Ironmaking in a Roman Furnace*

By HENRY CLEERE

The paper describes experiments in ironmaking using a facsimile of second/third-century furnaces from the Weald. Iron was produced, along with other types of waste material (slag, burnt clay, etc.), similar to that found on archaeological sites. Indications were obtained about yields, process times, and manning requirements, which will help in the interpretation of excavation results.

IN the past few decades, the spread of the knowledge of ironmaking technology from its origins in the Near East throughout the Old World has been the subject of considerable study. Archaeologists and metallurgists have collaborated in the investigation of technological material, notably furnace remains, slags, and iron artefacts. Slowly a coherent picture is beginning to emerge, but many questions remain unanswered.

One of the most important fields of research is that of the practical operation of early smelting furnaces, known as 'bloomeries'. Iron artefacts of the prehistoric, Roman, and early medieval periods reveal, on metallographic examination, structures often difficult to interpret in terms of their production processes. The excavated remains of smelting furnaces are usually fragmentary and the relation-

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ships between these and their raw materials on the one hand and metal artefacts on the other are not always easy to establish. The archaeologist is faced with another problem, less technological but just as important in terms of his research. Many early smelting sites have enormous slag banks, accumulated over long periods. These can be related from dated finds such as coins and pottery directly to the period of occupation of the site, but it is necessary to have some idea of process time and yield in order to be able to assess the man-hours that the slag heaps represent. Complete excavation of extensive sites is rarely practicable, and so the man-hour content of the slag heaps can give valuable information about the population of the associated settlement.

For the early periods there are no written records available. Some indication of the technology involved can be obtained from modern pre-industrial societies; the comprehensive review by Tylecote[1] is of enormous value in this connection. However, furnace types and raw materials vary greatly, and it has proved necessary for those studying the early technology of ironmaking to carry out their own experiments, using facsimiles of specific types of early furnace and raw materials approximating to those used in antiquity, in order to gain first-hand data. Experiments of this kind have been carried out in Austria,[2] Czechoslovakia,[3] Denmark,[4] Germany[5] and Poland.[6] In addition, important laboratory investigations are being carried out by Tylecote and co-workers in Britain.[7]

The present investigation was carried out to study the ironmaking technology in the Weald of Kent and Sussex during the first half of the Roman occupation of Britain (first to third centuries A.D.). The Wealden industry was a large-scale operation, perhaps second only to that of Noricum (modern Steiermark, Austria) during the Roman period. There is a strong presumption that it was at least partly a state enterprise, operated by the British Fleet (*classis Britannica*),[8] and as such it is at present the object of co-operative study by members of the Wealden Iron Research Group, of which the author is Joint Convener.

THEORY

The earliest ironmaking technology made use of the *direct process*, i.e. iron was reduced directly from the ore, without passing through an iron–carbon alloy stage, followed by refining, as in the modern blast-furnace process. It was a relatively low-temperature process, the metal never attaining its melting point but collecting as a sponge of metal at the bottom of the furnace. The basic problem was that of separating the stony part of the ore (the gangue) from the reduced

[1] R. F. Tylecote: *Journ. Iron and Steel Institute*, **203** (1965), 340–8.

[2] H. Straube, B. Tarmann, and E. Plöckinger: *Erzreduktionsversuche in Rennöfen Norischer Bauart* (Kärntner Museumsschriften xxxv), 1964, Klagenfurt.

[3] R. Peiner: *Památky archaeologické,* lx (1969), 458–87.

[4] R. Thomsen: *Kuml*, 1963, 60–74, and private communication.

[5] J. W. Gilles: *Unser Werk*, 1957, 12; *Stahl Eisen*, **12** (1958), 1690–5; *ibid.*, **14** (1960), 943–8.

[6] E.g. A. Mazur and E. Nosek: *Materialow Archaeologicznych*, **7**, 19–38.

[7] E. J. Wynne and R. F. Tylecote: *Journ. Iron and Steel Institute*, **190** (1958), 339–48; R. F. Tylecote, J. N. Austin and A. E. Wraith, *ibid*, **209** (1971), 342–63.

[8] H. F. Cleere: *Vita pro Ferro* (Festschrift für R. Durrer), Schaffhausen, 1965, 91–102; and Sussex Archaeological Society Occasional Paper No. 1 (1970).

metal; this was achieved by the formation of a slag, i.e. an artificial mineral with a relatively low melting point. The determining factor in the process was in fact not the reduction temperature nor the melting point of the metal, but rather the temperature at which a fluid slag could be obtained. In modern ironmaking practice the gangue (largely silica–SiO_2) is removed by the addition of limestone (CaO) as a flux. However, the use of fluxes is not attested until well into the Middle Ages (at least in Europe: the development of ironmaking technology in ancient China followed a completely different course). The gangue could only be separated from the ore by sacrificing a considerable amount of iron. The major constituent of all ancient bloomery slags[9] was fayalite ($2FeO.SiO_2$), the melting point of which is *c.* 1,215 °C.[10] The slags were not pure fayalite, and their actual melting points probably lay up to 50 °C. lower, depending upon the natural lime content of individual ores. However, it was axiomatic that temperatures in excess of 1,100 °C. should be obtained before a proper separation could be ensured between metal and slag.

The earliest type of furnace was probably a simple hollow in the ground, lined with clay and filled with ore and fuel: the so-called 'bowl-furnace'.[11] Blown with bellows, this would produce a quantity of small lumps of reduced metal in a matrix of slag. The metal would have to be separated by hand, as in modern Indian primitive practice[12] and worked up into a bloom of consolidated iron. The developed version of the bowl-furnace was the shaft-furnace[13] of which there are many design-variants in both the archaeological and the anthropological record. This had the important advantage of making provision for the removal of molten slag, either by running it out of the furnace, as in the Austrian and German furnaces[2,5] or by consolidating it below the hearth of the furnace, forming the *Schlackenklotze* of the Danish and Polish furnaces.[4,6] The shaft furnace consists of what its name implies, a simple hollow cylinder with an internal diameter of 9–18 in. and standing 4–6 ft. high. An aperture at the base was used for three purposes: inserting the bellows, running off the molten slag, and removing the spongy 'bloom' of iron. It was fed from the top with a mixture of iron ore and charcoal. Slag would have been tapped off once it began to form, either periodically or, as the present experiments suggest, continuously; and at the end of the process the sponge of metal would have been removed. This would then have been repeatedly heated and hammered, so as to remove entrapped slag and to consolidate the metal.

THE BACKGROUND TO THE EXPERIMENTS

The experiments were based on the industry of the Weald during the Roman period. Iron was being manufactured in this area before the Roman

[9] G. R. Morton and J. Wingrove: *Bull. Hist. Met. Group*, **3** (2) (1969), 55–61; *Journ. Iron and Steel Institute*, **207** (1969), 1556–64.
[10] B. G. Baldwin: *Journ. Iron and Steel Institute*, **177** (1954), 312–16.
[11] R. F. Tylecote: *Metallurgy in Archaeology*, London, 1962, 195–8: but see H. F. Cleere, *Antiq. Journ.* (in the press) for a discussion of the bowl furnace.
[12] H. F. Cleere: *British Steelmaker*, 1963, April, 154–8.
[13] R. F. Tylecote: *Metallurgy in Archaeology*, London, 1962, 220–4.

invasion of A.D. 43; Caesar refers to the industry in his *Gallic War*.[14] It was based on the carbonate ore of the Wadhurst Clay, a reducible material with an average iron content of 40 per cent. This very heavy clay also produced the other raw materials needed: it supported a mature forest-cover of hardwoods which produced excellent charcoal, and the clay itself was refractory enough for furnace construction.

The Roman industry began immediately after the invasion of 43 in the Hastings-Battle-Sedlescombe area. By the mid-second century the ore and fuel resources in this area were considerably depleted, and it would appear that the centre of the industry began to move to the High Weald, between East Grinstead and Wadhurst.[15] This survived until the mid-third century, when the deforestation and over-exploitation of the ores resulted in a virtual closure, apart from some small sites such as that at Withyham,[16] which survived until the end of the Roman period. Supremacy as the major ironmaking region would appear to have passed to the Forest of Dean, although this area has not been studied as thoroughly as the Weald.[17]

The organization of the Wealden industry is far from clear. There were certainly some very large establishments; at Beauport Park, Battle, for example, the slag heap is estimated to have contained some 50,000 tons of slag before being largely quarried away for road metalling in the nineteenth century. The hand of some central authority might be inferred from the scale of operations, and this is reinforced by the finding of tile fragments stamped with the CL BR monogram of the Fleet at Beauport Park and at the High Weald settlements at Bardown (Sussex) and Cranbrook (Kent).[18] Mineral rights in the Roman provinces were vested in the Emperor. Generally, only precious metals were exploited directly on his behalf by the provincial *procuratores*: for the most part, licences for iron-ore exploitation were assigned to private enterprises, as attested by inscriptions from Lugdunum.[19] In Britain, however, these rights seem to have been assigned, in part at least, to the Fleet, which was in many ways a supply arm of the Army rather than a fighting arm at this period.[20]

Excavations on Roman sites in the Weald by the author and others[21] provided the data on which the experiments were based. The archaeological record has produced indications in great detail of furnace design and construction, ore selection and preparation, and fuel sources and production; the experiments were designed to encompass the variations observed and inferred. The smelting furnace itself was based on a group excavated by the author at Holbeanwood,

[14] *De bello Gallico*, v, 12.

[15] H. F. Cleere: *The Romano-British Industrial Site at Bardown, Wadhurst*, Sussex Archaeological Society Occasional Paper No. 1 (1970).

[16] J. H. Money: unpublished report.

[17] C. E. Hart: *Archaeology in Dean*, 1967, 28.

[18] A. G. Brodribb: *Sussex Arch. Coll.*, **107** (1969), 102–25; for Bardown see H. F. Cleere, op. cit. (note 15); for Cranbrook, M. C. Lebon: *Arch. Cant.*, **76** (1961), p. xlviii.

[19] E.g. *CIL* xiii, 1811.

[20] G. Webster: *The Roman Imperial Army*, London, 1969, 158f.

[21] C. S. Cattell: *Bull. Hist. Met. Group*, **4** (1) (1970), 18–20; H. F. Cleere, op. cit. (note 15); M. C. Lebon, op. cit. (note 18); and information from A. G. Brodribb and J. H. Money.

Sussex,[15] the only shaft-furnaces of this type known from the Weald. However, other examples are known from Ashwicken, Norfolk,[22] from Stamford,[23] and elsewhere.

RAW MATERIALS

Iron Ore

The iron industry of the Weald was based, until its last phase in the seventeenth century, principally on the carbonate ores of the Wadhurst Clay, a formation in the Hastings Beds (Lower Cretaceous). The ore occurs at the base of the Wadhurst clay in the form of carbonate nodules ranging from 2 in. to 18 in. across. The nodules are enclosed in a skin, up to 1 in. thick, of limonite (hence the name 'boxstone' frequently applied to them). In antiquity the ore, which occurs in a discontinuous layer, was dug in opencast pits. These are very common in the Weald, and are now usually filled with water. Dr. R. G. Thurrell of the Institute of Geological Sciences drew the author's attention to an exposure of the ore in a brick-clay quarry at Sharpthorne, near West Hoathly, and about 12 cwt. were quarried by hand. It was found that the nodules could be disengaged quite easily since the limonite matrix was friable, and that the ore was quite clean, with little or no adherent clay. This observation was important, since ore washing has been postulated as having been necessary in the Weald; this would appear not necessarily to be so. Analysis of the ore showed it to contain *c.* 50 per cent. of iron, the remainder being *c.* 10 per cent. SiO_2, 3 per cent. CaO, and considerable CO_2 and water. It is an easily reducible material and so it was easy for the ancient ironmaker to smelt it.

Charcoal

The hardwoods of the mature forest-cover of the Weald provide an excellent source of fuel. Charcoal burning is still carried on in the region, although most of it is now made in retorts rather than in the traditional heaps. It had been hoped to burn the charcoal for the experiments in the old way, but this proved impracticable, and so the material was purchased from a Sussex manufacturer. Observations on excavated sites suggested that about 1 in. cube was the preferred size in the Roman period, and material of this size was purchased. In the earlier trials this was sieved to remove material less than 1 in., but it was recognized that the proportion of smaller pieces was only about 5 per cent. maximum, and so in the later experiments unsieved material was charged.

Examination of a random sample of the charcoal showed that birch and oak predominated; this compares with observations made on sites such as Bardown. It reflects the general distribution of trees in the mature Wealden forest. However, other materials had found their way into the retorts, as illustrated by an unmistakable piece of carbonized plywood from a jigsaw puzzle.

[22] R. F. Tylecote: *Journ. Iron and Steel Institute*, **200** (1962), 19–22.
[23] (I. M. Smith): *Bull. Hist. Met. Group*, **4** (1) (1970), 24–7.

EXPERIMENTAL FURNACES

Ore-Roasting

Carbonate nodules may be presumed to benefit from roasting. Heating to 300–400 °C. for short periods converts the carbonate to Fe_2O_3 and drives off water. There is ample evidence for ore roasting in the archaeological record; PL. XXIV A shows a structure excavated at the Bardown site[24] in 1964. It consisted of a trench about 8 ft. long dug in the natural clay; it was lined with blocks of sandstone and closed at one end, the interior being lined with clay, leaving an effective volume of 8 × 1 × 1 ft. It was flanked by a deep deposit of roasted fine ore less than ½ in. in size and the clay lining was reddened by heat.

The experimental ore-roasting furnace was dug in the clay to the same proportions but was not faced with stone. However, the sides were lined with puddled clay (PL. XXIV B). The ore nodules were broken with hammers to a maximum size of 2–3 in. cube and the ½ in. material was sieved out. They were then charged to the furnace in shallow layers, alternating with 1 in. layers of charcoal. For the first ore-roasting a deep charcoal layer was laid first at the bottom; this was then ignited and combustion was allowed to proceed without any forced draught. The ore was roasted in this way, but the process was very slow indeed and so it was decided to apply a blast. There is archaeological evidence to justify blowing the ore-roasting furnace, since the bed of ore fines associated with the Bardown furnace contained several flagon necks which had been neatly trimmed off to form hollow cylinders and showed signs of heating; these are interpreted as having been used to support and protect the nozzles of bellows, which were probably made of wood. Use of an old vacuum cleaner as a blower proved very effective and the ore was roasted rapidly. It was found that too much blowing caused partial reduction of the ore; it was converted to magnetite very quickly. The effect of the roasting was judged by eye: the natural carbonate ore varied from creamy-pink to light-grey in colour, and changed to a maroon shade when converted to Fe_2O_3. Further reduction to Fe_3O_4 resulted in a second colour change, to blue-black.

Roasting was a somewhat hazardous process: the ore lumps tended to explode violently, thereby producing very effective degradation. The hand splitting of nodules in the later stages was therefore less thorough since it was recognized that roasting produced effective breakdown. As an experiment, several lumps of 9 in. cube and greater were roasted whole; when these did not explode they roasted slowly, and were much easier to break up with hammers than in the freshly mined condition. However, this process was a slow one, and it is assumed that a preliminary hammer-crushing to about 3 in. cube was the most efficacious method. Roasting went on continuously throughout the working day, roasted ore being raked away from the hot zone immediately in front of the blower and allowed to cool slowly, and unroasted material mixed with equal amounts of charcoal being added. The cooled material was shovelled out and screened to retain material between ⅜ and 1 in., the undersize fines being discarded.

[24] *JRS*, lv (1965), 218–20.

Weighed amounts were put into polythene bags, ready for charging to the smelting furnace.

Smelting

The furnace used was based on a group of early third-century Roman furnaces excavated at Holbeanwood, an outlier of the Bardown settlement,[15] in 1968. PL. XXV A shows the best preserved of these furnaces. As excavated, they consisted of truncated cylinders, 1–2 ft. high with an internal diameter of 12–15 in. and walls 9–12 in. thick. They were constructed entirely of clay; only No. 4, that shown in PL. XXV A, contained any stone. In this case a block of sandstone was used to form the top of the front arch, a half circle of 6 in. radius. The clay, which is yellow in its natural state, showed progressive colour changes across its thickness, from yellow on the outside through pink and red to light grey on the internal surface; the bottoms of the furnaces were also grey in colour, but with a much narrower heat-affected zone, as would be expected. The bottoms of the furnaces showed a slope of 10–15 degrees down from the back wall to the front arch, at which point the slope increased slightly into a shallow depression 4–6 in. deep and roughly 18 in. in diameter in front of the furnace. The latter was also lined with heat-affected clay.

Samples from the Holbeanwood furnace were examined in order to establish whether any filler material (chaff, grog, etc.) had been used. No traces were found; the material was identified as a sand-clay, corresponding to the Ashdown Sand that overlies the ore-bearing Wadhurst Clay and outcrops at Bardown, Holbeanwood and Horam. It was decided therefore to build the experimental furnace of Ashdown Sand from the Horam site, without adding any filler material. The clay was dug from the site at an exposure near the proposed smelting area. It was puddled with water and trodden with bare feet in order to homogenize and consolidate it. Occasional sandstone nodules were removed by hand.

The design of the experimental furnace is shown in FIG. 1. It was built up with roughly moulded lumps of puddled clay, which were consolidated by hand round a cylinder made from flexible PVC sheet. It seems likely that a former of some kind was used by the Roman furnace builders; Tylecote[22] suggests that a tree-trunk was used for the Ashwicken furnaces. The interior and exterior of the furnaces had been finished off with a clay slurry at Holbeanwood, and the same technique was used for the experimental furnace. The furnace was built originally to a height of 2 ft. 6 in.; however, after the first trial, it was raised to 3 ft. by the addition of a collar of clay keyed into the previous top. The final form of the furnace is shown in PL. XXVI A. After building, the furnace was left to dry in air for six days. Some superficial cracking was observed after that period, and this was made good by the application of clay slurry. A fire of green wood was then lit and kept going for about six hours, the bottom aperture being left unblocked. On the following day, this fire was rekindled and stoked with charcoal. The front was closed with roughly-preformed lumps of clay, a clay nozzle or tuyere being inserted, and the furnace was blown using a vacuum cleaner. Cracking was observed on the exterior and further parging became necessary. During the

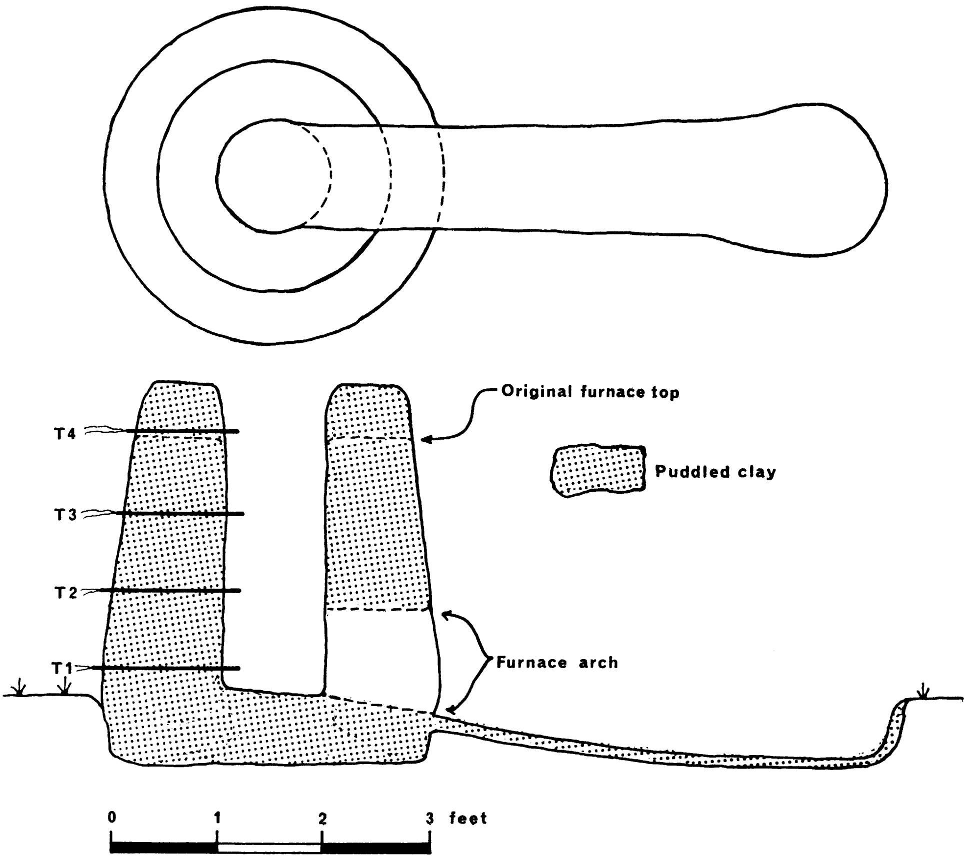


FIG. I
The experimental furnace.

course of the trials, further cracking was experienced, in a much more severe form. However, few of the later cracks appeared to penetrate through the thickness of the wall. Parging with clay (to which some grog derived from the bottom-arch filler-material had been added) sealed these cracks quite effectively; in any case, gas/air tightness was ensured by the build-up of slag on the inside walls (see below). As a safety precaution, wire bands were put round the furnace. However the structure was very robust; the hearty use of a crowbar at the end of the final trial, to remove bloom and slag, appeared to have no effect on its stability.

Tuyeres

No examples of Roman bellows are known. However, it has been assumed that these would have had nozzles of wood. This view is reinforced by the frequent finds of clay nozzles or tuyeres on early smelting sites during excavations. Two types of tuyere are known from the Weald in the Roman period: a simple trumpet nozzle and a twin-channel type, the latter known only in this area.[25] For the experiments, facsimiles of both types were made, using Ashdown Sand from the Bardown area. These were moulded by hand, air-dried, and finally dried for about four hours at 300 °C. The tuyere was inserted into the frontal arch of the furnace. The exact position and angle of the tuyere were varied during the trials (see below). The nozzle of the bellows or blower was then inserted into the trumpet-mouth of the tuyere; in Trial 1 it was fixed with clay wedges, but this practice was abandoned for the later trials. Examples of the tuyeres used are shown in PL. XXVII.

EXPERIMENTAL DETAILS

Instrumentation

Although the purpose of the trials was to reproduce Roman ironmaking practice, some instrumentation was used, primarily to record results rather than for control purposes. Gas analyses were made at 30-minute intervals during Trials 2 and 3. Measurements of O_2, CO_2, and CO were made during Trial 2 and of CO_2 and CO in Trial 3. No measurements were made during Trial 4 because of shortage of operating personnel. Thermocouples for temperature measurement were inserted into the back wall of the furnace at the points shown in FIG. 1 and protruded 2 in. into the interior.

Blowing Equipment

It has been established by other workers (see notes 3, 4, 7) that introduction of a volume of 300 litres of air per minute gives the optimum results in early furnaces of this type. Unfortunately it did not prove possible to obtain a suitable blower, and so the trials were carried out using an electric blower that produced about 450 litres per minute and an old vacuum cleaner which gave about 200 per minute. Attempts were made to reduce the volume delivered by the former by withdrawing the nozzle from the mouth of the tuyere. The vacuum cleaner was used principally for the ore-roasting furnace.

Procedure

The charge was prepared by screening both charcoal and ore to reject material below $\frac{3}{8}$ and over 1 in. Weighed amounts were put into polythene bags and stored alongside the furnace; the amounts varied as follows:

	Charcoal lb.	Ore lb.
Trial 1	4	4
2	$1\frac{1}{2}$	3
3	1	2
4	1	2

[25] H. F. Cleere: *Sussex Arch. Coll.* 101 (1963), 48–53.

The furnace was kept hot overnight by filling it with charcoal and closing the arch with clay and the top with a steel sheet. The arch was refilled with the tuyere in position in the morning and the sheet was removed. (At this point the bloom would normally be removed—see below.) The stack was then filled with charcoal and blowing began. The stock level was maintained with charcoal for about 15–30 minutes, at which point the top gas was ignited and the first charge of ore was made. The stock level was kept constant at the level of the furnace top (except in Trial 4) with additions of ore and charcoal for the rest of the trial. The blast was taken off periodically in order that a sight might be taken through the tuyere. A steel rod was inserted through the tuyere into the furnace, so that the amount of slag formed could be estimated. It was also necessary to clear cold slag from the nozzle of the tuyere with the rod from time to time.

The front arch was stopped with clay alone in the first two trials; slag could only be tapped by removing most of this material. In Trial 3 the bottom part of the arch was filled with a sandstone block, which it was hoped to remove to allow the slag to run out; unfortunately the attempt to do so was left too late and it had become welded indissolubly into a mass of cold slag at the base of the furnace. In Trial 4 a turf was used, with conspicuous success, as a stopper. The organic material in the turf was burnt away by the hot slag (at a temperature above 1,200 °C.) and the slag ran out continuously, being kept fluid by the flame which burnt at the aperture. When charging of the ore was completed, extra charcoal was added and blowing continued until the stock level had dropped about 1 ft. At this point, the furnace was closed up and left overnight (for Trials 1 and 2 only) or for several hours. The bloom, which had built up behind the arch, bridging the furnace, was then loosened from above with a crowbar and removed with tongs through the arch. The slag that had collected at the base of the furnace was broken up with crowbar and hammers and removed through the arch; after repairing the inside wall, the cycle could begin again. It was found that the bloom and slag could be removed in about 30 minutes, and that the furnace remained reasonably hot during this operation.

RESULTS

Trial 1

The furnace was lit at 09.55 and 30 lb. of charcoal had been charged by 11.10, blowing being by means of the vacuum cleaner. The stock level was maintained to the top of the furnace throughout this trial; it should be remembered that the furnace in this trial was 2 ft. 6 in. high. The first ore charge was made at 11.35 (10 lb.). Equal 4 lb. additions of ore and charcoal were made at intervals up to 15.40 as the stock level dropped. The blower was substituted for the vacuum cleaner at 13.45. An unsuccessful attempt was made to tap slag at 14.40; cold slag built up at the base of the furnace while the arch was open, and by 15.55 it was recognized that the furnace had gone cold. It was therefore closed up and cleared on the following morning.

It was realized that the ore additions had been too large and had cooled the furnace too much, and also that the vacuum cleaner did not supply an adequate blast; the 300 °C. rise at thermocouple 1 when the blower was put on emphasized this. The slowness in clearing the arch and in attempting to tap slag cooled off the combustion zone so severely that it became impossible to achieve adequate temperatures. No iron was produced in Trial 1; the resulting slag was in effect fused ore, since temperatures in excess of 1,200 °C. were not achieved. Trouble was experienced in this trial with slag blocking the tuyere. The tuyere had been positioned in the centre of the arch, inclined upwards at an angle of about 5 degrees.

Trial 2

The furnace was raised to 3 ft. internal height, and the tuyere was positioned at the top of the arch, inclined upwards at about 15 degrees to the horizontal. The furnace bottom was also built up, with a slope of about 15 degrees to the horizontal from front to back (FIG. 1). An extra thermocouple (T4) was added. After 30 minutes preheat, ore and charcoal were added in the ratio of 1 : 1·5 from 09.00 to 11.00; the ratio was then changed to 1 : 1 for the remainder of the trial, the last addition of ore being made at 18.21. The electric blower was used throughout the trial; from 09.30 to 10.05 and again from 10.40 to 11.40 an intermittent blast was used, the nozzle from the blower being screened from the tuyere for 2 seconds in every 5 seconds. This tended to depress the temperatures and also resulted in rapid descent of the burden in the furnace, owing to the fluctuations in pressure.

An unsuccessful attempt to tap slag at 11.40 was quickly abandoned, and blowing resumed, without any obstruction; the temperature at T1 rapidly rose to 1,300 °C. Fluid slag ran out at 12.00 and continued running from a small aperture for 30 minutes; the T1 temperature quickly came down to about 1,100 °C. The aperture was widened at about 12.50, the bellows-nozzle being inserted directly into it. By 13.55 the slag at the bottom was cold and solid, but once the crust had been broken with a crowbar slag began running again and continued to do so throughout the remainder of the trial. However, continual clearing of cold slag was essential. After the final ore addition at 18.21, two more lots of charcoal were added. Blowing was reduced by gradual withdrawal of the nozzle, and the furnace was finally closed down at 19.30.

This was the most successful of the trials, nearly 20 lb. of iron being produced from 201 lb. of ore and 265·5 lb. of charcoal. However, the open-arch practice cooled the bottom zone severely, and there was ample evidence of reoxidation of the lower part of the bloom.

Trial 3

Blowing began at 10.10 and the first ore charge was made at 10.37; the ore-charcoal ratio used was 2 : 1 (2 lb. of ore, 1 lb. of charcoal). The last ore charge was made at 13.50 and the furnace was closed up at 15.00. It was reopened at 18.00 and the bloom and slag were removed. The electric blower was used throughout the trial. The experiment with the sandstone plug in the tapping arch proved disastrous; when an attempt was made to remove this at 12.20 it was found to have become welded to the cold slag on the hearth. Moreover, it had splintered under heat. The furnace was off blast for 30 minutes while attempts were made to move the block. Heat was lost in the bottom zone, as in Trial 1, and there was considerable reoxidation of the bloom, although this had formed properly. No more than 2 lb. of iron was recovered from the 12 lb. bloom by magnetic separation when it was broken up with hammers.

The comparative failure of this trial is adjudged to have been due to inability to tap the slag (which caused the furnace to clog up at the base with cold slag) combined with use of an over-powerful blower.

Trial 4

Blowing began at 10.39 and the first 2 lb. ore charge was made at 11.05. The ore-charcoal ratio was 2 : 1, as in Trial 3. The last ore charge was made at 13.35 and the furnace was closed up at 14.05. During this trial, the stock level was maintained at 6 in. from the top, i.e. at the level of thermocouple T4. This trial was less serious than the others, since the experimental site was associated with a charity event and there was some onus on the operators to 'put on a show' for the benefit of visitors. A small quantity of ore was charged, and the bloom was removed at 17.00, with a good deal of showmanship.

The most successful aspect of this trial was the use of a turf to stop up the lower part of the arch. This had burnt through by 11.50 and slag ran out steadily throughout the remainder of the trial. The aperture was about 6 in. wide by 2 in. deep, and a flame burnt over the emerging slag. It was clear that the blast from the tuyere went both upwards and downwards inside the furnace; the combustion of charcoal below the tuyere level produced a hot flame which kept the slag fluid. It appears therefore that a 'running slag notch' is effective in the bloomery process. The iron yield was disappointing, however: only about 2 lb. of iron, as in Trial 3. This was probably due again to the use of the electric blower, which produced highly oxidizing conditions inside the furnace and re-oxidized the bloom as it formed.

EXAMINATION OF PRODUCTS

Iron

The nature of the bloom is illustrated in PL. XXVIII. In this portion of the main mass, the reduced iron is embedded in a matrix of slag. However, in Trial 2, from which the specimen illustrated was produced, attempts to tap slag were not successful. Better furnace-operating conditions would have resulted in a more consolidated iron sponge, with considerable slag inclusions.

Iron from the raw bloom was first worked by repeated heating and hammering (to expel entrapped slag and weld the metal particles) into small blanks for further working. A typical microstructure is shown in PL. XXIX A. The degree of consolidation was poor, as shown by the voids and slag inclusions. Some small arrowheads were made from the semi-finished blanks. The shaft of one of these was examined metallographically. As PL. XXIX B illustrates, the consolidation was not perfect even at this stage; slag stringers and voids remain. Variations in carbon content were observed which would be expected from material forged from small discrete particles of reduced iron and repeatedly heated in a charcoal fire. The microstructures observed are very characteristic of bloomery iron, and can be paralleled by innumerable examples from objects derived from archaeological excavation.

Slags

Since no flux was used in antiquity, none was used in the trials. The gangue was removed only at the expense of the iron yield, and slags from antiquity are always principally composed of fayalite. Two distinct materials produced during the trials were examined; material remaining at the base of the furnace at the end of a smelt, and tap slag. The former was a coarsely crystalline material, enclosing much charcoal and with pores encrusted with fayalite and with hercynite ($FeO.Al_2O_3$). The principal minerals present were fayalite, hercynite, wüstite, and iron monticellite ($CaO.FeO.SiO_2$) in an interstitial finely crystalline silicate matrix; small amounts of metallic iron were also present. The large size of the fayalite crystals (up to 3 mm.) is due to the slow cooling of this material in the furnace.

The tap slag is a massive mamillated dense material, with pieces of refractory and glassy material included. The main components are fayalite, hercynite, wüstite, magnetite, and iron monticellite. Metallic iron and, in oxidized regions, hematite also occur, and there are lime-rich pockets with dicalcium silicate and various calcium ferrite compounds (e.g. $2Ca.Fe_2O_3$) or anorthite ($CaO.Al_2O_3.2SiO_2$) crystals set in a glassy matrix.

Furnace Structures

On examination after the trials were completed, the furnace showed the features observed in the Holbeanwood furnaces. The colour-change sequence from the outside was from yellow through pink and red to grey, and there was a coherent coating of slag on the inside of the furnace, which had built up to about ½ in. during the four trials. The lumps of clay used for stopping the furnace arch, particularly those used when the furnace was being preheated using charcoal alone, exhibited vitrification on the face that had been on the inside of the furnace. This was presumably due to the combination of alkalis in the charcoal with the silica in the clay. The slag lining was seen to have attacked the clay wall of the furnace, but there was no evidence that it had been hot enough to melt and run down the furnace. Thus the composition of the slag can be related solely to the ore and fuel compositions, contrary to the view expressed by some workers in the field that the refractory lining played a part in the formation of slags.

CONCLUSIONS

Ironmaking Technique

The experiments were hampered by the inadequate blowing equipment available. However, iron was produced and certain observations could be made that help in the greater understanding of the primitive process. First, it appears that an ore-charcoal ratio of 1 : 1 gives the best results. This observation should perhaps be viewed with some caution, since it holds good only for the blowing rates used in the trials. Tylecote and others[7] claim good results with a ratio of 2 : 1, but using a blowing rate of 300 litres of air a minute. It is clear that small frequent additions of ore and charcoal are more effective than large additions. The 4 lb. ore unit of Trial 1 demonstrably caused considerable cooling of the reduction zone. No obvious distinction could be observed between the results using single and double tuyeres. However, they may be a reflection of the type of bellows used in antiquity; it is possible that double bellows were used with the double tuyeres, the bellows operating alternately so as to maintain a continuous blast.

The most important result was connected with the practice at the furnace arch. The process clearly operates most efficiently if slag can be removed continuously from the hearth area, without loss of heat. Breaking down the whole furnace arch is time-consuming (and disagreeable) and results in considerable heat loss while the blower is off. Continuous slagging with an open arch, with blowing maintained, is effective up to a point, but causes overcooling in the lower zone and severe reoxidation; moreover, the cold air from the blower cools the escaping slag quickly, and a weir quickly builds up. A removable stopper is a possibility, but this can become welded to the slag inside all too rapidly. The use of a consumable stopper of turf or some similar material seems to give ideal conditions, with continuously running slag, a source of heat to keep the slag fluid and no extra access of air.

As mentioned above, the main reason for the low yields in the trials is assumed to have been the over-powerful blower that was used. The considerable volume of cold air injected at the tuyere appears to have cooled the bloom as it formed. Some degree of reoxidation would be inevitable under these conditions. The non-metallic portion of the bloom is high in fayalite, i.e. slag, which was unable to run away at the tapping hole or arch because it was solidified at the bloom level. The low temperatures at the front of the hearth zone prevented both the proper disposal of slag and the completion of the reduction process. It is thus essential to maintain this zone at a temperature of at least 1,200 °C., and to reduce heat loss during slag-tapping to a minimum.

Archaeological Considerations

The trials produced valuable data for archaeological studies in three main fields:

1. *The durability of furnace structures.* The furnace proved to be very tough; after four trials it was still strong, and with more skilled operation combined with proper maintenance and repair it could easily have lasted for at least a dozen smelts. The Holbeanwood group of furnaces[15] all showed signs of rebuilding; the twelve furnaces found so far must between them have represented at least forty separate builds. If a life of twelve smelts is assumed for each and an average production of 40 lb. of iron per smelt (this is to assume that the ancients were at least twice as skilled as the author and his team, which is probably unfair

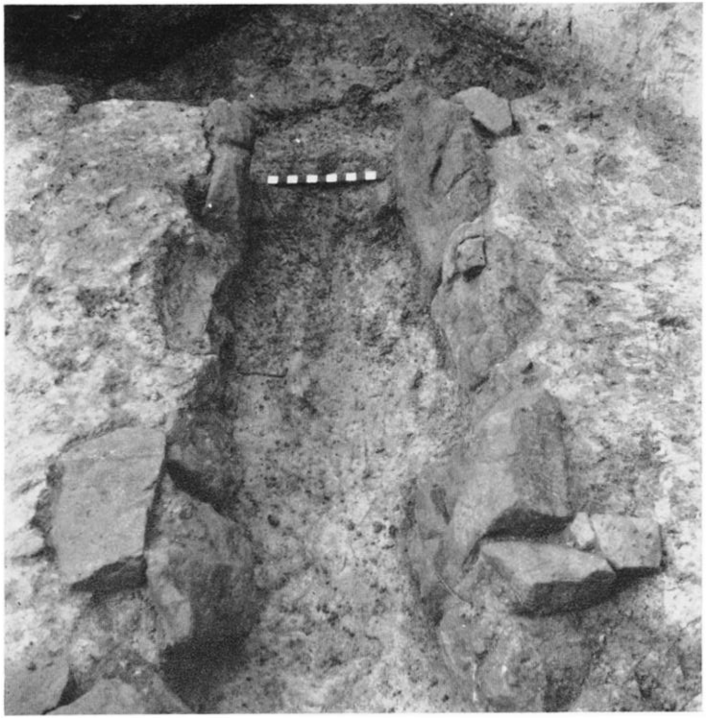
to the Romans), a minimum production of over 8 tons of iron may be postulated from this group of furnaces.

2. *Identification of products and waste materials.* The distinction between the different types of slag produced became much clearer once these materials had been seen in the course of production. It is hoped that this evidence will permit more positive identification and classification of slag materials found on future excavations. The lumps of clay used for stopping up the furnace arch also exhibited characteristics (e.g. finger grooves made by the furnaceman when forming them, vitrification on the inner surface, etc.) with parallels in the archaeological record which have never been properly explained before.

3. *Manning requirements.* It was found that a minimum of four people were needed on the site, to operate the ore-roasting and smelting furnaces, weigh out the charge material and screen it, clear away slag, etc. If it is assumed that at least three men would be needed to operate hand- (or foot-) powered bellows on each furnace, working in shifts, the minimum manning per basic furnace unit of ore roaster and smelter would have been ten.[26] This enables deductions to be made about the possible population of ironmaking settlements such as Bardown.

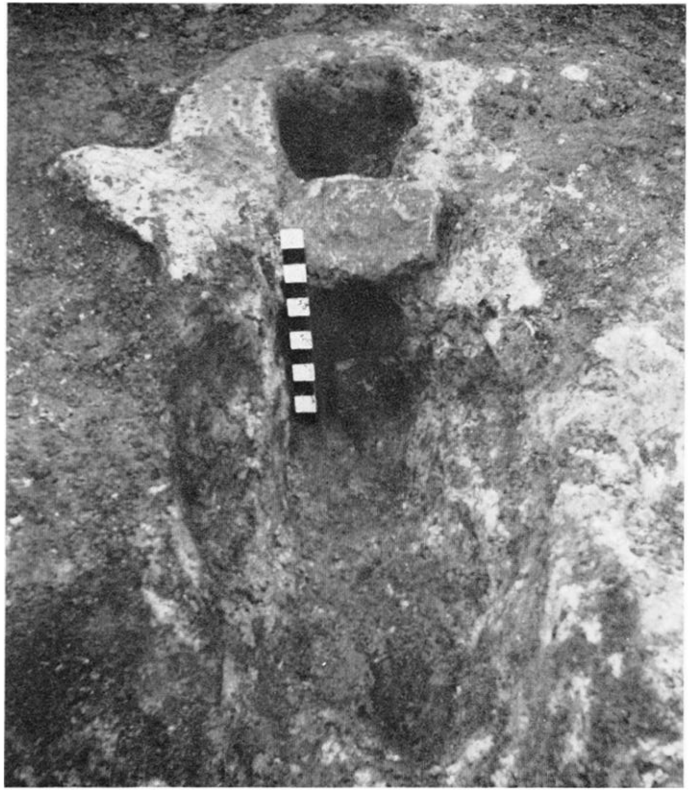
50 Madeira Road, London, SW16 2DE

[26] However, more recent studies by the writer (*Bull. Historical Metallurgy Group* 5 (ii), 1971, in the press) suggest that ore-roasting and smelting were not carried out simultaneously, and so the manning figure could be 5–6 per furnace.

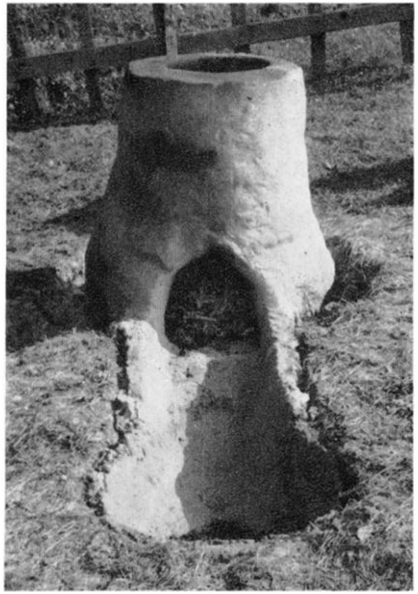


A. Romano-British ore-roasting furnace No. 2 from Bardown, Sussex (p. 208).

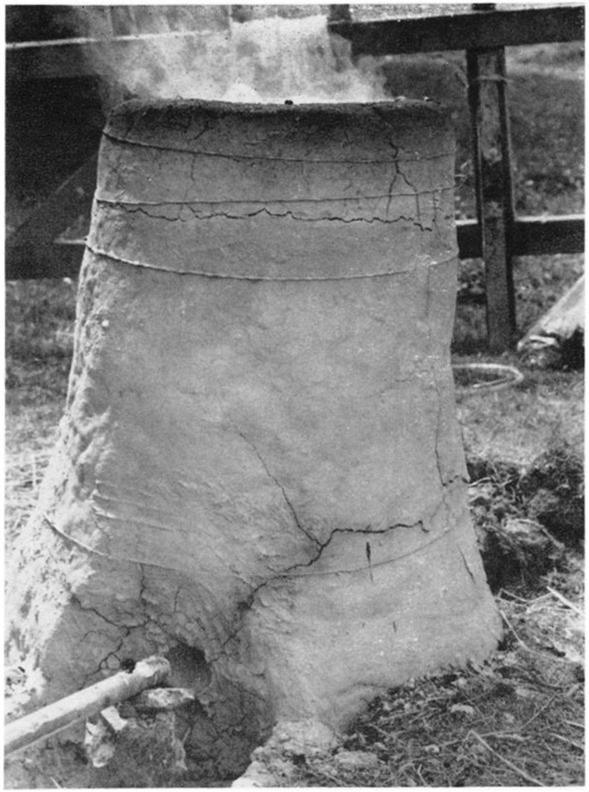
B. Experimental ore-roasting furnace at Horam (p. 208).



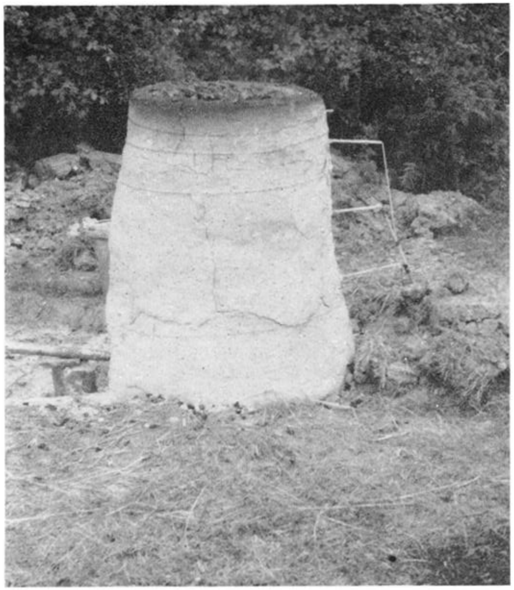
A. Romano-British smelting furnace No. 4 from Holbeanwood, Sussex (p. 209).



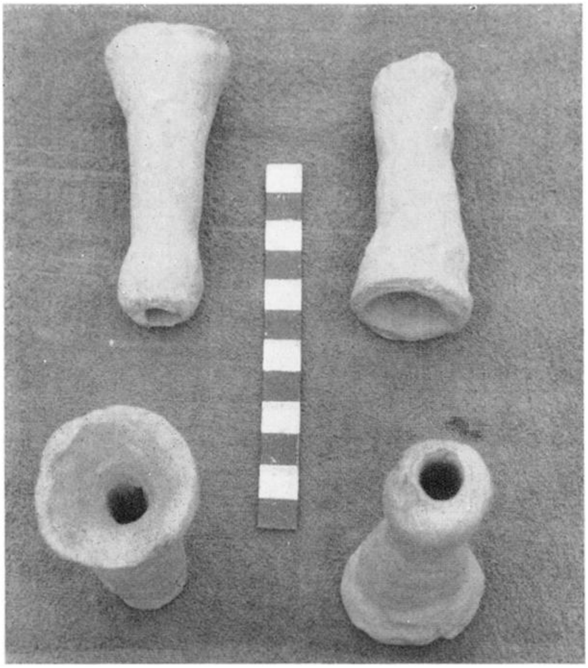
B. The original 2 ft. 6 in. experimental furnace preparatory to drying (p. 209).



A. The enlarged experimental furnace, showing method of stopping up the furnace-arch (Trial 2) (p. 209).

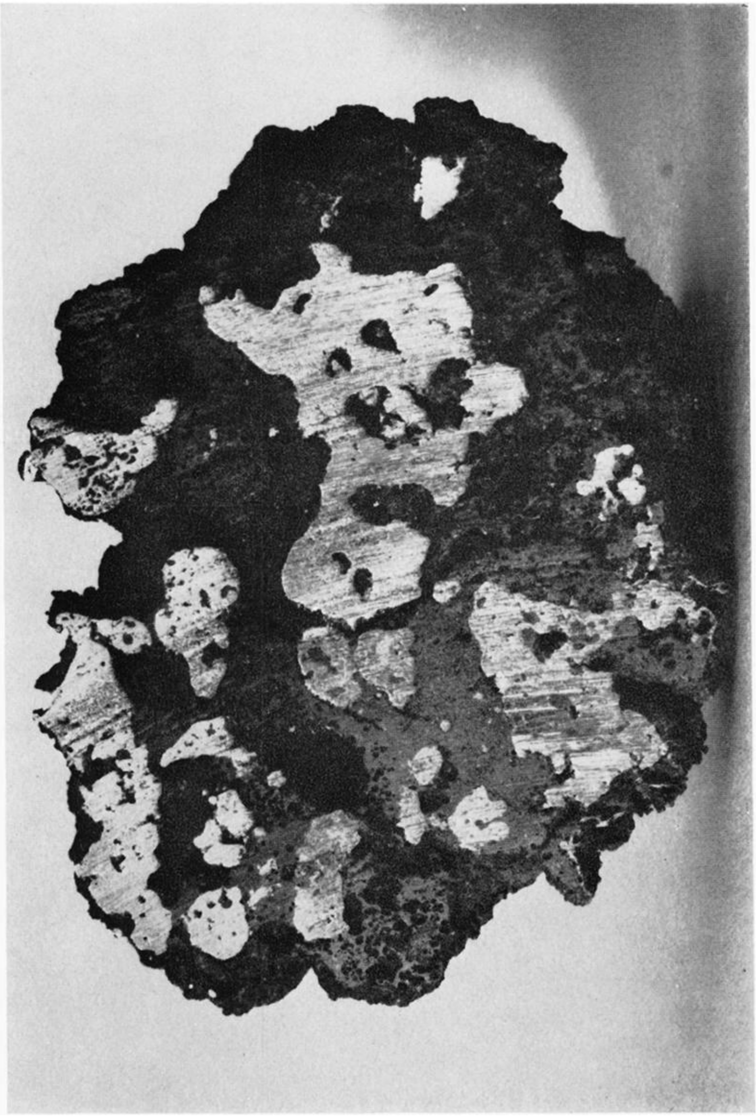


B. The furnace as enlarged, showing thermocouples (T1 is not visible) (p. 211).

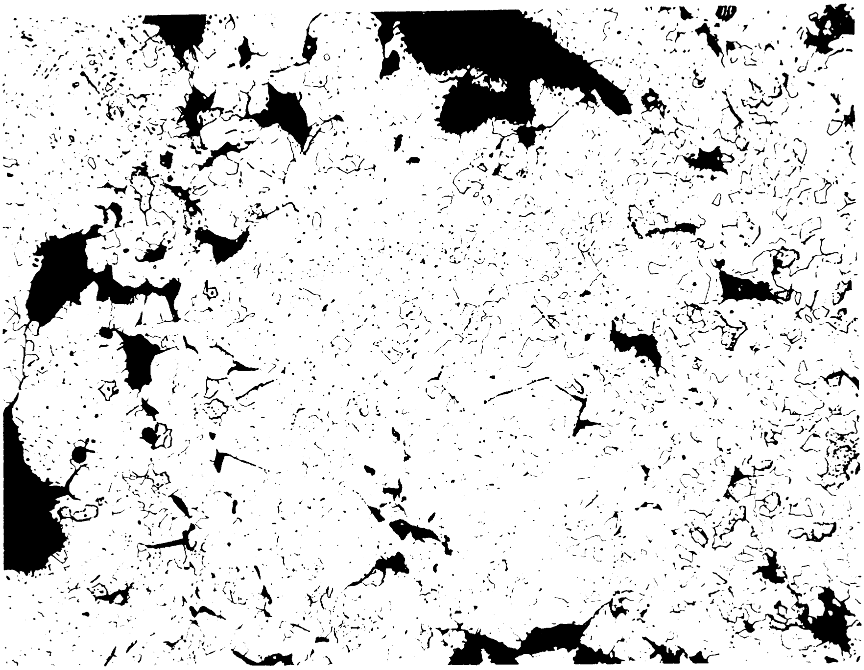


Experimental clay tuyeres, A. single.

B. double (p. 211).



Section of bloom, light areas iron, dark areas slag ($\frac{1}{1}$) (p. 214).



A. Microstructure of partially worked iron (× 50) (p. 214).

B. Macrostructure of forged shaft (× 15) (p. 214).