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THE MANUFACTURE OF MAIL IN MEDIEVAL EUROPE: A TECHNICAL NOTE

BY
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THE oldest specimen of interlinked mail yet found has been excavated from a 3rd cent. B. C. Celtic grave in Romania,[1] and this was probably developed from protective garments made up of rings threaded onto cords, like netting. A fragment of such a garment has been found in a Hallstatt grave, perhaps 8th cent. B. C. in Bohemia.[2] Representations of Roman soldiers prior to the 1st cent. A. D. show them clad in mail-shirts rather than in plate.[3] Mail returned to favor in the straitened economic circumstances of the Migration Period, and, indeed, remained the basis of most personal armour in the Middle Ages until gradually replaced by plate again in the 15th cent. The methods of making mail have received some attention, E. M. Burgess[4] and C. S. Smith[5] having discussed them in recent years, and A. J. Arkell[6] described how mail was made in the Sudan within living memory. Wire was made, either by drawing, or by slitting a plate into thin strips, and then coiled into a cylinder around a mandrel. Links were then cut from this cylinder, joined into groups of (usually) five, and then connected by the master-craftsman into the shape desired. The links would then be closed by riveting their ends together. Much of this work could be done by semi-skilled workmen employed by the craftsman, and only small pieces of metal had to be worked at any time; these factors, coupled with the flexibility of mail,

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[1] RUSU, M., «Das keltische Fürstengrab von Ciumesti in Rumänien», *Germania* (1972), *50*, 267.

[2] HRUBY, V., «Ein Ringpanzer der Hallstattzeit», *Sbornik Praci Filosoficke Fakulty Brnenske University* (1959), *8*, 33.

[3] ROBINSON, H. R., «The Armour of Imperial Rome» (London, Arms and Armour Press, 1975), *passim*.

[4] BURGESS, E. M., «The mail-makers' technique» *Antiquaries' Journal* (1953), 33, 48, and «Further research… into mail», *ibid*. 193.

[5] SMITH, C. S., «Methods of making chain mail», *Technology and Culture* (1960), *1*, 60.

[6] ARKELL, A. J., «The making of mail at Omdurman», *Kush* (1956), *4*, 83. He includes photographs of the processes being operated at that time, which probably did not differ much from the Medieval European method.

which meant that accurate fitting was unnecessary, ensured its widespread popularity for centuries.

Smith examined 11 specimens of European and 5 specimens of Oriental mail. All had been made from true drawn wire, and all showed signs of annealing, although some had subsequently suffered cold deformation. None had been punched. All had been made from wrought iron except 3 of the (16th cent.) European specimens, which had been made from steels, and hardened by some form of heat-treatment.

Some time ago, I obtained samples of 6 of the specimens of mail collected during his work on the subject by E. M Burgess, and their composition is discussed here, together with that of 7 other specimens from various museums.

I have discussed the possible materials of which swords could have been made in the Middle Ages in earlier papers [7] and basically, wire or strip, would have to have been made from similar materials to swords.

The commonest material used for arms and armour in the Middle Ages was *wrought iron*, i.e. low-carbon iron made by direct reduction of iron ore with charcoal, in the «bloomery hearth.» Specimens 1,5,8, 11 and 12 are all made from wrought irons. Their hardnesses are around 80 $kg.mm^{-2}$ (determined with the Vickers diamond pyramid hardness tester).

The raw material might be hardened by carburisation, either by leaving the bloom in the furnace for some time[8] or else by packing the bars or plates produced in charcoal or other organic material and heating above 900°C for a prolonged time. Such a procedure is described by Theophilus the Monk in the 12th cent.[9] Subsequent working might spread the carburised layer out into a streak or streaks of steel within the iron. Such a «streaky steel» was apparently employed for specimens 2 and 3. Continued working will have the effect of homogenising the steel, and this may well have been the source of the steels employed in specimens 4, 6, 7, 9 and 10. Indeed, the ferrite banding still visible in specimen 4 suggests that its starting material was folded and forged at some stage.

The carbon content of some of these was determined and found to be in the region of 0.4 per cent. This might give a typical hardness of

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[7] WILLIAMS, A. R., «The manufacture of swords in the Middle Ages», *Gladius* (1977), *13*, 75 ff and *ibid*. (1978), *14*, 97 ff.

[8] PLEINER, R., «Problems of direct steel production in early ferrous metallurgy», *Steel Time* (1968), 312, and also; TYLECOTE, R. F. et al., «Mechanism of the bloomery process in shaft furnaces», *Journal of the Iron and Steel Institute* (1971), *290*, 342.

[9] Theophilus Presbyter, translated and edited by DODWELL, C. R., «De diversis artibus» (London, Nelson 1961), 72.

160 kg. mm^{-2} or double that of wrought iron. But the most dramatic improvement in the properties of steels is brought about by heat-treatment, i.e, quenching them to harden them. Above the Critical Range of carbide solubility (usually above 800°-900°C) carbon in steels is dissolved in the iron as the crystalline material *austenite;* on cooling, the austenite may break down in different ways, dependant on the rate of cooling:

(1) On cooling at an equilibrium rate, the carbon will separate out as a lamellar material of iron carbide. This may be microscopically identified as *pearlite*. Very slow cooling=, i.e. in the furnace, may cause pearlite lamellar to spheroidise.

(2) More rapid cooling may produce an iron carbide material of different crystalline form and greater hardness. This may be microscopically identified as an acicular material, *bainite*, but a clear distinction between bainite is generally formed mixed with the others. Such mixtures may be formed by a delayed or interrupted quench, or by employing a less-drastic quenchant than cold water, e.g. oil, lead, or boiling water. It is not now generally possible to decide which procedure was used, but they are collectively called «slack quenching.» Specimens 2, 3, 7 and 10 were slack-quenched, and their hardnesses range from 230 to 380 kg.mm^{-2}.

(3) Cooling at a sufficiently rapid rate, i.e. plunging red-hot steel into cold water, may suppress the separation of iron carbide altogether, and form a solid solution of carbon in iron called *martensite*, which is very hard (its hardness depends its carbon content) and can be microscopically identified by its lath-like appearance. Its brittleness may be reduced, without too great a decrease in hardness by *tempering*. This is done by careful reheating or else by premature withdrawal from the quenching bath, so that residual heat tempers the martensite. This may, of course, produce some bainite as well if the transformation is incomplete. A separate, subsequent, reheating is the preferred modern method of hardening armour in 1589 by Giambattista della Porta.[10]

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[10] PORTA, G. B della, «Natural Magick» (Naples, 1589), translated into English in 1658 and reprinted by Basic Books (New York, 1957), 308: How an Habergeon or Coat of Arms is to be tempered. «Take soft Iron Armour of small price, and put it into a pot, strewing upon it the Powders abovesaid; cover it, and lute it over, that it have no vent, and make a good Fire about it: then at the time fit, take the Pot with iron pincers; and striking the Pot with a Hammer, quench the whole Herness, red hot, in the foresaid water: for so it becomes most hard, that it will easily resist the strokes of Poniards. The quantity of the Powder is, that if the Harness be ten

Specimens 6 and 9 of the 16th cent. have both got martensitic microstructures, 6 apparently having been tempered after quenching, and have hardnesses of 530 and 590 $kg.mm^{-2}$. It is noteworthy that by the 16th cent. mail links could be made that were seven times as hard as those of the Migration Period. I believe that my research now in progress will show that a similar improvement took place in the plate armour of the Renaissance.[11]

The weakest part of a mail shirt would have been the joints of the links. These are generally riveted, and the decarburisation around the rivet found in specimens 6, 7 and 10 confirms that the rivetting was done by heating, perhaps with a small blowpipe flame, because the remainder of those links consist of a fairly homogenous steel. The subsequent heat-treatment which the links have undergone to harden the mail have not affected the carbon-free areas, which have consequently become conspicuous by etching a different colour.

Acknowledgements

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or twelve pounds weight, lay on two pounds and a half of Powder, that the Powder may stick all over: wet the Armour in water, and rowl it in the Powder, and lay it in the pot by courses. But, because it is most hard, lest the rings of a Coat of Male should be broken, and flie in pieces, there must be strength added to the hardness. Workmen call it a return. Taking it out of the Water, shake it up and down in Vinegar, that it may be polished, and the colour be made perspicuous: then make red hot a plate of Iron, and lay part of the Coat of Male, or all of it upon the same: when it shews an Ashcolour, workmen call it Berotinum: cast it again into the water, and that hardness abated; and will it yield to the stroke more easily: so of a base Coat of Male, you shall have one that will resist all blows. By the mixture of Sharp things, iron is made hard and brittle; but unless strength be added, it will flie in pieces with every blow: therefore it is needful to learn perfectly how to add strength to it.»

[11] WILLIAMS, A. R., «Technical studies on armour» *Archaeologia, 106*

SPECIMENS OF MAIL (IRON AND STEEL)

1 Roman mail. Württemberg Landesmuseum (date ?).
2 Medieval mail. E. M. Burgess (probably 14th cent.).
3 Medieval mail. E. M. Burgess (probably 15th cent.).
4 Medieval mail. E. M. Burgess (probably 15th cent.).
5 Medieval mail. E. M. Burgess (probably 16th cent.).
6 Medieval mail. E. M. Burgess (probably 16th cent.).
7 W 34. Bavarian National Museum (German, 15th/16th cent.).
8 W 345. Bavarian National Museum (German, 16th cent.).
9 E. M. Burgess (16th cent.).
10 Cat-Nr. 13. Landeszeughaus (Graz, 1580-90).
11 Oriental mail 1889. 71, Royal Scottish Museum (Edinburgh, Persian, 1506 A. D.).
12 Oriental mail 1905. 475, Royal Scottish Museum (Edinburgh, probably Persian, 17th cent.).

Specimen 8 is from the armoury of Schloss Hohenaschau.

Specimen 1 was excavated from a Roman site in Württemburg, but all the archaeological evidence was lost during the last war. It is included here for the sake of comparison, but it should be remembered that its date cannot be precisely ascertained. Specimen 3 is a gusset from a plate armour to protect the armpit. Specimens 7, 8, 9 and 10 are from mail shirts.

SPECIMENS OF MAIL (BRASS)

Brass ring from the decorative edging of Specimen 10 (Graz).

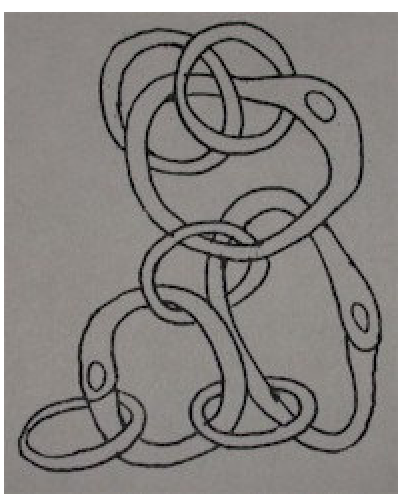
Brass ring from an excavation at Nottingham Castle --- Specimen 13.

SPECIMEN 1

Link from (?) Roman mail. This fragment consisted of links arranged as shown in the accompanying sketch. The material which would have given it an archaeological provenance was destroyed during the war, but it is included here for the sake of comparison.

The microstructure shows only course, equiaxed grains of ferrite, and slag. It is a wrought iron that could have been produced at any time during the Roman or Migration Periods.

X 80. Ferrite and slag



Fragment of Roman mail made up of alternating rows of punched and riveted links. N. B. a riveted link was sectioned and is discussed here.

SPECIMEN 2
(probably 14th century)

The structure mainly consists of (undistorted) ferrite grains, among which are seen streaks of a dark-brown-etching material with a fine structure. At higher magnification, this appears to consist of bainite, or possibly tempered martensite.

The wire from which this link was made was evidently drawn from a bar of very heterogeneous composition. It is possible that this bar was itself made by forging several billets of varying carbon-content.

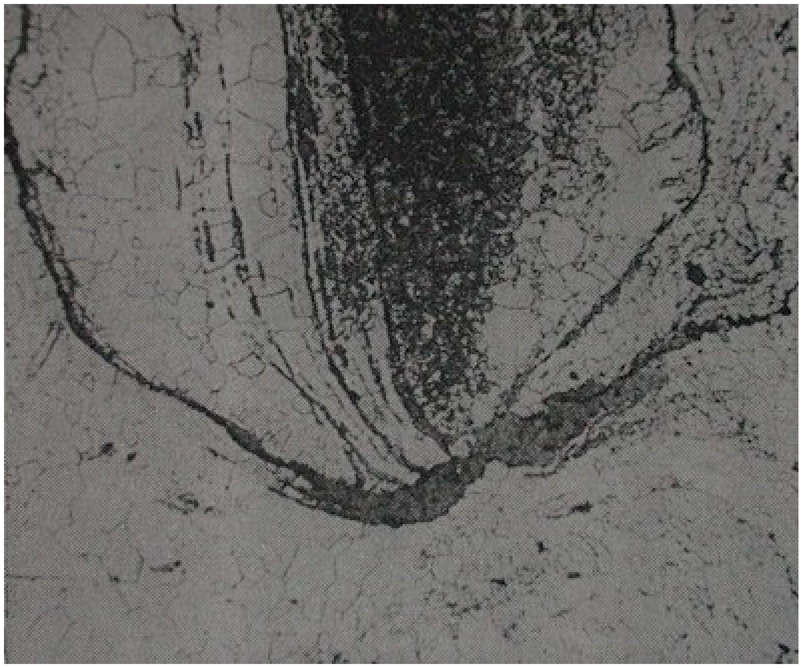
After (or during) fabrication the link has been heated above the A_3 temperature and then (probably) slack quenched to give a bainite structure. This might be the result even of water-quenching if the carbon content (unfortunately unknown) is low enough.

A little slag is visible.

Approximate grain size (ferrite) = 7 ASTM.

Average VPH (ferrite) = 123
(bainite) = 314

X 100
Mostly ferrite with streaks of a dark-etching material.



X 100
An area around the joint in the link

X 500
One of the dark-etching streaks (bainite)

X 850. Bainite

X 2000. Bainite

SPECIMEN 3
(probably 15^{th} century)

The structure consists of bands of (undistorted) ferrite grains alternating with bands of a brown etching material.

At higher magnification, these bands are seen to consist of a mixture of areas of a light brown irresolvable material (probably upper bainite) outlined by ferrite grains, some of which are in spiny form, and a little pearlite. The ferrite makes up about a quarter of the dark-etching areas.

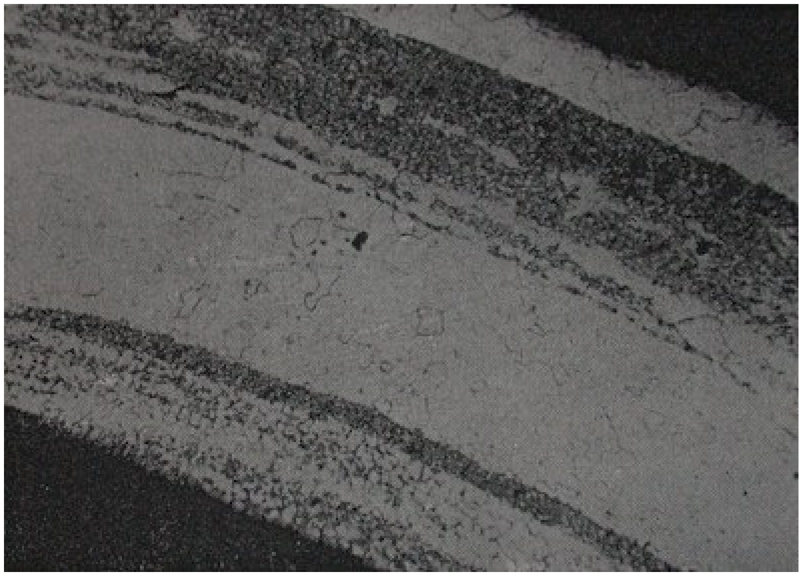
The wire from which this link has been made was evidently drawn from a bar of very heterogeneous composition.

After (or during) fabrication, the link was heated to above the A_3 temperature and then cooled fairly quickly to give a slack-quenched product. It is possible that it was quenched into a bath at an intermediate temperature to perform a holding quench. If the carbon content is low enough, then even water-quenching might achieve this.

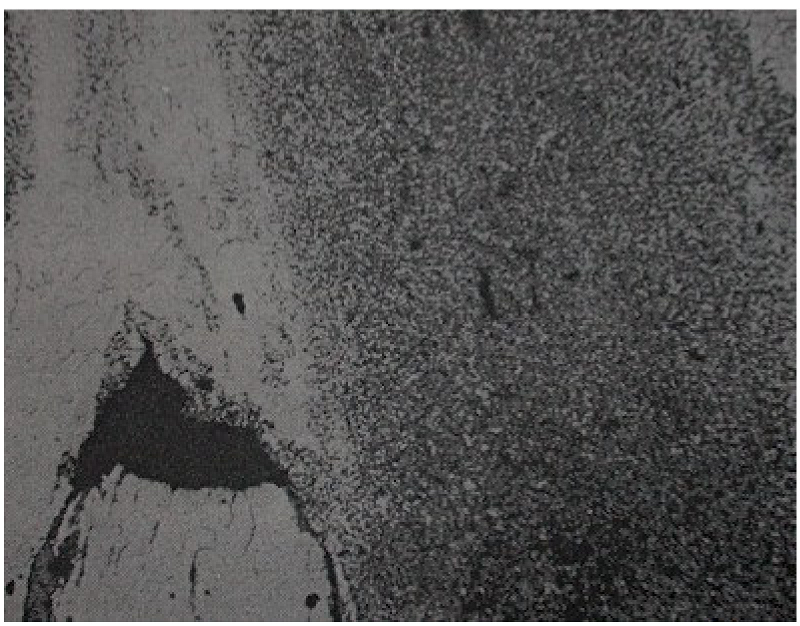
Only a little slag is visible.

Approximate grain size (ferrite) = 7 ASTM.

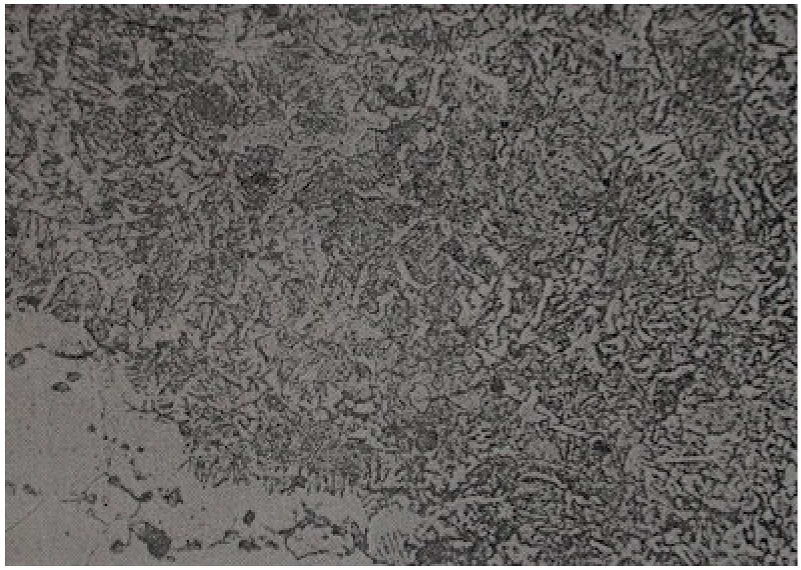
Average VPH (ferrite) = 168
(bainite) = 235



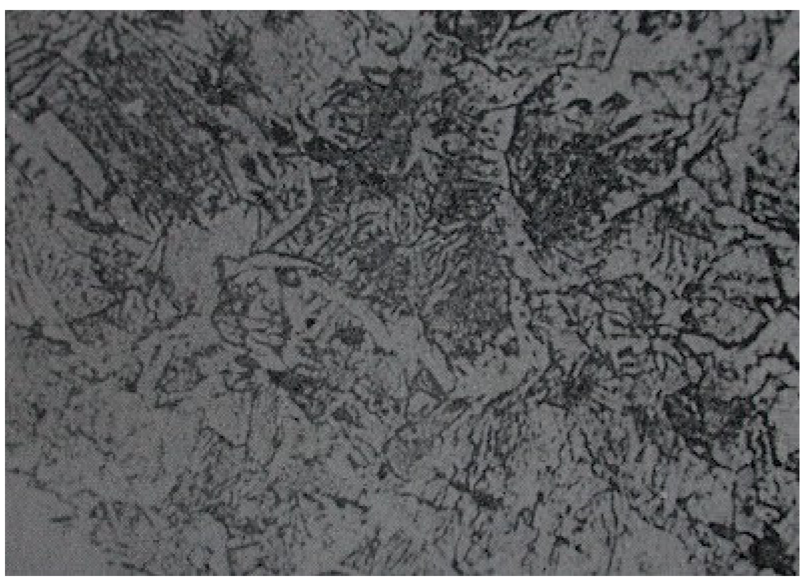
X 100. The heterogeneous nature of the steel from which the wire was drawn is apparent from the banding in the link.



X 100. The area around the riveted joint.



X 570



X 1040

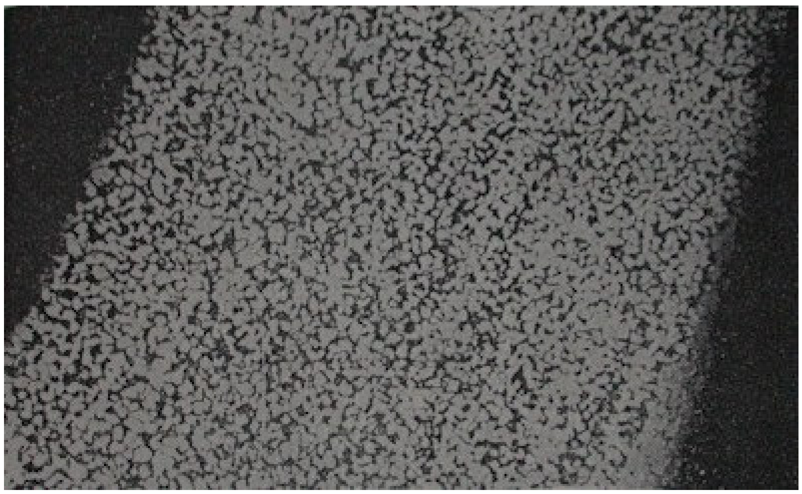
SPECIMEN 4
(probably 15th century)

The structure consists of a fairly uniform mixture of ferrite and pearlite (perhaps 0.2% C). There is a little decarburisation near one edge. Only a little slag is visible.

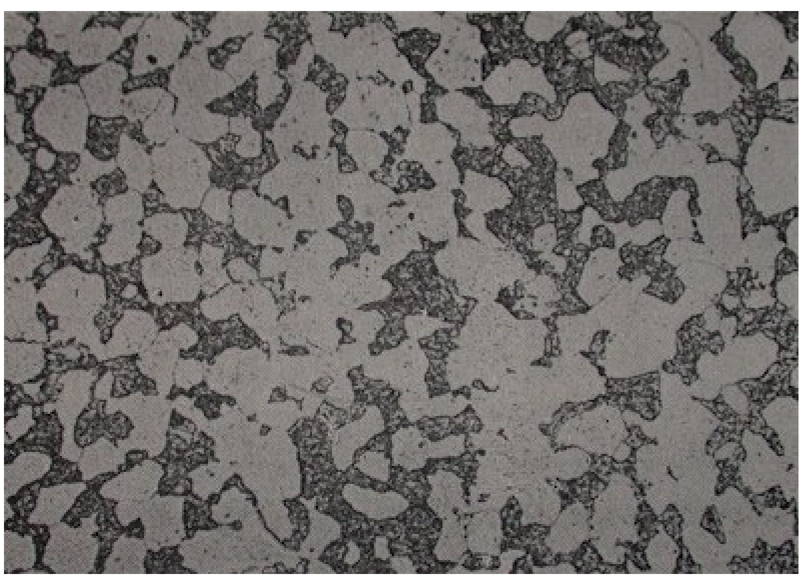
This link has been made from a fairly homogeneous mild steel wire. After (or during) fabrication, it has been heated to above the A_3 temperature and allowed to cool slowly.

Approximate grain size = 8 ASTM

Average VPH = 160



X 100. A fairly uniform mild steel



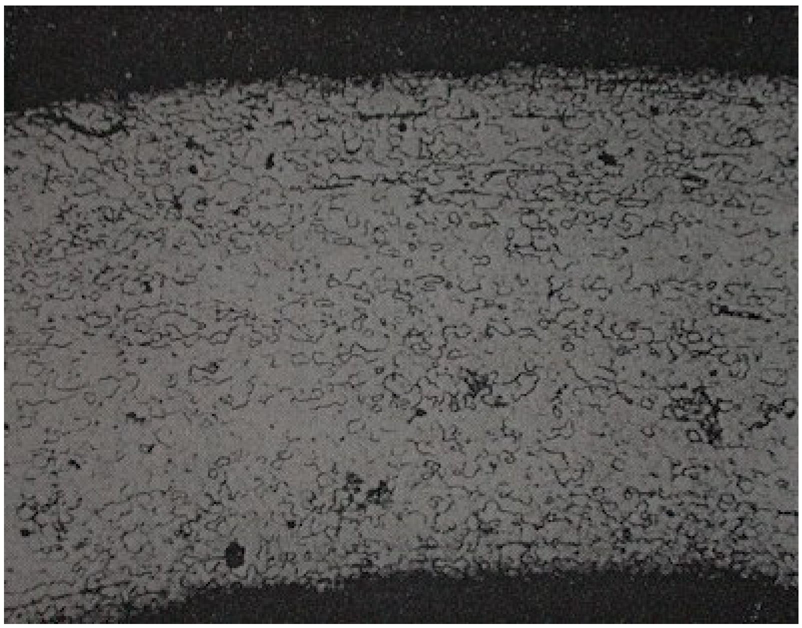
X 500. Ferrite and pearlite

SPECIMEN 5
(no date, perhaps 16^{th} century)

The structure consists entirely of (undistorted) ferrite grains, with a little slag.
This link has been made from a wrought iron wire. After (or during) fabrication, it has been heated above the A_3 temperature, to allow the ferrite to recrystallise.

Approximate grain size = 8 ASTM.

Average VPH = 123.



X 100 mag. Ferrite and slag

SPECIMEN 6
(no date, perhaps 16^{th} century)

The structure consists almost entirely of a fine dark-etching material. At the (riveted) joint, and also near the edges, there are decarburised patches, where the structure consists entirely of ferrite.

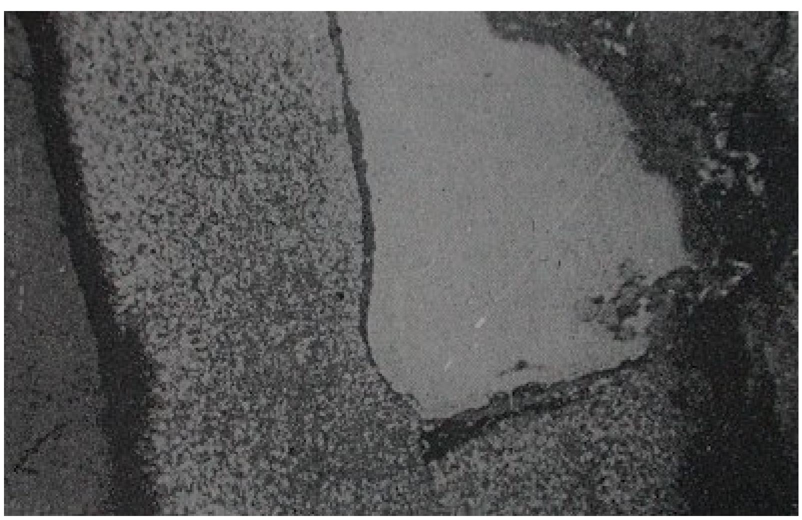
As can be seen at high magnification, the greater part of the structure consists of tempered martensite and a mass of tiny carbide particles can just be resolved.

This link has been made from a fairly homogeneous steel wire, which, after (or during) fabrication, has been heated A_3 temperature, quenched to give martensite and tempered by gently reheating.

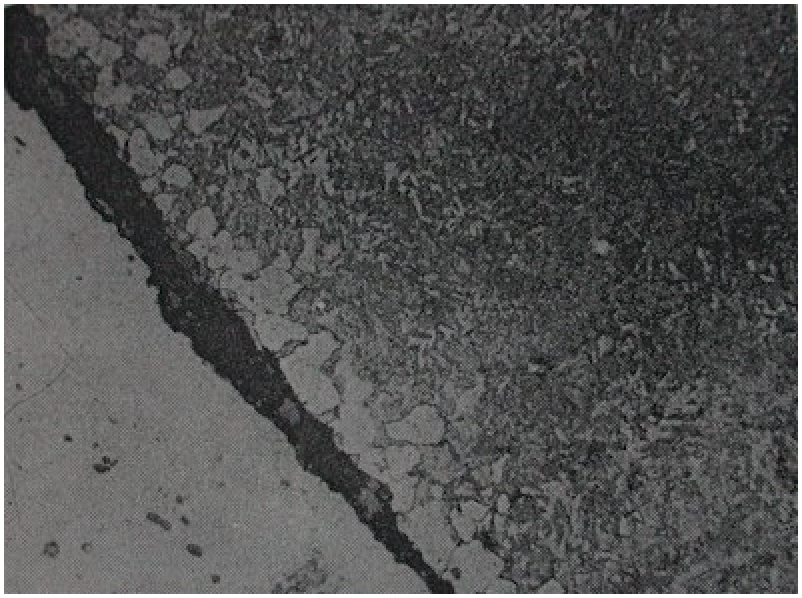
Average VPH = 527.

Carbon content = 0.32%.

X 100 mag.
Tempered martensite decarburised at joint



X 100 mag.
Tempered martensite decarburised at joint



X 500. Martensite partly decarburised to ferrite at the joint

X 2000. Tempered martensite, showing a mass of tiny carbide particles

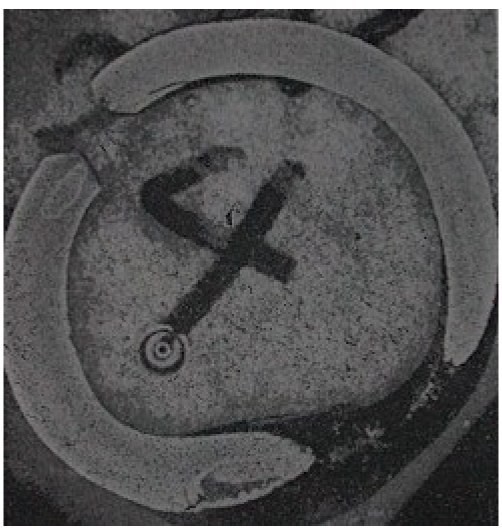
SPECIMEN 7

BAVARIAN NATIONAL MUSEUM

W 34 --- Ring from a Mail Shirt German, sixteenth century

The ring was sectioned in the place of its circumference. Except for a decarburised area in the vicinity of the rivet, the microstructure was a fairly uniform dark-etching fine structure. At high magnification this could be resolved into tempered martensite and an acicular material which is probably bainite. This ring has been made from a fairly homogeneous steel, and has suffered decarburisation due to heating while rivetting the ring closed. Afterwards, it has been hardened by some for of slack-quenching.

Average hardness = 360 VPH.



X 7.5

X 80

Note the homogeneity of the ring

X 340

X 1400. Martensite

Bainite

X 320. The decarburised area around the riveted joint. The low-carbon area is light-etching.

SPECIMEN 8

BAVARIAN NATIONAL MUSEUM

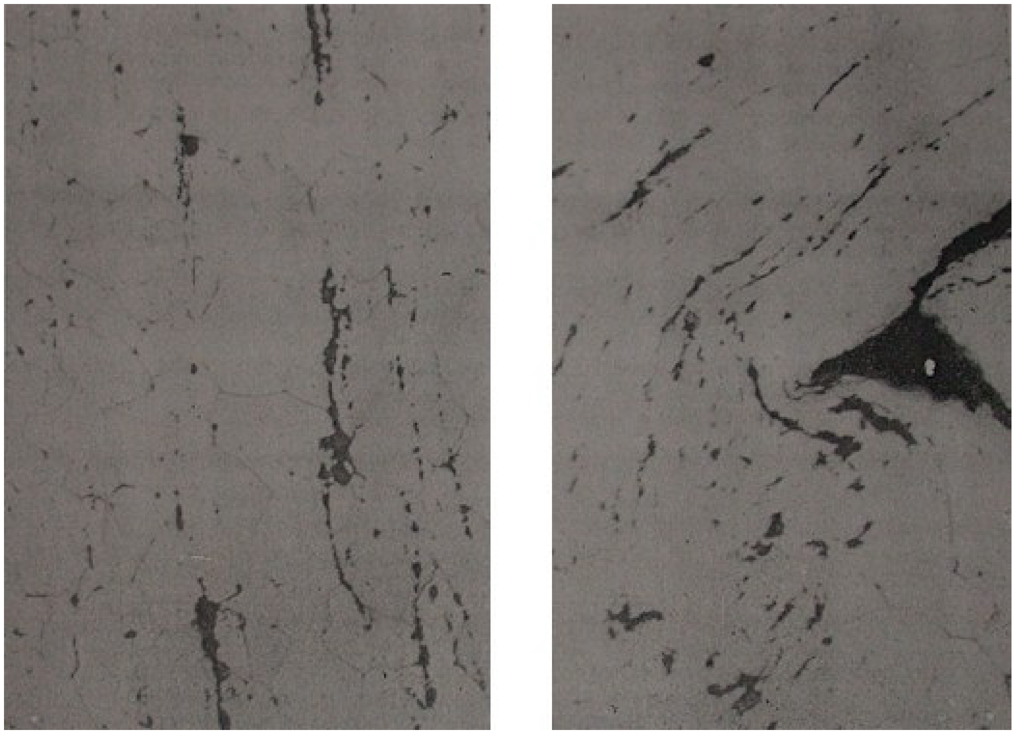
W 345 --- Ring from a mail legging obtained from Schloss Hohenaschau

The microstructure contains only ferrite (equiaxed) and slag inclusions, which are circumferential.

This is a wrought iron wire which has been either hot-drawn or else cold-drawn and then annealed.

Average microhardness = 88 VPH

X 80. Ferrite and slag



X 320
Near the riveted joint

SPECIMEN 9
(16^{th} century)

The structure consists almost entirely of a fine golden-brown-etching material, with a moderately large number of slag inclusions.

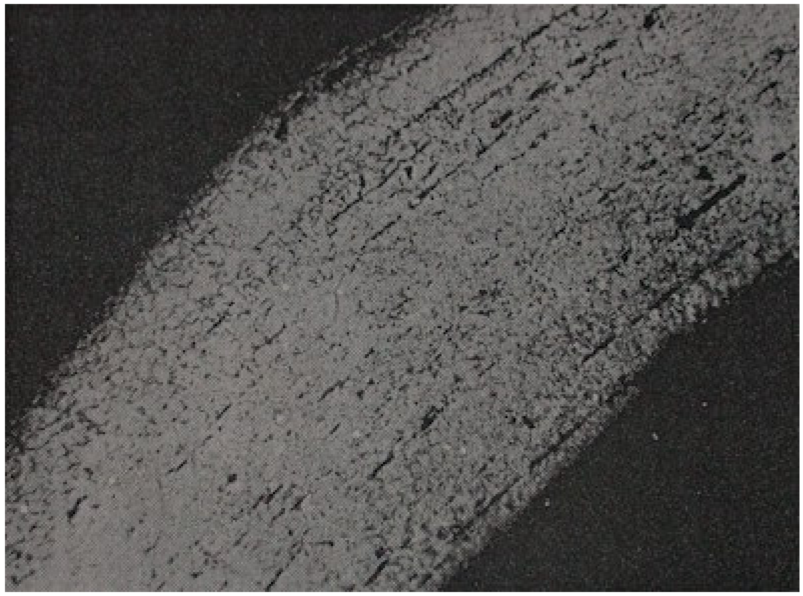
At high magnification, the brown material is seen to consist mostly of martensite but with some grains of a twofold composition included.

These contain ferrite and a dark material, probably bainite.

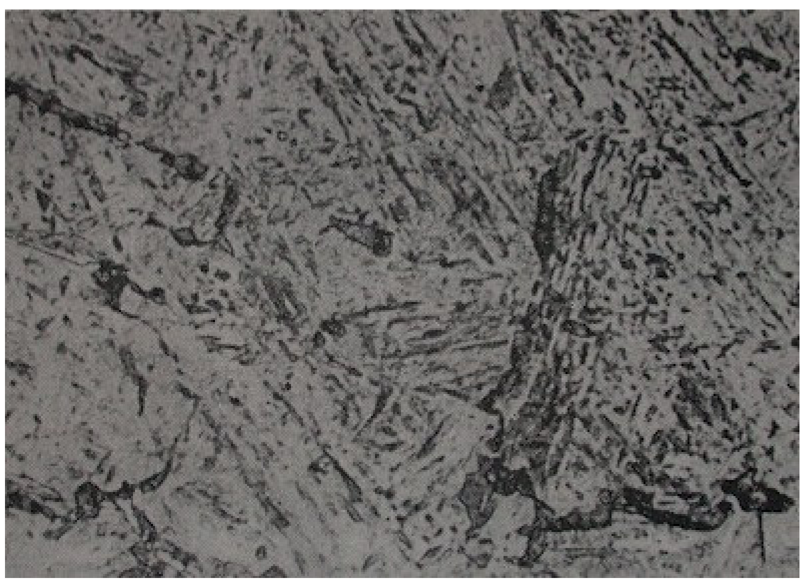
This link has been made from a fairly uniform steel which after (or during) fabrication has been heated above the A_3 temperature and quenched to give, principally, martensite, but not quite fast enough to avoid the separation of some ferrite and bainite.

Average VPH = 587.

Carbon content = 0.42%.



X 100



X 500. Martensite, with some bainite and ferrite

SPECIMEN 10

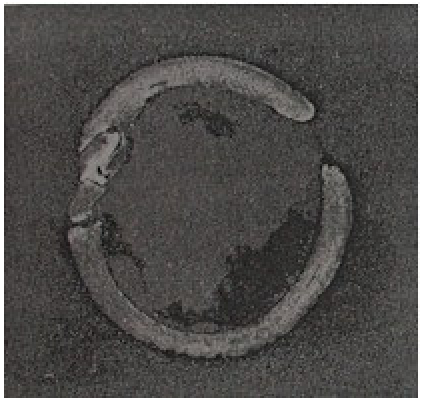
Link detached from a light cavalryman's armour («husarische rüstung»)
Made in Graz, 1580-90, now in the Landeszeughaus, Graz, cat. No. 13

The microstructure consists largely of a fine brown-etching material, except for a patch near the riveted joint where complete decarburisation to ferrite has taken place.

At high magnification, the fine material is found to consist mostly of martensite, together with a dark-etching irresolvable ingredient (probably bainite) and ferrite. The ferrite occurs in association with the dark material, as proeutectoid grains outlined the prior austenite grains. This has been made from a steel which has been slack-quenched after fabrication. It has apparently been heated above the Critical Range and then cooled; slowly at first, allowing ferrite and bainite to separate, and then more quickly, to transform to martensite.

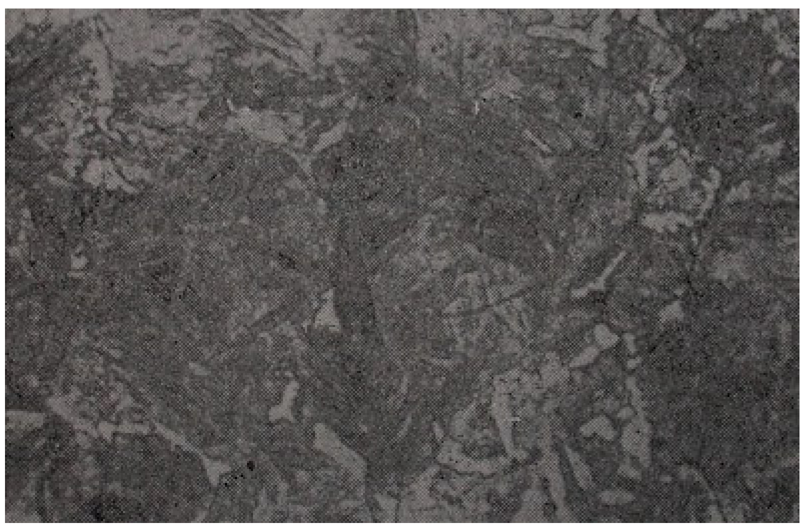
Carbon content = 0.38%.

Average hardness = 380 VPH.



X 5

X 64



X 1100

SPECIMEN 11

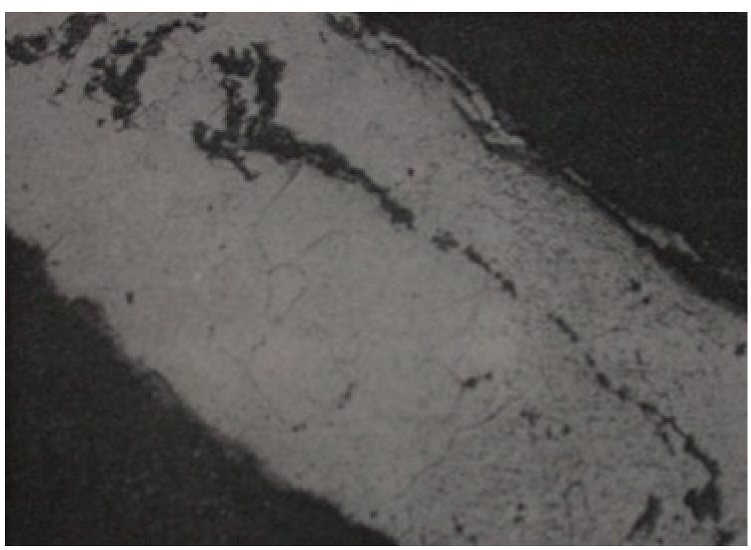
Link from a mail shirt, Persian, dated 912 A. H./1506 A.D. Inv. No. 1889.71

SPECIMEN 12

Link from a mail shirt, probably Persian, 17th cent. A.D.

Both links consist entirely of wrought iron, and both are approximately circular in section. Both have microstructures containing only ferrite and slag. Both have been drawn from carbon-free iron, formed into links, and afterwards annealed. Both have been closed by rivetting.

X 80



X 80

SPECIMEN 13

A punched ring from an excavation at Nottingham Castle, obtained in a layer of 14th cent. debris. Reference number 70 DH III B.

A punched ring from mail of alternate punched and riveted rings, c. 1400.

The microstructure shows equiaxed grains of what appears to be an *a* brass, with annealing twins and numerous small inclusions.

This has apparently been punched and then annealed afterwards.

Electron microprobe analysis was performed on the brass and it was found to contain:

Cu	79 %	Ni	trace
Zn	21 %	Ag	no trace
Fe	trace	Sn	no trace

The small inclusions were found to be lead-rich, containing up to 12 % Pb.

It is possible that lead was added to the melt before casting, for some reason. This is the only ring examined that was punched from a sheet. Except for specimens 1 and 5, which have approximately rectangular sections, the links from the other specimens have approximately circular or ovoidal sections, suggesting that they have been made from drawn wire, whereas specimens 1 and 5 have been made from slit sheet. It should be observed that none of the specimens examined shows deformation of the grains. After fabrication, they may have been annealed, if not given a heat-treatment to harden them.

Specimen 10 --- brass ring.

The section of this ring is oviodal, implying that this has not been punched but made from drawn wire. It has been closed by an iron rivet.

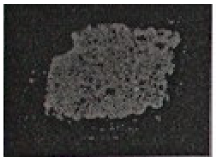
It has been annealed after cold-working, as the microstructure shows annealing twins, like specimen 13.

Electron microprobe analysis was performed on this ring and it was found to contain:

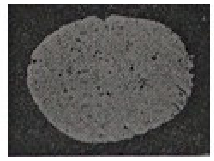
Cu	70.2 %
Zn	28.8 %
Fe	0.1 %
Ni	0.2 %
Ag	no trace
Sn	no trace
Pb	no trace

Average hardness = 95 VPH

Sections through links from some of the specimens (all X 20 mag.)



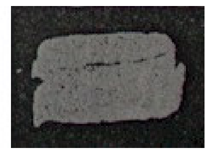
Specimen 1 (unetched)



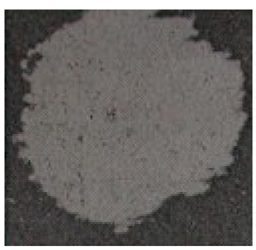
Specimen 3 (etched) and (unetched)

Specimen 2 (unetched)

Specimen 4 (unetched)

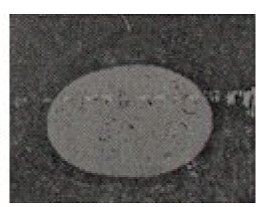


Specimen 5 (unetched)



Specimen 6 (unetched)

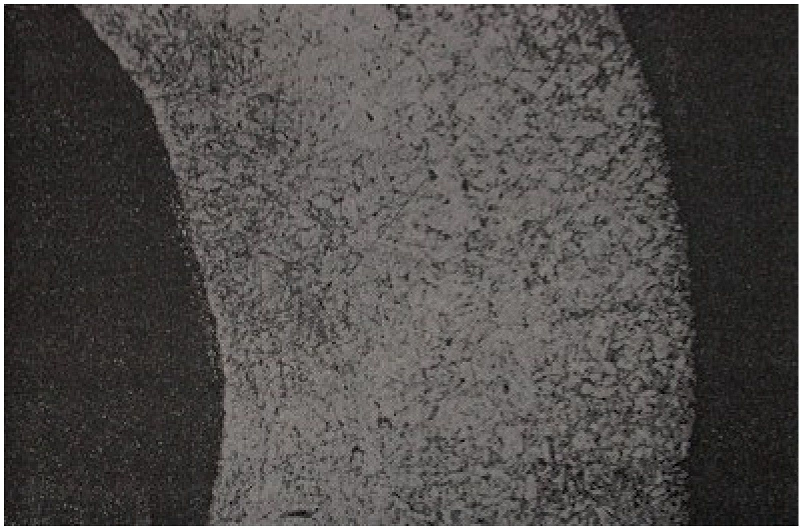
Specimen 9 (unetched)



Specimen 10 steel link (unetched) and brass link (unetched)

Nottingham 1970 DH III B.

A punched brass ring from mail of alternate punched and riveted links, c. 1400. From a layer of 14th cent. debris below make up of late 17th cent. brick floor.



X 50. Note the small inclusions

X 100. Note annealing twins and slip lines