Metallurgical Analysis of Viking Age Amulet Rings

and

Comparison With Cutting Tools

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Abstract
Artefacts known as amulet rings, a kind of Viking age jewellery, have often been encountered during archaeological excavations of Viking Age sites. The rings do not appear to have any practical use, but are rather considered to be of cultural or religious importance. Their exact function is however unclear, as are the details regarding the production and material choices for the rings.

This study mainly examines the microstructure of samples from Viking Age amulet rings found in Dalecarlia, Sweden. To be able to conclude how much effort that was put into the rings a comparison with medieval cutting tools was conducted. Thus, the knives were made with more care in order to obtain the material properties required to give the knives the sharpness and hardness they need to function. The analysis shows that the amulet rings were made from heterogeneous low-carbon steel, indicating little or no welding and a poor-quality starting material. Were as the microstructure of the knives had homogeneous microstructures often involving perlite, showing decent carbon content. Thus, it appears that the Viking Age smiths forged the amulet rings without putting too much effort into the process.

This study also involved the manufacturing of a new knife from low-carbon steel, this was done to see if it was possible to redeem carbon into the surface while forging. This however, was difficult when not having todays technical equipment at hand, thus the result was insufficient.

Keywords: Amulet rings, morphology, forging
Sammanfattning
Historiska föremål, kallade amulett ringar vilket är ett slags vikingatida smycken, har hittats vid arkeologiska utgrävningar av vikingatida boplatser. Man har inte hittat något praktiskt användningsområde för ringarna, utan de tros vara av kulturell eller religiös betydelse. Deras funktion är dock oklar, likaså detaljerna angående tillverkningen och materialvalet för ringarna.


Denna studie innefattar också smidet av en ny kniv från ett lågkolhaltigt stål för att se om det är möjligt att lösa in kol i ytan genom smidet. Detta var dock svårt att göra utan dagens tekniska utrustning vilket gjorde att resultatet inte visade någon uppkolning.

Nyckelord: Amulett ringar, morfologi, smide
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1. Introduction
Artefacts known as amulet rings are often encountered during archaeological excavations of Viking Age sites. The rings do not have any known practical use, but are thought to have a religious or cultural meaning. The rings can be of various size and can have pendants on them or be carved with runes [1]. Archaeologists have presented numerous theories regarding the purpose(s) of these rings, often drawing inspiration from rings mentioned in tales and written documents. Iron from this age was created from bog-ore in a shaft-furnace, which produced steel with a low carbon content with much slag inclusions. The forging can be of varying quality depending on the area of use for the product. Few metallurgical analyses have been made to find out more about the producing technique [2]. Still loads of conclusions are made on how and why blacksmiths did different things. Based on what have been found in excavations and the lack of documentation, Viking age forging was seen as a ritual [3]. To the best of our knowledge, however, no metallurgical analyses have been conducted in order to learn about the production of the rings.

1.1. Purpose
This study presents a metallurgical analysis of samples of amulet rings from a Viking Age site in Dalecarlia, Sweden. As it is believed that these rings had a high religious or cultural value, it is was interesting to know the amount of time and resources that were put into manufacturing them. To estimate this, a comparative metallurgical analysis is conducted of cutting tools, such as knives. Cutting tools needed to be sharp and durable, and consequently much time and resources were put into their production. The analysed cutting tools originate from a mediaeval smithy excavated at the island Saaremaa in modern-day Estonia. In earlier times the island Saaremaa was under Swedish influence, both politically and technologically. By comparing the microstructures of the amulet rings and the cutting tools, it is likely to estimate how much work went into their respective production.

This report also investigates the process of carbon diffusion into iron and steel. It has been suggested, but not fully proved, that the processing techniques used during the Viking age were only able to produce steel with a low carbon content. Therefore, it is interesting to investigate to what extent carbon diffusion could be used, during the forging or in other steps of the process, to increase the carbon content of the material. A particular research-question is if it was possible to raise the carbon content enough to harden the steel to martensite. To examine this, a knife was forged from low-carbon steel and then parts of it was carburized and hardened. Thereafter, the microstructures were compared to the corresponding different processing steps, i.e. untreated, forged/carburized, and hardened material.

Limits needed to be set to be able to accomplish the decided purpose properly. Therefore, no scanning electron microscope (SEM) was executed during this project even though it might be of interest to see if the slag composition was the same in all samples. The investigation of amulet rings was limited to one finding and not all knives where investigated since they were not comparable with the amulet rings. Only one new knife was forged which might give an insufficient result, with data from only knife, no certainty in the result is definitive. There would also be interesting to do hardness test on all samples to learn more about both the hardness of the Viking age steel and do hardness test on the new material to see how hard it could get from forging.
2. Background
To be able to examine and compare the rings investigated in this report it was crucial to understand the process of forging, and in particular what happens in the material during forging and how forging was done in the Viking Age. It also examines iron production during the Viking age and the case hardening procedure. All of this is presented as background information in this chapter.

2.1. Amulet rings and cutting tools
In the last part of the Iron age, the Viking age takes part, in the Scandinavian countries it lasted between 800 and 1050 A.D.. Archaeologists have during this era found rings in varying sizes, and sometimes with amulets on them, which may have been used as a sort of jewellery [4].

These rings, also known as amulet rings, occur in various sizes from around 3 to 15 centimeters, sometimes bigger and with different pendants on them. Examples of pendants include small rings, axes, or sickles that archaeologists believe to have been hanged on the rings for several reasons such as battle luck or in hope of a good harvest [5]. Occasionally the rings also have engraved runes on them that explain how the rings were used [4]. The amulet rings are often found in places suggesting that they were placed there for a reason, for example in post holes for the house or at house entrances. The amulet rings are not known to have had any practical function but rather served a religious or cultural purpose [5].

Archaeological findings, picture stones and old written sources indicates that amulet rings and swords were things which you swore oaths and pledges of fidelity to in the Scandinavian Viking society. Several fairy-tales and old texts tell of rings that were used to pledge oaths on in different situations or litigations, for examples could the ring first be drenched in blood from a sacrificed animal and thereafter the oath was taken. Archaeologists have also found amulet rings that they believe have been hanged on doors, especially doors to important buildings, and sometimes laid on altars [4].

Tales often tells of bangles which are interpreted to be amulet rings worn on the arm. In one tale, the pagan god Odin wears a ring on his arm and pledges an oath on it [4].

2.1.1. Found rings in Sweden
In Sweden, many rings of different kinds have been found in archaeological excavations. The difficult part is to know if the rings encountered are mere jewellery or if they had a larger cultural meaning.

Häckelsängsringen was found around 1880 A.D. when a new road was constructed. It was remembered to have been found with several small rings and a hammer of Thor attached to it, which archaeologists believe supports the dating of the ring to the Viking age. The ring has a closed diameter of 26.4 centimeters and the inside of the ring is adorned by small hooks that are turned alternately left and right, this is shown in figure 1. The ring can be opened by a locking device of two hooks turned perpendicular to each other which gives the ring an open diameter of 30.2 centimeters. On the bigger ring a smaller ring can be found that has a diameter of 4 centimeters [4].
Forsaringen is dated to around 900 A.D. even though the dating has been disputed for a long time [6]. The ring, shown in figure 2, is completely round and has one spike and two curlicues showing how the runes on the ring are supposed to be read [4].

The rune inscription declares:

uksa (a) uis kilan auk aura tuA staf at fursta laki: uksa tuA auk aura fiura (a)t athru laki : in at thrithia laki uksha fiura (a)uk aura (a)ta staf: auk alt aiku i uarR if an hafsk aki rit furiR suath liuthiR aki at liuthrati sua uas int fur auk halkat: in thAR kirthu sik thita (a)nunr A tarstatham: auk ufakR A hiurtstatham: in uibiurn fathi [4].

This is how the professor in ancient linguists Stefan Brink interprets Forsaringen in Swedish:

"En oxe och två öre (i böter) till "stav" för att återställa vi i gillt skick första gången; två oxar och fyra öre för andra gången; men för tredje gången fyra oxar och åtta öre; och all egendom i kvarstad, om han icke gör rätt för sig. Det som folket äger att kräva enligt landets lag, det blev förr stadgat och stadsfäst. Men de gjorde sig detta, Anund i Tåsta och Ofeg i Hjorsta. Men Vibjörn ristade” [4].

A rough interpretation of Stefan Brink's translation of the rune inscription:

“One ox and two penny (fined) to "rod" in order to restore the sacred place its original condition the first time; two oxen and four penny for the second time; but for the third time four oxen and 8 penny; and all property seized and held, if he does not do the right thing. What the people said to require according to the law, it was enacted and vindicated. But they did, Anund in Tåsta and Ofeg in Hjorsta. But Vibjörn carved. “

2.2. Iron production during the Viking age

There have been several studies of iron production where archaeologists have studied excavations of furnaces from the Viking age. From these excavations, they have done experimental reconstructions until they finally got iron and slag with the same quality as that found during excavations.
The raw material used to produce iron during the Viking Age was bog-ore [2]. Bog-ore can be found in mires and in some watercourses and was produced when some rock types were dissolved in water. When this groundwater came up to the surface it reacts with oxygen which causes the iron to convert from unstable Fe⁡²⁺ ions to more stable but less soluble Fe³⁺ ions, which readily precipitate as hematite, Fe₂O₃. Bog-ore also contains many other substances which must be reduced in order to obtain workable iron [8]. It is also important to have an ore with god slagging properties to be able to obtain a good result [9].

To be able to process the ore to iron, charcoal is needed. Charcoal is produced in coal dust pits which normally are 1.5 meters wide and 2 meters deep. The process begins with the wood, which was placed in the bottom of the pit and covered with turf grass and soil and thereafter lit on fire which made the water bound in the wood evaporate. When the temperature was high enough the wood starts to decompose but since the combustion is incomplete charcoal is produced. It takes around two days for the pit to burn out [10].

Before the bog-ore could be put in the oven it had to be roasted. The roasting was important to burn away all the organic material as plant residues and to dry the ore from moisture and bound water. The roasting process was done on a stack of cross-piled wood where the bog-ore was placed and everything was then lit on fire, resulting in charcoal mixed with roasted ore. If the ore became magnetic the roasting process had been successful [2].

To reduce the ore to iron an oven was used. Diverse types of ovens have been found, both soaking pits and shaft-furnaces, but the shaft-furnace was the most common and will therefore be described below. The furnace was often built with rocks and clay and was usually around 80 centimeters high with an inside diameter around 25 centimeters. It also contained an air intake at the bottom as well as a slag tap. The furnace was filled with charcoal and ore alternately, about 1/3 ore and 2/3 charcoal. The iron never melts completely but instead resembles a glowing, rubbery lump, unlike the slag which melts and lies at the bottom from where it can be tapped. This produces steel with low carbon content [11]. Later, archaeologists have found proof indicating that at some places, additional qualities of iron was made during the Iron Age, such as curable steel and iron with low phosphorus content [2]. Air had to be blown into the process continuously and exactly how often was determined by the dimensions of the furnace. It was also important that the size of the charcoal was not too big or small to get a good air flow [11].

When the process was done the lump of iron, also called sponge iron, was lifted out of the furnace and placed on a working bench where it was worked on with a wooden hammer until it was solid and thereafter it was often split into smaller pieces. It was also possible to forge it into the desired shape [12] [13].

2.2.1. The mystics of iron production
One study investigates the importance of iron by looking at graves and the iron slag that has been found in them. Iron slags occurrence in Viking graves have mainly been considered to reflect the economic importance of the iron making.

Archaeologists believe that blacksmiths were considered highly skilled with a status above normal people because of their honourable work. There was no scientific basis for how the iron production worked, and therefore it was likely thought to be quite a ritual. If this ritual was followed correctly the blacksmiths pleased the higher powers and got a good result.

There is not much scientific evidence for these speculations about how iron making was seen during the Viking Age. But the reduction in the shaft-furnace was quite dramatic and made mystical sounds
that, with no knowledge of what was going on in there, might have been something from the gods [3].

2.3. Processes for production of rings and cutting tools

This chapter covers the technical part of the process to produce rings and knives. To be able to get a high hardness in steel with low carbon content case hardening or carbonization was important, since it gave the steel the nice quality of a ductile core and a hard surface. To get a full understanding for the process of case hardening the background for carbon diffusion is necessary. Forging is also described to get a full understanding for the shaping of the rings and knives.

2.3.1. Carbon diffusion

Carbon diffusion in metals is an interstitial process since the carbon atoms are significantly smaller than the metal matrix. To get carbon diffusion through the surface the metal needs to be subjected to an environment with high carbon content, which nowadays is produced with an oven with controlled carbon content, but before this technique was developed, bones and charcoal were used to produce the carbon rich atmosphere. An increased temperature, somewhere in the austenite area where it is easy to redeem carbon, is also needed, seen in the phase diagram in figure 3.

Figure 3. The y-axis resembles the temperature from 400-1600 degrees Celsius, the x-axis shows the weight percent carbon. The austenite area is referred to as γ-Fe [14].

Depending on the atmosphere around the material, which can be both carburizing and decarburizing, the carbon potential should be considered. To redeem carbon into the surface, the carbon potential in the atmosphere must be high. If it is too low the steel will be decarburized instead.

In the austenite area, several carburizing reactions take place.

\[
\begin{align*}
CH_4 &= C + 2H_2 \\
2CO &= C + CO_2 \\
CO + H_2 &= C + H_2O [14]
\end{align*}
\]

Where C is redeemed carbon in the steel surface. Since the last of the three reactions is the fastest, it is the rate determining one. The carbon monoxide and the hydrogen react, which makes the carbon react with the steel surface and the water vapour goes back to the atmosphere. This, for a successful carburization, makes it important that the carbon activity is greater in the gas than in the steel. The
reaction is often controlled by adjustments to the carbon dioxide concentration. In the beginning of
the redemption process it is the transmission between the gas and the surface that determines the
speed of the process, but as time goes the rate starts to be more regulated by the diffusion which is
rather slow, as can be seen in figure 4.

![Image](Figure 4. In the beginning of the carburization, the carbon flow is very high due to the fact the
determining factor then is the transaction between the gas and the surface. Thereafter the flow gets
slower due to a change of determining factor, which now is the diffusion [15].

The carburization normally lasts until a carbon depth of 0.1 to 1.5 millimeter is reached, but
sometimes an even deeper carbon level is desired [16].

2.3.2. Case hardening

When case hardening, the component is exposed to a carbon rich environment at an elevated
temperature, somewhere around 850-900 degrees Celsius which is in the austenite area. After the
carburization the steel is cooled, this can be done in many ways like air, oil, water or saltwater
cooling to be able to get martensite. The cooling rate depends on the curability of the material,
which depends on the composition of the steel. Upon cooling compression stresses occur due to the
martensite formation which increases the fatigue strength on the surface.

After the cooling process, the material is often tempered since the martensite structure is very brittle
and prone to crack due to tensile residual stress. When case hardening, a low tempering
temperature is often used, around 160 degrees Celsius, but it can be done between 160 to 650
degrees Celsius. The tempering is usually done directly after the cooling to prevent cracks.

Nowadays a thermometer is often used to determine the correct temperature but in history the
temperature was determined by looking at the colour of the steel which can be seen in figure 5.
The case hardening process is often used for components that are exposed to high strains since it gives a hard surface with a yielding core which gives the material a high wear resistance, strength and toughness [16].

### 2.3.3. Forging

During forging, the right equipment is needed, the most crucial part being a forge. In a typical fire the temperature reaches around 700 degrees Celsius, wherefore the forge needs two functions, the ability to accommodate a fire and an air intake where it is possible to blow in air with bellows. The bellows increase the oxygen supply and thereby raise the temperature in the forge to around 1150-1200 degrees Celsius, or any other desired temperature, which gives the steel a yellow or straw colour and makes the iron malleable. The hearth can have various designs but the main purpose for it is to be able to contain the wood/charcoal. The steel is then placed in the hearth and when it has acquired a yellow/straw colour the blacksmith takes it out to the workbench and starts to form it with a hammer and other tools. When worked on, the material cools quickly and needs to be reheated. After this process, it is possible to harden the item if necessary, for example when making a knife. [18]
Blacksmiths has throughout history been very secretive about their work, which has led to them either having been made fools of or given a magician’s status. Since their knowledge was their greatest asset they guarded it carefully and did not write much down, if they passed on their knowledge it was by mouth. This makes it hard to know how much they knew about what they were doing. But in the few texts that have been found, it is stated that they used common sense, great knowledge about the material and just a bit of superstition. The blacksmiths might not have had the knowledge about the material that we have today, or the means to find out, but they rather had an understanding based on trial-and-error [19].

The first text written down about metalworking was in 1100 by a monk named Theophilus. The text is rather about the scale of the operation than the nature of the process [20].

One of the glitches the blacksmith had to overcome in one of their most important tasks, making swords, was to get a high enough carbon content in the sword edge to get a high curability. This could be done in many ways. One way was to carburize the surface of the material and thereafter case harden it, this was used to get a sword with a hard edge and a yielding blade. They could also use two other methods that gave them the same result, either laminate the iron or combine iron with different carbon content so that the surface got a higher carbon content than the core. The Scandinavian Vikings were thought to get steel with an even carbon content and a homogenous structure.

In Japan, they created swords with a very sharp edge and an insignificant risk of breaking, the swords instead had a risk of bending if the edge did not hit the target correctly, this since the swords only had a hardened edge and the rest of it was rather soft. A common misunderstanding is that the many layers of steel affected the sharpness of the swords, but the truth was that it only had an aesthetic purpose which was a sign of high quality products [19].

A similar technique was also used in Europe. Vannoccio Biringuccio published his work “Pirotechnia” on metallurgy in 1540, which was the first book in this area [20]. Biringuccio disclosures includes how the iron product was bathe in cast iron with a high carbon content and a low melting point to rise the carbon content. This process gave a heterogeneous steel which needed forging and welling to get rid of slag and inclusions, when worked on the carbon content also evened. This last part is very like the Japanese way but unlike the Japanese swords the many layers of steel was not visible on the Europeans swords. European blacksmiths also solved the hardening in a separate way, probably because of the difference in fighting technique and different combat gear. The blacksmiths made a very thin resilient blade which was very effective when cleaving something in two. They also made swords with two edges which meant that even if one side was dull the other one could still be sharp. Biringuccio also wrote about the cooling process where it was very important to get perlite, bainite and martensite to obtain at perfect toughness [19].
3. Materials
The samples analysed in this report were found at various places. Some information about the experimentally forged knife is also stated below.

3.1. Rings
The landscape of Dalecarlia in Sweden consists predominantly of valleys. The valley bottoms consist of soft settling ground free from stones, and the higher grounds consist mostly of rocks. Most building residues in Dalecarlia are found at the bottom of the valleys and are made of wood which makes it hard to know exactly how the buildings were placed and how they looked because the wood often has decayed. But from post holes and some well-preserved buildings archaeologists have established an idea of the typical building design.

The Vikings generally built longhouses which could be virtually as long as needed. These houses often consisted of only one room and had low walls and a big and impressive roof span. Traces of so-called pit houses have also been found. These houses could have been used for cooking, as workshops or as cattle sheds and were typically square with sides between 2-3 meters and dug 0.5 meters down in the ground.

The amulet rings in this project were found in Åselby in Dalecarlia because of an archaeological excavation conducted before a road construction. The site contained one big long house, 25 meters long and 8 meters wide, and at least one more house and 3 pit houses. Remains of coal pits and shaft-furnaces were found together with a deposit of rings which can be seen in figure 6 below.

Figure 6. The rings were found in the orange square in the left corner at the bottom of the picture and the longhouse can be seen on the right side [2].

The rings investigated are all from the finding in Åselby, Stora Tuna Socken. Most of the rings were documented in pictures before they were prepared for microscopy. This can be seen in figure 7-16 below.
Figure 7 to the left. A schematic picture of how the remaining pieces of ring 27 could have been placed. Figure 8, to the right. Shows the correct placement of the bigger piece. The smaller one in figure 7 was cut of the small ring to the far right in figure 8.

Figure 9, to the left. The samples from ring 1 had corroded and therefore no metal could be found, only slag. The piece marked with X in the upper left corner in figure 9 were a piece saw of from the ring, the pieces not marked with X where fragments found in the container. Figure 10, to the right. The part marked with X in figure 9 is cut from the right end of the upper half ring in figure 10.

Figure 11 & 12. Ring 17 is one of the smaller ones attached to the actual amulet ring, the radius is about 5 centimeters.
Figure 13 & 14. Ring 20 was covered in mud but traces of metal could be seen.

Figure 15. Only a small piece of one of the small rings of ring 15 was sawn of.

Figure 16. A small piece of the big ring was taken as a sample of ring 16.

3.2. Medieval cutting tools

The middle age cutting tools used in this project to compare with the rings were excavated in the parish of Kaarma, located on the island Saaremaa, west of Estonia. The excavation was big and consists of four smithies found below each other, the only thing that seems to have been the same over time is the forge. The knives were found in the first smithy built, which is dated to sometime around 1400 A.D., and the outer walls are shown in figure 17, this is also the largest smithy found at 8 x 5.4 m. [1]
Figure 17. The knives were found within the red lines which show the placing of the outer walls, the square marked with green was the forge base [1].

3.3. Newly forged knife
The forged knife was made with the help of a blacksmith, Torsten Almén, in a traditional simple smithy. The knife was made from a square bar with the measurement 1x1 centimeters. The final dimension of the knife was a blade that was 2.5 centimeters high, 6 centimeters long and had a depth of 1 millimeter at the edge and around 4 millimeters at the top. The whole knife was carburized and around 3 centimeters was also hardened [18]. The knife can be seen in figure 18.

Figure 18. The forged knife made with help from the smith Torsten Almén.

The original material had the composition Fe, 0.17C, 1.40Mn, 0.035P, 0.035S, 0.012N, 0.55Cu wt%
4. Method
This study contains two investigations, one metallurgical analysis of amulet rings and knives containing a comparison between the two, and one analysis of a newly forged knife to see if carbon is redeemed in to the surface through forging. All samples investigated are stated in table 1.

Table 1. Listing all samples investigated and then presented.

<table>
<thead>
<tr>
<th>Amulet rings</th>
<th>Medieval cutting tools</th>
<th>Experimentally forged knife</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ring 15</td>
<td>Cutting tool 3</td>
<td>Original material</td>
</tr>
<tr>
<td>Ring 16</td>
<td>Cutting tool 27</td>
<td>K1</td>
</tr>
<tr>
<td>Ring 27 A</td>
<td>Cutting tool 118</td>
<td>K2</td>
</tr>
<tr>
<td>Ring 27 B</td>
<td></td>
<td>M1</td>
</tr>
<tr>
<td>Ring 27 C</td>
<td></td>
<td>M2</td>
</tr>
<tr>
<td>Ring 27 D</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

4.1. Samples
Amulet rings was collected from Dalarnas museum which they had collected after an excavation before a road construction. The archaeologist there dated the rings to sometime around the Viking age era using other objects found that were typical for the period. Dalarnas museum had around 50 rings of various conditions, of which only the ones that was not interesting to preserve could be collected for this project. This since, when working with pieces of historical importance documentation is of high priority, especially when the historical pieces is taken apart, which makes it lose its historical value. Therefore, several photographs and videos have been made to document the entire process and the documentation can be seen in the previous chapter, 3. Materials.

To be able to observe the microstructure, the samples had to be cut into appropriate pieces. The larges piece, from ring 27, was originally around 6 centimeters and cut into 4 approximately equal sizes, and named A-D, this can be seen in figure 19 below.

![Figure 19. This sample was cut into four pieces to see differences in structure throughout the sample. 1-4 resembles A-D in the labelling.](image)

The other samples, rings 15 and 16, were smaller samples and only one sample from each were examined. These were cut directly from parts of rings. There were also other samples collected that were loose from the beginning and therefore did not had to be cut off.

The knife samples were borrowed from another study done in Estonia and therefore the documentation of these objects is not in this report.
The morphology of the samples was performed in LOM. Not all the samples were prepared for this study but have been investigated before. But for this report all samples were reground to get a clean surface to work with. Some samples that were prepared from scratch for this project where too fragile to cut in half to get a cross section, therefore they were ground down from one side.

4.2. Light Optical Microscope
Light optical microscope (LOM) was used to study the morphology of materials. Microstructures, grain boundaries, grain orientation and defects can be observed depending on the etchant. This, since the light from the microscope is reflected differently depending on the effects the different etchants have had on the material, thus emphasizing different structures.

The amulet rings and knives were documented in various magnifications, 5-fold, 20-fold and 50-fold in a LEICA DMRM with the software LEICA QWin V3. [14]

4.3. Forging
A cutting tool was forged for this project, it was made from modern steel, a square bar with the measurement of 10x10 millimeters, with a low carbon content at 0.17 wt% carbon. The forge used was a traditional forge with charcoal as combustion material and handheld bellows for air flow. The forging technique was simple and as similar as possible to the technique thought to have been used during the Viking age. The steel bar was forged into a knife of appropriate measurements, leaving the top to be the same width as the base to get an even result. Thereafter the process of increasing the carbon content of the surface began. The knife was held in the heat for 20 minutes, and to control the temperature, the colour of the knife was studied. The desired colour was a darker yellow which resembled around 820-850 degrees Celsius. Thereafter the knife was cut in two and one piece was left to cool in room temperature. The other part was re-heated and then cooled rapidly in water at about 15 degrees Celsius [18]. Thereafter, the pieces were labelled and prepared for an examination in LOM.
5. Results
Here are the results of the microscopy presented, with a full clarification of what structures the samples contain.

5.1. Amulet rings
The amulet rings shown below are the ones that contained steel or iron. The structures found were particularly ferrite and perlite. The rings named 27 A-D are all from the same sample but were cut into four pieces for a proper examination of this sample.

In ring 1, 17 and 20 only slag and mud could be observed therefore they are not presented in microstructural pictures. Only the microstructure of the metal was interesting to compare with the cutting tools and therefore ring 1, 17 and 20 are left out.

5.1.1. Ring 27 A
In ring 27 A some different structures are seen. Figure 20 shows the middle of the sample with quite big grains and slag inclusions. In figure 21 this is clearly shown, near the edge, in a bigger magnification in figure 22 and figure 23 the different structures are shown. In the 50-fold magnification in figure 24 the darker areas are perlite and the lighter areas with spikes is Widmanstätten ferrite. In figure 25 the centre is shown and there was a quite large grain structure and the dark areas in the same figure are slag.

![Figure 20. 5-fold magnification of the inner part of the sample.](image1)

![Figure 21. 5-fold magnification of the edge of the sample.](image2)

![Figure 22. 20-fold magnification of the inner of the sample.](image3)

![Figure 23. 20-fold magnification of the edge of the sample.](image4)
5.1.2. Ring 27 B

In ring 27 B, different structures are shown in different areas of the sample. In figure 26 various sizes of grains are shown and the darker fields are areas of slag. Figure 27-30 shows magnifications of the different areas that this sample contains.
5.1.3. Ring 27 C

Figure 31 and 32 show the two kinds of structures found in this cross section of ring number 27. In a greater magnification in figure 33 the darker areas are perlite and the lighter are ferrite. In figure 34 which displays another part of the edge of the sample, there is less perlite. This figure also shows slag stretches in one direction. Figure 35-37 are the greatest magnifications of this sample, in these details of the structures are seen.
Figure 33. 20-fold magnification of the edge of the sample.

Figure 34. 20-fold magnification of the edge of the sample.

Figure 35. 50-fold magnification close to the edge of the sample.

Figure 36. 50-fold magnification of the inner of the sample.

Figure 37. 50-fold magnification of the edge of the sample.
5.1.4. Ring 27 D

Sample D of ring number 27 was the most corroded part and therefore in figure 38 and 39 most parts of the sample are visible. In figure 39 there are borders of different structures due to bad welding. Figure 40-42 are magnifications of the areas with different structures.

Figure 38. 5-fold magnification of the edge of the sample.

Figure 39. 5-fold magnification of a great part of the sample.

Figure 40. 20-fold magnification of the edge of the sample.

Figure 41. 50-fold magnification of inner of the sample.

Figure 42. 50-fold magnification of the edge of the sample.
5.1.5. Ring 15
In figure 43 an inhomogeneous structure with ferrite and a small amount of perlite can be seen. In figure 44 and 45 a magnification of the structure can be seen.

Figure 43. 5-fold magnification of a large part of the sample.

Figure 44. 20-fold magnification of the edge of the sample.

Figure 44. 50-fold magnification of the edge of the sample.

5.1.6. Ring 16
In figure 46 the hole of the sample can be seen and shows grains of ferrite with a small amount of perlite, both in the grain boundaries and in larger areas. Figure 47 and 48 shows the sample in larger magnifications.

Figure 46. 5-fold magnification of the hole of the sample.

Figure 47. 20-fold magnification of the inner of the sample.
5.2. Medieval cutting tools
The Medieval cutting tools, knives, shown below are the ones that had similar compositions as the amulet rings. Both ferrite and perlite has been found, and in some samples traces of martensite. Three cutting tools are shown below, there were more sample of cutting tools that had similar microstructure as seen in cutting tools presented, these were left out since they only confirm the result existing.

5.2.1. Cutting tool 27
In cutting tool 27 small grains of ferrite and grain boundary perlite can be seen. Some slag stretches of different length is also found. The sample had the same microstructure in the hole sample which can be seen in different magnifications in figure 49-51.
5.2.2. Cutting tool 118

In figure 52 microstructural differences can be seen across the sample. The lighter areas consist mostly of ferrite and the darker areas contain much perlite. In figure 53 and 54 signs of Widmanstätten ferrite and much perlite can be observed, unlike sample 55 where grains of ferrite with some grain boundary perlite is seen. In figure 56 and 57 greater magnifications of these areas are shown.
5.2.3. Cutting tool 3

In cutting tool 3, martensite is observed. The structure in this sample is very fine, therefore only figure 58 in 50-fold magnification is shown since not very much is seen in lesser magnifications. The sample has a homogenous structure.

Figure 58. 50-fold magnification of the sample, the same structure was observed through the whole sample.
5.3. Newly forged cutting tool
The microstructures below are from the newly forged knife, in different steps of manufacturing and from the original material used. The cutting tools named K are only carburized and are two different cross sections of the same sample. The samples labelled M are both carburized and hardened and are also two different cross sections of the same sample. Ferrite, perlite and martensite can be seen in the different samples.

5.3.1. Original material
The original material which is a steel with a carbon content of 0.17 wt% consists of small grains of ferrite with a little bit of grain boundary perlite. This can be seen in figure 59-61 in various magnifications.

Figure 59. 5-fold magnification of the inner part of the sample.
Figure 60. 20-fold magnification of the inner part of the sample.
Figure 61. 50-fold magnification of the inner of the sample.
5.3.2. Cutting tool K1
In cutting tool K1 small grains of ferrite with surrounding grain boundary perlite can be seen in a homogenous structure throughout the sample. Figure 62-64 shows the sample in different magnifications.

5.3.3. Cutting tool K2
In figure 65-67 different magnifications of the same sample is seen. These show small grains of ferrite and grain boundary perlite which is homogenous throughout the whole sample.
5.3.4. Cutting tool M1

In figure 68 a very fine pattern of martensite can be seen. Figure 69 shows a gradient towards the edge of the sample. Except for the edge the sample has a homogenous structure throughout, figure 70 and 71 shows different magnifications of the middle of the sample.

Figure 67. 50-fold magnification of inner of the sample.

Figure 68. 5-fold magnification of inner of the sample.

Figure 69. 20-fold magnification of the edge of the sample.

Figure 70. 20-fold magnification of inner of the sample.

Figure 71. 50-fold magnification of inner of the sample.
5.3.5. Cutting tool M2
Cutting tool M2 had a fine grid of martensite which can be seen in different magnifications in figure 72-74.

![Figure 72. 5-fold magnification of inner of the sample.](image1)

![Figure 73. 20-fold magnification of inner of the sample.](image2)

![Figure 74. 50-fold magnification of inner of the sample.](image3)
6. Discussion
Since archaeologists believed that the amulet rings have mostly had a cultural or religious purpose the hypothesis made, is that much time and energy was put in to their manufacturing. To investigate this hypothesis, a comparison with the microstructure of cutting tools was investigated, since the work invested in them had to be good in order to produce a functional knife.

6.1. Analyse of results
The results of the medieval knives and the amulet rings were investigated and compared. The experimentally forged knife was also analysed and a compared between the different processing steps.

6.1.1. Medieval Knives
The knives that can be seen in this study, have microstructures that are homogenous throughout the entire material. Only small irregularities are seen, even though the structure varies from knife to knife. In all knives, a carbon content can be seen, due to the presence of perlite or martensite. In cutting tool 27, seen in figure 20-42, very fine grains of ferrite can be observed. This can be conceived through strain hardening or from the original material which in the case of the Nordic Viking age not was of high standard. A considerable amount of grain boundary perlite can also be observed in the sample, approximately 40 percent perlite and 60 percent ferrite, which indicates high carbon content. Cutting tool 118, seen in figure 46-51, however, do not have such a homogenous structure. There are areas that have higher carbon content than other areas which can be a sign of no or little welding of the material. In parts of the sample Widmanstätten ferrite can be seen, this in the areas where there is more perlite, and therefore more carbon. And in other areas grains of ferrite with a small amount of perlite is observed. All of this concludes that not much work has been put in to cutting tool 118. In cutting tool 3, figure 58, martensite can be observed which indicates a high cooling rate and knowledge of hardening techniques.

6.1.2. Amulet rings
When comparing the knives with the amulet rings from Dalecarlia the microstructure shows that there are few similarities between the rings and the knives. The inadequate homogeneity seen in the hole of ring 27 implicates that the rings have not been welded before forging, this can be observed when looking at the sharp edges between different areas with much perlite and areas with more ferrite. Unlike all the knives were a very homogeneous microstructure is observed in all samples, even though they have different microstructures. There are also some likenesses to, in ring 16 seen in figure 46-48 a clear similarity can be seen between this sample and cutting tool 27 seen in figure 49-51. Unfortunately, this is only seen once, which makes it impossible to see any trend. Much slag can also be seen and the structure of the slag in the microstructure also indicates that the material has not been worked on much but merely formed, this since the slag particles have not been dragged out or shattered in to smaller pieces. The microstructures in the samples seem to mostly have come from the original material attained from the shaft-furnace. That can explain why the material has areas with more carbon, because those areas have been in a position where carbon could be redeemed in to the surface in the shaft-furnace. This becomes clear in ring 27 were 4 cross-sections was taken, when comparing figure 19, figure 26, figure 29 and figure 39 many different structures can be seen in the same ring, and some time even in the same figure.

Concluded from this is that not much effort and knowledge has been put into the manufacturing of the amulet rings. This is not a proof that the rings had a great cultural or religious meaning, since that can be achieved in other ways, such as rituals or oaths.
6.1.3. Experimentally forged knife
The hypotheses was, based on modern technology, that it would be possible to carburize a knife when forging and after that case harden it. This was not successful, when looking at figure 60 of the original material and figure 63 of the forged material, there was merely no difference at all between the original material and the carburized one. It was possibly slightly more perlite in the forged material, and the grains may have looked a little different, but it was a too small difference to draw any firm conclusions. This can depend on many things, perhaps many things at the same time. All elements that are needed where present, it was possible to reach the right temperature and get a carbon rich environment. The difficulty was to accomplish this without today’s technology at hand, since the experiment was to perform this with as much likeness to the way Viking age forging was thought to have been performed. The temperature was decided trough the colour of the steel and the colour of the flames, trying to have the knife at the most carbon rich environment in the hearth by looking at the colour of the flames. In this experiment only one knife was made, if more knives had been made with different techniques it could perhaps be possible to achieve a carburization and case hardening.

6.2. Sources of error
When working with this kind of old objects there are many insecurities. The composition of the original material is unknown, which makes it hard to know if there has been any carbon diffusion that have raised the carbon content in the entire material. Therefore, the conclusions about whether the rings have been case hardened might be faulty. Also, these rings are greatly corroded and if there had been any carbon diffusion near the surface those areas might have corroded and disappeared. There is also no exact dating of the objects, instead their approximate dating is based on other findings from the same excavation. There is no sufficient information, at least not from this examination, to say where the original material is from or if it is the same in all the rings. The rings or the base material could be brought from somewhere else and therefore the investigation of forging from Dalecarlia during the Viking age could be misleading if the materials were not from there.

If Scanning Electron Microscope, SEM, had been performed in the examination some of the error sources above could have been excluded. What could be stated from a SEM examination is the content of the material and especially the slag, if it is the same slag composition in all the rings it is most likely that they have been produced at the same place.

In Sweden, not many objects found from excavations are of good quality, therefore it is importatnt to preserve the objects that are found. Museums that have exhibitions of historical objects usually have ware houses where they preserve the objects not exhibited at the time. These objects could be considered for a new exhibition at any time and therefore are most museums not always eager to give away samples for analyses that damage the sample. This makes it hard to get suitable samples to analyse.

6.3. Further investigation
The conclusions from this investigation are not as accurate as they could be. Further investigations will be needed to figure out more about these rings. The rings might have been imported from other areas or other countries even. To collect data from more rings, maybe from different areas, will hopefully give a wider perspective on how local these traditions might have been. To see the composition of the slag could be relevant to see what kind of ore was used and if rings found in the same place have the same composition, or if some were imported. To make hardness tests on both the amulet rings and the medieval knives and compare the results would be interesting. In the experimentally forged knife, hardness tests should also be done to compare the original material with the carburized and case hardened.
If further investigations do not show any results that confirm that the rings were of material importance, which does still not rule out the fact that they could have had a cultural or religious meaning. This however will be extremely difficult to find out unless writings will be found.

6.4. Ethical, social and economic aspects
What is stated about what blacksmiths could and could not do, especially when producing bog-iron is primarily based on the findings from this age. When reconstructions of the shaft-furnace have been made, it has shown a wider use for the shaft-furnace than what is believed that the Vikings used it for. This information is based on what have been found in excavations, but steel is sensitive to corrosion and therefore a lot of things produced 1000 years ago do not exist anymore.

What could be important with objects of cultural or religious relevance is if the object was of good quality, if the handcraft is well executed and what kind of material it was produced in. This can be seen in any religious building of value, gold-plated objects or carefully painted paintings and sculptures. But not all items of religious value need to be made in fancy materials or sculptured to perfection. There could be rituals or oaths sworn upon the item which gives it great importance still. This means that even though these rings might not have been made with that much effort they could still have had an important cultural part. However, this is much harder to find out since it cannot be seen in any metallurgical analysis.

To measure society development one need to look at history. The history makes us understand reasons why and how we do different kind of things today. A lot of things are easier to understand if it is known where it originates from. To help us understand how cultures have been shaped and how people have moved around the earth, analysis of historical findings can give answers.

The need to know about our history is great and interesting since it can explain a lot about how people live, act and do different things today. A somewhat intact piece of history contains a lot of information only from where it was found, its appearance and surface. But sometimes that is not enough information to get the whole truth. Maybe an analysis of a cross section could give data that increases the accuracy of the information about the historical piece. But an object cut in to pieces is impossible to restore to its original intact form.

One thing that needs to be considered when making metallurgical analysis of historical samples is if there is more value in the data from the analysis then from the intact piece. One can never be sure in advance. When making greater findings of objects that are similar to each other, there might be a value in sacrificing some of the samples for analysis where the sample need to be split apart which results in that is loses all of its historical value it had when intact. But if the data from the analysis is interesting it might raise the value of all the other intact pieces.

It is possible to make some analysis on the inside of a piece without breaking it apart, which might give an indication of what the sample contains. X-ray is one example where it is possible to see differences in density allowing some conclusions to be drawn about the inside materials. There have been recent attempts to investigate swords from the Viking age with neutron tomography [21].

There is also always the financial aspect, someone needs to finance an analysis, but that might not be interesting if there is no guarantee that the analysis will show anything that makes it worth it or not. This is one more thing to consider before deciding whether any further analysis should be done, even if it is worth sacrificing some samples for analysis, the economic value might not exist.
7. Conclusion
What could be concluded is that definitely not all amulet rings were made with much effort. Some rings have a similar structure to some cutting tools but it is impossible to see a trend. If these rings had a religious or cultural meaning, it might not have been related to the material importance.

It was difficult to carbonize the material during forging when not having today's technique at hand, thus our result was insufficient. This does not rule out that a skilled blacksmith could raise the carbon content during forging.
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