The Evolution of Materials in Arms and Armors: Disunity Period in Imperial China

With a Focus on the Dao

An Interactive Qualifying Project Report

Submitted to the Faculty
Of the
WORCESTER POLYTECHNIC INSTITUTE

By:
Bryan Benson
Ryan Coran
Alberto Ramirez

Date: 04/27/2017

Submitted to:
Professor Diana A. Lados
Mr. Tom H. Thomsen

Table of Contents

Table of Contents 2

List of Figures 4

Individual Participation 7

Authorship 8

1. Abstract 10
2. Introduction 11
3. Historical Background 12

3.1 Fall of Han dynasty/ Formation of the Three Kingdoms 12

3.2 Wu 13

3.3 Shu 14

3.4 Wei 16

3.5 Warfare and Relations between the Three Kingdoms 17

3.5.1 Wu and the South 17

3.5.2 Shu-Han 17

3.5.3 Wei and the Sima family 18

3.6 Weaponry: 18

3.6.1 Four traditional weapons (Qiang, Jian, Gun, Dao) 18

3.6.1.1 The Gun 18

3.6.1.2 The Qiang 19

3.6.1.3 The Jian 20

3.6.1.4 The Dao 21

3.7 Rise of the Empire of Western Jin 22

3.7.1 The Beginning of the Western Jin Empire 22

3.7.2 The Reign of Empress Jia 23

3.7.3 The End of the Western Jin Empire 23

3.7.4 Military Structure in the Western Jin 24

3.8 Period of Disunity 24

4. Materials and Manufacturing During the Period of Disunity 25

Table of Contents (Cont.)

4.1 Manufacturing of the Dao During the Han Dynasty 25

4.2 Manufacturing of the Dao During the Period of Disunity 26

5. Reconstruction of the Dao 27

5.1 Materials 27

5.2 Overview of the Reconstruction Process 27

5.3 Reconstruction 28

5.3.1 Practice Dao 28

5.3.2 Reconstruction of the Full-sized Dao 31

6. Analysis of Materials 36

6.1 Background to Phase Diagrams 36

6.2 Material Analysis of the Dao 44

6.2.1 Predicted Analysis of the Dao 44

6.2.2 Actual Analysis of the Dao 47

6.2.2.1 Analysis of Initial Samples 47

6.2.2.2 Analysis of Quenched Samples 49

6.2.2.3 Analysis of Tempered Samples 51

7. Conclusion 53

Appendices 54

Works Cited 60

List of Figures

Figure 1. Map of Three Kingdoms Era of China……………………….………..…….…………..13
Figure 2. Portrait of Sun Quan ……………………………………………….…………………..14
Figure 3. Portrait of Liu Bei ……………………………………………….…...……….……......15
Figure 4. Portrait of Cao Cao…………………………………………………….….….………...16
Figure 5. Sketch of the Gun…………………………………………………….….……………..19
Figure 6. Sketch of the Qiang ……………………………………………….....…………………20
Figure 7. Sketch of the Jian ……………………………………………………..…………………20
Figure 8. Sketch of Wu's Hook Sword ………………………………………………….……...21
Figure 9. Sketch of the Dao………………………………………………….....…………………22
Figure 10. Provinces and Commandery Units of Western-Jin, circa 280 CE….………..…………....…23
Figure 11. Three dao swords from the Han Dynasty ………………………….…….…..……....25
Figure 12. A dao with a shorter and wider blade……………………………….…….………26
Figure 13. Physical data for the 1075 steel………………………………..…….………………27
Figure 14. SolidWorks model of the Dao……………………………………………..……....28
Figure 15. SolidWorks drawing of the Dao ……………………………………………….………28
Figure 16. Bryan working on practice metal……………………………………..………...29
Figure 17. The scrap metal being heated in one of the forges……………………….…………..29
Figure 18. Cutting the analysis sample pieces from the metal……………………..…………29
Figure 19. Smaller practice dao at the end of Day 3 of forging………………………………………30
Figure 20. The tool used for shaping the blood groove………………………………………………30
Figure 21. Close up of the blood groove on the smaller practice dao at the end of Day 5 of forging……………………………………………………………………………………………....30
Figure 22. Grinding the practice dao …………………………………………………………....30
Figure 23. Close up of the practice dao at the end of Day 7 ……….……….……….……….…..31
Figure 24. The practice dao after quenching…….……….……….……….……….…….……………31
Figure 25. Full-sized actual dao at the end of Day 3 of forging…………………………….………..31
Figure 26. Full-sized actual dao at the end of Day 4 of forging……………………………..……….32
Figure 27. Close up of the thickness of the tip of the full-sized actual dao at the end of Day 4 of forging………………………………………………………………………………………………32
Figure 28. Close up of the edge of the larger dao at the end of Day 5 of forging………………………32

List of Figures (Cont.)

Figure 29. The coal-powered forge……………………………………………………………..33
Figure 30. The started blood groove on the larger dao……………………………………….....33
Figure 31. Grinding the larger dao ……………………………………………………………....33
Figure 32. The larger dao after day 9 of forging………………………………………………..33
Figure 33. The hand guard after the tenth day of forging………………………………………..34
Figure 34. The larger dao after the tenth day of forging…………………………………………34
Figure 35. The finished hand guard……………………………………………………………...34
Figure 36. The hole being bored into the handle by the heated tang…………………………...35
Figure 37. The assembled dao at of the eleventh day of forging…………………………………35
Figure 38. The dao after the twelfth day of forging ……………………………………………35
Figure 39. The assembled dao before quenching and tempering…………………………………35
Figure 40. The assembled dao before adding the cloth …………………………………………...36
Figure 41. The final, assembled dao ..……………………………………………………………..36
Figure 42. $Fe-Fe_3C$ phase diagram ……………………………………………………………37
Figure 43. Graph showing new eutectoid carbon composition based on various alloying elements.......37
Figure 44. Graph showing new eutectoid temperature based on various alloying elements..…………38
Figure 45. (a) Ferrite and (b) austenite microstructures...…………………………………………...38
Figure 46. $Fe-Fe_3C$ phase diagram with a highlighted hypoeutectoid composition……………………...39
Figure 47. Image of Microstructure for hypoeutectoid metal after equilibrium cooling………………39
Figure 48. $Fe-Fe_3C$ phase diagram with a highlighted eutectoid composition…………………………40
Figure 49. Image of pearlite microstructure…………………………………………………..……...40
Figure 50. $Fe-Fe_3C$ phase diagram with a highlighted hypereutectoid composition……………………..41
Figure 51. Image of microstructure for hypereutectoid metal after equilibrium cooling……….……...41
Figure 52. 2nd $Fe-Fe_3C$ phase diagram with a highlighted hypereutectoid composition……...………..42
Figure 53. Another $Fe-Fe_3C$ phase diagram with a highlighted hypereutectoid composition…...……..42
Figure 54. Continuous-Cooling Transformation diagram……………………………………............43
Figure 55. Image of martensite microstructure ……………………………………………………...43
Figure 56. Image of bainite microstructure.………………………………………………...…………...44
Figure 57. $Fe-Fe_3C$ phase diagram with a highlighted composition……………………………………45
Figure 58. Phase diagram with a highlighted dao composition (predicted)..46

List of Figures (Cont.)

Figure 59. Possible transformations for austenite..……………………………………………………...46

Figure 60. Initial microstructures on all three cross-sectional planes………..………………………….....48

Figure 61. Quenched microstructures on all three cross-sectional planes………..……………………...50

Figure 62. Continuous-Cooling Transformation diagram with Oil-Quenched Cool Rate; the calculated cooling rate for the actual quenching of the samples is represented by the black line.……….……….…50

Figure 63. Tempered microstructures on all three cross-sectional planes………..……………………....52

Figure C1. The teams page changes on the website.…….…….……….…….…….……………......56

Figure C2. The dao forging page changes on the website.…….…….…….…….……...…………57

Figure C2. The dao forging page changes on the website (Continued)...58

Figure C3. The Chinese history changes on the website.…….…….……….……………….…....59

Individual Participation

Bryan Benson: 40 hours

Ryan Coran: 40 hours

Alberto Ramirez: 41 hours

Authorship

Bryan Benson:

Table of Contents

1. Abstract

2. Introduction

3.5 Warfare and Relations between the Three Kingdoms

3.7 Rise of the Empire of Western Jin

3.8 Period of Disunity

4. Materials and Manufacturing During the Period of Disunity

5.2 Overview of the Reconstruction Process

5.3 Reconstruction

Appendix

Website Changes

Sample Imaging

Editing & Formatting

Ryan Coran:

Table of Contents

3.1 Fall of Han dynasty/ Formation of the Three Kingdoms

3.6 Weaponry:

6.2.2 Actual Analysis of Dao

Conclusion

Editing and Formatting of Entire Report

Alberto Ramirez:

Table of Contents

List of Figures

3.2 Wu

3.3 Shu

3.4 Wei

5.1 Materials

6.1 Background to Phase Diagrams

6.2.1 Predicted Analysis of the Dao

Editing of 6.2.2 Actual Analysis of Dao

Works Cited

Conclusion

Editing & Formatting

1. Abstract

The Period of Disunity in Imperial China (220 CE - 580 CE) was an era of great strife, ridden with warfare. However, during this time, many innovations took place, especially with regards to weapons and armor. One such weapon, the dao, a curved, single-edged sword used by the Chinese during this period, is the main focus of the second section of this paper. This project first study the historical background during this period, then dive into the specifics of the dao. Once the background is finished, the next step is to build a replica of the dao, and describe the processes and materials that go into making the weapon, both now and during the Period of Disunity.

2. Introduction

Before the Three Kingdoms era started, the Han dynasty was stricken with a bout of civil wars. These wars led to the fall of the dynasty, and led the majority of the people to separate into three kingdoms: the Shu-Han, Wei, and Wu.

These three kingdoms fought over the land and power. Each of the leaders sought to claim the imperial title for themselves. There were a series of internal conflicts within each kingdom, so they were all fighting wars, both externally and internally. This period was also filled with intrigue, as various factions within the kingdoms fought to gain and retain power. In 265 CE, the Sima family took over the Northern region of China, eventually conquering the three kingdoms by 280 CE. This Western Jin Empire lasted until 314 CE, when they were overrun by foreign peoples for the North and infighting within Sima family.

The period of turmoil between the fall of the Han Dynasty and the reunification of China in 589 CE after the fall of the Western Jin is known as the Period of Disunity. The four traditional weapons used during this era were gun, the jiang, the qiang, and the dao. The dao had replaced the jiang as the primary weapon for fighting cavalry by the emergence of the Western Jin Dynasty. In this paper, one of the focal points will be on the dao, its manufacturing process, its use, and its history. This project will require the construction of a replica of the dao using the original forging techniques from the Period of Disunity, and then analyze the materials that went into creating the weapon.

3. Historical Background

3.1 Fall of the Han Dynasty

In 189 CE, Han Emperor Ling died. He was a teenager. After his death, Shao inherited the throne. Army generals Yuan and Jin were offended with the control that eunuchs had over the emperor. This led to a militaristic struggle between the eunuchs and the army. Zhou was a court official of the Han Dynasty. During the struggle with the eunuchs, Zhou camped his forces in Luoyang. With this deceptive maneuver, Zhou defeated Shao and placed Xian as the ruler of the empire. However, imperial officials and the public did not think highly of Zhou's actions. This eventually led to a Civil War. This became known as the Huangjin Peasants' Uprising (25-220 CE).

In 193 CE, Zhou was assassinated. Tensions continued for three years, during which, many military officials struggled for power. After three years, powerful divisions were established by Cao Cao and Liu Bei. Their military groups were largely located around the middle section of the Yellow River. Cao Cao eventually won over Emperor Xian and reinforced his army. In 200 CE, there was a battle between Cao Cao and Liu Bei known as the Guandu Battle. With his new army, Cao Cao won this battle and unified the region north of the Yellow River.

Afterwards, he began to conquer Southern China, including the city of Jinzhou. In the southern region, Sun Quan controlled the eastern areas and Liu Bei controlled the Western areas (both south of the Yangtze river). Zhuge Liang was the military counselor of Liu Bei. Zhuge Liang advised Liu Bei and Sun Quan to join forces against Cao Cao, since Cao Cao's forces were much stronger. With their combined forces, they decidedly defeated Cao Cao at the Chibi Battle or Battle of Red Cliffs (208 CE). Cao Cao retreated back to his kingdom in the north.

After Cao Cao's defeat, the region was divided into three spheres of influence. Cao Cao was a leading figure who attempted to control the whole empire, but he ultimately helped bring it down in the end. He died in 220 CE.

Cao Cao's son Cao Pi forced the emperor, Emperor Xian to give him his throne that same year [12]. He went by the name Emperor Wen before he died in 226 CE. He set up his castle in Luoyang. Even though Cao Cao is generally regarded as the first emperor of Cao Wei, it was Cao Pi that became the first emperor of Wei to sit on the throne. Cao Cao's son, Cao Pi, crowned himself emperor of the Wei Kingdom, abandoning the last emperor of the Eastern Han Dynasty. He controlled the north with Xuchang as his capital.

A few months later, in 221 CE, Liu Bei named himself the Emperor of the Han Dynasty and established the Shu empire with Chengdu as the capital city [13]. Later that year, Sun Quan established the Wu Empire in "the lower reaches of the Yangtze River. " [2] He established the capital city in Wuhan. He later changed the name of the city from Wuhan to Nanking. Sun Quan was the former ally of Liu Bei.

The Kingdom of Wei controlled the northern region, the Shu Kingdom controlled Southwest China, and the Wu Kingdom controlled the southeast region.

Figure 1. Map of Three Kingdoms Era of China [2].

3.2 Wu

The Wu's survival depended on the population growth and territorial expansion. Sun Quan led the expansion to the Jing province to expand the land, but encountered some troubles. This resulted in Sun Quan defeating Guan Yu and the defense against Liu Bei. The government of Wu had extended its influence further south during these times. Sun Quan appointed Bu Zhi as governor in the year 210 CE. Bu Zhi had made an agreement with Shi Xie which led to tributes and hostages being sent to Sun Quan.

In 220 CE, Lü Dai replaced Bu Zhi and Shi Xie died. The sons of Shi Xie surrendered to Lü Dai, and Lü Dai ordered them to be executed and sent the heads to Sun Quan. His authority kept peace within the sea trade. After obtaining much wealth and influence, Sun Quan went after the imperial title. Sun Quan had no legitimate reason to inherit the imperial position. He called the Cao family from the Wei criminal usurpers. The Wu had more of a defensive strategy than the others. Sun Quan chose Jianye to be the capital which provided control of the lower Yangzi.

Figure 2. Portrait of Sun Quan [10].

Sun Quan died in the year 252 CE, which led to a struggle to appoint his successor. The first son, Sun Deng, died before Sun Quan, so the next in line was Sun He. He also died before Sun Quan did, so decided to pass the mantle to his youngest son, a seven year old named Sun Liang, with guidance from Zhuge Ke. Zhuge Ke was assassinated in the attack against Hefei. Sun Liang gave the order to assassinate Zhuge Ke while under the influence of an imperial cadet named Sun Jun. Sun Jun died which led his cousin, Sun Lin, to take care of Sun Liang and to take control. In 258 CE, Sun Liang wanted to take control, but the sixth son of Sun Quan, Sun Xiu, dethroned Sun Liang, and arranged a coup to get rid of Sun Lin.

The leadership of Sun Xiu was lacking and ineffective. Sun Xiu died just about the same time when the state of Shu-Han surrendered to the Wei. The next successor was chosen to be Sun Hao, the son of Sun He. Sun Hao had limited success in ruling due to the surrender to the Jin state in 280 CE [11].

3.3 Shu-Han

If the Wu was comprised of military success of a local family and supporters, then the Shu-Han empire of the west was the work of a wandering warlord with mercenaries. Some of the information of the founder Liu Bei and his second in command, Zhuge Liang, has been altered by romantic tradition. History of the Shu-Han has been altered in such a way that it describes certain people like this:

"Liu Bei as a hero of chivalry and Zhuge Liang as a master of warfare and magic. While Cao Cao is described as the powerful, proud and arrogant usurper of the imperial mandate, and the men of Wu are often ineffectual and self-seeking, sometimes treacherous, the government of Shu-Han is lauded as the true successor of the fallen empire and the centre of wisdom, courage and loyalty." [11]

Liu Bei experienced warfare for the first time during the Yellow Turban rebellion in 184 CE. He allied himself with warlords, which led him to hold a brief moment of power over some territory in North China. In 200 CE, Cao Cao's forces defeated Liu Bei, and Liu Bei fled to Liu Biao. When Liu Biao died, Cao Cao went to the South to claim his land. Liu Bei appointed himself as chief and opposed Cao Cao, but Cao Cao defeated Liu Bei swiftly. In 211 CE, the governor of the Yi province, Liu Zhang, invited Liu Bei to assist in defending the northern borders. Liu Bei, with an army, made Liu Zhang surrender.

Figure 3. Portrait of Liu Bei [9].

In 219 CE, Liu Bei won against Xiahou Yuna which gave Liu Bei control of the Han valley, and this gave a reason for Liu Bei to go for the imperial title. After many defeats, the Shu-Han lost land and never recovered from those defeats. Liu Bei died in 223 CE, and his second in command, Zhuge Liang , took over since Liu Bei's son, Liu Shan was only seventeen. Before Zhuge Liang died, he established an alliance with the Wu. Jiang Wan took over Zhuge Liang's role and faced the Wei. In 244 CE, Jiang Wan was ill, stepped down, and died two years later. Liu Shan, now forty years old, retook control, but his interests laid elsewhere.

Jiang Wan was never a serious threat to the Wei. His successor for the position of chief minister on the frontier was Fei Yi, who was assassinated by a renegade of the Wei. The next chief minister was Jiang Wei. He led a attack on Hanzhong, but failed for years. In the 260's, the Sima family made their move on the Shu-Han. As the Jiang Wei's army was heading to a different location, the Sima family made Liu Shan surrender and assassinated any resistance. Jiang Wei and his followers were killed afterwards. Liu Shan was exiled. [11]

3.4 Wei

The kingdom of Wei was built by Cao Cao, who is known as the most effective leader right after the fall of the Han dynasty. The Wei kingdom had seventy percent of the original population of the Han dynasty. Cao Cao had difficulty reuniting the fallen kingdom due to Sun Quan's military might and Shu-Han's independence. Cao Cao created many agricultural garrisons. These garrisons were open fields where the Cao Cao's government would place refugees to work and grow sustenance. In 220 CE, Cao Cao was succeeded by his son, Cao Pi.

Figure 4. Portrait of Cao Cao [4].

In order to ensure no internal conflicts within the family, Cao Pi had his brothers removed and sent to remote areas to be observed. In 226 CE, Cao Pi died and his son, Cao Rui, took the throne. Four advisors were chosen to help him out: Generals Sima Yi, Cao Zhen, Cao Xiu, and Minister Chen Qun. A couple years later, all of the advisors but Sima Yi had died,and Sima Yi became the senior minister and commander of the military. The Sima family was well respected by the Cao family. Sima Yi was in command on the field during the battles against the Wu and the Shu-Han.

In 239 CE, Cao Rui died, and with no legitimate heir, the adopted son, Cao Fang, took over. Cao Fang chose two advisors, Cao Shuang and Sima Yi. Cao Fang was too young to be in charge of the military so Cao Shuang was in charge of the military while Sima Yi was tutoring Cao Fang. In 247 CE, Sima Yi pretended to be ill and retired.

As Cao Fang and Cao Shuang visited Luoyang, Sima Yi gathered troops for a coup to kill Cao Shuang and his followers, and took over the Wei kingdom during the year 249 CE. Once Sima Yi died in 251 CE, his son, Sima Shi, took over, attacked the Wu, and replaced Cao Fang with his cousin, Cao Mao, on the throne. Sima Zhao was next in line when Sima Shi died, and he focused on conquering the Shu-Han. In the year 264 CE, Sima Zhao won and took the title as King of Jin but died the following year. His oldest son, Sima Yan, took the mantle as king to start the new dynasty [11].

3.5 Warfare and Relations between the Three Kingdoms

3.5.1 Wu and the South

In 219 CE, the Wu expanded into Jing province, leading to the destruction of Guan Yu, while the Wu government extended its power into the far south.

In 220 CE, Lü Dai succeeded Bu Zhi. Dai kept the Wu's position in Nanhai and Cangwu, and extended his reach over present-day Guangdong and Guangxi. When Shi Xie passed away in 226, Lü Dai took Xie's power by arriving at the Red River with a fleet and an army, forcing the the Shi Xie's sons to surrender. Lü Dai promptly had them executed. His territory stretched all along the southern shore down to present-day Cambodia.

During the reign of Sun Quan, the armies of Wu were not able to defeat the armies of Wei along the Huai River, despite attacking them several times. In any case, Wu's strategy was mostly defensive. They had garrisons and naval bases spanning all along the Yangzi [11].

3.5.2 Shu-Han

Though he had plans to attack, Jiang Wan of the Shu never really threatened the Wei. The Shu had a plan at one point to attack the Wei from Hanzhong down the river. However, they decided against it due to the difficulty of retreating upstream, in case they were defeated. In addition, the Wei had consolidated their power using a new system of agricultural garrisons. By contrast, the morale and energy of the Shu-Han were severely depleted by the many years of failed campaigns, making any further attack infeasible [11].

3.5.3 Wei and the Sima family

In 226 CE, Sima Yi took command of the Wei for the first time, driving back the Wu. The next year he was given command of the military along the Han River. He was a competent general, and, over the next decade, his armies held their ground in the south against the armies of Wu and in the west against the armies of Shu.

In 238 CE, Sima Yi took command of a campaign against Manchuria. In a fast, effective series of battles, he defeated Gongsun Yuan's defence along the Liao River, took his capital Xiangping, and destroyed the warlord's government. In doing so, he brought the northeast into the Wei's domain [11].

3.6 Weaponry

3.6.1 Four traditional weapons (Qiang, Jian, Gun, Dao)

China has been a very prosperous nation for centuries. Over the years, they have had many different weapons. Due to the many fights and conflict around the time of the Three Kingdoms Era, there were many weapon inventions and advancements during this time. Included in these weapons were China's four traditional weapons; the gun, qiang, jian and dao. The gun is a type of stick or staff, the qiang is a type of spear, the jian is a type of sword, and the dao is a single-edged sword [14].

3.6.1.1 The Gun

The gun, or long rod, was generally made of hard wood, such as birch or oak. "The wood was often immersed in wood oil to increase its strength and resilience." Sometimes, the gun was made of brass or iron, and they could be either solid or hollow. The metal versions "had the distinct advantage of being invulnerable to bladed weapons." In the south, the rod was long enough to reach the wielders eyebrows. In the north, the rod was long enough to reach the wielder's wrist "when his arm was extended over his head." The gun "is one of the most convenient and easily utilized weapons." [14]

There were three popular versions of the gun. The first was simply a straight rod. This version was the most common. The second was known as the "Water-Fire Rod." This version had "metal caps covering both ends of the rod, but neither end was sharp." The third was known as the "Rod Spear," it had "one tapered end that could be used for piercing." [14]

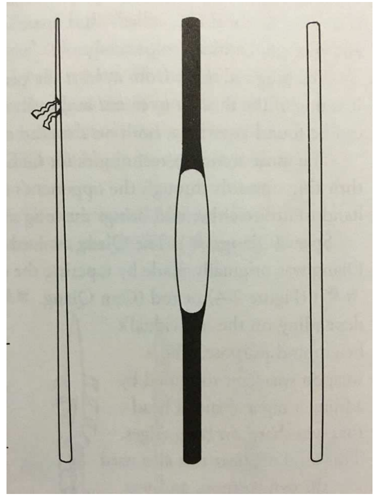


Figure 5. Sketch of the Gun [14].

3.6.1.2 The Qiang

The Qiang, or spear, was originally made from a piece of bamboo with the end tapered. It was later modified by the addition of "a tapered metal head that was sharp on both edges." Horsetail tassels, known as the "blood stopper," were also added because they both "distracted the enemy" and "stopped the flow of blood from the blade to the handle." [14]

The Qiang was made of "white wax wood" from Northern China. "Rattan was also utilized, especially in Southern China. Both materials are extremely tough and flexible." To increase the wood's resiliency and strength, it was often "soaked in oil for several months."

The Qiang was very versatile. It was used while mounted, on foot, or in chariots. It is also known as "King of the long weapons" due to its superiority over other weapons. The Qiang was designed from the Mao, or lance, "which was longer and heavier." Over time, it gradually evolved into the Qiang. During the Jin dynasty (265-420 CE), the Qiang "became shorter and lighter." [14]

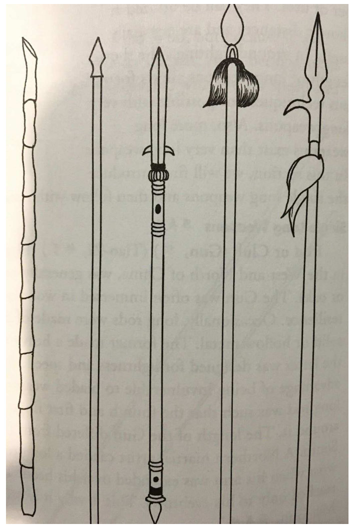


Figure 6. Sketch of the Qiang [14].

3.6.1.3 The Jian

The Jian, or "narrow blade sword," is a sword that is narrower than a sabre, has two sharp edges, and both the handle and blade are straight. "The metal protrusion protecting the hand flares out perpendicular to the blade." The blade is usually less than 1.5 inches wide. The third nearest the handle is dull, the middle third is sharper, and the third furthest from the handle is extremely sharp. The swords were generally longer in the northern regions than the southern regions.

During the Wu dynasty, "a hook was added near the tip of the sword." This sword was known as "Wu's Hook Sword." "Both edges of the hook were sharp." The hook made fighting techniques more complicated and made it more deadly. However, the sword could not be sheathed.

The Jian was considered to be the most versatile ancient weapon. It was also referred to as the "king of short weapons." The sword was capable of piercing through the body of an enemy. The lower two-thirds of the blade was used defensively. "The flared piece at the top of the handle" was capable of locking an opponent's weapon.

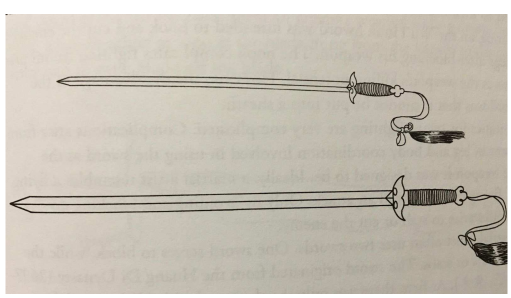


Figure 7. Sketch of the Jian [14].

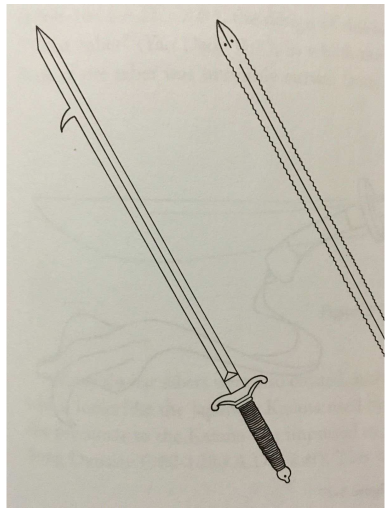


Figure 8. Sketch of Wu's Hook Sword [14].

3.6.1.4 The Dao

The dao, or saber or wide-blade sword, had a single blade that was more than 1.5 inches wide. "The handle was often sandwiched between two pieces of wood, and then wrapped with cloth to absorb sweat." There was also a circular or semicircular metal guard to protect the hand. Often, there was a handkerchief the length of the blade hanging from the handle to distract the enemy and wipe blood off of the handle.

While there were many different versions of the dao, there were three things that remained consistent among all of them. The back end of the blade was dull, except near the blade, the furthest one-third of the blade from the handle "was considerably sharper than the" other two-thirds, and "each side of the blade had a blood groove." The blades used in Northern China were slightly longer than those used in Southern China, but they were not very heavy.

"The saber is the foundation for all short weapons. The techniques learned for the saber can be applied to all other short arms." The dao was often used defensively. The back end could block attacks, and then the wielder would follow-up with a stab or cut with the sharp end. "The curvature in the blade provides for a violent, powerful repulsion, with less curvature producing less power." As the foundation for short weapons, beginning in the Song Dynasty (960-1280 CE), many variations were made on the dao for various reasons and fighting styles.

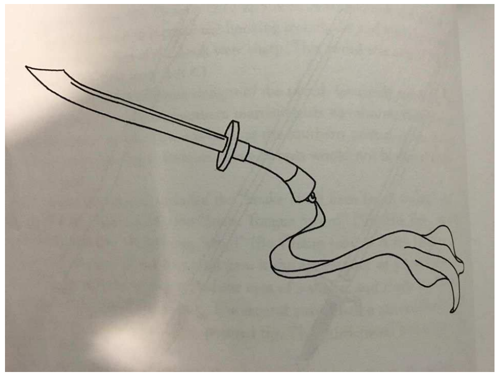


Figure 9. Sketch of the Dao [14].

3.7 Rise of the Empire of Western Jin

The Western Jin Empire ruled from 265 CE until 314 CE. It began when Sima Yan usurped the Wei Kingdom form Cao Haun, and ended after northern forces and internal strife tore the empire apart.

3.7.1 The Beginning of the Western Jin Empire

In 265 CE, Sima Yan took over the Wei kingdom from Cao Huan by force, thus founding the empire of Jin. The Sima were supported by the populus because they were seen as the representative of the forces allied against the Cao family, who had ruled before them. Many saw their reign as strong and honorable.

Unlike the Han and Wei kingdoms before them, the Sima put many members of their family in positions of power, with Sima Yan making twenty seven of his relatives princes. However, since the Sima had gained rule through intrigue and promotions within the family, rather than conquest like the Wei or centuries of rule like the Han, their rule was initially surrounded by an air of uncertainty.

Sima Yan did not believe he had the kingdom strength to defeat the Wu to the south at the beginning of his rule. However, by 280 CE, the Wu had been under constant attack by immigrants who had risen up and attacked them. Although these rebels were eventually defeated, they had sufficiently weakened the Wu enough for the Jin to mount an attack. The Jin flanked the Wu, with Sima Zhao mounting an attack to the south and Wang Jun sailing down the Yangzi Gorges with a fleet of ships, opening the way for the regular Jin troops to advance down the Han. On May 1, 280 CE, the Wu surrendered to the Jin [1].

3.7.2 The Reign of Empress Jia

Sima Yan passed away on May 16, 290 CE at fifty-five years old. His thirty-year-old son, Sima Zhong, then replaced him on the throne. In 272, Zhong had married Jia Nanfeng. Jia's family was composed of a series of powerful ministers, and, since Zhong was generally considered to be somewhat unfit to rule, the Jia clan performed a coup, where Empress Jia took control of the government on April 23, 291 CE. However, on May 7, 300 CE, Sima Yi's son, Sima Lun, and his allies took over the capital, and forced Empress Jia to commit suicide [1].

3.7.3 The End of the Western Jin Empire

The Jin family, now back in power after the brief reign of the Jia clan, held power for several years. However, during this time, immigrants in the empire were constantly plaguing the frontiers of the empire. In addition, armies from the north sided with these rebels, until they eventually overthrew the capital and plunged the former Jin Empire into the era of chaos known as the Period of Discontinuity. The Western Jin Empire ruled from 265 CE until 314 CE, when the last members of the Jin rulers were killed by rebels and armies from the north [1].

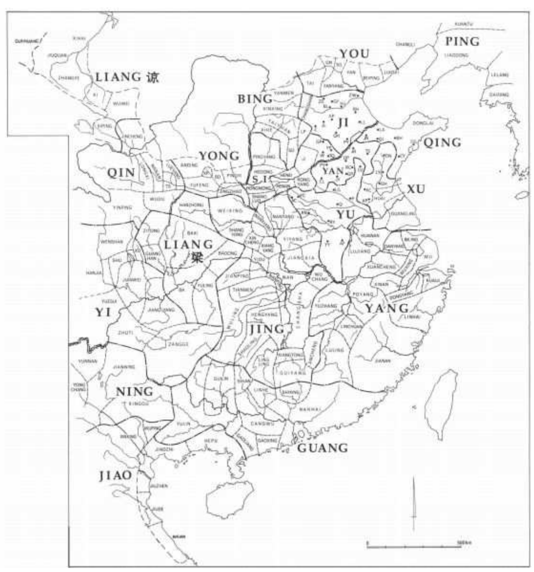


Figure 10. Provinces and Commandery Units of Western-Jin, circa 280 CE [1].

3.7.4 Military Structure in the Western Jin

The official armies of the Wei and Western Jin dynasties used a pattern of military service very similar to the *buqu* forces. The *buqu* loosely translates to 'troops,' and are regular units of military organization. When a commander died, a family member would assume control of their troops, since the command was not reliant on individual commanders but rather wealthy families and the farmers that served as troops under them. The *buqu* were absorbed into the government armies, which supplied a large reservoir of military might. Military families were held in cities, where they could be used as hostages if need be.

The military structure of the Jin was inherited from the Wei. They had an inner army, situated in the capital of Luoyang, of about one hundred thousand, and a much larger army consisting of garrisons in the provinces. The inner army was controlled by the imperial court, while the outer army was controlled by regional commanders, called *dudu*, who were appointed by the court. The Jin army was largest shortly after the conquest of Wu in 280 CE, at about 700,000 men.

In addition to the *buqu*, the Western Jin utilized the people of the steppe as skilled cavalrymen. During this time horse armor (*makai*) became prevalent, along with use of the saddle, which greatly enhanced the usefulness of the cavalry. This seems to have taken place in response to the invention of the saddle, and led to heavily armored, elite cavalry troops being vital to Chinese armies. They also used the dao, a curved sword, to kill either foot soldiers or other cavalry on horseback. The dao is the weapon that will be focused on in the next section of this report [8].

3.8 Period of Disunity

After the fall of the Western Jin Empire, power in China consisted of non-Chinese peoples for the first time. In 304 CE, a Sinicized Xiongnu chieftain, Li Yuan, became the king of Han and began conquering northern China. With support from Chinese rebels, he conquered the homeland of Chinese civilization. The fall of the two major Chinese capitals, Luoyang in 311 CE and Chang'an in 316 CE, marked the end of Chinese dynastic rule in the north, a state of affairs that would last for centuries. Although in the northeast and interior areas of China, local kingdoms occasionally were able to maintain themselves for some time, the entire North China Plain became a discordant collection of barbarian states, together known as the Shiliuguo or Sixteen Kingdoms.

The era consisting of the Han Dynasty through the end of the Period of Disunity was a period of turmoil in Imperial China. However, along with this turmoil, came many military advancements, in weaponry, armor, and tools, as well as manufacturing. A major target of these advancements was the dao. This sword, its materials, and how it was manufactured will be the subject of the next section [5].

4. Materials and Manufacturing During the Period of Disunity

The Period of Disunity was a time of great strife and war in China. As such the development of weapons was accelerated, and the dao was no exception. It went through several changes in its design, spurred by the violence of war.

4.1 Manufacturing of the Dao During the Han Dynasty

Although bronze swords of surprising strength were still used until the late Han Dynasty, they had fallen out of favor, and were replaced by swords of steel. This was due to the fact that converting iron to steel had become much more easily managed by this time, and steel was a significantly better material for weaponry.

During the Han Dynasty, straight or slightly curved dao with ring pommels, or *huan shou dao*, became immensely popular and were eventually exported to Japan [15].

Figure 11. Three dao swords from the Han Dynasty [15].

During the middle period of the Han Dynasty, the techniques of making iron and steel swords became incredibly advanced. Iron was folded many times during forging, as well as heated and hammered. Also during forging, carbon was added to the iron to change it into steel. The number of folds, varying between thirty and fifty, and sometimes even more, provided a measure of the eventual quality of the steel. In another popular technique at the time, batches of steel of varying quality were combined together to form high-impact blades that retained cutting quality. Quenching technology was also very advanced during this time, as were the knowledge of timing and temperature, and polishing and sharpening skills as well.

This polishing showed the veins of the blade, and allowed masters of *xiang dao*, or “observing” to determine the quality of the blade [15].

In terms of quenching techniques, the first part of a blade that enters the quenching water will become the hardest part of the sword. This is due to the fact that the more quickly a blade’s temperature cools, the harder it is. Because of this, dao were easier to quench than double edged blades, such as Jian, as they would be put into the quenching water tip and edge first, meaning that the back and lower sections of the blade would end up softer. This method of quenching was also done for more practical, warfare-based reasons, given that the softer sections absorb shock better, and thus were easily used for defensive measures [6].

4.2 Manufacturing of the Dao During the Period of Disunity

The manufacturing of high-quality dao became widespread during the Three Kingdoms Period, and the ring-pommel style detailed above became the most popular. Long-handled dao were especially favorites of cavalry. During the widespread civil wars in the three hundred years following the Three Kingdoms Period, the development of sophisticated weaponry rapidly accelerated. This included changes in the shape of the dao: it became wider and more curved, and its length was shortened to less than 100 centimeters. The blade also was made thicker. It is thought these changes occurred due to the development of the saddle and the stirrup, which allowed cavalry to be more maneuverable.

Figure 12. A dao with a shorter and wider blade [15].

The manufacturing processes of the dao during the Han Dynasty through the end of the Period of Disunity evolved to be much more robust and advanced as time went on. Similarly, the shape and size of the dao also evolved, seemingly in tandem with the political, social, and military climate at the time. The next section will focus on our own reconstruction of the dao, the processes which was followed, and the materials that were used, in accordance with one of the evolutions of the dao throughout this time period [15].

5. Reconstruction of the Dao

5.1 Materials

The metal that was chosen to construct the dao was 1075 steel. This metal has 0.76 wt% C with dimensions of 48 inches long and 1 ½ inches wide by ¼ inch thick. This metal also has 0.24 wt% Si, 0.35 wt% Mn, 0.1 wt% P, and 0.01 wt% S in its composition. The dao sword is around 36 inches, or one meter long, so the remaining foot can be used to practice forging techniques as well as collecting metal samples. The metal has been annealed before it was acquired. The annealing process will heat up the metal to about 1050°C, and the furnace will cool down slowly. Based on the Figure 13, the metal weighs about five pounds. There are more physical traits in the Figure 13.

Density (lb / cu. in.)	0.284
Specific Gravity	7.86
Specific Heat (Btu/lb/Deg F - [32-212 Deg F])	0.107
Melting Point (Deg F)	2760
Poissons Ratio	0.3
Thermal Conductivity	360
Mean Coeff Thermal Expansion	6.7
Modulus of Elasticity Tension	30
Modulus of Elasticity Torsion	11

Figure 13. Physical data for the 1075 steel [16].

5.2 Overview of the Reconstruction Process

The reconstruction of the dao has three stages: preparation, forging and shaping, and finishing touches. The preparation stage first consists of designing the dao as a CAD model, cutting the original metal bar into two pieces, one for the full-sized blade, and one for the smaller, practice blade. The samples for analysis are then cut from the practice blade. After that, the diagonal edge for both blades is cut off to make shaping easier, and then the forging and shaping stage can begin.

In this next stage, both blades and repeatedly headed in a forge and hammered into shape. This stage is the longest of the three, and takes several sessions to complete. Once both blades are shaped, the blood groove (an indention on the non-sharpened side of the blade) is hammered into the blade using a heavier mallet that the one used for shaping, and a tool to shape the groove.

Once the blood grove is finished, the blade is polished and the wooden handle is attached, along with the cloth attached to the handle for wiping sweat and blood off the blade. After these finishing touches have been added, the reconstruction of the blade is complete.

After the dao is finished, this is what it should look like:

Figure 14. SolidWorks model of the Dao.

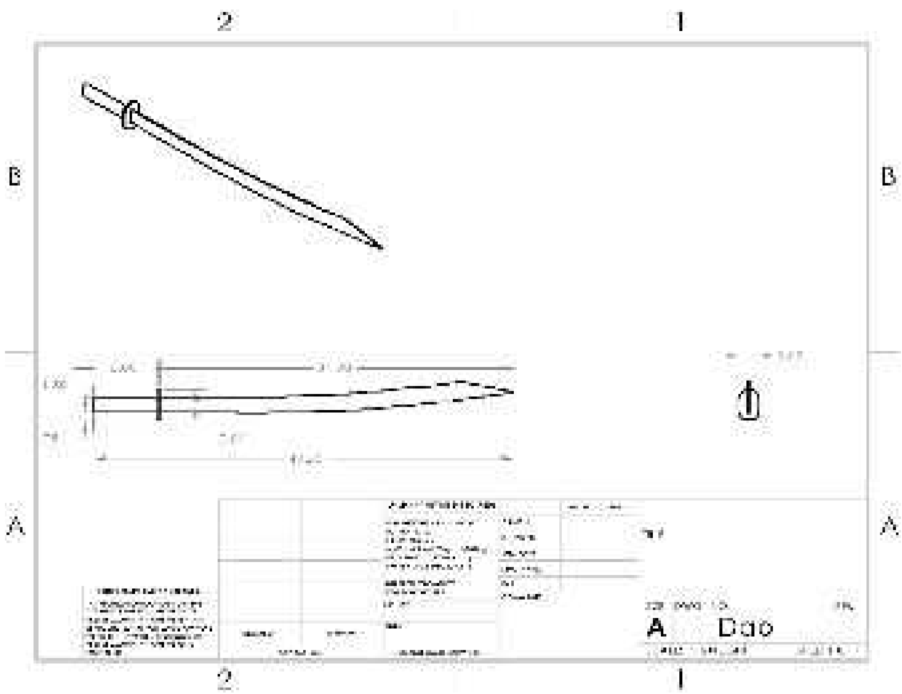


Figure 15. SolidWorks drawing of the Dao.

5.3 Reconstruction

5.3.1 Practice Dao

The reconstruction of the dao began by practicing forging on scrap metal. We were instructed on how to work the forges, heat the metal properly, and hammer it into shape. The team members took turns heating and shaping scrap metal, in order to prepare for shaping the actual metal. This was done for the first day of forging, as well as the second. On the second day, the forging and shaping of the smaller, practice dao began.

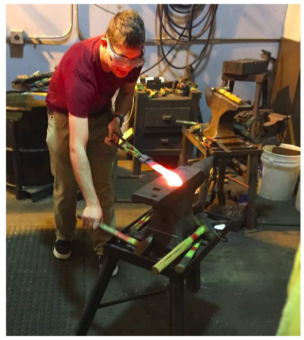


Figure 16. Bryan working on practice metal.

Figure 17. The scrap metal being heated in one of the forges.

In addition to working on scrap metal, on the second day the the cube samples were cut from the practice dao for the material analysis of the metal used to construct the dao. A circular hand saw was used to cut the material for analysis.

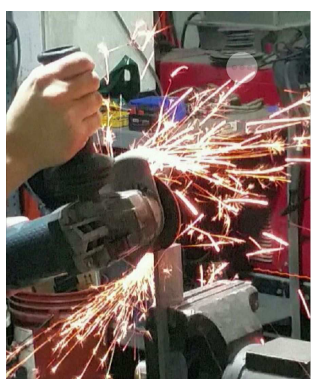


Figure 18. Cutting the analysis sample pieces from the metal.

On the third day of working, forging of the smaller, practice dao continued. In addition, the edge of the practice dao was cut off at an angle with a circular saw, in order to shape the point of the blade more easily.

Figure 19. Smaller practice dao at the end of Day 3 of forging.

On the fourth day of forging, the initial shaping of the smaller dao was completed, and work began on adding the blood groove to that dao. There was a tool, that had a long rounded section on one end of it, which was crucial to create the blood groove. A sledge hammer would hit the tool on the back to create the blood groove.

Figure 20. The tool used for shaping the blood groove.

Figure 21. Close up of the blood groove on the smaller practice dao at the end of Day 5 of forging.

On day seven of forging, the next step is to grind the practice dao to smooth out the grooves that had developed during the forging process.

Figure 22. Grinding the practice dao.

Figure 23. Close up of the practice dao at the end of Day 7.

On day 8 of forging, the practice dao was heated to a cherry-red glow (about 1375ºF). It was then immediately quenched in water until the bubbling stopped (25.67 seconds). After quenching, the second set of samples were cut from the practice dao for material analysis.

Figure 24. The practice dao after quenching.

5.3.2 Reconstruction of the Full-sized Dao

On the third day of forging, a circular hand saw was used to cut off the angled edge of the full-sized blade. After this was completed, the forging and shaping of the full-sized dao began, and decent progress was made. At the end of the smithing session, the dao was allowed to cool below 700ºC, then quenched in water to cool them faster without changing their microstructures.

Figure 25. Full-sized actual dao at the end of Day 3 of forging.

On the fourth day of working, the larger dao continued to be shaped, and the curve of the sword became more pronounced. The process of waiting for each dao to cool and then quenching them in water continued.

Figure 26. Full-sized actual dao at the end of Day 4 of forging.

Figure 27. Close up of the thickness of the tip of the full-sized actual dao at the end of Day 4 of forging.

On the fifth day of forging, the larger dao continued to be shaped, almost to completion. The blade became much flatter and more curved. Various parts of the blade were focused on. The blade was heated and hammered repeatedly up and down the length of the blade, flattening the blade more with each iteration.

Figure 28. Close up of the edge of the larger dao at the end of Day 5 of forging.

On the sixth day of forging, the blacksmith was out of propane, so the coal forge had to be used. This was a very different experience from the propane forges, as it required manually loading the coal and stoking the flames. The heating process took much longer than it did using the propane forges, so not a lot of work was completed. However, it was valuable experience into how forging was done back in imperial China, as propane forges did not exist then, and coal forging was prevalent. The coal forge is significantly harder to use, and therefore made it difficult to make any progress.

Figure 29. The coal-powered forge.

On the eighth day of forging, the shaping of the larger dao finished, and inconsistencies in the edges were smoothed out. Creation of the blood groove on the larger dao was started.

Figure 30. The started blood groove on the larger dao.

On day nine of forging, the larger dao was straightened to have more of a regular curve. After that, grinding on the day was started, making the sword polished and getting rid of the pockmarks that had accumulated during forging.

Figure 31. Grinding the larger dao.

Figure 32. The larger dao after day 9 of forging.

On the tenth day of forging, the team continued to grind out the divots in the larger dao. The sword was shortened to the required length. The tang was also cut into the bottom of the sword. In addition, the hand guard for the blade was cut off the end of the severed piece, and was shaped using sanding to a rounded oval. The hole in the hand guard was started by drilling into the center of the blade.

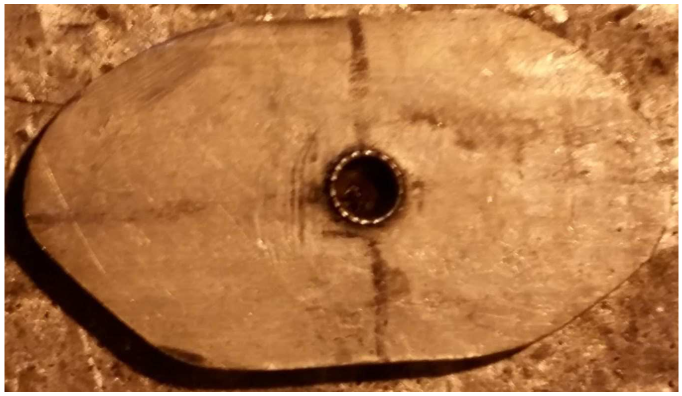


Figure 33. The hand guard after the tenth day of forging.

Figure 34. The larger dao after the tenth day of forging.

On the eleventh day of forging, the grinding down of the blade and blood groove continued. The hand guard was finished, by drilling into the center and then fileing the holes to be the correct shape and size. The tang was shaped to be more tapered. The wooden handles was cut to the correct size, and a hole was drilled in it for the tang to fit into. The tang was then heated with a blowtorch, and used to burn the correct sized hole into the handle.

Figure 35. The finished hand guard.

Figure 36. The hole being bored into the handle by the heated tang.

Figure 37. The assembled dao at of the eleventh day of forging.

On the twelfth day of forging, the grinding of the dao was finished, using the angle grinder for the deeper notches in the metal, then using a coarse, then fine belt grinder to smooth out the dao as a whole.

Figure 38. The dao after the twelfth day of forging.

On the thirteenth day of forging, holes were drilled in the handle and tang for the pins to attach the handle to the dao. Once the first hole was drilled through the handle, the pin was placed in the first hole to hold the tang more stable in the handle for the drilling of the second hole.

Figure 39. The assembled dao before quenching and tempering.

On the last day of forging, the sword was heated to a dull red, then quenched in oil, in order to lessen the chance of cracking. Once the sword cooled, it was tempered by using a blow torch run slowly down the length of the blade. Next, the blade was grinded to make it shiny again. Then the pins are glued into the blade and handle to keep the handle in place, sanding them down to a smooth surface.

Figure 40. The assembled dao before adding the cloth.

Finally, the cloth was attached to the handle using a screw and some glue, to create a finished product.

Figure 41. The final, assembled dao.

6. Analysis of Materials

6.1 Background to Phase Diagrams

The 1075 steel bar will have its microstructures change many times during the processes of heat treatment and quenching before the end of the construction of the dao. In order to understand the possible scenarios the steel's microstructures will form, the knowledge of all forms of iron should be viewed.

The major components of the material are iron and carbon, which can make many different materials. Materials can vary based on the percentage of carbon, how the material cools, and so much more. These variations can be shown on a phase diagram. A phase diagram gives information about the changes of a phase structure, which are controlled by the following variables: temperature, pressure, and composition [3]. The following phase diagrams have a constant pressure, and the other two variables will vary. The Fe-Fe_3C phase diagram shows the different phases the iron carbide alloy can go through.

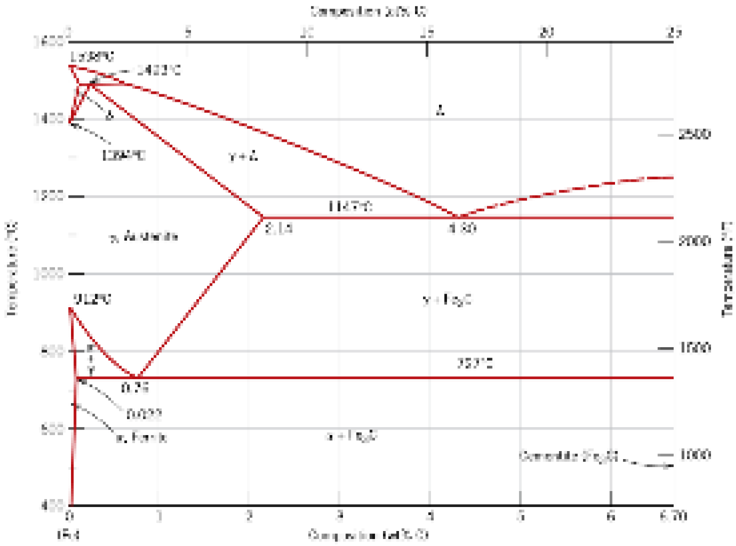


Figure 42. Fe-Fe_3C phase diagram [3].

If this is done with equilibrium cooling, which is letting it cool down naturally without any form of quenching, the metal can be of a mixture between these four different microstructures: ferrite, austenite, cementite, and pearlite. Based on temperature, the microstructures can change and form different variations. Once heated to the appropriate temperature required. The metal will cool down and from gradual changes until reaching room temperature.

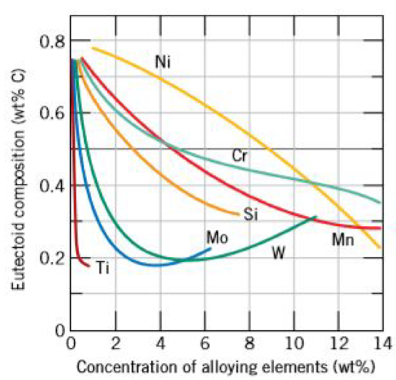


Figure 43. Graph showing new eutectoid carbon composition based on various alloying elements [3].

There are other alloying metals that would change the phase diagram [3]. Such elements are as follows: Titanium, Silicon, Chromium, Nickel, Manganese, Tungsten, and Molybdenum. The amount of these elements can change the eutectoid composition of carbon. These components are inversely related to each other. These elements also change the eutectoid temperature. Most of the elements mentioned will increase the eutectoid temperature with an increasing composition. The only two that decrease the temperature are Manganese and Nickel [3].

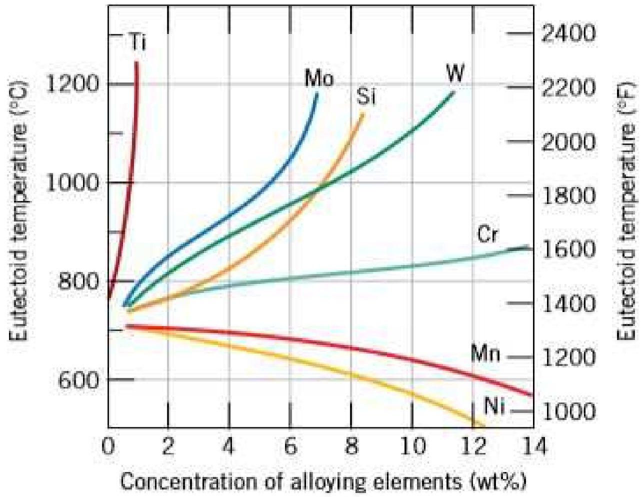


Figure 44. Graph showing new eutectoid temperature based on various alloying elements [3].

(a) (b)

Figure 45. (a) Ferrite and (b) austenite microstructures [3].

A hypoeutectoid steel alloy has under 0.76 wt% C in it, so the changes between the microstructures will be based on Figure 46 if it uses an equilibrium cooling treatment.

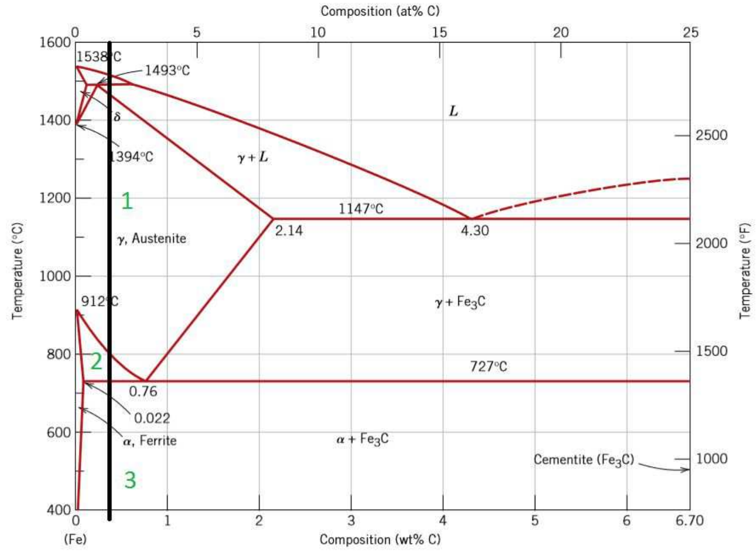


Figure 46. Fe-Fe_3C phase diagram with a highlighted hypoeutectoid composition.

In this example, the alloy has around 0.4 wt% C. For proper heat treatment, the metal would be heated to a temperature around 1200°C. This would change the metal's microstructure to be pure austenite, and this is shown in the phase diagram above where the one is. In this example, the steel will change slightly and include ferrite in the microstructure along with the previous austenite once it cools down to the 800°C. This is in the area on the phase diagram above that is represented by the number two. Once the metal has cooled down to temperatures to 730°C and below the austenite will change to ferrite and iron carbides. The ferrite that was already forming during the phase before will become a proeutectoid ferrite. The austenite will become into two things: proeutectoid ferrite and pearlite. Figure 47 shows an example of what the microstructure would look like.

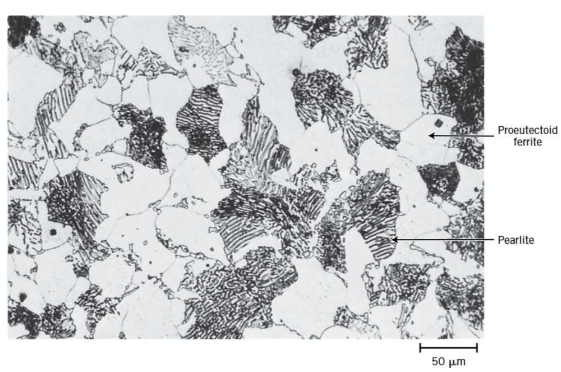


Figure 47. Image of microstructure for hypoeutectoid metal after equilibrium cooling [3].

The other case for steel is a eutectoid alloy, where the carbon percentage is exactly 0.76. So this is one of the few cases where it has two stages as it goes through equilibrium cooling. The first stage for the eutectoid alloy is the same as both hypoeutectoid and hypereutectoid steel alloys. When heated to around 1200ºC, the microstructures of the alloy become austenite, but eutectoids are the special case where there is not a middle stage. The other steel alloys start to form some ferrite or cementite as temperature drops, but the eutectoid alloy will be the same until the alloy cools down to reach the final stage, which occurs around 700ºC. The eutectoids second and final change is when the microstructures become only pearlite.

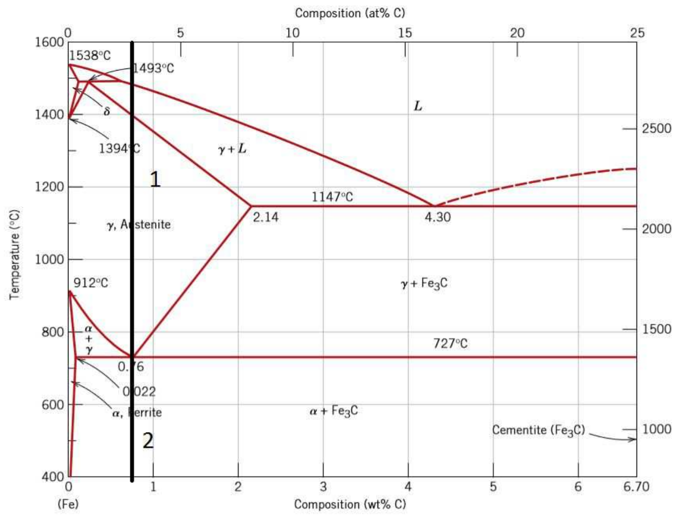


Figure 48. Fe-Fe_3C phase diagram with a highlighted eutectoid composition.

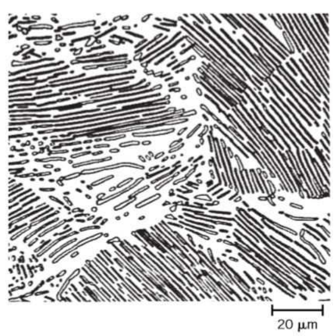


Figure 49. Image of pearlite microstructure [3].

Another example can be done with a hypereutectoid steel alloy, which have greater than 0.76 wt% C in it. Based on Figure 50, this steel has about 1.3 wt% C. When the metal is heated, the temperature is once again around 1200ºC, and this is the area on the phase diagram below that is numbered as one. During this treatment, the microstructures of the metal is purely austenite. Once the metal cools down to around 900ºC, the microstructures will start to alter and have some cementite along with the austenite, which occurs in the second state of the phase diagram below.

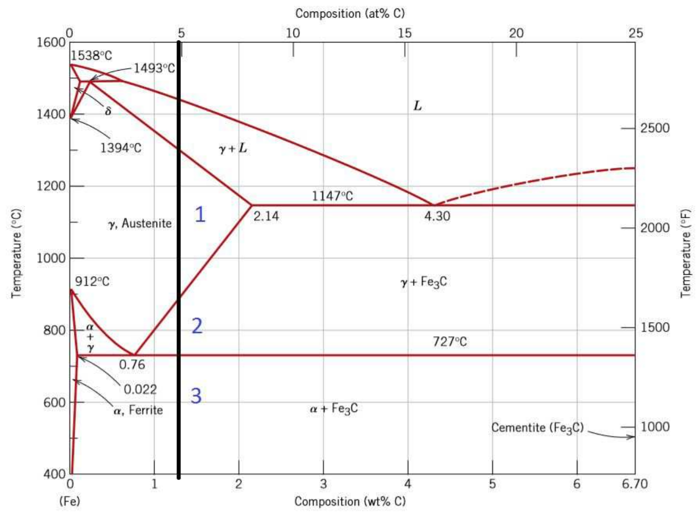


Figure 50. Fe-Fe$_3$C phase diagram with a highlighted hypereutectoid composition.

Once the metal cools down even further from a form of equilibrium cooling, the microstructure will alter one more time. The cementite and austenite combination from before will change to two new things. The cementite will become a proeutectoid cementite, while the austenite will become pearlite. This microstructured can be seen below.

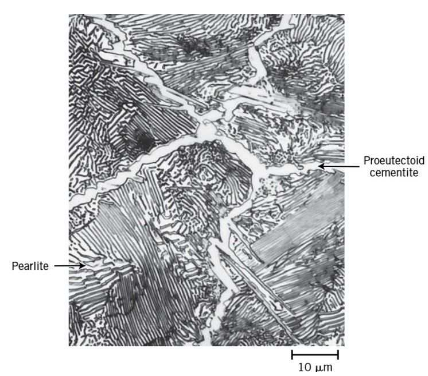


Figure 51. Image of microstructure for hypereutectoid metal after equilibrium cooling [3].

Alloys that have more than 2.14 wt% C are classified as cast iron instead of steel. So there are two cases for cast iron. The first one occurs when the alloy has a carbon percent that is less than 4.3. Figure 52 describes this example.

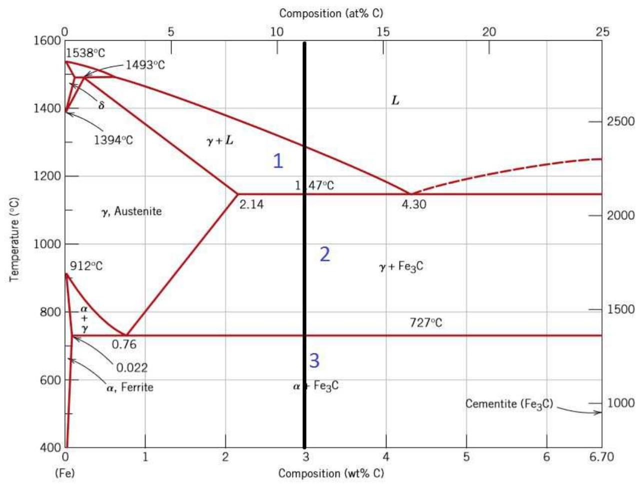


Figure 52. 2nd Fe-Fe_3C phase diagram with a highlighted hypereutectoid composition.

At the temperature of 1200ºC, the cast iron alloy would form an austenite microstructure, but the metal would most likely be in a liquid form. The alloy will solidify quickly since the temperature required to change state is 1147ºC. Once it solidifies, the microstructure will also start to form cementite. Once the temperature drops below the eutectoid temperature, the microstructure will change to something similar to the hypereutectoid steel alloy.

The other case for the cast iron alloy is when the carbon percentage is between 4.3 and 6.7. This alloy would melt at the same temperature where the other alloys form austenite. Once the temperature drops below 1147ºC, like before, the alloy will be solidified and form austenite with cementite. This will form pearlite and cementite microstructures when the temperature drops below the eutectoid temperature (727ºC).

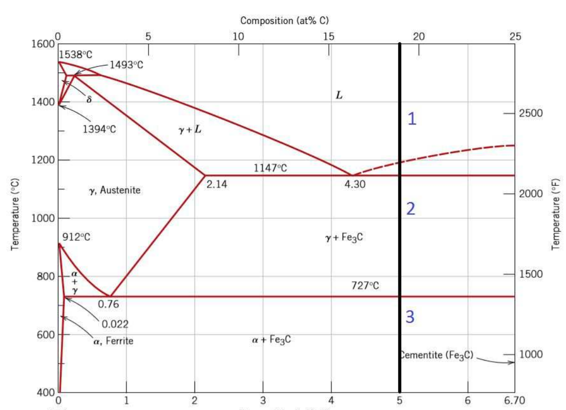


Figure 53. Another Fe-Fe_3C phase diagram with a highlighted hypereutectoid composition.

For non-equilibrium cooling, there are two more microstructures that can be formed, which are martensite and bainite. In order for the microstructures to contain bainite, the time it takes to bring the metal's temperature back to room temperature must be between a minute to a day. Martensite will always be present if the metal is quenched, but the percentage of martensite will vary based on the cooling rate.

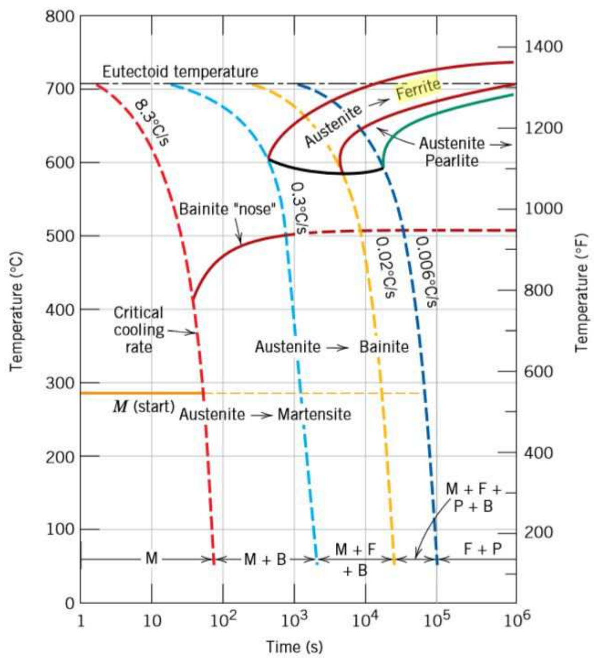


Figure 54. Continuous-Cooling Transformation diagram [3].

When the steel alloys are heated to form austenite microstructures and are cooled down by a method of non-equilibrium cooling, the microstructures will form martensite and possibly bainite. If the heated metal was quenched by water, the temperature would drop to room temperature within less than two minutes. The microstructures will transform into pure martensite.

Figure 55. Image of martensite microstructure [3].

If the heated metal was quenched by oil, the time it will take to reach normal temperatures will be within 2 to 20 minutes. This will change the microstructures from austenite to martensite and bainite. As the non-equilibrium cooling process gets slower, the microstructures appear closer to those of an equilibrium cooling process. The cooling down process only matters when the temperature reaches at the eutectoid temperature and drops from there.

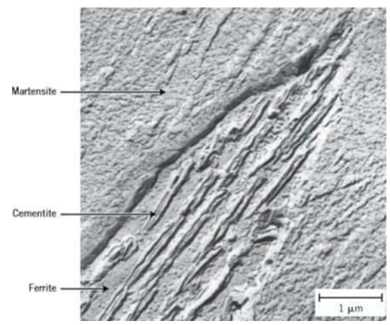


Figure 56. Image of bainite microstructure [3].

6.2 Material Analysis of the Dao

6.2.1 Predicted Analysis of the Dao

The steel has 0.76 wt% C which makes it a eutectoid alloy, but the manufacturers mentioned the steel is actually a hypoeutectoid alloy. The Figure 57 has a green line that represents the possible transformations for a 0.76 wt% C, steel alloy. The composition of the metal does include two elements that will affect the eutectoid temperature and the carbon percent. Since the silicon and manganese are very low, it will not affect the eutectoid temperature nor the eutectoid carbon percent. This line would be very accurate for equilibrium cooling, but the metal shall be quenched, so there will be martensite and possibly bainite in the microstructures. The metal will be heated first around 1200^{o}C, so the microstructure would be completely austenitic.

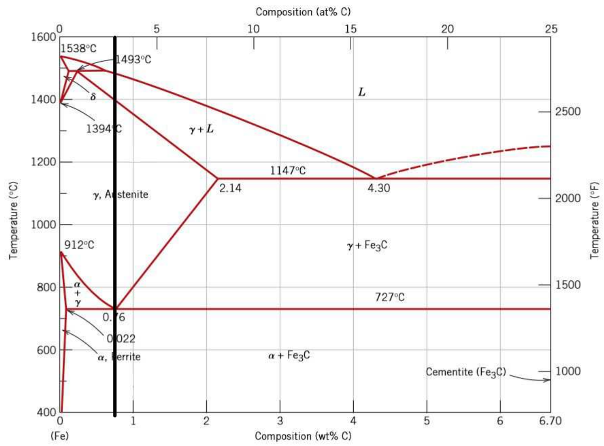


Figure 57. Fe-Fe_3C phase diagram with a highlighted composition.

The steel alloy was annealed before acquiring the metal. The manufacturer's website mentions the annealed structure is 92 %. Since this is supposedly 0.76 wt% C, it seems like the 92 % is the fraction for amount of pearlite transformed from the original alloy. With this information, the actual percent carbon can be found by using the following equation [3].

$$w_p = \frac{C-0.022}{0.76-0.022} \qquad (1)$$

$$C = w_p * (0.76 - 0.022) + 0.022 \qquad (2)$$

W_p is the percentage of the microstructures becoming pearlite. The numbers 0.76 and 0.022 are the possible ranges for a hypoeutectoid steel alloy's carbon percentage. The more pearlite the microstructures will have if the carbon percentage is closer to the eutectoid percent, 0.76. Since the structure's percent is 92, the percentage would replace the w_p in the equation. The "C" in the equation is the carbon percent of the alloy, which can now be determined.

$$C = 0.92 * (0.76 - 0.022) + 0.022 = 0.70096 \qquad (3)$$

So based on the third equation, the actual carbon percentage of the 1075 steel is 0.70. With this, the amount of proeutectoid ferrite and pearlite can be found. The calculation of the proeutectoid ferrite can be shown in the fifth formula. Using the first formula, the sixth formula shows how pearlite makes up 92 % of the microstructures.

$$W_\alpha = \frac{0.76 - C}{0.76-0.022} \qquad (4)$$

$$W_\alpha = \frac{0.76 - 0.70096}{0.76-0.022} = 0.06096/0.738 = .08262 \approx 8\ \% \quad (5)$$

$$w_p = \frac{0.70096-0.022}{0.76-0.022} = 0.67896/0.738 \approx 92\ \% \qquad (6)$$

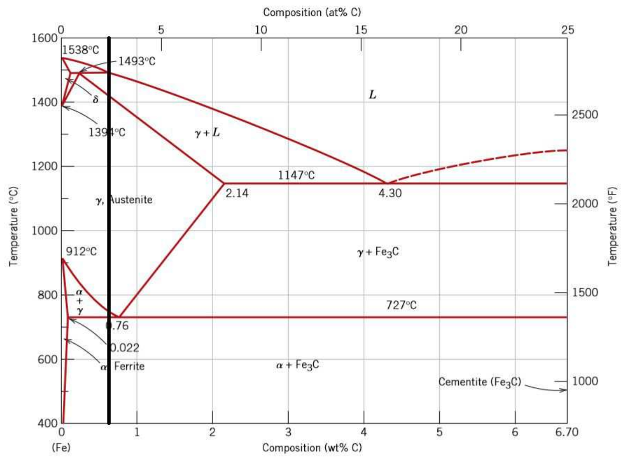


Figure 58. Phase diagram with a highlighted dao composition (predicted).

If the alloy is quenched to room temperature within two minutes, there won't be any bainite in the microstructure. If the quenching takes up seventeen more minutes, ferrite and eventually pearlite will start to form. Since the dao will be quenched in water, the process is method of nonequilibrium cooling. Since quenching takes less than a few minutes to cool down the metal, the dao will most likely be pure martensite. Since this is a sword, martensite will not be favorable since this would make the sword very brittle. The best option would be to reheat the metal to temper the martensite, which would make the material more pliable.

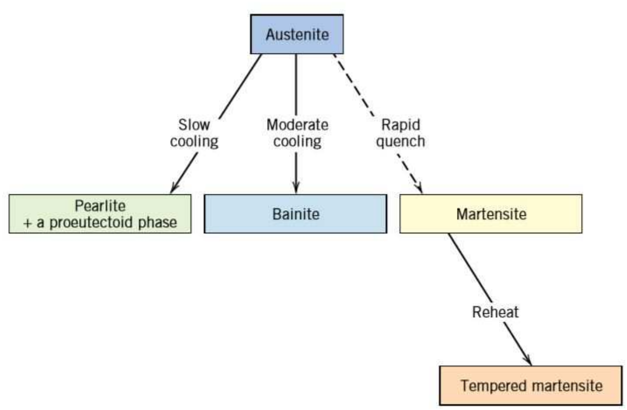


Figure 59. Possible transformations for austenite [3].

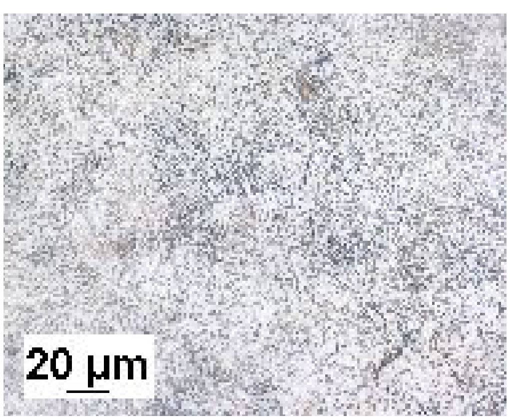
6.2.2 Actual Analysis of the Dao

The samples are cut out from the metal before starting the construction of the dao. Using these samples, the metal was analyzed from all three directions (xy-plane, xz-plane, and yz-plane). These are referred as Ixy, Ixz, and Iyz. After quenching our sample sword, three more samples were taken and analyzed those samples from all three directions. These samples are referred to as Qxy, Qxz, and Qyz. After tempering the sample sword, three more samples are taken. These are referred to as Txy, Txz, and Tyz. These samples were analyzed the same way as the other 6 samples.

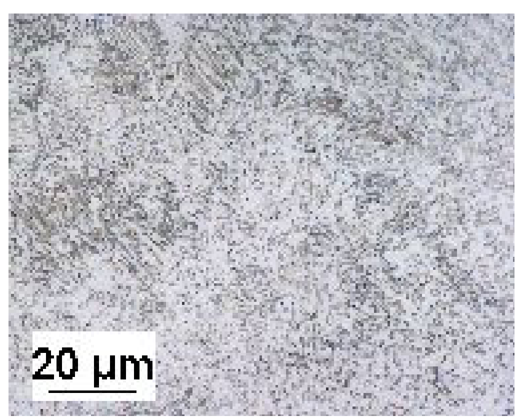
6.2.2.1 Analysis of Initial Samples

A sample of the 1075 metal was tested to see the actual carbon percentage. There were four collections taken from the metal, but the results varied from each collection. The first result showed that the metal had 0.6 wt% C, but the second sample resulted in 0.54 wt% C. The third and fourth test showed 0.63 wt% C and 0.67 wt% C, which led to an average of 0.61 wt% C. The carbon percentage of 0.70 wt% C used in the calculations is slightly higher than measured, but the predictions of the microstructures will be similar.

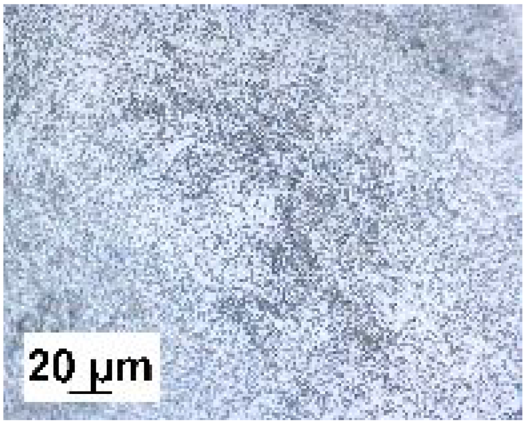
Once the samples are mounted, grinded, and polished, the samples are taken to be etched. The samples are etched by dipping them in a 5% nital solution for three seconds (1 mL of nitric acid, 19 mL of ethanol). The samples are washed and dried before they are viewed in an optical microscope. The following images show what the results of the microstructural analysis are.



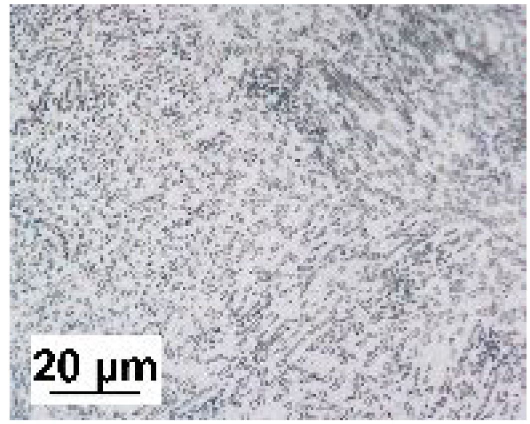
(a) Ixy-50x cross section



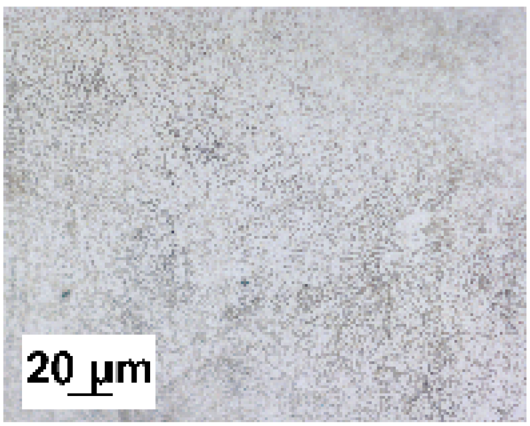
(b) Ixy-100x cross section



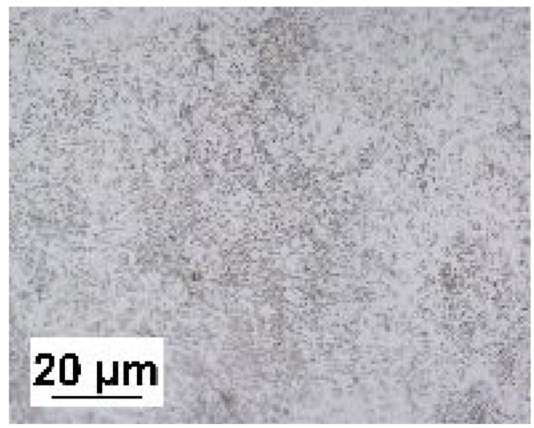
(c) Ixz-50x cross section



(d) Ixz-100x cross section



(e) Iyz-50x cross section



(f) Iyz-100x cross section

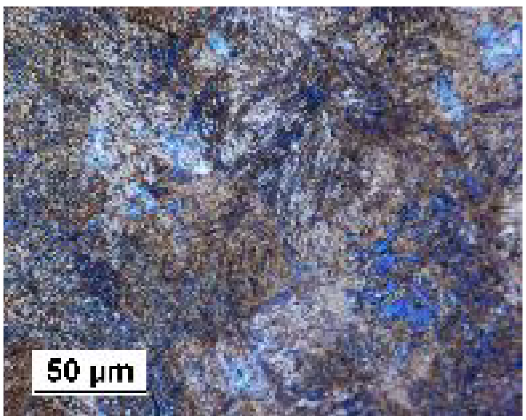
Figure 60. Initial microstructures on all three cross-sectional planes.

The microstructures of the initial samples resemble spheroidite rather than pearlite. This is expected as high and medium carbon steels are usually too tough to machine, and therefore most of these metals are heat-treated or annealed to develop spheroidite [3]. For high carbon steels, it is normal for the annealing process to occur twice, but the second time happens at a lower temperature in the 700 - 900^{o}C range [7]. The resulting spheroidite microstructure makes the metal easier to machine since it increases its ductility.

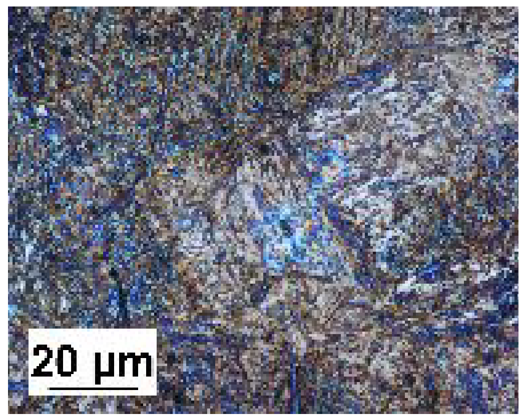
6.2.2.2 Analysis of Quenched Samples

When quenching the practice sword, the metal was heated up to 1500ºF, or 815.5ºC. The metal took 25.67 seconds to cool down to room temperature. Based on the seventh calculation, the cooling rate is 30.88ºC per second. Since the cooling rate was beyond the 8.3ºC per second, the microstructures are guaranteed to be martensite. The samples were mounted, polished, and etched the same way that the initial samples were.

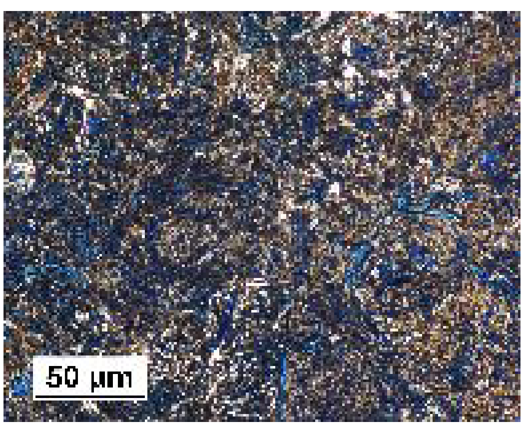
$$\frac{1500^{o}F-73^{o}F}{25.67\ s} = 55.59\ ^{o}F/s\ * 5/9 = 30.88\ ^{o}C/s \quad (7)$$



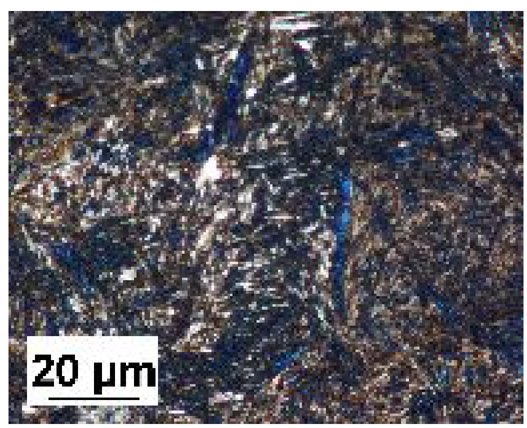
(a) Qxy-50x cross section



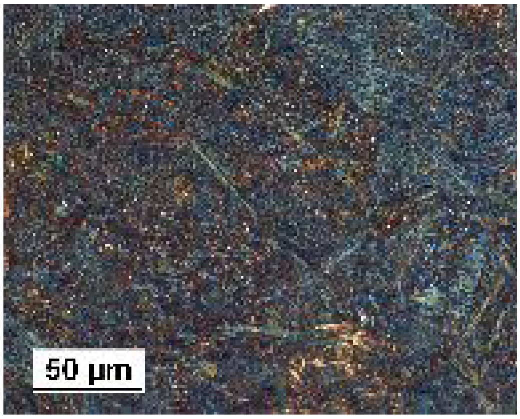
(b) Qxy-100x cross section

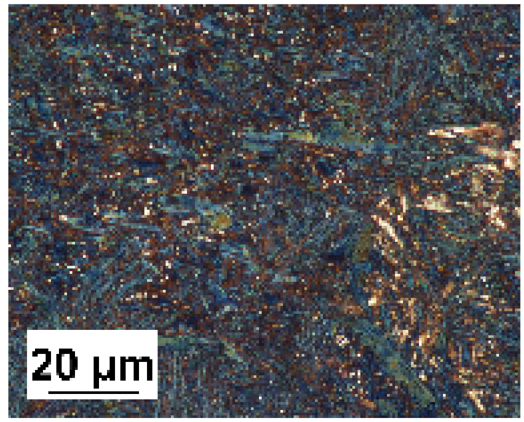


(c) Qxz-50x cross section



(d) Qxz-100x cross section





(e) Qyz-50x cross section

(f) Qyz-100x cross section

Figure 61. Quenched microstructures on all three cross-sectional planes.

Rapid quenching was used to quench the metal, so our estimate for the composition of the metal was 100% martensite. Our estimate was correct, as the images confirm that the metal is 100% martensite. Although the process for the dao was different; it would be more beneficial to the 1075 metal if it were quenched in oil than in water. Water has a higher chance of cracking the metal when quenching, and oil quenching will make the metal more ductile than the water quenching. After a quick analysis (Shown by the eighth formula), the cooling rate is 28.12ºC per second, which is beyond the required 8.3 to form martensite.

$$\frac{1500^oF - 150^oF}{26.67\ s} = 55.59\ {}^oF/s * 5/9 = 28.12\ {}^oC/s \quad (8)$$

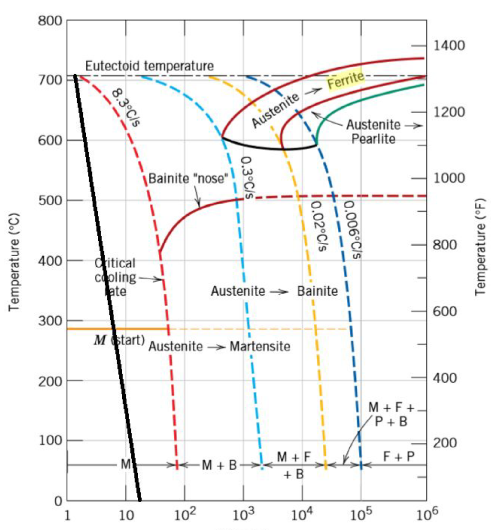
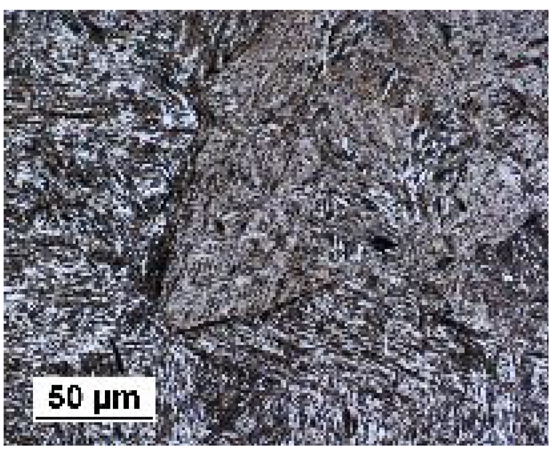


Figure 62. Continuous-Cooling Transformation diagram with Oil-Quenched Cool Rate; the calculated cooling rate for the actual quenching of the samples is represented by the black line.

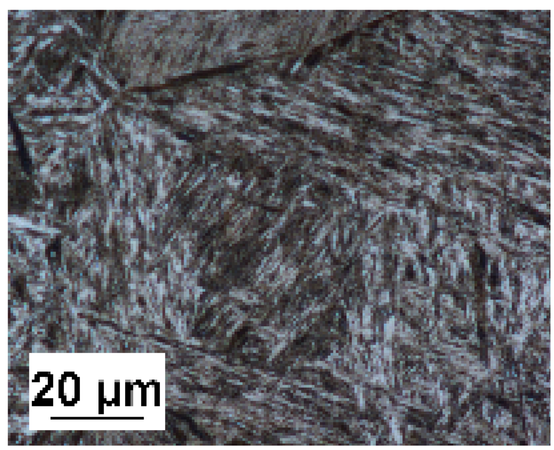
Figure 62 shows where the cooling rate for the 1075 steel quenched in oil would be around. As shown on the figure, the trendline is within the left side of the minimum martensitic cooling rate. This would make it reach the point where martensite starts to form. It would not create any bainite in the microstructure since the time and temperature requirements to form bainite are not met.

6.2.2.3 Analysis of Tempered Samples

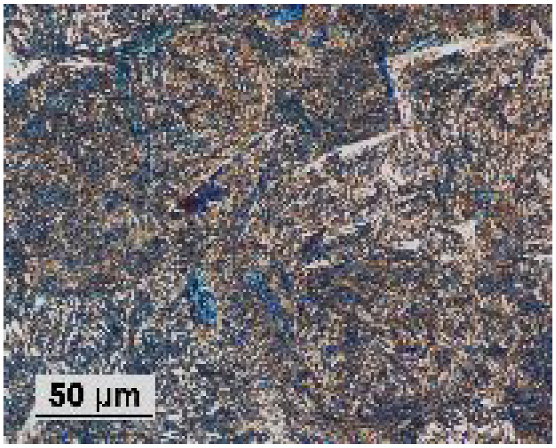
After the metal was quenched, it was tempered at 540ºF (280ºC)for an hour and a half. This was done with the sample sword by having it sit in a toaster for a few hours. Afterwards, it was cooled to room temperature. This process should not have changed the material structure, but instead should make it less brittle. Then, the samples were grinded, polished, and etched through the same process as the previous sets of samples.



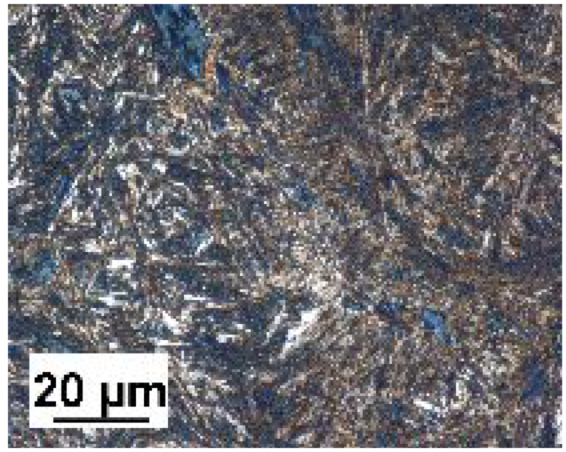
(a) Txy-50x cross section



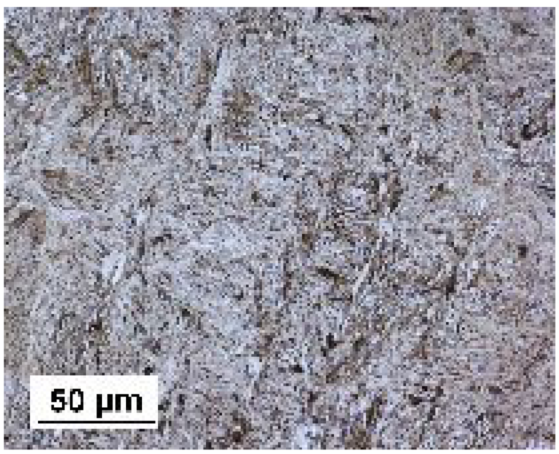
(b) Txy-100x cross section



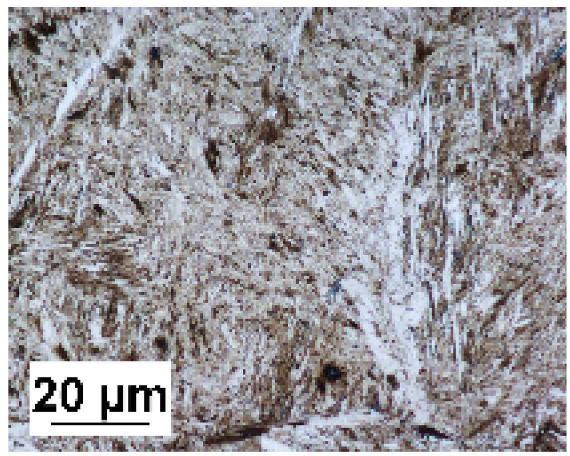
(c) Txz-50x cross section



(d) Txz-100x cross section



(e) Tyz-50x cross section



(f) Tyz-100x cross section

Figure 63. Tempered microstructures on all three cross-sectional planes.

The prediction was that the material would not change between quenching the metal and tempering the metal. The images confirmed that the material did not change, and that it is still martensite (tempered martensite). The material structure stayed the same, but the material properties changed, making the metal harder and less brittle.

7. Conclusion

This report went over the history of the Three Kingdoms periods, which was mostly focused on the warfare between the three kingdoms. The fighting between all of the kingdoms caused their weaponry to advance at a rapid rate. The four main weapons were the gun (staff), qiang (spear), jian (narrow-blade sword), and dao (wide-blade sword /saber). This project also focused on their most improved weapon, the dao. The dao varies based on geological location and personal preferences, but most had a curved wide blade. It also changed over time. This project required the recreation the basic version of the dao. The dao has a basic edge guard and a cloth that is long enough to wipe the blood off the blade and could also wrap around the handle for better grip. There is also a blood groove along the entire back end of the sword, on both sides. Throughout the reconstruction process, there was an effort to make sure not to change the material structure until the end. At the end of each session, to cool the blade down, the blade was dipped it in water. There was a bit of time to wait for the blade to cool down a bit first, though. If the blade was quenched too soon, the microstructures would change to martensite, and the sword would become too brittle. Once the forging process was finished, the sword was quenched, tempered, and analyzed at each phase. The quenching caused the material structure to change to martensite, where the blade became stronger, but also, more brittle. By tempering the sword, it became less brittle and more ductile. These techniques helped to make the dao a very prominent weapon in China for a very long time.

Appendix

A. Timeline

- 25 CE: Huangjin Peasants’ Uprising Begins
- 189 CE: Han Emperor Ling dies
- 193 CE: Emperor Zhou assassinated
- 200 CE: Cao Cao wins Guandu Battle
- 200 CE: Cao Cao Dies; Huangjin Peasants’ Uprising Ends
- 206 - 220 CE: Techniques of iron and steel sword manufacturing advance rapidly
- 208 CE: Cao Cao defeated at the Battle of Red Cliffs
- 221 CE: Liu Bei becomes Emperor of the Han Dynasty and Founds Shu Empire
- 265 CE Jin Dynasty Founded; Qiang starts to “become shorter and lighter.”
- 280 CE: The Wu surrender to the Jin
- 314 CE: Jin Empire Ends

B. Steps for Replica Creation

- Obtain Steel (1075, 4’).
- Cut 1 foot off of steel for practice dao.
- Cut samples for material analysis off of practice dao.
- Cut angled edge for both practice and full-sized dao.
- Shape both blades
    - Heat blade in forge until orange.
    - Hammer until blade is cooled (dull red), thinning the edge of the blade and curving it.
    - Repeat until blade is required shape.
- Place blood groove.
- Grind out imperfections
- Create tang
- Create handguard
- Drill holes in handle and tang
- Quench blade in water.
- Temper blade.
- Add handle.

C. Website Changes

- IQP Report Page
    - Added “2016-2017” with finalized report.
- Resources Page
    - Added additional sources for the history of the Dao
- IQP Teams Page
    - Added “2016-2017” with team member information.

▼ **2016-2017:**

Bryan Benson, Computer Science, Class of 2018
Ryan Coran, Civil Engineering, Class of 2018
Alberto Ramirez, Robotics Enineering, Class of 2018

Figure C1. The teams page changes on the website.

- Replica Construction Page
  - Added “2016-2017” with picture of our replica dao.
  - Added procedure for reproducing replica dao.

Forging a Replica Dao

Overview

This page details the forging of a replica Dao.

The Forging Process

Figure 1 - Our starting point: Stainless Steel with 0.76 percent carbon and dimensions of 48 inches long and 1 ½ inches wide by ¼ inch thick.

From the stock we cut roughly a 36' piece and began by using an angle grinder to cut off the end of the sword at an angle to shape the tip.

Figure 2 - Shaping the metal.

The next step in creating the Dao was to forge it into shape. It was heated up in a propane forge until it was a light orange (about 1700 F to 1800 F). Once heated, the dao was hammered into shape for about 30 seconds, then heated again. This process was repeated for several hours a week over a period of several months, until the edge and shape of the blade had the desired properties.

The Blood Groove

Figure 3 - The started blood groove on the larger Dao.

After the shaping of the blade was finished, the blood groove was added to the Dao. For the blood groove, we used a tool that had a long rounded section on one end of the tool. We used a large hammer on the back end of this tool to create the blood groove.

Figure C2. The dao forging page changes on the website.

Grinding the Dao

Figure 4 - Grinding the Dao.

After the blood groove was added, we began grinding the Dao, making the sword polished and getting rid of the pockmarks that had accumulated during forging. We realized that the grinding also would erase part of the blood groove, so we had to grind the blood groove back to the right depth and width every coulple of iterations of grinding.

Figure 5 - The finished hand guard.

While we were grinding the sword, we also cut about six inches off the end of the Dao, as we realized it was too long. We then ground the end of the sword to a taper for the tang that would go into the handle. After that, we used a small portion of that to form the hand guard. This was made by cutting off the edges using a band saw. The hand guard was then ground into an oval. The center was then cut out using a milling machine, and filed to the right size using a file.

Finishing Touches

Figure 6 - Burning the hole into the handle.

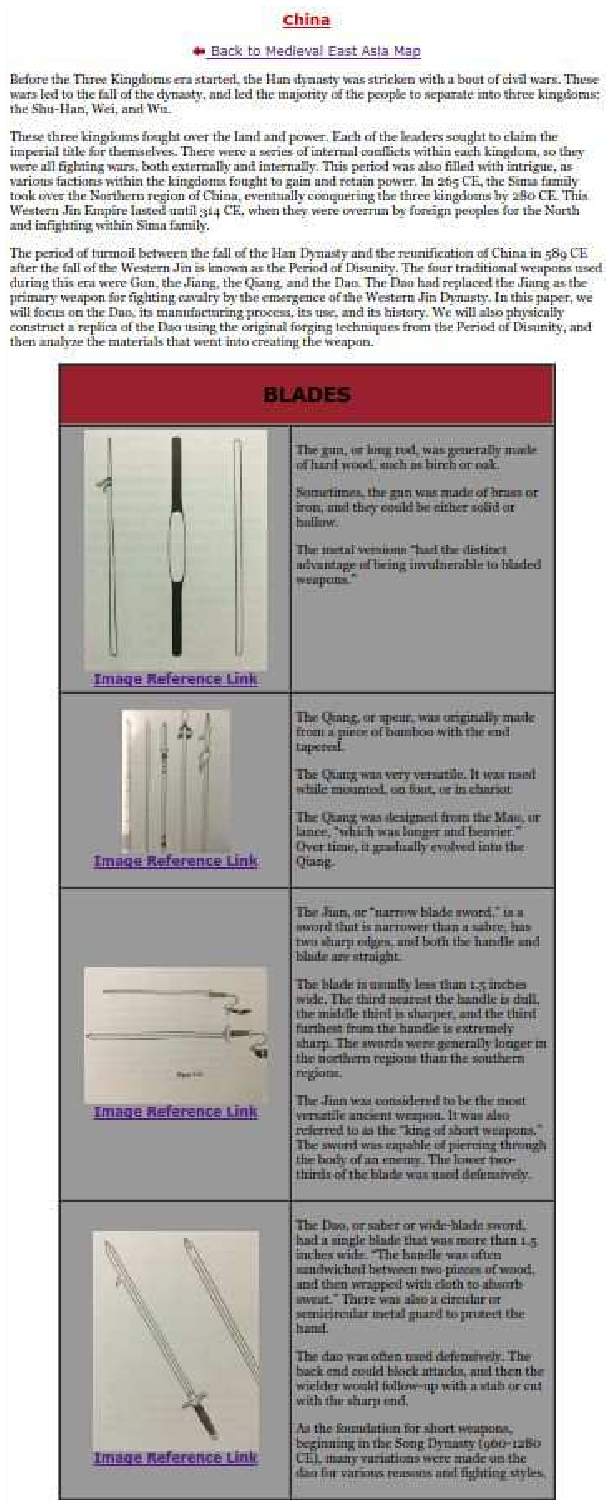
After we created the hand guard, we created the handle. We drilled a hold equal to the length of the tang minus the thickness of the hand guard into the wooden stock that we were using. We then heated up the tang using a blowtorch, and burned the hole that the tang would go into with the heated tang into the handle.

Figure 7 - Final replica of the Dao.

After the handle was created, we finished up grinding, then drilled two holes into the handle and tang for the pins to hold the handle in place. We then heated the Dao up to 1500 degrees Fahrenheit and quenched it in oil. After that, we tempered the steel by heating it up with a blowtorch. Finally, we attached the handle to the tang by fixing the pins in place with epoxy, then added the cloth to the handle with a screw and some more glue.

Figure C2. The dao forging page changes on the website (Continued).

- East Asia World Map Page
    - Added more weapons under China from China background section.
    - Added history of the Three Kingdoms era of China.



China

Back to Medieval East Asia Map

Before the Three Kingdoms era started, the Han dynasty was stricken with a bout of civil wars. These wars led to the fall of the dynasty, and led the majority of the people to separate into three kingdoms: the Shu-Han, Wei, and Wu.

These three kingdoms fought over the land and power. Each of the leaders sought to claim the imperial title for themselves. There were a series of internal conflicts within each kingdom, so they were all fighting wars, both externally and internally. This period was also filled with intrigue, as various factions within the kingdoms fought to gain and retain power. In 265 CE, the Sima family took over the Northern region of China, eventually conquering the three kingdoms by 280 CE. This Western Jin Empire lasted until 314 CE, when they were overrun by foreign peoples for the North and infighting within Sima family.

The period of turmoil between the fall of the Han Dynasty and the reunification of China in 589 CE after the fall of the Western Jin is known as the Period of Disunity. The four traditional weapons used during this era were Gun, the Jiang, the Qiang, and the Dao. The Dao had replaced the Jiang as the primary weapon for fighting cavalry by the emergence of the Western Jin Dynasty. In this paper, we will focus on the Dao, its manufacturing process, its use, and its history. We will also physically construct a replica of the Dao using the original forging techniques from the Period of Disunity, and then analyze the materials that went into creating the weapon.

BLADES	
Image Reference Link	The gun, or long rod, was generally made of hard wood, such as birch or oak. Sometimes, the gun was made of brass or iron, and they could be either solid or hollow. The metal versions "had the distinct advantage of being invulnerable to bladed weapons."
Image Reference Link	The Qiang, or spear, was originally made from a piece of bamboo with the end tapered. The Qiang was very versatile. It was used while mounted, on foot, or in chariot. The Qiang was designed from the Mao, or lance, "which was longer and heavier." Over time, it gradually evolved into the Qiang.
Image Reference Link	The Jian, or "narrow blade sword," is a sword that is narrower than a sabre, has two sharp edges, and both the handle and blade are straight. The blade is usually less than 1.5 inches wide. The third nearest the handle is dull, the middle third is sharper, and the third furthest from the handle is extremely sharp. The swords were generally longer in the northern regions than the southern regions. The Jian was considered to be the most versatile ancient weapon. It was also referred to as the "king of short weapons." The sword was capable of piercing through the body of an enemy. The lower two-thirds of the blade was used defensively.
Image Reference Link	The Dao, or saber or wide-blade sword, had a single blade that was more than 1.5 inches wide. "The handle was often sandwiched between two pieces of wood, and then wrapped with cloth to absorb sweat." There was also a circular or semicircular metal guard to protect the hand. The dao was often used defensively. The back end could block attacks, and then the wielder would follow-up with a stab or cut with the sharp end. As the foundation for short weapons, beginning in the Song Dynasty (960-1280 CE), many variations were made on the dao for various reasons and fighting styles.

Figure C3. The Chinese history changes on the website.

Works Cited

1: ANU. (1991, December). The Continuation of Papers on Far Eastern History. Retrieved September 10, 16, from http://www.eastasianhistory.org/sites/default/files/article-content/02/EAH02_07.pdf

2: By shawn (myanmar) | Jul. 31, 2014 18:21. (n.d.). Three Kingdoms Period. Retrieved September 5, 2016, from http://www.chinatour360.com/history/three-kingdoms-period

3: Callister, W. D., & Rethwisch, D. G. (2014). *Materials science and engineering: An introduction*. Hoboken, NJ: Wiley.

4: Cao Cao [Digital image]. (n.d.). Retrieved October 4, 2016, from https://www.britannica.com/biography/Hua-Tuo/images-videos/Cao-Cao-portrait-by-an-unknown-artist/115354

5: China - Dong (Eastern) Han. (n.d.). Retrieved September 10, 2016, from https://www.britannica.com/place/China/Dong-Eastern-Han

6: Differential Heat Treatment and Quenching. (n.d.). Retrieved November 01, 2016, from http://enlightenmentsword.com/heat-treatment

7: Fritz, J. D. (2004). *ASM Handbook* (9th ed., Vol. 4D). Retrieved April 25, 2017, from http://products.asminternational.org/hbk/index.jsp

8: Graff, D. A. (2004). *Medieval Chinese warfare: 300-900*.

9: [Portait of Liu Bei depicted in Tang Dynasty]. (2014, December 8). Retrieved October 4, 2016, from https://upload.wikimedia.org/wikipedia/commons/thumb/3/34/Liu_Bei_Tang.jpg/220px-Liu_Bei_Tang.jpg

10: [Portait of Sun Quan]. (n.d.). Retrieved October 4, 16, from https://openresearch-repository.anu.edu.au/html/1885/42051/3KWJin.html http://www.thehindu.com/multimedia/dynamic/01595/Th24-ChineseVIl_TH_1595211e.jpg

11: The Three Kingdoms and Western Jin. (2009, June 7). Retrieved September 19, 2016, from

12: The Three Kingdoms Period. (n.d.). Retrieved September 5, 2016, from http://www.chinahighlights.com/travelguide/china-history/three-kingdoms.htm

13: The Three Kingdoms Period (220-280) – Chinese Imperial History Facts. (n.d.). Retrieved September 5, 2016, from http://totallyhistory.com/the-three-kingdoms-220-280/

14: Yang, J. (1999). *Ancient Chinese weapons: A martial artist's guide*. Boston, MA: YMAA Publication Center.

15: Yun, Z. (2009). *The complete Taiji Dao: The art of the Chinese saber*. Berkeley, CA: Blue Snake Books.

16: 1075 Carbon Steels Material Property Data Sheet - Product availability and request a quote. (n.d.). Retrieved December 11, 2016, from http://www.suppliersonline.com/propertypages/1075.asp