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Stone-Working Axe Heads Fabricated by Convicts at an Early Australian Colony

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The axe heads are thought to have been manufactured before 1857 by transported convicts in a jail at Fremantle, Western Australia, which was then a remote and isolated British colony. They were of a type used to quarry and dress building blocks from a soft, local limestone and had been fabricated by joining on a central plane by forge welding two plates of puddled wrought iron, a central region being left unwelded to form a shaft hole. A section of crucible steel was then inset into the bit edge, also by forge welding (a process known as "steeling"). This procedure obviously required a high level of blacksmithing skill, and at least a reasonable level of skill had been achieved at the Fremantle jail. However, a number of fabrication abnormalities were present in the axe heads, drawing attention to some intrinsic deficiencies in the fabrication procedure. Examples are the difficulties of achieving weld bonding in regions adjacent to the shaft hole and that of avoiding "burning" in both wrought iron and steel during the steeling operation. High-carbon hypereutectoid steels had been used in the inserts, but they were in a normalized condition; that is, they had not been quench hardened as might have been expected if full advantage were to be taken of steeling. This may have been due to ignorance of quench-hardening heat treatment or to a lack of skill in its application, but it may have been by choice. It may have been realized that the properties of the normalized steel were adequate for the intended use, to which fact one of the axes examined bears witness, thus avoiding the hazards of quench hardening. Even in this event, it would be unnecessary and even undesirable to use insert steels with carbon contents as high as those actually used. Their use may have been due to ignorance in steel selection or it may simply indicate that smiths in such isolated communities had to use whatever materials happened to be at hand. © *Elsevier Science Inc., 1996*

INTRODUCTION

Australia was first colonized by Europeans in the eastern coastal regions, where England founded a number of prison colonies. The first and the largest of them was established in 1788 at the site of the present city of Sydney, one objective being to relieve the gross overcrowding of jails in the home country. Undoubtedly, however, a further objective was to establish a permanent presence on the continent to confirm England's claim to possession. Later, it was judged that a presence was also needed in the western regions of the continent, but this time a cost-conscious British government decided to leave settlement to private enterprise and to free settlers. A Crown Grant was given to a company, Thomas Peel & Co., and the first group of investor-settlers arrived in 1829 at the southwestern corner of the Australian continent. They established a town that they named Perth on the banks of a river that they named the Swan River and a port at the mouth of this river that they named Fremantle. These must have been among the most isolated European settlements of any time. More-

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over, the settlers were ill prepared for the local conditions, which turned out to be much harsher than had been expected, and they were soon struggling for survival.

Consequently, they campaigned for a supply of cheap, disciplined labor—namely, transported convicts. This arrangement was eventually agreed to by the British government, and the transportation of convicts commenced in 1850 at a time when it was being phased out in the eastern Australian colonies. It continued until as late as 1868. The convict population in the intervening years averaged about 1500, all men, when the free population barely reached 10,000. The convicts were used to construct roads and a number of substantial public buildings for which purposes a large supply of iron hand tools must have been required. A blacksmith's forge is known to have been established on the grounds of a jail complex at Fremantle, and its site has been identified [P. Bindon, Western Australian Museum, personal communication, 1994]. Tools were presumably fabricated and repaired at this site, but the raw materials required would have had to have been imported, almost certainly from England. Materials of this

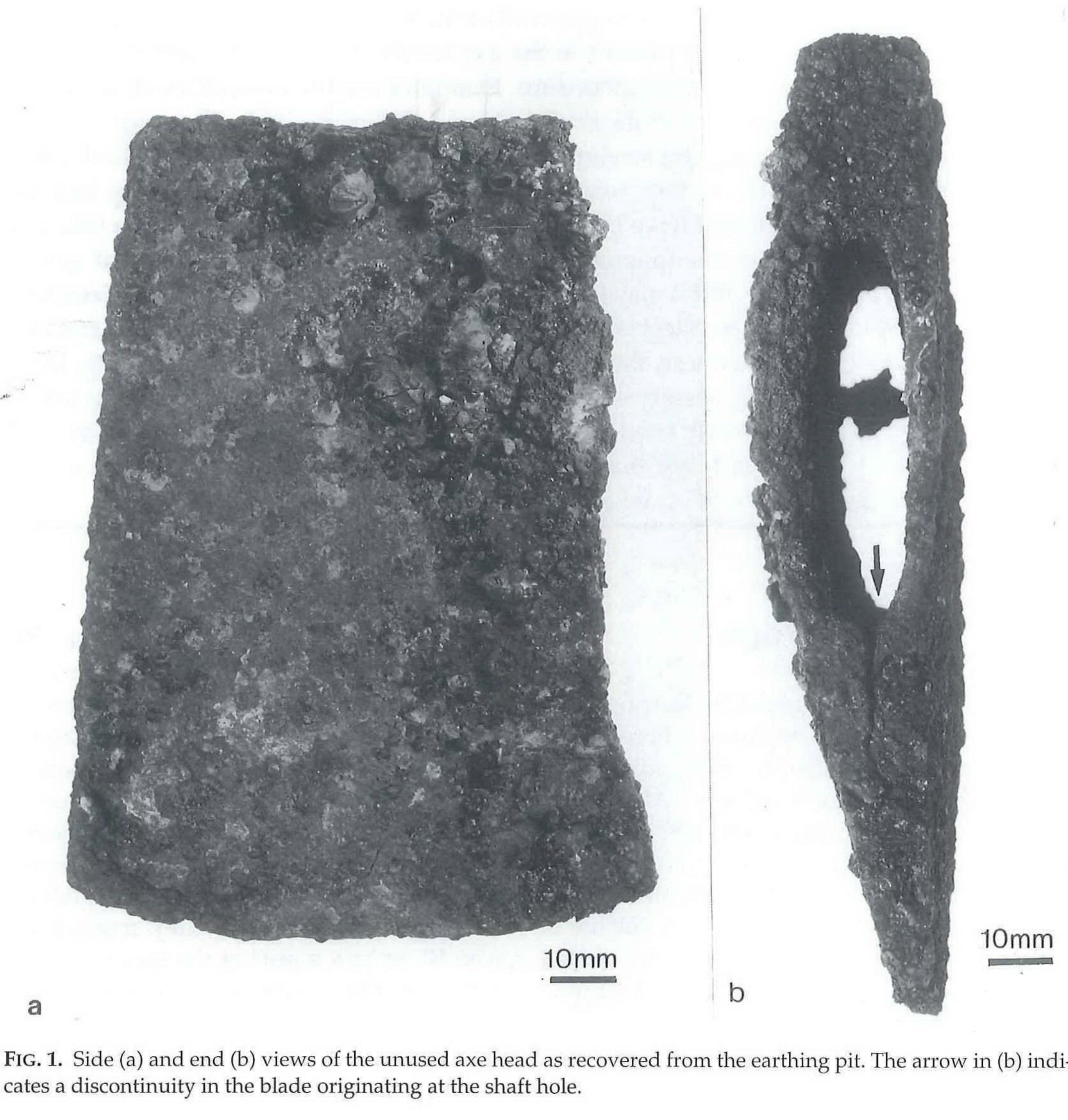

FIG. 1. Side (a) and end (b) views of the unused axe head as recovered from the earthing pit. The arrow in (b) indicates a discontinuity in the blade originating at the shaft hole.

nature are indeed known to have been imported. For example, the wreck of the *James Matthews*, ex. London, which foundered in 1841 while unloading at Fremantle has recently been investigated. Bundles of iron bars were found among its cargo [1].

Among the buildings constructed by the convicts was a large jail barracks at Fremantle, which was completed in 1857. This building continued to be in use until quite recently, when it was decommissioned as a jail and conservation as a jail museum commenced. To this end, archeologists investigated a number of sites, one being a pit that had been constructed to earth (ground) the building's lightning conductor. The pit was found to have been filled with a number of objects that appear to have been gathered from the scrap pile of a blacksmith's shop [2]. Most of them were axe heads, the majority being of a type that is known to have been used for splitting and dressing the local limestones (calcarenites and aoelianites), which were widely used as a building material. A distinguishing characteristic of an axe head of this type is the section contour, which is flat on one side of the blade and convex on the other.

Two axe heads recovered from the earthing pit were kindly made available by the Western Australian Museum for destructive examination. One of them (Museum Ref. No. 93.503) appeared to be unused. It contained a manufacturing abnormality, which was also present in a number of other recovered axe heads [I. MacLeod, Western Australia Maritime Museum, personal communication, 1993]. The second axe head (Museum Ref. No. 93.515) clearly had been used to the extent that it had been irreparably damaged.

EXAMINATION OF THE AXE HEADS

UNUSED AXE HEAD

Physical Characteristics

The axe head was comparatively flat on one side and slightly convex on the other [Fig. 1(a)], as is characteristic of stone-working axes. The bit edge was squared and showed no indication of having been used. A discontinuity was visible on the end faces of the blade [arrowed in Fig. 1(b)] and extended from the eye toward the bit, emerging along part of the length of the convex blade surface at a position some 400mm from the bit edge [Figs. 1(a) and 2].

The head had been fabricated by forge welding together four pieces of iron or steel (Fig. 2). These pieces were: two plates of puddled wrought iron [labeled 1 and 2 in Fig. 2(c)] joined above and below the eye

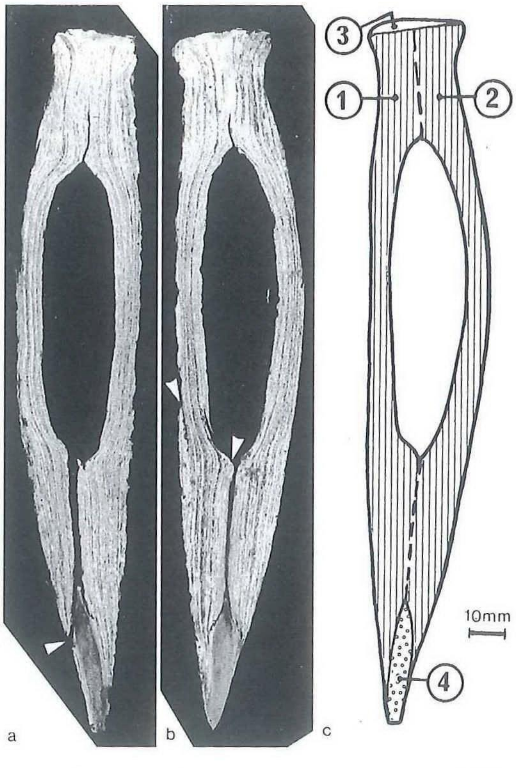

FIG. 2. Etched sections of the unused axe head. The two sections, (a) and (b), were cut 25mm apart at about the midwidth of the blade. The four units from which the axe head was fabricated are identified in (c). Note the asymmetric cross section of the head and the discontinuities extending from both the crown and the root of the shaft hole. The discontinuity in the blade extends to one of the blade surfaces at the position identified by the arrow in (a). The grain flow in the region identified by the arrow at the root of the shaft hole in (b) indicates that the two plates from which the blade was fabricated had not been brought into contact at this position. The other arrow in (b) points to a small surface forging fold. Etched in 10% aqueous nitric acid.

(shaft hole) to form the blade and poll, respectively; a strip of iron [labeled 3 in Fig. 2(c)] welded to the back surface of the poll; and a strip of steel [labeled 4 in Fig. 2(c); see also Fig. 3] inset into the bit at the working edge.

Blade Body

The microstructure of the plates used for the blade was characteristic of a puddled wrought iron,* consisting of a matrix of equiaxed ferrite grains in which was dispersed numerous elongated nonmetallic inclusions (Fig. 4) with a duplex structure of a continuous phase of an iron silicate [dark in Fig. 4(a)] and a dispersed phase of an iron oxide [light grey in Fig. 4(a)]. The grain of the forging, as indicated by the alignment of the inclusions, ran from the poll to the bit (Fig. 2). The grain size of the matrix ferrite was reasonably small (50μm average grain diameter) and uniform throughout both pieces of iron. The volume fraction of the inclusions varied in segregated bands [cf. Fig. 4(a, b)], as is usual with wrought irons, each band representing a different puddling batch. In general, however, the volume fraction and size of the inclusions were comparatively large. This iron in this respect was of only moderate quality.

The chemical compositions of the irons (Table 1) were also typical of puddled wrought irons except that the phosphorus content was higher than the 0.05% that was considered at the time to be the upper limit acceptable for good-quality wrought irons [3]. It was thought that phosphorus induced brittleness at ambient temperatures and hence needed to be kept to low levels, but modern work [4] has established that these fears were largely unfounded. Phosphorus in amounts of up to 0.3% actually increases the tensile strength of low-carbon irons, particularly after cold working, without deleteriously affecting toughness. It is not likely, therefore, that the phosphorus content of the irons in the axe heads would have detrimentally affected their performance in service. The hardness of the irons

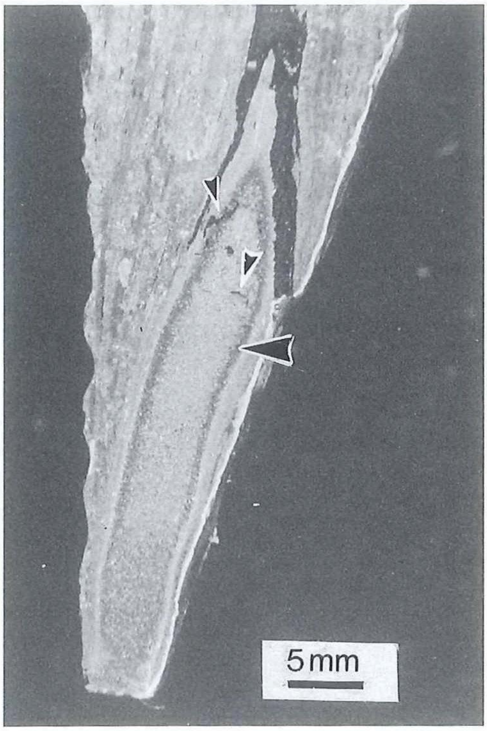

FIG. 3. Etched section of the steel insert in the bit of the unused axe. The discontinuity extending from the eye bifurcated at the crown of the insert and then extended along a path slightly removed from the weld plane, the location of which is indicated by the large arrow. The discontinuity then extended to the blade surface on one side of the insert. The small arrows indicate cracks developed in the insert as a result of partial liquation during welding (see Fig. 10). Etched in 2% nital.

*Puddled wrought irons were the dominant engineering structural material for most of the nineteenth century. They were made by refining blast-furnace cast irons by selective oxidation at high temperatures in the solid state, the process being called *puddling*. The product was an iron of low carbon content in which was dispersed a considerable amount of the nonmetallic reaction products of the refining process. As much as possible of these reaction products was squeezed out by hot forging in an operation called *shingling*. The shingling also formed the mass into a rough bar suitable for further shaping. The particles of reaction product that remained after shingling constitute the nonmetallic inclusions found in the final product. The shingled bars were variable in composition and inclusion content. A more homogeneous product was made by hot forging or hot rolling groups of bars together, this so-called *piling* process perhaps being repeated a number of times. A range of quality grades was produced, depending on the skill and thoroughness with which these various processes were carried out.

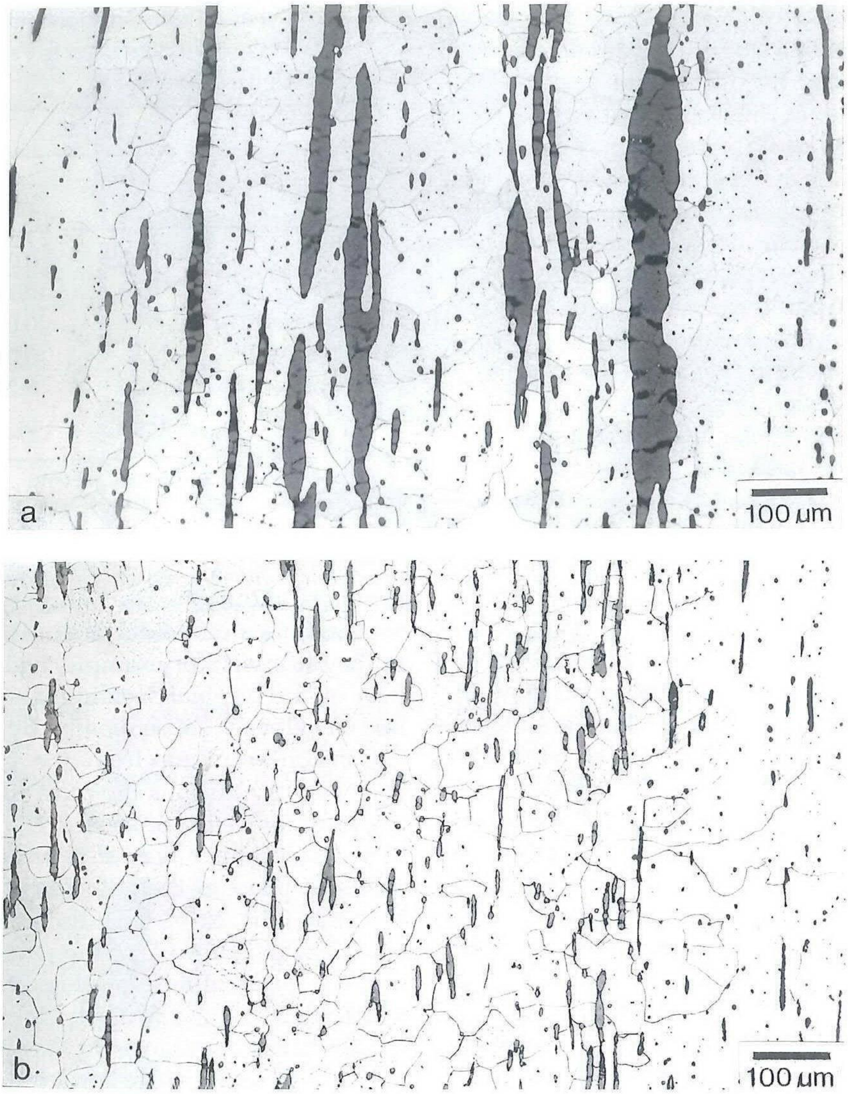

FIG. 4. Representative microstructures of the wrought iron plates used to fabricate the blade of the unused axe head. Area (a) is representative of bands containing a large volume fraction of nonmetallic inclusions and area (b) of bands containing a smaller volume fraction of inclusions. The base structure in both is composed of small equiaxed grains of ferrite. A duplex structure is visible in the inclusions in (a). Light micrographs; etched in 2% nital.

varied somewhat but was everywhere within the range listed in Table 1; these values are normal for wrought irons.

The two plates had been forge welded together along the approximate midplane of the head, a mandrel having been positioned at an appropriate position to shape the shaft hole. Separate forge welds thus would have had to be effected to form the blade and poll, respectively (Fig. 2). During this process, the asymmetric section shape characteristic of a stone-working axe was established by bending one of the plates farther around the mandrel than the other. A strip of iron had then been welded over the end face of the poll, the poll having been upset a small amount in the process (Fig. 2). The blade had been tapered down to the bit edge and a 4mm × 30mm strip of steel inset into the edge.

A few superficial forging laps developed in the blade surface [one is indicated by an arrow in Fig. 2(b)], but otherwise the grain flow smoothly follows the external contour of the head. The discontinuity visible on the end faces of the blade begins at the root of the eye [Fig. 1(a)] and extends along the full length of the eye. It extends along the central joint plane toward the bit insert, where it bifurcates to follow the contour of the insert [Fig. 2(a)] along a plane slightly removed from the insert-blade interface (Fig. 3). For about half the bit length, the discontinuity then extends to the blade surface on one side [Figs. 2(a) and 3(b)]. The discontinuity at the midplane contains a considerable amount of a layered corrosion product (rust) but also contains extensive patches of a nonmetallic material with a duplex structure (Fig. 5). This material clearly was welding slag that had not been expelled from the weld plane, as would be necessary to achieve metal-to-metal bonding.† Moreover, the forging grain flow at the root of the eye indicates that the surfaces of the two blade plates had not been brought into contact in this region [Fig. 2(b)].

The discontinuity is thus primarily an area over which bonding was not achieved during welding, because the surfaces of the two plates had not been brought into intimate contact. It is possible, nevertheless, that the original forging discontinuity extended during burial owing to expansive forces induced by the growth of corrosion products within the discontinuity. The bifurcated parts of the discontinuity adjacent to the bit insert, for example, had not been part of the original welding discontinuity but developed subsequently by fracture. Expansion resulting from the growth of corrosion products is the most likely driving force for such a process.

A discontinuity was also present along the weld plane at the poll side of the shaft hole eye [Fig. 2(a)]. This discontinuity extended from the root of the eye for up to half the depth of the poll [Fig. 2(a, b)] and was largely filled with a material that had a duplex structure similar to that illustrated in Fig. 5. Layered corrosion products were also present. This discontinuity can again be attributed to failure to bring the two surfaces into intimate contact when welding was being attempted.

†Forge welding is based on the principle that two surfaces of a solid will bond if they are pressed together at a suitable temperature, provided that contaminant films, such as oxide films, are not present to prevent intimate metal-to-metal contact. This condition is achieved with iron if the surfaces are heated to a temperature (approximately 1375°C) at which the iron oxide melts (more strictly, flows freely). The temperature required can be reduced by sprinkling a fluxing material over the surface. Sand can be used, for example; this forms an iron silicate slag that has a lower melting point than that of iron oxide. The welding temperature is then about 1175°C. (Puddled wrought irons are self-fluxing in this manner because they contain inclusions rich in iron silicate, which, when molten, can dissolve iron oxide.) The surfaces have to be pressed firmly together when the welding temperature has been reached, preferably with a shearing action to help to break up and expel the molten oxide or slag from the weld plane.

Table 1 Chemical Composition and Hardness of the Materials Used to Fabricate the Unused Axe Head

	Blade		
	Flat side	*Convex side*	*Bit insert*
Carbon, wt.%+	0.025	0.06	0.86
Silicon, wt.%*	0.13	0.14	0.08
Manganese, wt.%*	0.03	0.03	0.05
Sulfur, wt.%*	0.01	0.01	0.01
Phosphorus, wt.%*	0.22	0.24	0.03
Hardness, HV(10)	125-145	120-125	285

+Analysis by Analabs Ltd., Western Australia.
*Analysis by Chemistry Centre, Department of Minerals and Energy, Western Australia.

Cover Strip, Poll Face

The strip welded over the face of the poll was approximately 2mm thick and composed of two pieces of different materials. One was a puddled wrought iron containing an unusually small volume fraction of nonmetallic inclusions [Fig. 6(a)]. The hardness of this material was 125HV(10). The other was a low-carbon steel estimated from its microstructure to contain 0.2%C [Figs. 5, 6(b) and 7]. Most likely, it was a

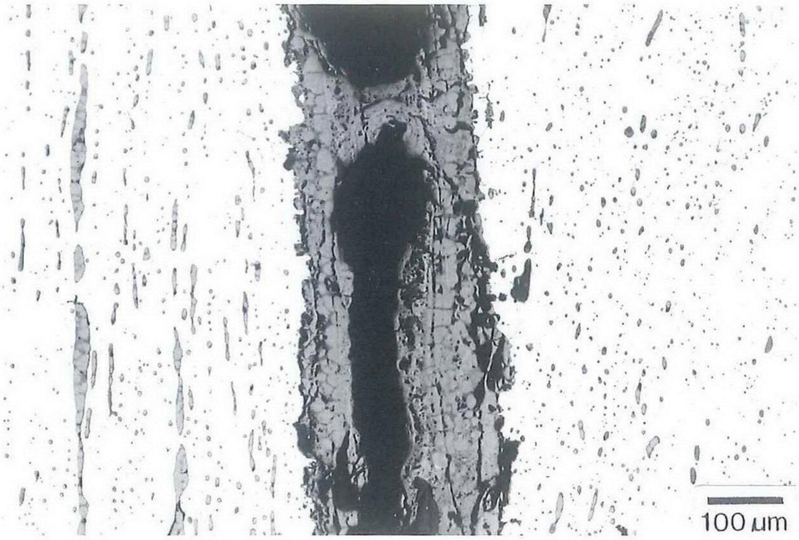

FIG. 5. Section through the discontinuity in the blade of the unused axe. An area located close to the shaft hole is shown. The duplex structure of the nonmetallic material in the discontinuity indicates that it is welding slag that was not expelled from the weld interface. Light micrograph; etched in 2% nital.

piece of decarburized crucible steel. Its microstructure consisted of fine-grained ferrite and a small volume fraction of degenerate pearlite (Fig. 7). The hardness of this material was 285HV(10). The degenerate structure of the pearlite can be attributed to a low manganese content, which is to be expected in a crucible steel derived from a

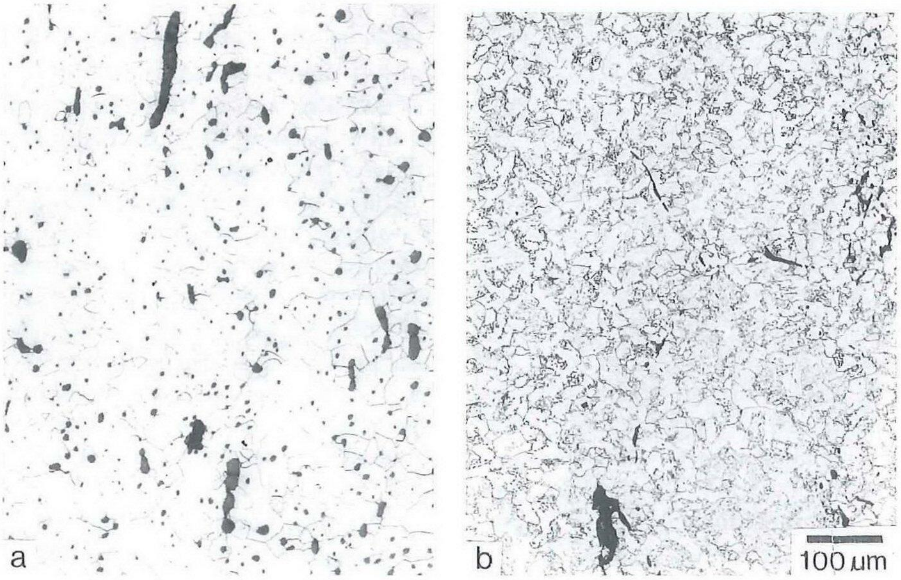

FIG. 6. Microstructures of the two materials used in the strip covering the back surface of the poll of the unused axe. The section plane is parallel to the poll surface. (a) This structure is characteristic of a puddled wrought iron but contains an unusually small volume fraction of nonmetallic inclusions (cf. Fig. 4). The grain of the inclusions is parallel to the back face of the poll; that is, perpendicular to that in body plates. (b) This structure is characteristic of a low-carbon steel in the slowly cooled condition. The material contains networks of inclusions that are probably a result of partial liquation during forging. Light micrograph; etched in 2% nital.

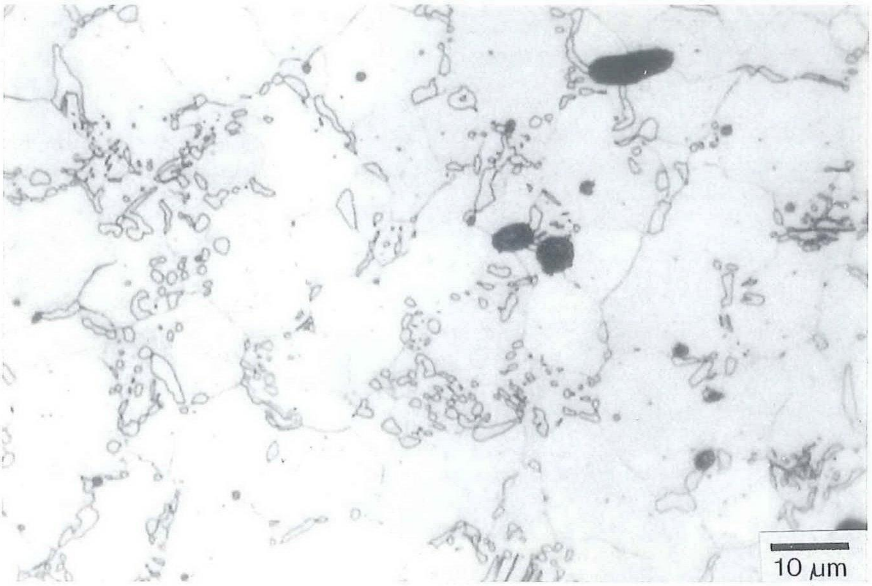

FIG. 7. Microstructure of the low-carbon steel used in the cover strip on the poll of the unused axe, a matrix of small equiaxed grains of ferrite and colonies of degenerate pearlite. Light micrograph; etched in 2% nital.

wrought iron. Oxide inclusions arranged in networks [Fig. 6(b)] also were present in this material, probably as a result of partial liquation during welding, a phenomenon that will be discussed later. The weld bonds between the two constituents of the strip and between both of them and the main body of the axe head were good.

It was common practice in iron works, and presumably also in blacksmith shops, to forge together miscellaneous scraps of iron and steel that had accumulated about the works [3]. The product was called *bushelled iron*. Presumably, the objective of the poll cover strip was to negate deleterious effects of the end grain that would otherwise have been exposed at this surface. In this event, the use of a low-grade product such as a bushelled iron would have been acceptable, particularly if the material contained few nonmetallic inclusions, as did the material used in this axe head.

Insert, Bit Edge

A steel strip had been inset by forge welding along the full length of the bit edge (Figs. 2 and 3), a common practice with wrought iron edged tools before the advent of cheap steel-making practices toward the end of the nineteenth century. The practice was known as *steeling* and was designed to use the relatively expensive steel only where it was actually needed. It also afforded the advantage that a hard but perhaps brittle steel would be supported by a tougher backing, thus reducing the probability of fracture in service.

The strip was first tapered to an edge at its upper end, which enabled it to be blended smoothly into the wrought iron blade plates between which it was sandwiched (Fig. 3). It appears that it was normal practice to shape bit inserts in this way [5, 6]. The layers of wrought iron that covered the sides of the insert were comparatively thin and were thinner on one side than the other (Fig. 3). It was through the thinner side that the midplane discontinuity extended to the blade surface (Fig. 3). The insert was inclined at an angle of 1–2° to the midplane of the head away from its convex side (Fig. 3), and it seems that this was a consequence of the procedure used to develop an asymmetrical section in the blade. The inclination would perhaps have been advantageous when side dressing stone blocks but not when cutting blocks.

A fully bonded weld had been achieved completely around the insert (Figs. 3 and 8). Diffusion of carbon had occurred across the weld plane, resulting in carburization of the adjacent wrought iron and decarburization of the steel, each to a depth of 125μm (Fig. 8). This diffusion is characteristic of forge welding because the weld regions remain at high temperatures for a lengthy period of time. The austenitic grain size in the diffusion zone was small (50μm average grain diameter). Large nonmetallic inclusions in the wrought iron immediately adjacent to the weld plane had been fractured into small segments (Fig. 8), another characteristic of forge welds.

The steel of the insert can be taken to be a *crucible steel*.‡ Chemical analysis indicated that regions remote from the bit edge and the weld plane contained 0.85%C (Table 1). It also indicated that the manganese content was low compared with that of modern steels but was of the magnitude to be expected in a crucible steel made from a puddled iron. The phosphorus content also was low, much lower than that of the wrought irons used for the blade (Table 1). It was the practice to select irons with low phosphorus contents when manufacturing steels by the cementation route because phosphorus greatly reduces the rate of carburization. The phosphorus contents of typical English wrought irons were undesirably high from this point of view, so it was normal practice in England to use selected Swedish irons as the starting material for crucible steels [7, 8] The low silicon content of the insert is characteristic of a product originating from a pig iron produced in a charcoal blast furnace, which also points to a Swedish source. It can be concluded that the steel used for the insert was of high quality for the time.

The microstructure of the insert steel in regions remote from the bit edge consisted of thin grain boundary allotriomorphs of

FIG. 8. Section of the forge weld between the wrought iron (right) and the steel insert (left) at the bit of the unused axe. The weld line is indicated by the light-etching band (arrows). Good bonding was achieved along the weld and diffusion of carbon occurred across the weld plane from the steel into the wrought iron. Note that the inclusions in the wrought iron adjacent to the weld are much smaller than those remote from the weld [cf. Fig. 3(b)] because the original inclusions were fragmented by the strains imposed during welding. Light micrograph; etched in 2% nital.

‡Crucible steels, sometimes called *cast steels*, were made in two stages. First, carbon was diffused into the surface of puddled wrought iron bars by heating up to 1100°C for several days while buried in charcoal in an airtight container. This stage was called *cementation*; it is called *carburization* in modern terminology. The carburized iron bars were undesirably inhomogeneous. The carbon content varied with depth and the inclusions of the parent wrought iron were either still present or replaced by cavities. A more uniform product was made by melting the carburized bars in small crucibles, the melt having been cast into ingots that were then hot rolled to final shape. This was the principal method used to make steel in England from the middle of the eighteenth century to the late nineteenth century, during which period England was the world's major supplier of quality steels. In the late 1800s, the crucible process began to be replaced by large-scale cheaper processes in which cast iron was refined in the liquid state. Nevertheless, the crucible process continued to be used for quality steels until well into the twentieth century.

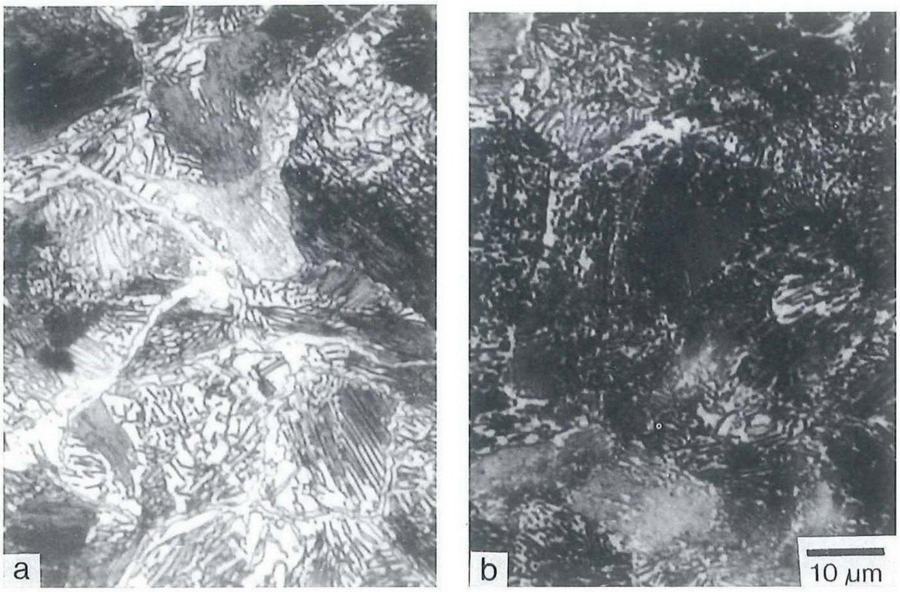

FIG. 9. Representative microstructures of the bit insert steel of the unused axe. (a) A region close to the crown of the insert. Thin grain-boundary allotriomorphs of proeutectoid cementite surround colonies of fine lamellar pearlite. (b) A region close to the bit edge. The proeutectoid phase is ferrite, only a small volume fraction being present. Light micrograph; etched in 2% nital.

proeutectoid cementite surrounding colonies of fine lamellar pearlite [Fig. 9(a)]. The steel thus appears to be slightly hypereutectoid, which is consistent with the analyzed carbon content. The austenitic grain size was comparatively small (approximately 50µm average grain diameter). The volume fraction of proeutectoid cementite decreased

FIG. 10. Microstructure of the crown region (identified by an arrow in Fig. 3) of the insert in the unused axe. The crack and cavities indicated by the white arrows are the result of partial grain boundary liquation during welding. The weld line is indicated by the black arrows. Light micrograph; etched in 2% nital.

as the bit edge was approached until the structure became near-eutectoid [Fig. 9(b)]. The carbon content in these regions is estimated from this microstructure to be approximately 0.75%. Thus slight decarburization of the steel had occurred toward the bit edge during manufacture. Nevertheless, the hardness of the insert steel was reasonably uniform throughout, being in the range 280-290HV(10).

A noteworthy feature of the insert was that partial grain boundary liquation had occurred in a localized region remote from the bit edge (Fig. 3). In modern terminology [9], the steel had been *burnt* in this region during heating for forging. As a result, networks of oxide-filled cracks and occasional cavities are present (Fig. 10). These liquation structures establish the locations of the austenitic grain boundaries at the time of forge welding the insert and so establish that the austenitic grain size of the insert steel immediately after forging was about 1mm. This in considerably larger than that currently existing (about 50μm), from which it can be deduced that the axe head must have been subjected to a grain-refining heat treatment after forging. The current microstructure suggests that the head had been heated to 800–850°C (*austenitized* in modern terminology) and then cooled in air (*normalized* in modern terminology). Note that an attempt had not been made to *quench harden* the insert steel. This would have required that the insert region be quenched in water after austenitizing. A recognizably different distinctive microstructure and a much higher hardness would have been produced.

An unusual structure is also present in the wrought iron in a region adjacent to the one in which burning occurred in the bit steel. The nonmetallic inclusions in the iron were relocated in a network around what can be presumed to have been the austenitic grain boundaries that existed at the time and temperature of forging (Fig. 11). It seems that the inclusions melted, penetrated along the boundaries while molten, and then subsequently solidified at these boundaries. This structure can also be taken to indicate that an undesirably high temperature was attained locally during the insetting operation. This structure indicates

FIG. 11. Microstructure of a region in the wrought iron blade of the unused axe adjacent to the weld to the bit insert and close to the area at which partial liquation had occurred in the insert. Nonmetallic inclusions in the wrought iron appear to have melted and penetrated along the austenitic grain boundaries that existed in the iron at the time. Light micrograph; etched in 2% nital.

that the grain size at the forging temperature was considerably larger than that from which the current microstructure was generated, again indicating that the material had been subjected to a grain-refining heat treatment after forging.

Steeling

The unused axe head was steeled by insetting a strip of high-carbon steel, but advantage had not been taken of the possibility of quench hardening this material. Many steeled-edge tools and edged weapons manufactured through the centuries have been investigated, and the steeling in most, but not all, has been found to have been quench hardened and often also to have been tempered after hardening [5]. Wood-working axes recovered from a remote site in Canada and thought to have been manufactured early in the eighteenth century had been quench hardened and tempered [6]. The techniques of quench hardening and tempering were certainly well known, if not understood, by the mid-nineteenth century and were, in fact, being used in the routine manufacture of edged tools in England [7]. Moreover, the implementation of quench hardening in the present instance would have required only that the edge region be quenched in water instead of being cooled in air after the austenitizing treatment to which the head is thought to have been subjected after forging. A subsequent tempering treatment would, however, also have been required with steels containing more than about 0.5%C.

The question that consequently arises is, Why was this axe head not quench hardened? It is possible that a decision was made not to bother to quench harden this particular head because a decision had already been made to discard it, because of the central discontinuity that it contained. It is also possible, but not particularly likely, that the Fremantle smiths were not skilled in the technique of quench hardening. It is even possible that experience had shown that quench hardening was not necessary for axes used to work the soft Fremantle limestones. It was in an attempt to resolve these questions that a used axe head was examined.

USED AXE HEAD

The poll face of the axe selected had been hammered to such an extent that the poll was severely distorted and the midplane weld in the poll separated [Fig. 12(b)]. The axe appears to have been used as a wedge, its edge having being held against the surface of the stone being worked and its poll surface then hammered. Nevertheless, the working edge, which had been sharpened to a convex shape [Fig. 12(a)], seems to have withstood these service conditions well. A small spall developed at one position [identified by an arrow in Fig. 12(a)], but the edge remains reasonably sharp and no wear of the side faces is evident. This edge may, of course, have been resharpened repeatedly during the life of the axe but, if so, not to a great extent, because very little of the edge region was removed in total. Moreover, the existing edge must have survived at least the period of service in which the poll finally split.

This axe head is of the same general type as the unused head and was fabricated by the same sequence (Fig. 13). The bit insert was larger (15 × 50mm) than that in the unused axe; as a consequence, it was better supported by the blade [cf. Figs. 2(a) and 13]. Full bonding of the insert weld had again been attained, but burning of the insert steel had not occurred during welding. The microstructure of the insert steel consisted of discontinuous allotriomorphs of cementite surrounding colonies of comparatively course pearlite (Fig. 14). The austenitic grain size was similar to that of the unused axe. From this, it can be deduced that the carbon content of the insert steel was approximately 1.1% (higher than that for the unused axe) and that the insert had been austenitized at a temperature similar to that for the used axe but that it had been cooled more slowly. Consequently, it was somewhat softer [hardness 205–220HV(10)]. In modern terminology, it can be said to have been *annealed*. Note that, again, it had not been quench hardened.

FIG. 12. Side (a)
emerged at the s
split in the poll.

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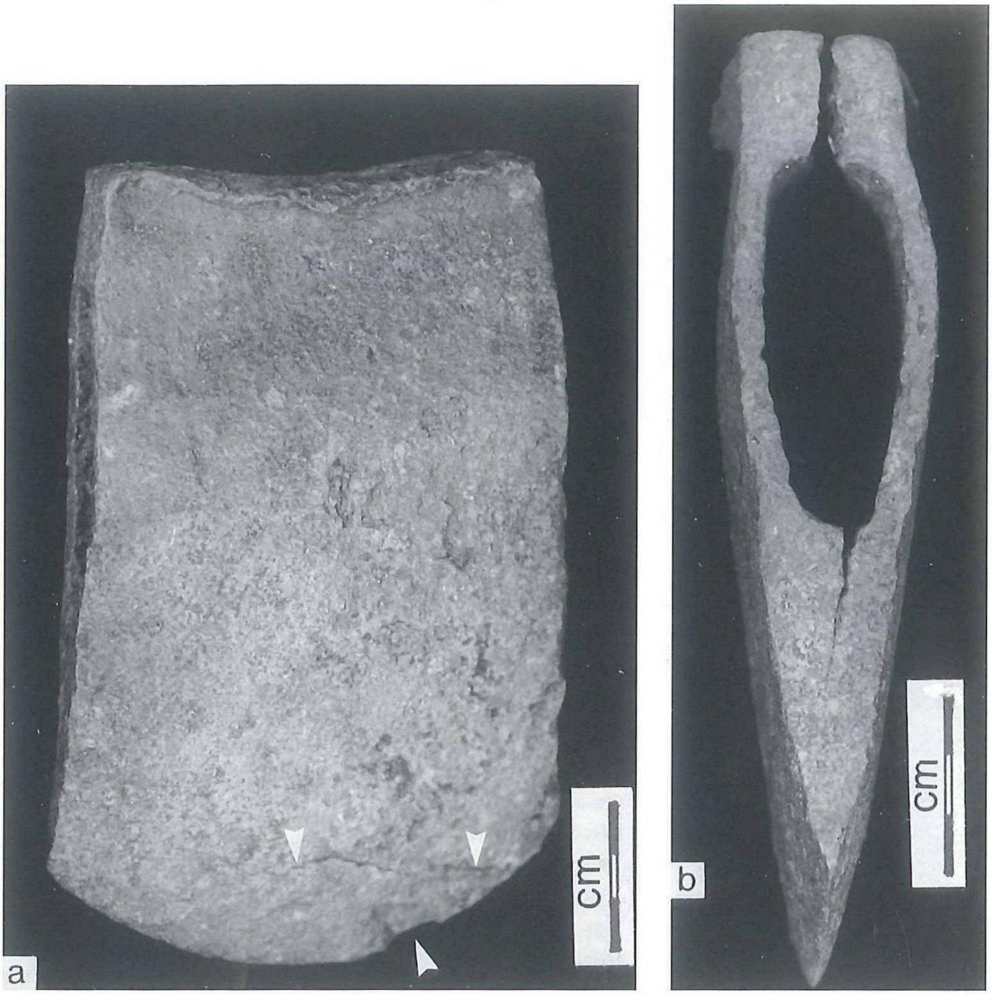

FIG. 12. Side (a) and end (b) views of the used axe head after derusting. The arrows indicate a discontinuity that emerged at the side face of the blade and a chip in the working edge. Note the distortion of the poll surface and the split in the poll.

The blade of this axe also started to split along its midplane, and the split bifurcated around the bit insert to extend to the blade surface at some positions (Fig. 12). Although a weld discontinuity could have been present in the blade and contributed to the splitting in service, an additional factor probably made the major contribution. The insert had, in effect, been driven into the blade by the service stresses, thereby developing fractures in blade material in regions remote from the weld plane (Fig. 13). It seems that a blade of this type might be split by this mechanism even in the absence of a weld discontinuity.

DISCUSSION

The axe heads were fabricated by joining two plates of wrought iron by forge welding. A central length of the interface was left unwelded and shaped into a shaft hole, and the blade and poll were formed to an asymmetric section characteristic of stone-working axes. A strip of high-carbon steel was inset into the bit edge of the blade and a strip of low-carbon iron was welded over the poll surface to cover the end grain of the body plates. The finished forging is thought finally to have been given a grain-refining austenitizing heat treatment; the unused axe

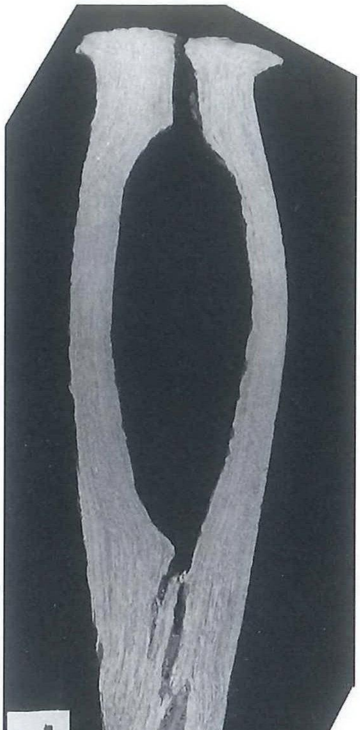

FIG. 13. Etched section of the used axe head. The insert had driven into and begun to split the blade in this region. Etched in 10% ammonium persulfate.

was probably cooled in air from an austenitizing temperature of about 850°C and the used axe was cooled somewhat more slowly.

The forging procedure is one that was commonly used to fabricate axe heads from wrought iron and is one that clearly required a high level of blacksmithing skills. A reasonable high standard was achieved in the smithing of the used axe, which appears to have been driven as a wedge by hammering the poll. The standard of forging in the unused axe, however, was not particularly high, and it could have been a reject forging. In any event, it provides examples of the difficulties to which the fabrication method was prone.

Perhaps the foremost difficulty was that of obtaining a bond over the full area of the interface between the two body plates. A mandrel must have been inserted between the two plates during welding to form the shaft hole, and its presence impeded, in immediately adjoining areas, the flow necessary to bring the two surfaces into intimate contact. The consequence was a tendency for bonding not to be achieved in these regions. An extensive unbonded area of this nature was present in the blade of the unused axe and may have been the reason why it was abandoned. A much larger bonded area was obtained in the blade of the used axe, and this weld withstood severe service conditions without parting extensively. Internal fractures were initiated in this blade, but this appears to have been the result of the insert being, in effect, driven into the blade. The weld in the poll of the unused axe also contained an extensive unbonded region adjacent to the shaft hole, the unbonded region occupying about a quarter of the intended weld area. The quality of the weld in the poll of the used axe could not be assessed, because the weld had separated in service, but it did so only after the poll had been subjected to severe battering. The need for a poll weld appears to be a weakness of this method of fabrication if the poll is to be hammered. An alternative fabrication procedure has sometimes been used in which a plate is folded around a mandrel and a weld made in the blade only, obviating the need for a weld in the poll.

The unused axe head also contains an example of a phenomenon common to all wrought iron implements steeled by forge welding; namely, partial liquation at the austenitic grain boundaries due to an excessively high temperature. This phenomenon in known as *burning* in modern terminology [9]. Melting at the austenitic grain boundaries would commence in an 0.8%C steel at a temperature of about 1350°C. A temperature exceeding 1150°C would have to be attained to achieve a forge weld, so a blacksmith would have to judge the forg-

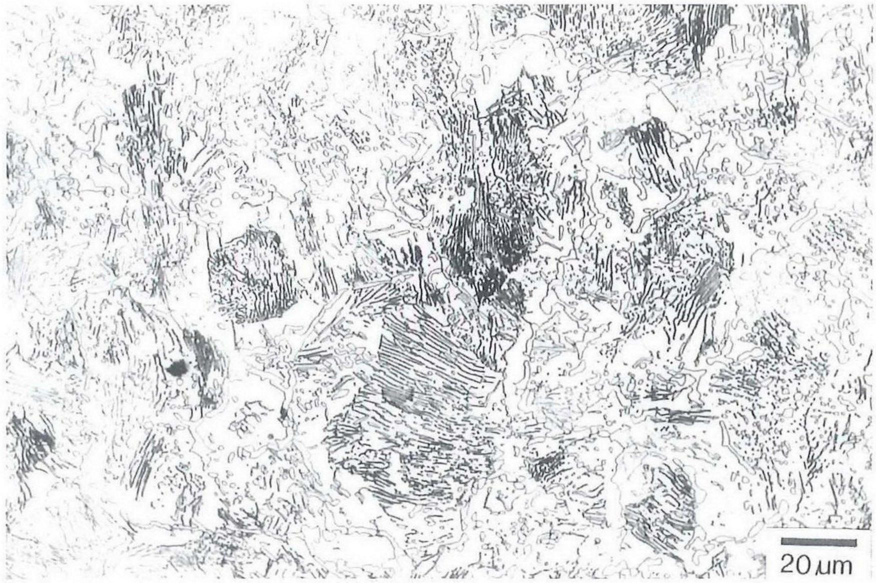

FIG. 14. Representative microstructure of the insert steel of the used axe, in which discontinuous idiomorphic films of proeutectoid cementite surround colonies of course lamellar pearlite. Light micrograph; etched in 2% nital.

ing temperature to within about 200°C to produce a fully bonded weld without burning the insert. The permissible temperature range would be larger for iron-to-iron welds but smaller the higher the carbon content of the insert. Judging temperature within these limits is no mean feat, considering that temperature had to judged solely from surface color. An excessively high temperature had been reached in a small volume at the root of the insert in the unused axe, a location where the cracklike features and cavities produced by burning could have promoted detachment of the insert in service. On the other hand, burning had not occurred in the used axe, in which the insert was of higher carbon content. This is perhaps indicative of an understandable variability in the control of the welding process.

The steel inserts in the two axes examined differ in dimensions and carbon content. The common feature is that they were not quench hardened. The insert in the unused axe was probably cooled in still air from an austenitizing temperature (in modern terminology, it has been normalized) to produce a hardness of about 280HV. The used axe was cooled somewhat more slowly after austenitizing to produce a hardness of about 210HV. Much higher hardnesses would have been produced if the bit edge had been quenched in water from the austenitizing temperature instead of being cooled in air; that is, if it had been quench hardened. It might seem at first that the omission of this apparently simple change in the heat treatment procedure to a large extent negated the point of steeling the bit edge. Yet the softer of the two inserts apparently performed satisfactorily in the particular application in which they are assumed to have been used.** Probably, therefore, the use of inserts in the normalized or annealed condition was deliberate because the local smiths had learned that the result was adequate for the purpose. The inserts were, after all, twice as hard as the wrought iron in which they were con-

**It is thought that these axes may also have been used to split wood. If so, this would only reinforce the conclusions reached here. However, it does not necessarily follow that normalized inserts would perform satisfactorily when working hard stones or when cutting wood, particularly Australian hardwoods.

tained. Possibly the smiths had even learned that quench hardening was best avoided because of the distortion and cracking that could result. They may even have learned that quench-hardened steels of the type used were excessively brittle in certain applications. Quench-hardened hypereutectoid steels are brittle in impact unless the proeutectoid cementite is spheroidized before austenitization; austenitization is carried out within a specific narrow range of temperatures, and quenching is followed by tempering at an appropriate temperature. Such a sophisticated heat treatment can scarcely be expected to be implemented by a blacksmith anywhere, let alone under the conditions that probably prevailed at Fremantle.

In the event that normalizing or annealing was deliberately chosen for the final heat treatment, it follows that the same hardness and similar wear resistance [10] could have been obtained with steels of lower carbon contents (perhaps as low as 0.7%). Higher carbon contents than this are even undesirable because, as indicated earlier, the steels are then likely to be more susceptible to burning during forging. Crucible steels of appropriate lower carbon contents were available in England [8], but whether they were available in Fremantle and whether these distinctions were appreciated there is another matter. Perhaps a steel was just a steel in the Fremantle smithy, as it still is in some undeveloped parts of the world such as Mali [11] and eastern Turkey [M. McConchie, University of Melbourne, personal communication, 1996]. Perhaps, moreover, the smiths were forced to use whatever steel types and sections available at the time.

A side effect of steeling was observed in the used axe; namely, the insert tended to be driven into the blade, developing internal splits. The hardness of the insert would have had to be about twice that of the blade for this to occur, but the effect would not have been greatly enhanced by a further increase in hardness. It would have been affected to some extent by the shape of the crown of the insert. It seems, however, that failure of an axe is likely to occur by other mechanisms before this one becomes significant.

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