

Weapons of Princes, Weapons of War?

An experimental analysis of pattern-welded swords from
northwestern Europe, 400-1100 AD



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Introduction

Tales of heroes and monsters seem to dominate the early middle ages, a period of violence and chaos, but also of art and craft. The perfect blend of both craft and violence is of course the weapon of legends: the sword. Many swords from the early middle ages still exist and these weapons are a testament to the craftsmanship of ancient metalworkers. Foremost of all is the pattern-welded sword, whose beautiful patterns have been forged into the steel itself. These blades were honored and passed down through the generations, maintaining an ever growing legend and history. The well-known *Quernbiter* and *Hrunting* are but two of these swords, famous for their hard edges and supreme flexibility. Naturally, not every warrior was able to afford such a princely weapon, which could only be crafted in a slow and painstaking process by a master-smith. These warriors made-do with simpler, mono-steel blades.

However, were these pattern-welded blades truly so wondrous or were they mere pieces of decoration; symbols of wealth and status? In this thesis a study shall be made to answer the question: “were pattern-welded blades of a higher functionality than mono-steel swords or did the patterns serve a purely decorative purpose?” The reason for examining these swords is the ongoing discussion regarding the function of these inspiring blades. Many times the evidence has been revisited, but no definitive conclusion to this argument has been reached. To present some new insight to this discussion it was decided to try an experimental approach; hence this thesis.

In addition to this main question, several secondary aspects of both ironworking and swordsmithing will be examined. Most importantly a chaîne-opératoire will be established for the creation of a sword. In addition estimations shall be presented of the time and materials involved in both bloom- and swordsmithing. Other, more direct questions which will be treated here are: “why did pattern-welding become popular and when did it fall out of use?”, “to what kind of tests were swords subjected, and how well do the replicas hold up to these?” and “might there have been other considerations to which pattern-welding owes its popularity, like for instance an established savoir-faire?”.

The focus of this thesis is on swords of the migration and Merovingian period, roughly the 5th to the 8th century, but also adjacent periods will be examined thus encompassing the whole of the early middle ages, from the 5th to the 11th century. The area of interest is northwest Europe, including Scandinavia and Britain. This thesis will consist of three parts; first a short overview will be given of what is known about swords from this period, followed by an examination of the historical texts dealing with weapons of this kind. The last and largest part of this thesis will describe a series of experiments conducted in which two swords are recreated and tested to compare their abilities and qualities.

These experiments were all performed by the author himself, who has had a lifelong interest in early weapons and metalworking. In addition to this theoretical basis, the author has several years of metalworking experience by recreating weapons and pieces of armour, the most notable of which was the reproduction of two heavily decorated helmets from early medieval Sweden as part of my Bachelor-thesis. All experiments were conducted to the highest standards possible, so as to gain proper insight in the making of these swords, as well as to ensure that the results of the tests were applicable and scientifically sound. However, it should be noted that due to strict limitations in time and budget some sacrifices had to be made. None of the changes made in the production methods should influence the final results, but this will be expanded upon in chapter 3, *The Experiments*.

The discussion surrounding pattern-welded swords is an old one. Many myths exist about the quality of these weapons, as well as a general vagueness regarding their construction and use. Nevertheless, in general, researchers maintain either one of two points of view. The first view is that pattern-welding is functional (except for thin patterned inlays) and as such represents a statement of quality (France-Lanord 1949; Salin 1957; Tylecote 1976). According to others however all pattern-welding is purely decorative, as attested by patterned inlay and the use of visually-stunning, complex patterns (Lang & Ager 1989; Tylecote & Gilmour 1986; Williams 1977). Arguments for both views will be presented in chapter 1: *The Archaeology of Swords*.

It should be noted that the discussion not only focuses on the period from the 5th to the 11th century, it is also confined to it. Pattern-welding is accepted to have been a practical solution for the lack of large-scale metalworking before the 5th century. By combining many smaller pieces of iron in a single object expenses in material could be saved (Hrisoulas 1991, 255). Also it has been noted that the earliest forms of pattern-welding show a clear combination of low- and high-carbon steel (Tylecote & Gilmour 1986, 251), thus suggesting an increased functionality compared to low-carbon mono-steel swords. From the 11th century onwards pattern-welding becomes increasingly rare, and those examples which are known from this later period show a clearly decorative use of the technique (Lang & Ager 1989, 107). In the discussed period however, it is as yet unclear whether pattern-welding remained popular because of its beauty, or because of its constructional quality.

In the discussion described above, and examined in more detail in chapter 1, no definitive conclusion can be reached by merely theorizing about these objects. Too much of the interpretation is subjected to our own view of the past, and thus biased. As can be seen in chapter 1, arguments for either side of the discussion are plentiful. Ultimately the only way one can hope to answer this question is by gaining practical experience in the matter, and then reaching a conclusion through logic. Of course this is still aided by the archaeological evidence. Practical experience means, in this case, handling weapons of this kind, both originals and replicas, and as such become accustomed to their purpose and use. When one is familiar with these swords, it is possible to recreate these

weapons and compare their qualities. This type of research should of course be classified as experimental archaeology. This, however, will again be expanded on in chapter 3: *The Experiments*.

Chapter 1

The Archaeology of Swords



Introduction

Many swords, several thousands, dating to the early medieval period have been found in Europe. A fair number of these swords was pattern-welded, a technique which reached the pinnacle of its use in the 7th century. The swords in the pattern-welded style, though, seem to have been used during the whole period from the 5th to the 11th century. It should be noted that despite the long period of their use, it is clear that pattern-welded swords were only favored until the 8th century¹. The main body of these weapons comes from northwestern Europe; however, swords with a similar construction from adjacent areas will also be examined to provide a solid reference.

As long as iron swords have been used there have been mono-steel swords; blades forged from a single type of iron or steel. However, in the migration period pattern-welded weapons started to appear in larger quantities. As many as four-fifths of the swords found at 4th century Nydam were of the patterned type (Davidson 1962, 32). Later, during the 5th-8th century pattern-welded swords become increasingly common until by the 7th century over 90% of the swords seem to be patterned (Tylecote & Gilmour 1986, 244-245). From the 8th century onwards pattern-welding starts to gradually fall out of use, while at the same time an enormous increase of high-quality swords with a mono-steel construction can be observed (Oakeshott 2002, 7). From this point onwards it is possible that pattern-welded swords were no longer made in any number, but the remaining blades were certainly passed on and used until the 11th century. By the start of the 12th century patterned blades have become very rare and never regained the popularity they once enjoyed.

Swords, especially those of the migration and Merovingian periods are usually classified by their hilts. These classifications and typologies are based on the shapes of the cross-guards and pommels, sometimes with the hilt decorations as an added aspect (Halsall 2003, 164). The most often used classifications are those of Behmer² (1939) and Petersen³ (1919). There are several other typologies, alternate typologies are for instance given by Wheeler (1927), Menghin (1983) and Geibig (1991), but these are not generally used. Though these hilt-typologies are very useful, it should be noted that hilts are usually more indicative of the last use and geographical origin of a sword. Since swords were considered precious, they were often handed down through several generations before actually being buried⁴. Because of this practice sword-hilts were replaced or redecorated when necessary while the blade was not (Bone 1989, 63).

¹ See pp. 16.

² 4th – 9th century

³ 9th – 11th century

⁴ Evidence for this practice can be found in both historical texts like the *Beowulf*, *Grettir's Saga* and the *Kalevala* (see page 30 of this thesis), as well as in Anglo-Saxon wills (Davidson 1962, 118-120). Archaeological evidence is rare, since it is nearly impossible to prove a sword-hilt has been replaced or is from an older date

When attempting to date swords it would be better to work from a blade-typology; for instance as the one proposed by Oakeshott in 1964 for later swords. However, even when the blades of these early swords are intact, there is such diversity in style that it is still almost impossible to date these blades by type alone.

Despite the dating problems, a fair number of swords could be dated by contextual evidence to the time of their deposition. These dates have provided a broad enough body of information to understand the value and use of these weapons in the examined centuries. The swords can be roughly classified in two constructional types: mono-steel and pattern-welded. Each of these types displays several structures and variations thus enabling a sub-categorization like that presented by Gilmour (Tylecote & Gilmour 1986, 246)⁵. However, there is, and apparently always has been since their discovery, an ongoing discussion about whether pattern-welding was employed to increase a weapon's flexibility or merely for decorative purposes. Several arguments for either shall be presented in this chapter.

The decorative use of pattern-welding

One of the main arguments in favor of pattern-welding for decorative purposes is based on the presence of pattern-welded inscriptions on otherwise mono-steel sword-blades; thus pattern-welding in a non-functional context (Lang & Ager 1989, 109-110). However, it should be noted that the mono-steel blades with pattern-welded inscriptions all date to the 9th century or later (Oakeshott 2002, 7). This is several centuries past the heyday of pattern-welding and already an age in which higher-quality steels are exploited (Moilanen 2009, 4). The best known examples of pattern-welded inscriptions are the Ulfberht- and Ingelrii-blades (Oakeshott 2002, 7-9).

Another argument following the same line of thought is based upon the occasional presence of an iron strip sandwiched between the pattern-welded layers making up the sword core⁶. The apparent preference of the ancient smiths for an iron sword-core, even when employing pattern-welding techniques, seems to suggest a decorative purpose for the patterning (Davidson 1962, 29).

Gilmour (1986, 251) states that his research as well showed that pattern-welding mainly served a decorative purpose. He reaches this conclusion by analyzing the composition and complexity of pattern-welded steel throughout the period. His research showed that the pieces used

than the deposition would suggest. However, one example comes from Kjuloholm Island in Finland. This sword, the Köyliö-sword, was found in a Merovingian grave, but featured a pommel from the migration period (Theuvs & Alkemade 2000, 423). The huge diversity in swords from this period complicates the analyses even further.

⁵ See figure 1.1.

⁶ Gilmour's type VI, fig. 1.1

in pattern-welding were generally of a low carbon iron, sometimes combined with carbon-free iron. Because of the lack of carbon these elements do not seem to increase the overall qualities of the swords. In addition, the chemical composition of the pattern-welded elements shows no improvement throughout the period while steel in general does. The varying phosphorus-contents noted by Gilmour can be explained as a means to improve the contrast visible in the finished and etched blade. A last argument presented by Gilmour is the continuing popularity of pattern-welded swords in the 7th – 9th centuries, while at the same time mono-steel blades are continually increasing in quality (Tylecote & Gilmour 1986, 253).

The constructional use of pattern-welding

One of the oldest arguments for the constructional use of pattern-welding comes from the first finds of this technique. It is generally accepted that pattern-welding was originally employed for practical reasons; probably to increase functionality by distributing carbon more evenly throughout the length of the sword (Tylecote & Gilmour 1986, 251) and to combine small pieces of iron in a large massive sword (Hrisoulas 1991, 255). This theory was simply extrapolated to the later finds of patterned swords, resulting in the logical conclusion that pattern-welding served to increase quality and production (Hrisoulas 1991, 255).

Another argument for the constructional use of pattern-welding can be found in the decrease of pattern-welded weapons from the 8th century onwards. During the 8th century an increase in mono-steel swords of higher quality can be observed; these blades employ better steel, advanced hardening techniques and a slight change in geometry resulting in a lighter weight and increased handling characteristics (Oakeshott 2002, 7). Apparently these later mono-steel swords, obviously more advanced and better weapons than the previously employed patterned swords, became popular because of their quality. Obviously swords can be assumed to reflect the best in early military technology (Halsall 2003, 164). This would suggest that patterned blades owe their popularity in the 5th - 7th century to their increased functionality compared to contemporary mono-steel swords.

The next argument is based on considerations of value. Swords in the early middle ages were expensive to such a degree that every sword was treasured and passed down through the generations (Davidson 1962, 12 & 171-173). Until the 5th century swords were relatively uncommon since few people could afford them; pattern-welded swords were even more expensive and rare. In the course of the 7th century however, almost all swords seem to have been patterned (Lang & Ager 1989, 107). Unless there was a significant advantage of using these swords they would not have been so common, since their expensive nature would have made them near-unobtainable for common

warriors (Halsall 2003, 164). Another piece of evidence for this theory comes from the finds of pattern-welded swords with plain and undecorated handles⁷. If one makes the extra expense of pattern-welding for decorative purposes the handle would reflect this as well since a sword is generally kept in a scabbard, which would keep the blade covered. However, the occurrence of plain-handled swords with intricately patterned blades suggests a practical use for pattern-welding.

In addition to the theoretical arguments presented above some practical research has been performed as well. France-Lanord tested some patterned blades and concluded that patterned swords were three times stiffer than their mono-steel counterparts (Salin 1957, 65). France-Lanord (1949, 19) and Salin (1957, 65 & 72) also noticed while examining original swords that the patterned swords were extremely hard and razor-sharp. These conclusions of course support a practical reason for pattern-welding, instead of a purely ornamental function, despite the fact that the decorative qualities of patterning cannot be ignored.

All in all this discussion has become increasingly complex, and until some new evidence is presented no conclusion will be reached. In older literature pattern-welding is considered to have been purely functional, with the patterns as a by-product. In more recent literature it is usually suggested the patterning was ornamental. Hopefully the experiments performed in this thesis can shed some light on the true performance of pattern-welded and mono-steel swords.

The construction of pattern-welded swords

It is necessary to explain the characteristics of pattern-welded steel; what is it, how was it made and which techniques are employed in its fabrication? Pattern-welded steel is, opposed to 'regular' steel, a heterogeneous mixture of steels welded together to create patterned bars. These bars are forged into knives and swords and then polished and possibly etched⁸ to reveal the different colours of the steels used and thus reveal their patterns. It should be noted that pattern-welded steel is not the same as damascened steel, despite the two terms often being used as synonyms (Maryon 1960b, 52). Damascened steel, like pattern-welded steel, shows patterns on its surface. However, in damascened steel these patterns are the result of the heat-controlled crystallization of carbon-rich steel. This steel consists of carbide- and iron-structures which, after hardening and polishing, can be observed as a subtle, random pattern of different gray lines of various shades. This process is in no way related to the pattern-welding as discussed below.

⁷ Several examples of these can be found in Peirce's *"Swords of the Viking age"* (2002). See for instance C24217 (pp. 40) and JPO 2249 (pp. 52).

⁸ See also pp. 15

The pattern-welding process is a difficult one; it requires an extensive knowledge of metals and their properties, as well as mastery of advanced forging techniques. All pattern-welding starts with the stacking of strips of iron or steel. These strips are of varying composition, both to utilize the qualities of each component and at times to increase the colour-contrast between the layers. The composition and preparation of the strips is discussed below. Usually the stack consists of seven to ten strips, alternating between iron and steel. This stack is then forge-welded to create a billet. This billet is then twisted, sometimes with the direction of the twist varying along the length of the billet, and lengthened to create a rod. Then several of these twisted rods, generally three (Lang & Ager 1989, 91), are welded together lengthwise to create the sword-core. This core is again shaped, and subsequently to steel edges are welded on either side; thus creating the sword-blade. This sword-blade could then be finished and rough-ground. After rough-grinding it is hardened in the heat-treating process. The final step in the process is the polishing of the blade and possibly etching, so as to reveal the patterns. A handle is made which is slipped over the blade's tang, and then secured by peening the end of the tang.

The strips used in the making of a patterned blade are of differing composition. Usually half of the strips are 'true' wrought iron⁹. This iron is the direct result of the smelting process and only refined by forging. Wrought iron contains no or very little carbon and other elements, however, it does contain small pockets of slag which have been worked by forging. These slag-pockets provide the metal with a 'grain' because they are lengthened in the direction in which the metal is worked. This wrought iron is very pliable, but also soft. Due to its pliability this material is virtually unbreakable, something which was considered a very important aspect of a sword.

The other half of the strips is 'steel'. However, fairly often this is not steel in the modern sense of the word, but more a sort of tougher or harder iron. These steels vary enormously in composition; usually they do contain elevated carbon-contents or fairly large amounts of phosphor. A carbon increase in iron creates true steel; as the iron becomes harder but also more brittle with the addition of carbon. The carbon-contents of historical steels can vary from as little as 0.2% (in modern terms this would be considered 'mild steel') to as much as 1.2% (which is similar to modern high-carbon spring steel) (Davidson 1962, 25 & 47). Steel is hardenable when it contains at least 0.4% carbon, though it will only properly harden when the carbon content exceeds 0.6%. Steel is tougher and harder than iron, and as such it is required to reduce the softness and bendiness of an iron

⁹ Wrought iron is also the term commonly used to describe the end-product of a forging operation, often in an artistic context. It is important to note that wrought iron in that context is usually not pure iron with slag but simply a homogenous modern-day steel. 'True' wrought iron has only been worked to clean and homogenize the bloomery iron; thus resulting in almost pure iron with small slag particles evenly distributed throughout the material.

sword. By combining iron and steel in a blade an object is created which is flexible, yet not soft, and hard enough to maintain a proper edge without breaking.

The process in which carbon is introduced into the iron is 'carburization'. In essence carburization is a simple process; iron is heated in the presence of carbon which will cause some of it to be absorbed by the metal. However, there are many ways to achieve this effect and carburization is a very slow process which is hard to control. To overcome this problem long thin strips of iron are carburized and then folded and welded together. This process is repeated several times so as to disperse the carbon evenly throughout the metal. The end-result is usually called 'piled steel'; a piece of steel with more or less homogenous carbon content, consisting of several dozens to several hundreds of small layers. Depending on the use and size of the end-product the amount of folding and carburization varies. For instance, a piece of steel in a pattern-welded sword-core could very well have a carbon content below 0.4% and only as few as two or three layers. This low carbon-content make the steel unhardenable but does toughen the metal considerably. The low-layer count can be used because the individual steel strips in the sword-core are less than a millimeter thick and thus easily carburized evenly. The sword's edge on the other hand should retain its sharpness and shape and should have a much higher carbon content to provide the necessary hardness. The layer-count on the edge will also be much higher because the piece of metal used is more massive than the thin strips in the core, and the even-distribution of carbon is exceedingly important to ensure an even hardness near the edge. If the sword-edge is not uniform in hardness this will damage the sword during use, but also will it make sharpening of the sword more difficult since some parts grind away faster than others.

The other addition often encountered in ancient steel is phosphorus. The addition of phosphorus serves the same purpose as the addition of carbon; increasing the blade's hardness while maintaining proper flexibility (Hrisoulas 1991, 28). Phosphorus however, unlike carbon, also introduces several unwanted properties to the steel. The most obvious of this is cold-shortness; when a metal is cold-short it is very brittle when forged cold or at low temperatures. To overcome this problem the iron can be forged at much higher temperatures, however, this does result in an increased fuel-usage and a higher material-loss due to oxidation. Also, though phosphorus does increase the material's hardness, this increase is a lot less than the increase caused by carburization. Phosphorus however, does also have several other positive qualities. For instance, an advantage of using phosphorus is its natural occurrence in iron-ore, especially in bog-iron. This negates the need for endless heating of the metal in the carburization process, as such saving fuel, materials and time. Another important characteristic of phosphorus is its distinctive reaction to etching; it remains bright due to its larger grains while carbon steel, with much smaller grains, etches dark (Tylecote & Gilmour 1986, 251).

When all the strips are prepared they are forge-welded together. Forge-welding or fire-welding is an ancient technique dating back to the onset of ironworking. In essence, when forge-welding, the iron is heated to near its melting point, which is approximately 1300 degrees Celsius for low-carbon iron¹⁰. Right before the metal actually starts to melt it is taken from the fire and the pieces are then firmly, but not heavily, hammered together. The outside of the pieces will be in a (partially) liquid state and as such will fuse together. When the metal is worked a little more afterwards they fuse together completely, creating a nearly invisible joint. To prevent oxidation of the heated metal, and subsequent burning, the iron is coated with a flux. This flux, today usually borax-salt (disodium tetraborate), melts at a relatively low temperature (600-700 ° Celsius) and then coats the metal as a glass-like substance. When the pieces are hammered together this flux is squeezed from between the welding surfaces which results in weldable, un-oxidized surfaces. In earlier centuries fine silver-sand was probably used in welding¹¹, since this sand exhibits the same properties as borax-salt. However, silver-sand, being heavier, has to be manually brushed off the welding surfaces; this takes time, and time is precious when welding since most welds have to be set within a few seconds after the metal has been removed from the fire. For ease of working borax-salt was, whenever necessary, used in the experiments of chapter 3.

Another technique required in sword-smithing is fullering. The fuller, the lengthwise groove in a sword-blade is either forged or cut. Forged fullers are essentially stronger, but they require more skill to finish properly. Cut fullers can either be cut with hardened chisels, or simply ground with a shaped grinding stone. In the experiment the fullers were mainly ground, as will be explained on pages 52 and 56. Fullers served to strengthen a sword and not, as is often suggested in popular literature, as blood-grooves. Blood-grooves, so want some authors us to believe, are necessary to allow the blood of the sword's victim to run freely and as such prevent the sword blade from being trapped in a vacuum. This is a purely romantic fiction, since blood does not trap a sword, nor would a groove help to prevent this if it were so. It should be noted that fullers seem to have been rare and, if present, very shallow in the 4th – 7th centuries, becoming more pronounced and very common from the 7th century onwards (Tylecote & Gilmour 1986, 247).

The final stage in forging a sword blade is its heat-treatment. After the forging and rough-grinding the blade can be hardened by heating and quenching. It is clear that not all swords were heat-treated; many will just have been air-cooled and remained quite soft, but tough (Tylecote & Gilmour 1986, 248-249). However, on those blades which have been hardened two methods can be distinguished. The first method, the full-quench, is rarely encountered (Tylecote & Gilmour 1986,

¹⁰ The melting-temperature of steel varies with its carbon content. Carbon-free iron has a melting-point of 1534 degrees Celsius, while high carbon steel can have a melting point as low as 1100 degrees Celsius.

¹¹ However, it may not have been necessary to use a flux at all when working with wrought iron. See pp. 48-49.

248-249), despite it being the standard method in later periods (Williams 1977, 78). When a piece of steel is treated with a full-quench it is heated until non-magnetic¹² and then submerged in a quenchant (usually water or brine). The resulting thermal shock and rapid cooling rate produce a very fine crystal matrix called martensite and thus provides maximum hardness. However, steel quenched using this method becomes exceedingly brittle and should be tempered to produce a usable object. Tempering is a slight reheating of the metal to reduce its hardness enough to create a flexible but tough object. Depending on its composition the steel is tempered at a temperature somewhere between 240 and 300° Celsius; the smith gauges the temperature by the colour of the steel¹³.

The second method, most often encountered in this period, is slack quenching (Williams 1977, 77). The slack-quenching process is very similar to the full-quench; the metal is heated to its austenitic stage¹⁴ and then cooled using a quenchant. However, during slack-quenching the piece is not cooled as rapidly as in a full-quenching operation. To achieve this decreased cooling the metal can be plunged in the quenchant and rapidly pulled out, before submerging again. This is done several times until the metal has cooled enough to be allowed to remain in the quenchant for some time. Another technique is quenching the heated steel not in water but in a slower cooling medium like oil. This is easier to control than the previous technique but slightly more dangerous due to the ignition of the oil when the hot metal is submerged. The experimental swords were quenched in oil. Oil was the quenchant of choice since it allowed for a greater degree of control over the quenching process. Historically oil was probably available (Ottaway 2009, 12) and preferred since the effect of a proper oil-quench is equal to that of a proper slack-quench in water, while easier to perform. Slack-quenching results in a martensite/pearlite mix in the steel; this mixture is not as hard as a fully martensitic structure (Williams 1977, 77). However, it is as a direct result also less brittle and thus reduces the need for tempering. Despite the obvious advantage of slack-quenching it also has its drawbacks; the first and foremost is a lesser degree of control over the cooling rate of the metal which can sometimes yield unexpected results. Another disadvantage of slack-quenching is that the final product will always be softer than a fully-quenched and tempered weapon, thus arguably of lower quality.

¹² The metal becomes non-magnetic upon reaching the austenitic stage; depending on the steel this is somewhere between 730 and 900 ° Celsius

¹³ See *appendix I: additional techniques*.

¹⁴ See note 12.

After heat-treatment the swords were finished by polishing and possibly etching. Most patterned swords do exhibit clear topography in their blades¹⁵; however, it is by no means certain this is the result of an active etch in antiquity or just an effect of corrosion and time.

The analysis of pattern-welded swords

The analysis of these swords consists of three possible techniques. The first is a simple hands-on examination consisting of a close inspection of the blade with or without low magnification. In addition measurements are taken such as length, width and thickness. This method is employed on all published swords. This visual inspection provides information that is not necessarily trustworthy. However, it is often possible to discern pattern-welding as well as any other obvious constructional features.

The second method is analysis through radiography. Using this technique several radiographs¹⁶ are made of the swords which usually reveal any pattern-welding present, as well as the type of pattern-welding. The biggest disadvantage of using radiographs is the superimposed nature of the photos. Because of this it can be very hard to distinguish individual sides or elements since they are distorted by the elements from the opposite side of the object (Lang & Ager 1989, 93-94). Even so, radiography does provide a non-destructive analytic method in those cases where corrosion obscures the patterns and construction. Another use of radiography is its ability to reveal the amount of original metal within a corroded piece, thus providing information about the rate of corrosion and the condition of a sword.

The third method is metallography¹⁷. In metallography small sections are taken from the material to be examined. These sections are ground, polished and etched. Then these sections can be viewed using a (light optical) microscope. Results of the metallography of swords vary; sometimes it is only used to distinguish individual layers in pattern-welding¹⁸, but at other times it is used to make a detailed analysis of the heat-treatment and slag-inclusions in a sword blade¹⁹. The main disadvantage of this method is that it requires original material to be present in the sword; a fully corroded weapon cannot be examined metallographically. Some samples of the pattern-welded

¹⁵ See for instance the pattern-welded examples in Ian Peirce's *Swords of the Viking Age* (2002) or those described in Jaap Ypey's article *Een aantal vroeg-middeleeuwse zwaarden uit Nederlandse musea* (1961).

¹⁶ X-ray photos

¹⁷ See for examples and uses David Scott's *Metallography and Microstructure of Ancient and Historic Metals* (1991).

¹⁸ For example by Tylecote & Gilmour in *The Metallography of Early Ferrous Edge Tools and Edged Weapons* (1986).

¹⁹ For example by Williams in *Methods of Manufacture of Swords in Medieval Europe: Illustrated by the Metallography of some Examples* (1977).

sword replicated in chapter 3 were analyzed metallographically by the author at the *Laboratory for Conservation and Material Studies (LCM)* of the *University of Groningen*. The results can be found in *Appendix III: Materials*.

Three original swords were examined by the author under supervision of Dr. Egge Knol of the *Groninger Museum*. These swords, which can be found in the catalogue as numbers VI, VII and VIII, were photographed, measured and detailed drawings were made. Since all other swords mentioned in this thesis have been inspected by various researchers, no further results or information shall be given of the hands-on examinations. Radiography and metallography however, have yielded some interesting results and as such shall be treated here in greater depth.

The main radiographic research of early medieval swords has been performed by Janet Lang and Barry Ager (1989). They radiographed 142 swords at the request from the *Department of Medieval and Later Antiquities*; all examined swords dated to the Anglo-Saxon or Viking period and all were the property of the *British Museum* in London. Due to the large number of blades examined, the results of this research have provided a good overview of pattern-developments through time. For instance, as their research showed, about half of the swords radiographed from the 5th – 6th century were pattern-welded, while 77% of those dating to the 6th century were. Another result was a 100% pattern-welding rate for the 7th century. No swords from the 8th century were examined; from those dating to the 9th – 10th century 45% was patterned. Though these numbers only give a general indication of the occurrence of pattern-welding, they do show a steady increase in pattern-welding towards a peak in the 7th century (Lang & Ager 1989, 107). Subsequently the percentage of pattern-welded blades decreases again in the following centuries. According to Lang and Ager's research pattern-welded inscriptions did not appear before the 9th century (Lang & Ager 1989, 107).

Gilmour (Tylecote & Gilmour 1986) has examined a large number (39) of Anglo-Saxon swords metallographically. The examination revealed the constructional methods which were employed in the forging of these sword blades; this resulted in a general structural categorization of sword blades from this period (figure 1.1). Typically, the metallography was able to show the structural composition of the swords, which heat-treatment they received and what sort of slag-inclusions were present. Remarkable is the wide variation in constructional methods and treatments to which the sword blades were subjected. A few examples of structural types are presented below²⁰.

Another important result of the metallographic analysis performed by Gilmour was again the proportion of pattern welded swords versus the non-patterned blades. From Gilmour's sample it showed that 90% of the swords dating to 5th – 7th centuries, 100% of the swords from the 7th – 9th century and 45% from those dating to the 9th – 11th century were patterned. It should however be

²⁰ See page 19.

noted that only two swords from the 7th – 9th century were examined. Gilmour's examination clearly shows the same increase in pattern-welding from the 5th – 8th century as did Lang and Ager's research, again with a decrease of pattern-welding from the 8th century onward.

The steady increase of pattern-welded blades towards the 7th century might be attributed to several factors. The first of these is inheritance. As explained earlier in this chapter many swords were family heirlooms. If for some reason patterned swords were passed on for a longer time than mono-steel blades, this might explain the increase in patterned swords throughout time, and the decrease of their mono-steel counterparts. Possibly patterned swords were of a better quality than mono-steel weapons, or perhaps they were more treasured, which could result in the preferential treatment of these blades as heirlooms.

Another reason for the observed increase of pattern-welded swords might be found in the form of an established savoir-faire for the production of these weapons. Though there is not yet any real evidence to support this theory, it is very well possible that swordsmiths in the 6th and 7th century simply followed a traditional procedure for the forging of these blades, without regard for their true functionality or the reasons for this technique. If at some point in history, for whatever reason, pattern-welding was deemed superior for the manufacture of weapons, then slowly but certainly most, if not all, ironworkers would have adopted the technique for this purpose. This would then have been both the result of the client's expectations, and the smith's education.

In addition, popularity by itself might have been reason enough for the increase in pattern-welding throughout these centuries²¹. If pattern-welded swords were at first owned by the social elite, almost as a form of prestige weapon, then other, lower warriors might have imitated this by trying to obtain similar weapons. Such weapons would of course enhance their status. However, since not every warrior was able to afford such a complex sword, many will have considered cheaper, low-end reproductions sufficient. This would result in due time in an increased number of pattern-welded weapons, which were not necessarily of high quality. Then, after a few centuries, the elite had implemented a new, even better, prestige weapon. This new weapon is the improved mono-steel blade of the type which appears in the course of the 8th century. From this moment onwards pattern-welding starts to fall out of use, and is eventually abandoned in favor of good mono-steel arms.

Gilmour states that his research shows that the pattern-welded swords dating to the 7th century and afterwards display a much higher overall quality, both in material and construction, than those dating to the 5th – 7th centuries (Tylecote & Gilmour 1986, 249). The same increase in quality was observed in the non-patterned blades. These were crafted from a low-carbon iron in the earlier

²¹ Personal Comment from Dr. J.A.W. Nicolay, August 2010.

centuries, while in the later centuries these weapons were made from more homogenous steels with a higher carbon-content and showed evidence of various heat-treatment methods as well (Tylecote & Gilmour 1986, 249). Hardness values obtained showed that the earlier swords were usually harder and more serviceable than their wrought structures would suggest, however, they are still of a much lower quality than the swords from the 7th century onwards. Gilmour suggests a more ceremonial use of swords for the earlier periods with an increase in functional use from the 7th century onwards (Tylecote & Gilmour 1986, 249). However, there is no evidence supporting this ceremonial use other than the low quality of these swords.

In my opinion there is no reason for swords to have been solely made and used for ceremonial purposes. It is important to note that the weapon of choice in this period was the spear (Halsall 2003, 164-165), making swords secondary weapons. As such, swords would not usually see extensive use in battle, other than the odd duel or heroic act. Another important aspect of early medieval warfare is the lack of armour. Warriors rather relied on their large wooden shields than on cumbersome and expensive body armour (Halsall 2003, 167-168). When using a cutting implement like a sword in these battles it will mainly cut soft tissue²². In later centuries, with the increase in maille-armour and even plate-armour, swords were required to be harder to be able to defeat this armour or at least remain undamaged when coming into contact with other iron. With the increase of armour the requirements which a sword had to fulfill changed, thus the weapons themselves changed. In this early period a hard sword would have been preferable to a soft blade since it would perform better in battle and be more durable. However, soft swords would still make very serviceable weapons and should certainly not be classified as ceremonial without any additional evidence.

²² The typical 'clanging' of blade upon blade in a sword fight, as seen in many movies is not historical, as any practitioner of historical swordsmanship is aware. While a sword could be used to parry or block another blade, it would usually be kept clear of other hard objects so as not to damage it. Most cuts can be avoided with the warrior moving out of range or catching the blade upon his shield, instead of running the risk of ruining his sword.

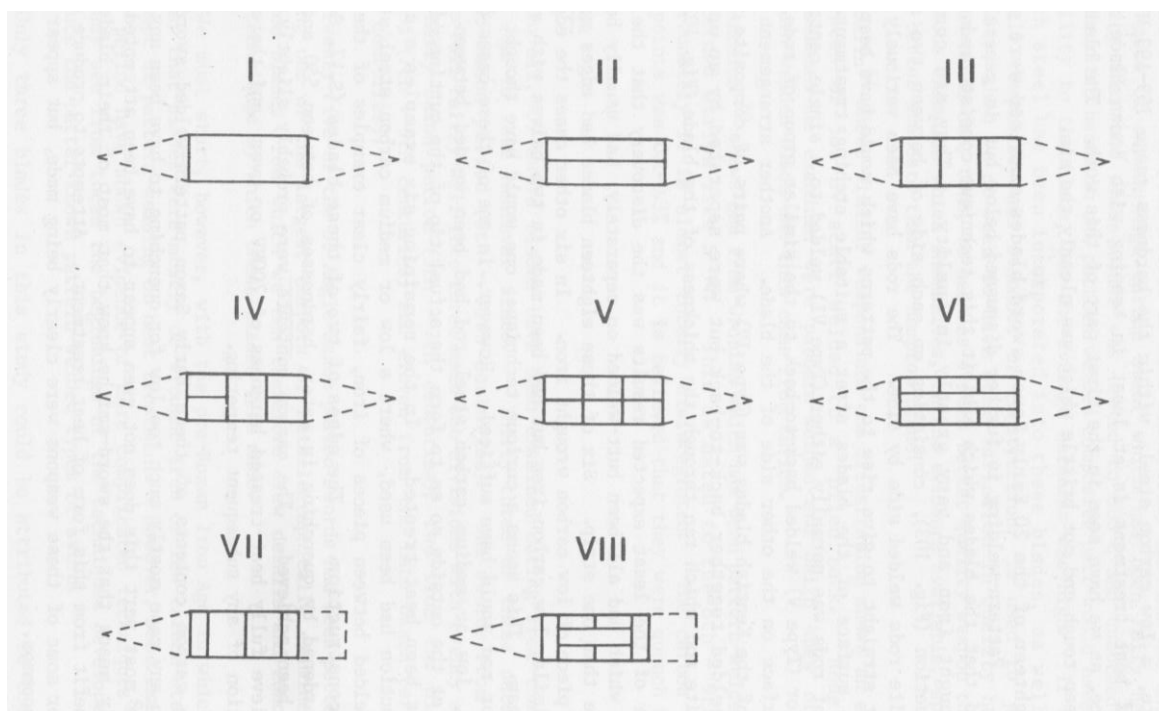


Fig. 1.1: blade structures in section according to Gilmour (source: Tylecote & Gilmour, 1986, pp. 246).

Gilmour's Structural Types²³

Weapons of Gilmour's structural type I are very common, though usually they are not represented very well in publications. The reason for this might be their rather un-impressive appearance when compared to pattern-welded blades. These swords consist of a single piece of steel which is forged to a simple blade-shape. This single piece of steel however, is often more complex in composition than is obvious at first sight. Usually this steel is folded and welded several times in the process called piling²⁴. Also, these bars of steel are sometimes several pieces welded together; probably because of the abundance of small pieces of iron and the lack of large bars. Despite their hidden constructional qualities, these blades are quite plain. Swords of structural type I have, for example been found at Nydam (Davidson 1962, 32), Funtham's Lane (catalogue number I) and in the Thames (catalogue number II).

Swords of type II should in my opinion also be categorized under type I, because piling and the welding together of small pieces to create one larger bar of, more or less, homogenous iron is in both types the reason for any variations in the material structure. Type II blades are blades constructed from at least two pieces of similar steel which have been welded together to create a sword-blank. These blanks are, despite their welded construction, classified as mono-steel because

²³ As shown in figure 1.1.

²⁴ See chapter 3: *Piling the bloom*, pp. 43.

there is no clear variation between the different components. This constructional technique was also used in the experimental mono-steel sword²⁵. Since the construction and end-product of type I and II swords are so similar, it is often a matter of perspective whether a sword is classified as type I or II, and not a variation in the material itself.

Type III swords are comprised of blades with a core made up of two or three rods. These swords seem to be among the earliest 'true' pattern-welded blades, only preceded by Celtic blades of piled structure²⁶. Examples of this type of pattern-welding come from Nydam in Denmark (Davidson 1962, 32) and Antum in the Netherlands (catalogue number III). Though these swords could benefit most from their pattern-welded construction, they are generally of fairly low quality. The pattern-welding as well as the edges are often composed of wrought iron or low-carbon steel and left unhardened. Pattern-welding contrast is usually achieved by variable phosphor-contents; these swords will have been rather soft but also very tough (Tylecote & Gilmour 1986, 251).

Structural type IV is less common than types III, V and VI. However, it is a very important structural type because it is described in literature; probably most historical references to a phenomenon called the 'serpent in the sword' refer to this construction²⁷. Its structural features are a core-construction of three bars. The outer two are twisted while the central bar is left untwisted and has its sides exposed. The outer two bars can each be a single twisted rod, or could consist of two rods welded together to form the opposite faces of the blade. The central bar is almost always a single rod which is either straight or worked to present a curving pattern; this curving pattern between the two twisted rods gives the impression of a snake-like form crawling over the length of the blade. A sword like this has been found at Aylesford in Britain (catalogue number IV). A blade of similar appearance but with a slightly different construction comes from Nijmegen in the Netherlands (catalogue number V).

The next groups of swords, types V and VI, are the most common (Tylecote & Gilmour 1986, 250). These swords feature a double core consisting of two separate billets of pattern welding which have been welded together on their flat-side along their whole length. In the swords of type VI a strip of iron has been sandwiched between the two separate core-halves. Usually the pattern-welding in these swords consists of two or three rods and the two sides of these swords are not necessarily symmetrical. Swords of this construction are commonly encountered from the sixth century onwards and remain the most common type in the following centuries. Several Dutch examples of these blades are known, for instance the swords from Wieringhuizen (catalogue number VI) and Eekwerd (catalogue number VII).

²⁵ See chapter 3: *Forging the swords*, pp. 49.

²⁶ For more information about Celtic swords, see Radomír Pleiner's *The Celtic Sword* (1993).

²⁷ See *Kormak's Saga* in chapter 2, pp. 24.

Types VII and VIII can be found occasionally but are rare and as such no extra attention to these groups is given. Some swords are known which feature structural type III, V or VI but are composed of a much larger number of rods. An extreme example is the sword from Bamburgh, Northumberland which dates to the seventh century. This sword is comprised of 12 pattern-welded rods; two sides each having six rods side-by-side. Other impressive swords are the ones uncovered at Sutton Hoo, Suffolk (Ypey 1983b, 495-498), and at Loveden Hill in Lincoln (Tylecote & Gilmour 1986, 185). These blades are made of ten pattern-welded rods; again split in five on each side. Swords like these, with an extremely fine construction, will have taken hundreds of hours to produce (Hrisoulas 1991, 256). Though it is arguable whether these swords were of a higher functionality, they certainly were blades of beauty and a clear symbol of a person's standing.

Conclusion

Much research has been done regarding the early medieval swords of northwestern Europe, especially on those which exhibit pattern-welded structures. Many sword-finds from this period are known, and much time has been devoted to understanding how these weapons were made. Despite the many finds it has proven hard, if not impossible, to date and classify these blades. Hilts, which are commonly used as time-indicators, were often replaced thus prolonging the use of a certain blade. As a result of this hilts should be viewed independently of the blades to which they are connected. Despite the dating problems, it is possible to discern different constructional methods in the early medieval swords. Some weapons were welded together from several pieces; some were forged from a single piece of iron. Some exhibit twisted strands of layered steels, while other only contain a stacked structure. These structural types were classified by Gilmour in 1986 (Tylecote & Gilmour 1986, 246). In the classification and examination of sword-blades several techniques can, and have, been employed like radiography and metallography.

Despite, or possibly because of, all the previous research an ongoing discussion has formed regarding the function of pattern-welding. Some archaeologists maintain this technique solely served ornamental purposes (Lang & Ager 1989; Tylecote & Gilmour 1986; Williams 1977) while others view pattern-welding as constructively functional (France-Lanord 1949; Salin 1957; Tylecote 1976). Since this discussion has been going on for several decades it is evident no conclusion can be reached without new input, hence the next chapter. In chapter 3 some new data will be presented regarding the properties of early medieval blades with the use of experimental archaeology.

Chapter 2

The History of Swords



Introduction

When studying weapons, or any historical artifact for that matter, it is important to find out what has been written in contemporary sources. Historical texts do not just complement the information gathered by archaeological research; they also provide a context for the object in question. This context allows the researcher to better understand the value and meaning which was attributed to the object in its own time. A good starting point for researching the historical references to pattern-welded blades is *the Sword in Anglo-Saxon England* by Hilda Ellis Davidson (1962). Her work concerning the sword in history is especially valuable to those who are not proficient with the reading of ancient languages like Latin or Old-English. This chapter will lean heavily on Davidson's work, since it already deals with the subject of swords in a very broad manner. In addition to Davidson's book several other sources will be utilized as well.

Description of swords in contemporary texts

References to swords can be found in, for instance, heroic literature. A remarkable description comes from the poem *Guðrúnarkviða II*:

“In they came like kings, a company of long-bearded men. They wore red cloaks, short mailcoats and towering helmets, and were girt with swords.”
(Davidson 1962, 105)

The image sketched here is one of military prowess. These men entered resplendent by their arms and armour. Since warriors of this period were measured by their arms' value (Bazelmans 1999, 212); these men, in full armour and with swords, must have seemed kings indeed.

Usually, however, more attention is given to the swords specifically; for instance in the Anglo-Saxon poem *Elene*, written by Cynewulf somewhere between the eighth and the tenth century. In this poem a certain sword is described as:

“The hard-edged blade with its woven patterns quivers and trembles; grasped with terrible sureness, it flashes into changing hues.”
(Davidson 1962, 123)

The sword described in *Elene* is very probably a pattern-welded weapon, since it has “woven patterns”. Also this sword is described as being a sword of quality, since it is a “hard-edged blade”, something which is very often used to describe the best of weapons (Davidson 1962, 123-124).

Another description from a pattern-welded blade comes from an Arabic source. A ninth century Arab scholar by the name of al-Kindi describes pattern-welded blades as tapering and “with a broad channel running down the centre of the blade, which resembles a stream of water” (Zeki Validi 1936, 19). He describes the background of the patterns as being red when the blades are finished. This is something which is not described anywhere else; however, this might indicate intentional rusting of the blade prior to polishing, so as to create a reddish-orange background for the silvery pattern²⁸. It must be noted that this is pure speculation, since no evidence has been found of intentional colouring of iron or steel in this early period.

A very specific form of pattern-welding appears to be the subject of an instruction given in *Kormák's Saga*:

“The management of it may seem difficult to thee,
A covering goes with it and thou shall leave it quiet;
The sun must not shine on the upper guard,
Nor shall thou draw it except thou preparest to fight;
But, if thou comest to the fighting place,
Sit alone, and there draw it.
Hold up the blade and blow on it;
Then a small snake will creep from under the guard;
Incline the blade and make it easy for it to creep back under the guard.”
(DuChailu 1889, 443-444)

This is generally considered a reference to a patterned blade (Jones 1997, 5). More specifically this might refer to the blades which were made out of several twisted rods with one untwisted but wave-shaped rod welded in the center. This center-rod is often thought to have resembled a snake crawling along the centre of the sword; perhaps granting it special powers.

At least 8 swords are mentioned in the *Beowulf* (Bazelmans 1999, 213). Of these, two are described in detail, while the others are only mentioned in passing. The two swords which are given more attention are:

²⁸ A possible technique which can be used to this effect is lightly coating the blade with brine. This results in an instant and even oxidation of the steel. Several coats may be needed to achieve the desired colour (McCreight 1991, 37).

- Hrunting, the sword of Unferth which Beowulf borrows to fight Grendel and his mother.
- The Giant sword, found by Beowulf in Grendel's lair.

The sword Hrunting is described extensively, the first time as the sword is lent to Beowulf:

"(...) the foremost of ancient treasures. Its edged blade was of iron, coloured with twigs of venom and hardened by the blood of battle; never yet had it failed any man who grasped it in his hands in warfare."

(After Davidson 1962, 129)

The description presented here warrants an interpretation as a pattern-welded sword. Though it mentions that the blade was iron, this might be synonymous for 'steel' since blades of other materials were not in use in this period. If iron is read as steel this might represent a statement of quality. "Coloured with twigs of venom" can of course be interpreted as a reference to a pattern-welded construction. There is the question of the reference to venom which is made in this sentence, which can be interpreted either as referring to the acid used in the etching of the sword blade (if this was done in this period) or "twigs of venom" could be meant as a metaphor for snakes or serpents; creatures which have often been used to describe pattern-welding (Davidson 1962, 129). Later in the *Beowulf* the sword is mentioned again, this time as the sword fails to hurt Grendel's mother:

"He (Beowulf) swung his sword of battle with a mighty rush, and his hand did not fail in the stroke, for the sword with curving patterns sang a greedy song of battle upon her head."

(After Davidson 1962, 129)

Here it is clearly stated that the sword is pattern-welded. A similar description is given a few lines later in the poem, when:

"The enraged warrior (Beowulf) flung down the sword with twisted patterns and bound ornaments, hard and steely-edged, so that it lay upon the earth."

(Davidson 1962, 129)

Despite the obvious quality of this blade, being pattern-welded and steel-edged, it failed against Grendel's mother. It is described as having "bound ornaments"; this most probably refers to the handle which might have been wrapped with precious metal-wire. This sword is discarded by Beowulf in search of a more suitable weapon. This he finds in the form of a huge sword which hangs

on one of the walls of the cave-dwelling of Grendel's mother. This sword, though nameless, is described as:

“(...) an all-conquering weapon, ancient sword of giants, doughty of edge, a treasure among warriors. It was a most excellent weapon, but too huge for any other man to wield at the battle-scene: a trusty and splendid sword, wrought by giants. The Champion of the Scyldings grasped the wired hilt and drew the sword with its curving patterns.”

(After Davidson 1962, 135)

Again there is the reference to pattern-welding, as well as the statement that the sword was 'wrought by giants'. This should not just be interpreted as referring to the sword's huge size, but also does this refer to the sword's quality. In Anglo-Saxon texts giants were often considered in the same sense as dwarves in Norse folklore; being highly talented craftsmen, and especially metalworkers. With this sword Beowulf manages to decapitate Grendel's mother, however, in doing so the sword is destroyed:

“The blade with its interwoven patterns had now melted and burned away, such was the heat of the blood and so poisonous was that strange being who had perished there.”

(Davidson 1962, 135)

Because of the apparent acidity of the creature's blood only the sword-hilt remains. This hilt is presented by Beowulf to king Hrothgar upon his return to the surface. The sword-hilt is then described as being crafted from gold and inscribed with runes. These runes are said to form the sword's first owner's name as well as provide a reference to a myth in which the Giant-folk is destroyed by a flood. However, there is not enough detail in the poem regarding the way in which this reference is made, nor is the original owner of the sword named.

Construction of swords in contemporary texts

There are several texts dealing with the making of sword-blades. Though these texts are usually not precise enough to discern constructional details, they often do provide a general insight in the making of swords. Some bits of text are exaggerated. These however, usually still seem to be based on real practices or events.

A clear example of this is the sword made by Velent the Smith for the king in *Thiðriks Saga*²⁹. *Thiðriks Saga* is a 13th century Norse Saga, but the story is loosely based on the life of Theodoric the Great, and as such the contents might be dating back to the 6th or 7th century. At some point in this Saga Velent the smith has forged a sword for his king, though his king is very pleased, Velent himself is not. Thus he takes the blade and files it to dust; he then mixes this iron-dust with ground wheat and feeds it to his chickens. Later he gathers the birds' droppings and smelts these to regain the iron, which he subsequently forges into a new and better blade. The story then repeats itself since Velent still is not satisfied. Ultimately Velent has forged a final and perfect weapon. It is mentioned though that this sword is slightly smaller than the swords he usually forges; this is probably due to the loss of metal in the repeated refining process. Though the process, as presented here, seems rather extreme, a similar process could very well have been used. Whether the chickens actually ate the metal is not in itself relevant, the use of their droppings however, is. Heating iron in the presence of phosphorus or nitrogen will dissolve these elements into the metal; bird's droppings are rich in both. There is archeological evidence for the presence of both phosphorus (Tylecote and Gilmour 1986, 251-252) and nitrogen (Davidson 1962, 160) in sword blades. Phosphor was probably used in sword-blades to increase their hardness while retaining their flexibility; nitrogen can be added to steel as an aid in preserving the steel's surface and impede corrosion.

Another historical source which provides information on the making of swords is the Finnish national epic, the *Kalevala*. The *Kalevala* is in fact, like the Norse Edda, an agglomeration of folklore and consists of several stories. However, unlike the Edda, the stories from the *Kalevala* feature in the main the same characters, which are portrayed almost like demi-gods. A very important figure in the *Kalevala* is Ilmarinen, the first smith. Ilmarinen is in many respects similar to Greek Hephaestus and Roman Vulcan. He is incredibly strong, skilled at making things, even those not from metal, and he is considered ugly. Another aspect shared between Hephaestus and Ilmarinen is that they both built girls from gold; Hephaestus built two girls to assist him with walking, Ilmarinen built one because he was so lonely.

At some point in the *Kalevala* two main characters, Väinämöinen the Wizard and Ilmarinen the Smith, decide to travel to the dark Northland to retrieve a magic object, the Sampo, from the queen there. To do so they need proper weapons and thus Ilmarinen makes a sword for Väinämöinen:

"Smith Ilmarinen, The everlasting Craftsman,
Thrust some iron in the fire, some steel among the embers,

²⁹ This saga is again well-described by Hilda Ellis Davidson in *The Sword in Anglo-Saxon England* (1962) on pages 159-160.

A whole handful of gold coins, a fistful of silver coins;
He made the serfs puff, and the hirelings press.
The serfs puffed and flapped, the hirelings pressed well:
The iron as gruel stretches, the steel bends as dough,
The silver as water gleamed, the gold rippled as a wave.
Then the smith Ilmarinen, the everlasting craftsmen,
Looked down in his forge, at the brim of his bellows:
He saw a sword being born, a gold-tipped one taking shape.
He took the stuff from the fire, snatched the good matter
From the forge to the anvil, the hammers, the sledgehammers;
He forged the sword as he liked, the best brand of all-
He shaped it with gold, worked it with silver.”
(Bosley 1999, 516-517)

Though this text is again rife with metaphors and figures of speech, several aspects of sword-smithing can be deduced from these lines. First of all it is very clear that the smithy is manned by several people, serfs and hirelings, and not just by Ilmarinen himself. Though this may not always have been the case, it is only logical that in a time when materials are costly and man-hours cheap most smiths will have had several helpers. In this source the iron which Ilmarinen forges is likened to “a whole handful of gold coins, a fistful of silver coins”; this may refer to the costs of raw iron/steel. Since ferrous metals will have been expensive, even more so quality steel, it could be emphasized in this text to show the importance and status of Ilmarinen’s work. The last line of the text probably refers to the sword-handle, which could be decorated with gold and silver.

When Ilmarinen looks in his forge and then “snatches” the good matter this could be interpreted as him gauging the temperature of the steel by its colour³⁰, and when he decides the temperature is right he instantly removes the metal from the forge and places it on his anvil to be worked by several hammers. A common practice in later period metalworking is the master-smith holding the steel and using a regular hammer for forging, while at the same time one or two apprentices use sledgehammers to speed up the shaping-process.

The next bit of text is quoted by Davidson (1962, 105-107) and is one which is, also according to herself, often cited in relation to early-medieval swords. It concerns a letter written by Cassiodorus in the early sixth century. Cassiodorus was the secretary of Theodoric the Great, a Teutonic king, and the letter is written to thank another ruler, someone who is considered the King

³⁰ The colouring of steel upon heating can be found in *Appendix I: additional techniques*.

of the Varni, for a gift of swords. Despite the letter having been quoted often, here it shall be presented in full, as Davidson has done. The reason for presenting the full text is the lack of clear translations of this text and the importance to this research. This is the translation presented by Davidson herself:

“Together with musical instruments of pitch-black wood and boys with the fair skin of their race, Your Fraternity has chosen for us swords capable even of cutting through armour, which I prize more for their iron than for the gold upon them. So resplendent is their polished clarity that they reflect with faithful distinctness the faces of those who look upon them. So evenly do their edges run down to a point that they might be thought not shaped by files but moulded by the furnace. The central part of their blades, cunningly hollowed out, appears to be grained with tiny snakes, and here such varied shadows play that you would believe the shining metal to be interwoven with many colours. This metal is ground down by your grindstone and vigorously burnished by your shining dust until its steely light becomes a mirror for men; this dust is granted you by the natural bounty of your land, so that its possession may bestow singular renown upon you. Such swords by their beauty might be deemed the work of Vulcan, who is said to have perfected his craft with such art that what was formed by his hands was believed to have been wrought by power not mortal but divine.”

It is generally accepted that the swords described here are pattern-welded (Davidson 1962, 107). The most obvious clue for this interpretation are the “tiny snakes” which apparently seem to show on the blade. Though these tiny snakes have been interpreted in many ways it is highly likely these “snakes” represent the s-shaped lines which show in a pattern-welded blade made from twisted and ground rods. The “many colours” with which the blade seems to be interwoven could either describe the different shades of grey of the pattern-welded steels, or they could refer to a light sheen of oil on the highly polished blade; if the steel is polished well enough and oiled this creates the effect of “oil on water” in that, with varied lighting, many different colours will be visible.

In this letter it is said these blades are “capable even of cutting through armour”. This clearly refers to a high hardness of these swords, even though the armour in question is not specified. This could be maille, but might also be leather³¹ or horn³². In the context of this letter it might even be an exaggeration to illustrate the high quality of the swords, since armour is designed to withstand the abuse of warfare and as such should stop the sword. If a sword were able to defeat the armour it would be among the best of weapons indeed.

³¹ Though it is very probable that leather armour existed, no evidence for it has been found. Other leather finds, like shoes, are common from this period.

³² Horn plates were sometimes used to create armour. A good example of this is the horn helmet found at Bentley Grange in Great Britain dating to the 7th-8th century (Bruce-Mitford, 1974).

The letter also provides the reader with some details concerning the construction of swords. In this text it is clearly stated that blades are usually finished with files and grindstones and polished with a powder. Twice the blades are said to act as mirrors; so they must have been brought to a high polish, something which takes considerable time and can only be achieved with the finest of polishing agents. The “shining dust” mentioned in this text is probably such a polishing agent and Davidson (1962, 108-109) suggests *kieselguhr*, a fine silica, as the powder referred to. The part of the blades which is so “cunningly hollowed out” obviously refers to the fullers or lengthwise grooves cut into the blade. These fullers serve to strengthen the blade and are in this period usually very wide and shallow.

That the weapons “might be thought not shaped by files but moulded by the furnace” could refer to bronze-casting. When casting objects, and especially weapons, it is possible to make a model or mould with a very high degree of finish, both of decoration and for instance of edges. When a near-perfect model is properly cast the result will also be near-perfect. This process is easier to control than forging and grinding, and the result is usually finer. Likening these blades to casts is another way to emphasize their high quality and finish. The last bit of text, concerning Vulcan, is clearly intended as a compliment, referring to the work of the Roman god of fire and metalworking.

Another author who comments on the construction of the swords is al-Biruni, an Arab scholar of the eleventh century (Zeki Validi 1936, 19). He writes that the Rus³³ make swords in which they weld together a central panel of soft iron and steel. This panel is then edged with strips of steel. Al-Biruni also notes the patterns in these swords are created deliberately. This can be interpreted as an argument for the use of pattern-welding because of its decorative properties. However, it should be kept in mind that, even though Al-Biruni writes in a time when pattern-welded blades were still in use, it is already several centuries past their heyday. As such pattern-welding, if still performed, may have become a technique solely used to represent wealth.

Testing of swords in contemporary texts

Unfortunately there do not seem to be any other historical sources dealing with the creation of (pattern-welded) blades. However, many sources make mention of tests through which the swords are put to determine their quality. The two reproduced blades of chapter 3 will be put through similar tests to compare their quality.

The most commonly described form of testing is a cutting test. Most often the swords are used to cut something which has only a very low resistance, so as to test mainly the sharpness of the

³³ Swedish Vikings, though this could refer to Scandinavians in general.

blade, and not so much its effect in a battle simulation. Testing materials are often pieces of fabric, either falling or floating in a river. A clear example of this practice comes again from *Thiðriks Saga*, where Velent the Smith cuts a piece of felt floating on a river to test the sword's edge. Another reference to this practice can be found in the *Volsunga Saga*; the story of Sigurd the Volsung and his fight against the dragon Fafnir. Here it is written:

“(…) then he (Regin the Smith) bade Sigurd take his sword, saying that he knew not how to make a sword if this one failed. Sigurd cut at the anvil and sliced it in two at its base, but the sword neither shattered nor broke; he praised the sword greatly, and went to the river with a strand of wool and threw it up stream, and it was cut in two when it touched the sword; then Sigurd went home satisfied.”

(Davidson 1962, 163)

If the swords were truly able to cut strands of wool or pieces of felt like this they must have been razor-sharp. Though this is not impossible at all, it would be quite another thing for a blade to retain this fine edge. Sigurd also tests his sword by cutting through the anvil's base. This is a test which is recurring as well; for instance in the *Kalevipoeg*, the Estonian national epic, in which three swords are tested on hard surfaces:

“He then whirled it round his head,
and struck at the massive rock which stood in the smithy with all his
might. The sparks flew from the stone and the blade shivered to pieces,
while the old smith looked on and swore.”

“(…) the Kalevide chose
a huge sword, which he brandished like a reed in his right hand, and
then brought down on the anvil. The sword cut deep into the iron, and
the blade did not fly, but the sharp edge was somewhat blunted.”

“(…) Then he turned and brought down the keen edge like a flash of lightning
on the great anvil, and clove it to the ground without the sword
receiving the slightest injury.”

(Kirby 1895, 59-60)

It should be noted however that while this poem states the sword cut through the anvil, it is very likely this is not, in fact, the steel anvil but the wooden base. There are several reasons to assume this is the case, even though the text states otherwise. Early medieval anvils were, unlike 'modern' anvils very small, usually weighing no more than a few kilos (compared to 'modern' anvils which weigh anywhere between 50 and 300 kilos). These small anvils usually had a pointed base which was hammered into a large wooden stump, to provide the weight and stability needed for forging. Of course, cutting through a wooden stump with a sword is an impressive feat, however, it can be considered within the realm of possibilities while cutting through an iron or steel anvil cannot³⁴.

Another description of a similar cutting practice comes from the Finnish *Kalevala*:

"Then he took his mail of copper,
Took his ancient battle-armor,
Took his father's sword of magic,
Tried its point against the oak-wood,
Tried its edge upon the sorb-tree;"
(Crawford 1888, 424)

Here both the sword's point and the sword's edge are tested on pieces of wood. Another reference to the testing of a sword's cutting power comes from *Haralds Saga*:

"King Aethelstan gave Haakon the sword with guard and grip of gold; yet its blade was of even greater worth. With it Haakon cut a millstone to the centre, and ever afterwards the sword was called Quernbiter; this sword was the best that ever came into Norway, and Haakon had it till the day of his death"
(Davidson 1962, 163)

Though it seems far-fetched that a sword could actually cut in half a millstone, this story does again state that swords had enormous cutting power and were put through variable tests to determine their quality.

³⁴ Despite the huge difference in hardness of a fully hardened martensitic sword-edge and a soft, annealed iron anvil, a sword is not likely to cut through it. For one, the edge geometry would not allow it; the edges are very thin and sharp whereas an anvil surface is more or less flat and massive. Also, anvils were usually not soft (Pleiner, 2006, pp. 93-97)

Another valued aspect of sword-blades is their flexibility. The flexibility of a sword-blade was usually determined with the use of bending; the sword blade was severely bent and then it would either shatter, follow the bent or return true. This test, which is fairly easy to do, is often described in historical literature. Again in the *Kalevipoeg*, the Estonian poem, it is written:

“The Kalevide picked out the longest (sword) and bent it into a hoop, when it straightened itself out at once.”

(Kirby 1895, 59)

Another example comes from the *Kalevala*:

“In his hand the blade was bended,
Like the limber boughs of willow,
Like the juniper in summer.”

(Crawford 1888, 424)

However, not all swords were of sufficient quality to spring back after this test, as is evident from the following texts:

“Then Thorolf took off his own sword and gave it to him; it was a good treasure and well ornamented. Thorstein received the sword and drew it forthwith. He took the point and bent it between his hands so that the point up to the hilt. Then he let it spring back, and it had lost all its elasticity. Then he gave back the sword to Thorolf and bade him get another and stronger weapon, ‘for this switch will not do for me’. Thorolf took the sword and judged it to be spoilt.”

(Davidson 1962, 164)

So it is written in the Svarfdala Saga. This sword evidently did not pass the flex-test and was ruined.

Another sword which is tested but fails is one of the blades presented to the Emperor of the Carolingian Empire, Louis the Fair, in a scene described by Einhard in the early ninth century:

“(He) took one (sword) by the hilt and tried to bend the tip of the blade right back to the base; but the blade snapped between his hands which were stronger than the iron itself. Then one of the envoys drew his own sword from its sheath and offered it like a servant to the Emperor’s service, saying ‘I think you will find this sword as flexible and strong as your all-conquering right hand could

desire.’ Then the emperor (...) bent it like a vine-twigg from the extreme point back to the hilt, and then let it gradually straighten itself out again.”

(Davidson 1962, 113-114)

Though these tests may seem wasteful, considering the number of swords destined to fail, it should be remembered that these weapons were intended for use in battle and not just for show. When a (rich) warrior’s life dependent on a weapon it is not so hard to imagine he wanted to make sure his equipment was of the highest quality. Despite the risks entailed by these tests, they are also applied to the finished blades of chapter 3. Each sword shall put through a cutting, edge retaining and flexibility test similar to those to which the original swords were subjected.

A last test to which blades were often subjected was a practice of a much kinder nature; swords were measured. Though it is clear from several texts warriors preferred their swords as long as possible³⁵, there also existed the tradition of measuring swords at the start of a duel. This is for instance described in the Finnish *Kalevala*:

“He took his sword, bared the iron
Snatched the one of fiery blade
Out of the holder of hide
Out of the belt of leather.
They sized up, looked down
The length of those swords:
A tiny bit longer was
The sword of the Northland’s master
By one fingernail’s black speck
By half a knuckle.
Ahti the Islander said
The fair Farmhand spoke:
‘See, yours is the longer sword
So you should strike first.’”

(Bosley 1999, 388)

³⁵ See for instance the *Kalevipoeg* above. pp 33.

Conclusion

As evident from all these texts swords were considered special, even magical, in early medieval times, when there seems to be a lack of centralization and an abundance of heroes. Many sources mention the use, construction or beauty of blades. These sources are of varied origin, being Merovingian, Carolingian, Anglo-Saxon, Scandinavian, Finnish or even Arabic. More often than not it is not specified whether the author writes about pattern-welded or mono-steel blades, but all swords were subjected to the same tests: cutting, bending and measuring. The weapons, which did not fail at any of these, were very prized objects, which could be handed down in families and which were told of in the legends of the day.

Chapter 3

The experiments



Introduction

Experimental archaeology is a continually present part of the archaeological research and it is also a branch which is becoming increasingly popular. The scientific uses of experimental archaeology were already admitted in the late 1950's, when for instance in Lejre, Denmark, and several years later in Butser, United Kingdom, prehistoric houses were constructed using information gained from house-plans revealed at excavations and using only historical techniques (Stone & Planel 1999, 3). In general experimental archaeology serves to enhance our understanding of the past by examining techniques or processes about which could only be theorized before. John Coles (1979) divides experimental archaeology into two sections: the imitative and the utilizational section. The imitative experiments are concerned with the reproduction of archaeological objects and the processes involved, thus essentially establishing modes of production or chaînes-operatoire. The utilizational section is focused on the use and functional capabilities of archaeological objects.

In this thesis experimental archaeology will provide the means to understand the possible use and value of the swords through the thorough examination of both the reproduction and testing of these blades. As such, both of the above described aspects of experimental archaeology are presented in this thesis. This methodology provides practical information which can be added to the theoretical discussion³⁶, possibly swaying the argument, possibly not. Of course there are plenty of pitfalls in experimental research, as in every type of research, since it requires proper execution (Jones 1979, 2). This is an aspect which is often hard to check, but should not be ignored. Most experimental research is executed on a very limited budget and timescale, and sometimes even with limited experience on the part of the researchers. The results can still be viable, but care must be taken when performing and presenting experiments. Despite the complexity of experimental evidence and practice, this type of research is becoming increasingly important. Now that huge numbers of artifacts have been excavated and examined, many questions still remain. Experimental archaeology can very well be used to pave the roads towards final answers in many discussions.

The experiments associated with this thesis consist of three parts. The first part is the consolidating, cleaning and preparing of bloomery iron. This first experiment serves to aid in the understanding of working bloomery iron. The second experiment is the forging of two swords and the third is the testing of these blades. During the second experiment a chaîne-operatoire is established for the construction of swords, and indications of both time and material expenses are presented. In the third experiment more direct answers will be provided to the initial research question. In addition some insight will be gained in the mechanical properties of early medieval

³⁶ See page 8-10.

swords. The first two experiments are in fact necessary steps to provide the replicated weapons which will be tested. However, despite the necessity of these steps, this does not negate the fact that these experiments are part of a steep learning curve with regard to ironworking and weapon production. Much information and experience was gained while performing these experiments and hopefully these can provide the basis for additional, future research³⁷.

1. Working the bloom

The swordsmithing-experiment was originally designed to utilize only bloomery iron, however, due to a lack of time some iron was processed but the swords were made out of modern low-carbon steel. Still, the bloom was experimentally worked and some observations were made regarding the smithing of raw iron. The bloom was a gracious gift from Jan Jennissen; a hobbyist iron-smelter from Zoetermeer who also heads the workgroup 'iron' of the VAAE³⁸. It should be noted that this is not the only experiment concerning bloomsmithing. Similar experiments have already been carried out by for instance Cleere (1970), Crew (1991), Sauder & Williams (2002) and Tylecote (1976). However, the author felt that the refining of bloomery iron was an important part of the historical smithing process. Since the bloomsmithing was the first experiment performed in this series, it was hampered by a lack of tools and experience with this type of material. Several of the problems encountered could easily have been solved if the proper equipment had been present. For instance, the problems in the heating and splitting of the bloom were mainly the result of too small a bellows.

The bloom was made using the direct-smelting process; in this process iron is drawn from iron-ore without actually melting. Instead of melting the iron, only the impurities in the ore are molten. This results in a more or less spongy mass of iron with only relatively small slag-inclusions still present. In the case of this experiment the bloom was created in a shaft-furnace. This is a relatively tall chimney-like furnace made from clay and loam, usually measuring 50-120 cm high and 25-50 cm wide (Cleere 1972, 11). This shaft-furnace was charged with charcoal and the iron ore was added. The ore used in this experiment is bog-iron from Denmark; this bog-iron was chosen because it should be virtually phosphorus-free whereas most bog-iron contains large amounts of phosphorus.

The ore was roasted on an open fire to remove water and impurities, and then crushed in preparation of the smelting. When this crushed ore is added to the smelting furnace, and sufficient temperature is reached, the slag melts out and the ore is reduced to raw iron (Tylecote 1962, 183-

³⁷ See page 80.

³⁸ VAAE: 'Vereniging voor Archeologische Experimenten en Educatie', a Dutch organization which focuses on experimental en educational archaeology.

185). The molten slag was tapped at the bottom of the furnace. Ultimately, after several charges of charcoal and ore, and many hours, the furnace was opened and the bloom retrieved.

In modern times all iron is prepared from ore by the indirect-process; all the ore is molten and impurities and unwanted elements are removed from the molten metal after which any desired alloying elements are added. The indirect-process has many advantages over the direct-process; however, until the invention of the blast-furnace in the 16th century (Tylecote 1962, 300-301) it was impossible to melt and contain large quantities of iron.

The bloom was worked to create 'true' wrought iron³⁹. Making bloomery iron suitable for regular forging operations requires a long and complex procedure. In essence this is a cleaning and homogenization process; the bloom is worked again and again until most slag is dispersed and any remaining slag is distributed evenly throughout the material. Turning a bloom into wrought iron consists of two stages: the consolidation and the piling. The first step, the consolidation of the bloomery iron, is the most important step in the preparation of wrought iron and can never be omitted. As evident from previous experiments, the consolidation of any bloom requires many hours of hard work. Sauder & Williams (2002, 8) managed to consolidate a 7.7 kilogram half-bloom in 11 man hours and they estimated that the consolidation of the full-bloom would require 18.8 hours. For comparison, the smelting of this bloom required merely 16.5 hours. David Sim (1998, 29) calculated that, at best, he required 0.10 minutes per gram of refined iron. This equals 12.8 hours for a 7.7 kilogram bloom. Though these results are of course mere indicators, they do clearly show the amount of time which is necessary to refine a bloom. Both of the above experiments were performed by the authors themselves using only historical fuels and equipment. Most of the other experiments (Crew 1991; Senn & Fasnacht 1991) which have been performed in this field utilized modern equipment, like power-hammers, and fuels, like coal.



Figure 3.1.1: the un-worked bloom.

³⁹ See note 9, pp. 11.

Consolidating the bloom

The consolidation-process begins with a welding cycle; the bulk of the material is heated to welding temperature⁴⁰ and then placed on a suitable surface and hammered heavily to weld together most of the iron present, thus creating a consolidated chunk of iron and slag which should then be massive enough to handle properly. Prior to the consolidation the bloom contains fairly large air- and slag-pockets; welding the bloom closes most of these pockets and squeezes the slag out. According to Tylecote (1987, 249-250) bloom may contain as much as 20% of slag. The bloom which is worked in this experiment contained an even higher amount; parts of it consisted of up to 60% slag⁴¹. Usually a bloom is heated and welded at least a dozen times before it has become massive enough to be processed further. The bloom is subsequently heated again to at least 1150° Celsius and hammered to a rough bar-like shape. This high temperature is required to ensure that all the remaining slag is in a liquid state; if the temperature is too low the solid slag will crack and the bar will fall apart (Sauder & Williams 2002, 8). The finished bar has a lower slag-content, though still several percent, and is of a rather heterogeneous structure. These bars are now solid enough to serve as base material for regular forging. However, to prepare this rough bar for fine forging, like swordsmithing, it has to be further cleaned and homogenized by piling, as will be explained later in this chapter.

Generally the consolidation process is performed by a team of workers, and not by a single person. Sim (Sim & Ridge 2002, 67) suggests teams of at least two craftsmen; one smith and one semi-skilled striker. Strikers are workmen or apprentices who handle heavy sledgehammers and simply strike to heated iron, performing no other task and working per judgment and command of the master-smith.

This bloomsmithing experiment started out with a large bloom of 10.2 kg (see fig. 3.1.1); it measured approximately 28 X 25 X 17 cm. This bloom was found to be too large to heat and handle properly during consolidation, thus it was decided to cut it in half. When the bloom was received it had already been partially cut using an angle-grinder with a steel-cutting disc; the two halves were still connected by a center portion of approximately 8 X 0.2 X 3 cm. It was not possible to cut the bloom further using an angle-grinder since the discs used did not have a large enough radius to reach its center. In an attempt to break up the bloom it was heated to approximately 1000° Celsius in furnace I⁴² and placed on an anvil. Then a small hatchet was placed in the pre-cut groove; this hatchet was struck, with both a 1.5 kg forging hammer and a 3.5 kg sledge, to no effect. The axe-head got stuck in the tough metal but the bloom would not break. Using a crowbar and the

⁴⁰ See page 13 for more information on forge-welding.

⁴¹ This is expanded upon further on page 46-47.

⁴² For furnace schematics and descriptions of the equipment used, see *appendix II: equipment*.

combined strength of three men the axe-head was eventually removed from the bloom. Another attempt was made using the same technique but then with a sharpened stone-chisel, again without success. These failed attempts required a total of approximately 110 minutes. In the end the bloom was cut using a hand-held hacksaw, a maul and a lot of patience; it required another 108 minutes, fourteen saw-blades and several heavy strikes with a splitting maul to cut the bloom.



Figure 3.1.2: the first attempt to cut the hot bloom.

After the cutting the consolidation of one bloom-half could begin. For the consolidation process the smallest of the halves was selected, weighing 3.4 kg and measuring approximately 23 X 11 X 14. The decrease in size of the non-cut surfaces compared to the full bloom is the result of deformation of the bloom during the earlier splitting attempts. The piece was heated in furnace II and when it reached a bright orange colour⁴³ it was placed on an anvil and hammered using a 3.5 kg sledgehammer. This first round was a one-man operation, resulting in the piece of bloom moving around on the anvil with every blow since it could not be held in place with tongs. Probably because of this the hammering was not very effective.

From the second round onwards a helper was present who held the bloom in place using large tongs while it was struck. The piece was heated to welding temperature, placed on the anvil and worked with a 5 kg sledgehammer. This proved to be very effective, probably because of both the high temperature and the stabilized positioning of the bloom. The piece of bloom was heated and welded seven times in total, during which it was compressed heavily and shaped to a rough bar. The piece showed cracks along its surfaces and edges, ultimately resulting in the bar breaking in two during the last heat.

⁴³ Approximately 1000 degrees Celsius.



Figure 3.1.3: consolidating a heated piece of bloom.

Several problems were encountered during the consolidation process. The first and most important of these was that the furnace, of type II, had insufficient capacity to bring the whole bloom to a welding heat. The furnace had a distinct 'hot' side, being where the tuyère was connected, at which the bloom did reach welding heat. However, the parts of the bloom not in contact with this side of the furnace would not heat above approximately 900 degrees Celsius. This was probably the result of a lack of airflow from the bellows. Unfortunately, at the time no other air-source was available. To overcome this problem the bloom was heated for a long time, and every few minutes it was turned so as to present another face to the hot side of the furnace. Another problem which had to be overcome was the tendency of the bloom to fall apart upon hammer-impact. This was possibly the result of insufficient heating in the core of the bloom, and could not be overcome with the equipment available. To minimize the iron-loss the bloom was heated and the hottest parts were gently compressed with a light 3.5 kilogram sledgehammer, before being further compressed using a 5 kilogram sledge.

The end result, figure 3.1.4, of these seven rounds was a bar weighing 1237 grams and measuring 10.5 X 5 X 5 cm and a broken piece weighing 674 grams and measuring 6.5 X 5 X 4.5 cm. The total weight-loss during the forging operation was nearly 1.5 kilogram. This loss will mainly have consisted of slag which has molten out from the bloom, and partially this weight will be made up of the many small pieces of iron which have broken off the bloom during forging. The consolidation required 3.8 hours with two workers, or 7.6 man hours. The bars were considered ready for further processing because of their shape, size and increased hardness under the hammer, i.e. the increase in energy required to shape these pieces. However, it turned out that the bar was not yet consolidated enough, as can be seen in the following pages.



Figure 3.1.4: the two consolidated pieces of bloom.

Piling the bloom

The next step in refining the bloom is the process known as piling. When piling the metal is hammered into thin strips or plates which are stacked, welded and then lengthened. This lengthened bar could then be folded and welded onto itself after which the resulting bar is lengthened again. These steps are repeated until the iron is 'clean' i.e. can be worked thin without cracking. The folding of the strips results in piles of thin iron-layers, hence the name piling. Objects are often forged directly from a piece of consolidated bloom, thus skipping the piling process. Though a properly consolidated piece of iron is fine when making large or rough iron objects, it is still not very well suited for the production of delicate pieces like blades or sheet objects. Almost all medieval sword-blades were piled to increase their strength and homogeneity (Williams 1977, 75).

In this experiment piling was tried since it would have been required in a normal swordsmithing operation. The smallest piece of the broken bar created in the consolidation process was used. This piece was forged in an attempt to flatten it in preparation of the folding. However, the piece instantly started to break up into small fragments of 1-2 cm³ (fig. 3.1.5). Some more literature research was done but to no avail. The bloomsmithing literature and experiments have almost always treated bloomsmithing as a by-product of smelting, instead of treating it as a first step in artifact-production. The experiments which have considered bloomsmithing important enough to examine the required techniques do not deal with piling, nor is there an abundance of information regarding bloomsmithing-problems.

Lacking the required background information to solve this problem it was decided to start experimenting again. Several tests were done during which the metal was forged at different temperatures, with different hammers and other tools, but the results remained the same. The iron fell apart as soon as any moderate deformation took place. Several possible explanations for this

phenomenon were made up. The first possibility was that the iron, contrary to expectation⁴⁴, contained fairly large amounts of phosphorus. Phosphorus is a common impurity in bog iron and tends to render the material cold-short. Cold-shortness means that the metal is very brittle when it is worked at low temperatures⁴⁵. To test this hypothesis the material was forged at very high temperature, approximately 1200° Celsius, but no positive effect was observed; the metal still broke down. This ruled out phosphorus as the malefactor.



Figure 3.1.5: a piece of bloom which has crumbled upon hammering.

Another common impurity in bog ores is sulfur. Large amounts of sulfur cause red-shortness; this is an embrittlement of the iron when it is worked at high temperatures⁴⁶. However, large amounts of sulfur were unlikely to be present in the bloom since the ore was roasted in preparation of the smelting. Roasting serves to remove excess water from the ore, but also does it expel sulfur⁴⁷. If, however, any sulfur was still present in the bloom than that would mean that the iron could only be worked at low temperatures. To test this, a piece of iron was heated to a dull red, approximately 650° Celsius, and carefully hammered. This work was slow since the low temperature caused the metal to be very hard and tough under the hammer. Despite the slow working rate and decreased temperature the metal still fractured after a few rounds of hammering. Though the breakdown occurred slower, the amount of deformation was approximately the same as when the metal was worked at regular forging temperatures. So, it was concluded that no large amounts of sulfur were present in the material.

⁴⁴ See page 38.

⁴⁵ This is any temperature below 800° Celsius.

⁴⁶ This is any temperature above 800° Celsius.

⁴⁷ This is also the reason copper sulphide ores are roasted (Nijboer 1998, 144).

In a final attempt to understand the problems encountered during the bloomsmithing a small sample of the bloom was analyzed using Energy-dispersive X-ray spectroscopy at the *Department of Applied Physics of the University of Groningen*⁴⁸, which showed a surprisingly low iron-content. Analysis showed that the bloom had an average iron-content of approximately 36%⁴⁹ near the outside. It is likely that the iron-content near the core of the bloom was higher, perhaps even double the above amount, but 70% iron is still fairly low for a bloom (Tylecote 1987, 249-250). All the rest of the material apparently consisted of slag and impurities. Upon heating and hammering this slag would either breakdown or become liquid; both of these effects will cause the metal to breakdown unless properly welded together. Unfortunately this conclusion could only be reached after the chemical analysis of the bloom and by then it was already decided not to work the bloom any further due to the encountered problems and time-restrictions.



Figure 3.1.6: the stack of flattened pieces.

Despite all the problems in forging the bloomery iron one more experiment was conducted before this material could be analysed. Several of the small fragments to which the bar had broken down were heated to approximately 1200° Celsius and hammered flat with a few heavy strokes. Some of the pieces broke down further, however, nine were deemed usable for the next step in the experiment.

The nine pieces were stacked and secured to a thin strip of low-carbon steel with the use of an arc-welder, as can be seen in figure 3.1.6. This whole stack was then placed into the fire and a welding heat was taken after which the stack was carefully welded together⁵⁰. The welded stack was then heated again and hammered flat; during the hammering two of the pieces broke off. The

⁴⁸ See page 46.

⁴⁹ See *appendix III: materials*.

⁵⁰ The set-up is based on one proposed by David Sim (2002, 51).

experiment was continued with the remaining seven pieces. The low-carbon strip was removed after the flattening. The stack was heated again and then partially cut through lengthwise using a broad chisel after which it was folded and welded together. Again the stack was flattened and this time cut sidewise before being folded and welded again. This process was repeated five times after which a small bar of iron was obtained which was completely clean. This bar could from this point onwards be shaped as desired without breaking or tearing. A simple calculation shows that this small bar had a layer count in excess of 200; the bar measured 13 X 1.3 X 0.6 cm with the layers being stacked in the 0.6 cm space⁵¹. The original stack weighed 142 grams; the final bar had a weight of 86 grams. Of course it should be kept in mind that two of the layers of the original stack had broken off. Even so the end-product is approximately two-thirds of the original weight; the rest of the material was either slag or was lost as hammer-scale.

*Chemical analysis of the bloom*⁵²

Due to the strict time limits it was decided to forge the swords from modern steel⁵³, and stop the bloomery iron experiment. However, to provide answers to the problems encountered during the forging of the bloomery iron, attempts were made to have the bloom chemically analyzed. A proper analysis would not only yield important information about the components of the bloom and any related problems during the forging; it would also provide some information about the efficiency of the smelting process.

After many unsuccessful attempts and over three weeks of trying to persuade both individual scientists and larger companies to perform such an analysis, the author contacted Prof. Dr. Jeff de Hosson from the *Department of Applied Physics* of the *University of Groningen*. After a meeting in which the encountered problems and desired tests were outlined he introduced me to Mikhail Dutka, a research assistant from Russia, who would be able to help perform the necessary analyses. The analyses were performed using a SEM⁵⁴. Both the raw bloomery iron and a sample of the piled iron bar were analyzed. Additionally some modern pattern-welded samples were examined. However, these samples did not yield any unexpected results.

The bloom contained a fairly low percentage of iron, only 37% on average. Several tests were performed and all had approximately the same results. It should be noted that it is likely that the bloom contains a higher iron-percentage near the core while this sample was taken near its surface. In addition to iron the bloom contained large quantities of both silicon (16%) and oxides (30%).

⁵¹ See figure 3.1.7.

⁵² See *Appendix III: materials* for the complete results of the analysis.

⁵³ See *Forging the swords*, pp. 49.

⁵⁴ Scanning Electron Microscope.

Silicon and oxides are the main component of slag, so this is not surprising. The oxides are mostly present in compounds; thus combined with any of the other elements present in the sample.

Other important contaminations in the material are calcium (6%) and manganese (4%); both are common in bog iron. Contrary to expectations some phosphorus was present in the bloom, approximately 1.5%. All in all it can be concluded that, despite the relatively low iron-content, the smelting process is fairly efficient and results in a more or less homogenous, albeit not very pure, end-product. Also, the iron-content of the bloom was low enough, and the slag content high enough, to account for the breaking up of the bloom during forging. This problem might be overcome with the use of additional welding cycles during which more slag is expelled and the metal is compressed further, thus further consolidated.

An analysis was also made of the piled bar. First several analyses were made of the iron part of the bar; this resulted in an iron content of 100%. This might not be entirely true since trace elements are easily unnoticed during an analysis like this. Even so, this result is very good since it confirms the positive effect of piling to clean the iron. An analysis was also made of a slag particle in the bar. The results of this were fairly similar to those of the original bloom. The most distinctive differences are an elevated phosphorus content (5%) and a lowered manganese content (2%); a reduction in the percentage of oxides (20%) could also be observed. An iron content of 45% was measured in the slag; however, this is probably not iron in the slag itself, but more likely the underlying iron which is also registered since the analyzed slag particle is very thin.



§Figure 3.1.8: Mikhail Dutka performing the analysis of the bloom.

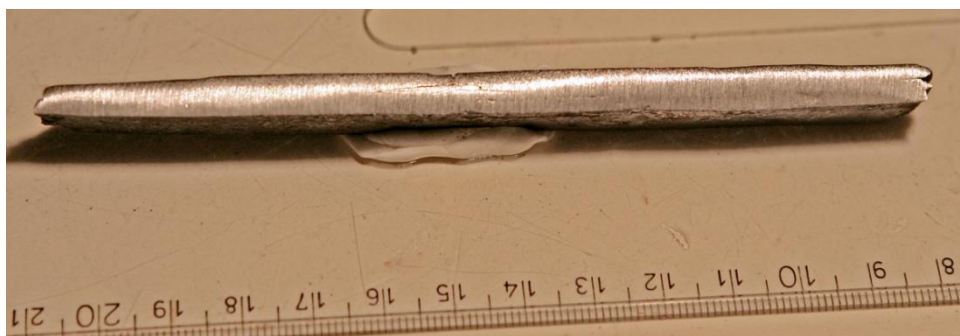


Figure 3.1.7: the piled and finished bar.

It can now be concluded that bloomery iron can indeed be made very workable through piling; however, piling is not as easy as it seems, and requires a lot of time. The preparation of this small bar, from flattening the individual pieces to shaping the finished object, required 4.5 hours⁵⁵. This would mean that just over 50 hours is required to prepare one kilogram of quality iron. This number seems excessive; a somewhat more experienced metalworker should be able to easily reduce this time by half. However, it should be kept in mind that piling is an advanced refining technique. Not all bloomery iron will have been piled; in fact, most will only have been consolidated since this yielded a good enough material for regular use (Sim 2002, 72).

If the bloom was only consolidated the required times will have been less. Sauder & Williams (2002, 10) managed to refine one kilogram of iron in 9.76 man hours. The author refined his iron a lot faster, spending only 2.17 hours on one kilogram. However, since the consolidated bars which were produced fell apart upon hammering, probably due to the large amounts of slag present, it can be concluded they were not yet cleaned enough. Assuming that the bars required another seven welding heats, thus doubling the time spent on refining them, a bloom of 3.5 kilogram would require 15.2 man-hours to rough-smith. This translates to 4.3 hours per kilogram. According to calculations done by David Sim (1998, 34-35) this is still too long. Sim was able, after lots of practice, to prepare one kilogram of bloomery iron in 30.5 minutes. According to him this is approximately the maximum amount of time which could have been spent on the rough-smithing of iron, based on the proposed needs and production of iron in Roman Britain. Of course, an important factor in the refining of blooms is the quality of the bloom. High quality blooms will be cleaned faster and easier than low-quality blooms. It is likely that in history most blooms were of fairly good quality, since they were the main source of iron and as such had to be produced rather efficiently.

Another observation made during the piling process is the superfluity of flux during the welding of bloomery iron. In the experimental piling no flux was used, despite the extensive welding of the folded stack. The slag in the iron melted upon heating; coating the metal and providing a welding surface free of oxidation or contamination. It is still probable that a flux was required when

⁵⁵ See table 3.1.

crafting complex welded objects like patterned blades. Due to the extensive heating, forging and welding the amount of slag in the metal will diminish. At some point there will not be enough slag left to properly coat the metal during welding; at this point a smith might have added silver-sand.

Process	Time required	Fuel required
Splitting the bloom	3.7 hours	8 kg charcoal
Consolidating the first bloom-half	7.6 hours	24 kg charcoal
Preparing the stack	0.7 hours	-
Piling the stack	3.8 hours	6.5 kg charcoal

Table 3.1: time and fuel requirements as noted during the bloomsmithing.

2. Forging the swords

Since the swords were crafted from modern materials these had to be selected. To ensure an experiment which would be fair, it was decided to use only one kind of steel for all parts of both sword-blades. The steel used is S235 structural steel⁵⁶. Since swords were hardened historically the steel should contain at least 0.6% carbon⁵⁷; however, both swords should also have unhardened low-carbon steel in their cores. To achieve this differential hardening some of the S235 was carburized; thus increasing the carbon content sufficiently to make it hardenable. The untreated steel contains too little carbon to respond to heat-treatment. Both sword blades were sized after the original sword from Wieringhuizen⁵⁸.

Forging a sword is a complex multi-stage process. The number of steps required in this process is determined by the type of sword made, as well as by the techniques used. See table 3.2 for the chaîne-opératoire as relevant in swordsmithing. This chaîne-opératoire is as much a step-by-step in the making of swords, as an expression of a cultural tradition which determines the ‘how’ and the ‘why’. Steps 1 and 5-10 can never be omitted when forging a sword; steps 2 and 3 are only relevant when making pattern-welded swords while step 4 is sometimes necessary in mono-steel blades as well⁵⁹. There are several other researchers who have examined early-medieval swordsmithing experimentally. Most notable of these are Anstee & Biek (1962), who have created a basis for all present research regarding pattern-welding, and Mikko Moilanen (2009), who has thoroughly examined and recreated pattern-welded inlays and is currently writing his PhD-thesis on the subject.

⁵⁶ See: *Appendix III: materials* for composition details.

⁵⁷ See page 11.

⁵⁸ Catalogue number VI. See *Appendix IV: sword catalogue*.

⁵⁹ See: *Step 4: welding the parts together to create sword-blanks*, pp. 55.

Despite the chaîne-opératoire presented in table 3.2, this is not the only way to create a sword. Which techniques are adopted in the chaîne-opératoire is as much subject to tradition and savoir-faire, as to performance requirements. For instance, it is very well possible to simply grind a superb sword-blade out of a simple bar of good steel. This technique, usually referred to as *stock-removal*, does not require forging, and as such tools like a forge, anvil, hammers, tongs, etc. are not necessary. In fact, a full blade could be shaped with nothing more than a file or grindstone and lots of patience.

Obviously, this was not the way it was done; probably both for time-considerations and because of the high material-loss. It is likely that in early-medieval times swordsmithing was a craft which was performed as efficiently as possible, and that the swords produced were at least of adequate quality. The chaîne-opératoire as presented below is based on the modern savoir-faire of swordsmithing. Now, in the 21st century, there are still swordsmiths around, and these have of course found their own ways to produce these arms as efficiently as possible. As such, the presented steps might be slightly different from the historical process. However, considering what is known about the materials, tools and products of the time, it is very likely that the process has not changed much since ancient times.

Step	Action
1	Selecting and preparing the materials.
2	Welding the stock together to create rods.
3	Twisting and squaring the rods.
4	Welding the parts to create sword-blanks.
5	Forging the sword-blanks to shape.
6	Rough-grinding the blades.
7	Heat-treating the blades.
8	Fine-grinding, polishing and finishing the blades.
9	Making the handle-parts .
10	Peening the handle and blade together.

Table 3.2: The chaîne-opératoire as applicable for the production of swords



Figure 3.2.1: steel strips ready for processing.

Step 1: selecting and preparing the materials

The first step in the sword-making process determines for a major part which other steps have to be taken, as well as how much time is required to finish the blade. Proper materials in the desired sizes can easily save tens to hundreds of hours of production time.

The material selected for this project was regular S235 structural steel. This steel was chosen because it is common, cheap and of a low-alloy composition⁶⁰. Despite the availability of this steel it could not be obtained in all the sizes necessary. This resulted in an obligatory two-part construction of the mono-steel blade. For this sword two strips of 6 X 30 X 1000 mm were welded together lengthwise to create enough mass to forge the blade from. For the pattern-welded blade several material sizes were used; 2 X 10 X 1000 mm strips for the core (21 strips total) and a 10 X 10 X 2000 mm bar for the edge. The edge-bar was folded in half to create a piece which could envelop the core, thus creating an unbroken edge.

After selecting the base-materials some pieces had to be carburized and all pieces had to be cleaned. Most of the steel was coated; either with a thin layer of chrome, a layer of paint or a layer of milling scale⁶¹. Both the chromed and the painted parts had to be ground clean; the scale layer would easily dissolve when the metal was heated.

Some pieces were carburized after they were cleaned. A trial carburization was performed on six of the 2 X 10 X 1000 strips; these were placed under a large wood fire in furnace type III⁶², which was continually kept burning for approximately six hours. After leaving the strips and fire to cool for

⁶⁰ See: *Appendix III: materials.*

⁶¹ Milling scale is the oxidation layer which forms on hot-rolled steel during processing.

⁶² See: *Appendix II: equipment.*

several hours, the still warm strips were removed and spark-tested⁶³ for carbon. Some parts of the strips showed a slight increase of carbon, however, the overall result was unsatisfactory. None of the strips had absorbed enough carbon to become hardenable.

The next trial was done using the same strips by placing them in a much hotter wood-fire and letting them gradually sink deeper between the coals and ashes of this fire. This time all strips were heated to 1150° Celsius for at least 45 minutes. The results were disappointing; none of the strips showed much of an increase of carbon, and some even seemed to display a decrease of their carbon-content. A possible, and likely, explanation of these results was the presence of oxygen near the steel. If the steel is heated in the presence of air some of the carbon from the steel will bind with oxygen creating carbon-monoxide or carbon-dioxide and leaving the steel carbonless.

The next trial carburization was done using a slightly different technique: case-carburization⁶⁴. First an all-steel case had to be made which was large enough to contain the strips and charcoal-dust. This case⁶⁵ was made using a piece of square 20 X 30 X 1000 mm steel tubing which was welded shut on one end. By bending and welding two pieces of 1.5 mm thick sheet steel a cap was made to seal of the other end. The case was charged with six new strips of steel, charcoal-dust, and some finely crushed charcoal. With the cap in place this container was placed horizontally in a wood-fire in furnace type III. This fire was maintained for almost four hours and then it was allowed to gradually burn down. During the process the case (except for the cooler ends) was always between 800 and 950° Celsius. After cooling the case was removed and the strips were extracted. Spark-testing⁶⁶ indicated a severe carbon-increase in the strips varying from 0.3% to 0.6-0.7 % carbon with the lowest being near one end and the highest amount present in the middle of the strips.

Since this technique proved to work well it was repeated for the edge-bar and another three strips for the rest of the blade. The edge-bar was too large for the original case so a new case was fashioned from 1.5 mm sheet steel⁶⁷. This new case was sized so that it could also accommodate a full-sized sword-blade; something which would be necessary later in the forging process when the mono-steel blade would be carburized⁶⁸.

After these preparatory works, stacks were made of seven strips, three carburized and four un-worked. These were tack-welded, using an arc-welder, at several points in preparation of the forge-welding.

⁶³ See: *Appendix I: additional techniques*

⁶⁴ Ronald Frank Tylecote extensively describes carburization-methods in *The Early History of Metallurgy in Europe* (1987, 258-280).

⁶⁵ See: *Appendix II: equipment*.

⁶⁶ Again, see *Appendix I: additional techniques*

⁶⁷ See: *Appendix II: equipment*.

⁶⁸ See: *Step 7: heat-treating the blade*, pp. 58-59.



Figure 3.2.2: welding a stack of strips.

Step 2: welding the stacks together to create rods

The next step was the forge-welding of the stacked strips to create the rods for the patterned sword-core. Originally it was assumed that two core-rods would be enough for the sword, but later in the process it became clear a third was required so the necessary steps were repeated to make it.

Welding a stack of strips is a simple repetitive process. However, like all forge welding, it requires proper judgment from the smith to create adequate welds. A stack was placed horizontally and sidewise⁶⁹ in the fire and, starting on one end, heated. The strips were brought to near-welding temperature and then removed from the fire for fluxing. As a flux borax-powder was used⁷⁰; this was lightly sprinkled on the hot metal. After some bubbling and boiling it melted, as such creating a thick glassy coating on the steel. Then the steel was placed in the fire again and heated until at welding temperature. As soon as this temperature was reached, the stack was removed from the forge, placed flat on the anvil, and firmly hammered together. This way a sound weld was created. This process was repeated until the whole stack was welded to a long thin rod. With each heat approximately 5 cm was welded, and including overlap it took between 25 and 30 heats to reach the other end of the rod. After the first welding cycle the whole welded stack was turned around and re-welded from the other side. After this the corners of the rod were rounded and the whole piece straightened in preparation of the twisting. The full-welding and straightening of each stack took approximately 5 hours.

The steps described above were repeated until three rods were created, ready for twisting and further processing.

⁶⁹ Sidewise: with the thin sides of the strips facing down towards the fire.

⁷⁰ See pp. 13.



Figure 3.2.3: twisting a rod.

Step 3: twisting and squaring the rods

Each rod required close to 20 heats to twist it along its whole length and a total time of about 1 hour per rod. The twisting of the rods was done using vice-grips and a bench-vice. A section of rod was heated, then one end was secured in the vice and the rod held close to its heated section with tongs. The tongs were turned 90-180 degrees, twisting the rod to the same degree. By repeating this twisting motion over and over it was possible to twist the rod over its entire length with a total of approximately 100 twists. By careful heating and mounting in the vice the twisting process could be controlled and kept uniform; twisting is hard to do evenly. During twisting any faulted welds will show because they open up. If a rod has several faults in one section there is a chance the rod will shear off during twisting; a clear indication that the quality of the rod was not high enough for use in a blade's core.

After twisting the rods they had to be squared in preparation of the core-welding. To ensure proper welding in the core of the rods, each section was brought to a welding heat, fluxed and welded carefully after which the rod was squared in the same heat. This process required approximately 70 minutes for each rod, and again over twenty heats. After squaring each rod was inspected carefully. Some faulted welds still showed, but the overall result was considered acceptable.

When all rods were properly twisted, squared and straightened they were ready for the next step.



Figure 3.2.4: welding together the patterned sword.

Step 4: welding the parts together to create sword-blanks

Usually, when welding together a pattern-welded sword-blank, either the core is welded and then the edges added, or the piece as a whole is welded at once. In this experiment however the core was welded in two parts; first two rods were welded together along their length, and then later the third rod was prepared and added to increase the width of the patterned core. All core parts were welded twice to reduce the risk of weld-failure. If a weld was not properly set it might break apart during the use of the sword, possibly splitting the blade along its whole length. When the core was complete, which required a total of 8.5 hours, the edge was prepared. Preparation of the edge took 40 minutes and consisted of forging the edge to a tight fit on the finished core.

Then the edge was welded onto the core. This was a complex process because the welding had to start at the point on the sword. To weld the point, both edge and core were brought to a welding heat and then the sword, with the edge in place, was positioned vertically on a tree-trunk and the point was hammered to fuse the parts together. Welding the point required three heats. When the sword-point was done the rest of the edge was welded onto the core in approximately 3.5 hours. When the edge was fitted the whole edge was re-welded in a second 3 hour course, again in an attempt to ensure sound welds.

Not only the patterned sword had to undergo welding, but also the mono-steel blade. This sword was constructed from two identical strips which were welded together lengthwise to create enough mass for the forging of the blade. These strips each measured 6 X 30 X 1000 mm; welding these two strips together required, including re-welding, approximately 11 hours. The rough blanks were ready for shaping when all the parts were completely welded together.



Figure 3.2.5: Welding together the mono-steel sword.



Figure 3.2.6: Shaping the pattern-welded sword.

Step 5: forging the sword-blanks to shape

Both blades were now essentially heavy bars of steel. They measured approximately 9 X 30 X 1150 mm. Shaping the bars to true blanks required approximately 3.5 hours each. During this forging the bars were heated and hammered both flat and wide. When the blanks were close to their final dimensions the points were finished, the edges hammered and a shallow but wide fuller was lightly forged into the blades. As a last step the blank was cut to size, and the tang was lengthened and shaped. Any welds, which opened up during the shaping process, were instantly repaired.



Figure 3.2.7: Rough-grinding the patterned sword.

Step 6: rough-grinding the blades

After the swords were forged to shape, they had to be ground; their shape was still rough and their cross-sections thick. Grinding started with the use of an angle-grinder and course flap-discs; the thickness was reduced and a rough profile was established. After this a stationary belt-grinder with a low rpm⁷¹ and increasingly fine belts was used to establish the flats of the blades. After establishing the flats the fuller had to be ground. Initially this was done by hand using a shaped hardwood sanding block. However, this turned out to be a tedious job with unsatisfactory results. It was decided to continue this using a grinder but lacking the appropriate machinery, a custom grinding disc was fabricated specifically for this purpose⁷². The rough-grinding required 8.5 hours for the mono-steel blade and 4.5 hours for the patterned sword using these modern grinders. The time difference is both the result of increased techniques and differing metal-hardness. Historically, grinding of the blades would have been even more time-consuming since even a water-powered wheel would grind very slowly. After rough grinding both blades had an identical profile, though the patterned blade was slightly thicker, approximately 0.5 mm, than the mono-steel sword. The edges were left approximately 1 mm thick to reduce the deformation which can occur during the heat-treating process.

⁷¹ Rotations per minute

⁷² See: *Appendix II: equipment*.



Figure 3.2.8: Furnace III heating a blade for hardening.

Step 7: heat-treating the blades

The most crucial step in the making of any blade is the heat-treatment. This process decides whether a sword is hard yet flexible, or soft and malleable. Proper heat-treatment can create a blade with the best characteristics achievable from its construction and material. Bad treatment on the other hand results in a piece of iron which is not only un-useable for its intended function; it is also rendered useless for any other purpose. The heat-treatment process is described in more detail in chapter 1⁷³.

For these experimental blades, it was decided to try and achieve a maximum functionality in the swords; this is the only possible course when trying to compare these blades fairly. To this effect it was decided to put the blades through a slack-quench in oil. The quenching was done in sunflower-oil. This is a light vegetable oil which cools the blade sufficiently to harden it but not so much as to make it unduly brittle. If water or brine was used for the quench the blades would have become harder, but this would have increased the chance of stress-cracks⁷⁴.

The blades were heated to approximately 900 degrees in furnace type III. This heating had to be done evenly to ensure a constant hardness. The furnace was charged with 4.5 kilogram of charcoal and lighted. When the coal was properly burning, some firewood was stacked on top to increase the heat-flow in the fire. The mono-steel blade was placed in the coals, only slightly covered. Airflow was created on one end of the furnace by fanning with a piece of board. After an hour of slow heating the blade was removed from the furnace and its colour judged. Despite the presence of a clearly cooler area at approximately one-third of the sword it was decided to quench the blade. The hot sword was lifted with the use of tongs and then quickly lowered point down in the quenching

⁷³ See pp. 13-14.

⁷⁴ Stress-cracks are diminutive cracks or tears in the metal which occur as a result of rapid cooling. These cracks cannot be repaired and result in weak spots in the metal.

tank⁷⁵. A flash-fire and some bubbling from the cooking oil occurred. After one minute the blade was removed from the oil and rinsed with water. The whole sword got a thin black coating as a result from the hot oil and it showed two fairly serious bents. These bends probably appeared as a result of build-up stress in the sword-blade as a result of uneven hammering or grinding during the shaping of the steel. When the blade is rapidly cooled these stressed areas tend to shrink at a different rate than the surrounding metal, thus bending it.



Figure 3.2.9: quenching the pattern-welded blade.

A file-test⁷⁶ was then performed to determine the results of the hardening process. First some strokes were made on the unhardened blade-tang; these strokes served as gauging marks. Then some strokes were made along the edge of the blade, at approximately every 15 centimeter. From these strokes it was concluded that the first half of the sword was properly hardened, with the second half being mostly unhardened but still slightly harder near the point of the blade than near the middle. This differing hardness was the result of the uneven heating of the blade but it was judged to be impossible to harden the blade better with the equipment used. After hardening, the blade was cleaned and then tempered to a dark yellow, approximately 250° Celsius, to relieve any build-up stress and achieve a proper balance between hardness and flexibility.

The second blade, of pattern-welded construction, was heated similarly in the same furnace. When it reached the desired temperature it was removed and quenched in the oil. After rinsing and file-testing this blade showed much the same result as the first blade; the first half of the sword had hardened properly, but the rest was still soft with a slight hardening near the point of the blade.

⁷⁵ See: *Appendix II: equipment*.

⁷⁶ See: *Appendix I: additional techniques* and figure 3.2.10.



Figure 3.2.10: file-testing the mono-steel blade.

Because of these limited results from the hardening process it was decided to retry and harden the blades. A closed furnace of type IV was built which was filled with charcoal and lit. To one end of the furnace a bellows was connected, which was worked to provide a constant, though low, draft. The furnace was, when the charcoal burned well, opened on the far side. A sword was placed in the hot coals and slowly heated to its critical temperature⁷⁷. When this temperature was reached the blade was quickly removed and again quenched in oil. This heating took just under an hour for each blade. The result of this re-hardening was better than with the precious furnace, however, there were still some softer spots in the swords.

With a furnace of type IV it is possible to harden these blades still more evenly. However, due to the limited time available, this could not be practiced to achieve optimal results. Another problem encountered was that due to the repeated heating of the blades in the hardening process severe decarburization took place. If these swords were hardened again a lot of grinding would be required to remove the decarburized areas. More grinding might also result in the blades becoming too thin to be useable. It was decided to finish them in their present state and then perhaps revisit the hardening of swords in the future.

⁷⁷ This is its austenitic stage, see also page 14.



Figure 3.2.11: the unfinished pattern-welded sword. Both the black quenching-coat and the pattern are visible.

Step 8: Fine-grinding, polishing and finishing the blades

The final step in finishing a sword blade is the grinding and polishing. This finishing process serves to reveal the beauty of a patterned blade. But also is it necessary to straighten the edges and consolidate the profile.

After heat-treating the blades were cleaned from the black layer which had formed during quenching. Some of this layer could simply be chipped off using a pocket-knife; the rest had to be removed with the help of an angle-grinder. This angle-grinder, with a 120 grit flap-disc, was also used to clean up the profile and pre-shape the edges. Care had to be taken to ensure the blade did not overheat during grinding, for this would undo the hardening.

After grinding, the fuller was deepened and rough-polished using 240 grit sandpaper and a shaped hardwood sanding block. The edges were filed to rough-sharpen and thin them, after which these too were finished with 240 grit paper. When all parts of the blade were evenly sanded they were polished using 400, 600 and 1000 grit sandpaper. This resulted in a well-shaped, well-polished sword. Usually a sword blade is then finished by buffing with a cotton wheel and a polishing medium⁷⁸; however, in the case of the pattern-welded sword this was not possible. The grease from the polishing tends to coat the blade, preventing any etching later on. It was decided to provide both blades with a similar finish, thus neither was buffed. The swords were cleaned with acetone and then lightly etched in a 5% ferric-chloride solution. After etching the etchant was neutralized using baking soda and the blades were cleaned by scrubbing with steel wool and ammonia. Then the swords were

⁷⁸ These polishing mediums are called 'rouge'. Rouge consists of grease or tallow mixed with fine cutting particles; these could be fine sands but also diamond-powder or metals.

finished by buffing with a cotton wheel and a fine polishing compound; not too much polishing could be done because that might have erased the etched surface and thus obscured the patterns again.

The total time which was required to grind and sand the blades up to the 240 grit sandpaper was approximately nine hours. Of this time about five and a half hours were spent on the patterned sword since this blade was still slightly thicker than its mono-steel counterpart, and as such not only had to be finished but also carefully reduced in size.

The polishing required a little over three hours, and the etching took one hour per sword to complete. The final buffing and cleaning of the blades was done in approximately 30 minutes. At the end of the process detailed measurements from both swords were taken. The sword blades now measured 76.4 cm and at the base the blades had a width of 4.8 cm. The maximum thickness is 4.3 mm. The original blade from Wieringhuizen was 78.6 cm long, 4.6 cm wide and a maximum of 5 mm thick. The reproduction-swords were slightly shorter, thinner and wider than the original artifact, but still similar in shape and handling characteristics. Both experimental blades were checked on a scale: the patterned sword was, with 866 grams, slightly heavier than the mono-steel blade which weighed 823 grams. This weight difference is probably the result of slightly uneven grinding.



Figure 3.2.12: inlaying the pommel with copper.

Step 9: making the handle-parts.

Both swords were tested without handles; however, it was felt that to completely understand the sword-making process at least one sword should be finished completely. The pattern-welded sword was chosen to hilt and finish as if it were a weapon as used in the early medieval period. A wrought iron cross-guard was made, as well as a two-part pommel from the same material. The handle was covered with wood and leather.

All iron parts were first rough forged to shape and then finished using grinders, files and sandpaper. The hardest part in the creation of these parts was the fine-fitting over the tang of the blade. Both the cross-guard and the lower pommel-half had slots cut into them using a drill and a jewelry saw. These slots were then filed to fit using needle-files of various shapes. When these parts were finished the upper pommel-half was shaped in a three-lobed style using files. The total time spent on the iron parts of the hilt was eight hours, three of which were taken up by the filing of the slots.

All the iron parts were then sanded up to 320 grit sandpaper. At this point all surfaces would be fairly smooth and the shapes would be well defined. Since many original handles were decorated, it was decided these also should be. The decoration was done using inlaying. In this technique grooves are cut in the base material in which non-ferrous metal is inlayed and secured. The inlayed design used consisted of simple straight, copper lines across all parts of the handle. Several engravers were made specifically for this purpose. These engravers are essentially hardened steel pins with shaped and sharpened heads. By tapping the butt-end of these pins, while moving the heats across the base material, designs can be cut into the metal. After the grooves were cut, all of them had to be 'undercut'. This undercutting was done by placing the graver's edge against the wall of the groove at an angle. By light tapping and moving the graver, the groove is widened near the bottom. If the undercutting is done well, the copper inlay will fill the grooves and be secured because it is allowed to spread more at the bottom of the groove than at the top. The inlaying is done by placing annealed and squared copper wire in the groove. This wire is then spread by tapping with a dull punch. When the wire is secure any excess material is filed off and the whole piece polished. The grooves used on these parts were approximately 1 mm wide. The time required to completely finish the inlays was just under seven hours.

When all the metal parts were finished a wooden grip was made. This grip consisted of two pieces of pine-wood which were made to fit tightly over the tang with the use of chisels. These wooden grip-halves were then glued together over the tang. After the pieces were glued and dried their outer shape was refined with rasps and files. The finished grip-core was covered in thin goatskin

which was wetted and then sewn over the handle. As the leather shrinks when it dries, this results in a very tight fit over the handle. Making the wood-and-leather grip required about two hours.



Figure 3.2.13: the sword-handle as finished.



Figure 3.2.14: The finished blades without handle.

Step 10: peening the handle and blade together

The final step in the finishing of a complete sword is the peening together of all the parts. For this the last centimeter of the tang is annealed by heating and slow cooling. Then all handle pieces are slipped over the tang of the blade. The peening itself is then done by hammering the butt-end of the tang into a mushroomed shape. By mushrooming, or spreading, the tang all the pieces are secured into place. The tang-end is then finished by light hammering to smoothen it. During peening care has to be taken to make sure all parts are tight, but not so tight as to cause cracks in the wooden handle.

When the tang is peened the upper half of the pommel is placed on the end of the sword. This upper half is then secured to the lower pommel half with the use of two long rivet-shanks which pass through both pieces and are also peened into place, riveting the two parts together.

The preparing and peening of the sword was a short operation and required less than 20 minutes.

Step	Pattern-welded Sword	Mono-steel Sword	PW + MS Sword
1	16	-	16
2	15 (3 X 5)	-	15
3	6.5 (3 X ± 2.2)	-	6.5
4	15.6	11	26.6
5	3.5	3.5	7
6	4.5	8.5	13
7	3	3	6
8	8.5	6.5	15
9	17	17 (if this had been done)	34
10	0.3	0.3 (if this had been done)	0.6
Total excl. step 9 & 10	72.6	32.5	105.1
Total incl. step 9 & 10	89.9	49.8	139.7

Table 3.3: timetable for the forging and finishing of the swords.

3. Testing the blades

Both swords were put through a series of tests to determine their qualities. Three categories were established: cutting ability, edge retention and flexibility. These tests can of course be classified as utilizational experiments.



Figure 3.3.1: Cutting a free-falling piece of fabric.

Testing the cutting ability of the blades

Probably the most typical, and possibly the most important, test to which each sword is subjected is the cutting test. There are several ways to do this, but in this experiment it was opted to perform the cutting test on pieces of fabric as is described in historical texts⁷⁹. The main purpose of the cutting test is to show the sharpness of the sword-edge; thus giving an indication of how it would perform in battle.

A length of thin cotton weave was taken approximately 100 cm long and 20 cm wide. This piece was dropped from 200 cm height and then cut while falling. The results were noted in table 3.4. Each sword was used three times to perform this test.

⁷⁹ See pp. 31.

	Monosteel sword	Pattern-welded sword
Cut number	Results	Results
I	1 cut, 11 cm long	2 cuts, 2 & 5 cm long
II	2 cuts, 14 & 13.5 cm long	No cut
III	No cut	1 cut, 9 cm long

Table 3.4: cutting a free-falling piece of cloth.

The next cutting test also served to establish the cutting ability of the sword. This time a similar piece of cotton was taken but then twisted so as to create a cotton rope. This rope was fastened at a height of 180 cm and a 600 gram weight was added to the bottom to create constant tension in the rope. Then the rope was cut. This test was again performed three times; each time the rope was shortened thus increasing the tension. The results were noted in table 3.5.

		Monosteel sword	Pattern-welded sword
Cut number	Cloth length	Results	Results
I	70 cm	1 cut, 1 cm long	3 cuts, 1.5 & 1.5 & 0.5 cm long
II	60 cm	No cut	3 cuts, 2.0 & 1.5 & 1.0 cm long
III	50 cm	2 cuts, 2.5 & 0.8 cm long	2 cuts, 5.0 & 2.5 cm long

Table 3.5: cutting a twisted piece of cloth under tension.

Because of the poor results of the second test an additional experiment was performed. The same situation was created as in the previous test, except that the piece of cloth was hung wide instead of twisted. This presented merely a one layer thickness to be cut through. Two cuts were made and the results noted in table 3.6.

		Monosteel sword	Pattern-welded sword
I	70 cm	7 cuts, all between 0.3 and 1.5 cm long.	1 cut, 1.5 cm long.
II	50 cm	2 cuts, 1.5 & 0.3 cm long.	1 cut, 38 cm long

Table 3.6: cutting a single layer of cloth under tension.

Obvious from these tests is that even if a sword is just sharpened, it still has trouble cutting multiple layers of fabric. A single layer of fabric does not present a problem; however, it is also not easily cut all the way. The successful cutting of a floating piece of felt or fabric as described in the sagas is very unlikely, but still not impossible.



Figure 3.3.2: the cotton 'rope' and the single layer tensioned weave.



Figure 3.3.3: the patterned blade mounted in the cutting-contraption.

Testing the edge retention of the blades

This test was also very important as it served two purposes. First this was used to show how a sword would perform in battle; would it easily dull or would it remain sharp during use? The next purpose of this test was essentially to check the hardness of the edges. The blade was subjected to cuts on a fairly hard material and it was noted how well the weapon retained its edge. In essence, these tests are similar to the practice of cutting anvils or anvil-bases in history⁸⁰.

To perform this test a contraption was build in which a blade could be mounted on a rotating axle. Then, by dropping a weight attached to the sword-tang, the blade is moved in a rotating downward motion; thus representing a chopping motion. First the sword was used to chop a piece of hardwood⁸¹ of 40 X 40 mm. After the cut the edge was examined. This test was performed three times and the results can be found in table 3.7. After this the same test was performed but this time on a softer material: a potato. Potatoes were selected because they are soft yet firm, and because they are fairly consistent in structure throughout. After the cut the penetration depth was noted, as well as any other remarkable effects, and the blade examined. This test was again performed three times and these results can be found in table 3.8.

⁸⁰ See page 31.

⁸¹ Hardwood was considered an appropriate material for this test because it is hard enough to clearly damage a soft metal edge, but soft enough to deform a little upon impact. This wood-deformation ensured that the edge of the blade would only fold if it was too soft, instead of tearing/notching as might happen if a piece of metal was struck.

Cut number	Monosteel sword	Pattern-welded sword
I	Edge undamaged, clear indentation in the wood (1 mm deep)	Edge undamaged, clear indentation in the wood (1 mm deep)
II	Slight edge damage, clear indentation in the wood (1 mm deep)	Edge undamaged, clear indentation in the wood (1 mm deep)
III	No further edge damage, clear indentation in the wood (1 mm deep)	Edge undamaged, clear indentation in the wood (1 mm deep)

Table 3.7: edge retention when striking a piece of 40 X 40 mm hardwood.

Cut number	Monosteel sword	Pattern-welded sword
I	Edge undamaged, potato cleanly cut	Edge undamaged, potato cleanly cut
II	Edge undamaged, a 2 mm thick cleanly cut sliver removed from the potato	Edge undamaged, a 1 mm thick cleanly cut sliver removed from the potato
III	Edge undamaged, a 1 cm thick slice cut from the potato	Edge undamaged, a 1 cm thick slice cut from the potato

Table 3.8: edge retention when striking a potato.

Testing the flexibility of the blades

This last test is also the one which is best described in historical sources⁸²: the flexibility test. To perform this test the blade was mounted point-up in a bench-vice. The vice held the sword at 8 cm above its tang. The reason for this was to ensure no deformation would take place at the weakened point where the blade is reduced to the width of the tang. A piece of leather, mounted to a pulling scale, was attached 9 cm from the sword-tip. Then the sword-blade was bent, using this scale, to a marked number of degrees. The energy required for this bend was noted. The blade was held in position for three seconds, after which it was gently allowed to straighten out again. Then the 'follow' of the blade was measured. The follow is the amount of permanent bending sustained by the blade due to the test. If the follow exceeded 20 cm the sword was deemed unusable and thus no further testing was done. A blade was considered 'ruined' when the amount of force required to bend the blade lessens while additional deformation occurs at a previously damaged part of the blade. All results were noted in table 3.9.



Figure 3.3.4: performing the flex-test.

It was remarkable that the patterned blade required a lot more force to bend; however, it was already 'ruined' when it had sustained a little over 5 cm of follow. This can be compared to the mono-steel blade which did not yet show signs of being permanently damaged when it had sustained 22 cm of follow and thus had become unusable.

⁸² See pp. 33-34.

	Monosteel sword		Pattern-welded sword	
Degree of bend	Force required	Amount of follow	Force required	Amount of follow
10	-	-	2.0 kg	-
20	0.5 kg	-	3.5 kg	1.2 cm
30	1.2 kg	-	5.0 kg	5.5 cm
40	2.0 kg	-	5.0 kg	15.0 cm
50	2.5 kg	2.0 cm	4.8 kg	26.5 cm
60	3.0 kg	5.5 cm	-	-
70	3.2 kg	13.5 cm	-	-
80	3.8 kg	22.0 cm	-	-
90	-	-	-	-

Table 3.9: degrees of bend, force and damage as applied to the swords in the flexibility test.

Conclusion

The first experiment performed in this series helped to reveal some of the problems which can be encountered when working with historical materials. The properties of these materials, in this case iron, can differ extremely from those of modern materials, thus necessitating a wholly different approach.

The main problem encountered during the working of bloomery iron was the crumbling of the stock upon heating and hammering. It is most likely that this is the result of large amounts of slag still present in the bloom, as observed during the chemical analysis of the material. This problem can most likely be overcome by further consolidation of the bloom; however, this will also result in higher material loss. To increase the yield and decrease the production time of bloomery iron a solution might be found in a set-up as proposed by David Sim (1998, 67). In his set-up a pair of broad tongs is used to keep the hot bloom in place, while a steel disk is placed on top of the bloom and hammered in between the tongs. This results in severe compression, and thus consolidation, of the bloom, while reducing material loss by working the metal in the confined space between the tong-jaws, the steel disk and the anvil.

Another observation made during the experiment was that the slag present in the iron is sufficient to coat the material upon heating, and thus successfully negates the need for any additional flux.

The second experiment, the forging of two sword blades, provided a lot of insight in both the processes and time involved in the creation of these weapons. The making of any item can be described in a *chaîne-opératoire*, with the number of 'links' or 'steps' in the chain dependent on the type of artifact made. In this experiment the minimum number of steps required to create a sword was seven, and the maximum was ten.

Forging swords like these can require anywhere between several tens of hours to several hundred of hours, depending on the complexity of the blades. In this experiment the author was able to forge a triple-core patterned sword in about 90 hours. David Sim (Sim & Ridge 2002, 93) forged a similar sword in 110 hours, and John Anstee (Anstee & Biek, 1962, 222) forged one in only 43 hours. However, Anstee employed modern fuel and tools in his experiment. In history, the iron used in the forging process had to be cleaned and prepared first, adding many more hours.

The testing of the swords in the third experiment yielded both expected and unexpected results. Both blades were tested on three aspects. The first, cutting tests showed that both swords were able to cut more or less equally. The results were seemingly random, with both swords clearly able to cut cleanly through fabric but the length of the cut apparently varied more as a result of chance and technique, than of blade-quality.

The second test, which served to check the edge retention of these blades, gave similar results. The swords cut equally and both remained equally undamaged. A slight folding was observed in the edges of the mono-steel sword while cutting hardwood, but both swords still performed equally on the cutting of potatoes. Obvious from these tests was the cutting power of these blades.

The last and most important test did reveal some differences. During this test both swords were bend to examine their flexibility. It was not possible to bend these weapons into hoops, as suggested in some historical texts, without damaging them. However, the mono-steel blade was indeed very flexible. It proved to be able to withstand severe bending, but also did it require very little strength to flex. The pattern-welded blade on the other hand required four to five times more energy to bend, but was less able to withstand deformation. This is similar to the difference suggested by France-Lanord (Salin 1957, 65). His tests showed pattern-welded sword being up to three times as stiff as their mono-steel counterparts.

If these swords were used in a fight it is very likely that the patterned blade would fairly easily cut through hard materials like wood, bone or armour. However, if bend, this sword would first have to be straightened to remain useable. The mono-steel sword is most likely better able to cut soft tissue, since hard materials would cause the blade to deform. On the other hand, this blade would usually return true on its own, thus making it also very useable in a battle situation. Another distinct advantage of the stiffness of a pattern-welded blade is that it might be made thinner than a mono-steel blade of similar stiffness, thus reducing its weight and increasing its handling characteristics. Lightweight weapons will have had the advantage over heavier ones since a warrior would be able to reduce the energy required with each swing and as a direct result tire not so easily. Of course, too light a weapon would result in weak blows being struck since one would not be able to transmit all the force of a strike through the weapon. However, patterned swords weighed approximately one kilogram which is only slightly lighter than weapons from slightly later periods.

Conclusions



Conclusions

Both archaeology and history have shown that the pattern-welded sword was held in high esteem; by the contemporary owners as well as by the modern researchers who examined these blades. These experiments have shown that this was with good reason, for pattern-welded swords clearly exhibit improved stiffness, and as a result significant advantages over mono-steel blades. So, these swords were indeed of a higher functionality than their mono-steel counterparts. The decorative effect of pattern-welding served a secondary, but valued, purpose.

Mono-steel blades were used during the early middle ages; however, pattern-welded blades were preferred as is evident from the increase in these swords towards the 7th century. There is, and has been for over 40 years, an ongoing discussion about the purpose of pattern-welding. Many arguments have been presented, from metallographic evidence to logical conclusions (France-Lanord 1949; Salin 1957; Tylecote 1976, Lang & Ager 1989; Tylecote & Gilmour 1986; Williams 1977), for either of two views: pattern-welding served a functional or an ornamental purpose. Despite all the evidence no definitive conclusion has yet been reached. In this thesis some new input for the discussion was created with the help of a series of experiments.

When reviewing the archaeological evidence regarding these swords several statements can be made. Although the patterned sword has its roots in the late iron age, it did not become popular until the second century AD (Tylecote & Gilmour 1986, 249). From this moment onwards these swords gained in popularity until by the 7th century almost all swords appear to have been fashioned using this technique (Tylecote & Gilmour 1986, 249; Lang & Ager 1989, 107). From the 8th century onwards an increase can be noted in the use and production of mono-steel blades (Oakeshott 2002, 7). These mono-steel weapons were of a distinctly higher quality than their earlier counterparts. The design of these later swords was more advanced than that of the earlier swords, resulting in better handling characteristics. Also, the steel used, was of a homogeneity and quality not encountered before.

Of course, the question remains, why were patterned swords preferred in the first place? As is evident from metallographic analyses the earliest pattern-welding was performed using high quality materials and thus produced functional weapons (Tylecote & Gilmour 1986, 251). However, the pattern-welded swords in the 4th to the 11th century do not clearly show this intent, since many were made of low-grade materials. However, it can be concluded that patterned swords indeed had an advantage over mono-steel swords in battle. As was suggested by France-Lanord (Salin 1957, 65) patterned weapons were a lot stiffer than their mono-steel counterparts. The same was concluded in the experiments performed in this thesis; the pattern-welded sword was four to five times stiffer

than the mono-steel blade. This increased stiffness might also increase the raw cutting power of these weapons, and in addition it allowed patterned swords to be made thinner than mono-steel arms and thus lighter. A light-weight sword would obviously be preferred since a warrior would be able to continue fighting for a longer time without tiring.

It is very well possible that pattern-welding also owes its popularity to other factors than quality. For instance, pattern-welding might have been so incorporated in the early medieval view of weapons, that it had become an essential part of a good sword. In other words, it was believed that patterned swords were better than simple mono-steel weapons. As such pattern-welding would have been preferred not only for practical reasons, but mainly because of a conviction among warriors that pattern-welding was always better. This view of this technique might have been caused by the complexity of pattern-welding. Patterned weapons were even more expensive and time-consuming to produce than regular mono-steel arms, and the early elite might have preferred these blades just for that reason, if not any other practical considerations. Since lower-class warriors will have sought ways to enhance their status, they might have tried to obtain such respected patterned weapons for themselves. However, not all warriors could afford such arms, despite preferring them, but to fulfill the demand many smiths will have started to produce patterned arms. These weapons may have been of a much lower quality than the 'original' pattern-welded swords, but they did suffice for the common warrior. The production of pattern-welded swords increases until at some point it has become part of a tradition of swordsmithing. By this time pattern-welding has become an obligatory part of the savoir-faire of swordsmithing, and as such it is a technique both expected and widely practiced.

When somewhere in the 8th century the improved mono-steel swords make their appearance a new standard is set. The elite, being able to own the best of arms, start to prefer these new swords for their quality and handling characteristics. From this point onwards other warriors, who might own patterned weapons, would like to obtain these beautiful mono-steel swords as well. The same process occurs as before and within a few decades all weapons produced are mono-steel. Pattern-welding slowly fades to the background until it is soon a technique all but forgotten.

In addition to archaeological evidence, some contemporary literature was examined. Historical sources often mention swords; especially in heroic sagas. Some of these texts, like the *Beowulf*, are very well known and some, like the *Kalevala*, are not. However, many of these texts describe swords, also pattern-welded ones. By reading these texts a lot can be learned about the legend of the sword; but also about value, construction and use of a blade. Also tests and practices are described to which the swords were subjected.

Both experimentally produced swords were put through cutting, edge retention and flexibility tests in much the same way as described in the sagas. In the cutting test it was obvious that

even a properly sharpened sword will not easily cut through multiple layers of fabric. However, it is certainly possible that a single layer of fabric or felt of low resistance could be cut, as described in historical texts. The edge retention tests showed clearly that these swords exhibit great cutting power. Whether or not one would be able to cut through anvils might be debated, but a stiff patterned sword, wielded by a strong arm, will certainly have been able to deliver devastating strikes. The third test, for flexibility, provided the most distinct results. The patterned sword was obviously a lot stiffer than its mono-steel counterpart of similar dimensions. Still, despite the stiffness and flexibility observed in these blades it is unlikely that historically swords were bend into a loop to test their quality. It is possible, if an excellent sword were made of exceptional good and homogenous steel, to perform such a trick. However, the vast majority of weapons would be ruined by such severe deformation.

The evidence obtained during these tests might be used in an attempt to answer the research-question of this thesis. Did pattern-welding serve a constructional or ornamental purpose? The experiments as presented here show there is little difference between the two weapons in cutting performances or edge-retention. However, a clear difference was observed in the flex-test and it can be argued that the pattern-welded sword would generally perform better in a battle-situation since it is so much tougher than its mono-steel counterpart. Despite that pattern-welding may have served a constructional purpose, there is no reason to disregard its decorative characteristics, nor is the evidence for a constructional advantage of this technique overwhelming. Hopefully in the future these experiments can be revisited and more blades can be tested to even better understand the nature of these weapons. Of course, there are also several more types of pattern-welding (Tylecote & Gilmour 1986, 246) (figure 1.1 in this thesis) which could then be put to the test.

The other two experiments, as performed in this thesis, were of the imitative-type, as described by Coles (1979, 1). The first experiment was neither unique nor original (Cleere 1970; Crew 1991; Sauder & Williams 2002; Sim 1998; Tylecote 1971); some bloomery iron was worked to create a small bar of usable wrought iron. The bloomsmithing presented the necessary problems but in the end several of these could be overcome and a good result was obtained. The assessment that one kilogram of high-quality wrought iron required over 50 hours to refine is probably incorrect; however, without any more experiments no proper re-evaluation of the work required can be made. It was also noted that the consolidation process has to be carried out more extensively to produce good iron at an acceptable rate. The amount of consolidation required, and the quality of the resulting material, is as much dependant on the quality of the bloom as on the experience of the smith.

The second experiment was necessary in preparation of the third, testing, experiment. During the second experiment two swords were forged; one mono-steel and one pattern-welded. These swords were made from modern S235 structural steel, but this was treated using only historical techniques. Some short-cuts, like the use of grinders, were made to save on time. However, these were all short-cuts which did not alter the end-result: two swords, similar to their historical counterparts except for their higher-quality base-material. A chaîne-opératoire was suggested for swordsmithing, both pattern-welded and mono-steel.

All in all, a lot is known about the swords of the early middle ages. Information can be derived from archaeology, history and modern practical experiments. As shown by the experiments a distinct difference can be observed between pattern-welded and mono-steel swords. Pattern-welding considerably increases the stiffness of a blade, which can result in increased cutting power, a lighter weight and better handling characteristics. In addition a chaîne-opératoire for swordsmithing has been described and a small experiment was done regarding bloomsmithing and more importantly, piling. As to why pattern-welding became popular, and how it became part of the swordsmithing tradition, several suggestions have been made. Hopefully, in the future, this subject can be revisited and more experiments can be performed to examine the qualities of pattern-welding more thoroughly.

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Appendix I: additional techniques

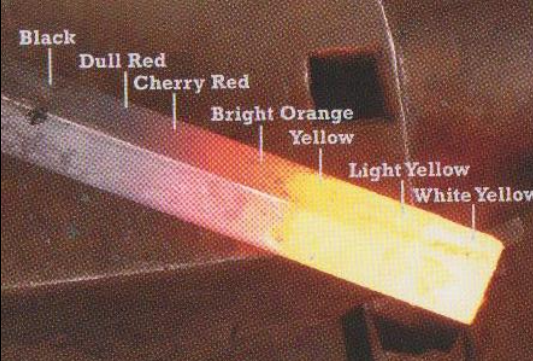
Colour gauging

When a piece of iron or steel is heated it changes colour. These colours can be used by an experienced blacksmith to gauge the steel's temperature. This is important during forging, but even more so during heat-treating or welding. When forging iron the temperature is important for if the temperature is too low excessive strength is required to shape the metal. If, on the other hand, the temperature is too high the metal will oxidize heavily and might even 'burn'. This burning results in very brittle spots in the steel.

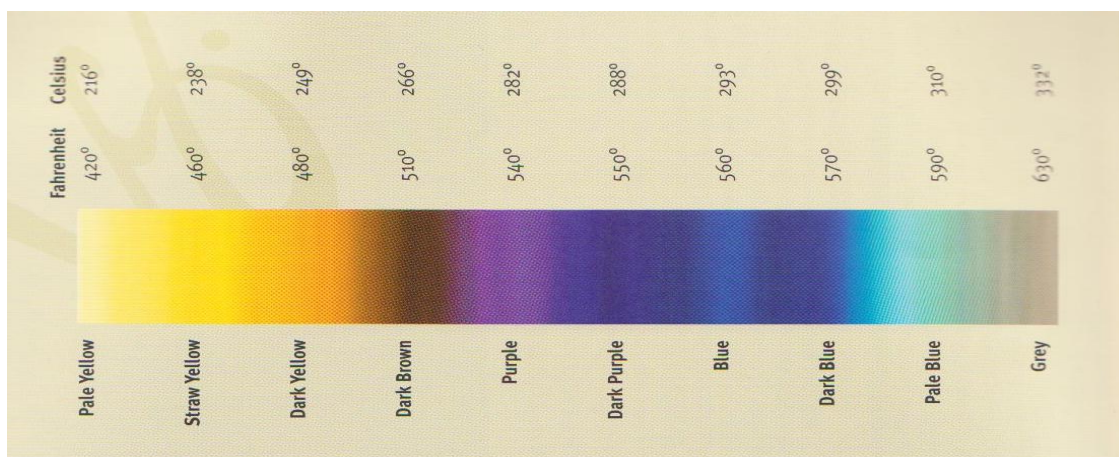
Iron and steel display two colour schemes; the first is the colour the steel emits at high temperatures (colour scheme 1); these colours are always visible on heated steel. These are also the colours used in forging or heat-treating.

The second scheme is the change in colour at low temperatures; these colours are only visible on a polished surface and are used when tempering a steel object. If after hardening an object is slowly heated again this will allow some of the atoms present in the material to redefine their position in the metal-structure, as such relieving any localized stress in the material. However, if tempered too much, the metal will be normalised and the martensite which was formed during quenching will dissolve, resulting in a once again soft piece of steel. To what temperature steel should be tempered depends on the composition of the material, but even more on the intended use of finished object. A knife for instance can be tempered only lightly, this will result in a hard edge which does not often require sharpening. However, the steel will be more brittle. Most knives, however, are so short that not much pressure is put on the blade during use, reducing the risk of breakage. Swords on the other hand require a certain tough flexibility to overcome the violence of warfare, as such they are tempered a little more. This reduces hardness slightly but at the same time increases flexibility until the proper balance is achieved.

Colour	Temperature in °Celsius
Black	<600
Dull red	680
Cherry red	760
Bright orange	980
Yellow	1150
Light yellow	1260
White yellow	1300
White	>1316



Colour scheme 1: forging and heat-treating temperatures (Sims 2006, 59).



Colour scheme 2: tempering temperatures (Sims 2006, 120).

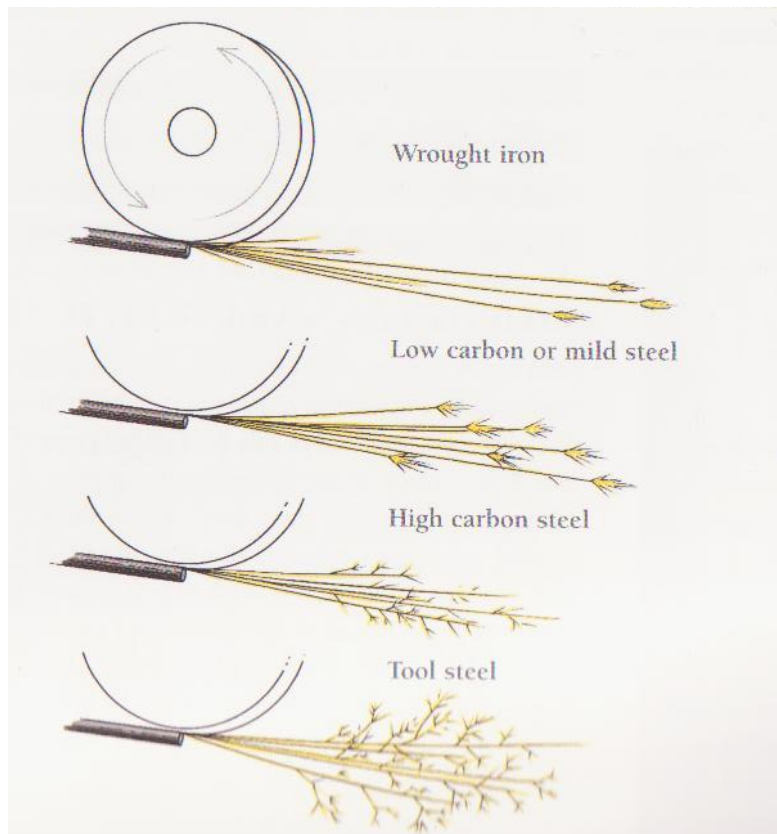
Spark testing

Spark testing is a technique which can be used to gauge the carbon content of steel. When applying this technique a piece of steel is ground with a high speed grinding wheel; this results in sparks from the hot metal. The type of spark is directly linked to the amount of carbon in the steel. This method is not exact, but it does give a good indication.

It is possible to discern the presence and amount of other elements in the steel, however, this is a science all by itself. The general use of this technique is to gauge the carbon content, since this is easily and reliably done. The presence of other elements might be noted during spark-testing but without a lot of experience no more can be discerned.

Material	Carbon content	Spark
Wrought iron	<0.08%	Long yellow/red sparks, no or minimal explosion.
Low carbon steel	0.10-0.45%	Long yellow/red sparks, slightly explosive.
High carbon steel	0.45-0.95%	Short yellow sparks, fairly explosive.
Tool steel	>0.95%	Very short yellow/white sparks, very explosive with multiple branches.

Spark-testing 1: description of the typical sparks observed (after Sims 2006, 48).



Spark-testing 2: different sparks with different steels (Sims 2006,48).

File testing

This technique can be used to gauge the hardness of iron or steel. A sharp, finely cut file is pulled across the metal. By feeling the 'bite' of the file on the steel the hardness can be gauged. A file has a sharp bite on soft iron or steel, leaving deep gauges and taking a fair amount of effort to cut. As the steel becomes harder the bite is less; the cut becomes superficial and the effort lightened. As soon as the steel is as hard as, or harder than the file, it won't bite at all, it will simply slide across the metal without gauging it.






This technique is useful, but it is important to keep the pressure on the file-strokes even, else the results are unreliable. Also, it is helpful if the hardness of the file is known or, even better, if several files of different hardness are tested. File-sets are made specifically for this purpose. These sets are generally produced for use by bladesmiths and often comprise of five or six small files with marked hardnesses. Usually the hardness-difference between each subsequent file is 5 on the Rockwell scale. However, lacking such a set, which is expensive if even available, any quality-file can be used.

Appendix II: equipment

This appendix serves to describe the most important equipment, such as furnaces, used in the experiments.

Furnaces

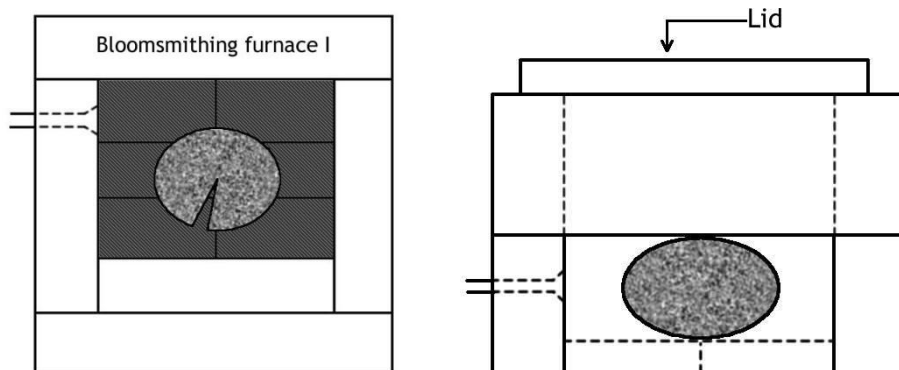
All furnaces were built from stacked Autoclaved Aerated Concrete (AAC) blocks. The furnace floor was laid from heat-resistant bricks. These furnaces were all slightly dug in the sand to provide better insulation. Because of the high-temperatures reached during use these white AAC-blocks had to be replaced very often since they melted and crumbled. This problem could only be solved by constructing the furnaces of other materials, for instance refractory cement, but these were not available when the experiments were performed.

	Description
	Near wall
	Far wall
	Furnace bottom
	Bloom

Furnace Legend

Furnace I

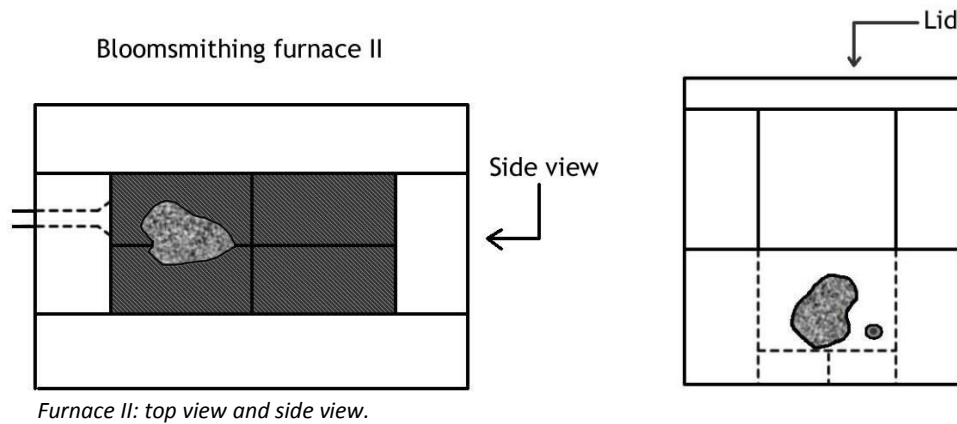
This furnace was build to heat the whole 10.2 bloom, as received from Jan Jennissen (see page 40). The furnace measured 60 X 60 X 40 cm on the outside, with in inside chamber of 40 X 40 X 40 cm. A lid was placed on top of the furnace cavity to contain the heat; a hole was drilled through one side to allow a bellows to be connected with the use of a copper tuyère.



Furnace I: top view and side view.

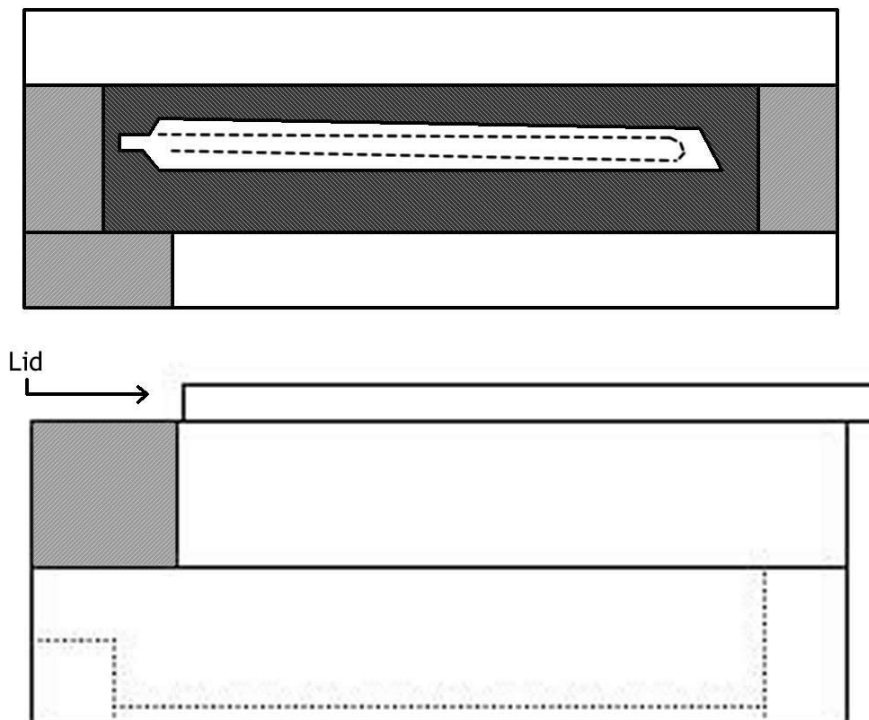
Furnace II

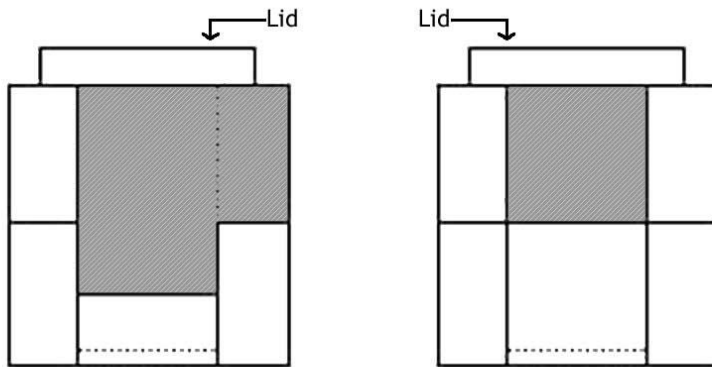
This furnace was built to heat the partial bloom after splitting. Essentially this was a smaller version of furnace I, measuring 60 X 40 X 40 cm on the outside and 40 X 20 X 40 cm on the inside.



Furnace III

This furnace was designed to accommodate a carburization case, thus it measured 120 X 40 X 40 cm on the outside. The chamber measured 100 X 20 X 40 cm. This furnace had the ends opened up to allow for the wind to serve as a constant draft; the bellows did not have enough capacity for this long furnace. A lid was again placed on top, both to raise the temperature and to increase the draft.

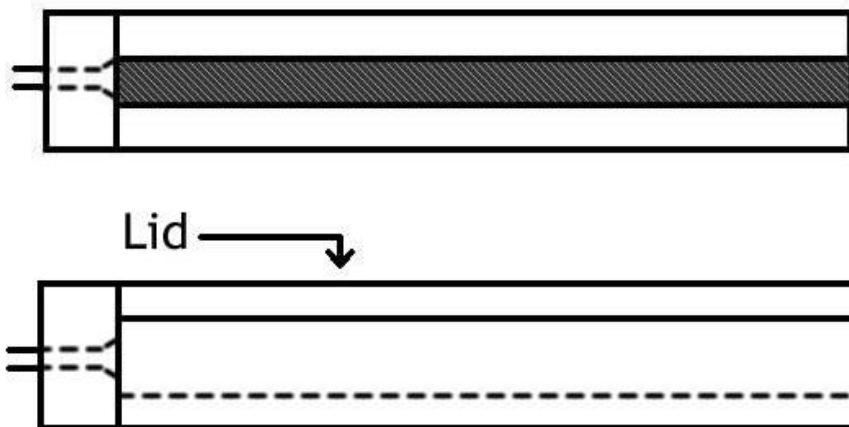




Furnace III: front view and hind view.

Furnace IV

Furnace IV was constructed to aid in the heat-treating of the blades. This furnace was long and had only a small inside chamber so as to allow it to be filled completely with charcoal. It measured 120 X 30 X 20 cm, with an inside chamber of 110 X 10 X 20. The bellows were connected on one end, while the other end was left open to create the effect of a horizontal chimney. This furnace was filled with charcoal which was lighted near the tuyère and with gentle pumping, the fire spread throughout the whole length of the furnace. When the charcoal near the tuyère had burned away some new charcoal was added on the other end of the furnace, with the whole contents being pushed towards the bellows side again. This provided a continuous supply of fuel so as to maintain an even heat. When all the coals were properly burning a sword could be placed in between them and evenly heated.



Furnace IV: top view and side view.

Carburization Cases

As part of this experiment two carburization cases had to be fashioned. These cases were filled with the piece to be carburized, charcoal powder and crushed charcoal. Then the case was closed more or less air-tight and placed in furnace III.

Case I

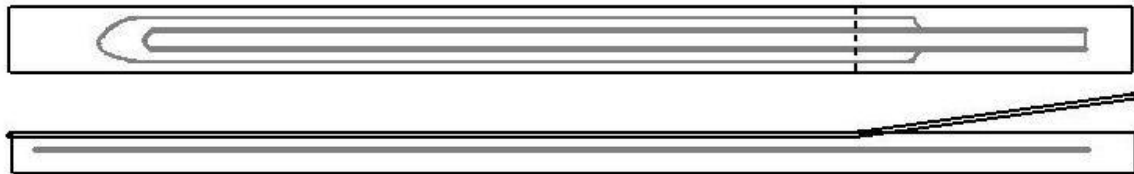
This case was made from simple steel tubing measuring 2 X 3 X 100 cm with a wall-thickness of 1.5 mm. One end was welded close with a piece of 1.5 mm steel sheet. For the other end a cap was fashioned from 1.5 mm steel.



Case I: side view and top view without the end-cap showing the position of the strips to be carburized.

Case II

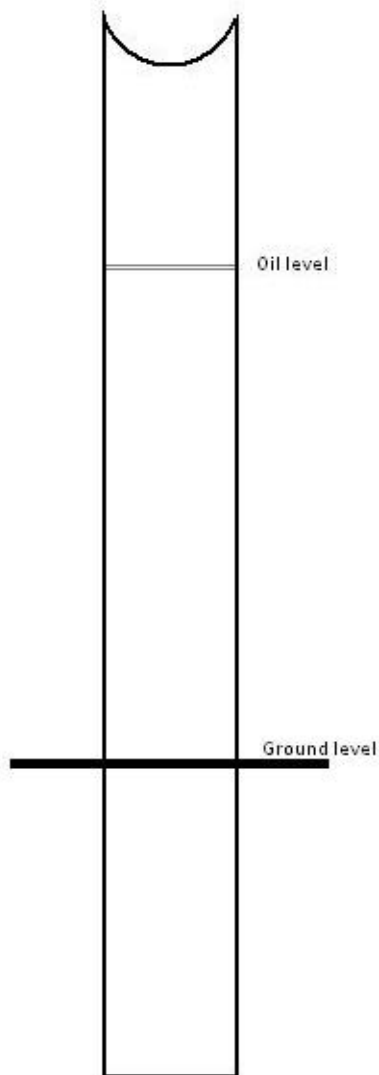
To accommodate larger pieces in the carburization process another case was made. This case was completely hammered and welded from 1.5 mm steel sheet. It measured 100 X 15 X 6 cm. The lid on this case was welded on and could be opened for 25 cm by simple bending.



Case II: top view and side view, showing position of lid and sword blade.

Quenching Tank

To heat-treat the blades a quenching tank was required which could be filled with oil. This tank was made from 10.1 cm inner diameter steel tubing. This tube was 120 cm long and had a wall thickness of 5 mm. One end was welded shut with a piece of 5 mm thick steel sheet. The other end was left open. The open end was rounded, which allowed for another piece of tube of the same diameter to serve as a lid when the tank was not in use. The finished tank was partially (40 cm) dug in the ground and filled with approximately 9 liters of sunflower oil. The oil did not reach the top of the tube, since it would expand upon heating during quenching.



Quenching tank: side view.

Grinding wheel

As described on page 57 a custom grinding wheel was made to aid in the shaping of the fullers. This grinding wheel was hand-turned from a glued and pressed stack of four, 8 mm thick, pieces of MDF (Medium Density Fiberboard). A hole with a diameter of 12 mm was drilled through the center of this stack so as to mount it on a short threaded steel axle. The stack was then secured with the use of washers and nuts. This axle was placed in a drill-press which was then run at high speed. The turning stack of MDF was subsequently rounded and shaped using rasps, files and sandpaper. The reason for using a drill-press was the lack of a wood-turning lathe. After shaping a wooden grinding disc was obtained with a diameter of 20 cm and a thickness of 32 mm. A 4 cm deep cut was made in the side of the disc parallel to the axle-hole. This cut was used to secure coarse linen sanding-band. The band was cut to length and then simply doubled in this cut, while the rest of the band was pulled tightly around the outside of the disc. The coarseness of this band itself secured it into place. The grinding wheel was mounted on a stationary grinder and used at a speed of 2700 RPM. It served very well for the rough-grinding of the fullers since the width and profile was exactly right. However, due to its construction it could only be used with coarse sandpaper since fine sandpaper did not provide enough friction to secure the band.

Appendix III: materials

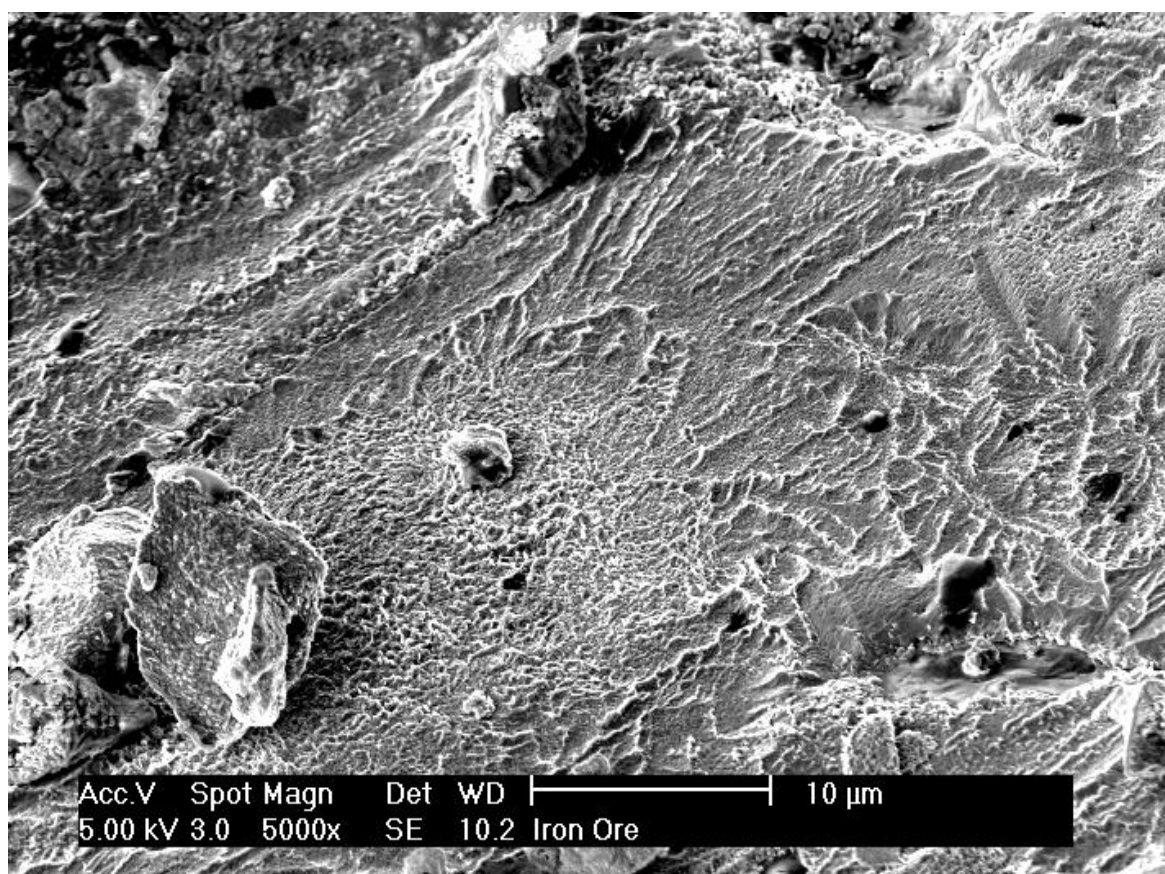
In the experiment two materials were used: bloomery iron and S235 structural steel. Below a table is presented with the components of the S235 steel. The bloomery iron was analyzed using energy dispersive x-ray spectroscopy; the results are presented below.

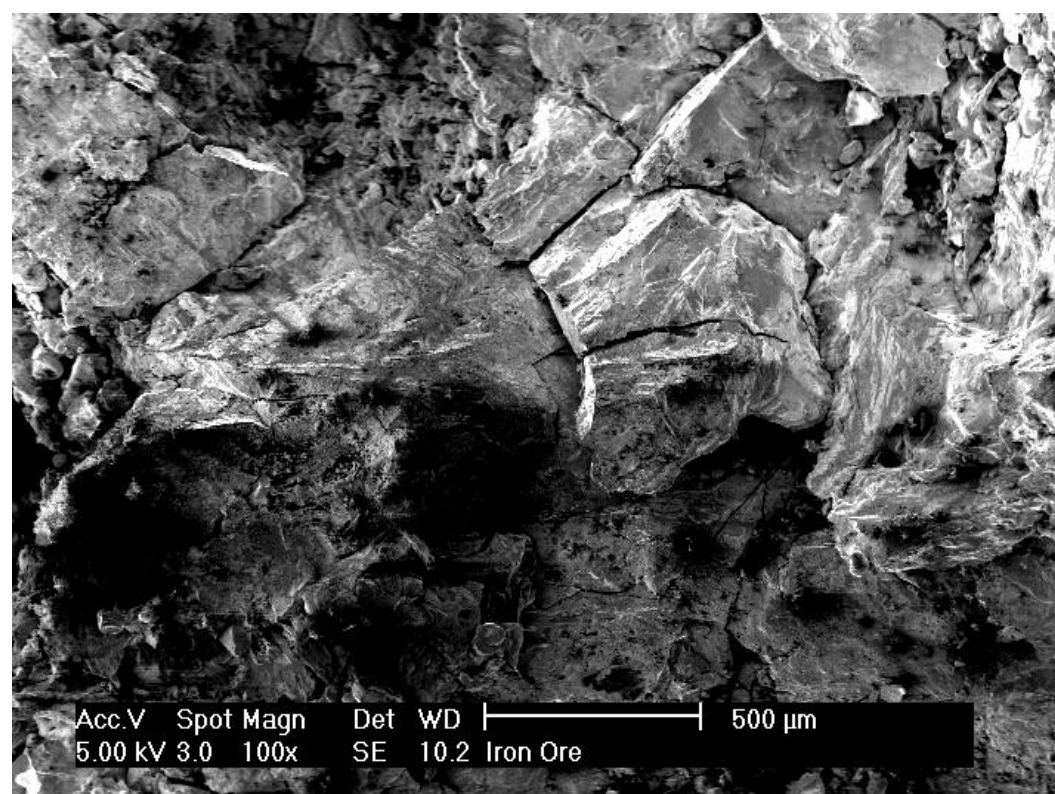
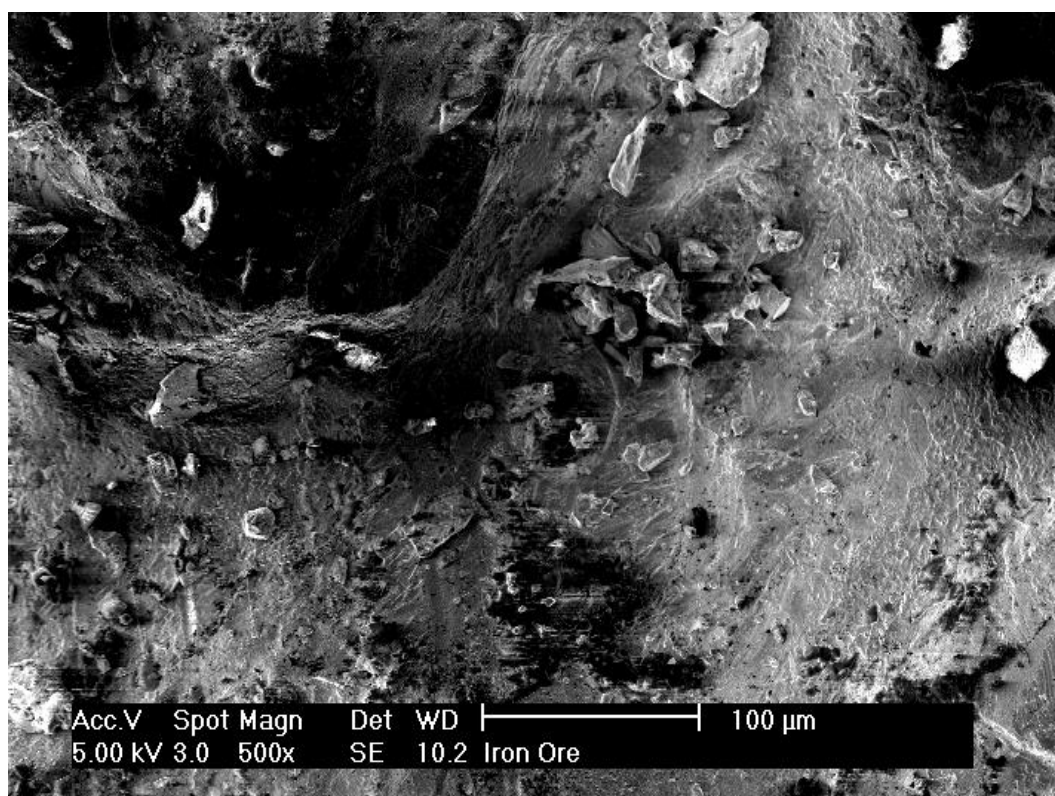
Element	Amount
Carbon	Max. 0.22%
Manganese	Max. 1.60%
Silicon	Max. 0.50%
Sulfur	Max. 0.050%
Phosphorus	Max. 0.050%
Iron	Min. 97.60%

The components of S235 structural steel according to the EN 10025.

Several pictures of the surface of the un-worked bloom:

Note: in the below picture and the following pages “iron ore” should be substituted with “iron bloom”.





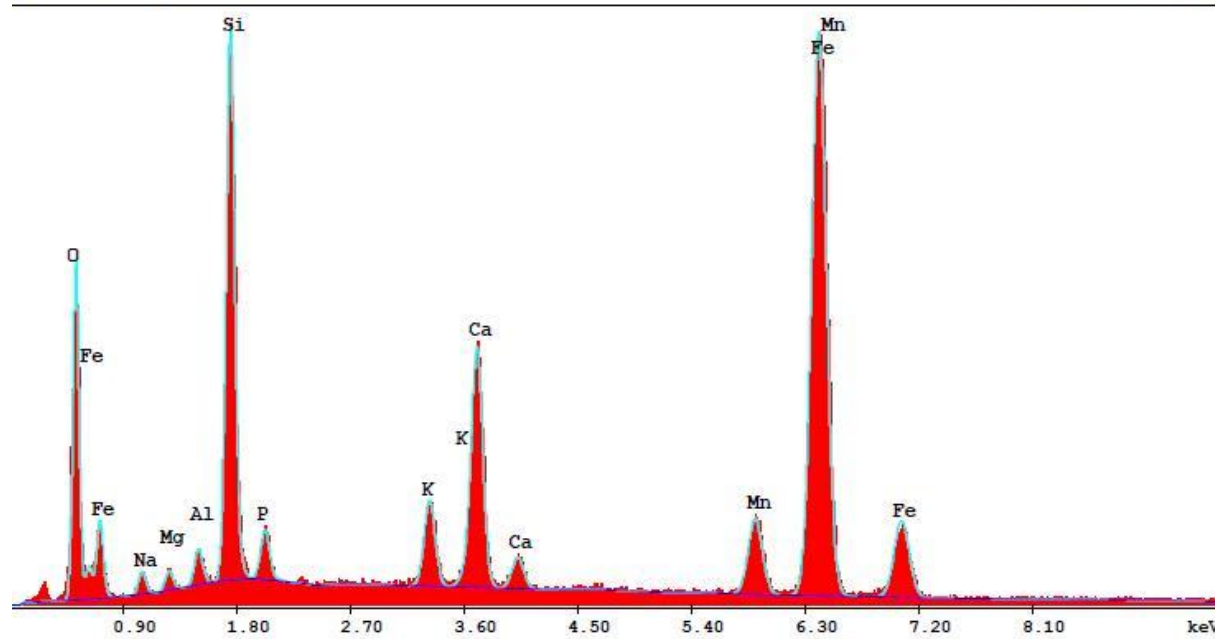
c:\edax32\genesis\genspc.spc

Label:10-05-2010 Ore analysis 1

kV:25.0 Tilt:0.0 Take-off:35.3 Det Type:UTW+ Res:131 Amp.T:51.2

FS : 4567 Lsec : 100

10-May-2010 14:13:56



Element	Wt %	At %
O K	29.34	51.67
NaK	1.56	1.91
MgK	0.90	1.04
AlK	1.19	1.24
SiK	15.67	15.72
P K	1.65	1.50
K K	2.29	1.65
CaK	6.58	4.63
MnK	4.26	2.18
FeK	36.57	18.45
Total	100.00	100.00

Element	Net Inte.	Bkgd Inte.	Inte. Error	P/B
O K	129.81	2.28	0.89	56.93
NaK	9.98	5.82	4.66	1.71
MgK	9.41	9.12	5.59	1.03
AlK	17.73	12.53	3.69	1.42
SiK	299.30	17.09	0.61	17.51
P K	29.23	19.39	2.82	1.51
K K	60.59	17.48	1.61	3.47
CaK	171.89	16.19	0.83	10.62
MnK	64.90	11.48	1.44	5.65
FeK	506.05	10.59	0.45	47.79

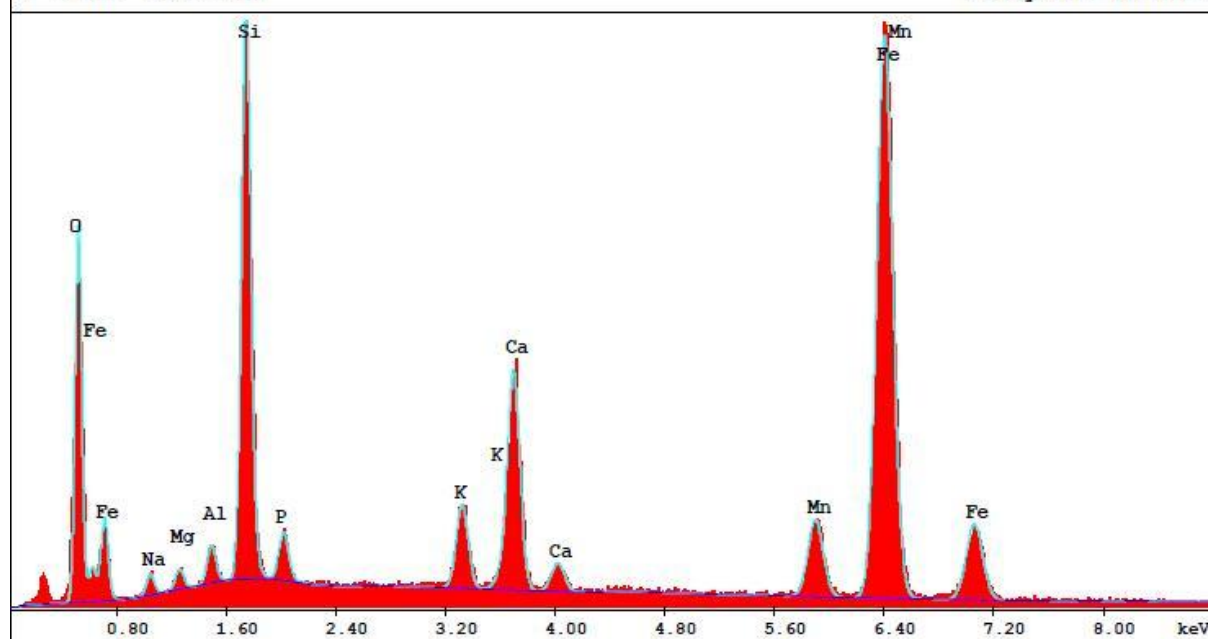
c:\edax32\genesis\genspc.spc

Label:10-05-2010 Ore analysis 2

kV:25.0 Tilt:0.0 Take-off:35.2 Det Type:UTW+ Res:131 Amp.T:51.2

FS : 4681 Lsec : 100

10-May-2010 14:24:06



Element	Wt %	At %
O K	30.89	53.43
NaK	1.42	1.71
MgK	0.91	1.03
AlK	1.23	1.26
SiK	15.92	15.69
P K	1.57	1.40
K K	2.19	1.55
CaK	5.92	4.09
MnK	4.24	2.14
FeK	35.72	17.70
Total	100.00	100.00

Element	Net Inte.	Bkgd Inte.	Inte. Error	P/B
O K	148.05	2.16	0.83	68.54
NaK	9.64	6.72	4.98	1.43
MgK	10.02	11.45	5.73	0.88
AlK	19.42	15.28	3.64	1.27
SiK	321.68	19.95	0.59	16.12
P K	29.30	21.15	2.89	1.39
K K	61.02	17.89	1.61	3.41
CaK	162.91	16.23	0.86	10.04
MnK	68.17	11.55	1.40	5.90
FeK	521.41	10.55	0.45	49.42

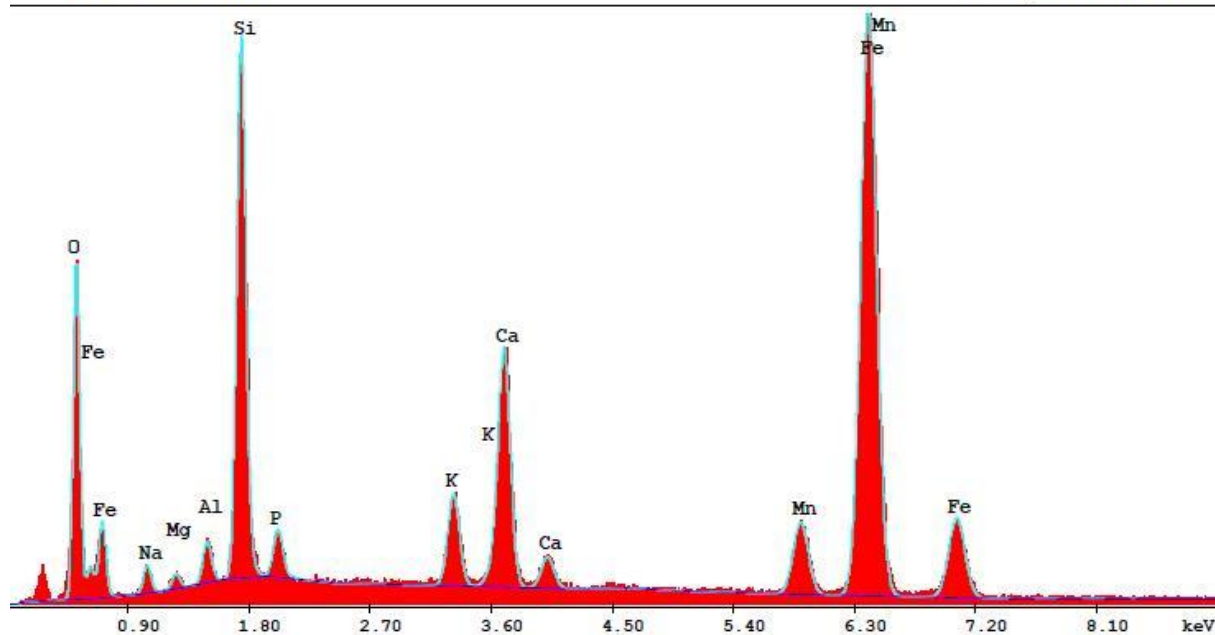
c:\edax32\genesis\genspc.spc

Label:10-05-2010 Ore analysis 3

kV:25.0 Tilt:0.0 Take-off:34.9 Det Type:UTW+ Res:131 Amp.T:51.2

FS : 4539 Lsec : 100

10-May-2010 14:32:45



Element	Wt %	At %
O K	28.55	50.78
NaK	1.91	2.36
MgK	0.70	0.82
AlK	1.38	1.45
SiK	15.32	15.52
P K	1.58	1.45
K K	2.42	1.76
CaK	6.47	4.59
MnK	4.00	2.07
FeK	37.66	19.19
Total	100.00	100.00

Element	Net Inte.	Bkgd Inte.	Inte. Error	P/B
O K	126.73	2.16	0.90	58.67
NaK	12.22	5.84	4.00	2.09
MgK	7.27	9.44	7.03	0.77
AlK	20.50	13.20	3.34	1.55
SiK	291.60	18.02	0.62	16.18
P K	28.13	20.55	2.96	1.37
K K	64.78	16.81	1.53	3.85
CaK	170.86	15.66	0.83	10.91
MnK	61.78	10.51	1.47	5.88
FeK	528.38	9.39	0.44	56.27

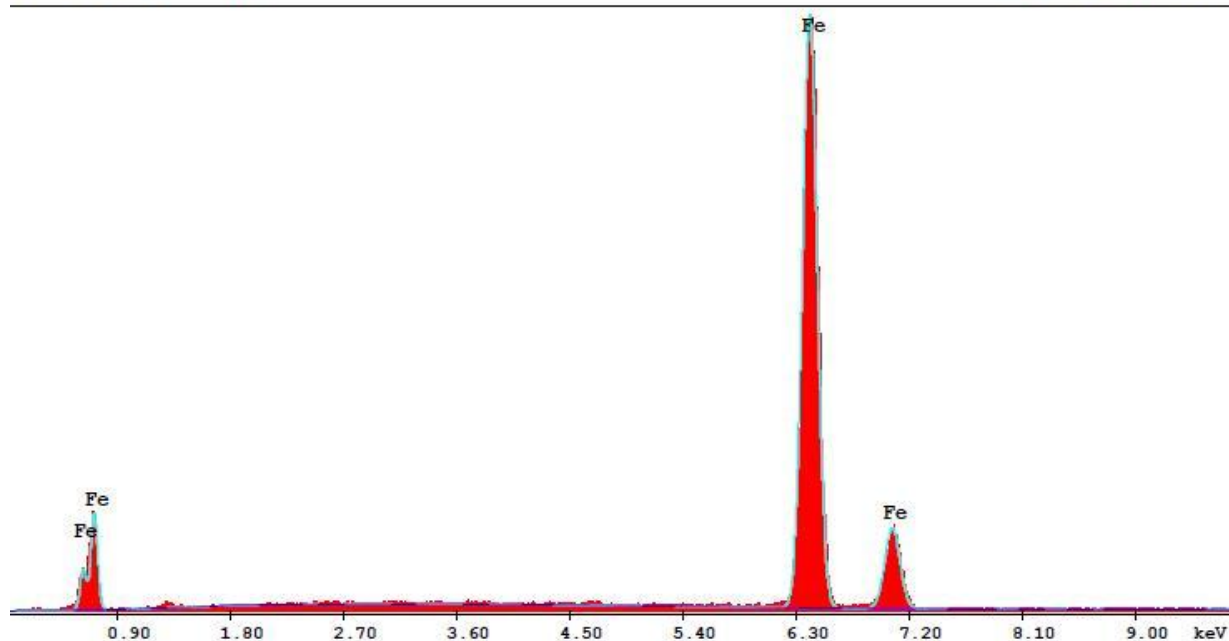
c:\edax32\genesis\genspc.spc

Label:10-05-2010 Wrought Iron 1

kV:30.0 Tilt:0.0 Take-off:35.2 Det Type:UTW+ Res:131 Amp.T:51.2

FS : 5789 Lsec : 100

10-May-2010 15:24:34



Element	Wt %	At %
FeK	100.00	100.00
Total	100.00	100.00

Element	Net Inte.	Bkgd Inte.	Inte. Error	P/B
FeK	673.94	4.71	0.39	143.09

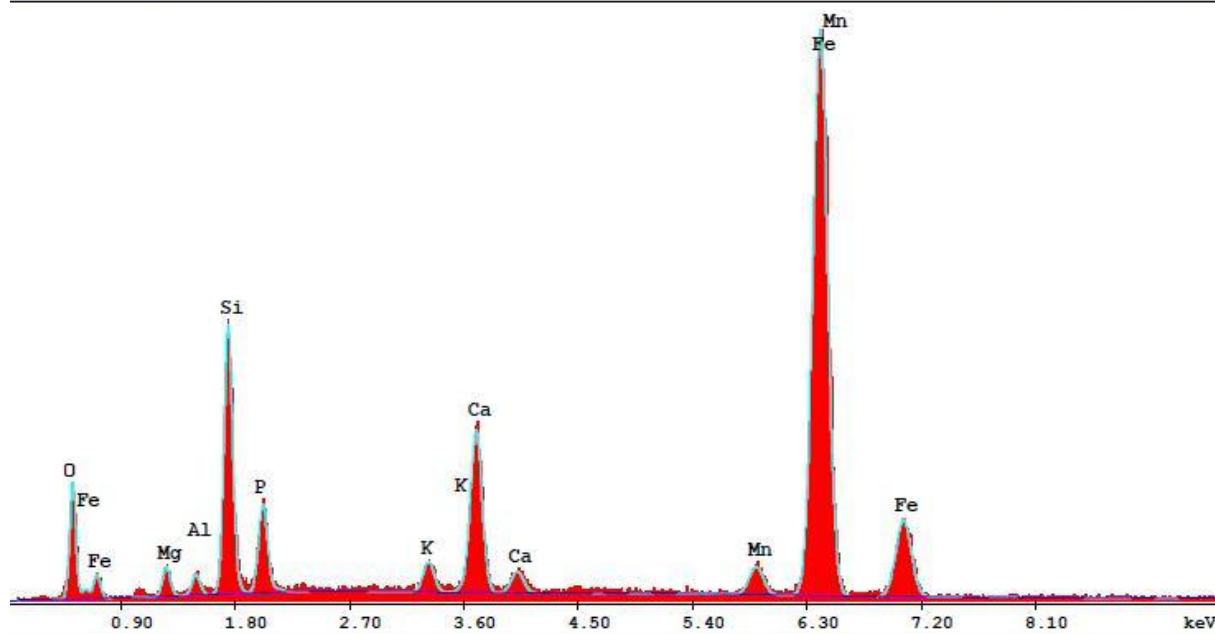
c:\edax32\genesis\genspc.spc

Label:10-05-2010 Wrought Iron Slag

kV:30.0 Tilt:0.0 Take-off:35.3 Det Type:UTW+ Res:131 Amp.T:51.2

FS : 2713 Lsec : 100

10-May-2010 15:38:34



Element	Wt %	At %
O K	20.64	40.45
MgK	2.71	3.49
AlK	1.37	1.59
SiK	14.54	16.23
P K	5.31	5.38
K K	1.21	0.97
CaK	6.43	5.03
MnK	2.00	1.14
FeK	45.80	25.71
Total	100.00	100.00

Element	Net Inte.	Bkgd Inte.	Inte. Error	P/B
O K	26.29	0.56	1.99	46.95
MgK	8.54	1.72	4.05	4.97
AlK	6.12	2.13	5.26	2.87
SiK	86.58	2.88	1.11	30.06
P K	30.76	3.75	2.01	8.20
K K	12.52	5.02	3.79	2.49
CaK	69.19	4.80	1.28	14.41
MnK	14.21	4.12	3.33	3.45
FeK	302.76	3.74	0.58	80.95

Metallographic research at the Laboratory for Conservation and Material studies (LCM)

As part of this thesis a few samples were taken from the core of the pattern-welded sword-replica. These samples were then analyzed metallographically. Under supervision of Gert van Oortmerssen MA the author prepared the samples by casting them in epoxy-resin and subsequently sanding and polishing the pieces. The samples were finished to 4000 grit wet sandpaper. To enhance the contrast in the metal structures the samples were then etched for 60 seconds in a 2% nitric acid-solution. They were viewed using a light optical microscope and pictures were taken with the help of a digital camera which was mounted to the microscope. Though the pictures have yet to be analyzed and examined, they do show a clear layering in the patterned-core, as well as obvious differences in the normalized structures of low- and high-carbon steels.

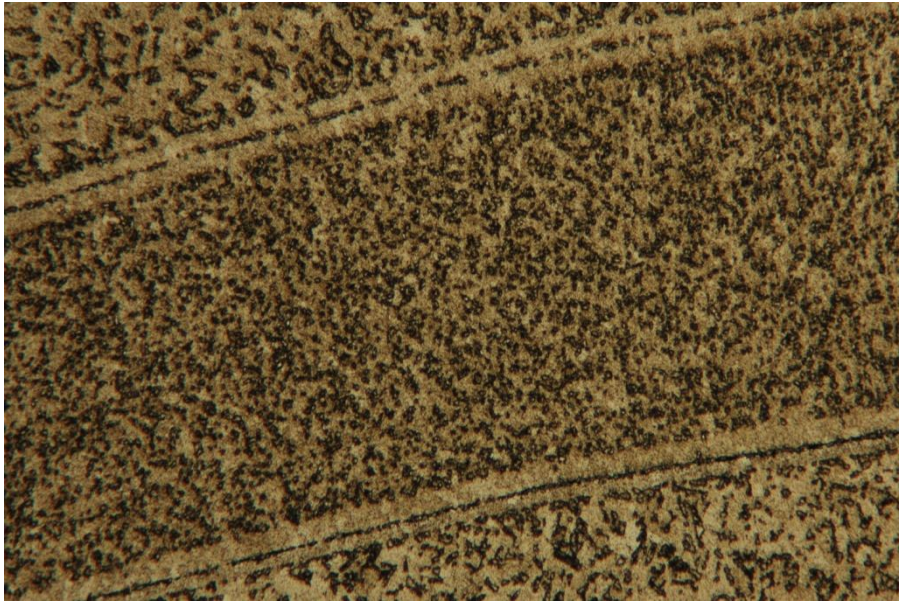


Figure 1: Three of the pattern-welding layers are visible with clear weld-lines in between. The upper and lower layer are low-carbon steel, the middle layer is high-carbon steel. Magnification 50X.

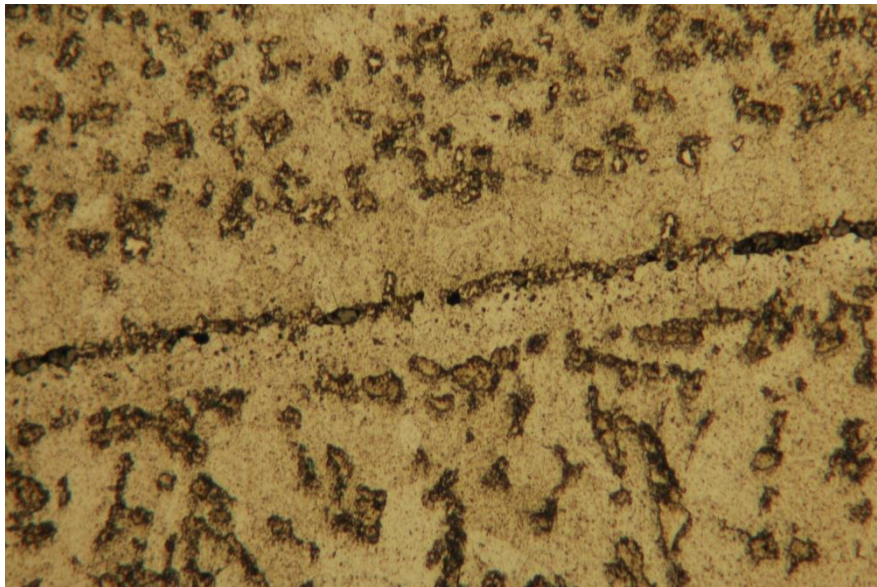


Figure 2: The same sample as above, but at a higher magnification. Low-carbon steel is below, high-carbon steel is above. Magnification 200X.

Appendix IV: sword-catalogue by number

Number I

Sword name/number: 28:65

Find location: Funtham's Lane, Whittlesey, Great Britain.

Collection: Peterborough museum, Peterborough.

Structural type: I

Total length: 720 mm

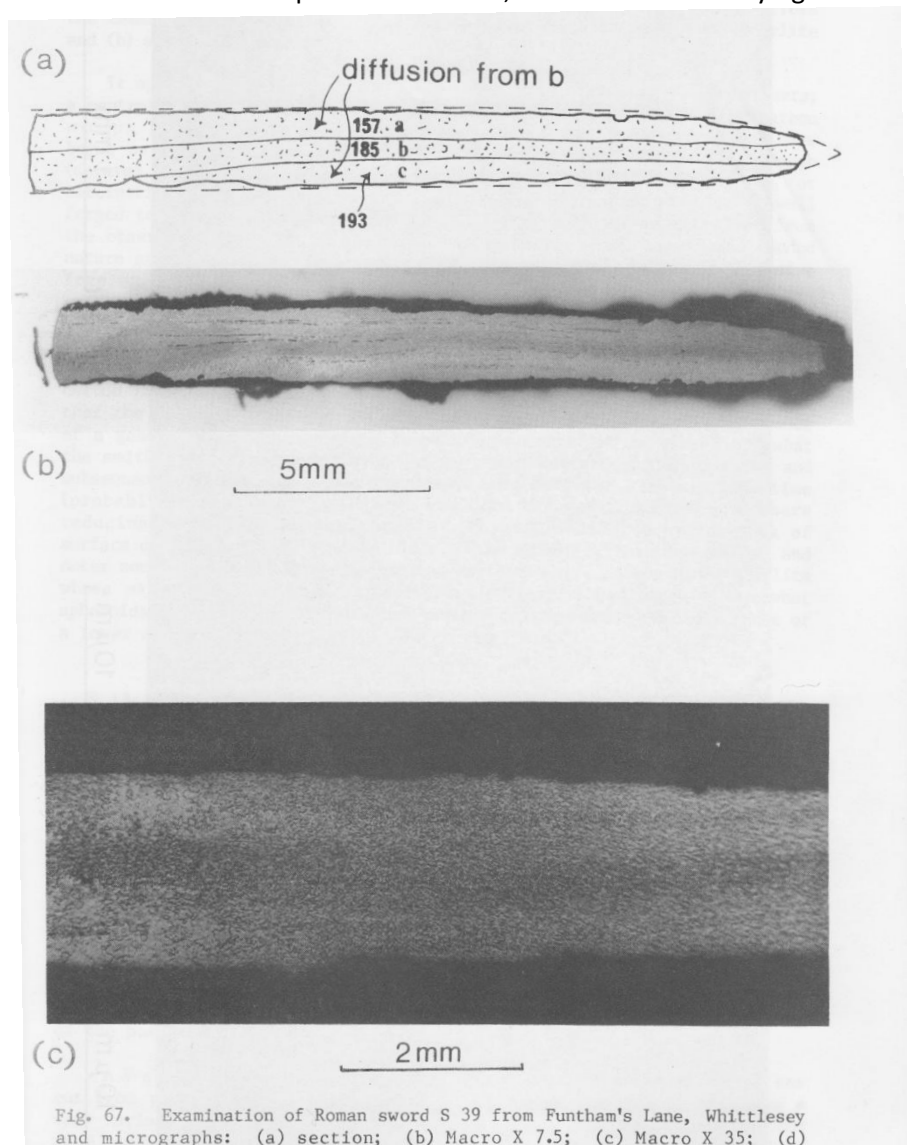
Maximum width: 47 mm

Maximum thickness: 3 mm

Date: 1st – 2nd century AD

Literature: Tylecote & Gilmour 1986, pp. 164-167.

Other information: A very well preserved blade; this sword appears to be constructed of three flat strips which were welded together; however, no clear weld-lines can be distinguished. The carbon content varies from approximately 0.3% near the edges to 0.2% near the core. The whole sword appears to have a ferrite and pearlite structure, with hardnesses varying from 157 HV to 193 HV.



Number II

Sword name/number: C 2260

Find location: the Thames in London. Great Britain.

Collection: Museum of London, London.

Structural type: I

Total length: 625 mm

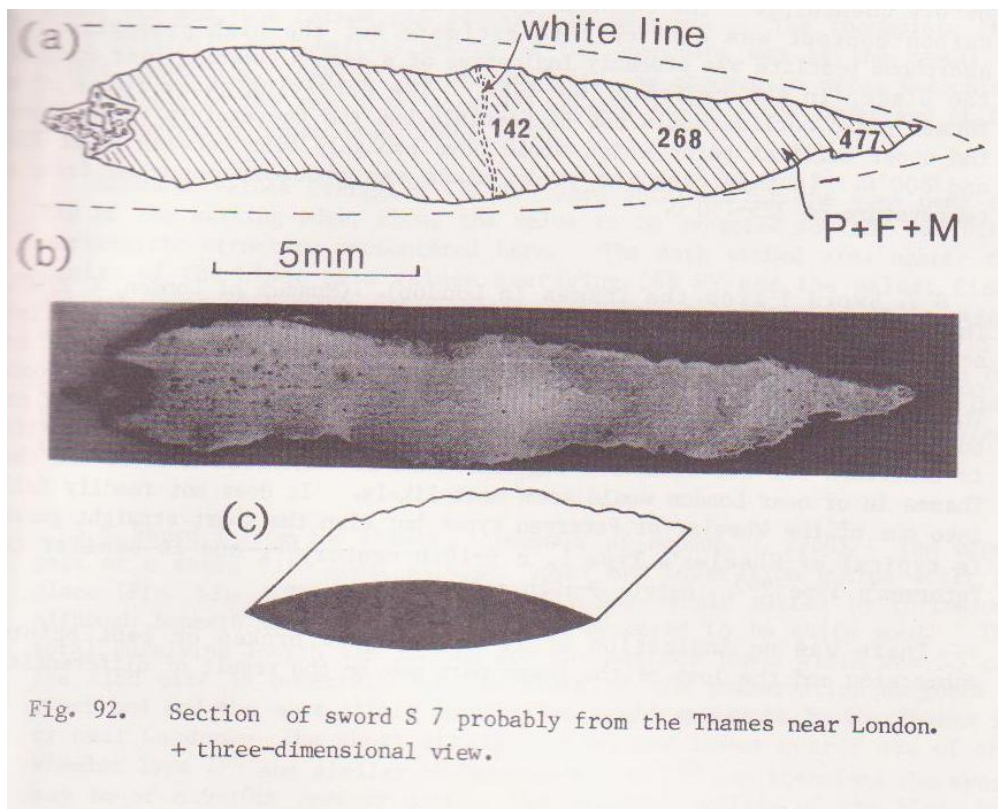
Maximum width: 52 mm

Maximum thickness: -

Date: 9th – 10th century AD

Literature: Tylecote & Gilmour 1986, pp. 220-221.

Other information: This sword is not completely preserved. This blade was quenched but not tempered, resulting in a mix of ferrite, pearlite, troostite and martensite near the cutting edge. The carbon content seems to vary between 0.3% and 0.6%; however, it seems likely that most of the blade was near the lower end of this amount.



Number III

Sword name/number: 1906/1 2 & 1906/1 2a

Find location: Antum, The Netherlands.

Collection: Groninger Museum, Groningen.

Structural type: III

Total length: 970 mm & 858 mm

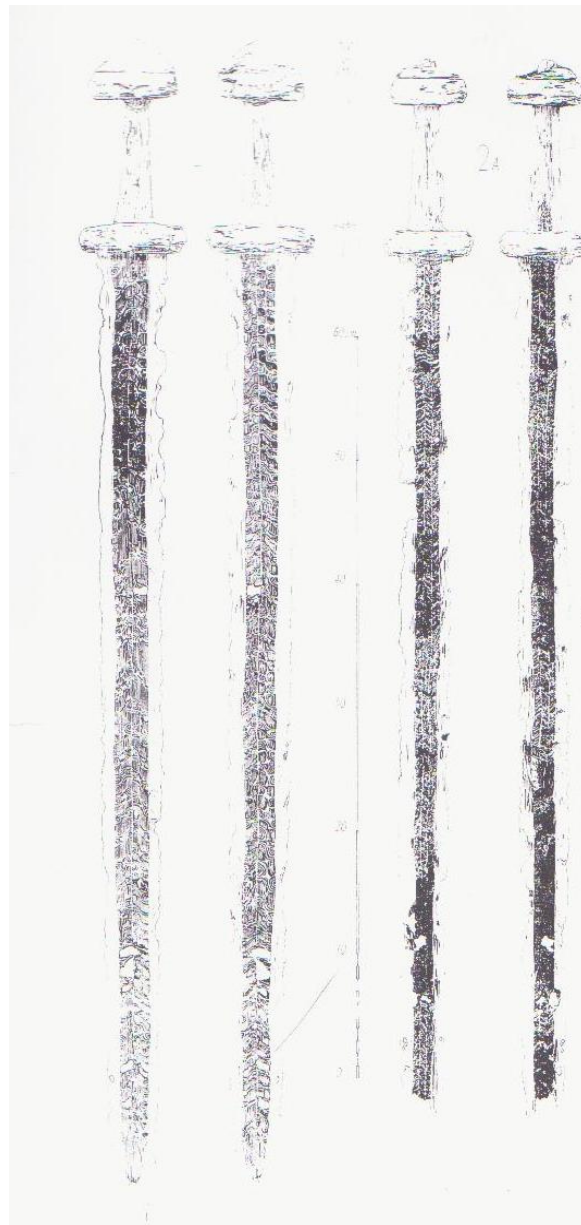
Maximum width: 56 mm & 50 mm

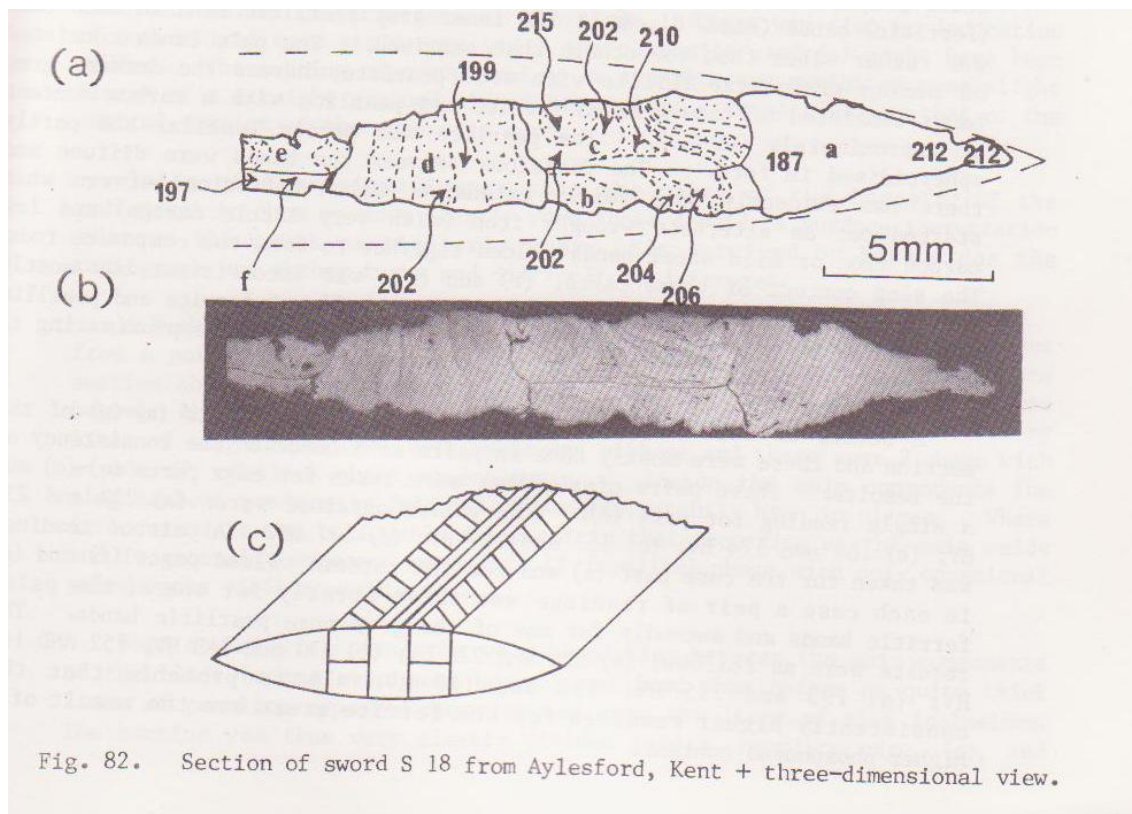
Maximum thickness: -

Date: late 8th century AD

Literature: Ypey 1961, pp. 372-376

Other information: These two swords both feature type III pattern-welding. 1906/1 2 has a core of two rods, while 1906/1 2a has a core consisting of three rods. Both swords come from Antum; one from a horseman's grave (1906/1 2a) and one (1906/1 2) was found in close proximity but is probably unconnected to the first blade.





Number V

Sword name/number: -

Find location: The Waal near Nijmegen, the Netherlands.

Collection: -

Structural type: IV

Total length: -

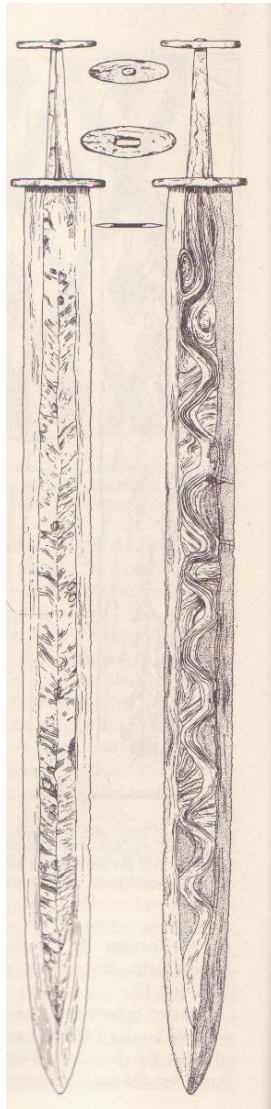
Maximum width: -

Maximum thickness: -

Date: 9th century AD

Literature: Ypey 1983, pp. 199-201.

Other information: This sword is similar to a type IV in appearance, however, in construction it is different the other swords. First it should be noted that this sword has many small faults; indicating either an inexperienced smith or a troublesome material. Due to the bad forging of this blade it is mostly thinner than 3 mm and it has a very irregular appearance. On one side of this sword the core is constructed of two twisted rods in a herringbone pattern, on the other side it features a wave-like piece of pattern-welding. It appears that the wavy piece is overlaid on top fo the two twisted rods, possibly to increase the sword's thickness and flexibility.



Number VI

Sword name/number: 1911/VI I

Find location: Wieringhuizen, the Netherlands.

Collection: Groninger Museum, Groningen.

Structural type: VI

Total length: 922 mm

Maximum width: 45 mm

Maximum thickness: 5 mm

Date: 8th – 9th century

Literature: Ypey 1961, pp. 376-378.

Other information: This sword was found during a dig in a dwelling mound and subsequently bought by the Groninger museum. This sword is in excellent condition; parts of the hilt decoration and original surfaces are still present. The blade still retains some of its flexibility and is fairly thick. The sword features several bits of decoration; brass strips and wire on the handle and a folded strip of pattern-welding on the blade just below the grip.



Fig VIII: The sword from Wieringhuizen. I. full view, II. handle detail, III. folded strip of pattern-welding, IV. original blade surface showing patterning.

Number VII

Sword name/number: 1896/XII I

Find location: Eekwerd, the Netherlands.

Collection: Groninger museum, Groningen.

Structural type: V

Total length: 787 mm

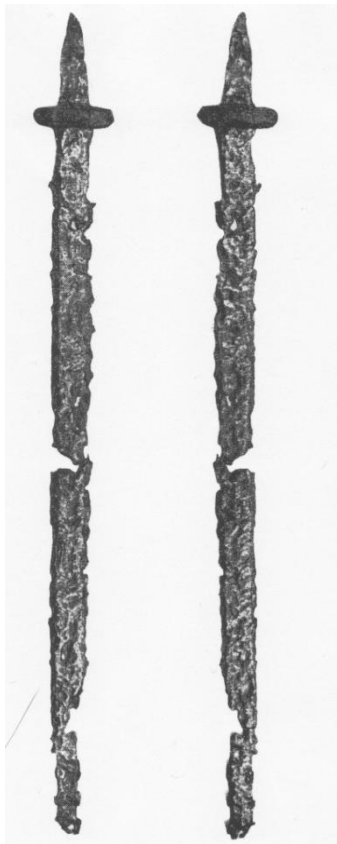
Maximum width: 45 mm

Maximum thickness: 3.5 mm

Date: -

Literature: Ypey 1961, pp.370-372.

Other information: this fragmentary blade was also found at a dig in a dwelling mound. Since there is no clear artifact-context, nor is its pommel present, it was not possible to date this sword. The sword is too corroded to take any other accurate measurements. The core of this sword is made up of four twisted rods, two on each side.



Number VIII

Sword name/number: 1884/I 3

Find location: Saaxumhuizen (however, see below), the Netherlands.

Collection: Groninger museum, Groningen.

Structural type: V

Date: 9th century

Total length: 971 mm

Maximum width: 53 mm

Maximum thickness: 4 mm

Literature: Ypey 1961, pp. 368-370.

Other information: This sword is in fairly good condition; all the hilt-parts are present and the blade is complete though corroded. The core is made up of two or four twisted rods; two are visible on each side. If this sword features only two rods it should be classified as a type III blade but the exact construction cannot be discerned without the use of metallographic sectioning. The hilt-furniture of this sword is made of iron. All hilt parts however are cracked on one side which suggest that the parts were folded over the sword and then welded shut to create a proper fit. These weld-seams probably opened due to heavy corrosion.

In the literature this sword is referred to as found in Saaxumhuizen in the province of Groningen; however, this is incorrect. The sword comes from a small hamlet named Lutje Saaxum, also in Groningen, and was probably part of a grave. This misunderstanding regarding the original find-spot is the result of a mistake made by Pleyte; in his "Catalogus van het Kabinet van Oudheden der Provincie Groningen" (1879) he states this sword comes from Saaxumhuizen. The find is correctly noted in Folmer's "Beschrijving van eenige crania uit verschillende tijdvakken" (1881). I am grateful to Dr. Egge Knol from the *Groninger Museum* for providing clarity regarding this confusion.

