Roman Chain-Mail: Experiments to Reproduce the Techniques of Manufacture
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Roman Chain-mail: Experiments to Reproduce the Techniques of Manufacture. David Sim writes: Protective armour made from interlocking rings of metal (*lorica hamata*) was developed by the Celts and later adopted by the Roman army.[120] This type of armour is often referred to as chain-mail. It afforded adequate protection against cuts from edged weapons such as swords, and thrusts from wide-bladed spears. Although it is known to have existed in the Republican period, the extent of its use then is uncertain. The subsequent use of this sort of armour throughout the Roman period and beyond shows that it was popular with those who had to rely on it for protection.

Previous experiments by the author have shown that the making of chain-mail coats is a time-consuming undertaking. The making of a single mail coat is a daunting task and it follows that manufacturing mail on even a modest scale represents a considerable investment in material and, more importantly, time.

The manufacturing techniques used to make chain-mail in the Roman period have been studied and a possible method using shaped punches was suggested by Biek,[121] but experimental work to show possible methods of manufacture may lead to a better understanding of this area of Roman technology.

There are several methods of constructing mail coats, such as using only butted rings with no riveted rings, or all the rings riveted. The method of coat construction studied here is a solid ring with four riveted rings through it (FIG. 7). This may be the strongest system of making mail coats. The riveted rings are made from wire; the solid rings have no joints or welds. The purpose of this paper is to explain experimental methods that were undertaken to suggest possible methods of manufacture of both wire and solid rings. The first part of the paper will consider the making of the solid rings. While the fabrication of the riveted rings is clearly understood, this is not so for forming the wire from which they are made. This issue will be considered in the second part of this paper.

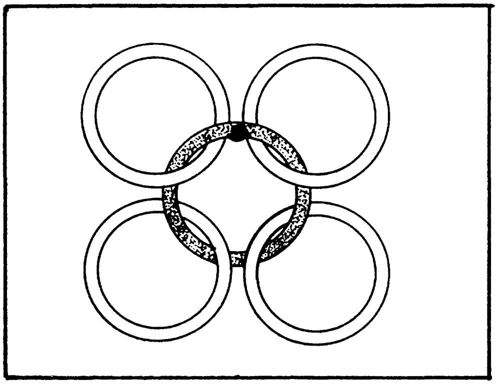

FIG. 7. Four solid rings joined by one riveted ring.

Lorica hamata was worn throughout the Roman period by legionaries and auxiliaries, both infantry and cavalry. Very little survives from the Republican period but there are representational examples from the first century B.C.[122]

The styles of coats and methods of ring construction have many variations. These may be related to the quality of the finished product, and it is possible some coats were designed to fulfil a definite function, such as those that gave protection to the body but not to the arms. It was not the object of this set of experiments to address these specific questions.

CONSIDERATION OF SOLID RINGS

In this article rings that have no obvious method of jointing, such as welds or rivets, will be referred to as solid rings. Such rings could easily be produced today using modern punch tools, whose manufacture

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[120] M.C. Bishop and J.C.N. Coulston, *Roman Military Equipment* (1993), 59–60; 85, 167.

[121] L. Biek, *Archaeology and the Microscope. The Scientific Examination of Archaeological Evidence* (1963).

[122] H. Russell Robinson, *The Armour of Imperial Rome* (1975), pls 463–6.

requires precision machinery which is thought not to have existed in the Roman period. It is naturally assumed that precision punching was not the method used to produce solid rings. However a high degree of precision can be achieved without the use of high precision machines. A set of experiments was conducted to show that a punch and die can be made to a high degree of accuracy using only unsophisticated tools.

Examination of original rings

The analysis of Roman chain-mail rings of iron presents many difficulties due to their generally poor condition and the very small number in existence. It is also very difficult in some cases to be certain if the rings are of Roman manufacture or were made outside the Empire but copying Roman patterns. In many cases the amount of information that can be determined is limited because the rings are fused together with iron oxide and, when examined, are often found to consist of a thin shell of iron with a hollow centre. Such is the case with the rings found at Lower Bridge Street, Chester in 1993.[123] Also examined were iron rings from Thorsberg and Nydam,[124] for which Raddaz[125] has proposed a date between A.D. 150 and 250. As these rings were found outside the Empire it is not possible to say if they are of Roman manufacture or were made by barbarian tribes copying Roman originals.

Many mail rings from the Roman period are fused together into solid lumps and it is not possible to detach single rings for examination. Some individual rings exist and were made available to the author for examination. These include twenty fine gilded bronze rings from Leiden which were found in 1902 in a town called Ouddorp, on the island of Goedereede, Province of South Holland and are illustrated by Robinson.[126] The context is unclear but the armour was found beneath a layer of clay under some Roman pottery. Iron rings from Caerleon[127] were also examined.

The rings from Thorsberg, Nydam, and Caerleon are made from iron, while those from Leiden are non-ferrous.

Non-ferrous rings

The non-ferrous rings from Leiden, Holland, were assembled so that a single riveted ring had four solid rings inside it (FIG. 7). Six solid rings were examined under a microscope and measured on a shadow graph (see Table 1).

The outside diameters of the solid rings measure 3 mm. When examined under a microscope the shape of the solid rings showed that these rings were probably made by punching from a solid sheet. If the technology was in existence to punch small rings from non-ferrous metal then it is possible that the same technology was used to punch rings from sheet iron. Some solid ferrous rings from Caerleon[128] were examined under a microscope and measured on a shadow graph (see Table 2).

A set of experiments was conducted to show that punch tools of high consistency could be produced by the technology available in the Roman period and did not require the use of precision machinery. Thus some Roman chain-mail rings could have been produced by a combination of punching and finishing on a mandril. The time taken to produce solid rings was recorded. The rings were measured on a shadow graph and the results presented (see Table 3).

The outside diameter of the Caerleon rings varies by the order of ± 0.6 mm as does the inside diameter. These ranges/variations are very close despite the wear and corrosion of the Caerleon rings, and this would suggest that the Roman tools had a high degree of accuracy. In order to produce rings of such consistency it is likely that punches were used. The use of more than one set of punches could account for any variation in the outside diameter. The production of such rings requires a punch tool

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[123] The Grosvenor Museum, Chester, Small finds Nos 245, 252, and 257.

[124] C. Engelhard, *Denmark in the Early Iron Age Illustrated by the Recent Discoveries in the Peat Mosses of Slesvig* (1866).

[125] K. Raddaz, 'Religionsgeschichtliche Probleme des Thorsberger Moorfundes', in H. Jankuhn (ed.), *Vorgeschichtliche Heiligtümer und Opferplätze in Mittel- und Nordeuropa* (1968), 190.

[126] Russell Robinson, op. cit. (note 122), 164–73.

[127] Caerleon chain-mail rings found in *via principalis* 207 Phase 5B from stores near the tribune's house, second century. Unpublished.

[128] Caerleon, see note 127.

TABLE 1

NON-FERROUS RINGS FROM LEIDEN, HOLLAND

Ring No.	Position	Outside Diameter	Inside Diameter	Thickness
1	1	3.110	2.212	0.51
	2	3.147	2.123	0.58
2	1	3.057	2.209	0.61
	2	3.013	2.257	0.63
3	1	3.174	2.203	0.48
	2	3.062	2.212	0.52
4	1	3.147	2.129	0.54
	2	3.133	2.209	0.59
5	1	3.054	2.268	0.60
	2	3.100	2.257	0.57
6	1	3.197	2.213	0.61
	2	3.196	2.234	0.58

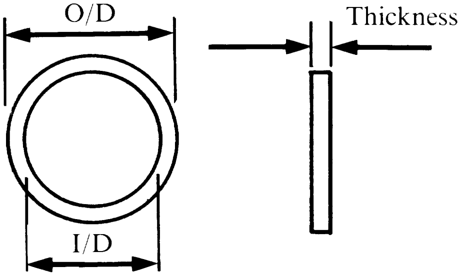

TABLE 2

FERROUS RINGS FROM CAERLEON

Ring No.	Position	Outside Diameter	Inside Diameter	Thickness
1	1	6.957	4.968	0.989
	2	6.990	4.869	0.948
2	1	6.761	4.865	0.852
	2	6.948	4.765	1.513
3	1	7.381	4.791	1.263
	2	7.344	4.909	1.177
4	1	7.401	5.169	1.119
	2	7.513	5.465	1.116
5	1	6.703	5.024	0.864
	2	6.945	5.006	0.929
6	1	7.087	4.827	1.071
	2	7.247	5.042	1.036
7	1	7.605	4.818	1.501
	2	7.503	4.761	1.431
8	1	6.645	4.413	1.126
	2	6.609	4.356	1.071
9	1	7.850	4.939	1.393
	2	7.736	4.820	1.441
10	1	6.871	4.567	1.239
	2	6.974	4.465	1.441

that is made up of two parts, a punch and a die (the punch is the male part of the set and the die the female part). Preliminary experiments showed that punching an *annulus* in one hit is very difficult with simple tools, because the design of the punch tool makes it too weak to withstand the forces required to bring about shearing of the iron strip. Rings can be produced by using two sets of punches and dies. The first set punches the inside diameter of the ring and the second set the outside diameter.

In order to make the punch and die to punch the inside diameter of the ring, a piece of medium carbon steel was forged into a rod using a pair of swages as shown in FIG. 8a. One end of the bar was then forged into a tapering point and the bar cut in half. The tapered punch, 6.0 mm in diameter (A in FIG. 8a), was

TABLE 3

EXPERIMENTAL RINGS. DIMENSIONS IN MM

Ring No	Position	Outside Diameter	Inside Diameter	Thickness
1	1	9.491	6.371	1.52
	2	9.000	6.402	1.59
2	1	9.557	6.364	1.51
	2	9.679	6.540	1.56
3	1	9.419	6.231	1.48
	2	9.322	6.474	1.49
4	1	9.750	6.294	1.52
	2	9.623	6.316	1.58
5	1	9.560	6.495	1.59
	2	9.625	6.288	1.61
6	1	9.524	6.315	1.46
	2	9.819	6.603	1.49
7	1	9.550	6.533	1.59
	2	9.389	6.277	1.49
8	1	9.464	6.291	1.47
	2	9.505	6.365	1.41
9	1	9.698	6.544	1.54
	2	9.551	6.382	1.55
10	1	9.610	6.405	1.51
	2	9.629	6.647	1.69

used to punch a hole through a block of iron 25 mm square that had been heated to 950°C (FIG. 8b). The punch was quite badly damaged in this operation but was quickly repaired. On cooling, the diameter of the hole shrank by 0.074 mm which meant that the unused piece of bar (B in FIG. 8a) was too large to fit in the hole. The bar was hardened and tempered. The bar had to be made to fit the hole with the minimum of clearance between the two. This was done by mixing finely powdered glass with water to make a grinding agent. The mixture was smeared on the punch, the bar was then put over the hole and a bow drill used to impart a reciprocating motion to the punch. This caused the punch and die to be ground to fit each other and, as the punch was hardened it is likely that most of the metal removed came from the die(FIG. 8c). Great care was taken to keep the punch vertical. A smooth sliding fit between die and punch was achieved in 12 minutes. A slot was then cut into the end of the bar as shown in FIG. 8d. The slot was made 0.5 mm wider than the strip to be used to make the ring to allow clearance between the slot and the strip. FIG. 9a shows the punch and die with the strip in place. The strip was punched and produced a hole that would become the inside diameter of the ring.

In order to make the punch and die to punch the outside diameter of the ring a pair of swages (FIG. 9b) was used to produce a bar with two separate but concentric diameters, the larger equal to the outside diameter of the ring and the smaller to the inside size corresponding with the holes in the strip. The form of this punch is a tenon. Tenons are made by blacksmiths as a method of fixing two pieces of iron together (FIG. 9c) . The die was heated to 950°C and a hole was drifted with the same punch as was used in the last die (FIG. 8b). The stepped punch was then used to make a stepped hole as shown in FIG. 9d.

The punch was lapped to fit the die by the use of a bow drill with finely powdered glass as an abrasive. FIG. 10a shows the punch and die being used. The smaller diameter of the punch located the hole in the strip and then was located in the small hole in the die (FIG. 10b). The punch was then struck with a hammer and the ring cut out. This system was used to produce thirty rings.

The Caerleon rings have no remaining external markings such as would have worn off with use of the coat, so it is impossible to determine if any further work was carried out after punching. Microscopic examination of the rings from Thorsberg and Nydam shows small flats on the outside diameter of the ring whilst the inside is very smooth. It is possible that the ring had been hammered on a mandril. To test this theory, two of the rings from the previous experiment were placed on a tapering mandril and

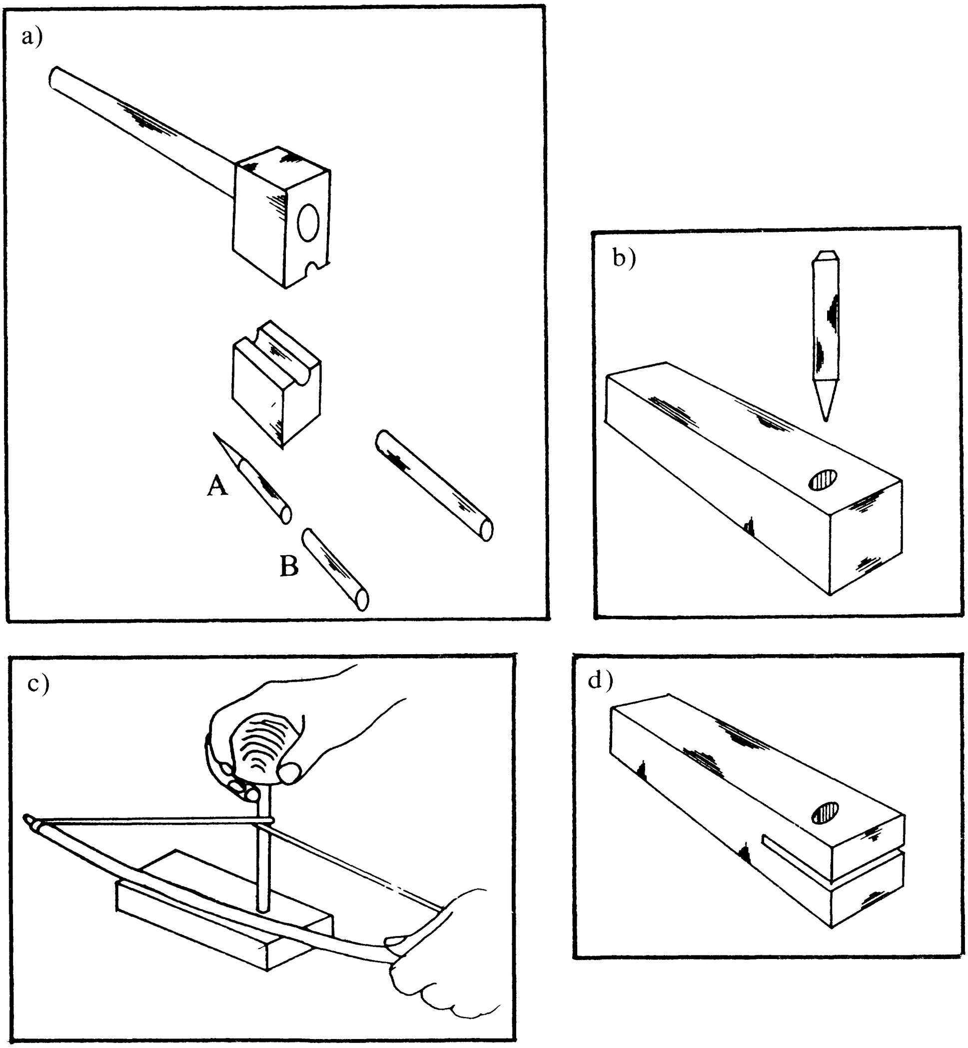

FIG. 8. Stages in producing a punch and die. (a) Steel rod made between swages; (b) Tapered punch used to punch a hole; (c) Bow drill used for lapping punch into die; (d) Slot cut into the end of the bar.

hammered (FIG. 10C). This had the effect of thinning the ring thickness and increasing the width. The two rings were examined side by side with the originals and the hammer marks on the surface were almost identical. In PL. XXXIIA the rings on the left and in the centre are originals from Thorsberg, the ring on the right was produced experimentally.

It is likely that rings such as these were produced by punching, followed by hammering on a mandril. Experiments showed that as the punch and die start to wear the rings become somewhat distorted. The distortions are easily removed when the ring is hammered on a mandril.

Vickers Hardness tests were carried out on the rings from Thorsberg and Nydam and were compared with some of the rings produced experimentally. It is always desirable to try to compare results with a known standard. Two samples of wrought iron were forged down to a square section and then left to cool in air (normalised). Sample A was forged between a hammer and an anvil, Sample B between

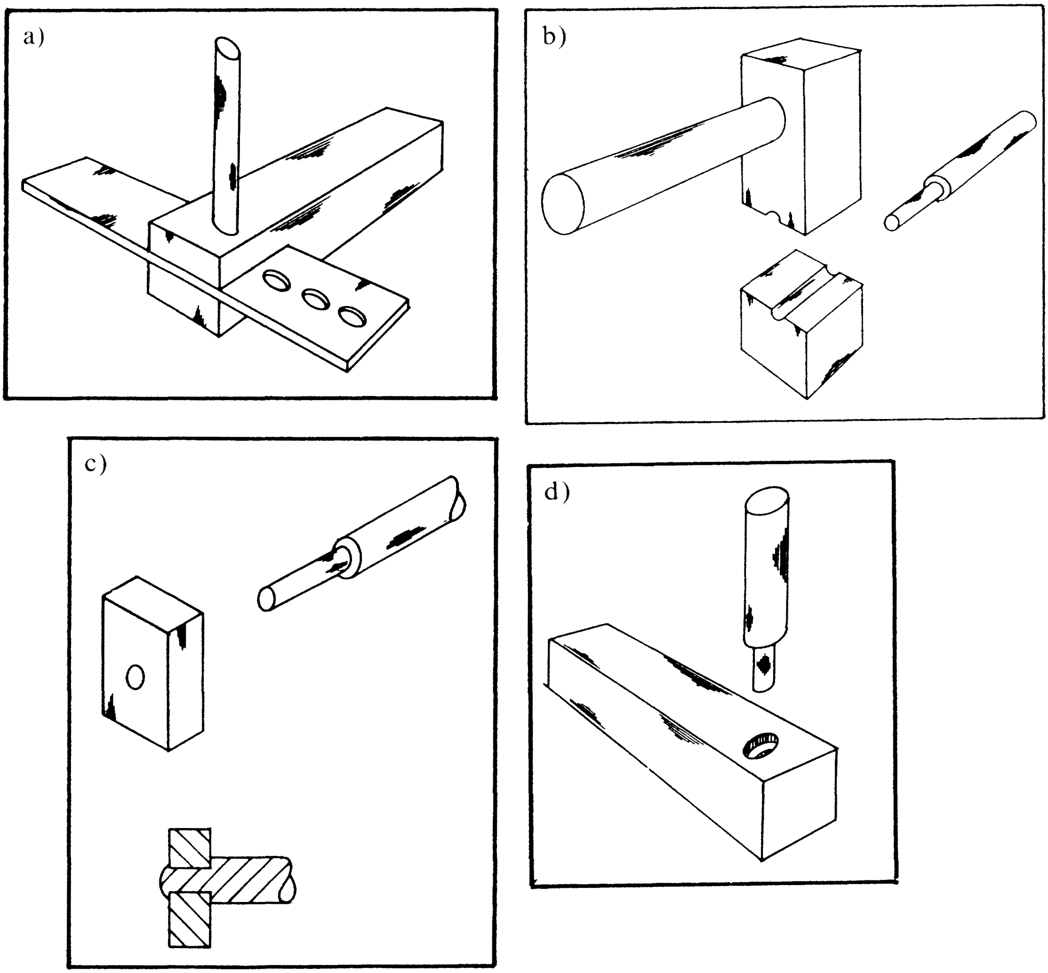

FIG. 9. Stages in producing a punch and die. (a) Punch and die with the strip in place; (b) Swage forming stepped punch; (c) Tenon; (d) Stepped punch used to make a stepped hole.

swages. The Vickers Hardness test was then conducted on the end of each sample and it can be seen that there is only a slight difference between the hardness numbers.

It can be seen that the experimental ring which was hammered on a mandril after punching is harder than the ring that has only been punched, indicating that some work-hardening has taken place. The experimental punched ring had a hardness value of 146 VPN, which is very close to the 149 VPN of the metal from Sample A. This indicates that punching did not produce any significant work-hardening. The experimental ring that was hammered on a mandril increased in hardness from 146 VPN to 210 VPN which is in the same region of hardness as the Roman originals. The hammer marks together with the hardness of the rings would suggests that work-hardening was brought about by hammering. Thus hammering on a mandril both improves the hardness of the ring, because of work-hardening, and also the appearance of poorly punched rings.

The specimens from Nydam and Thorsberg were polished and etched and then examined and photographed. A similar procedure was carried out on two rings that had been produced experimentally. The first ring had only been punched and the inside edge shows the deformation associated with

TABLE 4

VICKERS HARDNESS TESTS ON SOLID RINGS

Sample A (hammer and anvil)	Vickers Hardness 149
Sample A (swaged)	Vickers Hardness 138
Thorsberg ring	Vickers Hardness 191
Nydam ring	Vickers Hardness 187
Experimental ring (punched)	Vickers Hardness 146
Experimental ring punched then hammered on a mandril	Vickers Hardness 210

punching. The second ring had been punched and then hammered on a tapering mandril. This had distorted the grains and left little evidence of the previous punching. When the latter was compared with the ancient examples it was found that there are some similarities in the structure. A full study of the metallurgy of these ring is in preparation together with a statistical analysis of the measurments.[129] To produce one solid ring by punching took 21 seconds, while hammering it to shape on a taper mandril took 50 seconds. With further practice the author was able to reduce this time to 32 seconds. As with any skill, practice increases speed and the time to punch and hammer the ring on a mandril was reduced to one minute.

Conclusions

The experiments to make punches and dies using simple technology have shown that such tools can be made to a high degree of precision using the level of technology that would have been available in the Roman period. Such tools could be produced quickly and maintenance was quite simple. When a die wore out, a new die could have been made in less than twenty minutes. The comparison of the sizes of the ancient Roman rings with experimental rings shows that the size ranges/variations are within the same order as those found in the ancient rings. Thus, they could have been made using punches and dies similar to those made experimentally.

The Roman rings that have hammer marks have a hardness that is almost the same as that of experimental rings made by punching and hammering on a mandril. The hardness of the ancient rings is higher than the hardness of pieces of wrought iron that have been forged and normalised, indicating that work-hardening has taken place. It is suggested that this hardening is produced by hammering the outside of the ring and, as the rings are circular, it is probable that the hammering was carried out on a (possibly tapering) mandril. A ring can be punched from a sheet and hammered into shape in 60 seconds.

THE MANUFACTURE OF WIRE FOR THE PRODUCTION OF RIVETED RINGS

Solid rings cannot be joined together unless the joining ring can be opened to fit the solid rings in it. The joining rings can be made by several methods such as butting the ends of the rings together, welding them together, or joining them by riveting. The manufacture of welded rings and butted rings is still the subject of investigation, so only riveted rings will be considered in this paper. To make a riveted ring wire is prepared, then wound round a cylinder to create a coil. The coil is cut down its length to give a series of rings. The ends of the rings are flattened and a hole punched in each flat. The rings are closed by putting a rivet through the hole. Rivets are made from a softer metal than the metal to be joined (for riveting iron wire, copper or brass rivets could be used).

Experiments were conducted to determine the possible methods that could be used to produce the wire to make riveted rings. Very little is known about the wire used to make chain-mail because there are so few samples to examine. However a certain amount can be gained from work on other artifacts that can be applied to wire. Steel and wrought iron are the only ferrous metals used in the Roman world.

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[129] D.N. Sim and A. Williams, *Roman Chain-mail Rings, Production and Metallography* (forthcoming).

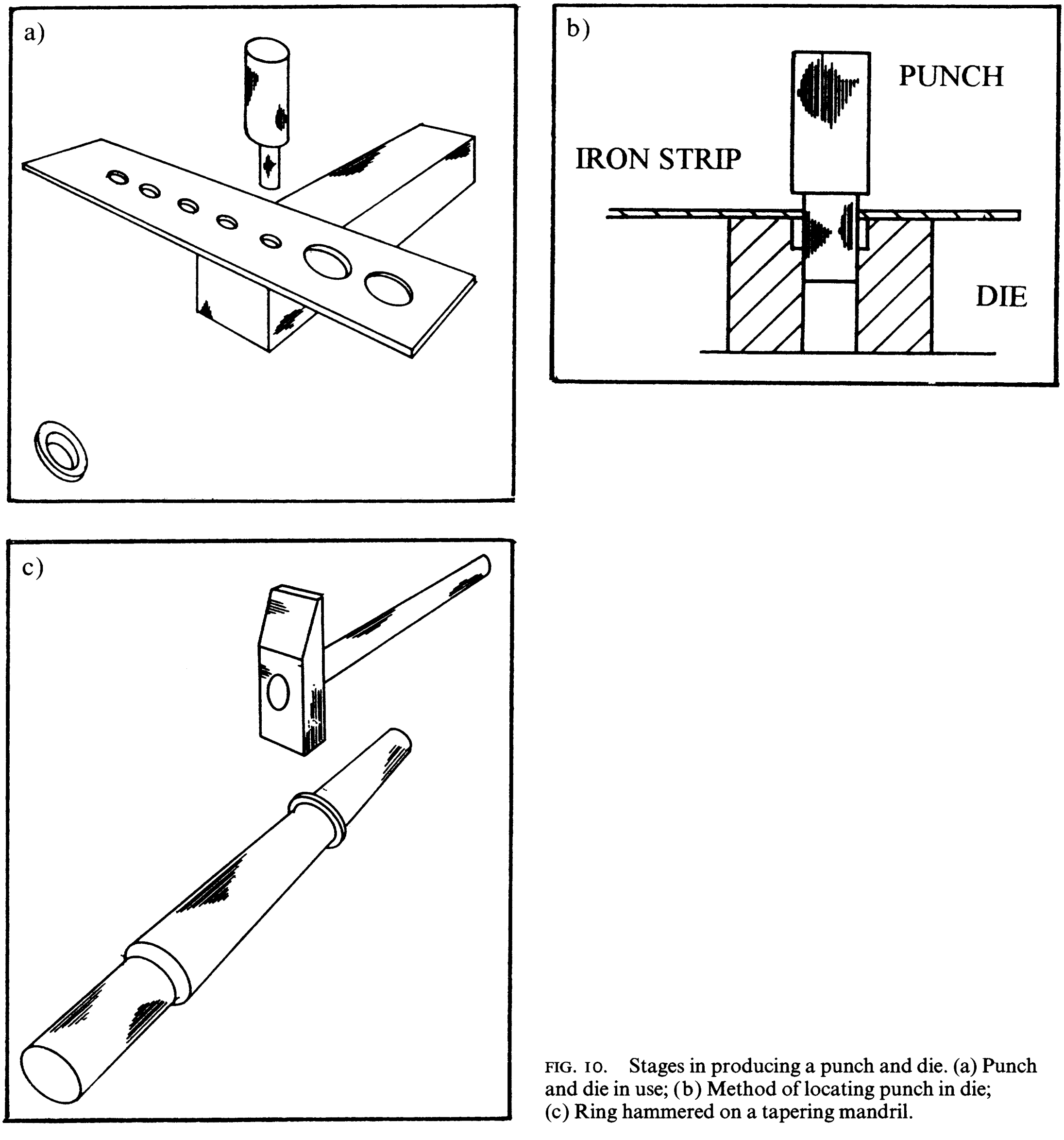

FIG. 10. Stages in producing a punch and die. (a) Punch and die in use; (b) Method of locating punch in die; (c) Ring hammered on a tapering mandril.

Steel is thought to have been too expensive to manufacture chain-mail so the only other metal left is wrought iron (the iron produced from the bloomery process). Experiments by the author have shown that as the cross-sectional area of the metal decreases, splitting and cracking will occur unless the iron has had most of its slag reduced to such a size that it will not assist in forming cracks.[130] So we can infer that the material used for making chain-mail was good quality wrought iron. Wire drawing is performed by pulling a piece of metal through a die plate in which there are series of holes that decrease by

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[130] D.N. Sim, *Beyond the Bloom; Bloom Refining and Artifact Production in Roman Britain,* PhD thesis, University of Reading (1994).

approximately 10 per cent of the wire diameter per hole. The decrease in hole size can be less than 10 per cent, but if it is larger, the force required to draw the wire is greater than the tensile strength of the metal and so it fractures.

To gain accurate dimensions for the reproduction of chain-mail, ancient rings were measured to obtain the size and shape of the wire and the diameter, and the method of assembly of the rings was examined. Ferrous chain-mail rings from Caerleon,[131] Wales, and also some from Thorsberg, Germany, were examined. The rings were made from wire which was square or rectangular in section, rather than circular.

According to Singer[132] draw-plates for drawing wire were unknown until the tenth century A.D. and wire was first produced by forging. However Thomsen and Thomsen[133] have stated that non-ferrous wire from Persia of sixth- to fifth-century B.C. date could only have been made by wire drawing. Northover[134] has argued that two bronze plates found at Isleham, Cambridgeshire, thought to belong to the Late Bronze Age, are draw-plates. These draw-plates are assumed to be for drawing non-ferrous metal. The drawing of iron wire is more difficult because the higher tensile strength of non-ferrous metals requires a much greater force to bring about drawing.

Thomsen and Thomsen[135] have shown that wire can be drawn through a plate made of the same metal as the wire to be drawn, and they have drawn gold, silver, and copper wire. If this theory holds true for iron, then draw-plates for drawing iron would not have to have been made from hardened steel. In another paper Thomsen and Thomsen[136] have shown that if the hole in the die is in the form of a taper, drawing will take place if the draw angle is 2 degrees and 50 degrees. A series of tapering holes can easily be made in a piece of iron by making a tapering punch and driving it into the plate to different depths. This would be done as a forging operation.

In a chain-mail coat there could have been as many as 12,000 riveted rings if the ring diameters were in the region of 12 mm, and even more for smaller rings. Examination of Roman chain-mail rings has shown that their dimensional accuracy is very tight. Experiments by the author[137] show that making wire by hammering and filing is unlikely to be able to produce wire to the tolerances found in Roman chain-mail coats or in the necessary quantities.

A draw-plate was made to test the proposition that iron wire can be drawn successfully through an unhardened iron draw-plate and that the punch for forming the holes was square tapering and made from plain carbon steel. The draw-plate, 4 mm thick by 36 mm by 120 mm, was forged from a piece of wrought iron bar stock 20 mm in thickness. A series of square holes of increasing size were punched with a square section punch (FIG. 11a). All forging was conducted at forging heat (100°C) and the iron was quenched after the final heat. There was no cold working. The times to make the punch and the draw-plate are given in Table 5.

Before forging, the draw-plate had a hardness number of 108 on the Vickers scale (108 VPN) after forging it increased to 127 VPN . This indicates that some work-hardening had taken place.

The first stage of preparing the wire for drawing was to forge a length of wrought iron down to 3.5 mm square and then anneal it by heating to red heat and burring it in wood ash. After annealing the hardness was 100 VPN scale. The wire was lubricated by wiping it with beeswax and drawn through holes 1–5 inclusive on the draw-plate using an INSTRON 4206 Universal Testing Machine. No annealing was conducted between each drawing and due to work hardening of the finished wire, the hardness had further increased to 159 VPN which is harder than the holes in the draw-plate which was 127 VPN. It should be noted that because hardness values are not on a linear scale the relative hardness of the draw-plate to the annealed wire is misleading.

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[131] Caerleon, see note 127.

[132] C. Singer, E.J. Holmyard, and A.R. Hall (eds), *A History of Technology* (1954), II, 75.

[133] E.G and H.H. Thomsen, 'Drawing solid wires through soft dies in antiquity', *Transactions of the ASME Journal of Engineering for Industry* (1976), 1–5.

[134] P. Northover, 'Late Bronze Age Draw-plates in the Isleham Hoard', in B. Schmid-Sikimić and P.D. Cassa (eds), *Trans Europam: Beiträge zur Bronze- und Eisenzeit zwischen Atlantic und Altai: Festschrift für Margarita Primas*, Antiquitas 3,34 (1995), 15–22.

[135] op. cit. (note 133).

[136] E.G. and H.H. Thomsen, 'Early wire drawing through dies', *Transactions of the ASME Journal of Engineering Industry* (1974), 1216–21.

[137] D. Sim, *Experiments to Forge Bloom Iron into Wire* (forthcoming).

TABLE 5

SEQUENCE OF OPERATIONS, AND TIME FOR PRODUCTION OF AN IRON DRAW PLATE

Operation	**Time (minutes)**
Forging the punch	11
File to shape	10
Polish on sandstone	15
Forge wrought iron 40 mm × 20 mm down to 4 mm × 36 mm	12
Punch 6 holes	21
Total time	1 hour 19 minutes

It can be seen that the force to draw the wire is substantial but it is possible that this could be supplied by man-power. However this would be working almost to the limits of human strength and it is uncertain how long an individual could keep on exerting this sort of force. It is possible for the Romans to have had a winding device, to provide the power to draw iron wire. In fact a small capstain, or windlass, would have been sufficient to provide the necessary power to draw the wire through the plate.

This simple experiment shows that iron wire can be drawn through a soft iron plate and that a draw-plate and the tools to make it can be produced in 1 hour 19 minutes. It is possible that some work-hardening will take place on the inside of the holes and annealing of the wire, in between drawings, would reduce the power needed for drawing.

Roman draw-plates from Germany and Britain

The use of draw-plates by the Romans has been established by Thomsen and Thomsen,[138] who describe a draw-plate in the Burg Altena Museum in Altena, Germany. The draw-plate from Altena in Germany (near Dusseldorf) (PL. XXXIIIC) whose dimensions are given in Table 4 exists as a cast, the original having been lost. It has been dated by the museum to *c.* A.D. 45 and is thought to be of native/Roman origin, but no more details are available. The similarities with a second draw-plate from Vindolanda are apparent, not only in form but also in size. The main difference is that the Altena plate has a groove down the centre. The purpose of this is not certain but it could have been for holding a lubricant such as wax or animal fat.

The iron object shown in PL. XXXIIIB was found at the Roman fort of Vindolanda.[139] The general appearance of this object indicates a well-made tool. There are no hammer marks visible and care has been taken to produce fairly flat and smooth surfaces. There is a small amount of corrosion inside some of the holes, but otherwise the find is in excellent condition.

The plate is pierced by four holes and, at the broken end, there are the remains of a fifth hole. Reference to FIG. 11b and Table 7 shows the sizes of the holes on both sides of the plate and inspection revealed that the holes taper. They are not perfectly circular but the deviation from true circularity is so small as to be negligible. The holes are fairly evenly spaced along the centre line of the plate.

Examination with a microscope at magnification x 60 shows wear marks inside the smaller ends of the holes, although in two holes (diameters respectively 2.8 mm and 3.2 mm) some of the wear marks have been obliterated by corrosion. Until an X-ray is available it is impossible to describe with absolute certainty the exact form of the holes.

Method of manufacture of plate

From inspection of the side of the plate it can be seen that it has been made of at least three pieces of metal, pile-welded together. Considering the difficulties of drilling iron using a hand-powered drill, the holes were most likely to have been made by punching. It can be seen by consulting FIG. 11b in

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[138] op. cit. (note 136).

[139] Found at a depth of 4.3 m, in an area described as 'a handymans workshop'. It came from Period 3 which is dated between A.D. 97 and A.D. 104.

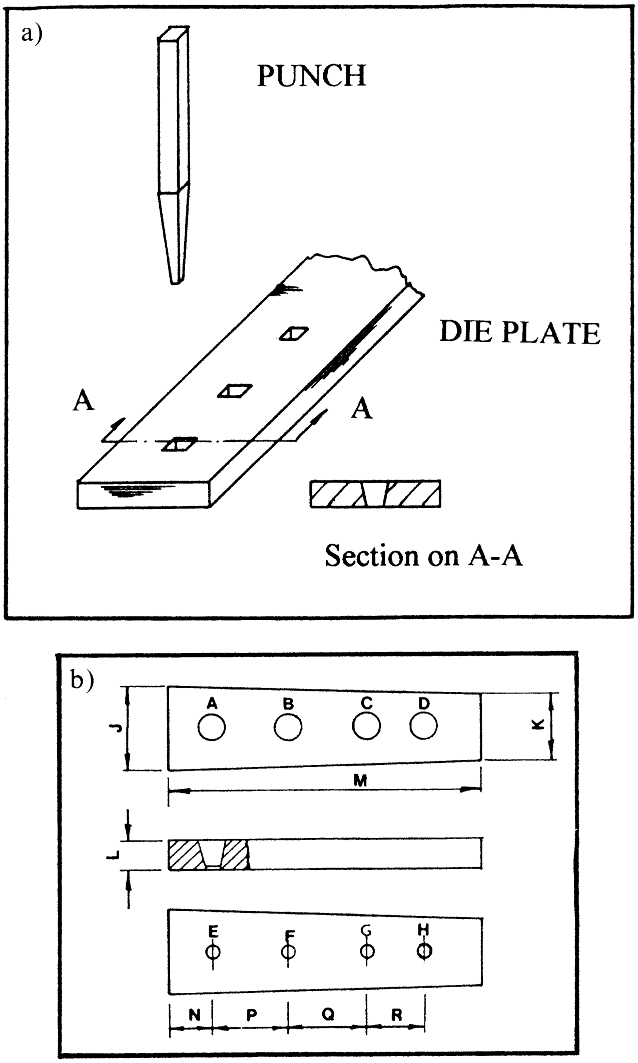

FIG. 11. Draw-plates. (a) Experimental draw-plate and punch; (b) Schematic view of draw-plate from Vindolanda.

TABLE 6

FORCE REQUIRED TO DRAW WIRE THROUGH THE DRAW-PLATE

Hole Number	Maximum Load (N)
1	1415
2	2094
3	2199
4	1146
5	1194

TABLE 7

COMPARISON OF HOLE SIZES IN DRAW-PLATES FROM VINDOLANDA AND ALTENA (ALL DIMENSIONS IN MM)

Dimension	Vindolanda	Altena
A	6.20	6.90
B	6.20	6.62
C	6.30	6.02
D	6.30	4.94
E	3.20	4.78
F	2.80	3.82
G	2.60	3.23
H	2.30	3.14
J	26.00	38.80
K	20.00	25.00
L	13.70	19.00
M	93.00	105.00
N	25.00	19.60
P	19.80	17.25
Q	18.50	22.26
R	16.80	27.81

conjunction with Table 7 that the large holes on one side of the die are almost the same size and were most probably made with the same punch. This punch would have been tapered in order to punch holes to within 2 mm to 3 mm of the front face of the draw-plate. The smaller holes would have been made with a small punch and then the ends of the holes could have been smoothed with a file. The taper in the holes provided the angle necessary to draw wire.

FIG. 11b is a schematic representation of the two draw-plates, the letters A to R indicate the dimensions. The dimensions are shown in the table below and the sizes of the two plates are compared in Table 7.

We have seen that in order to function as a draw-plate it is necessary to have a piece of metal with a tapering hole where the angle of the taper is greater than 2 degrees but less than 50 degrees. The draw-plate from Vindolanda has a series of tapering through-holes that are positioned in ascending order of size, and it thus fits the criteria for a wire-draw-plate as described above.

DISCUSSION

The size of the smallest rings (3 mm diameter) and the intricacy of the work involved in punching the holes for riveting puts this sort of work outside the normal work conducted by blacksmiths or armourers. The use of mandrils and tiny punches is more the type of work conducted by a jeweller. It is not being suggested that the making of chain-mail was carried out by jewellers but that the equipment and the nature of the work would have employed the skills and tools of a jeweller rather than those of a blacksmith.

If we consider a mail coat made of a series of solid rings, with four riveted rings passing through it where the rings are 6 mm in diameter, then the whole coat, will require 170,353 rings (42,588 riveted rings and 127,764 solid rings). If each solid ring takes 1 minute then
1 (min) x 127,764 (rings) = 2,129 hours
If it takes 3 minutes 47 seconds to make a riveted ring (this includes making the copper rivet) then,
42,588 (riveted rings) x 3 minutes 47 seconds (per ring) = 2,684 hours 41 minutes
Total time 2,129 hours + 2,684 hours = 4,813 hours (1.3 years, given a working day of approximately 10 hours).

It is impossible to estimate how many coats were in use at any one time. Not all soldiers in a legion wore the same type of armour. But if one considers a single legion at full strength, with every legionary wearing the same armour then, if every man has one coat and there is one coat per man in store to act as backup then it would take

6,000 x 4,813 hours 41 mins = 28,878,000 man-hours of work.
This is a staggering amount of time to invest in armour. It is possible that mail coats had a long life and it is known from some medieval mail that they were frequently repaired. But we are not sure how long a coat lasted or how much of the army were using mail at any one time. It is possible that there are other methods of manufacture of which we have no knowledge that might reduce the production time.

Certainly the use of solid rings reduces the time to make a coat. If the coat described above had been made of all riveted rings then it would have taken;
170,353 rings x 3 minutes 47 seconds (per riveted ring) = 10,458 hours
10,455 hours as opposed to 4,813 hours 41 minutes, a difference of 5,644 hours per coat. One possible reason for making a coat that is constructed from one riveted to every four solid rings is the amount of time saved.

CONCLUSION

The measurement of ancient Roman solid rings has shown that they were able to produce rings to a high degree of accuracy, greater than that expected from hand methods such as forging. It seems likely that a punch was used to make these rings. Experiments have shown that:

1. Simple technology can be used to produce a punch and die that are capable of punching rings from sheet iron.
2. That the die and punches can be made in 45–50 minutes.
3. That wear on the die can easily be rectified by putting the punch in the die and striking a single blow.
4. The die can be made from soft iron but the punch needs to be made from steel or case-hardened iron.

When experimental rings were compared with originals, the amount of deviation from the mean was similar in both cases. It is suggested that solid Roman rings were made by punching with a punch and die similar to that used in the experiments. These punching sets were easy to produce and required no precision machinery.

Two iron plates from the Roman period have been shown to exhibit all the characteristics of draw-plates, but it cannot be proved that they were used to draw iron wire. However, experiments have shown that iron wire can be drawn through iron draw-plates and that such draw-plates are simple to produce. During experiments the force required to draw iron wire was between 1415 N and 2094 N. Exerting this force by hand reaches the limits of human strength, but a simple system of pulleys would have been able to produce the necessary force.

The dimensional accuracy of the wire used to make Roman riveted rings was to a level that the author could not reproduce by forging and filing or by swaging. It is suggested that the accuracy of the rings and the time to produce the necessary quantities of iron wire for riveted rings means that the wire was probably made by drawing it through draw-plates. The apparent scarcity of equipment for drawing iron wire can perhaps be attributed to some draw-plates having been misidentified as nail-heading tools, as well as the fragile nature of iron items in the archaeological record.

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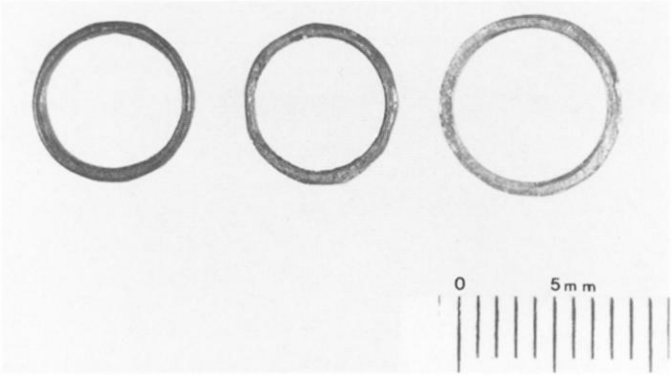
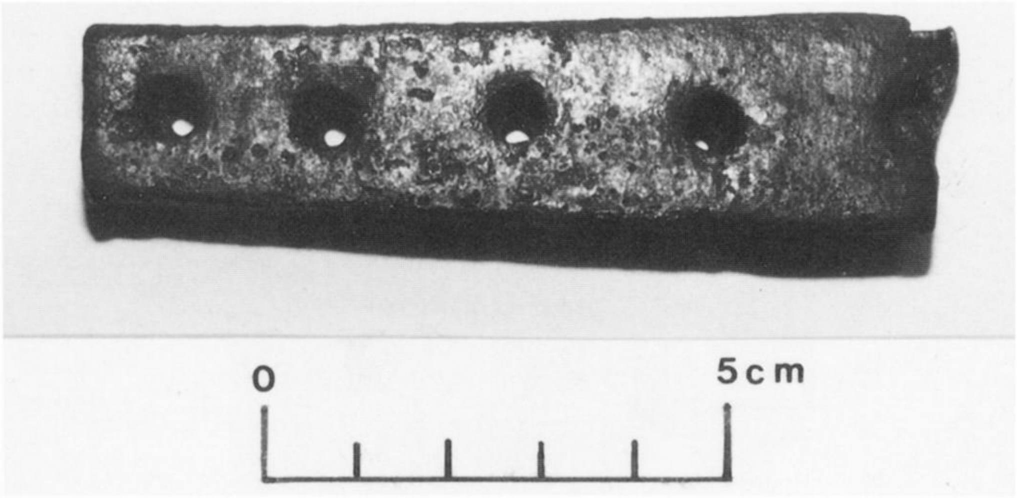
PLATE XXXIII



A. Rings on the left and centre are originals from Thorsberg, the ring on the right was produced experimentally. (p. 363)



B. Draw-plate from the Roman fort of Vindolanda. (p. 368)

C. Draw-plate from Altena (Germany). (p. 368)