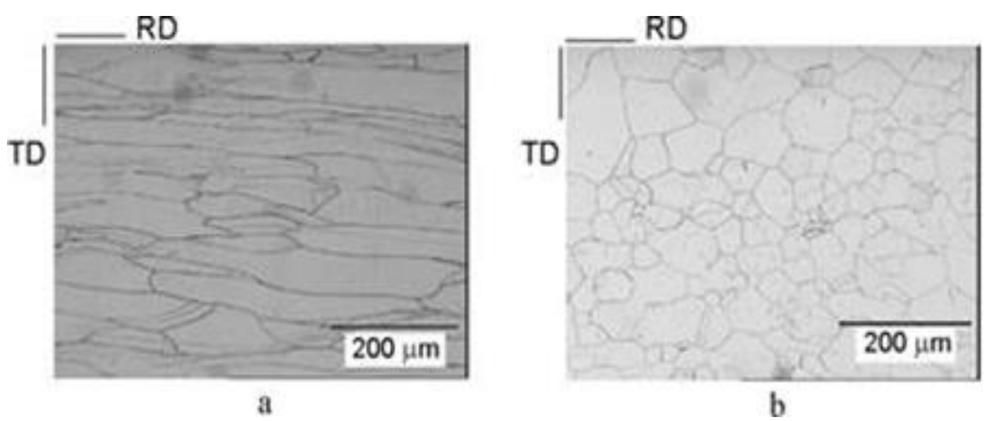


Figure 43. Cold Rolled (a) vs. Annealed (b) Microstructure of a Metal (Google Images).

We predict our microstructure of our initial annealed metal to be similar to that of the annealed microstructure. This makes it much easier for us to forge the metal into the shape we desire.

10.5.2 Samples 4 – 6

After the forging process, we expect the grains to become elongated in the direction of the blade. This would cause the blade to become much harder in the direction in which the grains were elongated. This makes the blade and point directions much stronger that if we were to hit the blade from its side. This is beneficial in preventing the blade from becoming dented when it is used but much weaker if hit from the side. The post-forged microstructure will be similar to the cold rolled microstructure as discussed previously.

In addition to the elongated grains, we expect a high dislocation concentration in our post forged axe. These dislocations are the result of adding mechanical energy to the material through hammering. This mechanical energy is stored within the material in the form of dislocations in the metal microstructure. The higher the dislocation density, the harder and more brittle the material becomes. We avoid brittle failure in the forging process by heating the metal up to get rid of some dislocations. After the metal is cooled, many dislocations remain and can be observed in the microstructure. An image of dislocations observed in a metal is shown in Figure 44.

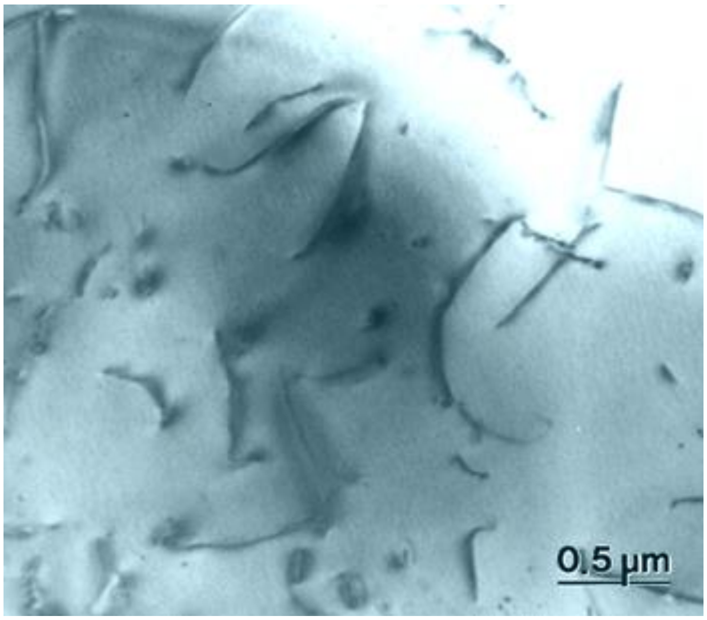


Figure 44. Dislocations in the Microstructure of a Metal (Google Images).

After we finish forging our axe, we will heat the axe until is glowing hot then quench the piece in order to create martensite. Martensite is a very hard but brittle form of steel which only forms when the metal is cooled very rapidly. Martensite forms a distinctive microstructure because the rapid cooling prevents the material from forming the equilibrium microstructure. After quenching and forging, our microstructure should look similar the Figure 45 which is of the martensitic microstructure.

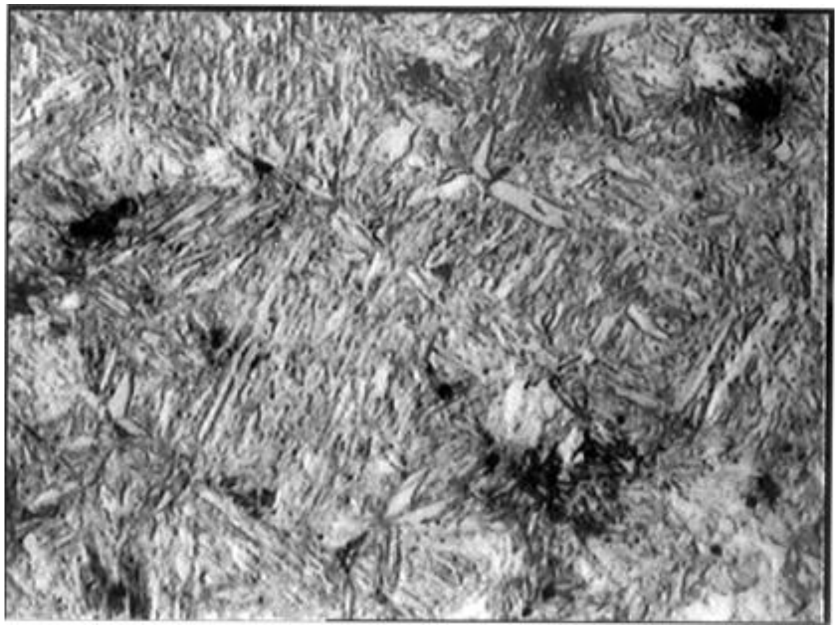


Figure 45. Martensite Microstructure (Google Images).

11. Results and Discussions

11.1 Changes in Microstructure

After studying the pictures of the microstructure we took using the optical microscope and comparing with photographs of known microstructures in the ASM materials handbook, we determined that several different phases appeared in our microstructure. The phases that appeared in our steel samples before forging were ferrite and pearlite. Ferrite would appear as the solid white portions of the microstructure while the Pearlite would be the darker sections. In the pearlite, a clear lamellar structure can be observed in Figure 46 by the alternating cementite and ferrite bands creating a "zebra" striped appearance in the microstructure. There is a larger portion of pearlite because our 1045 steel is a hypoeutectoid steel which means that our carbon content is less than the eutectoid composition of 0.76%.

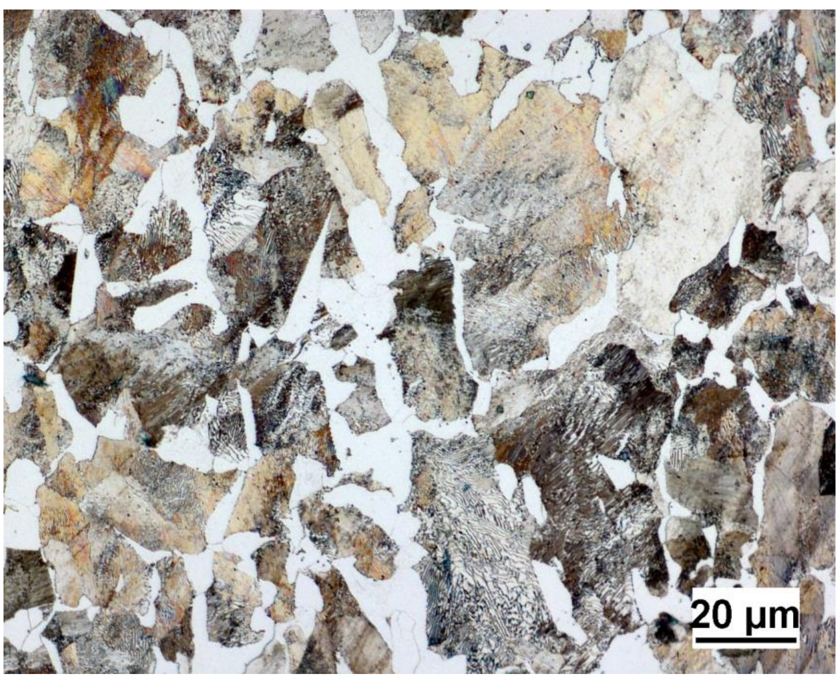


Figure 46. Our Pre-Forged 1045 Steel Microstructure.

After the forging process, the microstructure of our samples changed dramatically. We heated the metal up above the eutectic temperature which transformed all of the steel into austenite. This was confirmed by placing a magnet on the surface of the steel; because when steel is transformed into austenite, it loses its magnetic properties. This allowed us to cool the steel rapidly and create non-equilibrium phases such as martensite and bainite. We transformed most of our steel into martensite with some bainite (darker phases), Figure 47. Bainite forms on specific crystallographic planes of austenite. Some retained austenite and carbides are also observed in the microstructure.

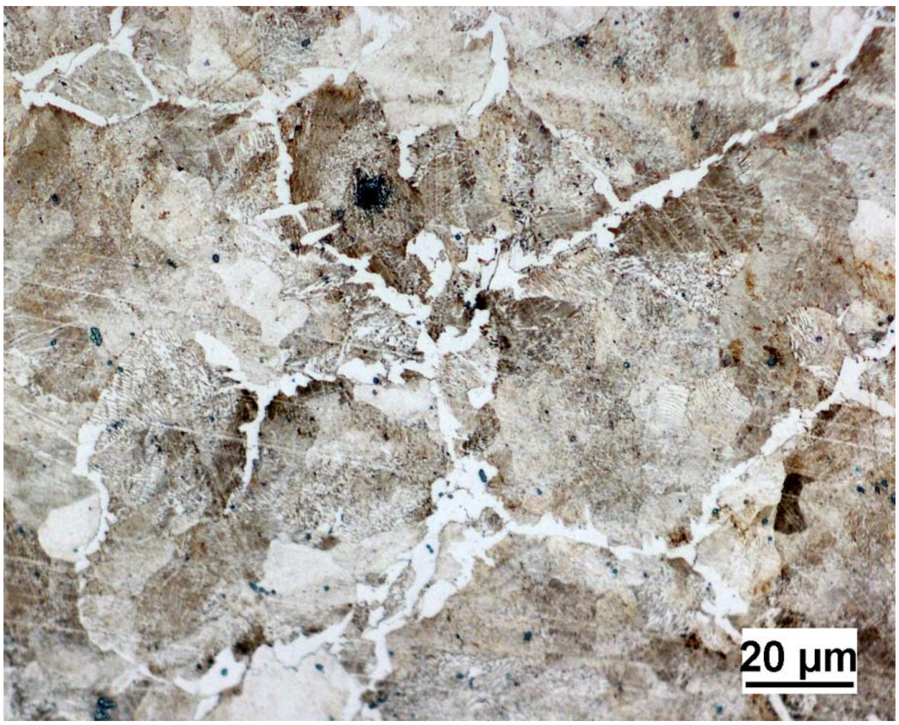


Figure 47. Our Bainite-Martensite Post-Forged Microstructure.

This mixed structure is ideal because the martensite is an extremely hard but brittle phase while the bainite softer but more ductile phase. This mixed phase steel microstructure creates the strength and hardness that is required for a cutting weapon but is not too hard to where it could shatter if struck on a hard object.

We achieved a tempering effect on our cutting edge by heating the piece to above the eutectic temperature then quenching just the blade and point end in water. This caused the ends to transform into martensite initially. The cutting edges were then self-tempered by allowing the heat from the main body to flow back to the cutting edge. This creates tempered martensite which is desirable for our application. Tempered martensite retains much of its hardness while gaining a large increase in ductility. Therefore, the tempered martensite cutting edges remain hard but will resist cracking, chipping, or shattering much better than if we had left the entire piece as non-tempered martensite.

11.2 Differences of Construction Processes

For the most part, our method of constructing a replica of the medieval battle axe was very similar to that used during the medieval times. Just like in the past, we decided to use hot forging (coal fired forge), utilized a hammer and an anvil as our main source of shaping the metal, and a punch to make a hole in the axe head. There came a few times where shortcuts had to be taken to reduce the workload, and increase the safety and reliability.

One of the main differences of the construction process was that we decided to drill a small pilot hole before starting the forging process. This was because trying to punch through the entire 1.5 in block of steel would have been very time consuming and would require a sharp punch that Josh didn't exactly have. This easy step allowed us to still get the feel of using a punch, just like they did in the medieval times, while using the pilot hole as a guideline. So with the given equipment, time, and to ensure a solid end product, the pilot hole had to be drilled.

Another big difference was that we decided to weld a long steel rod to the axe head so we could heat it and when it was time to take it out of the forge, it could be held on the anvil while wearing gloves. This was an important addition because without the rod, we would have compromised the safety of the group members and it would have made the entire shaping process of the axe head extremely difficult.

11.3 Difficulties Faced

11.3.1 Construction of Replica

A few problems arose during the forging process. The greatest of which was the lack of time. Scheduling a time in which the group members could all go to the forge at the same time while balancing other classes and daily life meant that some modern tactics had to be used while forging. Tapping a pilot hole for the handle and filing down the barb as well as the top and bottom faces of the piece when they began to fold would have taken hours. As far as the actual forging process, a couple addition problems arose. A few times, we almost burned the metal. The key sign to burning is if the metal would began to spark. Forging at this heat would cause the piece to crack and we would have had to restart from the beginning.

Also sides of the blade and the barb would fold into itself, which would also cause the piece to crack, sending us back to the beginning. With the actual design of the piece, we worked to taper the bottom edge of the piece. But we were unable to get as much of a curve as we wanted without changing the shape of the blade or the top face of the piece. Most of these difficulties come with the lack of the group's skill at blacksmithing and could have been mitigated by working with a master blacksmith sometime before the project began.

12. Conclusion

12.1 Overall Project

The Medieval Era was a period marked by social unrest and violence as different powers fought against each other to control a limited amount of resources. Large standing armies became commonplace and required even more resources to maintain. Steel arms and armors had recently been developed and were making their way into every major army. Steel was much stronger and harder than iron or bronze and provided a huge advantage on the battlefield. Any army that was not equipped with steel weapons could be easily defeated. Therefore, the art of blacksmithing steel into arms and armors became highly demanded. Wealthy persons would surround themselves and fill their cities with skilled blacksmiths who would keep their armies well equipped.

We focused our attention on one particular piece of medieval armament, the battle axe. The battle axe was a commonly used melee weapon in the medieval era due to its versatility and reliability on the battlefield. The battle axe combined a sharp cutting edge with a pointed hammer edge making it useful against an enemy with or without armor. The hammer end could be used to crush bones beneath steel armor by concentrating a blow to a small point while the cutting edge could be used to chop off exposed limbs. This ability to damage opponents wearing armor became a key advantage for the yielder of a battle axe.

An even bigger advantage which led to the proliferation of battle axes was that axes had been made by blacksmiths for generations. A blacksmith could apply his knowledge of axe forging to the creation of a battle axe. The art of forging an axe is not easily learned as we found making our replica. We had difficulties drawing the metal using similar methods to a medieval blacksmith. In order to expedite our replica making process, we had to make some concessions to historical accuracy but mostly relied on traditional methods that have been used for generations. Using modern material science technology, we were able to analyze what changes the material underwent during the forging process. This analysis revealed how medieval blacksmithing techniques could create a weapon that was both hard and strong despite their limited knowledge of materials science.

12.2 Improvements

General improvements to the project as a whole are logistical. First, a dedicated time and place scheduled on myWPI or Bannerweb for advisor meeting times. This way everyone shows up to the same place at the same time and be kicked out of rooms or wait for another meeting to finish will not be a problem. Another improvement would be a dedicated professor, outside the advisors, or graduate student team that shows the project teams how to properly use some of the equipment and allow access to the labs the project groups may not usually have access too. Finally as this project has a website and small computer science portion, allowing access to the website sooner would allow project groups to work on that sooner and be able to make changes to it as necessary.

13. Appendix – Updating the Website

According to the previous groups, the website was primarily designed using Adobe Dreamweaver, which can help with the HTML and CSS coding of the web pages. The current public domain website of IQP: Evolution of Materials in Arms and Armor is http://www.wpi.edu/academics/me/IMDC/IQP%20Website/index.html. There are icons that can be clicked that take the user to different web pages; Home, World Map, IQP Teams, IQP Reports, Replica Construction, Resources, and Acknowledgements. As part of the ongoing IQP, the final task was to update the information on the website and add the project highlighted in this paper.

13.1 Website Homepage

Something this group found was that one of the links on the homepage was invalid because it did not exist on the WPI website anymore. This hyperlink was called IQP and it was supposed to bring users to a page that described what the Interactive Qualifying Project at WPI is about. The group decided to take the initiative and update the website to a new web page that was valid.

IQP = *http://www.wpi.edu/academics/igsd/iqp.html*

13.2 World Map

To thoroughly update the information on the website, most of the web pages were changed to add additional details. On the World Map web page, the general area ("Europe"), the timeframe ("Medieval Era: 400 AD – 1800 AD), and region ("Western Europe") already existed. One addition that had to be made was another paragraph introducing the Medieval Ages weaponry. Before this team's project, only armor and more specifically helmets, were under this specific region and era. Also added was an actual "Weaponry" section that had a picture of our finished

Medieval Battle Axe, as well as information such as origin, weight, and just a quick description of the weapon. Shown in Figure 48 are the new changes for the "World Map" section.

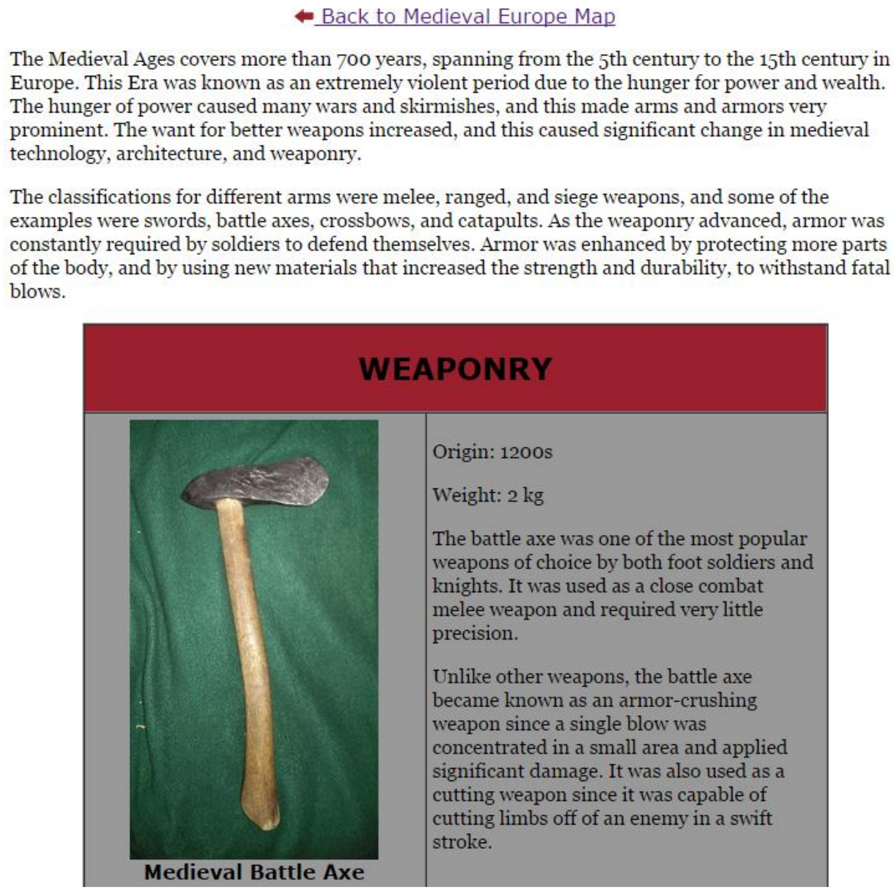


Figure 48. New Weaponry Section on Website.

***Paragraph**: "The Medieval Ages covers more than 700 years, spanning from the 5th century to the 15th century in Europe. This Era was known as an extremely violent period due to the hunger for power and wealth. The hunger of power caused many wars and skirmishes, and this made arms and armor very prominent. The want for better weapons increased, and this caused significant change in medieval technology, architecture, and weaponry. The classifications for different arms were melee, ranged, and siege weapons, and some of the examples were swords, battle axes, crossbows, and catapults. As the weaponry advanced, armor was constantly required* *by soldiers to defend themselves. Armor was enhanced by protecting more parts of the body, and by using new materials that increased the strength and durability, to withstand fatal blows."*

Title*: Battle Axe*

Origin*: 1200s*

Weight*: 2 kg*

Description*: "The battle axe was one of the most popular weapons of choice by both foot soldiers and knights. It was used as a close combat melee weapon and required very little precision.*

Unlike other weapons, the battle axe became known as an armor-crushing weapon since a single blow was concentrated in a small area and applied significant damage. It was also used as a cutting weapon since it was capable of cutting limbs off of an enemy in a swift stroke."

13.3 IQP Teams

Another web page that was changed easily was IQP Teams. Basically a new section was added for the 2014 – 2015 Project Teams and our names were added in the following format: Name, Major, and Class Year.

Team 2014 - 2015:

Christopher Cahill, Aerospace Engineering, Class of 2016

Bryan Jung, Industrial Engineering, Class of 2016

Omesh Kamat, Mechanical Engineering, Class of 2016

Miles Schuler, Aerospace Engineering, Class of 2016

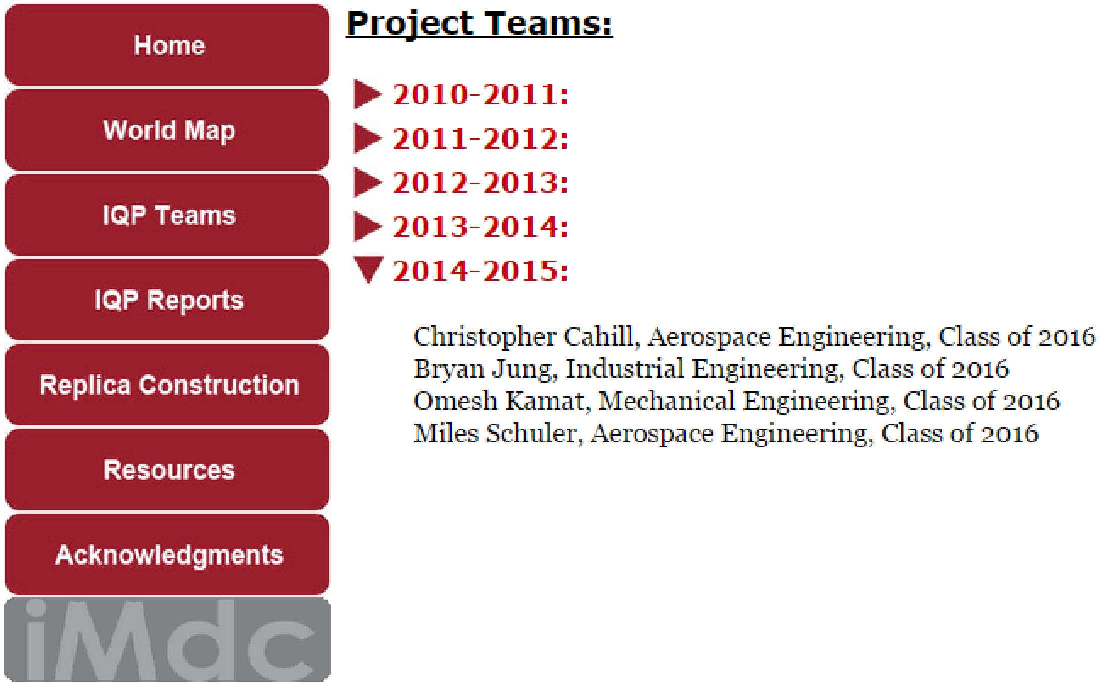


Figure 49. New Project Teams section on Website.

13.4 IQP Reports

Another web page that was easily updated was IQP Reports. Here, a new section was added for the 2014 – 2015 reports and this team's Evolution of the Medieval Battle Axe IQP report was hyperlinked. By clicking on the hyperlink, a new web page opened which was the PDF of the final IQP report.

Figure 50. New IQP Reports section on Website.

13.5 Replica Construction

A big addition that was put into the website was under the Replica Construction web page. A section for the 2014 – 2015 Projects was added, and a link was put with the title "Making of a Battle Axe". Clicking on this link loaded a new web page which went through this group's entire process of the battle axe creation; from the 1045 stock Steel to the heating, hammering, and grinding, to the picture of the final finished battle axe replica. Shown below are pictures of the web page:

Figure 51. Making of a Battle Axe section on website.

By clicking on the link "Making of a Battle Axe", the user would be sent to another webpage on the website that shows the procedure the team took to make the battle axe, with step by step instructions, pictures, and even a video! Shown below is the information:

Making of a Battle Axe Replica

Overview:

Making a battle axe can be a complicated procedure and it requires several major steps for creation. Our team made a Medieval Battle Axe using blacksmithing techniques that were common during that time period. Detailed explanations about each step are mentioned further down this page:

Axe Barb:

Starting with a bar of 1045 Medium Carbon Steel, a 5-inch section was cut off of a 3 feet rod to forge into the axe head.

Figure 1 - 1.5 in by 1.5 in by 36 in 1045 Steel stock.

An initial ⅜ in pilot hole was drilled into the stock where the axe handle would go, just to mark the location and make it an easier process for when the time came to create and expand the hole.

Figure 2 - Drilling of Pilot Hole.

The first objective in the forging process was the point of the axe, known as barb. The steel bar was always heated in the forget to a light orange color and had one person holding the piece with gloves at a 45 degree angle near the edge of the anvil, while another hit it with a small hammer as guidance, and the last person hit with a sledgehammer, using precision and accuracy to do the most amount of shape changing.

Figure 3 - Creation of the Axe Bard.

Metal from the four corners started folding over each other, which created an air bubble in the point. This had to be cut off with a band saw and after multiple repetitions, a point was finally created. Near the end, two small hammers had to be used for smaller changes in shape.

Axe Handle Hole:

The next objective was the axe handle hole. A big enough hole had to be created to be able to fit a wooden axe handle. Thanks to the pilot hole, this was a pretty simple process but required a lot of repetition. First, a small punch was used, put into the hole and then hammered in. The group had to be careful to not keep the punch in there too long because it could start melting or get stuck there if the axe head cooled down too much. After slowly increasing to bigger size punches, an initial hole was created.

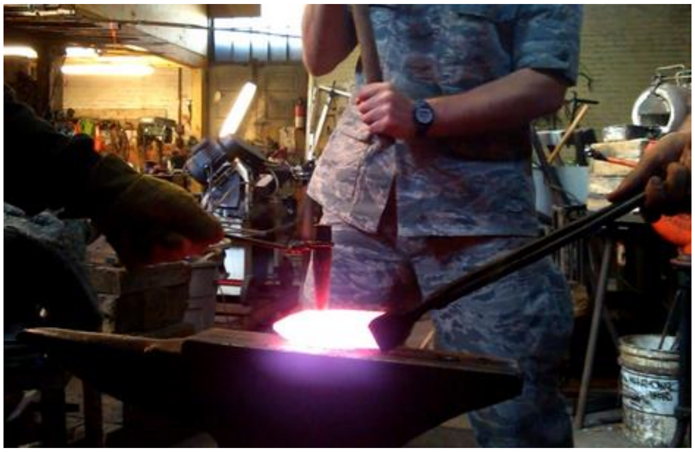


Figure 4 - Punching an Axe Handle Hole.

Axe Blade:

The next and most time consuming objective to conquer was the main component of an axe, the blade. Looking at the difficulty of holding the hot metal with a pair of tongs, the team decided to weld a steel rod to the barb side, for ease and the sake of safety. To first elongate and push out the metal and then start angling it, a peened sledgehammer was used. Going back and forth between the peen and the flat head fanned the blade out. Also the horn of the anvil was used to curve the metal, but due to inexperience, the curve of the blade had to be compromised.

Figure 5 - Drawing Out the Axe Blade.

The next few quick steps were to remove the welded steel rod, and then grind back down to reveal the axe barb point. For a nice and clean look, the edges were grinded down with the use of a power grinder.

Figure 6 - Grinding the Axe Head.

Axe Handle:

The next objective to finish the axe was finding, cutting and smoothing, and attaching an old hickory handle to the axe head. A lot of precision was required to make sure that not too much was cut off to make the notch to fit the axe head, because more can always be removed, but if too much wood is removed, it can't be added back.

Figure 7 - Attaching the Axe Handle.

Finishing Processes:

Several options were available for finishing the axe head. The group decided to quench the blade and the barb. Quenching is a process where a work piece is rapidly cooled from a hot temperature to gain certain material properties such as hardness. The blade was heated up one last time to a dark orange color, basically until the blade and the point were non-magnetic, and then were carefully dipped in water.

Figure 8 - Quenching the Axe Blade and Barb.

Additionally, to authentically finish the axe head, the top coat of the metal was filed and brushed. Then oil was applied to prevent rust from forming on the raw metal surface, and an additional layer of rust preventive solution was applied.

Finished Medieval Battle Axe:

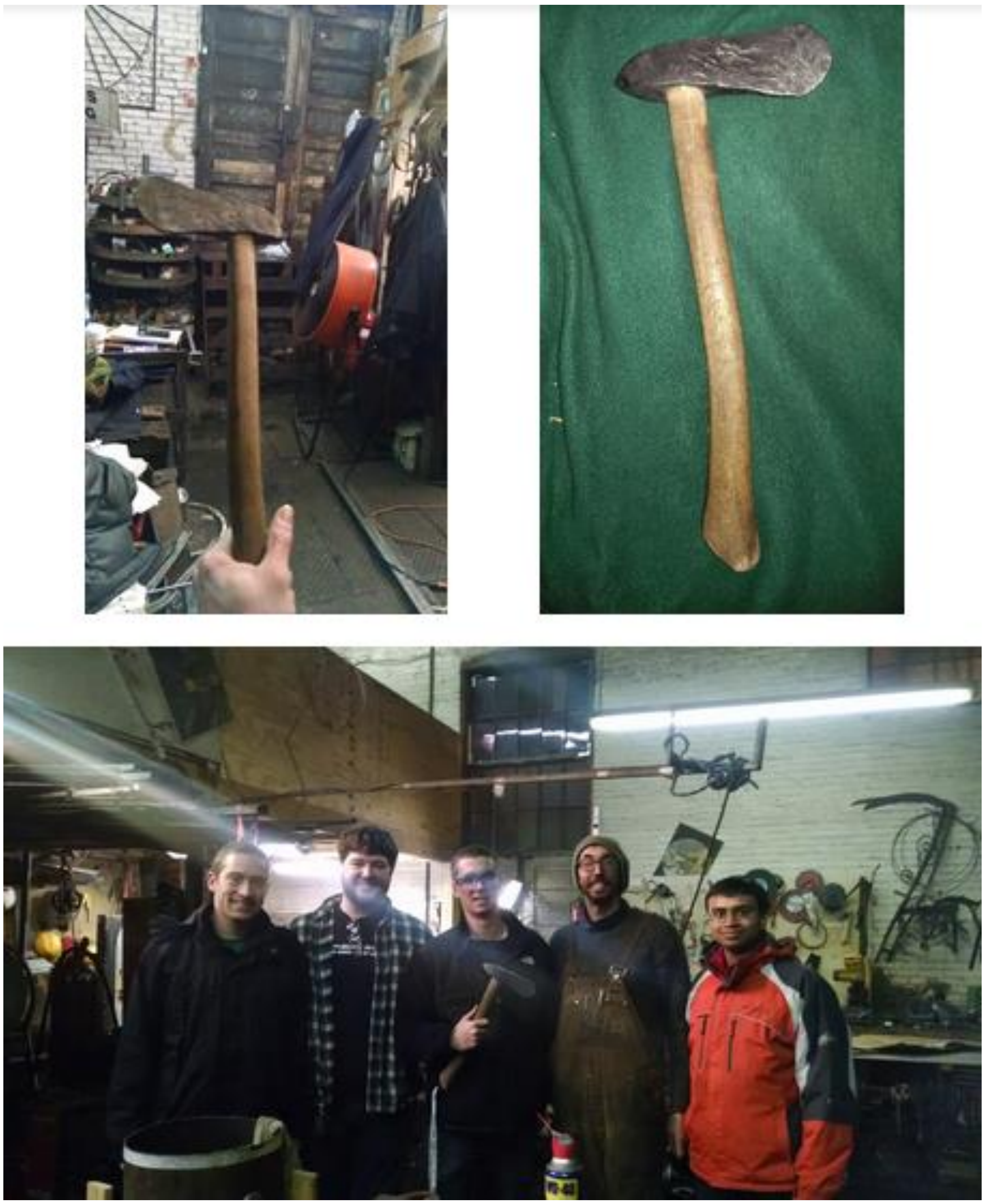


Figure 9 - Finished Medieval Battle Axe and the IQP Team with Josh.

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