Investigation of a 16th-century gun powder chamber from the Tudor warship Mary Rose

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ABSTRACT: Work on the gun powder (breech) section of a wrought-iron port piece has provided information about the manufacturing process, as well as the structure and properties of the iron used.

The Mary Rose and her guns

The warship *Mary Rose* was commissioned by King Henry VIII and completed in July 1511. The earliest inventory, dated 1514, demonstrates that the vessel had a formidable array of weaponry. During her 35-year service the Mary Rose had at least one major re-build which upgraded her from 600 to 700 tons and enabled the weight of ordnance carried to be increased. The main hull, built with flush carvel planking, can accommodate gun ports with watertight lids. When she sank in 1545, her inventory listed 39 guns mounted on carriages, 50 smaller ship-supported anti-personnel guns, 50 handguns, 250 longbows and 300 staff weapons. The excavation and raising of the Mary Rose has provided an opportunity for a much greater understanding of the construction and use of ordnance at sea in the middle of the 16th century and enabled the identification of many types of gun by comparison of the archaeological evidence with the historical inventory (Hildred 1988, 55). The keel length is 32m with a total length of 45m, breadth of 11.7m and a draught of 4.6m. The guns were deployed over three decks, the lowest a continuous deck within two metres of the waterline. It was on this main gun deck that the majority of the heavy ordnance (up to three tonnes) was carried, either seven or eight large guns on each side.

These guns were situated at gun ports which had fitted lids, possibly added as late as 1539. The guns of the Mary Rose included breech-loading guns of forged (wrought) iron, small muzzle-loading cast-iron guns and some cast-bronze guns. By far the most numerous are the wrought- iron guns all of which have separate chambers to contain the gunpowder. The largest of these, the port pieces, had bores of up to 200mm in diameter and fired a round stone shot of up to 9kg or a lanthorn-shaped canister filled with flint or small pebbles of up to 14kg.

Port pieces are the commonest type of large gun carried on warships of this period and the Mary Rose had twelve (Fig 1). These appear to be a relatively new development, with their name possibly suggestive of their position at lidded gun ports, although the form dates back to the 15th century (Smith 1993). The discovery of wrought-iron breech loaders on the Mary Rose has caused a reappraisal of their importance and questioned the long held belief that they were slow to use, dangerous, inaccurate and obsolete (Archibald 1840). This culminated in a project to manufacture and

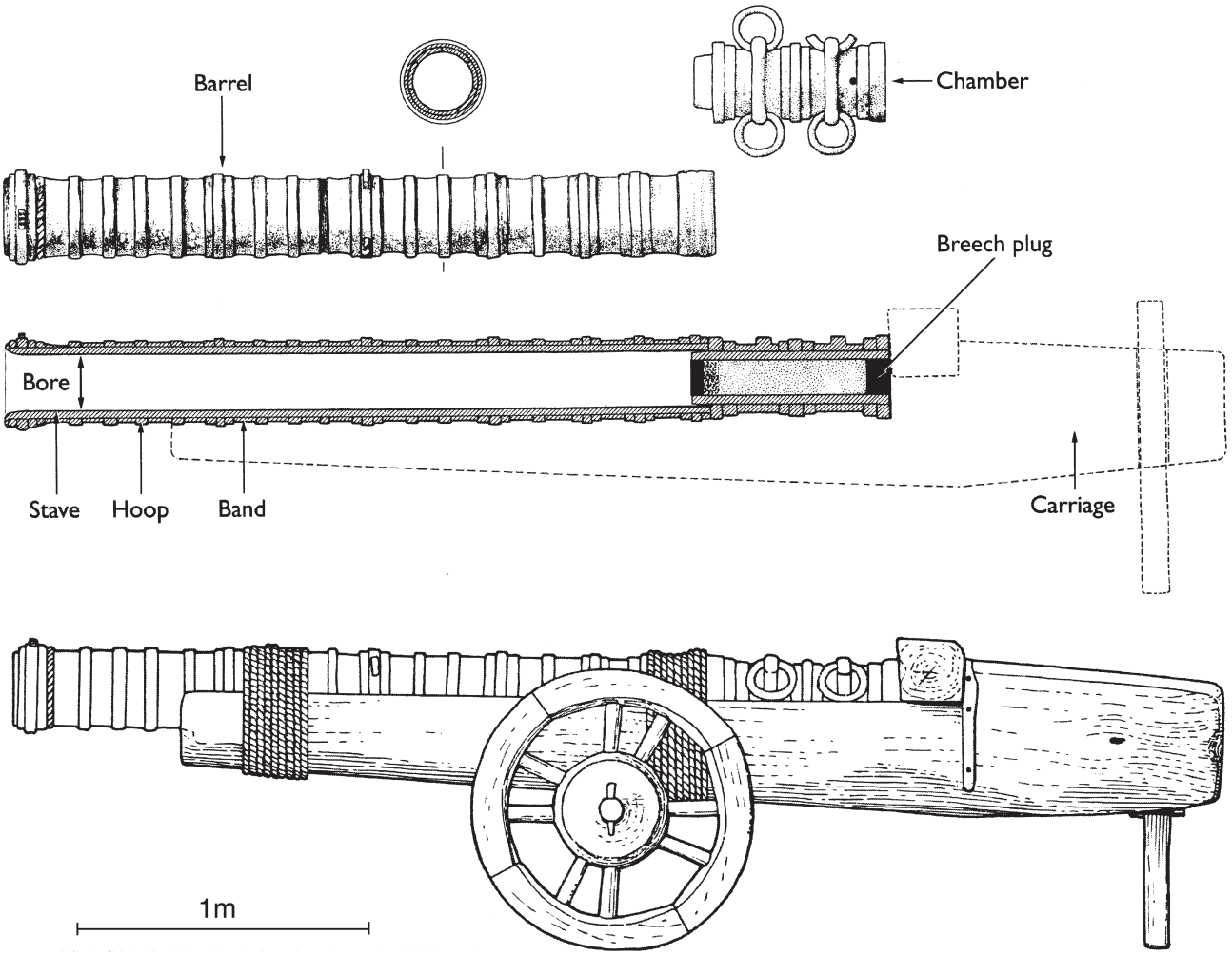

Figure 1: Drawing of one of the port pieces from the Mary Rose (MR 81 A2604) with reconstructions showing how the barrel was tied down to the gun carriage and the powder chamber wedged into position with its neck fitted into the back of the barrel.

fire a replica of one of the larger Mary Rose port pieces (Hall 1998). The study outlined below is of the original powder chamber (MR 82 A0792) associated with one of these guns (MR 81 A3001).

The port pieces were fabricated by making a tube of iron staves and heating forged bands and hoops so that they expanded and could be slipped over the tube to provide a second layer which shrank upon cooling to provide circumferential strength. The breech, or powder chamber, was made in a similar fashion with a plug welded at one end to form the back of the chamber (Hall 1998). The shot was placed into the rear of the tube forming the barrel and the powder chamber was then inserted into the barrel, hence the term breech loading. A similar method of construction was employed for the famous medieval muzzle-loading gun, Mons Meg, built in 1449 in Flanders which weighed 6046kg and was 4.04m long (Smith and Brown 1989). Wrought-iron guns are now considered one of the major products of the iron industry in the 15th and 16th centuries (Teesdale 1991). An iron cannon made in the 15th century and used in the Battle of Lepanto, has been examined (Vanden Hazel 1989) and found to be constructed of wrought-iron straps held together by iron hoops. Pomp and Spies (1940) found that a wrought-iron cannon of the 15th century was built of longitudinal bars kept together by transverse rings. Between the bars and rings there was an intermediate layer of a non-metallic nature, mainly oxide, and macro- and microscopic etching showed that the iron had an irregular structure. Hence it may be concluded that many of these cannons were individually built but all constructed in a similar manner. Further details of the construction of wrought-iron artillery can be obtained elsewhere from more comprehensive papers (Smith 2000; Simmonds 1992).

All guns recovered from the sea need to be treated to reduce or prevent further corrosion. The breech chamber examined in this work has been mechanically cleaned

and immersed in a solution of sodium hydroxide. The corrosion and preservation of iron artefacts have been reviewed elsewhere (*eg* Walker 1982; 1996).

Production of wrought iron

The wrought iron produced to make cannon was very heterogeneous with anisotropic properties due to the method of manufacture. It is therefore useful to consider briefly the production of this material.

In Britain, until the end of the 15th century, all iron was made by smelting ore using charcoal as a fuel. Because the maximum temperature of these furnaces was only 1150–1200°C, which is below the melting point of iron (1535°C), the iron did not melt but formed a bloom, a spongy mixture of pasty metal and slag. The size of the blooms produced, probably 100–300mm in diameter, depended upon the availability of the ore, the size of the furnace, the maximum temperature attained and the strength of the blacksmith. The blooms were consolidated and the metal is commonly known as wrought iron; the term 'wrought' means 'that which has been shaped by forging, rolling or drawing' during which most of the slag was squeezed out. Piling and faggoting (smithing) were carried out and the morphology of the remaining slag became fibrous with the elongation in the direction of working. Hence the properties of wrought iron are very anisotropic.

The resulting iron consisted of a mixture of relatively pure ferrite, a solid solution of iron containing minor amounts of dissolved impurities, and 1–3% slag, which is a non-metallic, glass-like mixture of silicates and oxides. The strength and ductility of the metal are greatest parallel to the slag stringers. Further details on the production, microstructure and properties of wrought iron are given elsewhere (*eg* Walker 2002).

Examination of the original gun

As part of the project to replicate and fire one of the port pieces, as much analytical information as possible was obtained from the original. The method of manufacture of the gun barrel was evident from a visual study backed up by gamma radiography of selected areas. The tube forming the barrel was made up of nine staves 11.6mm thick and reinforced by a single layer of 17 bands alternating with 38 hoops or hoop sets. The length of the tube was three metres and the internal bore 175mm.

The breech chamber construction appeared to be more complex, and radiography did not provide the detail

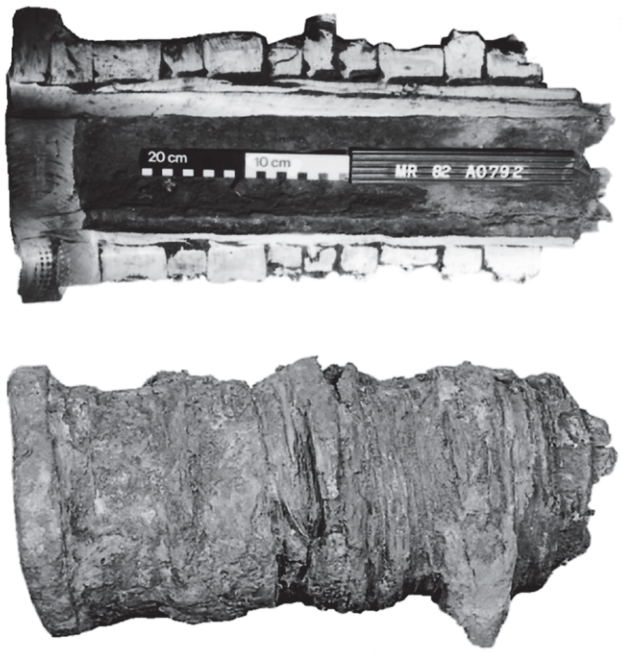

Figure 2: The powder chamber (MR 82 A0792) showing the cut section and the outer surface.

necessary to replicate it. The length of the chamber was 560mm, excluding the neck projecting into the barrel (70mm), the internal diameter at the back was 90mm and at the neck 115mm. In order to understand its internal construction the chamber was sectioned. This revealed that it was manufactured from two layers of staves, the inner layer formed of four staves 20mm thick, and the outer layer of three staves 15mm thick; the junctions of the staves were staggered. When examined there were visible gaps between the outer staves of up to 30mm. Figure 2 shows some of the third layer which totalled 11 hoops and bands, varying in thickness from 20–40mm and in width from 30–60mm which was heat shrunk over the staves. It was obvious that the rings and bands had been individually forged. Between these sections there is a hard black compound (see below).

Experimental work

This involved cutting samples from the powder chamber which had been sectioned longitudinally (Fig 2). Figure 3 shows the location of samples A–H. Area A is on one of the inner staves, area B on an outer stave. A cross-section of one of the hoops, area C, was also cut. The samples were mounted, ground flat, polished to a 0.25μm diamond finish and their microstructures examined under an optical microscope before and after etching in 2% nital. A scanning electron microscope was used to give higher magnifications, and a microprobe analyser to give the composition of the ferrite matrix and different regions of the slag. Microprobe analysis was also carried out

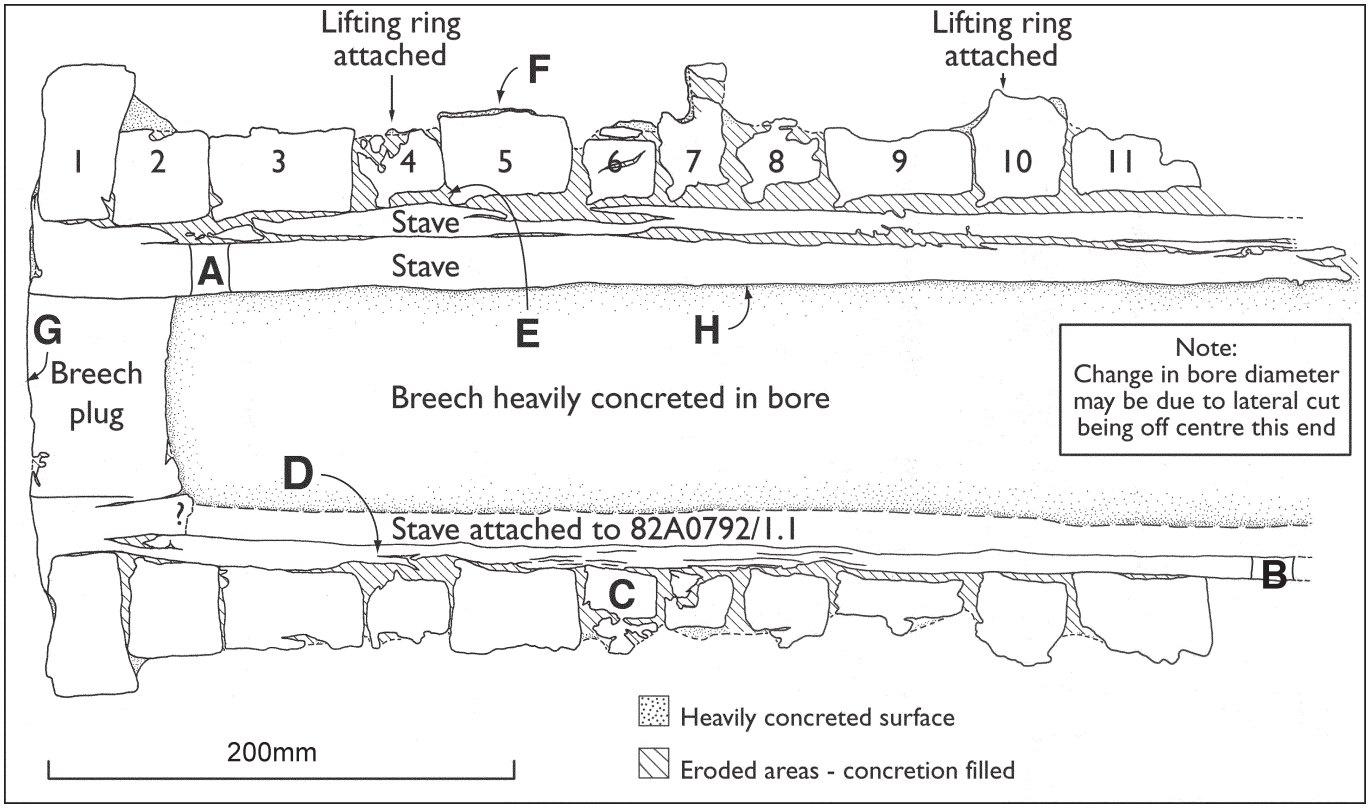

Figure 3: Drawing of cross-section of wrought-iron breech showing positions of sample sites (A–H).

on the black substance in the gaps between the staves (area D) and the hoops (area E), and used to identify the compounds present on the outer surfaces of a hoop (area F) and the plug (area G), and the inner surface of a stave (area H).

Microhardness measurements were taken of the different phases revealed by metallographic examination, using a Leitz Wetzlar Microhardness tester with a 100gf load. Line scans were also made of the microhardness at regular intervals across the samples (from an outer face to an inner one) to indicate whether surface hardening had occurred. X-ray diffraction patterns were obtained to identify the chemical compounds present in the slag; this technique, using a Philips diffractometer PW1050/70, can indicate the substances present but not their quantities.

Table 1: Calculation of temperature needed for autofrettage

Outer diameter of smaller end of chamber	= 155mm	
Circumference	= 487.1mm	
For gap of 1mm all round, heated diameter	= 157mm	
Circumference of heated ring	= 493.4mm	
Expansion needed in length	= 493.4 – 487.1	= 6.3mm
Coefficient of expansion of iron up to 800°C	= 15.2 x 10^{-6} °C^{-1}	
Temperature needed for expansion of 6.3mm	= (6.3/487) x 15.2 x 10^{-6}	= 851°C
But the ring expands around neutral axis so that the internal diameter is reduced due to internal expansion.		
For a hoop 4mm thick:		
Internal expansion on heating to 851°C	= 2 x 15.2 x 10^{-6} x 851	= 0.26 mm
Temperature needed to expand by 6.56mm	= (6.56/487) x 15.2 x 10^{-6}	= 886°C
Increase in temperature required is approximately	890°C	

Figure 4: Piece of wrought-iron hoop showing the cut surface (Fig 3, area C).

Assembling the gun

The method of applying the final layer of hoops and bands to both the barrel of the gun and the breech chamber is the technique known as autofrettage. This, according to Thewlis (1951, 338), is 'a process in gun manufacture in which a plain tube is initially stressed so as to simulate the required stress distribution in a compound cylinder'. This process involves heating each hoop so that it expands to give a larger internal diameter and then sliding it over the cylinder staves and hammering it into its final position to give a tight fit. On cooling the hoop contracts to give a strong clamping action.

The temperature needed to give the required expansion has been calculated (Table 1). The outer surface of the staves that made up the cylinder would have been slightly rough due to the hand-made method of manufacture. In order for a hoop to slide on, it may be assumed that a gap of 1mm in radius or 2mm in diameter would be necessary to allow for the surface roughness. This was found to be satisfactory when the replicate gun was manufactured. This heating process could be repeated with the appropriate sized hoops to cover the whole of the tapered section of the breech.

Heating wrought iron to about 900°C changes the microstructure because it enters into the austenitic region of the phase diagram. The change depends on the time spent above 900°C and is caused by diffusion processes, so that a short period at elevated temperature might have little effect. The microstructure would also be affected by the rate of cooling which could be slow if cooled in air or very fast if quenched, *ie* if water or oil were poured on to the hot metal (this would save time when manufacturing). The microstructure of the rings and staves showed that oil was used on the breech plug and neck.

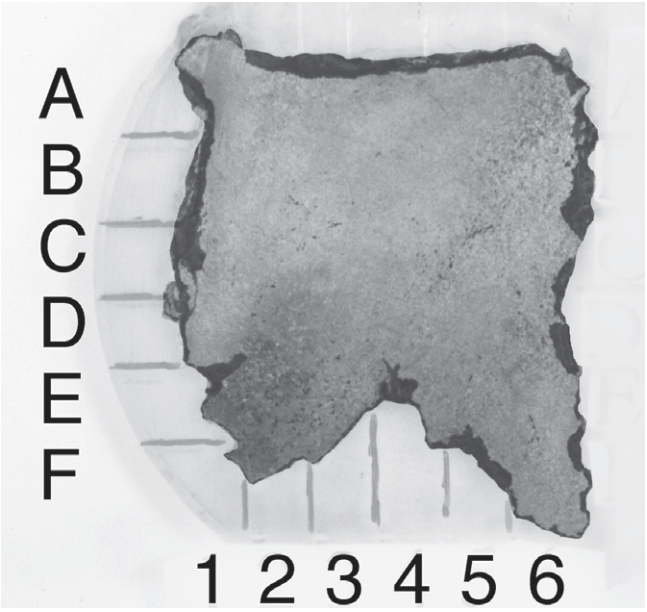

Figure 5: Cross section of hoop (area C) with labelled zones. The inner surface, next to the staves, is at the top. Width of piece 31mm.

Corrosion of the hoops

As part of this investigation, the corrosion which had occurred to the breech chamber was studied. A piece of one of the hoops was cut (Fig 4) and the prepared cross section was divided into labelled segments, each ~5x5mm (Fig 5). The outer surface would have been more exposed to sea water and silt and so suffered more corrosion. The sides and outer surfaces (Fig 4) have the characteristic fibrous appearance of corroded wrought iron, similar to that of wood.

The rate of corrosion of the outer region of hoop 6 can be estimated by examination of area C (Fig 3). If the hoop is assumed to have had a rectangular cross-section when originally fitted, with a flat outer surface, the present irregular surface (Fig 5) has been caused by the local rates of corrosion due to the anisotropic nature of wrought iron. The deepest recesses are 12mm so the rate of corrosion, in this area, is at least 12mm during the 437 years it was immersed. It is interesting to compare this with the figure of 20mm for the extent of corrosion of wrought iron in contact with lead in a composite shot recovered from the *Mary Rose* (Walker and Hildred 2000). This latter figure is expected to be higher because it is enhanced due to the galvanic coupling effect. In general, corrosion products were observed on the surfaces of the hoops and staves and were limited to the outer millimetre or so (Fig 5). It is, of course, always possible that some of the corrosion products were either soluble, so did not remain on the surface, or were brittle and fragile so broke off before, during or after recovery. It has, however, been suggested that wrought iron in sea

water tends to dissolve and the products formed build up a surface layer of cemented calcite and iron compounds (Oddy 1975).

Sometimes this coating may not be protective and corrosion can continue, to give a concretion with a hollow centre. Often the rate of corrosion is not uniform and this may be explained by the zonal character of the iron. Chilton and Evans (1955) have discussed this and identified three zones which they called Q (quickly corroding), R (resistant) and V (very resistant).

Microstructure of a hoop

The microstructure of hoop 6 (area C) was examined with an optical microscope. The wide range of structures visible suggests that the hoop was not made simply from a single piece of wrought iron.

As discussed above, it is assumed that the hoops were heated and slid down the staves which, on cooling, became tightly clamped. The inner sections of these hoops would have been in close contact with the cold staves so would have cooled relatively fast. This would have limited diffusion and given the Widmanstätten structure (ferrite and pearlite formed by cooling at a moderately fast rate) shown in Figure 6, zone 3A, which comes from the inner edge of the hoop close to the stave. This is a typical formation produced by relatively fast cooling and/or by cooling relatively large grains of austenite. When iron is cooled the solubility of dissolved impurities decreases and precipitates start to form at the austenite grain boundaries and/or the highly directional octahedral planes within the grain to give the characteristic appearance. A little deformation is also indicated by the distortion of some of the precipitate needles, possibly due to hammering during application or internal stresses originating from the cooling. The microstructure in zone 2A (Fig 6) also shows some Widmanstätten structure but only at the edge closest to the cold stave (right side). This supports the idea that there were differential rates of cooling across this sample.

Other areas of the cross-section of the hoop have equiaxed grains with a fairly uniform shape and size which indicates easy diffusion and hot working with recrystallization and little or no deformation. This is shown for zone 1E and also, with a smaller grain size, for zone 6B (Fig 6).

A very different structure is present in zone 6F (Fig 4). The central region has very fine equiaxed grains with much larger grains on either side. This could be the result of welding three different pieces of wrought iron with different structures together, but these would have been very small. Alternatively, local variations in deformation may have occurred and been followed by grain growth—possibly due to tapered sections being hammered into position. Although on a very different scale, an example of pieces of iron welded together to give a large structure, is the Roman iron beam from Catterick Bridge (Wright 1972). This may explain the differences in the microstructures observed in this hoop.

Microstructures of the staves

In both samples (areas A and B in Fig 3) the microstructure of the staves showed the distribution of the slag was irregular and the elongation direction of the stringers was, as expected, along the stave so the maximum strength was achieved.

Some regions of the inner stave consisted of all ferrite, iron with very little carbon. Other areas contained grains of ferrite and separate grains of pearlite, a mixture of alternative plates of ferrite and cementite (Fe_3C). Some places were almost all pearlite so the local carbon content would be about 0.8%). Some Widmanstätten structure was present close to the outer edge. From the presence of pearlite and the Widmanstatten structure it can be inferred that there are variations in the carbon concentration and hence in the microhardness (Table 2); it is particularly advantageous to have the better wear characteristics that hardness imparts at the surfaces.

The reason for the variations in carbon content may be due to diffusion of carbon from areas with a high concentration. Alternatively if the staves were constructed from many small wrought-iron blooms with different quantities of carbon, the same effect would be achieved. It should be noted, however, that in some local areas the quality of the iron is very poor with regions of slag which represent areas of weakness.

Microhardness measurements

The microhardness values (Table 2) give information about the microstructure, grain size and carbon content of the metal. Therefore samples were taken from the staves and the hoops and the hardness measured for different typical regions. The softest areas corresponded to the ferrite phase which is nearly pure iron and has a hardness of 110 ± 5 Hv (Maddin *et al* 1997). Almost all the values recorded were greater than this which is probably due to the hardening effect of any dissolved elements. The larger ferritic grains are softer than the smaller ones because there are fewer grain boundaries which block dislocation diffusion during deformation. Pearlite is harder than ferrite because it is an aggregate

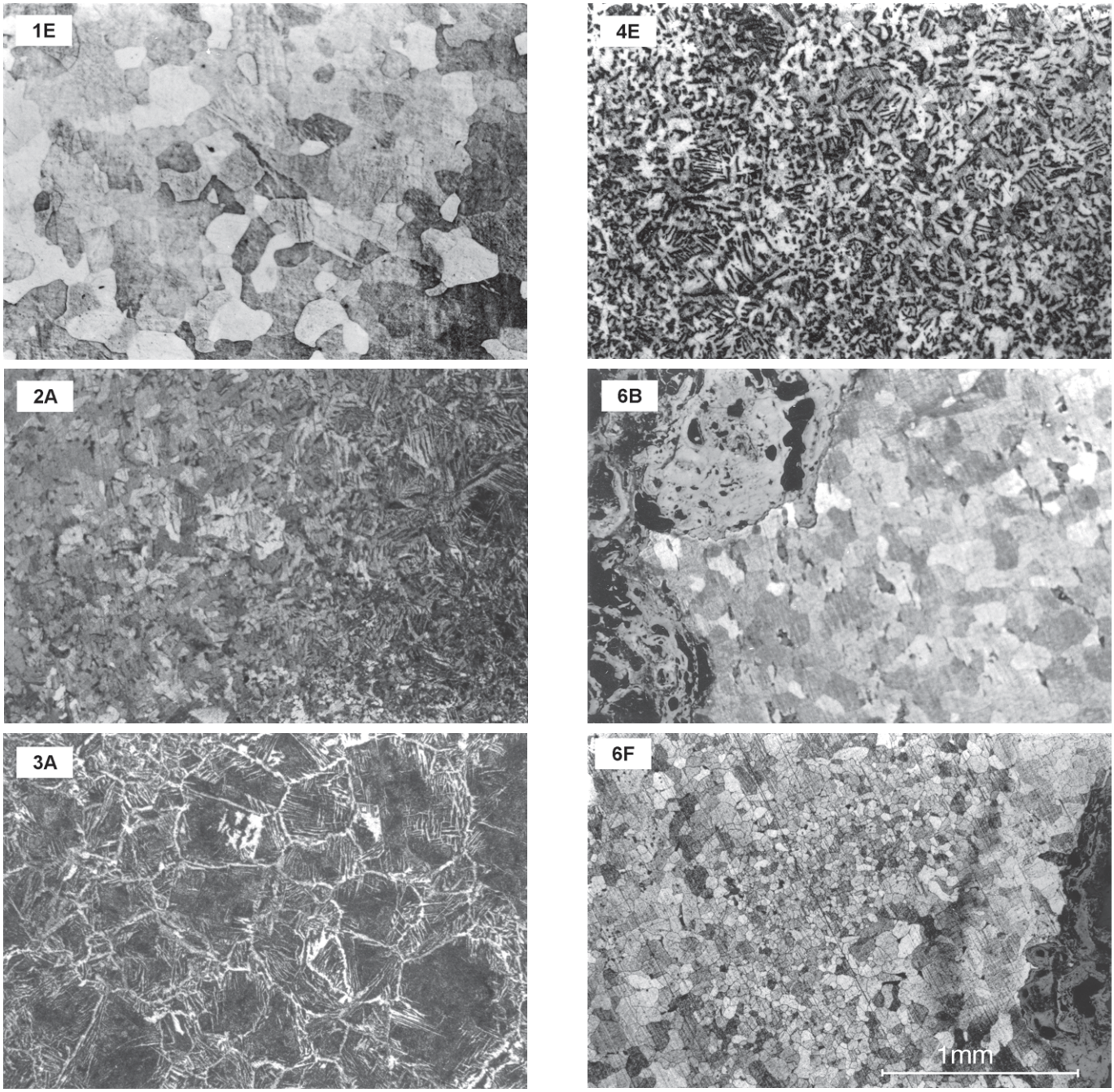

Figure 6: Microstructures of zones of the cross-sectioned hoop, labelled as in Figure 5. Images are 2.7mm wide.

of soft ferrite and hard brittle cementite (Fe_3C, which has a hardness about 600 Hv) with a lamellar structure of alternating planes of each constituent and a typical hardness of 225 ± 20 Hv (Maddin *et al* 1997). This value is reduced with smaller amounts of cementite, and also as the coarseness of the structure increases.

Table 2: Microhardness (Hv_{100}) of different regions on staves and hoops.

Sample No	Slag inclusion	Pearlite	Widmanstätten	Ferrite	
				Large grains	Small grains
1T	623	176	192	102	164
2T	701	141	189	107	124
4T	685	197	202	132	186
5A	732	210	202	143	195
Range	623–732	141–210	189–202	102–143	124–195

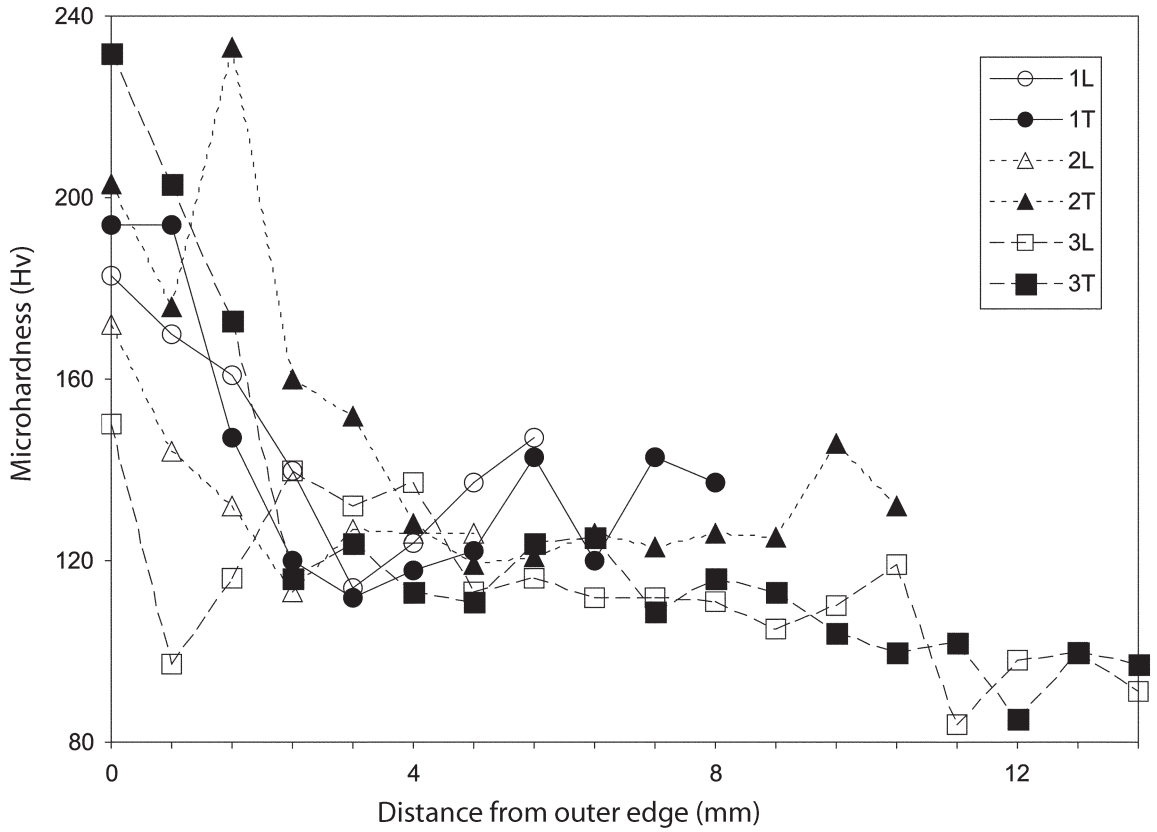

Figure 7: Microhardness across staves and hoops. L = longitudinal cross section, T = transverse crosssection. 1 = inner stave near hoop 3, 2 = inner stave near hoop 10, 3 = hoop 6.

The Widmanstätten structure is a latticed arrangement of ferrite and pearlite formed by cooling at a moderately fast rate. This means that the diffusion of dislocations is again limited and the hardness is about 200 Hv. This structure is more frequently observed in areas with a high carbon concentration.

Slag inclusions are based on iron silicate which is inert, glass-like and very hard. The composition of the slag depends upon that of the ore. The hardness of the slag depends upon the content of several metal oxides. From the values (Table 2) it can be seen that the hardness varies considerably.

Even within small regions of the samples there was a marked variation in structure and hardness. Hence a series of microhardness measurements was taken across sections of the staves and hoops (Fig 7). With the exception of two high readings, possibly due to slag inclusions, these microhardness plots show a consistent change with the highest values at the outer edges. This is highly desirable because this is where the greatest resistance to wear is required. The increased hardness was shown by metallographic examination to be due to a very fine pearlite, small ferrite grains or Widmanstätten structures. It is interesting to note that the hardness was greater at the surface of the transverse sections than the longitudinal, *ie* the inner and outer surfaces were harder than the middle. This indicates that the manufacturers of the cannon were able to produce the increased hardness at the surface and so achieved the optimum properties.

Scanning electron microscopy and microprobe analysis

These techniques were employed to study the microstructure and the chemical composition of the cross-sections. The energy dispersive X-ray (EDX) mode was used to identify the elements present in the areas when the predominant phase was either ferrite or pearlite. The ferrite contains very little carbon and traces of other elements but is quite pure. The pearlite, as expected, contained a little more carbon due to the presence of the cementite phase but otherwise the compositions were very similar.

The general definition of slag is a non-metallic product resulting from the mutual dissolution of flux and non-metallic impurities in smelting and refining processes. Several slag particles were examined and a typical one consisted of phases which appeared bright, mid- and

dark-grey. EDX revealed that the bright area consisted almost entirely of iron and oxygen so it is probably wustite (FeO). The mid-grey region contained iron, oxygen and silicon so was probably fayalite (Fe_2SiO_4), a common component of iron slags. The dark-grey phase had high levels of iron, calcium, phosphorus, oxygen and silicon and was an interstitial glass.

X-ray diffraction studies of the slag

X-ray diffraction line-patterns were obtained for the three different areas of the slag in order to identify the compounds present. The d-spacings were calculated and compared with the standard values in the powder diffraction file for inorganic phases. The values suggest the slag contained many oxides, including iron oxide, as well as fayalite (Fe_2SiO_4), phosphorus pentoxide (P_2O_5), silica (SiO_2), alumina (Al_2O_3), magnesia (MgO), lime (CaO) and potash (K_2O). All these elements were also found during the microprobe analysis of the slag and, due to the method of manufacture, would be expected to have originated from the ore and be present as oxides. Fayalite (Fe_2SiO_4) is a common constituent of slag and is probably the mid-grey material seen in the slag particles in the SEM. XRD also supports the microprobe analysis which suggested that the bright regions seen in the slag were wüstite.

Black substance between hoops and staves

In the gaps between all the hoops and staves there is a hard black substance, the origin of which is unknown. In order to try to identify it microprobe analysis was carried out on samples taken from between the staves (area D in Fig 3), and between the hoops (area E). In both samples the major constituent is oxygen with iron at a lesser concentration. There is also about 5% carbon in both as well as some sulphur. It can therefore be concluded that the black material is almost certainly an iron oxide (with some carbon and sulphur). The most probable oxide is magnetite (Fe_3O_4) which is black in colour. It forms by oxidation of iron at high temperatures to form a surface layer, well known to archaeologists as hammer scale . It probably formed during the high-temperature assembly of the powder chamber. Alternatively, it may have been produced by corrosion of iron immersed in water with a limited supply of oxygen.

For comparison and possible identification, samples of the compounds present were also taken from the outer surface of a hoop (area F in Fig 3), the outer surface of the plug at the sealed end (area G), and the inner surface of a stave (area H). These were all either black or dark in appearance. In all these samples the main elements identified were oxygen and iron. The sample F also contained several elements which are often found in a marine-formed scale as well as some silicon, probably present as sand, but there was no carbon. Sample G had no carbon but some silicon as well as oxygen and iron. Sample H, taken from inside the barrel where there would have been limited access of oxygen, had some sulphur present, possibly due to the action of sulphate-reducing bacteria, but no carbon was detected.

The lack of carbon in these three regions is in contrast to the situation in the gaps between the staves and the hoops where there is about 5% C. This carbon could not have accumulated as a result of the corrosion of wrought iron because the concentration in the metal is very low, typically only 0.03%. It is unlikely to have originated from the sea because there is no evidence of it in Samples F–H. The carbon between the iron sections must therefore either have been there when they were assembled or have diffused there since manufacture. The more probable explanation is that it got there during the assembly when a carbon-rich material may have been used to help the hoops slide along the staves or to seal the gaps between the hoops and staves. It may have changed form due to the high temperatures (about 900°C) used when fitting the heated hoops which would break down many carbon compounds.

The presence of up to 5% carbon in the gaps may enable carbon diffusion to occur when it is in contact with the heated wrought-iron staves and hoops. If this occurred it would be on a relatively limited scale and only into the surface layers. It could account for the increased hardness at the edges of the hoops (Fig 7). This hardening process is known as 'case hardening' or 'carburization' and defined as 'the adding of carbon to the surface of iron-based alloys by heating the metal below its melting point in contact with carbonaceous solids'. From this work, however, it cannot be determined whether in this powder chamber it was a deliberate or an accidental process. The presence of the carbon can also explain the increased Widmanstätten pattern observed in the microstructures of the edges of the hoops. Maddin *et al* (1977) have shown that the addition of 0.2 wt% C in bloomery iron was beneficial because it increased the yield strength from 150 to 260MPa.

Conclusions

From the work described in this paper it can be concluded that:

- in order to slide the hoops over the staves during construction the hoops had to be heated to at least 900°C to give sufficient expansion
- the variation in microstructure and microhardness across the hoops and staves suggests that deliberate

surface hardening occurred
- microprobe analysis and X-ray diffraction studies of the slag showed that fayalite, wustite, magnetite, lime, potash, alumina, magnesia and phosphorous pentoxide were present; these are consistent with wrought iron produced from furnaces fuelled with charcoal
- the rate of corrosion of wrought iron immersed in sea water and then covered with silt is at least 12mm in 437 years
- the hoops and staves were probably made from small blooms which were joined together by hammering. This process produced the very diverse range of microstructures observed which include ferrite (almost pure iron), pearlite (a lamellar structure consisting of ferrite and cementite) and a Widmanstätten structure (a latticed structure of ferrite and pearlite formed by cooling at a moderately fast rate)
- some of the wrought iron is of poor quality with non-continuous regions of slag which gives areas of weakness; this was confirmed by the blacksmith who tried to re-work some of the iron
- a black substance was observed between the hoops and staves and this was shown to contain carbon which may have diffused into the surface of the iron and changed the microstructure and hardness.

The construction of this gunpowder chamber does represent considerable skills and expertise both in the materials used and in the manufacturing processes.

Acknowledgements

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