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WHAT CAN SCIENTIFIC ANALYSIS TELL US ABOUT THE EFFECTIVENESS OF MEDIEVAL ARMS AND ARMOUR?

Many attempts have been made to quantify the performance of medieval armour and weapons. While the velocity of missiles can be measured, and hence their kinetic energy, the effectiveness of armour is much more difficult to predict.

The seminal papers of Krenn and McEwen have given us detailed information about what the guns and bows of the Middle Ages and Early Modern period might have achieved, although, perhaps surprisingly, no-one has yet performed such an exercise with the crossbow.

The earliest systematic tests were carried out by Saxton Pope (1974) who conducted a series of experiments shooting both an English longbow with both bodkin and broadhead arrows, and other bows. He estimated the striking force by shooting blunt-headed arrows at a block of paraffin wax.

A bow of 50 lb draw-weight had a striking force of 20 ft. lbs (~170 J) at 10 ft range, and one of 75 lb draw-weight had a striking force of 25 ft. lbs (~212 J). The larger bow may have offered an initial energy comparable to a crossbow.

He noted that broadhead arrows penetrated animals much further because the barbs cut a path through the flesh, thus reducing friction on the shaft of the arrow. Indeed, he claimed to have killed several grizzly bears using broadhead arrows. An arrow with a smaller point would have been more suitable for attacking an armoured man.

He tried shooting a bodkin-headed arrow from a longbow (75 lb draw weight) at a mail shirt hung on a pine box 7 yards away. The mail shirt weighed 25 lb and consisted of links of approx. 1/2" (13 mm) diameter and 22 gauge wire thickness.

The arrow went through the mail and both sides of the box. He did not try a broadhead arrow on this target.

McEwen (Bergman et al. 1988) carried out extensive tests on shooting different bows with accurate measurements, and found that from a yew longbow of 36 kg (80 lb) draw-weight, a 50g 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. He also measured the velocity of a modern target bolt (62 m/sec) shot from a crossbow of 41 kg (90 lb) draw weight, so the initial energy of a 100 g bolt would have been 192 J.

Allowing for considerable variation between individuals, archers with powerful bows were able to shoot arrows at their opponents delivering as much as 200 J initially, but of course less at distance because air resistance would slow down the missile.

Krenn (1990) carried out extensive tests, using modern gunpowder, to load a selection of representative 16th & 17th century guns from the very large number available in the Graz Arsenal, and found that, for example: a 16th century matchlock arquebus (760mm barrel) had a muzzle velocity of 449 m/sec, and a muzzle energy of 1752 J.

A 16th century musket (1000 mm barrel) had a muzzle velocity of 456 m/sec, and a muzzle energy of 3125 J. An even more powerful weapon was a 16th century wheellock wall- musket (1100 mm barrel) which had a muzzle velocity of 482 m/sec, and a muzzle energy of 4444 J. At 100 m this could put a lead bullet (38 g, 19 mm) through 2 mm mild steel sheet. Even a wheellock pistol had a muzzle velocity of 438 m/sec and so offered 917 J.

It is clear that firearms were weapons which offered a different order of magnitude when it came to delivering energy, even after allowing for the fact that the missiles were generally spherical rather than pointed. They offered 5 to10 times as much energy to attack a target, and required far less skill to use.

Thickness of some armour has been measured by some workers employing ultrasonic devices, but unfortunately this is often an unreliable method because medieval metal frequently contains delaminations within the plate. These were a consequence of manufacturing the plate by folding and forging a heterogeneous bloom, and not invariably welding all the layers together successfully. The ultrasonic beam will be reflected by such a delamination, thus giving an erroneous result for the thickness of the armour.

There is a continuous production of armour from the mid–15th to the mid–17th coffairly constant thickness. Breastplate thickness between 1.5 and 3 mm corresponds of course to an armour of comfortable weight. The limbs would have been protected with thinner armour. But there is a steady rise in the maximum thickness, from around 2 mm in the 15th to around 6 mm which is regularly found by the late 16th century. This suggests that while many customers may have preferred armour of the accustomed thickness and weight, there was a growing market for bulletproof armour, notwithstanding its greater weight. As a consequence, while 14 and 15th century armour seldom weighed more than 15 kg, by the late 16th century this had risen to 25 kg.

Apart from contemporary references such as the many missile injuries to the face recorded when knights lifted their visors and collected by Strickland (Strickland, Hardy 2005) it has always been an aim of some scholars to prove or disprove the effectiveness of armour. The problem is that there are so many variables involved, and they must be studied separately if any generally useful conclusion is to be reached.

Analysis of the thickness and shape of any armour plate has to be coupled with knowledge of its metallurgical properties, so not merely hardness, but also slag content which determines fracture toughness, has to be measured.

Much theoretical work has been done (with modern materials) on the elastoplastic fracture of sheet metal. Wierzbicki's equation relates the energy needed to pierce a metal plate with the thickness of the plate raised to the power of 1.6. In other words doubling the thickness of a plate trebles the work needed to pierce it (Atkins & Blyth, 2001). But considerable corrections have to be made to this if it is to be applied to pre-Bessemer metal, since the slag inclusions present will reduce the fracture toughness of the metal.

Experiments which this author and some of his students (Williams 2003) carried out suggest that an arrow would have needed 55 J to defeat 1 mm of mild steel plate (110 J to defeat 1.5 mm and 175 J to defeat 2 mm). This was an attack on flat plates struck normally, so that an addition has to be made for arrows striking a glancing blow. More importantly, although mild steel might be taken as being *roughly* equivalent to munition armour, especially from the 15th century, knights would have been wearing armour that was harder and stronger. Destructive tests cannot be carried out on historical objects, so estimates have to be made from tests on modern materials, with allowance for the different slag inclusion content. Replacing the mild steel with a medium-carbon steel, an equivalent of which most Italian armour would have been made from the late 14th century onwards, showed that an arrowhead with 100 J behind it would only penetrate by 9 mm. Bearing in mind that a padded undergarment would have lain below the plate, this means that the plate protected the wearer. Armour of quality was sold by Milanese armourers as "proof against the crossbow" with good reason.

A less encouraging view of the usefulness of scientific analysis may be had from some recent efforts at "authentication".

A sword of 15th century form was kept for many years in the Spanish Army Museum (at that time in Madrid) called *Tizona* and said to be the sword "of the Cid".

A work of 1857 mentioned this sword as being then in the possession of the Marques de Falces. (Leguina 1898, pp. 69—70) In 1999 the present Marques offered to sell it to the Spanish government for a very large sum, but the offer was refused. He then tried to export it for sale abroad, only to be prevented by Royal Decree 1414/2002 which declared it to be an object of national cultural interest. The decree contained the information that the tradition attached to the sword is that it was presented to the first Marques by King Ferdinand the Catholic (1452—1516). It was formerly kept at the Castle of Marcilla in Navarra, the family seat. More recently, it was the subject of several articles by a team of Spanish scientists led by Criado, and subsequently bought in 2007 by the Autonomous Community of Castile and Leon for 1.6 million euros; it is currently on display at the Museum of Burgos.

The starting point with the sword *Tizona* was metallography (microscopic examination) which was carried out on the surface, and on samples extracted from several areas of the blade. A cross-section, which would have been more informative, was (understandably) not permitted by the Army Museum because of the well-preserved condition of the intact blade of this famous sword.

The microstructure of this sword blade was described as having a higher carbon content at the edges and a lower carbon content in the centre. The edges contain a ferrite-carbide aggregate identified by the authors as bainite, giving way to fine pearlite nearer the centre. This differs little from many other examples of medieval swords, axes and knives. Since steel was expensive, it was usually made to go as far as possible. Steel edges might be welded onto an iron core, or the iron edges might be converted to steel by "case-carburising" (packing in charcoal or organic matter and heating for days).

No hardness values were quoted, but cooling this blade somehow at a rate faster than air-cooling, but slower than water-cooling, might perhaps create the microstructure described, which would be harder than pearlite but less hard than martensite. A reasonable gain in effectiveness, with less risk of cracking, would be attractive to medieval bladesmiths. Such a blade might have been produced almost anywhere in Europe over a thousand years from Roman to Early Modem times. Where this study becomes controversial, however, is in the authors' deductions from the morphology of the pearlite present (Criado *et al.* 1998; 2000).

It is argued that the lamellae of iron carbide in pearlite will gradually over time transform into spheroidal globules of iron carbide (since spheres have a smaller surface area than plates of the same volume, they are stabler). This process may take an indefinitely long period at room temperature, but will happen more quickly at elevated temperatures (for example, if the steel is annealed). The authors quote an equation, ascribe values to the variables, and so perform a calculation to their own satisfaction, which gives an answer of 950 elapsed years. Unfortunately, in fact, unless the prior thermal history of the artefact is known, the rate of change of the pearlite cannot be deduced. Later in the same paper, they deduce from X-radiography that the blade had been repaired at some time in the past. So that even if pearlite spheroidisation were a valid method of estimating age, it could not be applied in this case. Unfortunately, it is not even a valid method. There is an extensive literature on the metallography of iron and steel artefacts from Roman and even Assyrian archaeological sites, with which the authors do not seem to be familiar. A few may be mentioned (Lang 1988; Pleiner 1979; Maddin *et al.* 1979), as examples which show microstructures in which the pearlite has remained lamellar, despite the thousands of years available for its spheroidisation.

Then elemental analysis was carried out by Mass Spectrometry and yielded results for the trace elements present in the steel (as parts per million): 4.1 Pt, 8.9 W, 3.8 Mo, 61 Co, 74 Ni, 178 Cu, and Sb 4.

From these data, although without quoting any results for the trace elements present in different Spanish ores, the authors deduced that the metal was smelted in Andalusia, which may well be correct. No values for manganese, sulphur, or phosphorus are given, so no conclusions can be drawn about the smelting process. All that can be positively stated from the evidence given is that this sword was made of iron, with steel edges, and that its hardness was increased by some method of accelerated cooling after forging.

Modern analytical methods can indeed detect tiny quantities of all the elements present, but such results have little significance in isolation. They can only be assessed by comparison with a database of the analyses of other contemporary objects. There is such a database of results in the case of medieval iron and steel objects, built up over more than thirty years by many authors and the subject of an annual bibliography by Pleiner since 1967:

Le Comité pour La Sidérurgie Ancienne de l'Union internationale des sciences prehistoriques at protohistoriques has published its bibliographies in *Archeologicke Rozhledy* (in English) from 1967—2001 (Prague).

It was intended that they would be published electronically in the future. *http://www.arup.cas.cz/ww_e/aktivity/ aktivity.htm*

But floods in Prague delayed this effort and abstracts may now be found at:

http://cpsa.webplus.net/abstracts.html

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