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The manufacture of armour in Medieval Europe

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Mail

The precursor of plate armour was mail. It seems to have been a development of the late Iron Age, apparently by the Celts. Mail is described as a Gallic invention by Roman writers such as Varro (Robinson 1980, passim) and the Roman legionaries of the republic were generally armoured with a shirt of iron mail. Their officers frequently wore armour of a traditional Greek pattern, and a number of bronze helmets have survived. These would probably have been as effective as the available iron ones (none have ever been analysed), but many times more expensive. Despite their cost, copper alloys continued in use as a material for armour. A Roman lamellar cuirass of copper-alloy was excavated in 1993 from a late 2nd century context near the village of Cifer north of the Danube in modern Slovakia (Ruttkay 1995). The "lorica segmentata", or segmented plate armour, which had partly replaced mail during the 1st century CE, seems to have remained in use until the 3rd century.

The manufacture of body armour followed a similar pattern in Early Medieval Europe to that of the Late Roman Empire. There would have been enormous quantities of arms and armour made for the Roman army, both legionaries and Germanic auxiliaries, which has been estimated as reaching perhaps 435.000 in extent by the 4th century (Anderson 1974, 85). So this would imply 435.000 helmets, and 435.000 body defences of some sort, of which (hypothetically) 100.000 were mail shirts in Europe and the Mediterranean area. It is very unlikely that these would all have been discarded, especially during a period of relative economic decline, and the largest part must have been adapted and re-used by subsequent generations.

An unusually well preserved helmet was the 8th century Anglian example from York (Tweddle 1992, passim). The skull of this helmet consisted of a brow-band (572 x 87 mm), a nose-to-nape band (493 x 87 mm), two lateral bands (125 x 82 mm, and probably 82 x 82 mm), and four infill plates, rivetted together. The dimensions of these bands suggest that they had an earlier history as lorica plates. There seems to be no other reason why two of the four bands should have the same width, and the other two also have the same width as one another. This must remain speculation however, until more analyses have been undertaken.

Much early medieval mail might have had a Roman origin, although this material cannot now be positively identified. Mail, by its nature, lends itself to recycling. The method of repair or alteration is the same as the method of manufacture. New pieces of mail are simply attached by joining a row of links at each edge. As a recent review (Callori 1989, 93–99) points out, mail was popular because of its adaptability to different sizes of wearer, and comparative ease of manufacture. Shape could be given to the limbs of a mail garment by varying the numbers of links in a row.

Excavated mail is usually too severely corroded for its method of manufacture to be deduced, but the mail attached to the York helmet mentioned above (8th century) was found in unusually good condition, and its consistent diameter suggests drawn wire (O'Connor 1992).

The bulk of the Frankish army by the 9th century was mounted and armoured, costly though this was. The prices of their equipment have been quoted by Verbruggen (1997, 23–25) and they included: helmet 6 solidi, brunia (byrnie, hauberk) 12 solidi, sword 3 solidi, and leggings 6 solidi, when an ox might cost 2 solidi. The body armour of an armoured cavalryman might thus cost the equivalent of 12 oxen, but this enormous sum was justified by the complete supremacy on the battlefield that this eqipment gave them. In Western Europe the man who fought on horseback was known from the 10th century onwards, as a knight, whatever his precise social status. He had to be a full-time soldier, as the cost of his equipment and the training required to use it effectively left little time for any economic activity.

While the body defence made entirely of mail had reached a peak of completeness by the 13th century, some of its limitations were becoming apparent. The threat from crossbows (and perhaps longbows) meant that mail was regularly reinforced by some sort of rigid defence from at least the 13th century onwards (Blair 1958, chapter 1). Crossbows (more powerful than the average bow) had come into use, and they had been (quite ineffectually) banned by Pope Innocent II at the second Lateran Council in 1139. In addition, it is probable that mail was not very effective against weapons such as maces, which would be more likely to break the limbs beneath the mail because the flexibility of mail presented less resistance than plate to the blow, whereas arrows were at least impeded by mail. It must however be remembered that mail was never worn alone, but in conjunction with a quilted undergarment (gambeson) to absorb the shock of impact.

The energy available: Attack on armour

The kinetic energy of any moving object is given by the expression

Energy = 1/2 X mass X velocity X velocity

The units of energy are joules (J). So a 100 g (0,1 kg) missile travelling at a velocity of 40 m/sec will have a kinetic energy of

1/2 X 0,1 X 40 X 40 = 80 J.

Throughout the Ancient World as well as the medieval period, swords, spears and axes would have been employed in hand-to-hand combat, and such blows might deliver anything between 60 and 130 J (Blythe 1977). By comparison, modern police body armour is supposed to resist an attempted stabbing, which may deliver about 50 J or more (Horsfall 1999). Of course, the area of impact is of equal importance to the energy available; the smaller the point, the greater the threat of penetration.

Longbows were simply large bows, of heavier draw weight than usual, which required intensive practice. Nielsen (1991) carried out some recent experiments, which included shooting at a (dead) pig clad in mail, which gave it some protection, but unfortunately he did not measure the energies involved. McEwen and others (1988) carried out extensive tests on shooting different bows with accurate measurements, and found that from a yew longbow of 36 kg draw-weight, a 50 g field arrow might travel at 53 m/sec, and a 90 g broadhead arrow at 43 m/sec. So these would have had an initial energy of 70 and 83 J respectively. They also measured the velocity of a modern target bolt (62 m/sec) shot from a crossbow of 41 kg draw weight. The initial energy of such a 100 g bolt would have been 192 J.

Of course, the further a projectile travels, the more it will be slowed down by air resistance, and so the less kinetic energy it will possess. After 50 m, for example, the velocity of an arrow might have fallen from 43 to 37 m/sec and so its kinetic energy would have fallen to 61 J; the velocity of a bolt might have fallen to 45 m/sec, and its energy to 101 J. i.e. about half its initial energy. The feathered arrow is not the most aerodynamic of shapes, and loses velocity (and therefore kinetic energy) relatively quickly. The crossbow bolt is shorter and fatter, and therefore generates proportionally even more drag (Rees, pers.comm. 2001).

Handguns offered even more energy than crossbows. Lasson (1956) constructed a replica of a 14th century handgun of about nine calibres (200 x 23 mm), loaded it with 38 g of uncorned powder and a 50 g lead ball, and fired it from 30 m when it penetrated a "suit of light armour" of unspecified quality. The muzzle velocity was not recorded, but seems unlikely to have been less than 100 m/sec, which would have indicated a muzzle energy of 250 J. So this early handgun, while possessing considerable scope for further development, was already more powerful than the crossbow. This author used 20 g of uncorned ("serpentine") powder to fire 20 mm bullets from a gun of variable barrel length (Williams 1977). The muzzle velocities quoted are averages of a series of results. The muzzle energies quoted assume a 40 g bullet (see table 1).

Although handguns appeared in the 14th century, the first widespread use of handguns seems to have been in the early 15th century wars of the Hussites (Bohemian peasant revolutionaries) against their (largely German) feudal lords. The dimensions of a number of Hussite guns from Plzen have been published by Fryda (1988). Most of these are in the range of 30 to 40 calibre, so their muzzle velocities on the evidence of the results quoted above would have been around 250 m/sec. The average muzzle energy would therefore have been in the region of 1000–1200 J.

So, in conclusion, we have various weapons available to attack armour, offering the following approximate energies. The missile weapons, when used at a distance, might deliver only a fraction (perhaps half?) of the initial energy (see table 2).

The energy needed: Impact tests

Impact tests were carried out with a variety of simulated weapons in an instrumented test rig (Rosand IFW5) in the Engineering Department at Reading University (Williams 2002, chapter 9, passim).

The weapons used included

- i a simulated halberd or sword blade (40 mm long);
- ii a simulated lance head (with a 60 deg point),
- iii a simulated bodkin arrowhead (with a 18 deg point),
- iv a 20 mm diameter lead bullet.

The protective materials tested included (see tab. 3):

- a) Some modern (mild steel) mail, backed by a quilted jack.
- b) A piece of 15th century mail also backed by a quilted jack. This consisted of a gusset piece made of low-carbon steel hardened by quenching, and 17 x 22 cm in size. The mail had been made of a low-carbon steel hardened by quenching. The performance to the modern mail was closely similar, but slightly inferior.
- c) A flat plate of "Swedish" Wrought iron sheet of 1.9 mm thickness, corresponding to munition armour of low quality. Knightly armour would generally have been much better. The effect of curvature also must also be taken into account. A missile striking an inclined surface at an angle of 30E will deliver only a proportion of its energy (the cosine of 30E in fact) so the energy required for defeat would need to be augmented by at least 20 %.

"Serious damage" means that one or two links were broken, and more dented. So the mail was damaged but by no means defeated. "Complete defeat" implies penetration of the jack as well.

At 100 J impact, the jack behind the (mild steel) mail was holed; at 120 J the mail was completely defeated, that is two links were opened out, three others bent, a 5 mm diameter hole put through the jack, and a 35 mm dent made in the "Plastilene" (a material approximating in behaviour to human flesh) behind.

So, in general, any form of bow that could deliver a point with 120 J to the surface of mail would defeat it. An arrow was a more efficient way of attacking mail than a lance or sword because the energy is concentrated on a smaller area.

While this plate armour generally requires more energy to defeat it than mail, it is not enormously better armour. But it offered other advantages. Mail is a simple form of armour to make, but very labour-intensive; plate armour on the other hand requires considerable capital to set up the large furnaces necessary for its manufacture, but is then faster to make.

It has recently been estimated that a knee-length mail shirt might contain between 28,000 and 50,000 links depending on the length of the sleeves and the size of the links (Metcalf, pers.comm.). The smaller might take a modern craftsman 100 man-days to make, although experience would doubtless shorten this time considerably. The use of half riveted and half solid links might reduce this figure to 75 man-days. Verbruggen (op. cit. 170–171) quotes the Ghent Archives for 1304 as making payments for one (short) mail tunic of 10 s to 15 s Flemish, and for another mail tunic (perhaps with a coif?) 20 s, at a time when an artisan might earn 3 s a day. So a mail shirt would cost between 60 and 120 days' wages. If the mail was made denser (with smaller links) to improve it, then the labour required to make it would be even greater.

When labour costs rose after the Black Death, the price of mail rose accordingly. In an era of rising prices it ceased to be an economically attractive way of making armour. Indeed, by the 15th century the cost of a mail shirt (4.59 gulden) at Iserlohn was notably greater than the cost of plate armour (4.33 gulden). The manufacture of armour in Westphalia is frequently mentioned from the 14th century onwards. For example, in 1388 the purchase of 41 mail shirts in Iserlohn for 188 guilders is mentioned in the Nürnberg archives (Chroniken 1862, 260; 271). In 1437, one Gerhard Stacke of Iserlohn and Johann Levenicht of Soest received 1300 Rheinische Gulden for 300 armours (Dässeler 1958, No. 135, 55). It may be noted that in contrast to the 8th century Frankish mail shirt, leggings and helmet which cost 12 oxen (quoted above), by 1600 a horseman's armour in Graz would only cost just over 2 oxen but by then the production of armour had increased enormously in efficiency (Roth 1971).

The use of plates to improve the performance of mail had started to come into general use during the 13th century. The knees and shins, the parts of a horseman most vulnerable to sword and axe-cuts from infantrymen, were protected by reinforcing plates of metal (or perhaps cuir-bouilli) from the middle of the 13th century, and arm defences were added later in the century. By the mid-13th century an extra protective breastplate, apparently made of several plates riveted together (called the "coat-of-plates"), was frequently worn on top of the customary hauberk of mail.

During the course of the 14th century the plates of the coat-of-plates became larger in size but fewer in number, until they could be regarded as a rudimentary breastplate with some smaller plates attached. The logical next step was the complete replacement of mail as far as possible with plate, which offered better protection for no extra weight, indeed perhaps for less weight than the combination of mail and extra plates (a typical mail shirt might weigh 9 kg). This change began in the 14th and was completed by the early years of the 15th century. At Churburg, there is a one-piece breastplate from the late 14th century and weighing 2.6 kg (Boccia 1967, pl. 28–30). In Munich (Bavarian National Museum, W.195) there is a one-piece breastplate dated to around 1400; it weighs 4.5 kg and is covered in red velvet (Seelig, pers.comm.). One-piece helmets from the 14th century (such as Poldi-Pezzuoli Museum, 3599) weigh around 1.8 kg.

length mm	calibre (length/bore)	average muzzle velocity m/sec	muzzle energy J
254	13	149	440
381	20	239	1100
914	48	255	1300
1372	72	343	2300

Tab. 1.

Period	weapon	initial energy
all	sword, axe	60–130 J
11-12c	lonbbow arrow	80–100 J
	crossbow bolt	100–200 J
14c	early handgun + serpentine powder	250 J
15c	Hussite handguns + serpentine powder	500–1000 J

Tab. 2.

Weapon	15th century mail	mild steel mail	wrought iron plate
Blade 170 J	complete defeat	200 J serious damage	190 J fracture starts
Lance 140 J	complete defeat	200 J serious damage	100 J fracture starts
Arrow 120 J	complete defeat	120 J complete defeat	80 J a 5 mm hole
Bullet 400 J	complete defeat	–	900 J complete defeat

Tab. 3.

Horse armour was made of several plates, each of a size comparable to a breastplate, riveted together. The earliest surviving complete horse armour which dates from around 1450 (and is now in the Museum of the City of Vienna) weighs approximately 60 kg (Mattl, pers. comm.) and is made up of 11 large and some 30 smaller plates. Although this horse armour has not been dismantled in recent years, the presumption must be that the larger plates weigh around 4 kg each.

Once plates of this size (2.5–4.5 kg) can be made, then the whole body can be covered with a complete armour of articulated plates, except for the joints of the limbs. But perceiving the advantages of plate armours does not automatically make their manufacture easy. A plate of armour which weighs between 2.5 and 4.5 kg will pose new problems to the producers. Billets of metal of 10 kg or more may be needed to make such a plate, and their production from a bloomery is difficult. Forge-welding many small plates together entails the loss of considerable amounts of metal and, if unskilfully done, incurs the risk of increasing the slag content. The metal itself must be reasonably low in slag (if not as uniform as modern steels) if its mechanical properties are to be suitable for armour. However, during the 14th century in Italy, these large plates did appear, and they are generally plates of steel.

Ironmaking in bloomeries

For the Ancient World, and the early Middle Ages, the only ferrous material available for armour was "bloomery iron". This was the product of heating iron ore with charcoal in a small (perhaps 1 or 2 m high) furnace. The iron ore was reduced to iron, but never melted, and therefore never entirely separated from the slag formed by non-metallic impurities. The lump (or "bloom") of iron formed might be forged out into plates which would still be full of slag inclusions. These plates would not make particularly good armour for two reasons; they would be too small and the metal would be too full of slag.

Tylecote (1971) reported that during his experiments with a simulated Roman "high-bloomery" of 1.75 m height he obtained unforged blooms of variable carbon content from 3.8 to 6.5 kg in weight (and even one which melted, to form cast iron). To make armour plate, the bloom must have been somewhat larger than the plates desired. Experiments by Crew (1991) suggested that working a bloom into an artefact entails a wastage of three-fourths, so plates of 3 or 4 kg must have come from blooms of 9 or 12 kg in weight. But Sim (1998, 55) has recently described his experiments with simulated Roman bloomsmithing in which he reduced the loss rate to around half. (The Roman army seems to have been supplied with iron ingots of around 5kg–7kg.) On balance, it would be reasonable to assume that making armour plates required starting blooms of at least 10 kg. The furnaces supplying 14th century Italian armourers must have been substantially larger than Tylecote's "Roman" ones if they could supply blooms of 10 kg (or even more). Certainly, there were very large iron-making furnaces in 15th century Italy. Baraldi (1998) has found evidence for a furnace of 4.5 m height in 1463, at "Ferriere di Val nure" near Piacenza; and one of nearly 6m height in 1497 at Fornovolasco. These furnaces and their products were the results of applying water power to bellows and, perhaps more importantly for making sheet metal, trip hammers. They also entail the ability to control the output of a shaft furnace in order not to produce cast iron, if steel blooms were required for armour.

In the second place, bloomeries made iron which was full of slag. The inclusions made it ductile in 1 plane, but brittle in 2 planes (Hensel/Hengstenberg 1932). It is brittle in the direction of attack; no doubt wrought iron plates were tried as armour, and found to be unsatisfactory; their fracture toughness would be low and so prior to the 14th century, most armour would have been made out of small plates of wrought iron riveted together, or formed into wire and interlinked as mail, the gaps between the units acting as crack-stoppers.

An efficient antidote to this is to reduce the slag content by making steel in the bloomery instead of iron. If the bloomery is operated under more reducing conditions, then the bloom will absorb more carbon. Some of the carbon will react with iron oxide, reducing it to iron, and so removing it from the slag; as follows:

$$FeO + C = Fe + CO$$

(iron oxide / carbon / iron / carbon monoxide)

The volume of slag will become less (but its freerunning temperature will rise, so a higher operating temperature will be needed). The

products will be a bloom of steel, containing less slag, and a slag of lower iron content (Gordon 1988).
Toughness tests carried out by the author show a close correlation between slag inclusion content and fracture toughness. The best armour would be that made from metal with the fewest slag inclusions, and the best armour WAS made of steel. There would be additional benefits in that the steel would, of course, also be harder and stronger because of the carbon present (as iron carbide). On top of that, the steel would be further hardenable by quenching, if the armourer felt able to undertake this extra heat-treatment.

North Italian armour and its marks

By the 14th century ironmasters in Lombardy were employing furnaces large enough, and whose output they were evidently able to control, that they could supply the armourers with the large pieces of better metal, usually steel, which they needed to make armour plate.
It was suggested by Buttin (1901) that the use of multiple marks was an indication of the protection offered. However, there is no correlation between the number of marks and the quality of the metal.
There is however a correlation between its quality and the presence of a mark or marks. The author has examined 72 components of North Italian armour with marks (Williams 2002, section 4, passim).

Out of these:
4 were made of iron,
33 were made of low-carbon steel,
35 were made of medium-carbon steel,
28 were apparently air-cooled, i.e. unhardened,
29 were partially hardened by an attempt at heat-treatment,
19 were hardened by a successful heat-treatment (i.e. 60 % of the total examined were heat-treated, 37 % successfully).

Out of these, 35 examples had double-marks. Of this latter group 14 were hardened successfully and another 7 less successfully (or 60 % heat-treated and 40 % successfully). So it is clear that there is no significant metallurgical difference between armour with a single mark, and that with a double mark.
But, armour bearing any armourer's mark is of a decidedly better quality than armour without such a mark. 45 out of 72 marked armours were hardened, compared with only 12 out of 44 unmarked.
Evidently a mark indicated that an armour was worth paying a higher price for, as it would offer the customer better protection. The number of marks seems only to reflect workshop practice. Study of the 9 components of the AVANT armour from the Corio workshop (Williams 1986) suggests that heat-treatment was carried out as almost the last operation, as all the components made by different subcontractors show the same heat-treatment. Variations in the outcome are simply due to variations in the carbon content of the steel.

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