PITT RIVERS MUSEUM
UNIVERSITY OF OXFORD

Notes on Prehistoric and Early Iron in the Old World

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INCLUDING

A Metallographic and Metallurgical Examination of specimens selected by the Pitt Rivers Museum by courtesy of the Director of Research and Technical Development of Messrs. Stewarts and Lloyds

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PREFACE

THE author of the present *Notes on Prehistoric and Early Iron in the Old World* has already published *Notes on the Prehistoric Metallurgy of Copper and Bronze in the Old World* in this series, and the steady demand for this book and requests for a similar work on iron have led us to offer such a work as the eighth of our *Occasional Papers on Technology*. Mr. Coghlan is well qualified to follow our general method in this series. In his early days as a pupil in a large engineering works he learned the actual methods and practice in the forge and foundry. Before devoting his attention to archaeology and ethnology and later to the direction of a museum, he had over twenty years of experience as a chartered mechanical engineer, and had much experience in the laboratory testing the materials of construction, including especially iron, copper, and bronze. His interest in prehistoric and primitive metallurgy began during his work in Burma, where he had ample opportunity to study primitive metallurgical processes at first hand.

For some years he has been Chairman of the Ancient Mining and Metallurgy Committee of the Royal Anthropological Institute, of which the Curator of the Pitt Rivers Museum is also a member, and for this book they have been most fortunate, through the good offices of the British Iron and Steel Research Association, to enlist the services of the great firm of Messrs. Stewarts & Lloyds, whose Director of Research and Technical Development gave permission for the metallographic and metallurgical examination of a number of important specimens, the work being carried out under the direction of Mr. T. H. Williams, Manager, Chemical Research, and of Mr. P. Whitaker, Manager, Metallurgical Research. We are deeply grateful to them for the care and interest they showed in the preparation of reports on iron objects ranging from about 800 B.C. to after A.D. 1000, thus helping us towards making a skeleton picture of what the blacksmith knew over a long period of time, and helping materially to fill gaps in the collected records of other workers. In some examples, further information could have been given if the terms of reference had allowed sectioning of the objects.

One of our considerable duties was to find iron from so many periods and areas which was capable of yielding useful results to the analysts, for iron is a most perishable material, and much of the evidence for which we

sought would have vanished with corrosion. Thus we had to collect a great deal of material in order to choose some that was sound enough to be worth analysing. We are glad here to record our thanks to Mr. D. B. Harden, Keeper of the Department of Antiquities in the Ashmolean Museum for iron from Syria, Jugoslavia, and elsewhere in Europe, ranging from 600 B.C. to Mediaeval times, to Miss Olga Tufnell of the Wellcome-Marston Archaeological Research Expedition to the Near East for iron from ancient Lachish of the sixth century B.C., and to Mr. Richard Barnett of the Department of Egyptian and Assyrian Antiquities of the British Museum for iron from Nimrud of the eighth century B.C. To Dr. Karl Kromer of the Prähistorische Sammlung im Naturhistorischen Museum, Vienna, we are indebted for Hallstatt iron of about 600 B.C., and to Professor Dr. Alfred Bühler of the Museum für Völkerkunde of Basel for obtaining two La Tène swords of about 50 B.C. from the Historisches Museum, Basel, which we were allowed to analyse. Mr. W. A. Smallcombe, Director of the Reading Museum and Art Gallery, kindly lent us a Roman axe of the fourth century A.D. from Silchester, and a Saxon axe, and the author supplied the fine Danish axe of the ninth century A.D. Among others who helped us in our search for suitable iron, we are happy to thank Mr. Seton Lloyd of the British School at Ankara, Dr. Claude F. A. Schaeffer of St. Germain-en-Laye, Mr. A. H. S. Megaw of Nicosia, Mr. W. F. Grimes and the Roman and Mediaeval London Excavation Council, Dr. G. H. S. Bushnell, Curator of the University Museum of Archaeology and Ethnology, University of Cambridge, and Mr. H. St. George Gray. To name all who have helped would indeed be difficult. The file of letters about this book, if printed, would be as long as the book.

For permission to reproduce figures and use material already published, we are indebted to M. Edmond P. Fouss, Conservateur, Musée Gaumais, and M. A. France-Lanord, Mr. J. W. Lillico, Professor Dr. R. J. Forbes, Messrs. Johann Ambrosius Barth (for work by Weiershausen and Ohlhaver), Dr. Menzel of the Römisch-Germanisches Zentral-museum, Mainz, for permission to use figures by Lindenschmit, the Deutsches Archäologisches Institut, Frankfurt, for the use of figures by Witter, Professor Gordon Childe for permission to use figures published by the University of London Institute of Archaeology, and to Professor R. Pittioni.

Our thanks are due to Mr. G. C. Boon of the Reading Museum for advice and information concerning heavy Roman iron forging, to Mr.

W. L. Brown of the Ashmolean Museum for most valuable advice and information in the preparation of Chapter IV, to Mr. H. J. Case of the Ashmolean Museum for reading the chapter and advising us, and to Dr. William Cohn of the Museum of Eastern Art for much help and advice. We are glad, too, of the opportunity to thank Professor Joseph Needham of the University of Cambridge for a long and valuable correspondence in which he placed at our disposal much of the material on ancient Chinese cast iron which he has collected for future volumes of his great work on *Science and Civilization in China*, now being published by the Syndics of the Cambridge University Press.

Finally, it is a great pleasure to thank Mr. K. H. H. Walters and Mr. I. M. Allen of the Pitt Rivers Museum for all the time and care they spent in sorting and preparing illustrations for the Press, Mr. R. C. Gurden, Secretary and Librarian of the Museum, for work on the bibliography and text, and the Staff of the University Press for the care and trouble and beautiful craftsmanship they always spend on our books.

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Chapter I

THE IRON ORES AND ANCIENT MINING

IRON ORES AND THEIR DISTRIBUTION

FROM a technical and cultural point of view it may be considered that the discovery of iron was not an event of the same importance as that of the discovery of how to extract copper from its ores, for it may be argued that copper and its various alloys could, in some measure, have taken the place of iron, although at a greatly increased cost and with much reduced efficiency. However, it cannot be disputed that the discovery of iron was also of the very greatest importance in the evolution of metallurgy. The discovery opened up an entirely new field in that it led to the availability of a vast quantity of relatively cheap metal which was of a nature much more suitable to the manufacture of tools and weapons than the non-ferrous alloys could be. Also iron is, of course, well suited to a wide range of domestic and general use. In dealing with early iron we must consider that obtained from two sources:

(*a*) Iron which is obtained from the ores.
(*b*) Meteoric and natural iron.

Consider, first, metal obtained from the ores. It is of course well known that iron ores do not resemble in appearance the metallic iron which can be extracted from them. In many cases the ores are earthy-looking substances bearing no superficial relationship to the desired metal. Heat and the chemical process termed reduction are required in order to extract the metal from the parent ore; this is also known as the smelting process. The ores from which iron is obtained are extremely plentiful and widely distributed; indeed, next to aluminium, iron is the most widely distributed of all the metallic elements. The quantity of iron contained in the various ores varies considerably, and in order that the ore may be worth working the percentage of iron which can be extracted by smelting must be reasonably high, for example, 20 per cent. and upwards. Iron ores are usually classified as sedimentary, crystalline, and replacement. In general, it is not necessary for the archaeologist to concern himself with the complex details of the mode of formation of the metalliferrous ores. The

following remarks by Fearnsides and Bulman (1944, p. 115) will indicate the differences in the general classification:

> Most iron ores carry the metal in the form of oxides, carbonate or silicate, and contain at least 20 per cent of iron. The usual classification is into sedimentary, crystalline and replacement ores. A sedimentary ore is a deposit of hydrated oxide, carbonate or silicate, formed by precipitation, which is part (sometimes nearly the whole) of a bed of sediment; in a replacement ore, the iron has been brought in subsequently by solutions, which by interaction have replaced the original, generally calcareous, rock. There are also high-grade magnetite ores, formed at high temperature by crystallization of excess of iron in igneous and metamorphic rocks. These last are of great importance in Sweden, Russia and Eastern America.

Of the various iron ores, some are suitable for smelting by a primitive people, while others are unsuitable for primitive methods of smelting. This aspect of the question will be considered later on. The following ores may be mentioned:

OXIDE ORES.	Haematite, Fe_2O_3.
	Magnetite, Fe_3O_4 (sometimes known as lode-stone).
	Limonite, $2Fe_2O_3 3H_2O$.
SULPHIDE.	Iron pyrites and Marcasite, FeS_2 (iron disulphide).
	Pyrrhotite, Fe_7S_8 (the magnetic sulphide)
CARBONATE.	Spathic ore or Siderite, $FeCO_3$.

Rastall (1923, p. 314) gives the following figures of the iron content for certain ores:

Magnetite.	Iron content	when pure	72·4 per cent.
Haematite.	,,	,,	70·0 ,,
Goethite	,,	,,	62·9 ,,
Limonite.	,,	,,	Variable.
Pyrite.	,,	,,	46·6 per cent.

Chalybite (Siderite), Spathic iron ore $FeCO_3$, content of 48·3 per cent.

Haematite, magnetite, and limonite were of importance in the early processes. Of these Professor Park (1925, p. 185) says:

> MAGNETITE. This mineral is commonly found in igneous and crystalline rocks. It occurs in thick beds, irregular masses frequently of great extent, and as small grains disseminated throughout many igneous and altered rocks. In rocks subject to weathering it changes first to the carbonate and then to the brown or red peroxide. Hence sands, gravels, and compact rocks containing magnetite soon assume a rusty-brown colour on the surface when exposed to the action of air and water.
>
> HAEMATITE. This valuable ore of iron occurs as beds interstratified with sedimentary and schistose rocks, and as a constituent of many mineral veins.

LIMONITE. This ore occurs in beds and irregular deposits in stratified formations, and as the gossan or cap of sulphide lodes. In the form of bog-iron[1] it is frequently found in irregular sheets on the lake bottoms and in marsh lands where it has been deposited by the action of organic acids or iron bacteria. This is the oxide of iron which gives the prevailing yellow or rusty-brown colour to soils, clays, sands, and many sandstones.

Concerning the iron content of the following ores, Forbes (1950, p. 381) gives some figures of interest:

Limonite (Brown iron ore, Brauneisenerz) has a theoretical iron content of 59·9 per cent., and a practical iron content of 25–58 per cent.
Oolithic iron ore. Practical iron content of 24–46 per cent.
Bog-ore (Limonite, Raseneisenerz) has a practical iron content of 35–55 per cent.
Spathic iron (Siderite, Spateisenstein) has a theoretical iron content of 48·3 per cent., and a practical iron content of 30–44 per cent.
Blackband (Kohleneisenstein), practical iron content of 36–40 per cent.

The actual distribution of iron ore in the Old World is a matter which cannot here be gone into in any detail. As we have previously mentioned, iron ores are so common and so widely distributed that it would be a long and difficult task to give anything like a comprehensive list of the known deposits. The famous Hallstatt iron, and other important European deposits, are well known. For the most ancient iron working certain deposits are of considerable importance and the following mentioned by Gowland (1912, pp. 281 ff.) are of interest. In western Asia there are two important districts where iron ores are of very extensive occurrence: one is the region on the south-east of the Euxine (ancient Paphlagonia and Pontus), extending from the modern Yeshil Irmak to Batum; the other is the Taurus and Anti-Taurus region on the south-east of Asia Minor, extending on the west from Cape Anamur to the borders of Syria and in Syria to Aleppo, the Euphrates, and Lebanon. Iron ore is also found in the Tiyari Mountains to the north-east of the site of Nineveh and in the neighbouring part of Kurdistan. It is also recorded that Ashur-nasir-pal (885–860 B.C.) obtained iron in the neighbourhood of Carchemish. In

[1] Park's *A Text-Book of Geology*, London, 1925, p. 443, defines bog-iron ore as 'an impure hydrated peroxide of iron which frequently forms on the bottom of swamps and shallow lagoons'. Of the mode of deposition he says (p. 32), 'Rain water in its passage through rocks containing sulphides frequently becomes charged with iron salts. When the water issues at the surface the iron, through the action of the atmospheric carbon dioxide, is converted into the ferrous carbonate. The carbonate is rapidly oxidised by the oxygen of the air into the hydrous oxide, which falls as a yellow or foxy brown precipitate. In this way are formed the limonite (hydrous peroxide of iron) veins so frequently found traversing ferruginous sandstones and altered igneous rocks. The variety of the hydrous peroxide known as bog-iron ore is formed in the bottom of swamps and lagoons by the same series of reactions, aided by the operations of certain species of bacteria.'

northern Persia, in the neighbourhood of Parpa, between Kerman and Shiras and not far from Persepolis, there are extensive remains of early iron workings which were doubtless the source of the vast numbers of iron implements and objects found on the plain in the vicinity of that ancient city. Also in northern Persia in the Karadagh district mounds of prehistoric iron slag of enormous extent have been found. Gowland also states that in India iron ores have been worked in early times in the North-West Provinces, the Western Ghats, Mysore, Madras, and Hyderabad, also in central Asia.

For a more detailed survey, Professor R. J. Forbes (1950, pp. 380 ff.) may be consulted with advantage. He gives a most useful map showing some of the more important iron ore deposits of the Ancient Near East.

ANCIENT MINING

The study of prehistoric iron calls for some consideration of mining in general, of copper as well as of iron. Ancient mining long predates the discovery of iron, for in the Neolithic period of western Europe pit and gallery mining go back to the well-known flint mines such as Grimes Graves in Norfolk and Spiennes in Belgium, where shafts reached to as much as 50 feet in depth.[1] This was the mining of flint and other stone for the production of tools and weapons. According to Professor R. J. Forbes (1950, p. 43) the earliest traces of such mining go back to Palaeolithic times when certain centres mined flint and exported it over considerable distances. However, in the Neolithic period the trade materially increased and became important. The history of ancient mining is a subject which covers a vast field. Much work has been accomplished by Oliver Davies, C. E. N. Bromehead, and the invaluable research of Professor Pittioni and others. However, owing to the relatively small amount of field work, and evidence from mining experts, it cannot be said that the study is as yet far advanced. There is still need for further examination of ancient mines in the manner of von Miske's work on the early Hallstatt mines at Velem St. Veit in western Hungary, and of Professor Pittioni's and Dr. Franz Hampl's researches in Austria.

Although there is now evidence to prove the early smelting of the sulphide ores of copper in the European Alpine zone, iron ores are so plentiful and widespread as compared with those of copper that there would have been no need for intensive mining (Clark 1952, p. 201). Hence, it is probable that the material for the first prehistoric iron smelting was not

[1] For a modern review of flint mining see Clark (1952, pp. 174–82).

mined in the modern sense of the term, the ore being merely collected from surface workings. In an important paper on the 'Evidence for Ancient Mining' Mr. Bromehead (1940, p. 110) says that in certain Iron Age workings in Jutland the ore used was a superficial limonite pan, and that such workings must have been common all over Europe. Evidence for these superficial workings is no doubt difficult to detect, but there is little doubt that they may account for much prehistoric iron production. Of a far more advanced nature were the Velem mines, of which Bromehead remarks that the original open-cast was 40 feet in diameter. This was fully explored to a depth of 18 feet, but it was considered that there must have been a shaft to 200 feet. The ore was siderite, and a roasting operation involving charcoal fuel appears to have been used; fire-setting was employed, and the extracted ore was broken up by means of heavy stone mauls. These and other tools are illustrated in von Miske's report (1929, p. 82).

In Britain we have little evidence for actual iron mining before the Roman period. Iron was worked in this country from late Hallstatt or early La Tène times, but the ore was probably obtained by collecting or open-cast methods rather than by true mining. Bromehead (1947, p. 361) states that in and around the Forest of Dean there were many iron works, and in some cases extensive mines. At Coleford a large pit 20 to 30 yards in diameter was excavated and the ore vein followed by galleries. Again, at Great Doward is a large cavelike aperture with galleries running from it. At Lydney there is a sloping shaft which bears the marks of pointed picks on its walls; the entrance to the shaft was blocked by a Romano-British hut dating from towards the end of the third century A.D., by which time the mine must have been abandoned.

When suitable iron ore could be obtained by the extremely simple open-cast system it was naturally adopted during Roman and later times as indeed it is today. In his paper on 'Practical Geology in Ancient Britain' Mr. Bromehead gives evidence in support of this practice. Even during the Bronze Age mining had progressed to the extent of employing what is known as fire-setting to facilitate the extraction of the ore, and the miners' tools had also improved. Oliver Davies (1935, pp. 32–38) makes the following useful comments upon ancient mining tools: The Greeks and Romans normally used iron tools. As similar needs have evolved similar types, there is little difference between the pre-Roman, Roman, and Mediaeval tools. For earth or soft rock a pick was used which

was little longer than the modern geological hammer, but at Laurium specimens up to 15 inches in length have been found. For harder rock a gad was used which was driven in with a hammer. Crowbars were no doubt also used to lever out pieces of rock, and iron or bronze hammers were also very necessary. Of these, specimens have been recorded.

Wooden picks were used in the Cornish placers as late as the early Middle Ages, and wooden shovels also survived to at least the same time. At the Mitterberg Pittioni records short-handled wooden shovels which were used for loading ore into wooden troughs and tubs. Long-handled shovels no doubt existed like those from the Hallstatt salt mines. Horn is too soft for rock working and was probably replaced by iron before the Roman period. Implements of copper or bronze are also unsuitable for work on a rock face, being more expensive than iron, and either too soft or too brittle. Although iron is likely to have replaced stone as a material for chipping tools, stone remained long in use for the hammer. Rilled hammers, or grooved stone mauls, are particularly associated with mining, and they have a very wide distribution. In form, these stone mauls are very simple, consisting of an ovoid, or sometimes conical stone with a groove cut around the circumference at about the middle, the purpose of the groove being to provide an anchorage for the hide thongs by which the maul was secured to its haft. The weight of the maul varies widely: usually it is from 5 lb. to 8 lb., but mauls weighing up to 30 lb. have been recorded. Such extremely heavy hammers would no doubt have been handled by two men (Coghlan, 1945–7, p. 191). The grooved stone maul is of considerable antiquity, appearing during the third millennium B.C., in the Near East. The type is very well represented in mining districts of Spain and Ireland, and may well have survived the Roman period in Europe.

In many prehistoric mines the tools used by the miner were mainly stone mauls and deer-antler picks. Such implements would not be efficient for breaking up and extracting the ore. But fire-setting could have made the work, if not easy, at least quite practicable. In this operation a large fire was built up against the ore-face, and the heat from the fire and subsequent rapid cooling caused by throwing cold water upon the heated surfaces, caused a certain disintegration or shattering of the rock; this shattering would extend to some depth. After the fire had burnt out the ore could easily be picked away from the face of the working. Fire-setting has been recorded from several ancient European mines, and in his scientific research in the Austrian Alps (Salzburg and Tyrol regions),

Professor Pittioni (1948, p. 133) has shown that the development and extraction of the mines were carried out by fire-setting, the loosened material being detached by means of hammers of stone or bronze, and bronze gads. Oliver Davies points to evidence for probable fire-setting in the galleries in Etruria, at Aramo, as well as at the Mitterberg. The technique has the disadvantage that, unless some means of ventilation can be arranged, the smoke from the fire will render the mine workings uninhabitable.

The work of Pittioni, Zschocke, and Preuschen has thrown much light upon the mining technique of the alpine mining region. It is of interest to note Pittioni's statement that the prehistoric miner did not know of shaft-sinking or cross-cutting, but could only drive forward the open-cast at the outcrop on a slightly inclined plane. As a result of many years of work Zschocke and Preuschen have been able to reconstruct the prehistoric process of mining in the Alpine region (Pittioni, 1951, pp. 16–43). Fig. 1, pts. 1–4 (after Pittioni, 1951, pp. 22–23) will make the sequence of operations clear. First, with the aid of fire-setting and manual labour, a small inclined open-cast was made (Fig. 1 and A). As soon as the open-cast began to exceed a man's height, the cut was timbered over (Fig. 1, pt. 2), rejected parts of the lode body and rock debris being piled upon the timber roof. Hot air from the fire escaped upwards by the passage *F* while fresh air was induced through the gallery *S*. The resultant natural ventilation rendered the mine habitable. Sometimes another fire could be started as in Fig. 1, pt. 3, B. The extraction of ore had now passed the preparatory stage and it was usually advisable to start a second open-cast at some distance above the first one, Fig. 1, pt. 3, A. Eventually these two open-casts would join up (Fig. 1, pt. 4, B and C). It will be observed that, while the method of excavation is open-cast, the mine is of the inclined gallery type with ventilating passages. Pittioni mentions that when water seeped into the workings it was probably dealt with by building a dam at the bottom of the gallery and removing the water by bailing. Also, water from an upper adit could be drained off into a lower adit as soon as the exploitation of the lower adit had been completed. In recent mining these accumulations of water are dreaded because, should a modern working penetrate into a water-logged prehistoric gallery, disastrous flooding might result. At the Mitterberg the magnitude of the operations may be judged from the fact that the deepest point reached was 100 metres measured from the crest of the ridge. The thoroughness of the extraction is shown by the fact that the ore had

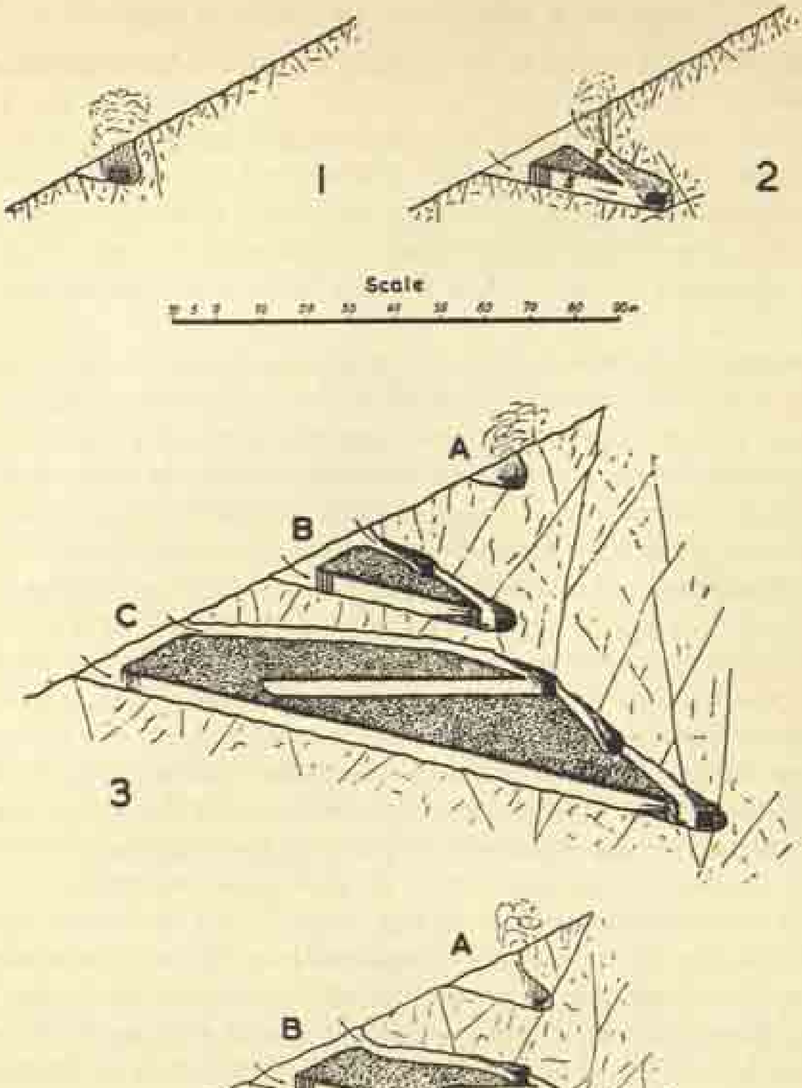


Fig. 1, parts 1–4. Stages in the development of a series of open-casts. (Pittioni 1951, pp. 22–23)

been completely removed in all parts of the lode where fire-setting had been used.

In general, it is doubtful if any true shaft mining for iron or copper was practised in prehistoric times. As Pittioni has shown, the important Mitterberg mines were worked by a combination of open-cast and adit mining. It is clear that it would have been pointless to engage in the more difficult operation of deep-shaft mining so long as ample supplies of suitable ore were obtainable merely by collecting, or through simple open-cast workings. When we come to Roman mines we find very considerable technical advance. The following points mentioned by Mr. Bromehead (1940, pp. 111–12) give some idea of this progress. In Roman mines the shafts were 2½ to 3 feet in diameter; in these small-diameter shafts foot-holds were cut and ladders were not used. The miners usually gained access to the mine through adits, while the shafts served for ventilation and winding. Sometimes the adits were of great length, one has been recorded as 2,000 yards in length. In the relatively deep Roman mines of Spain and Portugal water had to be kept at bay. One method of accomplishing this was by hand-bailing; a chain of water-bearers was engaged continuously in this laborious process.

In some Roman mines in Portugal the adits were of very considerable size, and contained a sunken channel to carry water along one side of the adit. In these mines the water was apparently raised by means of a chain of buckets worked by animal power. In some cases where the formation of a hillside made it possible, drainage could be effected by cross-cuts at a deep level; at the Rio Tinto mines in Spain thirteen such drainage tunnels were recorded. Another method of lifting the mine water was by means of water wheels; in the San Domingos mine, not far from Rio Tinto, there was a series of mine wheels 14½ feet in diameter working in a gallery which was inclined at 40 degrees. Again, the Romans used the Archimedean screw for lifting water. An example of an Archimedean screw pump was found in the Roman workings of the Centenillo mine in the Limares district.[1] These screw pumps were worked by slaves, and according to Rickard were clumsy and ineffective. The lift of the pump was only about 5 feet, so that 20 such pumps would have been needed to raise the mine water through a distance of 100 feet. With these primitive methods, pumping had to be carried out in stages and the total lift attained was limited.

[1] Rickard (1932, i, pp. 422–4, and fig. 49). San Domingos Mine: see Rickard, op. cit., p. 427, and Nash, *The Rio Tinto Mine* (1904, p. 35).

Forbes (1950, p. 55) considers that transport of the ore was arranged in the most simple manner. Wooden or wicker trays drawn along the gallery floor served for underground haulage. In later mines operated with shafts, manual labour, using baskets or leather sacks, would be employed to carry the ore to the pit-head. There does not appear to be any strong evidence to prove the general use of the pulley for lifting baskets in Roman mines, but Oliver Davies (1935, p. 31) mentions that the Brad museum possesses from Ruda two hubs which are almost certainly pulley axles, and another, perhaps pre-Roman, is reported from Selvena. Again, Forbes (1950, p. 56) says that in some cases, such as in mines at Paros, remains of hoisting machinery have been found. It is therefore probable that the pulley and windlass were used in some mines during Roman times. By then, it is clear that the technique of mining and the development of the mines had advanced to a considerable degree. Indeed, some of the large Roman mines may be said to be engineering works of considerable magnitude.

In this country iron working became an important industry under the Romans. Soon after the conquest the Kentish Wealden deposits were worked on a large scale. Here, slag heaps which have been dated to the Roman period are numerous and of very considerable size; the Forest of Dean was also a very important centre of the iron industry. The Weald of Kent and the Forest of Dean were, in fact, the great centres of Roman iron production, but iron was worked in many other parts of Roman Britain. Collingwood and Myres (1936, p. 232) mention Warwickshire, Northamptonshire, Rutland, Norfolk, Lancashire, Nottinghamshire, Cheshire, and Northumberland as other areas of production. Although nothing is actually known of the management and ownership of the iron mines of Britain, it is of interest to quote some observations made by Collingwood and Myres (op. cit., pp. 233–4).

> In the Empire at large iron was normally produced by independent labourers in the forests and this may have been so in many parts of Britain; but here and there such facts as the great size of the Wealden slag-heaps, the advanced mining methods of the Forest of Dean, or the concentration of smelting works at a town like Ariconium, suggest a higher degree of organization, whether depending on private companies and capitalists or on state ownership or control. It is possible that the state never asserted its ownership of the lesser British iron mines, and left it to develop in the hands of British owners; it may have confiscated the most valuable of them. The rapid development of output in the late first century does not suggest that the industry was left entirely to the enterprise of individual labourers.

Organization in some Roman mines even went so far as the provision of pit-head baths, although no doubt such facilities were only provided in very exceptional cases. Again, the miners sometimes had to prop the galleries and leave pillars to support the roof in the workings (Davies, 1935, p. 12). In general, except in dangerous ground, the narrow galleries of ancient mines did not require propping, but when necessary timber props and shores were used; where the galleries were opened out, natural pillars of around 3 feet square were left unexcavated so as to support the roof. It is useful to note that, according to Oliver Davies (1935, pp. 18–19), in early times the Roman miner always kept to the ore once he had found it, but later, prospecting adits were used, and the Romans also drove exploratory galleries at regular intervals from a main adit. Again, in pre- and post-Roman times the ore was often obtained by means of shafts sunk at frequent intervals; this method saved timbering and the shafts were abandoned when the ore in the vicinity of the shaft became worked out. The Romans, so far as is known, avoided pitting and used orderly underground workings with frequent communications between the galleries and the surface. Some Roman mines were worked by galleries which were driven at various levels; other Roman workings do not seem to have followed any orderly arrangement.

Chapter II

THE NATURE OF METEORITES AND THE WORKING OF METEORIC IRON. ARTEFACTS OF METEORIC IRON

THE NATURE OF METEORITES

Before dealing with iron which was produced in the normal way, that is, by extraction of metal from the ores of iron, we must consider another source—natural iron. Natural iron occurs in two forms, telluric and meteoric. For our study of prehistoric iron the telluric material can have little or no importance, for the only important occurrence of iron masses of possible telluric origin would appear to be in Greenland. Richardson (1934, p. 574) appears to be doubtful about the telluric iron of Greenland for he quotes Zimmer (G. F. Zimmer, 'The Use of Meteoric Iron by Primitive Man', *Journal Iron and Steel Inst.*, no. 2, 1916, p. 307) as saying, 'The specimens of telluric iron in our own national collection (if we except the dubious finds on the West coast of Greenland) can be held in the hollow of one hand; there might be enough for a few beads, but not for larger objects.' However, there is reliable evidence concerning the Greenland iron, for in 1870 Adolf Nordenskiold found several large masses of iron at Ovifak on Disko Island. Nordenskiold considered this iron to be of meteoric origin because it contained from 1·39 to 2·48 per cent. of nickel. Also, when polished it was supposed to exhibit a characteristic Widmanstätten structure (Rickard, 1941, pp. 58 ff.). Later research by Steenstrup and others showed that the Ovifak iron was of terrestrial origin and further analyses gave a percentage of nickel ranging from 1·74 to 2·85. It has been established that the Eskimo used this telluric iron for making knives. One mass of native iron is in the Royal Academy at Stockholm, weighing no less than 19 tons. A smaller mass of 8¼ tons is in the Copenhagen museum. In a private communication dated 20 November 1953, Professor Arne Noe-Nygaard of the University Mineralogical Museum, Copenhagen, kindly informed me that the possibility evidently does not exist that the iron at Ovifak on Disko Island could be meteoric and not telluric, since the basalt containing the big iron lumps is for many miles

speckled with tiny pieces or drops of iron. In the Professor's personal opinion the iron on Disko Island has been formed through a natural reduction process in which the underlying bituminous shales have been active, setting free various hydrocarbons. In view of the evidence quoted above, we may be satisfied that the Ovifak iron is probably of telluric origin.

According to Dr. Rickard telluric iron has been detected in many localities as far apart as Arizona and Bohemia, but it is unlikely that such telluric iron was ever used by early man. Not only is it extremely rare, but much of it no doubt occurred in the form of small grains or pellets in some of the basalt formations, in which form it would have been quite useless to a prehistoric people. Indeed, Rickard mentions that the Ovifak native iron is unique in that it alone has been used by man for implemental purposes.

Turning to meteoric iron we have a considerably wider field to cover. The nature of meteorites varies within wide limits and they are classified in accordance with the proportion of stone and iron which they contain. Those who are interested in the nature and structure of meteorites are advised to consult Perry (1944) who gives a very full account, but owing to its technical nature much of the text is suited to the metallurgist rather than to the archaeologist. The following information which is of value to the general student is taken from Perry's work.

In general meteorites are classified as:

AEROLITES. These are composed of stone.

SIDEROLITES. These are composed of a mixture of stone and iron.

SIDERITES. These are composed wholly of metal.

From our point of view siderites are the most important. Again, these are subdivided into three groups—hexahedrites, octahedrites, and ataxites. In brief, the distinguishing features are:

HEXAHEDRITES. Comprised of a single structural component, kamacite (kamacite is alpha nickel-iron). Under the microscope hexahedrites generally show systems of parallel lines, known as Neumann lines, but these lines are not invariably observed. The material has a nickel content of less than 6 per cent., the proportion of nickel being uniform at around 5·5 per cent. Cobalt is apparently always present, the combined percentage ranging from about 6 to 6·5 per cent.

OCTAHEDRITES. Octahedral iron is characterized by what is known to the metallurgist as the Widmanstätten structure, a network of bands

crossing each other in two, three, or four directions. According to Dalton (1950, p. 186) octahedrites are subclassified according to the width of the kamacite plates of the Widmanstätten figures, thus:

Coarsest, plates of 2·5 mm. or wider.
Coarse, plates of 1·5 to 2 mm. in width.
Medium, plates of 0·5 to 1 mm. in width.
Fine, plates of 0·2 to 0·4 mm. in width.
Finest, plates narrower than 0·2 mm. in width.

According to Perry (1944, p. 5) the nickel content of the coarsest and coarse octahedrites is roughly 6 to 8 per cent., of medium octahedrites 7 to 9 per cent., and of fine and finest, 8 to 13 per cent. It is impossible to generalize more exactly because analyses show variations from these averages, and many of the older analyses cannot be accepted as accurate.

ATAXITES. Ataxites appear to the eye to be without structure and under the ordinary microscope show only a fine matt texture, though high magnification with central illumination reveals a rich microstructure. Ataxites may be said to fall into two sub-groups, nickel poor, and nickel rich. In the former the nickel content is approximately that of the hexahedrites; in the latter it commonly varies between about 12 and 20 per cent., with a few showing much higher percentages.

In dealing with old analyses of meteorites it appears that some caution is necessary. We may here quote Perry's remarks on this point.

> In many old analyses the nickel content was greatly understated. Thus analyses of 25 irons (including many medium and fine octahedrites), of which only three were later than 1880 and 1870, show very low percentages, mostly from about 2·5 to 3·5, but fifteen of these irons analysed later showed in only one case less than 6 per cent and mostly 7 to 10 per cent. Of thirty analyses of low nickel irons (hexahedrites, coarse and coarsest octahedrites, and nickel-poor ataxites), made since Farrington's compilation (1907), not one shows less than 5·25 per cent of nickel; and of fifty-eight of the more recent analyses of all types of irons, only two show slightly less than 5 per cent, of which one is clearly erroneous. We may therefore fairly conclude that there are very few irons, if any, with less than 5 per cent of nickel.

The whole question of native iron, meteoric iron, and the nickel-bearing iron ores is somewhat obscure and further research by geologists and mineralogists would be very welcome. It is fortunate for the archaeologist that meteoric iron is, in general, easy to recognize on account of its nickel content, while the cobalt content ranges from a trace to some 3½ per cent. (Rickard, 1932, ii, p. 846). Nickel is not a common element in terrestrial

iron ores and, if present, it is usually in small percentage. For instance, Cuban iron ores may contain from 0·55 to 0·8 per cent. of nickel, and 1·17 to 1·51 per cent. of chromium. Hence a simple analysis to prove the nickel content will often indicate the origin of the iron. However, this cannot be taken as an invariable rule. Professor R. J. Forbes (1950, p. 380) says that there are some natural nickel-iron compounds of rare occurrence to be found in New Zealand, the Ural Mountains, and the Piedmontese Alps, also in Oregon, British Columbia, and California. But in general, he thinks that iron ores and the iron produced from them will not contain nickel, or only to a possible maximum of 2·5 per cent. On the other hand, I am indebted to Mr. P. Whitaker, Manager of Metallurgical Research at Messrs. Stewarts & Lloyds, for drawing my attention to the fact that apparently meteoric iron may also be very low in nickel and cobalt. Herr Otto Vogel of Düsseldorf (1891, p. 470) has pointed out that meteoric iron, such as that found in Hommoney Creek, North Carolina, may be quite low in nickel, cobalt, and sulphur, the analysis in percentage figures being:

Iron 93·225. Nickel 0·036. Cobalt 0·009. Manganese, Trace. Silicon 0·501. Phosphorus, Trace. Sulphur 0·543. Carbon 4·765.

The following figures show that a wide range of analysis of the separate elements contained in meteoric iron has been recorded:

Sulphur	0·08 to 5 per cent.	Phosphorus	0·08 to 1·5 per cent.
Nickel	0·07 to 60 ,,	Cobalt	None to 3 ,,
Manganese.	Tr. to 4 ,,	Silicon	0·02 to 0·8 ,,

With such wide variations in composition, under certain conditions one would expect that there would be difficulty in distinguishing the nature of the iron. Later, we shall see that such difficulty has in fact occurred.

Observed falls of meteorites are not very frequent, and for this reason it has sometimes been supposed that the quantity of meteoric iron available would have been very small. Of course this is true if the comparison be made with the enormous quantity of iron ores in the world, but when we consider the length of time over which meteorites have been falling, the quantity cannot have been negligible. In the British Museum collections alone there are probably several hundred meteorites which have fallen within the last hundred years, and these can be only a fraction of those which fell all over the world during the same period. Concerning the size of meteorites, they vary from large masses weighing many tons,

down to small pellets or even dust. Dr. Rickard (1941, pp. 58 ff.) mentions the following large meteorites. Three meteorites examined by the American explorer Robert Peary at Melville Bay in 1894 were named by the Eskimo the Tent (of 36½ short tons in weight), the Woman (3 tons), and the Dog (966 pounds). The Woman meteorite had been much used by the Eskimo so that it originally may have been twice as heavy. In 1913 a fourth meteorite of some 8 tons in weight was recorded from about ten miles north-east of the other three on the Cape York promontory. Analyses gave the composition of the three meteorites as:

Iron 91·47 per cent. Nickel 7·78. Cobalt 0·53. Copper 0·016. Phosphorus 0·188 per cent.

The Rodeo meteorite, discovered in 1852 on the Nazas River in Mexico, weighed 97 lb., and was used for many years as an anvil. It contained 8·79 per cent. of nickel with 0·28 per cent. of cobalt. At Descrubidora, in Mexico, a meteorite was found which weighed 1,265 lb. and contained 8·05 per cent. of nickel, and at Catorze in Mexico there was a meteorite of 92 lb. In Argentina, the Otumpa meteorite originally weighed 8 tons and had a nickel content of 5·11 per cent. What Rickard states to be the largest of all known meteorites is that of Hoba in south-west Africa. The estimated original weight was approximately 88 tons. The nickel content is high, 16·24 to 16·76 per cent., cobalt 0·76, and copper 0·03 per cent. In Europe and Asia the recording of meteorites does not seem to have been at all complete. Wainwright (1936, p. 6) remarks upon some of the more famous ones and others are quoted by Rickard in his paper on the use of meteoric iron. Others from Europe and Asia are given in Table I, which has been extracted from Zimmer's very complete list of the known falls of meteorites (see p. 36).

There can be little doubt that a great number of meteorites have never been observed or found and therefore remain unrecorded.[1] It has been estimated, although any such estimate can only be very approximate indeed, that between 100 and 400 meteorites may fall every year. We cannot, of course, estimate what proportion of the total number of meteorites which fall contains a useful quantity of nickel-iron. The known finds of meteoric iron are related in some measure to population density, and

[1] In the *Illustrated London News* of 8 August 1953 it is reported that two large meteorites were being studied by the Special Meteorite Committee of the U.S.S.R. It is stated that the Tunguska meteorite fell in Central Siberia in 1908, but was not studied until after the October revolution. In 1947 a huge meteorite burst in the air in the Sikhote-Alin district north of Vladivostok and fell as a shower. One hundred and twelve craters were found, yielding fragments varying in size from 1 ton 14 cwt. to one of 0·18 grams.

a similar factor may well have influenced the utilization of the metal. Certainly, there is an apparent scarcity of meteorites in the Old World.

THE WORKING OF METEORIC IRON

Before discussing such meteoric iron as is known from prehistoric contexts it is well to take another side of the question into consideration, that is, the difficulty or otherwise of working meteoric iron. While this iron cannot be said to be an easy material to make use of, it has been proved that some use was made of it by prehistoric man, and some examples of its use by modern primitive people are of value in showing how the iron was worked. With primitive tools it would be very difficult, if not impossible, to obtain or work pieces of meteoric iron of any considerable size. In Greenland the Eskimo had iron knives, but the blades were not as a rule made in one continuous piece as in a modern knife, but consisted of a number of small segments of iron set in a groove formed in a handle of bone or ivory (Fig. 2, and pp. 177–9). Concerning the actual process of detaching small pieces of iron from the parent meteorite, the Eskimo hammered narrow edges or ridges of the mass with stone hammers until small flakes, of about 1 centimetre in diameter, were detached. The time and labour required must have been enormous; indeed, Rickard mentions that the 'Woman' meteorite, which had been used by many generations of Eskimo, had accumulated around it a pile of stones, some 18 to 20 feet in height, which had been used as hammers. Analyses have proved that the North American Indians also used meteoric iron; tools and ornaments were found in the Turner mounds in Ohio. Copper tools would be of little help in detaching pieces of iron from a large meteorite, but apparently copper was sometimes used for wedges in an endeavour to split off fragments from a large mass. Such was the case with the previously mentioned Descrubidora meteorite where a broken copper

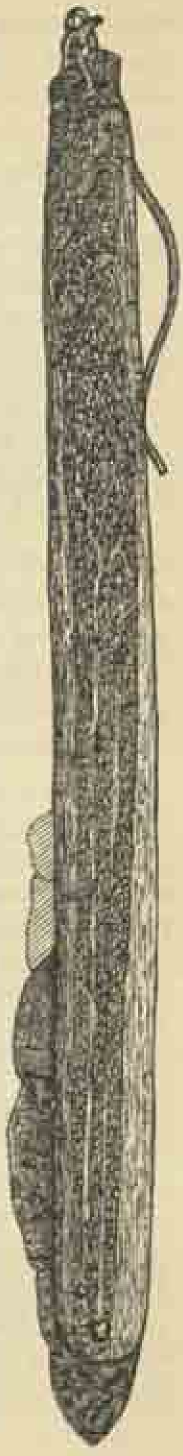


FIG. 2. Eskimo knife of small pieces of meteoric iron set in walrus ivory, collected by Captain (later Sir) John Ross, R.N., on 13 August 1818 from Prince Regent's Bay, North Greenland, now in the Pitt Rivers Museum. (See pp. 177–9.)

chisel was found wedged in a gap in the meteorite. Also a chisel of native copper was found stuck in a cavity of the Catorze meteorite. Smaller meteorites would no doubt have proved more suitable to the methods available to prehistoric or primitive man.

As Rickard (1941, p. 62) says:

> Some siderolites, partly stone and partly iron, such as those of L'Aigle and Estherville, consist of pieces of iron enclosed within a stony matrix, commonly a hypersthene-olivine complex, from which the useful metal can be detached easily by hammering. In these stone-iron masses, known as pallasites, the iron is embedded like raisins in a pudding, and can be detached with comparative ease. Occasionally the stony matrix has become so much decomposed and eroded as to cause projecting points of iron to become detachable. These thorny masses of rock would attract the attention of primitive man. A loose fragment might yield a piece of flat iron already pointed and ready for use.

Some confusion has been caused by statements to the effect that meteoric iron is not malleable. Such general statements are not correct, and while meteoric iron may not be so malleable as a modern mild steel, there is no technical reason for doubting that it is often malleable. As Zimmer has pointed out, the nickel which is always present in meteoric iron cannot impair its malleability because nickel itself, or nickel as an alloy with iron, is malleable. Zimmer says:

> It is well known that the artificial alloy of iron and nickel (nickel steel) combines the ductility of homogeneous iron (fluss iron) with the advantages of hard steel, and is the best kind of modern iron. Wolf, who first introduced artificial nickel-steel, brought it on the market as 'Meteor Steel'. The addition of only one per cent. of nickel renders the iron hard and tough, up to three per cent. improves the alloy (modern armour plates contain, by the way, 3¼ per cent. of nickel, and do not crack even when deeply penetrated by a projectile), and with more than 9 per cent. the nature of the alloy gradually changes from that of nickel-iron into that of nickel.[1]

On the other hand, there is no doubt that some meteoric iron is exceedingly tough and difficult to cut. Some interesting research by new methods upon the microhardness testing of meteorites has recently been carried out by F. K. Dalton (1950, pp. 1–11 and 185–95; 1951, pp. 77–78) who, when cutting a specimen which had fallen near the Canyon Diablo crater in Arizona, destroyed eight special hacksaw blades where two should have sufficed. This agreed with Foote's experience in 1891, when he destroyed several chisels and a grindstone in his attempts to cut some of these meteorites. After Dalton's first specimen was polished,

[1] See pages 177–9.

small areas with a tarnished appearance could be seen spread over the section. These small areas were found to be extremely hard. Upon this point Dalton remarks:

> The hexahedrites are quite consistent at about 180 on the Knoop scale. Kamacite in the octahedrites, having higher nickel, has hardness of approximately 260 while the still higher nickel-iron of taenite borders in octahedrites is much harder, ranging from 430 to 750. These materials may be compared with well known artificial steels, as follows, and it will then be seen that the natural steels are of very high grade indeed.

Structural Steel	170	Knoop hardness.
Spring Steel	290	
Tool Steel, annealed	305	

Dalton also found inclusions of great hardness in meteorites. For instance, schreibersite in Canyon Diablo specimens ranged from 1100 to 1360 Knoop hardness. Harder still were carbonados, or black diamonds, discovered on several occasions. In view of these results, the difficulty experienced in cutting certain meteorites is explained, and specimens containing inclusions of such extreme hardness must have been valueless to prehistoric or primitive man.

If a piece of meteoric iron of suitable size and shape was not found ready to hand, it would be necessary to forge the iron. Here difficulty may well arise. As we have seen, there is no doubt that the nickel-iron obtained from meteorites is of much superior quality and strength as compared with primitive wrought iron obtained by direct smelting. On the other hand, the nickel-iron would almost certainly be more difficult to forge. Richardson (1934, p. 574) made certain experiments in the forging of meteoric iron which point to the process as not being an easy one. The experiments were carried out on eleven small pieces from the San Angelo meteorite, a medium octahedrite, of which the analysis was:

> Iron 91·96 per cent. Nickel 7·86. Carbon—Manganese—Silicon 0·011. Phosphorus 0·099. Sulphur 0·032. Cobalt—Copper 0·04 per cent.
>
> Hardness, approximately 250 Brinell.

Richardson first experimented with melting of the material, but to us melting is not of interest in connexion with the early use of meteoric iron, for it could never have been carried out owing to the high temperatures required. In the forging experiment a piece weighing 66 grams was heated to a medium cherry red (1,250° F.), then reheated to light cherry (1,550° F.), and to salmon (1,650° F.). It was then forged on an anvil with a ballpene hammer. The iron was found to be ductile and yielding

under the hammer, but in forging it showed a tendency to open up along the boundaries of the kamacite plates. With the temperature increased to a welding heat (2,200° F.), it was found that the metal would not weld or flow into a solid piece because of cracking along the cleavage planes. Concerning these experiments Richardson says that it is perhaps reasonable to conclude, if conclusions are possible from a single experiment, that most of the hexahedrites and many of the medium octahedrites were beyond the simple technique of primitive man. Long prior to Richardson's experiments, Dr. Beck (1892) had experimented with a piece of the meteoric fall from Toluca, Mexico. Beck's first experiment was unsatisfactory for he found that, while the material was ductile when cold, it would not adhere under welding heat and broke up under the hammer. In a second and later experiment Dr. Beck obtained a satisfactory result. He found that the iron worked well under the hammer at a moderate welding heat and the piece was forged into the form of a small rod, and this rod of meteoric iron was welded to a similar rod made of ordinary iron, a sound weld being obtained. Beck attributed the failure of his first experiment to penetration by moisture along the crystalline surfaces of the meteoric iron so that thin films of rust prevented adherence when an attempt was made to weld the material. Zimmer (1916, pp. 315–16) also quotes experiments by other workers which confirm that a high proportion of meteoric iron is both malleable and may also be welded.

ARTEFACTS OF METEORIC IRON

We may now examine what is known of meteoric iron artefacts in prehistoric times. Unfortunately the list is a short one, and is no doubt incomplete. After all, as the Eskimo worked and used meteoric iron with very primitive equipment, we cannot deny that prehistoric man may well have done the same thing, indeed we have proof that this was so. First, we have the iron beads which Wainwright (1936, p. 7) found at Gerzah in Egypt, about fifty miles to the south of Cairo. The beads were in two groups, roughly contemporary at S.D. 60–63, and analysis showed the metal to contain 7·5 per cent. of nickel, clearly proving their meteoric origin. In the XVIIIth-dynasty tomb of Tutankhamun were several iron objects, a dagger, miniature head-rest, an amuletic eye, and sixteen miniature implements (Lucas, 1948, p. 272). We cannot tell if this iron is of meteoric origin as an analysis has not yet been made; in view of the advanced date, and the fact that Lucas mentions that the head-rest has been badly welded, we take the view that this iron

is of terrestrial origin and was an import into Egypt. Certainly of meteoric origin is a small amulet which has a silver head and an iron blade. This amulet is from Deir el Bahari, in Egypt, and is of the XIth dynasty. The iron blade was analysed by Professor Desch and found to contain 10 per cent. of nickel (Lucas 1948, p. 271, and Desch, RBA 1936, p. 309). Several other finds of early iron in Egypt have often been quoted, but as there appears to be considerable doubt about their origin and dating, it would be unwise to include them in our list.

In one of the Royal Tombs of Ur in Mesopotamia, Sir Leonard Woolley found some fragments of iron (Peake, 1933, p. 641, and Desch, 1928). These fragments contained 10·9 per cent. of nickel, and were therefore of meteoric origin. There are two objects from Treasure L of Troy II or III, but doubt was expressed whether these pieces were really iron, and analyses were therefore carried out in the Königliche geologischen Landesanstalt und Bergakademie in Berlin, whose director, Professor Dr. Finkener, was of the opinion that the pieces were not metallic iron, but a mineral ore. The analyses (Dörpfeld, 1902, p. 423) show a nickel content of 2·44 and 3·91 per cent., and do not appear suitable to derive from any of the ordinary iron ores. On the other hand, the analyses do not appear to be those of meteoric iron. Hence, it is unwise to consider that the Treasure L find is of meteoric origin. It is also significant that artefacts of relatively low nickel iron have been recorded from period III of Alaca Hüyük. These are an iron pin with gold-plated head, Al/a, MC 34, and a fragment of a crescent plaque, Al/a, MC 33. Both objects have been analysed with the following results (Koşay, 1944, p. 189):

Al/a. MC 34. Pin.		Al/a. MC 33. Plaque.		
	72·20 per cent.		76·30 per cent.	Fe_2O_3
	3·44 ,,		3·06 ,,	NiO.
	4·69 ,,		0·99 ,,	CaO.
Total	80·33 ,,		2·65 ,,	Al_2O_3
		Total	83·00 ,,	
By calculation		By calculation		
	94·92 per cent. Fe.		95·7 per cent. Fe.	
	5·08 ,, Ni.		4·3 ,, Ni.	

In view of the above figures it is possible that a low-nickel meteoric iron is here in question. Przeworski (1939, p. 143) says that there were early finds of meteoric iron from a Tholos near Platamos, and at Mavro Spelio, but he does not comment on the nickel content. Peake (1933, p. 641) mentions that in 1927 a cube of iron was discovered at Knossos

in Crete in a Middle Minoan grave dating from about 1800 B.C. It had evidently been regarded as a precious object, and is likely to be of meteoric iron. The same is probably true of the iron finger-ring, believed to date from 1550 B.C., found at Pylos in the Peloponnesus.

In the case of artefacts of the lower nickel ranges, unless there is careful metallographic examination as well as the analyses, a certain confusion would appear possible because of the mineral pyrrhotite (an iron mineral which occurs in grains or massive form impregnating metamorphic or crystalline rocks). For example, concerning the important Ras Shamra axe (see my p. 63), the analyst Leon Brun said (Schaeffer, 1939, p. 110): 'The axe-body is steeled iron. The very oxidized iron in the mass contained no trace of manganese. Also no chromium, copper, tellurium, or vanadium, were found.' At first Brun thought the iron was meteoric, but the analysis and the microscopic examination showed that the iron was probably made from pyrrhotite, a magnetic material containing from 2 to 5 per cent. of nickel. Examination of the impurities supported this opinion. On the other hand, Dr. Witter did not agree with this view. In his opinion (1942*b*, p. 55) pyrrhotite is a magnetic pyrites which contain about 60 per cent. of iron and about 40 per cent. of sulphur. Since many magnetic pyrites contain some nickel (from a weak percentage up to 5·6 per cent.), this mineral is used to obtain nickel. Up to the present this sulphur-iron ore has not been used for the production of iron, and in prehistoric times that would have been quite impossible. Witter thinks that the iron used to make the Ras Shamra axe was meteoric, and from an ataxite without structure, this class of meteoric iron being difficult to distinguish from terrestrial iron. Meteoric iron of similar chemical composition to the Ras Shamra specimen has been found elsewhere.

Here we find two undoubted authorities in conflict concerning a fundamental matter. While we must agree with Witter that it is highly unlikely that prehistoric iron smelters could have made use of the mineral pyrrhotite, unless the whole matter be re-examined we must favour the opinion of the scientist who carried out the research, especially since he was well aware of the possibility that meteoric iron might be in question.

Lower in the nickel range, there is the strange case of the British currency bar examined half a century ago by Professor Gowland (1903–5, p. 194). Two bars, designated *A* and *B*, were examined with the following results:

	Bar A	*Bar B*
Carbon	trace	0·08
Silicon	0·09	0·02

	Bar A	*Bar B*
Phosphorus	0·69	0·35
Manganese	nil	nil
Nickel	0·23	nil

In the report it is stated that 'Sections of bar *A* presented no slag patches such as are universally found in wrought iron, but closely resembled meteoric iron.' Again, 'Bar *A* has hence apparently been made from meteoric iron. The use of meteoric iron must, however, have been quite exceptional.'

While one hesitates to doubt the statement of so eminent an authority as the late Professor Gowland, it is difficult to accept that bar *A* was in fact forged from a meteorite. First, ordinary bloomery iron must have been relatively common when these currency bars were made. Again, in England it may be exceptional to find a meteorite large enough to make a substantial bar, although the Rowton, Shropshire, meteorite weighed 3·87 kg., but here the nickel content was normal at 8·56 per cent. Secondly, the nickel content of the bar at 0·23 per cent. is low for meteoric iron in general. On the other hand, iron with similar nickel content is not unknown. There is the piece of iron from the Saalburg in Germany which contained 0·242 per cent. of nickel (Weiershausen, 1939, p. 227).[1] There may well be other examples of a like nature although, in general, an appreciable nickel content is decidedly rare in primitive iron.

As we have mentioned, the list of authenticated objects of meteoric iron is all too short. Writing as long ago as 1912 (p. 277), Professor Gowland held the view that native iron, whether of meteoric or telluric origin, can have played no part in the rise and development of the Iron Age. In view of the rarity of archaeologically attested specimens of meteoric iron it is difficult to know whether, or to what extent, meteoric iron may have influenced the discovery or development of smelted iron, but, as Wainwright (1936, p. 5) has pointed out, man must have first come to know of iron through meteorites.

We must await further discoveries and analyses of very early iron before we can form an opinion of the degree to which such iron was used in the Old World. From the foregoing it will be seen that, while the available evidence is scanty, it is clear that a certain use was made of meteoric iron during prehistoric times. We have also ample evidence for

[1] See also the spear from Deve Hüyük, Syria, dating around 600–500 B.C., which showed 0·32 per cent. of nickel. See p. 137.

the use of meteoric iron by modern primitive peoples in the New World. In prehistoric times meteoric iron may well have been the first iron known and used, but such knowledge and use can never have constituted anything remotely approaching an Iron Age in any part of the Old World. As we have already mentioned, there were various factors which must have limited the use of meteoric iron. First, there was the difficulty of finding the iron, and in obtaining a piece of suitable size and shape. Having found the iron, there was next the possible difficulty of forging it, but here we must remember that the meteoric iron (at least in certain cases), could have been shaped by means of a measure of cold-working and grinding. Prehistoric people had a long tradition of stone-grinding behind them, and they would not have been slow in applying the grinding technique to the new metal. Again, an even greater limitation must have been caused by the relative scarcity of meteorites, and by the fact that the major quantity most likely remained unrecognized.

TABLE I

Meteorites—Europe and Asia

Extract from Zimmer's table. *J. Iron and Steel Inst.* xciv. n. 2 (1916), 324–35.

Name	Date of fall or find	Original weight in kilos.	Per cent. Iron	Per cent. Nickel	Remarks
AGRAM. Hungary	26 May 1751	48·75	96·5	3·5	Malleable.
ALT-BIELA. Austria	1898	3·9	85·34	12·89	..
ARVA. Hungary	1840	1,700	90·18	3·09	Nearly as hard as steel; yet malleable.
AUGUSTINOVKA. Russia	1890	400	91·91	7·7	Malleable.
AVCE (near Trieste. Austria)	31 Mar. 1908	1·23	..	..	..
BISCHTÜBE. Asiatic Russia	1888	48·75	91·52	7·12	Malleable.
BITBURG. Prussia	1802	1,650 about	..	..	Ductile, even cold.
BOHUMILITZ. Bohemia	1829	47 about	92·47	5·67	Malleable, close and firm.
*BRAHIN. Russia	1810	100 about	88·96	11·04	Malleable.
BRAUNAU. Bohemia	14 July 1847	40·71	91·88	5·52	Dense, tough, and ductile.
*BREITENBACH. Bohemia	1751	10·5	90·43	9·28	Malleable.
ELBOGEN. Bohemia	1400	107	89·9	8·43	Malleable.
FINMARKEN. Norway	1902	77·5	..	..	Resembles the Pallas iron in every way (Cohn), therefore malleable.

Those marked * are siderolites.

Name	Date of fall or find	Original weight in kilos.	Per cent. Iron	Per cent. Nickel	Remarks
Fisterhölzelrics, Bohemia	1909	..	..	..	Malleable.
*Hainholz, Prussia	1856	16·5	..	..	Non-malleable.
Kodaikanal, Madras	1898	15·87	..	..	..
La Caille, France	1828	575	92·5	5·9	Malleable.
Lenarto, Hungary	1814	108·64	90·15	6·55	Malleable.
Rafrüti, Switzerland	1886	18·5	89·87	9·54	Fine-grained iron.
Rittersgrün, Saxony	1833	86·5	..	..	Non-malleable.
Rowton, Shropshire	20 April 1876	3·87	91·25	8·58	Malleable.
São Julião de Moreira, Portugal	1883	162 over	89·39	8·27	Malleable.
Sarepta, Russia	1854	13·33	95·94	2·66	Malleable.
Schwetz, Prussia	1850	21·64	92·01	7·55	Malleable, wrought specimen in Göttingen Museum.
Seeläsgen, Prussia	1847	102	92·33	6·23	Soft and malleable.
Shirohagi, Japan	1890	22·7	93·52	5·92	Malleable. Sword was wrought from a fragment.
Sytromolotovo, Asiatic Russia	1873	220	92·64	7·1	Very soft and malleable.
*Steinbach, Saxony	1751	1,000about	..	..	..
Tabarz, Germany	1854	0·05	92·76	5·69	Malleable.
Tanokami, Japan	1858	172·87	90·11	8·56	Malleable.
Toubil River, Asiatic Russia	1891	21·96	95·14	3·53	Malleable.
Toubil, W. Siberia, Russia	1891	22	95·18	3·88	Malleable.
Tula, Russia	1846	246	93·5	2·5	Malleable, mostly utilized.
*Veramin, Persia	May 1880	51·4	92·06	6·96	..
Verkhne-Dnieprovsk, Russia	1876	0·5	..	..	..
Verkhne-Udinsk, Asiatic Russia	1854	18·5	91·02	7·31	Malleable
Marjalahti (Viborg, Finland)	1 June 1902	44·8	92·28	7·13	Malleable.
*Morradal, Norway	1892	2·75	79·67	18·77	Malleable.
Muonionalusta, Sweden	1906	7·53	91·1	8·02	..
Nagy-Vazsony, Hungary	1890	1·89	..	..	Malleable.
Nedagolla, Madras	23 Jan. 1870	4·54	92·61	6·2	Malleable.
Nejed, Central Arabia	1863	59·8	91·04	7·4	Soft and easily cut with a hack-saw.
Nenntmannsdorf, Saxony	1872	12	94·5	5·31	Soft malleable iron.
Oberkirchen, Germany	1863	41	92·45	7·55	Soft and ductile.
Okano, Japan	7 April 1904	4·73	94·85	4·44	..
*Pallas Iron, Asiatic Russia	1749	750	..	..	Malleable.
*Pavlodar, Asiatic Russia	1885	6	..	..	Malleable.
Petropavlovsk, Asiatic Russia	Prehistoric	7·16	97·29	2·07	Malleable.

Of a total of 287 falls which are given in the complete table, 250 are malleable, 5 non-malleable, and 32 undetermined.

Chapter III

THE SMELTING PROCESS AND THE MECHANICAL PROPERTIES OF IRON

THE SMELTING PROCESS

We may now consider how iron is obtained from the ores which are so abundantly distributed all over the world. Although iron was known and obtained in small quantity from meteorites, it was not until the discovery was made of how to win iron from the ores that the metal could be obtained cheaply and in any quantity desired; in this matter we must endeavour to give some idea of what the smelting process means, and also to avoid confusion between ancient and modern methods. As Straker (1931, p. 16) has so clearly pointed out, there may be said to be two processes, direct and indirect. The direct or bloomery process was that used in general by prehistoric and primitive man. Here the iron is produced in small quantity, and by one operation a sponge iron is obtained, which after simple treatment may be at once forged into the desired tools and weapons. The indirect process, now associated with the blast furnace, produces cast iron and is a complex and recent development of iron founding. Hence, in this work we are concerned almost entirely with the original bloomery or direct method.

In the actual reduction, or smelting, of the iron ore, a chemical change is involved. For the production of iron by the direct process the oxides of iron, such as haematite, limonite, and magnitite, would be suitable. Prehistoric man would not have been able to make use of the sulphide ores.[1] Iron pyrites is not suitable for iron smelting; only in modern practice is some iron obtained from pyrites as a product in the manufacture of sulphuric acid. In the reduction of an oxide ore the chief consideration is to rob the ore of its oxygen and so to obtain metallic iron. If the fuel used in the reduction furnace be charcoal, the carbon of the fuel will combine with the oxygen of the ore and metallic iron is released.

It is practically certain that the fuel used by the first iron smelters was charcoal, hence in a simple reduction furnace the carbon of the charcoal will burn to carbon monoxide, and this gas will take oxygen from the ore

[1] But the work of Professor Pittioni (1951) and others would point to the possibility that the sulphide ores of copper were worked in Austria at least by the late Bronze Age.

to form carbon dioxide. However, a certain balance must be preserved, as Professor Read has stated (1934, p. 384):

> No amount of heat alone will reduce a mixture of iron oxide and iron sulphide to usable metal. When iron sulphide alters to oxide in nature, the reaction commonly proceeds to the end, and a natural mixture of iron sulphide and iron oxide is much less common than a natural mixture of sulphide and oxidized ores of copper and lead. Furthermore, iron sulphide is so soluble in the metal and makes it so brittle that usable iron could not be produced in this way, even if it were otherwise possible. To produce usable iron the metallurgist must employ only iron oxide together with both heat and carbon, the latter performing an essential chemical function in the operation. There must be a sufficient excess of carbon so it will burn to carbon monoxide, not dioxide; whenever the ratio of dioxide to monoxide rises above a number that varies with temperature, metallic iron reoxidizes. The primitive metallurgist never understood this role of carbon in iron production; he merely knew that if he did things in a certain way he got a certain result. All the early attempts to produce metal from iron oxide must have ended in failure until it was empirically discovered that sufficient excess of carbon must be present to keep the carbon dioxide concentration down to where the reduction of iron oxide to iron can take place.

Within reasonable limits, a high furnace is more efficient for smelting than a low one; the reason being that the chimney effect of the high furnace gives the carbon monoxide gas a better opportunity to act upon the ore. Also, the success of the primitive smelting operation largely depends on a charcoal fuel and on the exclusion of oxygen from the ore while it is being smelted. The temperature at which reduction takes place has an important bearing on the smelting process. In general, reduction may be obtained at temperatures as low as 700 to 800° C., but as Richardson (1934, p. 577) has pointed out, when iron oxide is reduced at temperatures below 900° C., a dark grey and very porous substance is formed which would be impossible to forge. With temperatures in the range of 1,000° to 1,050° C., the result of the smelt will be a loosely coherent mass which would be exceedingly difficult, if indeed possible, to forge. Not until the temperature range is increased to 1,100–1,150° C. does the iron begin to flow together forming a pasty, semi-fused, and somewhat porous mass; this is a bloom, and it may be worked and forged so as to give the well-known wrought iron of early times.

From the above considerations it follows that, if we are to obtain a useful bloom of iron, sufficient temperature in the furnace and a good reducing atmosphere with the exclusion of oxygen from the ore are essentials. Again, the primitive reduction process was wasteful in material.

Much charcoal fuel was used, and much of the iron was lost in the slag. Forbes (1950, p. 393) mentions that in furnaces of the type found near Tarxdorf, in the Tyrol, Schmaltal, a semi-fused bloom of about 50 lb. in weight demanded the consumption of some 200 lb. of charcoal, plus another 25 lb. of charcoal for the subsequent forging operation. Also, starting with a charge of about 300 lb. of ore the founder would only obtain something like 25 lb. of fairly good iron. Concerning the loss of iron to the slag, Forbes points out that one of the main difficulties is the gangue of the ore. The gangue of an iron ore is largely siliceous, and the silica of the gangue combines in the furnace with part of the ferrous oxide of the ore to form a fusible slag. In the primitive direct process the slag does not separate easily, and a high proportion of the iron is lost in the slag. In modern practice lime is usually added to the charge as a flux. The flux renders the slag far more fusible, so that it readily separates from the iron. Hence, productive efficiency is greatly increased by the selection and use of a suitable flux. It is interesting to note that so rich in iron were some of the ancient slags that they have been reworked with profit in recent times.

FLUXES

As the matter is of such importance in the smelting process, we must endeavour to make clear the nature and use of a flux for iron smelting. A furnace charge of ore and fuel will usually contain more or less extraneous matter. To separate and get rid of this extraneous matter certain materials known as fluxes must be added to the furnace charge so as to form a slag. To give an idea of the various fluxes which will serve the purpose, we cannot do better than quote the principal earthy fluxes, as used in modern practice, given by Professor Roberts Austen (Austen, 1923, p. 295):

(*a*) Lime, which acts as a powerful base for removing silica. Lime is used in a pure state or as carbonate. Limestone is largely used in iron smelting as most iron ores contain an excess of silica. Dolomite, the carbonate of lime and magnesia, is specially useful.

(*b*) Fluorspar (calcium fluoride), which is a useful flux for ores containing silica, barytes, or gypsum. With the two latter it easily fuses. It is also used in the open-hearth furnace to increase the fluidity of the slags and for the removal of sulphur.

(*c*) Barytes, which acts as a powerful base and it is a good sulphurising agent. In the concentration of nickel speise, the copper present with the speise is removed and a regulus formed.

(*d*) Alumina-bearing rocks, such as clay-slate, are used in smelting ores which are very rich in lime, but as a rule the charge is so mixed that argillaceous and calcareous ores are present in suitable proportions.

(*e*) Siliceous materials, such as quartz, natural silicates, siliceous slags, are used when the ores contain an excess of basic materials that have to be removed.

(*f*) Oxides and carbonates of iron, basic iron slags, &c., are used in the smelting of siliceous ores, especially of lead and copper.

From the above it will be seen that, in modern practice, the flux may be adjusted to the nature of the charge with considerable accuracy. For primitive working, some archaeologists quote the use of lime as a flux, and indeed one would consider lime as the flux most probably used at an early stage in the evolution of smelting. May (1904, p. 13), however, did not consider that it was in use at Warrington even during Roman times. In his view,

> the result of many analyses of iron and slag from the small reverberatory furnaces, sow kilns and bloomeries of the Roman period proves that lime was not used as a flux to extract pure iron from the ore as in modern practice. The Roman blacksmith (Faber Ferrius) chose the easier method of conveying the red-hot spongy mass to the anvil with a long pair of tongs and expelling the last dregs of impurity by repeated blows of a heavy hammer. The sparks which fly in all directions from the anvil when a blacksmith is at work consist of impure iron and slag, and when the sparks cease to fly the workman knows that his iron has 'come to nature' and can be converted into steel by cementation and tempering.

SLAGS

The refuse from the smelting process are known as slags, or, expressed in more technical language (Austen, 1923, p. 296), 'the silicates formed in metallurgical processes by the combination of silica with the earths and metallic oxides are termed slags'.

According to Roberts Austen, the bases (mostly combined with silica) which are formed in silicate slags are lime, alumina, magnesia, rarely ferric and manganic oxides, ferrous oxide, &c. Further, there are certain oxides and earths, such as those of zinc oxide and alumina which interfere with the fluidity of the slag and would therefore hinder the primitive smelter. Perhaps a clearer definition of a slag is that given by Alexander and Street (1946, p. 187): 'glass-like compounds of comparatively low melting point, formed during smelting when earthy matter contained in an ore is acted on by a flux. If the earthy matter were not deliberately so converted into slag it would clog the furnace with unmelted lumps. The

fusibility and comparatively low density of the slag provides a means by which it may be separated from the liquid metal.'

With our modern methods of iron production, slags with varying physical and chemical properties are produced as furnace refuse, some of which is used commercially. In prehistoric times no use was made of the slag. In the Weald of Kent, however, the Romans did make use of slag for road foundations. Modern uses are for railway ballast, tar macadam, cement, fertilizers, and slag wool for heat insulation. As the refuse or slag from an iron-smelting furnace is practically indestructible, the examination of such slag is useful in various ways. First, it often leads to the discovery of the smelting site which would otherwise possibly never be found. Secondly, the slag gives us a good indication of the ore used and of the smelting process in force. Further, analysis and examination of the slag will, in many cases, allow the approximate period of the smelting operations to be determined. Certainly prehistoric or Roman slag may be differentiated from the modern slags. It is, however, dangerous to attempt a chronological dating of slags by inspection of their external quality. The quality and appearance of a slag depend upon various factors of the furnace technique. Many furnaces of the Middle Ages have produced slag similar to that produced by prehistoric furnaces.

Straker has shown the value of such study by means of analysis and micro-sections of the Wealden iron slags. The following table (Straker, 1931, p. 94) is of particular interest in showing the composition of a bloomery slag or cinder from the 'ox-bone', North Wood, Guestling, and of the extreme variations of analyses from other localities.

North Wood	*Per cent.*	*Others (per cent.)*
Silica	32·4	29 to 38
Alumina . . .	7·1	2 to 7
Iron Oxide . . .	53·4	31 to 59
Manganese oxide . .	1·8	2 to 12
Lime	3·2	2 to 8
Magnesia . . .	1·3	1 to 3

The limits given by Straker can be exceeded, as witness the analysis of a prehistoric or Roman slag from the excavations at Blewburton Hill, Berkshire, in May 1950. The analysis was made for the Royal Anthropological Institute, Ancient Mining and Metallurgy Committee, by Messrs. Alfred Herbert, Coventry.

Silica (SiO_2). 10·15 per cent. Phosphorus Pentoxide (P_2O_5). 0·96 per cent.
Sulphuric Anhydride (SO_3). 0·08 per cent. Lime (CaO). 5·70 per cent.
Magnesia (MgO). 0·40 per cent. Alumina (Al_2O_3). 1·10 per cent.
Manganous oxide (MnO). Traces. Titanium Dioxide (TiO_2) Traces.
Copper, nickel, zinc, cobalt. Not detected.
Ferrous iron (calculated to FeO). 61·54 per cent.
Ferric iron (calculated to Fe_2O_3). 19·69 per cent.
Total iron (calculated to Fe). 61·79 per cent.
The sample is slightly magnetic.

During the course of excavating Roman iron furnaces and forges at Wilderspool and Stockton Heath, near Warrington, T. May devoted considerable attention to the iron slags (1904, pp. 20 ff.). Three of these analyses are given below:

Slag from Iron Furnace I. Wilderspool

Silica	59·65
Alumina	13·41
Manganic oxide	0·20
Ferrous oxide	18·14
Ferric oxide	3·84
Phosphoric acid	0·48
Iron pyrites	1·46
Carbonaceous matter and moisture	3·18
	100·36

Slag from Hearth II. Wilderspool

Ferrous oxide	51·80
Ferric oxide	6·73
Manganese	0·26
Alumina	5·20
Lime	3·00
Magnesia	1·17
Silica	28·07
Phosphoric acid	0·43
Sulphuric acid	0·19
Organic matter and water	1·70
	98·55

From Refining Furnace I

A small globule of cinder from the wall of the furnace, underneath the calcined lining.

Silica	73·800
Ferrous oxide	17·5
Ferric oxide	1·2

Alumina	1·7
Magnesia	0·55
Phosphoric acid	0·724
Sulphuric acid	1·650
Alkalis, &c.	2·876

Mr. Ruddock (Public Analyst, Warrington), inferred that such a slag as this would be obtained by reducing an ore containing appreciable quantities of phosphorus and sulphur. May also remarked:

(1) The composition of the slags varied from about 80 per cent. of silicate of alumina and other impurities and 20 per cent. of oxides of iron to about 75 per cent. of the latter and 25 of impurities.

(2) The small proportion of lime present in the slags shows that it was merely an accidental impurity, and was not added intentionally as a flux.

(3) The quantity of alumina in the slag and a large number of specimens prove that clay-band ores were principally used.

(4) Pure silica in the form of pounded white quartz pebbles appears to have been added as a flux (for the haematite ores), the black glassy specimens of slag when pounded being found under the microscope to contain a large proportion of these white particles, with occasional lumps half an inch in diameter.

These few analyses of various slags are instructive in showing the wasteful results of early iron working processes, and in some cases the exceedingly high loss of iron to the slag. The Warrington analyses are also interesting as an indication of the widely varying properties which may be found in slags even when found at the same site. May's view that the lime present in the Warrington slags was an accidental impurity should be considered in the light of the low figures (2 to 8 per cent.), quoted by Straker. Lime is usually accepted as an intentional flux in the earlier processes, but this is a matter which could be investigated further with advantage. The wasteful results of the early processes, involving heavy loss of iron to the slag, were again noted by May at the Golf Links site at Tiddington, Stratford-upon-Avon (Fieldhouse, May, Wellstood, 1931, pp. 11–12). Here 53 per cent. of iron oxide remained in one sample of furnace slag while a piece of fettle, or fused lining from a smelting furnace, showed 44·4 per cent. of contained iron. Further results may be found in an interesting table of analyses of prehistoric iron slags given by J. W. Gilles (1936, p. 258), in his work on the prehistoric iron smelting in Siegerland, Germany. Some figures for Etruscan iron slag will be found in Witter (1942*a*).

THE DISCOVERY OF IRON

As we shall see later on, the discovery of how to obtain iron by means of smelting the ores was made at a very early date. It has not yet been established how, where, and when this discovery was made. It is not an entirely simple matter to explain how the discovery of smelting may have been made, and the complete answer to the problem of the discovery is highly unlikely to become known. An old theory to account for the accidental discovery of smelting is that of the camp-fire, but this is clearly an over-simplification. It has often been asserted that iron is not a difficult metal to smelt, and that if a suitable piece of iron ore, such as haematite, was accidentally placed in a large and hot camp-fire, reduction would take place, so leading to the discovery of iron smelting. From technical considerations it seemed to the author unlikely that the camp-fire was the birth-place of iron smelting, and to test the matter a number of experiments were carried out (Coghlan, 1941, pp. 76–77). A number of charcoal fires were made to simulate camp-fires and various pieces of iron ore, haematite, limonite, &c., were embedded in the heart of the fire so as to give the experiments every chance of success. However, no matter how large and hot the fire was made, it was found impossible to obtain a true reduction of the ore. In most of the experiments it was found that the ore had merely been roasted; once or twice, when an almost complete smother-furnace had been made, it was found that the ore had been converted into a cinder-like form which powdered to dust when lightly hammered. Nothing in any way resembling a sponge iron was obtained, nor indeed anything which could have been recognized by prehistoric man as appertaining in any way to iron or other metal.

Again, the difficulty of accidental smelting in an open fire has been pointed out by Dr. Rickard (1939, p. 86), who said, 'The iron ochres, which are the minerals limonite, goethite, and haematite, could be a source of metal if smelted in a hot charcoal fire within a closed vessel, but, as has been suggested previously, the accidental product from such a reduction in the open air would be so strange as to be unrecognizable as metal to the early metallurgist, and so imperfect as to be of no use to the primitive artificer.' Quite apart from the question of the discovery, accidental or otherwise, iron is not an easy metal to smelt without an adequate knowledge of how to do it. In this connexion Richardson's opinion as a technician must carry weight (1934, p. 575). He said that

it is not so simple as many modern writers seem to believe, to reduce iron in a shallow hole either with or without an artificial blast. A series of ten unsuccessful attempts had convinced Richardson of this fact. In only two of the ten experiments was there evidence of reduction and the process appeared incomplete in the one, while the other was over-carburized. Lack of success does not mean that it cannot be done. But would that conviction be equally strong where there had been no prior experience? To summarize, we may say that there are three important factors in the production of a useful metal by the direct process:

(i) The ore to be smelted must be sufficiently protected by the fuel-bed against rapid oxidization which would be caused by contact with an excess of air.
(ii) Some form of smelting furnace is required. The furnace may be with, or without, forced or induced draught.
(iii) The furnace temperature must be high enough to enable the metal to reach a semi-fused or plastic condition so that a workable bloom be obtained.

It appears possible that certain pottery furnaces may have played a part in the discovery of smelted iron. First, it is clear that at a period well before the knowledge of how to smelt iron was discovered, there were developed pottery furnaces which could have attained the temperature necessary in order to reduce an iron ore. For example, some of the Tell Halaf pottery was fired at high temperature, from 1,000° to 1,200° C. (Speiser, 1927–8, p. 50). Concerning actual furnaces, large and elaborate pottery kilns have been discovered at Uruk, and at Susa in the second period. Again, in the levels of developed Tell Halaf and Samarra pottery at Arpachiyah, pottery kilns with domed roof and central pillar were discovered by Mallowan (1935, Pl. XXXI*d*). In such furnaces we know that the desired temperature could have been reached, and that the atmospheric conditions in the furnace could have been made reducing or oxidizing at will. Red ochre, or red oxide of iron, is a conspicuous and exceedingly widely distributed mineral, and we know that it was used by prehistoric man from Upper Palaeolithic times onwards; we also know that the red oxide was very widely used for the decoration of pottery from early times in western Asia. The point is worth consideration that, should some red ochre have been in one of these high-temperature kilns, and the atmospheric conditions in the kiln were favourable (that is, favourable to the reduction of the red ochre, but probably not the conditions desired for the production of fine high-baked pottery), a reduction

of the ochre to metallic iron may have taken place. An interesting association of the pottery type of kiln with iron smelting in very much later times is worthy of mention. Miners quarrying iron ore for the Frodingham Company in Lincolnshire close to the hamlet of Woolsthorpe, in the parish of Colsterworth, found a remarkably perfect furnace or bloomery of the Roman period (Hannah, 1932, pp. 262–8). The natural soil (Upper Lias) is the ironstone which was being quarried. The furnace has marked affinities with a Roman pottery kiln, but it is to be noted that tuyère holes were provided, apparently for the purpose of blast. When found, the furnace was nearly empty. At the south-eastern end were abundant pieces of charcoal, much wood-ash, and partly reduced fragments of ironstone with apparent slag runnings on their surfaces. The ironstone was of excellent quality. One small piece of almost pure iron came to light, and more iron was found near to the furnace. An examination by A. E. Musgrave of a specimen of iron found embedded in the accumulation of wood ash and charcoal near the withdrawal end of the furnace showed that the specimen exhibited slag inclusions, and examination under the microscope gave support to the view that the iron was produced through the direct reduction process. A half-size model of the furnace is preserved in the Grantham museum. This discovery lends support to the theory that iron smelting may have an association with the pottery kiln.

On the other hand, it is perhaps rather labouring the question to associate the pottery kiln too closely with the question of the discovery of iron smelting. The following points are relevant to the problem:

(i) That the discovery of iron smelting was preceded by a long tradition of copper smelting, and that by the time iron was discovered, prehistoric metallurgists had become highly skilled in, and had a very adequate knowledge of, copper smelting.
(ii) That the knowledge of how to construct and operate large, high temperature furnaces had long been in existence.
(iii) That it is not altogether unusual to find a deposit of rich iron oxide in the weathered outcrop of a copper lode (Rickard, 1932, ii, p. 837).

As an experienced engineer in the metal industry, Dr. Witter's opinion upon technical problems must be given due consideration (1942*b*, pp. 69–73). He considered that there is no doubt that the first intentional production of iron from ores was extremely difficult and laborious. Such a difficult operation as the first development of the iron technique could only have been undertaken by people who were familiar with the produc-

tion and working of copper and bronze. Where iron first appeared, there must without doubt have existed a well-developed metallurgy. At a very early period it may have occurred that, here and there, copper smelters accidentally won iron in small quantity but did not know how to make use of the soft iron. Perhaps the copper-smelters accidentally, or for curiosity, collected haematite (which may outcrop in a copper-mining region), and which somewhat resembles in colour and weight the copper ore cuprite, and smelted the haematite. This would give them, instead of the soft red copper, a poor-looking black product that the copper-smiths would have tested to see if it was of any use. However, the iron with its slag and charcoal inclusions could only be forged and consolidated with great difficulty so as to yield a very little workable iron which could not be cast or hardened. It was therefore regarded as a costly metal without practical application in everyday life. Again, Witter says that copper pyrites is often associated with spathic iron ore. Here, there is a possibility of accidental iron production as a *Bär* or *ofen-sau*. Such production would belong to a later period for it depends upon a preliminary roasting process, and a high-temperature shaft furnace as well.

Taking the evidence at present available, the author inclines to the view that the discovery of iron smelting was most likely due to the accidental smelting of some iron ore, such as a haematite, found in the weathered outcrop of a lode which was being worked for copper. Should this have happened a number of times, there is no doubt that competent smelters would realize that they had found a new kind of ore which gave a very different metal from the copper to which they were accustomed. The question of why the iron industry took so long to develop after the initial discovery is an interesting matter which will be mentioned later.

ORES OF SUITABLE NATURE

Before leaving the subject of smelting a few words may be said concerning which ores are suited to working by the primitive process, for although iron ore is to be found in almost every country, for the discovery of iron and the development of an iron industry it follows that the ore must be of a nature well adapted to a rudimentary technique. In other words, it is more the kind of ore than the quantity or quality which is the important factor. In certain regions an obvious lack of technical ability renders it unlikely that such places would have been responsible for the discovery and growth of an iron industry. Again,

given suitable iron ore, one would expect the discovery of iron to have been made in a locality where a sophisticated copper culture was already in being. Small and scattered objects such as rings, beads, &c., cannot be considered as evidence for a true iron industry or, to use a modern term, true production. The first indication of a real industry would be the appearance of iron tools, weapons, and implements in some quantity.

Iron ores vary considerably in their richness and suitability. For example, magnetite when pure has an iron content of around 72 per cent., haematite an iron content of some 70 per cent., and spathic ore (siderite), a content of 48 per cent. Many ironstones are very much lower in iron than these; for instance, the Frodingham stone of north Lincolnshire is decidedly low in grade, the iron content when pure being only 22·7 per cent. This ore has, however, the important advantage of being self-fluxing owing to the large proportion of lime present in the earthy matrix of the ore. The Sussex ore may be cited as an ironstone which occurs in nodules and thin seams in a clay formation. Here again the matrix contains the lime which is needed as a flux. In his paper which we have already quoted Richardson makes some interesting observations regarding the suitability of various ores for primitive smelting. Of the spathic ores his opinion is that, once it had been discovered that spathic ores were reducible, it would follow that the process would be applied to the more difficult haematites and limonites which are so widely distributed, but the resulting iron would lack the consistent quality of that made from spathic ore. Again, an important point in favour of the spathic ores is that the acids and bases are more nearly balanced in the spathics than in other ores, and this is of considerable help in smelting under the direct reduction process. We must notice, however, that the spathics require a roasting operation prior to the actual smelting. Some writers have considered that early iron workers may have smelted ferruginous river sands, but such a source appears an unlikely one for early primitive workers. Richardson (1934, p. 566) has carried out experiments in this matter, the result of which are best given in his own words:

> A series of preliminary experiments made by the author with black river sands, collected from various arroyas in southern Arizona, show that repeated washings are necessary to remove objectionable amounts of silica and gangue. This carefully done, a fine crystalline ore may be obtained with free iron running between sixty and eighty per cent. The ore particles after washing are so fine, however, that smelting in an open-fired furnace could never be carried out, no matter how carefully the drafts were controlled; hence the deduction that if the Chalybes smelted river sand, as Aristotle asserts, they must have evolved some

form of crucible process. But smelting carefully done in sealed crucibles with the addition of coal, or other carbonaceous material, would yield steel of varying hardness at will of the operator. It is suggested that possibly herein lies a solution of the traditional mystery of the excellence of Chalybean iron.

Przeworski (1939, p. 155) considers that in the prehistoric and early historic iron industry of Anatolia the only ores which would have been used were limonite and haematite, which were to be found in the upper surface. Magnetic iron ore he does not consider to be a suitable material for the early processes. Before 2000 B.C. there would not have been any intentional working of the haematite and limonite deposits and the isolated finds of iron objects point to an occasional gathering of ore. In Przeworski's view the preparation of the ore was as follows. In the primitive process the ore is first aired and the soluble compounds washed away, then follows roasting and crushing of the ore. Roasting (carried out in piles of burning wood), has for its purpose the removal of sulphur. Through archaeological finds we know that it was employed at Svanien, High Caucasus, around 1000–1100 B.C. Alluvial ore, that is, ore collected through natural causes in river beds, &c., needs only a simple washing process prior to smelting. However, Przeworski thinks that roasting and washing were commonly carried out in the Anatolian metal industry at least by the middle of the second millennium B.C. although direct archaeological evidence is lacking. As we have just mentioned, Przeworski postulates a roasting process as early as 1000–1100 B.C. in the High Caucasus, while Forbes (1950, p. 384) considers that washing and roasting of certain iron ores was an ancient practice in the Near East. However, he does not suggest any lower dating for the technique.

When we advance to Roman times there is no doubt that the practice of ore-roasting had become quite common. At Warrington (Wilderspool and Stockton Heath), Mr. May discovered smelting, roasting, and refining furnaces (1904, p. 23). At Stockton Heath clayband or impure ore was used as well as haematite. According to May the Romans as skilled metallurgists were most likely aware of the advantage of mixing these ores in order to obtain a more fusible charge and a better yield of iron, one ore supplying what the other lacked in the form of a flux to run off the combined silica and to set free the iron. Strangely enough the Roman founders at Warrington do not seem to have been acquainted with the use of lime as a flux.

Where it was available bog-iron ore was suitable for smelting with the direct reduction process. Weiershausen (1939, p. 92) points out that,

because of its porous structure, permitting easy access by the reducing gases of the furnace, this ore was easy to reduce and therefore well suited to the technique of the prehistoric smelter. Clark (1952, p. 202) considers that iron ore was widespread in the northern territories of the temperate zone where climatic conditions, particularly during the Sub-atlantic phase, favoured the formation of bog ore. He makes the interesting observation that

> Since the working of bog-iron survived down to modern times as a peasant industry in the northern countries, it has attracted a good deal of attention from Scandinavian researchers, and in Denmark at least has been shown to date back to the beginning of the local Iron Age. It is virtually certain that bog-ore similarly provided the main, if not the only, source of iron during early times in northern Britain.

We are unlikely to be able to determine which of the iron ores was first smelted by prehistoric man. It is of interest to note that Forbes (1950, p. 403), following Quiring, allows the possibility that magnetite was the first ore to be worked. Not, however, as a bloomery process, but as a crucible process and a by-product of the refining of gold.

> The Nile sand, and especially the gold gravels of Nubia, contains grains of magnetite of high specific gravity and an iron content of over 65 per cent. About half the residue of gold washing is magnetite, the grains gathering with the gold dust and nuggets in the residue of the pan. Now the gold was smelted in Egypt in crucibles in a reducing atmosphere using chaff of clover and straw, as the texts tell us. After the smelting a slag rich in iron would collect on the top of the mass in the crucible, a layer of pasty iron would form the middle course directly over the liquid gold. If this pasty iron was extracted, it would be immediately ready for forging. It is clear that the quantities of iron produced in this way were small only. This method of iron manufacture as a by-product of gold would not only account for the peculiar association of small pieces of iron with gold in early jewelry, but it would also explain the pygmy character of the early iron objects, such as the small models (?) of tools, amulets, etc., found in the grave of Tut-ankh-amen.

While this is an interesting theory it would need verification through experiment (simulating ancient conditions) before it could be generally accepted. Again, in Forbes's view:

> As early as the first half of the 3rd millennium B.C., pieces of man-made iron appear in Mesopotamia (Tell Asmar, Tell Chagar Bazar, Mari), and Asia Minor (Alaca Hüyük), and possibly Egypt too. It is still uncertain what ores were worked first. Such brilliant 'metallic' ores like magnetite, haematite, iron pyrites and some striking forms of limonite may have attracted the attention of primitive smelters first. The use of haematite for seal-stones was widespread in Sumerian

times and fragments of specular ore, a hard metallic variety of haematite, were found on the smelting site near the ziggurat of Ur (*Antiquaries Journal*, v, 1925, p. 391). On the other hand the ochres were used as pigments in prehistoric times, they are found in a soft form, rich in iron, and well adapted for rudimentary smelting operations.

From a consideration of these various views, and remembering that the problem may well have been a local one and not susceptible to any one solution, it appears likely that the first iron to be smelted came from an oxide (possibly of the ochre form). As experience was gained, carbonate ore would have been utilized, and finally sulphide ore in the form of iron pyrites will have been tested. It is almost certain that prehistoric miners would have noticed iron pyrites since it is very similar to copper pyrites both in colour and form, but it seems impossible that they ever successfully used an ore so difficult to smelt, and from which to obtain a sound iron. Somewhat similar difficulties were encountered, and finally overcome, in the case of the sulphide ores of copper, but for iron pyrites I do not know of evidence to suggest its use in early times.

MECHANICAL PROPERTIES

Although in antiquity the ferrous metal with which we deal was usually that known as wrought iron, to a limited extent we must take cast iron and steel into account. While remembering that steel is a modified iron, it is very necessary to avoid any confusion between the three metals, and to this end we cannot do better than to quote the definitions given by Straker (1931, p. 1), though his figures require some adjustment to conform with modern practice. Professor Forbes (1954, p. 595) quotes 1·5 to 5 per cent. of carbon for cast iron, and for steel a variation of between 0·15 and 1·5 per cent. of carbon.

> *Wrought Iron.* Slag-bearing or weld-metal series. Containing very little carbon, say less than 0·3 per cent. This does not harden greatly when cooled suddenly. Highly malleable.
> *Steel.* Intermediate between wrought and cast iron, containing between 0·3 and 2·2 per cent. of carbon, malleable, and capable of hardening by cooling.
> *Cast Iron.* Not as malleable, containing 2·2 to 5 per cent. of carbon.

From the above definition it will be noted that the very great difference in the physical properties of the three metals is in the major part due to the changing value of the carbon content. Further, concerning cast iron, it may be accepted for practical purposes that the metal is not malleable. Malleable cast iron can indeed be produced, but only by means of a

modern technique which was certainly unknown in antiquity. Early wrought iron was a direct product of the primitive smelting furnace, and was a metal which had never been melted; today, practically all wrought iron is made from cast, or pig-iron, which has been poured in a liquid state from a high-temperature blast furnace of anything up to 100, or even more, feet in height. This pig-iron is converted into wrought iron by what is known as a 'puddling' process in which the pig-iron is again melted under certain special conditions in a coal-fired reverberatory furnace. From the reverberatory furnace the iron is removed in the form of a pasty mass containing much slag. It is then well hammered and again heated to a welding temperature and rolled into the required bars or sections.

Most of our modern steel is now made by so treating blast furnace pig-iron as to remove impurities. Two highly important processes are the Bessemer and the Siemens Martin open-hearth method. A good and brief description of the two processes has been given by Alexander and Street (1946, pp. 96–102). Here, we can only say that, in essence, the Bessemer process functions through burning away the impurities in the pig-iron by means of a special furnace known as a 'Bessemer converter', which blows air through the molten iron through blow-holes, or tuyères, furnished in the base of the converter. The open-hearth furnace is so called because the molten metal lies in a comparatively shallow pool on the furnace bottom or hearth. The steel is made by treating molten pig-iron and scrap steel with various additions. Also, a system of heat regeneration is used for the furnace which enables a sufficiently high temperature to be attained to treat a large quantity of metal, and to cast it into ingots when the metal has been made.

Concerning cast iron, when a modern blast furnace is charged with the correct mixture of ore, coke, and limestone (to act as a flux), and blown with a powerful air-blast, the product is of course cast, or pig-iron. Before it is ready to be used for making machinery, &c., the pig-iron from the blast furnace is subjected to further refining processes; according to the pig-iron selected various sorts of cast iron are obtained. In general, they may be classed into two main groups—the white and grey cast irons. These irons are defined by Alexander and Street as follows:

> Both contain 2·5 to 4·0 per cent. of carbon, but the difference lies in the condition in which the major portion of the carbon exists in the structure of the metal. In the white cast iron all the carbon is present as cementite, and the fracture of such an iron is white. In grey cast iron most of the carbon is present as flakes of

graphite, and there is usually a remainder which is in the form of pearlite; the fracture of this type is grey.

The archaeologist need only remember that white cast iron is intensely hard and very brittle. In modern practice malleable castings are made from white cast iron by means of a special annealing process, but in early times such treatment was, of course, quite unknown. On the other hand, the grey iron is not nearly so hard and is also much less brittle.

The ultimate tensile strength of cast iron varies greatly. For instance, the following figures for the ultimate tensile strength in pounds per square inch are given by Roberts Austen (1923, p. 26).

Cast iron. Weak 13,400. Average 16,500. Strong 27,300.

Under compressive stress the cast irons are very much stronger, but, on the other hand, they are very brittle when compared with wrought iron and steel. For wrought iron and steel we find very different conditions and for comparative purposes it is of interest to take the same series of figures for tensile strength quoted by Roberts Austen. These are:

Iron, wrought plates	49,000	lb. per	square inch.
Iron, wrought bars	55,000	,,	,,
Steel, mild	50,000	,,	,,
,, medium	88,000	,,	,,
,, high carbon	132,000	,,	,,

GILLES. TAFEL 7

Vergleich der Festigkeitseigenschaften von vorgeschichtlichen und neuzeitlichem Eisen

(Abmessung der Zerreissprobe: 5 mm. Dmr., 50 mm. Länge: der Kerbschlagprobe: 5 × 5 × 60 mm., Spitzkerb; 45°, 1 mm. tief.)

Werkstoff		*Eisenfund 5/31*	*S.-M.-Stahl*	*Thomas-stahl*
Analyse: C	%	0·01	0·11	0·07
Si	%	0·00	0·01	0·01
Mn	%	Spur	0·41	0·49
P	%	0·078	0·012	0·043
S	%	0·011	0·028	0·03
Cu	%	0·02	0·14	0·08
Streckgrenze	Kg./mm.²	21·6	21·1	28·0
Zugfestigkeit	Kg./mm.²	31·8	34·1	40·7
Dehnung	%	23·0	36·0	31·0
Einschnürung	%	66·0	75·0	73·0
Kerbzähigkeit bei + 20° mkg./cm.²		2 u. 7	2·8 u. 2·8	1·4 u. 1·2
Brinellhärte		88	103	118
Brinellhärte, abgeschreckt bei 680°, 14 Tage bei 20° gelagert		126	170	180

Recently, enormous strides have been made in the development of high-quality alloy steels, so that we now have steels which possess tensile strengths of anything up to 100 tons per square inch. As not many investigations have been made upon the strength and properties of prehistoric iron, it is of interest to give the table by Gilles (1936) on p. 54, affording a comparison between a piece of prehistoric iron from the Siegerland, Germany, and two modern mild steels.

HARDENING, TEMPERING, AND CONVERSION TO STEEL

Before discussing the various methods of hardening iron we may here state the usually accepted meaning of the terms hardening, annealing, and tempering, as applied to steel. To anneal a steel of normal quality the metal is heated to a fairly high temperature, perhaps as high as a red heat, and then allowed to cool slowly. Unlike copper, steel cannot be annealed by heating and quenching; it is essential that the cooling be carried out slowly. Hardening, on the other hand, is the result of sudden cooling or quenching the highly heated steel. This treatment of high-carbon steel will render the material practically glass-hard and exceedingly brittle. The tempering of hardened steel is necessary to alter the structure of the metal so that it may be reduced in hardness while still retaining adequate strength and appropriate hardness for implemental use; to this end, the hard steel is again heated, but to a much lower temperature than was used in the hardening operation, after which it is allowed to cool. In this case, quenching in water or oil is usually resorted to.

Prehistoric iron was always made by the simple direct reduction process, and the product of the smelting furnace, that is to say a sponge iron, would have contained but little carbon, less than 0·2 per cent. It is well known that such iron cannot be hardened by heating and quenching in the manner that steel may be hardened. The carbon content of a modern steel which may be hardened usually ranges from 0·35 to 1·50 per cent., and it is this extra carbon content which imparts the property of hardening to the metal when it is heated and quenched; the extra carbon content is also one essential difference between prehistoric wrought iron and modern steel. Naturally one of the most important properties required in a tool or weapon is hardness, and although a certain measure of surface hardness may be imparted by hammering (that is, by work hardening), iron would only have become a really useful material from which to manufacture implements after the smith had discovered carburizing.

Adding a little extra carbon, or carburizing, may be achieved by high-temperature heating of the iron in contact with carbon as in the cementation process. The method used was to pack the iron in charcoal and to heat strongly for several days. This is a considered method, and while it is unquestionably an ancient one, from our point of view it may be a relatively late discovery. A similar result may be brought about (although naturally with much less exact control of the operation) by frequent heating and reheating of the iron in a charcoal fire. This must have been the method most anciently used, probably as an outcome of the hammering and reheating necessary to free the lumps of iron, as at first produced, from adherent slag and other impurities, also, to consolidate the metal which, as it came from the smelting furnace, would have been porous and full of blow-holes.

Even in pre-Roman times we have evidence to show that iron was subjected to some process whereby it was hardened. Two points are quite clear:

(i) Soft wrought iron as produced in a primitive bloomery furnace is too low in carbon to be hardened to any marked degree.

(ii) Steel, owing to its greater carbon content, may be hardened by heating to redness and suddenly cooling, as, for example, by quenching in water. As Rollason (1939, p. 94) points out: 'The essential difference between ordinary steel and pure iron is the amount of carbon in the former, which reduces its ductility, but increases the strength and the susceptibility to hardening by rapid cooling from elevated temperatures.'

Therefore to harden iron it must, at least in part, be converted to steel. Again, we must observe that, if a piece of steel is treated as mentioned under (ii), the material becomes hard and very brittle. In this condition it would be almost useless for implemental use and the further process known as tempering has to be resorted to in order to obtain a hard but serviceable metal.

In the tempering operation the hard steel is heated to a relatively low temperature and then quenched; the degree of hardness which the steel retains is relative to the temperature at which it is quenched. For instance, the lower the temperature at which the tempering is carried out, the less will the hardness of the steel be reduced. With modern thermostatically controlled furnaces there is, of course, no difficulty in the exact control of the process, but the ordinary working blacksmith tempers

steel tools in a much more ancient and simple manner known as the 'tint' method. If a portion of the surface of a piece of steel is polished and the steel then heated over a smokeless fire it will be observed that successive changes in the colour of the steel will take place; for example, the bright steel changes to a straw colour, then brown, blue, &c. Jones (1921–2, iii, p. 874) states that each of these colours represents a definite temper or state of hardness of the metal between the two extremes of soft and glass hard. Hence it follows that, if the metal is quenched at any one of the various colours it will retain the temper appropriate to that colour. As Jones points out, the tint method is far from satisfactory by modern standards because the colours depend upon the duration of the heating as well as upon the actual temperature attained. On the other hand, the tint method is very widely used and very good results can be obtained by an experienced workman in the tempering of his hand tools; he tempers his screwdrivers at a straw colour, chisels and drills at a purple shade, and so on. It is not possible to know the technique adopted by the Roman or pre-Roman smith for his tempering; probably he had no very clear idea of what he was doing. He must, however, have been guided by some observed results and it seems not impossible that he may have noticed the changing colours in a piece of carburized iron, which for some reason had been polished, and had associated the colour changes with temperature changes. As with the discovery of smelting, we can never know the exact circumstances which led to the important practical result. Finally, it is of interest to quote Richardson's remarks concerning the difficulty of the tempering operation.

> It is impossible as yet to affirm or deny that the Romans tempered their carburised iron. The broad assumption is that they did, for it is quite inconceivable that having advanced to this final, all-important phase of heat treatment they could fail to complete the cycle. On the other hand, successful tempering requires controlled temperatures regulated to the varying composition of the iron carbide alloy. Tempering would, therefore, be only possible in those favoured localities where repetitive operations with a uniform product afforded opportunity for observing the effects as measured by the various oxidation colours. Even at best the difficulties were enormous and the results always uncertain.

As we have already pointed out, in order to convert wrought iron into a steel which may be hardened, the essential thing is to increase the carbon content of the iron. In the earliest times this result was no doubt accidentally obtained by carburization which was due to repeated forging of the iron while heated in close contact with the charcoal of the smith's

hearth. As a special case, it may be noted that Forbes (1950, p. 409), while doubting the possibility of the direct production of steel by the ancients, considers that steel was accidentally produced under suitable conditions of ore and furnace. In his view there was a possibility of producing steel from a bloomery furnace when smelting manganese-bearing ores which were free from phosphorus, arsenic, or sulphur. If the bloom was not decarburized fully, a good malleable steel would be obtained. Some such conditions may account for the quality of the Celtic iron from Noricum, and Forbes thinks that the shaft furnaces of the region would have been well suited to the accidental production of such 'natural steel'. Such occasional production of natural steel need not be confined to the spathic ores of Noricum. It may have existed at other metallurgical centres, and may well be the reason for the renown of certain ancient iron cultures.

Again, Weiershausen (1939, pp. 192–3) considers that to make low-carbon steel in the early smelting furnace required no change in the furnace construction, but called for a different method of operating the furnace, and for the use of a suitable ore. In his opinion, 'brauneisenstein' is the most favourable ore to use and the following procedure was observed. The furnace was thoroughly preheated so that the highest temperature could be attained; also much more charcoal but less ore than usual was charged. The oxidizing effect of the air draught was reduced by suitable inclination of the air passages in the case of natural draught, or with forced draught the tuyères were set a little higher than usual. The bloom had the shape of the furnace-well on its underside, and the iron thus lay at a low level and so was less influenced by the oxygen in the air-stream. Long immersion in a slag bath has a decarburizing effect, but with a manganese-bearing slag the carbon content will remain constant for several hours. Hence, the use of brown iron ore is helpful in the above process.

The cementation process was certainly an ancient one. Here, the conversion of strongly heated but still solid iron into steel is effected by the passage of solid carbon into the interior of the mass of iron (Austen, 1923, p. 56). This change in the properties of the iron was usually brought about by a controlled heating of the iron, at elevated temperature, within closed receptacles containing carbonaceous matter, over a more or less prolonged period of time according to the nature of the steel which it was desired to make. Until quite recently (possibly even at the present time), a small quantity of commercial steel of special

quality was made by the cementation process. Lucas (1948, p. 275) points out that iron only became a thoroughly serviceable material for implemental use after the discovery of carburizing, and in his opinion carburizing may be brought about by allowing the iron to remain in contact with carbon at a high temperature when some small proportion of the carbon will be absorbed by the iron. The amount and depth of penetration naturally depend upon the length of time during which the hot iron and carbon are retained in contact. Experiment has proved that the absorption of carbon is greatest at the surface and gradually decreases towards the centre of the mass. For many centuries the method would have been purely empirical, and the smith can have had no understanding of the principle involved.

References to steel in pre-Roman or Roman times should be examined with care. Such material is generally that which has been modified by carburization until it exhibits some of the characteristics of what we now call steel. Again, it may be a steel by cementation. Sometimes the hardening is but a thin 'case'.[1] Carpenter and Robertson (1930, p. 417) have carried out valuable research treating of the metallography of some ancient Egyptian implements. From this work it would appear that, by means of carburizing and heat treatment, the ancient smith was able to impart useful properties to the tools made from primitive iron. Further, it seems that even the earliest iron examined had been carburized, iron of an intermediate period had been carburized and quenched, while the latest (of Roman period, A.D. 200) had been carburized, quenched, and finally tempered.

Some modern primitive iron workings afford a demonstration of how carburization must have been carried out in early times. In this connexion Rickard (1939, p. 98) points to primitive iron smelting as practised by the natives of Mashonaland, in Southern Rhodesia, an account of which has been given by Professor Stanley (1931). Here, the product of the smelting furnace is a lump of spongy iron of about 20 inches in diameter. The iron as recovered from the furnace is very cellular, containing marked inclusions of slag and charcoal, and when cool is broken into pieces of suitable size for forging. In Professor Stanley's own words:

> The number of heatings and forgings the metal undergoes, and the patience displayed by the artificers, are alike extraordinary to one used to modern methods but, of course, it is easy to see how the slag in some cases is hardly all beaten out,

[1] The new metallurgical research recorded in Chapter X is a most welcome addition to our knowledge of 'ancient steel'.

while the inclusion of actual pieces of charcoal in the sponge-iron, and its gradual absorption and diffusion during working, quite sufficiently explain the production of steely iron and the unhomogeneous structure.

The above account makes it clear that the iron undergoes some considerable measure of carburization during the repeated forging operations.

Also referring to African iron of primitive origin, Cline (1937, pp. 53 ff.) says:

> When we polish a section of native iron, lightly etch it with acid, and examine it under a low-power microscope, or even with the naked eye, we see that it has a very non-uniform consistency. The slag entangled with it will appear almost everywhere as dark swirls, ripples, and blotches on the light background of the pure wrought iron. Often, however, the surface is marked with several intermediate shades. These represent iron carbide, and a sufficient proportion of this compound to make the material harden at sudden cooling will bring it within the category of steel. If we separate and chemically analyse these areas of differing darkness we find that their carbon content ranges all the way from zero in the pure iron to 0·9 per cent. in the iron carbide.

It may also be noted that steel may directly be made by smelting certain classes of ore, but this would hardly have had any wide relation with the prehistoric process.

On the subject of hardening iron, Richardson (1934, pp. 53 ff.) makes some interesting observations concerning the part played by forced draught in the process. In his view, if unit production was only slightly increased by the employment of bellows, a marked improvement in quality may be traced to their use. This would be especially true with the manganiferous spathics of Noricum, from which the iron-master of the Empire could make steel or high-carbon iron at will. If a hard iron were desired, more and thicker charcoal would be added, and by continuing the process longer with a reduced draught carbon was absorbed in approximately the required amounts. To obtain a soft iron the process would be reversed.

Chapter IV

THE EARLIEST SMELTED IRON AND CAST IRON IN ANTIQUITY

ARCHAEOLOGICAL NOTES UPON THE EARLIEST SMELTED IRON

We may now consider the earliest finds of smelted iron in the Old World. Rare objects of iron have been found in the third millennium B.C., and in considerably greater quantity in the first half of the second millennium, while towards the end of the second millennium iron becomes well established in certain regions of the ancient Near East.

III Millennium Iron

At Tell Chagar Bazar in north Syria a fragment of iron was discovered in level V (Mallowan, 1936, p. 26), which the excavator considered to be not later than 2700 B.C. Professor Desch reported that the metal was completely oxidized, and contained 51·36 per cent. of ferric oxide, corresponding with 35·95 per cent. of metallic iron; the remainder would consist of foreign matter derived from the soil. The specimen contained no nickel and was therefore not of meteoric origin. Again, in 1937, Mallowan (1937, p. 98) said:

> Two fragments of iron supply further proof that the Habur was a very early centre for the working of iron in the third millennium B.C. Both these specimens come from level III and cannot be later than 2500 B.C. It is, I think, almost certain that these two fragments, which have yet to be analysed, will prove to be of terrestrial origin, as was the fragment of a dagger blade discovered in level V in the course of the first campaign.

Another highly important find is the bronze hilt which held the remains of an iron blade found at Tell Asmar. Of this, Dr. Frankfort (1950, No. 160) says:

> The temple service, a closed find, to which the knife belongs, was buried at the very end of the Early Dynastic period, say between 2450 and 2340 B.C. It is relevant that this blade of terrestrial iron was mounted in an openwork handle of bronze while the other objects of the hoard, some 75 pieces, were made of copper. The knife may therefore not have been of local manufacture.

The iron was analysed by Professor Desch (*RBA* 1933, p. 302) who reported the material to be rusted iron, converted as usual by long contact

with the earth into a hard magnetic, crystalline mass. The iron was free from nickel and was therefore not of meteoric origin.

A very fine dagger with gold-sheathed handle and iron blade is associated with the Royal Tombs at Alaca Hüyük in Anatolia (Koşay, 1951, p. 167, pl. lxxxii. 4). From the usually accepted dating for these tombs, the Alaca dagger no doubt belongs to the end of the third millennium B.C. Also, from period III of Alaca Hüyük came an iron pin with a gold-plated head, and a fragment of a crescent plaque. These are mentioned on p. 33, as the analysis suggests a meteoric origin for the metal. Recently, during the course of excavations at Geoy Tepe, in Persian Azarbaijan, Burton Brown came upon evidence for early iron working (Brown 1950, no. 4, 1951, p. 199). In the D period at Geoy Tepe (which the excavator places in the later part of the third millennium), a piece of iron was found. Analysis proved this to be of white cast iron. Such a remarkable piece can only be accounted for as the result of the serious overheating of a high-temperature furnace. The cast iron would, of course, have been useless, for it would have been impossible to work it at that time. However, further evidence for iron working was found in the D or C period, and again in the A period which can be dated to the beginning of the Iron Age.

II Millennium Iron

Mesopotamia. In Mesopotamia iron is first mentioned by the cuneiform tablets in the time of Hammurabi. From the Hurrian period there is a curious inversion in the use of metal in a dagger from Yorgan Tepe (Nuzi), where the blade of the weapon is of bronze, while the hilt is of iron (Starr, 1937, Tf. 125). Parrot (1938, p. 310) reports fragments of iron found at Mari near the remains of the pre-Sargonid temple of Ishtar. Forbes (1950, p. 446) states that iron weapons and tools appear in the Kapara period at Tell Halaf, together with a movable hearth, probably a brazier. The general use of iron tools and weapons in Mesopotamia was of late occurrence; probably not until 900 to 800 B.C. did their use become really general.

Persia. In Persia one would expect to find evidence for iron working during an early period. However, on the evidence so far available it would seem that the first Iranian iron production is relatively late. For instance, the iron objects of Tepe Giyan I and Tepe Sialk A are nearer to the end than to the middle of the second millennium, while the rich ron production of Luristan falls only within the first millennium B.C. In

Luristan, while bronze still prevails, many objects dating from around 1000 to 750 B.C. are composite, the working parts being of iron while the non-functional parts remain of bronze.

Syria and Palestine. In the first half of the second millennium iron remains very rare. After about 1500 B.C. there is quite a marked increase, and from around 1300 to 1200 B.C. we find evidence for the beginning of a true iron industry. During the first part of the second millennium iron was, of course, so rare that the iron objects are limited to those of a ceremonial or ornamental character. One of the most notable, although later, pieces is the very fine battle-axe discovered at Ras Shamra on the Syrian coast by Schaeffer (1939, pp. 110 ff.; Lamb 1940, p. 393). This axe was deposited *ex voto* in a little sanctuary apparently forming part of an important building dating from the end of the fifteenth century B.C., or to the first half of the fourteenth century. The axe was made from three different metals, copper and gold for the socket, and iron for the blade. The material of the blade would more accurately be described as a nickel steel (see p. 34), for analysis gave the following composition:

> Iron 84·95 per cent. Nickel 2·25 per cent. Sulphur 0·192. Phosphorus 0·39. Carbon 0·410. Oxide of iron 10·8 per cent.

Also from Syria Przeworski (1939, p. 141) mentions the following finds. A gold-plated iron amulet of the time of Amenemhet III was found in a Royal tomb at Byblos (Virolleaud, 1922, pp. 286 ff.; Fig. 6). Later there is mentioned in the temple inventory of Katna at the time of Thutmosis III seven iron objects of which six were gold-plated (Virolleaud, 1928, p. 92; 1930, pp. 334, 337, 339). In a late Bronze Age level at Gezer in Palestine was an iron ring, and two iron axe-blades which were found in a water tunnel, and may be ascribed to the same period (Macalister, 1912: i, p. 301; iii, pl. 63, p. 61; ii, pp. 269 ff., Fig. 417). From Tell el Mutesellim III (Megiddo) comes a tool with an iron handle (Schumacher, 1929, Fig. 98).

Finally, from Minet el Beida came beads and iron rings which were evidently regarded as of great value, since they were buried with gold and silver (Schaeffer, 1929, p. 292). At Lachish (Tell el Duweir), there is no record of very early iron. The iron excavated (Tufnell, 1953) dates back to about 1100 B.C., but the majority of the iron so far excavated is of considerably later date. According to Wright (1939, p. 459), in Palestine iron was introduced for a variety of implements in the late twelfth and eleventh centuries B.C. The sites with datable iron objects

from these periods are Tell el-Far'ah, Gerar, Beth-shemesh, Gezer, Tell el-Hesi, and Tell el-Ful.

Although the evidence is decidedly scanty, it appears possible that smelted iron was known in Palestine by the middle of the second millennium B.C., and even earlier in the north in Syria.

Anatolia and Trans-Caucasia. The occurrence of early iron at Troy is confused and doubtful. According to Forbes (1950, p. 450) useful iron may not appear before the destruction of Troy VI in the twelfth century B.C.

The oldest iron remains of Trans-Caucasia come from the late Bronze Age kurgan, number 28, of Helenendorf in the Gandža-Karabăg district. In Georgia and Armenia iron objects do not appear before 1200 B.C. and then they are rare (Przeworski, 1939, p. 139). It may be said that in general, iron is of late occurrence in trans-Caucasia.

Crete and Greece. We have mentioned some finds of early meteoric iron in Crete, and it would appear that smelted iron was also known, although but little used in the second millennium. Przeworski (1939, p. 143), following Mosso, mentions slag derived from the reduction of oxidized ores at the great Tholos of Hagia Triada. Objects of the finger-ring class appear to be known after 1500 B.C., but in general, iron in Crete only attained importance after about 1200 B.C. It is likely that iron in Crete was a foreign metal, for there are no notable deposits of iron ore in the island. A large and interesting class of prehistoric iron objects are the finger-rings (Childe, 1939, p. 28), mostly found in Mycenaean graves and usually built up of successive layers of different metals. They are in fact dry batteries, precursors of galvanic rings and so their magical value may rest on some basis of scientific fact. The Phaestos ring has a bronze core overlaid with gold for one-half of the circle and with iron for the other. A similar ring is in the National Museum at Athens. At Dendra, near Media in Greece, Professor Persson found four metal rings of which three are composed of four layers of metal in the following order from the exterior—iron, copper, lead, and silver. Excluding the iron ring found at Vorwolde, in Sulingen, Hanover, which merely consists of iron oxide, these composite rings are dated from *c.* 1500 to 1200 B.C. Iron comes into regular use for weapons, &c., in Greece with the Protogeometric period, at least in the less backward parts of the country. Desborough (1952, pp. 308–12) may be referred to for lists of this later iron.

For Greece and Crete a useful summary of the evidence is given by

H. L. Lorimer (1950, pp. 111–12), from whom the following list of iron objects of the Bronze Age found on Minoan or Mycenaean sites is quoted.

1. Small cube of iron from pit with MM II[1] contents in chamber-tomb in Mavro Spelio cemetery at Knossos; *BSA.* xxviii, pp. 279 and 296.
2. Ring from the Vaphio tholos tomb; period of transition from Shaft-grave culture to LH II; *Eph. Arch.* 1889, p. 147.
3. Front half and bezel of bronze ring partly overlaid with gold from tholos at Kakovatos contemporary with the Vaphio tholos; *AM.* xxxiv (1909), p. 275, pl. xiii, no. 35.
4. Iron nail from Knossos with an ornamental gold head; *BSA.* vi, p. 66. Not precisely datable; LM I or II.
5. Half of bezel of ring from an LM tomb at Phaistos; *Mon. Ant.* xiv, p. 593, fig. 55.
6. Three rings of iron, copper, lead, and silver from the King's Tomb at Dendra; Persson, *The Royal Tombs at Dendra*, p. 56; first half of fourteenth century.
7. Iron stud with gold head at either end from Chamber-tomb 2 at Dendra; Persson, ibid., p. 79; thirteenth century.
8. Iron pendant overlaid with gold from same tomb; ibid., pp. 102–3.
9. Fragments of an iron ring from Chamber-tomb I. i at Asine, end of LH II or LH III; Frödin and Persson, *Asine*, p. 373.
10. Two iron rings from Mycenaean chamber-tombs, presumably LH III; *Eph. Arch.* 1888, pp. 135 and 147.
11. Traces of iron on one of several lead clamps used for attaching door-jambs to walls of palace of Gha in Boeotia; LH III; Tsountas and Manatt, *The Mycenaean Age*, p. 381.

Egypt. Maspero's finds of iron from Saqqarah, Abusir, and Dahshur, as well as the piece of iron reported by Vyse as from the Great Pyramid, might be taken to indicate that the knowledge of iron smelting was early in Egypt. Actually, the evidence is not sufficiently satisfactory to enable us to place any reliance on their archaeological dating. The doubtful pieces of iron are:

(i) The well-known piece of iron from the Great Pyramid of Giza, supposed to belong to the IVth dynasty.
(ii) Various pieces of chisels from Saqqarah. Ascribed to the Vth dynasty.
(iii) Several pieces of a pickaxe from Abusir. VIth dynasty.
(iv) Some broken tools from Dahshur. VIth dynasty.
(v) A lump of iron rust, perhaps a wedge, from Abydos. VIth dynasty.
(vi) A large spearhead from Nubia. XIIth dynasty.

[1] MM. = Middle Minoan. LM. = Late Minoan. LH. = Late Helladic.

It is a distinctly suspicious list. The piece of iron from the Great Pyramid at Giza has been examined and found to be of smelted origin (Desch, 1928), but it appears doubtful whether the piece really is of the age which has been assigned to it; there is the possibility that the iron may have been a tool belonging to one of Vyse's own workmen which slipped down during the course of the excavations. The finds from Saqqarah, Abusir, and Dahshur are all reported by Maspero, and the evidence does not appear to be sufficiently satisfactory (to the modern archaeologist) to warrant these objects being considered authentic in regard to the dating proposed. Of the iron rust found by Petrie at Abydos, Lucas (1934, pp. 195–6) says that the rust was tested chemically and was not of meteoric origin, also that there is no proof that it was a tool or implement, and that it is a mystery how it came to be placed in the foundations of a temple at Abydos. There are various difficulties in the way of accepting the Nubian spearhead, although the finding and dating would appear to be in order, and the metal has been analysed and found to be of smelted origin. However, the type is modern (Wainwright 1936), and it seems unwise to accept this single specimen as evidence for iron smelting in the XIIth Egyptian dynasty. Of more importance is an iron deposit which was found on a flint wand by Reisner in the Mycerinus Valley Temple at Giza, IVth dynasty. The deposit in question (Dunham and Young, 1942) was spectrographically examined by W. J. Young, who stated that the material must have been iron in its ferric state. No evidence of nickel was observed, so that the iron was not of meteoric origin. The inference is that the 'magical set' found by Reisner included some piece of terrestrial iron. It appears probable that Egypt was one of the last of the ancient civilizations to enter the Iron Age. No doubt smelted iron gradually became known during the New Kingdom, possibly after 1400 B.C., but the metal cannot have been well established until many centuries later. Indeed, Lucas (1948, p. 273) considered that on the evidence so far available the earliest working of iron ores were the smelting operations at Naucratis in the sixth century B.C. discovered by Petrie, while Forbes (1954, pp. 596–7) thinks that the Iron Age proper does not begin before 600 B.C. It is not unnatural that the Egyptians should have been slow in adopting iron. First, because they had built up a very extensive industry in copper and bronze which no doubt seemed quite adequate to them for their needs. Secondly, while there are iron ores in Egypt, the ores may not have been easily worked, or of the quality required to suit the early technique. Again, iron could

not have been cast like copper and bronze and it is a far more difficult material to forge than copper. This would be a matter of considerable importance to the Egyptians in view of their limitations in tool equipment, and in particular of their traditional dislike of using the shafted hammer.

India and China. Evidence for the first occurrence of iron in India is uncertain, but in general it would appear that the Iron Age in India is relatively late. Forbes (1950, p. 436) considers that there is proof that iron was known in the Rigvedic Age. In his view iron was introduced into northern India by 1000 B.C. or even earlier. In southern India, not until between 500 and 200 B.C. do iron tools and weapons become common. In a recent work Colonel D. H. Gordon (1950, p. 67) considers that there is no material evidence to prove that iron was introduced into India or Pakistan earlier than the beginning of the first millennium B.C., and it appears likely that the event occurred sometime between 700 and 600 B.C., although such a date is speculative and not backed by concrete evidence.

Forbes (1950, pp. 440–1) considers the antiquity of iron in China to have been exaggerated, and that it has lately been proved that the transition from bronze was in the Tsin dynasty, 255 to 209 B.C., and in the early Han dynasty of 209 B.C. to A.D. 25. In the later Han dynasty, China was in the full Iron Age. The Chinese have a good claim to be the first people to have made really practical use of cast iron. Complicated objects such as stoves were cast in iron during the later Han dynasty. This is a remarkable technical achievement both in founding and in moulding. The key to the process would appear to be that the iron was melted together with coal in crucibles. The high phosphorus content of the coal had the effect of much reducing the melting-point and rendering casting easy. Castings of remarkable size were made. Forbes mentions a Buddha of 5 metres in height from Tsinanfu dating from the sixth century, while a cast-iron lion of A.D. 953 is quoted as being no less than 20 feet in height and 18 feet in length.

Archaeological Notes

During the early appearance of iron the use of the metal was very limited. In the Near East the first iron seems to have been used (on account of its scarcity and cost) for amulets and ornamental purposes only. Later, when more iron became available, although it was still a rare metal, iron was often incorporated in part of a weapon. For instance, in

a dagger the blade might be of iron while the hilt was of bronze: next, when iron came into more or less general use we find the whole tool or weapon made of iron and the forms of the various objects become conditioned to the properties of the new metal.

The objects of third- and early-second-millennium iron so far recorded are far too scanty to permit of a distribution map which would be of any real value in determining the focus of the first iron working. We can only indicate its probable origin as somewhere to the north, or north-east, of the Fertile Crescent. It may be helpful to mention some views expressed by Schaeffer in his latest work (1948, pp. 297, 546). In his view, the opinion that the most ancient objects of manufactured iron are of Assyrian origin can no longer be maintained. His view is that, given what has been learned from the El Amarna texts concerning the origin of iron in the fifteenth century B.C. and now that many objects of iron of such high antiquity have come from Asia Minor, it no longer seems prudent to refuse the paternity for the origin of iron to the Anatolians, and perhaps more particularly to the inhabitants of the Armenian regions. Due to their experience it is probable that the metallurgists of Asia Minor became the first producers of iron in quantity when, after the thirteenth century B.C., this metal supplanted bronze for the manufacture of arms and weapons in the Ancient East. Again, Schaeffer thinks that, having lost the monopoly of mineral exploitation, and of the manufacture of bronze hardened by appropriate alloys, the metallurgists of Asia Minor and Armenia were nevertheless able to guard the secret of the manufacture of iron. From the end of the third millennium they had been able to master the difficulties of extracting this metal. To judge from the discoveries actually known, iron was not in use anywhere during the Middle Bronze period, even for royal armament or decoration.

The disappearance of the metal after its first utilization at the end of the Ancient Bronze period, and its apparently total eclipse during all the Middle Bronze period, is a very curious and interesting phenomenon. Iron only appears to have been rediscovered during the Recent Bronze period and, from all the evidence, in the same region, that is, Asia Minor. This gave the metallurgists of the region an increased reputation and a new period of prosperity when, during the final Bronze phase (corresponding to the New Hittite Empire), iron commenced to be adopted, first for armament and then towards the end of the period for tools, by all the civilizations of Western Asia. The disappearance of iron after its first utilization, if indeed future research confirms that it did, in fact,

actually disappear, may perhaps be ascribed to the difficulty of working the iron without an efficient equipment of tools. We must remember that, unlike copper, iron has to be forged hot; for such work smiths' tongs are very necessary, but early in the third millennium they were almost certainly not available. As we shall see later, a second important reason is that iron made by the primitive process is soft, and of little value for cutting tools because it is not possible to impart sufficient temper to the blade to obtain a good and durable cutting edge. So long as the early iron blades had only soft copper tools to compete with, they would have been of value for they were, of course, considerably harder than copper. When good bronze became available the position was a very different one. Figures for the relative hardness of soft wrought iron, and bronze of around 10 per cent. tin content, clearly show that a good bronze when fully work-hardened is considerably superior in hardness to the primitive iron. Hence, it would not be so surprising if it were established that the introduction of bronze checked the development of iron for some centuries until the iron workers had discovered how to produce iron which could be hardened, and had also evolved a suitable kit of tools to deal with the forging and other processes.

The chief basis of the often repeated story of a Hittite state monopoly of iron-working is the well-known letter found at Boghazköi, *Keilschrifttexte aus Boghazköi*, i (1916), p. 14. As some of the far-reaching reconstructions built on this text have been frequently repeated as if they were proven facts, it is important to remember how hypothetical they are. The circumstances in which the letter was written are entirely obscure and all inferences about motives are unfounded guesses. The writer is generally, and reasonably, thought to have been Hattusilis III, but the addressee is unknown. There is no evidence for the older view that he was the Egyptian Pharaoh (Rameses II), and recent opinion inclines rather to Shalmaneser I of Assyria (so Cavaignac in *Rev. hittite et asianique*, ii (1934), pp. 233 f., and recently Goetze, *Kizzuwatna and the Problem of Hittite Geography* (1940), chap. III).

This letter and others among the Amarna letters show that iron weapons were rare, much prized and fit royal gifts. But as Goetze says (op. cit. 33), 'There is no reason whatever for the belief that the Hittites wished to monopolise the precious metal for themselves. Nothing indicates that sending the weapons would have involved military secrets. The contemporary Amarna letters are full of similar requests.' The Hittite king's failure to oblige his correspondent is capable of various

explanations compatible with the scanty evidence. That he was making excuses because he did not want to send iron is one such possible explanation, but there is no reason for doubting that there was a genuine shortage. It is possible that, as has been suggested, iron working may have been a seasonal occupation for the peasants at times when there was no other work (so Gurney, *The Hittites*, 83), or that there may have been religious or magical reasons preventing the work (Contenau, *Manuel*, iv, p. 1893). Nor does the Boghazköi letter imply that iron was *produced* at Kizzuwatna, but only that iron weapons were stored there. For the approximate location of Kizzuwatna there is now virtual agreement among scholars that it coincided, partly at least, with Cilicia. The arguments are given fully by Goetze (op. cit.).

While we cannot agree, it is only right to give Przeworski's opinion, although this dates back to 1939, as he made a valuable study of the Anatolian iron industry (1939, pp. 161 ff.). He considered that the formation of the iron industry in the east Mediterranean and Near Eastern region took place after many hundred years of development of iron working. Even in its first beginnings it was not confined to a definite find-spot, but was assignable to various lands at the same time; therefore a single source for the ancient oriental iron industry cannot be allowed. Its building up was the result of tedious general search and experiment of the whole Near Eastern world. Przeworski admits that these views contradict the frequently cited hypothesis that the Armenian–East Anatolian highland was the home of ancient oriental iron metallurgy; he considers that the early iron finds of the Near East in no way prove that Anatolia was in advance of other lands in any stage of development of iron metallurgy. The evolution of the early Anatolian iron industry was closely allied with that of the neighbouring regions, and in general ran a parallel course. If this view be accepted, the Asia Minor branch can have no pretentions to the discovery of iron technique, although it greatly assisted in its improvement and development.

Richardson (1934, pp. 556–7) considers that some regions made a rapid advance to a developed bronze culture, but seemed reluctant to take the next step and go forward with iron. Egypt offers a classic example, for no doubt Egyptian metallurgists had knowledge of iron, and some attempts may have been made to apply their knowledge, but at great cost a stable and profitable copper and bronze industry had been built up which met every present need, and so far as could be seen would continue to meet the Egyptian needs. The change over was delayed by

the fact that, while iron might be a metal of future promise, in the immediate present it was no better than bronze.

To conclude this very brief survey of the archaeological record, it may be said that there is a considerable amount of recorded iron as a result of excavation in various countries of the Old World but, particularly before the dispersion of the Hittite Empire in the twelfth century B.C., the evidence is scanty and inconclusive. The archaeological history of the development of the iron industry will remain dark until we have more material, and much more scientific examination, of past and future discoveries. Apart from the sporadic occurrences of iron objects in very early contexts which are known in the Ancient East, it may be said that the making of hard and useful iron was most likely achieved by the Hittites as early as the fifteenth century B.C.; while around 1200 B.C. there was an important general increase in the production of iron, and it may be said that a true iron industry dawned. For the transition of iron-working to Europe upon any extensive scale some considerable time was required. Clark (1952, pp. 199–200) mentions a first establishment of iron working in Greece and the Aegean around 900 B.C. From the eastern Mediterranean the knowledge was brought to Tuscany possibly by 800 B.C., but it was not until about the middle of the seventh century B.C. that iron working really became established in the Alpine regions, afterwards to be widely distributed in Central and western Europe under Hallstatt influence.

Cast Iron in Antiquity

The Material. As a material, cast iron is very different from wrought iron or steel. It is brittle and cannot be shaped by forging, but it has the advantage that it pours easily and can therefore be cast to any required shape in the same manner as the non-ferrous metals. Steel may of course also be cast, but that is a modern high-temperature process which could have no application in the times of which we treat. The basic difference between our primitive wrought iron and cast iron is that, when iron is liquefied in a blast, or other high temperature furnace, it absorbs from 3 to 5 per cent. of carbon and other impurities. It is this absorption of carbon which gives the iron hard and brittle properties when it solidifies. In modern practice the 'pig iron' from the blast furnace is not used without further refinement by which the original iron is controlled in composition and suited to the various manufacturing requirements. However, in general, there are two main classifications into 'grey cast iron'

and 'white cast iron', both containing between 2·5 and 4 per cent. of carbon (Alexander and Street, 1946, pp. 114–15).

For our purpose it may often be necessary to distinguish between these two varieties of cast iron, and the essential difference is in the condition in which the major part of the carbon exists in the metallic structure. The terms white and grey refer to the appearance of the metal when it is newly fractured. In the white iron, all the carbon is present in the structure in the form of cementite, while in grey iron most of the carbon is to be found in graphitic flakes with a remainder in the form of pearlite. Since cementite is extremely hard, it follows that white cast iron is very hard but brittle, while the grey iron is rendered soft and less brittle by the graphite flakes. Also, it is important to note the relatively low melting temperature of the grey iron, 1,140° to 1,200° C.

The following groups of cast irons, and Fig. 3 (see p. 73), showing some structures of cast iron, are taken from E. C. Rollason (see 1939, fig. 104 and p. 190).

Free cementite + pearlite, *d*, *b*—white, hard, unmachinable.
Cementite + graphite + pearlite, *f*—mottled, difficult to machine.
Graphite + pearlite, *e*—grey, machinable, high strength.
Graphite + pearlite + ferrite, *c*—grey, soft, weaker.
Graphite + ferrite, *a*—grey, very soft, easily machined.

As we have noticed in the case of iron and steel, the term 'cast iron' may cover very considerable variation in the actual composition of the metal. Hilton (1953, p. 97) gives the following range of variation which exists between the various grades of cast irons as now produced:

Graphitic carbon	1·0 to 3·75	per cent.
Combined carbon	0·2 to 3·0	"
Silicon	0·2 to 3·5	"
Manganese	0·2 to 1·5	"
Phosphorus	0·02 to 1·5	"
Sulphur	0·01 to 0·1	"

All the primitive iron of the period with which we are dealing was wrought iron as distinct from our modern iron which is very frequently melted and cast. In the normal primitive smelting process, as the ore becomes reduced and falls down through the various zones of the fire, the oxidizing flux causes a partial decarburization, the melting-point becomes raised, and the temperature is only enough to enable the iron to collect in a sponge-like form at the bottom of the furnace. There could

have been no question of melting the wrought iron after it had been produced by the founder, since the temperature required to melt wrought iron is approximately 1,530° C., considerably above the temperature range of any early furnace (Coghlan, 1941, p. 77). When furnace technique had advanced sufficiently and tall furnaces, blown with artificial

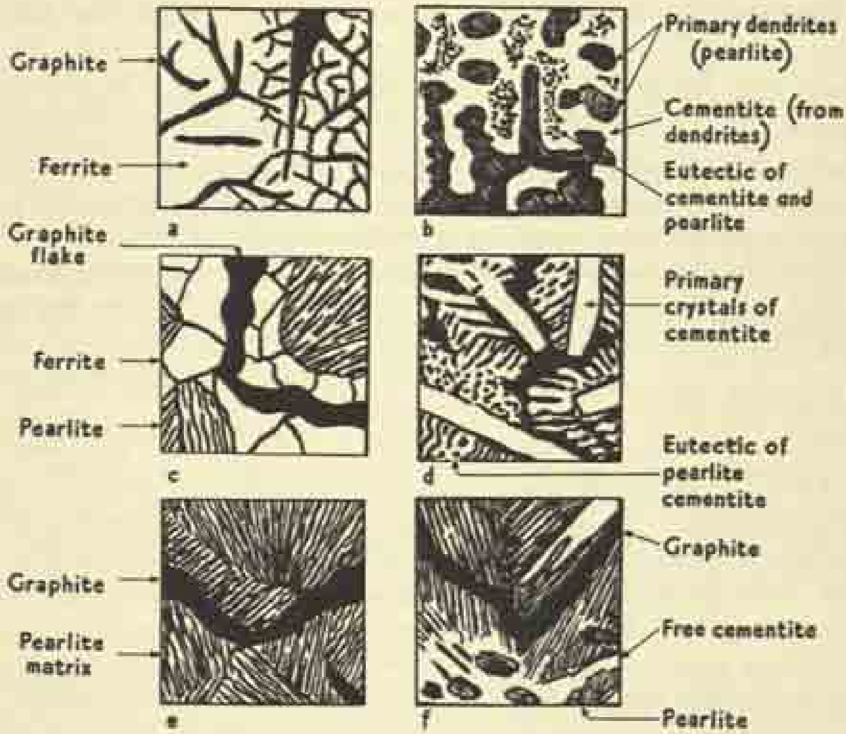


FIG. 3. Some structures of cast iron (*see* Rollason, 1939, pp. 189–190): 1. Free cementite and pearlite, *d* and *b*. 2. Cementite, graphite, and pearlite, *f*. 3. Graphite and pearlite, *e*. 4. Graphite, pearlite, and ferrite, *c*. 5. Graphite and ferrite, *a*.

draught, came into use, it appears that a little cast iron was accidentally produced. However, when a little cast iron was so made it would have been useless to the early smith, first, because the metal is quite unsuited to the manufacture of most tools or weapons, and secondly, without modern tools the smith would have been unable to make use of such a non-malleable material. This point is well illustrated by the care taken in working the large and high furnaces used until quite recently by some African tribes; the air-blast was carefully regulated in order not to allow the furnace to become over-heated and so to avoid the possibility of any

liquid iron collecting in the hearth. In general we may say that in all small prehistoric furnaces the metal never collects in a fluid state in the bottom of the furnace.

In connexion with the later discovery of cast iron as a useful material, we may quote A. R. Hutchieson's remarks (1950, p. 84):

> The distinction between malleable and cast iron and the purposeful production of the latter became established during the 15th century. The recent discovery of a solitary hollow 4 inch cast iron ring at Býčí Skála,[1] Moravia, dating back to 600 B.C. was an astonishing revelation and pointed to an earlier knowledge of this form of the metal, but it does not prove the existence of an industry. During the 14th century, the size of the furnace used for making malleable iron had been gradually increased to save fuel and to reduce the cost of manufacture. The accidental production of molten iron had become increasingly frequent, because the metal had been kept longer in close contact with the fuel and so had become more highly carburized, which had the effect of lowering its melting point. This phenomenon, once viewed with feelings of dismay, was later to become a basic factor in the process of iron manufacture.

ROMAN CAST IRON

In prehistoric times it is agreed that the direct process was practically always used for the production of iron, but when we come to Roman times we must allow the possibility that the indirect process was known. As long ago as 1904, this question was considered carefully by Mr. May[2] with the help of analyses and expert advice (May, 1904, pp. 23 ff.). From smelting hearth II, at Wilderspool, near Warrington, a piece of iron strip was analysed by Mr. Ruddock, Public Analyst, Warrington, with the following result:

Carbon combined	0·060
Silicon	Trace
Sulphur	0·027
Phosphorus	0·037
Manganese	Trace
Iron, by difference	99·876

In Mr. Ruddock's opinion 'this specimen was a pure variety of soft iron made from magnetic ore or red haematite, and purified from cast iron, as such a low percentage of carbon would have been practically impossible if made direct from the ore in this rude furnace'. Again, a

[1] But in this connexion see p. 78.

[2] Although it dates back half a century, Mr. May's work is worthy of close study. His methods were extremely careful, and it is important to note that he took expert advice upon metallurgical questions.

piece of wrought iron resembling a cotter or lynch pin was analysed with the following result:

Carbon	0·090
Silicon	0·060
Sulphur	0·031
Phosphorus	0·257
Manganese	Trace
Iron, by difference	99·562

The high proportion of phosphorus led Mr. Ruddock to consider that the iron was produced from an impure ore, also that it was probably made from cast iron and not direct from the ore. In view of the importance of this matter, and of the evidence found at Warrington for the use of coal for smelting during Roman times, we quote May's conclusions upon these points in his own words:

> The foregoing details of (1) the construction and surroundings of three different kinds of furnaces, viz., ore roasting ovens, smelting hearths, and crucible or refining hearths; (2) two kinds of fuel, cannel coal and ordinary mineral coal in the former, and charcoal in the latter, for the manufacture of iron; (3) the results of analyses of specimens of ore, slag, cinder, crude or cast iron, and finished iron derived from these furnaces; and (4) the opinion of an expert in regard to them, are strong evidence in support of the view that an indirect method of producing crude or cast iron in one furnace, and re-heating it in another with charcoal to convert it into pure or malleable iron, was practised in this locality. This view receives further support from the discovery this season on the south side of the oppidum of another similar group of furnaces to be described later.

Concerning the use of coal as a metallurgical fuel, it is very interesting to note that mineral coal, principally cannel, was in use by the Romans at Warrington, hence the use of coal as a fuel for smelting, far from having been introduced for the first time by Dudley in A.D. 1618, must be carried back to Roman times.

It would appear that the Romans could, and occasionally did, intentionally make cast iron. Proof is afforded by the following information from Fieldhouse, May, and Wellstood (1931, pp. 12–18, p. 33). At Wilderspool near Warrington, where the 20th Roman Legion had their iron foundries, a small block of cast iron was found from one of the purifying furnaces. This iron was analysed by Mr. F. G. Ruddock, Public Analyst at Warrington, with the following result:

Block of iron about 2″ × 1¼″ × 1″, coated with scale.

Carbon combined	0·230 per cent.
Carbon, as graphite	3·000 ,,

Silicon	1·050 per cent.
Sulphur	0·485 ,,
Phosphorus	0·756 ,,
Manganese	0·403 ,,
Iron, by difference	94·076 ,,

'A sample of cast iron extremely brittle, melted with coal from an impure ore, probably spathic, owing to the high phosphorous and remarkably high sulphur'.

Again, at Tiddington, from the Golf Links site, a bar of Roman or Romano-British iron was reported upon by Percy Rowley, B.Sc. The bar, which proved to be of cast iron, measured $6\frac{1}{8}$ in. length, the section being $1\frac{1}{4} \times \frac{7}{8}$ in., tapering to $\frac{7}{16}$ in. The weight was 1 lb. 4 oz. The analysis as given below is identical with that of cast iron commonly used in engineering practice today.

Total carbon	3·52 per cent.
Graphitic carbon	3·21 ,,
Combined carbon	0·31 ,,
Silicon	1·922 ,,
Sulphur	0·049 ,,
Phosphorus	0·765 ,,
Manganese	0·630 ,,

In the 'settlement' area at Hengistbury Head a considerable amount of iron slag indicated that iron smelting, probably of a poor and primitive nature, was carried on. The occupation of Hengistbury is dated by considerable finds of pottery and coins to the Iron Age and Roman periods. A most interesting piece of metal which proved to be cast iron was recovered from the settlement area. Upon this Professor Gowland (1915, pp. 76–77) reported as follows:

White cast iron. This was in the form of an irregular shaped mass, weighing about two pounds, encrusted with slag. Iron of this kind might be occasionally produced in the small primitive furnaces of the period when the temperature became higher than that required for the production of malleable iron owing to a temporary accidental increase of the blast. It is a hard, brittle metal and could not then be applied to any useful purpose. A much higher temperature is required for the production of grey iron suitable for castings, and this could not be attained in the low furnaces used for making malleable iron, so that no cast iron objects of the Roman period, or even later, until mediaeval times, have yet been found. Analyses by Mr. F. A. Harbord gave:

Carbon, graphitic	0·16 per cent.
Carbon, combined	3·33 ,,

Silicon	0·38 per cent.
Sulphur	0·035 ,,
Phosphorus	0·180 ,,
Manganese	Traces ,,

In the light of the evidence which is now available Professor Gowland's statement to the effect that *no cast-iron* objects of the Roman period have yet been found must be modified. It is more correct to say that such objects are exceedingly rare in western countries.

In the year 1877 a statuette of iron was found by one of the workmen while digging the iron slag at Beauport Part near Hastings, Sussex. It was acquired by the late Charles Dawson who claimed that it was Roman, and probably the earliest specimen of cast iron known in Europe. The statuette was sent to Dr. Kelner of the Royal Arsenal, Woolwich, for examination and analysis, and it was found to be without doubt of grey cast iron. However, opinion was divided as to whether the statuette was really genuine. Straker (1931, p. 337) said that, notwithstanding Mr. Dawson's belief in the authenticity of the find, there are some doubts on the matter. The sale of objects found was a valuable source of income to the diggers, and it is possible that deception may have been practised. Recently, as a result of the Piltdown forgery, the statuette has again come under notice and further investigations are in progress (Downes, 1954). All we can say at the present time is that it has not yet been proved that the figure is a fake, or genuine but of recent origin. As the find was not a result of archaeological excavation it would be unwise to accept it as undoubted evidence for Roman cast iron. The Hastings statuette would be less suspicious if we could point to other small cast-iron figures of a like nature, and of Roman dating, but so far we have no supporting evidence of that kind.

In May 1883 a cast-iron statuette 15 cm. in height was dug up in the garden of a villa in Plittersdorf, Germany (Schaaffhausen, 1886). This statuette was that of an Egyptian woman and was unstratified, but in the same garden Roman tiles, sherds, and coins were also found. Schaaffhausen remarks that a Roman sculpture in cast iron has not yet been found, and therefore great care is necessary before accepting it as genuine. He points out that in the time of the first Napoleon such classical pieces were popular, and such a casting could be of recent origin. However, in his opinion there was no question of a fake, but he bases his view upon the corrosion of cast iron compared with other materials; also upon the fact that he could not trace any records to show that such figures were recently

cast in France or Germany. We cannot accept the Egyptian statuette on such terms. It is indeed more likely to be modern than ancient.

In 1846 a small cast-iron statuette of Cupid, 7·6 cm. high, was found in a field at Hockenheim, east of Speier, Germany. Schaaffhausen examined this figure in 1885 in the Karlsruhe museum. Apparently a small bronze statuette of Cupid was also found at Hockenheim, and by mistake this was illustrated on p. 141 of Schaaffhausen's paper. The correct drawing of the cast iron cupid will be found in the *Bonner Jahrbuch*, Heft LXXXII, 1886, p. 199 (Schaaffhausen). From this illustration the figure appears to be a rather crude piece of work, and could well be Roman. However, as there is no true supporting evidence of an archaeological nature, the dating must be left an open question.

In a private communication Dr. Radomír Pleiner has kindly informed me that, at Tuklaty, in the Ceský Brod district of Bohemia, a small quantity of cast iron of the Roman period was found at a smelting furnace. But this cast iron was only a rubbish product evidently formed by the furnace having been overheated. We then have the well-known cast iron ring (already mentioned on p. 74), from Býčí Skála, north of Brno, and now in the Vienna museum. This Hallstatt ring, if it is indeed genuine, would be evidence of the highest value. Of even earlier date, although not from Europe, is the piece of cast iron found by T. Burton Brown in his excavations at Geoy Tepe in Persian Azarbaijan, belonging to the D period which the excavator would consider to be late in the third millennium B.C. The iron has been scientifically examined (Brown and Herbert, 1950) and has been shown to be white cast iron. It is to be regarded as the rubbish product of an overheated smelting furnace rather than an intentional product.

Since the Hastings and Hockenheim statuettes cannot be relied upon, and taking into consideration the other examples which we have discussed, it is clear that the evidence for Roman cast iron in the Western World is decidedly slender. We have only the cast iron from Warrington and Tiddington reported upon by Thomas May, and the cast iron ring from Býčí Skála, and it may not be too safe altogether to rely upon this isolated find. Dr. R. Pleiner has kindly informed me that the find complex from Býčí Skála may correctly be ascribed to the sixth, or to the beginning of the fifth, century B.C., and classified as of Horákov type (or better as of Podolí type), of the south Moravian Hallstatt group. However, in Dr. Pleiner's view, the circumstances of the actual finding of the ring are not certain. Other cast irons reported appear merely to be the

chance products of overheated smelting furnaces and therefore do not furnish evidence for the intentional production of iron as a cast material.

Again, it is suggestive that Dr. Otto Johannsen (1954, pp. 21–29) in his monumental work upon the history of iron does not appear to consider the possibility of Roman cast iron as of importance, nor does he mention Roman statuettes or other cast-iron objects of archaeologically proved context. From the evidence at present available to us, we can only say that cast iron apparently sometimes was made during Roman times, but that it was extremely rare, and of no importance to the iron industry until many centuries had elapsed.

CAST IRON IN CHINA

In China cast iron occupies a special place, and one of very considerable importance. Professor J. Needham, F.R.S., has very kindly furnished us with advance information and references from *Science and Civilisation in China*. In Professor Needham's view, it is generally agreed that iron came relatively late to China. No one would put it before the eighth century B.C. and the general view among western sinologists has been that the first reference to the metal is of 512 B.C. when a legal code was inscribed on cauldrons made of iron (Couvreur, tr. of *Tso Chuan*, vol. iii, p. 456). The strange conclusion emerges that the Chinese could cast iron almost as soon as they knew of it, for the technical term used (*chu*) means unmistakably that. Some argue that the word is a misreading, but others strongly disagree. If the *Tso Chuan* reference is laid aside, the next reference is probably that in *Mencius* (Legge, tr., p. 124), i.e. late fourth century B.C., where again a word (*yeh*), having definite implication of casting and pouring liquid metal is used. After that comes considerable evidence. Professor Needham has drawings of late Chou cast-iron agricultural tools which were excavated from tombs at Huihsien. If these tools really are of cast iron, which Professor Needham thinks possible, they antedate the Han iron dating from about A.D. 200 and described by Laufer.

When one comes to the Northern Wei period iron statues become plentiful; some are dated from the fourth to sixth centuries A.D. In later times great skill and ability were shown by the Chinese in iron castings of enormous size. What must be the earliest example of the use of cast iron as a building material is a most original application of the metal to pagodas. From Professor Needham we have the following special note on cast-iron pagodas:

A remarkable development of pagoda building was that which made them of

cast iron, or more often of bronze. The oldest existing iron pagoda, at Yü Chhüan Ssu at Tangyang in Hupei, which dates from +1061, is of very considerable size, being 70 feet high and having thirteen storeys. It is said to weigh 106,000 pounds. Another smaller one of nine storeys is at Kan Lu Ssu at Chenchiang in Chiangsu. Local tradition dates it from the time of Li Tê-Yu, the famous geographer and minister of State (+787/+849), who founded the temple, but more probably it was set up by Phei Chhü (+1078/ +1086). Yet another, at Chhung Hsueh Ssu at Tsining (Shantung), has eleven storeys. Smaller ones in bronze are quite numerous.

Professor T. T. Read (1937, pp. 30–34) mentions a very large iron casting of a lion standing in the yard of the Kai-Yuan monastery, Ts'ang-chou. This enormous hollow casting is about 20 feet high and 16 feet long. The metal walls vary from 1½ in. to 8 in. in thickness. It is made in one piece by pouring small sections of it at a time and the weak joints between the sections are quite evident. Such weakness would not greatly matter in the case of a religious art statue of this nature for it would not have to be moved, and therefore mechanical strength would not be an important consideration. Read says that there can be no doubt as to the date of this casting, A.D. 953, since, like a modern bridge or public building, the date was placed on it when it was made. In this connexion we may note that Read (op. cit., p. 31), says that:

> In the course of a recent visit to China search was made for smaller and earlier iron castings which bore an inscription shewing the precise date at which they were made, and a number were discovered; some bearing dates as early as 500 A.D. As might have been expected, these were mostly of a religious character since any ordinary object would be likely to be broken up and remelted when it became old and obsolete.

No iron casting bearing a date earlier than A.D. 500 came to Read's notice, with the exception of one which he considered as spurious. Without due investigation it is clear that a date cast upon the object cannot always be accepted as genuine, particularly in the case of the smaller castings. As Read considered one such date to be spurious, there may well be others of a like nature.

In an earlier paper, Professor Read (1934, p. 547) refers to the following iron castings:

> At Pingtingchow, Shansi, there is a large cast iron bell, which is dated 1079 A.D. At Chin-ssu, 10 miles south-west of Taiyuanfu, Shansi, there is an iron statue, larger than life-size, which is dated by the inscription on it as having been cast in the year 1097 A.D. Four similar statues at a temple at Tengfênghsien, Honan, are definitely dated 1213 A.D. In the 'Thousand Buddha Hall' of the

Hsuan-chung-ssu, about thirty miles south-west of Taiguanfu, there were in 1920, two hundred and twenty-five cast iron Buddhas, each about 30 inches tall. A stone in the wall of the hall gives the date 823 A.D. but B. Tokiwa (1926, pp. 2–3) thinks from their appearance that the statues were cast in 960–1127 A.D. In the same temple there is a stele that says, inter alia, that a man named Chan donated an iron statue of Maitreya to the temple in 738 A.D.

In the prehistoric period in China, it is difficult to be certain of the authenticity of cast iron. We may cite the famous Chinese iron stove which some have mentioned as 'probably the oldest cast-iron object still extant'. The stove is not archaeologically attested; Laufer (1917, pp. 79–80; pl. ii) obtained it from a dealer who stated that it came from a Han grave. However, Laufer did not see the grave and said himself that, while there is probability in assigning such cast-iron objects to the Later Han (A.D. 25–220), it is equally justifiable to extend the time of their manufacture over the entire third century of our own era. On such evidence, one can hardly accept the lower dating and, in view of its decidedly sophisticated appearance, may not such stoves belong to a far more recent period than that put forward by Laufer?

In 1910 Professor Read (1934, pp. 550–2) visited the iron district of Pingtingchow, Shansi, to observe metallurgical methods and to collect specimens. He found that iron castings were being produced by the ancient methods. The iron ore was mixed with coal and reduced by a crucible process in a natural-draught furnace, the product being a spongy bloom of wrought iron, and many smaller particles of iron. The malleable bloom was worked up into the usual objects of wrought iron; the smaller pieces of iron were again packed into crucibles with Shansi coal, and converted to cast iron in a forced-draught furnace. Read noted that the iron ore used contained only ½ to 1 per cent. of phosphorus. The cast iron made from such an ore in the ordinary way would not contain over 1 per cent. of phosphorus, but the finished castings contained from 5 to 7 per cent. The additional phosphorus can only have been taken up from the Shansi coal used in the crucible process, and by an additive which the workmen called *hei-tu*, which was associated with the coal and contained crystals of vivianite (iron phosphate).

Iron containing phosphorus in the region of 7 per cent. would melt at 980 to 1,000° C., that is, at an even lower temperature than that required to melt copper. If the early Chinese iron founders used the technique observed by Read in 1910, we have a good explanation of why they were able to cast in iron with apparent ease. According to Read the few

analyses of early Chinese cast iron do not show a high phosphorus content, so that the answer may lie rather in the low sulphur content of the Shansi coal which would render it a suitable fuel for smelting. Sulphur in the fuel is extremely harmful, and in England it was not until the eighteenth century A.D., when it was learned how to coke the coal, that this fuel replaced charcoal in the smelting furnace.

Concerning the composition and structure of ancient Chinese iron castings, Pinel, Read, and Wright (1938, pp. 174 ff.) examined the following specimens:

(1) 502 A.D. Two recumbent lions, 26 lbs. each. Date cast on.
(2) 508 A.D. Two ink slabs, 4¼ lbs. each. Date cast on.
(3) 550 A.D. Kwan Yin (Goddess of Mercy). 50 lb. Date cast on.
(4a) 558 A.D. Kwan Yin. 16 lbs. Date cast on.
(4b) 719 A.D. Panel showing Buddha and two attendants. 52 lbs. Not analysed.
(5) 923 A.D. Two panels with Buddhist figures. 25 lbs. Date cast on. One analysed.
(6) 953 A.D. 20 × 16 foot lion.
(7) 1093 A.D. One of 1024 cast iron panels. 7¼ in. × 7¾ in. 6 lbs. From a pagoda.
(8) 'Flying scissors' ? 300 A.D.
(9) Stove. ? 200 A.D.

Numbers 1 to 4a, 4b, and 5 have dates, even to months and days, cast on them. It appears that these pieces were bought by Read from a dealer in Nanking for so low a price that no one could have made them for profit as copies of originals. It is interesting to note that the metallographic study showed a wide diversity of structure, white, grey, and mottled irons, with relatively low phosphorus contents. Castings 1 to 5 were of grey iron, numbers 1 and 2 having a pearlitic structure, and the others containing ferrite in various amounts. Numbers 6 to 9 were white or mottled cast irons, numbers 6 and 9 being somewhat similar except for the presence of some mottled iron areas in number 6. Whereas the latter were hypereutectic, number 7 was definitely hypoeutectic. Number 8 was a mottled iron structurally between grey and white irons. Numbers 1 to 5 of grey iron were cast in sand moulds which, if their dating is reliable, furnish an early example of the use of sand moulding; the variations in the structure and analyses of each of the castings tend to confirm their authenticity, but naturally cannot be taken as proof of the dating put forward.

To the western metallurgist of today, the idea of such early production and utilization of cast iron by the Chinese is indeed strange and only to

be accounted for by special conditions of fuel, ore, and smelting. These conditions we have already remarked upon. Again, as Professor Needham has pointed out, a factor which must greatly have helped in the success of the conversion process is the antiquity in China of the double-acting

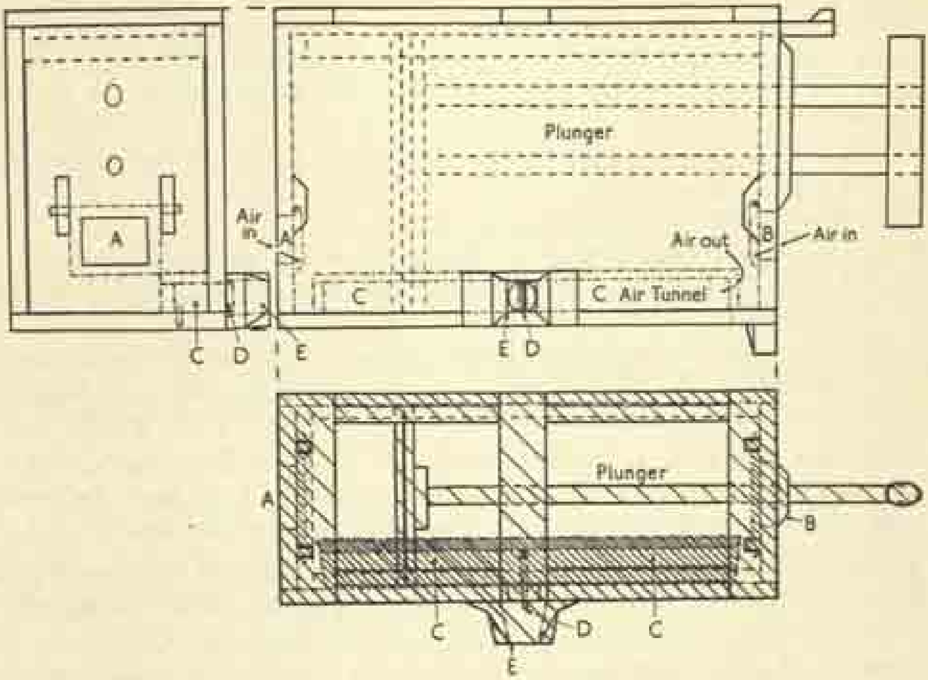


FIG. 4. Double-acting piston box-bellows from the Tibeto-Chinese border. Coll. by Sir A. Hosie, 1908. Pres. by Lady Hosie, 1934. Pitt Rivers Museum.

Withdrawing the plunger decreases the pressure on valve *A*, thus allowing the left-hand side of the chamber to fill with air; at the same time the air in the right-hand side of the chamber is compressed and forced through the air tunnel *C* which contains a tongue *D*. This automatically swings to the left allowing the air to pass out of the mouth *E*.

Reversing the direction of the plunger causes valve *B* to open, thus allowing the right-hand side of the chamber to refill with air. The air in the left-hand side of the chamber is compressed and forced through the air tunnel *C*. The tongue now swings to the right, allowing air to flow again through the mouth *E*.

If this oscillating motion is maintained, an almost constant pressure of air is obtained.

piston bellows which give a continuous blast (Fig. 4), and so would render the attainment of high furnace temperatures a relatively easy matter. Professor Needham's recent findings concerning the ancient and mediaeval Chinese iron and steel industry are of extreme interest and importance. We have been favoured by the Professor with the following brief

résumé of his research, the full account of which will in due course be published in *Science and Civilisation in China*, vols. 6 and 7, now in course of production by the Cambridge University Press.

(*A*) In China iron seems to have been known only from the 6th century B.C. onwards. Presumably the first product was bloom wrought iron, in 'Catalan' style.

(*B*) Cast iron appears from the 2nd century B.C. onwards, probably made by a crucible process. Factors connected with this early appearance probably were:

- (*a*) High phosphorus ores, or the addition of small amounts of high phosphorus minerals.
- (*b*) Availability of good refractory clays.
- (*c*) Coal, used from at least the 4th century A.D. onwards, perhaps long before (permitting a very hot pile, the sulphur being excluded by the crucibles).
- (*d*) The double-acting piston bellows from the 2nd century B.C. onwards, certainly in the 3rd century A.D. made of bronze with iron tuyères.
- (*e*) Application of water power to these as early as the 1st century A.D.

(*C*) Steel was produced, presumably by cementation, in Chou and Chhin (i.e. before the Han dynasty, starting in the 2nd century B.C.), from the blooms, and probably later from wrought iron puddled from cast iron.

(*D*) From the 5th century A.D. onwards at least, the Chinese made steel by co-fusion of cast with wrought iron, almost certainly by a crucible process.

(*E*) From the 5th century A.D. onwards at least, they were also able to make steel by heating and forging lumps of cast iron between faggots of wrought iron.

(*F*) By the 11th century A.D. at least, they made another class of steel by direct cold-blast decarburisation of cast iron, forging with air-stream till no further decrease in weight. As this steel was preferred, its carbon content was perhaps more uniform.

(*G*) In addition, some Wootz steel seems to have been imported from India from about the 5th century onwards.

(*H*) The forging together of hard and soft steels to make weapon blades seems to have begun in the 3rd century A.D. in China, and to have been transmitted in the 7th century A.D. to the Japanese, who in later times brought it to a great art.

To sum up, it seems doubtful that cast iron in China is so early in origin as some authorities would consider to be the case. However, it appears possible that the Chinese made serious use of cast iron from around A.D. 500, and established what may almost be called a heavy industry by A.D. 1000, in which case they would have been far in

advance of the Western World where cast iron was not widely or seriously used in any form prior to the fifteenth century A.D. Also, if we may accept the dating put forward for the Kai-Yuan lion, and the Yü Chhüan Ssu pagoda, the Chinese were the first people in the world to produce heavy iron castings on what may well be called an extensive, and even commercial, scale.

Chapter V

FURNACES AND FUELS

THE SMELTING FURNACE

To follow the evolution of the iron-smelting furnace is a difficult matter. First, the number of iron furnaces which have been found and excavated is not very great; also it is exceedingly unfortunate that evidence from the Ancient Near East is scarce and far from satisfactory. No doubt the Near East contains the cradle of the earliest iron working and a type series of smelting furnaces from these lands would be of the highest value. Unfortunately, so far such evidence is lacking. Another difficulty is that the fairly numerous furnaces found in Europe seem, according to the published reports, to represent a confusing number of types. It is unusual for a furnace to be found by the excavator in good condition, and all too often the upper portion is entirely missing. Under such conditions it is extremely difficult for an archaeologist to attempt any reconstruction of the furnace type unless he has guidance from an expert upon early furnaces. Even advice from a practical foundry man would have prevented some of the misleading, and even absurd, theories and reconstructions from which European furnaces have suffered much in the past. Further research will be required before we can present a clear picture of furnace evolution from the simple bloomery hearth up to quite advanced mediaeval designs. The most simple and primitive furnace is, of course, the bonfire. We need not consider this simple device for, although it may well be possible to smelt such an ore as cassiterite, the tin ore, in a simple bonfire built at ground level, because the reduction process requires but low temperature, such a furnace would not be applicable to iron smelting where a much higher temperature, combined with control of the atmospheric and other conditions in the furnace, is required.

It is natural to consider that the original iron-smelting furnace was of a simple nature, but before we can be certain of this we require dated examples of furnaces which may safely be ascribed to the earliest phases of iron smelting. A further complication arises from the fact that in many regions there must have been a long tradition of copper smelting behind that of iron working. Hence, the iron smelter may well have had the

advantage of a series of sophisticated copper-smelting furnaces behind him. We may here quote Professor R. J. Forbes's remarks (1950, pp. 405–6):

> The beginnings of the iron industry are still very dark from the technical point of view. All we can say is that the earliest bloomeries must have consisted of very simple clay-lined pot-bowl furnaces or simple bloomery fires (Rennfeuer) both worked with blast air and smelting ores of the limonite and ochre type or weathered haematite. We have seen that these simple furnaces developed into the peculiar shaft furnaces called 'Stückofen' by the way of the Catalan hearth, and how these Stückofen permitted the smelting of ores of the haematite and magnetite type. But the early iron industry will remain dark as long as the history of the smelting furnace is not known better in detail.

There is little point in trying to work out an elaborate series of furnace types which can only be based upon vague and often unreliable theories and reconstructions. Until much more excavation and research have been carried out it is wise to confine ourselves to major groups which are founded on good evidence. There appear to be three well-established types of early iron-smelting furnaces:

(*a*) The simple bowl furnace.
(*b*) The Domed furnace (sometimes called the Pot furnace).
(*c*) The Shaft furnace.

Again, there is a major distinction between furnaces worked with the aid of a forced draught, and those which rely upon natural draught alone. It by no means follows that the use of bellows to provide a forced draught in the iron-smelting furnace indicates a higher technique. While bellows-blown furnaces were used at a very early date, around 1500 B.C., in Egypt, there is evidence to indicate that some form of bellows and air-blast was known in Mesopotamia as early as the middle of the third millennium B.C. (Coghlan 1951, p. 69). On the other hand, natural-draught furnaces were used in the prehistoric Iron Age of Europe, in the Middle Ages, and even later. In some cases it is easy to tell if a given furnace belongs to the forced, or natural-draught, type. In built-in furnaces, such as those of Siegerland, where there was but one entry—the wind passage—natural draught was relied upon. On the other hand, furnaces such as those of Einzingen and Tarxdorf certainly used forced draught. It is not so easy to determine the question when the furnace excavated is in bad condition, or when sufficient of the furnace does not remain to allow of an accurate reconstruction. Here, it may be possible

by an examination of the slag to estimate whether it belongs to a blown- or a natural-draught furnace. Again, when tuyères of baked clay are found in association with the furnace, there is strong evidence for the use of a bellows and air-blast. It must, however, be remembered that (as in the case of some modern primitive African furnaces), a number of clay tubes spaced round the lower part of the furnace may be used to provide, or to regulate, a natural draught. Conical tubes or tuyères point to the use of the bellows rather than do cylindrical ones. Also, cylindrical tubes which are long enough to pass through the wall and lining of European furnaces do not, as yet, appear to have been recorded.

For iron smelting the bowl furnace was simple and widely used. As the name indicates, it consisted of a bowl-shaped hole in the ground, lined with clay which baked to a hard and fairly smooth surface. Artificial draught would appear to be necessary with this type of furnace and was probably provided by means of a bellows and blast-nozzle or tuyère. The charge of fuel and ore would be built up in the form of a cone, or dome, above the level of the top of the bowl, while the pipe leading from the bellows to the blast nozzle would pass over the rim of the bowl as indicated by Neuburger (1930, fig. 23) for the Kordofan bloomeries. It is by no means certain that this somewhat awkward arrangement of leading in the blast air over the rim of the bowl was the method most generally employed; the air-supply could have been introduced at a lower level with advantage. It is also doubtful whether means for tapping the slag were used in connexion with the early bowl furnaces. The bowl furnace was not an efficient one; there would be a very serious loss of heat from the open top of the fire, and there must also have been a very considerable loss of iron to the uncontrolled slag, but the simple bowl had a very long life and seems to have lasted on from prehistoric times into the Middle Ages. It is also known from modern primitive contexts. Again, it is early known in Egyptian paintings, and Oliver Davies (1935, p. 43) quotes various known finds in Europe. Professor Gowland stated that the bowl furnace was associated with Roman pottery in the tin workings of Cornwall (1899, p. 299). At Hüttenberg in Austria, interesting installations of bowl furnaces set in a stone pavement were discovered (Weiershausen 1939 p. 157). The installations were in pairs (Fig. 5, after Weiershausen Abb. 42), and it was thought that one of the bowls was used to roast the ore prior to the smelting operation in the other. It is not certain that a roasting process was, in fact, in operation at Hüttenberg. The second furnace may equally have been used for reheating to refine

the bloom after smelting. Evidence is lacking to show the method adopted for the necessary air-blast, and no passage which would have served to tap the slag was reported by the excavator.

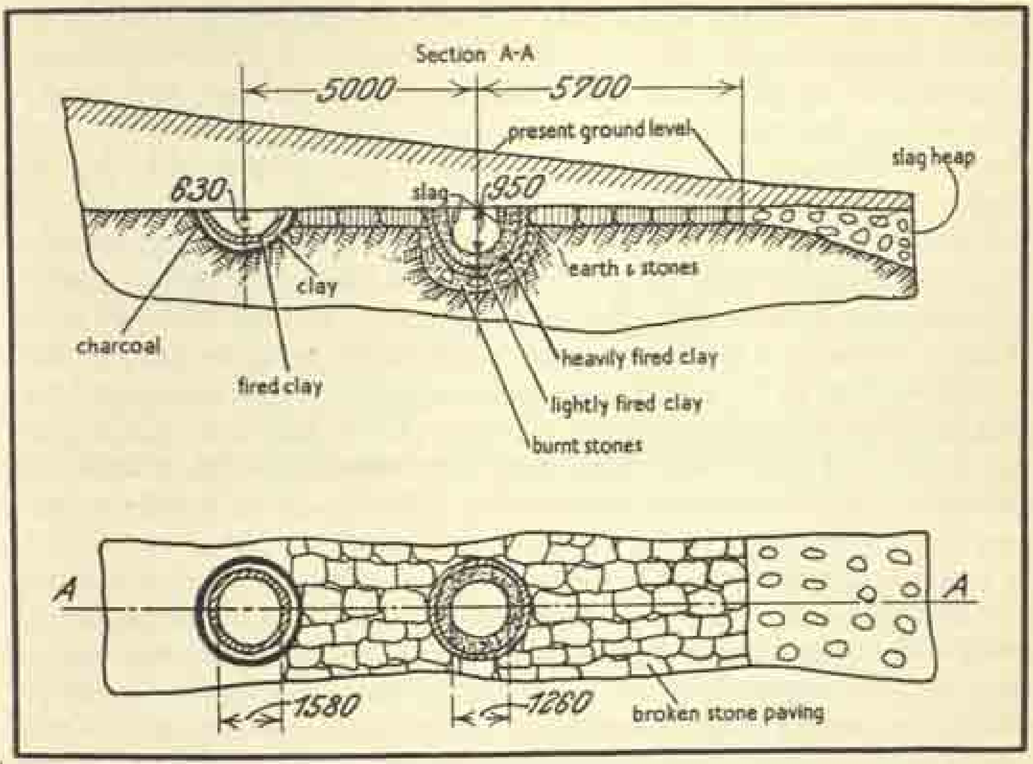


FIG. 5. Bowl furnaces at Hüttenberg in Austria (Weiershausen 1939, Abb. 42).

THE DOMED FURNACE

We may now consider that very important type, the domed furnace. Such furnaces have sometimes been called 'Pot' furnaces, but in the author's opinion 'Domed' is the better term since a pot may take many forms but a dome remains a dome. The type may quite possibly be a variant of, and developed from, the bowl furnace, but it may also owe its origin to the pottery furnace, for domed pottery kilns were in being long before the dawn of the Iron Age. The major constructional feature, the dome, may well have been borrowed from the older pottery kiln. In construction the furnace is simple; the circular hearth may be flat or hollowed to a dish-like form. Smelting is carried out in the domed chamber above the hearth, with a central chimney to carry off the

products of combustion. These furnaces may be built-in on the side of a hill, or they may be free standing. In general, the domed furnace of the European Iron Age relied upon natural draught.

Excellent examples of Iron Age domed furnaces for iron smelting were discovered from 1930 onwards in Gosenbach, Kr. Siegen, south Westphalia (Stieren 1935, pp. 12–20). The Siegerland finds revealed the existence of an important iron-smelting industry; in all, some ninety pre-Roman slag heaps and smelting sites were recorded. The pre-Roman furnaces belonged to the La Tène period of the Iron Age and were late rather than early in the period. They had clearly a very considerable tradition behind them. Furnaces built into the side of a slope and free-standing furnaces were found. The free-standing ones were in general similar to the built-in type, but the wind passage was omitted as air could enter all round, a number of wind or draught holes being provided round the base of the furnace. A reconstruction due to Krasa is given in Fig. 6 (from Weiershausen Abb. 2). Furnace number E. 25 in the Engsbachtal was in such good preservation that a complete reconstruction was possible. Both built-in and free-standing furnaces appear to have been in use at the same time. In the Engsbachtal furnaces the dome was roughly 1 metre in diameter and 1 metre in height, the dome had a low chimney for charging and escape of the combustion gases, and air was supplied by means of a tunnel or wind passage. The body of the furnace was built of clay and sometimes the floor of the hearth was of flat stones. In furnace E. 25 the wind passage was about 2 metres long and of square section, 30 to 40 cm. inside. Stone slabs were used to line the passage. A most interesting feature of these furnaces is that the wind passage is provided with nozzles or tuyères at the hearth end, one to three nozzles of from 6 to 8 cm. in diameter being used. Natural draught must have been relied upon for the operation of the furnace and it was evidently realized that, when a good wind was blowing into the wind passage, the velocity of the air could be much increased by the provision of tuyères, so obtaining a more intense heat in the furnace. In other words, the smelter combined natural draught with the principle of the bellows.

In recent years a most important work has been accomplished by Weiershausen (1939), who has studied what is known of the European furnaces, and has shown where certain reconstructions and theories cannot be accepted from the technical point of view. We may now notice some of the more important furnaces dealt with in his work. An important furnace, because sufficient remains were found to permit a reconstruc-

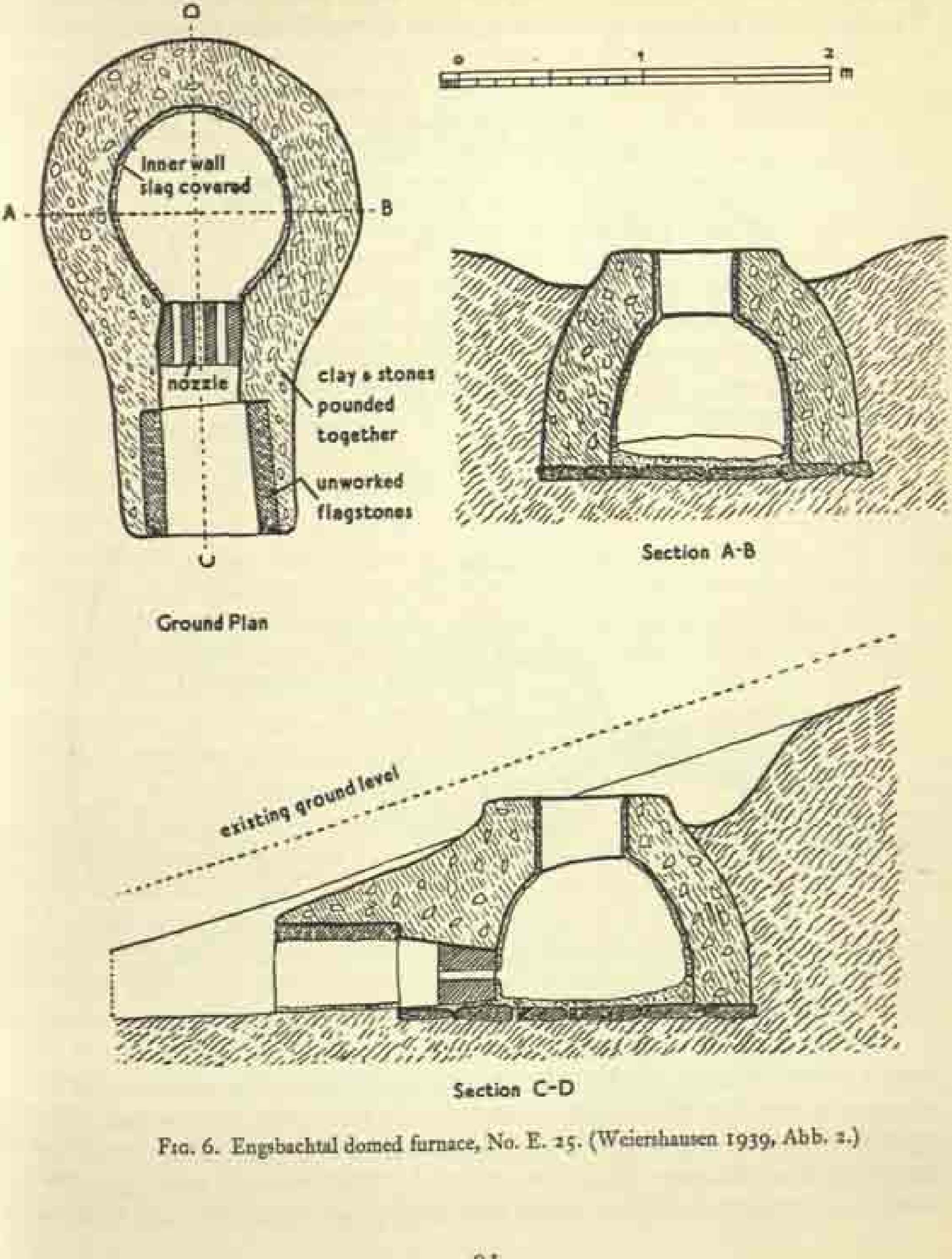


FIG. 6. Engsbachtal domed furnace, No. E. 25. (Weiershausen 1939, Abb. 2.)

tion, is that of Aalbuch, about 1 kilometre to the south of Tauchenweiler, in Württemberg, south Germany (Fig. 7 after Weiershausen Abb. 12). The furnace is of large size and is unusual in that it may have been built

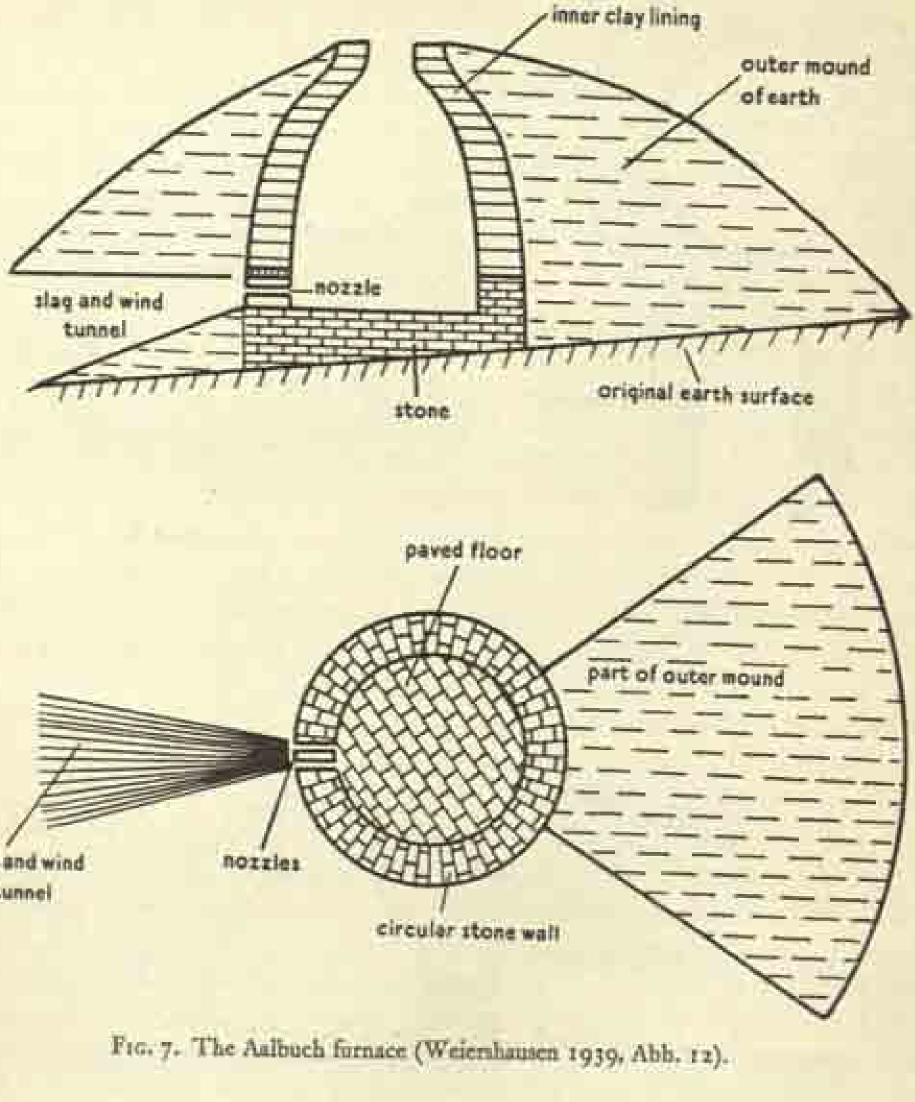


FIG. 7. The Aalbuch furnace (Weiershausen 1939, Abb. 12).

into a round barrow. Unfortunately dating material was absent, but it seems a typical La Tène furnace, and should belong to that period. The mound which contains the furnace is 8·5 m. in diameter, and 1·7 m. in height (Weiershausen 1939, pp. 66–69). The furnace was carefully built, a circular stone floor being laid down, and upon this was built a

stone ring-wall to a height of approximately 25 cm. The circular hearth was 1·7 m. in diameter. The furnace dome closed in from above the stone ring-wall to the usual contracted chimney or smoke opening. The smelting was carried out under natural draught, for which a westward-pointing combined slag and wind passage was provided. This passage apparently ended at the furnace-hearth with nozzles or tuyères as in the Siegen furnaces. The Aalbuch furnace is important as an example of an Iron Age furnace of considerable size operated under natural draught. The arrangements for withdrawing the bloom are not clear. The nozzles or tuyères may have been broken-out or otherwise removed after each smelt, but it cannot have been easy (if indeed possible) to withdraw the bloom and make good the nozzles in the small and lengthy wind passage shown in the reconstruction. In this case, we should be strongly inclined to the view that there must have been some other means of access to the furnace hearth, or that the wind passage must have been of larger dimensions than indicated by the reconstruction.

As an example of how easily confusion in furnace typology may arise, the furnaces of Tarxdorf, in Silesia, east Germany, may be mentioned with advantage (Weiershausen 1939, pp. 97–104, and figs.). These furnaces, of which there were apparently a great number, are very difficult to explain. The reconstructions put forward by Krause, Giebeler, and Humperdinck do not agree in all respects. Only the bottom portion of the furnaces which was below the present ground level was found, and it appears decidedly questionable if an upper part ever existed. The descriptions of the above mentioned authors would indicate the production of cast iron which is certainly incorrect. The date of the Tarxdorf furnaces does not appear to be well defined, although Hallstatt pottery was found. Bog-iron ore seems to have been smelted, and according to Weiershausen there is no need to consider that there was any upper part to these furnaces. Nothing of the sort was, in fact, found. It is more likely that the furnaces were of the free-standing bloomery type with a combined wind and slag passage, and that they would have produced the normal wrought iron. Krause and Giebeler have surrounded the Tarxdorf furnaces with complex theories which are technically impossible. Weiershausen's view that the furnaces are quite ordinary bloomery ones would appear, in the light of his technical explanation, to be acceptable and in all probability correct. Before the Tarxdorf furnaces can be brought into their correct typological place there is need for further examination and report by an expert technologist.

A well-preserved iron furnace of pre-Roman date was excavated at Krampniss in east Germany, by Bestehorn (Weiershausen 1939, pp. 123–33, and Figs. 31, 32). An important feature was that the iron working was carried out through the use of two furnaces, No. 1, which Bestehorn termed a reverberatory furnace (*flammofen*), and No. 2, a crucible furnace (*Tiegelgrude oder Tiegelschmelz*). The so-called *flammofen* is of great interest and quite advanced construction. Steps led down to a stokehold and firebox, and the firebox communicated by means of a duct with a domed chamber like that of the conventional domed smelting furnace. Hence, the furnace consisted of two separate chambers, but in each chamber a charcoal fire was operated. The so-called crucible furnace, No. 2, was considered by Bestehorn to be a pit in the ground containing a charcoal fire upon which the crucible was placed. According to him the operation of the complex was that an impure bloom of iron was produced in the domed smelting chamber of the *flammofen* No. 1, this bloom was next submitted to a crucible process (but not to crucible smelting), in the crucible furnace No. 2. For this purpose the bloom was placed along with charcoal in a clay crucible which was heated over a charcoal fire in the crucible furnace until the iron was refined and rendered of forgeable quality. During the process the iron would absorb carbon.

Weiershausen does not agree with this sequence and thinks that the so-called crucible furnace was in reality a forced-draught smelting furnace in which the iron was actually produced. He considers that there is no evidence to prove that a crucible existed, and that the pieces of the alleged crucible which was found were merely broken pieces of the inner lining of the smelting furnace. In the *flammofen*, No. 1, Weiershausen would see a furnace for converting the iron bloom into steel, or semi-steel. If correct, this is most important, for it gives us an example of a special furnace used for the conversion of wrought iron at an early period. It is not correct to term the conversion furnace a *flammofen*, or reverberatory furnace, because fuel was burnt in both chambers, and the same chimney draught applies to each. The firebox is really a pre-heating chamber, the charcoal fire in which was for pre-heating the charge and walls of the second or domed chamber which contained the wrought-iron bloom to be refined, and a second charcoal fire. In such early furnaces pre-heating of this nature would be most desirable, and possibly necessary in order to attain the temperature required to ensure an adequate increase in the carbon content of the iron under treatment. Pre-heating is, of course, a very common technique with the modern furnace. It also seems

to have been known and used in some peasant smelting furnaces of the Middle Ages in Germany. Weiershausen's theory appears to rest on a sound technical base. If the *flammofen* was merely a smelting furnace as thought by Bestehorn, there is no need for its elaborate design in view of the early dating of the furnace. On the other hand, as a refining or steeling furnace, the reason for its construction at once becomes clear.

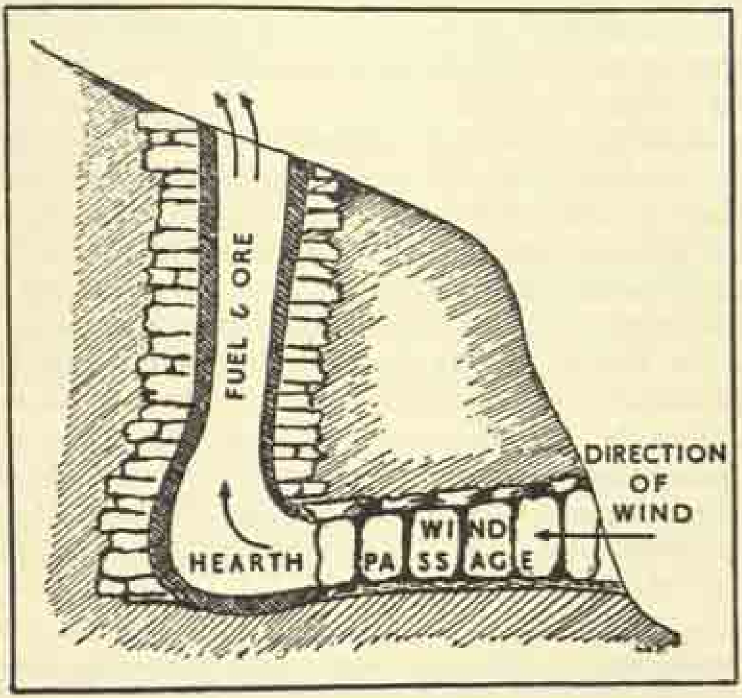


FIG. 8. The Jura Type shaft furnace (Coghlan 1951, Fig. 6).

THE SHAFT FURNACE

With the shaft or Jura type of furnace we come to a well-developed and important type. In its developed form the construction resembles a chimney shaft lined with baked clay with a wind passage leading into the bottom of the shaft (Fig. 8, Jura type). Such furnaces can be worked with natural draught. In the Jura furnaces the wind and slag passage is combined. Also, the bloom would have to be removed through this passage. Fuel and ore could be charged down the chimney while the furnace was in blast so that something like continuous operation may have been possible. In the shaft furnace we see the idea of the modern furnace, but unlike a modern coke-burning installation, the primitive

shaft furnace was limited in height by the nature of the fuel used, for charcoal fuel is not sufficiently hard to withstand heavy loads of ore such as occur when the furnace height rises beyond some 15 to 20 feet. As well as in the Jura, shaft furnaces have been found at Mitterberg and Velem St. Veit (von Miske 1929, p. 81). According to Oliver Davies shaft furnaces were apparently used at H. Sosti (Siphnos), in the sixth century B.C., and were in regular use at Laurium and in Etruria, while in Roman times the shaft furnace had become known in most provinces. The distribution of the type became wide and it had a long life (Davies 1935, pp. 44–48).

We may obtain some idea of the capacity of and mode of working these furnaces by analogy with the modern primitive shaft furnace from Burma which is mentioned by Gilles (1936, p. 256, Abb. 4). This furnace was over 10 feet in height and depended for its action upon natural draught alone. In the Burmese furnace the short but large wind passage terminated in no less than twenty tuyère tubes, each of 5 cm. in diameter. The furnace charge comprised about 210 Kg. of ore, and 219 Kg. of charcoal. After eight or nine hours the slag was tapped, and then tapping of the slag was carried out at intervals. After twenty-four hours an opening was made in the bottom of the furnace, and the smelted bloom of iron, weighing some 45 Kg., removed. With this, it is of interest to compare Richardson's (1934, p. 576) estimation of the yield of the smaller iron furnaces. He says:

> Like its copper smelting prototype, the Hallstatt furnace would be a shallow excavation, about two feet square and deep, lined with refactory clay. But where this excavation had formerly comprised the entire unit it was now merely the hearth; the smelting chamber proper rose above the ground to a height of two to three feet. Its inner wall, banked with sod, was enclosed by a rough stone facing, possibly twelve inches square at the top. This chamber gradually widened to twice that dimension at the hearth, into which a free-flowing stream of air was admitted through an opening pointed into the wind. Furnaces of this type might conceivably produce in eight to ten hours a semi-fused mass of iron weighing fifty pounds. In this operation alone approximately two hundred pounds of charcoal would have been consumed, while subsequent heating and working required at least one fourth as much more.

Of shaft furnaces, apart from those of the Jura type, that found at Lölling, in Austria (Weiershausen 1939, pp. 161–2), is highly important, for it gives us a plan and section of a furnace which was recovered practically in its original condition (Fig. 9, after Weiershausen's Abb. 44). This is a shaft furnace, with a shaft 1·26 m. in height (possibly

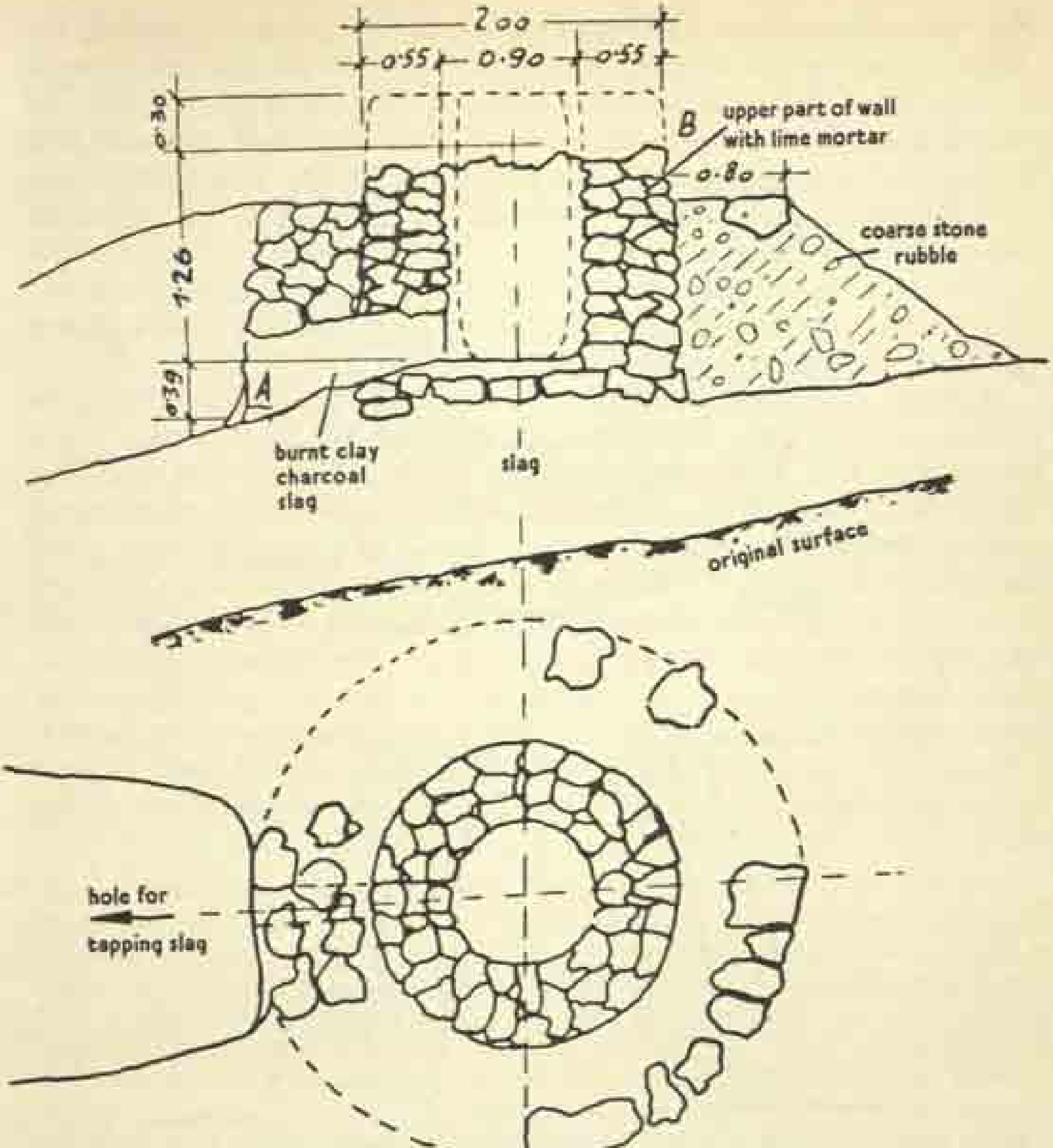


FIG. 9. The Lölling shaft furnace (Weiershausen 1939, Abb. 44).

originally slightly higher), and 90 cm. internal diameter. The shaft was built up in dry stone walling and the whole surrounded by a rubble mound. Originally the shaft and furnace pit were lined with baked clay as an insulating material. At one side of the furnace is a passage through which the slag was tapped, and on the drawing this passage resembles a

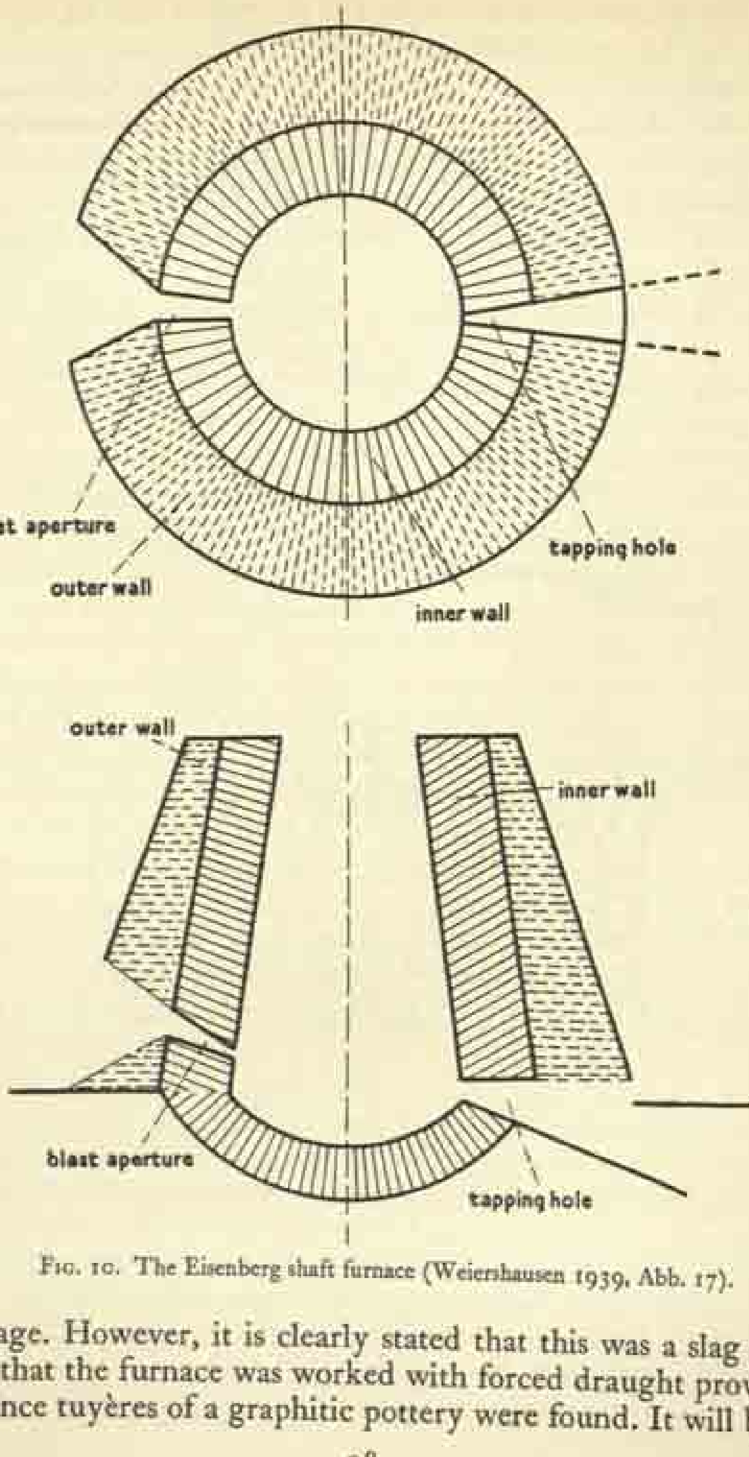


FIG. 10. The Eisenberg shaft furnace (Weiershausen 1939, Abb. 17).

wind passage. However, it is clearly stated that this was a slag passage. It is clear that the furnace was worked with forced draught provided by bellows, since tuyères of a graphitic pottery were found. It will be noted

that the slag-passage is inclined on the down-hill side of the furnace so that the slag can run down the passage by gravity, a feature which Weiershausen states that he has frequently noticed in furnaces belonging to the Middle Ages. The Lölling furnace appears to be undated. A furnace of somewhat similar design was found at Hüttenberg in Austria (Weiershausen 1939, pp. 159–61, Abb. 43). The Hüttenberg II furnace goes back to Roman times, and it may even possibly be earlier. This type of shaft furnace was frequently used in the Middle Ages and indeed according to Weiershausen similar furnaces were still in use by the Löllingen peasants for primitive smelting as late as the nineteenth century. The furnace was of relatively large size, standing up to 6 feet in height, clay-lined, with stone retaining walls. After the smelting operation, the bloom was removed through an aperture in the side of the shaft, the hole being luted with clay when smelting was in progress. Sometimes, at least, forced draught by means of bellows was employed. Some points about this furnace remain confused. For instance, there is no information given as to the means adopted to tap the slag from the furnace.

At the Eisenberg, Pfalz, south Germany, were found rich remains of iron smelting dating to the Roman period. Part of a small shaft furnace (Eisenberg, No. 2) was found. A useful reconstruction of this is given by Weiershausen (1939, pp. 81–82). Such furnaces (Fig. 10, after Weiershausen, Abb. 17) are probably typical of the smaller free-standing iron-smelting furnaces of the Late Iron Age, or early Roman period. The hearth is dished, and a slag passage leads away from its rim. At a slightly higher level a hole is provided through which artificial draught may be provided by a bellows. The shaft and hearth are lined in the usual manner.

Although used for copper smelting, we must mention a most important discovery of an Etruscan shaft furnace. The discovery was made by an engineer, Lorenzo del Mancino, in 1934 near the church of Fucinaia (Witter 1942*a*).[1] Fortunately, enough of the furnace was preserved to enable a very valuable reconstruction to be made (Figs. 11–13 after Witter, Abb. 7–9). The brick-lined furnace shaft which formed the smelting chamber was 1·80 m. internal diameter at its base. This shaft was separated from a lower chamber, or ashpit, by a floor in which there were two rows of holes, 5 to 7 cm. in diameter. This dividing floor was supported by a central pillar, and access to the ashpit was by a large passage as shown in Fig. 13 (Witter, Abb. 9). The charge of fuel and ore will have occupied the shaft in the usual manner. There must also have

[1] See also *Studi Etruschi*, xi, 1937, pp. 305–41, and figs. 3, 4, 5, 7.

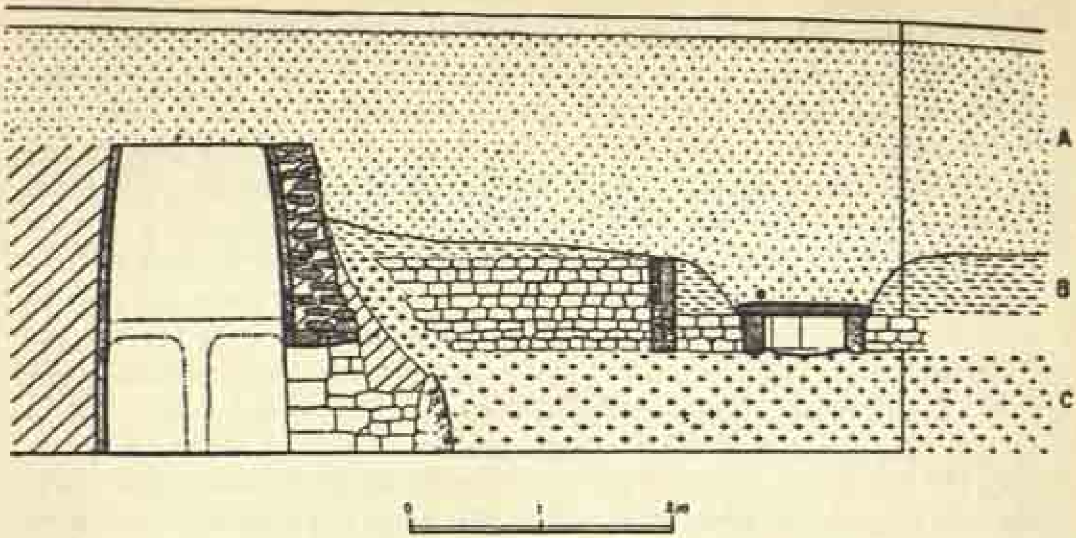


FIG. 11.

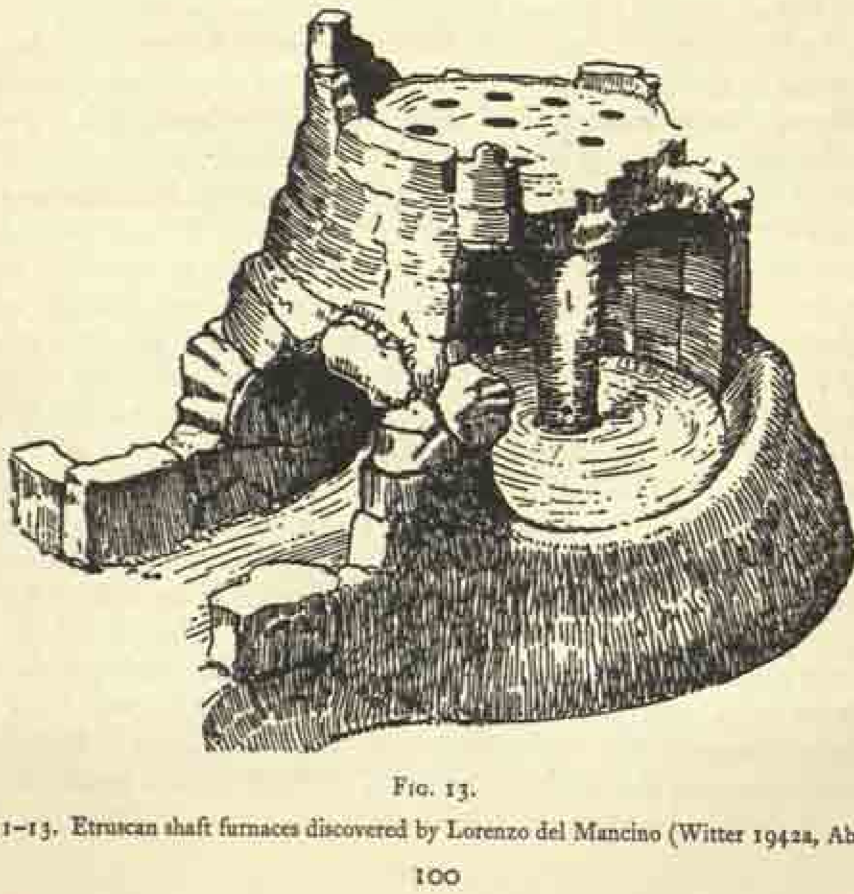


FIG. 13.

FIGS. 11–13. Etruscan shaft furnaces discovered by Lorenzo del Mancino (Witter 1942a, Abb. 7–9)

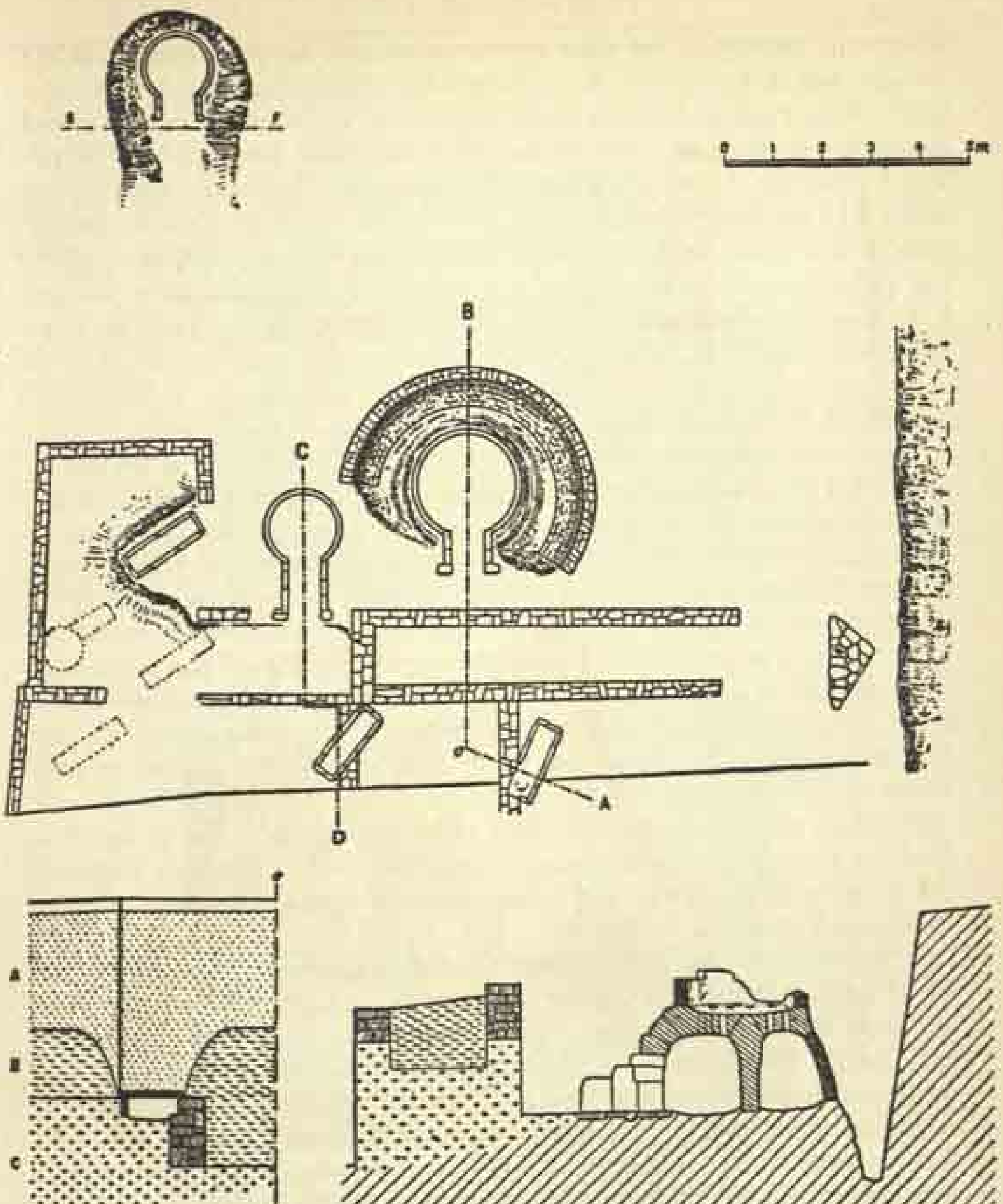


FIG. 12.

been some passage in the shaft for the purpose of tapping slag when the furnace was in operation. No such passage was found, but it may have been above that part of the shaft which was recovered intact. Natural draught was used, and the air supply would have been by way of the lower chamber, or ashpit, and then through the perforated floor to the shaft. The similarity in construction with the early Near Eastern pottery kilns is most remarkable. A furnace with domed roof and central supporting pillar was found at Arpachiyah in level TT8, while early pottery kilns with an ashpit and perforated dividing floor were found at Tepe Sialk and Khafaje (Coghlan 1942, pp. 27–29, Fig. 3).

VARIOUS FURNACES

There are a number of iron furnaces for which it would be unwise to attempt a classification because in some cases only the ground plan has been recovered, and sometimes the excavator's reconstruction cannot be regarded as reliable. Beck's well-known reconstruction of the Dreimühlenborn furnace, near Saalburg, west Germany, can only be relied upon in respect of the hearth and slag passage which were actually found by excavation. The reconstruction of the upper portion of the furnace is hypothetical; it is also possible that the furnace may belong to the Middle Ages, although Beck considered it to belong to the Roman period. The Epernay furnace in France has been illustrated in the past as an iron furnace. This furnace, which was built into the side of a hill, had one opening at the bottom and another of much the same size at the top. Such an arrangement would provide no effective draught and, whatever the purpose of the furnace, it seems clear that it would not serve for the smelting of iron ore.

A well-known series of furnaces which form a distinct type, and may well be of early origin, is the Catalan furnace (Fig. 14 after Newton Friend, and also Forbes, 1950, Fig. 81A). The Catalan type is a pit furnace with an air blast introduced about half-way up the smelting cavity. The original distribution of the type was in Catalonia, and in the Ariège in France. According to Forbes (1950, p. 390), these furnaces were still in use in northern Spain in the provinces of Navarra and Guizpuzcoa in the seventeenth century A.D.; however, in origin the type is unquestionably far more ancient. Another ancient furnace, although possibly not dating before the Middle Ages in Europe, is the Osmund furnace (Fig. 15 after Forbes, 1950, Fig. 81C). As the figure shows, this furnace is of unusual design. Its distribution is a northern one, Finland, Sweden,

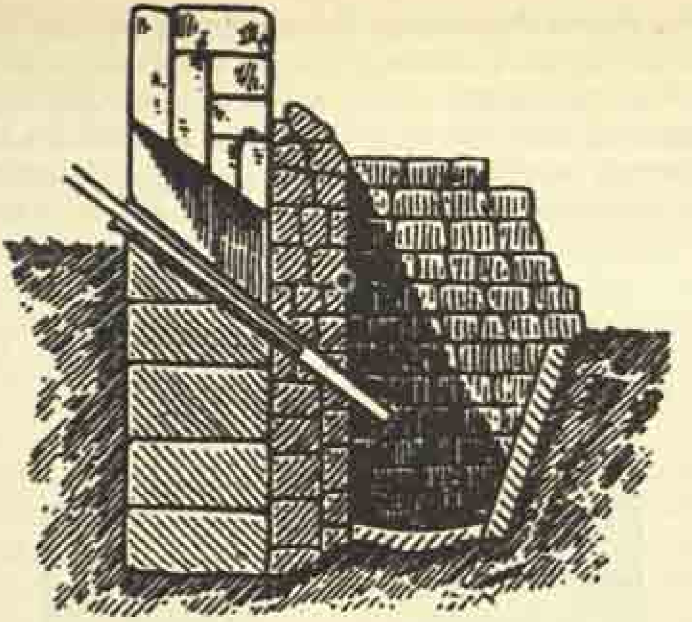


Fig. 14. The Catalan furnace (after Newton Friend, Forbes 1950, Fig. 81A).

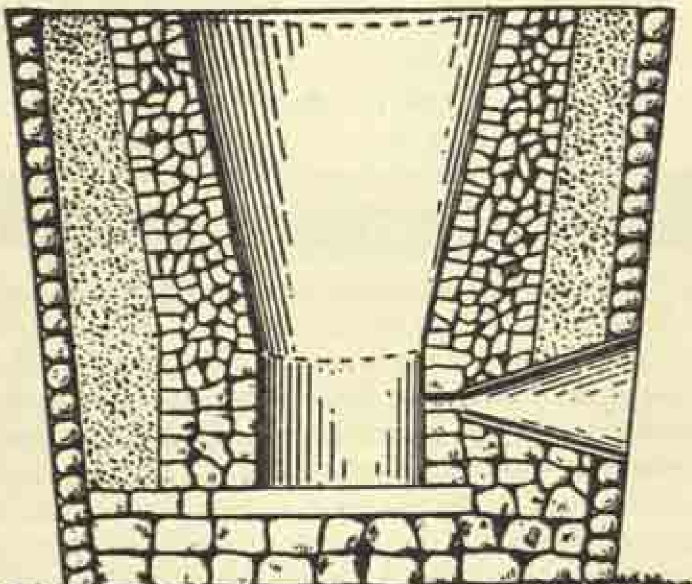


Fig. 15. The Osmund furnace (after Newton Friend, Forbes 1950, Fig. 81C).

and Norway. We mention it here because it may have led to the idea of the Stückofen (Fig. 16, Forbes 1950, Fig. 82). The Stückofen although late in date is a very important type, and in Professor Forbes's view these bloomery furnaces were worked in Carniola, Carinthia, Styria, Hungary, &c. The furnace may be described as two Osmund furnaces, one inverted over the other. In size they were up to 16 feet in height, and in

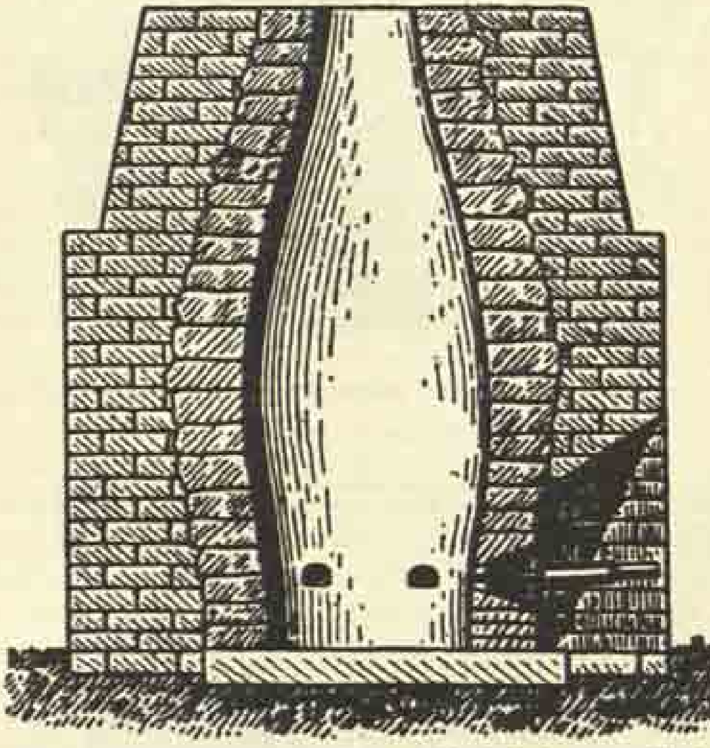


FIG. 16. The Stückofen (after Newton Friend, Forbes 1950, Fig. 82).

the large sizes forced draught was furnished by means of bellows worked by water power. No doubt the Stückofen was the prototype of our modern blast furnaces, for it is clear that although the normal function of the furnace was the production of a Stück, or bloom of iron, the construction and height of shaft combined with a powerful air blast would at times render the accidental production of cast iron likely.

Concerning the furnaces used in Britain, it is unlikely that the shaft furnace was used until the Roman period, and then perhaps only in the less backward provinces. Again, it is interesting to remark that the Romans do not appear to have invented water-driven hammers, or bel-

lows worked by means of water power. Under these conditions it follows that the size of bloom which it was possible to work was limited by the power of the sledge hammer. In a great measure this accounts for the early practice of forging or welding together a number of blooms when large and heavy pieces of iron were required. Under the Romans it is certain that the iron industry greatly expanded in quantity and quality, but they do not seem greatly to have advanced the technique of the iron furnace. Records and dimensions of Romano-British furnaces may be found in May's works to which we have already referred. Harold Dudley (1949, pp. 191 ff.) has recently given particulars of furnace and smelting sites in north-west Lincolnshire, and to various other authorities we have already given references.

Concerning primitive furnaces and iron smelting, a point of interest is the means adopted for the removal of the bloom and disposal of the slag. Here the evidence, when available, is often far from satisfactory. With small bowl furnaces the smelting process would not have been continuous, so that the furnace would have been extinguished, or, when of the contracted neck variety, even broken up, after the completion of each smelt. In such cases removal of the slag and iron of course would present no difficulty. With shaft and large domed furnaces the technique must have been different. In some cases liquid slag will have left the furnace through the wind passage, and as technique improved separate passages would have been arranged for the better control and tapping of the slag. As we have seen, it appears that in some of the larger furnaces the bloom was also removed through the wind passage. This cannot have been an easy or satisfactory method, and further evidence to throw light on this point is needed. A matter which we must remember is that the slag from prehistoric smelting must often have been far from liquid. Often it must have occurred when a suitable flux was not used that the slag would hardly liquefy, and would therefore remain in the furnace, from which it had to be removed when smelting was over. In some large furnaces this operation could have been carried out without much difficulty, but in some cases it would appear that a part of the furnace wall would have had to be broken away.

CRUCIBLES

There is evidence to indicate that the crucible process was connected with relatively early iron working, and Oliver Davies (1935, p. 58) points out that at Rudic crucibles with six tuyères were found. So far as I can

discover there is no evidence from the West to show that actual crucible smelting was practised; the crucible process was always confined to the conversion of wrought iron into steel by cementation. In a closed crucible containing charcoal and sometimes other substances, small pieces of iron would be converted into steel, as in the well-known crucible processes of the East. However, the crucible process would give but a very small yield as a result of considerable labour. Probably it was only applied at a relatively late period when material of specially high quality was desired. Carburization in a separate refining furnace was of course one method of partial conversion to steel, but it was also possible to obtain a semi-steel from the normal iron-smelting furnace, especially if the furnace was preheated so that higher than normal temperatures were attained. A suitable ore (such as brown ironstone) would have been necessary, and more charcoal than usual would have to be included in the charge. Accurate control of the air-draught would also have been necessary in order to reduce the oxidizing effect of the air entering the smelting zone of the furnace.

FUEL

In eastern and southern parts of the Old World fuel for the smelting furnaces must often have been rather a problem. To a very great extent the quality of the fuel determines the temperature which can be attained in the metallurgical furnace, therefore the smelting and melting processes were dependent to a considerable degree upon the availability of a good and suitable fuel. There is no doubt that, for general metallurgical purposes, charcoal was the fuel ordinarily employed, although ordinary wood (not converted to charcoal) may have been used too. Forbes (1950, p. 105) states that samples of charcoal have been found in early dynastic tombs at Naga el-Deir, and in a first-dynasty tomb at Saqqarah. Many kinds of wood, birch, oak, hazel, beech, &c., may be burnt for charcoal, but for good charcoal a close-grained wood containing the sap gives the best results. Mimosa, acacia, and tamarisk woods make good hot fires which may attain some 800 to 850° C. even without the application of an air blast. The normal process of charcoal burning by slow combustion in large heaps is well known, and can have varied but little from ancient to recent times. For those interested in the subject, a good account of the method of charcoal burning is given in Straker's book *Wealden Iron*, in the chapter which treats of fuel.

We know that charcoal was used from prehistoric times right through

to the seventeenth century, but it is rather remarkable to note how late its limited use as a fuel for smelting continued. In Great Britain the production of charcoal pig-iron from A.D. 1800 was solely in the hands of the Furness Ironmasters (Lord, 1945–7, p. 163), and in 1839 David Mushet noted that the making of charcoal pig-iron in Lancashire did not exceed 800 tons per annum. Again, in 1873 Hunt reported that the Newland furnace was operating with hot blast and a fuel mixture of four-fifths charcoal and one-fifth coke. In these cases, the limiting factor was the difficulty in obtaining the necessary charcoal in the large quantity required. Of even later date is the well-known Swedish charcoal iron which was produced in appreciable quantity (using birch wood for the charcoal fuel) certainly up to the outbreak of the Second World War.

Mineral coal is not a suitable metallurgical fuel owing to the fact that it contains harmful impurities, especially sulphur. It was not until the late seventeenth and early eighteenth centuries A.D., when it was discovered how to coke the coal and so to obtain a fine hard fuel free from noxious substances, that coal became the ideal fuel for the smelting of iron ore. Concerning the use of coal as a metallurgical fuel, some remarks by M. Jean Chevalier (1947–8, 1948–9, p. 60) are of interest. He states:

> Ever since Simon Sturtevant had suggested, in 1611, the substitution of pit coal for charcoal for the reduction of iron ore in the blast furnace, metallurgists, when endeavouring to work the process, had always come up against the impossibility of preventing the coal from caking when burning in contact with the ore. The mass of hot material formed a bridge or scaffold across the furnace, preventing the descent of the charge above and also causing the iron previously reduced to be 'burnt' by the blast.

It is, however, quite certain that coal was used by the Romans for domestic purposes, for there is evidence of finds of coal in the remains of Romano-British villas. It would also appear that the use of coal for metallurgical purposes was not unknown to the Romans. Small fragments of mineral coal found in association with iron slag at Tiddington indicated to May that coal was used for smelting in Roman times; he also found satisfactory evidence of the use of mineral coal on thirteen different sites (Fieldhouse, May, Wellstood, 1931, p. 15; May, 1904, p. 76). At Tiddington the cast iron found was considered to have been melted with coal from an impure ore. At Warrington both cannel coal and charcoal were in use, the cannel coal for the ore-roasting furnaces, and possibly for the actual smelting, while charcoal was used in the

refining hearths. As we have said, coal is not a satisfactory fuel for smelting or refining, and its use by the Romans for such purposes must have been extremely limited. The results were no doubt unsatisfactory, but it is important to note that some use was made of coal so long before the discovery of coking. At Velem St. Veit, Austria, a brown coal (lignite), was in early use to some extent.

Chapter VI

THE TOOLS OF THE IRON-SMITH

THE iron-smith is concerned with forging, that is, the transformation of the metal into different shapes. Forging may be done in various ways, for instance, by beating out with hammers or special tools, by drawing down or jumping-up the metal, and by bending. Also, the welding process is frequently employed in the course of forging. The normal forging of iron is carried out at a good red heat, while in the welding process a higher temperature, known as a welding or white heat, is used. Forging of iron is quite a different technique from that of copper and must be carefully distinguished from it. In general, the basic difference between the two techniques is that copper and bronze are practically always worked in the cold state, and with the aid of frequent anneals. On the other hand, for all practical purposes iron must be worked at a red, or even higher, temperature. To a very limited extent iron and mild steel may be forged cold; the closing of a cold steel rivet is a well-known example of cold forging. However, for general forging cold working is not practicable. Apart from the harder nature of the material, any considerable hammering would cause most irons to start cracking, and iron cannot be annealed to return it to its original soft condition with the same ease as copper (we may note that iron and steel may be 'normalized', but this is a delicate process and would not have had application in early times). Hence, it is a general rule that iron and steel are always forged in a heated condition, and it is therefore clear that a fundamental difference between the iron- and copper-smith's work is that, as the copper-smith forges with his metal in the cold state he does not necessarily require holding tongs, while the iron-smith should possess efficient tongs to hold his red-hot iron firmly while it is being worked on the anvil. But efficient hinged tongs must have taken time to develop and the first iron-smiths no doubt had to work without them.

Modern primitive cultures show us that decidedly simple, and indeed primitive, tools have been in use by native smiths even up to the present day. In an interesting article Dr. Jeffreys (1952, No. 75) gives some notes on the methods of the Bikom (British Cameroons) blacksmiths. These smiths use very simple tools. A granite block serves for the anvil, and

heavy granite hammers of about 35 lb. and 22 lb. are used to expel the slag and convert the smelted bloom to a pig, then roughly to shape the pig to the article required. The final shaping of the forging is done with granite hammers weighing about 15 lb. and 8 lb. respectively. It is important to note that all these stone hammers are simply unhafted pounders, merely held in one or both hands. For finer work iron hammers are used. In the course of the smelting operation Dr. Jeffreys says that the bloom was held with wooden tweezers or tongs which, although they had been soaked in water, burst into flames. Further evidence of iron working with stone hammers among the Tula of Northern Nigeria is given by William Fagg (1952, No. 76). Here, the forging was conducted with stone and iron hammers. Mr. Fagg remarks, 'The special advantages of the stone hammer would appear to lie in its great weight and mass, concentrated along a narrow line, and also no doubt in its low conductivity of heat.' A stone anvil was also used by the Tula smith. Highly interesting was the use of a hollowed stone mould or matrix into which the hot iron was beaten with a heavy stone hammer so as to give it the desired form for the hoe being forged. As Mr. Fagg points out, we have here much the same technique as used with our modern drop forging and pressing machines, a modern repetition method which one would hardly associate with stone hammers and anvils! For the Southern Sudan, Garland and Bannister (1927, p. 107) give evidence for the use by native smiths of stone anvils, stone hammers, and green sticks which serve as primitive tongs. In the Pitt Rivers Museum, Oxford, there are many examples of such tools. In particular, there is a good example of blacksmith's bamboo tongs, 10½ in. long, from the Konyak of Tobu Village, Naga Hills, Assam (Coghlan 1951, fig. 14).

What may be termed the basic tools of the jobbing blacksmith, even at the present time, are not numerous or complex. Before considering early tools, it is useful to mention the major tools as used by a modern smith, but care must be taken to avoid the error of working backwards from modern tools. However, the student should be acquainted with the basic equipment of a modern jobbing blacksmith, and there are marked points of similarity between certain tools, ancient and modern.

(i) *The Forge*

A small blacksmith's forge with its bellows is still a very simple apparatus. The most elementary form in present-day use is the small portable or rivet forge, merely consisting of a circular iron tray on a stand which con-

tains the coke and objects to be heated. Underneath the tray is a hand- or foot-operated bellows which supplies air to a dry tuyère, fixed in the side of the tray, for the provision of air-blast. The bellows of a small country

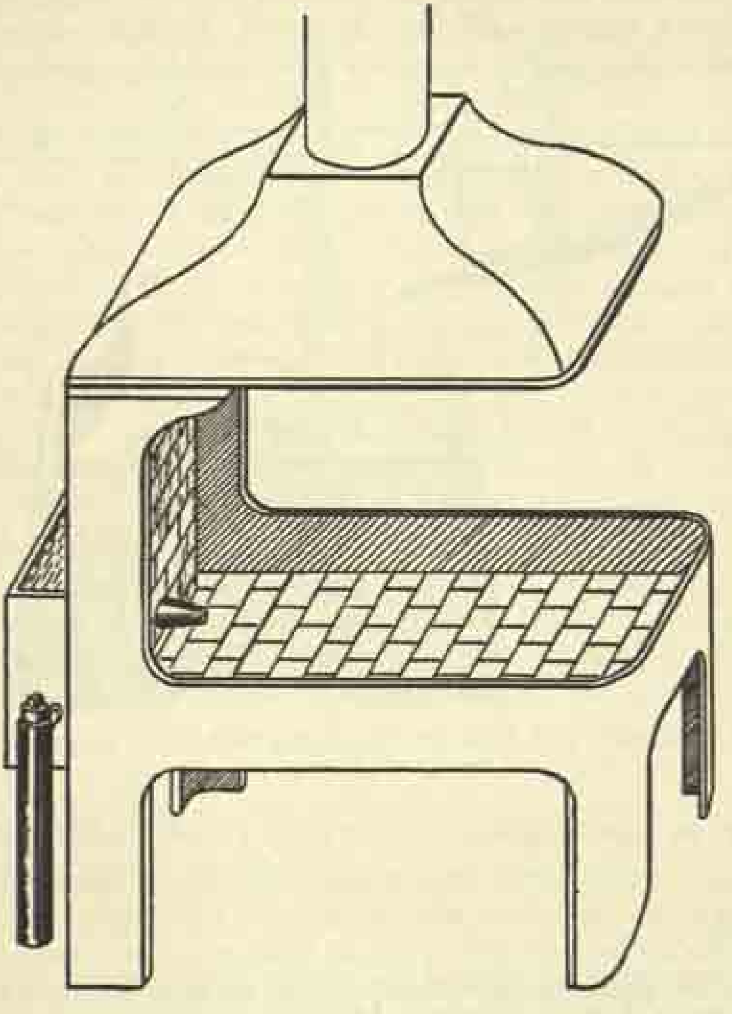


FIG. 17. Blacksmith's forge of cast-iron with water-cooled tuyère (Lillico 1949, Pl. 1). Average size, 4 ft. sq. and 8 ft. high.

forge may still be worked by hand, but an advance over a really primitive forge is that the tuyère, or blast nozzle, is now practically always water-cooled. Also a brick or iron hood is now provided over the hearth to carry off the smoke and fumes from the fire (Fig. 17, after Lillico 1949, Pl. 1).

(ii) *The Anvil*

A substantial anvil with horn, or bick-iron, is an essential part of the smith's equipment. The top or working face of the anvil is usually provided with one or more holes for the reception of auxiliary tools. The modern anvil is much heavier than its early prototype. An average anvil of wrought iron weighs up to some 3 cwt., and has a hard-steel working

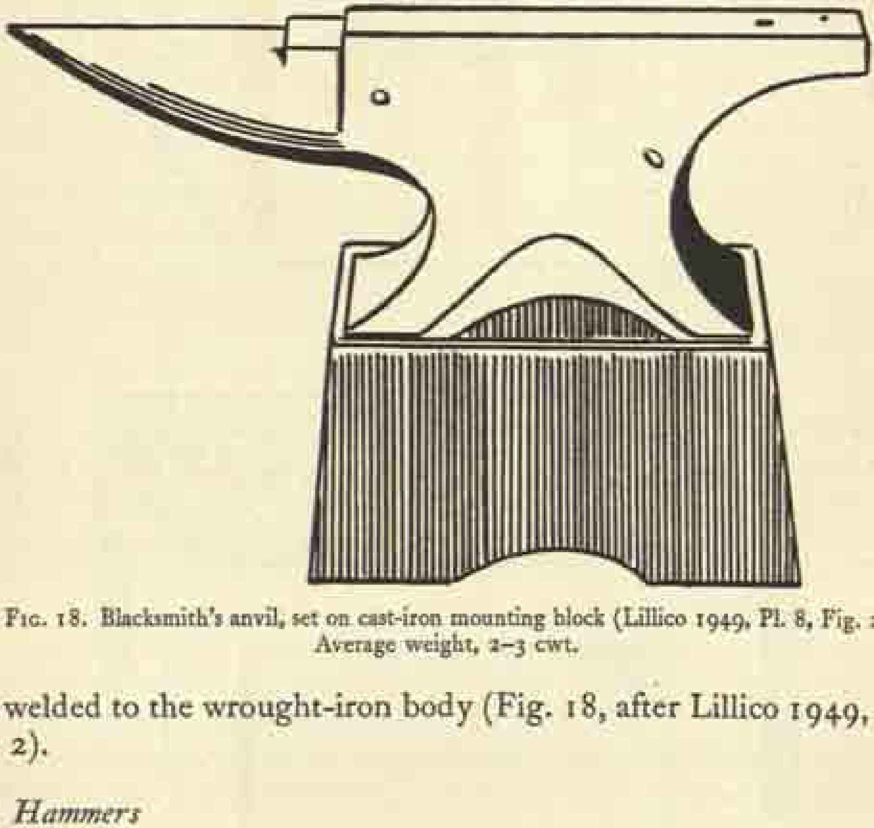


FIG. 18. Blacksmith's anvil, set on cast-iron mounting block (Lillico 1949, Pl. 8, Fig. 2). Average weight, 2–3 cwt.

face welded to the wrought-iron body (Fig. 18, after Lillico 1949, Pl. 8, Fig. 2).

(iii) *Hammers*

In type these may be divided into sledge and hand, the sledge being, of course, a two-handed hammer. Modern smiths use sledges weighing from 6 lb. to 14 lb. A number of hand hammers are required to suit various jobs. As a rule these do not exceed 1½ lb. to 2 lb. in weight. In this country the hand hammer is generally of the ball pene variety. When he is forging a square or rectangular section, the modern smith frequently uses a set-hammer. This tool is hafted and struck with a heavy hammer or sledge. Set-hammers are of two kinds, round- and square-edged. The round-edged hammer is used when working up to a radius, or fillet, on

the piece being forged, while the square-edged set is useful when a sharp corner, rather than a radius, is required. See Fig. 19 (Lillico 1949, Pl. 13, Figs. 10, 11).

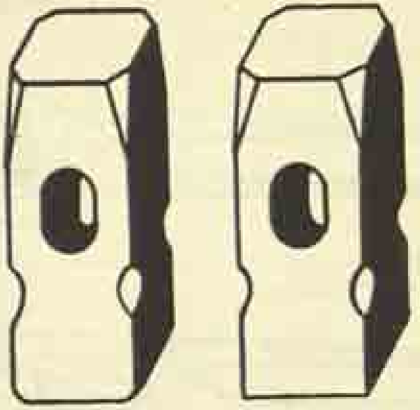


FIG. 19. Set-hammers, round- and-square-edged. 'As their name signifies, they set forgings' (Lillico 1949, Pl. 13, Figs. 10, 11). Average, 6 in. high; weight, 5 lb. or more

(iv) *Tongs*

The smith must be provided with a good range of tongs in various sizes. Hinged flat-jawed tongs are an essential, also pincer-like tongs for holding round stock. Again, there are numerous special tongs for specific work. Some of these are hollow-jawed and caliper-jawed tongs in various shapes and sizes (Fig. 20, after Lillico 1949, Pl. 10, Figs. 1, 2, 5; Pl. 11, Fig. 7).

(v) *Chisels*

The smith uses chisels with which to cut his material, either when hot upon the anvil, or in the cold condition. Blacksmith's hot and cold chisels, or sets, are stouter tools than the mechanic's cold chisel. Usually the body of the tool is from 1¼ in. to 1½ in. square, and the chisel is hafted in the traditional manner by means of a twisted iron rod, or with a wooden shaft. The hot chisel has a finer edge than the cold chisel (Fig. 21, Blacksmith's cold chisels or sets, Lillico Pl. 13, Figs. 3–5; Blacksmith's hot chisels or sets, Lillico Pl. 13, Figs. 6, 7).

(vi) *Fullers and Swages*

It is of interest to mention these tools for they are now used by every blacksmith. Fullers are used for the first operation in drawing down stock

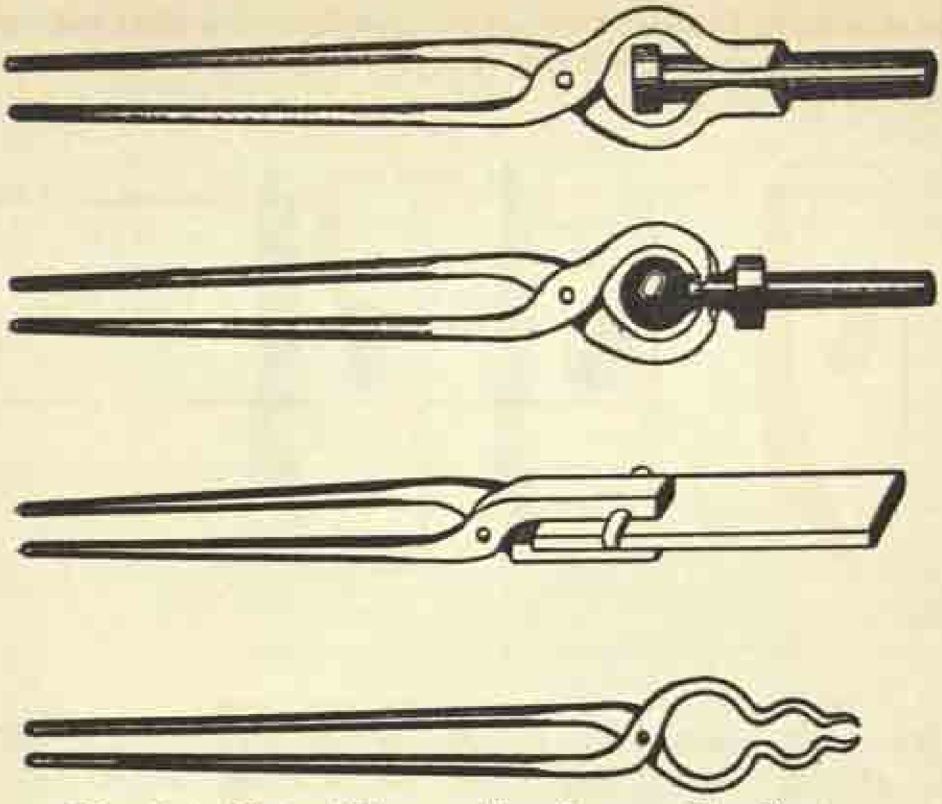


FIG. 20. Various blacksmith's tongs (Lillico 1949, Pl. 10, Figs. 1, 2, 5; Pl. 11, Fig. 7).
Usually 20–28 in. long; weight, *c.* 3–6 lb.

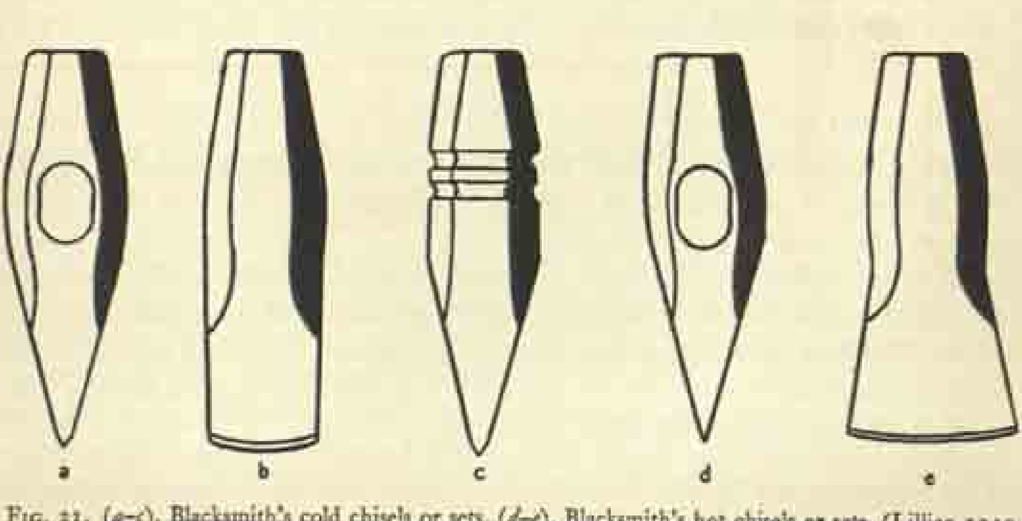


FIG. 21. (*a–c*). Blacksmith's cold chisels or sets. (*d–e*). Blacksmith's hot chisels or sets. (Lillico 1949, Pl. 13, Figs. 3–5; Pl. 13, Figs. 6–7.)
Average, 5–6 in. high; weight, 3–5 lb.

and in forming recesses, fillets, and a great variety of bent and curved work. They are made 'top and bottom'. The bottom fuller rests upon the anvil, while the top fuller is a hafted tool and is struck in the usual way

FIG. 22. Top fuller (Lillico 1949, Pl. 13, Fig. 14). *C.* 4 in. high; 5 lb. or more.

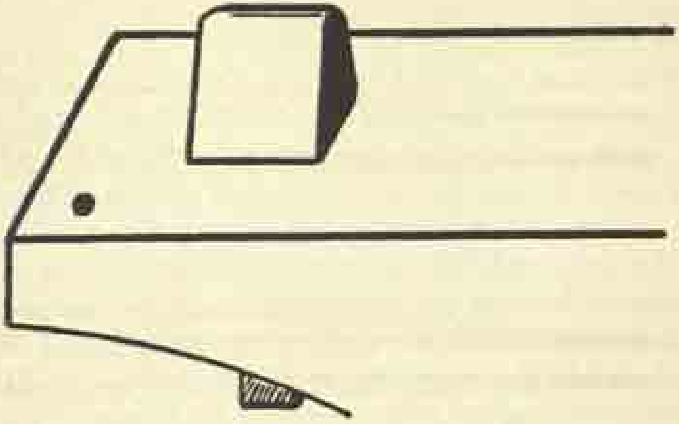


FIG. 23. Bottom fuller (Lillico 1949, Pl. 14, Fig. 3).

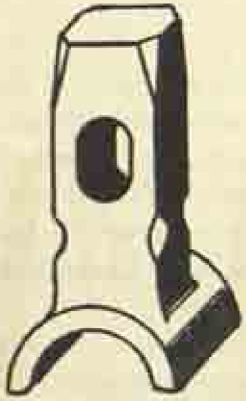


FIG. 24. Top swage (Lillico 1949, Pl. 13, Fig. 12).

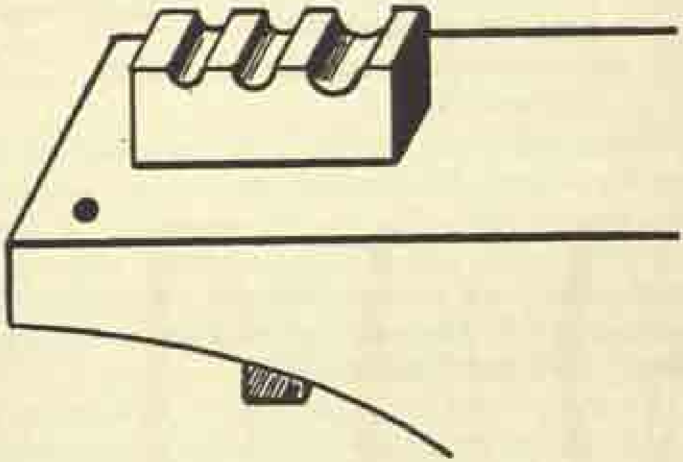


FIG. 25. Bottom or anvil swage (Lillico 1949, Pl. 14, Fig. 1).

with a hammer. In the same way, swages are 'top and bottom', and are used for working material into circular bars or rods. The bottom swage rests on the anvil, while the hafted top swage is held and guided by the smith whose assistant strikes the top swage down upon the work until a good and true bar has been forged. Fullers and swages were certainly

known by mediaeval times, but I do not know of evidence to prove a very early use. However, the idea of the swage is of very early origin, for the semicircular grooves cut in stone blocks, and in some bronze anvils, are in reality elementary bottom swages. See Figs. 22–25.

(vii) *Punches, Drifts, and Mandrels*

When iron is at forging heat it is relatively easy to pierce holes through it by punching. For instance, the shaft-hole in an iron hammer head may be made in this way. According to the shape of the hole which it is desired to pierce, the cross section of the punch may be square, rectangular, or oval. The method of punching will depend upon the size and shape of the hole, and also upon whether the metal is to be swelled-out round the hole. If it is not desired to swell-out the metal round the hole, a punch with a point but slightly smaller than the diameter of the shank is used. When the metal has to be swelled-out round the hole, as may be observed in many iron hammers of Roman date, a small hole is first punched through, and the metal is then opened out by the use of taper drifts. Mandrels are really long drifts, and form a convenient method of holding, and making solid, hollow forgings while they are being worked upon under a forging heat.

(viii) *Files and Saws*

These tools really belong to the mechanic who receives and finishes the smith's forging, but naturally the jobbing smith will have, and at times use, files and saws. The use and appearance of the modern file is too well known to call for any description here. A very large amount of the smith's cutting-off work is done with the hot or cold chisel on the anvil, but sometimes it is convenient to use a saw and therefore a large hacksaw is usually included in the tool kit.

Having given some slight idea of present-day smith's tools of a very simple nature, we may turn to the prehistoric and early historic material. Here, we at once encounter the difficulty that, owing to the nature of the material, iron tools are not very plentiful, and such material as there is has not received very detailed study. Indeed, the only serious works available to English students, and entirely devoted to prehistoric and early tools, would appear to be Petrie's *Tools and Weapons*, published in 1917; and more recently Ohlhaver's *Der germanische Schmied und sein Werkzeug*, Leipzig, 1939. A small but useful work is Professor Childe's *Story of Tools*, 1944. For the northern countries, Dr. Andreas Oldeberg's

important work, *Metallteknik under Forhistorisk Tid*, Lund, 1943, should be consulted. Here, illustrations and description of many early tools will be found. It is to these works that we must turn for much of our information.

The prehistoric smith's hearth would have been of simple construction. A bellows with blast nozzle and a paved hearth with some stone walling to contain the fire and conserve heat would meet the requirements of an Iron Age smith. Concerning the anvil, we have seen that the stone anvil has been used to the present day, and it must certainly date back to the very beginning of any form of metal working.

Anvils

Bronze anvils are not a tool of the iron-smith. We may, however, mention that such anvils, while never common, are a well-known type in Bronze Age Europe. The most simple form of bronze anvil is hornless, and is merely a conical or wedge-shaped block. This variety appears to be decidedly rare. The horned bronze anvil is a much more numerous and advanced type with considerable variations. A most interesting small bronze anvil comes from Chalons-sur-Saône, France. It has two horns and two separate anvil-faces. According to which of the horns is used as a tang, a different anvil-face is presented to the work. The same principle is found in an anvil from a hoard at Bishopsland, Co. Kildare, Ireland (see Raftery, *Prehistoric Ireland*, Fig. 182). Small anvils of special type for making needles or pins are provided with half-round grooves for forging or finishing the work. We have here an idea which later developed into the swage. A good example of such an anvil is that from Fresnés la Mère, Calvados, France (Fig. 26, from the anvil in the Ashmolean Museum).

According to Ohlhaver (1939, p. 32), the following types of iron anvil are to be found in prehistoric and early historic times:

(*a*) Anvils with one or two horns.
(*b*) Hornless anvils of most varied size.
(*c*) A small anvil for secondary work such as whetting scythe-blades by hammering, i.e. field or mower's anvils.
(*d*) Nail-making anvils, and anvils for special purposes.

In the European Iron Age the horned anvil (*a*) appears to be very rare. This is peculiar, in view of the fact that the horned anvil was quite well known in the Late Bronze Age. Even the Roman cultures do not appear

to have favoured the normal type of anvil with horn or bick-iron. At least for central and northern Europe this type does not become really important until around the sixth century A.D. Two of these late type

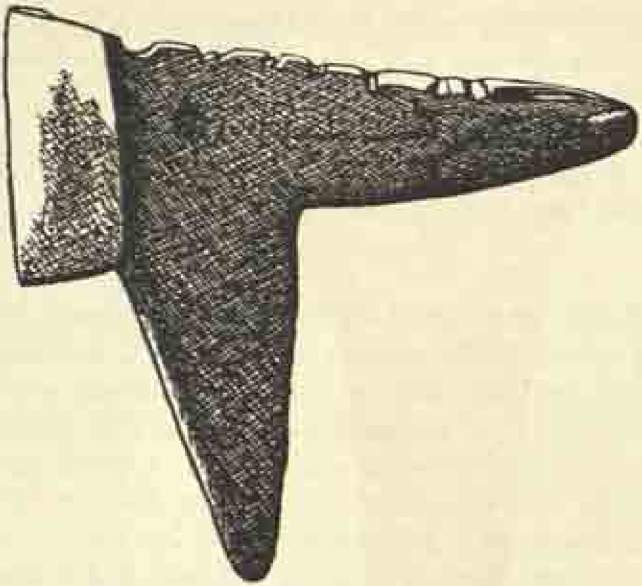


FIG. 26. Bronze anvil from Fresnés la Mère, Calvados, France, now in the Ashmolean Museum. Weight 10½ oz. Scale 1/1.

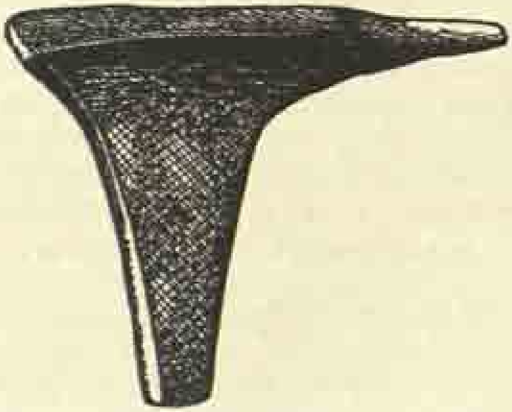


FIG. 27. Iron anvil from Norway (Ohlhaver 1939, Taf. 31, 1).

anvils are shown in Figs. 27, 28 (after Ohlhaver Taf. 31, 1 and Taf. 26). Fig. 27 (Ohlhaver Taf. 31, 1) is a good type of a single-horned iron anvil from Norway. It will be noticed that it has a long and thin bick-iron, and

in fact tends towards what is known as the L-shaped anvil, so called because such anvils resemble an inverted letter L. Fig. 28 (Ohlhaver Taf. 26), also from Norway, is of interest in showing a mediaeval iron anvil in which the horn, or bick-iron, comes off the top of the anvil body in the modern manner. It will be noted that both these anvils, although of relatively late date, are more or less tanged. That is, they do not stand

FIG. 28. Medieval iron anvil from Norway (Ohlhaver 1939, Taf. 26).

upon their own base like our modern anvils, but were secured by being driven into a heavy block of timber.

What Ohlhaver terms hornless anvils of varied size (*b*), are not of great interest. They are crude blocks of iron which have been used as anvils. Again, there are many smaller Provincial Roman anvils which are not always, except in size, clearly to be distinguished from small field, or mower's anvils. With the stake, field, or mower's anvil, we come to a large and important class. Such small anvils have been much used by country people for whetting, or work hardening by hammering, the blades of scythes, down to modern times. Indeed, they are probably still in use in some parts of Europe, for I have personally observed a small field anvil in use by a mower in France in the Dauphiné during 1936. They can

also, of course, be used by a smith for any other suitably light work. Naturally, if used by a smith they would only serve for making very small and light forgings. For such field anvils Ohlhaver (1939, p. 35)

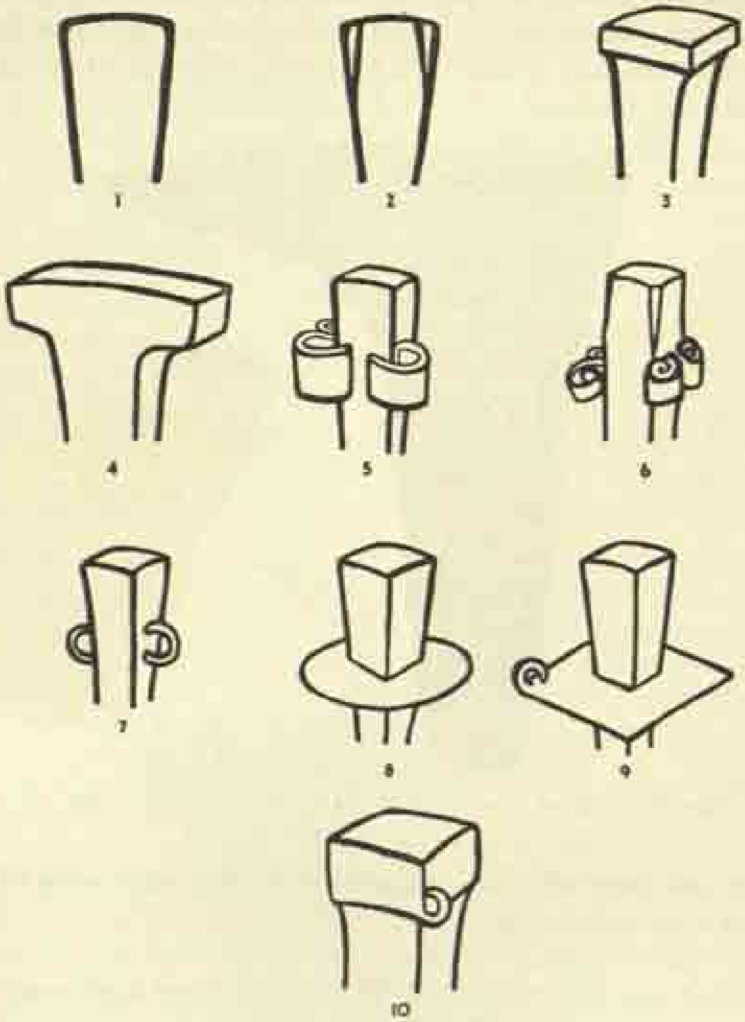


FIG. 29. Various field anvils of the Roman Period (Ohlhaver 1939, Abb. 10).

quotes an average length as between 15 and 25 cm., and a length of anvil face usually between 3 and 4 cm. In their most simple form these anvils are merely wedge-shaped pieces of iron of square or rectangular section (Fig. 29 after Ohlhaver, Abb. 10, various field anvils), as in Nos. 1 to 3. To act as a stop, the field anvil sometimes has a rectangular hole or slit through the body, through which are passed strips of iron, the ends of

the iron strips being curled into loops or spirals (Fig. 29, Nos. 5, 6). Special types are known in which instead of the anvil being pierced for strips, the function of a stop is performed by a square or circular plate through which the taper tang of the anvil passes, the stop plate wedging securely against the taper of the anvil tang (Fig. 29, Nos. 8, 9). Then there is the 'eyed' anvil which is suspiciously like a tent peg. However, at least in some instances it appears that the 'eyed' anvil is quite genuine (Fig. 29, No. 7). The anvils discussed above are of Roman date, and, so far as present records show, the true field anvil may be said to be Roman or later.

For nail-making, and large iron anvils, we must again turn to the Roman period. The Romans, and smiths working under Roman instruction, forged very substantial objects at times. Such work can be carried out on a heavy stone anvil, but a heavy iron one is better. These big anvils are often merely cubes of iron hollowed out underneath so as to give four feet which rest on the ground. In general, such big tools are hornless, but have an extension of the working table to one side, and a nail heading, or other device, at the opposite side (Fig. 30, Lindenschmit 1911, Taf. 46). Such anvils may be up to 30 cm. in height. They are not common, for Ohlhaver cites only five examples. The method used for making an iron nail, and the function of the nail-heading hole in the anvil, or of the separate nail iron, is shown in Fig. 31 (Ohlhaver 1939, Abb. 36). It will be seen that five operations are involved:

FIG. 30. Large Roman anvil, 21 cm. high, 18 cm. diameter, tapering to 8 cm. (Lindenschmit 1911, Taf. 46).

1. A round rod of iron, larger in diameter than the shank of the nail, is prepared.
2. The point of the nail is formed at the end of the rod.
3. The rod is drawn down on the anvil to the required diameter and length of the nail.
4. The rod is cut off, leaving enough metal from which to form the head.
5. The final operation is to forge the head, using the nail hole in the anvil, or a separate nail-iron as shown.

To form a square nail the same method is adopted, but the shank of the nail is, of course, forged to a square section.

A point which will strike those with some practical knowledge of iron forging is that, with the exception of the large Roman anvils just mentioned, the anvil appears very small and light when compared with the hammer. At first iron was not so very plentiful and the stone anvil was in

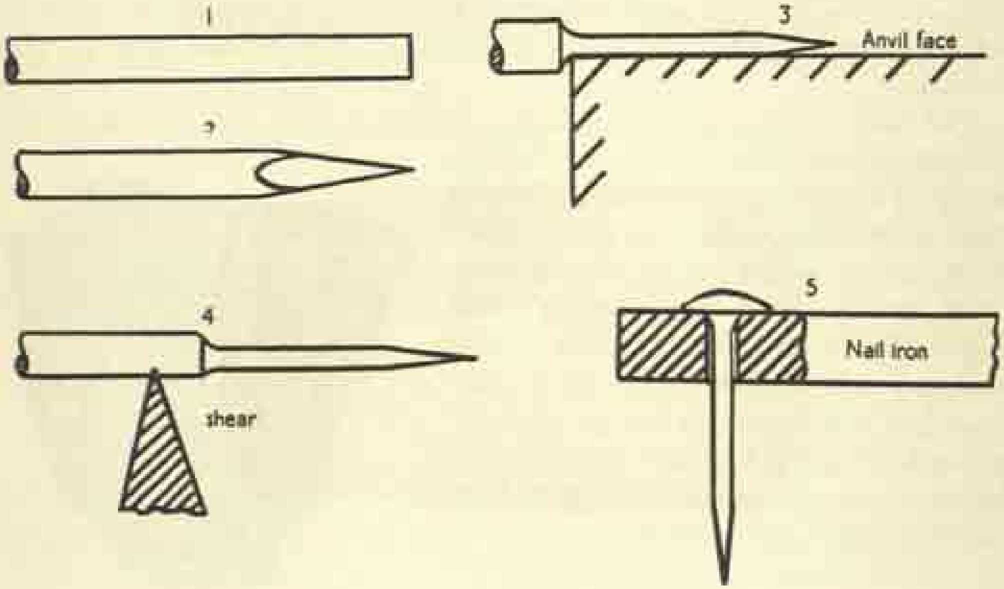


FIG. 31. Making an iron nail (Ohlhaver 1939, Abb. 36).

all probability much used. Here the smith would have plenty of weight at his disposal. Also, many qualities of stone would stand up to the stress of serious forging if a large homogeneous block was selected to serve for the anvil. In the mediaeval German anvils the dimensions remain surprisingly small. One would consider that most of the anvils recorded are for 'fine' work, rather than for that of the ordinary blacksmith.

Hammers

The hammer made of stone or wood is one of the oldest known tools and, of course, it long predates the discovery of iron. Stone hammers were used in the Palaeolithic and succeeding ages, and in many parts of the world the use of stone hammers continued down to recent times. In metal, we find the hammer well established in the Bronze Age. In western

Europe the socketed bronze hammer was a popular tool, but it was not heavy, being suited to light work only. Indeed, many of the socketed bronze hammers must have been used for fine work only (Fig. 32, bronze

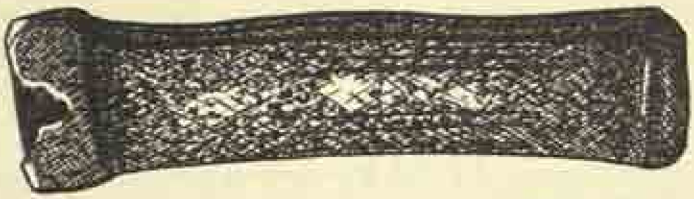


FIG. 32. Bronze socketed hammer from Fresnés la Mère, now in the Ashmolean Museum. Weight 4 oz., Scale 1/1.

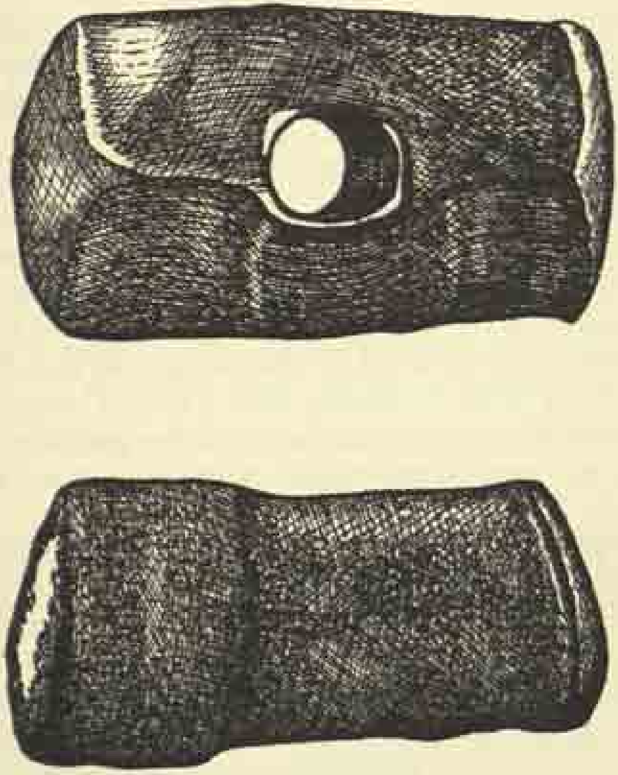


FIG. 33. Heavy bronze hammer from the Mitterberg, Austria. 15·7 cm. long, 7–8·5 cm. diameter, 4317 gr. weight (Pittioni 1951, Pl. IV, No. 2).

hammer from Fresnés la Mère, Ashmolean Museum). On the other hand, quite heavy bronze hammers with features in common with the modern sledge are known (Fig. 33, Bronze hammer from the Mitterberg,

Austria, Pittioni 1951; Pl. IV, No. 2). In general such bronze hammers predated the iron worker in Europe, and they are not a tool of the iron-smith, but with the coming of iron it was natural that the hammer should appear in this metal. However, iron hammers are not numerous before the Roman period, although various forms in iron do appear on the Continent in early La Tène times (Oldeberg 1943, ii, p. 11). There are two methods of making and shaping the hammer. First, a simple rectangular block is forged from which to make the tool. Through this block, where it is required that the shaft-hole shall be, a slit is cut out with the hot chisel; then the shaft-hole is completed by drifting through with round, oval, or rectangular drifts. After this operation the claw, when required, is drawn down. According to the size of the shaft-hole, the drifting operation expands the sides of the hammer around the hole, but it does not increase the thickness of the hammer when looked at in side view. Secondly, when it is not desired that the sides of the hammer should be swelled around the shaft-hole, the sides may be forged down using a mandrel in the hole, so that the shaft-hole retains its true shape during the forging. Naturally such forging will increase the depth of the hammer (when looked at in side view), around the shaft-hole. The difference between this method and the more modern technique in which the expansion of the metal is more or less avoided by the use of a blunt-ended punch will be noted. Various shapes of iron hammer heads are shown in Fig. 34 (after Ohlhaver, Abb. 14). Ohlhaver (1939, p. 43) considers that both the swelled shaft-hole and the parallel-sided forms of hammer are to be found in prehistoric contexts, and are certainly well established by the Roman period.

During Roman times the hammer assumed the form of some of our modern tools. The iron cross pene hand hammer was very similar to the mechanic's hand hammer as used in France and Germany today. It is interesting to note that the cross pene hammer with square-section body appears, even today, to be a continental type while the well-known ball pene mechanic's hand hammer seems to be a British development. As with the hand hammer, so the heavy iron sledge had taken quite a modern appearance under the Romans (Figs. 35, 36, Roman hand and sledge hammers, after Lindenschmit 1911, Taf. 46, Nos. 800, 799). We have mentioned that the modern smith uses a set-hammer, and it is interesting to observe that such tools go back to Roman times. One such is figured by Ohlhaver, from Dürnau, Reidlingen, Württemberg (Fig. 37 after Ohlhaver, Abb. 48).

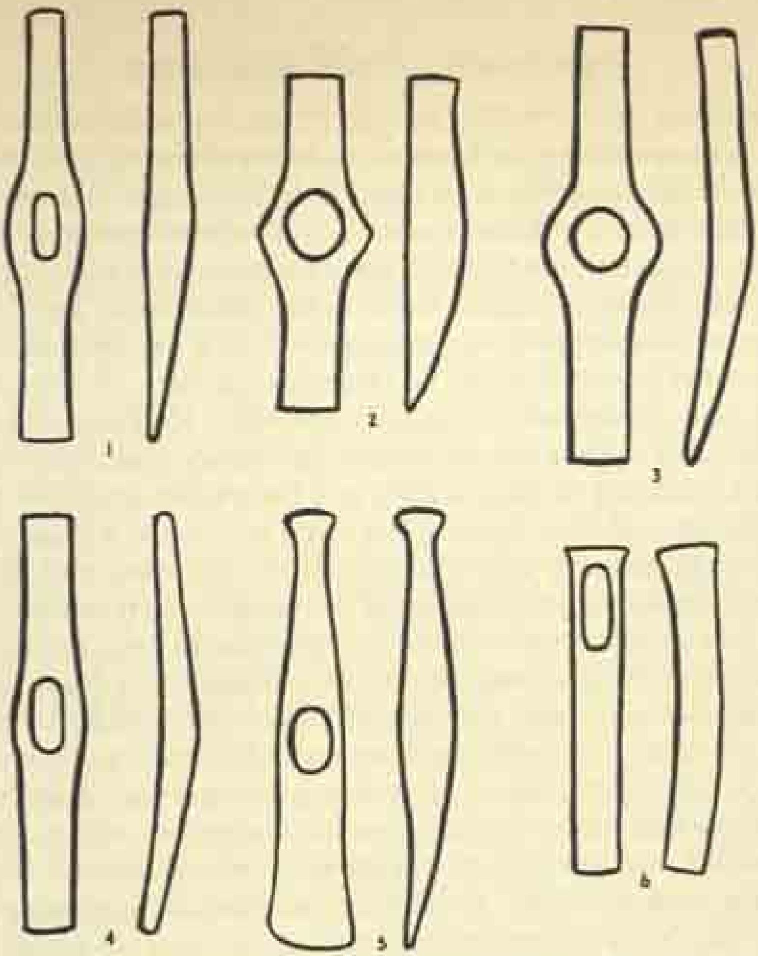


FIG. 34. Various shapes of iron hammer-heads (Ohlhaver 1939, Abb. 14).

FIG. 35. Roman hand-hammer 18·5 cm. long (Lindenschmit 1911, Taf. 46, No. 800).

FIG. 36. Roman sledge-hammer, *c*. 20·3 cm. long, shaft-hole 3 cm. wide (Lindenschmit 1911, Taf. 46, No. 799).

FIG. 37. Roman set-hammer from Durnau, Reidlingen, Württemberg (Ohlhaver 1939, Abb. 48).

Tongs

The earliest metal tongs used were no doubt of the simple spring-back variety, or, in other words, they were merely enlarged tweezers. Simple tweezers made from one piece of metal are of very early origin, for copper tweezers were found in the tomb of Semerket, one of the last kings of the first Egyptian dynasty. Again, the tweezers enlarged to form a spring-back tongs of considerable size are depicted in a drawing of Egyptian bronze-workers from the tomb of Hapu, of the date of Thutmosis IV, 1420–1411 B.C. (Coghlan 1951, p. 79 and Fig. 10). Tongs of such early date would have been made of copper or bronze and, while perfectly suitable for removing small crucibles or light objects from the fire, their value to the iron-smith, who needs a firm grip when forging his iron, may well be questioned. However, we must remember that the simple spring-back tongs has served as part of the smith's equipment to mediaeval times, and for other uses until today. Such tongs have been used until recently in the forging of springs and chain-links. They have the advantage of a constant grip, and are therefore comfortable and convenient for the smith to hold. Undoubtedly when provided with a slip-ring to increase the holding power the iron spring-back tongs is a useful tool.

Among modern primitive iron-workers a green withy frequently served as tongs, and there is no reason why, where suitable withies or other timber were available, they should not have been used by the prehistoric smith. More or less to hold, and at any rate to guide, a rough furnace bloom while it was being hammered upon a stone anvil to expel charcoal and included slag in the process of consolidating the iron would be within the capacity of withy tongs. For such use we have ample evidence from modern primitive smiths in Africa. For the actual forging of implements the withy tongs would be at a disadvantage owing to their low holding power and tendency to catch fire, but they could be used for the forging of simple objects such as spears, knives, and hoes, in which it would not be necessary to bring the whole of the metal up to a forging heat at the same time, or when a projection could be left on the object which would serve as a cooler portion to be gripped by the wooden tongs. For example, the Bikom blacksmiths (Jeffreys 1952, No. 75) used withy tongs or tweezers when shingling their iron bloom upon a stone anvil, and a form of wooden handle to enable the iron blank to be manipulated on the anvil when forging. The frequency with which spring tongs occur in the Middle Ages in Europe would lead one to suppose that they may have been more frequent in Roman and Iron Age times than the known

finds indicate. Ohlhaver (1939, p. 67) mentions a spring tongs of 20 cm. in length from the Hallstatt cemetery, and also an example from Býčiskála which may be of the same period. Of Provincial Roman finds,

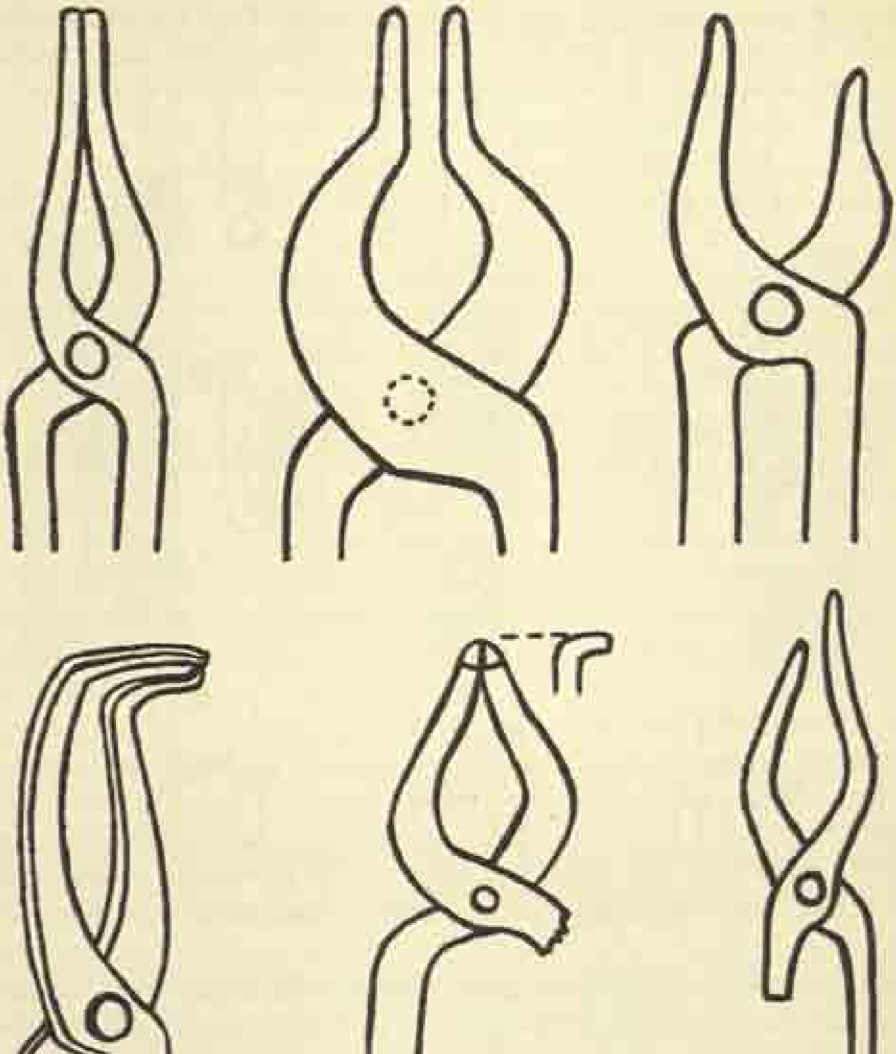


FIG. 38. Various tongs (Ohlhaver 1939, Abb. 24).

there is one from France. From 'German' finds, Ohlhaver gives but three examples.

The solution to the problem of an efficient tongs was, of course, the

invention of the hinged variety, and it is significant that in general this form appears with the coming of iron. Hinged tongs are certainly exceedingly rare, if indeed present, before the Iron Age in Greece when we find the modern form depicted upon an Attic vase which shows a Greek smithy of about 500 B.C., but Evans (1921, i, Fig. 70) does show an

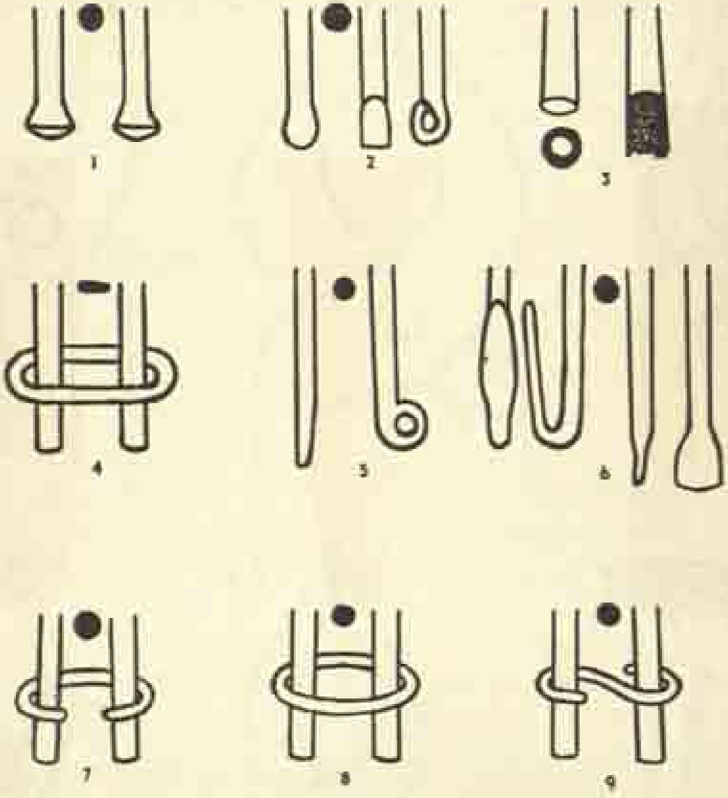


FIG. 39. Various tong-handles and methods of locking them (Ohlhaver 1939, Abb. 29).

example as early as Minoan II from Mochlos. From late in the Iron Age, and commonly in Roman times, large and well-designed hinged tongs are found. Fig. 38 (after Ohlhaver, Abb. 24) illustrates some types of jaw. It will be observed that the smith has advanced to the stage at which he forms a variety of jaws to suit the work in hand. Indeed, we may say that the Roman smith had a number of the shaped jaws which we use today. Again, some of the Roman tools exhibit the same means for locking the tongs upon the work which we still employ. Rings, hooks, S-clips, &c., were used to lock the handles (Fig. 39 after Ohlhaver, Abb.

29). Except for some special shapes, and better material, it may be said that with the heavy Roman hinged tongs 'terminal' development had been attained.

The Chisel

Of the many prehistoric chisels, it would be very difficult to separate those belonging to the iron-smith. However, we may say that only a semi-steel, or steel-tipped chisel would be of service to the smith. The small

FIG. 40. Bronze Age flat chisel, scale 1/1 (Pitt Rivers Museum, P.R. 1473).

FIG. 41. Roman flat chisel 11·5 cm. long (Lindenschmit 1911, Taf. 46, No. 798).

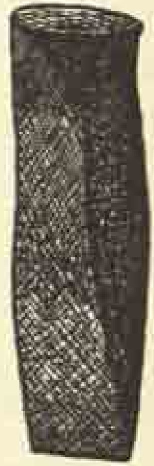


FIG. 42. Roman cross-cut chisel 10·5 cm. long (Lindenschmit 1911, Taf. 46, No. 814).

and light line and punching chisels much used for decorative work do not concern us. Since the iron-smith's chisel must be able to stand up to direct and heavy blows on its shank, it follows that we may exclude socketed chisels, and chisels which have long slender shanks. Also, chisels with widely splayed blades do not belong to the forge. The smith's chisel has changed but little in the course of the centuries. The modern tool is tapered down to the cutting edge at an angle varying between 15 and 30 degrees, while the cutting edge itself forms an angle of some 45 to 70 degrees. Such proportions may be observed in the early iron chisels, at least from Roman times onwards. The cutting edge of the chisel is, of course, hardened, while the butt and shank are left in a soft condition. As today, cross-cut and flat chisels are known (Figs. 40–42). Recent and

modern hot chisels are often hafted by means of an iron rod with a loop passing round the shank of the tool under its butt. This method of holding the chisel is necessary when large forgings at red heat are being cut upon the anvil. The work of the Iron Age smith would have been of a lighter nature, and he would no doubt have been able to hold his chisel with the tongs, or even in the hand.

Fullers and Swages

To the blacksmith, top and bottom fullers are most useful tools. However, I cannot find any evidence for their use in prehistoric or Roman times. It seems likely that these tools would be known to the more skilled Roman smiths, but unless evidence to prove their early use is forthcoming, we cannot consider them to be earlier than the mediaeval period. We have already mentioned that the swage must be of early origin, and that its prototype may be found in the semicircular grooves cut in some Bronze Age anvils. Evidence for the swage is extremely scanty, although Beck (1892, ii, Abb. 121, and p. 539) has recorded some Roman examples. Ohlhaver (1939, Taf. 16, and p. 2) illustrates an excellent bottom swage which is provided with a spigot for use as an auxiliary tool socketed into the top of an anvil. However, this tool is of mediaeval date and it seems probable that the swage only became popular at some time during that period.

Punches, Drifts, and Mandrels

Punches, drifts,[1] and mandrels[2] are the most simple of tools, and must have been used by the smith even in Iron Age times. They are so simple that no description is necessary. The punch, particularly when used upon cold sheet metal, requires to be adequately hardened.

Files

The file is a very important tool, and would have been used by the smith for smoothing and finishing his forgings. In the Bronze Age bronze files are known, but these would have been valueless for iron working and were what we should now term rasps, today being mainly used for wood-working. Files first become of value for cutting the harder metals with the introduction of iron, when we begin to find files of rectangular, square, and round cross-sections. Before it was discovered

[1] Tools for enlarging or shaping holes in metal.
[2] Rods round which metal is forged or shaped.

how to carburize the iron so that a reasonable temper could be imparted to it, the file was an inefficient tool although it would have had its value for cutting the softer metals. Also, a bad file was better than no file, for the traditional grinding process was slow and laborious. Apart from the metal used, the efficiency of a file depends upon the number and method of cutting the teeth. In general, for cutting the harder metals it pays to use a fairly fine file, that is, one with a large number of teeth. For wood, and very soft metals like lead and tin, a rasp-like file with a much coarser tooth is employed. As we have mentioned elsewhere (Coghlan 1951, p. 86), there are various ways in which the teeth of a file may be formed. Modern files are made with the teeth arranged as single or double cut. With the single-cut file there is but one series of teeth which are cut at an angle across the working face of the tool. For filing harder metals, double-cut files are more suitable. Here a second series of teeth is cut at the same angle, but crossing the first series. Hence, a large number of triangular cutting points are left standing up in contrast to the continuous cutting edges of a single-cut file. Cutting the teeth at an angle across the working face of the file is a method which renders the tool smoother in operation and more efficient. It would appear that the teeth of early files were cut with a chisel before the hardening was carried out.

Dr. Oldeberg (1943, ii, p. 104) remarks that in a considerable number of prehistoric files, especially in the Scandinavian area, the cut was usually perpendicular to the longitudinal axis of the file, and square over the whole width of the surface, while in other cases the teeth were obliquely inclined across the face. Possibly even before Roman times the double-cut system of the modern file may have been known. It certainly seems that the late Iron Age toolsmith had grasped the true principle of the file.

The hardness and temper of an iron file is, of course, a vital factor in the efficiency of the tool. Here, we unfortunately have very little information to go upon because hardly any early files have been examined by metallurgists. However, two files from Steinsburg, Römhild, Kr. Hildburghausen, Thuringia, Germany, have been examined by Hanemann (1921–2, pp. 95 ff.) He investigated a large and a small file, not later in date than Roman. Both were found to be made of an iron which had been converted into steel which was capable of being hardened. As in modern practice, the working part of the file had been hardened, while the tangs were left soft. Hanemann puts forward a theory as to how the file blanks were prepared, but this aspect is of more interest to the metallurgist. We may say that the investigation showed that the smith must have had

practical knowledge of how to carburize his iron up to the point at which hardening becomes possible, and, moreover, understood correctly the appropriate method for hardening his material. This agrees with Carpenter and Robertson's research which we have mentioned on page 59, where it is noted that carburizing, quenching, and tempering were practised by A.D. 200.

Concerning the antiquity of the file, Dr. Oldeberg[1] would consider that iron files appear at least during the sixth century in Assyria, while in Egypt an iron file was included in a workshop find at Thebes. This find is considered to be connected with the invasion of the Assyrians in Egypt in the year 663 B.C. During the La Tène period iron files are to be found in the south of Europe, and in the Roman period they become common. In Europe, the list of recorded files is a short one. For instance, for La Tène, and the early Roman period, Ohlhaver only gives particulars of finds from the La Tène settlement at Neuchâtel, Steinsburg in Thuringia, Stradoniss in Bohemia, Rondsen in west Prussia, and Neuguth, west Prussia; Petrie (1917, p. 44) mentions a 'crippled' file from the Auvergne, France, and a good one from Silchester (Evans 1894, pp. 139 ff.). He also states that the fine-cut file begins with the Assyrian group, where the rasp is also found in a perfect form, exactly of modern shape and detail.

Saws

The saw is a tool of great antiquity, for as long ago as the Magdalenian period in the south of France serrated flint blades were used as saws for cutting small objects of wood and bone. In the Ancient East, the metal saw is early, and in Egypt it appears to date back to the First Dynasty (Petrie 1917, p. 43). These first saws would have been of copper, later followed by those of bronze and iron. We do not know when the saw, as distinct from the bronze, and possibly iron saws used for wood cutting, became a part of the smith's equipment. Once it was learned how to temper a chisel so as to make a file, and to temper the file so that the teeth of the saw could be cut, technical difficulties had largely been overcome. Hence, there is no reason why an iron saw should not have been carburized and tempered so as to render it capable of cutting wrought iron during the late Iron Age in Europe. It is certainly significant that, from a large hoard of iron tools of the Roman period from the Heidenburg bei Kreimbach, north of Kaisersleuten, Rhenish Bavaria (Lindenschmit

[1] Private communication (also Coghlan 1951, pp. 86–87).

1911, Taf. 46), we find an iron saw with correctly raked teeth set in a metal frame (Fig. 43). This tool appears to be a prototype of our modern metal-worker's hacksaw, and should be quite capable of cutting wrought

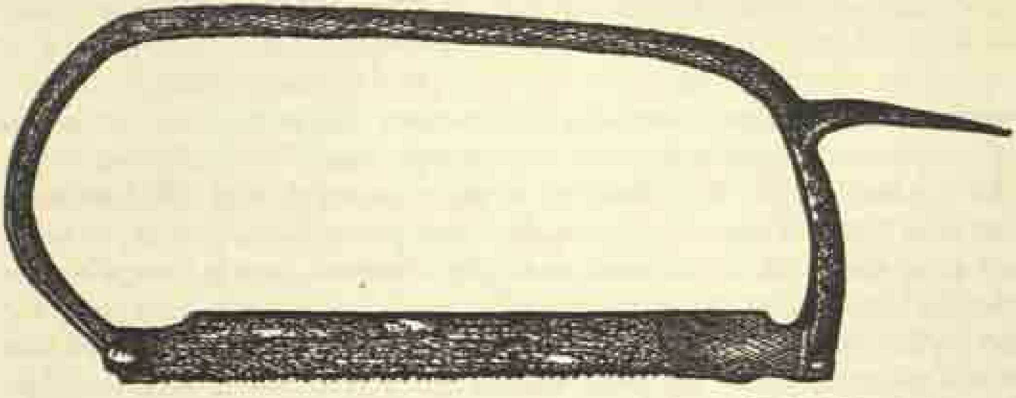


FIG. 43. Roman saw of iron in metal frame (Lindenschmit 1911, Taf. 46, No. 805).

iron. A very similar tool is also figured by Oldeberg (1943, ii, p. 104, Fig. 210), but here the blade is no less than 1 cm. in thickness, and Oldeberg refers to the tool as an arc-file. Hence, it is not quite clear whether we should consider the Swedish tool as a hacksaw with an unusually wide blade, or as a frame-mounted file. At least, it is clear that we may ascribe a saw, comparable to our metal-cutting hacksaws, to the Roman, if not to an earlier, period in Europe.

Chapter VII

THE TECHNICAL ART OF THE SMITH TO ABOUT A.D. 1000

To conclude these notes it is of interest to examine, in so far as the evidence available permits, the progress made by the smith in his art up to about A.D. 1000, by which time a high standard had been attained. Indeed, after A.D. 1000 there was probably no very revolutionary progress in the smith's art until the seventeenth or eighteenth centuries when the turning lathe, and other machinery, created the need for yet further development in tools and material. Again, we do not attempt to discuss art in iron-working in the generally accepted sense of the term because examples of artistic iron work of the La Tène, and other periods, will readily be found in archaeological textbooks.

The primary advance in the smith's art was to refine and improve the quality of his iron. If we except the use of iron as a semi-precious metal with small application to decoration and ornament, the bulk of the early iron produced was for the manufacture of tools and weapons. Primitive bloomery iron is not sufficiently hard to give the fine cutting-edge so necessary in a good tool or weapon; hence the first step in the evolution for which we must seek is some method of hardening the iron. This could be attained by carburizing. With primitive methods the penetration of the carburized 'case' would be slight, most likely adequate for a thin and slender object like a small knife, but not sufficient to be satisfactory for a substantial chisel or axe. For these heavier objects there was a method to overcome the difficulty—the piled or compacted structure. If a number of thin laminations of iron were separately carburized, and then piled and forge-welded together, the forging so obtained would have a reasonable diffusion of carbon throughout its mass. In this way the iron may be brought into the range of the steels, which may then be further hardened by heat treatment. As we shall see, this ingenious technique was actually developed in the prehistoric period. Such smith's work was far from primitive, indeed it may be called decidedly skilled. The technique still has a limited application in the manufacture of some special steels.

So far little attention appears to have been directed to the evolution

of the smith's art in early times and the evidence available has many gaps, leaving much to be desired. The best pre-war scientific research, at least by British workers, of which I am aware is that by Carpenter and Robertson in 1930 (pp. 417–54). In an endeavour to give some outline of the subject we shall make use of their investigations, together with much new research kindly carried out for the Pitt Rivers Museum by Mr. T. H. Williams and Mr. P. Whitaker of Messrs. Stewarts and Lloyds, arranged through the good offices of the British Iron and Steel Research Association. Of the specimens examined by Carpenter and Robertson, it is to be noted that the earlier examples, although found in Egypt, may well be imports because the Iron Age was of relatively late occurrence in Egypt.

We have the following specimens to consider:

EGYPTIAN KNIFE. *Period*, *c.* 1200 B.C.

Report. Carpenter and Robertson, 1930. Specimen no. 2.

This small knife was made by welding two pieces of metal together, the line of the weld extending along the whole length of the specimen to the point. The two pieces of metal had been brought to approximately the same composition by carburizing. The knife had been air-cooled, producing small specks of ferrite and fine pearlite, and the authors report that it was carburized so as to make the carbon content at the cutting-edge about 0·8 per cent., falling to about 0·6 per cent. in other parts. Brinell figures showed that the hardness varied between 269 and 302. These are high figures for unquenched steel, and it is interesting to compare them with the low figures obtained from a Roman sickle in which the material had been quenched but spoilt in an attempt to temper it.

EGYPTIAN KNIFE. *Period*, *c.* 1200 B.C.

Report. Carpenter and Robertson, 1930. Specimen no. 3.

The carbon gradient from the edge to the back of this specimen showed that it had been carburized. How the carburizing had been carried out is a matter of surmise, but after cooling, the metal was again heated into the critical range and then air-cooled. For technical reasons, the authors suggest that the carburizing process was not carried out by placing the knife in a charcoal fire, but by some other means that necessitated slow cooling, for instance packing in a crucible with charcoal and other instruments. Hardness at the edge of the knife near the hilt varied between 285 and 269 Brinell, and at the point between 255 and 269. At the back, the hardness varied between 179 and 197 Brinell.

EGYPTIAN AXE. *Period, c.* 900 B.C.

Report. Carpenter and Robertson, 1930. Specimen no. 8.

A variable structure was revealed in this axe. The carbon content is also variable, and in certain positions rises to around 0·25 to 0·3 per cent. The iron had been carburized and the authors conclude that the axe was finally heat-treated by quenching the cutting-edge. If water was the medium used for quenching, it would appear that only the cutting-edge was immersed. The Brinell hardness was also variable. At the edge the hardness is 207, rising to 229 a little higher up the point, and falling to 116 as the body of the tool was approached.

EGYPTIAN AXE. *Period, c.* 900 B.C.

Report. Carpenter and Robertson, 1930. Specimen no. 9.

As a result of carburizing, the carbon content of this axe decreased from about 0·9 per cent. at the cutting-edge to a very small amount at about 1 in. from the edge. The cutting-edge was quenched in water, and it is important to note the authors' statement that on withdrawing from the water the main part of the axe was still at a red heat, and conduction of heat from the body reheated and tempered the edge. It would be interesting could we know if this self-tempering was accidental, or intentionally sought for by the smith. Most likely it was intentional. The result was most successful, for the hardness figures increase from 62 Brinell in the ferrite of the body to 363, 388, and finally to the very considerable hardness of 444 Brinell at the cutting-edge.

EGYPTIAN HOE. *Period, c.* 800 B.C.

Report. Carpenter and Robertson, 1930. Specimen no. 7.

This hoe was simply forged from bloomery iron and had received no subsequent heat treatment. It is of interest in showing how variations in composition of the separate particles of the direct iron, and variations in the forging conditions, render a wide range in hardness in the same tool. For instance, near the tip where the ferrite grains were large the Brinell hardness was 116. Higher up the tool where the ferrite grains were smaller, the hardness was 137. Again, in an area where the structure was small-grained and contained some pearlite, the hardness varied between 149 and 187. In another area where the ferrite grains were large and the pearlite small, the hardness was 163.

TRIPOD. *Assyria, Nimrud. Period, late 8th century* B.C.

Report. Stewarts and Lloyds. For Pitt Rivers Museum.

Plate I, Fig. 2, and pp. 180, 202.

This specimen has been completely converted to iron hydroxide. No metallic portion was left, so that analysis was impossible. Examination of a section would indicate that it was made from piled wrought iron. This is valuable information as it indicates that the compacting technique was known at least as early as the late eighth century B.C.

EGYPTIAN CHISEL. *Period, c.* 700 B.C.

Report. Carpenter and Robertson, 1930. Specimen no. 6.

The investigation showed that, after forging to shape, this chisel underwent the following processes:

(*a*) It was carburized at the point.
(*b*) It was then heated at the point.
(*c*) It was finally quenched by immersing the point only.

According to the position in the chisel blade the carbon content varied from very low to about 0·4 per cent. Also, the hardness varied according to position from 137 to 302 Brinell. The maximum hardness was not attained at the cutting-edge itself owing to the fact that the material near the cutting-edge had to some extent been decarburized and particles of ferrite were fairly plentiful. It is clear that this tool was made by a skilled smith, as shown by the technique of heat treating and quenching at the point while leaving the body of the chisel unhardened as we frequently do today. Obviously the smith well knew what he was about, although it may be noted that he did not know of, or perhaps it is more likely that he did not wish to risk experimenting with, any further tempering operations after he had quenched the material.

SPEAR. *Syria, Deve Hüyük. Period,* 600–500 B.C.

Report. Stewarts and Lloyds. For Pitt Rivers Museum.

Plates II–IV, and pp. 180, 202.

The material of this spear is forged carburized steel made from reduced sponge iron. Average carbon content is 0·18 per cent., but in places as high as 0·6 per cent. The high nickel content of 0·32 per cent. is unusual. The spear has been forged from about fifty plates or layers of sponge iron piled into a block (Fig. 44, from the Report of Messrs. Stewarts and

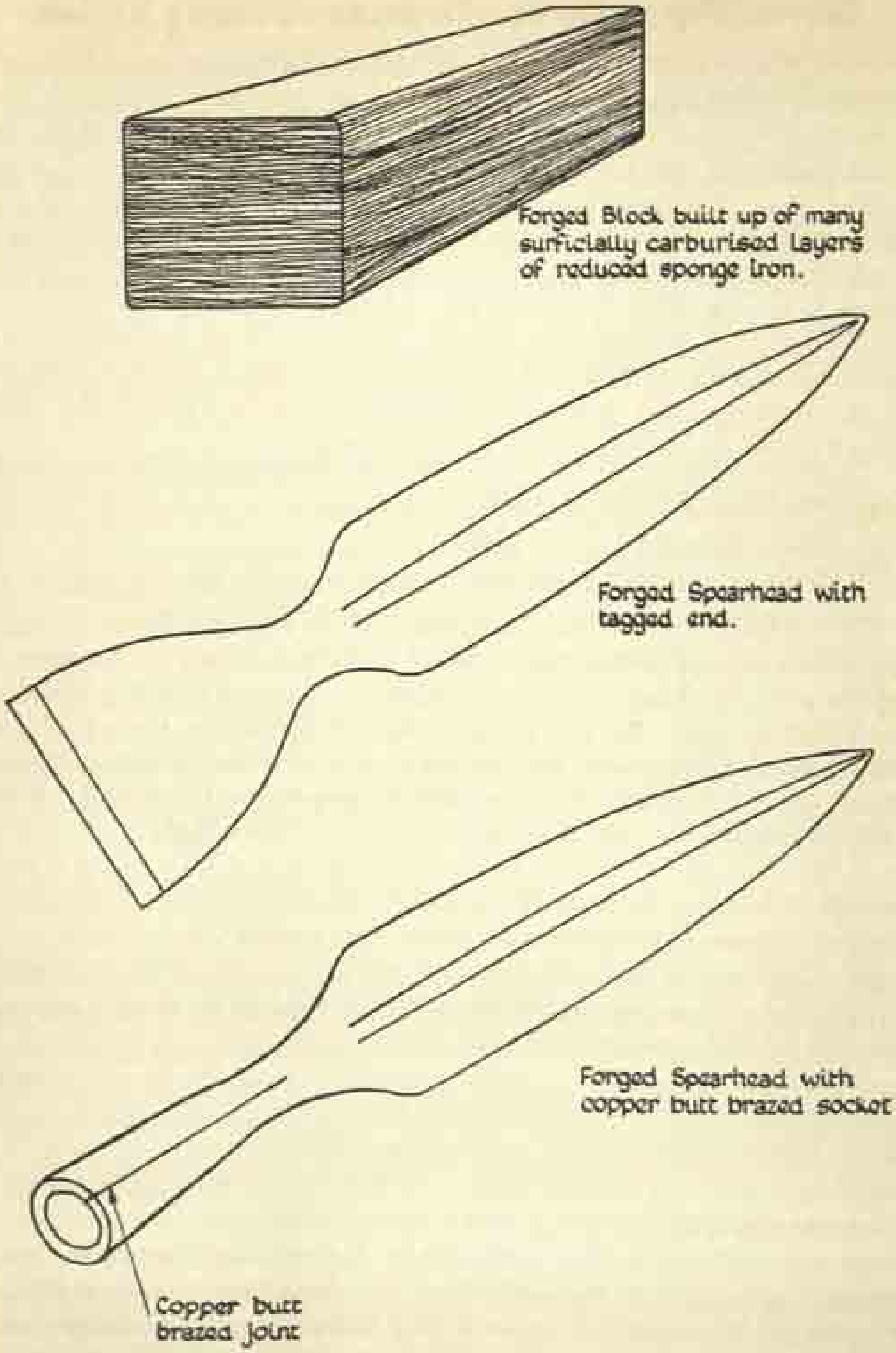


FIG. 44. Forging a socketed spear-head, 600–500 B.C., Deve Hüyük, Syria (from the Report by Messrs. Stewarts and Lloyds).

Lloyds). The majority of the plates have been surface-carburized during heating for forging, the compacted structure resulting in a highly developed water-marked pattern somewhat similar to damascene steel blades produced from cast steel. A noteworthy feature is that the tubular taper socket, which was forged from a 'tagged' end, has been brazed and forged together with impure copper. Hardness ranged from 108 Vickers in the low carbon zones to 153 Vickers in the higher carbon bands. There is no indication of hardening and tempering. A high degree of skill is shown in welding and forging. No doubt the smith could have hardened the spear had he wished. The hardness figures quoted are typical of a modern mild steel, the strength of which would be quite satisfactory for a mid-rib spear of such proportions.

SPEAR. *Jugoslavia, Vače. Period, 5th century* B.C.

Report. Stewarts and Lloyds. For Pitt Rivers Museum.

Plates VI–VII, and pp. 184, 203.

The report states that this spearhead has been forged from wrought iron with a very variable carbon content of from less than 0·1 to exceeding 0·6 per cent. locally. The hardness varies from 103 to 134 Vickers. The spear was made by rolling over a faggot of wrought iron to form a forge welded tubular section. The tubular section was completely collapsed at one end to form the point, but still retains its taper tubular form at the socket portion. The point of the spear is unhardened.

EGYPTIAN KNIFE. *? Europe. Period, c.* 300 B.C.

Report. Carpenter and Robertson, 1930. Specimen no. 4.

This small knife had been carburized but not quenched. The hardness of the small-grained structure in the middle of the knife varied between 137 and 143 Brinell; that of the remainder varied between 95 and 107. For its period, this seems a poor specimen and without features of any particular interest.

IRON PICK. *Palestine, Lachish. Period, Iron Age,* before 588 B.C.

Report. Stewarts and Lloyds. For Pitt Rivers Museum.

Plate V, Fig. 1, and pp. 182, 202.

This early specimen was made from a very pure base wrought iron which had been carburized prior to piling and forging. Production from a pure haematite or magnetite ore is indicated. Determination of carbon

gave 0·196 per cent., with hardness varying from 136 to 183 Vickers. The report of Messrs. Stewarts and Lloyds indicates that the point of the pick was quenched from a very high temperature. It would therefore appear that the smith who made this pick was aware that, at least under certain conditions, an increase in hardness was to be obtained by quenching from high temperature.

IRON SWORD. *Höganäs i Skåne. Period, Probably Hallstatt D.*

Report. Dr. Andreas Oldeberg, 'Ett märkligt järnsvärd från Höganäs i Skåne', *Vänersborgs Museums Skriftserie* 4, Vänersborgs 1952, pp. 27–70.

Dr. Oldeberg thinks that this unusual iron sword came from the east Hallstatt region, or from even farther to the east. If that be so, the sword would belong to the Hallstatt D period, or to the transition to La Tène. The relatively high copper content of the blade shows that a copper-bearing iron ore was used as the source of the metal. Perhaps it was siderite, which is to be found in the east Alpine region. The analysis of the blade was:

Ti	V	Mn	Fe	Co	Ni	Cu	Sn	Pb	As
0·01–0·1	<0·01	0·1–1	*grund massa*	<0·01	<0·01	0·1–1	–	–	<0·01

It will be observed that the iron contained an unusual amount of copper and manganese, approximately 0·1 to 1·0 per cent. in each case. The carbon content was variable, but was apparently about 0·5 per cent. The addition of manganese may be said to increase the strength and work-hardening properties of a steel (as in the modern low-carbon manganese steels with carbon of 0·2 to 0·3 per cent. and manganese 1·0 to 1·75 per cent.), while the addition of copper in the ranges up to 2·5 per cent. would presumably increase the yield point and impact value of the material. From Dr. Oldeberg's report it appears that the Höganäs sword was not quenched and tempered, nor was it work hardened after forging to any proved degree. Owing to the improved qualities of the copper-manganese blade, such post-forging was perhaps found to be unnecessary.

The construction of the sword hilt is of interest, and the assembly is of quite advanced design (Fig. 45 after Oldeberg's Fig. 7). First, there is a decorated socket which is seated on the blade. Next is a sheet-metal tubular hand-grip surrounding the tang; the longitudinal seam of this hand-grip has been brazed with a bronze alloy. Finally, the end of the

tang was riveted down upon a winged terminal, so securing the complete assembly. The composition of the brazing alloy is:

Ti	V	Mn	Fe	Co	Ni	Cu	Sn	Pb	As
<0·01	<0·01	0·01–0·1	1	<0·01	<0·01	*grund massa*	1–10	0–0·1	<0·01

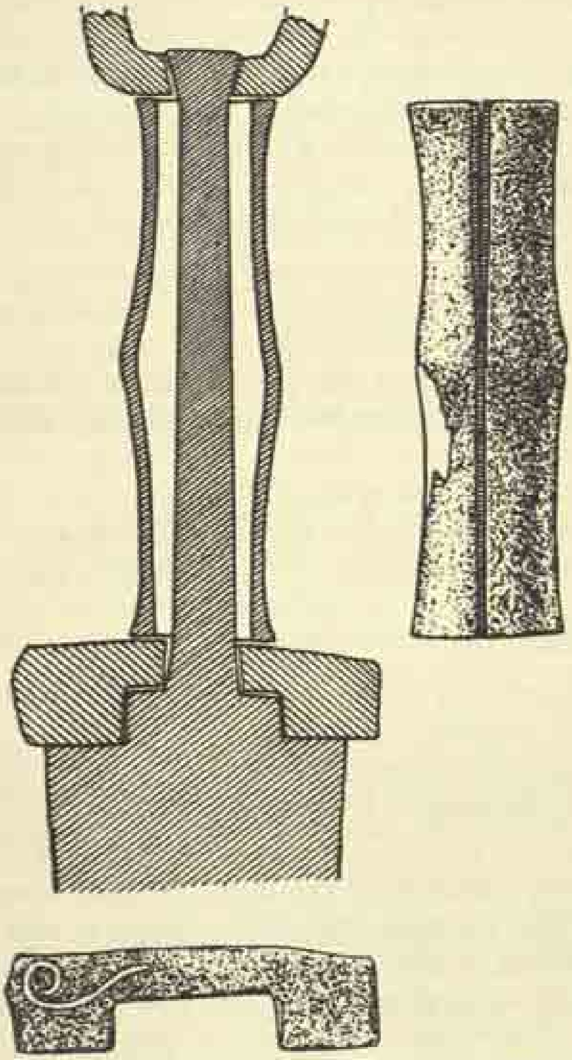


FIG. 45. Construction of the hilt of the Höganäs sword (Oldeberg 1952, Fig. 7).

It is clear that the swordsmith was highly skilled. He was able to forge the iron hand-grip to a series of graceful curves, and afterwards to braze the joint. Even today, the construction of the Höganäs hilt would rank

as quite a neat piece of smithing. During Hallstatt times the use of copper, or of a bronze alloy, in the brazing of iron must be relatively rare, although we have the use of copper for brazing the spear socket from Deve Hüyük (Cap. X, p. 181). It is remarkable that the technique of brazing bronze and iron was known and practised from very early times. This subject has been dealt with at length by Maryon (1949, pp. 108–12), who cites examples of early brazing, e.g. the Whittingham bronze sword of the late Bronze Age, and for iron, a ring of Roman workmanship from Uriconium, Wroxeter, Shropshire, dating from before A.D. 380, which had a welded joint and a second joint of which the brazing material was found to be copper. In a Hallstatt sword from northern Europe, Dr. Oldeberg (1943, ii, pl. xv, p. 215) finds evidence for the use of brazing with a silver alloy.

SAMPLE FROM AXE-EDGE. *No.* 22006.

Prähistorische Sammlung im Naturhistorischen Museum, Wien.
Loc. Magdalenenberg bei St. Marein, Jugoslavia, Tumulus II, Grave 1 and 2.
Period. Hallstatt, sixth century B.C.
Report. Stewarts and Lloyds. For Pitt Rivers Museum.
Plate V, Fig. 2, pp. 183, 202.

SAMPLE FROM LANCE-HEAD. *No.* 22016.

Prähistorische Sammlung im Naturhistorischen Museum, Wien.
Loc. Hallstatt, Gräberfeld, Grave 783.
Period. Hallstatt, sixth century B.C.
Report. Stewarts and Lloyds. For Pitt Rivers Museum.
Plate V, Fig. 3, pp. 183, 202.

The small sample taken from axe-edge No. 22006 was found to be of rather high-carbon wrought iron with numerous entrapped slag filaments. The hardness of the sample was 149 to 165 Vickers, and there was no sign of any attempt at hardening. The small sample from lance-head No. 22016 was of pure wrought iron with carbon of less than 0·04 per cent. Again, there were numerous entrapped slag filaments. The hardness of the sample was 145 to 154 Vickers, and there had been no attempt at hardening. Perhaps one would not expect much attention to hardening in a lance-head, but had the skill of the smith been at all high, one would expect some endeavour to be made to harden an axe. However, it will

be noticed that both specimens were untreated, and their hardness was approximately the same.

IRON SWORDS. *Italy, Esino and Bergamo. Period, La Tène.*

Report. Storti, C., and Mariani. E. 'Una spada gallica del III periodo di La Tène'. In *La metallurgia italiana, alti notizie*, no. 5, maggio 1953.

Doctors Storti and Mariani carried out a technical examination of two swords of iron belonging to the La Tène period. One was from the furnishing of one of three tombs at Esino Lario, and the other, from a private collection, came from the province of Bergamo. First, considering the Esino sword, it was found that in the core-metal of the blade there was an absolute prevalence of pearlite over ferrite. In the external areas ferrite tended to prevail. The material of which the Esino sword was made exhibits a steel structure with the surface layer definitely decarburized and with many inclusions, some of notable dimensions and generally elongated. In the authors' opinion, the billet from which the sword was forged consisted of a true steel, a steel with a noteworthy lack of homogeneity, but on the whole certainly approaching a pearlitic eutectoid steel with a carbon content averaging 0·7 to 0·8 per cent. The sword had not been subjected to any heat treatment or hardening (except hammer hardening of the cutting-edge), and exhibits a resistance comparable to that of a semi-hardened modern steel with a carbon content of about 0·5 to 0·6 per cent. with an ultimate tensile strength of 55–60 Kg. mm^2.

The metal of the Bergamo sword showed very different characteristics. As to slag, the material was exceptionally pure; in certain areas only were very small inclusions to be found. Here we are dealing with a soft and pure iron of formation similar to that of an Armco iron. Hardness determinations taken in certain typical areas showed that the ultimate tensile strength of the iron would not exceed about 32 to 33 Kg. mm^2. The Bergamo sword is of far less advanced technique than that of Esino. The material was very soft and could not be hardened or tempered. It would make an exceedingly poor sword for it could not be hardened, and although it would not break, it would bend with great ease. It is a good example of the 'soft iron sword' of textbooks, and far removed from Déchelette's (1914, pp. 1116 and 1129) view that La Tène swords were of highly advanced technique.

TWO IRON SWORDS. *Switzerland. Period, La Tène, c.* 50 B.C.

Report. Stewarts and Lloyds for Pitt Rivers Museum.

Plates VIII–X, and pp. 185–6, 203.

Through the kindness of the Director, Professor Dr. Alfred Bühler of the Museum für Völkerkunde, Basel, it has been possible to report upon two La Tène swords from the Historisches Museum of Basel. Sword number 1947–639 was found to be composed of very low-carbon piled wrought iron, in the as-forged condition. No attempt had been made to harden it by heat treatment. The hardness near the mid-rib was found to be 161 Vickers, increasing to 190 at the cutting-edge. Sword number 1947–640 is of good-quality wrought iron made from a large number of piled layers. A very rough estimate of these layers would indicate possibly some 50 to 100, many more than in the other sword. Again, the weapon is in the as-forged condition, and there is no evidence of hardening by quenching. The carbon content is variable. Near the central rib it is about 0·15 per cent., while close to the cutting-edge the carbon content rises to approximately 0·5 per cent. The hardness also varies from 161 Vickers at the low-carbon mid-rib to 286 in the coarse high-carbon zone at the cutting-edge.

We had hoped that these two swords would indicate that the La Tène sword-smith was familiar with the art of hardening and tempering. However, such was not the case, and we can only say that sword number 1947–639 is comparable to the La Tène sword from the province of Bergamo, examined by Storti and Mariani, that is, a sword of remarkably pure, but soft, wrought iron. Such a sword would be a very poor working weapon. On the other hand, sword number 1947–640 may be compared with the La Tène sword from Esino, also reported upon by Storti and Mariani, which is made from what may be described as a fair quality steel for its period. Such a sword, although not a 'quality' weapon, would be a working one, and possess certain advantages over the average bronze sword.

ROMAN CHISEL. *Chesterholm, England.*

This chisel was found by Mr. E. Birley during the course of his excavations at Chesterholm in 1932, and assigned by him to the second century A.D. (Pearson and Smythe 1931–7, pp. 141–5). The chisel is 8 inches

long with a square-sectioned body of about 0·4 inches. The following chemical analysis is given by Pearson and Smythe:

Manganese nil. Silicon 0·038 per cent. Phosphorus 0·016 per cent. Sulphur 0·011. Nickel nil.

Carbon was not determined analytically, for its distribution in the metal, as shown spectrographically, was so variable that an average value is of little or no significance. It will be seen that the metal is very pure, and there is comparatively little cinder; about half the chisel consists almost entirely of ferrite. The steely portions of the chisel consisting of pearlite and ferrite, or pearlite and cementite, appeared to vary from a dead mild steel to a high-carbon steel; the highest estimated carbon content observed was 1·3 per cent. About one-half of the chisel-edge consists of martensite and troostite, indicating that the edge of the tool has been heated approximately to 900° C., and then quenched in water. The absence of carbon in the other half of the cutting-edge nullified the hardening process locally. The report makes it clear that the hardening process had been confined to the cutting-edge. The authors made various hardness determinations with the Vickers machine. The average value of hardness in the metal comprising the body of the chisel, compared with the carbon contents roughly estimated from the structure at the points of indentation, are given as:

Carbon (per cent.) . .	0·0	0·1	0·2	0·3/0·4	0·5/0·6	1·3
Hardness. V.P.N. . .	136	114	149	169	214	233

On the whole, these figures agree with the values to be expected, though the hardness of the ferrite is higher than usual in unstrained metal. The deformed metal where the head of the tool has been hammered is of greater hardness, being 212 where the structure consists of ferrite only, and 218 where about 0·1 per cent. of carbon is present. The authors' remarks upon the heterogeneity of structure are of interest concerning the iron produced from the primitive smelting furnace:

In these, small blooms of pasty metal mixed with cinder were obtained, which with much hammering and many re-heatings were wrought into shape. Complete separation of cinder from metal was impossible, and the varying conditions in the furnace made it inevitable that some parts of the metal should be richer in carbon than others. Later forgings, though tending to equalization in composition, still left the metal streaky, bands of iron and of steel of varying composition alternating with one another.

While it is clear that the smith knew of the effect to be obtained from quenching, and possibly even aimed at some measure of tempering (compare with Carpenter and Robertson 1930, specimen No. 9, Egyptian axe), the Chesterholm chisel cannot be considered as a satisfactory piece of work. Because of the omission of adequate preliminary carburization, and the great variation in carbon content in different parts of the metal, about half the cutting-edge is martensitic with a hardness of 464 to 579 Vickers (say around 430 Brinell), while the other half consists of soft iron with a hardness of only 138 Vickers.

STEEL CHISEL. *Crayke, Easingwold, Yorkshire. Period, Viking.*

Report, by Dr. J. A. Smythe in *Hull Museum Publication*, No. 212, 1941, in a note, 'Metal objects made by the Vikings', by Thomas Sheppard.

'Cross-sections near the head, and side faces near the cutting-end, were examined metallographically. Near the head the metal consists almost entirely of steel containing 0·9 per cent. of carbon, in the condition, metallographically speaking, of sorbitic pearlite. However, there are patches of different composition, one containing about 0·4 per cent. of carbon, the other 1·2 per cent. of carbon, and each of these shows a well-marked Widmanstätten structure, which is evidence of heating to a high temperature, possibly 1,000° C. The hardness of this metal varies from 238 to 283 Vickers Pyramid Number. Near the blade of the tool, the structure is that of a quenched, high-carbon steel, consisting largely of martensite. The hardness is variable, but much higher than at the head, rising in places to the values 657, 782, and 870 V.P.N.

'It may be remarked that there are two essential processes in producing such a tool from wrought iron. The iron must first be carburized to a fairly high degree, and it must then be quenched from a temperature of 750° C., or above that. With respect to the carburization, this appears to have been done very satisfactorily, the average carbon content being that of a eutectoid steel (0·9 per cent. of carbon), considerable uniformity having been attained throughout, having regard to the fact that the steel was never melted. The hardening has also been skilfully done. It is clear that the tool has been heated to about 1,000° C. and only the cutting end hardened by quenching in water.'

The very high hardness figures at the blade will be noticed (compare with the Danish battle-axe of A.D. 895–6), and it would appear that the

temper had not been 'let-down'. Such a chisel would probably be too brittle for average heavy service upon the harder metals.

EGYPTIAN SICKLE. *Period, Roman, c. 2nd–3rd century* A.D.

Report. Carpenter and Robertson. 1930. Specimen No. 1.

The microstructure of the sickle blade was found to be typical of a low or medium carbon steel in the quenched and tempered condition. It was estimated that the carbon content varied from about 0·5 per cent. in areas of large grain size to about 0·35 per cent. in areas of small grain size. In the portion of the blade which was examined, the tempering had been carried out at such a high temperature that a very poor result was obtained. The Brinell hardness of the blade was only 116, and was not much harder than the back of the sickle, where the hardness was 96. Properly quenched and tempered, steel of the composition of this sickle should, of course, exhibit far greater hardness. As the authors state, the quenching and tempering had definitely spoiled the quality of the blade.

Tempering may approximately be controlled by observation of the oxidation colours, and without this guide the chance of successful tempering would indeed be remote. Even with modern knowledge of what the colours mean, it is quite easy to miss, or pass, the desired colour, and so have to repeat the whole operation in order to obtain a correct temper. Although he missed the temper, the smith who made this tool knew how to make comparatively pure and ductile iron and medium carbon steel. He also knew how to harden this steel by quenching and, further, how to reduce the hardness by tempering.

TANGED KNIFE. *England, Frilford, Berks. Period, 3rd–4th century* A.D.

Report. Stewarts and Lloyds. For Pitt Rivers Museum.
Plate XIII, Figs. 1–3, and pp. 189, 204.

The bulk of this blade had been converted to iron hydroxide, the only solid metal remaining being at the tang. Hence, an analysis was not possible, nor any determination of such matters as heat treatment, etc. A transverse cross-section showed a piled wrought structure and no doubt carburization had been used to increase the carbon content of the material, but no evidence was obtainable to indicate further stages.

TWEEZERS AND STAPLE. *Egypt, Harageh. Period, Roman.*

Report. Stewarts and Lloyds. For Pitt Rivers Museum.

Plate XII, Figs. 2–3, and pp. 188, 204.

This small Roman tweezers was examined in order to see if any special tempering was carried out in making the tool. The staple was examined as an example of Roman iron used for a non-cutting implement. The report states that the tweezer blades are made of a carburized wrought iron (carbon approximately 0·15 per cent.), with a Vickers hardness varying from 154 to 176. No special hardening technique appears to have been resorted to, but the medium degree of hardness attained should be quite well suited to give the springy material so necessary in a tweezers, and at the same time avoiding failure of the metal due to over hardening with consequent brittleness.

The staple was found to be made from piled wrought iron which carburization has brought into the range of a 0·25 per cent. carbon steel, the hardness varying between 189 and 336 Vickers. Such material should be well suited for a staple which might have to withstand considerable resistance while being driven home.

SHAFT-HOLE AXE. *England, Silchester, Hants. Period, Roman. 4th century.*

Report. Stewarts and Lloyds. For Pitt Rivers Museum.

Plate XIII, Fig. 4; Plate XIV, Figs. 1–3, and pp. 189, 204.

It was hoped that this very fine specimen of Roman shaft-hole axe would exhibit the technique of quenching and tempering. However, as Messrs. Stewarts and Lloyds' technical report shows, such was not the case, the hardness near the edge of the blade being only in the neighbourhood of 118 to 210 Vickers. In such a fine specimen it is perhaps surprising that the Roman smith should have been content with such moderate hardness for the cutting-edge of the tool. It is possible that it never was used, and would have been heat treated before being put into service. On the other hand, Mr. Whitaker has commented upon this point, saying,

> The hardness figures we quote are as reasonably near the edge of the blade as we could get, and, of course, an axe with such a hardness would necessitate frequent sharpening. On the other hand, the carbide rich zones would give some measure of resistance to wear, particularly as the grain size in these areas is exceedingly fine. The damascene sword blades discussed by Colonel Belaiew in

the Iron and Steel Institute Journal of 1918, No. 1 and 1921, No. 2 are hyper-eutectoid carbide steels with quite low hardness, the wear resistance being given by the carbides.

It is also quite probable that the user of the axe would have kept the cutting-edge in order by means of some measure of hammer hardening upon a field or other anvil. As we have mentioned elsewhere this is a well-known and undoubtedly ancient technique.

Tanged Knife. *Egypt, Oxyrhynchus. Period, Roman.*

Report. Stewarts and Lloyds. For Pitt Rivers Museum.

Plate XI, and pp. 187, 203.

This blade has been built up from a large number of faggots of wrought iron which had been forge welded in piles, leaving a blade exhibiting a wavy flow pattern. Numerous slag inclusions had not been expelled during the welding and forging. The material is exceedingly pure base wrought iron with a very low carbon content. No attempt was made to carburize or harden and temper the material. Neumann bands are observed in the microstructure, and have been formed by hammering the blade cold, after the hot forging. Such cold working is, of course, to increase the hardness which varies between 113 and 120 Vickers. Such hardness is typical of a modern low-carbon mild steel, and is harder than a normal wrought iron.

Shaft-hole Axe. *England, Reading, Berkshire. Period, Saxon.*

Report. Stewarts and Lloyds. For Pitt Rivers Museum.

Plate XIV, Fig. 4, and pp. 190, 204.

As an example of Saxon metallurgy, this axe does not attain a high standard. The axe has been forged from a piled structure with layers of varying carbon content, but the hardness of the edge is only 154 to 165 Vickers, and there is no indication of quenching and tempering. While the carbon content taken from drilling from the heavy portion of the section near the socket was 0·23 per cent., it is interesting to note the extremely low carbon content of below 0·04 per cent. close to the edge of the blade as a result of prolonged heating which has decarburized the thin portion of the cutting-edge. Also, that the presence of Neumann bands in the ferrite grains shows the cutting-edge to have been heavily cold-hammered. There is no sign of quenching and tempering and this

axe would certainly not hold a sharp edge. It is clear that the smith was working in the dark, and had no skill in empirical methods of hardening, otherwise he would not have spoiled the cutting-edge of the tool through excessive decarburization. The heavy cold hammering, as indicated by the presence of Neumann bands, was probably an attempt to render an unsatisfactory tool in some measure serviceable.

BATTLE-AXE. *England*, *Essex*. *Period*, A.D. 895–6.

Report. Stewarts and Lloyds. For Pitt Rivers Museum.

Plate XV, and pp. 191–2, 204–205.

This shapely battle-axe is a fine example of smith's work. It is properly quenched and hardened as indicated by the Vickers hardness figure of 450 for the cutting edge, as compared with a figure of 160 to 170 for the body. The axe has been made from low-carbon (0·049 per cent.) sponge iron. A feature of interest is the relatively high hardness of the body which is due to the high phosphorus (0·445 per cent.) content of the iron. To render it suitable for hardening, the cutting-edge has been locally carburized. In manufacture, the iron has been piled and repeatedly forged from faggots of sponge iron; the fibre or grain flow being parallel with the cutting edge. The shaft socket has been formed by lapping over a tongue from the forging, and forge welding this to one side of the blade. While it is not, of course, in the same class as a fine damascene sword, we may say that this Danish axe sets a high standard of ordinary work.

SPEAR. *England*, *Reading*. *Period*, *Viking*.

Report. Messrs. Alfred Herbert for Reading Museum (Beeny 1950, No. 199).

This spear was examined because it exhibited a stippled or herringbone pattern. Evidence was obtained that the pattern had, in fact, been intentionally welded into the blade, and it could be classed as a simple example of pattern welding. A cross section of the spear reveals that the weapon has been compacted from about twelve longitudinal rods, apart from the stippled layers. The central regions of the spear contain little carbon and are very soft (97·4 D.P.N.—1 kilo load), whereas towards the blade edges the metal has as much as 0·45 per cent. of carbon, and the hardness is consequently greater (219 D.P.N.—1 kilo load). The hardness readings

vary with the carbon content and there is no evidence of any attempt to harden the steel by quenching.

SOCKETED ARROW. *England, Woodeaton, Oxon. Period, Mediaeval.*
Report. Stewarts and Lloyds. For Pitt Rivers Museum.
Plate XVI, and pp. 192, 205.

This barbed and socketed arrow has been made from wrought iron with only 0·05 per cent. of carbon. No attempt has been made to harden the arrow, nor would hardening be possible with such low-carbon material. The socket portion has been formed from thin wrought iron sheet wrapped round a pointed former. The barbs and point of the arrow have been imperfectly forge welded on to the socket. The Vickers hardness varied between 115 and 153. One would expect an arrow of this period to be of purely 'utility' manufacture. This specimen is a poor piece of work, although no doubt quite good enough for an arrow, but of little interest in the evolutionary series.

From the foregoing account of analyses the first point which will be noticed is the very early appearance of carburization, and the very appreciable increase in hardness of the metal so obtained. When we remember that an average hardness for wrought iron is about 100 Brinell, and that many modern low-carbon mild steels have a hardness of from 110 to 150 Brinell, it will be seen that a very appreciable increase in hardness had been attained in the two Egyptian knives of about 1200 B.C. These two specimens show that the smith of this early period had made considerable progress, and could already make hard and useful iron.

The second step of great importance is the introduction of quenching the carburized iron or low-carbon steel. This we find in the two Egyptian axes dated to about 900 B.C. In one of these axes (Carpenter and Robertson, specimen 9), heat transfer from the body of the axe gave a temper which left the cutting-edge with the remarkable hardness of 444 Brinell, which is approximately equivalent to the hardness of a modern carbon-steel cold chisel. The Egyptian axe is indeed a most remarkable achievement for 900 B.C. In a measure this result was no doubt accidental, for the hardness of the other Egyptian axe of 900 B.C., which was treated in a similar manner, did not exceed 229 Brinell. In the Egyptian chisel of 700 B.C. hardness does not exceed 302 Brinell, while the Roman sickle of the second to third century A.D. had been quite spoiled in an attempt to temper it. Even during Roman times it does not appear that there

was any uniform application of hardening to the various cutting tools in use. One would expect a razor to be hardened by quenching, but such was not the case with a razor of Roman period from Stockstadt am Main, Germany, which was subjected to metallographic examination which showed that the material had been treated by a cementation process, but was not hardened.[1] Not until we come to the Danish battle-axe of A.D. 890 do we find really satisfactory hardening and tempering. When it was found that quenched iron, or rather quenched steel, was too hard and brittle for normal use the natural reaction of the smith would have been to try heating, so long associated with the softening of copper, and he would find that this did indeed soften his quenched material. We do not know how and when he discovered the colour guide to the temper ranges which are so necessary to control the temper. Of all the heat treatments, this operation would be the most difficult to perform, and for a long time its successful application may have remained the secret of a few smiths in selected regions of advanced metallurgy.

The preparation of a forging by forge welding together a number of layers or laminations of wrought iron, so giving a piled or compacted structure, was a most important aid to good carburization. It is noteworthy to find this practice attested so early as the eighth century B.C. (in the tripod from Nimrud), followed by the fine spear from Deve Hüyük, in Syria, at 600–500 B.C. After this time, no doubt, piled wrought iron was frequently used for making good quality tools and weapons which required to be hardened. Concerning forgings made from piled wrought iron, Mr. Whitaker has kindly given me a most interesting note:

> During heating for forging iron is preferentially oxidised to the copper, nickel, arsenic, phosphorus and other elements present even in small amounts which are less easily oxidised, so that the surface of the heated iron becomes enriched in these less easily oxidised elements. After many heatings the immediate surface of the iron can become so enriched that the analysis of the surface is very different from that of the main mass. After welding and piling the pilings can be counted and the resulting water markings or flow pattern clearly seen. See our report on the Syria, Deve Hüyük spearhead, Fig. 44, and the Silchester Roman axe, Plate XIII, Fig. 4. This surface enrichment due to the preferential oxidation of the iron sometimes results in iron which does not scale as quickly or corrode as quickly as the base material underneath the enriched surface layers. For instance, it is possible by heating a copper-bearing iron, say with only about 0·3 per cent.

[1] See *Freiberger Forschungshefte; Kultur und Technik*, D 6; Bernhard Neumann, *Die ältesten Verfahren der Erzeugung technischen Eisens*, Akademie-Verlag-Berlin, 1954, pp. 58–59.

copper in certain ranges of temperature, so to enrich the surface layers in copper, due to the preferential oxidation of the iron from the surface, to form a layer of nearly 100 per cent. copper on the surface, so that the faggot is coated with copper. Such surfaces are often very resistant to corrosion.

The specimens at our disposal are too few to permit of accurate conclusions being drawn as to the technical progress made in the various periods, but they serve to show the reason for the general expansion of the industry after about 1200 B.C., and the fact that there was relatively steady progress culminating in the fine swords of the Hallstatt period. We know that the best La Tène smiths were highly skilled in artistic work, but we have insufficient metallurgical evidence about the quality of the La Tène swords to be able to make any general statement. The examinations of La Tène material which we quote are disappointing in that they do not show any exceptionally high standard in iron metallurgy. We do not find support for Déchelette's view that La Tène swords were of highly advanced technique. However, without the examination of much more La Tène iron it would be unwise to be dogmatic upon this particular point. In general it is perhaps true to say that, from 1000 B.C., we must await the crucible steel of the East, and the damascene and pattern-welded swords, before we find the highest skill developed by the smith, coupled with really outstanding metallurgical progress.

In the West, the Roman smiths do not appear to have made very marked progress in actual technology, but rather appear satisfied to retain the old and well-established techniques, while much increasing the productive capacity of the iron industry. As the following examples indicate, it is true to say that by the Roman period very substantial iron forgings could be made.

Early Iron Forgings of Considerable Size

Perhaps the most famous iron forging of great size is the Delhi pillar. The figures given by various authorities as to the dimensions of this column do not always agree, but the following figures given by Richardson (1934, p. 581) may be taken as reasonably correct. The shaft itself is 12½ in. in diameter at the top, and 16½ in. in diameter at the base. It is nearly 24 feet long and weighs by estimate somewhat more than 6 tons. The date is usually considered to be approximately A.D. 300. Owing to the limited capacity of the smelting and forging furnaces available, it is obvious that a forging of over 6 tons in weight could not have been produced from one bloom of wrought iron. Hadfield

(1912, pp. 153–8) has given much information concerning the Delhi pillar which was probably forged together from a number of small billets each weighing around 80 to 100 pounds. The pillar has been kept in remarkably good condition, and free from corrosion. Hadfield gives the composition as:

> Carbon 0·08 per cent. Silicon 0·046. Sulphur 0·006. Phosphorus 0·114. Manganese nil. Iron 99·72. Total 99·966 per cent.

The material is a very good quality wrought iron, the low sulphur content of 0·006 per cent. indicating that a very pure fuel, almost certainly charcoal, was used in its manufacture and treatment. Wrought iron usually contains at least a trace of manganese, but the Delhi pillar did not apparently contain that element. According to Hadfield, the Dhār, or Dhārā, iron column (at Dhār, the ancient capital of Malava, thirty-three miles west of Indor) is of even greater size than the Delhi pillar. Three existing pieces measure 24 feet, 12 feet, and 6 feet in length, making an original length of some 42 feet.

In Europe, some large and heavy forgings of Roman iron are known. In the Roman settlement at the Saalburg, Germany, a forging of over 4 feet in length by about 5 in. square was found (Jacobi 1897: Taf. xlvii, pp. 237–8, 251, 258, 554). Also, three very heavy blocks of iron were found which had been used as window frames. Of course, such could not have been their original purpose, and they have the appearance of perhaps being rough-outs for making unusually large and heavy anvils. Another very large piece of iron is the anchor from Lake Nemi in Italy. This anchor belonged to a boat which has been ascribed to the Roman period. It was apparently forged from three billets and the whole weighed about 1,275 pounds (Speziale 1931, pp. 309–20; Calbiani 1939, pp. 359–70). At one time, what was thought to be the largest known mass of Roman wrought iron was the bloom found on the site of the Roman Corstopitum, near Corbridge on the north bank of the river Tyne (Bell 1912, pp. 118–35). It was found in what appeared to be a reheating furnace, and measured 39 in. in length. It is approximately 7 in. by 8 in. at one end, tapering to 5 in. by 4½ in. at the other end, and weighs about 340 pounds. The bloom had been built up by forge welding together a number of smaller sections which, according to Stead's examination, did not exceed a unit weight of 40 pounds. The whole block was probably used for an anvil. Analyses of the Corstopitum bloom gave the following average composition:

Chemical analysis, average, by Dr. J. E. Stead.
Carbon 0·097 per cent. Manganese 0·04. Silicon 0·046. Sulphur 0·025. Phosphorus 0·044. Copper 0·01. Arsenic 0·049. Cinder 0·380 per cent.

Even larger blooms of Roman iron have been found at the Roman Villa, Chedworth, near Cheltenham, Gloucestershire, of which the Curator, Mr. Norman Irvine, has kindly furnished the following particulars.

In the museum at the Chedworth Roman Villa there are three large blooms of iron. There cannot be much doubt that the blooms are of Roman origin as they were all found in a chamber in the north-west corner of the Villa, and there is very little evidence of a later occupation of the site. The following are the weights and dimensions of the blooms. The dimensions are given to the nearest half inch for length, and quarter inch otherwise. The weights are taken from an old guide book and due to loss by rust and scaling they are now perhaps on the high side, especially for numbers 2 and 3.

No. 1. Length 63½". 8¼" × 6½". Weight 484 pounds.

Shape. Like a cigar. Centre portion of 'square' section with unequal taper to the ends. The cross section is circular at, and near, the ends. This is the best bloom, and appears to be in original condition.

No. 2. Length 37". 7½" × 7¼". Weight 356 pounds.

Shape. Square section right through with slightly enlarged ends. One end is in original form, the other end evidently had been broken to provide metal for some purpose. The break appears to have been made 'cold'.

No. 3. Length 37½". 6¾" × 6½". Weight 256 pounds.

Shape. Roughly of square section. There is a slight taper from one end to the other, the larger end shows a fracture similar to that of No. 2. There appears a possibility that this bloom is half of an original similar to No. 1.

Wootz Steel and the Damascene Process

Finally, some reference must be made to the various damascene processes and their relation to Wootz steel of ancient origin. This is a complicated matter which has occasioned some measure of confusion in archaeological literature. A complete discussion of the various processes would be impossible within the space at our disposal; hence, the following notes must be limited to a general description of the major techniques employed. Given appropriate heat and mechanical treatment Wootz, the ancient Indian crucible steel, furnishes a true damascene pattern. Of this Professor Desch (1937–8, p. 191) has said:

The true Eastern Wootz process was essentially a crucible process. The material was enclosed in a kind of crucible and was run down into a cake,

which had to be exposed to a blast to render it malleable. . . . The true Damask steel was obtained first in the molten state; the very coarse crystals were formed in the molten mass and were forged out at a low temperature. That was quite different from the false Damask, which was made by welding together soft and hard steel.

We are justified in referring to the damask of the Wootz steel as a true damask, or damask of crystallization. Again, we also have the damascene patterns which were made by welding together either soft and hard steel, or pure iron and carburized iron. Also, there is the delicate forging operation which has been termed by Mr. Maryon 'pattern welding'. Finally, there is the false damascene effect which may be obtained by chemical surface treatment of the metal.

Rickard (1932, ii, pp. 863–5) considers that the earliest real steel was probably the Indian steel known as Wootz. This steel was exported from Mysore, possibly even before the beginning of the Christian era, and may have been known to the Roman world. It was smelted from natural magnetite sand, or some similar material, which had been washed and ground to a small size.

From Rickard's account it would appear that two processes were involved, first a smelting operation, and secondly a crucible process. The smelting was carried out in a small furnace about 4 feet in height, charcoal being used as fuel and no flux added to the charge. The furnace was of the usual rather conical form with clay tubes inserted near the base of the furnace to serve as blast nozzles which supplied forced draught. Slag was tapped at intervals during the course of smelting. The bloom obtained as a result of the smelt was a malleable iron with much included slag; so far as possible the slag was expelled by heating and hammering subsequent to the smelting. The efficiency of conversion was very low, a magnetite with an iron content of 72 per cent. yielding only 15 per cent. of its weight in bar iron. In the crucible process, the refined iron which had been obtained from the smelting and hammering operations was cut into small pieces; these pieces, to a weight of about 2 lb., were packed into clay crucibles in which some dry wood and green leaves were also included. Before firing, the crucibles were, of course, sealed with clay. Of the subsequent operation Rickard says:

Two dozen such crucibles were piled together in the form of a cone in a small furnace, into which charcoal was fed. This being lighted, a blast was maintained for 2½ hours; then the crucibles were removed, allowed to cool, and broken, yielding cakes of steel. These cakes were then heated for several hours at a

temperature just below melting, during which time they were turned over in a current of air from the bellows, so as to expel any excess of carbon and to produce a low fusing point. Finally the cakes were hammered into short bars ready for sale to the traders.

In a later paper Rickard (1939, pp. 100–1) again mentions Wootz steel, and points out that the Damascus blades, long associated with steel of ancient origin, were made from Wootz steel of Indian origin. Rickard says that the steel was made by the Chera Tamils in Hyderabad, and was exported from India shortly before the Christian era. It would seem that the cakes of steel obtained from the crucible process contained 1·33 per cent. of combined carbon, and 0·31 per cent. of uncombined carbon. For export, the cakes were no doubt forged into short bars.

Richardson (1934, pp. 580–1) is in agreement with Rickard in considering that Wootz steel was made from the black magnetite sands of Hyderabad, that it was exported, and was much prized by the Romans. He differs from Rickard in thinking that the manufacturing process was entirely a crucible one. In Richardson's own words:

The charge, consisting of black magnetite ore, bamboo charcoal and the green leaves of certain carbonaceous plants, was sealed in a crucible made from native clay. Several of these would be set in the hearth which was then filled with charcoal and the furnace lighted. Gradually raising the temperature to a point when the charge became molten (approximately 3000 deg. F.), an iron-carbon alloy was thrown out of solution and solidified in mass at the bottom of the crucible. This metallic button or mass, mechanically separated from its slag, was then alternately melted and cooled again four or five times, each complete operating cycle requiring a day. Then in round cakes about five inches in diameter and one-half inches thick, each of them weighing approximately two pounds, the metal was carried overland by caravan to the arms-making centres of western Asia, or if for export, to the various shipping points. A long normalising treatment preceded the forging operation which was done with great care, flowing the metal in two or more directions with light blows of the hammer. After prolonged annealing the blades were quenched and drawn to the desired hardness, then polished and etched. This last operation brought to the surface the damask inherent in the steel; and its pattern and background colour determined the quality.

Also made by a crucible process is the Persian steel, but in this the charge, which was treated in crucibles, was wrought iron and charcoal.

Forbes (1950, pp. 410, 437–8) mentions the production of Wootz steel through smelting the contents of clay crucibles which before sealing were charged with black magnetite ore, bamboo charcoal, and leaves of certain carbonaceous plants. As we have previously mentioned, this

operation gave the Wootz cake of steel. In a subsequent operation to make the Damascus blades the cakes were forged by flowing the metal in two or more directions, annealing, quenching, and tempering. Finally, the damask pattern was brought out by polishing and etching. Forbes points out that there are different descriptions of the Wootz process. For instance, Ure (*Dictionary*, vol. iii, 1867, p. 764) considered the ore to be first smelted in a bloomery furnace using charcoal as fuel, and with forced draught supplied by means of bellows ending in bamboo tubes feeding tuyères of clay. As described by Rickard, a crucible process then gave the cakes of Wootz steel. If the steel was not for export, but was worked on the spot, it was frequently forged and then polished and etched with acid to bring out the damask pattern, afterwards being glowed at a temperature not exceeding 700° C., and allowed to cool slowly.

From these various accounts of the making of Wootz steel, it will be observed that the process is a complicated one and must have been of long standing, the result of many years of experiment, trial, and error. In view of the technical difficulties of the process, and of the reference to alternate melting and cooling of the steel, it appears impossible that such steel should have been made in pre-Roman times. Concrete dating evidence appears to be absent, and one may well doubt if the whole technique was known to the Roman metallurgist. The production of the steel itself was far from simple, and the discovery of the subsequent technique of cross forging and etching in order to give the damask pattern would be noteworthy even in the Middle Ages.

Damascene Steel

Thanks to the valuable research of Col. N. Belaiew (1918, pp. 417–37), the methods by which the damask patterns are produced on some steels of ancient origin have been made clear. According to Belaiew there were three modes of making the true damascene steel:

(i) The old Indian. The steel being made by a crucible process using pure ore and the best kind of charcoal.

(ii) The, say, Persian. Here the crucible charge was of iron bars and charcoal or plumbago.

(iii) A heat treatment of steel, resembling very prolonged tempering.

A real damascene steel with its macro-structure appearing on a polished surface must not be confused with a 'wrought' damask which has been

produced by welding together a compound of iron and steel bars and wires. Full particulars and technical details of the damascene steel made by Belaiew will be found in his paper for the Iron and Steel Institute. In essence, the steel was prepared by placing a mixture of soft iron and graphite in the crucible which was heated for a period of more than two hours after the charge had melted; the damper was then closed and the hearth plastered up so as to retain the heat. Hence, the alloy cooled down slowly in the crucible together with the furnace. Such delayed cooling is an essential feature of the process in order to obtain the desired crystalline structure in the steel. The alloys prepared by Belaiew in this manner had carbon contents ranging from 0·45 to 1·80 per cent., and even more. A fine Oriental blade with a large motley pattern showed the following composition upon analysis (Belaiew, 1918, p. 427, and Fig. 2).

C	Mn	Si	S	P
1·49	0·08	0·005	0·05	0·10 per cent.

Analyses of other blades showed the carbon content mostly between 1·20 and 1·80 per cent. with, in a few cases, occasional drops to *hypo-eutectoids* with 0·60 to 0·80 per cent. of carbon. Not only had the composition of the steel from which the ancient Oriental damascene blades were made to be within certain limits, but the further heat treatment and forging were of the greatest importance. On this point Belaiew stated that,

> The alloys were, first, pure iron carbon alloys, mostly hypereutectoids and very rich in carbon; secondly, they were alloys of crucible steel, subjected to the highest possible degree and duration of heating and then slowly cooled down together with the furnace; thirdly, they were forged, quenched, and tempered very carefully, and never exceeding certain limits of temperature.

A very great amount of mechanical treatment, or forging, was expended on the best class of Oriental blades. According to the quality of the damask, and the skill of the workman in forging and cross-forging, wavy, motley, and vertebrae patterns were produced. Apart from the beauty of the finished work, damascene steel had also exceedingly practical advantages. When properly made, the steel was very strong and possessed a very high elastic limit. For instance, a good blade could not (in the ordinary sense of the term) be broken by bending, it could be bent to a right angle without breaking or losing its elasticity. Again, owing to its temper, an unusually sharp and durable cutting edge could be imparted to the blade.

In a contribution to the discussion upon a paper by C. H. Desch and

A. T. Roberts (1923) entitled 'Some Properties of Steel with Globular Cementite', Colonel Belaiew made the following remarks which further clarify the technology of damascene steel.

On two occasions, the authors (Desch & Roberts) stated, they were unable to develop the damascened structure, in spite of the fact that the cementite was entirely spheroidised. The structure of the damascened blades, however, was not the result of the spheroidised structure of the cementite particles; their structure, as was known from the blades in several collections, was the result of the primary structure of the damascened cake. There must be a certain agglomeration of masses of cementite parallel to the axes of the primary crystals in order to show that structure after forging. He suggested, therefore, that one of the possible reasons why the authors were unable to develop the damascened structure was that the primary structure and the axes of the crystals were not sufficiently developed. The old Indian maker was always at pains to produce, first of all, in his damascened cake that primary structure, and only afterwards, with infinite pains, did he try to forge his disc in a certain manner to develop that redistribution of the axes of the primary crystals which would show the wavy structure. The mechanical properties of damascened blades were due, to some extent, to that primary structure, and that was the reason why the damascened structure always appealed so much to the Asiatics, and to a certain extent even to Western metallurgists.

The importance of the microstructure, or the importance of getting the cementite spheroidised, lay in the fact that the carbon content in the old damascened blades was so high that it was impossible to forge such high carbon steel when the cementite was in needles in such big agglomerations. It was quite impossible to forge the steel with all those protruding needles, and, in order to be able to forge such a blade, it was first imperative to spheroidise the cementite. That spheroidisation of the cementite was carried out quite fortuitously by the subsequent forgings and heatings which formed a part of the old process. It was impossible to forge a large, or even a small, cake at once, because the heating arrangements were deficient; the temperature would never exceed, say, 800° C., and, during the forging, it would cool down after a few minutes. The first forging, therefore, would only result in that preliminary breaking up of the cementite lamellae. Afterwards, when the cake had cooled down, it was reheated and forged again and again, and all these forgings and heatings (which were applied, of course, quite unconsciously by the old smith) resulted in the breaking up of the cementite needles and the spheroidisation of the cementite. . . . In many tools, if the carbon content was high, the maker was, consciously or unconsciously, getting that damascened structure of spheroidised cementite, and the same was true to a certain extent in the case of alloy tool steels. . . . The structure of many blades and many tools, when their carbon content was high, was exactly the same structure as was unconsciously arrived at in India and Persia many thousand years ago.

As we have seen, the ancient Indian crucible steel known as Wootz

became known to the Romans. Clearly, it was highly prized, for a pure crucible steel would have been far in advance of any of the wrought irons, or semi-steels, of the western countries. Made from the same Indian crucible steel, true damascene steel probably did not appear in Western Europe until the Middle Ages. In spite of the fact that the basic material for making damascene steel was possibly known in India even before our Roman period of the West, it is not surprising, when we consider the complex and controlled metallurgical and mechanical processes required for the production of a true Damascus steel, that its appearance in Europe may well have been delayed until much later times. In the author's opinion it is a matter for wonder that so elaborate a technique should have been evolved so far in advance of modern knowledge of the structure and properties of steel.

Pattern Welding and Damascene Steel

A very complex forging technique, and one of extreme difficulty of execution, is known from about the third century A.D. to the Viking period. A large number of iron swords excavated during the years 1858 to 1863 from Nydam Moss, Schleswig, Denmark, were found to be decorated with twisted patterns giving a herringbone effect, the pattern being wrought into the material of the sword itself. This particular technique has been investigated and termed by Mr. Maryon 'pattern welding'. A sword of Nydam type has been recovered from Ely Fields Farm, near Ely, Cambridge, and has been reported upon by Maryon (1943–7, pp. 73–76). In general, the decoration of these swords is formed by a central band, or bands, composed of twisted rods, or bundles of flattened wire, running parallel down the length of the blade; the cutting edges, core, and twisted strips are welded together in one mass. The Ely Fields sword was composed of members forming the two cutting edges, then a separate core, and on either side of the blade the decoration formed from four twisted rods or bundles of strip. In the course of his research Maryon made experiments to copy this sword, and the extreme delicacy of the work is well indicated by his remark: 'The strips for that work must have been of metal not thicker than $\frac{1}{100}$ of an inch. And, moreover, careful examination shows that about two-fifths of the outer surface of the twisted rods was ground away after the welding was completed. This would be done during the grinding and polishing of the weapon.' As Maryon points out, the welding of these swords was excessively difficult, and it is indeed hard to see how complete fusion of

the delicate strips which had to form the pattern was prevented. Today, such delicate work is a lost art.[1]

In 1950 the Ancient Metallurgy Committee of the Royal Anthropological Institute arranged the examination on behalf of the Reading Museum and Art Gallery of a Viking period spearhead, probably derived from the bed of the River Kennet at Reading, which exhibited a herringbone pattern. Various points of interest were brought to light by the report (Beeny and Collins, 1950). First, it is of interest to note that very thin strips of soft steel were used for the decoration. These rippled strips running down the spear averaged about 0·015 inches in thickness, but in places increased to 0·025 inches. There was no orderly twisting of the strips as in the Nydam swords to account for the rippled pattern. Secondly, examination of a cross section of the spear revealed that the weapon had been compacted from about twelve longitudinal rods, apart from the stippled layers. It is not easy to see why the smith should have built up the central core of the spear from various layers of very soft low-carbon iron unless this technique be due to a desire to obtain a better penetration of carbon (by forging, or even by a cementation process) than could have been achieved had the spear been made from a solid forging. It is clear that a relatively high carbon content could be imparted to a number of thin laminations, and therefore a temper giving the spring-like steel so desirable to a good sword or even spear could be attained.

A structure compacted from a number of laminations is known in other contexts. In a spear from Deve Hüyük, Syria, dating to 600–500 B.C., it is estimated that the blade was built up from about fifty layers of sponge iron plates (see Cap. VII, pp. 137–8).[2] Again, in more recent times the compacting method was highly developed in the manufacture of Japanese swords. Dr. Chikashige (1936, pp. 90–92) speaks of a very great number of laminae in certain swords of high quality. The Reading spear does not appear to be pattern-welded in Maryon's sense of the term, but it may well be a degenerate form of the technique.

Damascene patterns exhibited by certain Merovingian and Carolingian

[1] For a further discussion of damascene steel see Neumann (1927, pp. 241–4) where the following analysis of one of the Nydam damascene swords of the Roman period is given:

Carbon 0·62. Silicon 0·15. Manganese 0·363. Phosphorus 0·054. Sulphur 0·073. All figures are expressed as percentages.

Again, for a technical discussion of sword-making, both plain and damascene, see Sommer (1924, pp. 127–43).

[2] This chapter also discusses other implements which exhibit a piled structure.

swords have been studied by Albert France-Lanord (1949, pp. 19–45). These swords are made by a delicate technique of welding and forging. On reflection, France-Lanord considered that the hypothesis of making damascene blades by surface welding of thread-like elements presented considerable difficulties, and a forging test led him to consider that such a procedure would be impracticable for the making of a whole blade.

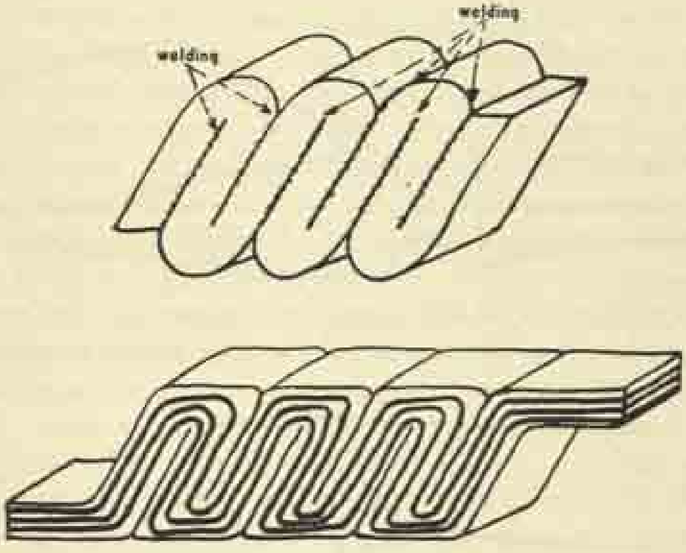


Fig. 46. Welding a damascene sword from pure iron folded with carburized iron (France-Lanord 1949, Figs. 5, 6).

His view upon the method of manufacture for the Merovingian and Carolingian swords is as follows:

Examination of a damascene blade shows a network of zones of pure iron and carburized iron. This network only covers the central part of the blade and is sharply separated from the cutting-edges which are in homogeneous iron. The line of separation between the central zone and the cutting edges is a weld; at the centre of the central zone runs another weld. Hence, the two cutting edges are welded to the central damascene zone. Also, down the length of the sword the central damascene zone is welded at its centre; in certain swords the central zone may be formed of two, three, or even four, welds. Micrographic examination (Pl. I, Fig. 1), showed that the metal in the pure iron zones was very pure, containing only some small inclusions. The carburized parts appeared as a hypo-eutectoid steel of variable carbon content of 0·1 to 0·4 per cent., the

mean of 0·2 per cent. corresponding to an extra mild steel. France-Lanord postulates that the central damascene zone was made by a band, or rod of iron, composed of a laminated structure (pure iron and carburized iron), which was bent on itself (Fig. 46), each fold being welded to the preceding fold so as finally to form a bar of a certain length of which the structure is at the same time stratified and folded. The welds

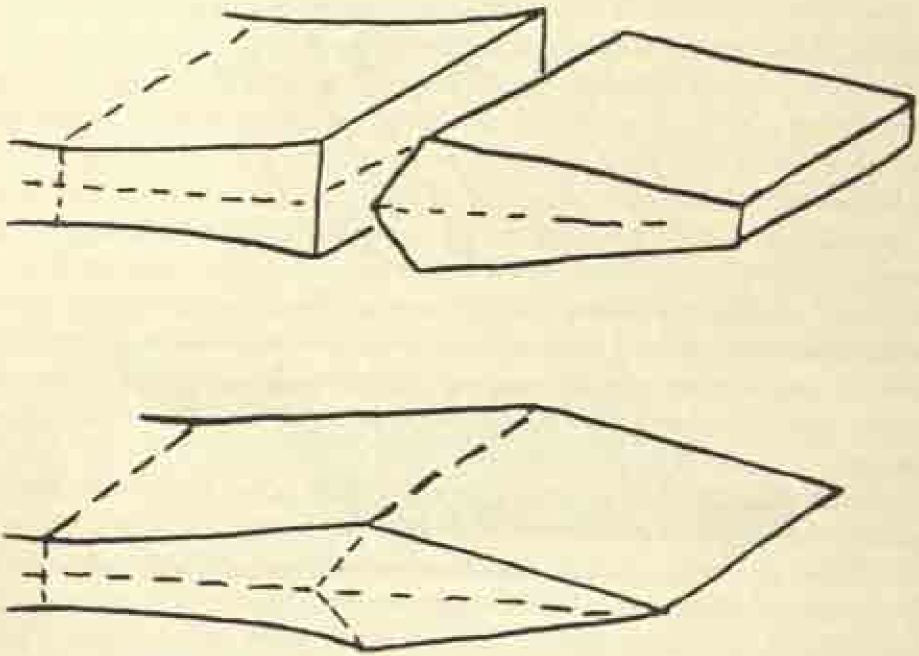


FIG. 47. Welding a hardened cutting-edge on a sword (France-Lanord 1949, Fig. 12).

were perfectly made and difficult to detect; some could not be seen. The bar was much forged and returned many times to the fire.

To give the bar its laminated nature, before folding it, it could have been made of three thin bands of iron of which the surfaces had been carburized during the process of forging. It is also possible that one wide band of iron was folded three times in its width, so as to make a single bar when forged. This bar would again be folded lengthwise as mentioned above. The cutting-edges of the sword, very slightly carburized, are welded to the central portion (Fig. 47) in such a way as to augment the surface of the weld and its solidity; the blade shows a swelling at this point. Towards the end of the sword, the cutting-edges join and terminate in the usual point. The metal of which these swords are made is pure

iron. No trace of tempering was found in any arm studied, and tempering would have been impossible because the carbon content is not high enough. By submitting swords in fairly good condition to deflection tests France-Lanord found that the mean resistance of damascene blades is 2·5 to 3 times that of ordinary swords. The conclusion is that the long and delicate forging and welding work in the damascene blades increases the elasticity and resistance. It is not the nature of the metal which is better, but the method of working it which enables improved results to be obtained. The hardness of the cutting-edges was obtained by long and careful hammering. Recent work (Klindt-Jensen 1952, pp. 218–28) shows that the Merovingian technique is traditional. In the great deposit at Vimose in North Jutland were no less than eighty-four swords, of which a number had pattern-welded blades, and they may be ascribed to the Roman period. Examination of a pattern-welded central portion showed it to be fashioned of weld-steel of two degrees of hardness, hard steel being used for the edges and spine of the blade, while the remainder consists of layers of hard and soft steel to give the blade strength and resilience. According to the author, this examination demonstrated methods of manufacture identical with that of the Merovingian weapons.

From the sixth to the eleventh centuries, according to France-Lanord, all good swords were made by the above method. Afterwards the technique was replaced by steel swords which became general. Nevertheless, the utilization of welded damask in quality arms continued through the centuries in various countries, and it was thus that the celebrated damascene gun barrels were forged until recent years, in particular in Belgium around Liège. At the present stage of our knowledge it is impossible to define the place of origin of the welded damascene blades. Several authors have thought they may be of Oriental origin and they have brought together the western welded damask and the eastern damask, or damask of crystallization, of which Colonel Belaiew has defined the nature. The Oriental blades, of hypereutectoid steel, have a high carbon content and are forged from a block of steel made in a crucible. The watered appearance of the surface of the blade comes from the crystalline structure of the metal itself. One cannot usefully compare the two techniques, and one must admit that the welded damascene technique examined by France-Lanord is the result, as he says, of an evolution made in western countries to improve the forging technique and permit the manufacture of good-quality weapons from metal which was only iron.

The Art of the Sword-smith in Japan

To conclude our review of the technical art of the smith, it is appropriate to mention the work of the famous Japanese sword-smiths. The finest Japanese swords are not of such early date as the damascene work which we have previously mentioned, but in their basic technique they certainly go back to the thirteenth century A.D., and may well be considerably more ancient.[1] This work must be classified as of the highest quality, and called for exceptionally highly trained and skilful smiths. A comprehensive account of the long line of qualified Japanese smiths will be found in the work of Joly and Inada (1913, pp. 69 ff.). They explain that such swords were forged from iron and steel welded together in various ways, the raw materials used being of Japanese origin except in the case of the so-called Namban Telsu swords. According to the authors the iron was smelted from titaniferous ores and from magnetic oxide. Charcoal smelting was used and an exceedingly pure metal obtained, the small proportions of phosphorus, manganese, and silicon being especially noticeable. The final operation of tempering the blade was of great importance and it is stated that

> The aim of the smith was to produce the hardened steel at the edge only, so that the blade retained a greater amount of toughness than if it had been hardened throughout. Hence the admixture of iron, which does not harden in the tempering process, and the use of a protective covering of clay (sabidoro) over part of the blade before hardening it. In European practice steel blades were hardened, then rubbed with some abrasive substance, so that the metal surface became bright, and then the temper drawn down to one of the 'colours' produced by the formation of a film of oxide, characteristic of certain degrees of hardness. The modern style of scientific tempering consists, however, in raising the metal to a definite heat, and in quenching it at that temperature. The Japanese swordsmith proceeded in precisely the same manner: the blade was heated over a fir-charcoal fire until it reached the desired heat, gauged by its glow and colour. It was then quenched.

The preparation of ancient Japanese sword steel of high quality has been very clearly described by Dr. Chikashige (1936, pp. 85–101), as follows:

> A piece of steel is first forged as a foundation, and to this a long rod of iron is welded to serve as a handle. Then another piece is heated and quenched in water, after which it is broken up and placed on the foundation piece; these are then heated and welded to form one sheet. See Fig. 48 (after Chikashige, diagrams on pages 90 and 91). The object of this process is probably to produce the

[1] The Pitt Rivers Museum has a sword by Iyetsungune, dated about A.D. 1138.

isotropic structure of the resulting steel. This sheet is now notched in the middle, the notch being at right angles to the centre line of the handle. Next, one half is folded over and the two welded together; this is the first welding of the folded

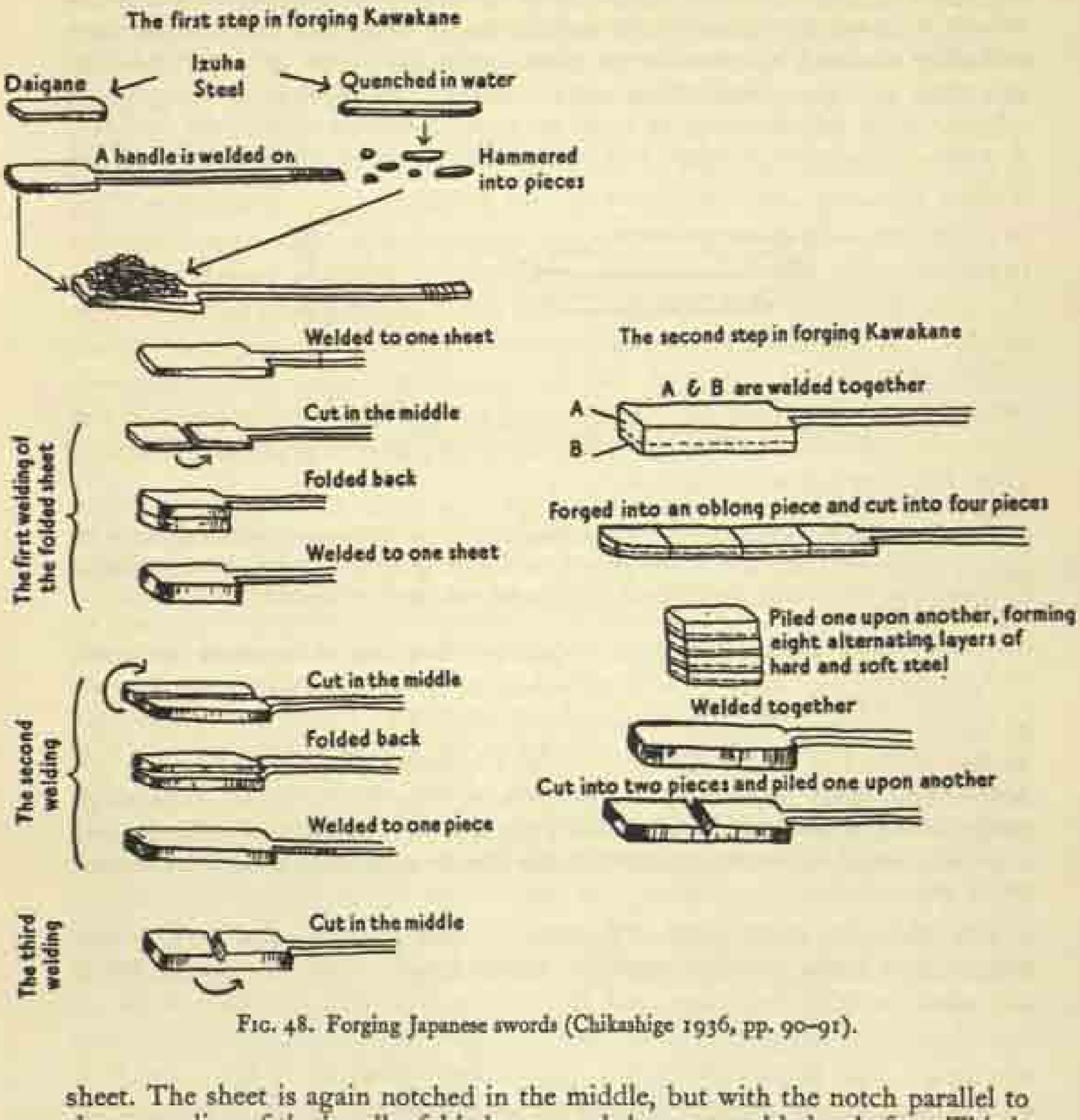


FIG. 48. Forging Japanese swords (Chikashige 1936, pp. 90–91).

sheet. The sheet is again notched in the middle, but with the notch parallel to the centre line of the handle, folded over, and the parts welded as before This is termed the second welding of the folded sheet and the process is repeated about ten times, resulting finally in a rectangular sheet which may be termed *A* (see Fig. 48). Next, a piece of soft iron is subjected five times to the 'welding of the

folded sheet' process, and forged to the same shape as *A*, but with only half its thickness; the resulting sheet is shown as *B* in the figure. *A* and *B* are now welded together, forged into a billet and cut into four equal pieces which are then piled one upon another and welded together. The resulting block is again cut in the middle, piled as before, and again welded. The forging now consists of sixteen alternating layers of hard and soft steel. The process as above described is further repeated, the number of layers being multiplied by each repetition and after, say, ten repetitions the steel acquires a fine laminated structure; the number of the laminae being as many as sixteen thousand in one inch thickness of metal. When the welding has been skilfully carried out the effect of the

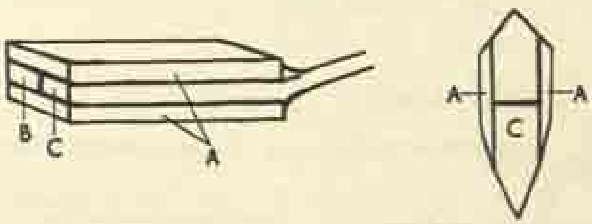


FIG. 49. Forging a Japanese sword (Chikashige 1936, p. 94).

diffusion of carbon is predominant, and apt to cause the boundaries of the hard and soft steel to be obliterated. As a consequence, the laminated structure may be almost indiscernible. It was commonly said among sword-smiths that excessive repetition of the folding and welding process was rather harmful.

A complete sword is forged together from three separate sections, cover, centre, and edge. The highly folded metal just described is known as 'cover metal', while the 'centre metal' should be composed of soft steel alone, which has been subjected to the welding and folding process, but not to the same degree as in the case of the cover metal. The edge metal is composed of hard steel. Fig. 49 (Chikashige 1936, p. 94) indicates what may be termed the standard method of forging a sword from the above-named pieces of steel. Two cover pieces, one centre piece, and one edge piece are used in combination, the centre and edge pieces being welded together before hand. Next, the three pieces are piled, welded together, and forged down to give the final shape of the blade. The ideal section of a blade forged in this manner is shown in the figure, and the actual section approaches this more or less according to the skill of the smith. According to the school of the sword-smith, other combinations for building up the blade may be used. We cannot go into detail here, but a discussion of other methods of forging, together with macrographs of sections taken from various swords, will be found

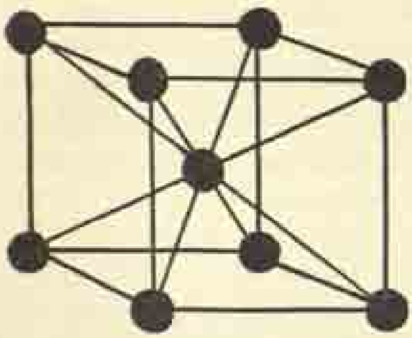
in Dr. Chikashige's work. To the modern technician, the technique described appears laborious and perhaps unnecessarily complex. However, it was built up as a result of long experience by master smiths and, with the resources available to the ancient Japanese smith, it was no doubt the best answer to the mutually contradictory requirements of a really fine blade.

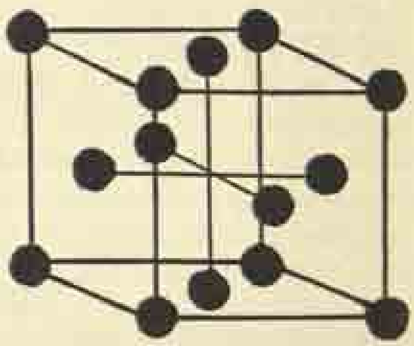
Chapter VIII

EXPLANATION OF SOME TERMS USED IN DESCRIBING THE METALLURGY AND METALLOGRAPHY OF ANCIENT IRON

By I. M. ALLEN

PURE iron may be regarded as a chemical curiosity, and its existence outside the laboratory is almost unknown. Objects which we denote by the name iron are in reality alloys of this element containing from 0 to 5 per cent. of carbon and usually at least one other major constituent, e.g. manganese, nickel, or chromium. Various impurities are also present in small and varying amounts depending on the ore, its source, and methods used in refining and reduction.





FIGS. 50, 51. α- and γ-iron lattice structures as revealed by X-ray examination.

Two crystalline structures are known for iron, denoted by the letters α and γ. α-iron possesses the body-centred cubic lattice (Fig. 50) and γ-iron the face-centred cubic lattice (Fig. 51). The body-centred cubic lattice is stable up to 900° C. Above this temperature, transformation to γ-iron occurs. γ-iron is capable of holding carbon in solid solution[1] (austenite).

If a specimen of uncorroded ancient iron or steel is polished, and etched with a weak solution of nitric acid in alcohol, a characteristic structure is

[1] The random dispersion of carbon atoms in solid iron.

revealed, and this may be seen with the aid of the metallographic microscope. Each structure is characteristic for a definite range of both temperature and composition (ratio of iron to carbon).

Iron-carbon alloys containing up to 1 per cent. of carbon are shown diagrammatically in Fig. 52 (iron-carbon diagram).

Iron-Carbon Diagram

It is evident from the metallurgical reports contained in this volume, and those of Sir H. C. H. Carpenter and J. M. Robertson (1930, pp. 417–54), that progress was made in the technology of iron and steel from 1400 B.C. onward, but until the nineteenth century this knowledge remained purely empirical and was governed by a greater or lesser degree of chance. By the middle of the nineteenth century chemical analysis[1, 2] had been introduced into the industrial study of metals. This revealed their qualitative and quantitative composition, but provided no means for checking either their macro- or microscopic structures. Towards the end of the nineteenth century vast strides were made in the microscopic examination of alloys. This type of examination consisted in studying the variation in microstructure which accompanies either an increase of the alloying element, or an increase in temperature. Each microstructure, as already stated, is characteristic for a definite range of both temperature and composition. The results of these investigations have been plotted diagrammatically to give 'thermal equilibrium diagrams' (e.g. iron-carbon diagram), and these provide a means by which a microstructure can be checked, and hence the properties of the alloy are accurately known.

Characteristic Microstructures

1. *Ferrite.* α-iron (ferrite) can contain in solid solution only up to 0·05 per cent. of carbon; it can, however, retain nickel, small amounts of manganese, phosphorus, and other elements. Its structure, which consists of a continuous network of polyhedral grains, is characteristic of pure and impure iron (Plate XI, Fig. 3). If impurities are present in considerable quantity, they may be retained undissolved in the form of mechanical inclusions; slag may often be observed flecking the ferrite grains in

[1] Simple methods for testing the purity of gold and silver are mentioned in the Bible by Zechariah (xiii. 9). Pliny (*Natural History*, Book XXXIII, 43 and 44) records the use of the touchstone for testing gold, and he also gives methods for testing the purity of silver.

[2] An account of the chemical methods of analysis used in the nineteenth century is given in John Percy's *Metallurgy*, 1864.

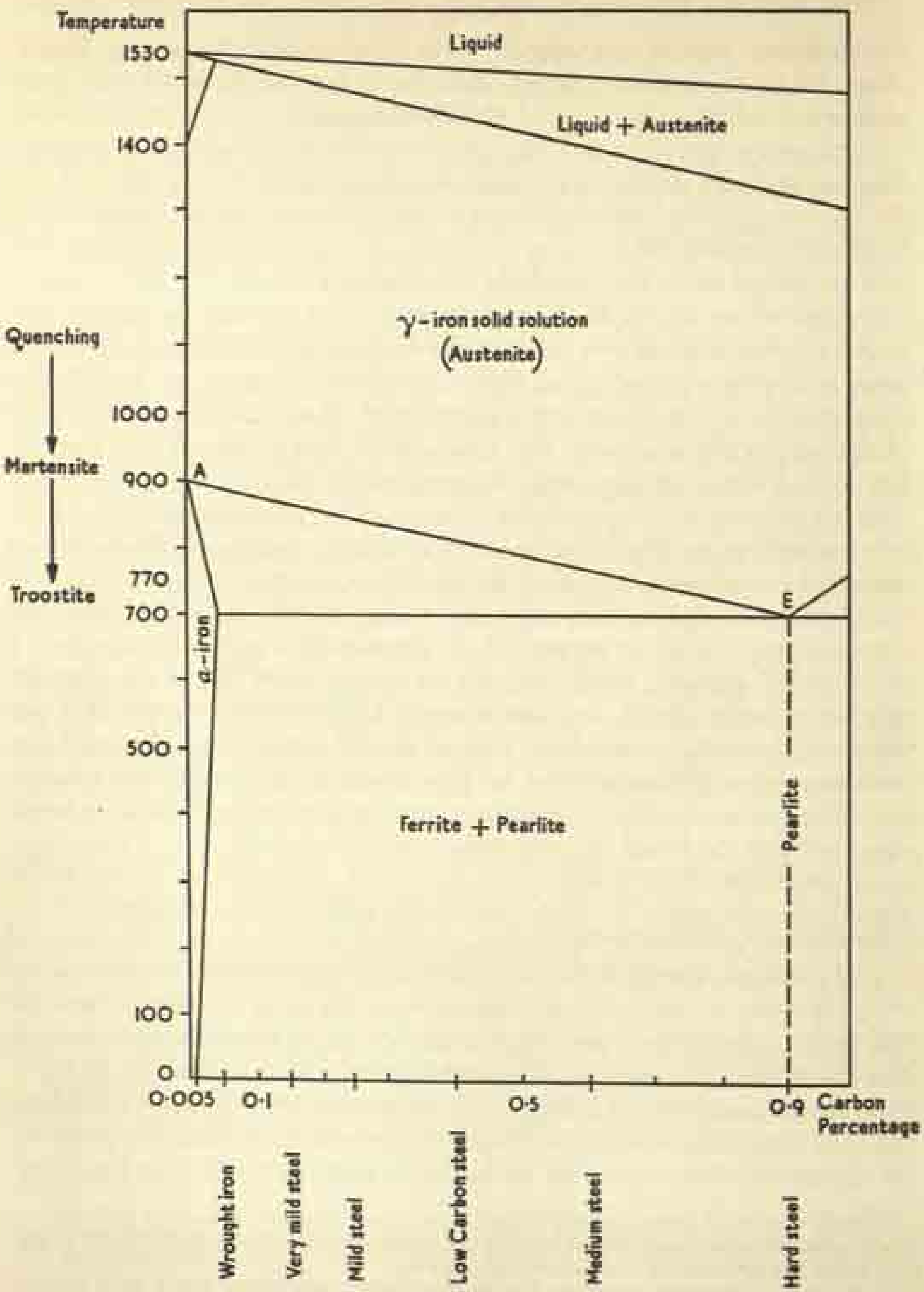


Fig. 52. The iron-carbon diagram.

this manner, and is a source of weakness, rendering the iron brittle. Should a ferrite structure be reported to the archaeologist, he may interpret it as evidence that little or no carburization has been carried out on the specimen in question. If the specimen has been subjected to severe hammering the grains may exhibit Neumann lines (Rosenhain and McMinn 1925, pp. 231–9). Most of the heavier tools and weapons of antiquity consist almost entirely of ferrite, though in some instances their cutting-edges have been hardened by carburizing.

2. *Cementite or iron carbide.* Brilliant white globular or massive free cementite occurs in low-carbon steels which have been subjected to hammering and annealed at about 680° C. (Whiteley, 1918, pp. 353–61) or have been forged in the critical ranges (700°–900° C.), particularly steels containing less than 0·15 per cent. of carbon (Plate XIV, Fig. 3). Cementite also occurs as bright laminae in pearlite.

If free cementite is reported present in the microstructure of a specimen of ancient steel containing less than 0·89 per cent. of carbon, it may be taken as evidence of forging and heat treatment.

3. *Pearlite.* Pearlite is a eutectoid[1] of ferrite and cementite containing about 0·89 per cent. of carbon. At low magnification pearlite appears as dark irregular grains, but at high magnification these can be resolved into alternate curved white and black lamellae consisting of cementite and ferrite (Plate VII, Fig. 3). Annealed steels of less than 0·89 per cent. carbon content (hypoeutectoid steels), consist of pearlite in a groundmass of ferrite. This structure is possessed by ancient carburized iron which has not been hardened or tempered.

4. *Austenite.* Austenite, as already stated, is a solution of carbon in γ-iron. It exists only at high temperatures in carbon steels and is not retained by quenching. Quenching produces martensite, and normal cooling pearlite in ferrite.

5. *Martensite.* Martensite is the hardest constituent of steel, and has the appearance of dark needles (Pl. XV, Fig. 3). Martensite is found in hardened but untempered ancient steel.

6. *Widmanstätten structure.* This structure (Pl. V, Fig. 1), which consists of large bars, needles, or plates, is produced in small forgings by overheating in the austenite range followed by fairly rapid cooling. Steel with this structure is brittle.

A similar structure exists in meteoric iron containing more than 7 per

[1] An intimate mixture of two phases (ferrite and cementite) possessing a fixed ratio of chemical composition.

cent. of nickel. The crystals of this structure are composed of three nickel-iron alloys named kamacite, taenite, and plessite. The structure is probably produced by slow-cooling and prolonged annealing (Buddhue 1948, vol. lvi, pp. 105–8).

Case Hardening

The method by which the ancient iron-smith introduced carbon into iron is known as *carburization*. This consisted of prolonged heating of iron below its melting-point but above 900° C. in intimate contact with charcoal.

Iron which has been carburized correctly will exhibit a graduation from 0·89 per cent. of carbon (pure pearlite) at the surface to a carbon-free iron core. In most specimens of antiquity the carbon content of the surface falls short of 0·89 per cent. In order to render the above treatment of value, the specimen would require hardening and tempering.

Heat Treatment of Iron and Steel

1. *Wrought iron*. Smelting iron ore with charcoal in the furnaces of antiquity before the fourteenth century A.D. usually[1] produced a type of iron which was very similar to modern wrought iron.

Wrought iron is essentially ferritic in structure, and its properties and characteristics have already been discussed under ferrite. The carbon content of ancient wrought iron was usually less than 0·1 per cent., but it was sometimes higher. It may then be classed as very mild steel and can be hardened by quenching from about 930° C.

Iron of less than 0·1 per cent. of carbon is little affected by heat treatment and quenching, although recrystallization with reduction of grain size occurs when it is heated above 900° C., due to the change in lattice structure. If the temperature is very high (1,200° C. or higher) inordinate grain growth may occur instead of reduction, and this produces brittleness. Inordinate grain growth also occurs if phosphorus is present in quantity. The influence of this element on grain growth is modified by its distribution and cold-working.

Wrought iron and very mild steel may be hardened to a certain extent by hammering, particularly between 250° C. and 425° C. (Sauveur and Lee 1925, p. 323).

Within this range of temperature, the metal is made very brittle by

[1] See, however, Chapter IV on Cast Iron, especially the section on China.

hammering, and therefore forging should be carried out at a higher temperature, preferably at about 900° C.

2. *Low-carbon steel, medium steel, and hard steel.* When the temperature of an annealed steel containing from 0·25 to 0·89 per cent. of carbon (pearlite in a groundmass of ferrite) is raised slowly to a temperature

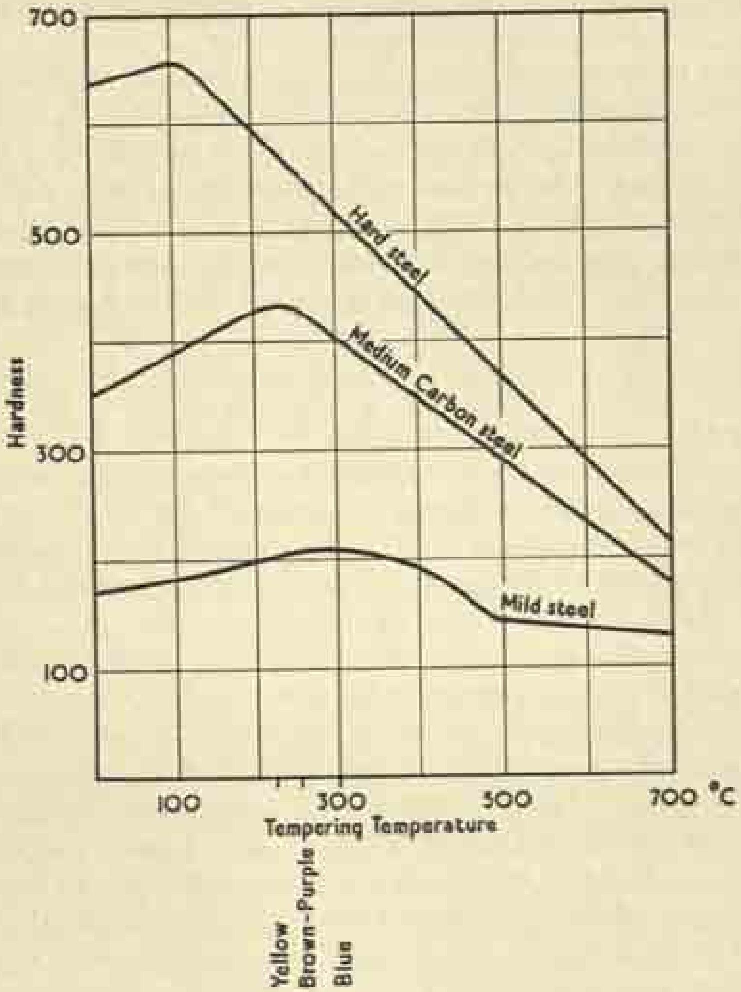


Fig. 53. Variation in hardness produced at different temperatures of tempering (modified from diagrams by Guillet and Portevin 1922).

above 900° C., a number of changes occur. Eventually, above 900° C. one phase will exist, namely, carbon in γ-iron solid solution (austenite). *Hardening* is then produced by quenching from about this temperature.

Quenching above the line AE (Fig. 52) will produce pure martensite, but for low carbon steels it must be drastic. Below the line AE ferrite–martensite is formed. Quenching from just below 700° C. produces the dark irresolvable constituent troostite. The tough temper variety of this constituent is found in correctly made swords and knives (Sommer 1924, 5, p. 140).

Hardness increases with increasing carbon content up to 0·89 per cent., and also with rapidity of quenching.

Tools and weapons hardened in the above manner are too brittle for use, and they therefore require a second heat treatment, *tempering*. This consists in heating to a temperature below 700° C. followed by fairly rapid cooling. This treatment causes the brittle martensite to break down into fine cementite. The treatment is adjusted by observing the oxide coloration produced on the metal at various temperatures. Fig. 53 shows the variation of hardness produced at different temperatures of tempering.

Chapter IX

AN ESKIMO KNIFE COLLECTED BY SIR JOHN ROSS

By I. M. ALLEN

An Eskimo knife collected on the 13th of August 1818 from Prince Regent's Bay, N. Greenland, by Captain John Ross, R.N., and illustrated on Plate 13, opposite page 102 in his *A Voyage of Discovery*, 1819, has been chosen to show how meteoric iron was used. This specimen (see Fig. 2) is not only of historic interest, but also provides an example of an iron weapon made with stone tools. When the specimen was compared with the illustration on Plate 13 it was seen that two sections of iron were missing, and we have since concluded that these were probably used by Dr. Wollaston for the nickel determination given in appendix No. III, LXXXIX of *A Voyage of Discovery*. This conclusion is based on pages 95–117 of the above work, from which it is evident that, although John Ross earnestly requested the Eskimo he encountered to bring him samples of the native iron with which they edged their weapons, there is no reference to their having fulfilled this request, though on several occasions they promised to do so (see pp. 104, 105, 111, and 112). There is also mention in *The Journal of Science and the Arts*, 1819, vol. ii, p. 369, of iron samples taken from implements collected by Captain Ross in the same area for nickel determination.

The following extract from J. Ross's *A Voyage of Discovery* (p. 104) describes the occurrence and working of native iron. 'He (Meigack) was now interrogated respecting the iron with which his knife was edged' (the knife is about 1 foot long and made of walrus ivory edged with meteoric iron) 'and informed us that it was found in the mountain before mentioned; that it was in several large masses, of which one in particular, which was harder than the rest, was a part of the mountain, that the others were in large pieces above ground, and not of so hard a nature; that they cut it off with a hard stone, and then beat it flat into pieces of the size of a sixpence, but of an oval shape. As the place where this metal was found, which is called Sowallick, was at least twenty-five miles distant, and the weather very unsettled, I could not venture to send a party to examine

it, being uncertain how soon we might be forced from our present situation.'

A metallographic examination of the nickel-iron (Fig. 54, *f, g.*) revealed that the metal had been severely distorted by mechanical working, and the presence of Neumann lines indicate that it had not been annealed.

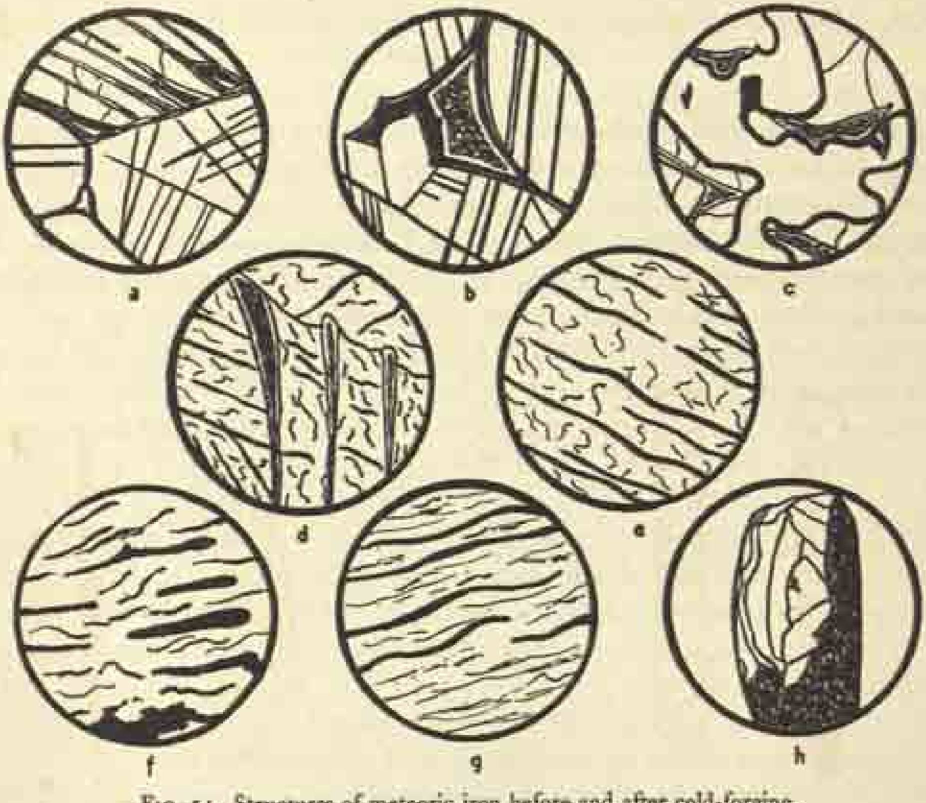


FIG. 54. Structures of meteoric iron before and after cold-forging.

Comparatively few inclusions were found in the section examined. The macrostructure (Fig. 54, *h.*) exhibited considerable cracking, and it is evident that the metal is now very friable. Its hardness averaged 227 Brinell.

Chemical analysis of the metal revealed that it consists of 88·0 per cent. of iron, 11·83 per cent. of nickel, and traces of cobalt and copper. The high nickel content proves it to be of meteoric origin, since this element rarely exceeds 2·5 per cent. in terrestrial iron. Terrestrial iron usually contains a high percentage of carbon (1·0–3·5 per cent.), and its structure is therefore either that of a high-carbon nickel steel or pig iron (Carpen-

ter 1935, p. 153; Löfquist and Benedicks 1941, pp. 1–96). The present writer examined a specimen of terrestrial iron from Blaafield, Ovifak, and found it to consist mainly of massive cementite and fine globular pearlite with inclusions of troilite.

Cold-forging of meteoric iron

Fig. 55*a* shows the macrostructure of a small billet of meteoric iron from which a small knife (Fig. 55*b*) was successfully cold-forged. The forging was made with a 1 lb. 4 oz. hammer. During the initial hammering, a small part of the billet broke off. The cause of this fracture appeared to be due to the presence of a large cohenite grain (Fig. 54*c*.). After this fracture, the remaining portion was forged to its present shape without further mishap. Fig. 54*a*, *b* show the microstructure of the metal before forging, and Fig. 54*d*, *e* after cold-forging. The average Brinell hardness before forging was 229, and after, 233.

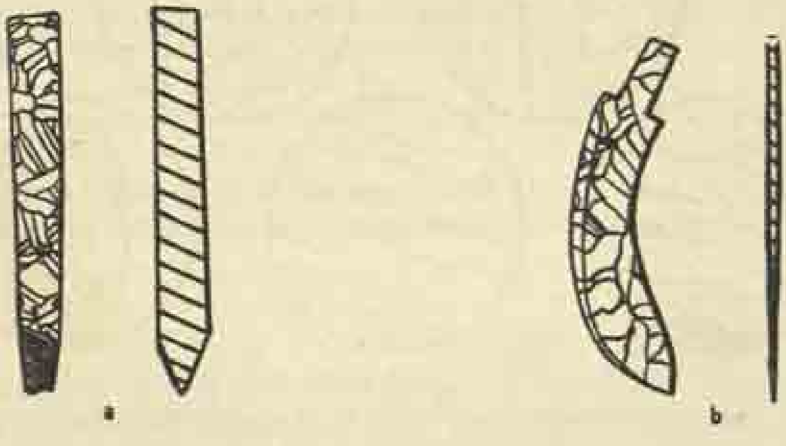


FIG. 55. Macrostructure of billet of meteoric iron before and after cold-forging. Scale 1/1.

Chapter X

A METALLOGRAPHIC AND METALLURGICAL EXAMINATION OF SPECIMENS SELECTED BY THE PITT RIVERS MUSEUM[1]

By Courtesy of

THE DIRECTOR OF RESEARCH AND TECHNICAL DEVELOPMENT OF MESSRS. STEWARTS AND LLOYDS

1. 1953.6.1. ASSYRIA, NIMRUD. TWO PIECES OF IRON FROM TRIPODS, LATE EIGHTH CENTURY B.C. Plate I, Fig. 2. PITT RIVERS MUSEUM.

Weight 92·62 grams.

Examination of this sample shows that it has been completely converted to iron hydroxide. Examination of a section shows a piled structure which would indicate that the tripod iron was made from piled wrought material. Analysis of the sample has not been carried out as there is no metallic portion left.

2. 1953.1.32. SYRIA, DEVE HÜYÜK. BROKEN SPEAR-HEAD WITH MID-RIB, SOCKETED, WITH BROKEN-OFF PIECE OF SOCKET. 600–500 B.C. PITT RIVERS MUSEUM.

Length 8½ in.
Total weight 107·0 grams.

Examination shows that this spear-head is of forged carburized steel made from reduced sponge iron. It has been forged from a large number of plates, the majority of which have been surface carburized during heating for forging.

The spear-head shows a pronounced piled water-marked structure, indicating a high degree of skill in the welding and forging operations.

The structure and hardness do not reveal any indication of hardening and tempering treatment.

A drawing of the spear-head is shown in Fig. 56, No. 6.

Before the examination commenced the spear-head was X-rayed to show which portions were still in the metallic condition.

[1] With Plates I, Fig. 2, to XVI and EXPLANATION OF THE PLATES, pp. 202–5, also Figs. 56 and 57 in the text.

Plate II, Fig. 1, is a print from a radiograph. It shows that corrosion has eaten away the metallic portions in the dark patchy areas, leaving the heavy midrib and some of the blade and socket still in the metallic state.

Careful machining, grinding, and polishing of the spear-head on one side reveals that the metal left in the blade is exceedingly thin, much of it having been converted to oxide. It was arranged that the material removed for analysis would be taken from one side, leaving the other face of the spear-head undamaged. Extensive corrosion, particularly at the socket end, made the sampling very difficult; some of the corroded portions fell away on removing the metal for analysis.

The analysis of the spear-head (see p. 182) shows that it has been made from steel with an average carbon content of 0·18 per cent. The low phosphorus and sulphur contents show the ore used for producing the steel was of pure grade. The nickel content of 0·32 per cent. is rather unusual in an implement of this type.

Macro- and microscopical examination have been carried out on the polished section, revealing a layered structure, Plate II, Fig. 2. Examination of the socket end, which was detached, shows the remains of a wooden shaft still in place. At this position, despite the heavier section, the steel is almost completely corroded away. The structure of the corrosion products, however, retains the layered pattern of the original steel interleaved in places with copper filaments, Plate IV, Fig. 2.

The socket portion is continuous with the blade. It has been formed by building up a tapered tubular shape and brazing and forging together with impure copper, Fig. 44. The copper is relatively untouched by corrosion, being more noble than the steel. The presence of copper at the socket end may account for the more extensive corrosion at this position.

The photomacrograph, Plate III, Fig. 1, and the photomicrograph, Plate III, Fig. 2, show the highly contorted layered structure, indicating that the metal used for forging the spear-head was built up from a large number of layers of iron plates resulting in a highly developed water-marked pattern somewhat similar to 'damascene' steel blades produced from cast steel.

Reduced sponge iron was forged into plates, piled into a block, and repeatedly forged, resulting in the water-marked structure. It is estimated that the spear-head contains about 50 layers. The sponge iron contains some entangled cinder and gangue which were not expelled during forging. In some places the fire welding of the various laminations has not

been complete, and particularly towards the shaft end extensive corrosion has penetrated into the layered structure.

Plate IV, Figs. 1 and 3, show high-power views taken from the same field as Plate III, Figs. 1 and 2.

The dark carbon-bearing areas at the junction of each layer, Plate IV, Fig. 1 ($\times 200$), show that the carbon content is in places as high as 0·6 per cent., indicating that the heating for forge welding was carried out under carburizing conditions, possibly on a charcoal fire, giving a localized surficial increase in the carbon content.

The structure at a magnification of $\times 1000$ is shown in Plate IV, Fig. 3; this is typical of material which has been forged on a falling temperature and has then been left to cool very slowly from about 450° C., possibly in hot ashes or at the edge of the smith's fire.

The grain size varies from 200 to 25,000 grains/sq. mm. This irregularity in grain size confirms that the final forging was carried on to quite a low temperature.

The Vickers diamond hardness varies from 108 Vickers in the low carbon zones to as high as 153 Vickers in the higher carbon bands. These hardness figures are typical of a modern mild steel.

There is no indication of the spear-head having been hardened and tempered.

Analysis:

Phosphorus . .	0·021 per cent.	Nitrogen . . .	0·006 per cent.
Sulphur . .	0·014 ,,	Copper . .	0·01 ,,
Silicon . .	0·10 ,,	Nickel . .	0·32 ,,
Manganese .	0·04 ,,	Arsenic . .	0·024 ,,
Carbon . .	0·18 ,,	Vanadium . .	0·01 ,,

3. LACHISH IRON PICK. AREA DESTROYED *c.* 588 B.C. (LACHISH, iii, Pl. 61. 3).

Examination of this pick shows it is made from a very pure base wrought iron which has been carburized prior to piling and forging.

The analysis is:

Carbon . .	0·196 per cent.	Chromium . .	Trace
Manganese .	0·013 ,,	Molybdenum .	0·010 per cent.
Silicon . .	0·010 ,,	Vanadium . .	Nil
Sulphur . .	0·005 ,,	Copper . .	0·004 per cent.
Phosphorus .	0·013 ,,	Arsenic . .	0·006 ,,
Nickel . .	0·008 ,,	Nitrogen . .	0·0035 ,,

An iron with such a pure base and such a low arsenic content would have been produced from a pure haematite or magnetite ore.

A general view of the pick is shown in Fig. 57. A photomicrograph, Plate V, Fig. 1, of a prepared area close to the point shows a very coarse Widmanstätten structure, indicating that the pick point was quenched from a very high temperature (over 1,000° C.). In the same field there are numerous slag filaments along one of the piling planes.

The hardness varies from 136 to 183 Vickers.

4. SAMPLE FROM EDGE OF A SOCKETED AXE, MAGDALENENBERG BEI ST. MAREIN, JUGOSLAVIEN, TUMULUS II, GRAB I UND 2, HALLSTATT PERIOD, SIXTH CENTURY B.C. PRÄHISTORISCHE SAMMLUNG IM NATURHISTORISCHEN MUSEUM, WIEN, NO. 22006.

A drawing of the axe appears in Fig. 57, No. 3.

The analysis of the sample (see Plate V, Fig. 2) shows a rather high carbon wrought iron with numerous entrapped slag filaments. There is no sign of hardening.

Grain size, 4,000 to 1,000 gr./sq. mm.

Vickers hardness, 149 to 165.

Analysis:

Carbon . .	0·10 per cent.	Chromium . .	Not indicated
Manganese . .	0·02 ,,	Molybdenum .	,,
Nickel . .	0·01 ,,	Vanadium . .	,,
Copper . .	0·020 ,,		

5. SMALL SAMPLE FROM BLADE OF A LANCE-HEAD, HALLSTATT, GRÄBERFELD, GRAB 783, HALLSTATT PERIOD, SIXTH CENTURY B.C. VIENNA MUSEUM AS ABOVE, NO. 22016.

A drawing of the lance-head appears in Fig. 57, No. 2.

The analysis of the sample (Plate V, Fig. 3) shows the blade to be of pure wrought iron with numerous entrapped slag filaments. There is no sign of hardening.

Grain size, 1,000 to 260 gr./sq. mm.

Hardness, 145 to 154 Vickers.

Analysis:

Carbon . .	Less than 0·04 per cent.	Copper . .	0·12 per cent.
		Vanadium . .	Trace
Manganese .	0·06 per cent.	Chromium . .	Not indicated
Nickel . .	0·09 ,,	Molybdenum .	,,

6. 1953.1.33. JUGOSLAVIA, VAČE. SPEAR-HEAD WITH SMALL POINT AND LONG SOCKET, FIFTH CENTURY B.C. PITT RIVERS MUSEUM.

Fig. 56, No. 1, shows a drawing of the spear-head. Extensive corrosive attack has occurred, and in places the material in the region of the shaft socket is completely converted to iron hydroxide.

A portion extending for 3¼ inches back from the point has been sectioned, polished, and etched to study the microstructure. Millings from this section have been analysed with the following results:

Silicon	Trace	Vanadium	Nil
Manganese	0·006 per cent.	Phosphorus	0·050 per cent.
Copper	0·01 "	Sulphur	0·012 "
Nickel	0·005 "	Carbon	0·319 "
Chromium	Trace	Arsenic	0·009 "
Molybdenum	Nil	Nitrogen	0·007 "

A photomacrograph of this portion at a magnification of about 1½ is shown in Plate VI, Fig. 1.

The examination shows that the spear-head has been forged from wrought iron with a very variable carbon content. In the lower portion of Plate VI, Fig. 1, the carbon content exceeds 0·6 per cent. locally, possibly by carbon pick-up from a charcoal fire, whereas in the upper portion the carbon content is less than 0·1 per cent.

The examination shows that the point has been formed by rolling over a faggot of wrought iron in the form of a forge-welded tubular section, which has been completely collapsed at one end to form the point, but still retains the tapered tubular form at the socket portion. The line of the welding can be seen extending from the point to the open end of the socket.

The grain size of the head varies from 20 to 15,000 gr./sq. mm., and the Vickers hardness varies from 103 to 134.

The section shows numerous streamers of non-metallic cinder which have not been expelled during the welding and forging operation. In the high-carbon areas (lower portion, Plate VI, Figs. 1, 2), the heating for forging has caused local burning in the high-carbon portion. This has resulted in numerous fissures shown in the lower portion of Fig. 2. A photomicrograph near to the weld line close to the point of the spear-head is shown in Plate VI, Fig. 3, and at a higher magnification in Plate VII, Fig. 1. At this position the structure resembles that of a normalized steel. At other positions close to the point, and on the flanks of the spear-

head, the carbon content is more typical of wrought iron. In places extensive areas of entrapped cinder are still evident (Plate VII, Fig. 2.)

The examination shows that no attempt has been made to quench and temper the spear-head. The higher carbon pearlitic areas, shown in Plate VII, Fig. 3, are typical of a steel which has been slowly cooled after forging.

7. LA TÈNE SWORD FROM HISTORISCHES MUSEUM, BASEL. SWORD NO. 1947.639.

A general view of the blade is shown in Fig. 57, No. 1.

Small areas have been prepared for examination at approximately the mid length of the blade and at the point. Microscopical examination shows that the material is very low-carbon wrought iron which is remarkably free from entrapped slag.

The grain size on the central rib is coarse and variable, in places the grains are very large, approximately 2 gr./sq. mm. (Plate VIII, Figs. 1, 2). The hardness near the central rib is 161 Vickers. At one position there is a small area which has a carbon content of about 0·6 per cent., possibly resulting from localized carburizing by contact with charcoal during the heating for forging.

At the cutting-edge the grain size is much finer, and the carbon content at this position is slightly higher than at the central rib. There are a few grains containing nitride needles.

In places at the cutting-edge the grains are distorted and are heavily veined, which indicates that the blade is in the as-forged condition and that the forging was carried out until the edge of the blade fell to a temperature of about 450° C., where complete recrystallization after forging would fail to take place (Plate VIII, Fig. 3). At the cutting-edge the grain size, although variable, is in places as fine as 2,000 gr./sq. mm.; the Vickers hardness is 190.

In patches near the central rib there are areas containing pronounced Neumann bands (Plate VIII, Fig. 2), indicating that the blade was hammered with very sharp blows in the cold condition. These Neumann bands may, of course, have been formed by straightening the blade by hammering cold at some time after use.

The analysis is:

Silicon .	Not indicated	Copper . .	Trace
Manganese .	Not indicated	Nickel . .	0·05 per cent.
Carbon .	0·1 to 0·04 per cent.	Chromium .	Not indicated

Grain size approximately 2 gr./sq. mm. to 2,000 gr./sq. mm.
Vickers hardness 161 to 190.

8. LA TÈNE SWORD FROM HISTORISCHES MUSEUM, BASEL. SWORD NO. 1947.640.

A general view of this blade is shown in Fig. 57, No. 10.

A small area has been prepared for microscopical examination about the centre of the length and at the point. The examination shows that the blade is a good quality wrought iron with a large number of piled layers (Plate IX, Fig. 1). Near the cutting-edge the layers are highly contorted due to hammering. The junctions of the layers are free from large particles of entrapped slag.

There is a variable carbon content from the edge to the central rib. Near the central rib the carbon content is about 0·15 per cent., and the ferrite grain size is approximately 1,000 gr./sq. mm.; a typical area is illustrated in Plate IX, Fig. 2. Close to the cutting-edge the structure becomes very coarse and acicular, and the carbon content rises to approximately 0·5 per cent. This coarse structure indicates that the final forging temperature was about 1,000° C.

During the final forging the central rib of the blade has received more hot forging than the cutting-edge; this has resulted in a much finer grain structure in the central rib, Plate IX, Fig. 2.

Examination of an area prepared close to the point of the blade shows the same coarse 0·5 per cent. carbon structure very similar to Plate X.

There is no evidence of hardening by quenching. The blade is in the as-forged condition, and the carbon content of the cutting-edge is a good deal higher than at the central rib and changes across the blade. This indicates that the edge of the blade was carburized, or that the edge portion had a higher carbon content in the original forged faggot used to make the blade.

The analysis of the blade is:

Silicon .	0·02 per cent.	Copper . .	Trace
Manganese .	Not indicated	Nickel . .	0·04 per cent.
Carbon .	0·15 to 0·5 per cent.	Chromium . .	Not indicated

The grain size varies from 1,000 gr./sq. mm. in the central rib to approximately 35 gr./sq. mm. at the cutting-edge.

The Vickers hardness varies from 161 at the low-carbon central rib to 286 in the coarse higher-carbon zone at the cutting-edge.

9. OXYRHYNCHUS, EGYPT. TANGED KNIFE 6·9 IN. LONG. ROMAN. PITT RIVERS MUSEUM.

Weight 37·2 grams.

A drawing of the knife is shown in Fig. 56, No. 5. When received the portion of the blade at the upper side of the photograph was approximately $\frac{1}{10}$-inch thick, while the edge at the bottom portion of the blade tapered off to a few thousandths of an inch in thickness; the blade and edge were heavily corroded and pitted; this made sectioning and examination exceedingly difficult. It was necessary to mount the whole of the blade in an air-setting plastic to allow the sectioning and preparation without distorting the edge.

A longitudinal section of the blade after grinding, polishing, and etching is shown in Plate XI, Fig. 1. The blade has been built up from a large number of faggots of wrought iron which have been forge-welded in piles leaving a blade with a wavy-flow pattern. The flow pattern developed by etching is highly contorted; there are numerous slag filaments at the junction of the layers which have not been expelled during the welding and forging (Plate XI, Fig. 2).

Due to the fragility of the blade, it was not possible to remove material for analysis without destroying the specimen, but portions have been arcked and sparked to allow a spectrographic examination to be made, with the following results:

Copper . . .	0·01 per cent.	Manganese	Nil
Tin	0·002 „	Nickel	„
Chromium . .	Nil	Vanadium	„
Molybdenum .	„	Titanium	„
Silicon . . .	„		

The material is an exceedingly pure base wrought iron with a very low general-carbon content. Certain layers of the blade, however, are higher in carbon content than others. This is possibly due to carbon pick-up from a charcoal fire by certain faggots during the repeated forging and welding operations.

Close microscopical examination along the edge of the blade shows that no attempt has been made to carburize or harden and temper the material by quenching and tempering. It is observed, however, that the ferrite grains contain numerous Neumann bands which occur on the slip planes of the grains. These Neumann bands have been produced by hammering the blade cold after the hot forging, possibly during the finishing stages of its preparation (Plate XI, Fig. 3).

The ferrite grain size is very variable, counts varying from 20 gr./sq. mm. to 20,000 gr./sq. mm. This variation in grain size is typical of wrought iron which has been hot-forged over a wide temperature range until the blade was cold.

The Vickers hardness of the blade varies from 113 to 120 Vickers which, although harder than normal wrought iron, is explained by the cold hammering. This hardness is typical of a modern low-carbon mild steel.

10. ROMAN SAW, OXYRHYNCHUS. PITT RIVERS MUSEUM.

A drawing appears in Fig. 57, No. 4.

Examination of a portion of the blade close to the teeth shows this saw has been made from piled wrought iron. The carbon content is about 0·1 per cent. See Plate XII, Fig. 1.

No analysis has been made as this would have necessitated destroying the specimen.

The grain size varies from 1,000 to 2,000 gr./sq. mm.

The Vickers hardness of the teeth varies from 127 to 140.

The microstructure is typical of a low-carbon steel which has been hot-worked until the temperature has fallen below a red heat. There is no indication that the blade has been quenched and tempered.

This saw would not remain sharp for very long when cutting even soft wood.

11. HARAGEH, EGYPT. ROMAN RING AND TWEEZERS, AND RING AND STAPLE, FROM NEWBURY MUSEUM.

Drawings appear in Fig. 57, Nos. 8, 9.

The tweezers (No. 8) have a ring made from wrought iron with a carbon content of approximately 0·15 per cent. The grain size varies from 20 to 2,000 gr./sq. mm., and the Vickers hardness varies from 145 to 165.

The tweezer blades are also made from a wrought iron which has been carburized (approx. 0·15 per cent.). The ends of the blades have been hot-worked on a falling temperature. This has resulted in a mixed grain size with the carbides highly agglomerated (Plate XII, Fig. 2). Some Neumann bands were observed near the end of the tweezers, showing that they had been hammered cold.

No analysis has been made of this item as it would have necessitated destroying the specimen.

The tweezer blades have a grain size varying from 140 to 8,000 gr./sq. mm. The Vickers hardness varies from 176 to 237.

Examination of the ring and staple shown in Fig. 57, No. 9, shows that the ring has been made from wrought iron with a very variable grain size, 20 to 2,000 gr./sq. mm. The Vickers hardness varies from 145 to 154. The carbon content is approximately 0·1 per cent.

The staple portion has a carbon content of about 0·25 per cent. The structure shows that the staple has been made from wrought iron as it shows piling with entrapped slag. The pointed ends of the staple have been hammered on a falling temperature; there is a considerable amount of cold work in the ends, the hardness varying from 189 to 336 Vickers.

Typical structures of the staple ends are shown in Plate XII, Figs. 3 and 4.

No analysis has been made of this item as it would have necessitated destroying the specimen.

12. 1953.1.34. FRILFORD, BERKSHIRE, ROMAN TANGED KNIFE, THIRD TO FOURTH CENTURY A.D. PITT RIVERS MUSEUM.

A drawing of this knife appears in Fig. 56, No. 4.

Plate XIII, Fig. 1, shows a print from an X-ray negative. Close examination of this negative shows a fibrous structure typical of wrought iron. The only solid metallic portion is at the junction of the tanged end at the beginning of the blade.

Plate XIII, Fig. 2, shows a transverse section from the end, displaying a piled wrought structure. Only small portions of the wrought material remain. The bulk of the blade has been converted to iron hydroxide.

A photomicrograph of the uncorroded portion shows the coarse ferritic grain size typical of low-carbon wrought iron (Plate XIII, Fig. 3).

13. SILCHESTER ROMAN AXE, FOURTH CENTURY A.D., READING MUSEUM.

Weight 734 grams.

A drawing of the axe-head is shown in Fig. 57, No. 7.

The whole surface is covered with a heavy layer of very hard rust.

Drillings for analysis have been taken from the heavy portion of the blade close to the socket. Only one hole has been drilled to avoid spoiling the specimen.

The analysis is:

Carbon . . .	0·319 per cent.	Chromium . .	Nil
Manganese . .	0·013 ,,	Molybdenum .	0·020 per cent.

Silicon	Trace	Vanadium	Nil
Sulphur	0·007 per cent.	Copper	0·015 per cent.
Phosphorus	0·061 ,,	Arsenic	0·071 ,,
Nickel	0·033 ,,	Nitrogen	0·0065 ,,

This is a pure base material which has been carburized. The arsenic content is typical of irons made from European siderite ores.

Metallographic examination has been made on a small prepared area running up to the edge on one face of the axe.

A photomacrograph of this area, Plate XIII, Fig. 4, shows the blade has been made from a large number of layers of piled carburized wrought iron, which have been welded together prior to forging the axe. The general orientation of the layers is roughly parallel to the edge of the axe, but they have a highly contorted outline as a result of repeated forging; they contain elongated slag filaments typical of those shown in Plate XIV, Fig. 1. The carbon content at the welds at the junction of each layer is in places below 0·05 per cent., and the ferrite grain size is in places very coarse. The dark central portions (Plate XIII, Fig. 4) of the layers have a carbon content of more than 0·6 per cent.

A typical structure near the centre of the layers is shown at a higher magnification in Plate XIV, Figs. 1, 2. The grain size (6,500 to 8,000 gr./sq. mm.) is very fine, with a ferritic background and a heavy network cellular carbide structure together with spheroidized carbide particles. This structure is typical of a medium-carbon steel, which has been forged on a falling temperature until it reaches about 700° C., and is then given a prolonged annealing in the range 650° C. to 700° C., where the carbides become agglomerated and spheroidized.

The hardness near the edge of the blade varies from 118 to 210 Vickers.

14. SAXON AXE, READING MUSEUM.

A drawing of the axe head is shown in Fig. 57, No. 5. A large piece has broken away from the upper portion of the edge.

The specimen is coated with a very heavy layer of hard rust.

Drillings have been taken from the heavy portion of the section close to the socket.

The analysis is:

Carbon	0·23 per cent.	Chromium	Not indicated
Manganese	0·01 ,,	Molybdenum	,,
Silicon	Not indicated	Vanadium	Trace

Sulphur . .	0·008 per cent.	Copper . .	0·01 per cent.
Phosphorus . .	0·130 „	Arsenic . .	0·049 „
Nickel . .	0·02 „	Nitrogen . .	0·005 „

Grain size 65 to 500 gr./sq. mm.

Hardness of edge 154 to 165 Vickers.

Microscopical examination on the top of the blade near the chipped portion shows a piled structure with layers of varying carbon content.

The structure is coarse and acicular, the carbide areas are spheroidized; this indicates that the axe was cooled from a forging temperature (over 1,000° C.) and was reheated to about 700° C. for a period which allowed the carbides to spheroidize.

The structure of a prepared area near the edge showed numerous Neumann bands in a practically carbonless ferritic background (Plate XIV, Fig. 4). The extremely low carbon content (below 0·04 per cent.) close to the edge is the result of prolonged heating which has decarburized the thin portion of the cutting-edge. The presence of the Neumann bands in the ferrite grains shows the edge has been heavily hammered cold.

There is no sign of quenching and tempering, and the edge of such an axe would quickly become blunt. The high phosphorus content would also make the edge brittle.

15. DANISH BATTLE-AXE. 895 OR 896 A.D. BED OF RIVER LEA NEAR STRATFORD, ESSEX. NEWBURY MUSEUM, No. 1898–5, NOW PITT RIVERS MUSEUM, 1954.11.11.

Weight 691 grams.

See Plate XV, Figs. 1–4, and Fig. 56, No. 3.

Examination shows that this Danish battle-axe has been made from low-carbon sponge iron which contains a small quantity of entangled cinder not expelled during the forging.

The analysis is:

Silicon . .	0·04 per cent.	Molybdenum .	Nil
Manganese . .	0·01 „	Vanadium . .	„
Copper . .	0·01 „	Phosphorus . .	0·445 per cent.
Nickel . .	0·07 „	Sulphur . .	0·011 „
Chromium . .	Nil	Carbon . .	0·049 „
Magnesium . .	0·005 „	Arsenic . .	0·042 „
Aluminium . .	0·04 „	Nitrogen . .	0·0085 „

The blade has a highly contorted layered structure, indicating that the iron has been piled and repeatedly forged from faggots of sponge iron; the fibre or grain flow is parallel to the cutting-edge.

The shaft socket has been formed by lapping over a tongue from the forging and forge welding this to one side of the blade.

The analysis and microscopical examination of the body of the blade show that the carbon content is typical of wrought iron; the relatively high body hardness of 160 to 170 Vickers is due to the high phosphorus content. The blade, and particularly the edge which is hardened, would tend to be somewhat brittle with such a high phosphorus content.

The immediate cutting-edge of the blade has been locally carburized by heating the edge in contact with carbonaceous material. The edge has been quenched and has a surface hardness varying between 350 and 450 Vickers.

The grain size of the main body of the blade is very variable, counts vary from 250 gr./sq. mm. to 1,500 gr./sq. mm. The structure is banded, and in places highly contorted, showing a marked wavy appearance typical of material which has been repeatedly forged.

16. 1953.1.35. WOODEATON, OXON. TANGED AND SOCKETED ARROW-HEAD, MEDIAEVAL. PITT RIVERS MUSEUM.

Length 2¼ in.

Total weight 13·7 grams.

See Plate XVI, Figs. 1–4, and Fig. 56, No. 2.

Analysis:

Silicon . .	Trace	Molybdenum .	Nil
Manganese . .	,,	Vanadium . .	,,
Copper . .	0·01 per cent.	Phosphorus. .	. .
Nickel . .	0·004 ,,	Sulphur . . .	. .
Chromium . .	Trace	Carbon . .	0·050 per cent.
Magnesium .	0·003 per cent.	Arsenic . .	0·008 ,,
Aluminium . .	0·01 ,,	N_2	. .

The arrow-head is made from wrought iron. It has a very variable grain size. The microstructure indicates that no attempt has been made to harden the point.

Grain size 20 to 25,000 gr./sq. mm.

Hardness 115 to 155 Vickers.

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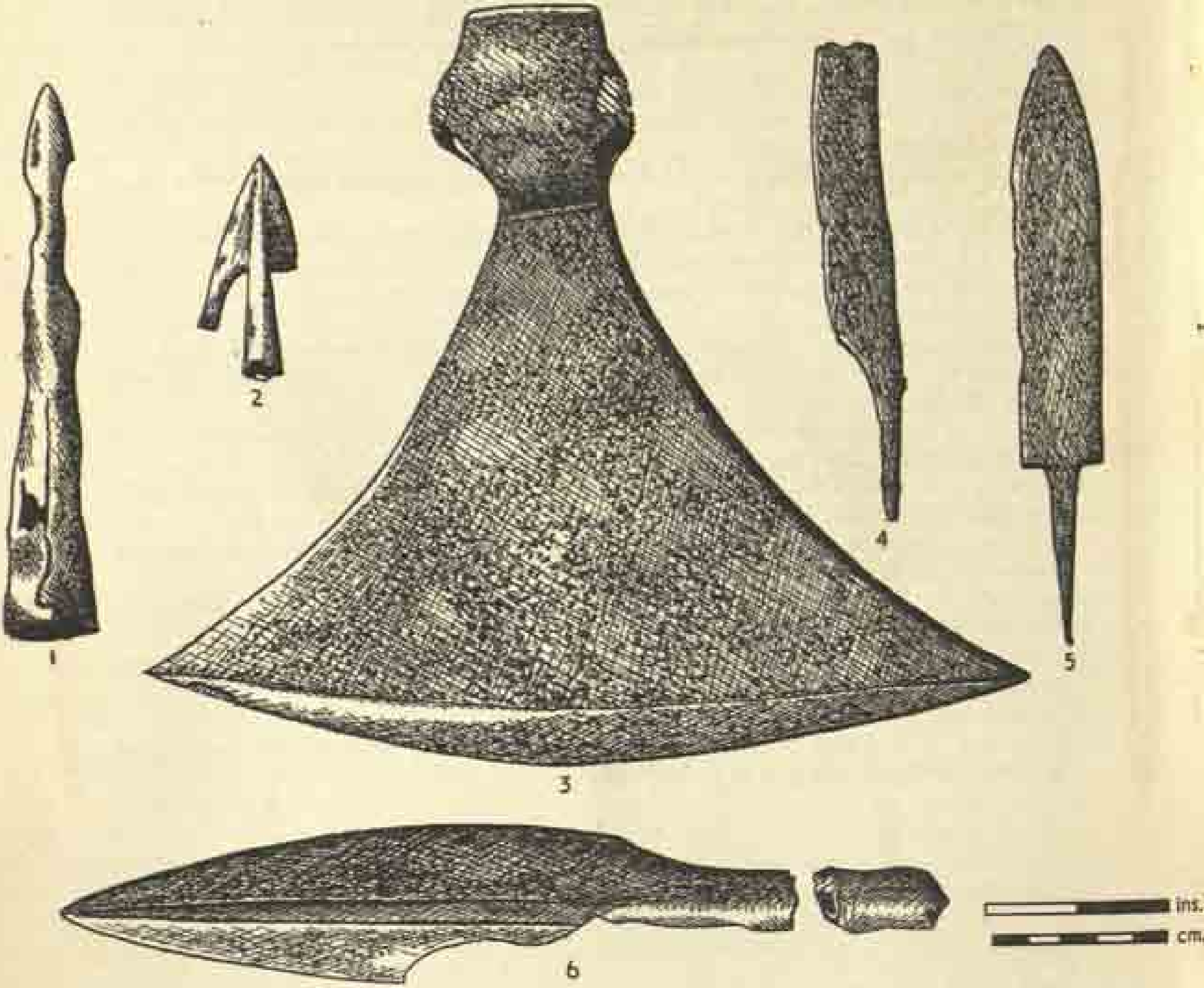
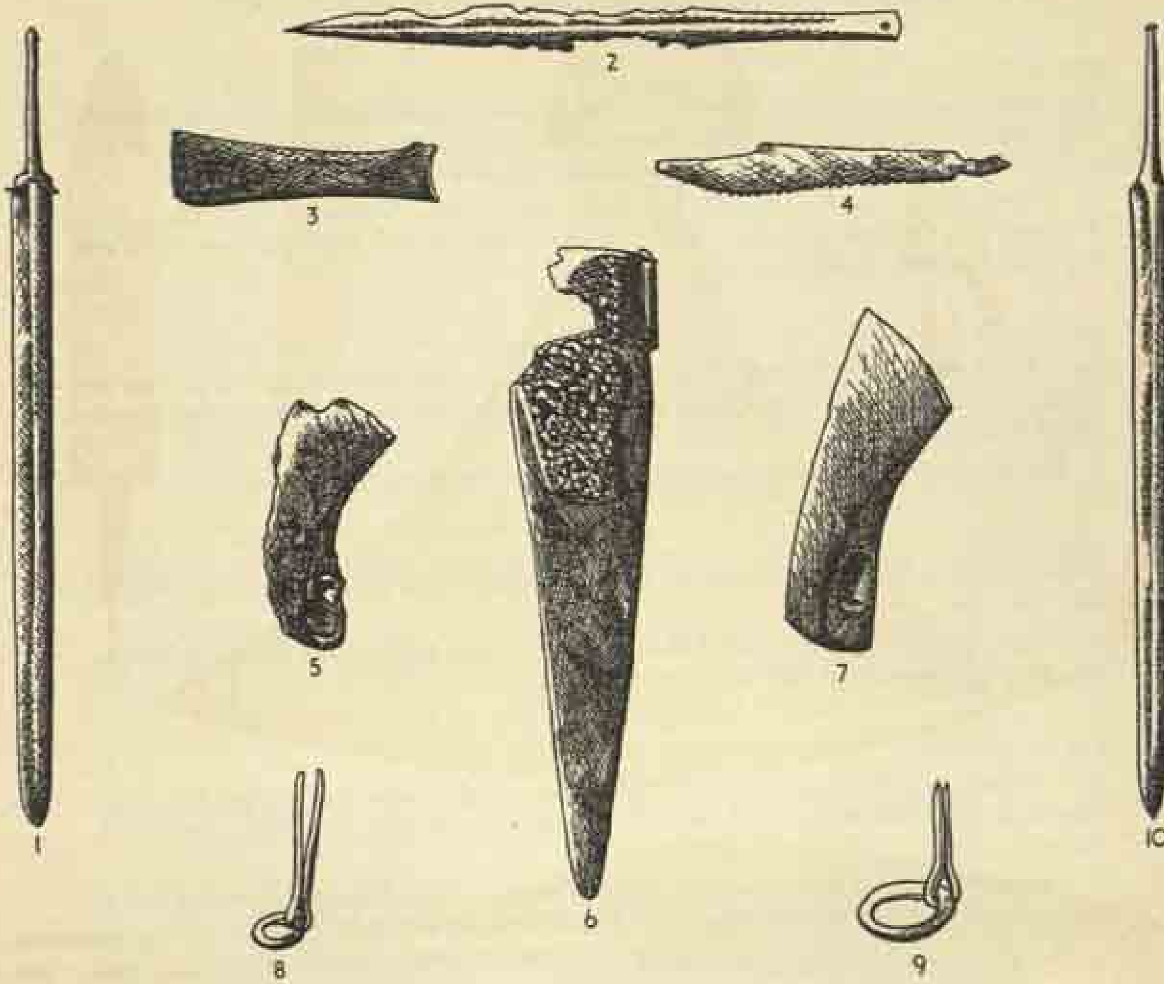


IRON OBJECTS ANALYSED FOR THE PITT RIVERS MUSEUM

FIG. 56. 1. Jugoslavia, Vače, spear-head, 5th century B.C. 2. Mediaeval arrow-head, Woodeaton, Oxon. 3. Danish battle-axe, 895 or 896 A.D., bed of River Lea near Stratford, Essex. 4. Tanged knife, Roman villa, Frilford, Berks., 3rd–4th century A.D. 5. Tanged Roman knife, Oxyrhynchus, Egypt. 6. Syria, Deve Hüyük, spear-head, 600–500 B.C.



IRON OBJECTS ANALYSED FOR THE PITT RIVERS MUSEUM

Fig. 57. 1 and 10. Two swords from La Tène, *c.* 50 B.C. (87 and 90 cm.). 2. Hallstatt, Austria, lance-head, 6th century B.C. (44 cm.). 3. Magdalenenberg, Jugoslavia, socketed axe, 6th century B.C. (20 cm.). 4. Roman saw, Oxyrhynchus, Egypt (12 cm.). 5. Saxon axe, Reading (13·5 cm.). 6. Pick, Lachish, from area destroyed *c.* 588 B.C. (24 cm.). 7. Roman axe, Silchester, Hants, 4th century A.D. (18 cm.). 8, 9. Roman tweezers and staple, Harageh, Egypt (9 cm. and 7·5 cm.).

EXPLANATION OF THE PLATES

PLATE I

1. Photomicrographs of the surface of a sword (France-Lanord 1949). ×40. *a*, *c*. Zones of carburized iron (mild steel) in ferrite. *b*. Large crystals of ferrite surrounded by carburized iron. *d*. Two zones of low-carbon (mild) steel and a zone of uncarburized (pure) iron.

2. Two pieces of iron from tripods, late eighth century B.C., Nimrud, Assyria (1953.6.1). Examination of a section shows a piled structure indicating that the tripod iron was made from piled wrought material.

PLATE II

Socketed spear-head from Deve Hüyük, Syria, 600–500 B.C. (1953.1.32): 1. Radiograph taken before sectioning, showing light areas still metallic, and dark patchy areas (metal converted to oxide).

2. Photomacrograph of polished and etched section showing layered structure.

PLATE III

Deve Hüyük spear-head, continued: 1. Photomacrograph at mid length showing contorted piled structure. ×4.

2. Photomicrograph at mid length showing contorted piled structure and variable grain size. The layering is associated with high-carbon bands. ×25.

PLATE IV

Deve Hüyük spear-head, continued: 1. Photomicrograph from same field as Plate III, Fig. 2 taken at a higher magnification, showing mixed grain size, banding, and high-carbon layers. ×200.

2. Photomacrograph of transverse cross-section of socket at fractured position showing layered structure and copper filaments adjacent to butt brazed joint. *c*. ×4.

3. Photomicrograph of spear-head showing fine pearlitic carbide structure. ×1000.

PLATE V

1. Photomicrograph of iron pick from Lachish (area destroyed *c*. 588 B.C.), close to point, showing entrapped slag at welding line and coarse Widmanstätten areas typical of material quenched from a very high temperature. ×100. (Specimen lent by Miss Olga Tufnell.)

2. Photomicrograph of axe-edge, Hallstatt period, sixth century B.C., from Magdalenenberg, Jugoslavia: rather high-carbon wrought iron with numerous entrapped slag filaments. No sign of hardening. ×200. (This specimen and the following sent by Naturhistorisches Museum, Vienna.)

3. Photomicrograph, lance-head, Hallstatt, sixth century B.C., showing blade of pure wrought iron with numerous entrapped slag filaments. No sign of hardening. ×200.

PLATE VI

Spear-head from Vače, Jugoslavia, fifth century B.C. (1953.1.33): 1. Photomacrograph of polished and etched section showing high-carbon (dark area) portion welded to low-carbon material. Severe burning of the high-carbon area has occurred during heating for welding and forging. ×1·6.

2. Enlarged photomacrograph of Fig. 1 showing central weld line, variable grain size, and local burning in (dark) high-carbon areas. ×4.

3. Photomicrograph towards centre of spear-head showing junction zone between low-carbon area and (dark) high-carbon area. Vickers hardness 103 to 134. ×60.

PLATE VII

Vače spear-head, continued: 1. Photomicrograph towards centre of spear-head showing fine ferrite grain size and (dark carbide) pearlitic areas. ×185.

2. Photomicrograph near to point showing low-carbon wrought iron, with a very coarse grain size and slag patches not expelled during forging. ×185.

3. High-power view of central portion of spear-point in relatively high-carbon area showing ferritic grain size with dark pearlitic carbide areas, indicating that spear-head was slowly cooled after forging. ×1,000.

PLATE VIII

La Tène sword, *c.* 50 B.C., Switzerland (Historisches Museum, Basel, 1947.639): 1. Coarse ferritic grain size adjacent to central rib of blade. ×200.

2. Blade at central rib showing large ferrite grains with numerous Neumann bands. ×200.

3. Structure close to edge of blade where grain size is fine and ferrite grains show pronounced veining. ×200.

PLATE IX

La Tène sword, *c.* 50 B.C., Switzerland (Historisches Museum, Basel, 1947.640):

1. Photomacrograph showing piled structure and corrosion pits. ×7.

2. Photomicrograph from central rib. ×200.

PLATE X

La Tène sword (1947.640) continued: Photomicrograph from cutting-edge. ×200.

PLATE XI

Tanged knife from Oxyrhynchus, Egypt, Roman period (Pitt Rivers Museum): 1. Photomacrograph (slightly enlarged) of polished and etched longitudinal section, showing contorted layered structure, indicating blade has been built up by welding and forging a number of wrought-iron faggots.

2. Photomacrograph of portion of blade showing layered structure and entrapped slag filaments. ×12.

3. Photomicrograph of body of blade showing ferrite grains containing numerous Neumann bands, indicating that the blade was hammered cold after forging. The structure shows numerous particles of entrapped slag. ×200.

PLATE XII

1. Roman saw, Oxyrhynchus, Egypt (Pitt Rivers Museum): Photomicrograph close to teeth showing structure typical of a low-carbon steel which has been hot worked on a falling temperature. ×200.

2. Roman ring and tweezers, Harageh, Egypt (Newbury, Borough Museum): Photomicrograph at end of blades. This structure is typical of a carburized wrought iron which has been hot worked on a falling temperature, followed by annealing at a low temperature where carbides have become agglomerated. ×200.

3. Roman ring and staple, Harageh (Newbury, Borough Museum): Photomicrograph of staple end showing piled structure with numerous entrapped slag filaments. The background structure is typical of a 0·25 per cent. carbon steel which has been hot worked on a falling temperature, resulting in a very mixed grain size. ×200.

4. Area similar to Fig. 3, enlarged. ×1,000.

PLATE XIII

1. Frilford, Berkshire, Roman knife, third to fourth century A.D. (1953.1.34): Print from X-ray negative. Close examination of this negative shows a fibrous structure typical of wrought iron. The only solid metallic portion is at the junction of the tanged end of the beginning of the blade.

2. The same: Transverse cross-section from end of tanged knife, showing piled wrought structure. Only small portions of the wrought material remain. The bulk of the blade has been converted to iron hydroxide. *c.* ×8.

3. The same: Photomicrograph of uncorroded portion showing coarse ferritic grain size typical of low-carbon wrought iron. ×400.

4. Roman axe, fourth century A.D., Silchester, Hampshire (Reading Museum and Art Gallery): Photomacrograph up to the edge showing piling and highly contorted flow lines roughly parallel to the edge (top). Lower right-hand side shows a heavy layer of hard rust and corrosion pits. *c.* ×10.

PLATE XIV

Roman axe, Silchester, continued: 1. Photomicrograph of light areas in Plate XIII, Fig. 4, showing elongated slag filaments in low-carbon bands at welding lines. ×200.

2. Photomicrograph of dark high-carbon areas shown in Plate XIII, Fig. 4. ×200.

3. Photomicrograph of similar areas to Fig. 2 showing ferritic background with partially spheroidized network carbides. ×1,000.

4. Saxon axe-edge (Reading Museum and Art Gallery). Photomicrograph close to edge showing large ferritic grain size and numerous Neumann bands indicating the edge was hammered cold. ×120.

PLATE XV

Danish battle-axe, A.D. 895 or 896, bed of River Lea near Stratford, Essex (1954.11.11): 1. Photomacrograph up to cutting-edge showing carburized zone on the immediate edge, and flow pattern due to forging. Background structure is of wrought low-carbon iron. ×4·5.

2. Photomicrograph of cutting-edge showing coarse martensitic structure. Vickers hardness 450. Dark areas non-metallic entrapped cinder not expelled during the piling and forging operation. ×250.

3. Higher-power view of Fig. 2 showing coarse martensitic structure of cutting-edge. Vickers hardness 450. ×1,000.

4. Background of blade, showing structure of wrought low-carbon iron and entrapped cinder. Vickers hardness 160 to 170. ×200.

PLATE XVI

1. Mediaeval barbed and socketed arrow-head, Woodeaton, Oxon. (1953.1.35): Print from X-ray negative. Light areas show corrosion pits and slag streaks.

2. Longitudinal cross-section polished and etched, showing heavily corroded areas and fibrous slag streaks. Socket portion has been formed from thin wrought-iron sheet wrapped round a pointed former. Wings and point of the arrow-head have been imperfectly forge welded on to the socket. ×2.

3. Enlarged view of socket, showing marked banding, cinder filaments, and mixed grain size. ×18.

4. Photomicrograph of portion of wings of the arrow-head, showing typical wrought-iron structure with ferritic grains and cinder filaments. The arrow-head is in the as-forged condition and no attempt has been made to harden it. Vickers hardness 115 to 153. ×200.

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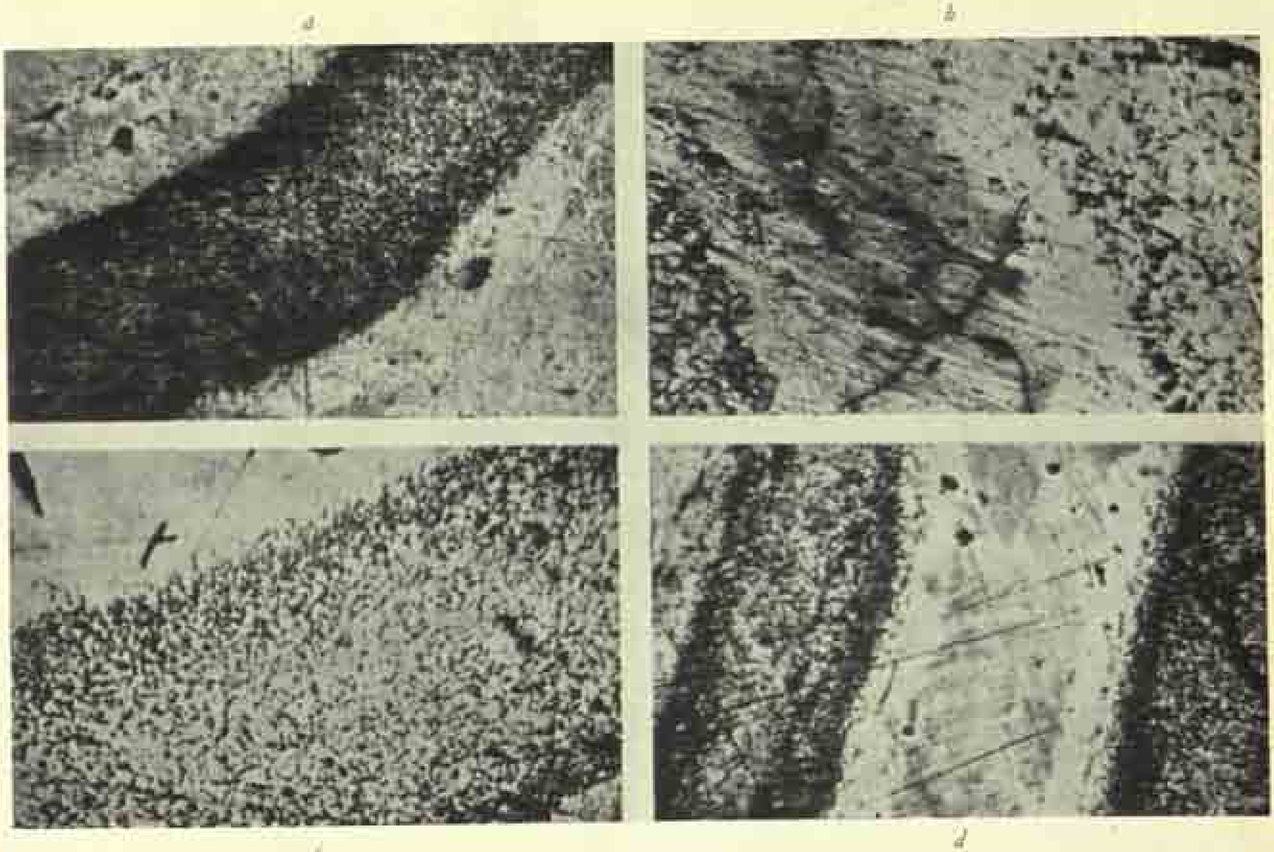
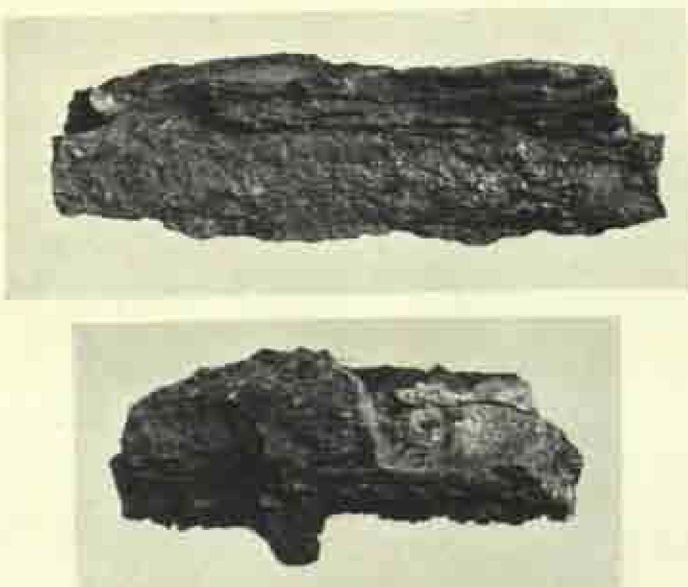


1. Photomicrographs of the surface of a sword (France-Lanord 1949)



2. Pieces of iron tripods, Nimrud, 8th century B.C.

See p. 202

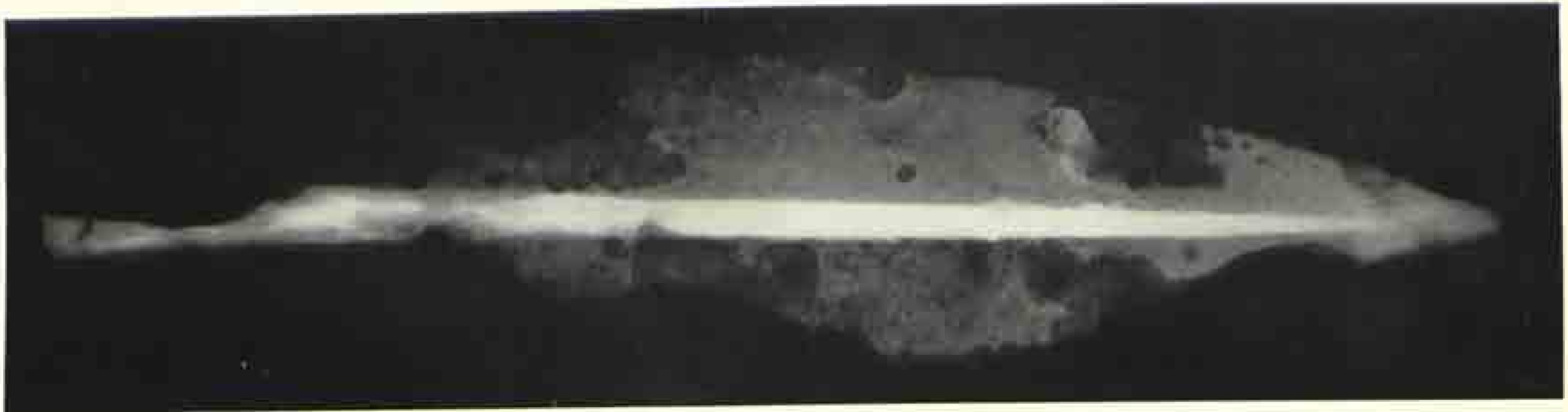


FIG. 1. Radiograph of Deve Hüyük Spear-head taken before sectioning, showing light areas still metallic, and dark patchy areas (metal converted to oxide)

FIG. 2. Photomacrograph of polished and etched section of above showing layered structure

See p. 202

FIG. 1. Photomacrograph of Deve Hüyük Spear-head showing contorted piled structure. $\times 4$

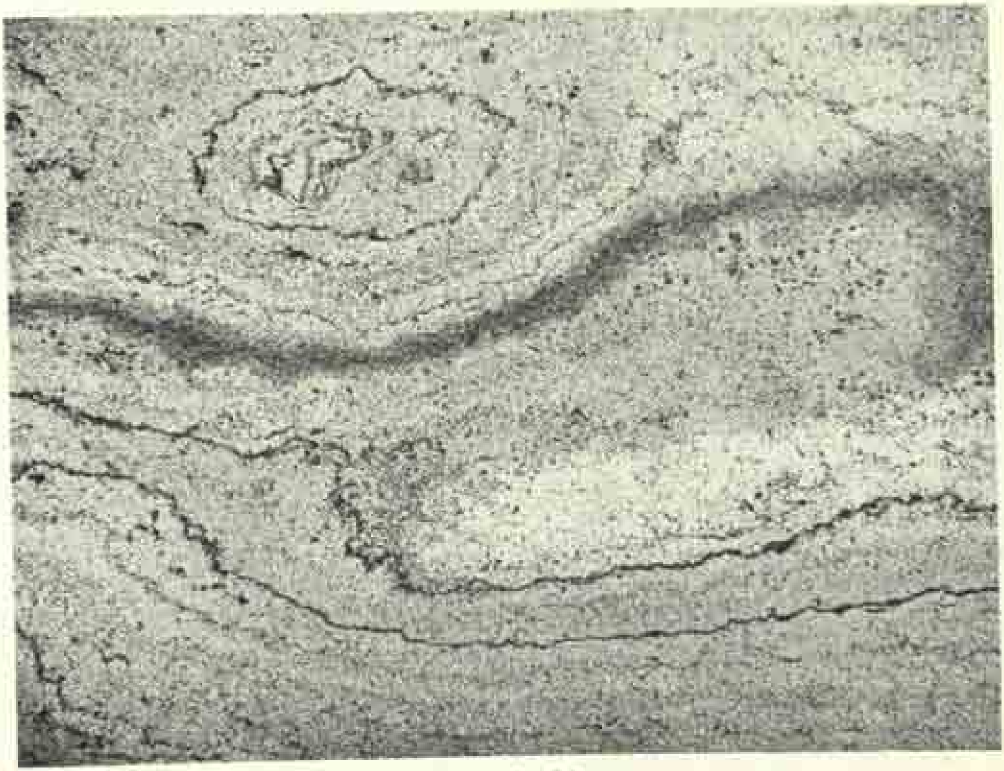


FIG. 2. Photomicrograph of the same. $\times 25$

See p. 203

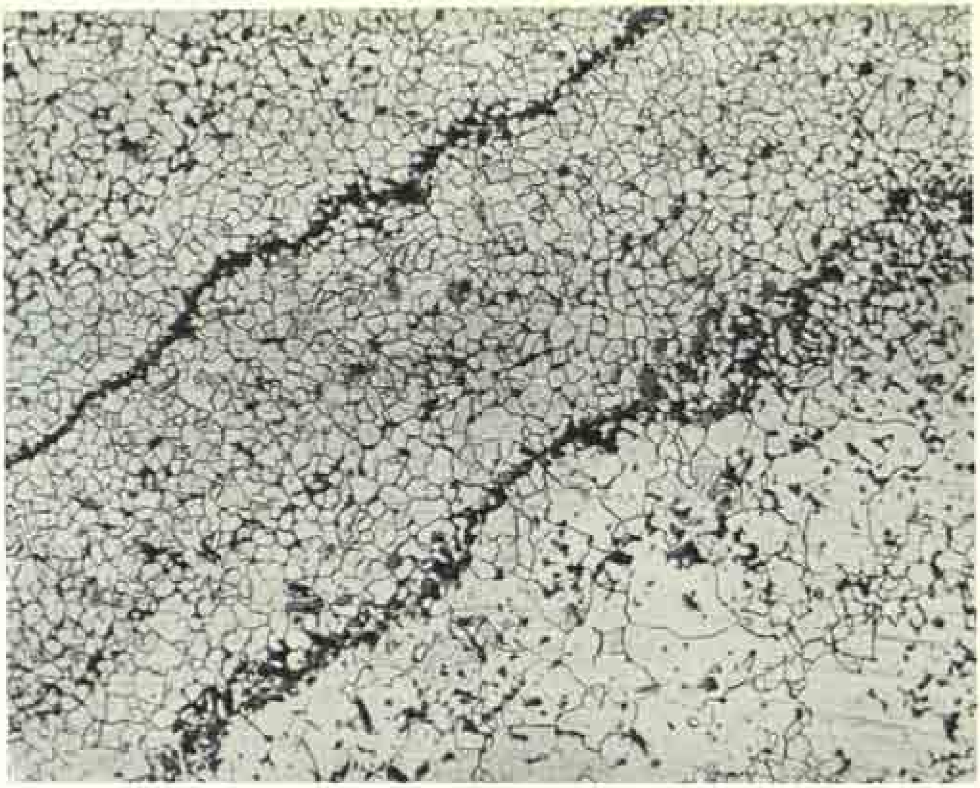


FIG. 1. Photomicrograph from same field as Plate III, Fig. 2. ×200

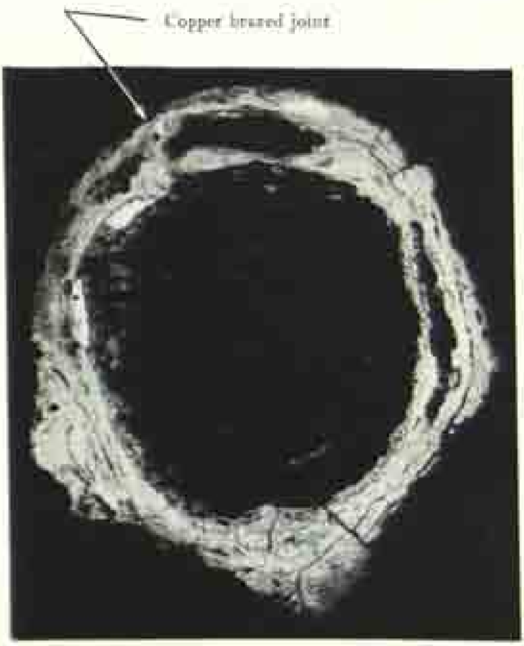


FIG. 2. Photomacrograph of cross-section of socket. *ca.* ×4

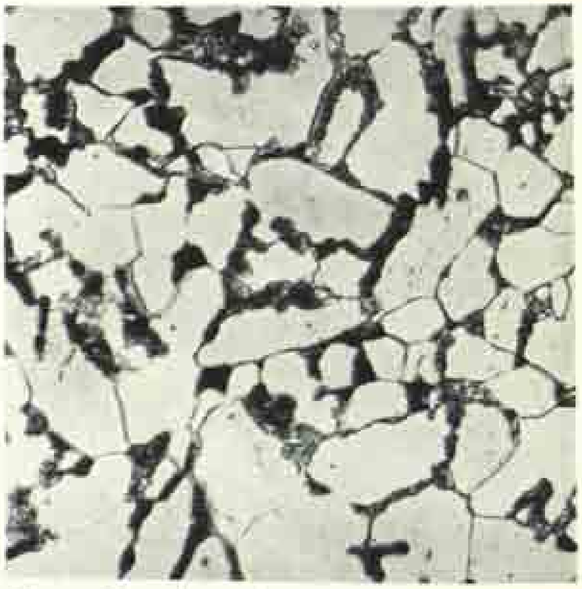


FIG. 3. Photomicrograph showing fine pearlitic carbide structure. ×1000

DEVE HÜYÜK SPEAR-HEAD

See p. 202

FIG. 1. Photomicrograph near point of Lachish pick showing Widmanstätten areas. × 100

FIG. 2. Photomicrograph, axe-edge, Magdalenenberg. × 200

See p. 202

FIG. 3. Photomicrograph, lance-head, Hallstatt. × 200

PLATE VI

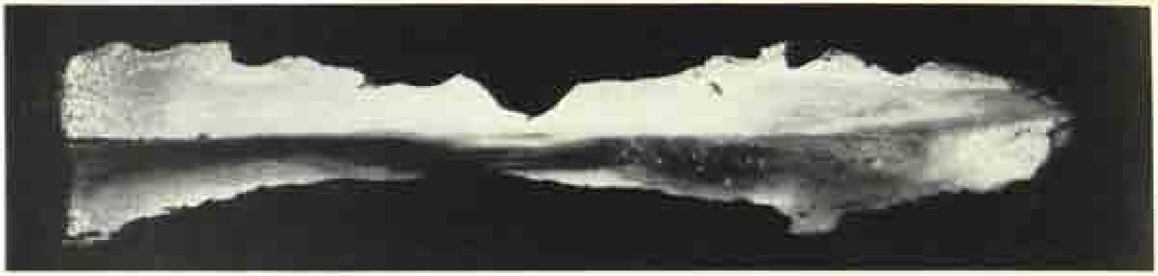


FIG. 1. Photomacrograph. ×1·6

FIG. 2. Photomacrograph. ×4

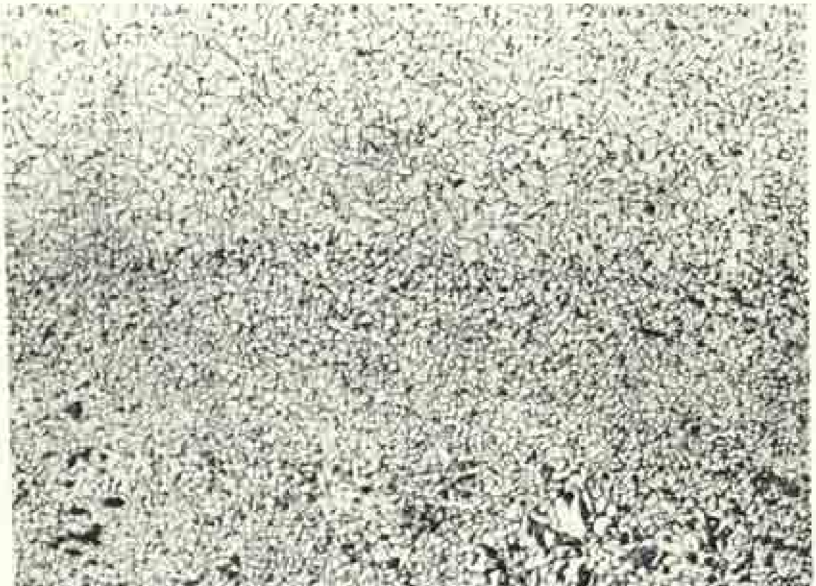


FIG. 3. Photomicrograph near centre. ×60

VAČE SPEAR-HEAD

See p. 203

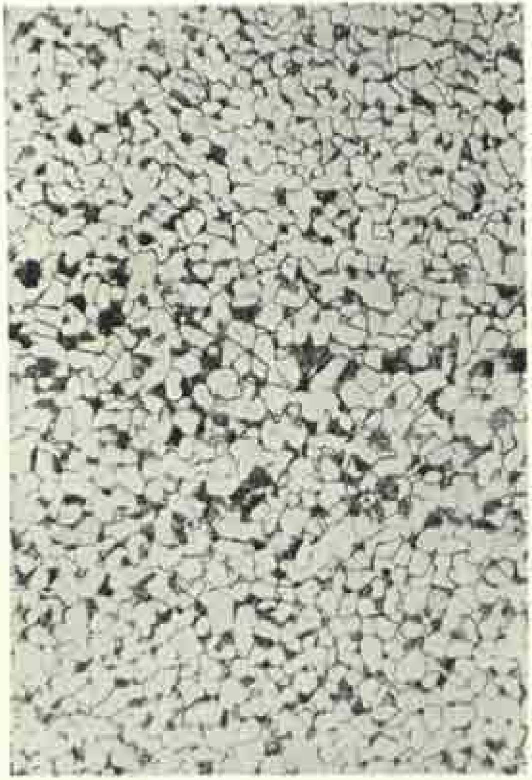


FIG. 1. Photomicrograph towards centre. ×185

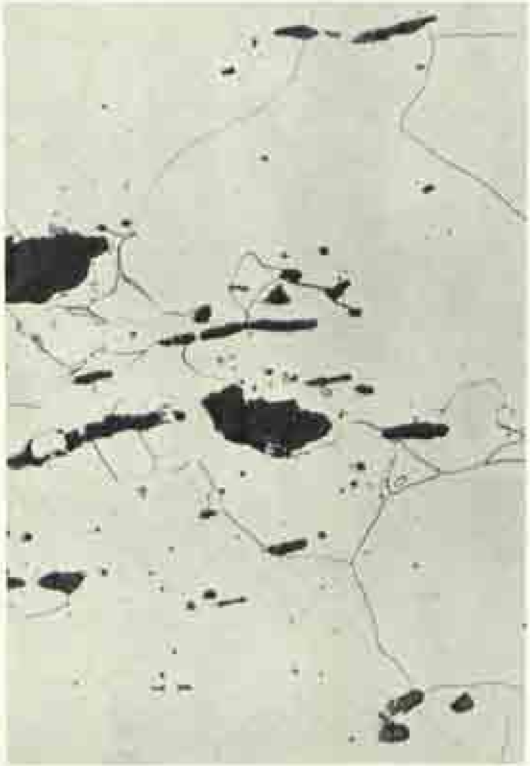


FIG. 2. Photomicrograph near point. ×185

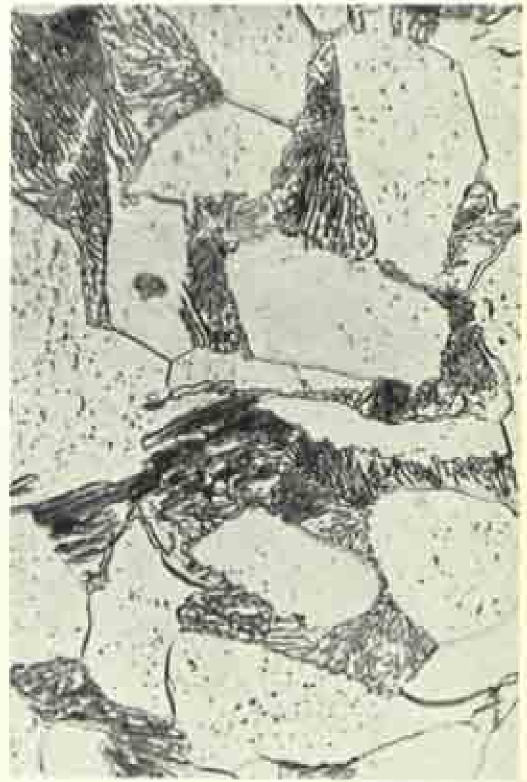


FIG. 3. Photomicrograph of central portion of point. ×1000

VAČE SPEAR-HEAD

See p. 203

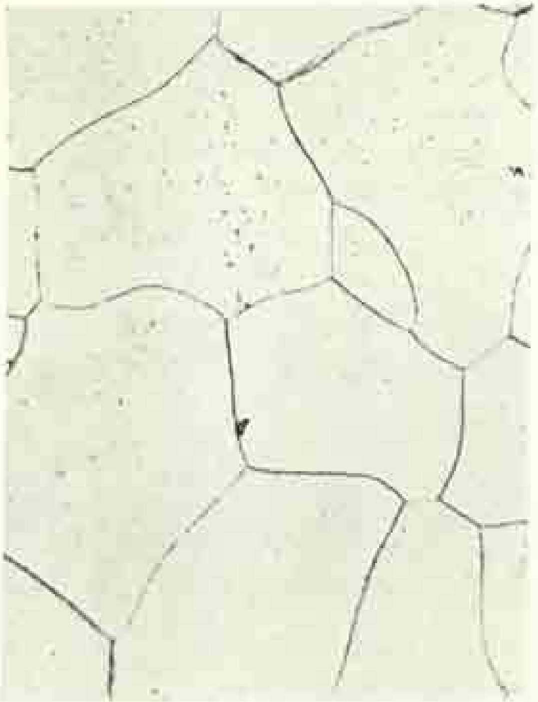


FIG. 1. Coarse ferritic grains near central rib. ×200

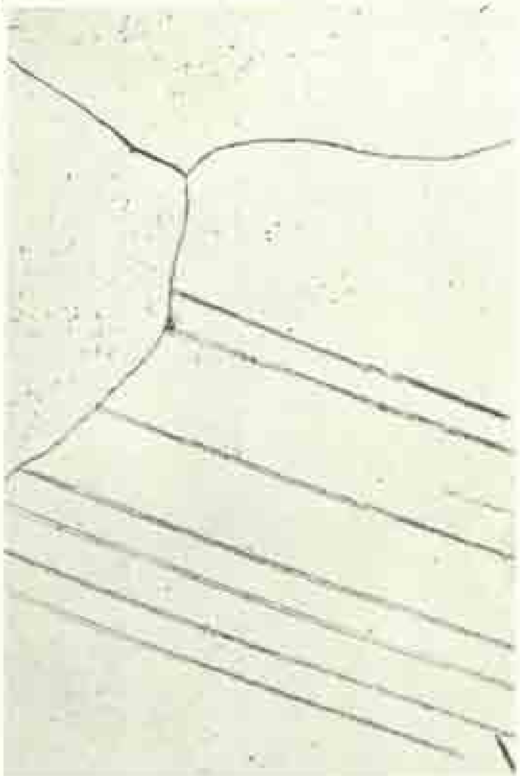


FIG. 2. Photomicrograph at central rib showing large ferrite grains and Neumann bands. ×200

FIG. 3. Structure near edge of blade where grain size is fine and ferrite grains show pronounced veining. ×200

LA TÈNE SWORD (1947.639)

See p. 203

FIG. 1. Photomacrograph showing piled structure and corrosion pits. ×7

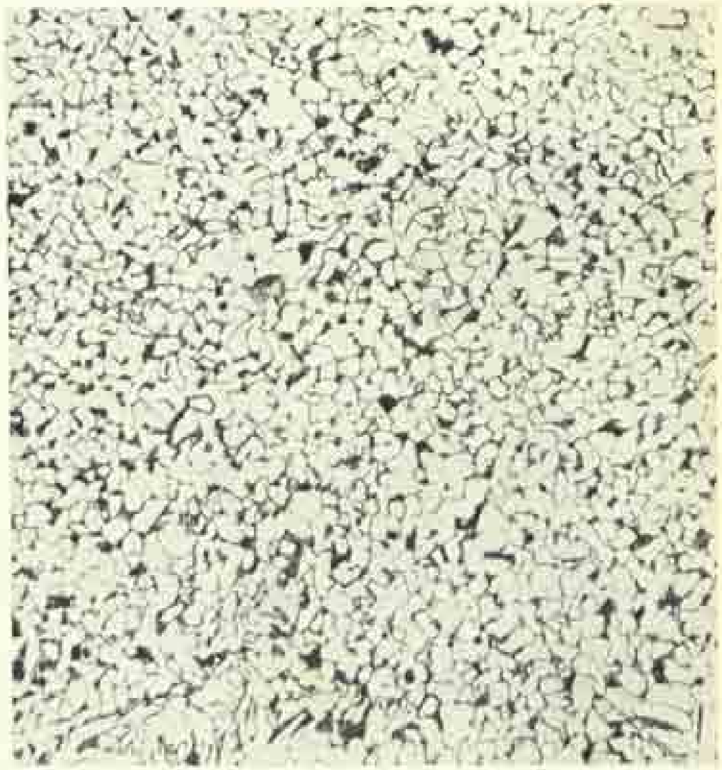
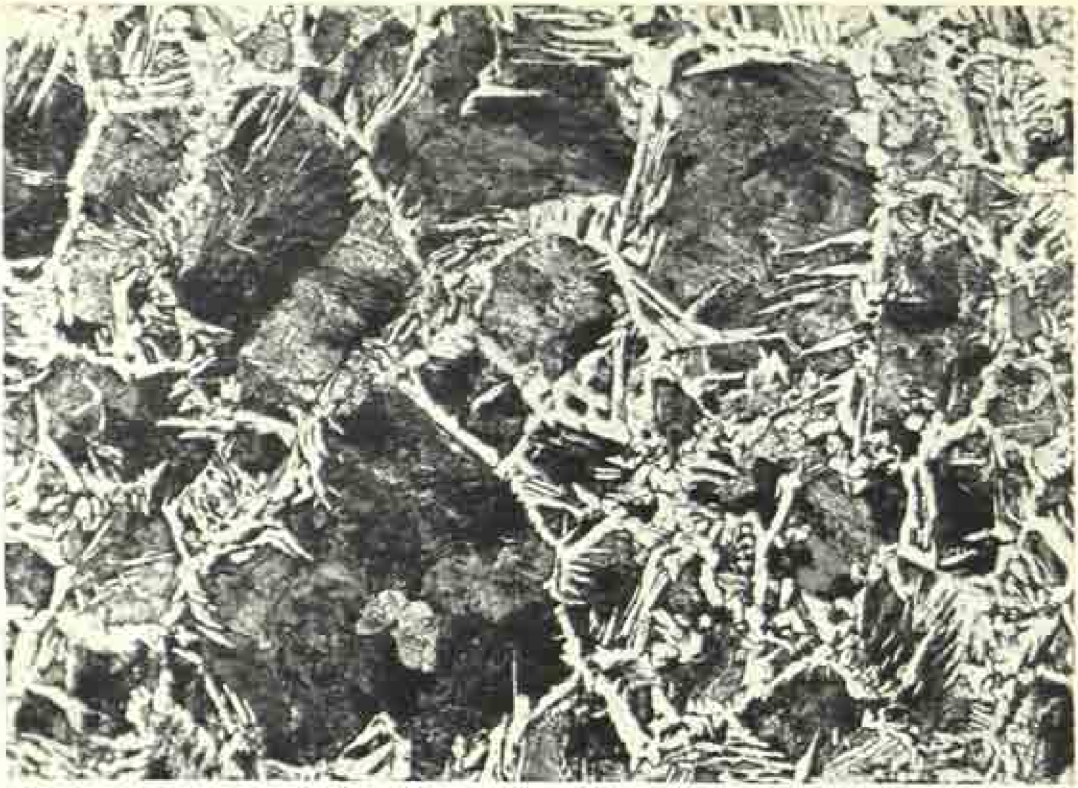


FIG. 2. Photomicrograph of central rib. ×200

LA TÈNE SWORD (1947.640)

See p. 203



Photomicrograph from cutting-edge. × 200

LA TÈNE SWORD (1947.640)

See p. 203

FIG. 1. Photomacrograph of Oxyrhynchus knife, slightly enlarged

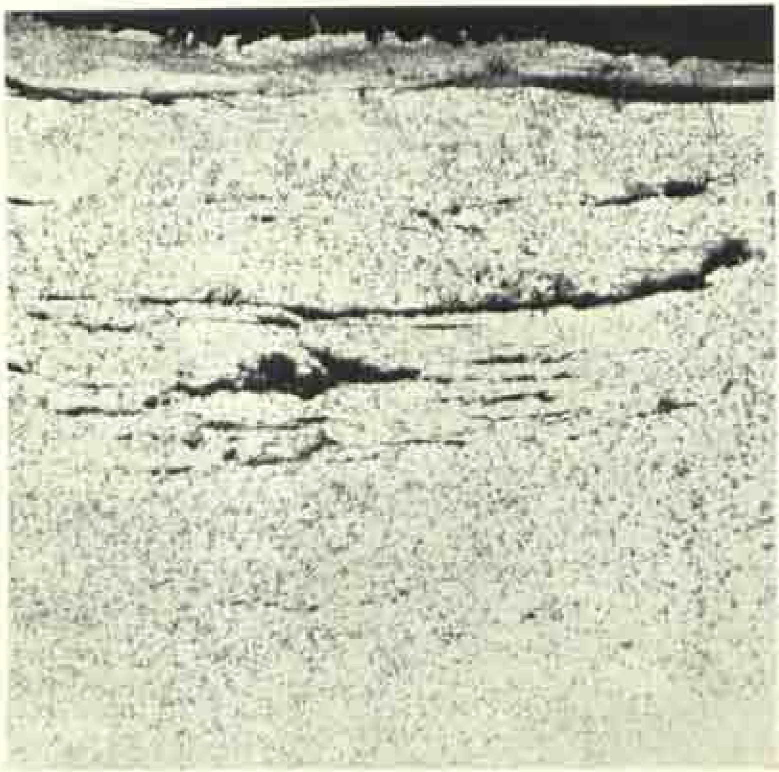


FIG. 2. Photomacrograph of part of blade showing layered structure. ×12

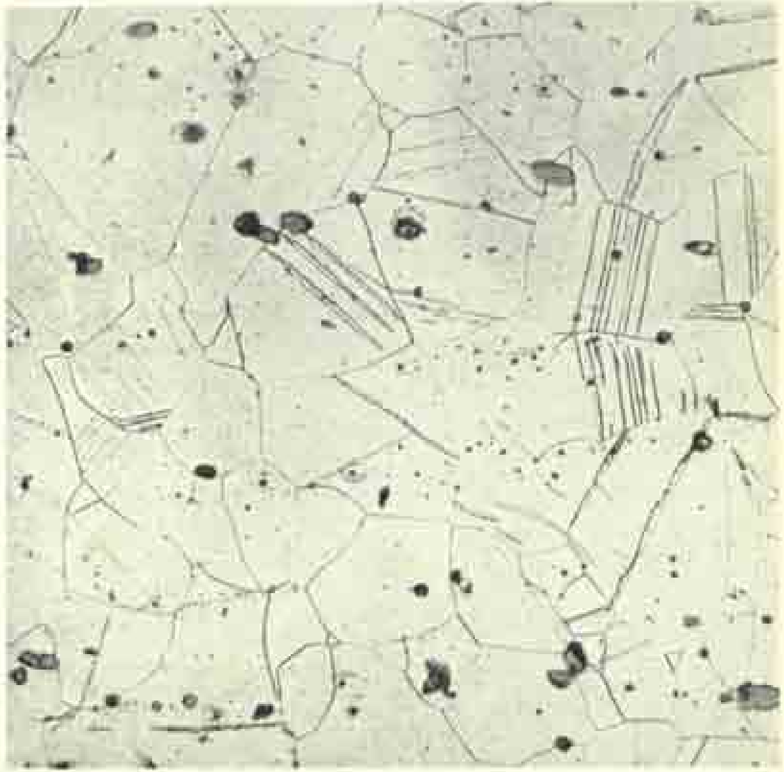


FIG. 3. Photomicrograph showing ferrite grains containing Neumann bands. ×200

See p. 203

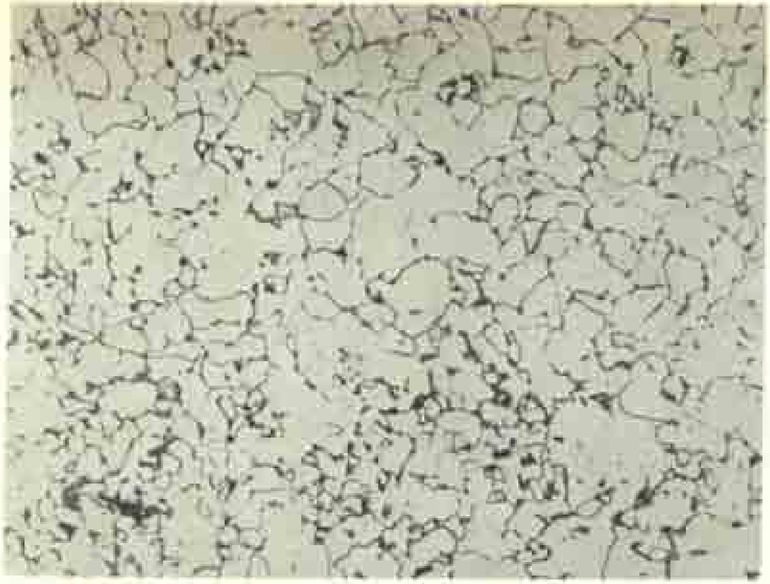


Fig. 1. Roman saw, Oxyrhynchus. ×200

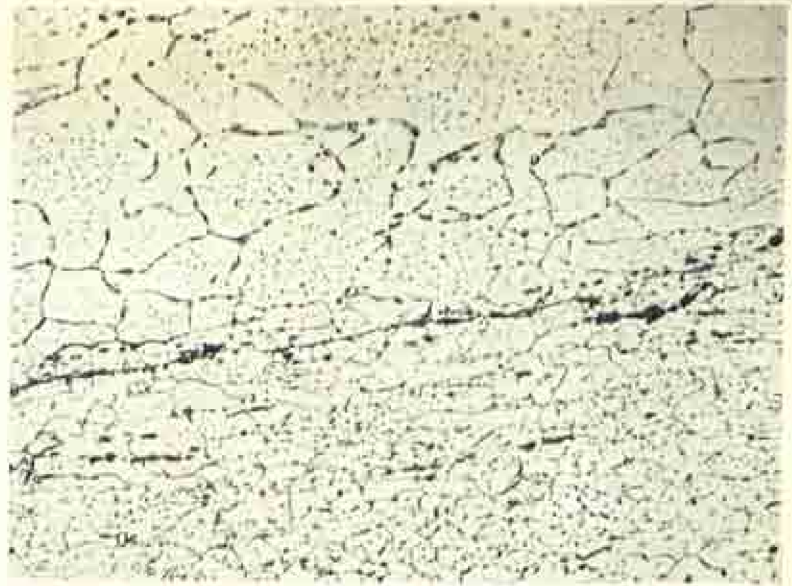


Fig. 2. Roman tweezers, Egypt. ×200

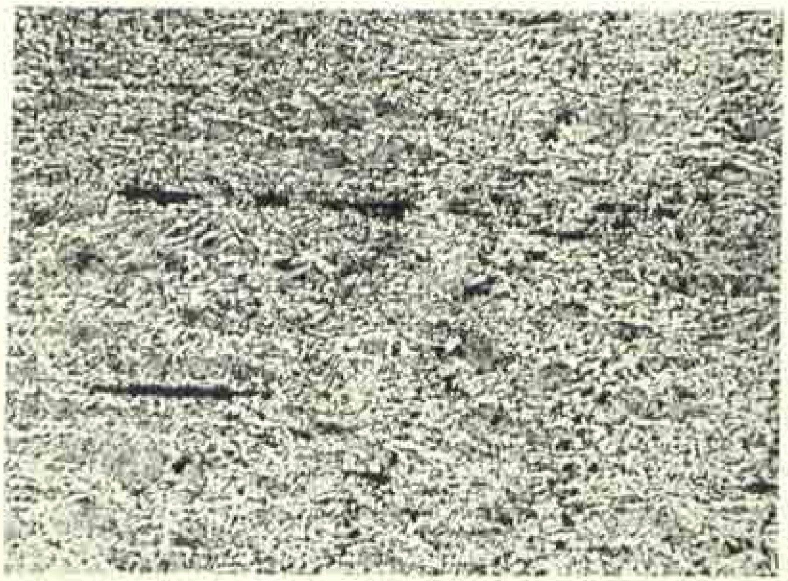


Fig. 3. Roman staple-end, Egypt. ×200

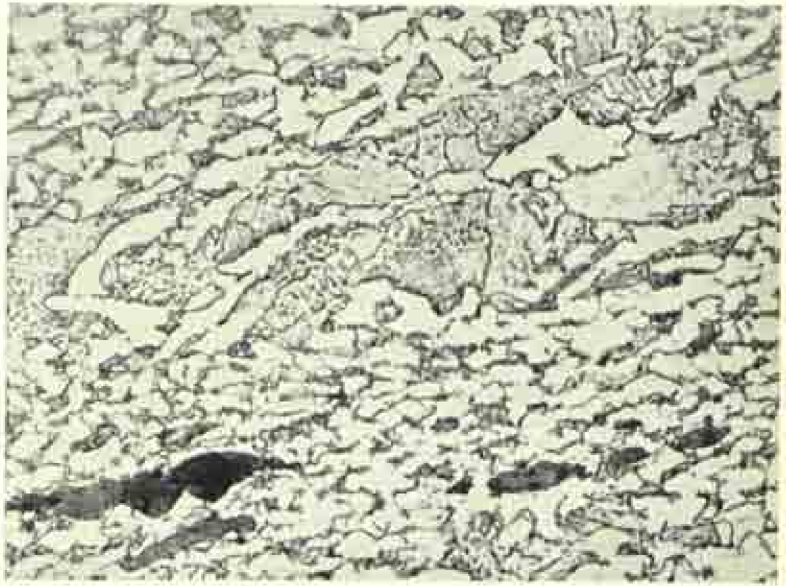
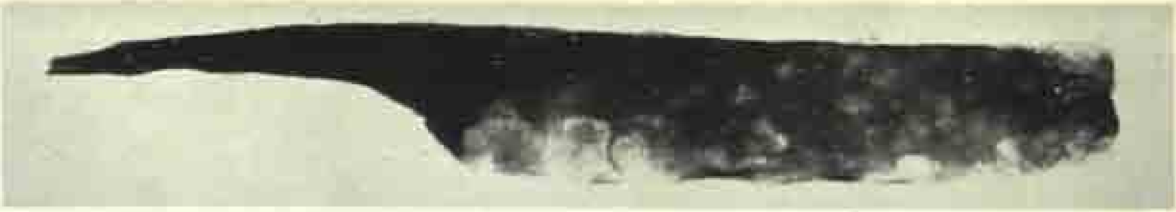
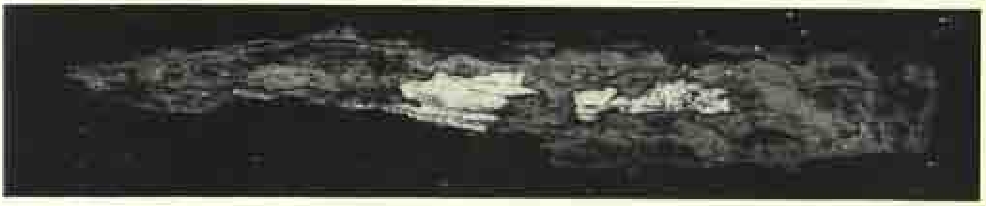


Fig. 4. As Fig. 3. ×1000





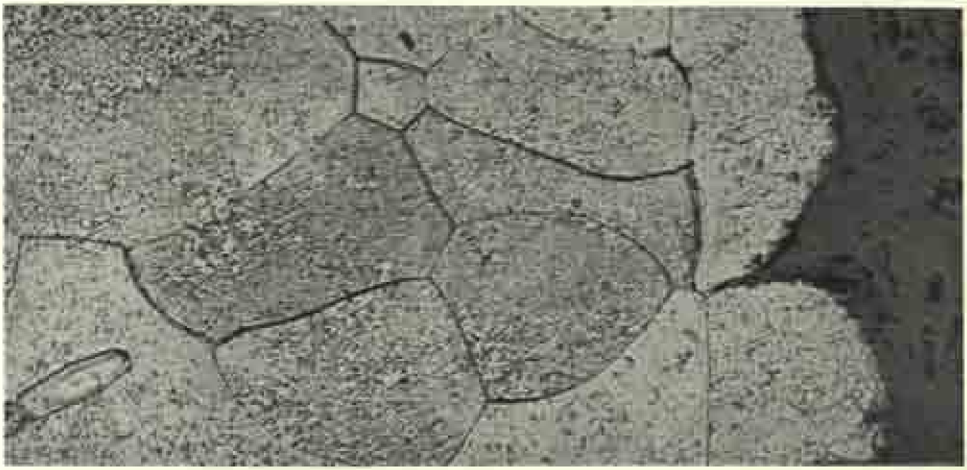


FIG. 1. X-ray, Roman knife, Frilford

FIG. 2. Cross-section from end of Frilford knife. *ca.* ×8

FIG. 3. Photomicrograph of Frilford knife. ×400

FIG. 4. Photomacrograph, Roman axe-edge, Silchester. *ca.* ×10

See p. 204

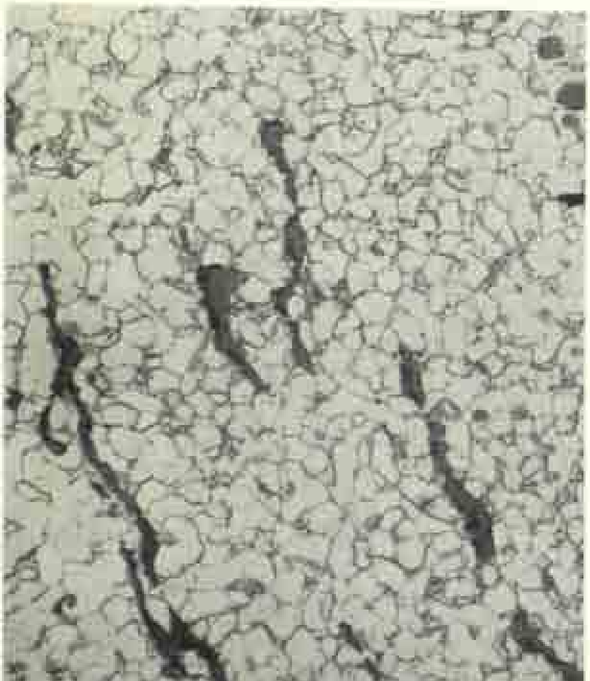


FIG. 1. Roman axe, Silchester. ×200

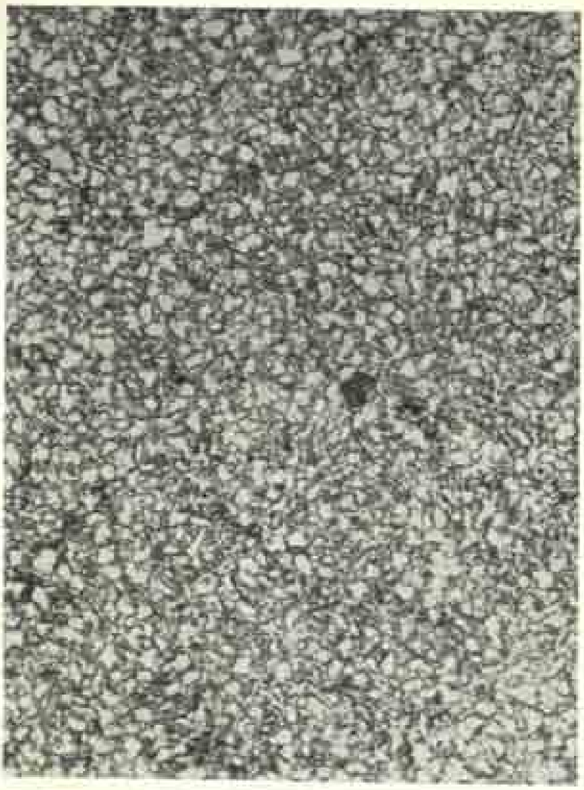


FIG. 2. Roman axe, Silchester. ×200

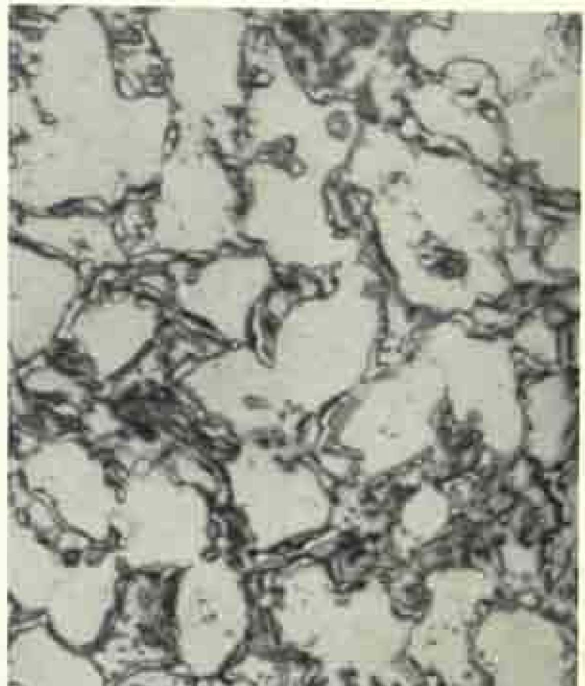


FIG. 3. Roman axe, Silchester. ×1000

FIG. 4. Saxon axe-edge. ×120

Fig. 1. Photomacrograph of Danish battle-axe, cutting-edge. ×4·5

Fig. 2. Photomicrograph of same, cutting-edge. ×250

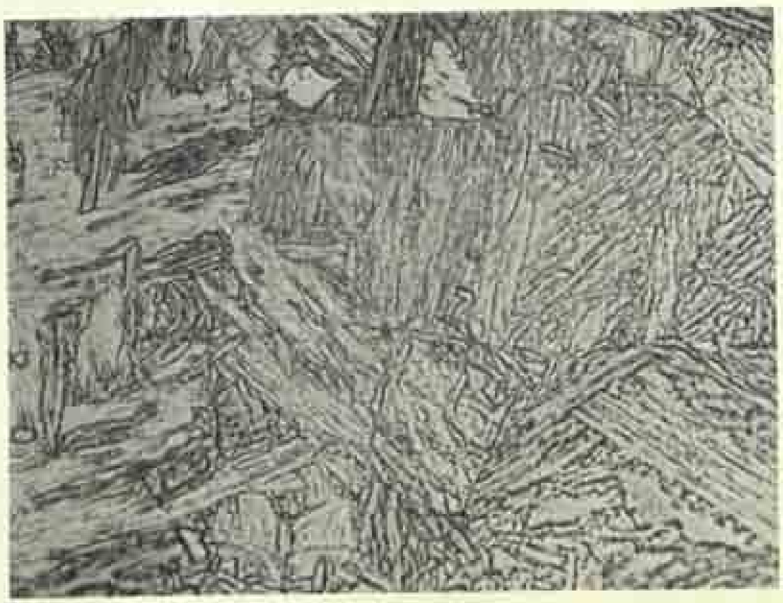


Fig. 3. As Fig. 2. ×1000

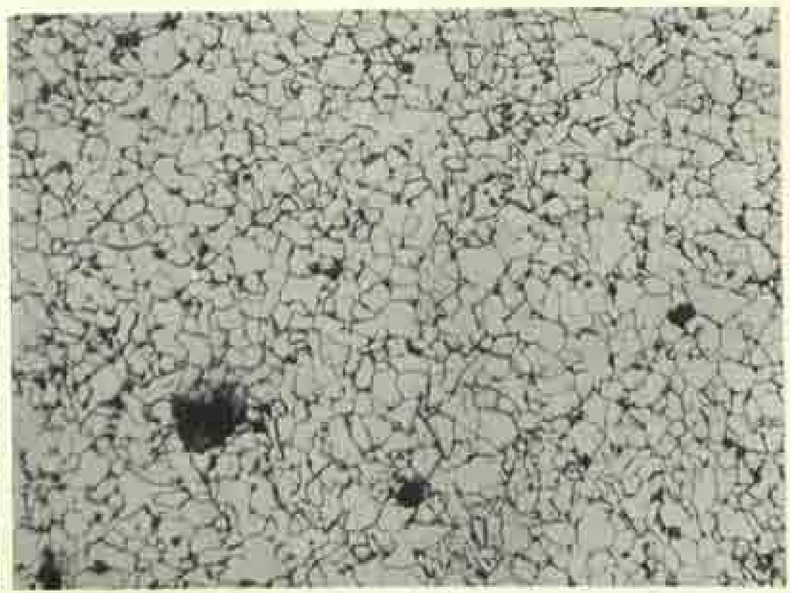


Fig. 4. Background of blade. ×200

See pp. 204–5

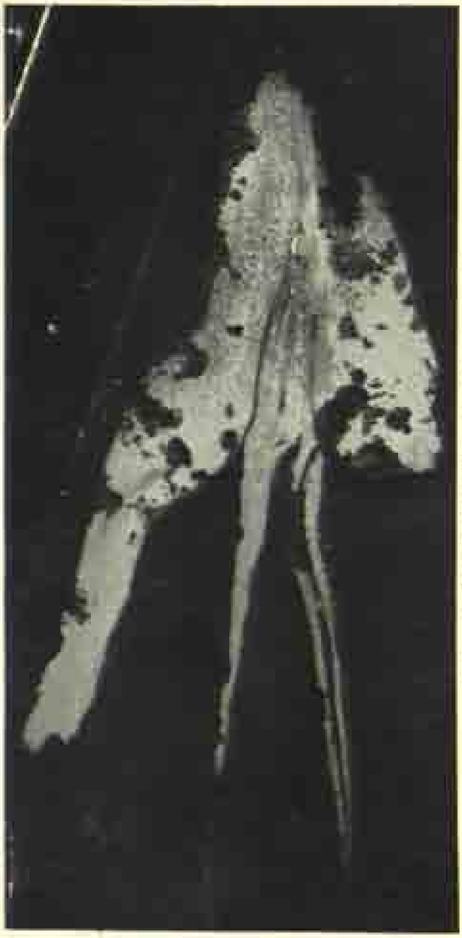


FIG. 2. Longitudinal cross-section. ×2

FIG. 1. X-ray