The Armaments of the Hundred Years' War and Their Effects on Western Europe

An Interactive Qualifying Project report submitted to the faculty of the
Worcester Polytechnic Institute

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Abstract

This project investigates the development of weaponry during the late medieval period, specifically focusing on the Hundred Years' War, fought between England and France between 1337 and 1453. As a part of this project, we will explore the historical background of this conflict and the changes to army organization, military technology, and tactics that resulted from it. Additionally, we will describe the construction of a warhammer, a staple of the conflict, and explore its material properties in an attempt to classify the general armaments of the time. Finally, we describe the changes made to WPI's Historical Evolution of Arms and Armors website with respect to adding content related to the project, as well as improving the inner workings of the site and providing a better user experience.

Individual Responsibilities and Contributions

- Christopher Beauregard
  - Forging: 22 Hours
  - Wood Working: 5 Hours
  - Sample Preparation and Analysis: 3 Hours
  - Introduction
  - Initial weapon construction research
  - Forging Logistics
  - Section 2.2: The English Longbow
  - Section 2.3: Guns and Gunpowder
  - Section 2.4: Resulting Developments
  - Section 3.7: Lever Rule Calculations
  - Section 4.2: Modeling the War Hammer
  - Section 4.3: Overview of the Forging Process
  - Section 4.4: Building the Spike
  - Section 4.5: Punching the Handle
  - Section 4.6: Shaping the Hammer Face
  - Section 4.7: Polishing and Deburring the Metal
  - Section 4.8: Forming the Langlets
  - Section 4.9: Heat Treatment
  - Section 4.10: Crafting the Handle
  - Section 4.11: Assembling the Hammer
  - Section 5.3: Grinding and Polishing the Samples
- Kyler Dillon
  - Forging: 22 Hours
  - Wood Working: 11 Hours
  - Sample Preparation and Analysis: 4 Hours
  - Section 2.5: Medieval Forging
  - Section 2.6: Medieval Metallurgy
  - Section 4.1: Materials
  - Section 4.3: Overview of the Forging Process
  - Section 4.8: Forming the Langlets
  - Section 4.9: Heat Treatment
  - Section 4.10 Crafting the Handle
  - Section 5.2: Mounting the Samples

- Tejas Rao
  - Forging: 22 Hours
  - Converting report to Latex, enforcing citations, checking formating
  - Content creation and translation
  - Abstract
  - Initial Web Design Research
  - Section 1.1: The Formation of the Kingdoms of England and France
  - Section 1.2: English Kings with French Claims
  - Section 1.3: The Aquitaine Situation
  - Section 1.4: The Treaty of Bretigny
  - Section 1.5: The Second Stage of the War
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  - Section 1.7: The End of the Hundred Years' War
  - Section 1.8: The Rise of France
  - Section 6.1: Website Maintenance
  - Section 6.2: The World Map
  - Section 6.3 New Content
- David Smieja
  - Forging: 22 Hours
  - Sample Preparation and Analysis: 5 Hours
  - Initial forging research
  - Section 3.1: Iron
  - Section 3.2: Steel
  - Section 3.3: Strength
  - Section 3.4: The Phase Diagram
  - Section 3.5: Microstructures and Non-Equilibrium Cooling
  - Section 3.6: Non-Eutectoid Steel
  - Section 4.1: Materials
  - Section 5.1: Cutting the Samples
  - Section 5.2: Mounting the Samples
  - Section 5.4: Discussion of the Final Microstructure
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  - Forging: 22 Hours
  - Sample Preparation and Analysis: 3 Hours
  - Travel Logistics

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- Section 2.1: Military Composition
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- Appendix

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Introduction

Originating from a dispute regarding the ownership of certain territories in France, the Hundred Years' War was a conflict between kingdoms of England and France, lasting between the years 1337 and 1453. It had a profound impact on the futures of the countries on either side. With effects ranging from the rise of artillery to the re-shaping of both kingdoms' futures, the developments which arose from this war shaped the political, geographic, and military attributes of their respective nations.

Throughout much of history, the driving force behind developments in materials was armed conflict, specifically the need to defeat or counter the weapons or armors used by one's enemies. Due to the sheer scale and length of the Hundred Years' War, this conflict saw many evolutions in both tactics and technology, such as the fall of chivalry and heavy cavalry, as well as the rise of guns and cannons. In our report, we will analyze the warhammer, a blunt force weapon used by both infantry and cavalry to break through heavy armor. As part of our analysis, we will be forging a replica of the war hammer using steel of a similar carbon content. We will then take samples from the material to analyze the microstructure of the finished item with our goal being to gain a better understanding of the state of medieval technology, and the forces that drove its progression.

Chapter 1

Historical Background to the Hundred Years' War

Warfare and politics were two methods that monarchs from the early Medieval ages used to establish rule over their lands. In order to be successful in both military and political campaigns, the need for advanced military technology and tactics became evident as weapons evolved in parallel with military composition. During these times, military strength was political power.

1.1 The Formation of the Kingdoms of England and France

On Christmas Day in the year 800, King Charles of the Franks was crowned Roman Emperor by Pope Leo III. The lands under his control stretched from the Atlantic Ocean to the eastern edge of the Alps, and from the North Sea to as far south as the Tiber River. But due to the nature of contemporary inheritance law, the following Emperor was forced to split his lands among his children, forming the kingdoms of West, Middle, and East Francia. Bloody wars ensued as his descendants fought among one another to claim more territory. To make matters worse, Vikings began their raids on Europe around this time. With a convenient base established on Great Britain that covered most of modern-day East Anglia, Lincolnshire, and Yorkshire, the northern coasts of West and Middle Francia became prime targets for raids. The boldest captains would travel up the Seine river to raid communities further inland, even Paris (Crouch, 2007, p. 2). In the year 911, one of these warlords, Hrólfr Ketilsson, was granted the land that he had conquered up to that point in exchange for becoming a vassal of the French king (Crouch, 2007, p. 4). Upon his acceptance, he became the first Duke of Normandy.

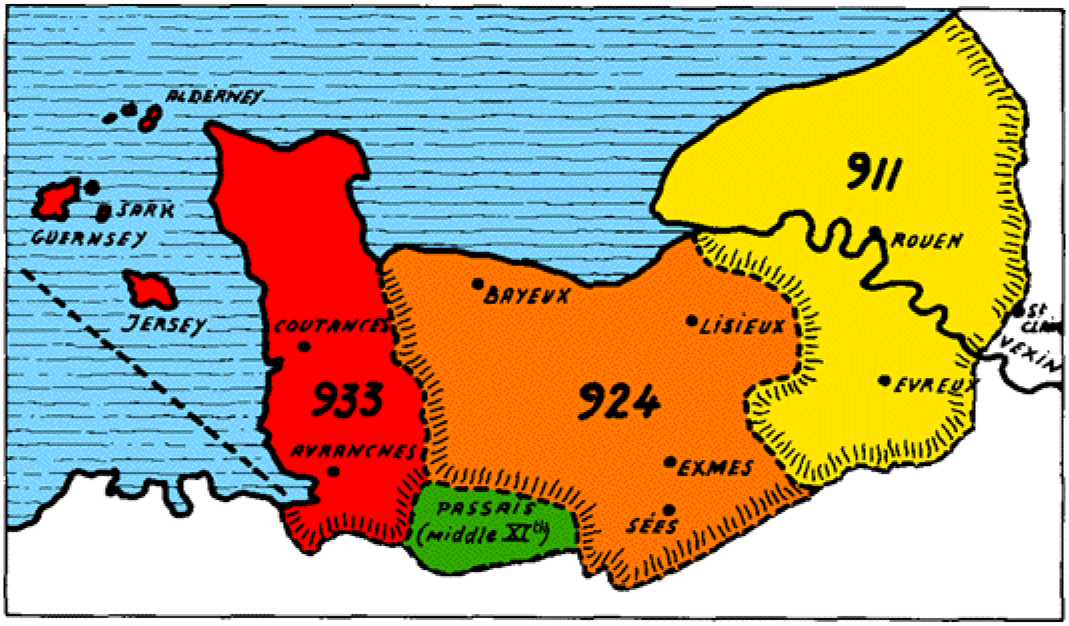

Figure 1.1: Map of Normandy and its expansion from 911 to 1066 A.D. (Skråmm, 2004)

In Great Britain, the coexistence between Anglo-Saxons and Viking rulers began to wane. The tenth century saw the Vikings ejected from Great Britain, and shortly afterwards, the resumption of Viking raids along the east coast of the island. Even though the English king at the time, Ethelred the Unready, agreed to pay tribute to the Danish king Sweyn Forkbeard (who also ruled over Norway), he still invaded England and was crowned king, cementing Norse rule over England for about sixty years (Blair, 2010, p. 61). Following the coronation of Edward the Confessor, who was the first Anglo-Saxon king following the Norse takeover, Harald Hardrada, the next king of Norway, believed he also had a valid claim to the English throne, and planned to press it upon the death of Edward the Confessor.

When the Danes conquered England, Ethelred the Unready and his family, including his son Edward, fled to the court of the Duke of Normandy, from which his wife hailed. The Duke who followed, Robert the Magnificent, was fairly active in affairs outside his duchy, getting involved in a civil war in Flanders and even organized an invasion of Danish England to restore Edward, his cousin, to the throne (Blair, 2010, p. 72). Even though this never happened, it is said that Normandy and England had very close ties once Edward the Confessor assumed the kingship.

Owing to this, the childless Edward supposedly offered the kingdom of England to Robert's bastard son William upon his death. When Robert died with no legitimate sons, William became the duke of Normandy, but faced much opposition at home due to his ignoble birth.

Anglo-Saxon noblemen on the island of England were understandably opposed to a Norman lord assuming the throne. Accordingly, after Edward died in 1066, Harold Godwinson, from a very powerful Anglo-Saxon noble family, was crowned king (Blair, 2010, p. 72). Harald Hardrada, Harold's brother Tostig, and William de Normandie found this offensive and massed invasion forces to take England for themselves. Harald arrived first, joined forces with Tostig in Northumbria, and attacked Harold at Stamford Bridge in Yorkshire (Blair, 2010, p. 74). The battle was highly destructive; Harald and Tostig were both killed and their army was routed, but Harold Godwinson's army was severely weakened. Not long after, William of Normandy fought Harold at Hastings in Sussex. There, Harold Godwinson met his end, and shortly thereafter William of Normandy became King William "the Conqueror" of England.

1.2 English Kings with French Claims

William and his heirs were faced with difficulties ruling England, being Normans whereas most of their subjects were Anglo-Saxons. As such, the Norman kings focused primarily on expanding their hold on the continent. After William's death, Normandy and England were ruled as separate entities; however, on multiple occasions, the duke of Normandy attempted and failed to conquer the kingdom of England, leading to his imprisonment and the confiscation of his duchy by the English king. In 1154 Henry II became the king of England following a brutish civil war; in addition to England and Normandy through his mother, he ruled over Anjou through his father and Aquitaine through his wife, Queen Eleanor. This marked the beginnings of the Angevin Empire under the Plantagenet dynasty.

It proved difficult to maintain control over the vast empire. King Henry II, his son Richard the Lionheart, and his brother and successor John all faced revolts from family members vying for the throne of the Angevin Empire. In 1204, King John lost Normandy to Philip II of France, and in 1214 all of his continental possessions but parts of Poitou and Gascony. This spiral continued until 1259, when King Henry III of England signed a treaty with Louis IX of France, establishing Henry as duke of Aquitaine but still a vassal of France (Wagner, 2006, p. 15). Henry III also gave up England's claim to the parts of the empire that John had lost. For much of the rest of the thirteenth century, kings of England paid homage to kings of France, preserving the peace but establishing France's supremacy over England.

In 1293, Gascon sailors sacked the port of La Rochelle after a diplomatic incident with French sailors. In response, the French king, Philip IV, demanded that the English king, Edward I, answer for it. Edward never responded to the summons, which led Philip IV to revoke Aquitaine (Wagner, 2006, p. xxx). This inevitably launched another war between England and France, and France's new ally Scotland. The conflict ended in 1303 with no change to the status quo; Edward II, the next king, was still forced to pay homage to the king of France. In an attempt to ease the tension, he married Princess Isabella, the daughter of the king of France (Wagner, 2006, p. 120). However, this only proved to make things worse; the marriage did not stay war between the two powers, and it gave the king's son, Edward III, a direct claim to the French throne.

To make matters worse, the king of France, Charles IV, had died without a male heir in 1328. French succession law demanded that the line of succession not pass through any women, which led to the coronation of Philip of Valois, from a minor branch of the Capetian dynasty, even though Edward was the closest living male to the Capetian line (Wagner, 2006, p. 121). Relations between France and England soured quickly; the final straw was that Philip VI had provided aid to Scotland during its war of independence against the English. Once Edward III had resolved the situation in Scotland, he appointed new landlords who served him in future conflicts, and supported levying taxes for war with France in Parliament. Once Edward III offered refuge to a particularly dangerous pretender to the French throne, and given how contentious Philip's accession was, Philip revoked the duchy of Aquitaine once more, leading to war. However, the stakes were higher this time, as Edward III proclaimed that he was the rightful king of France, prompting a war for the entire kingdom: the Hundred Years' War.

1.3 The Aquitaine Situation

Aquitaine was one of the largest duchies in medieval France. After being combined with the duchy of Gascony in the eleventh century, it comprised most of southwestern France and was

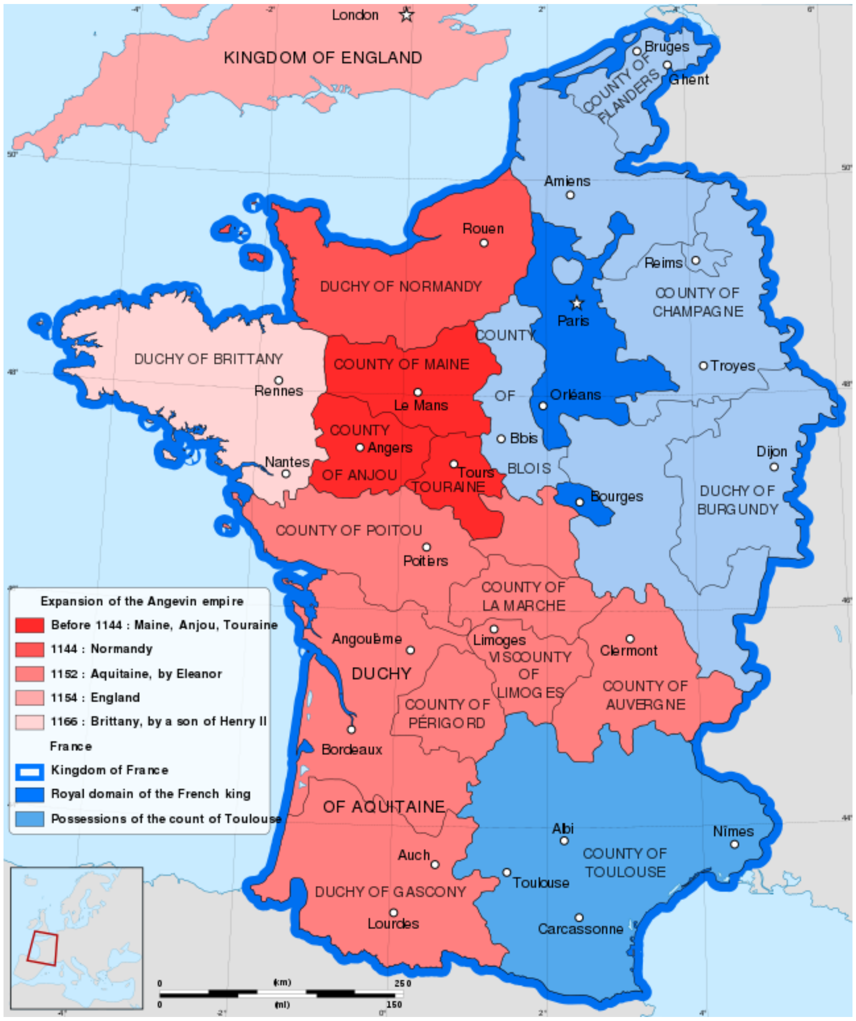

Figure 1.2: Map of the Angevin Empire at its height in 1166. Holdings in a shade of red are controlled by the Kingdom of England. (*France 1154*, 2014)

semi-independent in its own right (Wagner, 2006, p. 15). In 1152, Princess Eleanor of Aquitaine, the only child of the duke, married Henry Plantagenet, at the time the count of Anjou, to the north of Aquitaine. Two years later, when Henry became the king of England, his wife's land became his family's, forming the vast Angevin empire. Even after King John most lost of Aquitaine back to the French king, the status of the duchy was a thorn in both their sides: legally part of France, the French king wished to enforce that claim and have the duchy ruled by one of his vassals. On the other hand, because the duchy was *de facto* part of England, the English king wished for it to be stripped from the kingdom of France and ruled from Britain. In 1259, Louis IX of France and Henry III of England attempted to resolve this by signing the treaty of Paris (Wagner, 2006, p. 16), which codified Henry's rule over Aquitaine as a vassal of the kingdom of France if he gave up claims to other land in France. Further French involvement in Aquitaine's internal affairs caused this treaty to fall apart quickly, leading to two wars between England and France before 1337, both of which ended in a white peace.

When Edward III declared war on France to begin the Hundred Years' War, his goal was to obtain full sovereignty over the duchy in order to completely eliminate French interference in its governance. However, feudal custom was not particularly accepting of what amounted to a war of conquest. Fortunately, Edward was able to justify his war, and gain allies, by declaring himself the rightful king of France, to which he had a justifiable claim. As such, he was able to mass an alliance with landowners from Flanders and Germany (Wagner, 2006, p. 121), which started the Hundred Years' War on a strong English footing.

1.4 The Treaty of Brétigny

On 19 September 1356, Edward the Black Prince, the son of King Edward III, and King John II of France fought at Poitiers. The battle was a devastating win for the English, culminating in the capture of King John and three of his sons. However, this appeared not to be enough to demand the entire kingdom of France, or even half of it in full sovereignty, despite the fact that the French could not pay ransom for their king. To force the French to negotiate on his terms, Edward launched a march on Rheims in October 1359, where French monarchs were historically crowned (Wagner, 2006, p. 58). However, Edward was unable to take Rheims, and could not fight a battle with the evasive French army at the time. In May of 1360, he signed the Treaty of Brétigny, which granted him only a third of France in full sovereignty and ended the troublesome alliance between France and Scotland, on the condition that he renounced his claim to the French throne (Wagner, 2006, p. 59), and demanded only half a million pounds sterling for the release of the king over a period of six years. At the end of the treaty, Edward owned a much larger Aquitaine that had grown up the northern coast to include Poitiers, and a few holdings in the far north of France around Calais (Wagner, 2006, p. 59). He was unable to force the cession of Normandy, Brittany, and Anjou, which the Plantagenets had controlled in the past.

Unfortunately, the treaty's terms began to fall apart almost immediately. Neither Edward nor John had ratified the *C'est Assavoir*, the specific charter containing the terms of cession, and

France was unable to meet the payment terms that they had agreed to. In 1364, King John returned to London, supposedly to atone for his son Louis' escape from captivity, but more likely to negotiate directly with the king that the ransom be lowered (Wagner, 2006, p. 181). However, within a few months, he died of an illness, and his son Charles assumed the throne of France. Charles sought to deal with English encroachment on his land in due time, but waited for the right opportunity to present itself, which it soon did (Wagner, 2006, p. 86).

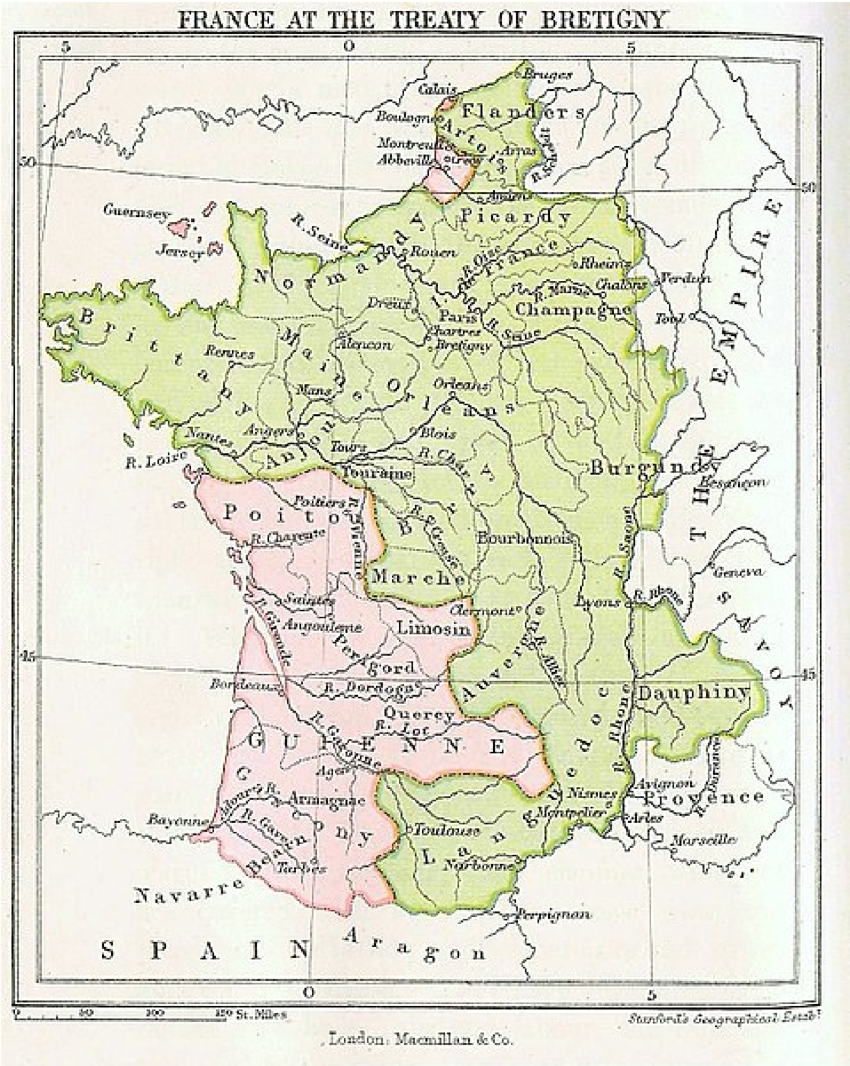

Figure 1.3: French and English continental holdings following the signing of the Treaty of Brétigny in 1356. (*France at the Treaty of Brétigny*, 2017)

In 1362, Edward the Black Prince was granted the duchy of Aquitaine by his father, the king of England, for winning at Poitiers. With his newly acquired resources, the ambitious prince fought in the Castilian War of Succession, backing Pedro I against his half-brother, Henry II, who was backed by Bertrand du Guesclin, a French military captain who had recently fought Edward in the Hundred Years' War. With Edward's help, du Guesclin was captured at Najera in 1367 and Henry was deposed (Wagner, 2006, p. xl); two years later, Charles V ransomed du Guesclin and Henry II was made king for good after killing Pedro. With Pedro's coffers unable to pay for the costs of the war, Edward was forced to levy a tax on his Gascon underlings. To escape this, a group of Gascon nobles asked that Charles V resolve their taxation dispute with Edward. For Charles to accept would lead to a resumption of the war, since it would indicate that Charles wished to exert sovereignty over Aquitaine, for which Edward would be more than willing to go to war. Yet for him to decline would be to acknowledge the loss of his family's sovereignty in the duchy. All this considered, he accepted, and summoned Edward to Paris, who flatly declined.

This time, it was France that was able to maneuver into a strong diplomatic position. Due to French aid in his assumption of the throne, Henry II of Castile became a firm ally of Charles V, and Edward's neighbors were able to incite a rebellious mood in Gascon nobles. With almost nine hundred appeals lodged against him in Paris by the end of November 1369 (Wagner, 2006, p. 15), Charles V invaded Aquitaine, and the Hundred Years' War had resumed.

1.5 The Second Stage of the War

Within ten years, the kingdom of France had reclaimed a great part of Aquitaine and was wreaking havoc on the kingdom of England, even going as far as raiding their coasts in 1377 (Wagner, 2006, p. xli) and landing on Great Britain itself in 1385. This was due in part to the leadership of France's new constables Bertrand du Guesclin, who played a role in the Castilian War of Succession; and of Olivier de Clisson, a Breton who proved to be skilled at avoiding being caught in a battle he was ill-prepared for (Wagner, 2006, p. 102). Additionally, France's new diplomatic position was even stronger than that of England's in 1337: Charles V had recently supported Henry II's bid for the throne of Castile, and had married the Duke of Burgundy to the only child of the count of Flanders, which effectively surrounded the kingdom of France with allies to the north and south.

The kingdom of England was in very poor shape as well. Both Edward the Black Prince and his father, Edward III, had died by 1377, leaving the Black Prince's second son Richard II to be crowned at the age of ten (Wagner, 2006, p. 269). In order to finance the defensive effort, Richard's administration (led by his uncle John of Gaunt, the duke of Lancaster) was forced to levy taxes against the general population, leading to a peasants' revolt in 1381, and considerable opposition from barons in the kingdom. In 1386, John of Gaunt went to Spain, leaving a sizable power vacuum which was filled by these rebellious barons, the "Lords Appellant". They formed the Merciless Parliament on 20 December and had many of John of Gaunt's allies and the young king Richard's advisors executed (Wagner, 2006, p. 269). Much more hawkish than Richard or John, the Lords Appellant attempted to continue the war against France, but ran out of money. Miraculously, France agreed began peace talks with England at Leulinghem in 1389, under the direction of the twenty-two-year-old Richard and the recently returned John of Gaunt, and Olivier de Clisson, acting in the king's stead.

Unfortunately for King Charles VI, the beginning of the fifteenth century would be fraught with major issues. He suffered major schizophrenic episodes starting in 1392, which incapacitated his administration and allowed a bitter civil war to erupt between the dukes of Orléans and of Burgundy between 1404 and 1419. During the civil war, the country was effectively ruled by the stronger of the two, with the king ill of mind and his sons simply pawns in the conflict (Wagner, 2006, p. 88). In 1396, he sent his daughter Isabella to marry Richard II in order to improve relations with England. This did little to help the relationship, though; Richard II had angered too many nobles in dealing with the errant Lords Appellant, and was imprisoned by John of Gaunt's son Henry of Bolingbroke, of the House of Lancaster, who became the king of England in 1400.

1.6 The Lancaster Dynasty Goes To War

Henry IV greatly wished to resume the Hundred Years' War and take advantage of Charles VI's mental illness and France's civil war. However, internal rebellions against his seemingly dubious claim to the throne and against English rule in Wales prevented him from making a move for most of his thirteen-year rule (Wagner, 2006, p. 148), and it fell to his son Henry V to accomplish those goals. He quickly asserted his ancestral right to the throne of France (being a descendant of Edward III), signing treaties with both the dukes of Orléans and of Burgundy then demanding unreasonable amounts of land and gold from both. Taking their refusal as an invitation to war, he landed at Harfleur in August of 1415 (Wagner, 2006, p. 150) and dealt a devastating blow to the French army at Agincourt only two months later, despite being outnumbered over three-to-one (Wagner, 2006, p. 1). Spurred on by his victory, Henry V returned to London a hero, and made it known that his ambition was not to take Aquitaine and Normandy from the king of France, but to become the king of France himself (Wagner, 2006, p. 150), and expand England's reach farther than it had ever been before.

To accomplish this lofty goal, Henry moved quickly to secure support from other rulers. In 1416, he formed an alliance with Sigismund von Luxemburg, the Holy Roman Emperor, and secured more funding from Parliament to continue the conflict. From 1417 to 1419, Henry waged war against French authorities in Normandy, culminating in the capture of Rouen in January. For his incompetence in managing the army, the de facto ruler, the duke of Burgundy, was murdered in Paris by the dauphin, prompting the next duke of Burgundy to abandon France and form an alliance with England instead (Wagner, 2006, p. 150). They imposed the Treaty of Troyes upon France, whereby Henry V was made heir and regent to the kingdom of France through a marriage to Catherine of Valois, ending the Hundred Years' War in England's favor and the French civil war in Burgundy's favor (Wagner, 2006, p. 303). When Henry V died in 1422, his six-month-old son became king of England; when Charles VI died three months later, that same boy, Henry VI of Lancaster, became the only ruler of both England and France (Wagner 2006, pg. 151). He did not live to go on to great things.

The former dauphin worked to start an effective rebellion, with the help of the d'Armagnac dukes of Orléans, who had lost the French civil war (Wagner, 2006, p. 90). From 1423 until 1428, he suffered loss after loss to the English and the Burgundians, who continued to push south to the Loire river, and laid siege to Orléans in 1428. The siege continued marvelously for the English until March of 1429, when Joan of Arc, who claimed that she was sent by God to help Charles become the king of France, became involved in the conflict. With her help, the English and Burgundians were ejected from the Loire Valley by June, allowing Charles to march to Rheims, the traditional coronation site of French monarchs, and crown himself Charles VII, king of France.

1.7 The End of the Hundred Years' War

The miraculous nature of King Charles' victory over the English in 1429 once again legitimized his claim to the French throne and provided him with popular support, as Joan of Arc's intervention made it seem as if his mission was "divinely inspired" (Wagner, 2006, p. 90). Despite the failure of Joan's attack on Paris in September 1430, her subsequent capture by the Burgundians, and denunciation and execution by the English for being a witch, the French army proved to be an unstoppable force. In 1435, with both France and Burgundy suffering from financial hardship, the two lands agreed to a peace at Arras which left Henry VI as the sole enemy of France in the war. Additionally, Henry's claim was hotly contested since the Treaty of Troyes, of fifteen years prior, only granted the kingdom of France to his father, Henry V (Wagner, 2006, p. 29). While the peace agreement gave far more land to Burgundy than Charles would have liked, it was necessary for Charles to end the war, for no longer would he have to contend with an enemy based on the continent. Returns on this agreement proved swift; in April 1436, the French recaptured Paris (Wagner, 2006, p. 30), and saw revolts break out in English Gascony and Normandy.

Henry VI's utter incompetence as a ruler did nothing to remedy his kingdom's situation. Since his coronation in 1431, the English war effort had suffered greatly, and his lack of care for the conflict did it no favors; rather, he spent money on institutions such as Eton and King's College, and freely gave out titles, lands, and even money to his courtiers (Wagner, 2006, p. 151). After a failed campaign by John Beaufort, the duke of Somerset in 1443, English and French lords met at Tours to negotiate a truce. The French refused to concede any land, but offered Margaret of Anjou, a niece of Charles VII, to Henry VI in marriage; this was a sharp move, because as Margaret was not a descendant of Charles, Henry's children through her could not press a claim to the French throne. The treaty lasted for about five years, aided by the fact that Henry's government readily conceded to the French when faced with military or diplomatic pressure (Wagner, 2006, p. 301); but by 1449, King Charles had become tired of waiting, and resumed hostilities by attacking Normandy. The 1450s saw the final two French campaigns of the Hundred Years' War: one in Normandy from 1449 to 1450, and one in Gascony from 1451 to 1453. Within three months, French armies had surrounded Rouen, the capital of Normandy, which fell in less than three weeks. Through new advances in tactics and the use of longbows as the English had, the French general Jean Bureau routed the English army at Formigny in April 1450, and the entire region had fallen within three months (Wagner, 2006, p. xlix). The Gascon campaign was slightly more contentious, as it was the only English holding on the continent save Calais. In June 1451, Bordeaux, the capital of the region, surrendered to the French in the midst of a massive naval blockade, but was recaptured a year later by John Talbot, the earl of Shrewsbury, the most famous English commander by the end of the war (Wagner, 2006, p. 79). In the summer of 1453, he marched to Castillon to dispatch a French army in the area. Unfortunately, his army was routed by extremely good positioning and powerful archers and artillery on the French side. With the English dispatched, the French marched into Bordeaux on 19 October 1453, effectively ending the Hundred Years' War. England had been removed from the continent (save the port of Calais), and this traumatic defeat would not only fully incapacitate Henry VI, but would also determine the kingdom's foreign policy for hundreds of years afterwards.

1.8 The Rise of France

After Henry VI's deposition, imprisonment, and murder during the Wars of the Roses, Edward IV, of the Yorkist branch of the Plantagenet dynasty, launched a following invasion of France in July 1475; however, Louis XI, the king of France, quickly dealt with him and paid him a pension in order to stay his invasion, as he had greater concerns on his mind: specifically Burgundy. After leaving the Hundred Years' War, Duke Philip of Burgundy had expanded his realm north into the Low Countries, seeking to build a greater power base by which his duchy could once again challenge France. His successor, Charles the Bold, continued, expanding eastward into the Holy Roman Empire. However, he proved to be too aggressive for those around him, and entered into conflicts with Lorraine and Swiss cantons. He died childless in 1477 while fighting around Nancy in Lorraine, triggering a succession crisis between the kings of France and the Holy Roman Emperors. After a five-year succession war, the two split the holdings of the duke; the Holy Roman Empire claimed much of the Low Countries, and France claimed most of the southern Burgundian lands. With her only errant duchy dispatched, France now found it possible to grow much more powerful than she had ever been before, cementing her status as a world power within a hundred years.

England, on the other hand, suffered through a devastating defeat in the Hundred Years' War followed by a particularly brutal civil war between the houses of Lancaster and York, both of which, being branches of the Plantagenet dynasty, claimed the throne of England. The conflict lasted approximately from 1455 to 1485, ending as Henry Tudor, a minor Lancastrian nobleman, defeated the Yorkist king Richard III at Bosworth Field to begin the Tudor dynasty. After the Wars of the Roses, England was utterly devastated, with no means to restore her former lands on the continent. Seven years later, however, Spanish sailors discovered the New World, opening up a major opportunity for England as a seafaring power. They quickly followed in Spain's footsteps, first with the subjugation of Ireland, then with the establishment of colonies and successful trading networks on the east coast of North America and in the Caribbean Sea, totally eclipsing them in 1588 with the defeat of the Spanish Armada by the Royal Navy under Sir Francis Drake. Their control over the seas and over international trade expanded to such an extent that, even to this day, the sun does not set on the British Empire.

Chapter 2

Military Technology of the Fourteenth Century

In order to gain the edge in military disputes, leaders of the time often sought out new and improved arms and armors to supply their troops with. Examples would be a swap from bronze to iron weapons, swords to guns, or chain-mail armor to plate armor. However, depending on the environment, equipment could change. Short swords could be favored over longer ones, and chain-mail could be favored over plate armor if mobility was valued over protection. Due to the changing time period where new technologies and tactics were constantly adapted and experimented with, military leaders had to change and adapt to situations in order to give their side the edge in battle.

2.1 Military Composition

The army compositions of the English and the French differed greatly during the Hundred Years' War. The English often had triple the number of infantry as they did mounted units, and for good reason. Infantry was far easier to recruit and replace as mounted units, and, with the use of the English longbow, could be as effective as their mounted counterparts. The footman become the core of the English army starting in the thirteenth century because of their frequent battles with the Scottish and Welsh (Wagner, 2006, p. 21). In these encounters, King Edward I realized the importance of having footmen in mountainous terrain where his mounted units were ineffective.

The French differed from the English in that they did not recruit their own footmen, but opted to draw troops from neighboring regions. The core of their military was the mounted unit. French people took chivalry very seriously, and as a result refused to use ranged weapons. This meant that the French could only respond to a hail of arrows from the English with a charge from their knights.

The knights of the English and French armies were both made up of nobles and members of the gentry. In England, the title of "knight" was eventually given to anyone who received mounted training and could bear the financial burden of purchasing their own arms and armors. In France this title was strictly hereditary. In regards to arms and armors, both countries used similar weapons with very slight variations. Knights used lances that measured ten feet in length, coupled with a small shield in the shape of a wedge. In addition to this, a straight one-handed sword was sheathed at the left side of the knight, with a dagger on the opposite side. French armor was far more advanced than English armor due to their reliance on a strong cavalry for their battles. French armor was fluted earlier, meaning that it no longer was there just to absorb blows, but instead to redirect them. This meant that French knights wore lighter, stronger, and more protective armor than their English counterparts. This also meant that French knights eventually discarded the larger wedge-shaped shield and opted for a small buckler, or discarded the shield completely and used a two-handed sword instead. Another area the French differed in was the helmet. French knights wore "bascinets", or visored helmets that offered full protection. English knights did not adopt the visor until later into the war. Instead, the English wore an open-faced helmet. English knights wore layers of protective gear (Wagner, 2006, p. 27). A padded cloth or linen was worn under a chainmail overall. Plate armor was then worn over the chainmail as the first layer of protection.

French use of mercenaries during the Hundred Years' War was commonplace. Due to their geographical advantage over the English in that they could source their resources from mainland Europe, the French had the liberty in maintaining their core of knights. Mercenaries from Germany, Italy, Spain, and other areas of Europe would flock to France during the war (Knighton 2016). The best known of these groups was the Genoese mercenary group. The Genoese were a defense force for the Republic of Genoa, or at times of peace, found mercenary work elsewhere. Both the English and French hired these mercenaries during the war. Genoese mercenaries were often associated only with the French army because of their defeat during the Battle of Crécy, where roughly 6,000 Genoese crossbowmen stood as the first line of defense against the English. The rain from previous nights soaked the crossbows of the French, while the English had animal hides to cover their bows. This caused the crossbows to have a shorter range, as well as have lower accuracy (Knighton, 2017). The first few volleys proved that the battle was futile from the Genoese side. The longbow could both out range and outfire the damaged crossbows that they used. When the Genoese commander ordered a retreat after he saw this, the French knights behind them cut them down.

Figure 2.1: Genoese crossbowmen at the Battle of Crécy. (Knighton, 2017)

War hammers consisted of a double sided steel hammer head mounted on a wooden pole of various lengths and specialized in crushing armor. As advancements in armor making resulted in reduced effectiveness of cutting weapons such as swords, the war hammer operated by using concussive force to injure the opponent, able the break bones and cause internal bleeding even without penetrating the armor. One strategy of fighting with the war hammer was to impact with the hammer face to severely injure or stun the opponent and the follow up with a killing blow from the spiked side, which would be aimed at the thinner areas of the armor. The spiked side could also be used to hook cavalry and drag knights off of their horses, although this technique was usually reserved for halberds, where the length of the weapon facilitated this maneuver. Another use of the war hammer was to dismount a knight by swinging at the horse's legs, crippling it. War hammers varied in length, ranging anywhere from the length of a mace to the length of a halberd.

Foot soldiers typically carried longer versions than mounted knights due to knights having only one hand to swing a weapon for the majority of their time mounted (*War Hammer*, 2013). The war hammer was used from the fourteenth century until the sixteenth century. Even with the introduction of gunpowder and artillery, the war hammer was still in use because of its cheap cost to manufacture, as well as its effectiveness to counter mounted units.

Figure 2.2: A replica of a medieval war hammer. (*Medieval Weapons and Armour*, 2010)

Infantry from both countries were most often equipped with the halberd. The halberd was a spear with an axe head, and resulted from the evolution of a one-handed axe. As the one-handed axe grew longer and larger, both hands were required to wield it. The two-handed axe was classified as a halberd when additional loops were added to the axe head, which caused the axe head to grow in length (Snook, 1979). The halberd was considered the peasant's weapon due to its low cost to manufacture. Because the halberd had a long wooden pole with metal attached to the end, producing halberds in large quantities was much cheaper than producing swords. By the 14th century, halberds were widely used across Europe. The simple design of the past was improved upon by adding a hook to the opposite end of the axe head, as well as adding a sharp pike in between the two. This allowed for the halberd to stab and slash from a distance, and also allowed for the user to disarm an enemy with the hook, or to dismount a knight (*Halberd Medieval Weapon*, 2014). The advantage of being able to attack from a longer range than other infantry weapons was an advantage, but also a disadvantage. Due to the long wooden shaft and heavy metal head, the halberd was ineffective in close range combat. During situations like this, the soldier would discard the halberd and use a side weapon. This weapon was a small dagger in most cases, or a small sword. In addition to the economical benefits from producing the halberd, namely being able to arm a large number of people for a small amount of money, as well as the ability to dismount a knight, the halberd quickly spread across Europe. The halberd saw use from the fourteenth century until the sixteenth century, when the spread of gunpowder and artillery reduced the number of knights fielded, which in turn reduced the need for the halberd (*Halberd Medieval Weapon*, 2014).

Figure 2.3: The head of a halberd replica. (*Medieval Weapons and Armour*, 2010)

Swords were the staple weapon of many armies during the fourteenth century. The simple design and purpose made the sword a weapon where if given to a peasant, the peasant could be effective with little to no training. There were many different types and designs of swords, but the major ones were the broadsword, otherwise known as arming sword, the falchion, and the longsword. The broadsword was a term which includes cavalry swords and military swords. Such swords could be either single or double edged, depending on the purpose. However, all broadswords had to be one handed. The falchion was the European version of the Persian scimitar

(*Medieval Weapons and Armour*, 2010). It was a sword with one edge and a curved blade. Due to the design of the falchion, the weight of the sword was concentrated towards the end of the blade. This made the falchion more effective for chopping or slashing, similar to an axe. Longswords were used in the late Medieval period of Europe, between the fourteenth and sixteenth century (*Medieval Weapons and Armour*, 2010). These swords had hilts that were designed for two handed use, often being ten to fifteen inches long. In addition to this, the blade itself was longer than forty inches, and typically weighed about three pounds. Although the longsword was designed for two handed use, in certain situations, the sword could also be used with one hand. This gave the longsword the nickname of a "hand and a half sword" (*Medieval Weapons and Armour*, 2010). The purpose of the sword was to slice and stab, made evident in its design. Other parts of the sword could also be used to hurt the opponent. The pommel, or base of the hilt, could be used to inflict blunt force damage to the opponent. The crossguard could be used in a similar manner. Longswords all had a similar design, but variations in blade thickness and width determined the most effective use of the sword (*Medieval Weapons and Armour*, 2010). Longswords with tapering blades were often used for thrusting, while longswords designed for cutting had broader and had thinner blades. As time progressed, longswords gradually became thinner and narrower. This was because armor was becoming more advanced, and blades could no longer cut into armor. This created the need for weapons specialized for thrusting, which brought about more modern weapons like the rapier.

Daggers were the cheaper, shorter version of the sword. Daggers were double edge blades used for stabbing and thrusting in combat, and were often only drawn when a soldier could no longer use his or her primary weapon. Daggers were popular among infantrymen because they were cheap, but were unpopular among knights because its use was viewed as cowardly (*Daggers*, n.d.). Having a weapon that could be concealed, drawn, and used without warning was against the code of chivalry (*Daggers*, n.d.). Different types of daggers include the anelace, stiletto, poignard, and rondel. The anelace was a longer dagger that was used in the Medieval period. Due to the length of the dagger, one could either be used as a parrying dagger or one more anelace could replace the primary weapon (*Medieval Weapons and Armour*, 2010). The stiletto had a long, slender blade that was designed to find cracks in armor and make a deep cut into the flesh. In addition to this, the stiletto was also given the alternative name "misericorde" or mercy,

Figure 2.4: A replica of a falchion. (*Medieval Weapons and Armour*, 2010)

because this weapon would be used to finish off fatally wounded opponents. Pignards were daggers used together with the rapier. If an opponent were to get too close to the user, the user would draw his or her pignard instead of continuing to use the rapier. Rondels were stiff-bladed daggers that were used as a utility tool, a jousting side arm for knights, and a weapon during war. What set rondels apart from other daggers is that the dagger guard was circular rather than a cross (*Medieval Weapons and Armour*, 2010). Daggers were a cheap way to create a secondary weapon for soldiers to use that were able to parry attacks, penetrate chainmail, take advantage of small holes in heavily armored knights.

2.2 The English Longbow

Measuring between five and six feet tall, the English or Medieval Longbow was a staple of the English army throughout the Hundred Years' War (Kaiser, 1980). The main body of the weapon consisted of a long staff, typically yew wood, bent into a D-shape and connected by a hemp rope on either end (Kaiser, 1980). Arrows fired from the bow were made of wood, tipped with metal arrowheads, and three feet in length (Hurley, 2011, p. 168). Estimated to possess a draw weight between 90 and 100 lb-ft, the English longbow had an effective range of 250 yards, at which it could pierce armor and kill warhorses, making it a powerful check to heavy cavalry (Kaiser, 1980). If the charge succeeded in reaching English lines, archers were armed with side weapons such as pikes, hammers, and axes to fend off attackers. Compared to other ranged weapons, such as the crossbow and early guns, the longbow possessed a much greater range and faster firing rate, with skilled archers being able to fire between ten and twelve arrows per minute (Hurley, 2011, p. 174). Despite these advantages, however, the longbow never escaped the stigma of being a peasant's weapon, and began to be phased out before its successors, the early muskets, had fully surpassed it in terms of effectiveness.

Originally used by the Welsh to repel English invasions, the English quickly saw the value in this weapon for its ability to pierce plate mail and stop heavy cavalry charges from a distance, well before they could reach their target. The English repeatedly used this tactic of forming fortified defensive positions where archers would stand in the front lines, protected by stakes to the front and cavalry to the sides, and fire upon the charging French cavalry. Through these tactics, the English were able to repeatedly defeat numerically superior armies; at Agincourt, 6,000 English soldiers triumphed over a better supplied army French army estimated to have 36,000 soldiers, inflicting thousands of casualties on the French side while only losing roughly fifty men (*Hundred Years' War*, 2014). Other battles in which similar scenarios occurred include Dupplin Moor, Poitiers, Crécy, and many more (Rogers, 1998, p. 237).

Contributing to English success was the French army's strict, and often self-destructive, adherence to chivalry, which glorified honor and hand-to-hand combat while instilling an aversion to ranged weaponry such as the longbow. French armies and their allies entered battles believing they would reenact the melees of old, neglecting ranged weaponry and relying on foreign soldiers to provide ranged support through the use of the crossbow, a weapon that while easier to train and use, fired more slowly, possessed a shorter range, and lacked the rain and water resistances of the longbow, putting them at a significant disadvantage (*Hundred Years' War*, 2014).

2.3 Guns and Gunpowder

First appearing around the turn of the first millennium A.D., gunpowder was invented in China, with early formulas dating back to the mid-ninth century. The *Essentials of the Military Arts*, a book of strategy released in 1043, presents the first definitive formula and provides instructions on how to mass produce it (Ebrey, n.d.). Gunpowder was a mixture of charcoal, sulfur, and potassium nitrate, and doubled as both an incendiary device and a psychological weapon, with powders used to burn, blind, cause distraction, and bruise (Ebrey, n.d.). Early uses of the weapon included flaming arrows with packets of gunpowder attached and as a way to ignite cattle tails, which would then stampede into the enemy. Another early weapon was the fire lance, a bamboo tube which housed a chamber of gunpowder that could be ignited to launch a small rocket at the enemy from close range (Ebrey, n.d.).

Later evolutions of the technology included the development of rockets, which were made able to fly straight through the use of counterweights and a technique of boring into the center of the gunpowder fuselage, in conjunction with a variety of bombs (Ebrey, n.d.). During the Song Dynasty, the variety of gunpowder based weapons expanded greatly, including gas, shrapnel, incendiary, and smoke bombs for siege and tunnel warfare, early flamethrowers in which tanks housing kerosene would be used to ignite enemies, and "eruptors," the forerunners to modern mortars, which would launch bombs at a target from a distance. The Tang Dynasty saw the innovation of using metal tubes to launch bombs from fire lances, and the first guns as well (Ebrey, n.d.). Early guns from these era consisted of a pole, held by the user, which would have a chamber attached to the end, housing the payload. Europe would not see gunpowder until the thirteenth century, likely arriving there through travel on the Silk Road.

Despite being used throughout the length of the Hundred Years' War, cannons used in the early phases of the war were far inferior to their final counterparts by the end, and were plagued by a myriad of problems such as immobility, slow rate of fire, and inaccuracy (Abels, n.d.). Many found usage on ships and were valued as the cutting edge of weapon, with Henry IV on the English side equipping all English warships with cannons, his personal flagship, Grace Dieu carrying a four-gun battery, and Jean de Vienne rebuilding the French fleet after the Battle of Sluys to incorporate cannons (De Vries, 1998, p. 390). The cannons used in naval skirmishes were anti-personnel weapons, sinking few to no ships but causing casualty by firing shrapnel at the enemy crew, though records on the number of deaths they caused are scarce (De Vries, 1998, p. 391).

While the guns of the early stages of the war rarely determined the fates of battles, advances in metallurgy techniques and founding gave birth to cannons which dominated the battlefields (Abels, n.d.). Some of these advancements included new methods of founding and forging, such as the introduction of blast furnaces possessing higher temperatures, the use of limestone as a flux or purifying agent in forging, and casting techniques that involved pouring the molten metal into molds, where earlier cannons were hammered together from separate scraps of metal (Abels, n.d.). These advancements allowed for longer barrels (roughly at a ratio of three-to-one compared to the diameter of a cannonball, where it had been three-to-two before) and thus greater accuracy and velocity of shots (Abels, n.d.). With a location on mainland Europe and greater proximity to Germany and Switzerland, two areas where some of Europe's earliest of the blast furnaces could be found, France was able to acquire this technology before England, and used it to devastating effect. Following the death of Joan of Arc, the French revitalized their military and adopted a new strategy based around the use of artillery. Organized by the brother Jean Bureau "the Treasurer" and Gaspard Bureau "the Master of Artillery", the French fighting force centered an artillery train that would dig into a position, build a bulwark, and then fire on whatever target was at hand, protected by cavalry and infantry soldiers (Abels, n.d.). Through these tactics, French forces were able to retake towns and cities such as Rouen and Bourg, which had previously held out for months and fell to starvation, in a matter of days. This culminated in the Battle of Castillon, in which French artillery destroyed the English army after a false report led to the English general to charge, effectively ending the war (Abels, n.d.).

2.4 Resulting Developments

As a result of the numerous technological and political factors occurring over the course of the Hundred Years' War, the armies of France and England underwent drastic tactical and structural changes by the end of the conflict. As mentioned above, one such change was the death of chivalry and the fall of heavy cavalry as a dominating force, made impractical and often suicidal by long-ranged armor piercing weapons such as the longbow and canonade (Hurley, 2011, p. 170). While revered on both sides as an ideal code of honor, chivalry lead to the deaths of thousands of French soldiers on multiple occasions, and its weaknesses lead to a number of changes to the French strategy as they searched for a way to defeat the longbow. French armies would initially

Figure 2.5: English cannons of the late medieval period. (*English Cannons*, 2007)

attempt to avoid fighting the English in open fields, using their better supply systems and greater mobility to attempt to out maneuver the English, however they would not possess a true counter to the longbow until they acquired the technology to build better cannons (Hurley, 2011, p. 170).

While she was captured and executed by the English only a few years after making her first appearance on the battlefield, Joan of Arc played a major role revitalizing the French military effort, and this in turn fueled the creation of new tactics, such as the French artillery train. Not only did the rise of cannons result in the fall of castles as stated above, but it also resulted in the return the infantry as a dominating force on the battlefield. Operated by trained infantry crews, they along with the English archers became some of the first foot soldiers in Europe to dominate battles in centuries, a trend that has carried on until the modern day. While cavalry would see use in attacking flanks and corralling enemy soldiers to be targeted by guns, they were much more lightly armed, usually with pistol and saber, and functioned in a supporting role instead of as the main unit (Hurley, 2011, p. 178).

Though dominant in the early parts of the war, the longbow was another weapon which was eventually outpaced by technology and left behind. While relatively cheap and simple to make, longbows carried a number of disadvantages with them, such as requiring years of training to use properly and possessing draw weights of close to one hundred pounds, making them much less attractive than guns, which while less accurate and reliable, required significantly less training to use, allowing for quicker drafting of gunmen than archers. Cannons also out-ranged archers, resulting in defeats such as the Battle of Formigny, where English longbow men dug in and fortified a position in a similar manners as Agincourt to await a charge, only to be fired upon by cannons and (ironically) forced to charge the guns. While they did succeed in capturing the French guns, the English were latter ridden down by French cavalry, killing or capturing over three thousand longbowmen, all of which proved difficult to replace (Abels, n.d.).

Figure 2.6: Illumination of the Battle of Formigny. (Niderost, 2016)

Owing to both political and tactical need, other structural changes occurred within the way armies were organized. At the start of the war, many of the soldiers were mercenaries or conscripts who would change sides for pay, and often wandered off and caused trouble during lulls in the fighting. Artillery pieces required crews and training to use effectively, resulting in the need for a common group of operators. These and other factors lead to the creation of the first professional armies in Europe in centuries, used to ensure loyalty, house soldiers in barracks to prevent further incidents, and train reliable teams to operate the emerging weaponry (Gabriel & Metz, 1992).

2.5 Medieval Forging

During the medieval era, blacksmithing practices in Europe advanced and changed steadily, with new technologies and methods becoming available within relatively short periods of time. Examples of this are the introduction of water-powered blast furnaces, and the movement away from pattern welding as a metalworking practice. The most important factors in driving these changes were material need, availability, and acquisition methods. The first and foremost difference between medieval blacksmiths and those that would come to be in the future was the use of charcoal as their main fuel source for forges. Coal was difficult and expensive to mine, whereas forests were plentiful at the time and easy to burn down to produce charcoal. As it happens, coal can also produce lower quality products as it is often naturally contaminated with sulfur, which negatively impacts iron or steel by making it much more brittle when heated, rather than plastic and pliable. Without this knowledge or the means to test and clean coal of sulfur contamination, it was widely accepted that charcoal simply produced better end products while also being less expensive, thus remaining the most popular fuel source for medieval blacksmiths. On the other hand, while charcoal was relatively less expensive than coal, it was still a fairly high priced commodity for a couple reasons; the first being that there was little to no infrastructure that could facilitate the transport of goods such as coal or iron long distances, and the second was the inconsistency of production. These two things combined made the price of charcoal (as well as many other raw material goods) unstable but always fairly high. Occasionally, there simply was not enough fuel to go around, so even if the smiths or local lords were willing to pay the price, it simply was not available, sometimes for months on end.

The second limiting reagent for blacksmiths besides fuel is of course metal, iron in most cases. During this time period, most iron was taken from surface deposits or bog deposits. Production of usable iron ore was reliant on two things besides availability of raw ore: fuel available, and a local moving water source. Fuel was used to smelt the iron ore into larger, more uniform pieces that could then be worked by blacksmiths. A flowing water source was crucial due to the development of water mills that powered bellows, industrial hammers, and blast furnaces, which immensely improved iron production in Europe.

The actual output of these iron ore refining facilities is very difficult to speculate on because

Figure 2.7: A 140mm-long sample of bog iron from Estonia. (*Bog Iron*, n.d.)

most of bloomeries that handled the smelting would move on once the local supply of wood (for fuel) was exhausted, leaving little to no documentation. It is estimated that during this time period, England produced between 5,000 and 6,500 tons of iron ore over the course of the war and imported upwards of 3,000 tons in just the fifteenth century.

2.6 Medieval Metallurgy

Many of the countries surrounding England and beyond also transitioned to water powered blast furnaces, making the production of pig iron and other metals a continuous one when compared to bloom furnaces, greatly increasing output. In fact, Switzerland, Sweden, and Germany are just a few of the countries who completely outpaced England, being the first countries to build and perfect blast furnaces. Some of these furnaces still stand today, with Germany housing over 100 of them, dating back to as early as 1205AD. Furnace description: OD 3m, ID 0.8m: Traditionally built from a few stones with the backside facing the slope of the basin, which is used as a natural charging platform, and had drainage built from stones to protect the materials being smelted

Figure 2.8: An interior view of a reconstructed forge with bellows operated by water power, located at the Saugus Iron Mill in Massachusetts. (*Saugus Iron Mill - forge with bellows*, 2006)

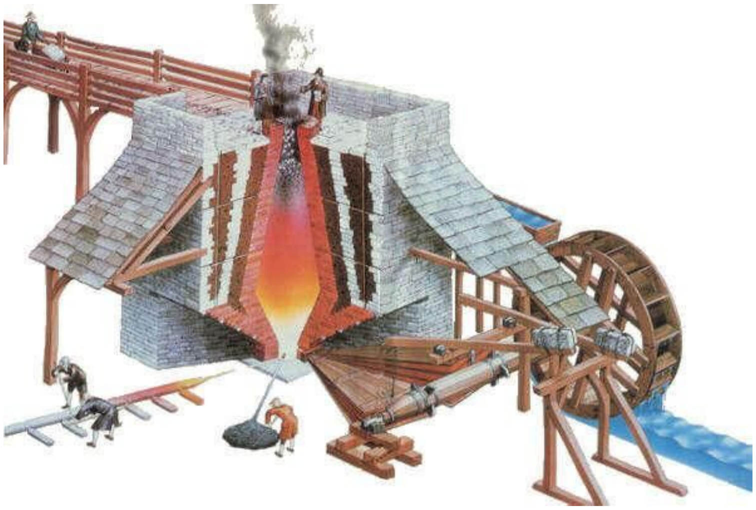

Figure 2.9: A cutaway view of a medieval European blast furnace. (Markiel, 2006)

from water, built on top of rivers or other flowing water sources to provide power. Through the introduction of heat, pressurized air, and a mix of metallic ore, flux, and coke liquid metal was produced (eventually pig iron). Coke is a fuel with very few impurities and high carbon content, usually and definitely in this case made from coal. Flux on the other hand has multiple metallurgical purposes, be it as a cleaning agent, flowing agent, or purifying agent, a flux can be used for one or all of those applications simultaneously. Pig iron was produced during the medieval era specifically with limestone as flux through reduction as the carbon and iron were in the presence of the flux agent. This method was introduced to England around the turn of the 16th century, with central Europe adopting it in the mid 1400's. As for specific with the smelting process and reactions, the furnaces were preheated between 900 and 1250°C, coke was introduced which formed carbon dioxide through combustion, raising the temperature of the furnace to around 1650°C. Starting at around 620°C, iron will absorb carbon up to 3.5% of its total composition by weight. This causes the metal to enter a eutectic phase, which flows as a liquid while heated, normally into molds. This specific metal is very high in carbon content, however cannot be shaped once cooled due to the hardness, so must be used in molding or worked on at very high temperatures achievable only by blast furnace at the time. Comparatively, bloomeries only produced red hot metals, which were worked on at around 370°C and had no carbon introduced into them. In a metallurgical comparison of eight middle-age blades (13th-15th century), in five cases they were carburized, heated to pure iron and then quenched in oil. Two were iron with forge welded steel added on, and the last was all steel welded together. Two methods were used in the quenching process; full quenching (dipping entire blade into coolant at once) formed an all-martensite structure (very hard crystalline structure). Slack quenching is a slower process which allows bainite and pearlite in addition to martensite, also allowing the metal to be heat treated afterwards if desired. Bainite is a plate-like microstructure with a very high concentration of dislocations, making the material much harder. Pearlite is actually a two phase layered structure formed via eutectic reaction which has an extremely high yield strength as well as flexibility, making blades less brittle overall.

Chapter 3

Modern Materials

The ability of iron to form alloys with other materials has been used to create materials stronger than itself. The most common alloying of iron is with carbon, where the carbon molecules prevent the iron molecules from slipping, creating a material that is stronger and tougher than iron. The internal microstructure of the resulting material can be calculated using the lever rule, which determines the percent of each phase present in a material given the temperature and material composition.

3.1 Iron

Iron is the 26th element on the periodic table, and the most common element on the planet Earth, due to its prevalence in the inner layers of the planet and the core. This prevalence also persists on the surface, which lead to the eventual usage of iron in tools and weapons throughout history. However, pure iron is a metal softer than aluminum. With a Body-centered-cubic structure, and a fairly high reactivity, not only does pure iron have a large amount of malleability, but it also does not remain pure for very long. This characteristic has been taken advantage of, as the reactivity of iron and it's ability to form alloys often results in a material stronger than the original ingredients of the mixture. As a result, specific formulas and names of iron alloys have achieved widespread production and recognition, such as stainless steel, cast iron, pig iron, wrought iron, and the wide reaching term 'steel', while other alloys such as Invar, a combination of iron and nickel, are common place but may not be a household name. Most modern tools or heavy duty machinery is made of some type of steel, as the carbon present within the iron has drastic effects on the materials strength.

3.2 Steel

Steel is an alloy of carbon and iron, two of some of the most plentiful elements in the Earth's crust. Iron is an element that naturally forms a body-centered cubic crystalline structure with its atoms, allowing it a decent amount of tensile strength and suitable mechanical properties to be forged into weapons. The mechanical properties shown in Table 3.1 are those of iron, to be later compared with those of steel.

Table 3.1: Properties of Iron (Callister, 2007)

Material	Tensile Strength (MPa)[1]	Young's Modulus (GPa)[2]	Melting Point (Celsius)[3]
Iron	210	211	1530

As shown, iron has a high tensile strength, but also a high melting point. This indicates that it is hard to work with in delicate forging, and it can corrode easily when it reacts with oxygen in water or the atmosphere. This resulted in the creation of cast iron, iron with a very high carbon percentage, which was very durable and nonreactive, but was impossible to rework if cast wrong, as well as very brittle. Eventually, a method was discovered to lower the carbon content of the iron, creating what is now known as steel. Table 3.2 (Thiele & Hošek, 2015) shows the properties of different types of bloomery steel.

As a general comparison of some of the relevant properties to determine ease of forging, Figure 3.1 shows the tensile strength, or the durability and utility of the metal, versus the melting point, or how easy it is to purify and work. Copper alloys such as bronze or brass fall below steel in both tensile strength and melting point, as a result being easier to work with than any iron alloy, but also they are also easier to degrade or warp. As discussed earlier, the strong metal basis of iron alloys both allowed and necessitated new weapons to be developed such as cannons and warhammers, in order to deal with the strengthened armor as a result of the same developments.

Table 3.2: Mechanical Properties of Bloomery Steel

Sample	Description	Microstructure	% Carbon by weight	% Phosphorus by weight
Fe-0.05 (n)	Bloomery wrought iron in normalized state	Ferrite with little pearlite	0.05 ± 0.02	0
Fe-0.21C-1.05P (n)	Bloomery phosphate iron in normalized state	Inhomogeneous, ferric with ferrite-pearlite layers	0.21 ± 0.06	1.05 ± 0.02
Fe-0.64C (n)	Bloomery steel in normalized state	Inhomogeneous, ferric with proeutectoid ferrite	0.64 ± 0.03	0
Fe-0.64C (h-1)	Bloomery steel in hardened and tempered state	Inhomogeneous, tempered martensite	0.64 ± 0.02	0
S235JRG2	Modern steel in normalized state (reference)	Ferrite with little pearlite	0.17 ± 0.00	0

3.3 Strength

Metallic alloys, including steel, often exhibit stronger and more desirable properties as compared to pure elements. This is an extension of the properties of a metal's crystalline nature, as each metal has a specific composition dependent on its processing and how the crystal structure shifts. A brief explanation as to why these alloys are stronger is similar to how having multiple stakes for a tent allows it to hold fast even in rain storms, as the metal is the tent, the most populous element, and the alloyed materials are the pegs, holding down the metal from shifting. Solid metal cannot be cooled perfectly evenly or simultaneously unless in a thin, impractical form for most applications, and thus, as a piece of metal is cooled, it forms boundaries in between layers of metal that have solidified at different rates. These faults in the metal, similar to the faults in the Earth's crust, are where the metal slips or stretches, and subsequently deforms. When an extra compound or element is added to the alloy, such as carbon to iron, it fills gaps in the crystal structure which helps hold these faults in place, increasing the tensile strength of the alloy directly. However, if there is no ability for the metal to move at all, such as in the case of cast iron, it results in a metal that is strong but brittle, akin to glass or ceramic. Therefore, the ideal iron-carbon alloy for most applications is steel that contains 0.5% to 2% carbon by weight, allowing for greater strength than wrought iron, but more flexibility than cast iron. One defining feature

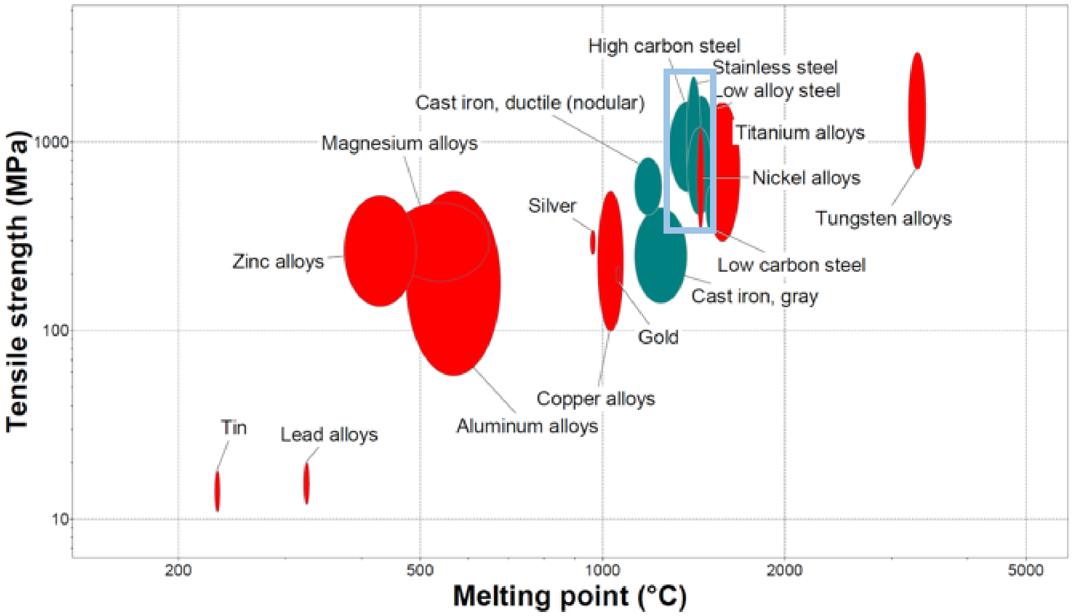

Figure 3.1: Tensile strength against the melting point of metallic materials. The various high and low carbon steels are located within the gray box. (*CES EduPack*, 2017)

that the carbon content of the steel determines is the phase composition of the steel, determined by a phase diagram as shown in Figure 3.2. Each phase of steel has varying properties from another, causing differing strengths within the piece of steel due to carbon content, which also causes faults within the metal. Another diagram shows the effect of cooling rate on the composition of the steel, the Time-Temperature Transformation diagram in Figure 3.4.

3.4 The Phase Diagram

As shown in Figure 3.2, the phase diagram is a tool used to predict the percentage of certain microstrucutres present in a given composition of materials. Displaying the percent composition of one of the components, in this case carbon, on the x-axis and temperature along the y-axis, the phase diagram allows one to determine which microstructures will be present within the alloy when these two characteristics are known. Plotted along the chart are a series of solid lines that indicate the boundaries between the different phase regimes and indicate at what composition and temperature the material will experience changes in what microstrutures are present. For example, steel that is 0.5% carbon by weight will be pure austenite, however if it cools to approximately

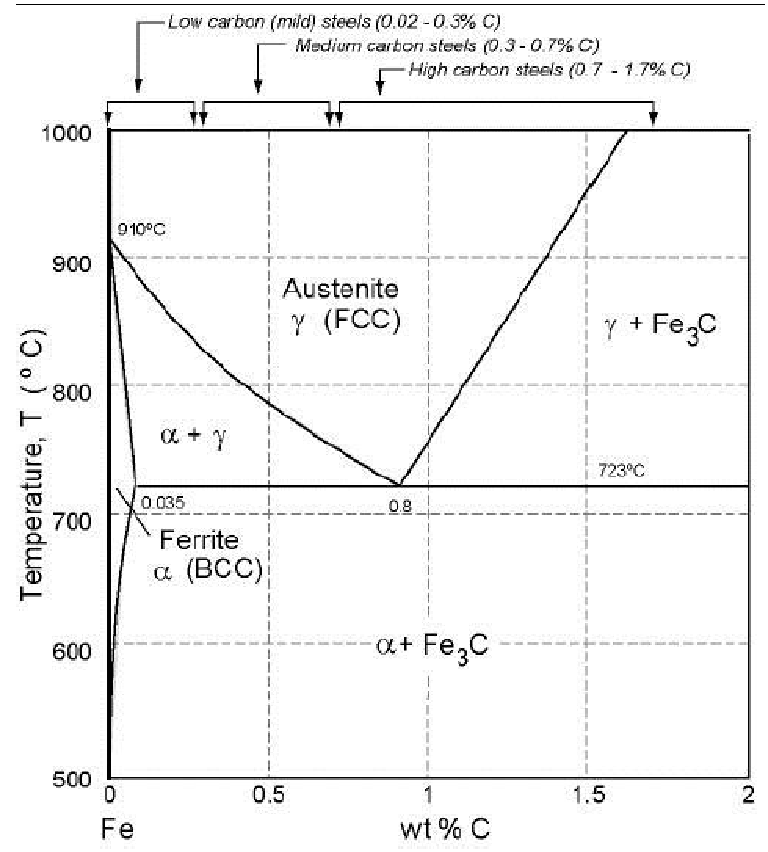

Figure 3.2: A phase diagram of iron-carbon alloys. (*CES EduPack*, 2017)

775°C then ferrite will begin to form.

When viewing Figure 3.2, one can see that for most carbon compositions the material will cool into either a ferrite-austenite or an austenite-iron carbide mixture. This however, does not hold true when the composition is approximately 0.76% carbon by weight, at which point it cools directly into ferrite and iron carbide. This scenario is called a euctic reaction, and has the lowest melting point across this carbon composition spectrum. Alloys that are lower than 0.76% carbon by weight are classified as being hypoeutectoid and those that are greater than 0.76% by weight are hypereutectoid. As such, our steel is considered hypoeutectoid For any alloy with greater than 0.035% carbon content by weight, all of the austenite will have cooled into either ferrite or iron carbide after 727°C. This boundary is the eutectic isotherm, and is represented on the Figure 3.2 by the horizontal line.

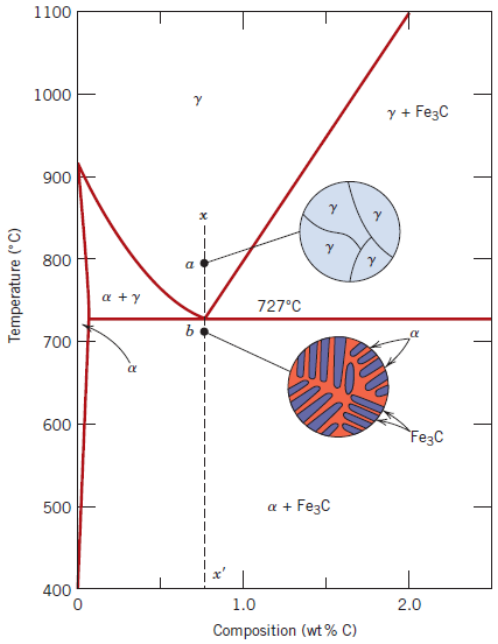

Figure 9.26 Schematic representations of the microstructures for an iron–carbon alloy of eutectoid composition (0.76 wt% C) above and below the eutectoid temperature.

Figure 3.3: A diagram of eutectoid steel. Page 293.(Callister, 2007)

3.5 Microstructures and Non-Equilibrium Cooling

While the carbon content of steel plays the major role in determining its strength and mechanical properties, the grains of steel in the bar which result from the process of cooling the bar also drastically change the mechanical properties. When cooling from a heated state, the molecules in steel shift in structure to form different compositions of iron and carbon, similar to adding rocks into a bucket of dirt, as the rocks will stay on the top, and when water, or heat in the case of steel, the rocks, similar to carbon, will drop down into the mud, and when the mud dries what is left is a soil with different composition as to the original piece of steel. Steel has a variety of grain compositions, with the one most similar to pure iron being ferrite, with a low carbon weight percentage, limited to at most 0.021% carbon by mass, and a BCC iron crystal with the possibility to be magnetized. The next most common form of steel is austenite, with an FCC crystal structure capable of absorbing far more dissolved carbon, up to 2.1%. Delta Iron, the form of iron directly after solidification from a liquid state, can only dissolve up to 0.09% carbon by weight, and has a BCC structure similar to austenite. Cementite is a precipitation of carbon in slowly cooled steels, where excess carbon from the austenite grains chemically binds with three iron atoms to form this stiff, almost ceramic metal compound. These are the four forms of steel most commonly found in the steelmaking process, and were all isothermal transformations, which followed the eutectic curve demonstrated in the phase diagram. The microstructures present in the phase diagrams at higher temperatures are inherently unstable and supersaturated, which leads to their decline to a stable, although structurally different form, a process which can be prevented with quenching steel, which will change the composition of the grains, introducing the possibility of martensitic steel, a supersaturated austenitic steel at room temperature, formed when heated austenite with higher than normal carbon content is cooled rapidly, with the internal structure forming within the steel at the velocity of sound within the steel matrix. Martensitic steel therefore cannot easily occur in the core of thick bars or plates of steel, but is used to otherwise increase the strength of thinner pieces of steel with a similar fault creation to mimic a ceramic structure. This allows Martensitic steel a greater tensile strength and prevents low stress fractures, but once the fracture does occur, it will cause catastrophic failure, necessitating consideration to be used if quenched steel is in fact the best solution for the application desired. Martensite is a metastable phase, which indicates that while normally present at room temperature, an application of heat that returns it to equilibrium will return it to eutectic phases.

While steel comes in a variety of carbon content and composition of grains, the microstructure of the steel grains also directly influences the strength of the material. The most common microstructure within medium carbon steels is pearlite, a naturally forming alternating-layer structure of ferrite and cementite, created when austenitic steel extrudes its excess carbon saturation to become ferrite, while this excess carbon chemically reacts with other austenite to form cementite, Fe_3C. After pearlite, bainite, a second mixture of ferrite and cementite, can form into plates, of which only electron microscopes may view significant differences from surrounding steel. This microstructure composition is nearly identical to that of pearlite, and is mutually exclusive, leading to the necessity of reheating the steel to austenite if pearlite is wished as a formation instead. The formation of bainite is a situational extension of the time-temperature-transformation diagram of pearlite as well, but still requires a slower cooling rate than martensitic steel, which leads to possessing properties in between that of pearlite and martensitic steel. The next microstructure to be easily formed is spheroidite, a result of leaving austenitic steel in a forge for an extended period of time, from upwards of eighteen hours. This microstructure has spheroidal pieces of cementite suspended in the ferrite solution formed from excess carbon diffusing into certain regions of the austenite from the surrounding steel. The regions in which carbon depletes from the austenite becomes ferrite, while the areas with excess carbon undergo a chemical reaction to form cementite. It may be alternately formed by leaving pearlite or bainite within a heat source to have the steel become closer to a solution than a cold solid, allowing the carbon atoms free movement within the material. This results in a naturally softer steel, as the excess carbon and therefore cementite is not in a formation which can provide structural support to the steel.

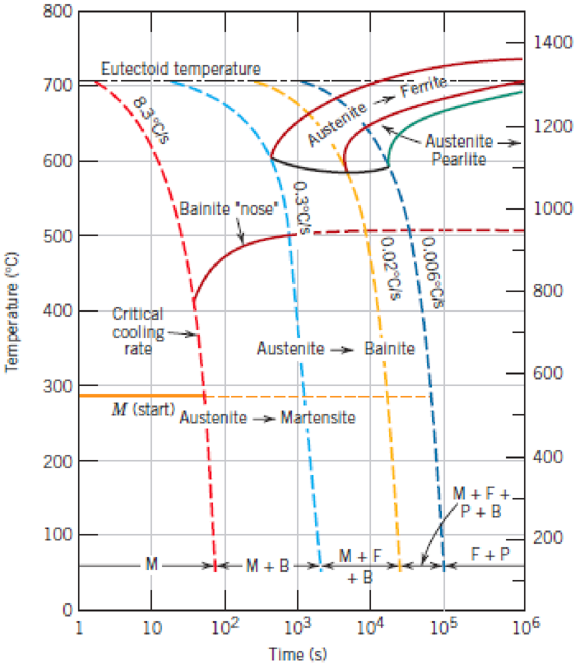

Figure 10.28 Continuous cooling transformation diagram for an alloy steel (type 4340) and several superimposed cooling curves demonstrating dependence of the final microstructure of this alloy on the transformations that occur during cooling. [Adapted from H. E. McGannon (Editor), *The Making, Shaping and Treating of Steel,* 9th edition, United States Steel Corporation, Pittsburgh, 1971, p. 1096.]

Figure 3.4: A Time-Temperature Transition graph for Fe-C alloys. (Callister, 2007)

3.6 Non-Eutectoid Steel

The concentrations of carbon content in steel is considered eutectoid when there is 0.76% carbon by weight. Below this boundary is hypoeutectoid steel, which heats up into a combination of ferrite and austenite before becoming a solution of pure austenite. Hypereutectoid steel, with greater than 0.76% carbon by weight, will form a solution of cementite and austenite instead, with higher concentrations of carbon hindering the formation of austenite. The eutectoid boundary determines whether or not there will be more than 2 transitional phases, as eutectoid steel will heat directly from a combination of ferrite and cementite to pure austenite, without any free particles of cementite or ferrite remaining. Once cooled, the eutectoid will form a pure layering of ferrite and cementite, known as pearlite, throughout, as the lack of free grains of other phases will lead the steel to naturally gather the excess carbon within the cementite layering of the pearlite, while the now carbon-poor layers form ferrite. As our steel is hypoeutectoid, instead of the purely pearlite composition, it will instead have grains of ferrite, often called proeutectoid ferrite due to being formed above the eutectic line, interspersed between the pearlite layers, if left to cool at room temperature without quenching. However, with quenching, the outer layers of the steel are to be assumed martensite, with an internal layer of bainite, and a core of pearlite and proeutectoid ferrite, pending further analysis.

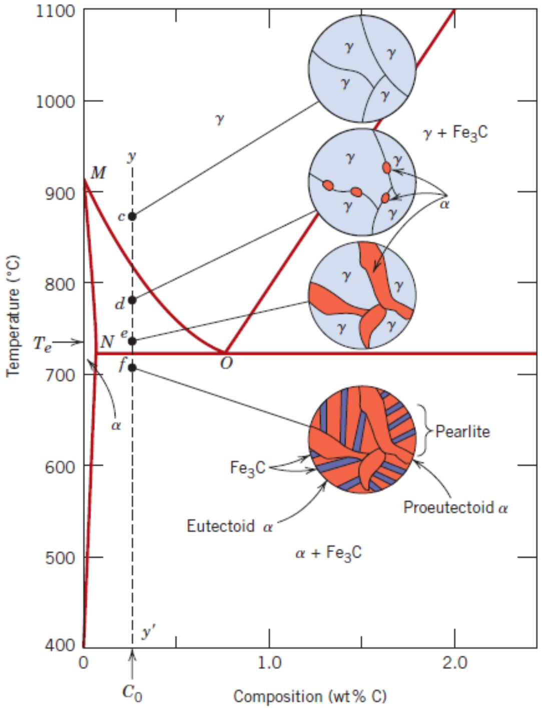

Figure 9.29 Schematic representations of the microstructures for an iron–carbon alloy of hypoeutectoid composition C_0 (containing less than 0.76 wt% C) as it is cooled from within the austenite phase region to below the eutectoid temperature.

Figure 3.5: A diagram of hypoeutectoid steel. Page 295. (Callister, 2007)

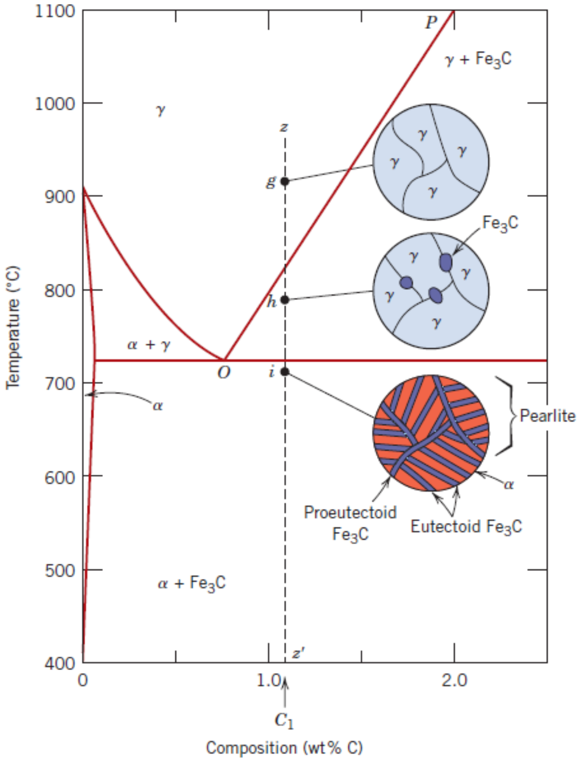

Figure 9.32 Schematic representations of the microstructures for an iron–carbon alloy of hypereutectoid composition C_1 (containing between 0.76 and 2.14 wt% C), as it is cooled from within the austenite phase region to below the eutectoid temperature.

Figure 3.6: A diagram of hypereutectoid steel. Page 298. (Callister, 2007)

3.7 Lever Rule Calculations

For practical uses in metal working from small scale forging to industry level mass production, quenching and other non-equilibrium cooling techniques are widely used to produce microstrucutres in the steel was advantageous properties that would not normally form if the material was allowed to cool through natural convection. For example, martensite is a non-equilibrium microstructure often desired for its strength and hardness and is used in dual phase ferrite-martensite steels to form the structural supports of automotive vehicles, as well as in longitudinal support beams for construction (*Phases and Microstrutures*, n.d.). Bainitic steel is a combination of ferrite and iron carbide formed by moderate cooling (though still faster than natural cooling) that has found use in railroad tracks for its durability (*Phases and Microstrutures*, n.d.). The mechanical properties of all steels, equilibrium or not, depends on the content ratio of the different microstuctures to one another, which means that the ability to predict these microstructures is vital to obtaining steel with the correct properties. In order to achieve this, an equation known as the lever rule is to determine the percent of each phase exisiting material at a given temperature and composition. The form of this equation is as follows:

$$Wl = (Cr - C1)/(Cr - Cl)$$

When determining the content of the phase with the lower carbon content and:

$$Wr = (C1 - Cl)/(Cr - Cl)$$

When determining the content of the phase with the higher carbon content. Within the equations, the term "W" is the weight percentage of the given microstructure while "C" denotes the carbon content at a certain point. The "l" and "r" terms correspond to the microstructures on the lower or higher concentrations of the chart, respectively. For example, if one was attempting to calculate a microstructure in the austenite-liquid phase, Cl would become Cgamma for austenite, C would become CL for liquid, and Wgamma and WL would calculate the % weight of austenite and liquid respectively. C1 is used to denote the carbon content of the material one is measuring. To demonstrate, we will show an example 1045 carbon steel (0.45 % carbon) when heated to 750°C (1382°F).

To begin, find the point on the phase diagram where temperature and the carbon content intersect. Plot this point on the phase diagram and draw a horizontal line extending from this point until it touches the boundary lines where the microstructures transition. In most cases these will be single phase regions, and in our scenario the lower carbon material will be ferrite and the higher carbon content material will be austenite.

Once these points are identified on the phase diagram, plot a line vertically downwards until it reaches the the horizontal axis displaying the carbon content of the steel. This will tell you what the carbon content of a given phase at specific temperature, or the saturation point of carbon before the material starts transitioning into another phase. Because the content of each phase varies linearly with the amount of carbon present in the material, the above equations to calculate the ratio of each phase by interpolating with the two saturation points. Below is an example of this technique using the conditions described above:

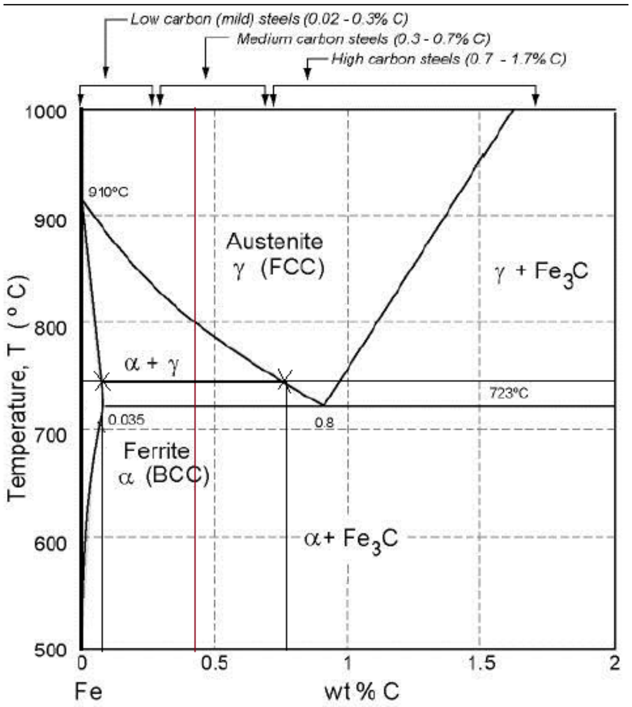

Figure 3.7: Locating our example steel on the iron-carbon phase diagram. (*CES EduPack*, 2017)

In Figure 3.7, two lines are drawn from the vertical and horizontal axis, one starting at 750°C (1382°F) and the other starting at 0.45 weight % carbon. The intersection is where the steel is located on the phase diagram under these conditions. Once this point is the the tie line is draw, with th points of intersection.

After finding the points of intersection between the tie line and the boundary, Figure 3.7 shows how the vertical lines are plotted to find the carbon content of the boundary conditions, in this case 0.03 weight % carbon and 0.70 weight % carbon. From these values, we can begin calculating the weight % of the microstrucutres in our steel with our two equations. Here, we will identify ferrite or "alpha" as the component with the lower carbon content and austenite or "gamma" as the component with the higher carbon content. We will begin by calculating the weight % of ferrite:

$$Walpha = (Cgamma - C1)/(Cgamma - Calpha)$$

$$Walpha = (0.70 - 0.45)/(0.70 - 0.03)$$

$$Walpha = 0.373$$

From these calculations, we have determined that by mass, 37.3% of the microstructure is ferrite. Next, we will calculate the weight percentage of austenite using the second equation:

$$Wgamma = (C1 - Calpha)/(Cgamma - Calpha)$$

$$Wgamma = (0.45 - 0.03)/(0.70 - 0.03)$$

$$Wgamma = 0.627$$

The use of the second equation determines the percent of austenite in the material by weight to be 62.7%, which agrees with our earlier calculation because their sum is equal to 100%. When predicting the microstructure of our warhammer prototypes, we estimated the temperature of the steel to be around 1150°C, with the assistance of the temperature chart in 3.8, locating it in the pure austenite phase, and without any secondary phases, eliminating the need for a level rule calculation. As we finished working the steel and it air cooled, it would slowly slide down the red line in the phase diagram of Figure 3.7, and pass through the eutectic phase lines, slowly becoming a combination of ferrite and austenite at the alpha+gamma phase, and then a combination of ferrite and Cementite after cooling down past 700°C (1292°F). The phase diagram does not demonstrate what happens below 500°C (932°F) as the changes within the grain composition are negligible, with the majority of the steel having been completely converted to a combination of ferrite and cementite, most likely to be pearlite. The majority of the steel, 80%, will have become ferrite, with only 0.021% carbon absorbed, while the remaining 20% will become cementite to absorb the excess carbon extruded from the formation of ferrite from the austenite. As future plans include the quenching of the steel warhammer head, the expected composition will change to martensite for a large portion of the outer volume, while the remaining inner volume will cool down slower and most likely form bainite. The only way to determine exactly how much of the warhammer head has remained bainite would be to take a core sample.

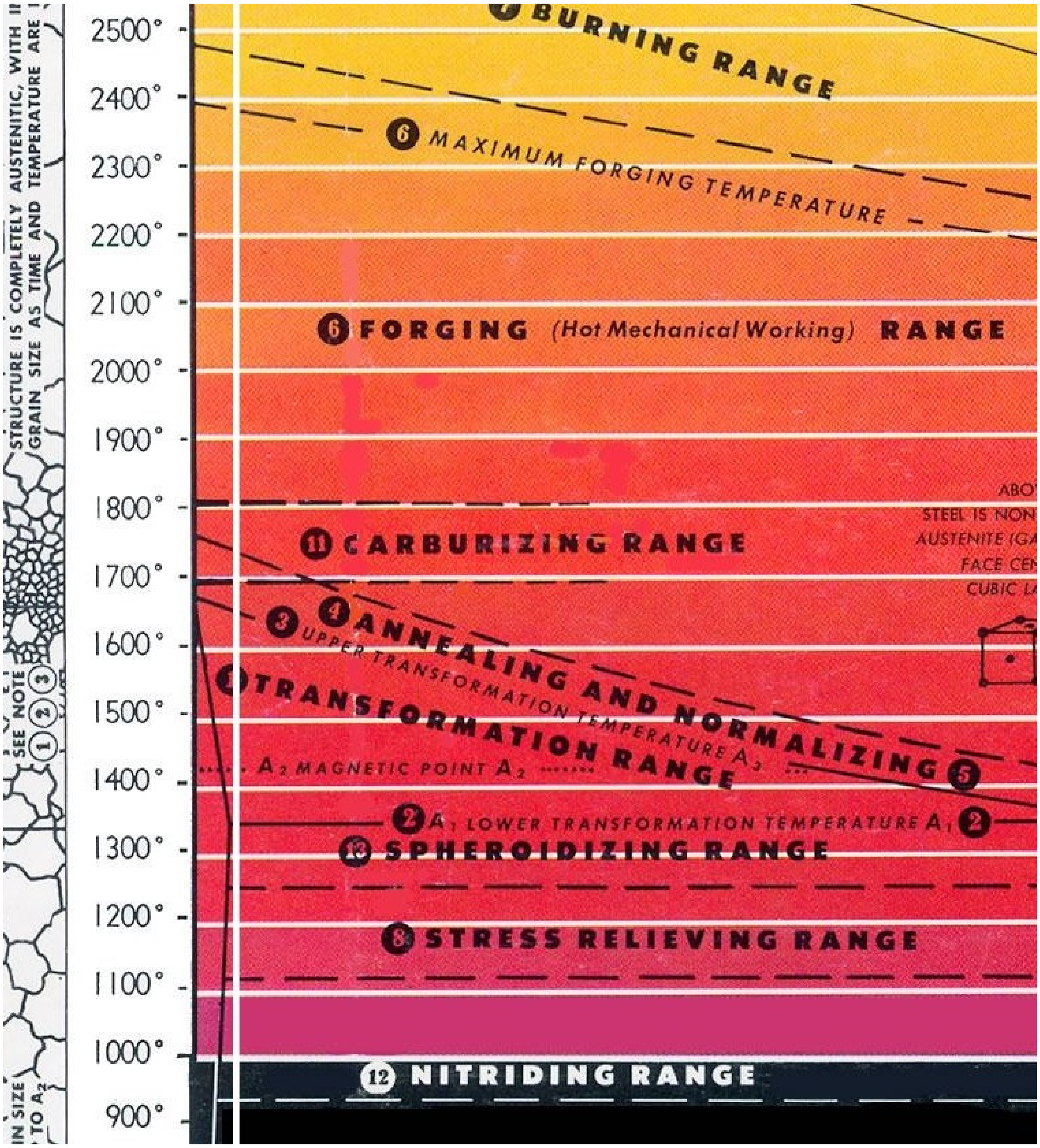

Figure 3.8: A guide to estimating temperature based on steel color. ("Tempil- Basic Guide to Ferrous Metallurgy", 2014)

Chapter 4

Replica Construction

To reconstruct a replica, 1045 carbon steel was chosen because it had properties that most closely resembled the properties of steel that were used in the Medieval ages to create weapons. A model in SOLIDWORKS was also created for representation purposes, as well as to guide the shaping of the replica during construction. The method used to construct the replica was a modernized method of forging, where instead of using coal as a fuel source, propane was used. The replica was then forged into shape using hammers, quenched in oil, and polished using sandpaper.

4.1 Materials

The steel chosen to forge the replica warhammer is normalized AISI 1045 carbon steel (hereafter referred to as "1045 steel"). This is a steel with 0.45% carbon by weight, as opposed to historically accurate bloomery steel (normalized AISI 1060 carbon steel), with approximately 0.6% carbon by weight. We choose 1045 steel due to its wider availability, as well as the fact that it exhibits similar properties to 1060 steel, as shown in Table 4.1.

Table 4.1: Properties of 1045 and 1060 Steel

Material	Tensile Strength (MPa)	Young's Modulus (GPa)	Melting Point (Celsius)	Price (USD/kg)
1045 Steel	530-650	208-216	1430-1510	0.64-0.77
1060 Steel	695-855	208-216	1380-1490	0.64-0.77
Cast Iron	410-830	165-180	1130-1250	0.42-0.44

As shown, the properties of the two steels are comparable, allowing them to be substituted with the one more readily available.

Table 4.2: Physical Properties of 1045 Steel

Size	1" square bar, 36" in length
Production	Cold rolled
Yield Strength	454 MPa
Elastic Modulus	200 GPa
Tensile Strength	585 MPa
Hardness (Brinell)	163

Of the three feet of steel obtained, approximately seven inches' worth is needed to build a single hammerhead.

Table 4.3: Elemental Composition of 1045 Steel

Manganese	0.820%
Carbon	0.470%
Silicon	0.240%
Chromium	0.120%
Copper	0.080%
Nickel	0.040%
Aluminum	0.026%
Sulfur	0.016%
Phosphorus	0.010%
Molybdenum	0.010%
Tin	0.006%
Vanadium	0.003%
Niobium	0.002%

4.2 Modeling the War Hammer

Before construction of the replica began, it was vital to perform background research on the dimensions and types of war hammers used during this conflict. Primarily, research was centered around museum pieces such as those on display at the Worcester Art Museum, however the final dimensions of the piece were taken from another replica sold by Windlass Steelcrafts, shown in Figure 2.2. With a head measuring 6.5" and a shaft 25.5" long, some of the reasons why this was chosen were that the size of features could be more easily determined from this piece, as well and the relative simplicity of the design of the head (*English War Hammer*, n.d.). Another for

Table 4.4: Physical Properties of White Ash Wood (*Wood Handbook: Wood as an Engineering Material*, 2010)

Moisture Content	12%
Specific Gravity	0.45 – 0.60
Modulus of Rupture (lbf/in^2)	6000 – 15000
Modulus of Elasticity (lbf/in^2 $\times 10^6$)	1.04 – 1.74
Work to Maximum Load (lbf/in)	11.8 – 16.6
Maximum Impact Bending to Grain (in)	43
Compression Parallel to Grain (lbf/in^2)	2300 – 7410
Compression Perpendicular to Grain (lbf/in^2)	350 – 1420
Shear Parallel to Grain (lbf/in^2)	860 – 2030
Maximum Tension Perpendicular to Grain (lbf/in^2)	940
Maximum Side Hardness (lbf)	1320

choosing this piece was that it was one of the few found to directly reference the correct location and timepiece of the Hundred Years War. Modeling of the replica was accomplished using the SOLIDWORKS program. Measurements of the various features were estimated from an image of the Windlass Steelcrafts replica and used to produce two parts, the head and the shaft. Once these two parts were made, a simple assembly was created, and an engineering drawing of the hammerhead was produced to use as a guide when building the replica.

4.3 Overview of the Forging Process

In order to create the replica shown in Figure 4.2, a small propane forge was used to heat the metal, generally until it was a glowing orange in color. The intensity of the flame was controlled by a nozzle used to adjust the amount of propane entering the system. Over the course of the project, two hammerheads were made, the first by hand, shaped by various hammers and smithing tools around the shop, and the second through the use of power tools. Due to an abundance of material, the initial hammer was used as a prototype when testing out different methods of shaping the metal, polishing, and attaching the langlets. Construction of a practice hammerhead began after the spike, hole, and hammer face of the first hammerhead were completed, such that both pieces were being built simultaneously, though they were at different phases of completion. The purpose of this practice head was to gain experience with using the power tools available in shop and to decide both the method and order in which to create the features of the second hammerhead.

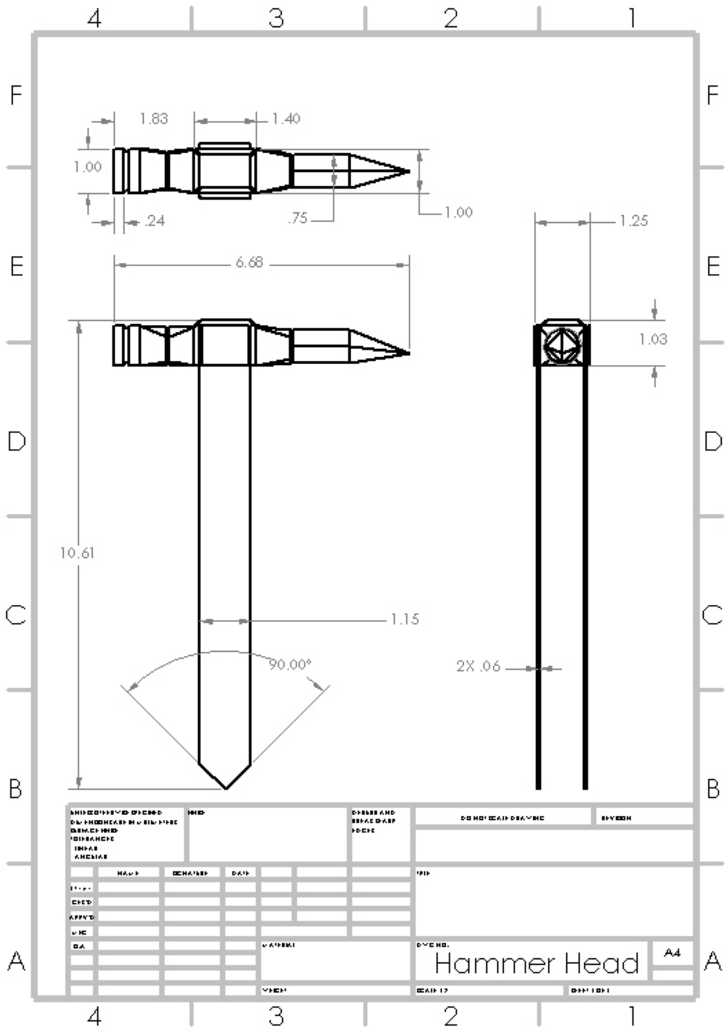

Figure 4.1: Initial drawing of the hammer head forged during our process.

Initially, the order in which features were created was such that the spike of the hammer was shaped first, followed by the punching of the hole for the shaft and the creation of the hammer face, at which point the piece would be cut from the stock material. Following these steps, the piece would be ground down to remove sharp edges, after which the langlets were attached, and then the piece was finally polished.

4.4 Building the Spike

Construction of the hammerhead began with the shaping of the metal forming the spike. To begin, we started with a 24" long, 1"-by-1" bar of 1045 cold rolled steel, which was heated in

Figure 4.2: SOLIDWORKS model of the English war hammer.

the furnace until the metal had turned a bright orange color. Once hot, the bar would be beaten to stretch out the metal. In the case of the first hammer, this was accomplished by placing the material on an anvil and striking the bar with a sledgehammer several times before the steel became too cold to work, at which point it was returned to the furnace. Once the bar was stretched to the appropriate length, the shaping of the spike could finally commence. A secondary tool called a flattener, which resembled a smaller hammer with a large flat face on one side of the head and a rounded back was designed to be struck by a larger hammer on the other side. Teams of three rotated through with this process, with one person holding the material and removing it from the furnace, another person holding the flattener to the bar, and a third person striking the flattener with the sledge hammer. The goal of this process was not only to smooth out the bar, but also to flatten down the four sides into a point at the end. A slight downwards curve or "beak" was added to the spike, as this was common for most hammers of the time.

Before the construction of the second hammerhead commenced, we used a scrap bar of roughly the same dimensions as our own and experimented with creating the spike through the use of the hydraulic press and power hammer. While these machines may have hasten the process, we did not have the correct die to form the metal in the way we wanted, and would have needed to manually beat the metal into the correct shape afterwards. Due to both these factors and our success with building the first spike, we concluded that the optimal method for creating this feature would be to manually shape it with the sledge hammers as we originally had, though

Figure 4.3: The metal glows during construction of the spike.

we did use the press to slightly lengthen the bar.

4.5 Punching the Handle

Once the spike was completed, the next step in forming the head of the hammer was to begin punching the hole for which the wooden handle would be inserted. When building the prototype, a punching tool consisting of a steel long rod which had a handle welded perpendicular to the top and tapered down a a filleted, rectangular face on the bottom was used to shape the hole. Before shaping the material, the width of the bar was measured and the midpoint between the two sides was marked on the top and bottom faces of the hammer. To begin the process, the bar was once again inserted into the furnace until glowing orange, after which it was removed and placed over a hole in the anvil commonly used to insert wedges or other tools. Three people would work together in similar fashion as to when the spike was being formed, however there were several differences for the individual holding the punch tool. Because the tool was prone to getting stuck in the material after repeated blows from the hammer, only a set number of strikes were allowed before the tool was to be removed and cooled off in a nearby water source. Before reinserting it into the hole, the end of the punch would be dipped in a graphene powder to prevent the tool from sticking to the bar, however one must let the tool cool sufficiently, or the powder would not stick to the tool.

Figure 4.4: Three person team punching the hole where the handle would be inserted.

The above method was also used when building the practice hammerhead, however in that scenario we formed the hole before attempting to shape the spike with the power tool, causing it to cave in. Another mistake present in the holes of both the first and the practice hammers was the lack of a taper from the bottom of the hole to the top. This feature aids in fixing the head of the hammer to the shaft because in allows the shaft to be expanded towards at the top of the head, preventing it from flying off when being swung. One aspect we did carry over from the practice hammer was the lengthening of the hole, which was extended to between one and a half and two times the length of the punching tool's face, and allowed us to better accommodate the wooden handle when inserted.

4.6 Shaping the Hammer Face

When shaping the hammer face, there were two objectives; first, to add the grooves which ran between the flat end of the hammer and the handle, and second, to form the flat face of the hammer. This process is shown in figure 4.5. The grooves were formed before the hammer face was created because forming this edge would require cleaving the hammerhead from the stock material, making it much more difficult to work with. When building the prototype, we began forming the grooves by beating the desired section over the rounded end of the anvil in order to stretch the metal and add a rough curvature.

Figure 4.5: Manually forming the grooves while shaping the face of the warhammer.

Once beaten to an appropriate thickness, the material was placed in a bobby pin-like tool attaching to the anvil and beaten until the groove became more pronounced. Once the grooves were formed, the flat face of the hammer was created but cutting the working piece from the rest of the stock material at the desired length using a wedge shaped tool attaching to the anvil an a sledge hammer. Once removed, the hammer face was then ground down until flat.

To create the grooves using the practice material, the hydraulic press was used with a cylindrical die. This method proved to be much faster and produced much cleaner grooves than our first attempt, and was carried over to the second hammer construction.

Figure 4.6: The hammerhead after being cut from the stock.

4.7 Polishing and Deburring the Metal

In order to polish and shape the metal, a series of belt sanders and angle grinders were used with coarse grit. For the prototype, we began by using one of the large belt sanders to polish and remove dents from portions of the top, bottom, and side faces. After achieving this, the sander was used to form the flat face of the hammer by removing excess material remaining after the cut. Once the these steps were completed, a circular belt sander was then used to smooth out the grooves before the flat face and the curved underside of the spike. One of the challenges of this method was matching the radius of the features to the radius of the machine, which proved difficult because the grooves of the hammer face were usually too deep (or possessed significant dents) for the machine to reach.

After accomplishing this step, we returned to the original belt sander to refine the point of the spike and smooth down some of the edges to make handling the piece easier. We then used a hand held angle grinder to clear out dents and divots that could not be reached with the previous tools, however this machine produced a noticeably different finish than the others, and required further polishing.

Figure 4.7: Deburring of the piece using belt sanders.

4.8 Forming the Langlets

Once the hammerhead was fully polished, we began construction of the langlets securing the hammerhead to the shaft. We began by practicing with a scrap piece of metal about 10" long, 1" wide, and roughly 3/32" thick. To shape the metal, we began by heating until glowing orange in the furnace and then beating it with one of the smaller hammers. After doing this several times, we then moved on to the power hammer to stretch and flatten the bar. Once the bar was the correct thickness, we formed the first corner of the U-shaped bracket by beating the material against the edge of the anvil until a right angle was formed. After that, the second corner was formed by placing a rectangular block of stock steel flush to the first corner and beating down the bar so it would form a second right angle. Once the general shape of the bracket was formed, the prototype hammerhead was placed inside the structure, and the material was beaten to form the general shape of the hammerhead. This method was problematic however, because the square faces of the anvil and hammers could not easily accommodate the grooves of the hammerhead, and the material was so thin that beating one side would deform the other.

4.9 Heat Treatment

In order to harden the metal and ensure that it would pierce armor instead of deforming on impact, weapons such as the war hammer would be heat treated to form a hard outer layer of martensite. This process had to be carefully done, as creating too much martensite in an initial step would lead to the piece becoming brittle and fracturing. To begin this step, we heated the metal in the forge to above 727°C, ensuring that our steel was purely austenite. Using the chart in Figure 3.10, we estimated that our steel was around 1150°C based off of the color of the metal. To test this property, a magnet held against the steel to see if it would stick. This would indicate that the metal is past the Currie point, in which steel loses its magnetic properties, and is a way to check that only austenite remains. After passing the Currie test, the steel was placed back into the forge to regain some of its heat and then immediately taken out and quenched in oil. The steel took between 15 and 20 seconds to cool, though it was left in the oil for around 2 minutes to ensure that it would be safe to transport, simply because steel that is too hot when it is removed from the vat of oil can ignite the oil remaining on its surface and potentially start shop fires, as well as release evaporated oil, which is a health hazard. Once the bar was quenched, we moved the hammerhead to an oven and began tempering the metal by baking it at 200°C for about 30 minutes. The hammerhead was later tempered for two additional periods of two hours each at the same temperature to relieve the metal of any stress caused by the rapid cooling process, limiting the chance of it cracking on impact or just from sitting in open air.

While the logic of this process can seem obscure, the reasoning behind it can be much more clearly explained if one looks at the Time-Temperature Tranformation graph in Figure 5.3. Following the graph, the steel begins in the austenic phase above 727°C and cools to roughly 150°C in around 15 to 20 seconds, placing it in the M + A regime, in between the 50% and 90 % martensite lines. At this point, the steel is roughly 60% martensite, most of which is located on the surface of the hammerhead. Following this, the hammer is baked in an oven an partially annealed at 200°C. This decreases the amount of martensite in the structure, making it far less brittle on a whole while still retaining the hard outer layer of martensite needed for breaking armor. Our final piece should contain roughly 15 to 20 % martensite, all located on the surfaces, which was supported by our later findings in the microstrucutral analysis.

4.10 Crafting the Handle

To craft the handle, we selected ash wood for our material; specifically swamp ash, one of the woods most likely used by the English when crafting similar weapons due to its flexibility and being lightweight. We began by cutting our piece down to the rough size of what would have been needed (2 in by 1.5 in and around 3 ft long). The end of the wood was cut down further to approximate the shape of the hole created in the hammerhead, after which it was further shaved down using spoke shaves and sand paper to produce a more exact fit. The work done with the spoke shaves can be done with simple knives, however it tends to be much more exact as the shaves are razor thin. The fit of the hammer was made slowly, millimeter by millimeter by hand sanding the wood slightly and attempting to fit the hammerhead on it, taking note of where it got stuck and sanding again. Once this fit was achieved, with about a quarter inch of material sticking out of the top of the hammerhead, a line was cut into the end of the wood in the direction running from the hammer face to the spike for inserting the wedge, a metal or wooden piece that would deform the wood to bite into the side of the metal and prevent it from flying off when swung. The hammerhead was then tapped into place lightly and then fitted down to the neck by hammering the bottom of the polearm handle while holding the entire piece upside down. Another reason this method was effective in securing the hammerhead, was that the hole was shaped in such a way that the top was wider than the bottom, allowing an “hourglass” to be shaped out of the wood when wedged, which prevented movement in the vertical direction. Due to our hammerhead having a hole that was less wide than traditional, only a metal wedge was used to fix it in place. In our first attempt, we used a wooden wedge and that cracked our mount clean off of the polearm, and we had to start the process from the beginning.

When attempting to wedge the handle, we found that our wood was too brittle and would break once the wedge was driven past a certain point. We found that ultimately our wood was too dry and required a soaking period of roughly one week to have a chance of properly working. Due to time constraints we decided to switch to hickory instead, as there was some on hand that wasn’t too dry to work with. The wedge for this handle was also not driven into a cut within the wood, but hammered into the side next to the extruded piece to limit the chances of cracking. The prototype hammer used an ash handle, and was not meant to be swung.

4.11 Assembling the Hammer

The first step in assembling the hammer was to wedge the hammerhead to the handle, as mentioned in the previous section. An epoxy coating used to fill the top of the hammer, as we thought it would help make up for the thinner wooden mount. after which we began the process of attaching the langlets. Unfortunately, we wer enot able to forge-weld the langlets onto the hammerhead at this juncture, instead we would just be attaching it only to the wooden polearm, which still preserved the traditional look of the warhammer and some of its sturdiness. Six holes were drilled into each side of the langlets, after which rivets were hammered in, connecting the langlets to the handle. Once the langlets were properly attached, both the hammerhead and the brace were polished, after which we began the process of applying polyurethane to the handle. Coats of the finish were applied once every two hours to the handle, with the end goal being to protect the wood and hands of the wielder from harm. At this point, the hammer was complete and could be confidently weilded without risk of it breaking within expected stress ranges.

Chapter 5

Microstructure Analysis

Samples from three different stages of the forging process were obtained through the cutting of the steel before it was worked, after it was worked, and after it was heat treated. These samples were then mounted using a mounting press in Washburn Shops at WPI. These mounted samples were then ground and polished using increasing grits of sandpaper in order to remove the rougher edges present. This allowed for more accurate viewing of the microstructure because it removed any visual obstructions.

5.1 Cutting the Samples

Prior to forging, our group cut a small section off of the stock material using a chop saw at Ferromorphics in order to analyze the material prior to heat treatment. Once we had this section, we returned to WPI to cut the individual samples from the piece. For this step, we defined three planes, an XY, a YZ, and an XZ, on three faces that were non-parallel to each other, with our objective being to view the material the material grains from three different sides. We cutting the samples, we marked the plane and a small 1cm by 1cm (or .394in by .3934in) square on each of the chosen faces, wither in the center or away from the corners. From there, we proceeded to cut out the flat samples through the the use of a hacksaw.

5.2 Mounting the Samples

With the assistance of Professor Li, we took our three 1 cm by 1 cm samples to the mounting press within the third floor of the Washburn Shops at WPI, where we proceeded with a set of standard steps to mount the metal samples onto a red phenolic disk in order to allow for easier handling. The first step involved was to clean the mounting machine with machine oil, to prevent any residue or dust on it from being pressed into the sample and creating distortions. After cleaning, the square of metal was placed on to the press, and a disk of red phosphorus on top of it to provide the mount. The machine was then set to run for a period of 4 minutes to press the material into the mount, with an additional 3 minutes to wait and have the mount cool off, as the pressures used in mounting would create an impressive amount of heat due to friction. Initially the disk was similar to chalk in appearance and behavior, whereas after mounting it became nearly identical to a piece of plastic. The back of the mounts were then etched with the same axis the samples were originally cut from to prevent confusion when analyzing at a later date.

Figure 5.1: A sample square of metal immediately after being pressed into a mount.

The remaining six samples acquired after the forging and heat treating processes were created using a similar method, however a different unit was used with a black powder instead of the phenolic discs.

5.3 Grinding and Polishing the Samples

After the samples were properly mounted, the next step was to grind and polish them down to a flat, smooth surface that could be analyzed under a microscope. Many of the samples we used had been cut apart using a combination of chop saws, hack saws, and other hand tools, and rough edges which needed to be removed to clearly view the microstructure. Both of these processes were accomplished using the same grinding machine, however there were some key differences between the two. The machine used for these purposes consisted of a powerful spinning magnet, several nozzles connected to either chemicals or water, and a control panel used to alter the speed of the disc, the flow rate from the nozzle, and other factors.

We began this process with grinding and used two separate grits, 180 and then 600. The sandpaper came in circular sheets with an adhesive backing on one side, allowing it to attach to a metal plate. This plate would be held in place by the magnet, and would be adjusted to fit flush with the disc. When running, a nozzle would be turned on and sprayed a continuous stream of water over the sandpaper to prevent it from getting hot. The sample would be held evenly on the surface of the sandpaper for roughly five to seven minutes. It was important to keep the sample in the same orientation so that the scratches from the sandpaper would all be in the same direction. After all nine sample were sanded with the 180 grit sandpaper we moved on to the 600 grit, following the same procedure except for rotating the sample 90 degrees, so that the new scratches would be perpendicular to the old ones. This step also took around five to seven minutes, with the way to tell if the sample was finished being that the scratches from the previous step were completely erased.

For polishing we used a similar process with some minor differences. Instead of a solid metal plate with a surface for adhesives to attach to, the polishing disc was a white, cloth-like surface that gained its abrasive qualities from a solution drip containing diamonds. A separate set of designated nozzles were set to periodically release droplets of the one of the three solutions, six micron, three micron, and one micron, depending on which step we were currently completing, starting with the six micron solution and ending with the one micron solution. Gloves were worn during this stage, and as before the the samples were rotated 90 degrees between each step. Polishing times were slightly longer than grinding, taking ten to twelve minutes per each sample. Once polished, the samples were then etched in order to better view the microstructure of the crystal colonies, whether they be ferrite, pearlite, or austenite.

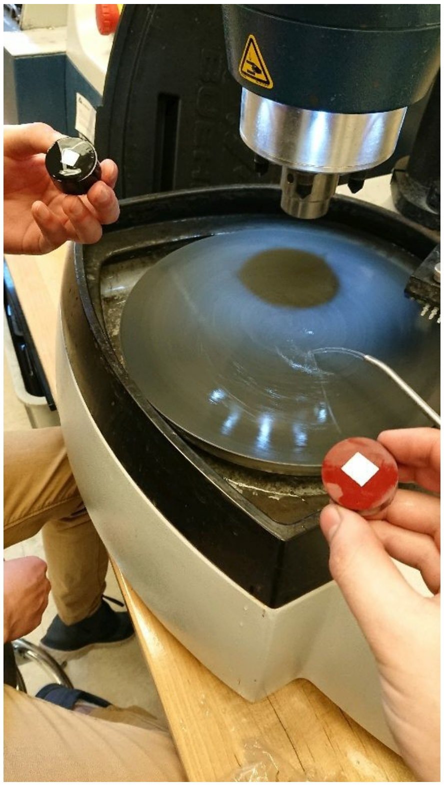

Figure 5.2: Pair of samples after grinding.

5.4 Discussion of the Final Microstructure

As analyzed and predicted, the majority of the steel in our warhammer head became martensite due to the quenching process cooling it down rapidly enough to lock in the extraneous carbon content from the austenite. As shown in Figure 5.3, the quenching which quickly cooled the reheated warhammer head prevented the austenite from degenerating into pearlite, preserving the strength of the steel from degenerating as would normally happen with air cooling. The martensite changed the cubic structure to that drawn in Figure 5.4, which demonstrates the larger grains within martensite due to the prevention of extruded carbon reactions.

However, initially the steel bar was an expected combination of pearlite and ferrite, with the majority of it being pearlite with ferrite colonies in between the grains. The ferrite would form when the liquid iron would cool sufficiently to excrete excess carbon and thus form the cementite in the layered pearlite structure, however as the steel is below saturation with carbon, and below the eutectic concentration of 0.76% carbon by weight, the ferrite colonies visible in Figure 5.5 below (the white streaks). This was shown in all facets of the sample of the unworked steel bar, along the

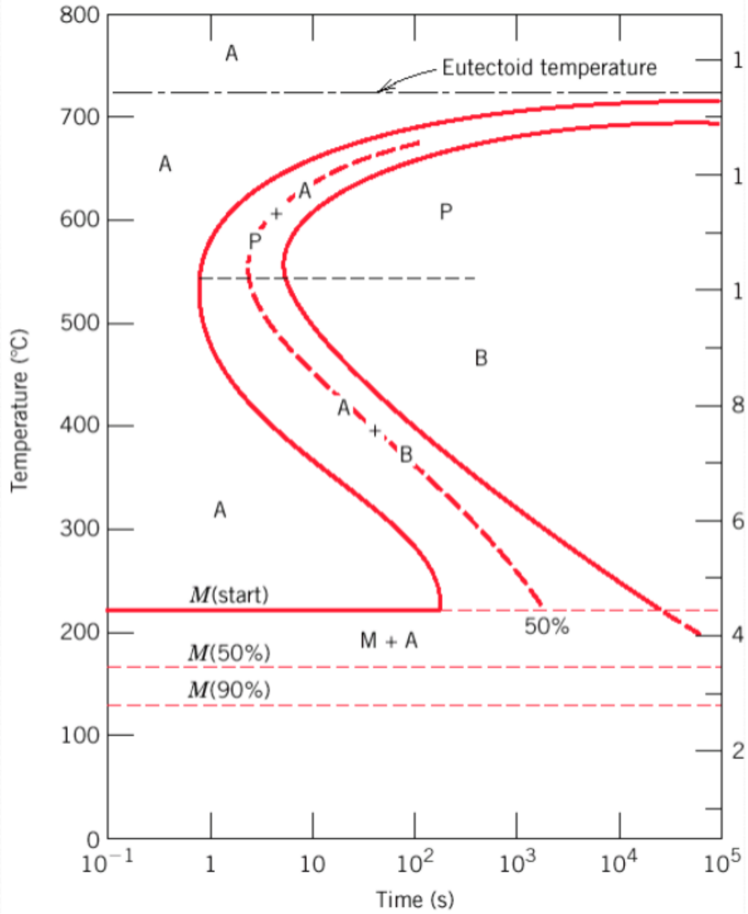

Figure 5.3: A time-temperature transformation graph of steel.

lengthwise, widthwise, and height wise axes, as shown in the subsequent figures, Figure 5.6 and 5.7. This microstructure composition was not quite following the expected design, as many cold rolled or cold drawn steels have elongated grains along the lateral, or XZ, plane, but the sample of the steel contained relatively uniform grain structure.

After forging and working the steel into a viable shape for a hammer head, the steel became far more uniform in structure, with a large majority of the steel transitioning to pearlite with ferrite faults becoming further apart, and the pearlite grains becoming larger and more aligned. This is demonstrated in Figure 5.8, where it is clearly visible that the forging process increased the size of the grains of pearlite.This is demonstrated unilaterally along all three Cartesian axes of the steel, in Figure 5.9 and Figure 5.10, which concurs with the fact all facets of the warhammer head were forged equally and with the same method.

This combination of ferrite and pearlite conformed with the expected micro-structure of the

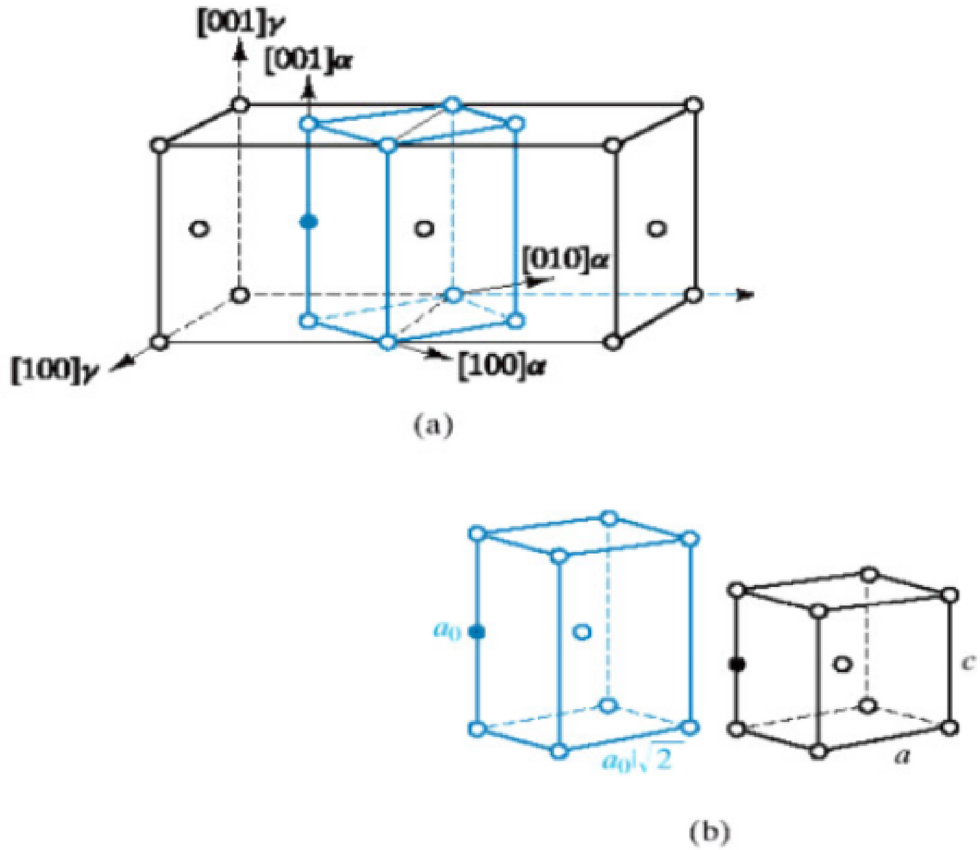

Figure 5.4: An example diagram of the cubic structure of martensite.

1045 as determined by the eutectic phase diagram at this concentration of carbon by weight, 0.45%. However, this micro-structure, due to the ferrite fault lines in between the pearlite grains, is prone to slipping and deformation, as the ferrite is very close to pure iron and thus very soft, while the pearlite grains, due to their alternating layers of ferrite and cementite, is reminiscent of rocks in a pile of sand, where a strong pressure upon them will submerge or otherwise shift the grains. As a warhammer is meant to be swung at strong armor and shatter the said armor, a metal that deforms upon impact is not suitable for use. Therefore, the next step in the forging process, the heat treatment, would entail heating the steel up until it became a thorough austenite microstructure, of which there is no available image due to the difficulties in imaging steel over 2000°Farenheit, and then quickly quenching the steel in oil to simultaneously cool it at a fast enough rate to form martensite, while preventing the surface from cooling faster than the inner core which would otherwise cause fractures to form in the steel piece. This generated the martensic micro-structure available in Figure 5.11, which in turn shows up in Figure 5.12 and Figure 5.13, proving the uniformity of the steel piece's martensic structure. All images provided in this section were taken at a 200x magnification on a microscope, which provided a resolution of 0.46 micrometers per pixel. The scale included in each image is accurate.

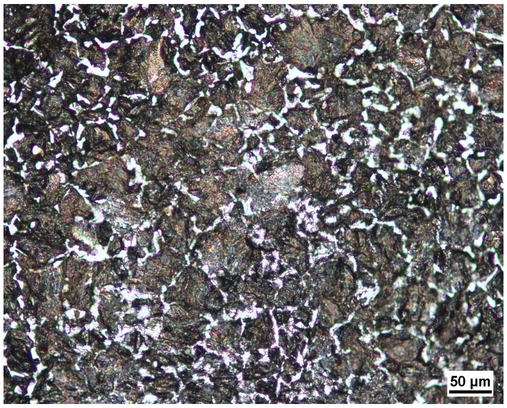

Figure 5.5: A cross-sectional view of the micro-structure of the 1045 steel bar before working, YZ plane.

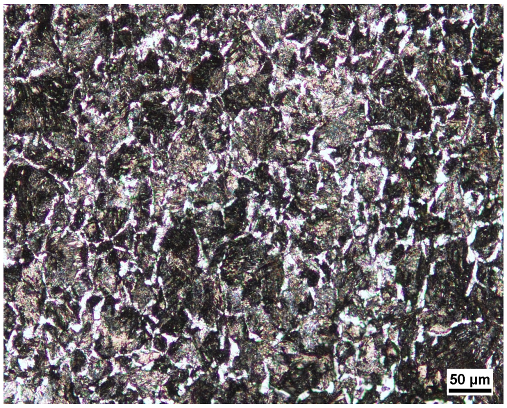

Figure 5.6: A cross-sectional view of the micro-structure of the 1045 steel bar before working, XZ plane.

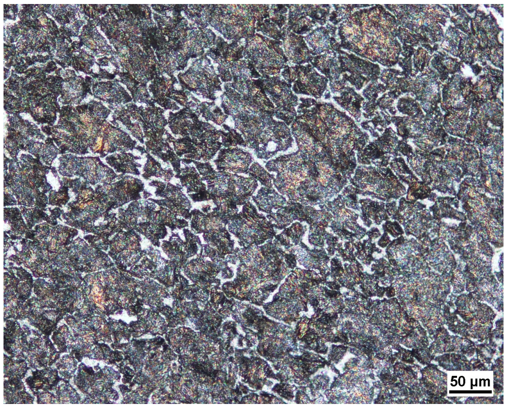

Figure 5.7: A cross-sectional view of the micro-structure of the 1045 steel bar before working, XY plane.

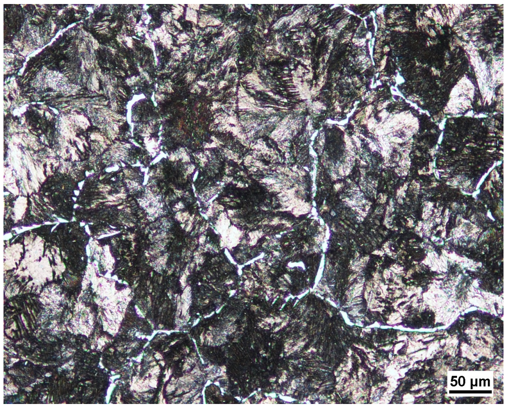

Figure 5.8: A cross-sectional view of the micro-structure of the 1045 steel bar after working, YZ plane.

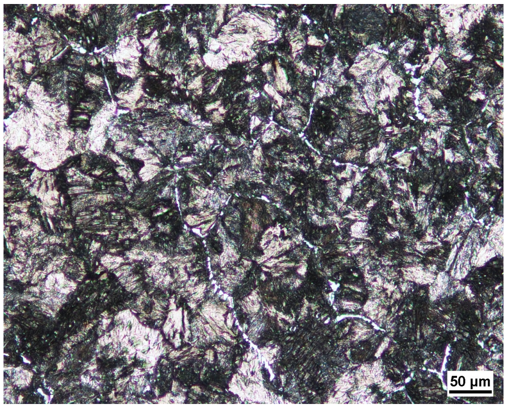

Figure 5.9: A cross-sectional view of the micro-structure of the 1045 steel bar after working, XZ plane.

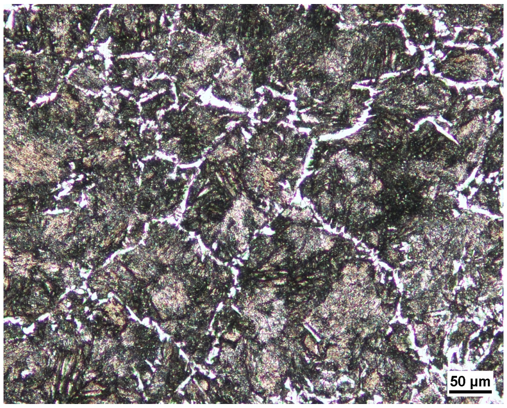

Figure 5.10: A cross-sectional view of the micro-structure of the 1045 steel bar after working, XY plane.

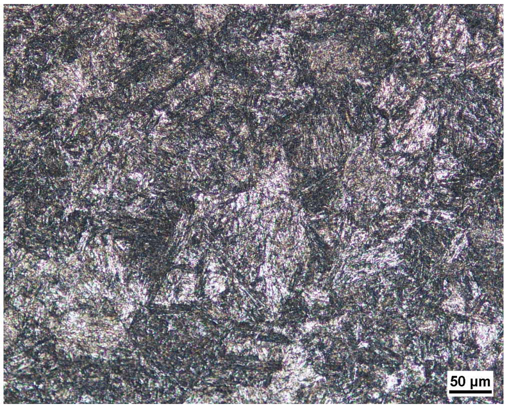

Figure 5.11: A cross-sectional view of the micro-structure of the 1045 steel bar after heat treatment, YZ plane.

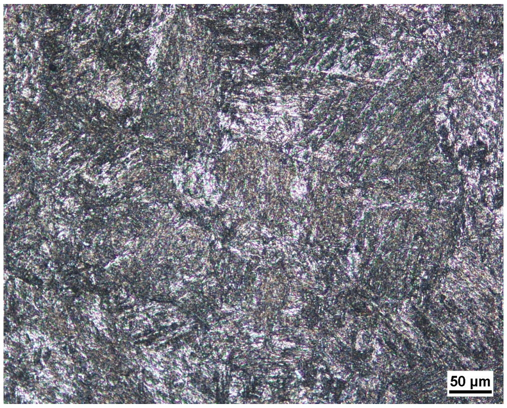

Figure 5.12: A cross-sectional view of the micro-structure of the 1045 steel bar after heat treatment, XZ plane.

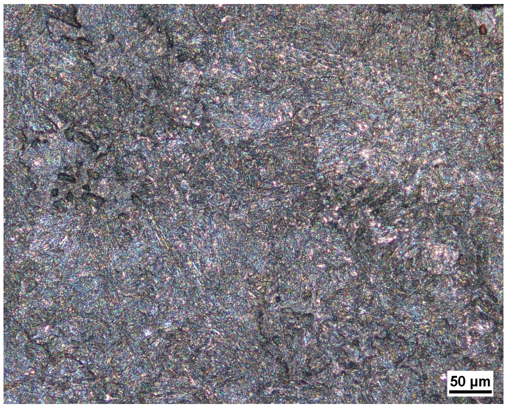

Figure 5.13: A cross-sectional view of the micro-structure of the 1045 steel bar after heat treatment, XY plane.

Chapter 6

Updating the Website

The Arms and Armors IQP[1] teams, in addition to constructing a replica, update a Web site with information learned from their projects, found at `https://web.wpi.edu/academics/me/IMDC/IQPWebsite/index.html`. The current iteration of the site has existed since 2010 (*Historical Evolution of Arms and Armors*, 2010), and being seven years old, deserves both an aesthetic and functional face-lift.

One major reason for this is to enable the use of the site on mobile devices; the site was originally created when mobile web browsing was in its infancy, and were the site to provide a great user experience on those devices as well, its viewership would likely increase. With recent talks of displaying students' work at the Worcester Art Museum accompanied with tablet computers displaying the relevant content on the IQP's website, this change would make the exhibit considerably more engaging and possibly even more popular.

We seek to add a few interactive visualizations to make the website more engaging. The World Map's position on its page is fairly awkward, as shown in Figure 6.1, and would be well-served as a fully interactive element. In addition, since the map is based on a static image, it requires a substantial amount of work to add new content to it. Since this group will be responsible for editing it at some point, it is in our interest to streamline that process.

Finally, the addition of basic templates for every page with a consistent look and feel will both streamline the development and the use of the site by the general public.

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[1] Interactive Qualifying Project

6.1 Website Maintenance

World Map

See what arms and armors were used across the globe!

Click on the location you'd like to explore below.

Figure 6.1: The old World Map, as rendered in Google Chrome 61 on a Windows 10 PC. (*Historical Evolution of Arms and Armors*, 2010)

While the original website was developed using the Adobe Dreamweaver software package (*Historical Evolution of Arms and Armors*, 2010), most modern web development is done using a basic text editor, but with the help of software packages using Cascading Style Sheets[2] or JavaScript[3] to provide dynamic content, which is difficult to model with a layout-based editor like Dreamweaver. Since the primary purpose of this upgrade is to add dynamic content, we will employ the latter strategy.

Being managed by the Worcester Polytechnic Institute, the color schemes and look and feel were designed deliberately to match the main site. The layout of WPI's website uses the Zurb Foundation library, a responsive front-end framework that allows desktop Web sites to be displayed in high quality on mobile browsers with little to no additional effort. It is also used by many well-known brands such as Amazon, Hewlett-Packard, National Geographic, and the Washington Post (*Zurb Foundation*, n.d.). Accordingly, we chose to use it for the Arms and Armors IQP website.

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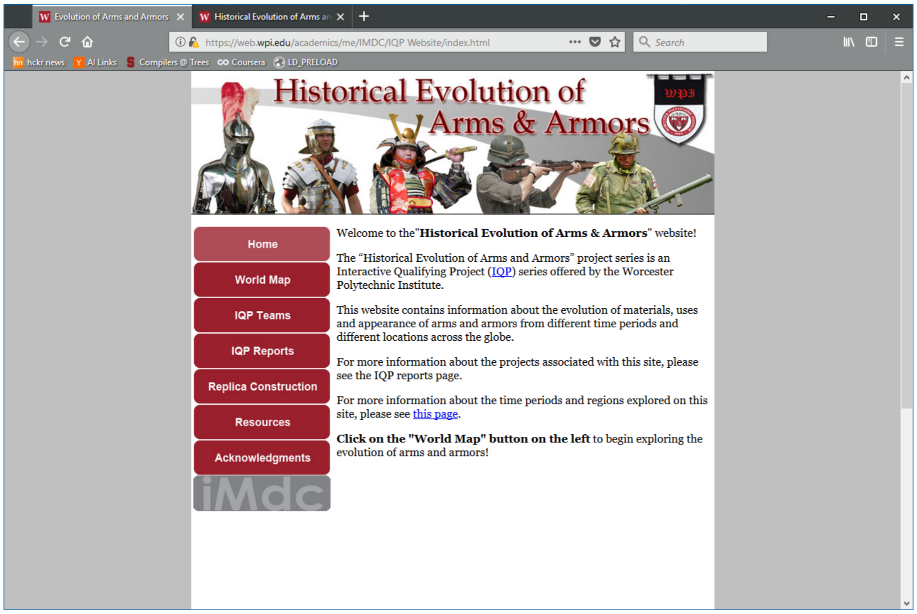
[2] Cascading Style Sheets are a way to provide rules for how content should be displayed in the web browser.

[3] JavaScript is a programming language that runs in the browser, and provides the means to create dynamic Web content.

Zurb Foundation employs color schemes central to the design of the site. To generate a consistent look and feel, we inspected WPI's website's stylesheets[4] for WPI's major and accent colors, primarily the dark red and the off-white central to WPI's branding.

With these considerations, porting basic content is trivial, especially for the home page (shown in figures 6.2 and 6.3) and acknowledgments page. In the home page, more of the neutral space in the page is used, and the wide, grey border is removed. The fonts and header of the page have also been modified to meet contemporary design standards at the time of writing.



Welcome to the"**Historical Evolution of Arms & Armors**" website!

The "Historical Evolution of Arms and Armors" project series is an Interactive Qualifying Project (IQP) series offered by the Worcester Polytechnic Institute.

This website contains information about the evolution of materials, uses and appearance of arms and armors from different time periods and different locations across the globe.

For more information about the projects associated with this site, please see the IQP reports page.

For more information about the time periods and regions explored on this site, please see this page.

Click on the "World Map" button on the left to begin exploring the evolution of arms and armors!

Figure 6.2: The home page of the original Arms and Armors IQP site, as rendered in Firefox 57 on a Windows 10 PC. (*Historical Evolution of Arms and Armors*, 2010)

From the beginnings of the Web to the mid-2000's, page layout was primarily done using tables (*Layout With Tables*, 2008). With the advent of responsive styling frameworks like Bootstrap and Foundation (*Zurb Foundation*, n.d.) and technologies such as Cascading Style Sheets grid layouts, this quickly fell out of favor because of its undue complexity. Much of the content original Arms and Armors IQP site is laid out in this way, and accordingly, the site is being modified to use responsive grids instead of static tables.

In an attempt to reduce the workload needed to migrate content from the old to the new system while updating the look and feel of the site, the authors began by writing a "web scraper" whose purpose was to extract meaningful content, such as headings, pictures, and paragraphs,

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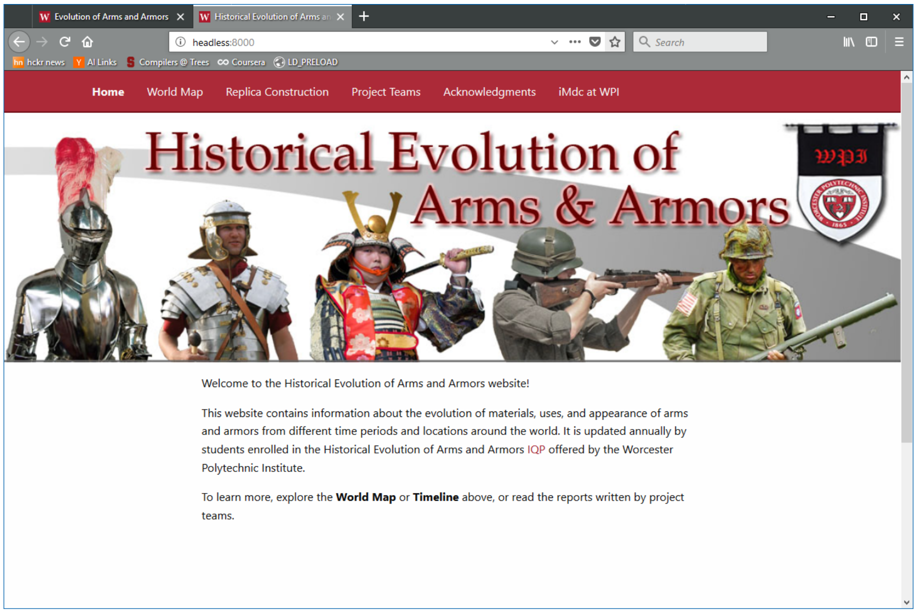
[4] CSS files



Welcome to the Historical Evolution of Arms and Armors website!

This website contains information about the evolution of materials, uses, and appearance of arms and armors from different time periods and locations around the world. It is updated annually by students enrolled in the Historical Evolution of Arms and Armors IQP offered by the Worcester Polytechnic Institute.

To learn more, explore the **World Map** or **Timeline** above, or read the reports written by project teams.

Figure 6.3: The home page of the new Arms and Armors IQP site, as rendered in Firefox 57 on a Windows 10 PC.

and insert them into a new page. We evaluated two frameworks for this process: using Python 3's HTML parser[5], and using JavaScript in the browser[6]; the latter was chosen, as it is far easier to navigate the page source using a language like JavaScript, optimized for the Web, as opposed to a general-purpose scripting language such as Python. However, while the content of the site is laid out in a reasonable manner to human eyes, the source code is considerably more complex, with a staggering number of unique situations even within one page. This would force the scraper to support more situations than writing it would be worth, so it became necessary to manually copy-and-paste content from the old site, while applying new formatting rules. This process was performed for all World Map pages and all Replica Construction pages, and its results are partially shown in Figures 6.4 and 6.5.

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[5] Python is a scripting language commonly used for tasks such as format translation and web parsing.

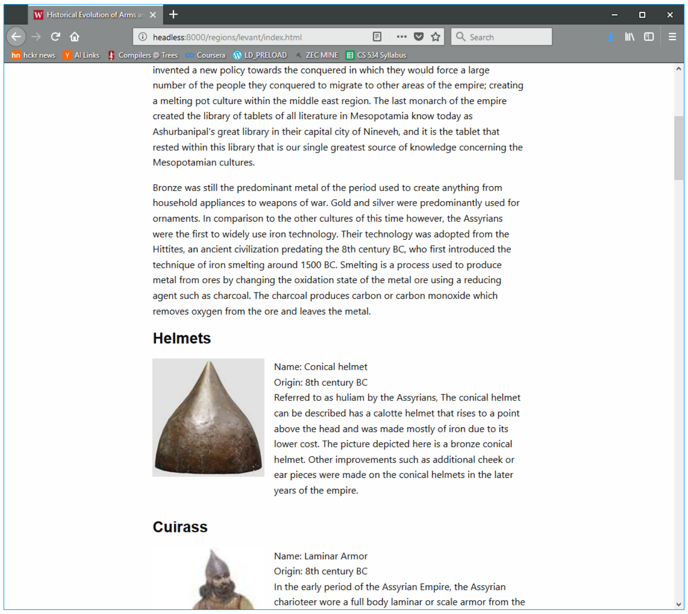
[6] JavaScript executes directly within the Web browser, allowing more complex operations to be performed on the code and data already in the page.

Replica Projects by Year

IQP reports are hosted here from 2010 onward.

- 2010-2011
- 2011-2012
  - Making of a Katana
  - Making of a Kopis
- 2012-2013
- 2013-2014
- 2014-2015
- 2015-2016
- 2016-2017

Figure 6.4: The new Replica Construction page, arranged by year and the piece that was built.



invented a new policy towards the conquered in which they would force a large number of the people they conquered to migrate to other areas of the empire; creating a melting pot culture within the middle east region. The last monarch of the empire created the library of tablets of all literature in Mesopotamia know today as Ashurbanipal's great library in their capital city of Nineveh, and it is the tablet that rested within this library that is our single greatest source of knowledge concerning the Mesopotamian cultures.

Bronze was still the predominant metal of the period used to create anything from household appliances to weapons of war. Gold and silver were predominantly used for ornaments. In comparison to the other cultures of this time however, the Assyrians were the first to widely use iron technology. Their technology was adopted from the Hittites, an ancient civilization predating the 8th century BC, who first introduced the technique of iron smelting around 1500 BC. Smelting is a process used to produce metal from ores by changing the oxidation state of the metal ore using a reducing agent such as charcoal. The charcoal produces carbon or carbon monoxide which removes oxygen from the ore and leaves the metal.

Helmets

Name: Conical helmet
Origin: 8th century BC
Referred to as huliam by the Assyrians, The conical helmet can be described has a calotte helmet that rises to a point above the head and was made mostly of iron due to its lower cost. The picture depicted here is a bronze conical helmet. Other improvements such as additional cheek or ear pieces were made on the conical helmets in the later years of the empire.

Cuirass

Name: Laminar Armor
Origin: 8th century BC
In the early period of the Assyrian Empire, the Assyrian charioteer wore a full body laminar or scale armor from the

Figure 6.5: The new page describing the Assyrian empire, reachable from the World Map.

6.2 The World Map

To address the World Map, we leverage the power of WebGL, an OpenGL-compatible[7] JavaScript API that allows the rendering of hardware-accelerated 3D graphics[8] in the Web browser,

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[7] OpenGL is an API that interfaces with graphics processors to render images on screen. It dates back to 1994, but has undergone multiple revisions as graphics processors' hardware has evolved.

[8] Algorithms to render 3D graphics benefit greatly when run on specialized hardware. When graphics is rendered in this way, it is said to be "hardware-accelerated".

and a companion wrapper library called *THREE.js*, which runs on top of WebGL and greatly simplifies tasks not directly related to graphics rendering, such as loading meshes and textures from other sources online. The World Map, shown in figure 6.6, now consists of a rotating globe that can be controlled by the mouse. When the user clicks on a point on the globe, it navigates them to the corresponding article for the nearest part of the world to that click (or not, if no point exists on that part of the world). To rotate the globe, the user will move his mouse to one of the edges of the screen, which causes the globe to rotate in that direction. Additionally, the globe is animated, featuring a rotating starfield in the background. This intuitive visualization makes the creation of new content much more flexible, and navigation through that content much more intuitive for users – they need only click on a part of the world they are interested in.

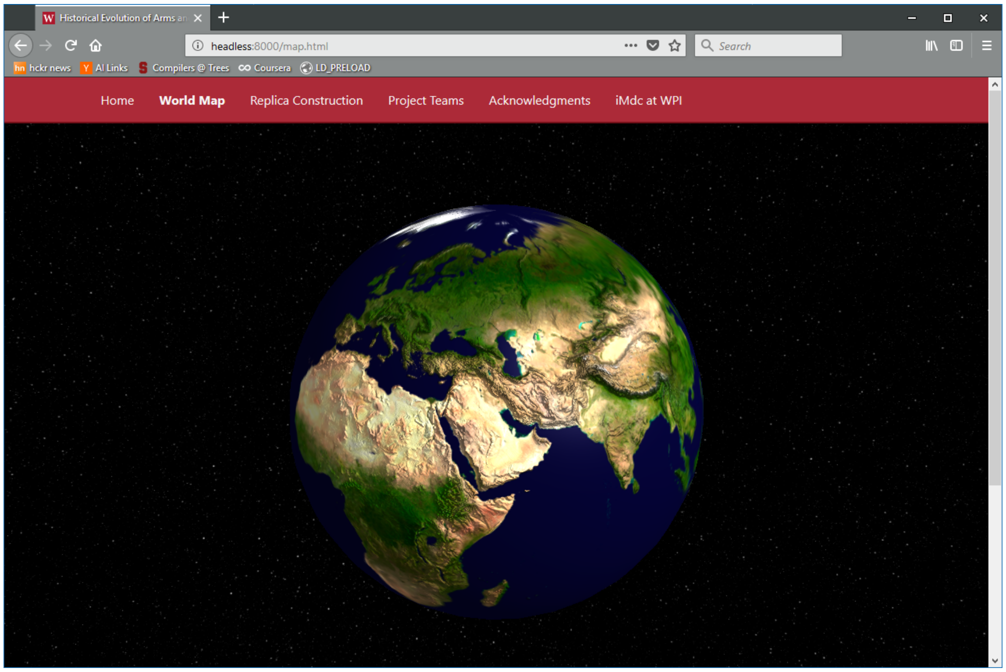

Figure 6.6: The world map of the new Arms and Armors IQP site, as rendered in Firefox 57 on a Windows 10 PC.

One of the more interesting aspects of this visualization is the selection of a point on the map, using a technique called "ray tracing". Based on the position of the mouse on screen, a virtual ray is fired from the camera towards the scene; *THREE.js*'s raycasting module is capable of reporting what object was hit by this ray, and where it was hit. If this ray strikes the Earth, it is possible to calculate the texture coordinates (u, v) on the Earth where the ray hit it. These coordinates can be mapped to a point location on the image texture file by multiplying u and v

by the width and height of the texture, respectively. Once this is determined, the closest defined points to the click location are calculated. If one point is far closer than the others (by a wide margin of 150%), the user will be redirected to that page; if it is ambiguous, the user will be given a choice in a pop-up sidebar.

Using a similar technique, it is possible to draw circles on the world map to indicate where the clickable zones are. This is done by creating a transparent texture upon which circles are drawn at the correct locations in a bright color, so that they are visible on the globe. Since the globe consists primarily of blue, green, and brown hues, a bright yellow color was chosen. The transparent texture is then applied to a sphere with the same center as the Earth, but slightly larger, thus becoming similar to an overlay. Since the texture applied to it is transparent, it is possible to view the Earth's terrain under the outer sphere.

6.3 New Content

The website must also document the history behind and the construction of the pieces built by both IQP teams this year. Since the website is intended to be a gentle introduction to the subject matter as opposed to an in-depth, scholarly work, we summarize the history behind the piece created in approximately one paragraph, and the entire process of replica creation in a series of paragraphs interspersed with images that *show* what was performed in multimedia.

In describing the war hammer's significance to medieval European history, we forgo much of the history behind it and simply describe its utility in the time period as opposed to other units, partially in an attempt to keep the subject matter of interest; few want to read about the politics behind the use of a weapon, and even fewer want to read about the dates during which the weapon was used.

The replica construction summary is presented verbatim in the appendix.

Appendix A

Appendix

The appendix contains information regarding the war hammer as it is presented on the website.

A.1 World Map Description

Origin: 1400's

Weight: 2 kg - 4 kg

The war hammer a two handed weapon with a double-sided hammer attached to a wooden handle. One side of the hammer was a flat face while the other had a long spike. The length of the handled varied, foot soldiers carrying longer versions to hook cavalry and mounted soldiers using shorter versions due to only having one hand available.

As the increasing effectiveness of armor lead to the decline of swords, the war hammer rose in importance for its ability to apply concussive force it a small area, causing severe trauma even when it failed to pierce the armor. Even with the advent of gunpowder and advanced artillery, the war hammer was retained for its effectiveness in fighting heavy cavalry and cheapness to manufacture.

Figure A.1: Image of the war hammer appearing on the website.

A.2 Replica Construction Summary

The first step in constructing the hammer was creating a CAD model to base our hammer off of. Next, we began the forging and heated our square bar until orange. We beat the spike into shape using a combination of hammers and mechanical presses. After building the spike we opened up the hole for the handle using a rectangular punch, and used the mechanical press with a rounded die to form the grooves. Next, we cut the hammerhead off of the bar and ground down the face and other sides until flat. We then heat treated the hammerhead by heating it above 727°C and immediately quenching it in oil, followed by baking it in an oven at 200°C for 30 minutes. We then cut a hickory shaft to the appropriate size to fit the hammerhead and inserted a wedge to keep the two of them together. The langlets were built concurrently to the rest of the hammer, and were made by heating and bending a flat piece of steel into a square, u-shaped bracket. This piece had small holes drilled into it in order to fit the rivets, which were hammered in to fix the langlets to the handle. The final step was to apply a polyurethane coating to protect the wood.

Figure A.2: Shaping the end of the steel bar to form a spike.
We placed the rod of steel onto the anvil after heating it in the forge. In order to form a spike shape, we rotated the steel every few hits with the hammer. This process would both elongate the steel rod, while also making a spike shape.

Figure A.3: Three person team punching the hole where the handle would be inserted. After creating the spike shape, we would drive a tapered steel rod into the middle of the bar. We placed the bar over the hole located in the rear of the anvil so when the steel rod penetrated the bar, the rod could create a larger hole. Every three hits, the tapered rod would be removed, cooled in water, and covered in graphite as a lubricant. If these three steps were not performed, the tapered steel rod would merge with the bar that we were trying to forge.

Figure A.4: The hammerhead after being separated from the rest of the stock material. We seperated the hammerhead shape from the rest of the bar by hammering the glowing metal onto a wedge, which slowly cut through the material until we were able to pry the hammerhead off with tongs.

Figure A.5: Smoothing and polishing the shaped head.
By using a motorized sandpaper wheel, we smoothed and polished any rough edges present on the hammerhead. Because of the heat created by the friction, the hammerhead was cooled every minute in the bucket of water located under the sandpaper in the figure.

Figure A.6: Quenching the hammerhead in oil after heating it past the Curie point.
We repeated the previous processes above for our final hammerhead. This was done because our first hammerhead was a prototype where we would familiarize ourselves with the forging methods used. After repeated these steps, we heat treated our final hammerhead by quenching it in oil. This would reduce the risk of it cracking compared to water because the hammerhead would not cool as quickly.

Figure A.7: The treated and quenched hammer head, before polishing.
This is what our hammerhead looked like before our second round of polishing. During the first round of polishing, we removed any large metal fragments sticking out of the surface.

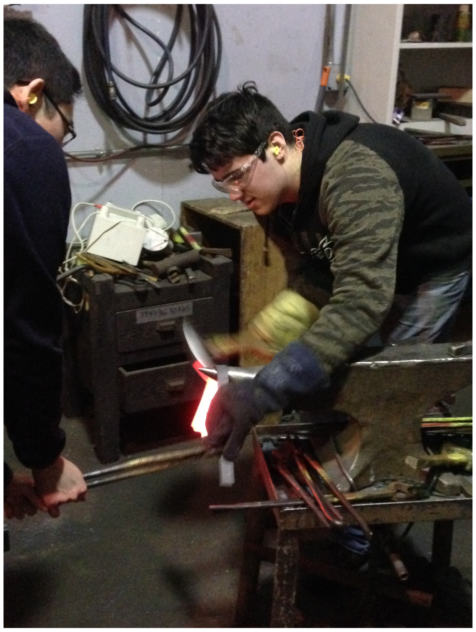

Figure A.8: Bending the langlet steel into a suitable shape to fit on the hammer. The langlets would serve to secure our hammerhead to the wooden handle created. The langlets were a thinner metal, so bending it into a suitable shape to fit the hammerhead did not require as much working as creating the spike for the hammer, but instead required more precision.

Figure A.9: Finished war hammer after attaching the langlets and applying the polyurethane coating.
After the langlets were bent into shape, several holes were drilled into each of the sides. The langlets were hammered to the shaft with the rivets, and a polyurethane coating was applied to the handle.

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