Examination of Ancient Scandinavian Archaeological Findings
From Tortuna in Västerås, Sweden
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Abstract

This study concerns the examinations of archaeological steel-objects from the Iron Ages, found in Tortuna outside Västerås, Sweden. Not many metallurgical analyses have been made on steel objects from the Iron Ages, most likely in order to preserve the findings. Therefore, very little knowledge about old steel materials exists. The main goal of this study was to investigate how steel-made items from the Iron Ages were created, what they have been used for, and determine what kind of metallurgical knowledge the blacksmiths of the Iron Ages had.

The experiments were conducted with light optical microscopy in order to investigate the morphology of the materials and with Vickers hardness test, to investigate the hardness of the materials.

The investigation gave varying results for the different iron-made objects. All of the objects have been forged in some way. Most of the objects, were made of heterogeneous low carbon steel with a mainly ferritic structure. Some items also showed a martensitic structure with a ferritic core, which concludes that the smiths probably knew how to quench and temper steel. Due to heavy corrosion on many of the items, further investigation is needed to strengthen the conclusions made in this report.

Keywords: Forging, microstructure, steel manufacturing, Iron Ages, bloomery furnace, amulet rings, edge tools, horse cleat, Vickers hardness.
Sammanfattning

Denna studie behandlar undersökningar av arkeologiska stålobject från järnåldern, hittade i Tortuna utanför Västerås, Sverige. Det har inte gjorts många metallurgiska analyser på stålobject från järnåldern, troligen för att bevara föremålen. Därför finns det lite kunskap om gamla stålmaterial.

Huvudsytet med denna studie var att undersöka hur föremål i stål från järnåldern tillverkades, vad de har använts för och bestämma vilken typ av metallurgisk kunskap dåtiens smed besatt.

Experimenten utfördes med hjälp av ljus optisk mikroskop för att undersöka materialets morfologi och med hjälp av Vickers hårdhetsprov för att undersöka materialens hårdhet.


Nyckelord: Smide, mikrostruktur, ståltillverkning, järnåldern, blästerugn, amulettringar, eggverktyg, hästbrodd, Vickers hårdhet.
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1 Introduction

The technology to refine and produce iron was introduced in Scandinavia during the Iron Ages, 500 BC-1100 AD. A smelter allowed the ancient smiths to melt iron and manufacture objects, which could be used for weapons, tools and other objects. The early smelters were called bloomery furnaces and produced steel with low carbon content with many inclusions, mostly in the form of slag [1].

In Scandinavia, archaeologists have discovered many iron-made findings from this period, including items like knives, hammers, axes, spears, swords and rings. The found objects differ greatly, based on their shape, size and function. To preserve the findings, not many metallurgical analyses have been made to gain more knowledge about the quality of the material and the manufacturing techniques used during the Iron Ages. Many archaeologists present numerous of their own theories regarding to the manufacturing process, quality and purpose of the findings.

At an excavation site at Tortuna, about one-hundred different iron objects were found in 2015 including different weapons, tools, jewelry and objects of unknown use. To learn more about iron objects from this excavation site and from the Iron Age, a more thorough analysis was needed.

1.1 Purpose
The main goal of this study is to investigate how iron-made items from the Iron Ages were made, what they have been used for, and determine what kind of metallurgical knowledge the blacksmiths of the Iron Ages had. By examining different archaeological findings from Tortuna, a greater knowledge about the materials properties and manufacturing process will be gained.

1.2 Limitations
To succeed with the purpose, limits were needed. A limit was set to focus on only Scandinavian iron-made items and manufacturing processes. The other limit was to primarily focus on metallurgical analysis with light optical microscopy, LOM.
2 Background

It is important to know the history of ancient items to have an understanding of the findings at archaeological excavations.

2.1 Iron-Ore

At the end of the Bronze Age, around 500 BC in Scandinavia, a technological revolution took place which brought the era to an end. Bronze was replaced by iron in almost every tool and weapon, because its mechanical properties were much better than those of bronze. The technology to refine iron came from central Europe, but unlike bronze, the iron did not need to be imported. The iron-ore could instead be found in small clumps below marsh pools and at the bottom of rivers. These kinds of iron-ore were called bog-ore or lake-ore and were an easy raw material to access. The ore contained many impurities and was of bad quality, but the Scandinavians developed and perfected techniques to extract usable iron by smelting it in simple furnaces. The skill to produce iron made significant progress over the centuries, by which followed greater complexity and quality of tools weapons [2].

2.2 Items

During this era weapons and tools had a big significant role due to the discovery of steel. Various shapes of the objects became known for different purposes.

2.2.1 Weapons

The most commonly used weapons during the Iron Ages were swords, battle axes, spears and maces. The sword, figure 1, was a single or double edged weapon with a typical length between 80 cm and 90 cm long. A sword has very special requirements, it has to be strong, hard, and sharp yet tough and flexible at the same time. A sword could be used to both hit and stab an enemy, other weapons can usually only do one. As a consequence, the sword was the most expensive weapon to make because it required the highest amount of iron and the most amount of work [1].
The battle axe, figure 2, was a common weapon used by the Vikings. It was made by a long handle in wood and a “head” in iron. Battle axes had low weight, were well balanced and could vary in both shape and size. The iron material used in the head was sturdy, which made them a very deadly weapon with a well-directed blow [4].

Spears were probably the most common weapon during this time because it required the least amount of iron to make. The head of the spear came in different shapes and sizes, from short to long spear heads. The shaft of the spear could be in wood or bone. The spear was an effective tool for stabbing and throwing at enemies [5]. A typical spear head during this era is shown in figure 3.
2.2.2 Tools

The earliest iron made tools were often made for multiple purposes, for example an axe, figure 2, could be used to both chop and split wood, and to be used as a weapon, if needed [7]. A hammer, figure 4, has a similar design as an axe, but have a flat head instead of a sharp one. Hammers were designed to deliver repeated blows and pounding and were commonly used during the iron ages, especially by blacksmiths. Knives, seen in figure 1, which could be described as “short swords”, were a good multipurpose tool and could be used for cutting, carving and stabbing.

2.2.3 Amulet rings

Besides tools and weapons, archaeologists have found unusual rings during the archaeological excavations in Tortuna. The main purpose and function of these rings is not yet certain, but the archaeologists think that they had some ritual connections. The rings have been found at different places at the excavation site, in graves, at corners of houses and also spread out at more non-residential areas. Some of the rings were more detailed than others, which indicate there was some sort of purpose behind the rings [9].

The rings can have various diameters, details and cross sections, depending on the ring. The cross section of the rings could either be round- or squared-shaped. The amulet rings have bigger diameters than other rings, which is also a part of how they got their current name. Some of the amulet rings have smaller rings hanging onto a bigger one. In other cases, there are small "hammers of Thor", see figure 5, hanging on smaller rings, which can directly connect the rings to its supposedly ritual purposes [10].
The production techniques of the amulet rings are also unknown for the archaeologists. The amulet rings have the shape of a circle and often the circle is assembled into one closed piece. To assemble the ring to one piece, the smiths have supposedly used a hammering method on where the two ends overlaps, which eventually forges them together. Other rings, which are not assembled into one piece, are instead bent at the edge into the middle. This has caused the smaller rings to stay on the bigger ring [11].

Figure 5. A typical amulet ring with smaller rings hanging onto it. With a small hammer of Thor besides [12].
3 Steel-Manufacturing Processes

During the Iron Ages, the manufacturing processes for iron developed throughout the period. It was the furnaces and the manufacturing techniques, which implemented the foundations for today’s processes. The iron was refined primarily form bog-ore and lake-ore, which could be found in marshes and rivers [2]. In order to extract the iron from the ore, the rocks needed to be heated to extremely high temperatures by a process called smelting [1].

3.1 Bloomery Furnace

In Scandinavia, a bloomery furnace, see figure 6, was used to melt the iron and was a fairly simple device. The furnace relied on natural draft to heighten the temperature in the furnace. Prevailing winds supplied the air to raise the temperature high enough to reduce the ore to a mass of metal and slag, but not high enough to oxidize or melt the mass. As a consequence, the forges were often built on sides of hills where strong winds could supply the oxygen required for the fire [1].

The early form of the low but wide chimney had an opening at the bottom for feeding in the air and manipulating the bloom. From the top it was filled with a semi-mixed layer of ore and charcoal, and eventually other appropriate fluxes, like limestone, were used to carry off or absorb impurities [1].

The ore used to create the iron was a critical point in creating the material for the tools. The ore could have many impurities which made the iron hard and brittle and therefore difficult to shape or work upon. Some common impurities in iron ore are sulphur, phosphorus and arsenic. Although phosphorus is often considered as an impurity, because it prevents carbon from entering the iron, phosphoric iron has some advantageous properties and was often used for various purposes in ancient times. But a few ores could contain natural high-quality alloys like manganese which strengthen the iron [14].

Bloom furnaces were not hot enough to completely melt the iron ore to a liquid state, instead it reduced the ore to a big block of mass with both iron and slag. To succeed with this kind of furnace, the proportions of air flow and heat needed to be carefully controlled, the carbon in the charcoal would cause the iron to aggregate
which reduced the oxygen of the iron oxide to carbon monoxide, according to equations 1-3 [15].

\[
3Fe_2O_3 + CO \rightarrow 2Fe_3O_4 + CO_2 \quad [1]
\]

\[
Fe_3O_4 + CO \rightarrow 3FeO + CO_2 \quad [2]
\]

\[
FeO + CO \rightarrow Fe + CO_2 \quad [3]
\]

This caused some of the impurities to burn away and others to melt as slag. After some time, all that is left is a large, red and spongy mass of the reduced iron and slag. This material is called bloom or sponge iron [1].

This “bloom” would then be dragged out from the furnace out at the opening, or in some instances, the whole furnace is needed to be dismantled to extract the spongy mass. In this form the material was completely useless. In order to be able to use the material, the iron needed to be repeatedly worked upon. This could be done by hammering out the impurities with a hammer and then reheating the iron to welding temperatures numerous times. Depending on the carbon content, the welding temperature is between 1200 and 1500 degrees Celsius.

This process, shifting back and forth with welding-forging-welding “burned off” the excess carbon in the atmosphere of the forge and forced out impurities with the deformation caused by hammering, bending or pressing. This process created steel which goes by the name of wrought iron [14].

### 3.2 Shaft- & blast-furnace

Iron processing began to play an even bigger role at the beginning of the Middle Ages, around 1100 AD, when the iron ore could be completely melted in a blast furnace. This made it possible to produce much larger volumes of iron than before. The blast furnace consisted of a high shaft with a semi mixed layer of iron ore, charcoal and limestone which was filled from above. At the bottom, air was blown in to make the fire hot enough to melt the iron. This was carried out using hydropower as an energy source to crush the ore. Water wheels were also used to drive hammer and stamps. The iron made from the blast furnace is called cast iron or pig iron and had high carbon content, around four percent, figure 7 illustrates a blast furnace.

There were different types of shaft furnaces. The various types of ovens have many different properties, which can occur separately, or in combination:

- It can be built as a funnel/semi-round pit or as a cylinder-shaped shaft. These two models are called “pit furnace” and “chimney oven”.
- It can be excavated in the ground or it can be built up in a high.
- It can be equipped with intake for blaster, or it not. The blaster intake is located in the front of the oven and the air (O\(_2\)), from one or two bellows,
enters to keep the temperature even. The oxygen has two functions in the manufacturing process.
  - To keep the operation running.
  - To facilitate the separation of the slag from the iron.
• It can be equipped with a tap to drain the slag from the oven or not. The slag that is removed from the iron ore is often collected in the bottom of the oven. Sometimes it is good to shed the slag during the process instead of shoving it out after the burn. If so, a passage was created from the oven to a pit in front of the oven where the slag can drain out [16].

Over time, the demand for iron increased and the blast furnaces became more efficient by making them larger and built in stone to cope with more stresses. [17].

Figure 7. Blast-furnace [18].
3.3 Forging
Forging is a manufacturing process which uses compressive force to shape a workpiece. The process is performed at “hot” or “cold” temperatures with forging-tools, which presses and squeezes the material in order to deform it. The deformation strengthens the material with a phenomena called strain hardening.

The most common and well known forging process is hot forging. The process enables highly customised parts with complex geometries, due to the large amounts of plastic deformation. Hot forging is performed above the recrystallization temperature, around 1150 degrees Celsius for carbon steels, the high temperature is needed to avoid strain hardening of the metal during deformation. This allows an increased ductility, but decreased strength of the metal. In order to optimize the metallurgical structure and obtain the required mechanical properties, a heat treatment is needed on the metal after hot forging [19]. Figure 8 illustrates a workpiece in steel which is being hot forged.

Cold forging is performed at room temperature. The metal is deformed with different techniques, including rolling, drawing, spinning, extruding, pressing and heading. The deformation starts at room temperature and changes the shape of the initial part until the wanted shape is acquired. During the deformation process, the steel part can reach a temperature up to 250 degrees Celsius since the friction are very high during deformation. In order to perform cold forging the carbon content of the steel needs to be below 0.5 wt%. A big benefit of cold forging is the lack of grain growth, which results in an exceptionally strong and resistant surface. Another benefit of strain hardening is that the mechanical properties is enhanced [21].
The main difference between the processes is that cold forging increases the strength of the metal through strain hardening at room temperature, while hot forging keeps the material from strain hardening at a high temperature. Resulting in optimum yield strength, low hardness and a high ductility [22]. Figure 9 illustrates a stress-strain curve, showing typical strain hardening plastic behaviour.

![Figure 9. Typical Stress-Strain curve of work hardening plastic behavior [23].](image)
4 Phases and Structures in Steel

When steel is made, depending on the treatment and manufacturing method, different structures will occur. Figure 13 illustrates a typical Iron-Carbon (Fe-C) phase-diagram with involving phases.

Ferrite, figure 10, (alpha-iron, α) is a solid solution and stable at room temperature. It has very low carbon content, less than 0.02 wt% and is soft, flexible and highly malleable. When the carbon content rises another structure appears, called perlite. It is structured with alternating layers of cementite and ferrite and the carbon content is 0.77 wt%. Perlite, figure 11, makes the steel more ductile and tougher, but is less malleable than ferrite. Cementite contains 6.7 wt% carbon and the material is hard and brittle. Cementite can frequently be found in cast iron.

![Figure 10. Ferritic structure](image)

![Figure 11. Perlitic structure](image)

Austenite, also known as gamma iron (γ), is an allotrope of iron and can dissolve up to 2.14 wt% carbon. Austenite is the phase where most of the steel making and different heat treatments begins. Austenite has a high formability and is not stable at room temperature under certain conditions. It is possible to obtain a stable austenitic structure in room temperature.
Martensite is formed when austenite is cooled, see figure 12, rapidly and is an exceptionally hard and brittle phase. The transformation from austenite to martensite is diffusionless transformation, which means that the atoms diffuse to new atomic positions instantly. Martensitic structure is extremely valuable for tools and weapons, to obtain hardened steel.

Figure 12. Martensitic structure [26].

4.1 Carburizing

Carbon diffusion is of great importance in order to understand what happens during the smelting and the manufacturing of steel objects.

Carbon diffusion in iron based metals, occurs when carbon atoms from an area of high concentration moves to an area of low concentration. Carbon diffusion is an interstitial process due to carbon atoms being significantly smaller than iron atoms. Therefore, the carbon atoms can diffuse between the iron atoms and move through the lattice.

Figure 13. Phase diagram of Fe-C in wt% [27].
Carbon diffusion only happens within a small area. To achieve carbon diffusion through the surface of a steel material, a rich carbon atmosphere is needed. This can be achieved by sealing the metal in a closed environment, like an oven, for several hours. To reach the desirable amount of carbon diffusion, with good tolerances, a controlled environment is needed, and during the Iron Ages this was very hard to accomplish. However, the carbon rich atmosphere could successfully be made by adding materials with high carbon contents in the furnace, like bones and charcoal [28].

This process is called carburizing and increases the carbon content on the surface. The process will also harden the surface of the iron, but not the core. Carburizing will only work if the iron has low carbon content to begin with, due to diffusion works according to the differential of concentration principle. That means, for example, iron with high carbon content is heated in a low carbon atmosphere, like air, the carbon will instead diffuse out of the iron, resulting in something called decarburization [29].
5 Investigated objects from Tortuna

The investigated items are from Tortuna, a livestock place from the older Iron Age, which is located outside Västerås in Sweden. The tools and items found at the Tortuna archaeological site date to between 300 and 1100 AD. In addition to the approximately 100 metal objects discovered, ceramics, fragments of weave fabric and some animal bones were also found. Figure 14 shows the excavation site of the old town Tortuna. The objects examined were found in the area at the middle of the map, at the dark brown area, marked with the black ring.

Figure 14. Map of Tortuna excavation site 2015.
The amulet rings originate from the 8th century, during the Viking Age. Some of the other discovered items might have been used to ritual purposes as well, but as different kind of offerings. The archaeologists have found some of the objects in combination with bones and cereal grains, which could be the remains of a ritual feasts. In the figures 15-24 there will be a description of what the archaeologists think the items were used for [30].

Figure 15. Sample nr 130.
Nail.

Figure 16. Sample nr 90.
Small knife.

Figure 17. Sample nr 86.
Handle of a knife blade.

Figure 18. Sample nr 7.
Horse cleat.
Figure 19. Sample nr 64.
To the left: piece of spear.
To the right: unclear piece.

Figure 20. Sample nr 46.
Big knife.

Figure 21. Sample nr 35.
Pot ear.
Figure 22. Sample 31 (left) and 24 (right). Cut amulet rings from excavations.

Figure 23. Sample 72. Small knife blade.

Figure 24. Sample 85. Unknown object.
6 Method

The items were first documented, by measuring and taking pictures. The objects were then cut with a discotom, see figure 25, into smaller samples. A discotom is a water-cooled cutting equipment which delivers a fast and accurate cutting in a safe environment. All samples were cut near the edge, to preserve as much as possible of the old object. The rings were cut two times to gain two independent smaller parts, while all the other objects were cut only once.

![Figure 25. Cutting equipment called discotom](image)

When all samples had been obtained, they were grinded with sandpaper to gain an even surface. This operation was necessary in order to cast them into pellets made by bakelite. The metal-pieces were placed in a pellet machine with the cross-section surface down into a stationary pellet form. One table-spoon with bakelite-powder was then poured over and around the pieces in order to cover them completely. The machine created the pellet with heat and pressure during 8 minutes followed by a 4-minute cooling process. The bakelite-samples were again grinded with sandpaper to smoothen the surface and later on polished with diamond paste and cleaned with ethanol, in order to reach an acceptable surface-finish.

As a last step, all samples were etched with the help of 4 %-nital, containing nitric acid and ethanol. It was very important to be thorough during the polishing and the cleaning step, otherwise cracks and small water bubbles on the surface could be seen, which can indirectly affect the end results. The etching was needed in order to see different structures on the samples, because the etchant affects the metal surface, which visualizes the grain boundaries and the different phases.

The samples were then analysed with light optical microscope and subjected to Vickers hardness measurements.
6.1 Light Optical Microscope

The metallurgical analysis was performed with a light optical microscope, LOM, and with the help of the software LEICA QWin V3. Grain boundaries, structures and defects could be distinguished depending on how well polished and etched the material was. Interesting areas on the samples were analysed and documented with pictures. Depending on the type of sample, between 2-6 pictures were taken and with the same, or with different magnifications. During the metallurgical analysis 5-, 10-, 20- and 50-fold magnification was used.

6.2 Vickers hardness test

The archaeological objects were categorized by their hardness and divided into three groups, see table 1.

<table>
<thead>
<tr>
<th>Category</th>
<th>Hv</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soft</td>
<td>0-150</td>
</tr>
<tr>
<td>Medium</td>
<td>150-250</td>
</tr>
<tr>
<td>Hard</td>
<td>250-infinity</td>
</tr>
</tbody>
</table>

Table 1. Hardness according to category.

To determine the hardness of the samples, a Vickers hardness test was performed. The hardness was measured with a hardened pyramid-shaped diamond tip, with a peak angle of 136 degrees, pressed with a given force into the material of the sample. For this analyse, a 200-gram load was used in every test. All samples underwent 3-4 measurements, at different places, on the surface of the material. This was to obtain a good average on the overall hardness of the materials. The software, LEICIA QWin V3, was used for measuring and calculating the diagonals of the pyramid-shaped diamond tip at 50-fold magnification.

The hardness is calculated with the equation 4 [32].

\[
HV = \frac{F}{A} \approx 1.854.L \frac{[kg*f]}{d^2 [mm^2]}
\]  

[4]

Where L, load, measures in [kg*f] and d, diagonal, measures in mm.
7 Results

The following results will be presented from the metallurgical analysis. For better overview of the metallurgical analysis see appendix A.

7.1 Amulet rings

All three amulet rings were much corroded and quite fragile, but the middle core parts contained some solid metal. The metal cores consisted mainly of ferrite with small parts of perlite. The rings below will be named 24, 31 and 80. The samples were very small and therefore the pictures below will be from both parts.

7.1.1 Ring 24

In ring 24, figure 26, ferrite can be seen with small inclusions of oxides, illustrated within the white circle in figure 27. The sample contains mostly of ferrite, the bright and grey areas, and oxides, the darker spherical parts.

The slag in form of oxides has round shapes, which shows that the material has not been significantly worked. Figures 27 and 28 show large size grains with elongated structures, indicating that the material has been somehow heat-treated. Figure 29 shows a mixture of big and small grains of ferrite and the edges show it has been deformed. In figure 30, which shows the core of ring, the microstructure consists of big ferrite grains with small inclusions of slag.
7.1.2 Ring 31

Ring 31, which can be seen in figure 31, consists mainly of ferrite together with small amounts of perlite, see figure 32-35. The bright areas represent ferrite and the darker areas represent perlite. Figure 32 has been estimated to hold 25%-30% perlite with the rest being ferrite. Figure 33 shows grain growth from the edge to the middle of the sample which indicates signs of recrystallization. Figure 34 and 35 show different parts of the ring with a similar structure in the core.
7.1.3 Ring 80

In ring 80, see figure 36, ferrite can be seen with small amounts of perlite and some corroded regions, shown in the white circle in figure 39. The bright areas represent ferrite and the darker areas represent perlite. As shown in the pictures the structure of this ring is unevenly distributed. In figure 37, an estimated 10% is perlite and the remaining is ferrite. Figure 38 and 39 shows much more perlitic structure with different magnification. The figure 40 shows another part from the sample.

7.2 Knives

The knives contained mostly martensite on the edges, while the core of the samples has a ferritic and perlitic structure. The light area is ferrite and the darker area at the edges is either perlite or martensite, depending on the microstructure. The knives below are numbered 64 and 90 and one sample was taken from each object.
7.2.2 Knife 46

Sample 46 contains of a mixture of a corroded surface layer, martensite at the edges and ferrite at the core, see figure 41. In figure 42, shows the overview of the sample.

Figure 43 shows how much the sample has corroded from the surface. Figure 44 and 45 shows the core of the sample in different magnifications which contains mostly ferrite with partly dissolved perlite. Figure 46 and 47 shows different magnifications of tempered martensite at the edge.
7.2.3 Knife 90

Sample 90 contains the structures of ferrite and martensite, seen in figure 48. Figure number 49 shows the overview of the sample. The figure 50 shows the ferritic structure in the core of the sample. Figure 51 and 52 show different magnification of martensite at the edge of the sample.

Figure 48. Sample 90.

Figure 49. 10-fold magnification, overview of sample 90

Figure 50. 50-fold magnification, middle of sample 90.

Figure 51. 20-fold magnification, edge of sample 90.

Figure 52. 50-fold magnification, edge of sample 90.
7.2.4 Knife 86

Sample 86, see figure 53, mostly consisted of ferrite structure throughout the sample and was also much corroded. It contained same grain size across in the whole material and due to corrosion there was little material left that were useful.

Figure 53. Sample 86.

Figure 54 shows an overview of the sample.

Figure 54. 10-fold magnification, edge and middle of sample 86.

7.2.5 Knife 72

Sample 72, sample 55, shows an inhomogeneous ferritic structure with varied grain size. Near some the edge, recrystallization has occurred, a smaller grain size and higher carbon content can be seen in these parts. Slag can be seen as well, in picture 56, they show up as black strips and small dots while in picture 57 they can be seen only as small black dots.

Much of the sample’s edge is corroded.

Figure 55. Sample 72

Figure 56. 5-fold magnification, overview of sample 72.

Figure 57. 5-fold magnification, overview of sample 72.
7.3 Horse cleat 7

Sample 7, see figure 58, shows only ferritic structure with big even grains. Figure 59 and 60 shows different areas of the sample. The black dots in the pictures are not oxides but water bubbles which did not disappear during the polishing step.

Figure 58. Sample 7.

Figure 59. 5-fold magnification, middle of sample 7.

Figure 60. 5-fold magnification, edge of sample 7.
7.4 Nail 130

Sample 130, see figure 61, shows a mixture structure of perlite and ferrite with different grain size through the sample. In figure 62 and 63, shows a varied grain size of the sample of ferrite, white areas, and perlite, the darker parts. The figures 64 and 65 show different magnifications of area with perlite and ferrite.

Figure 61. Sample 130.

Figure 62. 5-fold magnification, overview of sample 130.

Figure 63. 20-fold magnification, middle of sample 130.

Figure 64. 10-fold magnification, edge and middle of sample 130.

Figure 65. 100-fold magnification, middle of sample 130.
7.5 Spear shaft 64a

Sample 64a, seen in figure 66, contains ferrite with varied grain size, a bit of slag, and a thin surface layer of a copper alloy. The black strip in figure 67 is not part of the microstructure, it is just a crack in the material, which probably arose during the cutting stage.

Figure 66. Sample 64a. Figure 67 and 68 shows that the material has been heat treated in some way at the edge, see area in the white ring. In figure 68-70 a layer of copper can be seen at the bronze-colored area at the edge.

Figure 67. 5-fold magnification, edge of sample 64a.
Figure 68. 5-fold magnification, edge of sample 64a.
Figure 69. 5-fold magnification, edge of sample 64a.
Figure 70. 5-fold magnification, edge of sample 64a.
7.6 Pot ear 35

Sample 35, see figure 71, is very inhomogeneous containing varied grain size and a mixture of perlite and ferrite. Figure number 72 shows ferrite with very low amounts of carbon with mechanical twins. The small string in the middle contains a higher amount of carbon. Figure 73 shows that the object has been processed in some way. Figure 74 shows perlite with ferrite in grain boundary in the edge of the sample. In figure 75 shows the thickness of the oxide layer and ferrite grains with small amounts of perlite, the darker parts, on the edge of the sample.

7.7 Unknown samples

The unknown samples contained mostly ferritic structure with varied grain size. Perlitic structure can be seen as well, which is the darker areas. The two samples showed different structures with elements of unusual appearance.
7.7.1 Sample 64b

The sample 64b, seen in figure 76, contains varied grain size of perlite and ferrite. Figure 77, 78 and 79 shows an unusual appearance in the grain boundaries, which looks like dried liquid spots. Figure 80 shows the edge of the sample that has been elongated. Figure 80 and 81 shows varied grain size of perlite and ferrite in different parts of the sample.

Figure 76. Sample 64b.

Figure 77. 5-fold magnification, edge of sample 64b.

Figure 78. 10-fold magnification, edge of sample 64b.

Figure 79. 10-fold magnification, middle of sample 64b.

Figure 80. 10-fold magnification, edge of sample 64b.

Figure 81. 10-fold magnification, edge and middle of sample 64b.
7.7.2 Sample 85

The sample 85, see figure 82, contains varied grain size of mostly ferritic structure with small elements of perlite. Figures 83-85 shows different parts of the sample.

*Figure 82. Sample 85.*

*Figure 83. 5-fold magnification, edge and middle of sample 85.*

*Figure 84. 5-fold magnification, edge and middle of sample 85.*

*Figure 85. 5-fold magnification, middle of sample 85.*
7.8 Vickers Hardness test

The diagram in figure 86, shows how the Vickers hardness for every sample. Each colour represents a hardness category, soft, medium or hard. Knives 46 and 90 have been divided into two staples, one staple represent the core of the sample and the other staple represent the edge of the sample.

Table 2 shows the Vickers results in table form, figure 87 shows Vickers hardness for modern low carbon steel. All measurement data from the hardness test is concluded in appendix B.

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<td></td>
<td>64b</td>
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</table>
Figure 87. Modern low carbon steel values, interval from low to high values [32] [33].
8 Discussion

Many archaeological findings have been examined in this report, most of which have been a mystery for the archaeologists, regarding to function. The rings are believed to have been used for cultural or religious purpose, the horse cleat might have been used to be put on horse’s hooves, and some items the archaeologists have few or no suggestions what they have been used for. Much energy has been put into the items during their construction, some more, other less. To see if archaeologist’s hypotheses about the items are true or not, comparisons with the objects’ microstructures, literature study, hardness results and the archaeologist’s hypothesis have been conducted.

8.1 Manufacturing Method

Two furnaces have been described in this report, the bloomery furnace and the blast furnace. Both processes could have been used when creating the steel to the investigated items, but the bloomery furnace is much more likely to have been used in creation of the objects. This theory is primarily based on the time span, from which the items originate from, is much larger when the bloomery furnace was used, in comparison to the blast furnace. Another point is that all the finds contained ferrite, this indicates that the carbon content is very low, which is typical for a bloomery furnace.

8.2 Amulet rings

The amulet rings have been a mystery to the archaeologists at Uppsala University. The most likely use of the rings is as ritual objects, with little practical use. The amulet rings are bigger than normal jewelry rings, but smaller than necklaces, which strengthen this hypothesis. The rings have also been found under house foundations, at very specific positions which also entitles that the rings have some ritual purpose.

The shape of the rings shows that they probably have been hot forged. The ferritic structure reinforces this observation. Many other amulet rings have been found, not only at this excavation site but at other excavation sites in Sweden as well. The size of the rings can differ, but the shape is usually the same and they are found at similar places, which give an indication that the rings must have been used for a specific purpose.

To determine the actual use of the rings is very hard to make, what can be said is that the manufacturing process has been similar in almost all of the rings. There are of course deviations, ring 24 showed almost completely ferritic structure, but with signs of heat treatment, if this has occurred during the cutting stage or if it has arisen during the manufacturing is hard to conclude. The most likely suggestion is that it has arisen during the manufacturing, due to the discotom cools the metal piece with water when cutting. Ring 31 and 80 have mostly ferritic structure as well but ring 31 has signs of recrystallization and small areas of perlite, while ring 80 have bigger areas of perlitic structure. The inconsistency of the rings, according to the structure, indicates that they must have been made in accordance with their visual appearance.
rather than their practical function. As a ritual object the appearance is much more important than the practical use, which is why the blacksmiths must have had knowledge about what kind of material they were creating when manufacturing the amulet rings.

The reason why there is no data about sample 31 and 80 from Vickers hardness test is because they were categorized within the same group of use as sample 24. The samples contained mostly ferritic structure, which nearly all objects did. This concluded that sample 24 made a good representation for all of the rings that were included in the test, see table 3.

8.3 Knives
The edge tools 46 and 90 had very interesting structures. In these samples a martensitic structure can be seen at the edge and a ferritic structure at the core. This makes the edge very hard and the core more ductile. Pure alpha-iron is too soft to make a good cutting edge, because a good cutting edge requires higher carbon content. Therefore, carburizing must have been conducted to gain the harder martensitic structure, as well as quenching. Another thing to point out is that the martensitic structure can be seen very well, this indicates that the blades have been tempered in some way, otherwise the lenses that defines the martensitic structure would not have been visible.

Much energy and work has been put into both blades. The bigger knife blade, sample 46, is presumably more processed than the smaller knife, sample 90, which can be seen when taking a closer look on the shape of the slag. The slag in knife 46 is a bit more “drawn out” compared to knife 90, which indicates that a bigger effort has been put into the bigger knife.

The combination of a hard martensitic edge and a soft, ductile ferritic core in knife 46 and 90, shows that ancient blacksmiths knew how to quench, temper and harden steel. This leads to the conclusion that blacksmiths of the Iron Ages knew how to manufacture a high quality steel material.

Knife 86 and 72 showed only ferritic structure, this indicates that they most likely have not been used as practical knives. The structure in knife 72 also has signs of recrystallization, which might suggest that more work has been put into this knife. Two conclusions can be drawn from this, either the blades had another purpose, like a ritual one, or a harder structure on the surface have disappeared by the heavy corrosion.
8.4 Other Samples
The function of the “horse cleat” has troubled the archaeologists. They believe it has been used as a horse cleat, because they have found them in graves together with skulls of horses. The main purpose of a horse cleat is to reduce the risk of the horse falling. Sample 7, have supposedly been used for farming during summer and hunting and transports during winter time.

Today’s horse cleats have a different appearance and a different length than the Iron Age horse cleat. A horse cleat today, especially for grass is 14mm, almost twice as big as the found item. The material in a modern horse cleat is often stainless steel with a hard core.

The “horse cleat” contained a completely ferritic structure with big and even grains. This structure makes the material very soft and useless in an application as horse cleat. A horse cleat needs to withstand hundreds of kilos during a long period of time, which is unlikely for the found cleat. A much harder and a more durable structure is needed to withstand these kinds of forces, like perlite or martensite. Which makes it clear that this material has not been used as a horse cleat. However, the item is over 1000 years old and much corroded. There might have been another layer of a harder structure when it was made, because the size of it is very small and therefore a big chance that it has disappeared over the years. There is a small chance that it have been used as a cleat, but in order to strengthen this thesis, further research is needed on other similar horse cleats.

Sample number 130, the nail, showed both perlitic and ferritic structure with mixed grain size. The main thought of this item would have been that it could be used as some sort of nail. It has a sharp tip and wider head, but the structure and the Vickers hardness test indicates that the material is not strong enough to carry a high amount of load, which is needed when the nail is hammered into a wooden plank or similar material.

Sample number 64a is a part of a spear and with big certainty a piece of the spear holder, which holds the shaft made out of wood or bone. The microstructure of the spear shows mostly ferrite with even grain size, but around the edges, a clear surface layer of copper can be seen. The copper alloy covers the whole surface of the material. The steel material is soft due to the ferritic structure and a spear would benefit from a harder structure, much like the knives, for example perlite or martensite. One explanation could be that the tip of the spear was treated in another way to gain a harder structure, while the holder is softer, this might make it easier to fasten it to the shaft. Another explanation is that this spear has been used as a ritual object, much like the rings, and that the spear has been dipped in molten copper to make it appear as a more noble material.

The pot ear, sample number 35, has extremely inhomogeneous grains with both ferritic and perlitic structure. The shape of the item and the structure shows that it has been welded and worked upon, more in some parts, and less in others. Various processes has supposedly been used during the manufacturing, which explains the
interesting structure, but any conclusion about what the item has been used for cannot be drawn.

Sample 85 contain mainly ferrite in the core and partly perlite between the grain sizes of ferrite at the edges. The sample shows that the material has been worked somehow, due to the fact that the grains are elongated. Any conclusion about the item’s function cannot be drawn.

Sample number 64b is an unknown item with unknown function. The microstructure shows mostly ferritic structure with unusual “dry spots” at some of the grain boundaries. The dry spots have presumably been made during the manufacturing process of the material. Neither the shape nor the microstructure gives any information about the function, or use of this item. No conclusions can therefore be drawn.

8.5 Vickers hardness test
The values obtained by the Vickers hardness test are a good compliment to the metallurgical analysis. The conclusions that could be drawn from the microstructure, was strengthen by the hardness measurements. A comparison to modern low carbon steels showed that the values obtained in this study was well within the limits of modern steels. This show both that the hardness of a steel object from the Iron Age can withstand the shape of time very well and that much energy have been put into the creation of the materials.

8.6 Ethical aspects
It is difficult to make an assessment of how valuable the finds from Tortuna were. For archaeologists, it is normally very important to keep finds in as good condition as possible, in order to preserve it as long as possible. In this case, the archaeologists gave permission to cut, and if necessary, destroy the finds in order to accumulate new knowledge about the items and their manufacturing processes. From this excavation site, many similar items were found, which encourages that a few objects could be destroyed, to learn more information about the others. But if this reason can weigh up against the value loss of these old Iron Age objects is very difficult to estimate.

Another drawback of damaging the objects in order to analyze them is that there might be new methods invented in the future to investigate the finds. Therefore, it is very important to save the mounted samples for the future, in case other researchers would like to re-examine these finds.
8.7 Sources of error

Work involving experiments and analysis, it is common that uncertainties arise. Iron-made objects which have been underground for hundreds of years are exposed to corrosion, which is a big source for uncertainty. The finds in this report have no exact dating, which complicates the theories and the conclusions that can be made. The timespan for the finds according to the archaeologists is between the 4th and the 12th century, which is a huge time span, where many factors can change and affect both the structure and material qualities. Another uncertainty could be that the objects may have been removed and placed there, which obstruct their origin.

All of the finds were corroded, but many of them were heavily corroded, which means that all clean surfaces are missing. Corrosion happens naturally, and it is impossible to know how much of the material that has corroded away. This means that it will be impossible to know if they made special surface finishes, to some of the items in order to make them more suitable for their purposes.

In addition to the uncertainty about the material, there are also measurement errors that may have affected the results. It was important to have as many cross sections of the 11 samples as possible, to receive a good average. Some of the samples were so rusty that they fell apart when trying to sample them, and other samples were required to be preserved as much as possible, which limited the number of cross section that could be made. To get a better overview of the material’s properties and the manufacturing processes that were used, multiple cross sections are ideally needed from different parts of the objects.

When cutting the samples, the analyzed surface of the material was in contact with both heat from the saw and the cooling-water which was used to reduce the heat from the saw, this might have affected the results as well.
9 Conclusion

The finds which was examined contained mostly ferrite, with exception for some perlite, martensite and slag. The furnace most likely used to create the steel objects was a bloomery furnace, due to the time span from which the items originate from is larger when the bloomery furnace was used in comparison to the blast furnace.

The amulet rings have supposedly been used as a ritual object with little practical use. It is clear that the visual aspect of the rings was more important than creating a good material. The bigger knives were the only items with martensitic structure, which reinforced the hypothesis that it was a type of edge tool. The good workmanship of the knives show that the ancient smiths knew how to quench and temper martensitic steel, and to balance its hardness and brittleness by giving knives softer cores of ferritic steel. The “horse cleat” have not been used as a cleat, because the ferritic structure cannot withstand the large force which comes from a horse. But no conclusion can be drawn if there have existed another harder structure on the cleat which have corroded away over the years. Further research is needed to strengthen the results. The spear piece is a part of a spear holder. The spear had a thin copper alloy around the surface and have either been used as a ritual object or as a regular spear with a more noble character.

Vickers hardness test complimented the metallurgical analysis. A comparison to modern low carbon steel shows that the hardness of a steel object from the Iron Age can withstand the shape of time very well and that much work have been put into all of the objects examined.
10 Further investigation

Information provided by the analysis raises interest in further examination. The scattered finds varied in appearance and size. Similar items could occur in the same place or far apart. By having many objects of the same kind a comparison, no matter how far apart, will help to get a greater perspective and accuracy on the origin of the material. It would be interesting to compare finds from Sweden with other countries to see if there are similarities and to hear opinions from others. Without answer, we will not find out exactly what all the finds were used for during the Iron Age, but we can only speculate from the results above. One way to further investigate could be the use of Scanning Electronic Microscope, SEM. The composition of the slag could be of interest to investigate with SEM, to get a better and more nuanced view of where the raw materials can originate from.
11 Acknowledgement

We want to end this report by thank everyone who helped us to complete this bachelor’s thesis. Thanks to the archaeologist Anneli Sundkvist, from Uppsala University, who lent us different types of iron-age items and let us take part of the materials and analyze them. Without your help, this project could not be achieved. Also for the information we have received. All the help we received in the laboratory with the analysis of engineer Wenli Long at the material science Department at the Royal Institute of Technology, thanks to you.

In conclusion, we would like to express our sincere gratitude to our mentors Anders Eliasson at the Department of Materials Science at the Royal Institute of Technology and Sebastian Wärmländer at the Biochemistry and Biophysics Department at Stockholm University for all support and guidance.
12 References


## Appendix

### A. Experimental Data from metallurgical analysis in LOM

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