Examination of four Iron Age ferrous hammer heads from Bredon Hill (Hereford and Worcester), England

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Abstract

Four hammerheads, provisionally dated to between the late 4th century BC and the early 1st century AD, were examined by metallography and electron microprobe to determine principally the methods of manufacture and any technological enhancements. Samples, taken near the faces, were found to comprise low/medium carbon steels. Two hammerheads had been quenched and possibly tempered, another was probably quenched and subsequently severely reheated, and the fourth was air-cooled. Carburization in each hammerhead is interpreted as having derived from the bloom (primary carburization). The differences in the heat treatments applied were probably function related. The metallographic results are discussed in the context of other later Iron Age artifacts.

Introduction

The Iron Age hillfort on Bredon Hill (NGR SO958400) was partially excavated during 1935-37 (Hencken 1938). Five hammerheads were recovered (Hencken 1938, 73-4, nos 1-5, fig 6, 1-4), one of which (no 5) no longer survives and may have been lost soon after excavation. These form the largest number of ferrous hammerheads known from any Iron Age site in Britain. The four surviving hammerheads (Fig 1) were examined for metal structure and composition to determine principally the methods of manufacture and any technological enhancements which might correlate with function or chronology.

Hammerheads 1 and 2 are short, stout tools both of which have one heavily burred face. They may have been used for working metals, for striking other tools, or for constructional or other purposes. Hammerheads 3

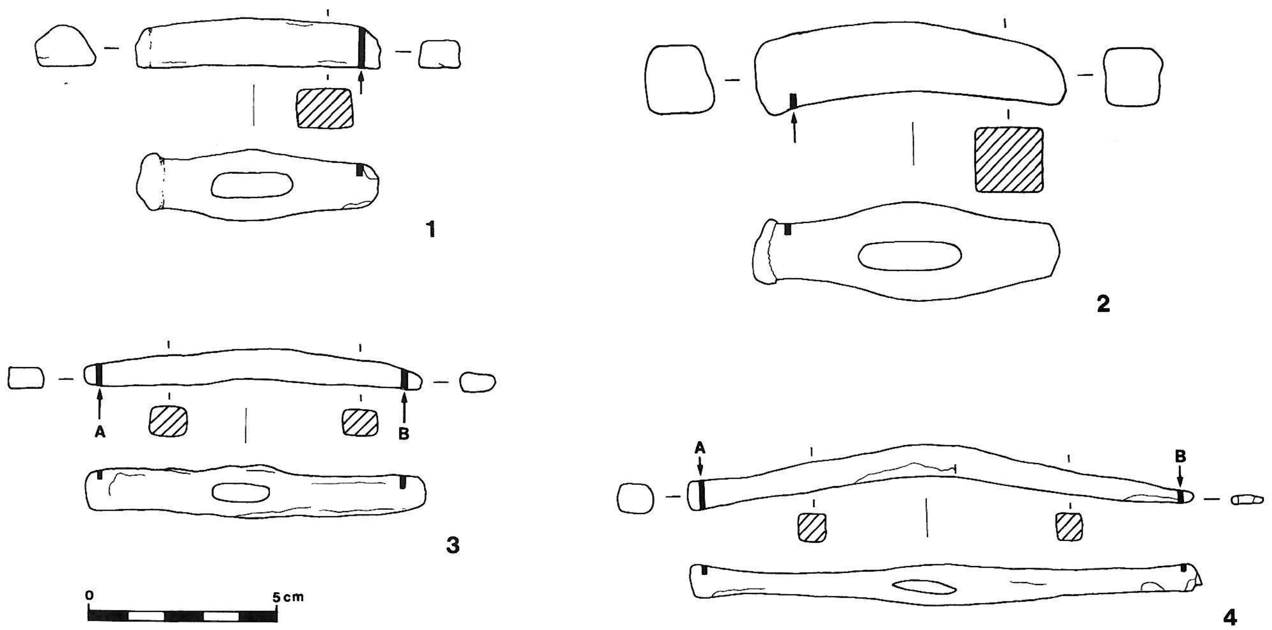

Fig 1: Hammerheads 1-4, showing location of samples.

and 4 are more slender and have small, well-formed faces which are slightly convex, and rounded at their edges. These were probably specialised hammerheads which, by analogy with more recent examples, may have been metalworking tools — perhaps for forming and finishing sheet metal artifacts. Like other Iron Age hammerheads, all have elongated eyes (*cf* Manning 1985, 6), though evidence of the handles has not survived.

On the basis of ceramic and metalwork evidence, the hillfort was originally interpreted as having been occupied from *c* 100-50 BC to the early 1st century AD (Hencken 1938). However, recent analyses of structural and material evidence from other sites in the region suggest that rather earlier dates should now be assigned for the phases of construction and occupation of the hillfort (*eg* Hogg 1975; Stanford 1981; Cunliffe 1991). Although the chronology of the hillfort remains uncertain, it was possibly founded as early as the 5th century BC (Stanford 1981, fig 69).

None of the hammerheads is necessarily contemporary. Nos 1 and 2 are from the massacre level in the inner entrance attributed to the destruction horizon of the hillfort (Hencken 1938, 24, 57, 73-4, nos 1 and 2). Hammerhead 3 is from a hut located behind the inner rampart, originally attributed to the first period of occupation (Hencken 1938, 30, 74, no 3). Hammerhead 4, and also the lost hammerhead (no 5) are from unstratified occupation levels behind the inner rampart entrance, originally attributed to late in the first period of occupation (Hencken 1938, 36, 74, nos 4 and 5).

According to the chronologies advanced recently for the hillfort's construction, occupation and destruction (Hogg 1975, 142; Stanford 1981, fig 69), the dates for the deposition of the hammerheads may lie within the following ranges: No. 3, late 4th - mid 2nd centuries BC; Nos 4 and 5, mid 3rd - late 2nd centuries BC; Nos 1 and 2, early 2nd century BC - early 1st century AD. It must be stressed, however, that these dates are provisional and open to reinterpretation.

Evidence of 'industrial' activity at the hillfort was limited to the base of a hearth behind the inner entrance and contemporary with its earliest phase of construction (Hencken 1938, 12-13, 40-2). On the basis of associated slag (comprising fused silicate, with some iron, zinc and copper), this was interpreted as the base of a metalworking hearth (Hencken 1938, 41). No other industrial features or residues were recorded, though in part this may have been because the excavations concentrated on the defences. The hammerheads may provide additional evidence of metalworking at the site but, as already noted, none can be ascribed a definite purpose. Furthermore, the occurrence of tools need not necessarily indicate their use at a site. A large quantity of other ironwork was recovered ranging from weapons to domestic fittings and implements, as well as tools for various crafts although none of the latter seems likely to have had a metalworking purpose. There are also wedges, rods and flat bars, broken knives etc, 'an unexpected amount of this junk iron', which was suggested may have been collected together for re-smelting (Hencken 1938, 71), although this interpretation should be treated with some caution.

In the immediate vicinity of Bredon Hill are other Iron Age sites which include the extensive settlement at Beckford (NGR SO984363) where considerable evidence of both ironworking and non-ferrous metalworking has been found (Britnell 1974; Linton and Bayley 1982; McDonnell 1986).

Methods of examination

The hammerheads had been consolidated with black synthetic coatings which incorporate corrosion products and other accretions from burial. Fissures in the coatings indicate recent corrosion. Initial examination was by X-radiography which suggested that metal survived fairly extensively in each hammerhead though not necessarily at the tips of the faces.

Owing to condition, samples for metallographic examination were taken as transverse sections a few millimetres away from the hammer faces in order to restrict any damage to a minimum so as to not interfere with any future typological interpretation of the hammerheads, or their integrity for display. However, the samples thus obtained may not be equivalent to the true faces with respect to composition and structure, though any heat treatments applied should be detectable. For the same reason, samples were not taken from less robust faces, nor from the eyes.

The samples were mounted, ground and polished to 0.25μm fineness according to standard metallographic techniques and etched initially with 1% nital. Hardness readings are Vickers Pyramidal values obtained using loads of 0.2kg (averaged) and 5kg. Carbon content was estimated optically according to pearlite present (hammerhead 1 only).

Minor and trace element compositions of the metal were determined by Chris Salter on an electron probe microanalyser (Cameca Semprobe). In order to examine specific phases in the metal, the metallographic specimens were analysed in the lightly etched condition. Elements were determined from Kα lines at 20 kV accelerating voltage and with a target area of 40 x 30μm.

Discussion of results

The results of the metallographic examinations are described in detail in the Appendix and summarised in Table 1. Results of the trace element analyses are given in Table 2. The principal metallurgical results relate to the nature and origin of the carburization, and the heat treatments which had been applied. These are discussed in the context of other Iron Age artifacts and more generally in relation to qualities sought in tools.

Carburization

Carbon content could be measured only in hammerhead 1 which had not been quenched. Nevertheless, it seems likely that each hammerhead comprises regions of medium-carbon steel (0.25-0.6%C) in the areas examined, or compositions approaching this carbon range. None of the sections exhibited carbon gradients characteristic of surface carburization. Nor were there intensely banded structures typical of piling, though it is always possible that evidence of welding was obliterated by later hot-work (*cf* Pleiner 1973; Scott 1990, 20). For these reasons, carburization in each hammerhead is interpreted as having derived from the bloom rather than from secondary carburization — any uneven carbon distribution reflecting variations which can be expected in bloomery iron (*cf* Tylecote 1986, 144, 167; Scott 1990, 16).

There was no evidence of welded-in features, or that the faces had been welded on, although it should be noted that the positions of the samples were not ideal to investigate the latter possibility. This is supported by the X-radiographs and is in keeping with analyses of other later Iron Age hammerheads which have been examined by X-radiography, or by metallography with multiple or longitudinal sampling (Fell 1990a, 115-17, 186).

No other ferrous artifacts from Bredon Hill have ever been examined by metallography as far as the writer is aware, but Iron Age artifacts from other British sites generally have low carbon levels with carbon-free and heterogeneous low-carbon irons predominating (*eg* Tylecote 1975; Salter and Ehrenreich 1984; Ehrenreich 1985). The principal exceptions are tools, in particular hammers (Fell 1990a, table 4:1) and chisels (Salter 1984, 435; Ehrenreich 1985, 63, table 4.3; Fell 1990a, table 4:1).

Heat treatments

Two hammerheads (2 and 4) were hardened by quenching, and at least one of these (No 4) was quenched at both faces though it is not known if quenching was simultaneous or if the faces had been selectively quenched. There is some evidence to suggest

No	Structural components in order of dominance	Carbon content	Microhardness HV 0.2kg	Hardness HV 5kg	Grain size ASTM
1	pearlite + ferrite	high	234	236	6
	ferrite + pearlite	low	130	142	7-8
2	martensite	low/medium	408-477	480	–
	nodular pearlite	–	–	–	–
	bainite in white lines	–	211	–	–
3A	ferrite + carbide	low/medium	155-168	157	7
3B	ferrite + carbide	low/medium	136-137	111	6
4A	bainite/ferrite	–	241-263	–	–
	martensite	low/medium	394-549	336	–
	nodular pearlite	–	–	–	–
	irresolvable matrix	–	138-153	–	–
4B	bainite/ferrite	–	157	162	–
	martensite	low/medium	589	423	–
	nodular pearlite	–	–	–	–

Table 1: Summary of metallographic results.

No	Component	P	S	Ti	Co	Ni	Cu	As
1	Low C region	0.003	0.003	–	–	0.016	–	–
	High C region	0.014	0.006	–	d	0.024	–	–
	Centre dark band	0.008	0.007	–	–	d	0.008	–
	Centre light bands	0.017	0.006	–	–	0.015	–	0.018
2	Martensite	0.006	0.004	d	d	0.014	0.027	–
	White lines	0.005	0.004	0.011	–	0.025	d	0.058
3A	Overall	0.003	0.009	–	d	0.059	–	d
3B	Higher C region	0.004	0.004	d	d	0.016	–	–
	Lower C region	0.004	0.004	–	–	0.023	–	d
4A	Martensite	0.005	0.003	–	–	0.016	d	–
	Bainite	0.018	0.005	–	–	d	–	–
4B	Martensite	0.004	0.020*	–	–	0.015	–	–
	Bainite	d	0.010	–	d	0.016	d	–

– = not detected d = detected * = raised S may be due to bisulphite etch.
Detection limits at 2 sigma (wt %) P: 0.002, S: 0.002, Ti: 0.005, Co: 0.010, Ni: 0.005, Cu: 0.008, As: 0.012
The following elements were sought but not detected: Cr, Mn, Zn, Mo, W.

Table 2: Metal composition – results of minor and trace element analyses (wt %).

that both these hammerheads may have been tempered, however this is by no means certain. The effects of low-temperature tempering are difficult to distinguish by optical microscopy (Samuels 1980, 374) and furthermore, similar modifications to microstructure and properties could have resulted from auto-tempering during quenching, or through heat transfer near a hearth or during use of the hammers on hot metal. It is probable that hammerhead 3 had also been quenched, but was later severely heated such that the prior metallurgical structure was almost obliterated. This hammerhead may have been reheated accidentally on a hearth, although it is conceivable that it was over-tempered, or even 'annealed' to soften an over-hardened and brittle tool if the technique of tempering was not known.

In other Iron Age artifacts, quench-hardening is not commonly reported. Tempering is rare and seldom, if ever, is the evidence unambiguous for deliberate tempering. Of the *c* 400 sampled artifacts from England and Wales published by various workers for metal structure or for elemental composition for provenancing studies, only nine are quenched. These are all blades or tools which date to the later Iron Age (4th/3rd centuries BC to mid 1st century AD): a knife from Winklebury Camp, Hampshire (Tylecote 1986, 152); a sword from Grimthorpe, Yorkshire (Lang 1987, 71, no 10); two woodworking chisels from Danebury, Hampshire (Salter 1984, 435, D157 and D139); two files from Gussage All Saints, Dorset (Spratling *et al* 1980, 284-5, no 822 [see also Tylecote 1975, and Fell 1988]; Fell 1985); two cold sets or wedges — one from Gussage All Saints (Spratling *et al* 1980, 284-5, no 283; see also Tylecote 1975) and one from Worthy Down, Hampshire (Salter and Ehrenreich 1984, 157); and a hammerhead from Whitcombe, Dorset (Fell 1990b). To this list can be added three axeheads from Co. Antrim, N Ireland, at least two of which date to *c* 7th-3rd centuries BC, but the dating of the third axehead is less certain (Scott 1990, 51-58, nos 2, 3 and 4). Other, unpublished analyses of artifacts from England (Fell 1990a, 115-7, table 3:3) suggest that hand hammers in particular may have been commonly hardened during the Iron Age since a further seven hammerheads have been found to be quenched (in total therefore 11 of 14). Two of these are from a hoard and may date from the late 4th century BC (Fiskerton, Lincs, nos 332 and 403) and the others are unstratified finds from 19th century quarrying on Iron Age hillforts (Bigbury, Kent, no. 35810; Hunsbury, Northants, nos D137 and D141; Ham Hill, Somerset, nos A1517 and 1901WWW). On the basis of form, these include principally hammerheads which may have been specialised tools for working sheet metal (e.g. raising and sinking hammers), as well as a few which are less readily attributed to any specific purpose. As with the Bredon Hill tools, none of the other sampled hammerheads has archaeological associations which suggest their original purpose.

Qualities of the hammers

The qualities sought today in tools such as hammers include strength, toughness and, depending on function, hardness and the ability to acquire and maintain a working edge. In early tools made from bloomery iron, these properties could be achieved by the employment of steels with additional enhancement, if required, through quenching and tempering.

Although the Bredon Hill hammerheads are technologically enhanced, they had not been hardened evenly, nor very satisfactorily when compared with recent tools. Nevertheless, moderate levels of hardness were attained in quenched hammerheads 2 and 4, and also in the air-cooled hammerhead 1. The reheated hammerhead 3 would have been tough but not hard. It is relevant to note, however, that all four hammerheads were sampled away from the faces (for the reasons given earlier), and the carbon levels, structure and hardness may not have been the same as at the tips of the original faces.

Experimental evidence suggests that smelting techniques could have been controlled in order to yield blooms of high carbon content (Clough 1987). In the case of the Bredon Hill hammerheads, it seems plausible that carburised portions of blooms were selected empirically on the basis of appearance on fracture, or through quench tests (*cf* Scott 1990, 33). As a corollary to this, there may have been selection for phosphorus-free iron for these hammerheads since phosphorus was not detected at significant levels in any of the metallographic sections. High hardness may be obtained through the cold working of phosphoric irons (Tylecote 1986, 146, table 75), but these are brittle ('cold short') and therefore would not confer useful properties for striking tools. In particular, this may apply to hammers whose purpose was to form or to finish sheet metal artifacts since damage to a hammer face might mark a work-piece.

Artifacts made from bloomery iron commonly contain large quantities of non-metallic inclusions which arise principally from entrapped smelting slag from the bloom, and iron oxide scales formed during forging (Tylecote 1986, 144; Scott 1990, 16). The specimens from the Bredon Hill hammerheads were obtained through transverse sampling and the inclusions were therefore visible in cross-section. Nevertheless, the specimens from hammerheads 1 and 4 clearly contained very high levels of inclusions whereas 2 and 3 were comparatively inclusion-free. Apart from localised groups of inclusions whose distributions probably had resulted from forging of the metal, it was uncertain if overall inclusion quantity in each hammerhead was determined by smelting technique and bloom composition (*cf* Clough 1987), or if inclusion quantity reflected the degree of bloom preparation and quality sought in the resulting metal (*cf* Scott 1990, 16). The metal compositions were otherwise relatively pure (Table 2) which is not uncommon in bloomery iron unless derived from ores high in phosphorus or arsenic (*cf* Tylecote 1986, 144; Ehrenreich 1985).

Technological context

The dates of deposition of the four hammerheads may span three or more centuries. Correlations could not be established between chronology and technological variations, although it could be argued that the potentially earliest (hammerhead 3) was the least successfully hardened. Functional requirements of the individual hammers probably account for the differences in the heat treatments which were applied, though technical knowledge may also have been a factor.

Hammerheads seem to be more frequently enhanced technologically in terms of both carbon content and quenching than other categories of Iron Age artifacts which have been examined so far from England (Fell 1990a, 201-3). However, the evidence from both Britain and the Continent suggests that the technology employed during the later Iron Age for hammerheads was generally different from that used for weapons and cutting tools. The latter groups are sometimes enhanced by surface-carburization (*eg* Pleiner 1980, tables 11.3 and 11.4; Lang 1987, 62, 71-2 nos 10, 14 and 16). Others have steel components incorporated into the structure (*eg* Pleiner 1980, tables 11.3 and 11.4; Salter and Ehrenreich 1984, 156-7) which implies considerable technical ability owing to the different hot-working temperatures of irons and steels (*cf* Pleiner 1980, 388). On the other hand, although hammerheads are not uncommonly well carburised and quenched (*eg* Pleiner 1962, 264, no. 38; Hennig 1986, 184-7, nos 2455/69 and 211/71; Fell 1990a, 115-7), complex constructions are very rare (*eg* Pleiner 1982, 92-3, no 463). The different technologies may reflect functional and cultural factors as well as specialisms of the iron-workers.

Appendix

Hammerhead 1 (Figs 1:1, 2 and 3)
A transverse section was cut 5mm behind the sub-rectangular face.
Non-metallic inclusions. Large, angular glassy inclusions were concentrated principally at one end of the section (Fig 2, top). At the centre were two narrow irregular bands of small, rounded, multi-phase inclusions.

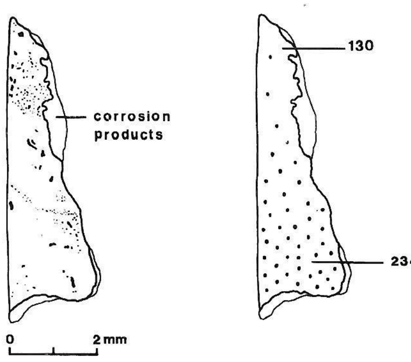

Fig 2: Hammerhead 1, diagrams of section showing (left) metallic inclusion distribution, and (right) carbon distribution and hardness (HV 0.2). Section is orientated with sample cut to the left, front of hammerhead at top, rear or underside at base.

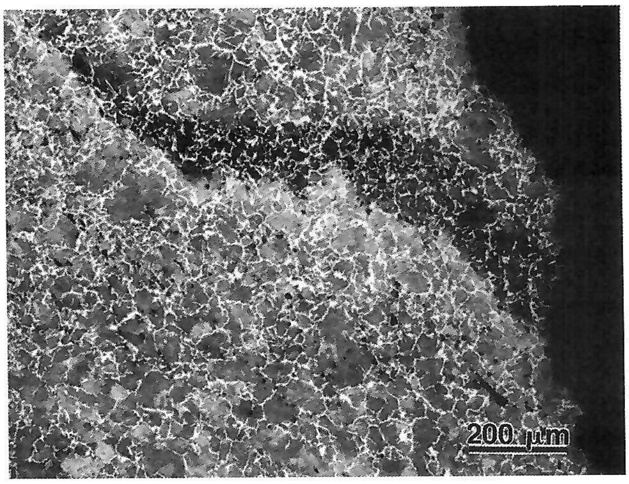

Fig 3: Hammerhead 1, medium carbon region at the centre of the section showing pearlite (dark) within a network of Widmanstätten ferrite (white). The darker-etching pearlite band extending from top left to centre right coincides with a line of non-metallic inclusion particles. Etchant: nital.

Microstructure. There was a gradient in carbon content across the section (corresponding to the depth of the side of the hammerhead), from *c.* 0.05%C, to *c.* 0.7%C. The low carbon region, which coincided approximately with the concentration of non-metallic inclusions, consisted of small-grained ferrite (ASTM 7-8) with grain-boundary pearlite. The greater area of the section comprised very fine pearlite with Widmanstätten ferrite (grain size: ASTM 6). The pearlite etched unevenly; near the two central bands of fine inclusions the pearlite etched darkly (Fig 3). Close by were lighter-etching bands of pearlite with slightly raised levels of phosphorus (0.017%) and arsenic (0.018%), and another light band bordered the inclusion concentration at the low carbon region.
Hardness. Low carbon: 130 HV 0.2; 142 HV 5.
High carbon: 234 HV 0.2; 236 HV 5.
Interpretation. The microstructure suggests that the hammer face was rapidly air-cooled from the fully austenitized condition, and furthermore, that the final heating cycle was brief. The carbon gradient was too broad and incorrectly orientated to indicate surface carburization of the hammer face and is likely, therefore, to reflect the use of an heterogeneously carburized bloom. The differently etching pearlite bands with associated inclusions and raised phosphorus and arsenic probably result from fold-welding, for example during bloom or metal preparation.

Hammerhead 2 (Figs 1:2, 4, 5 and 6)
A transverse section was cut 5mm behind the burred face through the rear corner of the side of the hammerhead.
Non-metallic inclusions. There was a small quantity of duplex and glassy inclusions most of which formed two alignments near the edges of the section corresponding to the side and the underside of the hammerhead (Fig 4).
Microstructure. Etching revealed lath martensite with a small quantity of grain-boundary nodular pearlite and upper bainite (Fig 5). Some of the martensite had a distinctly degraded appearance (Fig 6). At one corner of the section (top right in Fig 4, and Fig 5) were a few irregular light-etching lines (comprising mainly bainite) in which slightly raised arsenic (0.058%) was detected. Fine particles of metallic inclusions were associated with these lines.
Hardness. Martensite: 408-477 HV 0.2; 480 HV 5.
Bainite (in white lines): 211 HV 0.2.
Interpretation. The hammer face was quenched relatively severely from the fully austenitized condition, and then possibly tempered. The light-etching lines with raised arsenic levels are probably enrichment lines resulting from fold-welding of the metal. The alignments of non-metallic inclusions near the sides of the hammerhead (Fig 4) may indicate that this occurred during the forging of the sides to form the face. A low/medium carbon content is indicated by the lath martensite. The hardness of the specimen is only moderate which together with the variable microstructure may explain the heavy burring at the face.

Hammerhead 3 (Figs 1:3, 7 and 8)
SAMPLE A. A transverse section was cut 3mm behind the broader face (Fig 1:3, left).

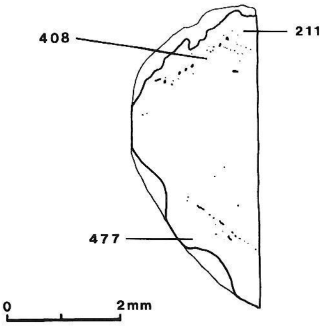

Fig 4: Hammerhead 2, diagram of section showing non-metallic inclusion distribution and hardness (HV 0.2). Section is orientated with sample cut to the right, side of hammerhead at top left.

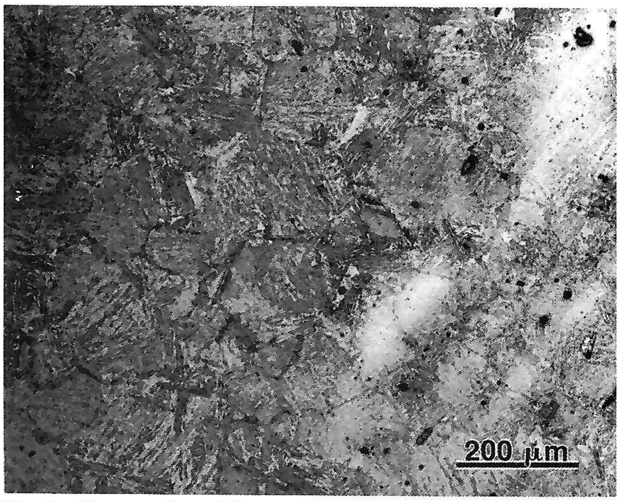

Fig 5: Hammerhead 2, martensite is the principal constituent, with traces of grain-boundary nodular pearlite and upper bainite. The light-etching lines at the right comprise mainly bainite. Etchant: nital.

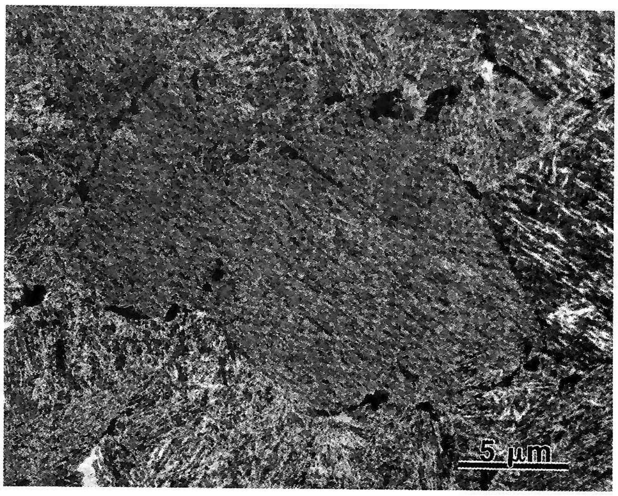

Fig 6: Hammerhead 2, detail of martensite (with traces of grain-boundary nodular pearlite); note degraded appearance of the martensite at the centre. Etchant: nital.

Non-metallic inclusions. There was a small quantity of scattered multi-phase particles, plus one alignment (Fig 7:A).

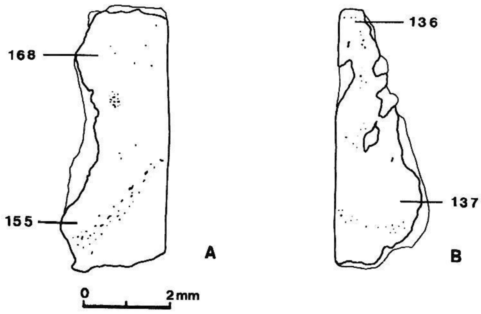

Fig 7: Hammerhead 3, diagrams of sections showing non-metallic inclusion distributions and hardness (HV 0.2). Left, sample A; right, sample B. Sections are orientated with sample cuts to centre, front of hammerhead at top.

Microstructure. Etching revealed fine-grained, approximately equiaxed ferrite (ASTM 7) with spheroidised carbides distributed at grain boundaries and within grains (Fig 8). The ferrite contained sub-grain boundaries which tended to be aligned within individual grains but orientated on different axes in adjacent grains. Where sub-boundaries were more concentrated, these were almost acicular in appearance and were associated with single or aligned fine carbide particles. A low/medium carbon content seems likely. Remanent carbides were present in the corrosion layers.
Hardness. 155-168 HV 0.2; 157 HV 5.

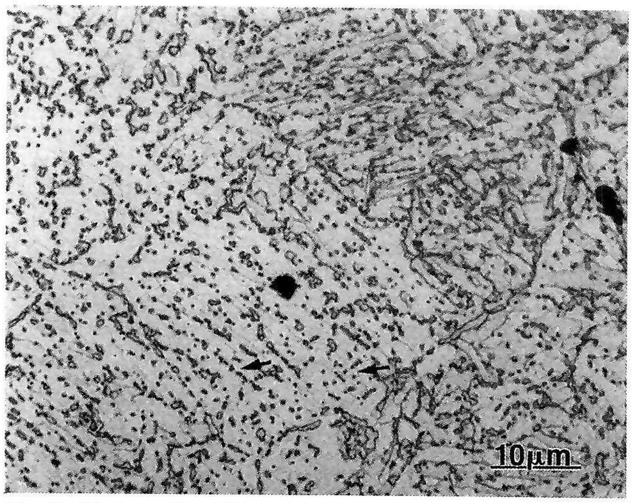

Fig 8: Hammerhead 3, sample A, carbide particles (arrowed) and spheroidised carbides aligned with sub-grain boundaries in the ferrite matrix. Etchant: nital + picral.

SAMPLE B. A transverse section was cut 4mm behind the narrower face (Fig 1:3, right).
Non-metallic inclusions. There were a few scattered single-phase and duplex inclusions (Fig 7:B).
Microstructure. The microstructure was similar to that revealed in Sample A (above) from the other face, though Sample B comprised a slightly lower quantity of carbides and these were less uniformly distributed across the section. There were fewer and less pronounced sub-boundaries in the ferrite; at one region there were a few polygonal grains devoid of carbides and sub-boundaries. Grain size was marginally larger (ASTM 6).
Hardness. Higher carbon regions: 136-137 HV 0.2; 111 HV 5.
Interpretation. The presence of spheroidised carbides in both sections suggests that the hammer faces had been either forged or reheated at temperatures just below the Lower Critical Temperature (A1). The sub-boundaries in the nearly equiaxed ferrite grains indicate that recovery but not complete recrystallisation had taken place (except in the polygonal carbide-free grains in Sample B where complete recrystallisation had occurred). The sub-boundaries and the acicular appearance of the ferrite, together with the fine particle size of many of the carbides, suggest that the prior structure may have comprised martensite — the carbides (precipitated during heating) inhibiting migration of the former lath boundaries during recovery (*cf* Samuels 1980, 374-5, fig. 98.8; Porter and Easterling 1981, 426, fig. 6.31). This interpretation is supported by the absence of features of hot work (during forging) or of cold work (during use). On balance, the evidence suggests that the hammer faces probably had been quenched but the hammerhead was subsequently reheated below A1, perhaps at around 600-700°C.

Hammerhead 4 (Figs 1:4, 9-14)
SAMPLE A. A transverse section was cut 4.5mm behind the rounded face (Fig 1:4, left).
Non-metallic inclusions. Abundant multi-phase inclusions were grouped in broad bands (Fig 9:A).
Microstructure. Etching revealed three structural zones between which there were gradients in microstructure, and no evidence of welds. The two outer sides of the section (corresponding to the front and underside of the hammerhead; Fig 9:A, top and lower) comprised martensite, nodular pearlite and a small quantity of upper bainite at the grain boundaries (Fig 10). At the central region (two-thirds of the section area) was a network of bainite structures. Figure 11 shows the principal constituents of the bainite zone, which comprise acicular ferrite, blocky ferrite (i.e. intersecting ferrite plates), and some irresolvable matrix; in Figure 12, fine particles of carbon or carbide are distinguishable alongside ferrite plates.
Hardness. Martensite: 507 HV 0.2; 336 HV 5.
Central region: overall, 188 HV 5; bainite, 241-263 HV 0.2; martensite, 394-549 HV 0.2; irresolvable matrix, 138-153 HV 0.2.

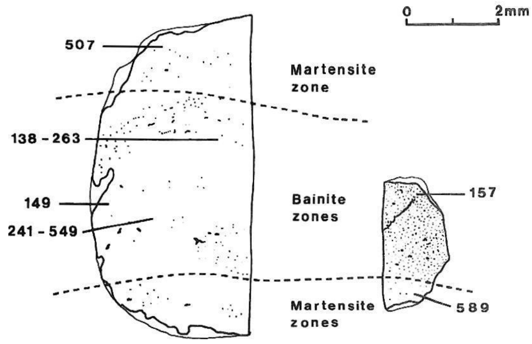

Fig 9: Hammerhead 4, diagrams of sections showing non-metallic inclusion distributions, structural zones and hardness (HV 0.2). Left, sample A; right, sample B. Sections are orientated with sample cuts to centre, front of hammerhead at top.

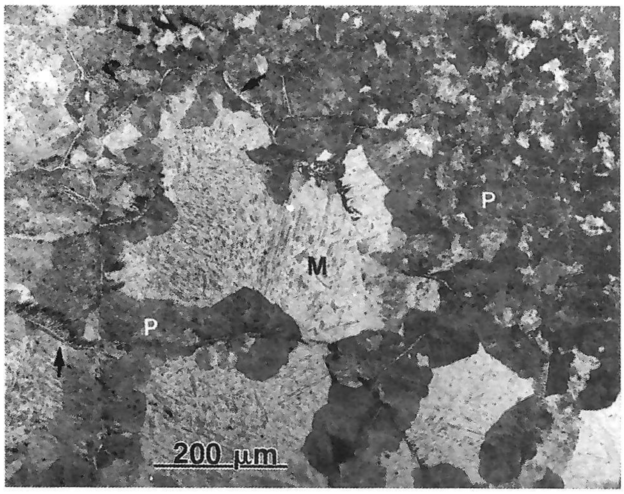

Fig 10: Hammerhead 4, sample A, one side of the section, showing martensite (M), nodular pearlite (P) and upper bainite (arrowed). Etchant: nital.

SAMPLE B. A transverse section was cut 4mm behind the narrow rectangular face (Fig 1:4, right).
Non-metallic inclusions. Abundant, rounded, multi-phase inclusions were concentrated over three-quarters of the section area; a broad corrosion line penetrated this region (Fig 9:B).
Microstructure. Etching revealed two structural zones which were related to the inclusion distribution, but between which there was a gradient in microstructure

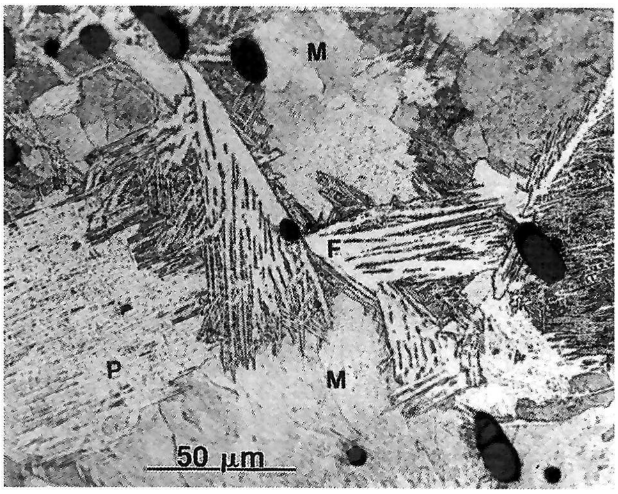

Fig 11: Hammerhead 4, sample A, micrograph taken at the centre of the section in the bainite zone, showing acicular ferrite (F), intersecting ferrite plates (P) and irresolvable matrix (M). Etchants: nital and bisulphite.

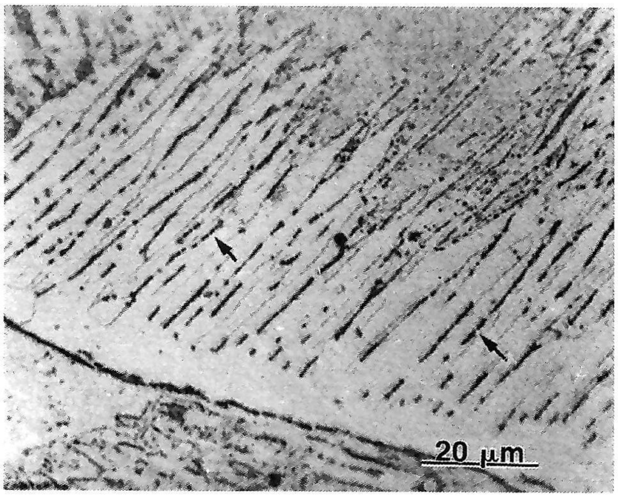

Fig 12: Hammerhead 4, sample A, bainite zone showing acicular ferrite plates (running from lower left to top right) with aligned particles of carbon or carbide (arrowed). Etchants: nital and bisulphite.

without any evidence of a weld (Fig 13). Where the non-metallic inclusions were less abundant, the structure comprised lath martensite with grain-boundary nodular pearlite and traces of upper bainite. The region which coincided with the concentration of non-metallic inclusions comprised bainite and ferrite (possibly a transition form), blocky ferrite, and some irresolvable constituents (Fig 14). Discrete carbon or carbide particles were clearly distinguishable in the matrix.
Hardness. Martensite: 589 HV 0.2; 423 HV 5.
Bainite: 157 HV 0.2; 162 HV 5.
Interpretation. Both faces of the hammer were quenched from the fully austenitized condition; the microstructures suggest relatively mild or 'slack' quenching, and the possibility of tempering. The faces may have been quenched under the same conditions and possibly simultaneously. The sections from both faces revealed similar microstructures and trace element compositions; the zonal variations in microstructure in each section may be due to local differences in carbon content sufficient to depress the critical cooling rate and the formation of martensite throughout. In Sample B, there was clearly a relationship between microstructure and inclusion concentration. A low, or low to medium carbon content seems likely.

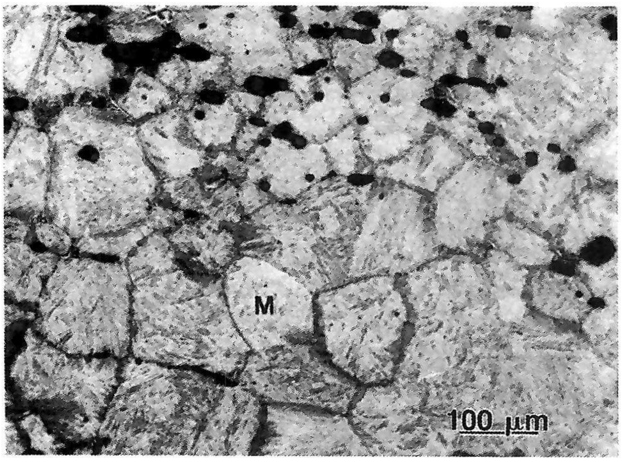

Fig 13: Hammerhead 4, sample B, showing gradient in microstructure and inclusion content between the two structural zones of the section. At the top is bainite and martensite, with non-metallic inclusions (dark), whereas the lower region comprises martensite (M) with grain-boundary nodular pearlite, and is almost devoid of inclusions. Etchant: nital.

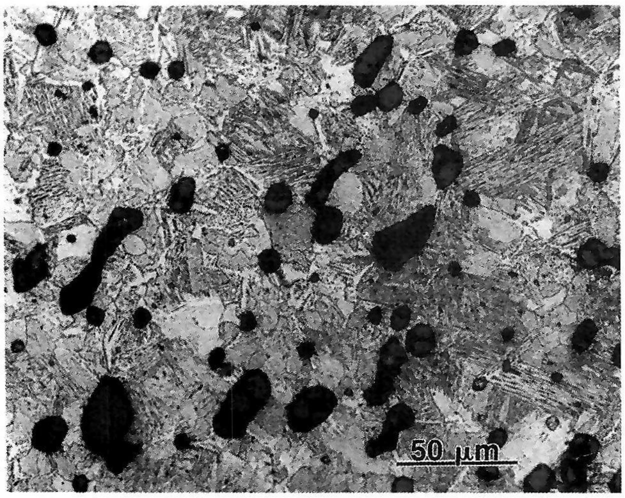

Fig 14: Hammerhead 4, sample B, bainite region showing multi-phase inclusions (dark) and the matrix (pale) which comprises bainite, blocky ferrite, and irresolvable constituents. Etchants: nital and bisulphite.

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