Ring weave

A metallographical analysis of ring mail material at the Oldsaksamlingen in Oslo

By Vegard Vike

University of Oslo
The faculty of History and philosophy - IAKK
Department of conservation studies
Semester assignment
May 2000

Abstract

This essay is a metallografic analysis of mail rings. It was written as part of the studies at the new conservation school in Oslo, Norway. Rings from three mail finds stored at Oldsaksamlingen in Oslo was studied. One of these was from the well known viking grave from Gjermundbu, Buskerud. The rings were studied both longitudinally and in cross section. Especially the distribution of slag lines and distortions in the structures were noted. The conclusion was that riveted rings was from premade wire and had been riveted using a tool with a negative impression of the rivetheads final shape, instead of directly with a hammer. Rings without any apparent joint was found to be punched from sheet metall. Some steps towards dating mail on the ring level is suggested.

A note on this version:

This is a translation into English from the original thesis written in Norwegian: *‘Brynjevev - metallografisk analyse av brynjemateriale ved Oldsaksamlingen i Oslo’* by Vegard Vike, 2000. The initial English translation was performed by Ny Björn Gustafsson in 2004. This version of the translation was updated by the author in 2023.

Front page image: Mail maker 1425 (Treue 1965)

Illustrations/images

All sketches and images of analysis by the author. Where illustrations are from other sources it will be stated in the caption.

Tables

Measure data for each of the three analysed finds are depicted in the surveys for each find.

Preface

My motivation to focus on ring weave as a material stem from a keen interest in processes relating to iron-work. I personally practice traditional forging techniques and perform reenactment fighting with weapons and armour from the Iron Age and Scandinavian Middle Ages.

Ring weave seemed to be a somewhat overlooked and deficiently researched find category with few metallographical analyses. In light of the fact that mail garments have been an important part of armours for more than 1500 years I felt that it deserved a closer examination. Everything indicates that the making of the ring weave takes a lot of effort. Thus it is interesting to understand the manufacturing process to further research placing mail armour into a social context. In the course of working on this thesis I discovered some investigations of mail having been performed in Denmark, Germany, England and the USA, but not all of them are equally convincing. In Norway the study of ring weave has been completely neglected despite the important Viking Age find from Gjermundbu consisting of an abundance of ring weave and a unique helmet. The samples analysed in this study stems from three finds kept at the Oldsaksamlingen in Oslo (C27317, C455, C2616).

The paper was written during the final semester at the Department of conservation studies in Oslo during the spring of 2000. The time accessible for this work has been very limited, in between exercises in object conservation and lectures in general.

Acknowledgements

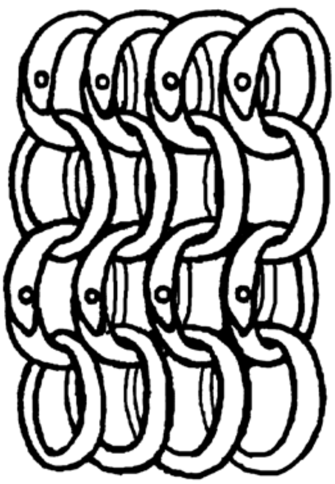
The author would like to thank: Kristin Sigurdardottir and Jerry McDonnel for introduction to metallographical analysis during the studies in conservation. Heid Resi at the Oldsaksamlingen in Oslo who made me aware of important literature. Arne Jouttijärvi’s work with Danish hauberks that gave me a better understanding of important features in the production of punched mail rings. Karin Knoph, collection manager at the Oldsaksamlingen, who was very helpful and obliging at studies and photo sessions at the museum’s storage. I also wish to thank Henriette Lyngstrøm and Arne Emil Christensen for kind answers to questions in relation to this paper. And finally my fullest gratitude to my fiancé Lise who endured with me - despite all the late nights I spent working on the analyses.

Table of contents Page

Introduction

The main aim of this paper is to present a detailed survey of three concrete Norwegian finds of mail garments, and to shed some light on the manufacture and technology used to produce the rings and the weaves. Attempts will also be made to approach a valid method for the dating of ring weaves based on ring-level details.

Ring weave is the term used for the metal mesh fabric discussed in this paper. This is a flexible material consisting of metal rings, usually from iron. Each ring is connected to four others. One way of understanding this material is to look upon it as rows of chain laid out alongside each other, then connected sideways. Ring weave can be oriented in two different directions with differing characteristics. The orientation depiction in the sketch below is what we find in the majority of garments of ring weave through history. All rings in a weave can be closed by riveting but half of them may also be from solid rings.



Ring weave

In addition to the analysed material some features of other ring weave finds will be mentioned and discussed. The paper deals with finds from the Scandinavian Iron Age and the Middle Ages. Scandinavian, English and some German material will be used for comparison when assessing the analyses.

A review of the other ring weave artefacts at the Oldsaksamlingen in Oslo has also been made in connection with this thesis, but there will not be space to present the images and information from these studies here. Some of the documentation from the analyses of the three mail garments will also not be possible to fit into this thesis. The aim is to get the complete material published in English later.

The use of tools in ring weave production will be only superficially reviewed. Some thoughts will be mentioned, but a more thorough analysis will have to be made within some other work, preferably after some experimental reproduction to test the probability of various hypotheses.

General state of the finds

A minor part of all ring weave finds consists of whole garments or pieces that can be reconstructed as such. Usually it is fragments or ‘clusters’ of ring weave that is found. Whether ring weave can be analysed or not depends fully on how well preserved it is. First and foremost it is dependent on the state of preservation of individual rings, simply because it is these individual elements that, in linked form, make up the armour garments. Some parts of a mail garment can be more corroded than other parts. Hence the shape of the garment can be totally lost while rings from various parts of it are so well preserved that they allow for a thorough analysis at individual ring level.

If the rings have a severely corroded and distorted original surface, a technological assessment becomes difficult. If no metal is preserved in the rings, they are difficult to study metallographically. If managing to make metallographic samples of areas that are corroded through, one could possibly assess slag streaks in what was previously metal. Much of the ring weave in the Swedish Vendel and Valsgärde finds from roughly AD 500 – 700 seems to be severely corroded and therefore hard to analyse, but that is certainly not the case with all finds of ring weave. X-ray photographs are the best starting point for an evaluation of whether a metallographical analysis can be performed or not.

Another fact to consider is that corroded and decayed iron is very perishable, even after it has been brought to and treated by the museums. Iron artefacts from archaeological context can sometimes be virtually impossible to protect against further degradation, even with proper conservation and dry storage. The severest ‘enemy’ is chlorides. Ring weave is especially prone to degredation due to the thin gauge in each individual ring, exposing a relatively large surface to corrosion. It might be rewarding to examine ring weave finds early and secure the information that can be gained from them, rather than to analyse them after a century or more of gradual decay and corrosion. Besides, a metallographical destructive analysis of ring weaves on ring-level does not take more than four rings per sampled garment or piece; two rings of each type. Considering that a mail hauberk consists of 20000–40000 rings, this is a very modest intervention.

The use of mail

Ring weave is a good material for armour. It possesses certain textile-like properties, like being flexible, but at the same time the metal protects against cuts and to some extent against thrusts and arrowheads. The flexibility limits the protection against blunt trauma. Hence ring weave is at its best when combined with a thick padding between it and the body. Ring weave material may also have been used as suspension chains, or in a small piece like a protective talisman against the supernatural.

The Iron Age: the use of mail garments during the pre-Roman and Roman Iron Age seems mostly to have been shirts covering torso, arms and thighs to a greater or lesser extent (for example Malifilâtre 1993). Later during the Iron Age (Merovingian/Vendel period, Viking Age) ring weave was also used to cover throat and face, suspended from the lower rim of helmets (Vendel and Valsgärde – 6th – 8th centuries, Coppergate-8th century). From Valsgärde 8 one may interpret the ring weave-fragments fastened to two iron splinter greaves and one vambrace as mail-mittens and foot coverings. The find was previously misinterpreted as a torso armour by Greta Arwidsson (1939, 1954).

The Medieval period: ring weave was used in armour covering the whole body during the early Middle Ages (hood, shirt, mittens and hosen). Especially during the 12th and 13th centuries ring weave was used for armour covering most of the body. Later, from the 14th century and onwards, metal plates gradually replaced it. Initially plate was only added for extra protection but later it replaced the ring weave. During the 15th and 16th centuries plate armour had taken over as general protection. At this time pieces of ring weave were mostly used to cover areas of the body that needed extra flexible armour (the groin section and in the bend of arms and knees), but full mail hauberks/shirts, sleeves and hosen were still in use.

In Arab cultural areas and India, mail armour was used right up until the 18th-19th centuries. In this more recent past, in places like Norway, one can also find pieces of ring weave used for suspension of knife scabbards and for suspension of cowbells. Today ring weave it is used in butcher’s gloves to protect the hands during the cutting of meat.

Bronze rings

Mail garments was usually made from iron, but for decorative purposes rings made from bronze and other copper alloys could be mounted in the ring weave, mostly along rims but also in simple patterns further into the garment (as on a garment from Visby 1361 – Thordeman 1939). Bronze rings as decoration seems mostly to be a medieval feature, but on the Coppergate helmet (8th century) a row of brass rings are mounted in the top of the mail aventail were it was attached to the helmet (O’Conner 1992).

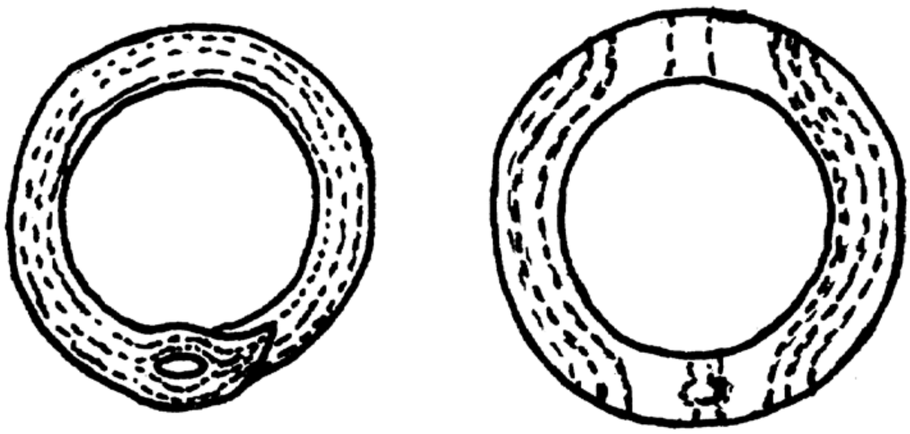
Analysis of the finds

This paper deals with three finds of ring weave. These are all kept in the Oldsaksamlingen in Oslo. The Gjermundbu find is the only one of the three that, due to its context, can be securely dated to the Viking Age. The other two lack such clear contexts since they were found very early without proper excavations (already during the 18th and 19th century).

The finds were analysed through samples of small, conjoined fragments of ring weave. Only parts of these samples were submitted to destructive analyses. Most of the rings from the sample pieces were carefully measured and recorded. Observations and assessments were noted along the way. A distinction is made between joined, riveted rings and whole, unriveted rings. All data on each find was summed up and registered separately. The measurements are intended, among other things, as an aid to see how regular or irregular the features of the rings are. This in turn can be used as a means to conclude how standardised the ring production was, and if possibly specialised manufacturing tools were employed. The registration of data was also meant as an aid for further research and will hopefully increase the accessibility of the finds, especially to foreign researchers. The idea is therefore to later develop this thesis into an article or dissertation in English.

The measurements were taken with a Vernier Caliper and registered with an accuracy of a tenth of a millimetre. Smaller details, such as rivet heads were measured under a Stereo Microscope (x40). The least corroded rings were selected for measurement. Heavily corroded and thus distorted areas were omitted as these would be misleading. Omitted measurements are indicated by a dash (-) in the tables. Where the length of overlap on riveted rings was not possible to measure it is indicated in the table with a question mark (?).

The making of metallographic samples was the more destructive part of the analyses. Metallographic examination depends on at least some uncorroded metal being preserved in the rings in order to get good results. Metallography involves making observations under a microscope of the distribution of slag streaks, weld lines, various alloying conditions and traces of heat treatment in the metal's microstructure. At least two rings of each type (two riveted and two whole) was needed for the metallographic examination. These were cast in epoxy (Struers epofix), one vertically and one horizontally. These samples were then roughly grinded on a rotating water grinder with 1200 grit. After the grinding the samples were polished with diamond paste with grain coarseness from 15 to 1. The samples were then studied to establish the distribution of slag lines before etching with 4 % Nital (nitric acid and alcohol). After etching the alloying and grain structures could be assessed. The samples were used to study the rings both in *plan section* and in *cross section*. When studying a rings plane section half the rings thickness is ground away exposing the full longitudinal cut of the metal wire. If there are a lot of slag streaks in the metal, the plane section can clearly show whether a ring was made from drawn wire or punched from sheet metal. Drawn wire will show slag streaks that follow the general curvature of the wire while slag streaks in punched rings will cross the ring and be visibly broken by the punch.



Slag streaks are distributed differently in plane sections of riveted rings (drawn wire) than in plan sections from punched rings (sheet metal)

Separate layers in forged sheet metal can be identified in the cross section of punched rings, partly in a deformed state. Deformation from cold working will show as flattened crystalline grains if the metal has not been reheated and thus recrystallized afterwards. Directional orientation and localization of deformations can give hints as to which processes have been carried out; punching of rivet holes, flattening of the ring wire and more. In samples made from riveted rings the rivet needs to be in the section along with the wire. A tangentially sectioned sample of the riveted area was also made on a ring from the Gjermundbu find as well as on one from the shirt from Verdalen. These made it possible to study the shapes and deformations of the rivets more closely.

There was no time to attempt analyses of trace elements in slag inclusions in the metal. This is used by some to assess the origin of the metal (Arne Jouttijärvi 1996). The trace element analyses require extensive electron microscope examinations and this was too demanding to carry out in the limited time available.

The riveting was opened in some rings to make it possible to study the joining more closely under a stereo microscope. Details were photographed and documented.

C 27317 i - Gjermundbu, Buskerud

The Gjermundbu find is a Viking Age burial dated to the 10th century (Grieg 1947). It was found and excavated in 1943, partly illegally, before the arrival of archaeologists at the site. The find consists of two different graves (I & II). Approx. 85 fragments of ring weave were found in grave I together with a large number of other artefacts, e.g. a double edged sword with a chape of bronze and a round helmet with a spectacle-shaped visor. The grave is a cremation burial.

Two mail rings are attached to the lower edge of the helmet. These indicate the possibly that not all of the ring weave fragments belonged to a shirt; some could have been parts of a neck protection suspended from the lower edge of the helmet (Munksgaard 1984). Several spectacled helmets from the Swedish Vendel period had such suspended ring weave protections (Arwidsson 1942, 1954, 1977). *"Right under the surface of the charred layer, which was not very deep, lay the shirt of mail like it had been folded neatly. Parts of it had slipped down somewhat and lay on its own by the side of the rest."* (Grieg 1947; Introduction). The piece of ring weave laying by itself could possibly be the neck protection of the helmet, the aventail.

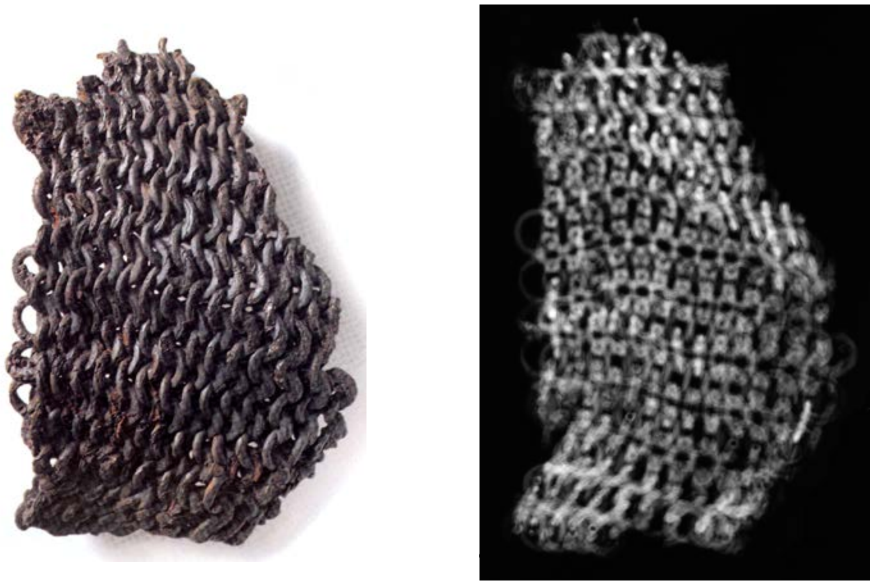
Preservation and current state

The ring weave appear to have been layed down in a folded shape prior to corrosion. The previously flexible material has become completely stiffened by deposited corrosion products and fixed in the folded shape. Several of the fragments have fractures where the cross-sections of the rings are clearly visible. In some areas of the fragments the ring weave pattern is clearly visible , but they are partially covered by corrosion. Some of the fragments have rings that appear thicker, probably swollen due to corrosion below the surface. The fragments have been treated with wax, but excess corrosion has not been removed.

Some of the larger and flatter fragments of ring weave from Gjermundbu are on display in the Viking Age exhibition in the Oldsaksamlingen in Oslo. They are mounted to a plate of plexiglass. This current montage was done for display at a large Viking Age exhibition in Paris in 1992. These fragments were conserved prior to the mounting on the plate; this included sandblasting (verbally relayed May 2000 by Torunn Klokkernes at the Conservation department at Oldsaksamlingen, Oslo). The author has not been able to track down any x-ray photos from this conservation.

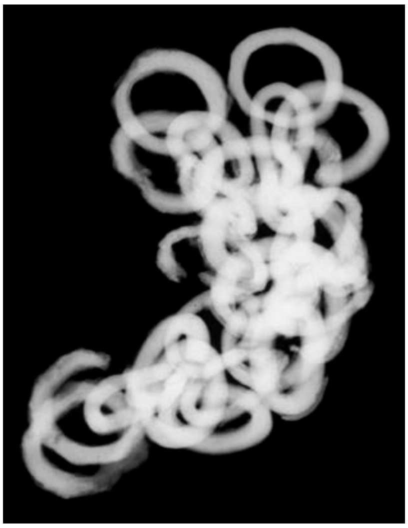
The fragments from Gjermundbu mounted for display (picture from conservation report 1991)

One of the fragments is currently on display at a traveling exhibition in the United States in connection with the turn of the millennium. The theme for that exhibition is the Viking Age. All Scandinavian countries contributed artefacts. This fragment was treated before the exhibition by conservator Torunn Klokkernes. An X-ray shows it to be in a very degraded state where many of the rings are hollow and consist of a fragile shell of corrosion. The possibilities for further conservation and examination of ring weave in this state are indeed very small.



The fragment on displayed in the USA (picture from conservation report 2000)

In contrast, not all the armour fragments from Gjermundbu are in this severely degraded state. The sample with 26 rings that was made available for analyses in this thesis proved to be very well preserved. On most rings, only the surface is corroded and large amounts of metal is preserved inside. Four rings are so corroded that they have an opening, but none of the rings are corroded firmly to each other. The sample was still slightly folded and stiffened by wax when the X-ray was taken, but fresh metal can be clearly distinguished in the core of the individual rings.



The sample fragment from Gjermundbu made available for analyses

In the corrosion layer the original surface of the metal is preserved on the majority of the rings. Many have some peeling of in this corrosion layer and some rings have swollen and become uneven and thicker as inner corrosion has pushed the surface outwards. The corrosion surface consists of a smooth, hard and black layer, presumably magnetite. In some places there are red areas on the original surface. This is probably hematite, an iron oxidation product that occurs when heated above at least 200 degrees. Hematite was to be expected on the metal; since the find comes from a cremation burial the ring weave has been submitted to heat in the funeral pyre.

The fragments mounted for display at the Oldsaksamling in Oslo appear to be in a good state of preservation. The other fragments in storage vary somewhat in their state of decay, but there is quite a lot of corrosion, mixed with conservation-wax on the surfaces of the rings. Radiography would tell a lot about the condition of the fragments.

The severely corroded fragment that was conserved for exhibition in the USA showed signs of active corrosion, and it would have been desirable to assess the state of preservation of the rest of the fragments as well. During the analysis of the rings copper residue was found on some of the rings in direct contact with the iron, below the corrosion layer. The copper could have contribute to increased corrosion of the iron acting as a sacrificial anode for the more noble copper. The state of the metal suggests an anaerobic and possibly somewhat alkaline soil condition; artefacts of bone were also recovered from the grave.

Examinations

The sample piece made available for analysis consisted of 26 rings. 6 rings were used in destructive analysis and the rest were later returned to the collection. 16 rings were solid, without trace of joints, while 10 were riveted.

The riveted rings are made from wire with a round cross-section. Rivet heads are only visible on one face of the rings, and all rivet heads are on the same face of the piece. On most surviving garments that side is the outside. The rivet heads are round and hemispherical and vary somewhat in size. On the rings with the best-preserved surface, it can be seen that the rivet heads have a smoothly curved surface without faceting. The even surface implies that a setting tool has been used to shape the heads of the rivets. The rivets are not visible on the 'rear' side of the ring. The overlaps by the riveted joints always run in the same direction – counter clockwise. The riveted areas on the rings from Gjermundbu are somewhat more varied than on the hauberk from Verdalen (C455) and somewhat less compressed in comparison to the wire. The less significant compression is probably due to the rivets being much thinner. Large differences in the riveting within the same mail mesh could be interpreted as traces of less standardized production, possibly simpler tools. The wire-ends in the overlaps tend to be pointed.

Examples of riveted rings

One ring had the riveted joint opened up, and both the joint and the rivet was studied. The rivet is fairly round in section, though more oval and wide towards the rear end. The rivet hole is not evenly round, more like a pointed oval formed from a widened split. This may be an indication that the tool used to punch the hole was not a round point tip, but rather a double-edged chisel shape.

Detailed pictures of the opened riveting joint

The riveted and the solid rings are consistently placed in every second row. The solid rings are of a heavier gauge than the riveted and they have a square cross section that is somewhat rounded-off on some.

The solid rings have an apparent square cross section

The solid rings tend to look somewhat irregular. At a closer examination of the best-preserved rings it could be established that the outer circumferences were quite round, while the inner circumferences tend to show four irregularities, almost like four corners. This brings to mind regular wear and tear. After all, each ring is hooked into four other rings that fit well into the four irregularities. A closer examination of the riveted rings show that they also have a tendency to form corners. Here, the metal has not worn away, but the metal wire seems to have given way and bent.

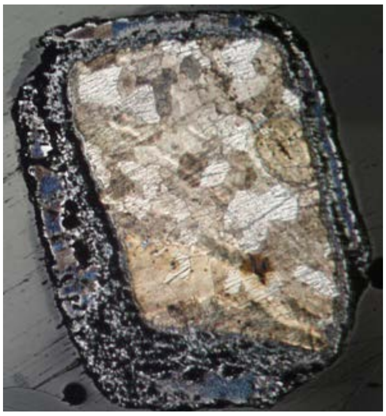
The rings tend to feature four corners

The metallography

The fact that the mail garment has been cremated is reflected in the metallography. The heat has caused the metal to recrystallize. Traces of cold working the metal are therefore gone. The slag streaks are unaffected by the heat and thus important information is still present. Both the whole and the riveted rings show coarse-grained and homogeneous ferrite in the plane section. The wire in the riveted ring is almost free of slag inclusions, but the few that do exist follows the curvature of the wire in a very precise manner, indicating that the wire was drawn. The solid rings have quite a few slag streaks. These break out of the ring in several places, a clear sign of a punched ring. A squarish cross section is also a sign that punching was the manufacturing method.

Plane section of a solid ring. Before etching

Slagg streaks that breaks out to the side of the ring. Plane section – 50X



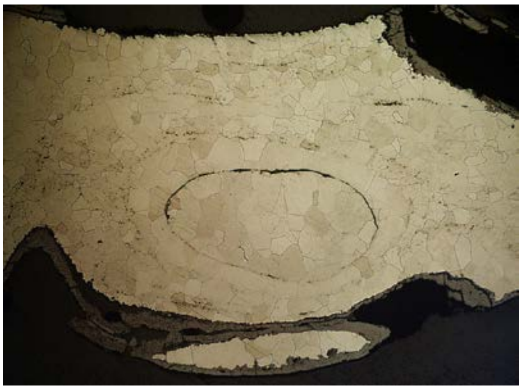
Cross section of a solid ring

The riveted ring turned out to have an intriguing and uncommon alloying. Needle-shaped structures was found within the ferrite grains in gradually increasing concentration furthest away from the riveting area. They turned out to be nitride needles, a sign of alloying with nitrogen (Samuels 1999:416-424). Nitrogen is absorbed into the iron interstitially in a similar way to carbon, but in larger quantities at a lower temperature than carbon. Carbon and nitrogen can join together in stable phases and form even harder structures. The strange thing is that the nitride needles were not to be found in the riveted area of the ring. A riveted ring ground in cross-section also display similare distribution of nitride needles - a lot of needles furthest away from the rivet area and none at the rivet. The nitride needles are not concentrated only at the surface of the metal, they are found to an equal extent in the core of the wire. Scattered nitride needles can also be observed in the solid ring, but

A full overview of a riveted ring

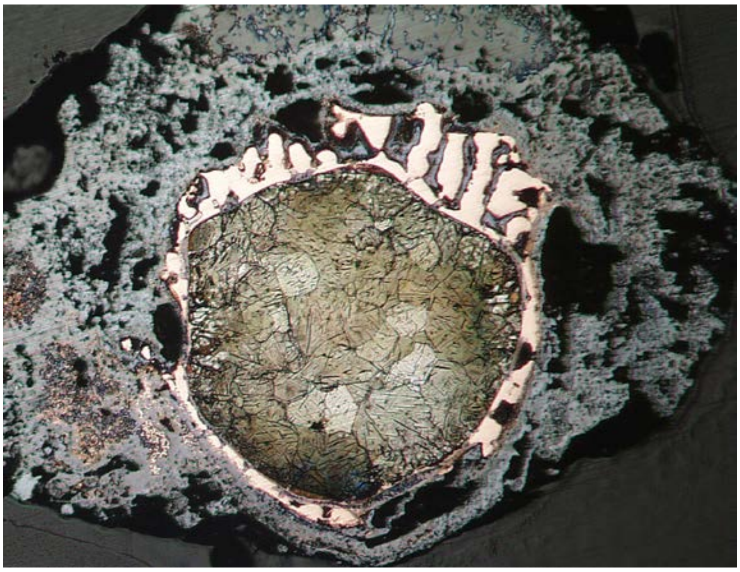
Ring section with nitride inclusions – 50X

Nitride needles – 200X



In the riveted area nitride needles are not present – 50X in smaller quantities.

Another interesting phenomenon that was particularly observed in the cross section of a riveted ring is copper on the surface of the metallic iron. It was observed to a lesser extent on other rings as well (both riveted and solid ones), but not on all examined rings. Metallic copper was present in an uneven layer in contact with the preserved iron in the rings, within what was the original surface of the ring. The copper was analysed in an electron microscope and was completely pure and unalloyed. An explanation for the copper could be an electrolytic reaction in the soil after the burial - as a result of copper being a nobler metal than iron. A bronze artefact has probably been corroding near the mail garment (for example the scabbard chape from the find).



Cross section of wire in riveted ring. Copper deposits and nitrides. 50X

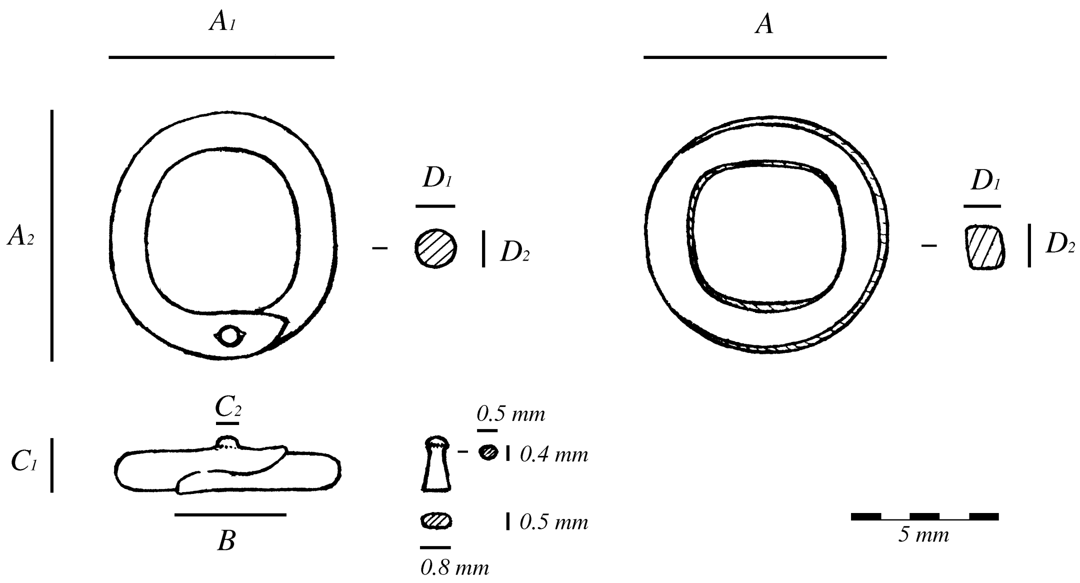
Detail of copper deposits, unetched. 200X

During the corrosion process, ions of copper will go into solution. When iron is present nearby, the copper ions that come into contact with the iron will precipitate as metallic copper and the iron acts as a sacrificial anode (corroding even more). The precipitation only takes place when the ions get in galvanic contact with the iron. This explains both that the copper is pure and that it is deposited below the rings original surfaces.

Weight (gram)

Total weight of sample	- 6.09 g
The solid rings	- 0.29 0.26 0.28 (average = 0.28 g)
The riveted rings	- 0.15 0.18 0.17 (average = 0.17 g)

The approx. 85 ring weave fragments have never been weighed and now many of the largest parts are mounted for display. The total weight is of interest, so an approximation will be made. The stored fragments weighed around 2900 gram. A tally of the displayed fragments gave an approximate number of 11 000 - 12 000 rings. Based on the average weight of individual rings the displayed fragments would weigh 2.6 kg. The total weight of preserved fragments would then be roughly 5.5 kg in total, and consist of 24 000 – 25 000 rings. Without a thorough study of all the fragments it is hard to tell how representative this is of how much ring weave there was in the grave to start with and how much has been destroyed by corrosion. The current weight indicates that it's much more than needed for a ring weave neck protection for a helmet. The amount is at the same time less than needed for a full mail shirt.



Measurements (millimeter)

Riveted ring no.			1	2	3	4	5	6	7
Ring		A^1	7.5	7.5	7.6	7.7	7.7	7.8	8.7
		A^2	8.0	8.2	8.2	8.1	8.1	7.4	7.9
Overlap		B	3.9	?	?	4.0	-	4.2	3.9
Rivet	- length	C^1	1.8	1.8	-	1.9	-	1.6	1.8
	- head	C^2	0.7	1.2	-	0.6	-	0.8	0.5
	- diameter	(based on one opened ring)							
			0.5 x 0.4 - diameter toward the rivet head						
			0.8 x 0.5 - diameter toward the back end						
Wire width at rivet			1.8	1.9	1.9	2.4	-	1.6	1.8
Wire		D	1.3	1.3	1.3	1.3	1.2	(1.0)	1.2
			1.4	-	1.3	1.3	1.2	(1.1)	1.2
			1.3	-	1.3	1.3	1.2	(1.2)	1.2

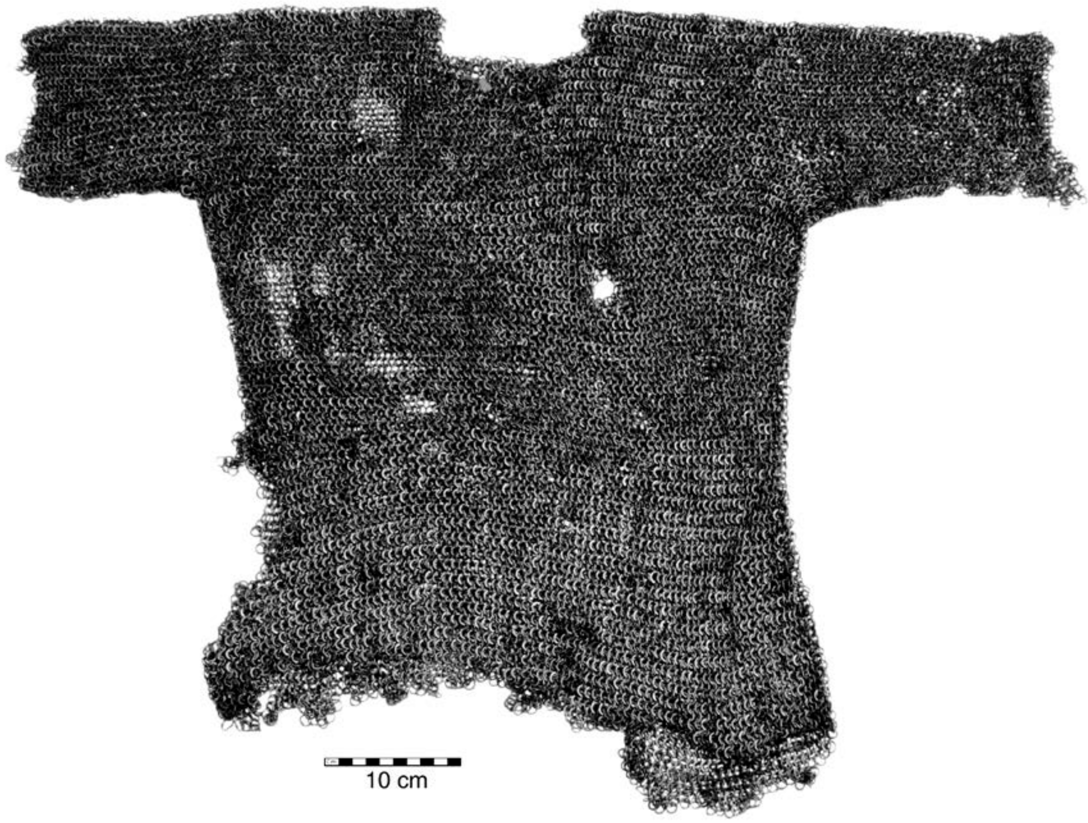
Solid ring no.		1	2	3	4	5	6	7
Ring	A outer	8.0	8.1	8.3	7.8	8.4	7.5	8.4
		8.0	8.1	8.2	8.0	8.0	8.4	7.8
	A inner	4.8	4.9	4.9	5.0	5.0	4.7	5.1
		4.9	4.9	4.8	4.9	5.2	5.0	4.8
Wire	D^1/D^2	1.3/1.3	1.4/1.5	1.6/1.6	1.9/1.4	1.3/1.7	1.7/1.6	1.6/1.6
		1.3/1.3	1.6/1.6	-	1.7/1.4	1.7/1.7	1.6/1.5	1.6/1.6
		1.8/1.7	1.2/1.5	-	1.1/1.4	-	1.6/1.5	1.4/1.5

(D^2 = wire gauge)

\- = misleading due to severe corrosion
? = could not be measured

C 455 – Verdal, Nord-Trøndelag

This is a mail shirt of uncertain provenience. It was kept in Verdalen (a village in Rogaland county, Norway) for a long time before it was deposited at the museum in 1833. The shirt is relatively well preserved, but has some holes and torn edges. The sleeves are of mid length and reaches roughly to the middle of the lower arms. The neck opening is fairly rounded. The metal in the rings is well preserved, but it has a layer of corrosion on the surface.



Measurements:

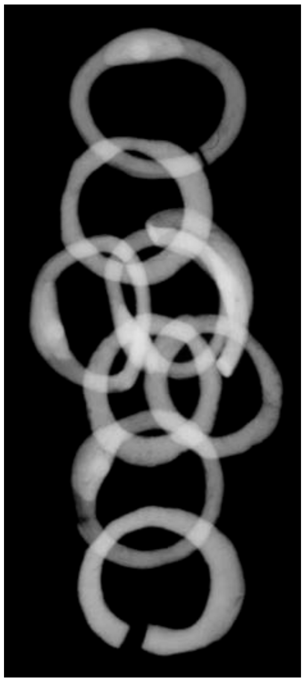
85 cm long

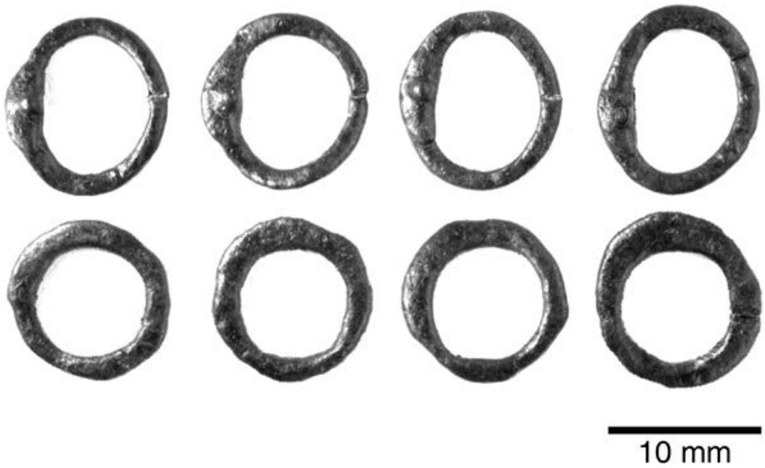
63 cm wide below the sleeves

Approx. 1 meter wide over the shoulders including outstretched sleeves.

After studying the shirt more closely, based on the shape of the garment and the individual rings, I would consider it to be from the 15th or 16th century. Several preserved German shirts from that period are comparable to C455 (Pfaffenbichler

1992). The shape of the individual rings also fits well with this dating (Smith 1959, Fredman 1992:23-55).





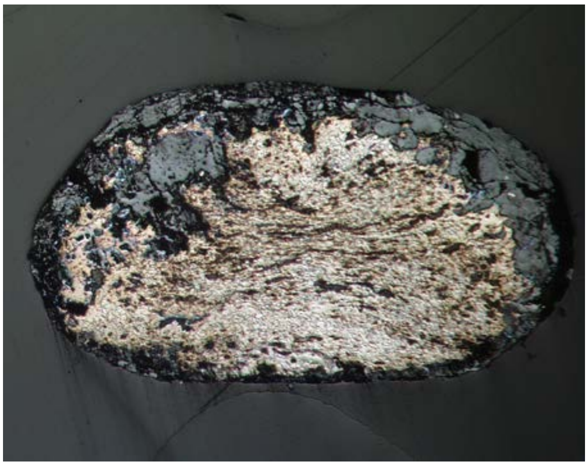
The sample was composed of 9 rings

The sample piece consisted of 9 rings, 5 riveted and 4 solid. The ring weave was covered by some conservation wax. It was necessary to cut the riveted rings through the side opposite to the rivet to free undamaged solid rings for the metallographic analysis.

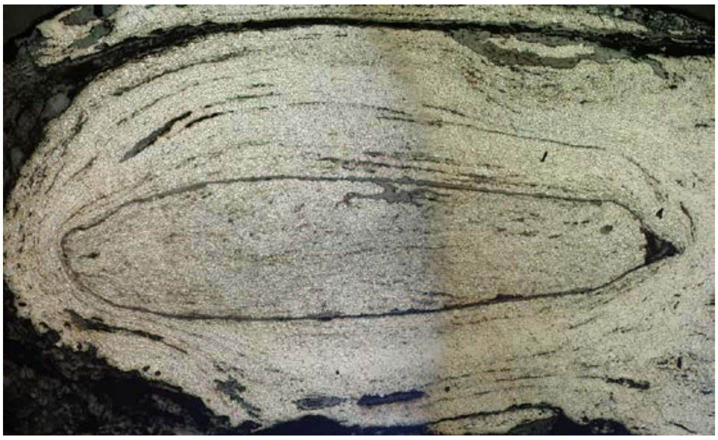
Riveted rings

Solid and riveted rings are mounted in every other row. Rivet heads are found on one side of the riveted rings only, and these always face toward the outside of the garment. All riveted rings overlap in the same direction, counter-clockwise. The wire ends of the rings are pointy in the overlapped area and the points tend to turn inwards towards the centre of the rings.

The cross-section of the wire in the riveted rings is oval. By means of the metallographical examination it could be established that the layers are compressed towards the middle of the cross section, and in the plane section it could be seen that the grain size was smaller towards the centre of the wire. This is probably the result of a round wire being compressed into an oval shape. The metal also has slag streaks that run smoothly parallel to the curvature of the wire. At the rivet, the slag streaks have been pushed to the sides but are not broken. The broad, flat shape of the rivet is clearly visible in the plane section. The tool that opened the rivet hole was evidently a flat, double-edged point. The exit hole at the rivet head is shaped as an extended, elongated slit along the direction of the wire. The metal of the riveted rings is homogeneously ferritic.

Cross section of riveted ring at the rivet and at a section of wire. Deformation is apparent.




Plane section at the rivet (elongated in direction of the wire) and at full width of the wire.

There are clear signs of a systematic approach in the riveting. The rivets have the same length on all examined rings, down to a tenth of a millimetre. The rivet heads have an even hemispherical shape that is exactly alike between the individual rivets. An interesting detail is that the rivet heads appear to be formed as much from the metal of the ring wire as from metal of the rivet itself.

A mail maker using a pair of tongs to assemble rings into a ring weave (Treue 1965).
A riveted ring from C455 display clear signs of a specialised tool being used for riveting.

This implies that the riveting was performed by means of a swage tool - an impression die with the negative shape of a rivet sunken into one face. It is tempting to interpret this riveting tool as a pair of tongs. Contemporary depictions from the 15th and the 16th centuries show mail makers using a pair of pliers in the mounting of ring weave. A simple swage and hammer could also have served the same purpose.

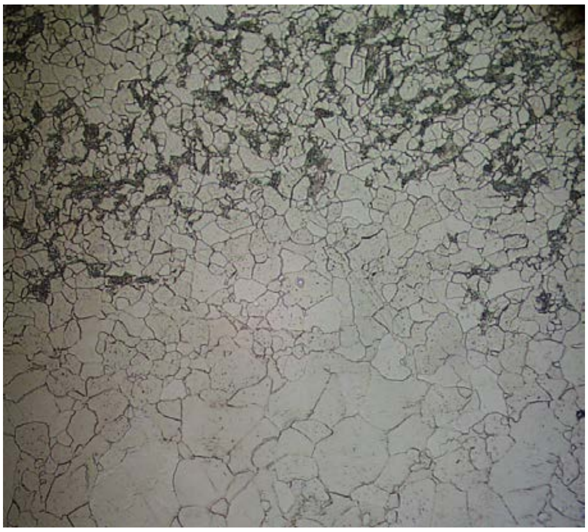
Two rings were opened in the riveting to allow a closer examination of the riveted area. One of these rings was later used to make a tangential section of the riveted area.

An opened ring with a rivet seen from the side. The special tool used to compress the rivet head has deformed the edges of the rivet.

Solid rings

The metal in the solid rings turned out to be much more heterogeneous than in the riveted ones. In the plane section, ferritic and pearlitic iron can be seen deposited in uneven bands that follow the curvature of the ring. An explanation for this phenomenon is given in the general discussion on technology in this paper. The perlithic areas seem to hold enough carbon to be on the verge of being hardenable, but hardening has not been attempted.

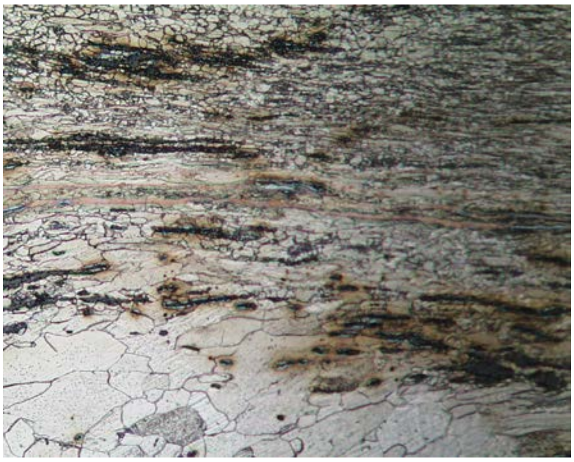
Heterogeneous layers can be observed in the plane section – 50X.



Perlite and ferrite intermixed – 400X

The slag streaks in the ring was quite obscure, but after studying the plane section of a second ring it became apparent that they ran partially across the direction of the ‘wire’, an indication of punched rings. The cross-section shows several indications of punching. Layers of pearlite, ferrite and impurities are visibly deformed towards the edges of the cross section. In addition to that, the grains are compressed and flattened in the plane of the ring. The metal has therefore not been annealed after cold working. In other words, the ring is punched from sheet in a cold state. The rounding of the edges of the cross-section does not appear to have deformed the layers further. It could therefore be reasonable to assume that the rounding has been achieved with grinding and not drop forging with a swage.

Cross section of solid ring displaying the layers that follow the plane of the ring – 50X



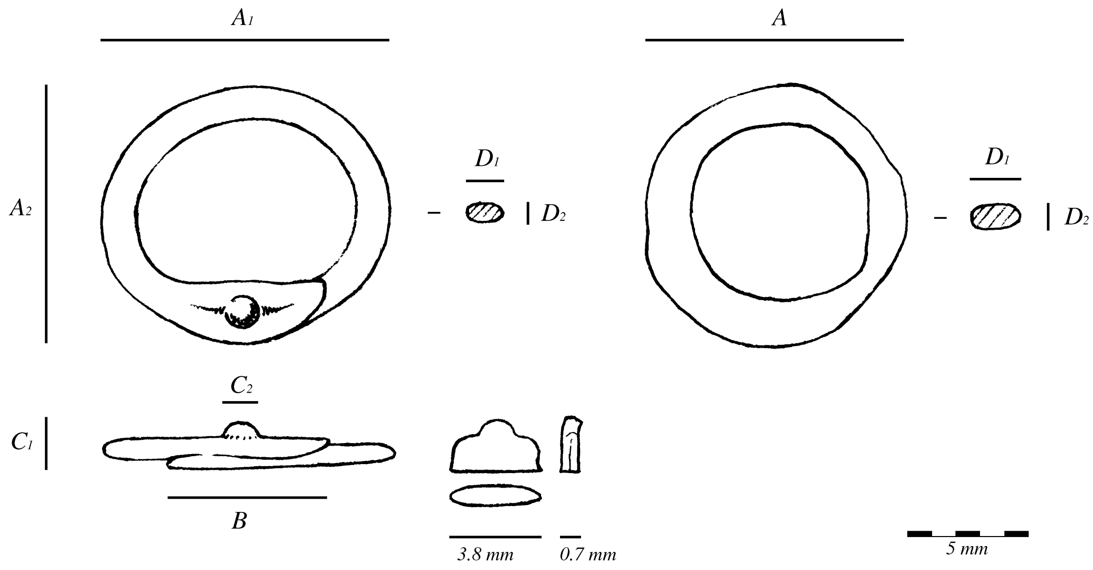
A detail of the cross section – 200X

Despite an uneven 'wire'-width the solid rings have a very uniform thickness. This fits in well with them being interpreted as punched from sheet metal. The width of the wire is extremely uneven though, possibly a result of grinding after the punching. Another explanation could be that the rings have been worn down by use, analogues to the ring weave from Gjermundbu (see the corner formation of C27317).

Weight (gram)

Total weight of sample	- 2,69 g	
The solid rings	- 0.31 0.25 0.41	(average = 0.32 g)
The riveted rings	- 0.28 0.28 0.28 0.29	(average = 0.28 g)

The whole mail shirt weighs approx. 8 kg. Based on the average weight of the rings, this amounts to a total number of approx. 27 000 rings.



Measurements (millimeter)

Riveted ring no.			1	2	3	4	5
Ring		A^1	12.5	12.6	-	12.2	12.3
		A^2	11.5	11.0	-	11.1	11.0
Overlap		B	5.8	6.4	7.0	6.2	6.4
Rivet	- length	C^1	2.0	2.0	2.0	2.0	2.0
	- head	C^2	1.4	1.5	1.4	1.6	1.5
Wire		D^1/D^2	1.5/0.8	1.6/0.7	1.6/0.7	1.4/0.8	1.5/0.8
			1.5/0.9	1.6/0.7	1.6/0.8	1.5/0.8	1.5/0.8

Solid ring no.			1	2	3	4
Ring						
	- largest	A_{outer} / A_{inner}	12.0/7.5	11.2/7.3	11.3/7.4	11.0/7.4
	- smalest	A_{outer} / A_{inner}	11.0/7.3	10.3/7.4	10.6/7.6	10.5/7.3
Wire						
	- largest	D^1/D^2	2.7/1.1	2.0/1.0	2.1/1.1	2.3/1.1
	-smalest	D^1/D^2	1.5/1.2	1.4/0.9	1.0/1.0	1.1/1.0

(D^2 = wire gauge)

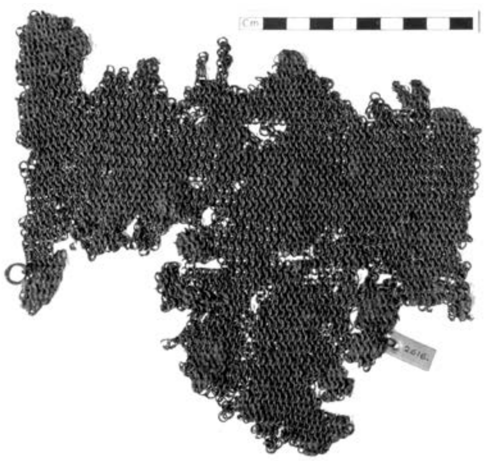
- = misleading due to severe corrosion

? = could not be measured

C 2616 – Mølledalen, Buskerud

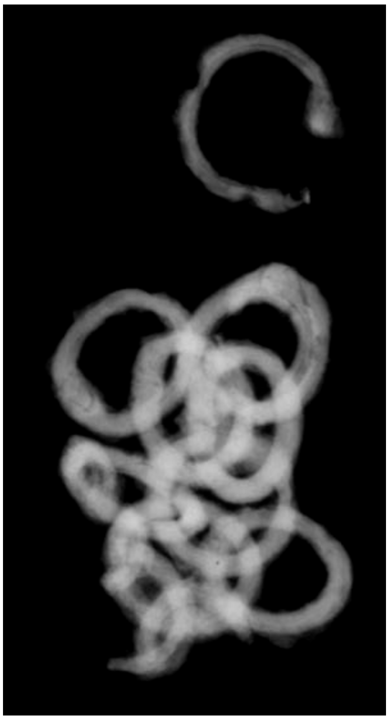
This is a fragmentary piece of ring weave that was deposited at the Oldsaksamlingen in the 19th century. The rings are unusually small. The fragment was found together with a mail hosen (C3250), a mail gorget (C3108) and part of a mail sleeve (C2314). Both 3250, 2314 and 2616 have rings of a similar size, but 3250 and 2314 are partially made up of rings of an even smaller size. The hosen (C3250) has a slit in the lower calf area, and along the edges of the slit there are several sets of lacing rings. The lacing rings are riveted rings twice the size of the other ring in the mail garment. The analysed fragment (C2616) has such a lacing ring along one edge and is therefore most probably part of the second hosen in a pair to C3250. The best preserved hosen is for a left leg, if the lacing was at the back of the calf. Based on that assumption fragment C2616 would have been part of the right hosen.

C3250 – the complete hosen



C 2616 – the analysed fragment. Notice the much larger lacing ring

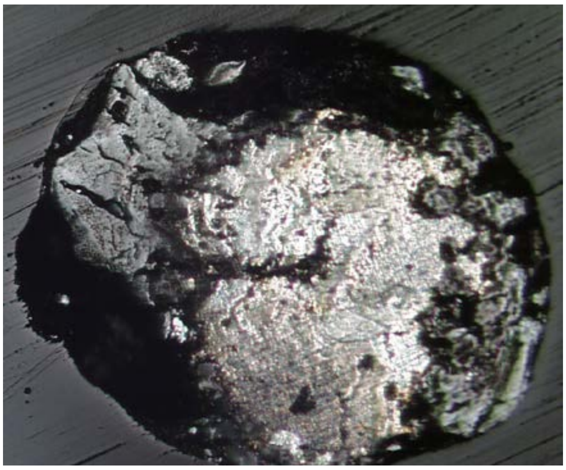
The state of preservation varies, but is generally good, especially taking into account how thin the wire of the rings is. All the four ring weave objects from Mølledalen seem to belong together. If that is true, they can typologically be dated to the 15th century based on the mail gorget (C3108).

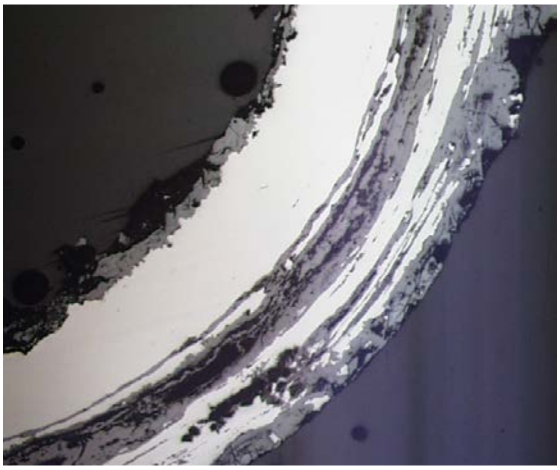


The sample piece from C2616 made available for analysis

The sample piece consists of rings with some surface corrosion and is not from the best preserved part of the fragment. The rings were covered in a reddish conservation wax. All rings are riveted and overlap counter clockwise. The rivet head was quite difficult to distinguish from the rest of the ring in some cases, but always seemed to face towards the same side of the garment. On the hosen C3250 the rivet heads are facing inwards, a fairly uncommon feature. The rivet heads were not particularly prominent, so which way they faced probably had little practical significance. The hosen might have been turned inside out at some point since two of the lacing rings are now positioned on the inside at some distance from the current edge.

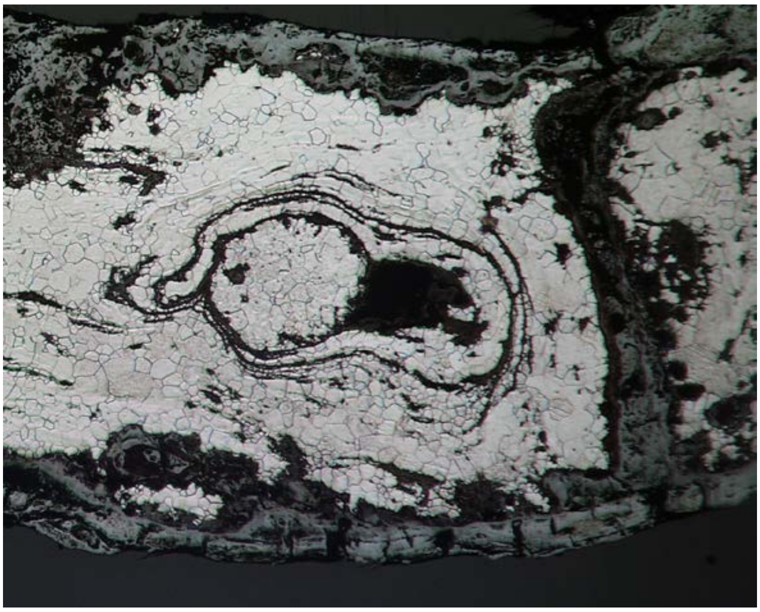
The riveted area of two opened rings were thoroughly studied and measured along with the rivets themselves. The wire ends are bluntly cut in the overlap and not pointy as is usual. The wire is round in cross-section. In plane section the metallography reveal a consentration of slag streaks near the core of the wire that follow the curvature of the wire. This implies that the wire was drawn. An explanation for the slag concentration in the core is given in the cross section; The cut of the wire is U-shaped with a concentration of impurities extending from the center. The wire is probably drawn from thin, flat iron strips cut from sheet metal. These have intentionally or accidentally folded into 'hollow tubes' during the wire drawing process.





The fact that the wire has been drawn from flat iron bands that have folded lengthwise can be observed by combining views of both cross section and plane section of the ring.

Further, the metallography display ferric iron, a round-sectioned rivet and deformations by the edges of the rivet hole. The rivet hole seem to have been larger than the rivet.

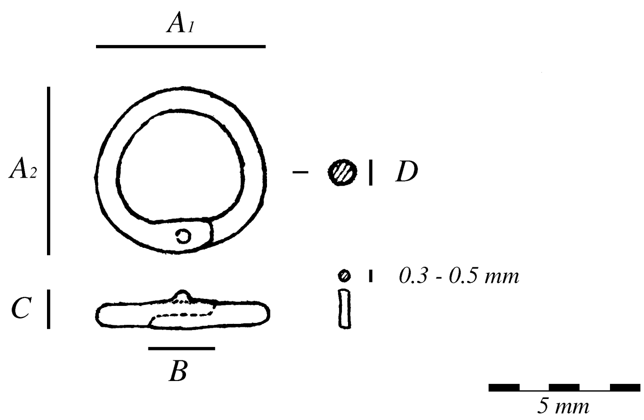


Details of the riveting area. The rivet hole is larger than the rivet itself – 100X

Weight (gram)

Total weight of sample	- 0.68 g
All rings are riveted	- 10 ½ rings in total average at 0,065 g/ring

C2616 is only a fragment, but the comparable complete hosen C3250 weighs 1533 gram. A complete hosen would thus contain approximately 24 000 rings.



Measurements (millimeter)

Riveted ring no.		**1**	**2**	**3**	**4**	**5**	**6**	**7**
Ring	A¹	-	5.0	5.5	5.6	5.5	5.4	5.5
	A²	-	5.5	5.4	5.4	5.5	5.3	5.3
Overlap	B	2.4	?	?	2.4	?	2.3	2.3
Rivet - length	C	1.3	1.5	1.2	1.3	1.2	1.3	1.3
- diameter		-	-	-	-	-	0.50	0.30
Wire	D	0.85	0.9	1.0	1.0	1.0	1.0	1.0
		0.8	0.7	1.0	0.9	0.8	0.9	0.9
(corroded surface)		-	-	0.9	0.8	0.8	-	-

\- = misleading due to severe corrosion
? = could not be measured

Dating and technological evaluation of ring weave

The vast majority of archaeologically found mail garments either stem from wetland deposits from the Roman Iron Age (Germany and Denmark) or from grave offerings in pre-Christian burials. Many mail garments from the 15th and 16th centuries have also been preserved by various collectors. Apparently very few mail garments have survived from the early medieval period. This quite contradictory to the fact that it was in the early part of the Middle Ages that mail armour saw its greatest use ever. The knights of the 12 – 14th centuries were virtually clad in ring weave from head to toe. In many ways contemporary depictions and written sources actually yield more information about early medieval mail garments than archaeological finds. The mass-graves dating from the Danish king Valdemar Attedag's conquest of Visby in 1361 make an important exception. In those graves large amounts of ring weave garments were found, coifs in particular, but also mail shirts. The contemporary depictions should be interpreted with a good deal of source criticism – as they are affected by artistic freedom, symbolism, misinterpretations, simplifications and travelling artists from other countries (for instance in church decorations). Despite the reservations these depictions are a valuable resource to discern which mail garments were in use during specific parts of the middle ages.

Typological features in ring weave are not easy to define, but certain tendencies can be traced. Since mail garments are often severely fragmentised it would be especially fruitful to be able to designate a time period to mail armour at the individual ring level, and not just based on the shape of the armour garment as a whole. Many of the tools and techniques used in the production of ring weave have left traces that still can be observed on the individual rings. This assumption is based on Per-Olof Fredman survey of ring weave in Swedish finds (Fredman 1992:23-55), my own observations and published surveys of for instance some Danish, English and German finds.

The wire used for rings in finds from the Iron Age is almost always round or nearly round in cross-section. This is the norm for both the riveted and solid rings. From the latter part of the Viking Age (the 10th century) and the beginning of the Medieval period the solid rings become more square or D-shaped in section. The solid, presumably punched, rings appear to be less reshaped and rounded-off after punching than during earlier periods. A closer look at the pre-Viking Age finds of ring weave actually reveal a tendency toward D-shaped cross-section also on these solid rings. Individual examples of D-shaped cross-section with the flat side turned towards the centre hole can also be observed in finds from Roman Iron Age (Vimose and Thorsberg – Jouttijärvi 1996:54). During the preparation of this paper the author himself examined a small fragment of ring weave dated to the Vendel period, the 7th century (C15968 – Oldsaksamlingen, Oslo). A vaguely D-shaped/elliptical cross section could be observed on those solid rings also.

The rivet area on rings from the Iron Age, Viking Age and early Middle Ages does not tend to be stouter than the rest of the wire and the rivets seem to have been made from round section wire. Further along, during the Medieval period, the rivets were often flattened and wide at the rear end. The rivet holes became more like slits along the wire rather than round holes. This makes the area around the rivet into a widened elongated outline, often with a ridge-like structure at the rivet head. In the early Middle Ages, the wire of the riveted rings was still usually round. Riveted rings with a flat or oval cross-section seem to become common only in the 14th century. Riveted rings with a flat or oval cross-section are not necessarily a reliable dating basis in themselves, but if the riveting is also elongated with a ridge formation in conjunction with the rivet head, one can be quite sure of a late medieval dating.

There are some extant examples of mail shirts with all rings riveted as early as the Vendel Period (Fredman 1992:46), but they seem to be uncommon prior to the Middle Ages. Fully riveted mail is very common during the 15th and 16th centuries, but not absolutely exlusive (for concrete examples see Smith 1959:62-64). This may be due to the fact that the rivet is indeed the weak spot in the ring. Only half of the rings actually need to be open during the assembly of ring weave, while the other half can be made solid and unjoined, thus stronger. That extra strength is important in providing enough protection against penetrating weapons like arrows and spears. Experiments with shooting arrows at mail armour confirm this (Nielsen 1991:144). How labour-intensive the manufacture of punched rings is compared to riveted ones is an interesting question in this context, but cannot be answered until varied and thorough experimentation with manufacture has been carried out. Production of solid rings by welding overlapped metal wire have been tried out and documented by some researchers (Smith 1959/60, Lang, Craddock, Hook 1992, O´Conner 1992).

Riveted rings

All riveted mail from all time periods and on all garments are found to consistently overlap in the same direction, anti-clockwise. This applies to all the Norwegian finds examined by the author, but also to all images and publications the author has come across. In principle, they could well have overlapped the other way as well. It might be caused by how the rings were made, and of the easiest way for a right-handed person to perform one or several stages in that process.

Wire ends in the overlap of riveted rings almost always have pointy ends. These pointy ends are normally bent slightly inwards towards the center of the ring. These features will appear if a coil of iron wire is wound on a metal rod and thereafter cut into rings with a chisel. If the coil is cut diagonally following its spiral, the resulting rings will have both a natural overlap and pointy ends. The "funnel" proposed by Burgess (1953) to compress rings into having an overlap would then be completely redundant.

The result of the authors own attempt at diagonal cutting of rings from an annealed wire coil to attain ready-made overlaped rings.

An original ring that seem to display the same traits achieved by diagonally cutting rings like described above (ring from C455)

The chisel used for cutting could have been hand-held, but would have been easier to control if it was attached to a stump or anvil with its edge facing upwards. Such a tool is called a "hardie" by blacksmiths.

Occasionally there are rivet heads on both sides of riveted mail rings, but the most usual by far is a rivet head on only one side. The rivet heads always face in the same direction, and on preserved garments that is towards the garments outside. Exceptions do exist, but those garments have probably been turned inside-out.

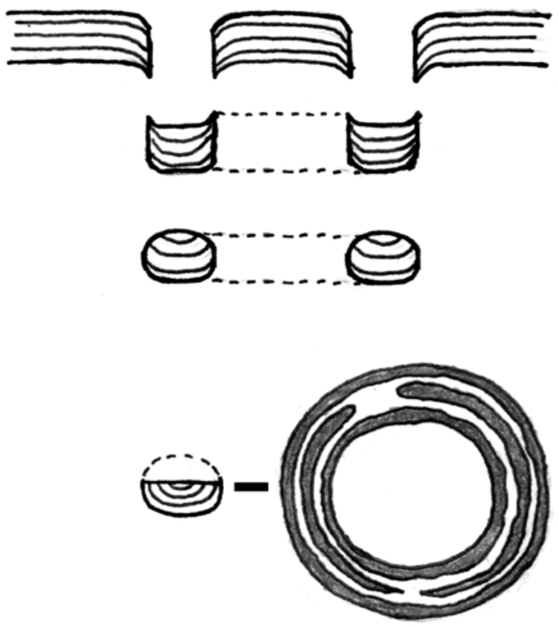
The rivet heads are almost always evenly hemispherical in shape, some flatter than others. There are no apparent facets left by hammer strikes to be observed on the rivet heads, not even on the oldest finds. Facets do appear on later repairs when rings have been added to existing ring weaves (Jouttijärvi 1996:54). The rivet heads don't consist solely of the compressed rivet shanks, even when they have a perfect hemispherical outline. Some metal from the ring wire itself is also incorporated into the hemisphere. That extra metal originates from the edges, the lips of the exit hole pierced through the wire overlap (See the analysis of C455 for pictures etc.).

The rivet heads must therefore have been formed with some kind of swage tool, with a cavity in the negative shape of the rivet head. The swage cavity would have been pushed onto the rivet by hammer strikes or by the force of the jaws of a pair of tongs (for an example – see the cover picture).

Onwards, during the Middle Ages, the riveted rings got more flattened or slightly oval in cross section. The production of these rings seem to be with a very regular and consistent finish (see C455 – wire gauge). The same shaping tool that was used to flatten the overlap of the rings could possibly also have been used to flatten the rings as a whole.

Punched rings

The solid rings could have been produced with one punch only, or with two punches – one for the inner hole and then one to cut the outside. Several examples of punched rings have been found. In this survey it could be established that the solid rings of both the two mail finds were produced by means of punching. Arne Jouttijärvi's metallographic surveys from 1996 also revealed all examined solid rings to be punched. Two other metallographic surveys hold welding in favour as the means of producing solid rings, but may not hold up to closer scrutiny (Smith 1959/60 and Lang, Craddock, Hook 1992). The documentation of the ring weave from Coppergate is somewhat unclear when it comes to the assumed welded rings. A picture of a cross-section is featured in the publication (Lang et al 1992:1024-1025). In it heterogeneous layers and flattened ferrite grains in plane with the ring can be seen. These features fit with punching cold rather than welding. Dr Smith in turn studied a large number of mail shirts from the 15th and 16th centuries. He studied the plane section of solid rings but seem to have lacked an evaluation of the related cross section. This could have led to misinterpretations, like confusing observations of slag streaks with formations caused by layered, heterogeneous iron (ferrite/perlite). These layers would be deformed by punching, causing them to be broken through in the plane section, looking like “wood grain”. The visual result after etching would be stripes partially following the curvature of the ring.



Finishing of punched rings seems to have been done by grinding to remove sharp edges and burrs. In a German manual from the 15th century such a treatment of rings can be seen (Treue 1965:54 – text on p. 116 in the text volume).

Ring maker, 15th century (Treue 1965)

In that illustration a multitude of rings are mounted on a thick 'bowstring'. These are ground into a curved groove in a leather-lined wooden block. This would explain a D-shaped wire cross-sections with a straight edge facing the hole in the ring (previously pointed out by Arne Jouttijärvi 1996). Hammering-shaping each individual ring while on a mandrel is also a possibility (suggested by Burgess 1959/60; Sim 1998), but much more laborious. Whole rings that have been given a fully round cross-section may in theory have been rounded in a double swage tool after punching as suggested for the Hedegård mail shirt by Malfilâtre (1993:44).

Laborious production

If one considers that the making of a mail shirt demanded thousands of rings to be produced and assembled it is easy to understand that it was an enormously laborious process. Metal wire and thin iron sheets had to be produced first. The wire would have to be wound into coils and solid rings would have to be punched out of the sheets. The coils would then have had to be cut to form overlapping rings and the raw, punched rings ground to remove burrs. All the rings then needed to be threaded together, each ring linked to four others. The rivet holes had to be drifted and riveting carried out. Now and then during assembly the ring weave pattern had to be adjusted to ensure that the garment attained the right shape.

Das Hausbuch der Mendelschen Zölfbrüderstiftung from the 15th century tells us that making a mail shirt was half a year's work (Treue 1965:112 of text volume). The mail shirt from Verdalen (C455) is made up by approx. 27 000 rings.

The shaping of a ring weave garment

Ring weave is a so-called isotropic material. It is assembled according to a pattern that is oriented in two directions and is more stretchable in one of these. The most stretchable direction is always horizontally orientated in mail garments (see the Introduction). On the shirts the ring pattern continues directly onto the arms without a change in direction at the shoulders. The typical ring pattern is the norm for all mail shirts with a few exception for early Roman and Celtic mail shirts that have the pattern turned at 90 degrees – the Hedegård shirt is one of them (Malfilâtre 1993). The typical orientation of the ring pattern is found on the laced hosen and gorget from Møllerdalen (C3250 & C3108 – Oldsak. Oslo). It is also upheld on the neck guard of helmets, for example in finds from Vendel and Valsgärde (Arwidsson 1935, 1939, 1942, 1954 and 1977) and on the Coppergate helmet (O'Conner et al. 1992).

The sleeves on the mail shirt from Verdalen (C455 – Oldsaksamlingen Oslo) are given better mobility in the arms by shaping the pattern under the armpits. This is akin to tailoring the shoulder joints on jackets and sweaters. The hosen from Møllerdalen (C3250 – previously erroneously interpreted as a sleeve) also feature subtle alterations in the pattern to provide a better fit. Among these an expansion wedge at the top inside of the thigh-part of the hosen. The gorget C3108 has an extension to provide sufficient space for the chin. It also features overlapping edges on each side of the chin section, probably to allow the edges to be laced snugly. This gorget is an uncommon artefact, and is probably stylistically dateable to the 15th century. The gorget is intact and in a very good state of preservation (C3108 – Oldsaksamlingen Oslo). Previously it was believed to be part of a sleeve, which is obviously wrong.

Chronological assessment of ring weave garments

Along with studying mail armour at ring level, the garments as a whole must also be assessed. In lucky cases, both can be studied at the same time by having a fully preserved piece of armour. Archaeological fragments of ring weave can sometimes be dated based on the other objects found with it, in a grave context for example. Entire garments can possibly be dated by comparing with contemporary depictions and written sources. Source criticism is important though, and many types of armour have been used for periods of several hundred years. But combined with an evaluation on ring level it is nevertheless interesting to look at images of mail armour depicted on Vendel period helmet decorations, images on the Bayeux tapestry from the late 11th century and Norwegian alter frontals from the late 13th and early 14th centuries. The Bayeux tapestry reproduces, among other things, the early use of ring weave hosen. Only Duke William himself and one of his closest associates are depicted wearing mail hosen. The ordinary knights of the Bayeux tapestry wear only mail shirts with a hood.

Also written sources such as Beowulf, the King’s Mirror, the early Scandinavian laws and the Hirdskraa all provide various forms of information on ring weave garments.

Conclusion

The limited material that was analysed in this paper cannot provide grounds for an all to conclusive interpretation, but the results fit well into the surveys on Danish ring weave performed by Arne Jouttijärvi. All the examined solid rings were punched and not welded. Ring weave made from half solid and half riveted rings was more common than expected, compared to the all-riveted mail. Some typological features on ring-level seem to be of significance for the dating of individual ring weaves, but the lack of finds from the first half of the medieval period renders large gaps in the typology. Generally speaking it seems like the production of ring weave was a particularly laborious and time-consuming craft. Special tools were used to shape the rivet holes and to perform the riveting, most probably long before the Middle Ages. The drawing of metal wire seem to have been a craft that was closely associated with mail making, but this paper does not attempt to make any in-depth survey of that part of the process. It's uncertain if the mail maker made his own wire or if other specialized craftsmen performed that process. Attempting to answer this and other question could help to place the mail maker in relation to his society.

The more symbolic aspects of ring weave, along with its use and efficacy in battle are in no way covered here. These may be topics for further reasearch.

Glossary

Swage	A tool with a depression that metal can be forced into to attain the shape of the depression.
Jaws, tong/pliers	The part of a tong used to grip hold of something.
Metallography	The grinding and polishing of a metal surface to enable microscopy study of alloying and structures related to the manufacture of objects.
Ring weave	A term used for the flexible material created when metal rings are linked together in a specific pattern. Used for armour in Europe from approx. 300 BC and into the middle ages to protect against cuts and wounds.

Literature

Arwidsson, Greta
1935 A new scandinavian form of helmet from the Vendel-time
Acta archaeologica 5:3, København

Arwidsson, Greta
1939 Armour of the Vendel period
Acta Archaeologica Vol.10, København
(Erroneous reconstruction of armour parts)

Arwidsson, Greta
1942 Die Gräberfunde von Valsgärde. 1, Valsgärde 6
Acta Musei antiquitatum septentrionalium Regiæ Universitatis Upsaliensis ; 1, Uppsala

Arwidsson, Greta
1954 Die Gräberfunde von Valsgärde. 2, Valsgärde 8
Acta Musei antiquitatum septentrionalium Regiæ Universitatis Upsaliensis ; 4, Uppsala

Arwidsson, Greta
1977 Die Gräberfunde von Valsgärde. 3, Valsgärde 7
Acta Musei antiquitatum septentrionalium Regiæ Universitatis Upsaliensis ; 5, Uppsala

Burgess, E. Martin
1959/60 A reply to Cyril Stanley Smith on mail making methods
Technology and Culture, I, 1: Winter 1959/60

Burgess, E. Martin
1953 The mailmaker's technique
The Antiquaries Journal 33, Oxford

Burgess, E. Martin
1953 Further research into the construction of mail garments
The Antiquaries Journal 33, Oxford

Grieg, Sigurd
1947 *Norske Oldfunn VIII*, Gjermundbufunnet – en høvdinggrav fra 900-årene fra Ringerike, Oslo

Fredman, Per-Olof
1992 *Ringväv - om ringbrynjor och liknande föremålstyper från förhistorisk tid og medeltid.*
Uppsats C/20p, Inst. för arkeologi Uppsala universitet . 55s

Jouttijärvi, Arne
1996 Fremstilling av ringbrynjer
Nettverk for tidlig teknologi / Early Iron, København

Lang, J., Craddock P.T. og Hook, D.R. - red. Tweddle, D.
1992 *The Anglian Helmet from Coppergate*
- Analytical results (s1017-1026)

Malfilâtre, Michel Kalsbøll
1993 *Ringbrynjen fra Hedegård – fremstillingsteknik og metode*
Konservatorskolen, Det Kongelig Danske Kunstakademi

Munksgaard, Elisabeth
1984 A Viking Age Smith, his Tools and his Stock-in-trade
Offa 41

Nielsen, Ole
1991 Skydeforsøg med jernalderens buer
Eksperimentel Arkæologi nr 1 1991, HAF-Leire

O`Conner - red. Tweddle, D.
1992 The Anglian Helmet from Coppergate, *The Archaeology of York* – the small finds 17/8
- Conservation of the helmet and mail (p. 907-935)
- The mail curtain (p. 999-1011)
- Technology and dating of the mail (p. 1057-1082 (1171))
- Catalogue of Scandinavian mail (p. 1183-1187)

Pfaffenbichler, Matthias
1992 Armourers, *Medieval craftsmen*, British Museums press

Samuels, Leonard E.
1999 *Light Microscopy of Carbon Steels*, ASM International, Materials Park (USA).
First edition 1922, edited 1980, revised and expanded 1999.

Scott, David A.
1991 *Metallography and Microstructure of Ancient and Historic Metals*, The Getty Conservation Institute, Arcetype Books (London/Singapore?)

Sheldon, Steven E.
1999 *Riveted mail – theory and technique.*
http://www.arador.com/forth2.html (downloaded March 2000)

Smith, Cyril Stanley
1959/60 Methods of Making Chain Mail (14th to 18th Centuries): A Metallographic Note, *Technology and Culture*, I, 1: Winter 1959/60

Sim, David
1998 Beyond the Bloom
BAR S725, Archaeopress

Dreshner, Hans - red. Raddatz, Klaus
1981 *Sörup I*, Neumünster

Thordeman, Bengt
1939 *Armour from the battle of Wisby 1361 – Bind I*
Uppsala

Treue, W. (red.)
1965 *Das Hausbuch der Mendelschen Zölfbrüderstiftung zu Nürnberger*, München
(separate text and image volume)

Tweddle, Dominic
1984 *The Coppergate helmet*, Jordvik Viking Center – York

Wyley, Stephen F.
The Gjermundbu Mail Shirt
http://www.geocities.com/svenskildbiter/ArmsArmour/mailshrt.html (downloaded 3rd April 2000)

Other relevant literature not used/studied by the author:

Burgess, E.M.
1957 The Mail Shirt from Sinigaglia, *The Antiquaries Journal 37*, Oxford

Burges W. & Baron de Cosson
1881 *Catalogue of the Exibition of Ancient Helmets and Examles of Mail*

Engelhardt, C.
1863 Thorsbjerg Mosefund, *Sønderjyske Mosefund 1*, København

Engelhardt, C.
1863 Thorsbjerg Mosefund, *Sønderjyske Mosefund 2*, København

Robinson, H.R.
1975 *The Armour of Imperial Rome*, London

Nicklasson, Påvel
1989 *Ringväv och sårsvett – om tillverkning och anvănding av ringbrynjor.*
C-uppsats (a study of Danish bog finds from the pre-roman and roman iron age)

Erik D. Schmid (a personal friend of David Edge at the Wallace Collection) has supposedly come a long way in practical understanding and reproduction of mail armour.