6. THE CONSTRUCTION AND CRAFTSMANSHIP OF VIKING AGE SWORD BLADES: A METALLOGRAPHIC EXAMINATION[6]

The aim of this study is to gain information about the Norwegian Viking Age blacksmith's technical skill, and his understanding of the materials with which he was working. Thus, it is interesting to study to what degree refined smithing techniques, which could improve the quality of an object, were common knowledge in Norway in the Viking period. Did a majority of the blacksmiths know how to utilise such techniques as carburisation of iron and heat treatment of tools and weapons in a predictable and successful way? Or were such techniques mastered by only a few specialists, who produced objects demanding much from their material composition and craftsmanship? Further, we will examine the composition and different methods of construction of sword blades. The types and frequencies of techniques, such as pattern- welding, piling, or inlaid design used either to improve the quality of the object or to give a decorative appearance to the metal surface, have also been studied.

There are indications of differing social status and levels of specialisation among the blacksmiths both from archaeological finds and from the sagas. Since the use of iron for weapons and tools, needed in households by farmers, hunters, fishermen, carpenters, shoemakers, warriors, not to mention decorative smithing of different kinds, was steadily increasing in the first millennium AD, specialisation among blacksmiths must have been inevitable. Variable quality and uneven craftsmanship observed in ancient iron objects show that Viking Age blacksmiths did not form a homogeneous group of craftsmen. In rural districts it is likely that resident peasant smiths were responsible for repairs and production of simpler objects for daily use, for their own personal needs, and for the local population. More intricate smithing, like the manufacture of edged tools and weapons, was probably achieved by specialised and better qualified smiths. The blacksmith was either resident in the area, or worked as an itinerant specialist serving the inhabitants of a larger district (Straume 1986). The craftsman whose main occupation was smithing is more likely to have worked in central areas and marketplaces, where the demand for high-quality products was stable and the general financial resources among people higher. The most complex pieces of smithing, like the best and most impressive weapons, in which quality as well as appearance were of great importance, are most likely to have been produced by highly specialised weaponsmiths, either to order or in the service of kings and chieftains (see discussion in Chapter 3).

Swords have been specifically chosen for this study. Being a weapon it can be expected that the most advanced technology of the time was employed in the production of a high quality sword. The quality of the materials, as well as the craftsmanship, is of crucial importance in a long, slashing weapon. The material needs to be fairly sophisticated metallographically in order to meet the requirements of close combat. Another reason which makes the Viking Age swords well suited for examination is that pagan rituals for burial still prevailed in Scandinavia at the time. Rich and abundant grave finds and single finds make the number of swords available for sectioning sizable. The unusually large number of Viking Age swords found in Norway indicates extensive production of swords in the country.

Pure iron is too soft a material for some purposes. Cold-hammering will harden the iron, though only moderately and not to the same extent as cold-hammering bronze. It was therefore necessary to master

6 I should like to express my sincere thanks to Professor Robert Maddin, Harvard University, for discussion of the work and for his most valuable comments, and Helfrid and Sten Modin, Stockholm University for sharing with me their valuable knowledge of the relevant metal structures. Further, I want to thank senior engineer Przemyslaw Zagierski, Physics Department, University of Oslo, for a helping hand and permission to use the metallurgical microscope, senior engineer/metallographer Gisela Berg for cutting the sections and for letting me use the hardness apparatus, senior engineer Jens-Anton Horst for carrying out the microprobe analyses, and other staff members at Materials Technology, SINTEF, Oslo, for further help and useful discussions. I am grateful to two of the archaeologists at the Institute of Archaeology, Numismatics and History of Art, University of Oslo: Charlotte Blindheim for her comments and assistance concerning archaeological information, and Professor Irmelin Martens for discussion of this work and our further study of Viking Age weapons. Finally, I am grateful to the Research Council of Norway for a grant supporting this work when it was in its infancy. – *Eva Elisabeth Astrup*

techniques that could harden the iron further. A harder material, which would be an improvement for a number of tools and weapons, could be obtained by alloying the iron. Carbon was the most common alloy material for this purpose, turning the iron into steel. It seems likely that the aim of iron production in the Viking period was to make a supple, workable material, meaning wrought iron with a moderate carbon content (Buchwald 1993). When, and to what extent, this was achieved by deliberate choice of production conditions is difficult to tell. However, products from the bloomery furnaces had a heterogeneous, mostly low carbon content, although certain areas of the bloom could have an increased concentration of carbon. The bloom would typically be exposed to oxidising conditions in areas around the tuyère, resulting in an iron product. The part of the bloom which was in close contact with the charcoal could absorb carbon by accidental diffusion during the process. It has been suggested that the carbon-rich layers were cut off from the blooms in order to utilise the harder material for special purposes (Buchwald 1993). It is, however, difficult to understand how the ancient smith could identify the higher carbon content layers. The iron blooms, produced in a solid condition directly as a result of smelting iron ores, contained various amounts of entrapped slag. The raw material had to be refined by repeated reheating and reforging in order to reduce slag content. A high content of slag would leave the wrought iron brittle and difficult to forge. The smith or the smelter could, to some extent, test the slag content of the iron and assure adequate malleability by forging the end of an iron bar flat (e.g. currency bars)[7].

The temperature needed to melt pure iron (1,537°C) is higher than that likely to be obtained by the Viking Age iron producer. Deliberate production of steel therefore had to be done in the solid state by diffusion of carbon into the iron at a temperature in the order of 900°–1,000°C. The absorption or diffusion of carbon into the iron, carburisation, is dependent upon the temperature and conditions in the smithing hearth in order to produce a sufficient supply of carbon atoms. The process of carburisation in prehistoric times could be difficult and time-consuming to carry out. The product, steel, was therefore expensive. Experiments show that even in the presence of an energiser to facilitate the process, and at temperatures above 900°C, a carburised layer of only 1.5 mm thickness could be expected after 8 hours in the hearth (Maddin 1991). Intentional carburisation of an object was in principle carried out by two different methods: either the surface of the nearly finished iron object was carburised (case-carburisation) in order to give it a steeled coating; or a thin sheet of steel was built into or fused onto the iron body by hammer-welding before the final forging of the object. A skilled blacksmith with proper knowledge of the carburisation process was required to produce quality swords and a number of other weapons and tools, especially those with cutting edges.

After successful carburisation, a further increase in hardness can be obtained by suitable heat treatment. Pure iron cannot be hardened by quenching. The heat treatment of carburised iron was carried out by somewhat different methods. A full quench is obtained by a sufficiently fast cooling of the object from a temperature of about 900°C, depending on carbon content. If carbon content is high, the result will be a very hard, but also very brittle, material. If overall carbon content is low, the result will be a material which is less hard and brittle. A full quench is recognised by an all-martensitic metallographic structure (Figure 6.3e). If the cooling rate is not fast enough to produce an all-martensitic structure, hardness as well as brittleness would be less (slack-quench). The metallographic structure might be that of a mixture of martensite, bainite, or pearlite (Figure 6.14c). An insufficient cooling rate could also be the result if the quench was interrupted too soon. There are many instances of insufficient or interrupted quenching indicated through examinations of tools and weapons. It seems possible that this was an intentional technique used by blacksmiths to obtain a less hard and brittle material than that resulting from a full quench. In cases where the quenching produces too brittle a material, a partial softening can be achieved by tempering (re-heating at 200°–250°C), in order to produce a high-quality sword blade. Analyses of cutlery from the 10th–12th centuries AD, mainly from the eastern parts of the

7 It is not correct that iron made from bog ores often shows elevated phosphorus content. This misunderstanding goes back to a paper by Olof Arrhenius whose analyses of pattern-welded objects presented average values of all the material from a sample. Many of the same objects were used for more general analyses during the study of the Helgö material, and later their phosphorus content was determined, showing low phosphorus values (Bergman 2005:65 with reference and Table 19:68). In Astrup's own chemical analyses of some of the metallographically investigated swords "phosphorus was found to be present in fairly low concentrations, too low to be of importance for this examination". Chemical analyses of slag from Møsstrond also show low phosphorus content (Rosenqvist 1988:Table 5 and 7). One should rather ask how widespread phosphorus-rich bog ores were and where they were found. These questions are relevant to the problem of pattern welding carried out in Norway. – *I. Martens*

continent show that heat treatments like quenching and tempering became common (Pleiner 2007:237; Kosta and Hosek 2014:277–279).

Iron products from Central Europe in the Hallstatt period (c. 700–500 BC) (Piaskowski 1969) and the late La Tène period (c. 500 BC– 0) (Emmerling 1975), show that the carburisation treatments were often uncontrolled and accidental. A thorough study of Celtic swords (c. 500–50 BC) (Pleiner 1993) proves that carburisation was a well-known process, and that blacksmiths knew how to do this successfully. Later on, South and Central European smiths seem in general to have mastered the process of hardening iron by carburisation followed by quenching (Maddin, Hauptmann and Baatz 1991). Thus far, however, it is not known at what time carburisation and heat treatment were initially carried out in Norway, nor from what time these processes were generally used in the production of weapons and tools.

Next to carbon, phosphorus is the alloy material most commonly found in old iron objects. Like carbon, phosphorus also increases the hardness of iron. Wrought iron with an elevated phosphorus content can compete with unquenched carbon steel. However, phosphorus causes a pronounced brittleness, which would easily result in unintentional chipping and breaking of the object and render the material difficult to forge (Nosek 1991). Unlike carbon steel, phosphorus-containing iron cannot be heat treated in order to obtain a further increase in hardness. While absorption of carbon into the iron tended to be an additional process of refinement, phosphorus derives from the ores. The presence of elevated concentrations of phosphorus in iron will hamper the diffusion of carbon into the metal. Any attempt to carburise such iron will not be successful.

To build a blade from various iron and steel parts they had to be joined together by hammer welding. Such welding was carried out by heating the metal pieces in a charcoal hearth to between 1000°C and 1200°C and then joining the hot metal strips together by hammering. However, the formation of surface oxides (hammer scale) produced at such high temperatures may prevent satisfactory welding. Problematic amounts of hammer scales can be reduced by cleaning the surface of the metal while preparing the weld and minimised further by using a flux, such as salt or sand.

There were different methods of constructing sword blades. A high quality blade should have the right combination of a resilient central part and hardened steeled edges. A skilled smith would probably choose a method in which a minimum of steel was used without reducing the quality or impairing the operational purpose of the weapon. After all, steel was time-consuming and difficult to make, and consequently more expensive than iron. Accordingly, the majority of iron objects were made by "steeling" or welding pieces of steel and wrought iron together. Blacksmiths may have had their personal preferences for sword blade constructions, compositions and welding techniques. Information on such techniques was most probably not disseminated much outside the workshop. The presence of technical characteristics might therefore indicate production methods at different workshops.

Since the end of the 19th century, a recurring question has been to what extent Viking swords were produced in Norway, or whether the numerous sword finds represent mostly imported weapons (as discussed in Chapter 3). The conclusions in published papers relating to import versus domestic production are based mainly on studies of the hilts and decorations on the blades. While the shape of the sword blades was subject to few alterations during the Viking Age, the hilts went through numerous changes. However, the hilt and the blade of a sword may not necessarily have been made by the same smith – not even in the same geographical area. As new hilts may have been mounted onto old blades or vice versa, a classification of blades cannot be based on an examination of the hilts. In the present work the construction of the blades will also be related to different types of hilts.

Although Old Norse and Irish literary sources are limited in relation to the description of the general appearance of sword blades, and even more so concerning origin of production, the quality of sword blades is mentioned in many places (Davidson 1962). The sagas mention poor-quality blades that had to be straightened with the foot, indicating that soft, fairly pure iron had been used. Furthermore, qualities like cutting power and durability are frequently referred to. The sagas reveal the importance of resilience for a good sword blade. In several cases they describe outstanding swords which had been handed down through generations. For hundreds of years the working of iron was surrounded by mysticism until Theophilus (Theophilus trans. 1963) in about 1,100 AD wrote down some of these secrets. One should bear in mind that the sagas were not put down in writing until a few hundred years after the Viking Age. Literature of Arabic origin (Zeki Validi 1936) dating from the time of the Vikings argues that in Europe the Rus, as well as the Franks, also produced swords. Today, many scholars claim that the Rus consisted of Russians and Scandinavians, at least East Scandinavians. Some types of smith tools do occur frequently in male Viking graves. Also, archaeological evidence of specialised weapon blacksmiths from the Viking Age has been found in Norway (Blindheim 1963). Grave finds of smith tools accompanied by a number of spearheads and swords, like those found in Bygland (Blindheim 1963), strongly indicate local production of weapons.

The swords studied in this investigation (Table 6.1) are all from the Viking Age. According to the archaeological classification of the hilts (Petersen 1919), they belong to the period from 800 AD until around 1,050 AD, mostly from the second half of that period. They have all been found within the same district of Norway, the county of Telemark (see map in Figure 6.1). Telemark has been chosen especially for this study because there must have been sufficient supplies of iron in all parts of the area. Large amounts of iron were produced in the mountainous areas of this district for centuries, including the period of interest for this work. An extensive work by Martens (1988) deals with iron production in the mountain areas of Telemark. Martens concludes that iron production had been going on in this area for a timespan of about 800 years, starting around 550 AD. A rough estimate of the annual production is 7,000–10,000 kg, depending on the technology employed, bowl furnace or shaft furnace. Easy access to raw materials was only one condition for a smithy. Equally important was the demand for weapons in society. To judge from the grave finds in Telemark – most of which date from the mid and late Viking Age – the county experienced a fairly steady level of prosperity with a few exceptions of considerable wealth. This implies that a demand for swords must have existed. Thus, easy access to raw materials and a reasonable demand for swords most probably resulted in a positive development of the craft in the area.

Although iron was produced in large quantities, recycling of scrap iron most likely also took place. This is confirmed by the many scraps and bent pieces of iron, including a bent axe, found in the Viking Age blacksmith's tool chest from Mästermyr on the island of Gotland, Sweden (Arwidsson and Berg 1999:Plates 12, 24, 30).

6.1 THE TELEMARK SWORDS

Around 220 swords from the Viking Age have been recovered in Telemark county. Except for some preferences in choosing certain districts in Telemark, the selection of blades in this work was purely random. A selection based on hilt types, pattern weldings, inlays or any other features has not been made. Although all the swords examined in the present work have been found in this county, it is not certain that they were all manufactured there. International trade at the time was extensive, as numerous finds from the Viking Age graves show. Therefore we must see if there are certain features in the smithing techniques or other clues that would make it possible to distinguish between domestic products and imports.

In this work 21 swords, recovered from all parts of the county, have been metallographically examined (Table 6.1). This represents 10% of the Viking Age swords found in Telemark. The swords have been selected, independent of pattern- weldings, inlays or any other features. In order to study potential local characteristics and varieties, several blades have been chosen from certain districts. Nineteen of the swords have been recovered from graves, that is from datable contexts. The remaining two were found during farming or construction work. Swords that have been exposed to prolonged heating at high temperatures after manufacturing (e.g. cremation burials), have tentatively been avoided in this study, as this might have otherwise interfered with the deliberate heat treatment by the blacksmith. Judging from the lack of iron oxide scales and the presence of metallographic structures due to quenching, many objects found in graves seem to have escaped prolonged heating. In this study, a single sword was most commonly found in each of the graves, in addition to other grave goods. In some cases, two or more swords have been recovered from the same grave. This may represent particularly rich graves, several burials in the same grave, or mixed finds. Eighteen of the swords are double-edged, and three are single-edged.

All the swords studied are today in the Museum of Cultural History, University of Oslo. Sampling the swords was restricted to those that were already fragmented and broken – a fairly common condition for sword blades recovered from this period, due to burial customs and soil conditions. Swords which were still in good condition and more or less complete have so far been avoided. The fragmentary swords represent about 60–70% of the total number of swords from Telemark, but their conditions vary considerably. By sampling already broken sword blades, it has been possible to cut sections across the blade from edge to edge. Although the cross-sections of the double-edged blades seem to have an axis of symmetry, a microscopic examination in some cases reveals some deviations from such symmetry relating to composition and forging techniques.

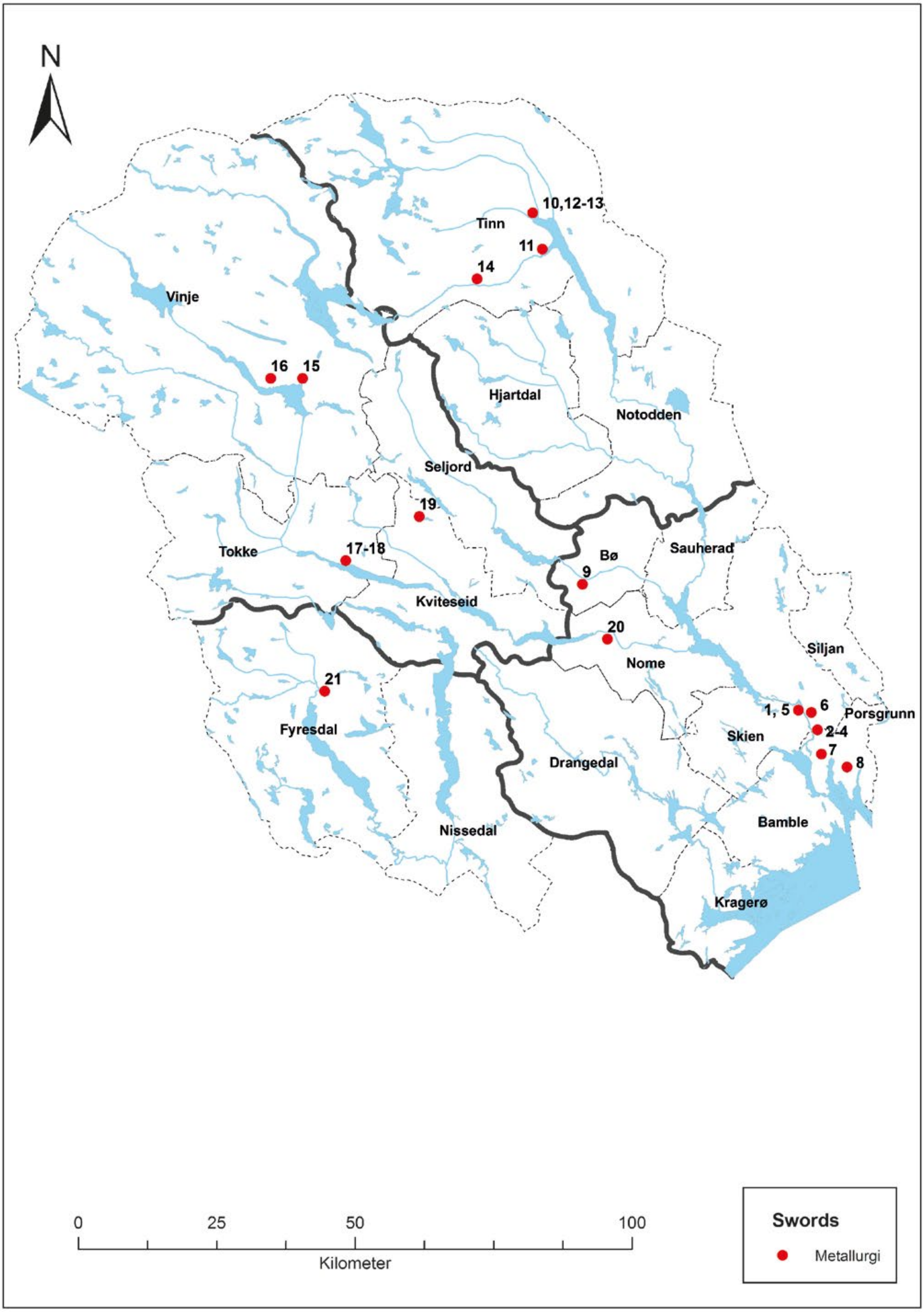


Figure 6.1. *Map showing distribution of metallographically investigated swords. Map: M. Samdal, KHM (CC BY-SA 4.0).*

Table 6.1. *The swords metallographically examined in this work.*

SWORD/ MUSEUM		FIND PLACE	HILT TYPE*	CONDITION
1	C.30067a	Skien, Solum, Kjerringteigen	M	highly corroded
2	C.29150	Skien, Gjerpen, Ris søndre	M	acceptable
3	C.35841a	Skien, Gjerpen, Ballestad nordre	V	highly corroded
4	C.35842a	Skien, Gjerpen, Ballestad nordre	M	fairly corroded
5	C.29227a	Skien, Gimsøy, Baugeidsgt. 19	M	highly corroded
6	C.23112	Skien, Gjerpen, Frogner	M	corroded
7	C.26360a	Porsgrunn, Eidanger, Bjørnstad	H	highly corroded
8	C.28460a	Porsgrunn, Eidanger, Stamland	Q/X	highly corroded
9	C.30049	Bø, Grave	Q	fairly corroded
10	C.28239a	Tinn, Marum-Suigard	LA	fairly corroded
11	C.26828a	Tinn, Møli	Q	corroded
12	C.29700a	Tinn, Marum	Xa	very corroded
13	C.29700b	Tinn, Marum	Xa	very corroded
14	C.23364	Tinn, Dal	Xa	acceptable
15	C.25111a	Vinje, Rauland g.33 b.7	Q	acceptable
16	C.21325a	Vinje, Kjelingtveit	H	highly corroded
17	C.23018a	Tokke, Åkre	Q	highly corroded
18	C.22568a	Tokke, Kvålo	Und	highly corroded
19	C.24793c	Kviteseid, Øvre Berge	Und	fairly corroded
20	C.19575	Nome, Lunde, Røymål	Q?	acceptable
21	C.23946a	Fyresdal, Brokke	M	fairly corroded

* Hilt types:
Und = undetermined or hilt missing

Comments on typology and dating

The problem of the origin of sword hilts and blades could not be considered when the selection of swords for metallographic analysis was made. A good chronological distribution was likewise secondary to the geographic one. As the majority of Viking Age finds in Telemark belong to the second half of the period, this is also the case for the analysed swords. For instance, no C-type swords, which mostly belong within 800–850 AD, have been analysed. Another drawback is that very few of the finds can be closely dated, the common types M and Q can only be dated to between 850–950 AD and 900–1,000 AD respectively.

Three swords cannot be accurately typologically determined. Sword 8 has only the lower guard preserved, but is either a Q or X-type sword, in both cases from the 10th century. Swords 18 and 19 have no guards preserved, but sword 18 was found with an H-type axe, again indicating the 10th century. Sword 19 is from a mixed find assemblage with only a general date within the Viking Age.

The earliest analysed sword, 16, has a type H hilt inlayed with a stepladder pattern. It was found with an axe of type D that narrows the dating of the grave to 800–850 AD. The reconstructed inlay pattern on the hilt indicates that it is not one of the earliest H-type specimens. The blade fragment has the remains of an inscription, and the origin is uncertain. The blade is of construction type I. The other H-type sword, 7, has a pattern-welded blade (PW 5), which is probably not of indigenous make.

The V-type hilts (sword 3) with their Ge3-type pattern are among the most enigmatic ones in terms of places of production. The hilt and blade could have been produced separately, and as construction type III was commonly mastered by Norwegian weaponsmiths, this problem is of secondary interest here.

The very late sword, 10, the only one analysed having a whole-steel blade, construction type V, was most probably not made in Norway.

A number of metallographic investigations of European iron swords have appeared in the literature. Many analyses are either limited to blades of isolated finds, or they focus mainly on certain techniques like pattern- welding or inlaid designs. More comprehensive examinations of larger numbers of blades of general character, like Celtic swords (Pleiner 1993), Roman period swords (Kedzierski and Stepinski 1989), and Anglo-Saxon swords (Gilmour 1986), elucidate sword blade technology for more than a thousand years. Only a few swords from Norway have so far been metallographically studied (Rosenqvist 1970; Arrhenius 1982; Liestøl 1951), and no systematic approach to mapping the forging technologies based on metallographic examinations, has so far been reported (as discussed in Chapter 5).

6.2 EXPERIMENTAL METHODS OF INVESTIGATION

In this investigation full transverse sections, including both cutting edges, have been cut from all the sword blades, one from each sword, using an abrasive cut-off wheel. For one of the swords (sword 18), two sections have been studied. X-radiographs were recorded for all the blades in order to estimate the state of conservation and the best place to extract sections. Also, the X-radiographs have been used to identify pattern welding or inlays, and to record cracks and bad welds that might be present. In order to cause minimum damage to the artefacts, the sections were cut as close as possible to existing fractures in cases where the X-radiographs reveal an acceptable state of preservation for sampling. Since many of the swords are quite corroded, parts of the edges and surfaces were not well preserved and often missing. However, numerous parts including pieces of the edge are still present in most of the samples.

The sections of the blades were mounted in a cold thermosetting synthetic resin. The samples were ground on wet abrasive paper ranging from 220–1,200 grade. Fine polishing was completed on rotating pads, using 3μm and 1μm diamond spray.

The distribution and shape of slag inclusions were studied on the polished, unetched samples. The polished sections were then etched in 2–4% nital in order to make the metallographic structure visible. The microstructure has been examined at magnifications from 20× to 1,000×. In order to locate the presence of significant amounts of phosphorus, all samples have been studied after etching with Oberhoffer's reagent. Sections showing positive reactions to an elevated phosphorus content with Oberhoffer's reagent were subjected to quantitative determinations by electron probe microanalysis (EPMA). Swords 7, 16, and 20 all show piled, pattern-welded or inlaid structures. The substances phosphorus, copper, manganese, arsenic, nickel, and cobalt have been analysed in steps across the layers to create concentration profiles. For swords 4, 11, 15, 17, and 19, microprobe analyses were carried out to provide information on the chemical composition and enrichment of certain elements, especially arsenic, nickel, cobalt and phosphorus, in the welds. For sword 2, a similar analysis was carried out across an area of several pale bands. The area of each analysis, varying from $10 \times 10\ \mu m^2$ to $25 \times 25\ \mu m^2$ in different samples, was chosen in order to even out small heterogeneities typical for archaeological material. Step lengths differ from 20 μm/step across welding seams to 30–50 μm/step in piled structures, depending on the thickness of the layers. In sword 12 single analyses were made in order to find out if the hard ferritic material was due to significant phosphorus content.

In all samples, hardness measurements have been carried out by DPH (diamond pyramid hardness) using a 1 kg load. The figures are given as HV (Vickers Pyramid Number).

Observations of the microstructure were made using metallurgical microscopes at the Research Park, Department of Physics, and at the Research Laboratory, Museum of Cultural History, University of Oslo. The electron probe microanalyses were carried out on computer controlled Cameca Camebax Microbeam equipment at SINTEF Materials Technology in Oslo. All microphotos and drawings in this chapter are by E.E. Astrup. "The magnification given in the captions refers to the original one applied in the metallurgical microscope". The hardness measurements were made using a Zwick 3202 hardness apparatus (SINTEF Oslo).

6.3 EXAMINATION AND RESULTS

It is not always easy to unearth the intentions of the blacksmith and the working technologies of ancient metal objects. Metallographic data offer much information, but the presence of natural impurities in the raw materials and accidental combinations of steel and iron can produce confusing pictures. Moreover, prolonged heating in the hearth may smooth out or obliterate welding seams between different parts, and cause unintentional carburisation or decarburisation of the material. Uncontrolled cooling rates may render a metal structure difficult to interpret. Due to such incidental reactions the metallographic structure may indicate certain processes of manufacture, which were not intentionally carried out by the smith. For examinations of most archaeological objects, and of large objects in particular, it would be of great help if several samples could be taken from different parts of the same object. That could differentiate between intentional and unintentional processes, and show whether the craftsmanship was good enough to produce

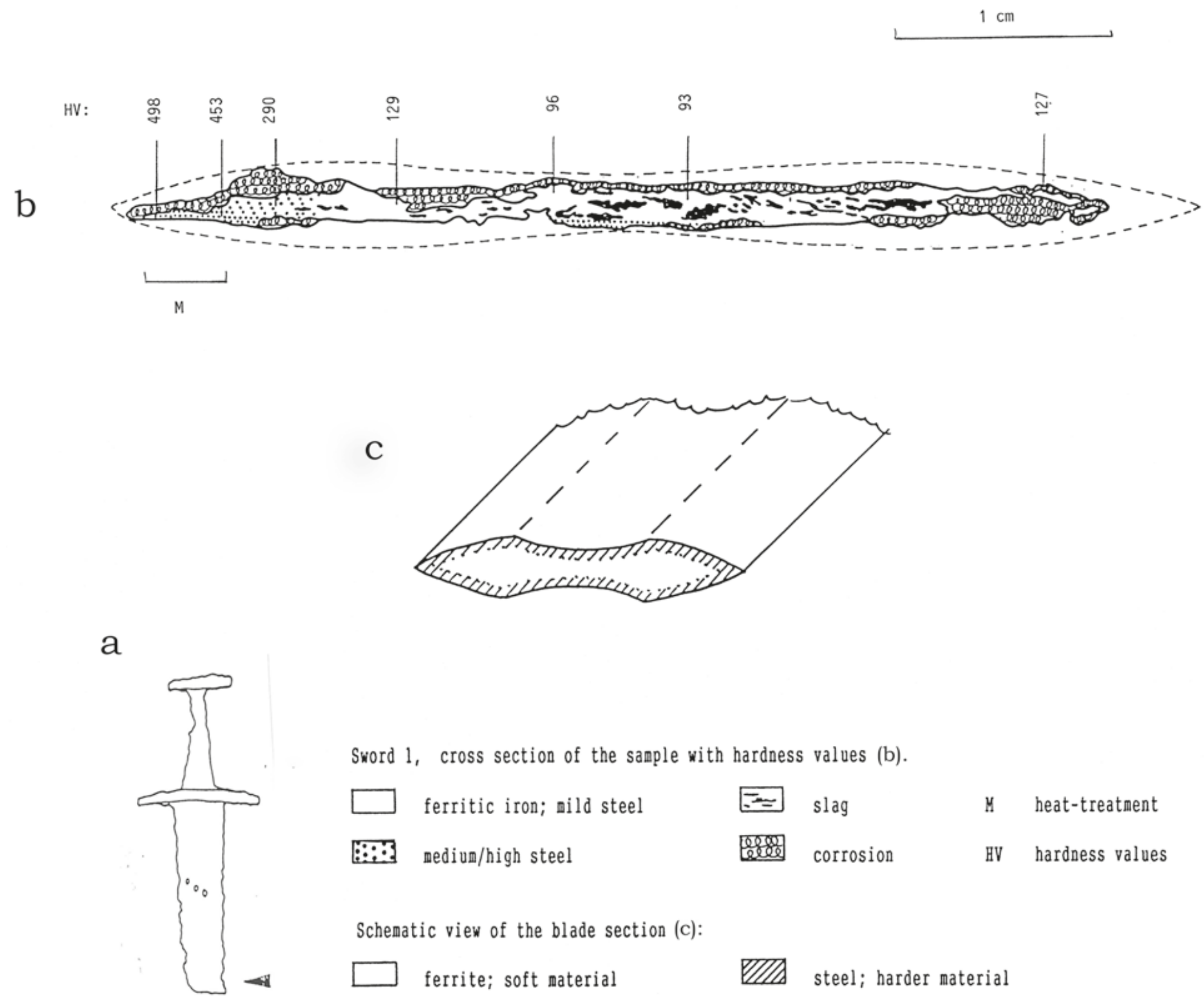


Figure 6.2a. *Sword 1. Cross-section of the sample with hardness measures (b), schematic view of the blade section (c) and outline of sword with section marked (a).*

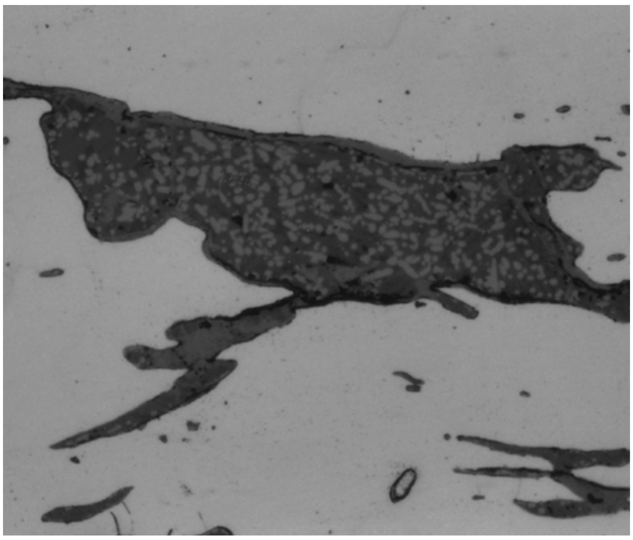


Figure 6.2b. *Sword 1. Slag consisting of a light grey spheroid phase, probably wüstite, in a dark matrix of iron silicates. (200 X).*

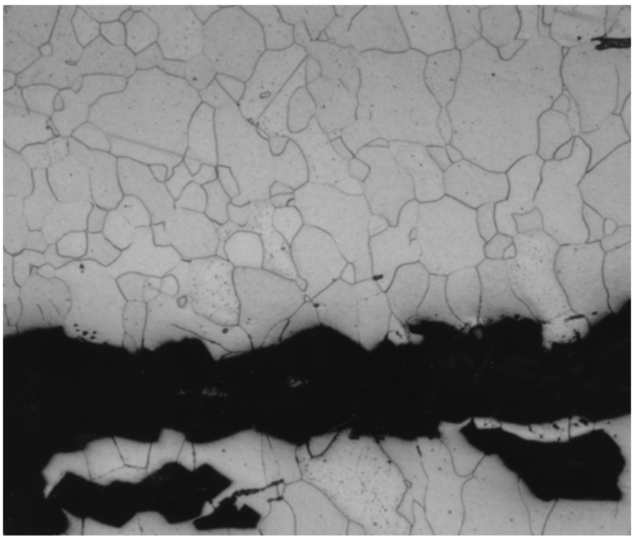


Figure 6.2c. *Sword 1. Etched. Ferritic iron with porosities and slag inclusions in a major part of the blade. (50x).*

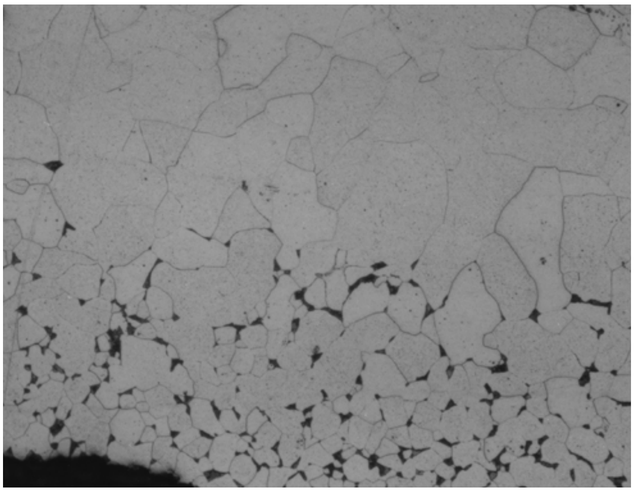


__Figure 6.2d.__ Sword 1. Ferrite and perlite in a small part of the section along the central surface. Carbon content is somewhat higher along the surface than in the core of the blade. (200x).

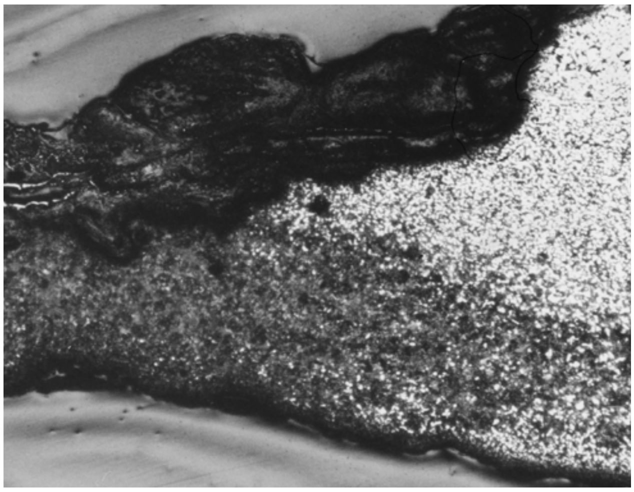


__Figure 6.2e.__ Sword 1. The tip of the cutting edge in the left part of the section contains high carbon content (dark). The dark part is corrosion. (50x).

uniform quality throughout the object. However, such sampling would ruin the object completely, and can be justified only in specific cases.

To compare the quality of sword blades investigated in this study a sorting scheme of four tiers has been applied. These have been ranked as: poor, fair, decent, and high quality. The point here is to estimate the sword blades' functional quality when used in battle, disregarding aesthetic aspects. Major contributing factors when evaluating this are:

- The construction method employed in joining and welding together iron and steel elements of the blade, and whether this craftsmanship was successful.
- The presence or absence of steel/carburisation.
- Whether quenching and heat treatment had been attempted to further increase the hardness of steel components, and if it was successful. Hardness measurements will indicate levels of softness and toughness versus rigidity, edge retention and brittleness.
- The amount of slag that can be observed in the metal, and if this could be considered detrimental to the functional quality of the blade.

A blade ranked as poor quality would typically represent a somewhat random construction method and consist mainly of soft iron. A high quality blade would require steeled edges, as well as having been subjected to successful quenching and further heat treatment.

SWORD 1 (Museum No.C.30067, found at Kjerringteigen in Solum, Skien municipality close to the limit of Skien city)

The sword comes from a man's grave, in which a spearhead was also found. The sword was in a highly corroded state, only the upper part of the blade and the hilt have survived in the ground (Figure 6.2a). The hilt is an M-type. The sword is double-edged with a fuller running along both sides of the blade.

Microscopic examination of the polished, unetched section shows porosities and numerous slag inclusions, particularly in the central part and in the edge area in the right part of the section in Figure 6.2b. Although there are some large spheroid slag inclusions, most of the slag structures are more or less elongated, results of the forging process. The slag consists of a light grey, mostly spheroid phase, probably wüstite FeO, in a dark matrix of iron silicates (Figure 6.2b). The spheroid shape of the wüstite phase indicates that the sword was heated after hammering.

After etching with nital, a microscopic examination shows that most of the central part of the blade, as well as the edge area with abundant porosities and slag inclusions (right), consist of a soft ferritic iron (Figure 6.2c). In the core of the section, an average hardness value of 95 HV was measured, consistent with soft iron with a pure ferritic structure.

In one area along the surface in the central part of the blade, the carbon concentration is found to be moderately higher than in the core (Figure 6.2d), while the opposite surface shows only ferrite. However, most of the original surface layers have been lost due to corrosion.

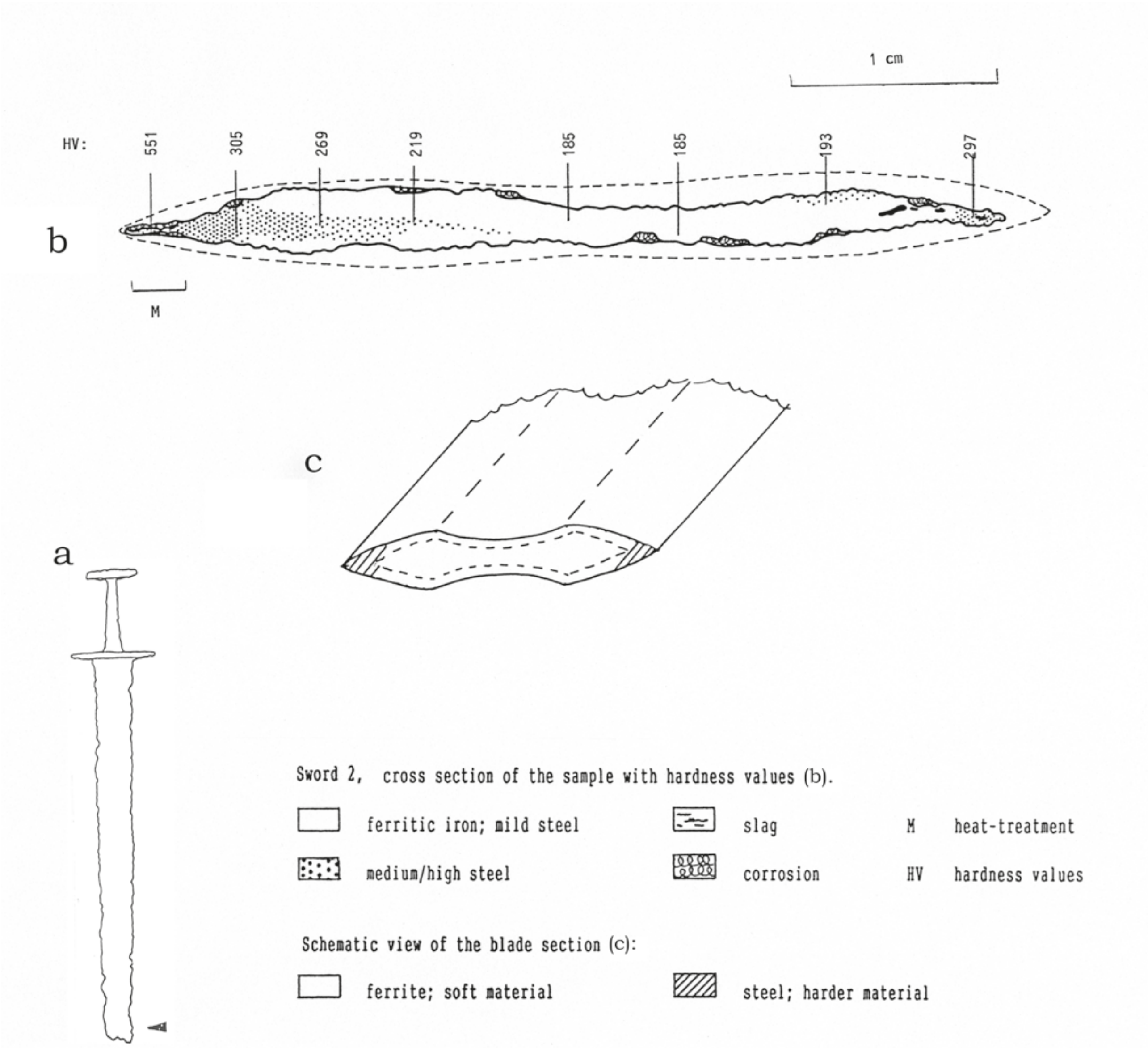


Figure 6.3a. *Sword 2. Cross-section of the sample with hardness measures (b), schematic view of the blade section (c) and outline of sword with section marked (a).*

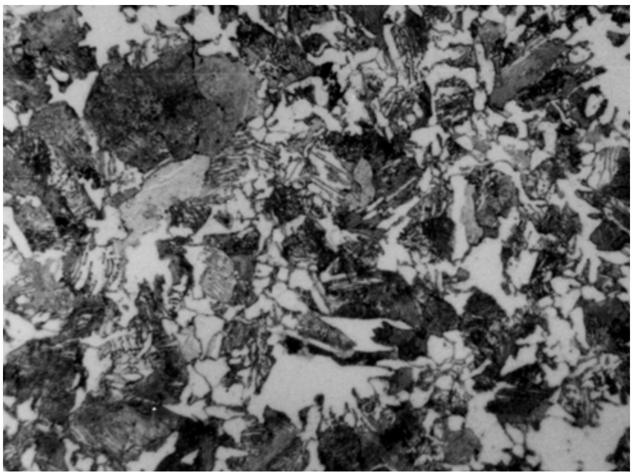


Figure 6.3b. *Sword 2. Medium carbon concentration in a generally heterogeneous structure. (1000x)*

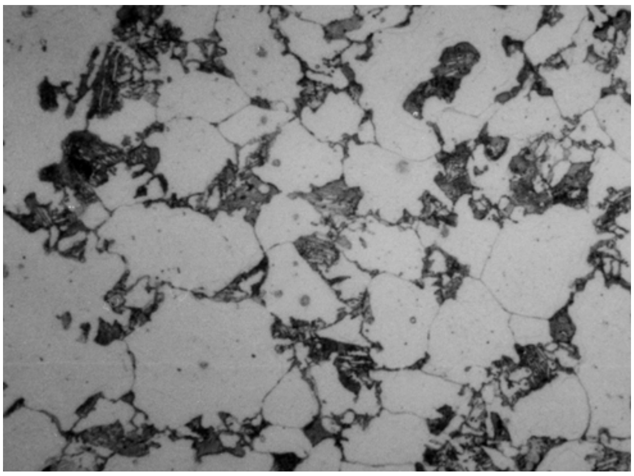


Figure 6.3c. *Sword 2. Low carbon concentration in a generally heterogeneous structure. (1000x).*

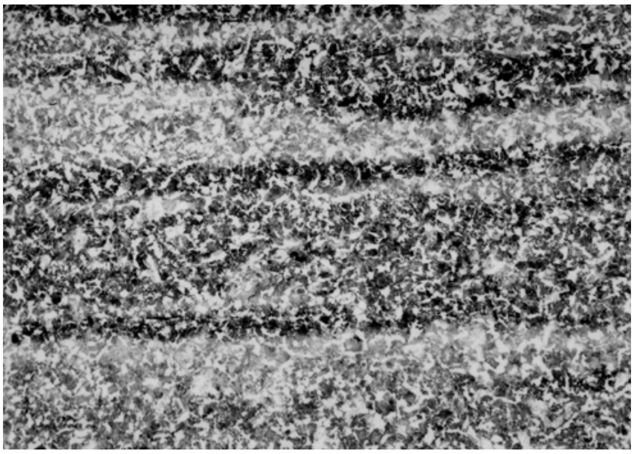


Figure 6.3d. *Sword 2. Light wavy structures, enriched with arsenic in part of the section. (1000x).*

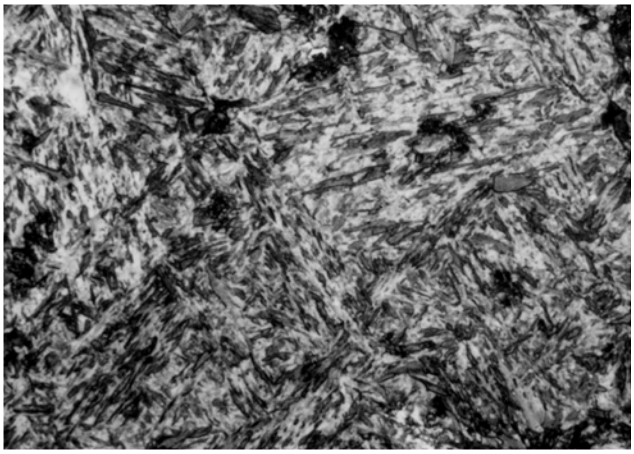


Figure 6.3e. *Sword 2. A martensitic structure due to quenching of the cutting edge in the left part of the section. (1000x).*

Part of the cutting edge on the left part of the section has been lost to corrosion. This edge, however, still consists of iron with a high carbon concentration (Figure 6.2e). The presence of a martensitic structure shows that the cutting edge has been quenched, although a full quench was not performed. This may have been done intentionally to avoid too brittle a material. The DPH hardness values (498 HV, 453 HV) show a fairly hard material.

The outer right part of the section shows only pure ferrite. To judge from the shape of the blade and the lack of carbon in this area, it seems reasonable to assume that the tip of the edge is missing due to corrosion. The hardness measured in the remaining part of this edge area is 127 HV.

Interpretation: The large amount of slag inclusions and porosities in the blade indicate poor craftsmanship or poorly refined iron, which would render the blade brittle. While the core and one of the edge areas consist of a soft uncarburised material, the other cutting edge and part of the remaining surface in the central part are harder, owing to an increased carbon concentration. Most probably a major part of the surface layers is missing, due to corrosion. It seems likely that higher carbon content might have been present in the entire surface of the blade.

In the present examination, no slag strings or weld seams were observed, which could indicate that a layer of higher carbon content had been welded to the core. Therefore, it seems that the blade had been carburised by a diffusion of carbon atoms into the iron in the last step of the forging process (case-carburisation). This conclusion is supported by the lack of a distinct gradient in the carbon concentration between the ferritic and the carburised areas. The presence of a high carbon content and a slack-quenched structure due to heat treatment in one of the edges indicate that the blacksmith was aware of the importance of hard steel in the cutting edges, and that he was able to carburise iron and to quench the steel, although the success of the process may have been somewhat accidental. Although the intentions and knowledge of the blacksmith in terms of making a good sword seem adequate, his choice of performing the heat treatment by slack-quenching indicates that a successful hardening was luck as much as skill. This sword is considered to have been of poor functional quality.

SWORD 2 (Museum No.C.29150, found at Ris in Gjerpen parish, Skien municipality)

The sword was found on a farm. As can be seen from Figure 6.3a, the blade is broken, and the outer part is missing. Otherwise the sword was in an acceptable state of preservation. The hilt is an M-type. The sword is double-edged and it has the remains of a shallow fuller along the blade.

The overall section shows only few slag inclusions. However, a couple of large, and some small, slag particles are observed close to the edges.

After etching with nital, part of the section was seen to have a heterogeneous composition of medium and low carbon content (Figures 6.3b, 6.3c). The uneven carbon concentration in the blade suggests that the material was forged together from pieces of varying carbon content in a somewhat random way, or from heterogeneous bloomery iron. In certain areas in the central part of the section there are light, wavy bands (Figure 6.3d). These bands represent an enrichment of arsenic formed by oxidation during smithing operations (Tylecote and Thomsen 1973). The elevated levels

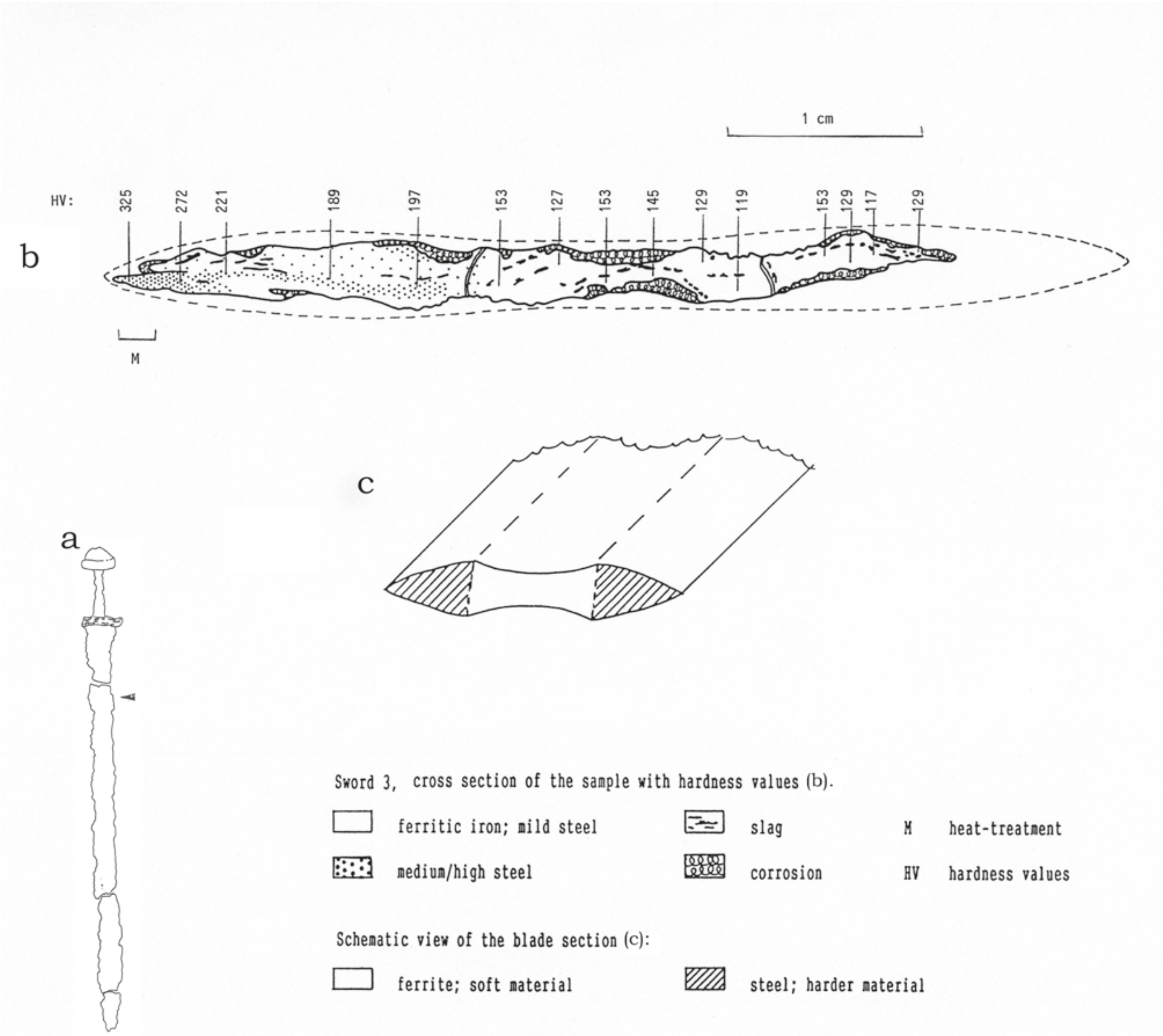


Figure 6.4a. *Sword 3. Cross-section of the sample with hardness measures (b), schematic view of the blade section (c) and outline of sword with section marked (a).*

Figure 6.4b. *Sword 3. Slag inclusions with an elongated shape due to forging throughout the section. (100x).*

Figure 6.4c. *Sword 3. The core of the blade consisting partly of areas with mostly ferritic iron. (200x).*

Figure 6.4d. *Sword 3. The core of the blade consisting partly of areas with fine grain pearlite. (200x).*

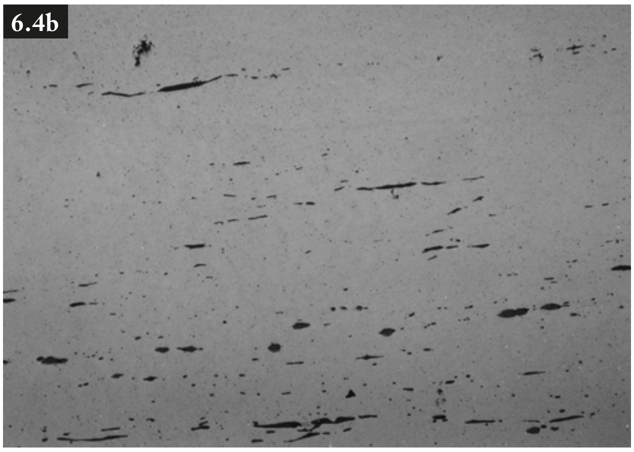
Figure 6.4e. *Sword 3. Pale line barely visible across the section, indicating welding seams between the central area (right) and the edge (left). (20x).*

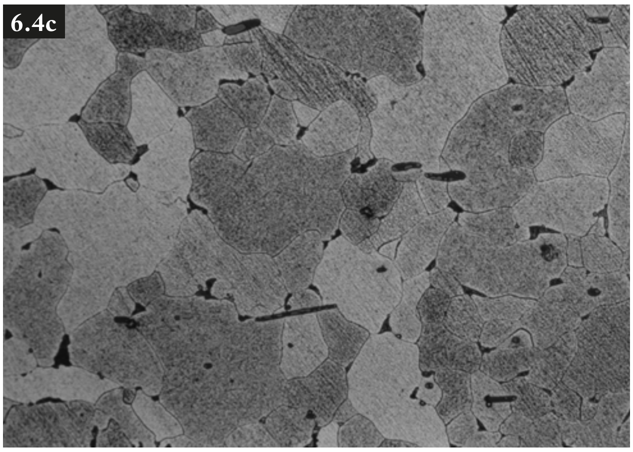
Figure 6.4f. *Sword 3. A deep crack from the surface into the left edge. (20x).*

Figure 6.4g. *Sword 3. The crack shown in 3/6. Decarburised areas on both sides of the crack resulting from lengthy heating. (100x).*

Figure 6.4h. *Sword 3. The carbon rich part of the left edge showing traces of martensite indicating quenching. (500x).*

Figure 6.4i. *Sword 3. Cutting edge of the right part of the section showing much lower carbon content than in the left edge. (100x).*


6.4b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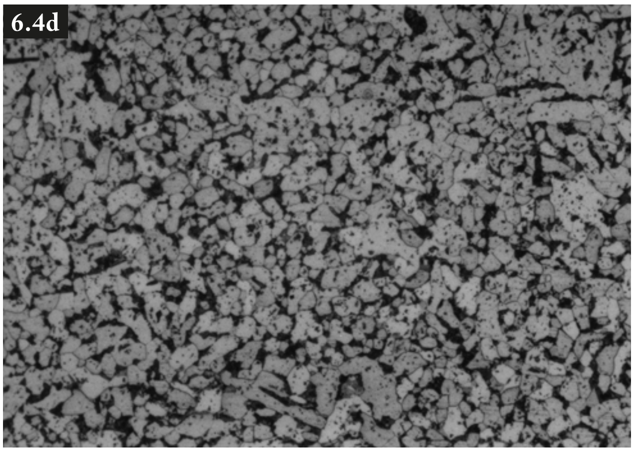
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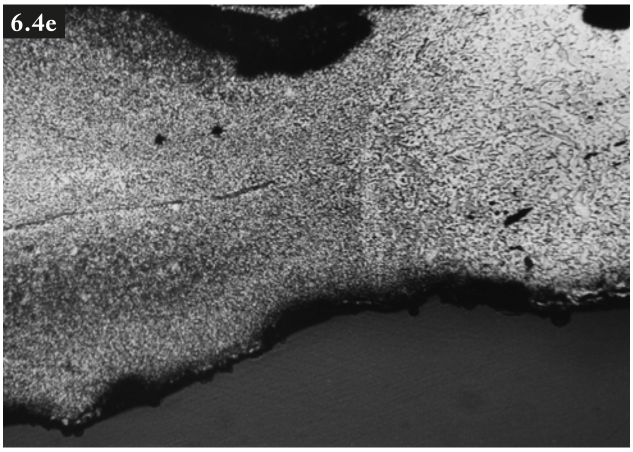
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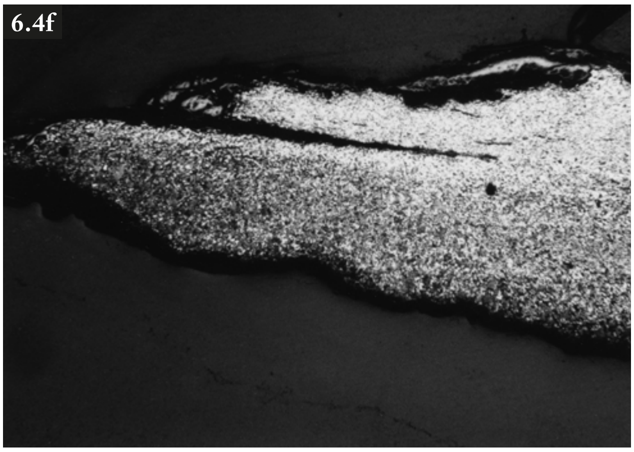
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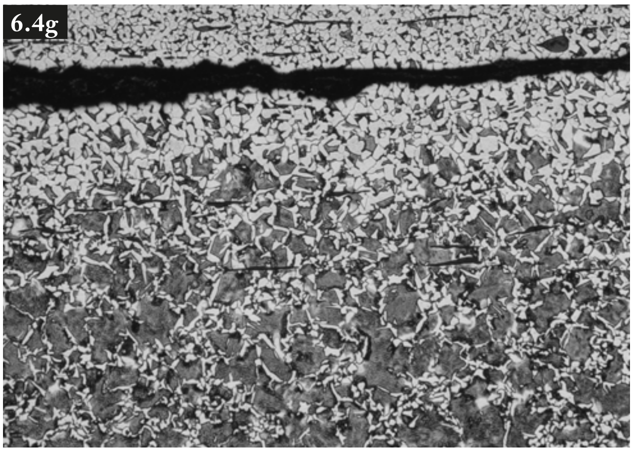
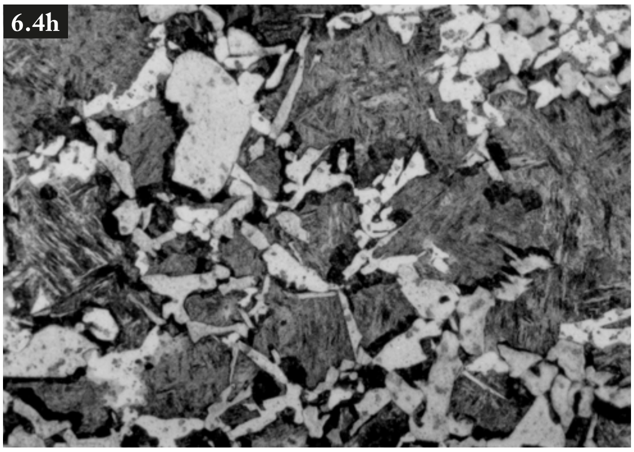
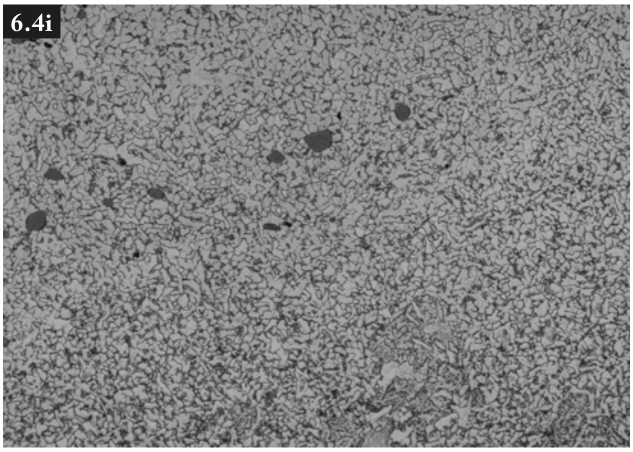

6.4g


6.4h


6.4i

of arsenic in the bands are confirmed by microprobe analyses. The arsenic concentrations are enriched from about 0.02 percentage by weight (hereafter wt%) in the bulk of the material to about 0.18wt% in the “pale lines”. The hardness values measured in the central part of the blade range generally from 185 to 219 HV.

The cutting edge in the left part of the section shows, for the most part, fairly high carbon content. The tip of this edge has a martensitic structure due to heat treatment (Figure 6.3e). The hardness in this part is found to be 551 HV. Further away from the tip, the structure shows a mixture of martensite and bainite/pearlite, indicating incomplete quenching, possibly self-annealing. The hardness values range from 269 to 305 HV (Figure 6.3a).

A similar structure of bainite/pearlite is observed in the right edge, but there is no martensite there. This edge has a lower carbon concentration. The hardness measurements within this area average 297 HV, which is still reasonably hard steel. The indistinct transition between the carburised edge and the low-carbon core material indicates that carburisation was accomplished by direct carburisation of the finished product.

Interpretation: The blacksmith produced a sword blade with only few slag inclusions. The cutting edges were carburised, although the carbon content appears to be different in the two edges. However, judging from the shape of the blade and the width where the section was taken, a fair part of the cutting edge with lower carbon content (right) seems to have been lost due to corrosion. The structure in the outer left edge shows that the blade was hardened by quenching. Some self-annealing or incomplete quenching occurred closer to the central area. In the right edge only the incompletely quenched area is present, with the harder tip now missing. There is no indication of a carburised surface layer along the rest of the section. It is possible that only the edges were carburised, but it seems more likely that the entire blade had been carburised by case-carburisation, and that the steel layer in the blade surface has been mostly lost to corrosion. The structure shows that the blacksmith was familiar with the importance of hard cutting edges, and that he had the skill to carburise and quench the edges. This sword is considered to have been of fair quality.

SWORD 3 (Museum No.C.35841a, found at Ballestad in Gjerpen parish, Skien municipality)

The sword belongs to a grave find, which also contained a spearhead, an axe head, and a number of other iron objects. The sword is double-edged with a fuller along both sides of the blade. It was in a highly corroded state and broken into several pieces (Figure 6.4a). The hilt is a V-type.

Microscopic examination of the polished, unetched section reveals a number of slag inclusions all over the sample, with an elongated shape due to forging (Figure 6.4b). Strings of small hammer scale inclusions across the sample imply that the edges of the blade had been welded to the central part.

After etching, the core of the blade shows areas with mostly ferritic iron (Figure 6.4c), and other areas with fine grain ferrite and pearlite corresponding to a carbon content of approximately 0.3% carbon (Figure 6.4d). The hardness values in the core range from 119 to 153 HV. The latter corresponds to relatively soft pearlite. Pale decarburised lines, barely visible, across the section indicate welding seams between the low-carbon central area and the somewhat more carbon-rich edges (Figure 6.4e). Some diffusion of carbon from the edge areas across the welding seams may be observed.

The cutting edge on the left side of the section (Figure 6.4a) has a rather heterogeneous carbon content. Figure 6.4f and Figure 6.4g show a deep crack from the surface into the edge. This might be due to bad luck when hammer- welding together smaller pieces of different carbon concentrations, or it could be a fatigue crack, which was later accelerated by corrosion. The carbon-rich part of the edge shows traces of martensite indicating that quenching had taken place (Figure 6.4h). The hardness measured in this part of the cutting edge is 325 HV, while that next to the crack in the less carbon-rich area is 185 HV.

The other cutting edge (right) generally has much lower carbon content (Figure 6.4i). The hardness values range from 117 to 153 HV, with a hardness of 129 HV in the remaining outer part. This is significantly lower than in the other edge. The outer part of the right edge may originally have had a carbon concentration somewhat similar to the other cutting edge. This part of the right edge is however missing. As can be seen from Figure 6.4a, only a minor part of the edge outside the weld remains in this part of the section.

Interpretation: Strings of hammer scale inclusions and decarburised pale lines across the section indicate that the edges had been welded onto the central part. This blade section has a significantly higher carbon concentration in one edge than in the other. Although it seems reasonable to assume that the cutting edge on the right part of the section (Figure 6.4a) was lost due to corrosion, this alone can hardly account for the differences in carbon concentration in the remaining parts of the edge areas. Since a decarburisation of only one edge seems unlikely, it is possible that the original material for the two edges differed in carbon content. One of the edges clearly shows that the blade had been welded together from pieces of varying carbon content. Except for a major crack showing a weak point in one edge, the welding seams between different pieces of iron and steel were skillfully carried out. Given that the right edge also had a higher carbon concentration, this sword is considered to have been of decent quality.

SWORD 4 (Museum No.C.35842a, found at Ballestad in Gjerpen parish, Skien municipality)

The sword was found in a grave, which also contained a spearhead, a sickle, and some iron fragments. The sword is broken and quite corroded, and the outer part with the point is missing (Figure 6.5a). The blade is double-edged and has a fuller along both sides. The hilt is an M-type.

Microscopic examination of the polished, unetched sample shows a number of pores and small spheroid slag particles, particularly in the central part (Figure 6.5b). Spheroid slag particles indicate lengthy heating of the blade after the last hammering.

After etching with nital, pronounced welding seams containing small hammer scale particles (Figure 6.5c) show that the sword blade consists of a central part to which the edges had been butt-welded. Decarburisation and a pronounced enrichment of cobalt and some enrichment of arsenic and nickel appear in the welding seams. Also, some diffusion of carbon has occurred across the seams due to heating. Microprobe analyses confirm an enrichment of cobalt from a general concentration of about 0.05wt% to nearly 0.7wt% in the weld (Figure 6.24d). Also, other welds are clearly visible in both the edge areas, showing that the edge material had been welded together from several carbon-rich pieces of iron (Figure 6.5d).

The central part consists mainly of ferrite with some pearlite (Figure 6.5a). The hardness readings at different positions in this part of the blade are 145 HV and 156 HV, averaging out at 150 HV.

Both edges are thoroughly carburised, having close to a eutectoid carbon concentration in one edge and slightly lower in the other. There is a martensitic structure in both edges, due to quenching (Figure 6.5e). This is consistent with the high hardness values, averaging 587 HV and 553 HV respectively.

In the left part of the section (Figure 6.5a), there is a crack starting at the surface (Figure 6.5f). The area close to the crack has a ferritic structure, although a major part of the material in this area of the blade consists of high-carbon steel. This crack must therefore have appeared before the last heating process, which has resulted in local decarburisation of the steel around the crack.

Interpretation: Examination of this sword shows that the smith possessed great skill and demonstrated competent technical achievement in welding together pieces of different carbon content. Still, the material in the core contains too much slag and porosities. The crack at the left edge must be due to the blacksmith's bad luck during forging. The sword blade was of high quality with a flexible core and hard (too hard?), quenched edges, and should have served its purpose well.

SWORD 5 (Museum No.C.29227a, found at Gimsøy, Skien municipality)

The sword was found in a man's grave together with a spearhead. The sword is single-edged. It was found in two pieces (Figure 6.6a) that were heavily corroded, especially along the edges. The sword has an M-type hilt.

Examination of the polished, unetched sample shows that the main part of the blade contains a number of bands of small slag particles, probably along the rims of smaller iron pieces which had been hammer-welded together to make the body of the blade. The slag is partly homogeneous and elongated, and partly two-phased with a light spheroid phase, probably wüstite FeO, in a dark matrix of silicates. The edge, however, is almost without slag inclusions.

After etching, the blade appeared to consist mostly of fine grain ferrite. The blunt part is mildly carburised (Figure 6.6b) (c. 0.3%C), appearing as fine grain pearlite. This is consistent with an average hardness of 178 HV in the back. The edge area, however, consists of large ferrite grains (Figure 6.6c). Hardness in most of the section is around 119 HV (Figure 6.6a). The variation in grain size throughout the section may reflect a composition of different pieces of iron, possibly bloomery iron.

Interpretation: The blade material is composed of a large number of pieces of iron with numerous small slag particles in the welding seams. The only carbon-containing area is found in the back. Although a band of a harder material in the back would improve the strength of the blade, the cutting edge is soft, and the blade would probably still easily bend in combat. The blade was of poor quality, made of soft material.

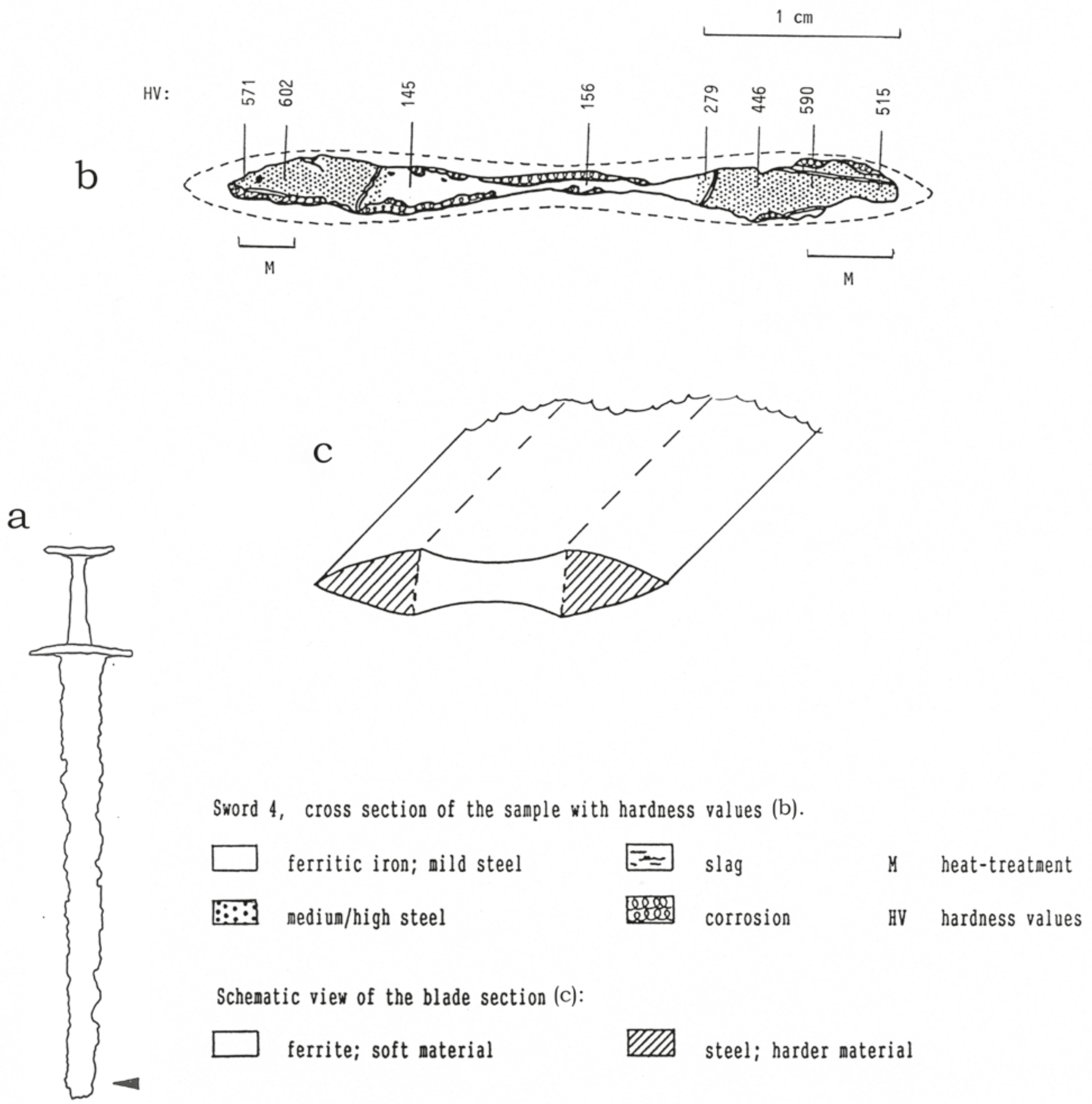


__Figure 6.5a.__ Sword 4. Cross-section of the sample with hardness measures (b), schematic view of the blade section (c) and outline of sword with section marked (a).

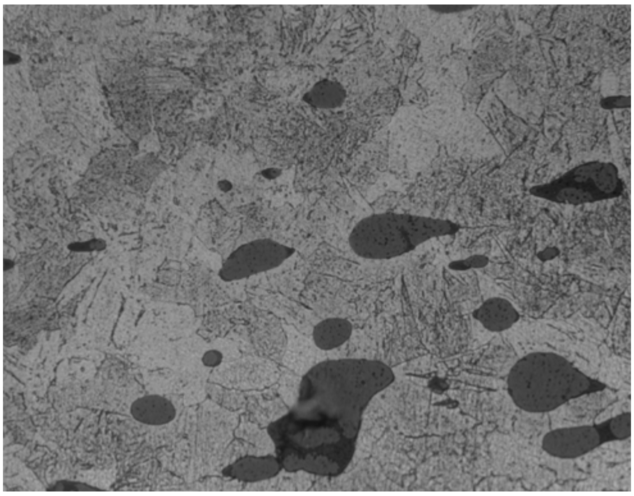


Figure 6.5b. *Sword 4. Lots of slag and pores particularly in the central part. (500x).*

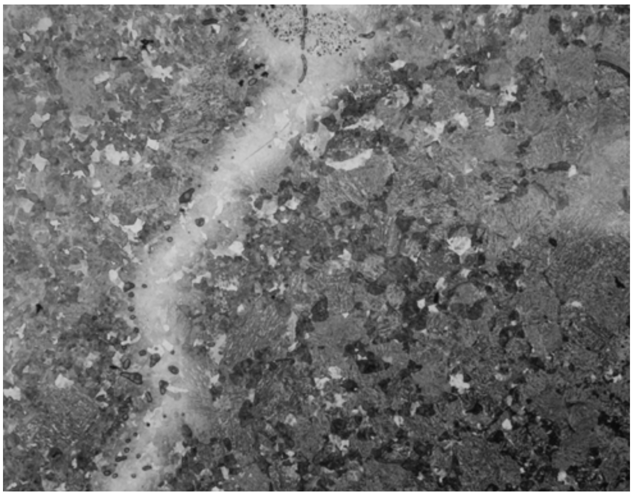


Figure 6.5c. *Sword 4. Welding- seam with small inclusions of hammer scale between the edge and the core of the blade. (100x).*

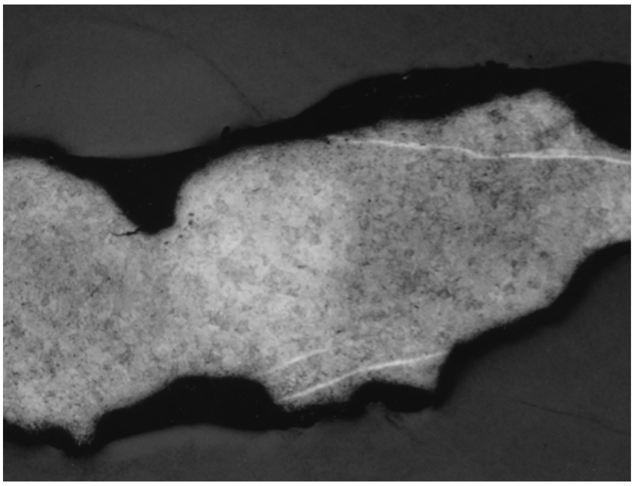


Figure 6.5d. *Sword 4. The carbon-rich (right) edge with welding seams between smaller pieces welded together. (20x).*

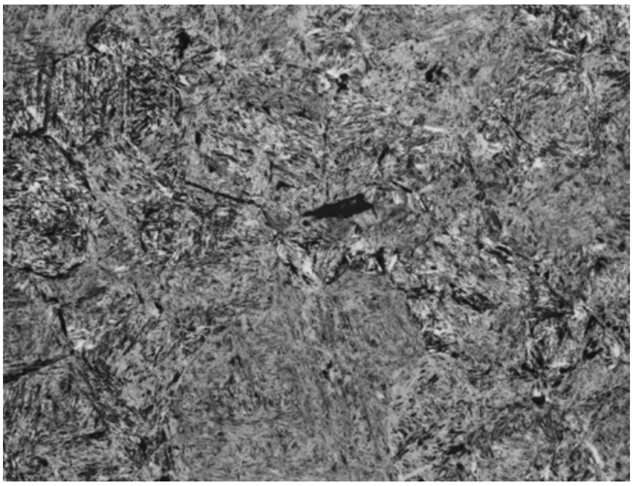


Figure 6.5e. *Sword 4. Martensitic structure in both edges due to quenching. (200x).*

Figure 6.5f. *Sword 4. A pronounced crack starting on the surface of the edge in the left part of the section. Decarburisation has occurred around the crack due to long heating time during forging. (100x).*

SWORD 6 (Museum No. C.23112, found at Frogner in Gjerpen, Skien municipality)

The sword was found in a grave together with an iron axe head and fragments of a shield boss, a spearhead, a sickle, a knife, nails and rivets, and fragments of whetstones made from slate. The sword, which is single-edged, is corroded and exists in several pieces (Figure 6.7a). The edge was significantly more corroded than the back, which is mostly in a surprisingly good state of preservation. The hilt is an M-type.

The polished, unetched sample shows only small amounts of slag. The slag inclusions are mostly elongated. Etching with nital reveals that the blade material is composed of several smaller pieces and sheets of somewhat different carbon concentrations. The pieces have been skillfully hammer-welded together, leaving hardly any hammer scale inclusions along the welding seams. The edge consists mainly of low-carbon iron with fairly large grain ferrite (Figure 6.7b), the average hardness values being 147 HV (Figure 6.7a). The back, also consisting of low-carbon iron, shows large variations in grain sizes (Figure 6.7c). A large part of the material, from the back to around the centre of the blade, is composed of longitudinal layers of different grain sizes corresponding to hardness readings ranging from 110 to 148 HV. An area in the right part of the section has somewhat higher carbon content (an average hardness value of 178 HV), and is (Figure 6.7a) the hardest part of the entire blade. Since a piece of harder material in this part of the blade has no function relating to the usability of the sword, this piece must have ended up unintentionally in the blade material. It is possible that the smith was ignorant of the properties of the individual pieces of iron and welded them together into a packet of sufficient size to make the blade.

Interpretation: The forging process had been carried out skillfully with only a few slag inclusions. An intentional carburisation of the blade does not seem likely, as the carburised parts appear to be randomly placed in the material. The edge is soft with practically no carbon. The quality of the sword was not particularly good. Since the blade is generally too soft it is considered to have been of poor quality.

SWORD 7 (Museum No. C.26360, found at Bjørnstad in Eidanger parish, Porsgrunn municipality)

The sword was found in a grave together with an iron axe head. The sword was extremely corroded with heavy incrustation and was broken into several pieces. It is a double-edged sword with a fuller along both sides of the blade. The hilt is incomplete and defective (Figure 6.8a), but can still be classified as an H- type.

Microscopic examination of the polished, unetched sample shows many elongated slag inclusions, some of which are rather large (Figure 6.8b). The slag is particularly abundant in the central part, while less plentiful in the edges.

After etching with nital, the sword was seen to be composed of a low-carbon central part, to which the two cutting edges of somewhat higher carbon content had been welded (Figure 6.8c, 6.8a). The curved shape of the welds indicates that the edges had been bent around the central part before welding. The surface layers in the central part of the blade consist of distinct sheets of alternating ferritic iron and medium carbon steel, hammer-welded together (Figure 6.8d), while the actual core consists mostly of ferrite of different grain sizes, interspersed with some pearlite. Etching with Oberhoffer's reagent suggests that the ferritic sheets in the surface, as well as parts of the core, contain a fair amount of phosphorus, which accounts for the considerable hardness of the ferrite, measured hardness values being 189-239 HV. Microprobe analyses made in steps across the layers show that phosphorus content in the low-carbon, ferritic sheets ranges between 0.25wt% and 0.40wt%, while the concentration in the medium carbon, pearlitic sheets is about 0.02wt%. The concentration of arsenic is found to follow the course of the phosphorus concentration, varying between 0.01wt% arsenic in the pearlitic sheets and 0.44wt% in the ferritic sheets.

The microstructure is consistent with a cut through a piled or pattern-welded surface layer, which has been welded onto a ferritic core. Pattern welding is also vaguely observable on the X-radiographs of the corroded sword blade. The design observed in the X-radiograph might be a "herring bone" – two piled strips twisted in opposite directions, possibly alternating with straight sections. However, the pattern is barely recognisable and impossible to interpret with any certainty. Owing to corrosion, most of the surface layers are now missing.

Both cutting edges have a heterogeneous structure of varying carbon content and grain sizes. One of the edges (Figure 6.8a, right) shows a patched structure of lamellar pearlite with a fairly high carbon concentration (Figure 6.8e). The hardness measurement of 263 HV at the tip of the edge (Figure 6.8a) indicates reasonably hard steel. Light, decarburised stripes (Figure 6.8f) in the edge area show that the edge is composed of smaller pieces of steel welded together.

The other cutting edge (left) shows mostly a somewhat lower carbon content (187 HV), except in the very tip where it is high. The original tip of this edge has been lost to corrosion.

Interpretation: This must have been an impressive looking weapon, with the pattern-welded blade surface made from sheets of mild steel and phosphorus-containing ferritic iron. The core of the blade has a lot of slag that could have been worked out. The carbon concentration of the material is adequate. In parts of the core, iron areas have a fairly high content of phosphorus. The cutting edges are harder than the core, owing to higher carbon concentrations. The two edges seem to be of somewhat different carbon content, although this may be explained by loss of material at the outermost left edge due to corrosion. There are no signs of quenching. For practical use in combat this sword blade is considered to have been of fair quality.

SWORD 8 (Museum No. C.28460a, found at Stamland in Eidanger parish, Porsgrunn municipality).

The sword was found in a grave together with a spearhead, an axe head, a rattle, and a sickle. The blade was found in two pieces which were heavily corroded. The blade is double-edged and has a fuller along the centre. The fuller was mostly corroded all the way through. The sample, taken across the blade, consists of two pieces broken along the fuller. The hilt is incomplete (Figure 6.9a). Only the lower guard remains, which makes it difficult to classify the hilt type. The slightly curved lower guard suggests a Q or possibly an X-type.

In the polished, unetched sample, small roundish slag particles are present. The section was easily etched with nital. Strings of small slag particles across the section and a slight discontinuity of the carbon concentration between the central part and the edge areas (Figure 6.9b) indicate that edges of higher carbon concentrations were welded to a less carbon-rich central part. However, welding seams are hardly visible, and the right weld especially is very corroded.

Both edges have a near eutectoid carbon concentration with retained austenite remaining from the quenching operation. In Figure 6.9c the characteristic appearance of martensite is evident. The hardness measurement values average 591 and 551 HV for the two edges respectively (Figure 6.9a).

Moreover, the scanty remains of the central part contain significant carbon content, although not quite as much as in the edges. Like the edges, the central part of the blade shows a partly martensitic structure due to quenching. The hardness values range from 339 to 439 HV.

Interpretation: The blacksmith was obviously familiar with the importance of hard edges and a somewhat softer central part. The forging had been carried out in a skillful way, and the blade had been heat treated. However, although this sword for the most part satisfies the requirements of a high-quality weapon, the central part of the blade was probably too hard and brittle, thus lacking the resilience of an excellent slashing weapon. An all-steel blade, which is rare (Tylecote 1986:2; Williams 1970:81), would also have been a waste of costly carburised material. This sword is considered to have been of high quality.

SWORD 9 (Museum No. C.30049, found at Grave, Bø municipality)

The sword was found in three pieces, in a fairly corroded state, during building activities on a farm (Figure 6.10a). Several small burial mounds were reported close by. The blade is double-edged with a double fuller running along the centre on both sides. The hilt is a Q-type.

Examination of the polished, unetched sample shows some slag particles, mostly as alignment of flat slag due to forging. The slag particles consist of two phases (Figure 6.10b), a light grey, mostly dendritic phase, probably wüstite FeO, in a dark matrix of silicates. Also, there are bands of hammer scale particles across the section, indicating welding seams for the two cutting edges.

After etching with nital, welding seams for both edges were seen to be decarburised light bands across the blade (Figure 6.10c). Both edges have carbon content close to a eutectoid concentration. The cutting edges have a martensitic structure due to quenching (Figure 6.10d). The hardness values in the cutting edges are measured as 613, 555 HV and 551, 557 HV respectively. Some diffusion of carbon is observed across the welding seams (Figure 6.10e). The edge to the right in Figure 6.10a has a somewhat heterogeneous structure. Pieces of medium carbon content have been forged into the edge material (Figure 6.10f).

The central part of the blade has medium carbon content in the areas near the welding seams (257, 321 HV), decreasing towards the centre of the blade (130–170 HV). The central area is heterogeneous with varying grain sizes and carbon concentrations. Figure 6.10g shows a coarse-grained ferrite and a fine-grained structure of higher carbon content.

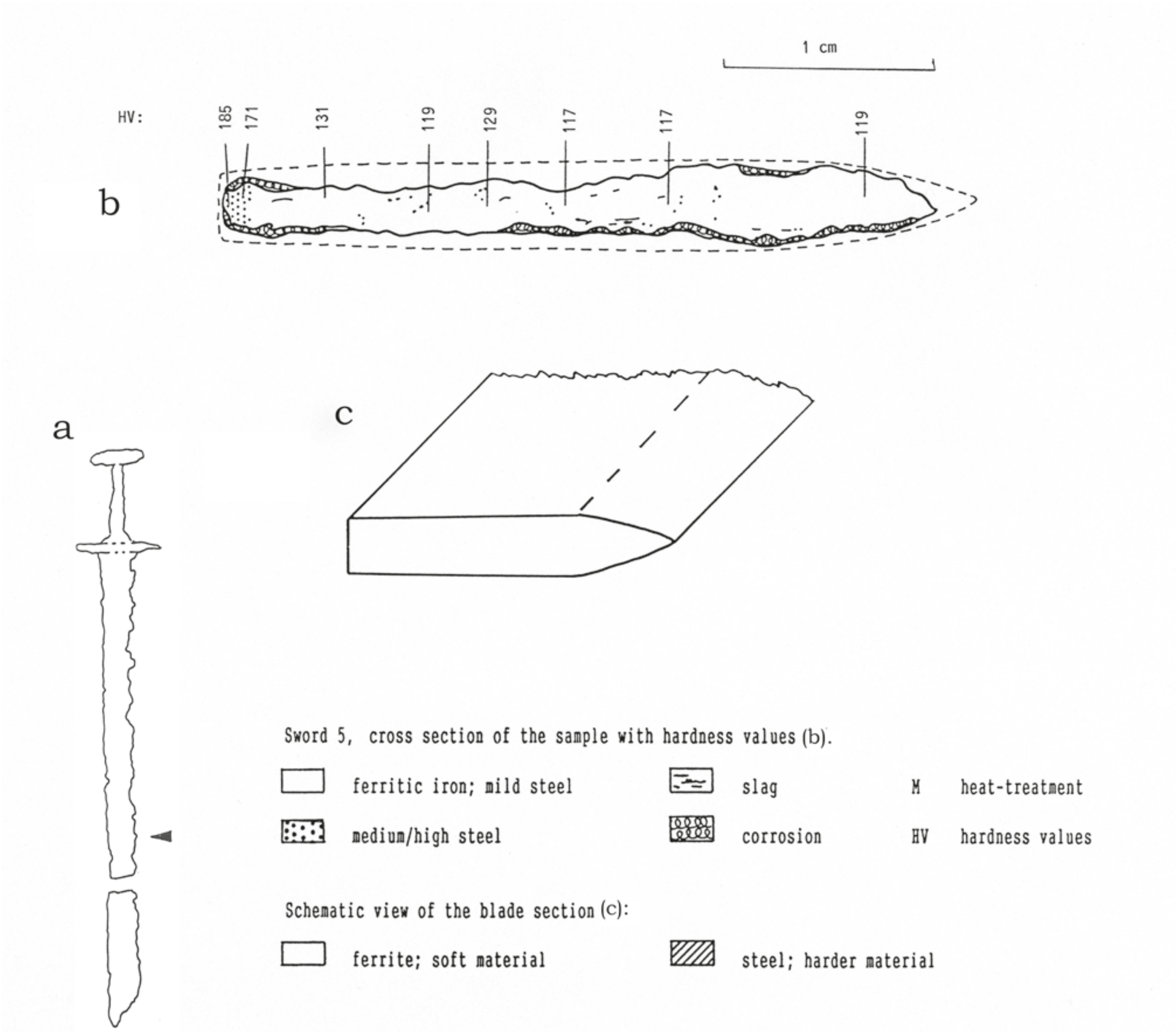


Figure 6.6a. *Sword 5. Cross-section of the sample with hardness measures (b), schematic view of the blade section (c) and outline of sword with section marked (a).*

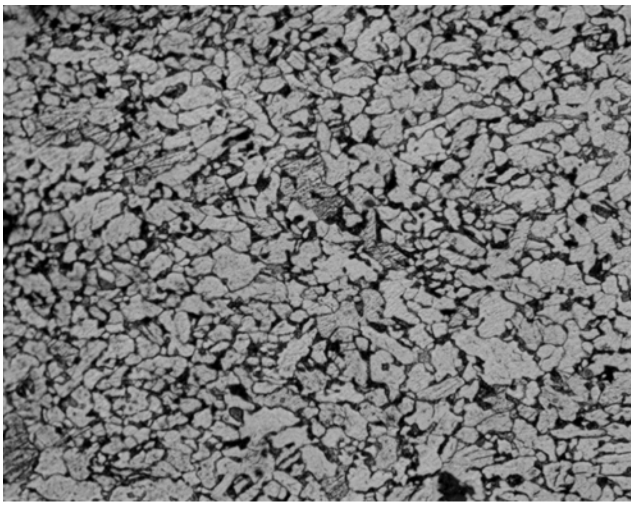


Figure 6.6b. *Sword 5. The back part is mildly carburised. (200x).*

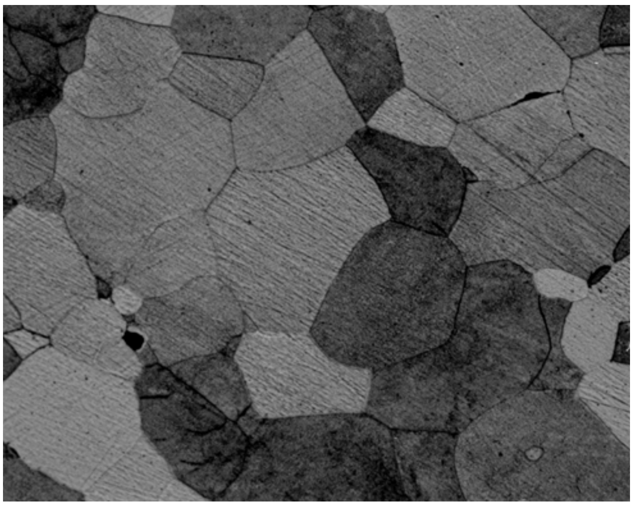


Figure 6.6c. *Sword 5. The edge consists of large ferrite grains. (200x).*

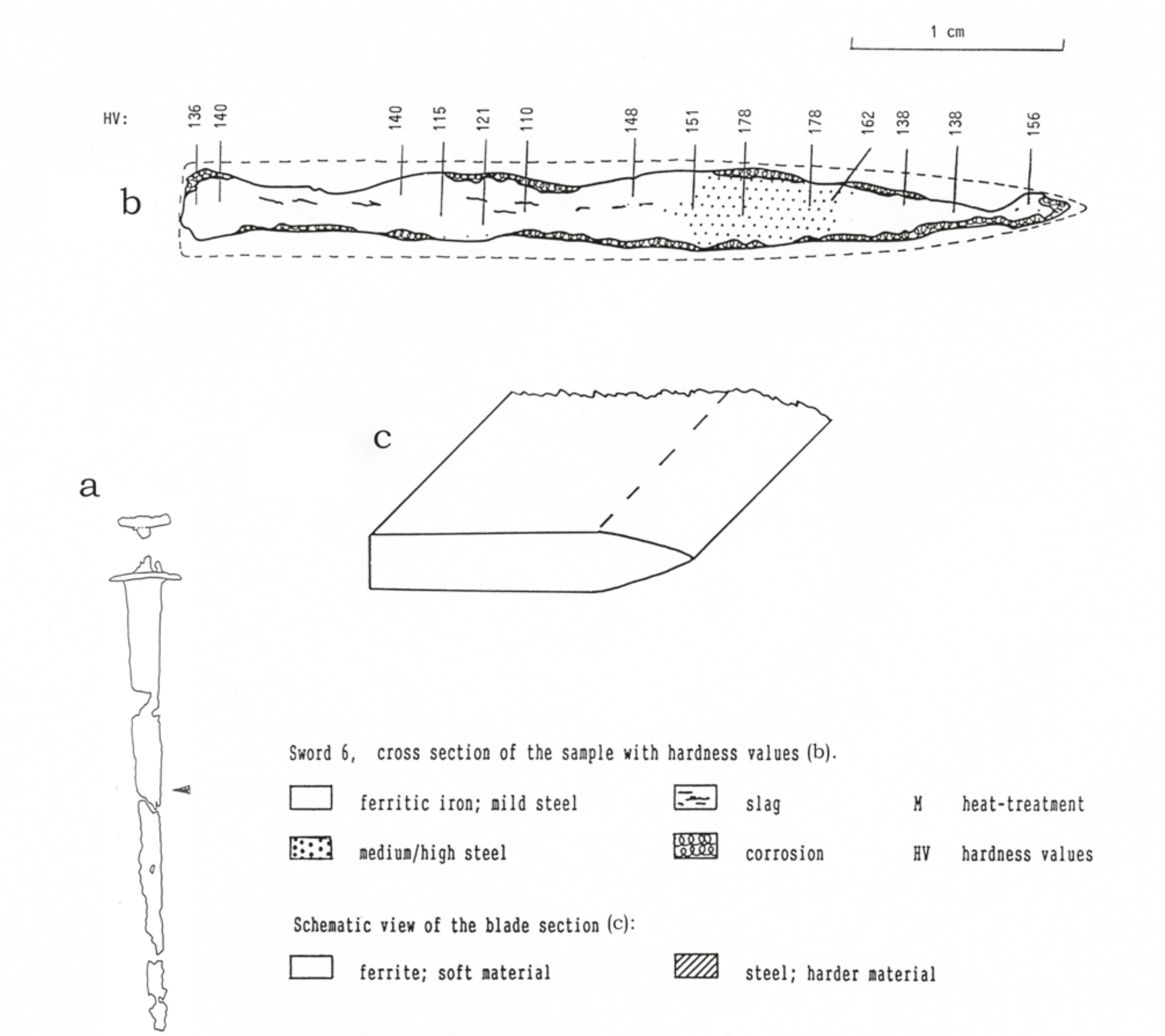


Figure 6.7a. *Sword 6. Cross-section of the sample with hardness measures (b), schematic view of the blade section (c) and outline of sword with section marked (a).*

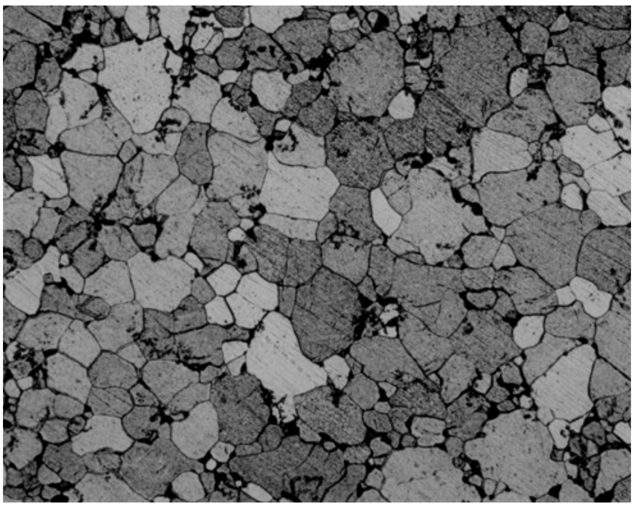


Figure 6.7b. *Sword 6. The edge has low carbon content with large grain ferrite. (200x).*

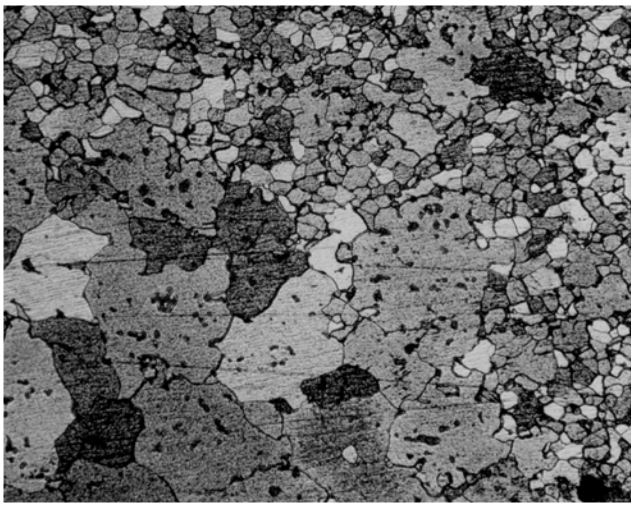


Figure 6.7c. *Sword 6. The back consists of ferrite with some pearlite showing large variations in grain size. (100x).*

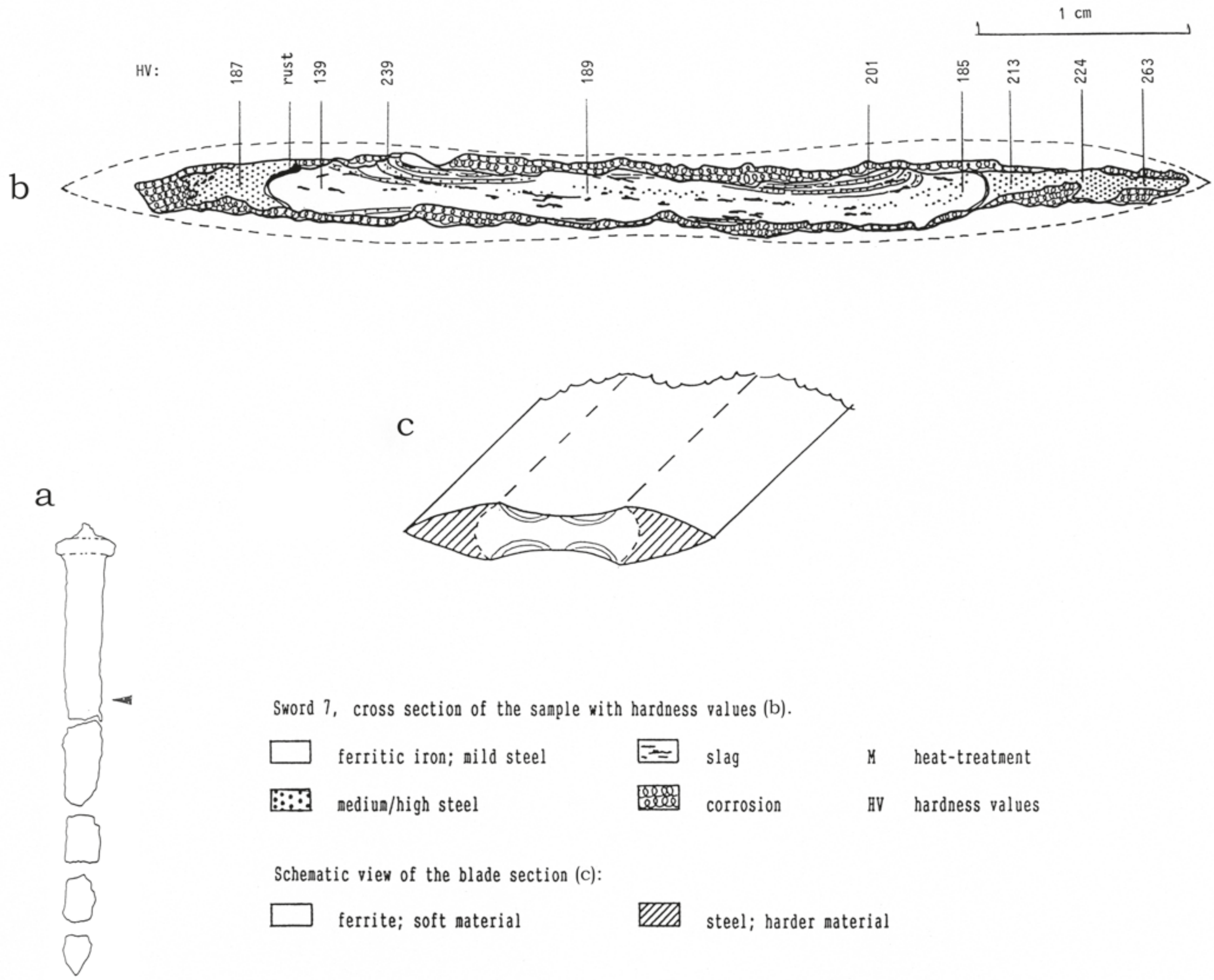


Figure 6.8a. *Sword 7. Cross-section of the sample with hardness measures (b), schematic view of the blade section (c) and outline of sword with section marked (a).*

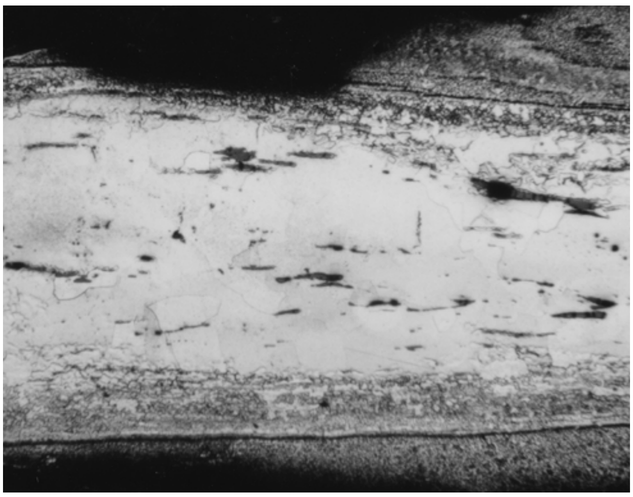


Figure 6.8b. *Sword 7. The central part has large amounts of slag inclusions. (20x).*

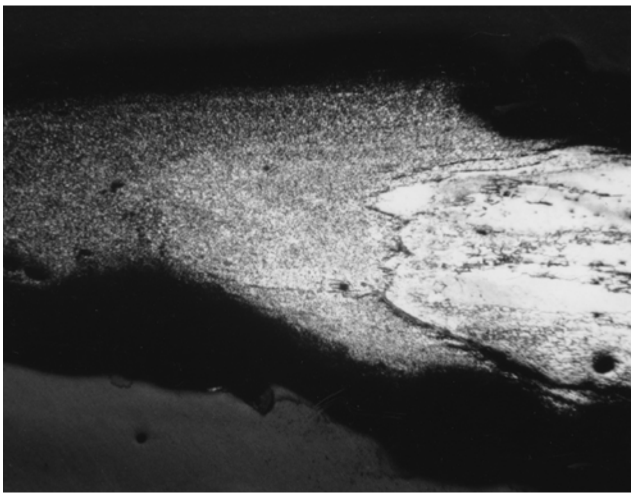


Figure 6.8c. *Sword 7. The blade is composed of a low-carbon central part (pale) onto which the cutting edges, with higher carbon content, are welded. Left part of the section. (20x).*

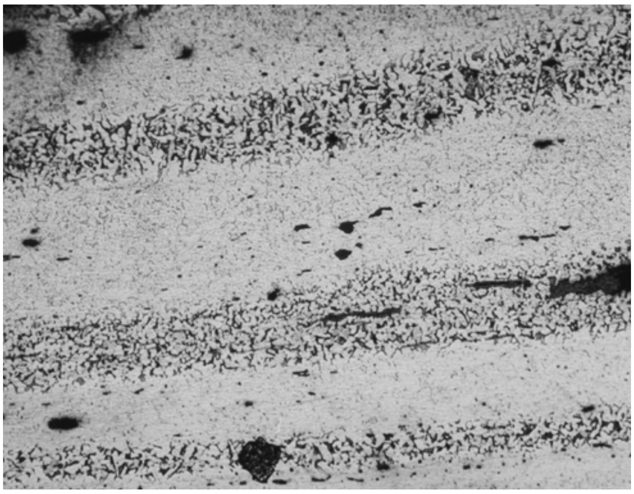


Figure 6.8d. *Sword 7. Layers of varying carbon content, representing pattern-welded sheets, run along the surfaces of the central part of the blade. (100x).*

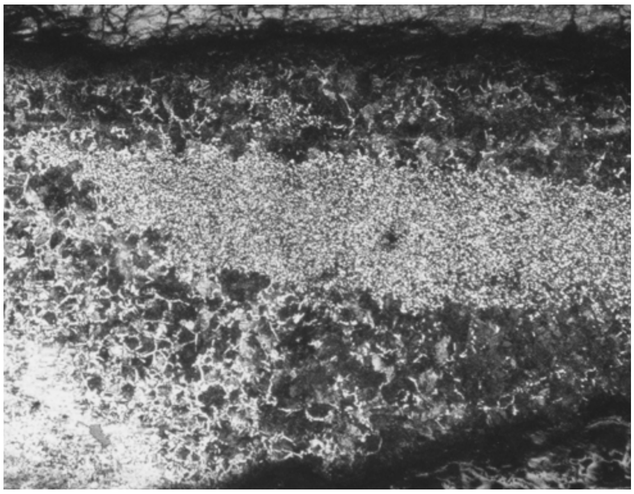


Figure 6.8e. *Sword 7. Patched structure of lamellar pearlite in the cutting edge (right edge shown). (50x).*

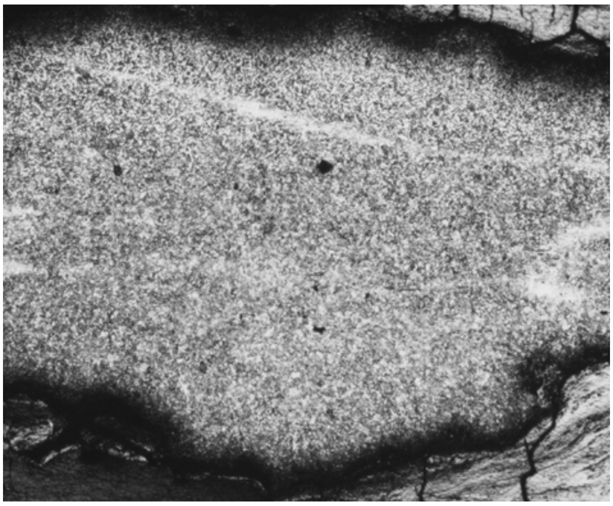


Figure 6.8f. *Sword 7. Light decarburised lines in the edge area (right part) showing welding seams between smaller pieces. (50x).*

Interpretation: The blacksmith had the skill to produce a sword with quenched steel edges, while the central part consists of a softer, more flexible material. The welding had, for the most part, been well done with only minor particles of hammer scale in the seams. This sword is considered to have been of high quality.

SWORD 10 (Museum No. C.28239, found in Mårem-Suigard, Tinn municipality)

The sword is probably a grave find, and was found together with a spearhead. The blade was broken and quite corroded – only the upper half with the hilt remains (Figure 6.11a). The sword is double-edged and has a fuller along both sides of the blade. The hilt is a late Anglo-Scandinavian type not included in Petersen's typology, by Martens named La, Figure 4.4.

The pommel and lower guard are decorated with silver ornaments in the Ringerike style (Fuglesang 1980). The hilt type is rare for Norwegian sword material, though one other item has been found at Såem, also in Tinn. Further, thin twisted silver wires remain around the grip. Stereoradiographs by Caroline Murstad (1996) revealed inlays shaped like two omega-like symbols with a cross potent in between on one side of the blade. On the reverse side a scroll or roundish symbol can be seen (Figure 6.11b). While the cross potent appears on the X-radiographs as twisted rods, a similar twist is not visible in the omega symbols or the scroll. Most likely the actual inlays in the latter two are missing, and only the prints of the inlays are left in the corroded layers of the blade. Similar designs are known from other swords (Figure 6.11c). A comparison between the present inscription and particularly those of swords 5 and 6 in Figure 6.11c, suggests that further figures could be present on the blade, next to the scroll. This was, however, not observed.

Regardless, the present sword must once have been an impressive looking weapon, though the quality of the weapon can only be judged from the metallographic structure of the blade.

Microscopic studies of the polished, unetched sample show a fair amount of small slag inclusions with a light spheroid phase, probably of wüstite FeO, in a dark matrix of silicates.

The section was easily etched with nital. The microscopic examination of the metallic structure shows that the entire blade has high carbon content, near a eutectoid concentration. The blade has a martensitic structure throughout, due to quenching (Figure 6.11d). Several welding seams are observed as light, slanting

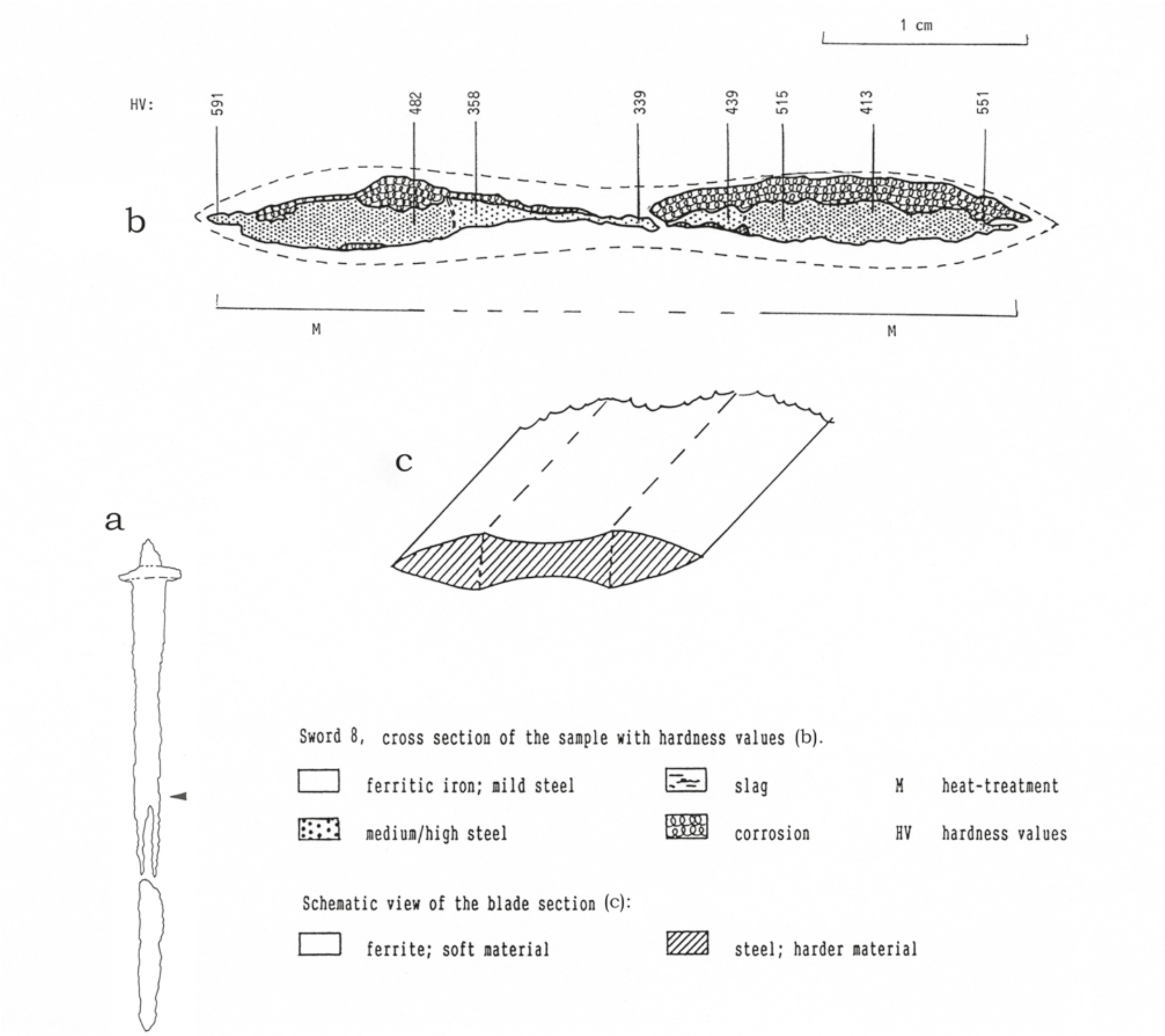


Figure 6.9a. *Sword 8. Cross-section of the sample with hardness measures (b), schematic view of the blade section (c) and outline of sword with section marked (a).*

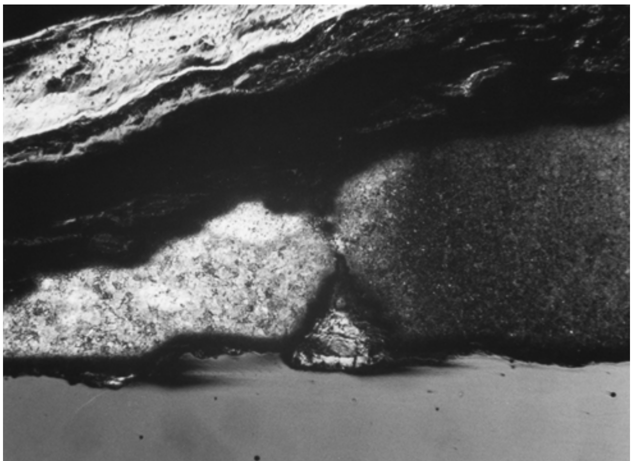


Figure 6.9b. *Sword 8. Corrosion almost separates the carbon-rich edge (right) from the less carbon-rich central part along the welding seam. (Light area top left is the surface corrosion layer). (20x).*

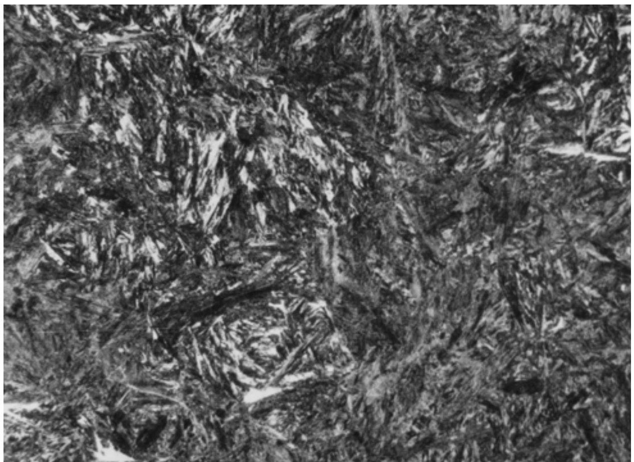


Figure 6.9c. *Sword 8. Both edges have a near eutectoid carbon concentration with a martensitic structure due to quenching. (500x).*

stripes running across the section in different places (Figure 6.11e). These lines show that the blade material is composed of several smaller pieces of carbon-rich iron. A crack, which seems to be the result of corrosion, runs through the central part (Figure 6.11a). The hardness values measured across the blade show a predominantly hard material, 636 and 446 HV were measured in the two edge areas respectively. Hardness values ranging from 515 to 571 HV were measured in the central part of the blade.

Interpretation: This fine-looking sword with a decorated hilt and inlays in the blade surface was made of carbon-rich material, which had been quenched. The material in the blade is fairly uniform with high carbon content throughout. The blacksmith mastered the technique of quenching. The edges were of excellent quality. The central part, however, must have been too hard. Blades made entirely of carbon-rich iron were not common (Tylecote 1986:2; Williams 1970:81). In the hardened state – as found here – this blade is brittle.

The blacksmith knew how to make inlays in the blade. The combination of omega symbols, scrolls and different kinds of crosses is known from other 9th –11th century swords found in England and Ireland (Lang and Ager 1989:101; Wilson 1965:42; Bruce-Mitford 1953:321; Read 1915), in Finland (Leppäaho 1964; Evison 1968) and in Russia (Kirpichnikov 1966:Figure18, 308; Stalsberg 1981) (Figure 6.11c). One of the English blades has a spiral scroll between the omega symbols and three crosses on the reverse side of the blade (Figure 6.11c, blade 5). The other English blade has a plain, equal-armed cross between the omega symbols and two transverse bars on the reverse (Figure 6.11c, blade 3). One of the Finnish swords features a cross potent between omega symbols on one side and a spiral scroll between two similar crosses on the other (Figure 6.11c, blade 6). Similar symbols can be seen on the Russian sword blade (Figure 6.11c, blade 4). A second blade found in Finland also has a cross potent between two omega symbols, while the reverse side has a different design, unlike those found on the other blades mentioned (Figure 6.11c, blade 7). The Irish blade and the third Finnish blade show very similar designs on both sides of the blade. The omega-like symbols on those blades are different from those on the other blades (Figure 6.11c, blades 1 and 2). The design on the present sword blade is most closely related to the English and the Finnish blades (Figure 6.11c, blades 5 and 6 respectively).

Normally, one would think that the elaborate design on the decorated hilt was the work of a specialised silversmith, while the steel blade with the inscriptions was more likely to have been made by a swordsmith or weaponsmith. The present sword differs from the others in this study with regard to the decoration on the hilt, its construction and composition, and the inlays in the blade. Ignoring the decorative aspects, this sword is functionally considered to have been of decent quality.

SWORD 11 (Museum No. C.26828a, found at Møli, Tinn municipality)

The sword was found in a grave together with some iron fragments and a few animal bones. The blade was broken into two pieces, but only a small part of the blade is missing (Figure 6.12a). Although the surface layers are missing due to corrosion, the sword is generally in stable condition. The blade is double-edged with a fuller running down the centre on either side. The hilt is a Q-type.

When viewed unetched, the overall slag content appears fairly low. In the left and the right parts of the section, there are a few slag bands running along the rims of small pieces of metal, which have been forged together. The central part of the blade is practically without slag. Only indistinct bands of tiny slag particles across this section indicate welding seams between the cutting edges and the core.

In the etched condition, however, welding seams are clearly seen between a low-carbon central part and the carburised edges (Figure 6.12b). The welding seams are clearly marked as pale lines. Microprobe analyses carried out in steps across the welds show that there is a considerable enrichment of cobalt (1.2wt%), and some enrichment of nickel and arsenic (0.16wt%) in the weld (Figure 6.24b). The general concentration levels of all three elements in the bulk of the material is about 0.03wt%. Phosphorus content is typically less than 0.01wt%.

The central part is mostly ferritic with small grains. The hardness values in the centre and the left parts of the core range from 152 to 162 HV. The right part of the core consists of ferrite of varying grain size. The corresponding hardness values are in the range of 104–129 HV. The ferrite crystals (Figure 6.12c) are seen to be more acicular than those observed for the more common equiaxed ferrite. Acicular ferrite is found to be superior in strength and toughness (Tither, Kewell and Frost 1971). The formation of acicular ferrite depends generally on composition, temperature and cooling rate, and was hardly intentionally produced in the Viking Age. The structure observed close to the welding seams shows that the blade had undergone prolonged heating during forging,

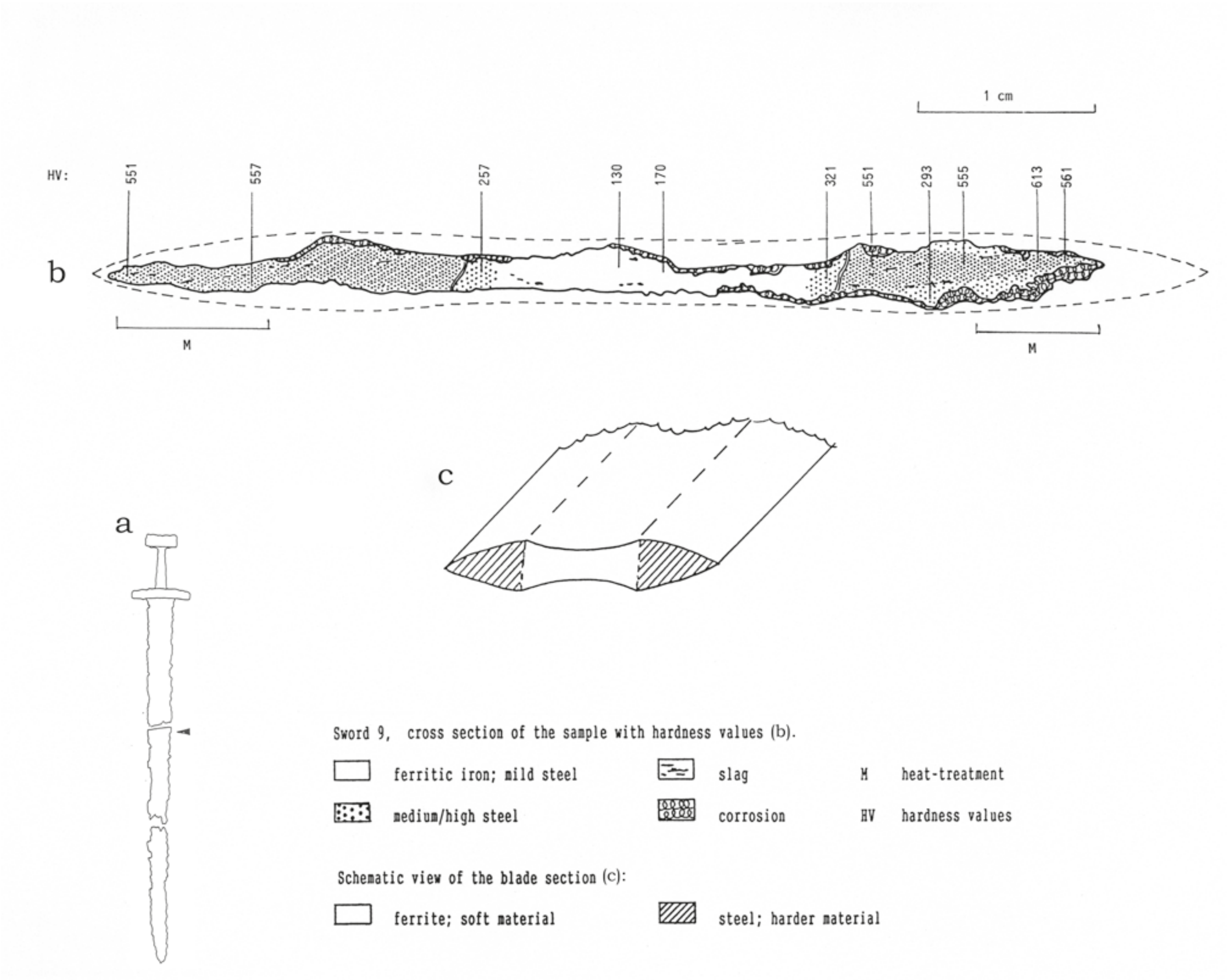


Figure 6.10a. *Sword 9. Cross-section of the sample with hardness measures (b), schematic view of the blade section (c) and outline of sword with section marked (a).*

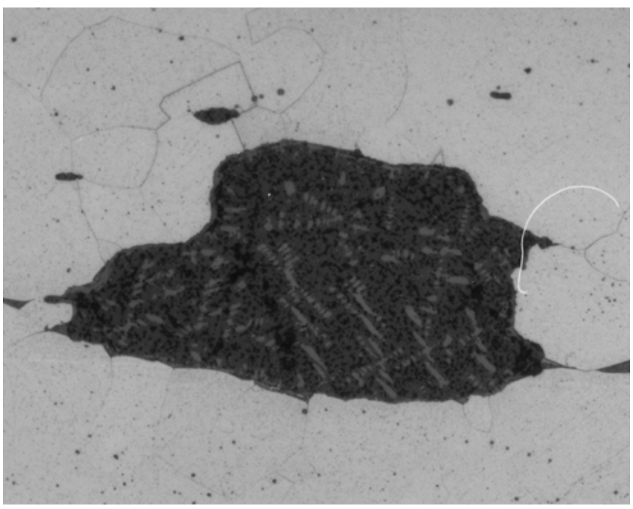


Figure 6.10b. *Sword 9. The slag consists of a light grey mostly dendritic phase (wüstite) in a dark matrix of silicates. (200x).*

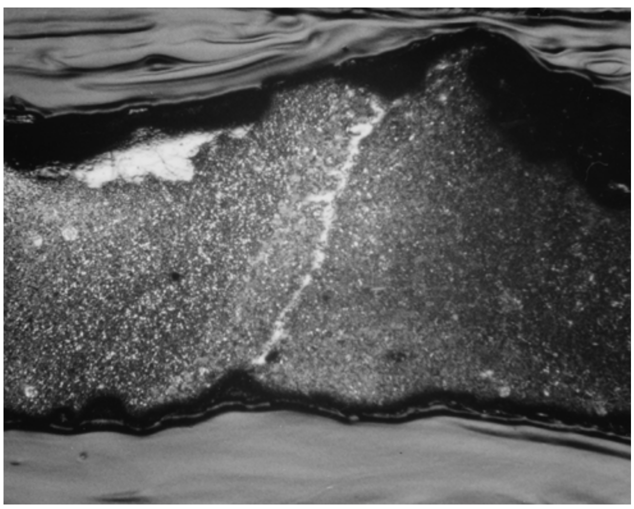


Figure 6.10c. *Sword 9. Welding seams for the edges are seen as pale decarburised lines across the sample. Right part shown. (20x).*

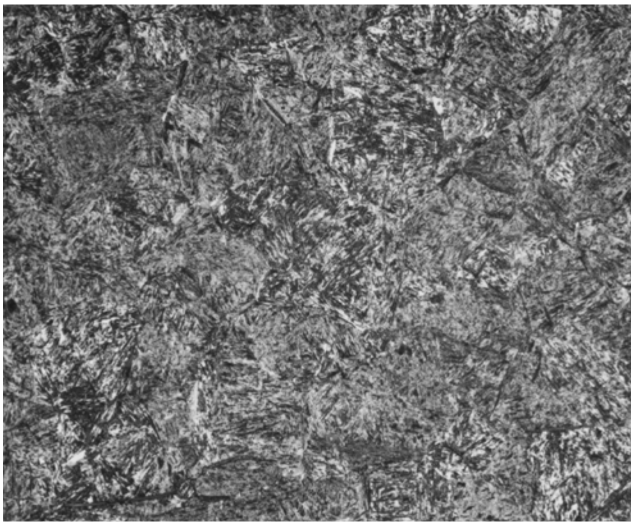


Figure 6.10d. *Sword 9. A martensitic structure in the edges due to quenching. Left part of the section shown. (200x).*

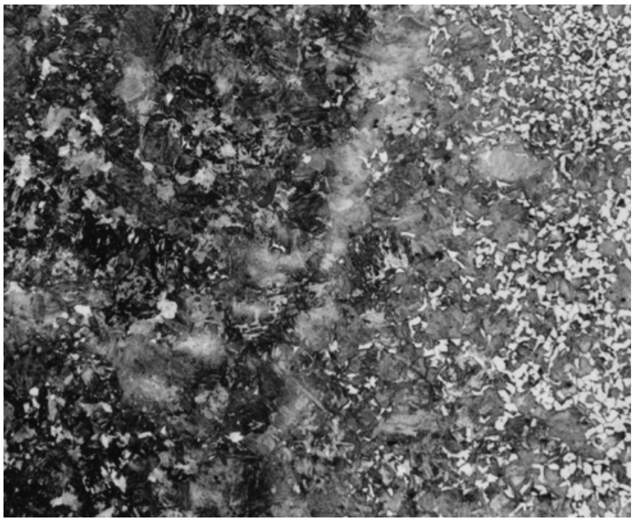


Figure 6.10e. *Sword 9. Some diffusion of carbon from the carbon-rich dark edge (dark part) across the welding seam. Left edge shown. (100x).*

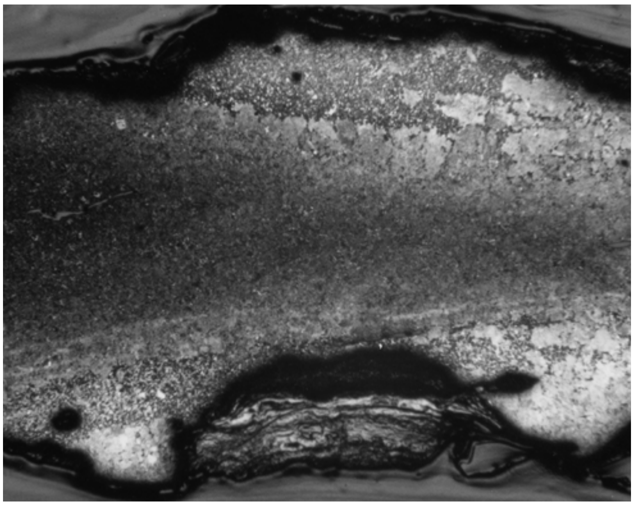


Figure 6.10f. *Sword 9. Pieces with medium carbon content have been forged onto the material in one of the edges (right). Pale welding seams are easily visible. (20x).*

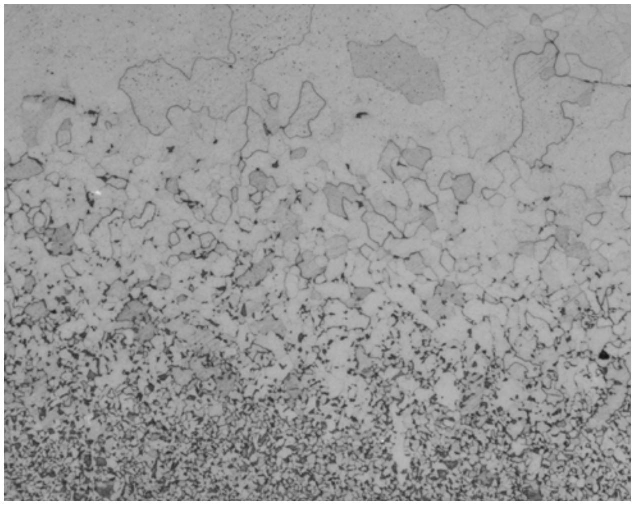


Figure 6.10g. *Sword 9. The central part is heterogeneous with some coarse-grained ferrite, and some fine-grained structure of higher carbon content. (50x)*

which caused a fairly extensive carbon diffusion across the welding junctions from the edges to the central part (Figure 6.12b). Hardness values measured in the diffusion zones along the seams are 167 and 175 HV, in the right and left part respectively.

The edge in the left part of the section (Figure 6.12a) shows mostly medium carbon content and a somewhat heterogeneous structure of ferrite and pearlite. Part of the surface area of this edge appears to have a lower carbon concentration than the rest (Figure 6.12d). Pale lines, probably oxidation enrichment bands in the welding seams, divide the lower-carbon from the more carbon-rich areas. The latter constitute the predominant part of the edge. The hardness values measured in the low-carbon area are 182 and 184 HV. In the higher carbon area, the hardness readings at three different positions are 201, 210, and 257 HV, averaging 223 HV. These hardness numbers are indicative of iron with significant carbon content quickly cooled (most likely air-cooled), but not quenched.

The edge in the right part of the sample (Figure 6.12a) appears to have a somewhat more homogeneous carbon content. The hardness values in the greater part of this edge are consistent with those in the left edge – 205, 219, 219, and 229 HV, averaging 218 HV. However, the tip of this edge shows somewhat higher hardness readings – 245-283 HV. Judging from the shapes of the remaining parts of the two edges, a significant portion of the surface layers of the left edge

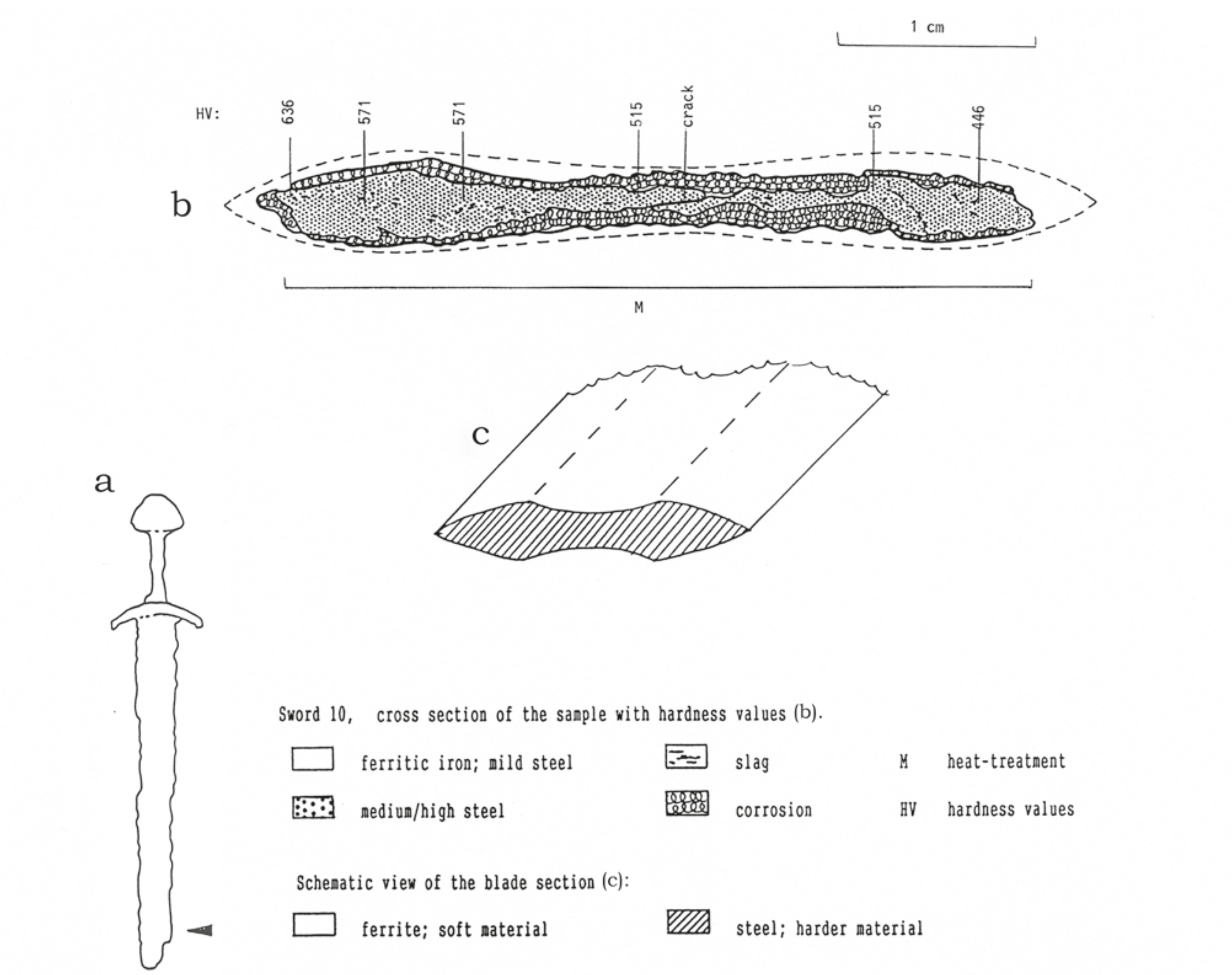


Figure 6.11a. *Sword 10. Cross-section of the sample with hardness measures (b), schematic view of the blade section (c) and outline of sword with section marked (a).*

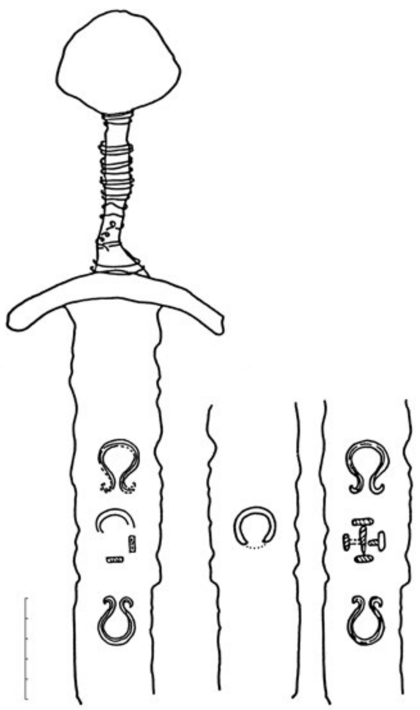


Figure 6.11b. *Sword 10. Outline of inlays in the blade as seen on stereoradiographs.*

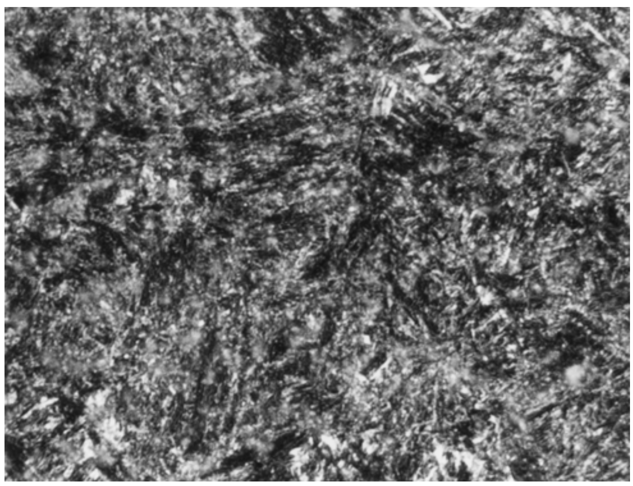


Figure 6.11d. *Sword 10. The entire blade is very hard and has a martensitic structure due to quenching. (1000x).*

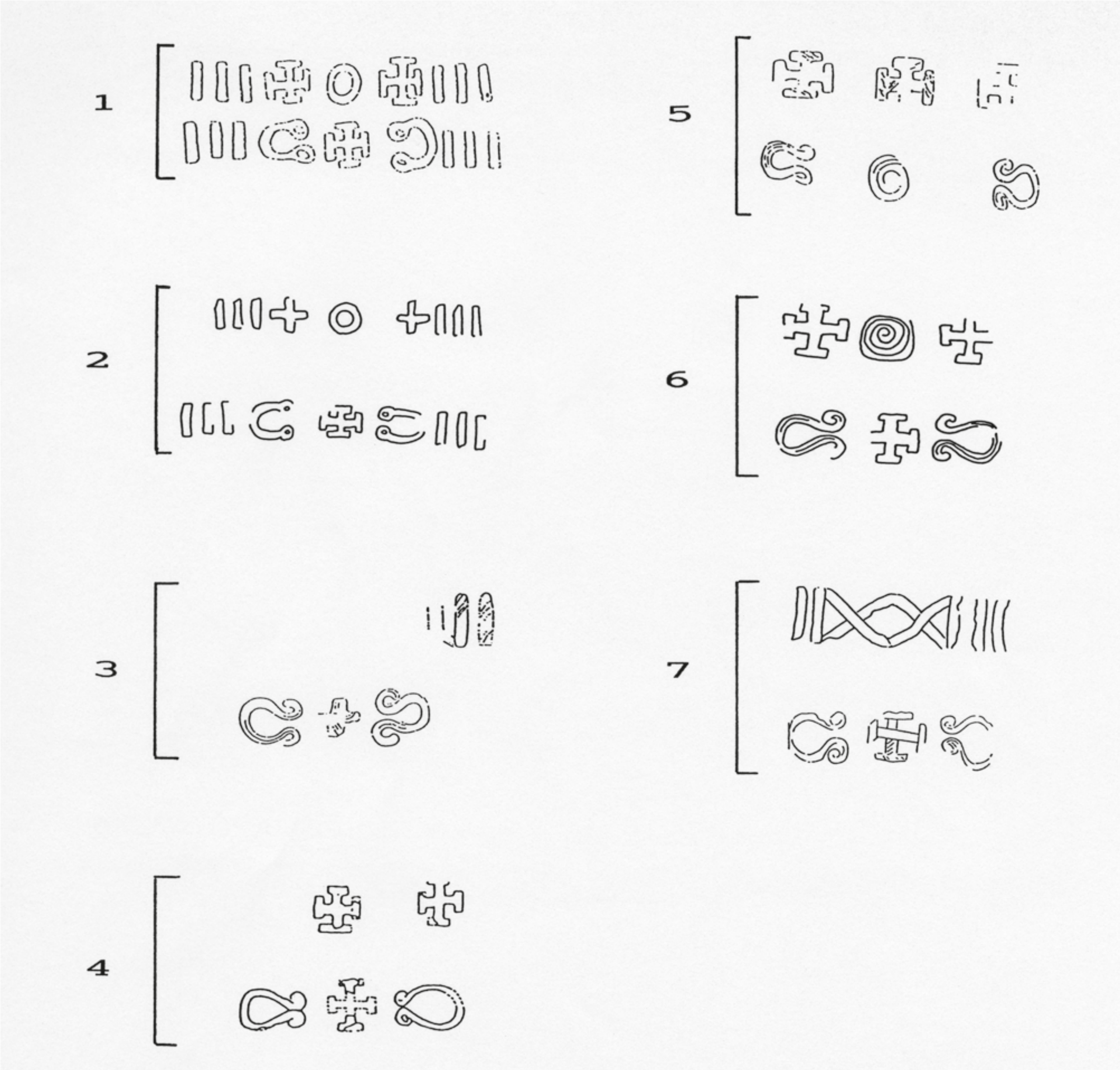


Figure 6.11c. Sword blade inlays comparable to sword 10: 1 Ireland; 2, 6, 7 Finland; 3 England; 4 Russia; 5 England.

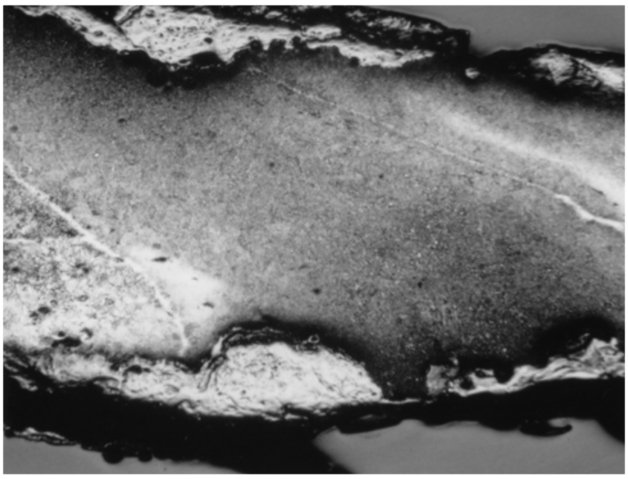


***Figure 6.11e.** Sword 10. The blade material has been made of several pieces of steel. A number of decarburised pale lines indicate the welding seams. (20x).*

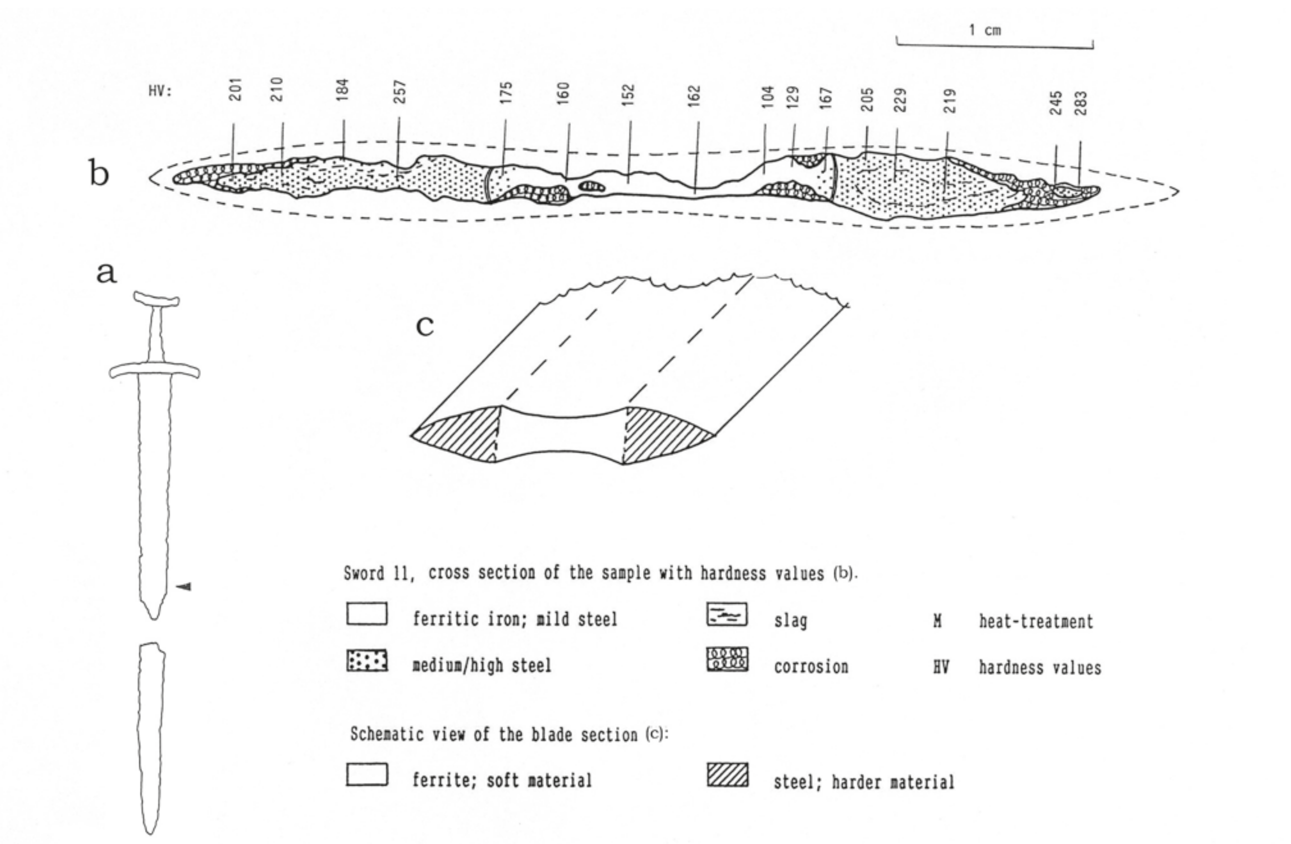
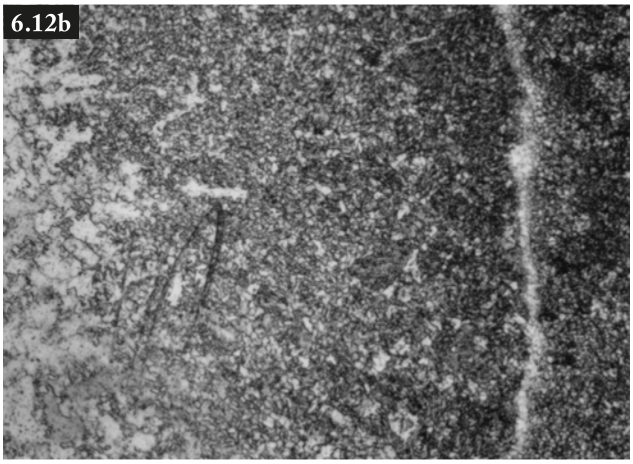


Figure 6.12a. *Sword 11. Cross-section of the sample with hardness measures (b), schematic view of the blade section (c) and outline of sword with section marked (a).*



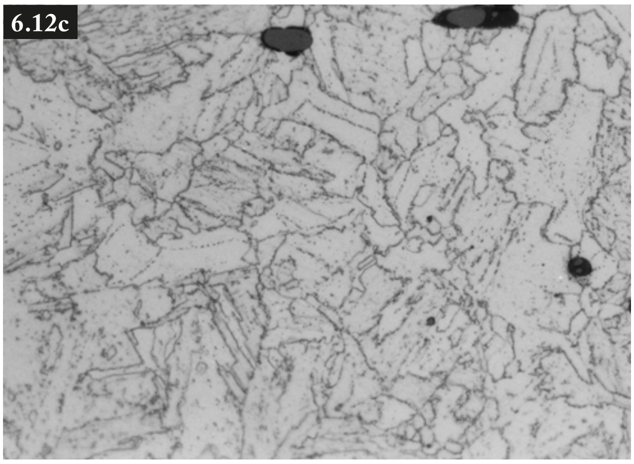


Figure 6.12b. *Sword 11. The weld- line between the core and the edge is clearly marked by a pale line. Diffusion of carbon has taken place across the weld (right edge). (100x).*

Figure 6.12c. *Sword 11. The central part is mostly ferritic with an acicular grain structure. (500x).*

Figure 6.12d. *Sword 11. The left edge with heterogeneous carbon content. Pale lines divide the lower-carbon (white) from the higher-carbon (dark) area. (100x).*

is missing. The outermost, and probably harder, parts of both cutting edges have been lost to corrosion.

Interpretation: The iron and steel materials in this sword have been worked well, with only a few slag inclusions. There are almost no slag or hammer scale particles in the welding seams. Carburised and harder edges were welded to a softer core. However, the blacksmith had not performed any quenching to obtain harder edges, possibly lacking the skill or knowledge to carry it out. Quenching and tempering would have made this sword even more serviceable. This sword is considered to have been of decent quality.

SWORD 12 and SWORD 13 were both found in Mårem, Tinn municipality, in a grave where two spearheads, two axe heads, a sickle, 21 arrowheads, two knife blades, a fire steel and some iron fragments, were also found. Further, some glass beads and a slate whetstone were found in the same grave. The types and number of artefacts in the find suggest that it may represent two burials in the same grave.

SWORD 12 (Museum No.C.29700a)

The sword (Figure 6.13a), which is double-edged, was extremely corroded. The fuller was corroded right through. The section taken for examination broke into two fragments when cut from the blade (Figure 6.13a). The core, as well as the tip of the edges, consists entirely of corrosion products. The hilt is categorised as an Xa-type.

Examination of the polished, unetched sample shows very large amounts of slag inclusions (Figure 6.13b). The slag is partly elongated, consisting mostly of silicates, entirely from corrosion products. The blade was broken, and the point missing.

The sample was not easily etched with nital, indicating that the carbon concentration is low. The whole sample is ferritic (Figure 6.13c) with a mixture of large and small grains. Etching with Oberhoffer's reagent indicates that phosphorus is present throughout the section. Microprobe analyses confirm that phosphorus content is somewhat variable, but mostly at an elevated level of 0.15wt%. This accounts for the comparatively high hardness values measured in the sample (153-178 HV, Figure 15/1), which are greater than expected for ferritic iron.

There is no evidence of pearlite in the micrographs. An attempt to carburise the material would have been hampered by the high phosphorous content. Generally, an increase in carbon content is most easily obtained in the austenitic phase of iron, where carbon dissolves tolerably well. However, if phosphorus is present, this will inhibit the iron from forming austenite, and only small amounts of carbon will dissolve.

Interpretation: If the blacksmith intended to carburise this sword, he was unfortunate in his choice of raw material, which contained too much phosphorus. Consequently, he would not have been able to introduce significant amounts of carbon. The choice of a phosphorus-containing raw material could also have been deliberate, as this makes the ferritic iron harder. The hardness values in this blade can be explained by the presence of considerable amounts of phosphorus. The substantial amount of slag indicates an unskilled smith, who probably did not know how to work the material, nor how to make a serviceable weapon. Due to the high phosphorus concentration and pronounced slag content, the blade was too weak and brittle to be classified as a good sword. This sword is considered to have been of poor quality.

SWORD 13 (Museum No. C.29700b)

The sword is double-edged with a fuller along each side of the blade, which was severely corroded. The actual point is missing (Figure 6.14a). Only part of the section, mainly the central part, still contains metallic iron. The sword is considered to have an Xa-type hilt.

Microscopic examination of the polished, unetched sample shows some flat slag, hammer scale inclusions and strings of slag particles, probably trapped in welding seams between pieces of iron. The slag consists of a light grey spheroid phase, probably wüstite, in a dark matrix of iron silicates.

After etching with nital, high carbon concentrations were observed along the remaining surfaces in parts of the blade (Figure 6.14b). The structure of the carbon-rich surface layers shows that the sword was quenched (Figure 6.14c). A mixture of martensite, bainite and pearlite indicates that the blade was not fully quenched. The hardness measurements in the carburised areas vary from 283 to 413 HV (Figure 6.14a), depending on the heterogeneous nature of the carburisation and the incomplete quenching. Carbon content shows a distinct drop between the surface layers and the core of the blade (Figure 6.14d). The core is made from almost pure ferrite or bloomery iron, which corresponds to the low hardness measurements ranging from 96 to 140 HV in the ferritic area (Figure 6.14e). This suggests that the iron is practically without phosphorus. The lack of phosphorus was confirmed by examining the structure after etching with Oberhoffer's reagent.

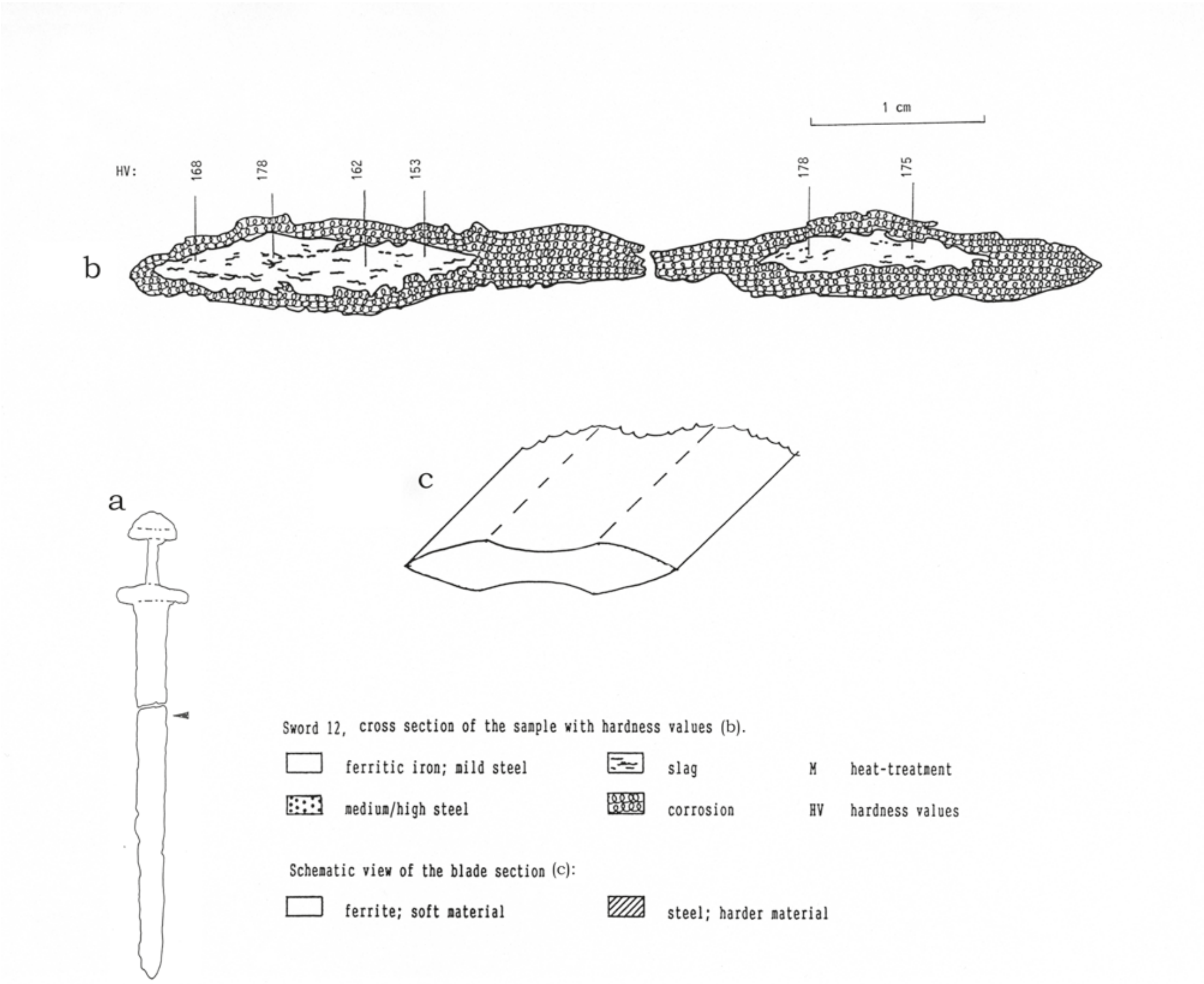


Figure 6.13a. *Sword 12. Cross-section of the sample with hardness measures (b), schematic view of the blade section (c) and outline of sword with section marked (a).*

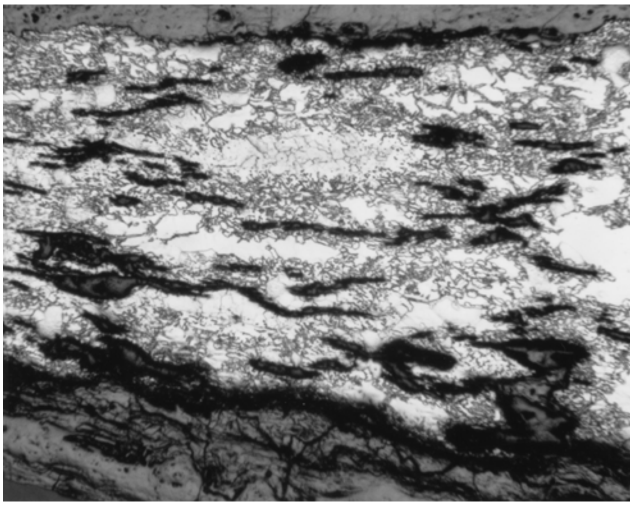


Figure 6.13b. *Sword 12. Large amounts of slag inclusions in most of the section. (20x).*

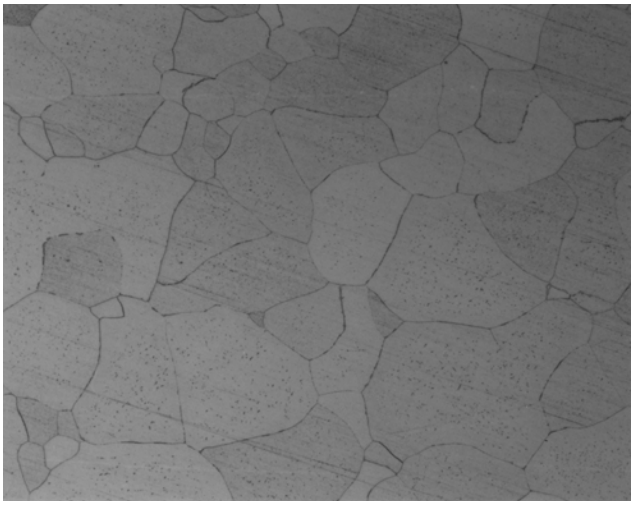


Figure 6.13c. *Sword 12. The entire sample consists mostly of pure ferrite. (200x).*

Interpretation: Although only a small part of the transverse section of the blade remains uncorroded, it may be assumed that this sword has been forged from a low-carbon material reinforced with a thin carburised surface layer. A distinct change in carbon concentration and strings of hammer scale particles in the transition zone point to a pre-made steel sheet welded onto an iron core. The blade has been quenched, but not fast enough to produce an all-martensite structure, which would have been harder and more brittle. Because the edges were lost to corrosion it is not possible to determine their quality. Judging from the scanty remains the sword was probably of decent quality.

SWORD 14 (Museum No. C.23364, found at Bøen in Dal parish, Tinn municipality)

The sword appeared during construction work. The blade was broken into two pieces, which represent more or less the complete blade (Figure 6.15a). The sword was in a fairly good state of conservation. The blade is double-edged with a fuller along each side. The hilt is an Xa-type from the late 10th century.

Examination of the polished, unetched section shows numerous small, mostly roundish slag and hammer scale particles running in parallel, wavy bands along the main axis of the section. There are also a few larger slag inclusions.

After etching in nital, the section appears to have a wavy structure of layers of low carbon content of somewhat different grain sizes running from edge to edge, suggesting that the blade material is composed of many sheets of similar composition welded together.

There is no indication of welded-on edges or any other welding seams across the section. Although parts of the blade surface are missing due to corrosion, the remaining surfaces on both sides of the blade appear to have dark etched layers of pronounced higher carbon content than the core. The core shows a mild steeled structure of ferrite and some pearlite, the hardness values being in the range of 151, 162, 169, 187 HV (Figure 6.15a). The welds between the high-carbon surface layers and the lower carbon core area are well indicated by bands of hammer scale inclusions (Figure 6.15b). This indicates that sheets of carbon-rich steel were welded onto the surface of the less carbon-rich core.

Both cutting edges show high carbon content. The edges show a martensitic structure (Figure 6.15c) due to heat treatment, the hardness values being 356, 371, 402, 420 HV. The carburised areas further away from the edges have the structure of martensite and bainite (Figure 6.15d), indicative of an insufficient cooling rate for a full quench, possibly deliberately so. The somewhat acicular nature of the ferrite in the pearlite areas also indicates relatively fast cooling, but the partly spheroidised ferrite near the centre may point to some self-annealing.

Interpretation: This sword has hardened steel edges and a core made from a layered material of low carbon content. A distinct gradient between the low-carbon core and the high-carbon surface suggests that a carbon-rich steel sheet had been welded onto the core. The blacksmith knew how to quench the steel. The low-carbon core had been worked competently, and the welding seams between the layers were done well. The slag and hammer scale particles are mostly small, resulting in no particular weak points in the material. This sword is considered to have been of decent quality.

SWORD 15 (Museum No. C.25111a, found at Rauland farm, in Vinje municipality)

The sword is a grave find, found together with the lower hilt and a fragment of another sword, two axe heads, five arrowheads, a knife blade, an iron bell, and three iron fragments. Judging from these finds, it seems reasonable to assume that the objects belong to two different burials in the same mound. Despite a corroded surface, the sword was in fairly good condition. The blade was broken into two pieces, which represent most of the weapon (Figure 6.16a). There is a fuller along each side of the blade, which is double-edged. The sword has a Q-type hilt.

Unetched, the slag content appears to be very low in the central part of the blade, and only some short ribbons of small slag inclusions, some flattened and some spheroid, were observed in the edge areas. A distinct crack is found in the edge area in the left part of the section (Figure 6.16a).

Etching of the section with nital reveals pronounced welding seams between the edges and the central part (Figure 6.16b). The two welds run as pale bands across the section, enriched with cobalt and arsenic. Microprobe analyses show an enrichment of cobalt from about 0.04wt% in the bulk of the material to about 1.0wt% in the welds. The enrichment of arsenic is somewhat less, from 0.04wt% to 0.7wt%. There is only a slight enrichment of nickel in the weld. The content of phosphorus is mostly low, around 0.01wt% (Figure 6.24a).

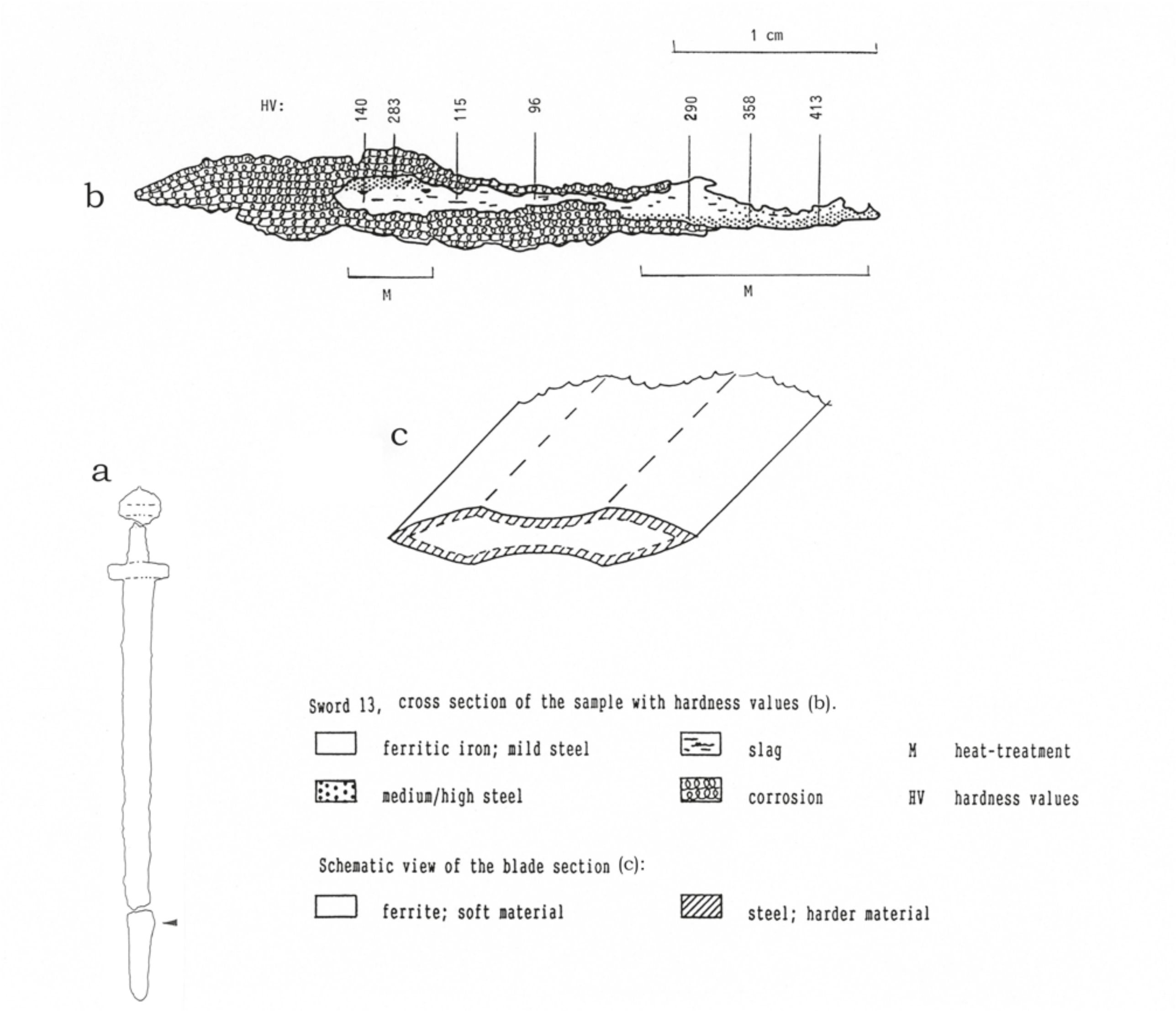


Figure 6.14a. *Sword 13. Cross-section of the sample with hardness measures (b), schematic view of the blade section (c) and outline of sword with section marked (a).*

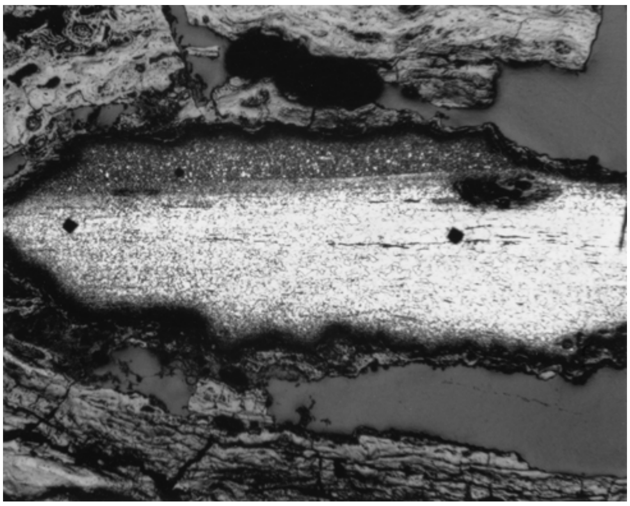


Figure 6.14b. *Sword 13. The blade has a surface layer of high carbon content and a mostly ferritic core. (Grayish corrosion products detached from the blade surface. Hardness impressions shown as two dark spots). (20x).*

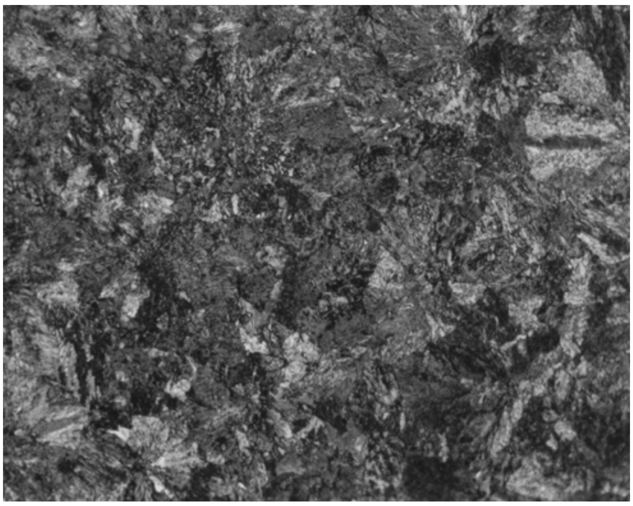


Figure 6.14c. *Sword 13. The carbon-rich area along the central part of the blade shows a mixture of martensite and bainite/pearlite, indicating incomplete quenching. (500x).*

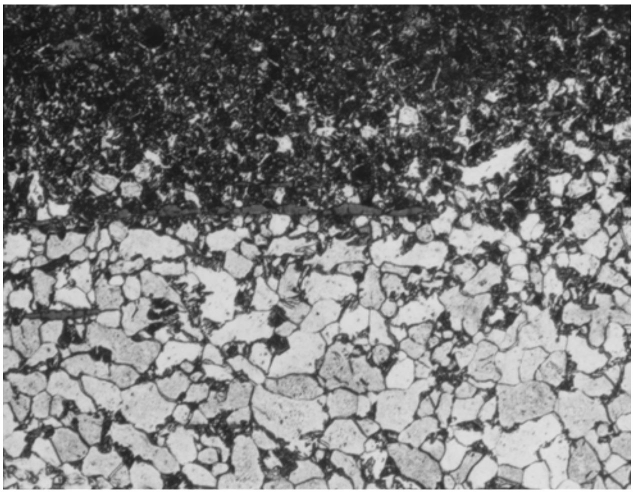


Figure 6.14d. *Sword 13. The carbon content shows a distinct drop between the surface and the core. A number of small hammer scale particles (grey) suggest a welding seam. (200x).*

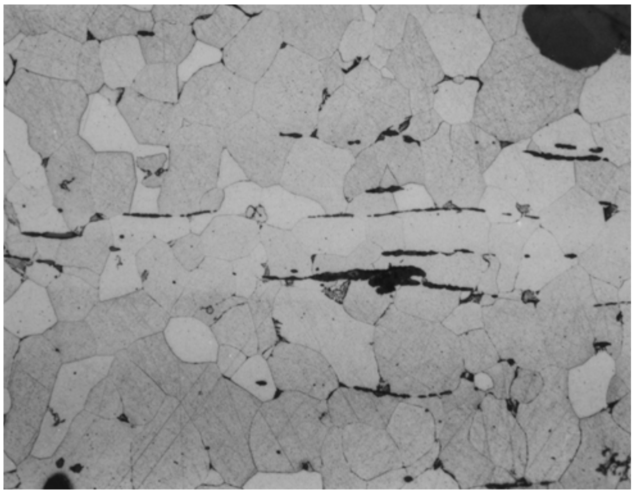


Figure 6.14e. *Sword 13. The core is mostly ferritic. (200x).*

The central part is largely composed of pure ferrite of mostly small grain sizes (Figure 6.16c). The hardness values are 86 and 91 HV, typical of a soft, fairly pure wrought iron. The zones close to the welding seams have slightly higher carbon concentrations. The hardness readings in the central part close to both welds are 119 HV. A small area with hardness values of 136 HV was observed in the core close to the weld for the right edge (Figure 6.16a). This piece was probably forged into the material unintentionally, or it is due to heterogeneous bloomery iron. This is probably also the case for a smaller piece in the middle of the core.

The material in the edges is composed of several pieces of fairly pure ferrite and mildly carburised iron. The highest carbon contents were observed in the actual cutting edges. The tip of the left edge has hardness values of 138 and 153 HV, and a structure of ferrite with some lamellar pearlite (Figure 6.16d). The major part of this edge area has a low and somewhat heterogeneous carbon content and some variation in grain sizes (Figure 6.16e), corresponding to hardness values in the range of 108–125 HV. A pronounced crack in the middle of this edge area may, to some extent, have formed a weak part of the blade.

The right edge shows mostly small grain ferrite with some pearlite. The hardness values range from 110 to 121 HV, about the same carbon concentration found in the left edge. The hardness values measured at the tip of this edge average 136 HV, which also corresponds quite well to the left edge.

Interpretation: It seems that the blacksmith knew the importance of having a soft, flexible central part and carburised harder edges in order to make a good sword. However, in the present sword the core would have been too soft and pliable, and the carbon content in the cutting edges only slightly higher than in the core. This sword would have been prone to bending in combat. It is possible that some decarburisation took place while welding the edges onto the core. There are no indications of quenching. Although some carburised iron is observed at the edges and the intention of the smith may have been the best, this sword is made up of materials too soft to make a quality sword blade. However, the blade shows good welding with very few hammer scale inclusions. This sword is considered to have been of poor quality.

SWORD 16 (Museum No. C.21325a, found in Killingtveit, Vinje municipality).

This sword was found under a large stone heap, probably a burial cairn, together with an axe head and an adze. The preserved part of the sword consists of the hilt and a small part of the upper blade (Figure 6.17a). The surface of the sword was very corroded. The blade is double-edged and has a fuller along the centre on each side. The hilt is an H-type. A close look at the blade surface indicates vague remains of inlays on both sides. This is confirmed by X-radiographs. However, there is so little left of the inlays that the reconstruction (drawing) is uncertain.

The unetched section shows mostly low slag content, except for a few small parallel slag bands along the axis of the sample, and some major slag inclusions in the welds for the inlaid designs observed in the blade surface (see below) (Figure 6.17a).

After etching with nital, the cross-sections of three inlays, two on one side and one on the other, are clearly defined (Figure 6.17b). There are no indications of

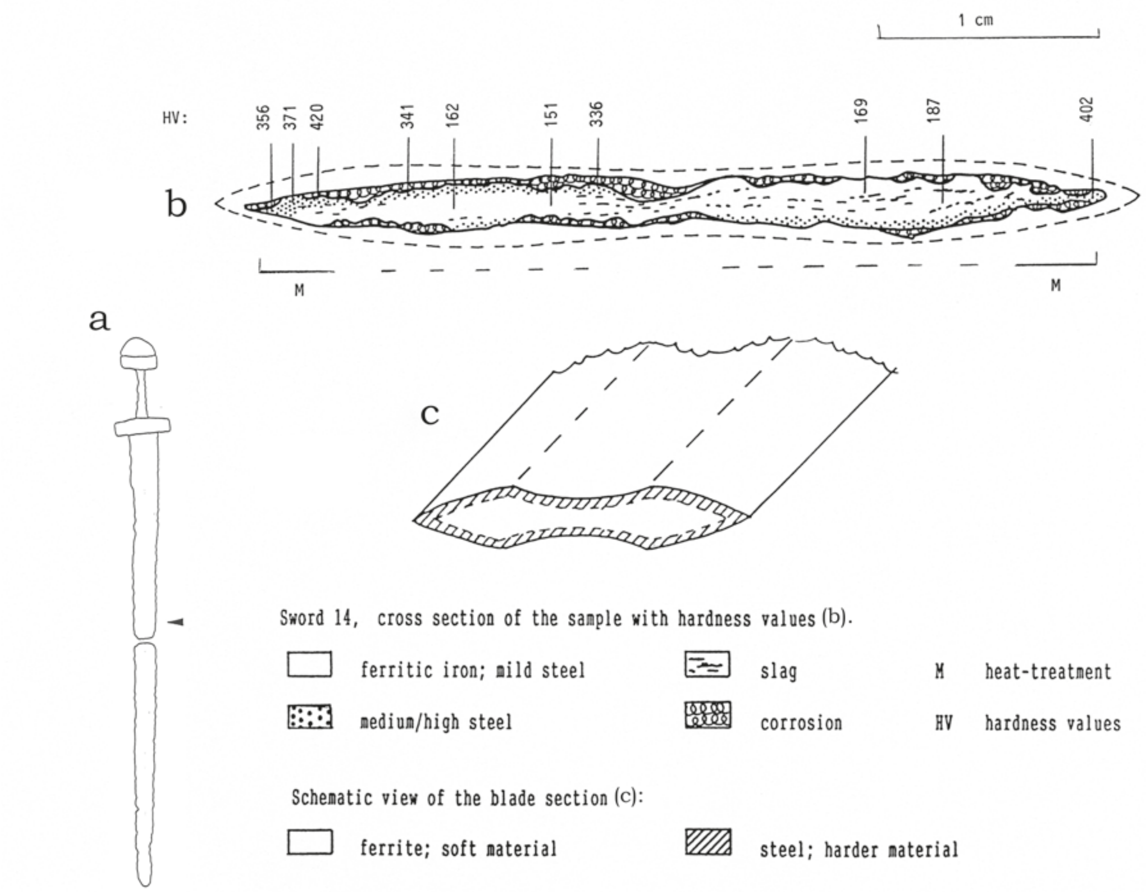
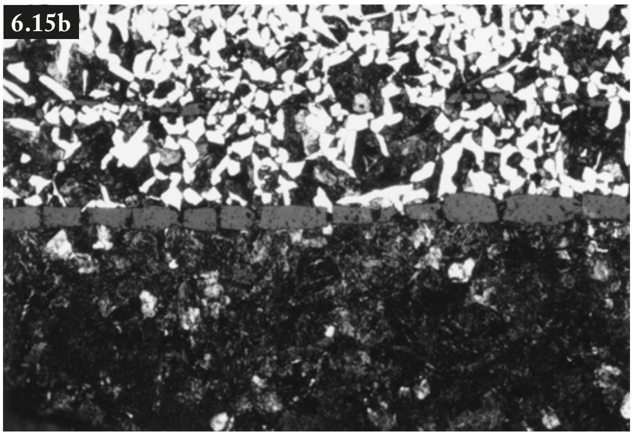
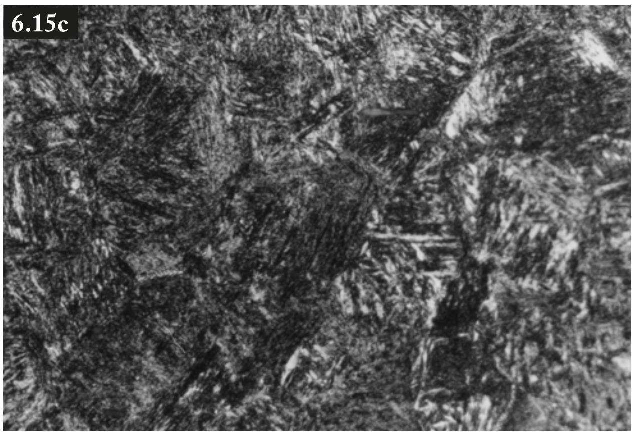


Figure 6.15a. *Sword 14. Cross-section of the sample with hardness measures (b), schematic view of the blade section (c) and outline of sword with section marked (a).*





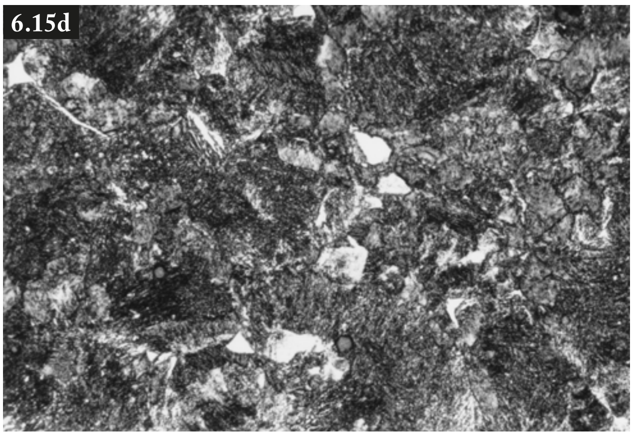


Figure 6.15b. *Sword 14. A carbon-rich steel layer has been welded onto a low-to-medium steel core. The welds are marked by slag bands. (200x).*

Figure 6.15c. *Sword 14. Both cutting edges show a martensitic structure due to quenching. (500x).*

Figure 6.15d. *Sword 14. The structure of the carbon-rich surface areas along the center of the blade indicate some heat treatment. (500x).*

welded-on edges of a harder material. Apart from the inlays, the structure of the entire section is almost pure ferrite (Figure 6.17c). Hardness values typically range from 103 to 143 HV, showing a soft material. The remaining outer part of the left edge, also of a ferritic structure, shows a slightly harder material – 153, 162, 165 HV, averaging 160 HV, possibly due to the elemental composition. The hardness values of the right edge average 119 HV. There is no indication of cold-working the edges. Large parts of both edges seem to have been lost as a result of corrosion.

The three inlays observed in the section show the cross-sections of a twisted structure of alternating layers of large grain ferrite and a darker, smaller grain low-carbon pearlite (Figures 6.17d). Etching with Oberhoffer's reagent (Figure 6.17e) reveals that the ferritic part of the inlays contains phosphorus, while a major part of the ferritic blade material is practically without it. Microprobe analyses of the different layers of the inlays show the phosphorus content in the ferritic layers to be about 0.25wt%, while that in the low-carbon layers is about 0.05wt%. The phosphorus content in the blade material is only 0.01wt% (Figure 6.25). Hardness measurements in the ferritic layers are 143, 162 and 171 HV in the three inlays respectively, while the carburised parts of the inlays show values between 189 and 193 HV. The inlays were produced by first twisting together a number of thin wires of low-carbon iron and phosphorus-containing iron. Then the composite wires were shaped into the preferred designs before they were placed, along with flux, on the surface of the already hot and consequently softer blade. A further heating, followed by hammer welding, would flatten and push the wire inlay into the blade surface at the same time as the metal surfaces bonded together. This technique has been shown by Kasper Andresen (1993) to be relatively easy to carry out and did not demand chased channels in the sword blades to hold the inlays, nor a punch to drive them into position (East, Larkin and Winsor 1985; Lang and Ager 1989:101). By hammer welding the inlays into the blade, the shape of their cross-sections has been somewhat distorted and flattened.

Interpretation: The material throughout the section of this sword is too soft. The edges would not last in battle and the blade would be easily bent. This once visually wonderful sword with inlays along the blade seems to have been designed and valued more as a prestige weapon than for its usefulness in combat. According to reconstructions, the forging of inlays is not particularly difficult to accomplish and does not prove outstanding skill. So, if the blacksmith had the skill to produce a high-quality weapon, he has certainly not exhibited that skill in this sword. Nevertheless, the inlays of mild steel and phosphorus-rich iron, in order to improve the appearance, indicate that the blacksmith had adequate knowledge of the materials. Most likely the simple blade was intentionally made in that manner in order to save steel and elaborate work. (See Chapter 7: The Hedesunda sword.) This sword is considered to have been of poor functional quality if used as a weapon in combat.

SWORD 17 (Museum No. C.23018a, found in Åkre, Tokke municipality)

The sword was found in a grave together with a spearhead, an axe head and a fragment of another axe head, a flat iron ring and an oval bronze brooch. The blade is double-edged and has a fuller along both sides. The sword was broken into two parts at about the middle of the blade (Figure 6.18a). The blade was very corroded, particularly in the area where it was broken. Due to corrosion, part of the blade is split along the fuller. Moreover, a large part of at least one of the edges has been lost (Figure 6.18a). The hilt is a Q-type.

Examination of the section before etching shows traces of hammer scale bands across the blade. This indicates welded-on edges. Only a few slag particles were observed in the central part. In the left part of the section (Figure 6.18a), there are some slag inclusions, particularly in the more carbon-rich areas. In the right part slag particles are abundant except in the outer tip.

After etching with nital, the section appears to have carburised cutting edges welded onto the central part. Both welding seams for the edges are clearly marked as light, decarburised lines across the section. Microprobe analyses carried out stepwise across the welding seam show a significant enrichment of cobalt from about 0.02wt% in the body of the blade to almost 0.5wt% in the weld, and only a minor enrichment of arsenic from c. 0.02wt% to 0.07wt% (Figure 6.24c).

The structure of the central part of the sword has mostly small grains and low carbon content (Figure 6.18b). Hardness measurements show an average value of 131 HV. Exceptions are the areas along the welding seams for the edges, where some diffusion of carbon across the welds has taken place (153, 164 HV). Also, in the thinner part of the core, a small piece of higher carbon content seems to have accidentally ended up in the core material.

Both edge areas are composed of several pieces of mild to medium carburised iron. The structure in the tip of the cutting edge in the left part of the section

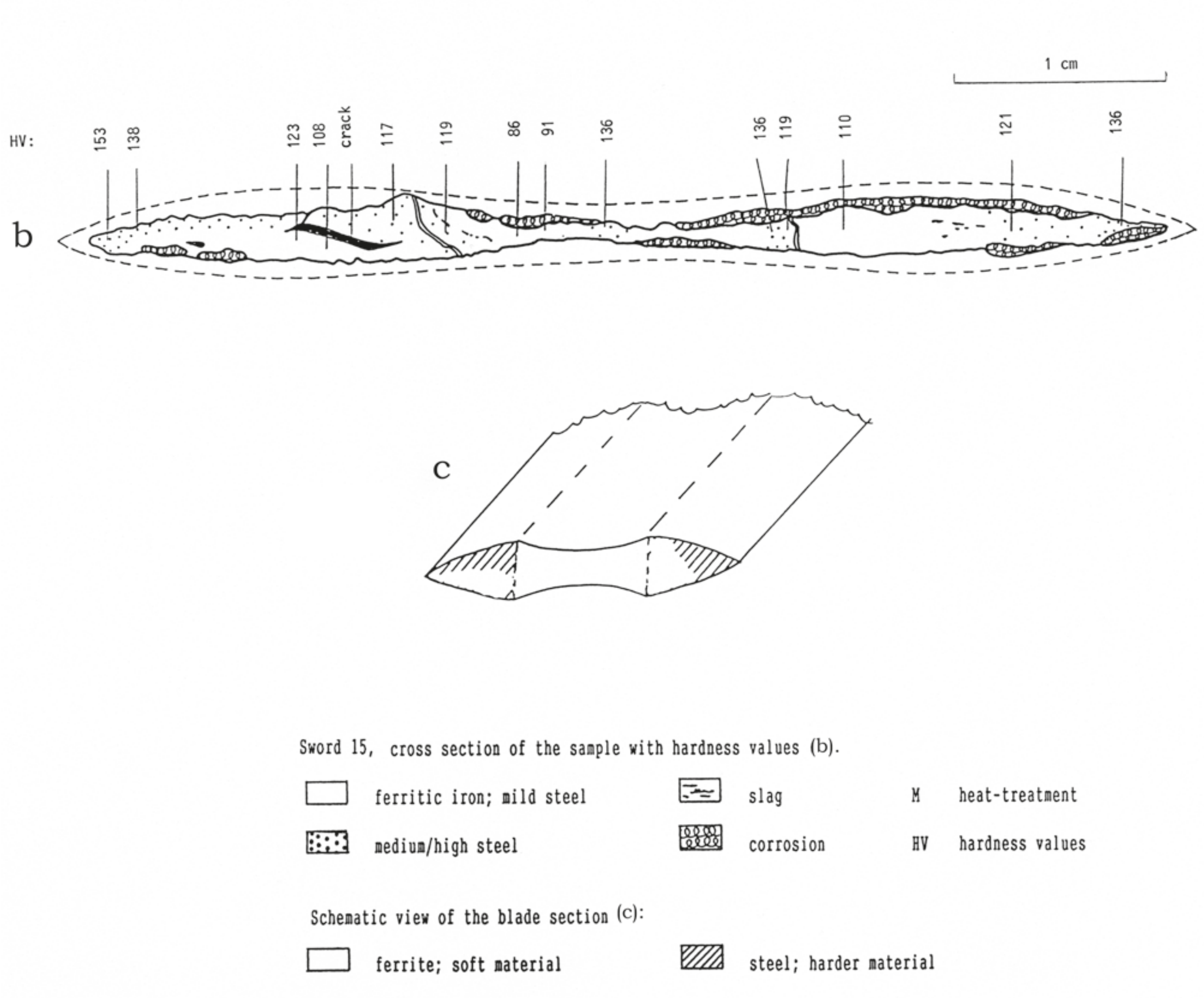


Figure 6.16a. *Sword 15. Cross-section of the sample with hardness measures (b) and schematic view of the blade section (c).*

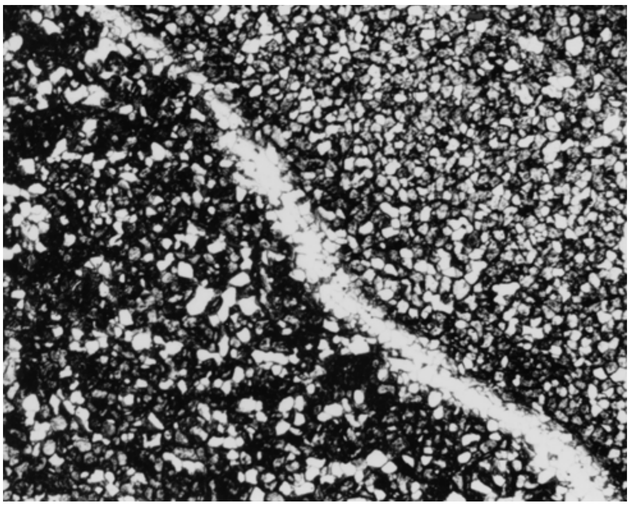


Figure 6.16b. *Sword 15. Pale bands across the section indicate welding seams between the central part and the edges. (100x).*

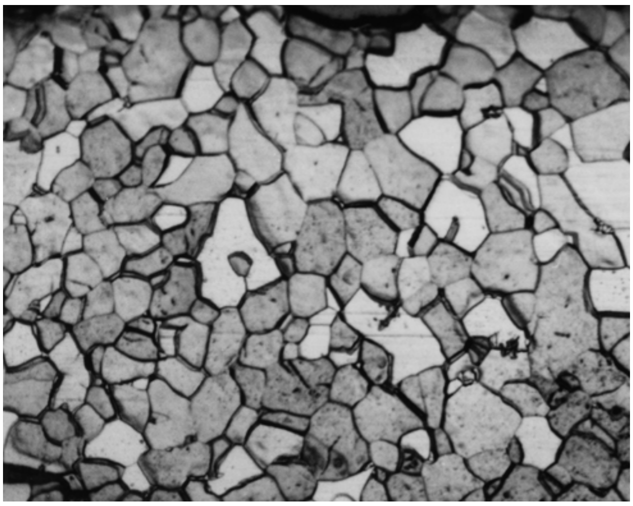


Figure 6.16c. *Sword 15. The core consists mostly of pure ferrite. (200x).*

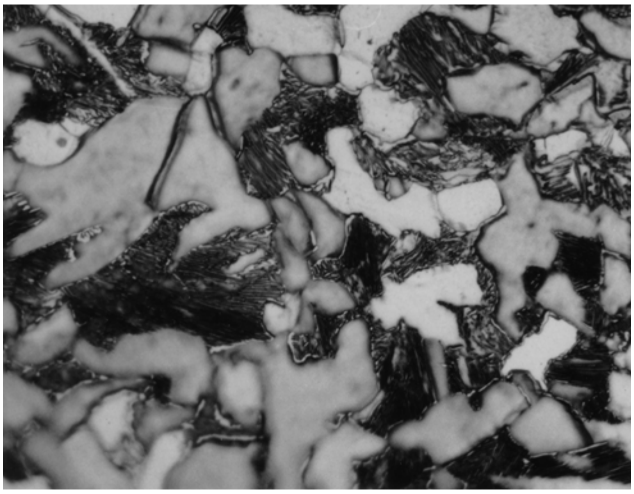


Figure 6.16d. *Sword 15. The tip of the left cutting edge with lamellar pearlite. (500x).*

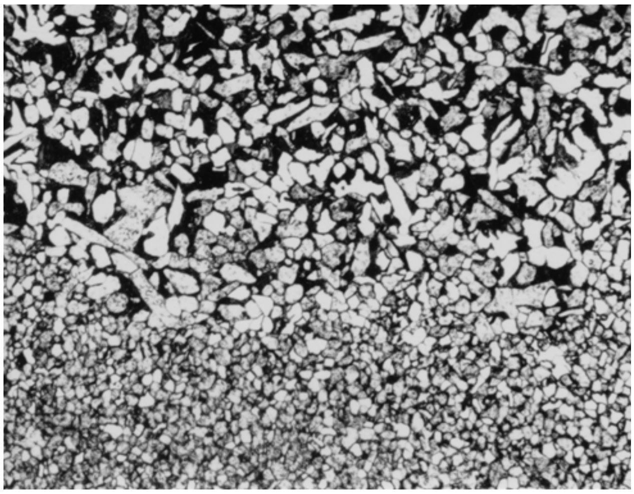


Figure 6.16e. *Sword 15. The left edge area shows a heterogeneous grain size. (100x).*

shows lamellar pearlite with a somewhat higher carbon content (Figure 6.18c), corresponding to an average hardness of 201 HV. The major part of this edge shows ferrite-pearlite with mostly medium carbon concentration (178 HV), while the area close to and along the welding seam shows increased carbon content and hardness values averaging 193 HV.

The right edge also shows lamellar pearlite with somewhat varying concentrations of carbon corresponding to hardness values in the range of 167 HV and 203 HV, and a hardness of 171 HV in the tip. As was the case with the left edge, increased carbon content is observed in a zone parallel to the welding seam (203 HV). There is no indication of quenching.

Interpretation: The blacksmith was aware of the importance of having harder edges and a softer central part. The welding seams between the edges and the core were well made. The edges have mostly medium carbon concentrations, but the blacksmith was not familiar with the technique of heat treating, which would have improved the hardness of the cutting edges and the quality of the weapon. This sword is considered to have been of decent quality.

SWORD 18 (Museum No. C.22568a, found in Kvålo, Lårdal parish, Tokke municipality).

The sword was found under a stone mound, probably a burial cairn, during farm work. An axe head and part of a sickle blade were also found with the sword. The extant parts of the sword consist of two pieces of the blade, which were very corroded. The hilt is missing (Figure 6.19a). There is a fuller along both sides of the blade. Since it was unclear whether the two pieces of the blade really were parts of the same sword, one section from each fragment has been studied (section A and B in Figure 6.19a).

Microscopic examination of the unetched sections shows quite a few slag inclusions. A few bent structures of hammer scale appear in the left part of section A shows that pieces of iron were folded and forged together (Figure 6.19b). The central and right parts of both sections show flat, parallel inclusions of slag and hammer scale, mostly as a long band through the section.

Etching with nital reveals a composition of distinct layers of soft iron and medium carbon steel running in a slightly oblique direction from one edge area to the other. A major part of section A has medium carbon content corresponding to hardness measurements in the range of 201–207 HV. The tip of the edge in the left part of the section (Figure 6.19a) shows higher hardness values, averaging 241 HV (Figure 6.19c), indicative of fairly high-carbon steel quickly cooled but not quenched. There is a pronounced distinction between the low and the higher carbon areas (Figure 6.19d), with some bands of hammer scale indicating welds. The ferritic or low carbon layer running through the section (Figure 6.19a) shows hardness values of about 120–179 HV. This is higher than expected for almost pure ferrite (Figure 6.19e). Perhaps the elemental composition could explain these high values. Etching with Oberhoffer's reagent showed no evidence of elevated phosphorus content. The grain sizes vary throughout the section.

The second section (B) cut from the other piece of the blade shows virtually the same structure and hardness measurements as section A. However, in this section the ferrite layer has a slightly lateral displacement such that both edges have increased carbon

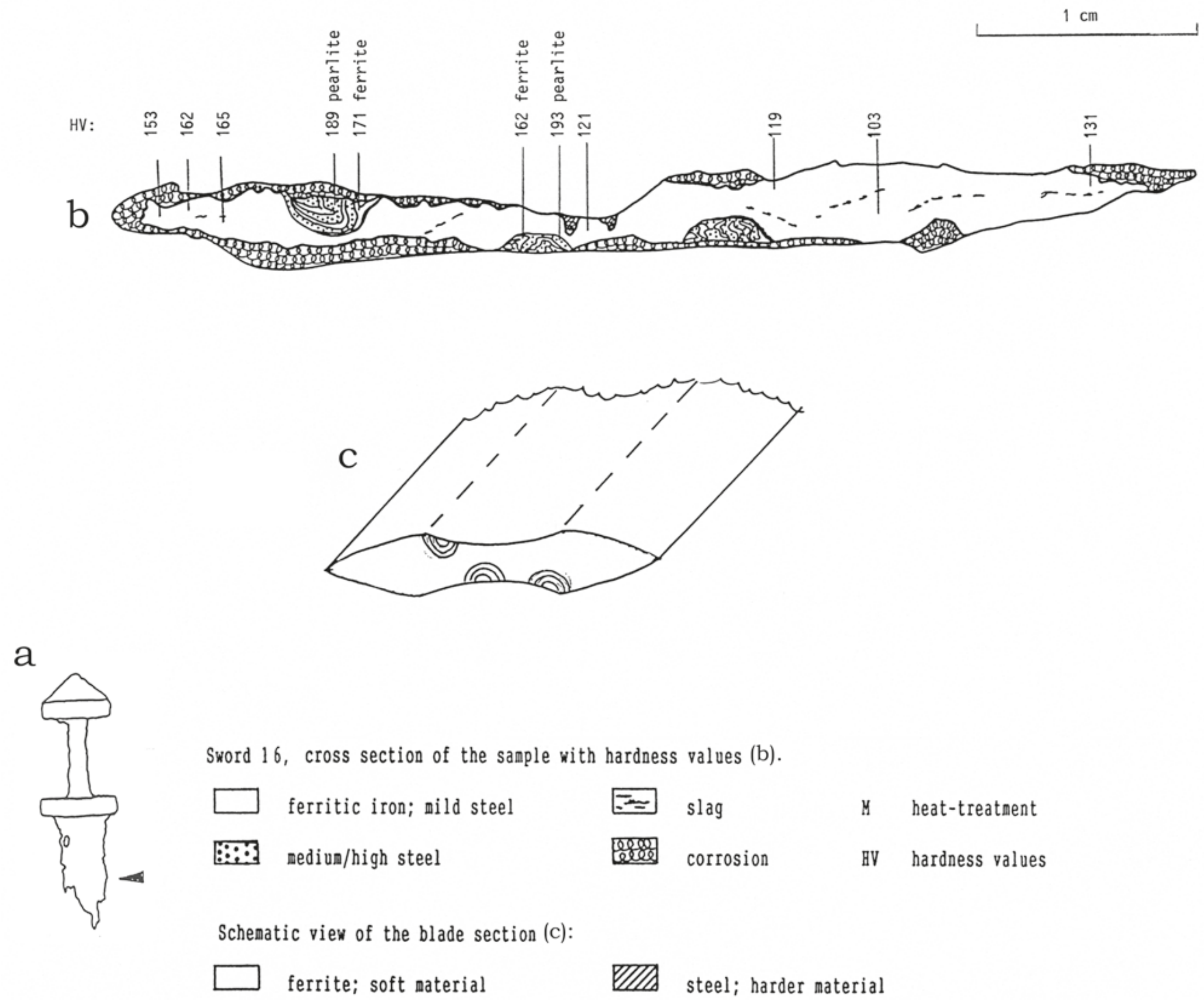


Figure 6.17a. *Sword 16. Cross-section of the sample with hardness measures (b), schematic view of the blade section (c) and outline of sword with section marked (a).*

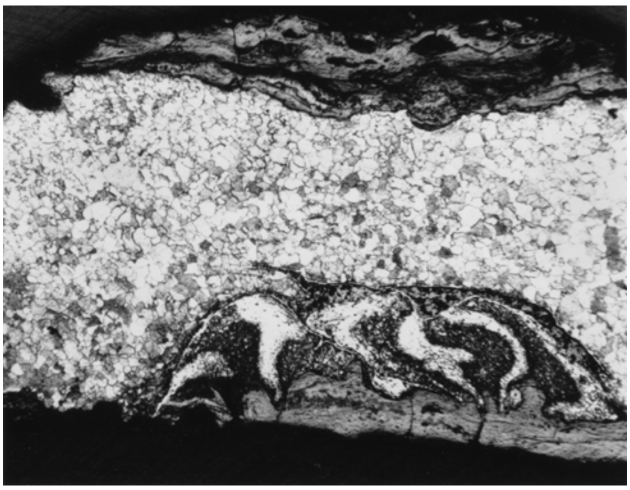


Figure 6.17b. *Sword 16. Cross-section of one of the inlays consisting of medium steel (dark) and phosphorus-containing wrought iron (white). The main constituent of the blade is almost pure ferrite. (20x).*

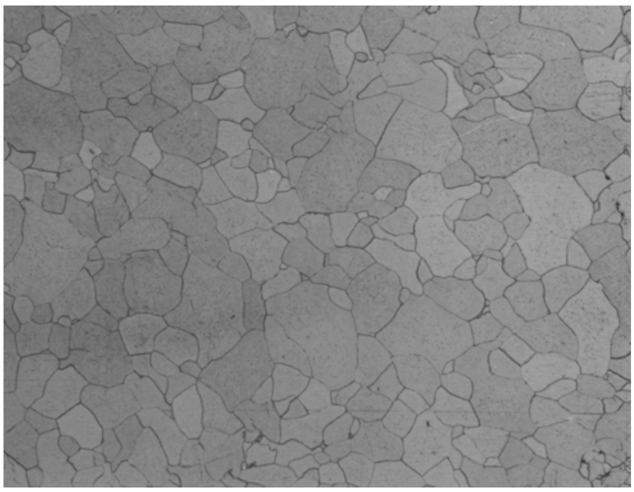


Figure 6.17c. *Sword 16. The blade is made of more or less pure ferrite. (100x).*

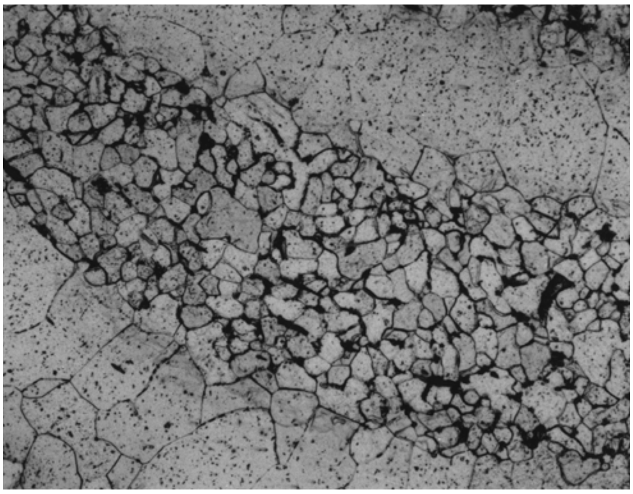


Figure 6.17d. *Sword 16. The inlays consist of layers of large-grain ferrite and small-grain ferrite/pearlite. (200x).*

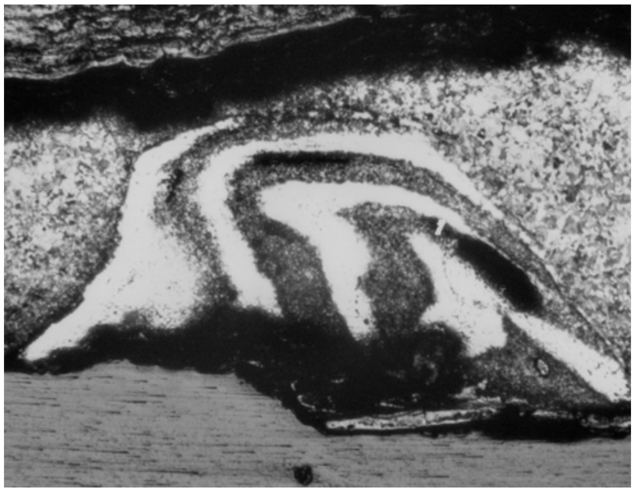


Figure 6.17e. *Sword 16. One of the inlays after etching with Oberhoffer's reagent, shows phosphorus-rich ferrite (pale) and mild steel (dark). (50x).*

content (Figure 6.19a). The ferritic layer appears to run somewhat obliquely through the centre of the blade.

Interpretation: Judging from the construction, the microstructure and the hardness values of the two sections, it seems clear that they belong to the same sword. It is difficult to form a definite opinion about the construction of this blade and the intention of the blacksmith. The blade could be the result of a body welded together randomly from pieces of harder steel and softer iron. However, the fact that two sections taken quite a distance apart in the blade show in principle the same construction and composition, may indicate that layered blade material could have been deliberately arranged from three flat bars – a wrought iron bar between two mild steel bars – with some lateral displacement (Figure 6.19a).

Both edges have been carburised in section B, while section A has only one carburised edge. This might be the result of corrosion of the other edge and loss of the carburised part, or it may be due to a certain displacement of the three bars during forging. The fact that the hardest parts of the sections were found at the very edges might indicate that the blacksmith performed a secondary carburisation of the tips of the edges intentionally, and that he had the knowledge of how to make an adequate sword. The blade has not been quenched. This sword is considered to have been of decent quality.

SWORD 19 (Museum No. C.24793c, found in Øvre Berge, in Kviteseid municipality)

The grave mound in which the sword was found probably contained at least three burials. The sword was found together with another double-edged and a single-edged sword, three axe heads of somewhat different types, an iron shield boss, a knife blade, three horse bits, an iron ring, a pair of scissors, a small bell, the lock of a chest, a fork-shaped tool, two fragments of some kind of iron blade, and some iron fragments. The sword blade was broken into two pieces and the hilt was missing (Figure 6.20a). The blade is double-edged and has a fuller running down either side.

Examination of the unetched section shows some slag inclusions. A few bands of slag or hammer scale particles in the left part of the section (Figure 6.20a) are parallel to each other and also to a major crack, slanting from the surface through a large part of the edge area. The hammer scale bands indicate welding seams between different sheets of metal forged together to make the edge material. A few parallel bands of scale or slag can also be seen in the right edge area. Some tortuous ribbons of hammer scale across the section suggest welding seams between the edges and the central part.

Etching the sample with nital reveals the blade to consist of a low-carbon central part with welded-on medium carbon edges. The hardness readings in the central part, consisting of practically pure ferrite (Figure 6.20b), are 96, 103 and 104 HV, an average of 101 HV. Higher carbon content was found close to the welding seams, where some diffusion of carbon had taken place. The welding seams for both edges are visible as three tortuous light lines across the section (Figure 6.20c). These welds are unlike other welds in this study. It is difficult to explain what kind of process could produce such welds. Microprobe analyses in steps across one of the welding seams show an enrichment in cobalt from about 0.03wt% in the blade body to about 0.18wt% in the weld, some enrichment of arsenic and only a slight enrichment of nickel (Figure 6.24e). The phosphorus content is mainly low (less than 0.01wt%), and at a constant level.

The cutting edge in the left part of the section appears to be composed of several parallel layers of mildly steeled iron of somewhat varying carbon content (Figure 6.20d). The hardness values in the main part of the edge are in the range of 163 to 185 HV. Between the layers there are pale lines representing the welds between the layers. Microprobe analyses across the layers of this edge reveal some enrichment of cobalt in the welds between the layers, which are approximately 0.3 mm thick. Further, the contents of arsenic, phosphorus and nickel were found to fluctuate around 0.02wt% in the layers as well as in the welds. A crack through the material runs between two layers. As can be seen from Figure 6.20e, the crack is surrounded by a decarburised ferritic layer. This indicates that the crack was present before the last heating of the blade, during which decarburisation occurred. The outer edge in the left part of the section, the area outside the crack, has a somewhat higher carbon concentration than the rest of the section. Hardness values average 201 HV. The structure in this part is quite uniform and shows a prior austenite grain size outlined by ferrite (Figure 6.20f).

In the right edge area, the carbon concentration is mostly homogeneous (hardness values of 178, 178, 185 HV). The tip of this edge has a hardness value of 182 HV, which is somewhat lower than that in the left edge. Piling of layers like those observed in the left part was not observed here, although a few slag bands running parallel to the blade surface through most of this edge may be indicative of welding seams.

Interpretation: The edges of this sword could have benefited from being somewhat harder. The blacksmith placed the harder material at the edges while the central part is more flexible, perhaps too soft. The left edge shows a structure produced by piling and welding together thin pieces or sheets of steeled iron to make up the necessary thickness of the body required for the edge. Although a similar structure is not clearly seen in the right edge, this may be due to extensive heating of the material, which evened out the variations in carbon content. There are no indications of quenching. This sword is considered to have been of fair quality.

SWORD 20 (Museum No. C.19575, found in Røymål, Lunde, Nome municipality).

The sword was found in a mound which probably contained several burials. Associated finds include a second double-edged and two single-edged swords, a spearhead, three axe heads, a number of arrow heads and knife blades, one or two shield bosses, one or two sickle blades, two horse bits, a whetstone and five beads. The blade was broken, and only the upper part with the hilt remained (Figure 6.21a). The surface layers were missing due to corrosion. The remaining part is in an acceptable state of preservation. The hilt is probably a Q-type.

Microscopic studies of the unetched section show lots of flat forged slag and hammer scale inclusions (Figure 6.21b), running in bands parallel to the blade surfaces indicating a piled structure.

Etching with nital shows that the blade has medium to high carbon content edges, which were welded onto a layered central part. The layers are partly ferritic, and made partly from low-carbon iron (Figure 6.21c). The ferritic layers, separated by lines of pearlite as well as hammer scale bands, run parallel along the section in the edge-to-edge direction (Figure 6.21e). Etching with Oberhoffer's reagent indicates that some of the ferritic layers have a considerable concentration of phosphorus (Figure 6.21d). Phosphorus content of about 0.3wt% was measured in some of the layers, while the others have about 0.05wt% according to microprobe analyses. The layers show hardness values partly in the range of 117–148 HV, and partly 173–197 HV due to variations in the phosphorus as well as the carbon concentrations. Some of the layers, mostly along the surface, were made from low-carbon steeled iron.

Compared to the other swords in this investigation, the edges of this particular sword are narrow and constitute only a smaller part of the section (Figure 6.21a). The central part makes up almost 80% of the entire section.

The welding seam of the left cutting edge appears as a pale decarburised line across the section, while a band of corrosion across the sample has replaced most of the weld between the right edge and the core. The welds between the edges and the core are somewhat curved. This may indicate that the edges were bent around the central part rather than being butt-welded.

Carbon content in the edges was considerably higher than in the central part. The cutting edge in the left part of the section shows a somewhat heterogeneous, patched structure of ferrite and pearlite. The hardness values measured at the very outer left edge are 245, 260 HV, averaging 253 HV. In the rest of this edge, the hardness measurements average 200 HV. The structure appears to be lamellar pearlite with medium carbon content (Figure 6.21f).

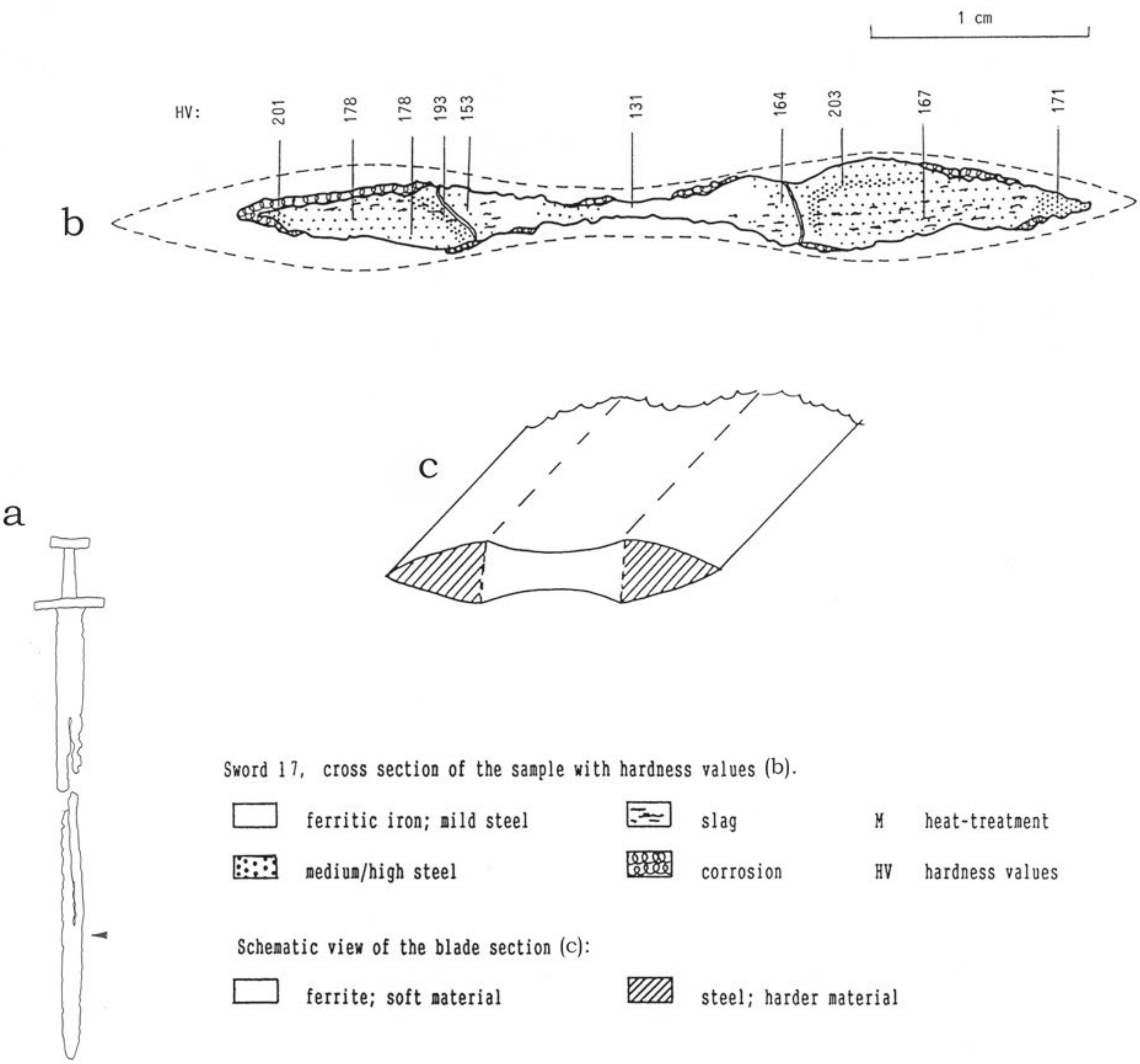


Figure 6.18a. *Sword 17. Cross-section of the sample with hardness measures (b), schematic view of the blade section (c) and outline of sword with section marked (a).*

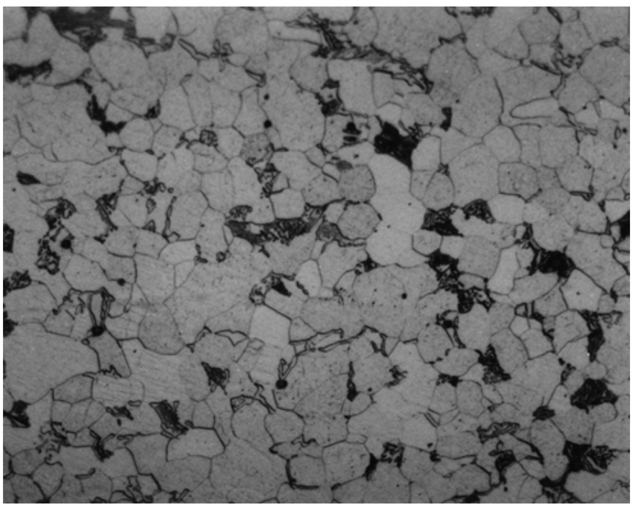


Figure 6.18b. *Sword 17. The central part has mostly small grains and low carbon content. (500x).*

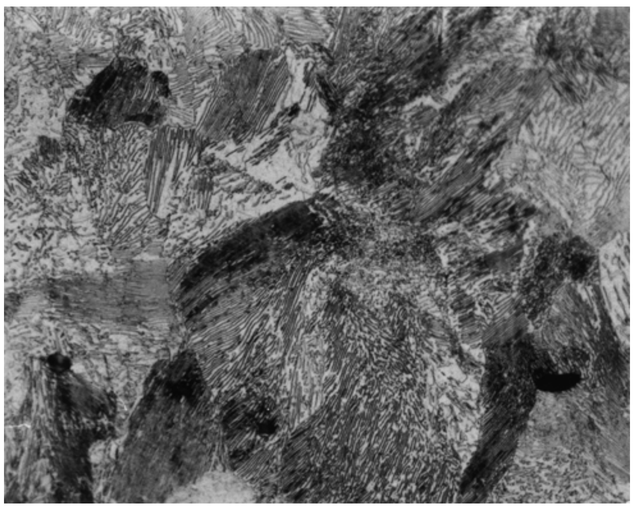


Figure 6.18c. *Sword 17. The tips of the cutting edges show lamellar pearlite and mostly high carbon content. (500x).*

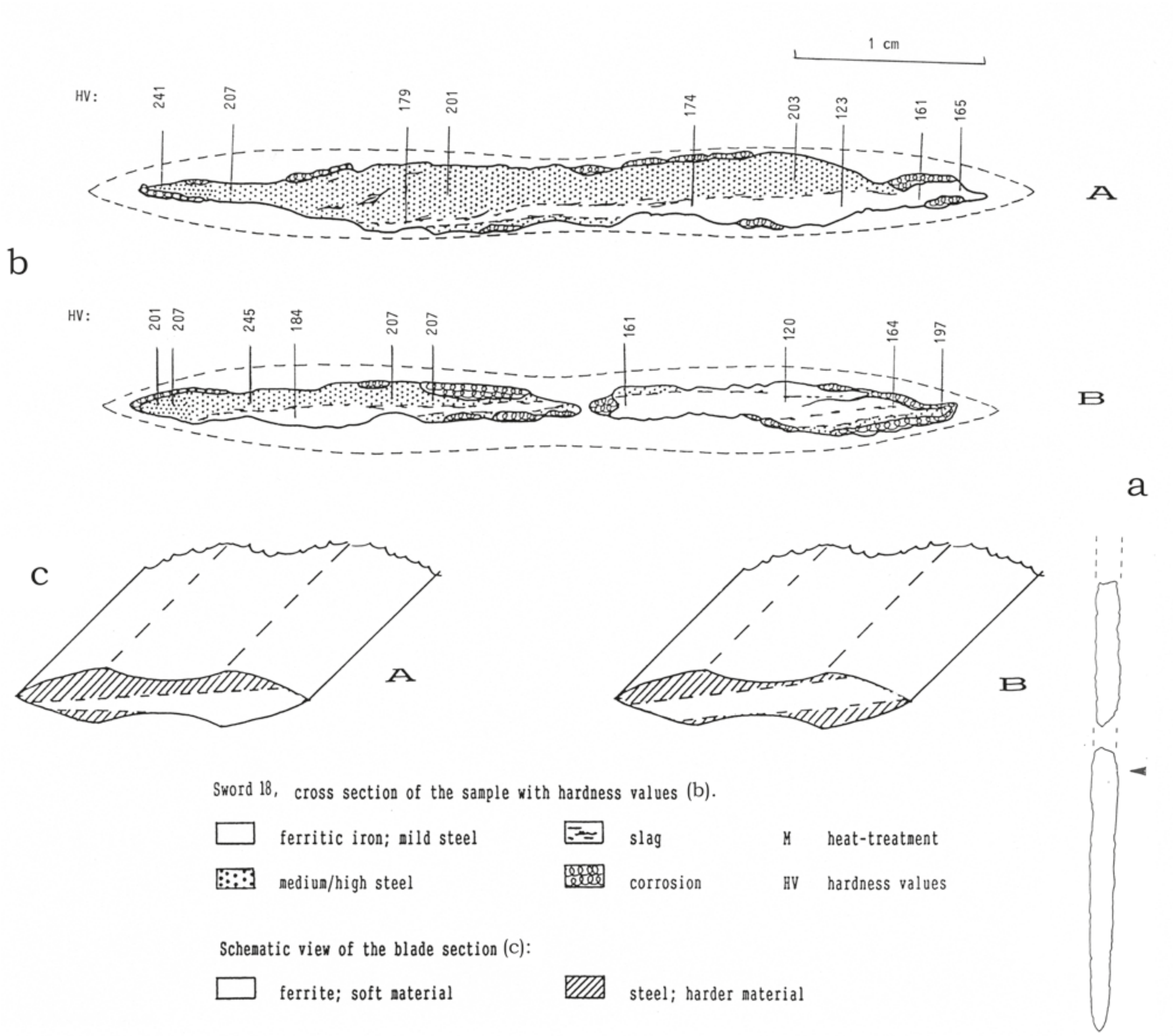


Figure 6.19a. *Sword 18. Cross-section of the sample with hardness measures (b), schematic view of the blade section (c) and outline of sword with section marked (a).*

Figure 6.19b. *Sword 18. Unetched. A few bent hammer scale structures in the left part of the section indicate that pieces of iron were folded and forged together. (50x).*

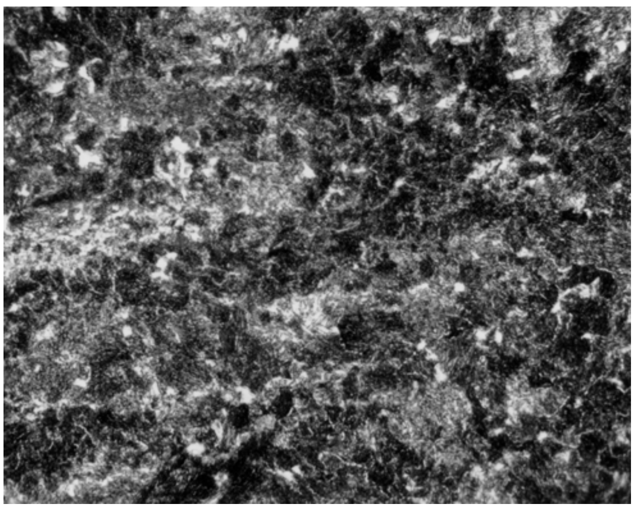


Figure 6.19c. *Sword 18. The outer left edge shows fairly high carbon content. It has been cooled quickly, but not quenched. (500x).*

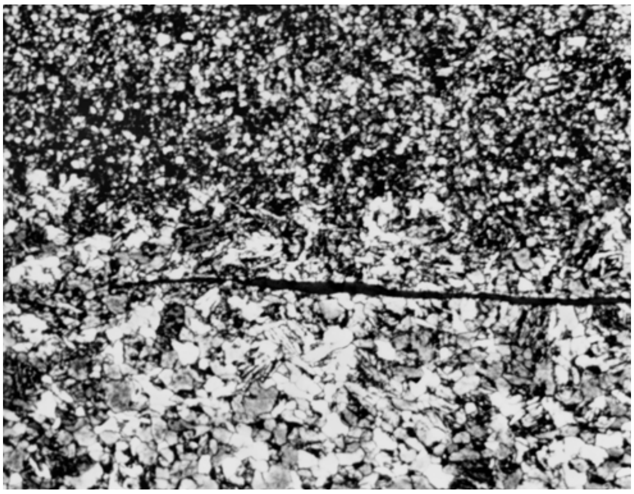


Figure 6.19d. *Sword 18. The blade is composed of sheets of low (pale) and high (dark) carbon content. A distinct border runs obliquely from one edge area to the other. (100x).*

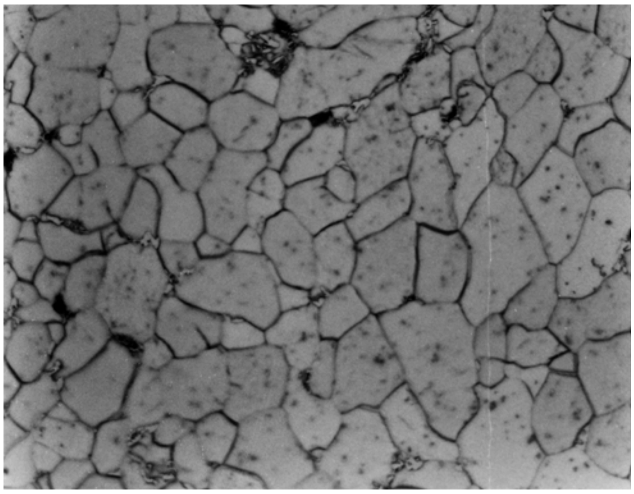


Figure 6.19e. *Sword 18. A ferritic layer runs obliquely in an edge-to-edge direction. (500x).*

The right cutting edge is somewhat harder than the left. Hardness values vary from 224, 250, 251 HV close to the weld, to 289 HV at the very edge. The edge consists of medium to high carbon content with cementite in the prior austenite grain boundaries (Figure 6.21g). None of the edges show any signs of quenching.

Interpretation: The central part is ductile. The amount of slag and hammer scale is somewhat high. The edges are considerably harder than the core. Quenching may not have been a technique familiar to the blacksmith. This sword is considered to have been of no more than decent quality.

SWORD 21 (Museum No.23946a, found at Brokke, Fyresdal municipality)

The sword is a grave find. An axe head, an iron reed and a frying pan were found together with it. Only a part of the blade and the lower guard of the hilt have survived (Figure 6.22a). The sword is single-edged. The remaining parts were quite corroded, particularly the sharp edge. The hilt is an M-type.

Unetched, the section shows some long, flat slag bands mostly along the central part.

When etched in nital, the sample reveals mostly low carbon content with typical hardness values in the range of 100–123 HV (Figure 6.22b). The hardness measured in the back part is 123 HV. Higher carbon content (Figure 6.22c) was observed along one surface of the blade, as well as in a band running along the axis of the section from near the back, slanting towards the surfaces near the cutting edge area (Figure 6.22a). Typical hardness values in the carburised areas are 159, 180, 182 HV. The remaining part of the edge consists partly of a ferritic area, and partly of a carburised area (Figure 6.22d). The hardness in the actual edge is 226 HV (Figure 6.22a).

The material in this sword blade seems to have been forged together from sheets or pieces of soft iron and mildly carburised iron. This may have been done intentionally in order to give some stiffness to the blade. Although a large part of the blade consists of nearly pure ferrite, examination shows that the actual cutting edge is carburised. There is no indication of quenching.

Interpretation: The question remains whether the blade was made from random pieces of ferritic iron and mildly carburised iron, or if it was deliberately piled from a few alternating sheets of different carbon content in order to increase its strength. There is no sheet of steel running through the tip of the cutting edge. Still, carbon content increases in the cutting edge, which may be due to a secondary carburisation of this part. The blacksmith seems to have been aware of the advantage of carburised iron in the cutting edge, and he knew how to carry out the process. However, it seems he did not have knowledge of quenching. This sword is considered to have been of decent quality.

6.4 DISCUSSION

In order to make a sword blade of high functional quality in relation to actual combat, it was necessary for the smith to have extensive knowledge of the materials with which he was working, and of the techniques for improving the strength and resilience of the materials by carburisation and heat treatment. He must also possess the adequate skill to perform these processes.

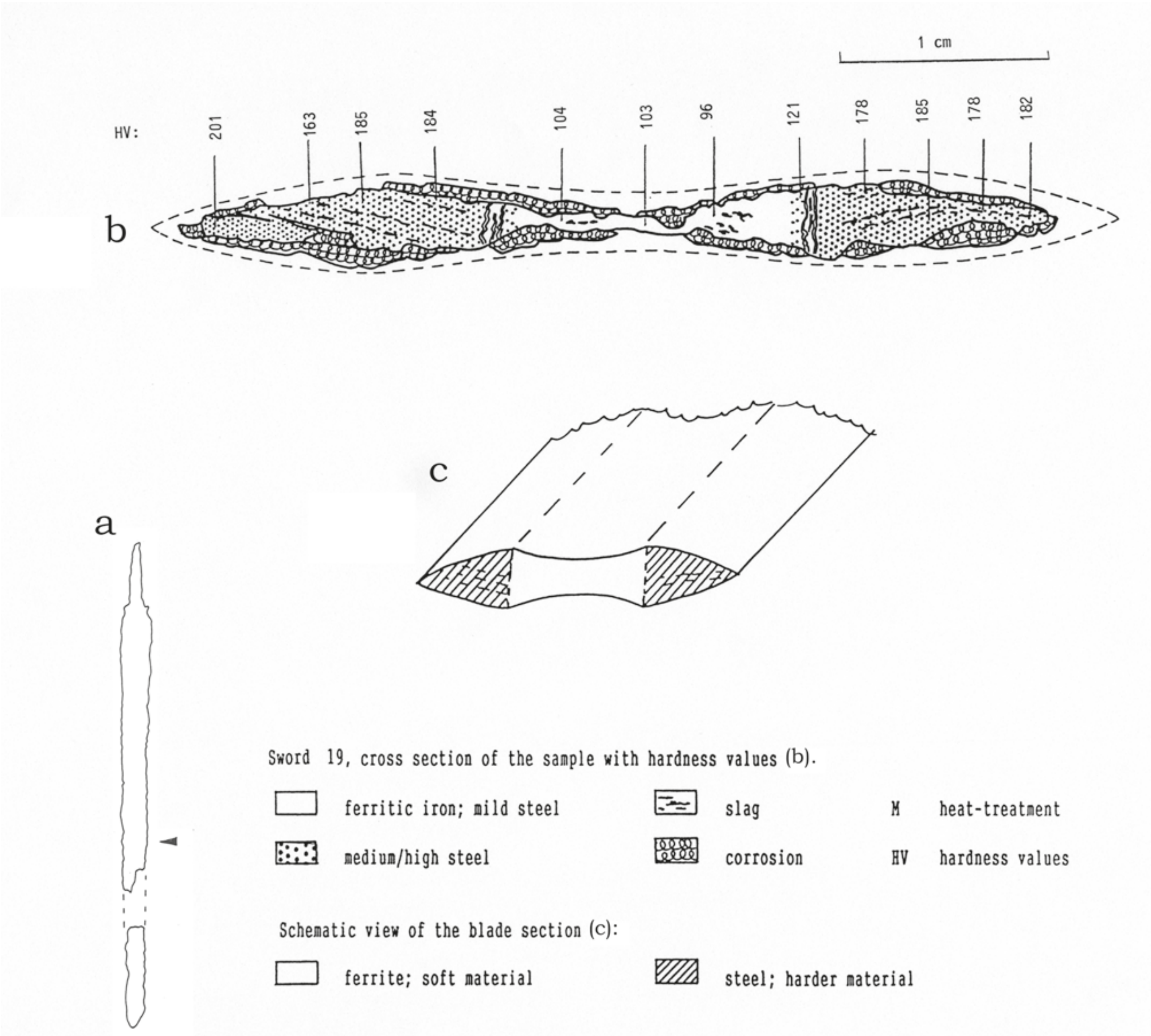


Figure 6.20a. *Sword 19. Cross-section of the sample with hardness measures (b), schematic view of the blade section (c) and outline of sword with section marked (a).*

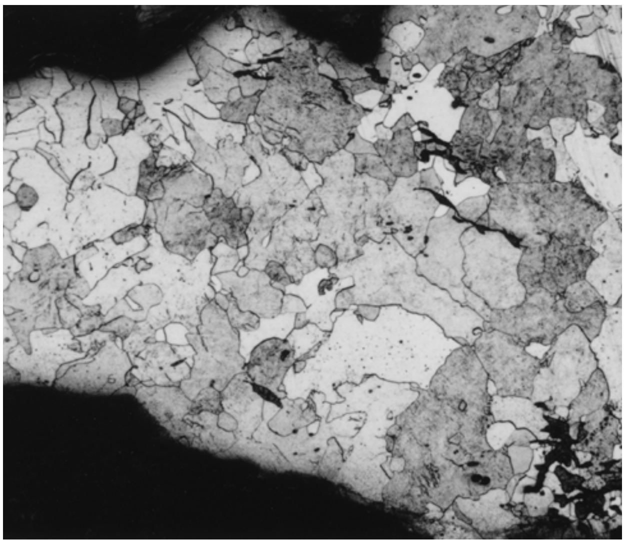


Figure 6.20b. *Sword 19. The central part is soft and consists of almost pure ferrite. (50x).*

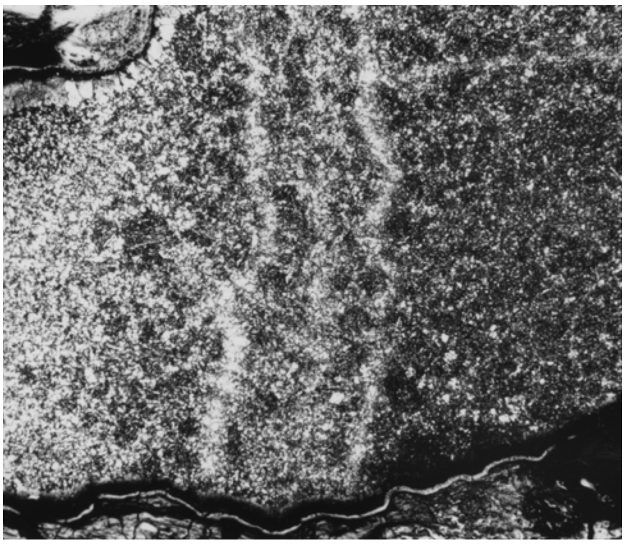


Figure 6.20c. *Sword 19. The welding seams for both edges are seen as three tortuous pale lines across the section. (50x).*

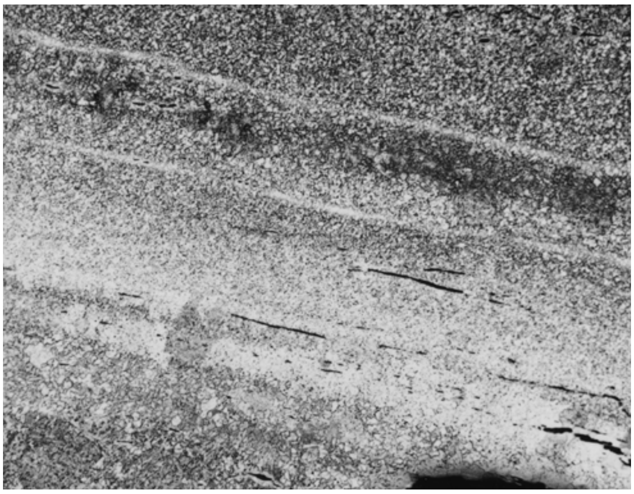


Figure 6.20d. *Sword 19. The left cutting edge is composed of several parallel layers as indicated by light welding seams. (50x).*

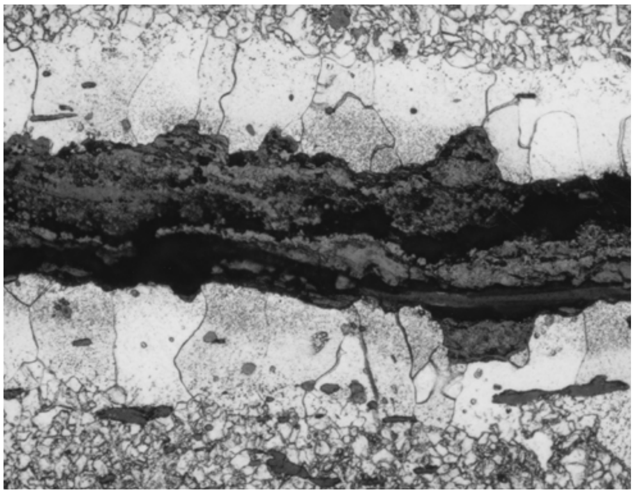


Figure 6.20e. *Sword 19. A crack through the material runs between two layers of mild steel. The decarburisation along the crack must have developed during the last heating of the blade. (200x).*

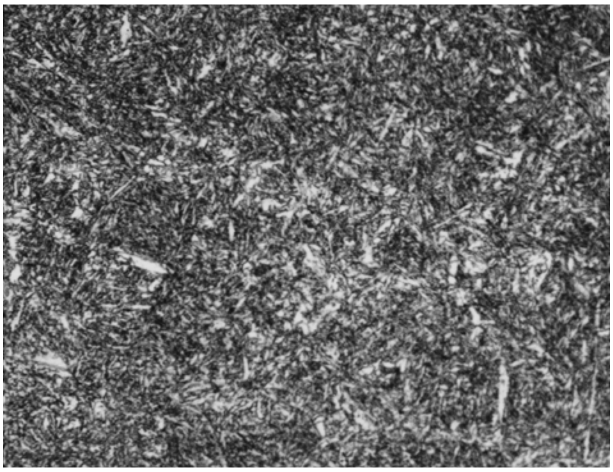


Figure 6.20f. *Sword 19. The highest carbon concentration is observed in the edge on the left part of the section. The structure is quite uniform. (200x).*

This along with other observations show that several different construction schemes were employed in the production of sword blades. Various sword blades may have similar constructions but still be remarkably different in terms of the composition of materials, and hence in the quality of the blades. Such differences have been revealed in the microstructure of the metal. The degree of heterogeneity of the raw material, the distribution and concentration of carbon and phosphorus, grain sizes, heat treatment, and hardness all affect the quality of the sword, independent of construction.

The blade material

Iron production methods in the Viking Age resulted in blooms consisting of a mixture of slag and pieces of metallic iron[8]. Hammering the blooms released pieces of iron which were welded together to form the necessary structure for further smithing and shaping. Currency bars occur frequently in Norway. Ancient iron objects were found to differ considerably in the amount of slag. Small slag inclusions can hardly be avoided, and they are usually not harmful to the quality of the objects. Some authors (Lang and Ager 1989:86) maintain that as long as the slag particles are small, they might even provide a certain strength and stiffness to the iron. Large inclusions, however, have an embrittling effect on the material. The quality of the object required that the blacksmith or smelter worked the material well enough to reduce the amount of slag to an acceptable level. The amount of slag in iron objects can therefore serve as an indication of the quality of the craftsmanship.

In the parts of the bloom that were in close contact with charcoal, some carburisation was likely to appear. However, most of the bloom consisted of iron low in carbon. Such bloomery iron is soft and ductile and needs to be hardened to serve the different purposes of many tools and weapons.

Although the carburised parts of the bloom may have been cut off and used where a harder material

8 Blooms found in Norway consist of iron without many slag inclusions. A.M Rosenqvist investigated two blooms and two lightly wrought blooms metallographically. One of the blooms was found at Møsstrond, and Rosenqvist states that this bloom is remarkably free of slag inclusions in the inner part, and the other three are not very different. The shape of the blooms attest to their being formed in shaft furnaces with slag-tapping from the side, which was the dominant furnace type in Norway in the Viking and Medieval periods. Rosenqvist also states that their phosphorus content is low. (Rosenqvist 1979) – *I. Martens*

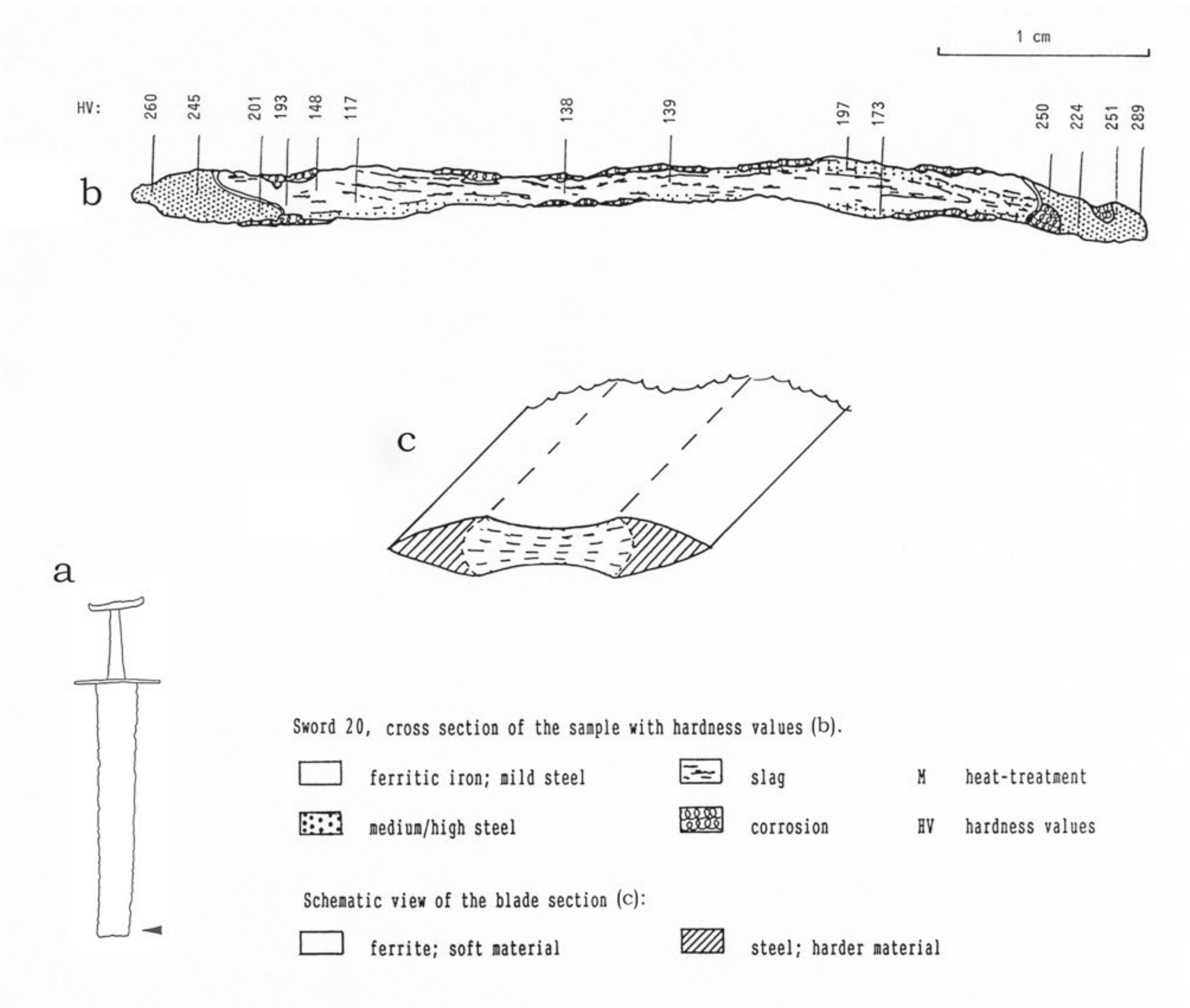


Figure 6.21a. *Sword 20. Cross-section of the sample with hardness measures (b), schematic view of the blade section (c) and outline of sword with section marked (a).*

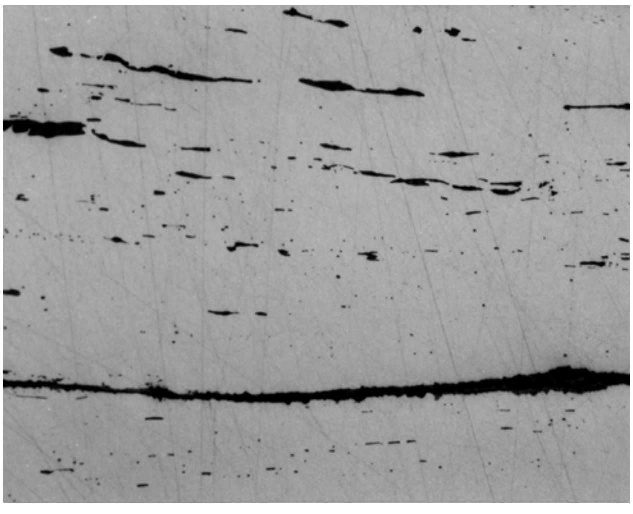


Figure 6.21b. *Sword 20. Unetched. Parallel, flat-forged slag and hammer scale inclusions all over the section indicate that the blade is composed of several layers piled and forged together. (50x).*

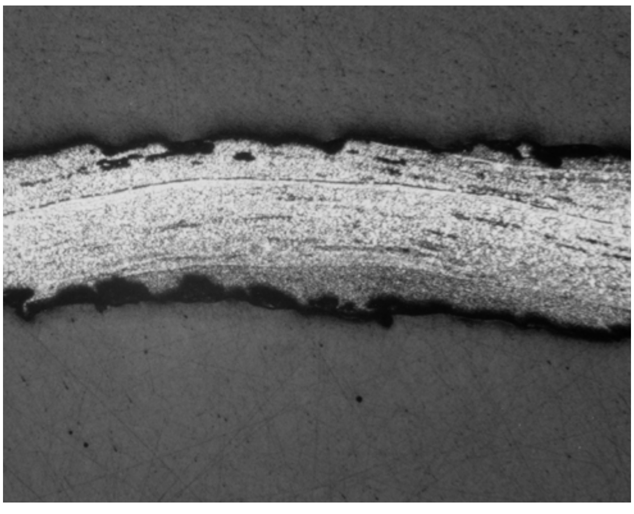


Figure 6.21c. *Sword 20. Most of the central part consists of layers of ferrite separated by numerous lines of pearlite and bands of slag and hammer scale running parallel from edge to edge. Etched in nital. (20x).*

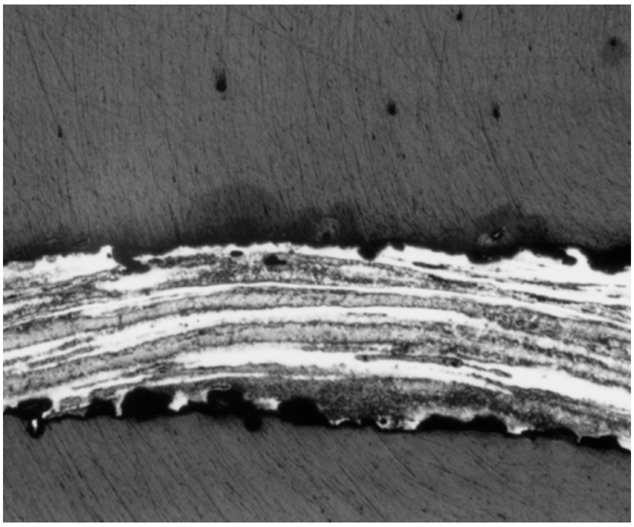


Figure 6.21d. *Sword 20. Same as 6.21c 20/3 etched in Oberhoffer's reagent. Pale layers of phosphorus- rich ferrite. (20x).*

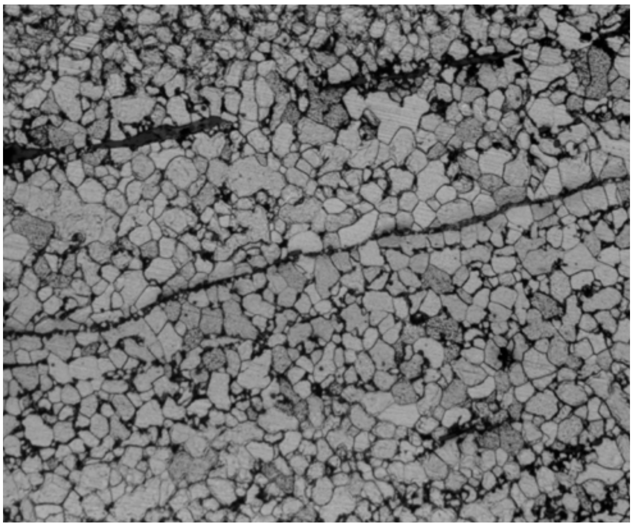


Figure 6.21e. *Sword 20. Ferrite layers separated by lines of pearlite and slag and hammer scale bands running across the entire central part. (100x).*

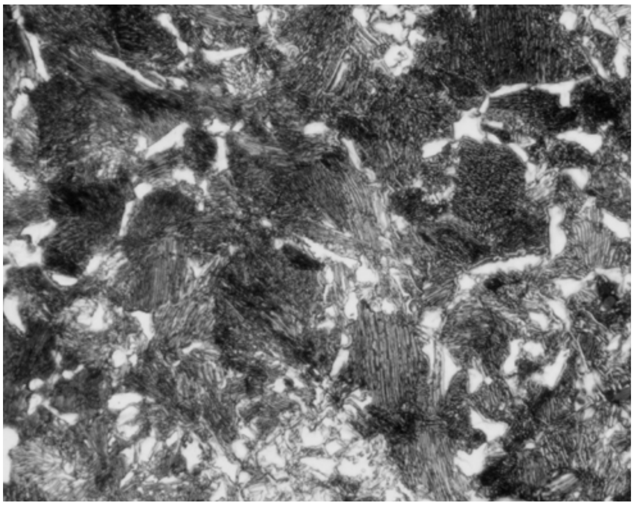


Figure 6.21f. *Sword 20. The left edge consists of lamellar pearlite with medium to high carbon content. (500x).*

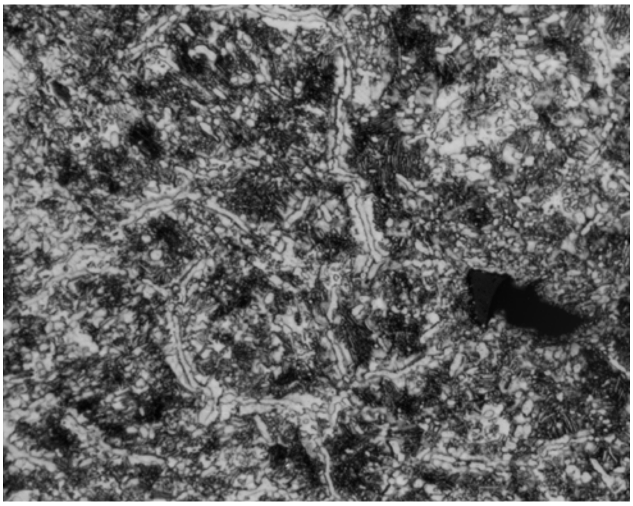


Figure 6.21g. *Sword 20. The right edge consists of medium to high carbon steel with cementite in the prior austenite grain boundaries. (500x).*

was needed, this alone could hardly account for the amount of steel that was used in the Viking Age.

When studying the prehistoric development of the use of iron and steel, and the skill of the blacksmiths, it is essential to examine to what degree hardening iron through carburisation and heat treatment occurred, and whether the harder materials were deliberately incorporated into the objects in places where their specific mechanical properties were most needed. Even if the blacksmith knew that carburisation and heat treatment would improve the hardness of the iron, and hence the quality of the object, he might still not have mastered a technique that was precarious and difficult to carry out successfully.

The presence of elements other than carbon can also increase hardness in iron. Ancient iron objects often show increased hardness as a result of elevated phosphorus content. Phosphorus makes the iron not only harder, but also brittle and difficult to work. Elements like arsenic, nickel and manganese are similar to carbon in their hardening effect on iron, but concentrations need to be several times higher than those of carbon in order to obtain the same level of hardness. Microprobe analyses of several of the blades in this investigation have shown that some of them have high phosphorus content. Except for one blade (sword 12), which is made mainly of phosphorus-rich iron, phosphorus is primarily connected to surface decorations, such as inlays and pattern-welded structures in a part of the blade where some increase in brittleness would not affect the quality of the weapon. The phosphorus-rich iron in these cases must have

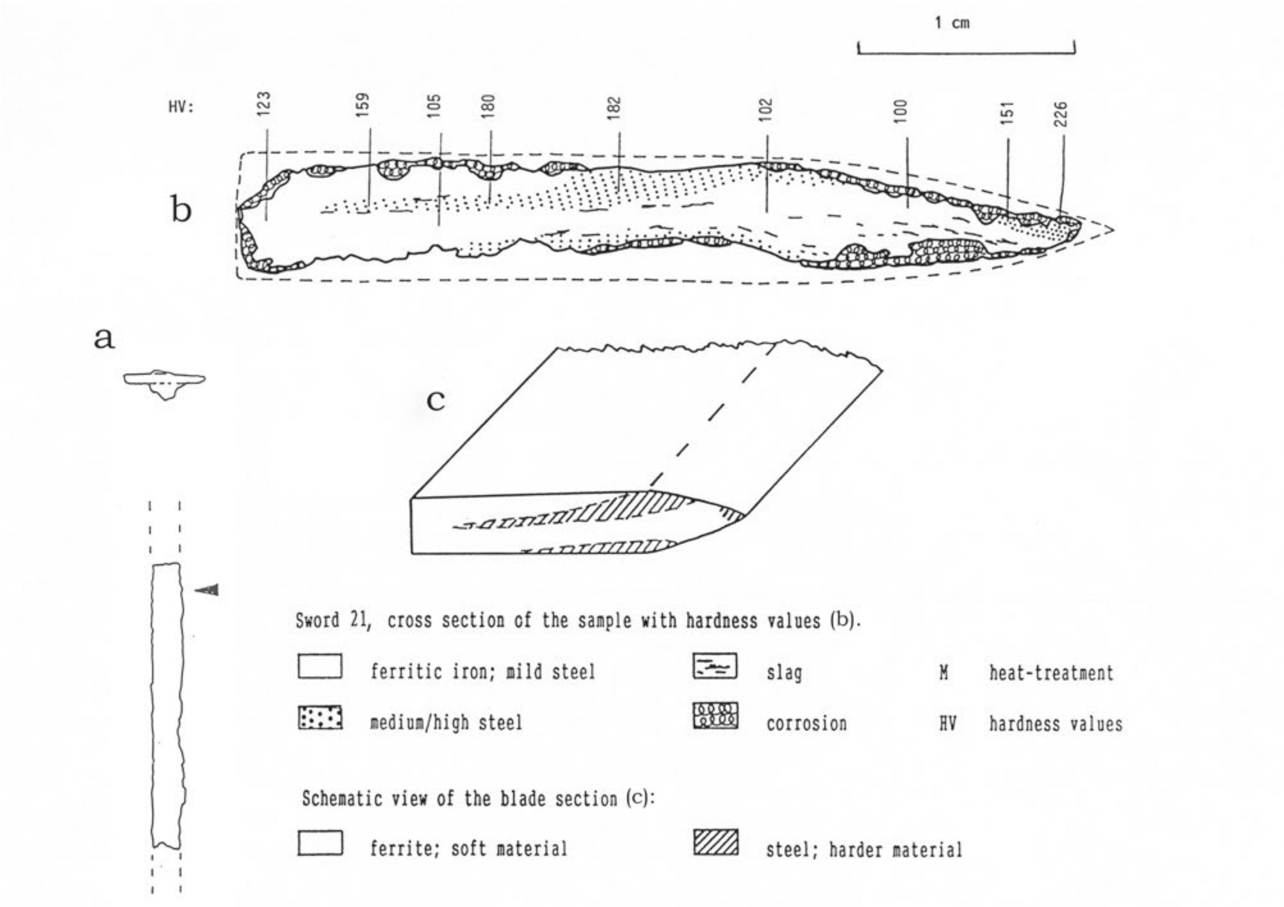
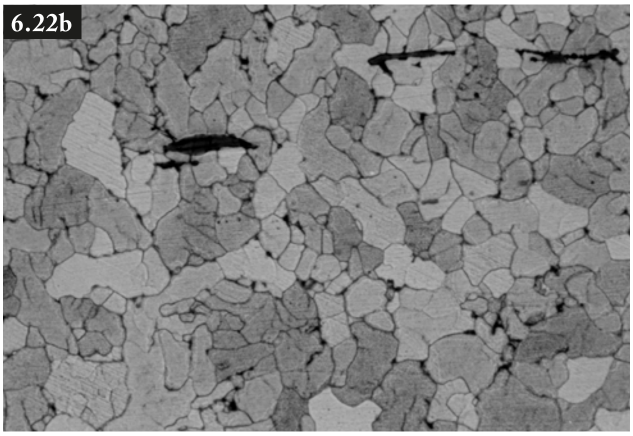
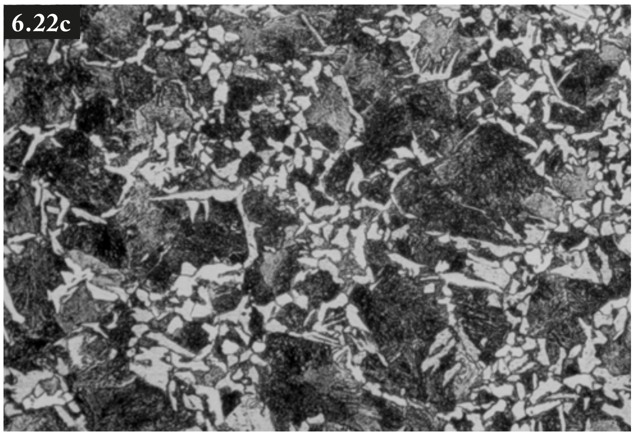


Figure 6.22a. *Sword 21. Cross-section of the sample with hardness measures (b), schematic view of the blade section (c) and outline of sword with section marked (a).*





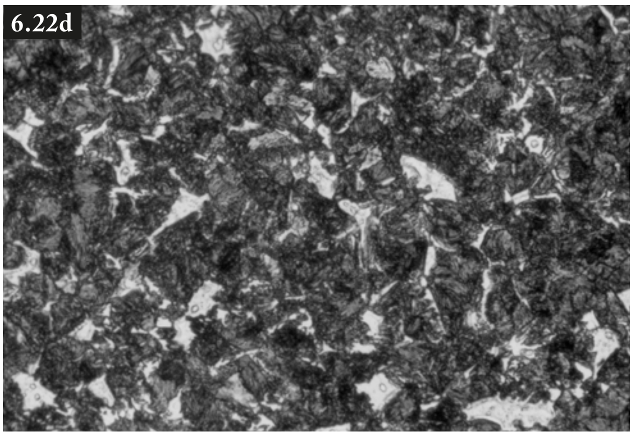


Figure 6.22b. *Sword 21. The sample reveals mostly low carbon content. The back is soft and consists of pure ferrite. (100x).*

Figure 6.22c. *Sword 21. A wide band with higher carbon content runs through a large part of the section and bends towards the surface as it approaches the edge. Pearlite (dark) with ferrite (light) grown/precipitated from the austenite grain boundaries. (200x).*

Figure 6.22d. *Sword 21. The highest carbon content is observed at the very edge. (500x).*

been used intentionally to improve appearance, and, after etching, show a distinct difference in carburised iron and iron rich in phosphorus. The levels of arsenic, nickel and manganese measured in this study are too low to have any significant effect on the material.

The construction and composition of sword blades

The different types of blades studied in this work are shown in Figure 6.23, based on their construction and the composition of steel and iron. Three of the blades are single-edged (swords 5, 6, and 21), the remaining 18 are double-edged. All the double-edged blades have a fuller or groove along the centre on both sides of the blade. The literature describes fullers that were cut into the blade (Bennett et al. 1982), and fullers that were forged (Lang 1984). Although the surfaces of most of the blades in the present work were damaged by corrosion, it is obvious from the slightly curved shape of slag bands in the central part that these fullers were produced by forging. Of the 21 swords that have been examined 19 can be described by one of the construction types I, II, III, V, defined in Figure 6.23. The construction of the remaining two blades are difficult to explain (construction type I or IV).

Construction type I. A blacksmith who had insufficient knowledge of materials and inadequate knowledge of carburisation was likely to make his products from bloomery iron, which was worked more or less adequately to get rid of slag, or he probably produced new objects by reusing pieces of old scrap iron of random hardness and elemental composition. The less skilled smith no doubt used whatever material was at hand.

In the present work such simple sword blades are ascribed to construction type I (Figure 6.23), blades made from a single bar where the central part as well as the cutting edges are made from a bloomery iron, or from a fairly uniform material, mostly from soft, ferritic iron, or from iron or mildly steeled pieces forged together randomly. The ferritic blades would be too soft and ductile for a good weapon, while blades of arbitrary composition would not utilise the specific mechanical properties of the materials in order to improve quality. The blacksmiths who produced such blades were not familiar with the properties of steel and how to make it. This kind of construction is represented by the two single-edged blades of swords 5 and 6 (Skien), and by the double-edged sword 12 (Tinn).

Moreover, the blade of sword 16 (Vinje) is a simple construction of soft, fairly pure ferritic iron throughout resulting in inferior functional quality. The blade is well worked. It has an inlaid design, made from twisted wires of mildly carburised iron and phosphorus-rich iron, indicating that the blacksmith had adequate knowledge of the materials. In this case it seems the main purpose was the fine appearance of the blade. In this particular sword this simple construction was most likely intentional, in order to save steel and intricate work (see Chapter 7, the Hedesunda sword).

A high quality sword blade should be constructed in such a way that the core is resilient – not so hard that it would easily break, not so soft that it would easily bend – and the edges should be hard, but not so hard that pieces would easily chip or break in combat.

It has been suggested that soft iron edges might be more advantageous than steel, because the notches acquired in combat could be easily repaired by the warrior himself simply by hammering. However, a soft-edged sword blade would work efficiently for only a short time compared with a steel-edged sword. Some increase in iron hardness can also be obtained by cold-hammering the material. However, such treatment would not improve the overall quality of the sword blade to any great extent.

Significant improvement of the simple iron sword blade was attained by introducing harder, carburised iron in the cutting edges. Metallographic examinations showing different ways in which this was done have been documented in the literature (Tylecote and Gilmour 1986; Kedzierski and Stepinski 1989; Pleiner 1993).

Construction type II. One method of creating steeled cutting edges is to carburise the entire surface of the blade to give it a harder "shell" around a softer core: construction type II (Figure 6.23). In principle this was done through different methods since the Celts (Pleiner 1993:134). Lengthy heating in the presence of charcoal will, under the right conditions in the hearth, result in a thin layer of increased carbon content due to the diffusion of carbon atoms into the surface of the iron blade (case-carburisation) (construction type IIa). However, as already mentioned, the diffusion process is slow, and the carburised steel layer will penetrate only a short way into the surface. It has been assumed by several authors that there might have been difficulties connected to heating the entire sword blade continuously for many hours at a constant temperature. However, judging from examinations of sword blades it seems that at least the specialised smiths had their ways of doing this successfully. Another method that would achieve a carburised surface layer was by hammer-welding a successfully pre-made carburised sheet of steel onto the iron core before finishing the forging of the blade (construction type IIb). The latter method probably produced more reliable results since good quality steel was produced before welding the sheet onto the core. The gradient between the carbon-rich layer and the low-carbon core can be used mostly to distinguish between the two methods of surface carburisation. The carbon concentration gradient is much more distinct, often with hammer scale bands, when a steel layer has been welded onto the core (Figure 6.15b). In case-carburisation the transition is recognised by a more gradual increase in carbon concentration (Figure 6.2d).

In the present work, type II constructions consist of blades forged mainly from fairly pure, soft iron or moderately carburised iron. In sword 1 (Skien), the steeled layer was attained by diffusion of carbon into the surface of the nearly finished blade (case-carburisation) (construction type IIa). In swords 13 (Tinn) and 14 (Tinn), a steel sheet was welded onto an iron core (construction type IIb). This investigation demonstrates that the blacksmiths not only accomplished successful carburisation of these blades, but that they also knew how to quench in order to harden the edges further. All three blades show a structure consistent with heat treatment. However, the result of the heat treatment did not always end up as successfully as was probably planned. Figures 6.14d (sword 13 (Tinn)) and 6.15d (sword 14 (Tinn)) show the steel layers of high carbon content welded onto the low-carbon core, where bands of small hammer scale particles between the steel surface and the iron core indicate welding seams.

Because of corrosion, it is difficult to interpret the construction of sword 2 (Skien) with any certainty. It is obvious that the edges had been carburised, and the tip of the left edge also shows heat treatment (Figure 6.3e). The transition between the carburised zone and the core is more diffuse than would be expected for a welded-on steel sheet, a fact indicating case-carburisation. There are, however, no traces of carburisation along the remaining surface of the blade section. Whether only the edges were carburised, or the whole blade, cannot be ascertained. It is possible that this blade originally had a fully case-carburised surface (construction type IIa), most of which has been lost as a result of corrosion.

The importance of good resilience in a sword blade can hardly be overstated. Thorough descriptions of the springiness of sword blades in Old Norse literature (Davison 1962:164) can only mean that the right combination of iron and steel in the core of the sword blade was well known and highly appreciated. Whether producing a core from more or less homogeneous medium carbon material, or producing piled or laminated core material from alternating sheets of steel and iron, sufficient springiness in the core could be achieved (Ypey 1984).

Construction type III. The superior combination of a resilient core and sharp edges necessitated producing steel edges and a more flexible central part, as shown in Figure 6.23, construction type III. Direct carburisation of the edges in an almost finished iron blade is possible, but the steeled material would be thin and could not survive many resharpenings. Forging techniques in which steel edges were welded onto a medium carbon core or onto a piled iron-steel core were easier to control, and produced more solid and long lasting steel. The steel edges were usually either butt-welded onto the core (Figure 6.23, construction type IIIa) or a steel sheet was bent and welded around the end of the core (Figure 6.23, construction type IIIb). In certain cases, a sheet of steel was welded to only one side of the edge in such a way that there was always steel in the tip, even after resharpenings (Figure 6.23, construction type IIIc). This method would require less of the costly steel.

All the blades with welded-on edges have been classified as construction type III, although the composition of the materials may range from fairly pure iron to high steel. The welded-on edges indicate that the blacksmith was familiar with the importance of having harder carburised edges and a more flexible central part. Otherwise there would not have been any incentive to implement this construction. However, the blacksmith may not have always had the skill to prepare the right materials and to produce an excellent blade.

From the present investigation, it is apparent that blacksmiths were familiar with the superior quality of this type of sword blade construction. Half the blades examined have this type of construction, including all of the best ones. Also, all the blades with this construction were found to have carburised edges. Only fairly small amounts of hammer scales were observed in the welds of most sword blades examined here. It also appears from the X-radiographs that the blacksmiths most often mastered the difficult technique of skillfully welding the edges to the central part all along the blade. Moreover, the technique of quenching appears to have been known to many Viking Age smiths, although not to all of them. In this work about

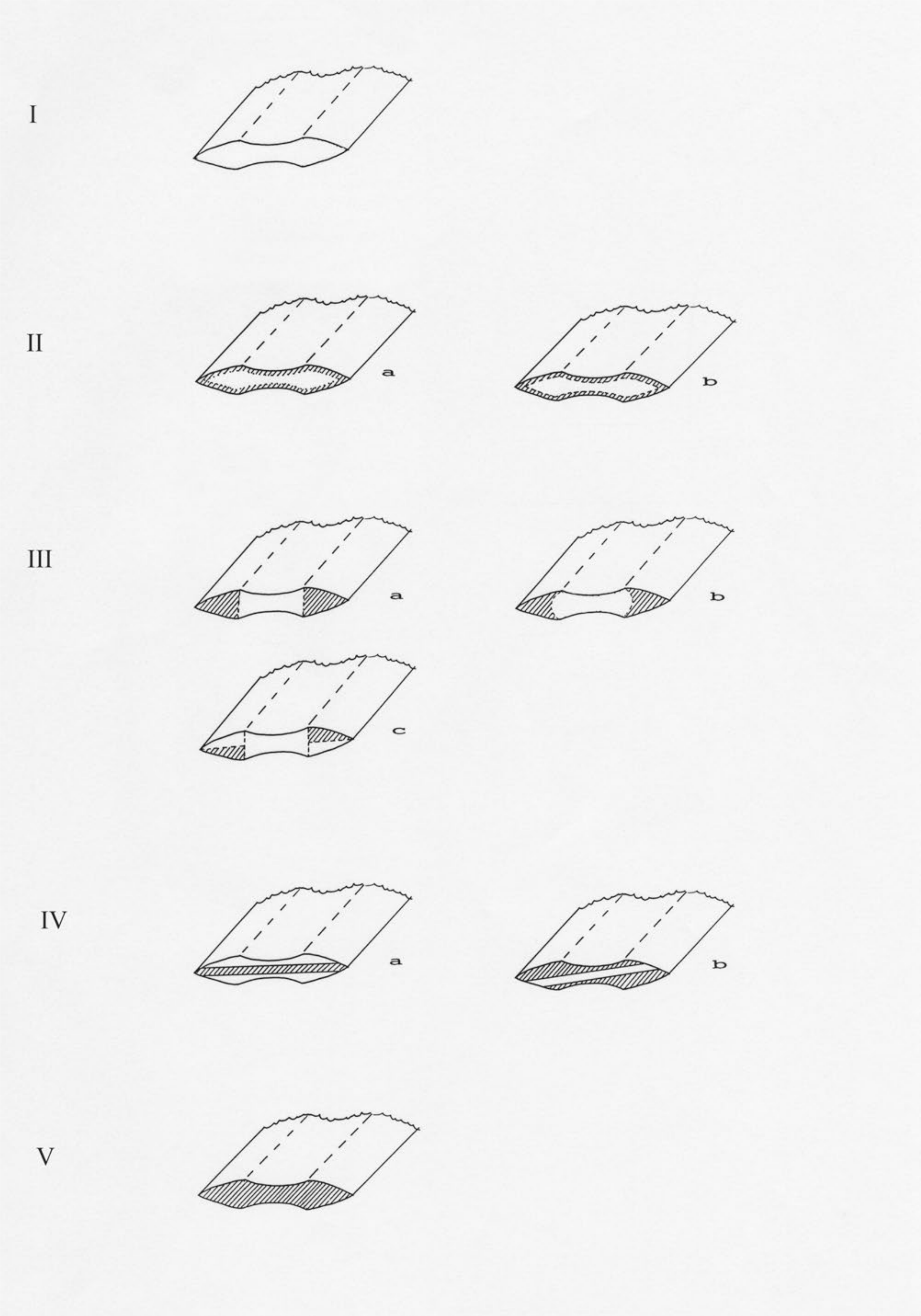


Figure 6.23. Construction types for Viking Age sword blades from Telemark.

40% of the blades of type III construction show more or less successfully quenched edges (Table 6.2).

This construction seems to have become well-known and fairly widespread in Telemark in the Viking Age, at least in the parts of the county covered by this study. This includes coastal zones, inland, valley and mountain areas (Kaland 1972; Martens 1995). Nine of the 21 blades found in eight of the nine municipalities studied have edges welded onto the core (Table 6.2: swords 3 and 4 (Skien), swords 7 and 8 (Porsgrunn), sword 9 (Bø), sword 11 (Tinn), sword 15 (Vinje), sword 17 (Tokke), sword 19 (Kviteseid), and sword 20 (Nome)). Nine of the 11 blades show butt-welded edges (construction type IIIa), one has the steel bent around the edge of the core (sword 7, Porsgrunn) (construction type IIIb). Also, sword 20 (Nome) probably has the latter construction. However, sword 20 deviates somewhat from the other swords in construction type III. The welded-on steel edges are unusually narrow, and the core has a piled, laminated structure throughout, the materials being soft iron and phosphorus-rich iron with bands of pearlite in between.

The obvious advantages of welding on pre-made steel sheets or steel edges to a core were: first, that the steel could be thicker and consequently longer lasting; second, that the smith knew he had a good piece of steel before it was introduced into the sword blade. The chance of bad luck during carburisation would be minimised.

In construction type III, only swords 3, 4, 8, and 9 had been heat treated.

Construction type IV. Another construction type which, according to the literature (Gilmour 1986), was fairly common in the Viking Age is the "sandwich" type, in which layers of steel and iron are piled and welded together in an edge-to-edge direction, so that there is always a steel layer running through the cutting edge (Figure 6.23, construction type IVa). This kind of construction would assure a varying degree of resilience to the blade, as well as providing the sword with harder, quenchable steel edges using a minimum amount of steel.

Different types of sandwich constructions are well known from swords, as well as from other cutting objects from the European continent and Britain (Tylecote and Gilmour 1986), and it is assumed that this method of producing sword blades developed from making knife blades.

The sandwich constructions may consist of one or more parallel steel layers piled alternately onto layers of iron. Steel layers may run either all the way from edge to edge (Figure 6.23, construction type IV) or they may be found only in the edge areas, which are then welded onto a separate core. In the latter case they would be classified as construction type III in this work.

It is not evident that any of the sword blades in this investigation have the edge-to-edge sandwich construction with a steel layer running through the actual tip.

Two of the examined blades cannot be easily placed within any of the mentioned types of construction. Sword 18 (Tokke) and sword 21 (Fyresdal), being double-edged and single-edged respectively, both have some kind of layered structures of fairly pure iron and mild steel.

Sword 18 (Tokke) has a kind of layered structure with a ferritic iron layer between two moderately carburised layers (possibly like Figure 6.23, construction type IVb). This may well be an intentional composition of alternating bars of steel and iron welded together in a somewhat oblique way. However, in one of the two examined sections of this blade only one of the edges coincides with the steel layer, while the other edge has fairly low carbon content. In the second section, carburised layers run through both edges (Figure 6.19a). The lack of steel in one of the edges in one section may have simply been due to somewhat unsuccessful forging. Similar structures of slanting layers of a softer material embedded between harder materials have been reported by Pleiner for Celtic swords (Pleiner 1993:136, 148). This construction, however, has not been reported in later sword blades from the Roman (Kedzierski and Stepinski 1989), the Anglo-Saxon and the Viking periods (Gilmour 1986). It therefore appears that the construction of this sword may be an accidental combination of sheets of steel and iron, or possibly a local construction type. This obliquely piled structure, when properly done, would have steel edges and some flexibility in the core. However, it does need more steel than necessary in a traditional sandwich construction, where one layer of steel running from edge to edge is sufficient.

The single-edged sword from Fyresdal (sword 21) has a different kind of layered structure, which may have been an unsuccessful attempt at making a sandwich welded together from layers of fairly pure iron and two layers of low-carbon iron (Figure 6.22a). The main purpose of a sandwich structure is to produce steel edges and adequate flexibility in the core using a minimum of steel. In sword 21 a carburised layer runs through the centre of most of the section, but ends up at the surface next to the edge. This may be due to bad luck during forging. The layers of carburised iron may also have been welded into the soft material just to stiffen the blade. A completely random composition of pieces of iron of differing carbon content is less likely, since the presence of a carburised tip of the edge shows that the blacksmith was far from unskilled. However, a random construction (construction type I) cannot be ruled out.

Construction type V, consisting of sword blades made entirely of steel, was not commonly found (Tylecote and Gilmour 1986:2; Pleiner 1993:138). After all, steel was time-consuming and costly to make. Also, the quality of the blade would not be improved compared to blades made of laminated sheets of alternating ferritic and steeled iron.

Sword 10 – the blade as well as the hilt – is clearly different from all other swords studied here. The blade material was made from a bar composed of several pieces of high-carbon steel. The blade has been quenched. The material is the same throughout the section, and the hardness values are high. This sword is, however, not indigenously made (see Chapter 4). Further, sword 8 (Porsgrunn) consists of a steeled material of medium to high carbon content throughout the section. However, as this sword has welded-on edges it has been classified as construction type III. It is assumed that the steel core, which is hard but softer than the edges, represents an attempt to make a flexible but not too soft material. It did not quite end up as such.

Chemical analyses. When etching the sections with nital, pronounced welding seams – particularly between the edges and the central parts in blades of construction type III – become visible as "pale lines". It was important to analyse such "pale lines" in order to find out to what extent reactions other than decarburisation, took place when welding the pieces together.

One weld in each of the following swords has been examined by microprobe analyses in steps across the "pale lines": swords 4, 11, 15, 17, and 19. The concentrations of arsenic, cobalt, nickel, manganese, copper and phosphorus have been determined. In these blades, phosphorus, copper and manganese were found to be present in fairly constant concentrations, too low to be of importance here. For all the examined sections the enrichment of cobalt is pronounced (Figure 6.24 a-e). Some arsenic enrichment was detected, but to a lesser degree than cobalt, while the enrichment of nickel is little or none. The general concentrations of cobalt, arsenic, and nickel in the bulk of the materials were quite low and typically less than 0.03wt% for all three elements. Enrichment of elements like cobalt, arsenic, and nickel in the welds was expected on the basis of results from other investigations of early iron (Tylecote and Thomsen 1973; Tylecote 1990; Modin and Modin 1988; Becher 1961; Thomsen 1971; Rosenqvist 1970). The suggestion in some of these papers, that an interlayer of high arsenic content had been introduced to facilitate the joining of iron and steel, has been questioned by Tylecote and Thomsen (1973). Arsenic-rich iron, in the same way as phosphorus-rich iron, suffers from severe hot-shortness, which would make forging down to thin sheets difficult. More probably, Tylecote and Thomsen suggest, the high-arsenic layers observed in the welds are due to the formation of arsenic segregates during forging. All three elements, cobalt, arsenic and nickel, oxidise slower than iron (Modin and Modin 1988; Tylecote and Thomsen 1973). During heating in the welding process the iron is oxidised, while cobalt, arsenic, and nickel are enriched in the surface layers. Phosphorus, being slightly less noble than iron, oxidises faster. Therefore, it does not accumulate in the weld during oxidation, but enters the oxide film (hammer scale) in the metal-oxide interface during forging.

The widths of the welds as estimated by the concentration profiles of cobalt enrichment are seen to be in the order of 0.07–0.12 mm (=70–120µm) in all the sections.

The structure of certain areas in the central part of sword 2 shows several parallel, light, wavy bands (Figure 6.3d). There are no other indications of welds, such as hammer scale particles or bands. Microprobe analyses across the pale bands confirm the presence of significant arsenic enrichment, and a slight enrichment of cobalt in the light bands (Tylecote 1990).

While the microstructures of the ferritic areas in some of the blades (swords 7, 16, 19, and 20) indicate fairly soft materials, hardness values show unexpectedly high readings. This was assumed to be due to the elemental composition of the materials, most likely the presence of phosphorus. As described in the experimental part, etching with Oberhoffer's reagent has been carried out on all the blade sections in order to map the presence of phosphorus in the iron. The blade sections which showed positive reactions to phosphorus segregations were further subjected to quantitative microprobe analyses. The presence of phosphorus-rich wrought iron was found to be connected mostly to surface decorations, such as inlays and piled structures where distinct and pleasing patterns were essential. Phosphorus-rich iron is found in the inlays of sword 16 (c. 0.27wt%, Figure 6.25) and in the piled structure of sword 7 (0.24–0.41wt%). Also, the layered structure observed in almost the entire central part of sword 20 was found to have elevated phosphorus content in the wrought iron layers (c. 0.28wt%). While the phosphorus-rich iron in the piled and pattern-welded parts of sword 7 and sword 16 must have been used deliberately, the use of phosphorus-rich iron in sword 20 is more difficult to explain. In this case the appearance cannot have been the intention, since the different layers are not visible on the blade surface. However, the presence of phosphorus not only influences the appearance, but also the hardness (and brittleness) of the material. It is therefore possible that this was used intentionally in the central part to produce a somewhat harder material. An accidental use of phosphorus-rich iron cannot be disregarded, but a skilled blacksmith would notice the difference between pure and phosphorus-containing iron during forging. The overall quality of sword 20 is decent. The smith was most probably a skilled specialist.

Only one blade (sword 12) is made almost entirely of phosphorus-containing iron. The material is somewhat heterogeneous with variable phosphorus content around 0.15wt%. This accounts for the increased hardness appearing in the ferritic materials.

In sword 19, one edge appears to be made from a layered material, while such layering is not observed in the other edge. Microprobe analyses across the layers indicate some enrichment of cobalt between the layers. However, the concentration is low, less than 0.05wt%. The concentrations of phosphorus, arsenic, and nickel are less than 0.03wt%, with no typical enrichment of arsenic and nickel in the welds. The presence of this layered structure must be due to some decarburisation in the welds of the material.

Surface decoration of the sword blades

A large number of Viking Age swords have been reported to have pattern-welded or inlaid blades. Lang and Ager (1989) and Kirpicnikov (1970) report that about half of the examined sword blades were made this way.

The characteristic decorative appearance of pattern-welded sword blades is usually due to a combination of sheets or rods of different materials such as pure iron, carburised iron, or phosphorus-rich iron. These materials react differently to etching, through which different patterns appear determined by cutting, twisting and forging the rods. Also, piled layers of the same material may produce the desired pattern when twisted and welded together (Anstee and Biek 1961), due to bands of trapped slag in the welds generating contours in the layers.

Whether the piled structures were twisted or just running parallel would probably not affect the properties of the core, though twisting the strips before polishing and etching the blade would certainly add to the fine appearance of the weapon.

Pattern welding has been considered to be a procedure used mainly to improve the flexibility and resilience of the blade. However, in recent years several authors seem to agree that pattern weldings served mostly as decorative elements (Tylecote and Gilmour 1986:1; Pleiner 1993:143). This opinion is based on the fact that extensive use of the pattern welding technique in sword blades began with wholly pattern-welded core materials around the 3rd century AD. On the continent, it developed into only thinly pattern-welded surface layers covering the blade core around the 5th century AD (Williams 1970; Lang and Ager 1989; Anteins 1968; Müller-Wille et al. 1970, 1982; Thomsen 1989; Thålin 1967). In the latter case it had no functional value, but the weapon still retained its impressive appearance. Later on, at the end of the 9th century AD, pattern welding becomes less common and is usually found only as inlaid letters and designs on blade surfaces (Müller-Wille et al. 1970:82, 1982:147,149). At this stage one realised that the same mechanical properties of the blade could be achieved through simpler methods. Sword blades of the 9th–11th centuries AD were frequently made by piling alternate pieces of iron and steel into a bar and forging them together without twisting (Williams 1970:75).

The blades in this study represent a selection of swords from within a certain geographic region, the county of Telemark (Figure 6.1). The presence of decorative elements such as pattern weldings and inlays is quite accidental. Only three of the 21 swords in this investigation have some kind of surface design (swords 7 (Porsgrunn), 10 (Tinn), 16 (Vinje)). The observed designs, whether inlays or pattern welding, are barely visible on the X-radiographs.

The piled structure of the pattern weldings in sword 7 (Porsgrunn) shows up in the micrographs as parallel layers of phosphorus and arsenic containing wrought iron and medium carbon steel respectively. The piled structures are present as thin sheets welded onto the surface of each side of the ferritic central part of the blade. Due to surface corrosion, the piled layers are partly discontinuous. Neither from the X-radiographs nor from the micrographs is it possible to recognise

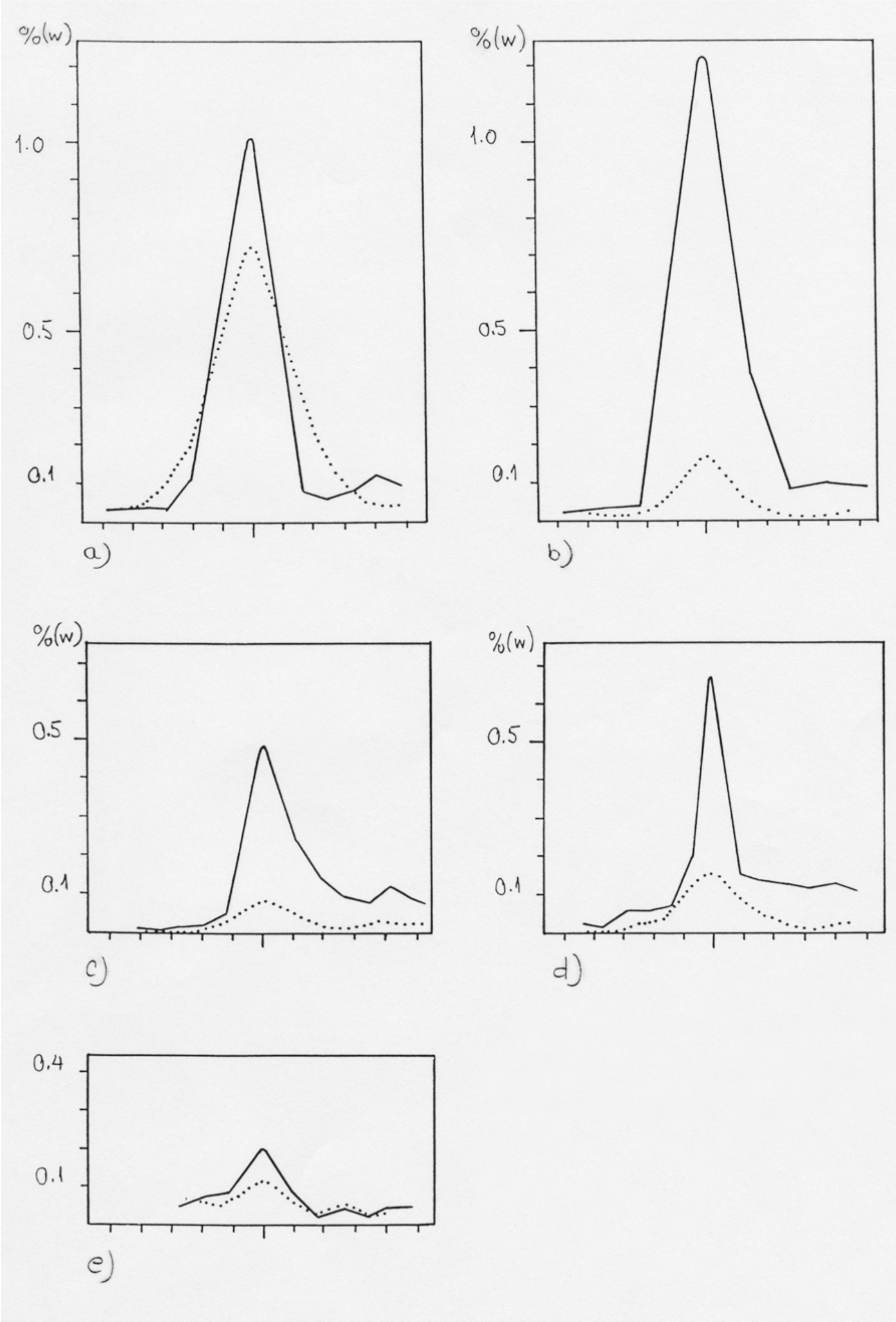


Figure 6.24. *Concentrations of cobalt – seen as a coherent line, and arsenic …? measured by electron probe microanalysis across the edge-to-core weld in: a. sword 15; b. sword 11; c. sword 17; d. sword 4; e. sword 19 (across one of the pale lines); and f. sword 16. The concentrations, shown on the ordinate, are measured in % (w); each step across the weld shows none.*

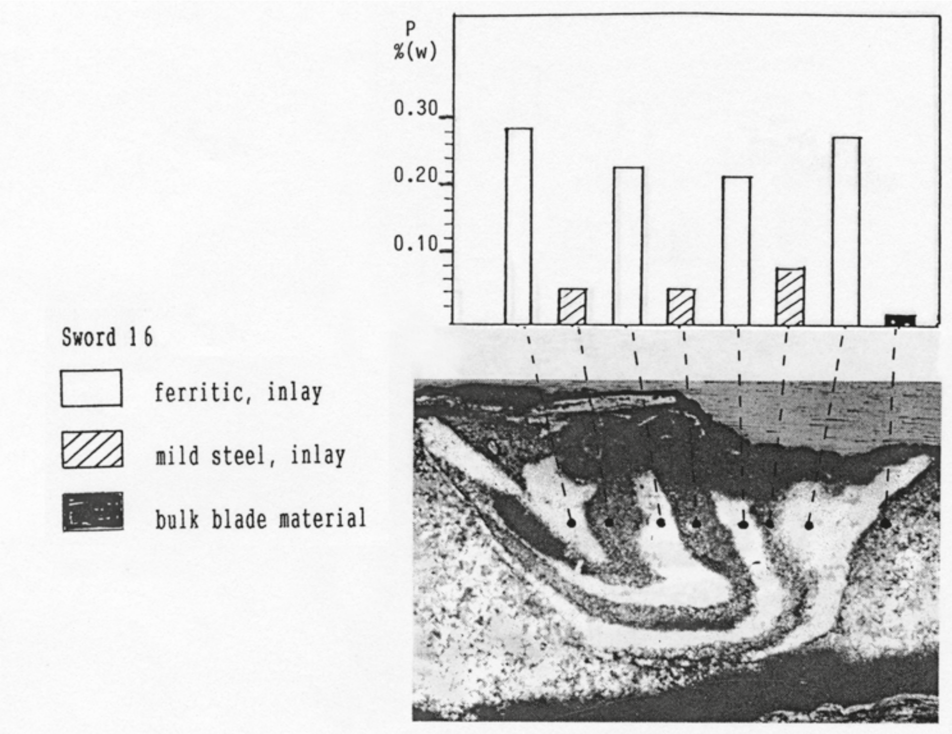


Figure 6.25. *Sword 16. The diagram (top) shows the phosphorus content in each layer of one of the inlays (bottom).*

the pattern with any certainty. However, parts of the X-radiographs seem to indicate two rods forming a "herring bone" pattern, i.e. two piled rods twisted in opposite directions.

Swords 10 (Tinn) and 16 (Vinje) both have inlaid designs in the blades. This is confirmed by X-radiographs. Stereoradiographs of sword 10 show two "omegashaped" inlays with a cross potent in between on one side of the blade. On the reverse, a roundish character is observed (Figure 6.11b).

Only the hilt and a small part of the upper blade remain of sword 16 (Vinje). Vague traces of an inlaid inscription on the surface can be seen, and also confirmed by X-radiograph. However, it is impossible to identify the characters. The section cut for the metallographic study runs right through some of the inscriptions on each side of the blade. This provides a good opportunity to study how the inlays were produced. Chemical analyses revealed that the inlaid characters were made from several wires of fairly pure iron, and iron with significant phosphorus content (0.27wt%, Figure 6.25). The wires were twisted, forged together and shaped prior to insertion into the soft, ferritic blade surface as described above.

6.5 CRAFTSMANSHIP AND THE QUALITY OF THE BLADES

A blacksmith who could produce high quality sword blades must have had solid and extensive practical knowledge of the specific mechanical properties of the materials with which he was working. During forging, he would notice the difference between wrought iron and steel. Moreover, phosphorus-rich iron would be recognisable because of its hot-shortness during forging and the brittleness of the finished product. Many of the same properties would appear in the case of high arsenic content, as phosphorus and arsenic have many common properties. However, such high arsenic content appears less frequently than phosphorus. Further, the presence of other elements in the iron may influence its material properties, but most likely this was not noticed by the blacksmith, since that would require an inconceivably high concentration of the elements. A competent smith obviously had the knowledge and ability to make good steeled iron through carburisation, and to harden the carburised iron sufficiently through heat treatment. Presumably he also had the practical skill to work the materials well enough to minimise the amount of slag and to avoid serious cracks, as well as to produce strong and solid welds between iron and iron alloys of different melting points. Further, he must have had adequate experience in how to combine the materials in order to attain good resilience in the core and the required hardness in the edges.

Based on the above, one can conclude that the blades examined in this work range from poor to high quality (Table 6.2). The table shows the quality of the sword blades from different find sites. A few of the blade sections in this work show remarkably high amounts of slag inclusions. Assuming that the sections are representative of the whole blade from which they were cut, such blades must have been weak and likely to break. High slag content, typical of materials having been insufficiently worked by the blacksmith, can be found in sword 1 (Skien) and sword 12 (Tinn). Sword 1 otherwise shows carburised surface layers (construction type IIa) which have been quenched. This indicates that the smith had fair knowledge of the production of sword blades, but that he did not practice his craft skillfully. The other blade rich in slag, sword 12, is made of phosphorus-containing iron throughout, which would improve the hardness of wrought iron but also increase brittleness significantly.

Those sword blades, which seem to be composed of random pieces of iron of varying composition, would be generally inferior in combat. The single-edged swords 5 and 6 (both from Skien) are typical examples of random composition (construction type I), soft materials, and poor functional combat capability. In addition, sword 15 (Vinje) must be classified as a relatively poor weapon. Although the blade has welded-on edges (construction type III) and a slightly higher carbon concentration in the edges, it is made from materials that are too soft throughout. This blacksmith obviously had some knowledge of the principles of making steel and of blade construction, which would normally result in a high quality blade. Unfortunately, he does not seem to have had the skill to carburise the iron sufficiently. As a combat weapon, sword 16 (Vinje) must also be classified as poor, since it was made from soft wrought iron throughout. As mentioned, the advantage of soft iron, which could be repaired by the warrior himself simply by hammering, can hardly compensate for the disadvantage of a sword that would serve its purpose for only a fairly short time in combat, due to bending and notching. However, the combination of soft blade material and inlays in the blade indicates

Table 6.2. *Features and Qualities of Metallurgically Investigated Blades.*

Sword No	Municipality	Hilt-type	Edges	Construction	Carburised	Quenched	Edge hardness (HV)		Slag content	Functional quality	Blade decoration
1	Skien	M	2	III(c?)	X	X	498		++	Poor	
2	Skien	M	2	IIa ?	X	X	551		0	Fair	
3	Skien	V	2	IIIa	X	X	325		+	Decent	
4	Skien	M	2	IIIa	X	X	590		+	High	
5	Skien	M	1	I			119	Soft	+	Poor	
6	Skien	M	1	I			156	Soft	0	Poor	
7	Porsgrunn	H	2	IIIa	X		263		+	Fair	Pattern-welded
8	Porsgrunn	Q/X	2	IIIa	X	X	591		0	High	
9	Bø	Q	2	IIIa	X	X	613		0	High	
10	Tinn	LA	2	V	X	X	636	Brittle	+	Decent	Inlayed signs
11	Tinn	Q	2	IIIa	X		283		0	Decent	
12	Tinn	Xa	2	I	Phos		178		++	Poor	
13	Tinn	Xa	2	IIb	X	X	413		0	Decent	
14	Tinn	Xa	2	IIb	X	X	420		+	Decent	
15	Vinje	Q	2	IIIa	X		153	Soft	0	Poor	
16	Vinje	H	2	I			165	Soft	0	Poor	Inscription
17	Tokke	Q	2	IIIa	X		201		0	Fair	
18	Tokke	Und	2	IV?	X		245		+	Decent	
19	Kviteseid	Und	2	IIIa	X		201		0	Fair	
20	Nome	Q	2	IIIb	X		289		+	Decent	
21	Fyresdal	M	1	IV (I?)	X		226		0	Decent	

Phos= phosphorus-rich iron.

that such swords might have been produced more as prestige weapons than for combat purposes. The nicely decorated hilt supports this assumption. A qualified smith would probably not have wasted precious steel where it was not needed.

The slag inclusions are denoted by 0; small amount and particles by +; moderate amount or numerous small, flat particles, ++; large amount, large particles, probably weakening the product.

LA = Late

Three of the four swords classified as fair quality have carburised edges. Three have welded-on edges (construction type III: sword 7 (Porsgrunn), sword 17 (Tokke), sword 19 (Kviteseid)), and one has edges that were carburised by direct carburisation of the nearly finished blade (construction type IIa: sword 2 (Skien)). Sword 7 shows a pattern-welded surface layer in the central part of the blade. Since the layers are only surface elements, they did not particularly improve the sword's mechanical properties as a weapon. Examination of these blades reveals that the smith had a fair understanding of sword blade constructions. However, these blades still cannot be classified as decent or high quality weapons, either because the degree of carburisation was too low or because heat treatment was lacking or insufficient.

Eight blades qualify as decent combat weapons, namely: swords 3 (Skien), 10 (Tinn), 11 (Tinn), 13 (Tinn), 14 (Tinn), 18 (Tokke), 20 (Nome) and 21 (Fyresdal). The makers of these blades were skilled craftsmen. The materials were worked well: the welds were carried out skillfully, and no severe cracks from the forging process were observed on the X-radiographs. The construction types of these blades (II, III, IV, Figure 6.23) and their compositions suggest that the blacksmiths also had adequate knowledge of the carburisation process and of sword blade constructions. All the blades have been carburised to an adequate level. However, five of the blades have not been heat treated. Still, the hardness in the edges of all these blades was measured to be above 220 HV, which is a fairly satisfactory material for a sword blade. Swords 13 and 14 have been heat treated. Both blades are type II constructions. The hardness measured in the steel layers, including the edges, is adequate, but especially in sword 13 the core is very soft and could easily bend in combat. It seems reasonable to assume that type II constructions are generally somewhat inferior to construction type III. Construction type II has a hard steel layer covering a softer inner iron core. This would provide less flexibility to the blade body. Most likely, a hard blow to the blade would easily result in cracking the thin steel layer.

Sword 10 (Tinn) is also classified as a decent weapon (construction type V). Despite the fact that this blade was highly carburised and successfully quenched, it was hardly an excellent weapon. Being made of highly carburised iron throughout, the core was also quenched to a hardness that makes the blade very hard and brittle. It lacks the resilience which is so important in sword blades.

The best blades examined in this work are sword 4 (Skien), sword 8 (Porsgrunn), and sword 9 (Bø). These blades show a favourable combination of high skill, solid knowledge, and an understanding of the importance of carburisation, heat treatment, blade constructions and craftsmanship. These blades are all type III constructions. The edges have satisfactory carbon content. In the case of sword 8, the core may perhaps be somewhat too hard and to some extent brittle. The heat treatments of swords 4 and 9 were found to achieve the right hardness of the edges and a suitable resilience of the core.

The significance of the sword in Viking Age society

Although the purpose of the sword must originally have been to serve as a weapon, it seems obvious that it has also served as a symbol of social status. This can be clearly seen from the time-consuming and elaborate work invested in many blades and hilts, which in no way improved the functional quality or combat capability of the sword. Indeed, a solid pattern-welded core in a sword blade contributed both to the marvellous appearance and to the resilience of the blade. However, comparable quality could still have been achieved through simpler but less visible and impressive techniques, like piling of the materials. For the large number of sword blades reported in the literature, in which inlays and pattern weldings are only surface features, such adornments had no influence on functional quality. As demonstrated in the present work (sword 16) and also pointed out by other authors (Gilmour 1986; Lang and Ager 1989), there are even beautifully decorated sword blades of poor functional quality. Therefore, it seems reasonable to suggest that such swords were made more as weapons of prestige than for combat purposes. On the other hand, the present work also shows that sword blades of high quality frequently appear without any decoration (swords 4, 8, 9). Thus, it cannot be concluded that swords with a pleasing appearance were necessarily high quality weapons or vice versa.

The difference in combat capability between poor and high quality sword blades is considerable, and the poor-quality swords would surely have performed badly in combat under otherwise equal conditions. Still, the number of poor blades appears to be significant. There may be several reasons for this. Poor blades produced by less skilled smiths were probably cheaper and easier to obtain. In order to handle a sword effectively in combat it was necessary to have had adequate training. It seems reasonable to assume that not every free man could handle a sword properly, and consequently did not invest in an expensive one. Or he simply could not afford the best that was available. Good weapons training was probably reserved mostly for men from the more prosperous segments of society. Especially in marginal areas, where society was less well organised than in central districts, one can easily imagine that a sword was handled and appreciated as a weapon to a lesser degree, but much more as a symbol of status. It was the privilege of the free man to bear weapons. Simply to own a sword – independent of quality and decorations – probably gave a man of lower social rank a highly appreciated status among equals.

However, men who first and foremost used their swords as weapons must have been able to distinguish differing quality, a fact also chronicled in Old Norse literature. These men would hardly run the risk of ill-matched combat due to a poor sword. Most probably, they would prefer a high-quality blade rather than a striking appearance, if they could not afford both.

6.6 CONCLUSION

Viking Age sword blades from Telemark have been analysed in order to gather comprehensive information on the construction and composition of sword blades, as well as acquire knowledge about iron manipulation and the craftsmanship of blacksmiths.

The study includes 21 sword blades recovered from coastal and central areas, from inland valley districts, and from sparsely and more densely populated areas. For certain districts, several swords have been studied in order to see if there were typical local features and variations in smithing techniques. The metal structures of the blade sections have been studied using metallographic analyses and hardness measurements. The elemental compositions of pattern welding, inlays and piled structures, as well as welding seams have been determined through electron probe microanalyses. This examination leads to the following conclusions:

1. The analyses show that the carburisation process became well-known to most blacksmiths, enabling this kind of weapon production during the Viking Age. Carburised iron and steel were deliberately incorporated into most of the blades in ways that improved the quality of the weapon. Eighteen of the blades were carburised, although a few of them not quite successfully. Successfully carburised sword blades have been found in every district included in this work (Table 6.2). This is hardly surprising, since carburisation of iron had already been successfully practiced for more than 2,000 years in the eastern Mediterranean by the time of the Vikings. Although dissemination of this technology was slow – probably intentionally so – the need for processes by which soft wrought iron could be hardened would nevertheless have been an incentive in the development of iron manipulation.

2. The metallographic structures and hardness measurements of the blades demonstrate that heat treatment or quenching of the blades was found in swords in the districts of Skien, Porsgrunn, Bø and Tinn, all of which were active and central areas in Telemark in the Viking Age. However, this technique was far from familiar to every smith. No heat treatment was observed in blades found in other districts included in this work (Table 6.2). Nine of the swords in this investigation (40%) indicate some degree of heat treatment. Some of the swords show a metallographic structure corresponding to a more or less full quench, while several swords underwent incomplete quenching. This may be due either to an unintentionally slow cooling rate, or to a skilled blacksmith who, on purpose, discontinued the cooling before a full quench was attained (slack quenching) in order to prevent the material from being too hard and brittle. The fact that quenched steel appears be present in the coastal and central areas, and absent in more remote districts, may indicate that the development of iron manipulation and the influence of foreign technical improvements were more pronounced in areas of higher activity and heightened contact with other countries. However, the lack of this more "sophisticated" technique in certain areas of Telemark may also reflect the limited number of swords examined so far.

3. The metallographic analyses demonstrate different ways in which sword blades were constructed (defined by construction types I, II, III, IV, V, Figure 6.23). Twenty of the blades can be ascribed to four different construction types (I, II, III, V). For two of the blades it is difficult to distinguish a deliberate construction from an accidental one. There is, however, some support for a deliberate, but not quite successful handling of both blades (construction type IV, Figure 6.23).

Ten blades (50%) were constructed with harder (steeled) edges welded onto a softer, more resilient core (construction type III). However, the attempts of the blacksmith to produce harder materials for the edges and resilient materials for the core were not always successful. One can deduce that this represents the most common blade construction observed in this work. This construction type is present in eight of the nine municipalities encompassed by this study (Table 6.2). However, with only one sword sample from the ninth (Fyresdal) one cannot conclude anything meaningful. Blade constructions in which a softer core is overlaid with a thin steel layer appear in four of the swords (construction type II). In two of these blades, the carburised surface layer was produced by direct diffusion of carbon into the nearly finished sword blade, case-carburisation (construction type IIa). In the other two, a pre-made steel layer has been welded onto the surface of a softer core (construction type IIb). Only one of the blades has a fairly homogeneous all-steel composition, forged from a single bar of high carbon content (construction type V), and possibly two blades seem to have some kind of "sandwich" structure (construction type IV). From this study the "sandwich" construction does appear to be typical for sword blades in Telemark in the Viking Age. A group of simpler blades (construction type I), considered to be inferior in battle to the construction types mentioned above, consisted of either random pieces of iron and mild steel, a fairly homogeneous material of phosphorus-rich wrought iron, or an almost pure soft wrought iron.

4. The craftsmanship demonstrated in the 21 blades in this work is mostly good. A few sword sections show minor cracks in the material. The X-radiographs of whole blades indicate generally good welding. Most blacksmiths exhibit fair knowledge of blade constructions and understanding of the specific properties of iron and steel. In a few cases, the blacksmith seemed to have had bad luck or insufficient skill to perform the carburisation and heat treatment as he intended. A few blades demonstrate a lack of knowledge and understanding of sword blade production (construction type I). An unacceptably high amount of relatively large slag inclusions in some sections indicates a less qualified blacksmith.

It is often assumed that blades with inlaid designs reflect particularly skilled smiths. However, recent reconstructions (Andresen 1993) show that this technique is not very difficult to execute. Consequently, no conlusions about the skill of the smith can be drawn from such decorations alone. Williams's metallographical investigations of 44 ULFBERHT swords demonstrated that these swords were made of very different materials and varied greatly in quality (Williams 2009).

Beautifully decorated sword blades often create the deceptive impression of also being of high quality. As is shown in the present study, this is not necessarily the case. Decorations that are only surface features, such as inlays and sheets of pattern weldings welded onto the surface of the core, do not influence the quality whether good or poor. Solid pattern-welded cores produce generally good resilience and strength to the blade. However, pattern-welded sheets cannot easily be distinguished from solid pattern-welded materials through visual examination of the surfaces.

5. While the general shapes of double-edged and single-edged sword blades were subject to few alterations during the Viking Age, the appearance of sword hilts underwent repeated changes – as a result of fashion and of the competence of the smith. However, blade dimensions do vary. The various blade construction types seem to have existed contemporaneously for several hundred years. Nevertheless, this and other investigations of Viking Age sword blades confirm the fact that different blade constructions display pronounced variations in composition, and hence in the quality of the blades.

Generally, there is no apparent correspondence between hilt types and types of blade construction. Yet it is striking that in this investigation all the swords with Q-hilts have the same blade construction, type III. However, the quality of the blades varies. The M and Q-hilts were the most common in Telemark in the Viking Age. Simpler blade constructions of inferior quality seem to predominate the M-hilts. All three single-edged blades in this work have M-hilts, and at least two of them are poor quality, owing to random composition and soft materials. The construction scheme of the third single-edged blade is difficult to interpret, but the quality is considerably better than the other two. Moreover, one of the double-edged blades with an M-hilt is fairly poor quality due to too much slag. The connection between Q-hilts and blade construction type III, and between M-hilts and inferior blade quality found in this work, may result from an insufficient number of blades examined. More reliable results will be available when further analyses have been carried out.

6. The observations in this investigation indicate that pattern-welded sword blades were not particularly common in the county of Telemark in the Viking

Age. The rare occurrence of pattern-welded blades in Telemark is further supported by X-radiographs of all the Viking Age swords from this county.

Only three of the 21 blades show some kind of surface decoration: one blade has a pattern-welded central part, and two blades have pattern-welded inlaid designs. Based on the results from other studies (Lang and Ager 1989; Kirpichnikov 1970) it was surprising to find so few swords with pattern weldings. However, the fact that there are many swords in Telemark in the Viking Age, but few decorated blades, may reveal a general impression, based on grave finds, of a steady level of prosperity with only few exceptions of great wealth in the county.

Elemental analyses of the materials responsible for the contrasts in the pattern-welded rods and in the inlaid characters in all three blades show that the design consists of alternating sheets or wires of phosphorus-rich iron and mildly carburised iron.

7. It is difficult to see special technical characteristics, which might distinguish clearly between different workshops. Further, it is difficult to point out any distinctive features, which can differentiate between domestic production and imports. Similar construction types were obviously present on the continent, in England, and in Norway for several hundred years. The skill or success of carburisation can only distinguish between individual blacksmiths, not between different regions.

It seems that only one blade can be clearly determined to be an import: the combination of an all-steeled blade (construction type V) with inlays that are closely related to "foreign design" strongly indicates an imported blade. This assumption is further supported by the type of decorations on the hilt, although in principle the hilt could have been a later addition.

It is, however, noteworthy that both blades of construction type IIa have been found in the Skien area, while both blades of category IIb were found in Tinn. In addition, the compositions and craftsmanship were comparable. As mentioned, the layered blade construction in which an iron sheet was welded in between two steel sheets (construction type IVb) was not common. Could this be a local construction, or just an accidental one, welded together from different sheets? The structure of the two blade sections of this sword suggests a deliberate construction.

The number of sword blades examined in this work includes only about 10% of the total known Viking Age sword material from the county of Telemark. The volume of Viking Age swords found in Norway offers an excellent opportunity to study blades on a larger scale. To ensure a solid foundation for conclusions relating to production techniques, quality and craftsmanship, and also to search for additional evidence for specific workshop traditions, this work needs to be followed by additional analyses of sword blades from other districts of Norway.

6.7 INTERPRETATION OF RADIOGRAPHS

Radiography is a fairly simple process to perform when facilities are available. Unlike metallographic analysis, radiography is non-invasive and much less time consuming. This makes utilising it on a large number of objects possible. There is also little need for specialised equipment to study traditional radiographs. The downside of radiography is that it cannot be trusted to reveal all welds and construction elements, elements that could easily be observed in a metallographic cross-section. Radiography allows some indication of the internal structures of the blades, though understanding the limitations of the method is paramount.

This study employed traditional two-dimensional radiography, mostly with analogue film. Some of the later batches of radiographs were acquired through a semi-digital system. The digital system had lower resolution (50 micron), but achieved better contrast than the analogue images. To get some sense of three-dimensionality, stereoscopic imaging was attempted during this project. The results here were limited. In the near future, extensive access to industrial strength microtomography (3D x-ray) could make systematic studies of radiographic cross-sections feasible.

The goal of doing radiography was to identify weld lines. Such lines were created when steel edges had been forge-welded onto an iron core, or some other variety of a composite blade construction. Not all weld lines are observable on radiographs, especially when limited to two-dimensions. The main factors affecting a possible positive identification are: the orientation or angle of the weld; how faulty the weld is; and how corroded the metal is. If the plane of the weld is parallel to the direction of the x-rays, then there is a good chance the weld will be visible in the images (a butt-welded edge, blade construction III). If the plane of the weld is oriented at a steep angle or 90 degrees to the direction of the x-rays, then the weld will usually not be possible to observe in traditional radiographs (welds oriented in the plane of the blade, blade construction II and IV).

Faulty welds are more visible in the radiographs, as these exhibit gaps and cracks. If such faults repeat along a line at a uniform distance from the edge, this is a good indication of a butt-welded edge. The state of degradation is also important, since heavy corrosion will "etch" lines or voids into the structures of the blade. Steel elements corrode more than areas of iron, differentiating them on the radiographs. Corrosion will also exacerbate gaps and cracks in faulty welds, making them wider and more discernible.

One should also be aware of the fact that somewhat haphazard weld lines observed in radiographs may represent earlier phases of forging. Such an early phase would be the refining of raw iron and patching together of iron pieces to construct a rough iron bar. Such an iron bar would then later be used either by itself to form a homogenous blade, or welded together with other bars of iron and steel to form a more composite blade construction.

6.8 RESULTS AND PRESENTATION

The total number of swords in this investigation is 221, including 15 items with only the hilts preserved. Of the total number of swords, 174 have been radiographed, and of these 167 are on film, 10 digital. Also, an additional 23 films have been digitalised, preferably those with uncertain (B) interpretations. Six swords have undergone all three procedures, and one sword was recorded on both a film and a digital radiograph. The digitalisation of films was done to find out if there were more welding lines to be seen, but the only result was that features we saw on the films became more distinct.

The remaining swords were either too badly preserved or not available to have radiographs taken, including the thirteen swords in Skien museum.

As our investigations relate to Norwegian blacksmiths' knowledge and skills, it is important to determine which of the metallographically investigated swords were indigenously made. There is no reason to doubt this for the M and Q-type swords, nor for sword 8, a Q/X-type, and sword 19. Of the indigenously made swords, no C-types are included, and none can be dated earlier than c. 850 AD. Sword 10, from the 11th century, is undoubtedly a foreign product (see Chapter 4). Swords 3, 7, 12, and 20 are of uncertain provenance.

Metallographic investigations have been instrumental in interpreting the radiographs. Firstly, we can compare the two methods on the metallographically investigated swords. Secondly, we can use this knowledge on the other radiographs. Of the five construction types found, categories I, II and V will not be visible on radiographs. Construction type IV is problematic. However, this construction type cannot be assumed to be numerous, based on our material.

Construction type III, with butt-welded edges, is the one most easily detected on radiographs. On several blades there are only vague indications of welding lines on very short parts of the blades (interpretation B). Two of the metallographically investigated swords, 15 and 17, have welded-on edges, but the welds are hardly detectable on the radiographs with only two 1 cm long lines on each. This proves that the majority of the swords with uncertain (B) interpretations most probably have welded-on edges, and that on other blades the welds can be invisible.

The radiographs demonstrate that the frequency of welded-on edges increased throughout the Viking Age, as did the frequency of double-edged blades. There are, however, a small number (four items) of single-edged blades of the Q-type, but none with X-type hilts.

Also, according to the metallographic results, hardly any single-edged blades have welded-on edges, independent of hilt types. Mostly they were equipped with indigenous hilt types, C, M and Q, though five of 15 radiographed specimens have H-type hilts. Of the double-edged H-type swords, two have certain, and two uncertain welded-on edges, including swords 7 and 16, with pattern welding and inscriptions respectively. The radiographs also confirm that few of the Telemark swords were pattern-welded or have inscriptions on the blade, but it is important to note that sword C.28352 from Fyresdal has the blade inscriptions +INGERIIIFECIT and CONSNVIIINS, which were not visible on any of the other four radiographs on film, but are visible on recently taken digital ones.