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Contents

An examination of a North Indian Sword (firangi) in the collections of the Pitt Rivers Museum, Oxford, and experiments in the forge-welding of low-carbon strips

P. WHITAKER AND T. H. WILLIAMS

Editorial Note

The greater number of the surviving "Khandas" from the Hindu areas of Northern India are mounted in the Hindu basket hilt, which is a later version of the Old Indian improved by the addition of a basket guard. It is probable that this development took place in the Western Deccan about 1600, and was prompted by contacts with European basket hilted swords. In the large tracts of Central India and Orissa that in the 18th century lay under Maratha dominion this basket hilt was adopted by the indigenous population from the rulers. It is a very good hilt indeed.

Most of the 18th century "Khandas" that survive have their blades reinforced with narrow fretted strips of steel running down the length of the reverse edge and several inches down the edge from the root of the blade. The reason for this is probably that the virtues of lightness, elasticity and strength can only be combined in a blade by the sacrifice of some of its stiffness, and the reinforcements compensate for the sacrifice.[1]

A general view of the sword is shown in Fig. 1. The museum number is 1884.24.44.

A portion at one side of the blade near to the riveted reinforcing rib was highly polished for micrographical examination. On etching with diluted Rosenhain and Haughton's reagent, a transverse stepped pattern was observed; this pattern was most marked in the grooved portion of the blade (Fig. 2). Towards the cutting edge and at the back of the blade the pattern tapered off into a slightly wavy piled structure.

Microscopical examination shows the blade to have been made from piled wrought iron of varying carbon contents. During the final forging of the blade, the piling in the grooved portion has been forged into a highly contorted stepped pattern by forging a series of transverse impressions; this cross-forging has caused the piled structure to become contorted in a transverse direction to the axis of the blade at each of the transverse impressions.

The two longitudinal grooves down the centre of the blade and the sharp cutting edge have been ground to the final contour so that the flow pattern of the stepped forging is cut in a longitudinal and transverse direction to show up the stepped layered pattern. Figures 3a-c are photographs of a layered wax model which illustrate each stage of the process and show that it is necessary to cut the grooves and edge profile to show the full effect of the flow pattern.

A close-up view of the prepared side of the blade is shown in Fig. 4; the sword has been illuminated to show the longitudinal grooves which cut across the forged steps.

Microscopical examination shows the blade has a coarse martensitic structure typical of a 0.3% carbon steel which has been indifferently quenched from about 950° to 1000°C (Fig. 5). This high hardening temperature has resulted in a large number of transverse quenching cracks which, in places along the back of the blade, extend almost across the section. The blade has been locally burned during the heating for hardening. The martensitic structure has a coarse Widmanstätten appearance due to the high hardening temperature; there is some ferrite precipitation along the octahedral planes and at the grain boundaries (Fig. 6). In places there is also pronounced troostite at the grain boundaries. The presence of ferrite and troostite indicates the blade was not quenched satisfactorily.

Hardness micro tests show variations in hardness from 146 Vickers close to the edge, where in places the blade has a low carbon content, to 610 Vickers on the first ridge of the grooved portion of the blade in a dark martensitic area at approximately 6 mm from the cutting edge. Typical figures show the marked variation in hardness at different positions from the edge:

Distance from edge, mm	Vickers hardness
0.9	146
1.2	235
1.3	173
4.9	270
5.2	530
5.8	510
6.0	610

Average hardness at the back of the blade: 495

The etched structure developed in Figs. 2 and 4 shows distinct light layers at the welded junctions of the piled layers. The material in the light areas is a good deal higher in phosphorus and arsenic; this is due to preferential oxidation of the iron during heating for forging, resulting in the surface layers of each of the faggots becoming higher in phosphorus and arsenic. In these zones there are quite marked streamers of iron oxide and silica grains entrapped between the various layers. The smith in welding the faggots together has used sand grains as a flux. In some places along the welding planes the layers have failed to weld, leaving a marked step which is now filled with corrosion products.

Polishing and examining the back of the blade suggest that it was forged from approximately 100 to 150 piled layers of wrought iron of varying carbon products.

The analysis of the blade is:

Carbon	0.04 to 0.3%
Silicon	0.18
Manganese	trace
Copper	0.013
Nickel	0.01
Molybdenum	0.01
Chromium	not indicated.

The blade is a beautiful example of the smith's art, but it has been spoiled by overheating and local burning during heating for hardening. After suitable etching, the blade shows a marked stepped pattern which has somewhat similar characteristics to Damascene blades, but the blade is not a Damascene steel as known from the work of Belaiew, Tchernoff, and Anossoff.

A true Damascene steel is hammered from a single cast cake. The light areas of the watermarked pattern are due to the presence of high-carbon cementitic areas which on etching with acid are not attacked, whereas the present blade has been made from carburized piled wrought iron; the light areas, which show on etching the structure, are low in carbon and represent the welding planes between the piled layers.

The authors are with British Steel Corporation, Northern and Tubes Group (Stewarts and Lloyds Ltd), Corby.

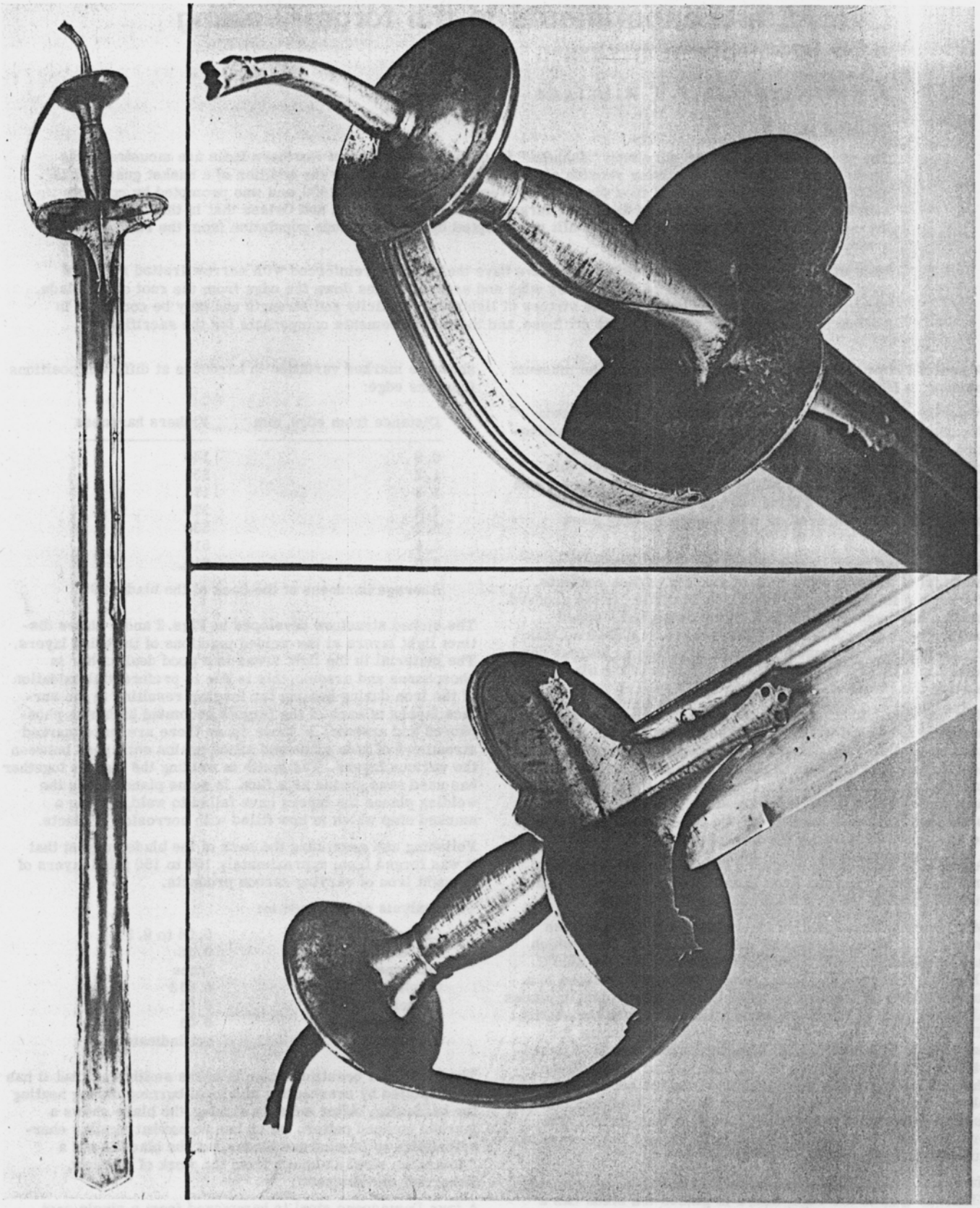


Fig. 1 — General view of sword and details of hilt

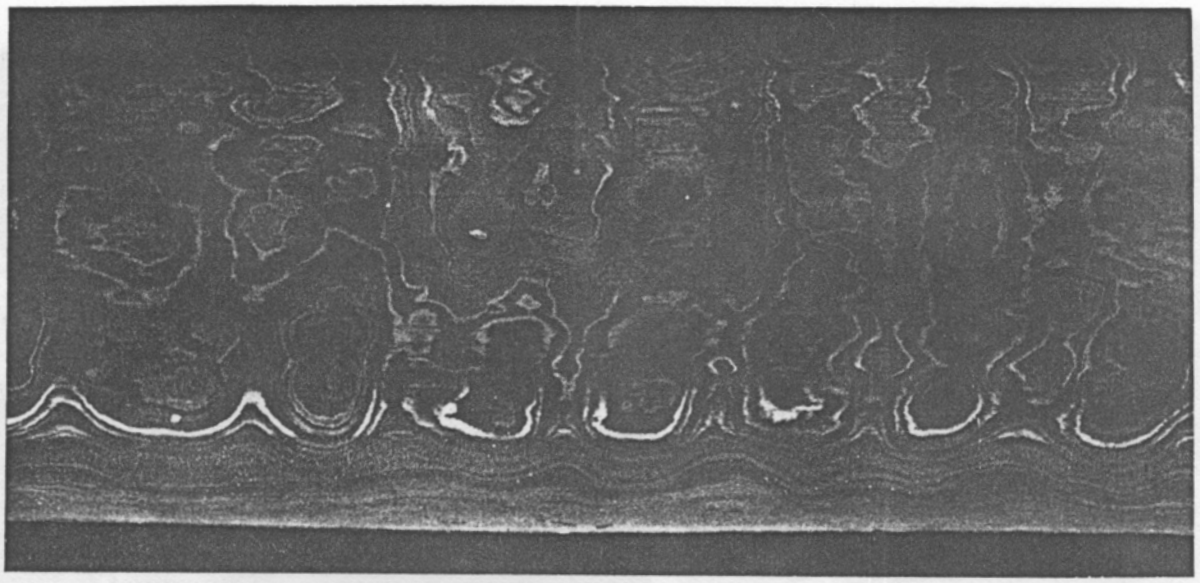


Fig. 2 — Photomacrograph of side view, showing edge and grooved portion of blade. White areas higher in phosphorus, piling at lower edge only slightly wavy. At grooved position, piled structure highly contorted owing to step forging. Polished and etched with Rosenhain and Haughton's reagent
Magnification ×2.5

TESTS ON FORGE-WELDING OF LOW-CARBON STRIP

A pile of strip samples approximately 1½ in wide × 6 in long × 0.04 in thick was heated in a graphite-lined heating chamber, the strips being placed on a refractory layer to prevent direct contact with the carbon furnace lining. On reaching a temperature of between 950° and 1000°C, the heated pile was quickly withdrawn from the heating chamber and forged with a hand hammer. Figure 7 shows the method of heating.

In the first experiment, samples were forge-welded after heating a pile of clean bright strips bound with wire. No powdered white cast iron was placed between the layers in this experiment. After forge-welding, the faggot was sectioned and examined microscopically; although the welding plane can clearly be seen, there was no entrapped non-metallic matter at the weld. Close examination showed a very slight carburized layer; this may have been due to the self-generated carbon-monoxide atmosphere in the heating chamber or to the very slight contamination of the strip surfaces by an oil film before the strips were heated (Fig. 8).

In the second test, a series of strips were heated with small quantities of finely powdered white cast iron placed between the layers. It was not easy to get a uniform distribution of the powder, but on heating and forge-welding a remarkably good weld was produced, which showed a slight increase in carbon content at the welded junction (Fig. 9).

In a third test a larger amount of powdered white cast iron was used between the layers, and the bundle was heated and forge-welded in the same manner. A higher carbon content was obtained at the welding planes, although this was somewhat variable due to the difficulty of making a uniform powder distribution (Fig. 10).

In the fourth test the amount of powdered white cast iron used between the strips was increased, and a welded pile was very easily obtained. A section of this is shown in Fig. 11. Some of the large particles of white iron are still entrapped between the piled layers as particles which have not diffused.

The fifth test strips were welded using a fairly large proportion of crushed iron lumps between the layers; a section of this specimen is shown in Fig. 12. Particles of powdered white cast iron still remain undiffused between the strips. Further heating and forging would unify the carbon distribution. On heating the sample from the fifth test (Fig. 12) for 8 h at 900°C, full diffusion of the carbon occurred, resulting in a faggot of eutectoid composition. Close microscopical examination showed only faint traces of the original welding planes (Fig. 13), and the material responded to hardening treatment in the same way as a eutectoid tool steel.

These experiments indicate that it should have been quite easy for a skilled smith to forge-weld wrought iron or low-carbon material with varying proportions of powdered white iron between the layers, provided that the heating was carried out in a suitable reducing atmosphere. As the proportion of powdered white cast iron between the strips is increased, a more uniform carbon distribution is obtained.

On annealing, or further forging, a uniform material of eutectoid composition is produced.

ACKNOWLEDGMENT

Sincere thanks are due to the Director of Research and Technical Development, Stewarts and Lloyds Ltd, who gave permission for the necessary metallographic and metallurgical work carried out.

Concluding note by H. H. Coghlan

It will be noticed from the general view of the North Indian sword that reinforcing ribs have been riveted to the back of the blade below the hilt. In Mr Whitaker's opinion it is possible that the smith who made the weapon knew of the numerous cracks and put on these ribs as a protection against the cracks developing. With the presence of such hardening cracks it is unlikely that the weapon was ever used, since it would undoubtedly break if used with any violence. The coarse martensitic structure would also make the blade brittle apart from the presence of the cracks.

The experiments concerning strips welded with and without powdered white cast iron between the layers are extremely instructive in offering (for the later periods) an alternative to the cementation process for the conversion of strongly heated but still solid iron into steel. These experiments are particularly relevant to China where there was much experience of, and use made, of cast iron. Indeed Professor J.

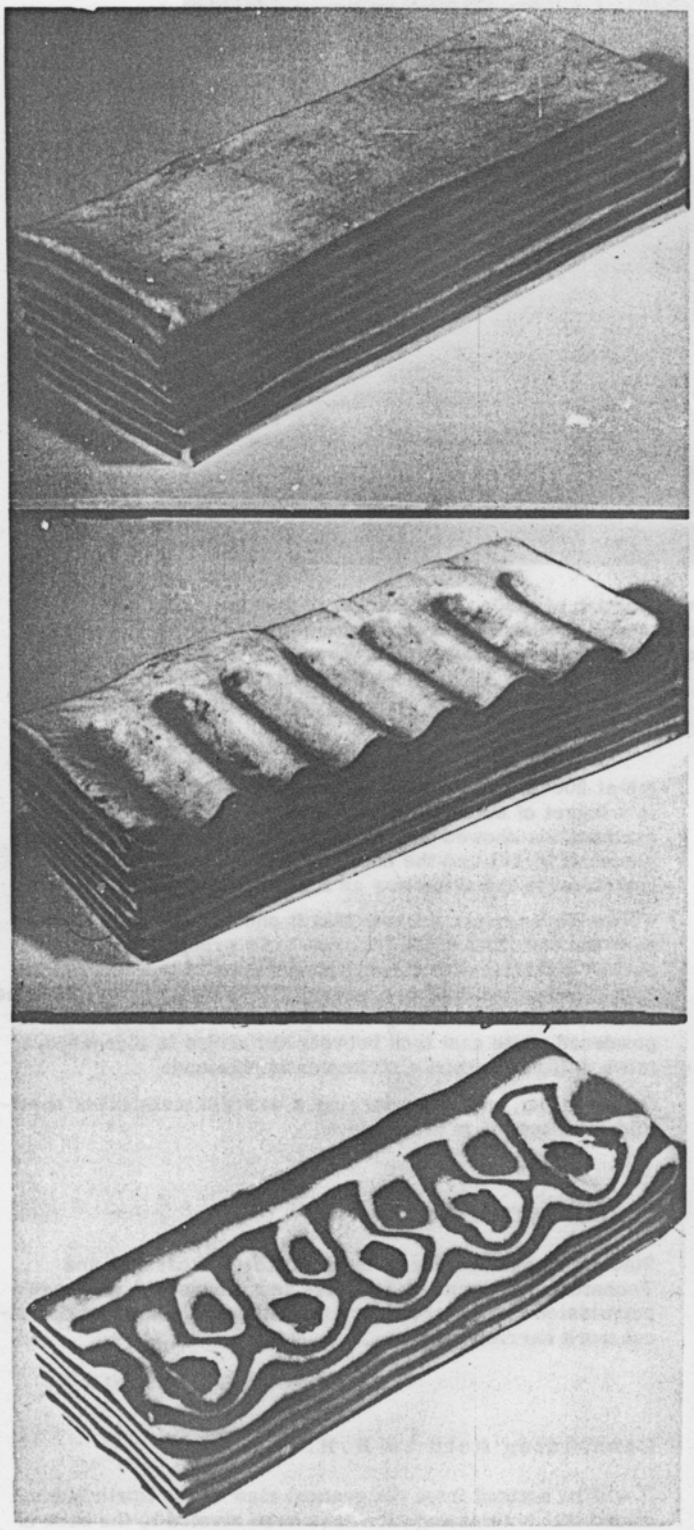


Fig. 3 — Layered wax model to illustrate piling: (top) as prepared; (middle) after transverse step-forging, showing wavy flow patterns under impressions; (bottom) after cutting the bevelled edge and forming the central groove by cutting, showing exposed transverse flow pattern

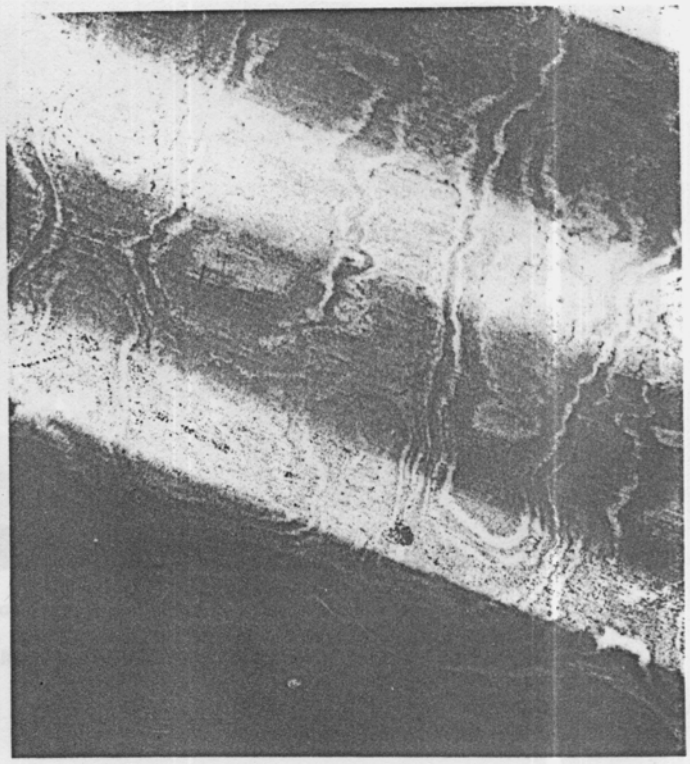


Fig. 4 — Side view illuminated to show contour of grooves in blade (edge at lower left-hand side)
Magnification × 4.5

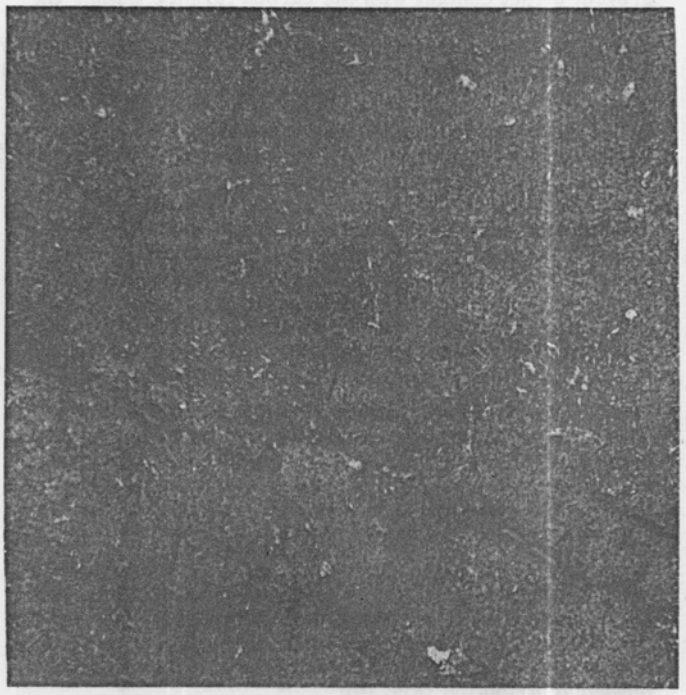


Fig. 5 — Photomicrograph showing coarse martensitic structure and streamers of iron oxide and silica
Magnification × 200

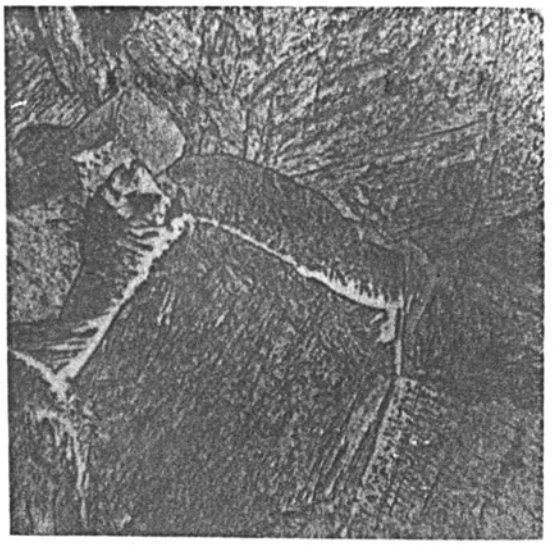


Fig. 6 — Coarse low-carbon martensitic structure, showing grain-boundary and octahedral ferrite due to poor quenching Magnification × 670

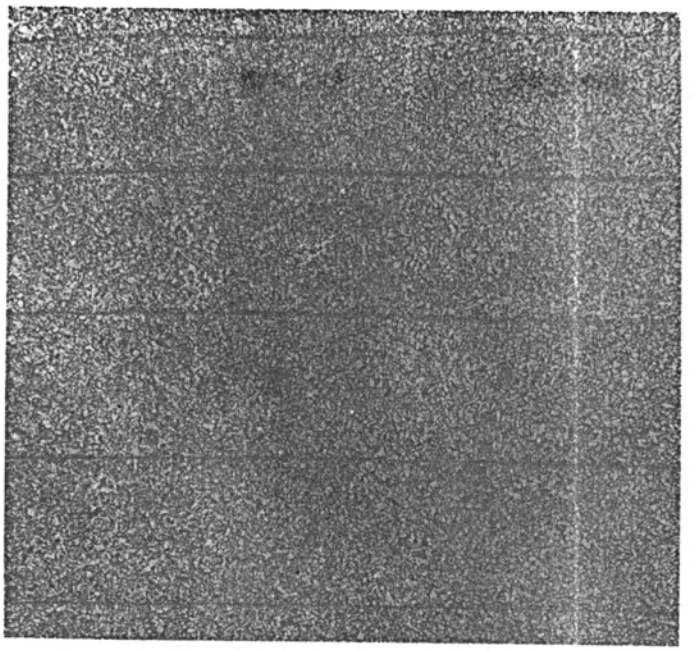


Fig. 8 — Photomicrograph showing slight carburizing at welding planes. Strips forge-welded without any powdered white cast iron between layers Magnification × 25

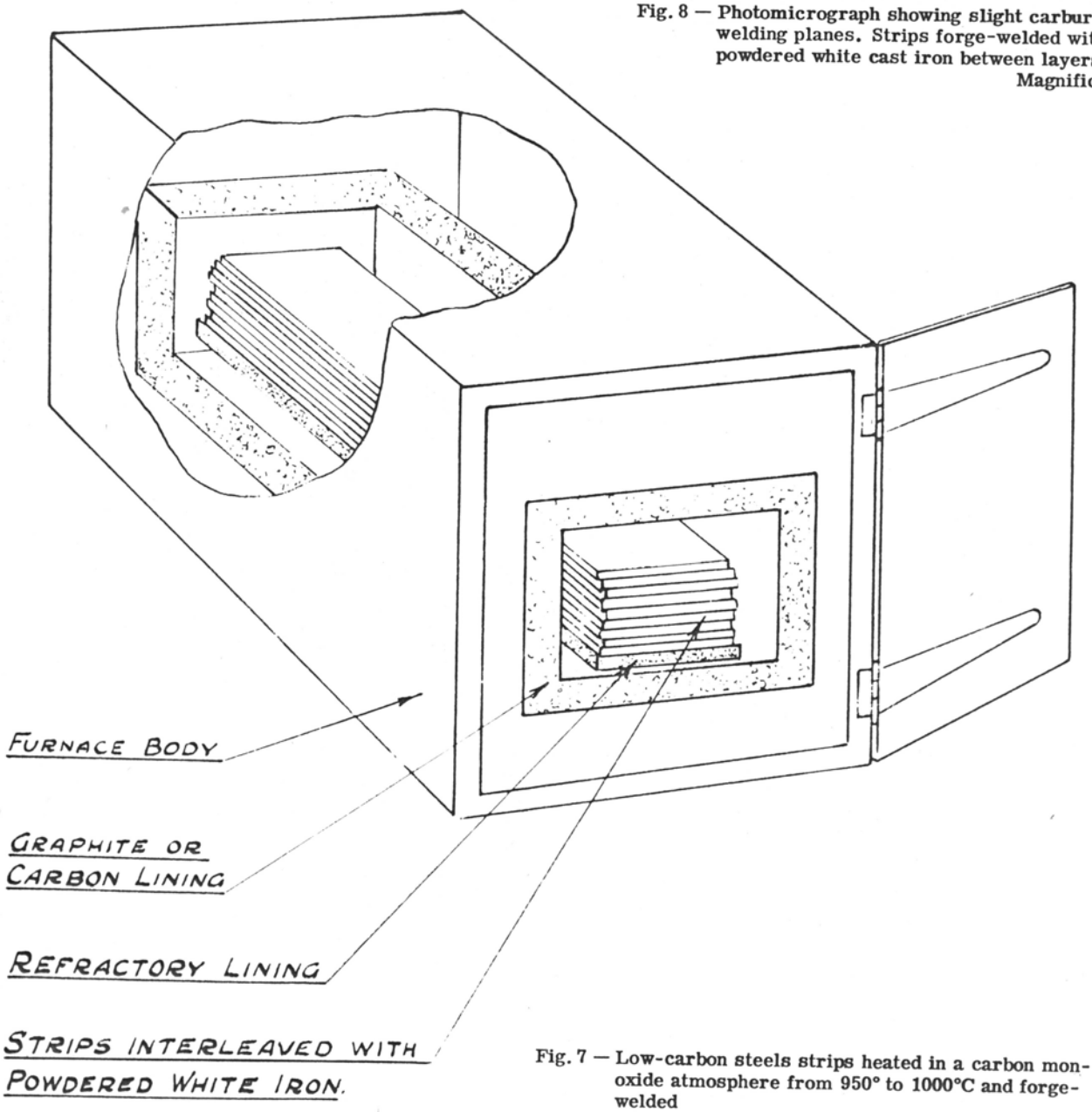


Fig. 7 — Low-carbon steels strips heated in a carbon monoxide atmosphere from 950° to 1000°C and forge-welded

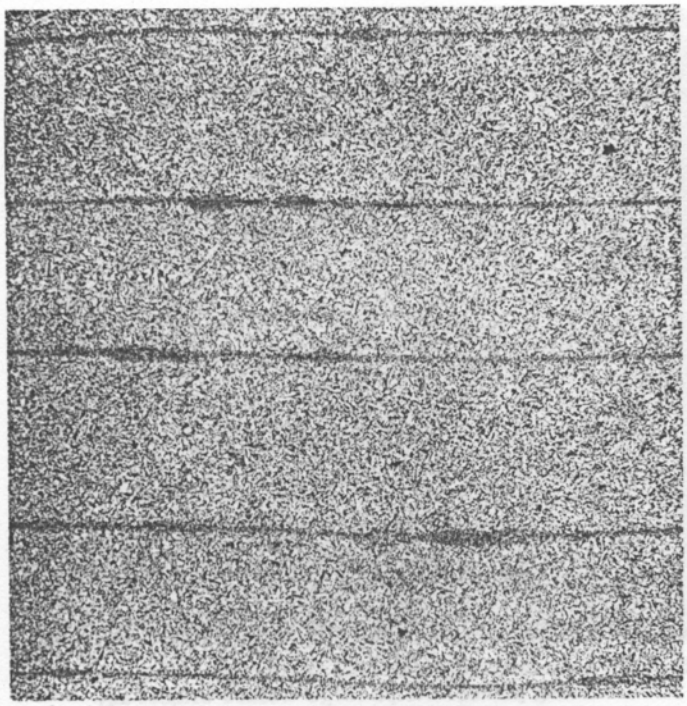


Fig. 9 — Photomicrograph showing increased carbon content at welding planes due to addition of small quantities of finely powdered white cast-iron particles between strips
Magnification × 25

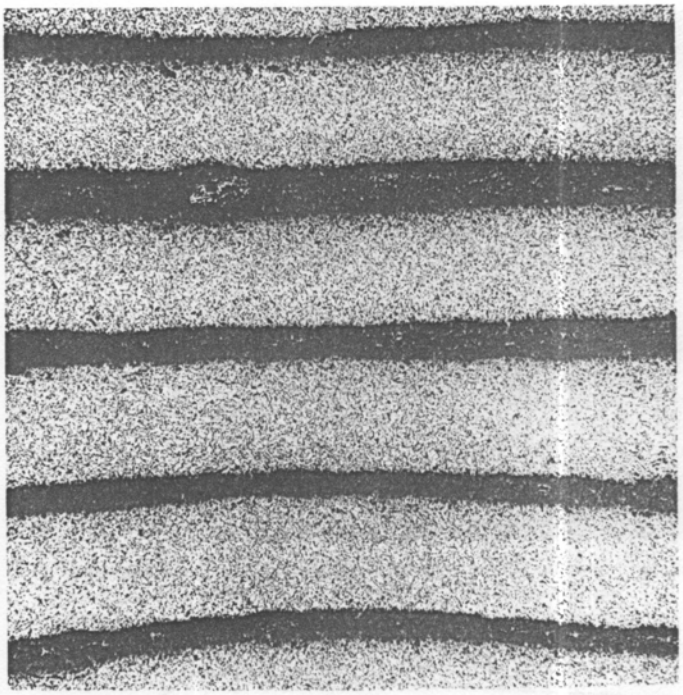


Fig. 11 — Photomicrograph showing more uniform carbon pick-up at welding planes due to more uniform distribution of particles of crushed white cast iron. Some of the larger particles have not yet diffused
Magnification × 25

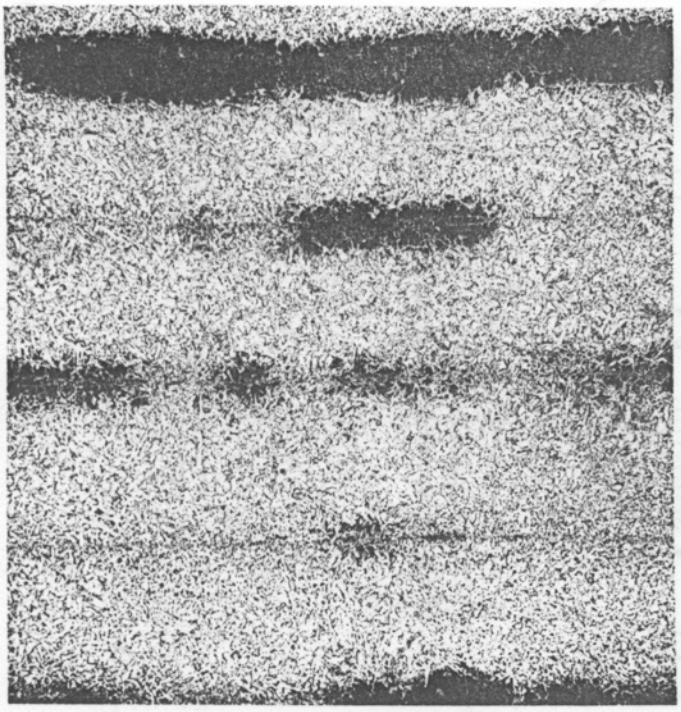


Fig. 10 — Photomicrograph showing increased carbon content at welding planes due to presence of powdered white cast iron between strips. Variation in carbon content is due to variability of distribution of crushed white cast-iron particles

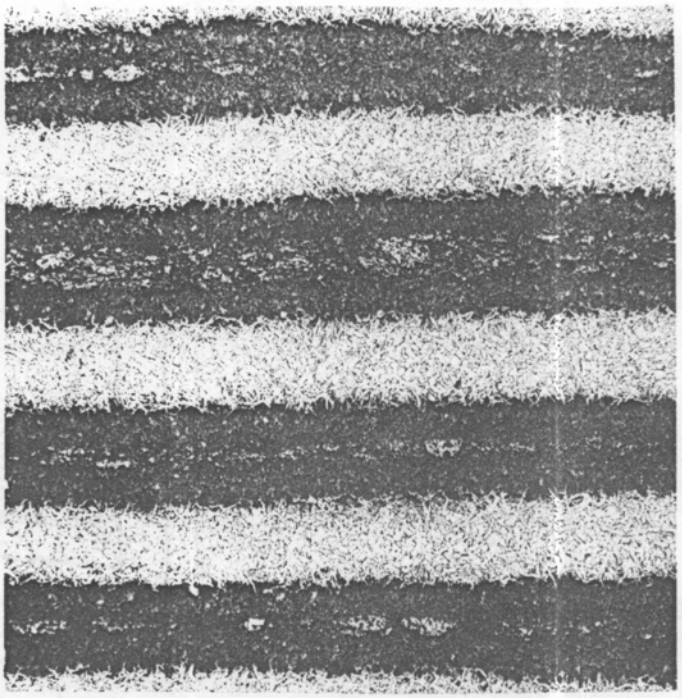


Fig. 12 — Photomicrograph showing increased carbon content at welding planes due to use of larger quantities of crushed white cast iron between strips. Note large amount of unabsorbed white cast iron at at the junction of each weld
Magnification × 25

Fig. 13 — Similar sample to Fig. 12, after allowing carbon migration to take place by heating for 8 h at 900°C, giving a carbon content of eutectoid composition. Welding planes only slightly visible
Magnification × 25

Needham has suggested[2] that, from the 5th century AD onwards at least, the Chinese were able to make steel by heating and forging lumps of cast iron between faggots of wrought iron.

NOTES AND REFERENCES

(1) Quoted verbatim from P. S. Rawson, "The Indian Sword", Copenhagen, 1967.

(2) Pitt Rivers Museum. University of Oxford: "Notes on Prehistoric and Early Iron in the Old World", by H. H. Coghlan. (Occasional Papers on Technology 8, Oxford, 1956, p. 84).

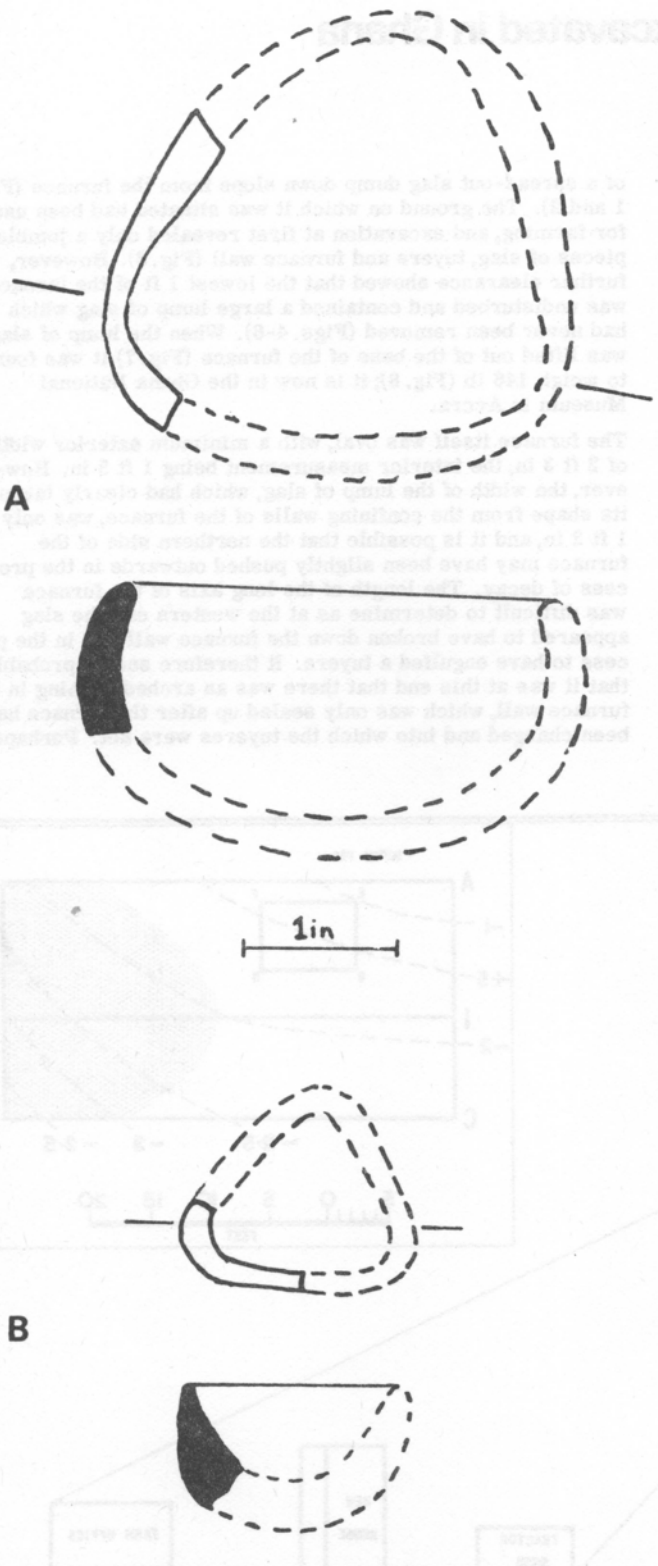


Fig. 2 — Triangular crucibles of Early Iron Age type (A probably unused)

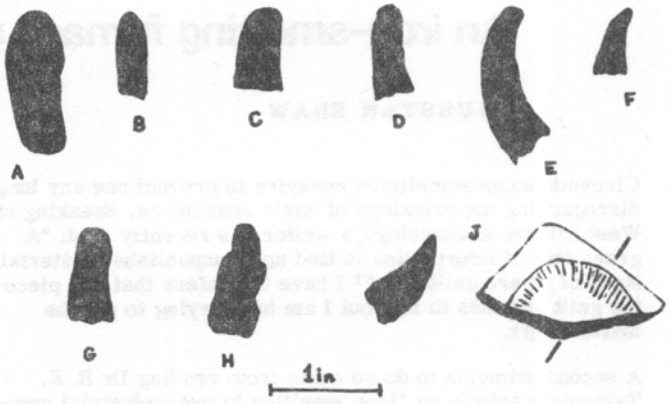


Fig. 3 — Crucible rim sherds: F dark-grey ware, remainder porous black

From under the path: thin strips of cast sheet for fibulae and buckles, clippings of sheet, various pins, parts of two decorated pins, a fibula (similar to Fig. 8, No. 6, in the British Museum Guide), a nail or rivet, a cast square pin, part of a bracelet with chevron marking (similar to Fig. 7, No. 8, of the British Museum Guide), the top of a fibula, the spring for a fibula, and a wire loop with what appears to be a fibula spring would on it. (It is possible that this shows the way of making springs for fibulae.)

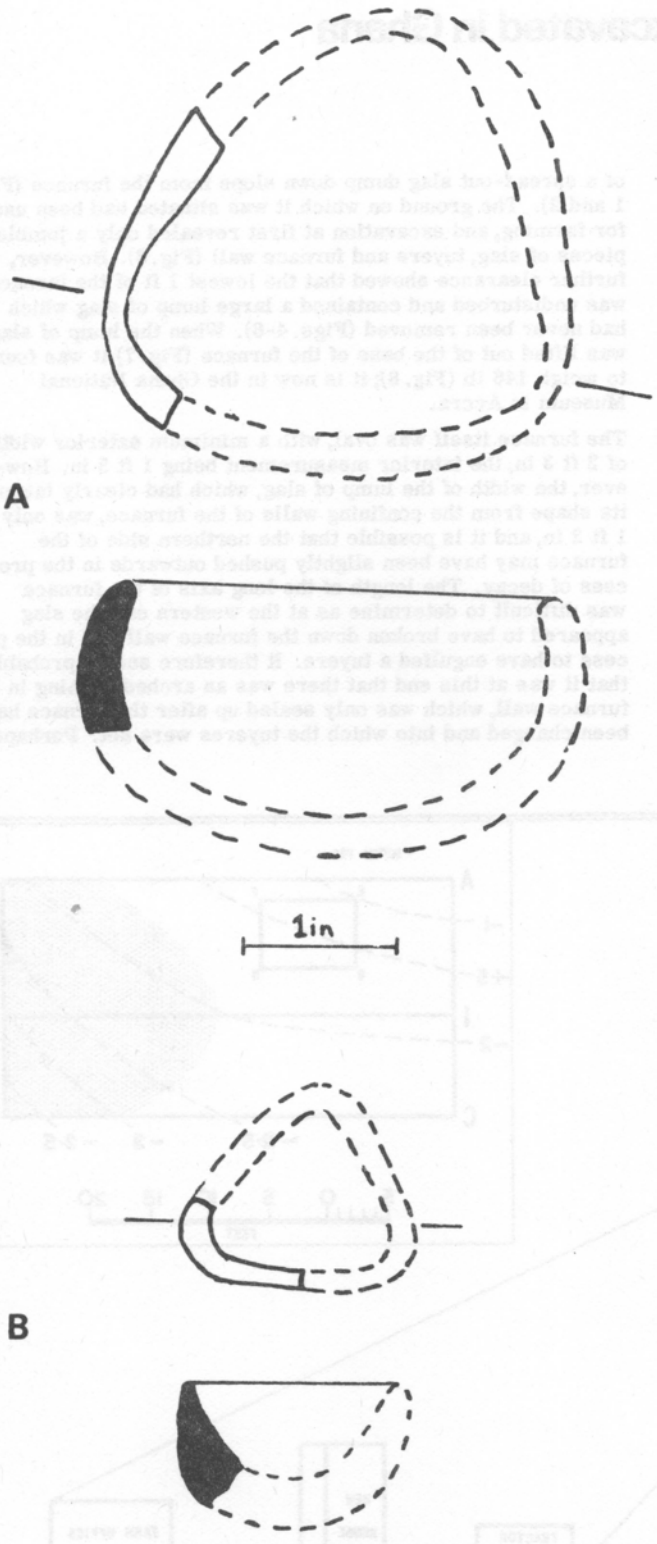
Dross from furnaces: drops of bronze and melting slag, a few pieces of very corroded artifacts; all were non-magnetic. There was no lead and no other smelting refuse. Five of the metallic drops were examined metallographically; they were found to be leaded tin-bronzes containing 5-20% lead. The hardness (HV) varied from 64 to 107. Four of these drops were in the cast state and had probably spilt from crucibles while pouring; the fifth had been reheated after spilling, probably by remaining in contact with the hot part of the hearth or furnace. A spectrographic examination of five drops showed that the zinc contents did not exceed 5%, suggesting that there was no intentional addition of zinc but that zinc, where present, had been introduced as an impurity by zinc-containing scrap.

AMONGST CRUCIBLES AND MOULDS

Two pieces of lead, two pieces of (?) bronze, and one piece of copper-base material with rust incorporated, which suggests part of a composite artifact of iron and bronze. One unidentified piece of an unsuccessful bronze casting.

REFERENCES

1. R. E. M. Wheeler: "Caistor, and a comment", Antiquity, 1929, 3, 182-187.
2. Donald Atkinson: Norfolk Archaeology, 1931, 24, 134.
3. F. R. Mann: J. Roman Stud., 1939, 29, 214.



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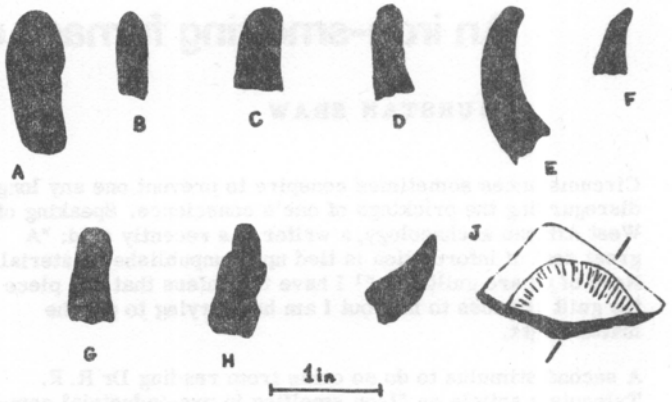

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An iron-smelting furnace excavated in Ghana

THURSTAN SHAW

Circumstances sometimes conspire to prevent one any longer disregarding the prickings of one's conscience. Speaking of West African archaeology, a writer has recently said: "A great deal of information is tied up in unpublished material. None of us are guiltless."[1] I have to confess that one piece of the guilt attaches to me—but I am here trying to put the matter right.

A second stimulus to do so came from reading Dr R. F. Tylecote's article on "Iron smelting in pre-industrial communities"[2] and from his request, while we were both present at the excavations of the Nok culture iron-smelting furnaces at Taruga in Nigeria,[3] for all known details of pre-industrial iron-smelting.

Accordingly I am writing this short note to put on record an iron-smelting site which I excavated on the Achimota College Farm in Ghana in 1938, assisted by Mr R. B. Nunoo. Part of the reason for previous non-publication is that for years the section and plan drawings made at the time, as well as the photographs, were lost to view in the course of my travels.

The furnace remains were situated on a gentle westward-facing slope, and a cutting 38 ft by 19 ft revealed the remains of a spread-out slag dump down slope from the furnace (Figs. 1 and 2). The ground on which it was situated had been used for farming, and excavation at first revealed only a jumble of pieces of slag, tuyere and furnace wall (Fig. 3). However, further clearance showed that the lowest 1 ft of the furnace was undisturbed and contained a large lump of slag which had never been removed (Figs. 4-6). When the lump of slag was lifted out of the base of the furnace (Fig. 7) it was found to weigh 146 lb (Fig. 8); it is now in the Ghana National Museum in Accra.

The furnace itself was oval, with a minimum exterior width of 2 ft 3 in, the interior measurement being 1 ft 5 in. However, the width of the lump of slag, which had clearly taken its shape from the confining walls of the furnace, was only 1 ft 2 in, and it is possible that the northern side of the furnace may have been slightly pushed outwards in the process of decay. The length of the long axis of the furnace was difficult to determine as at the western end the slag appeared to have broken down the furnace wall and in the process to have engulfed a tuyere. It therefore seems probable that it was at this end that there was an arched opening in the furnace wall, which was only sealed up after the furnace had been charged and into which the tuyeres were set. Perhaps

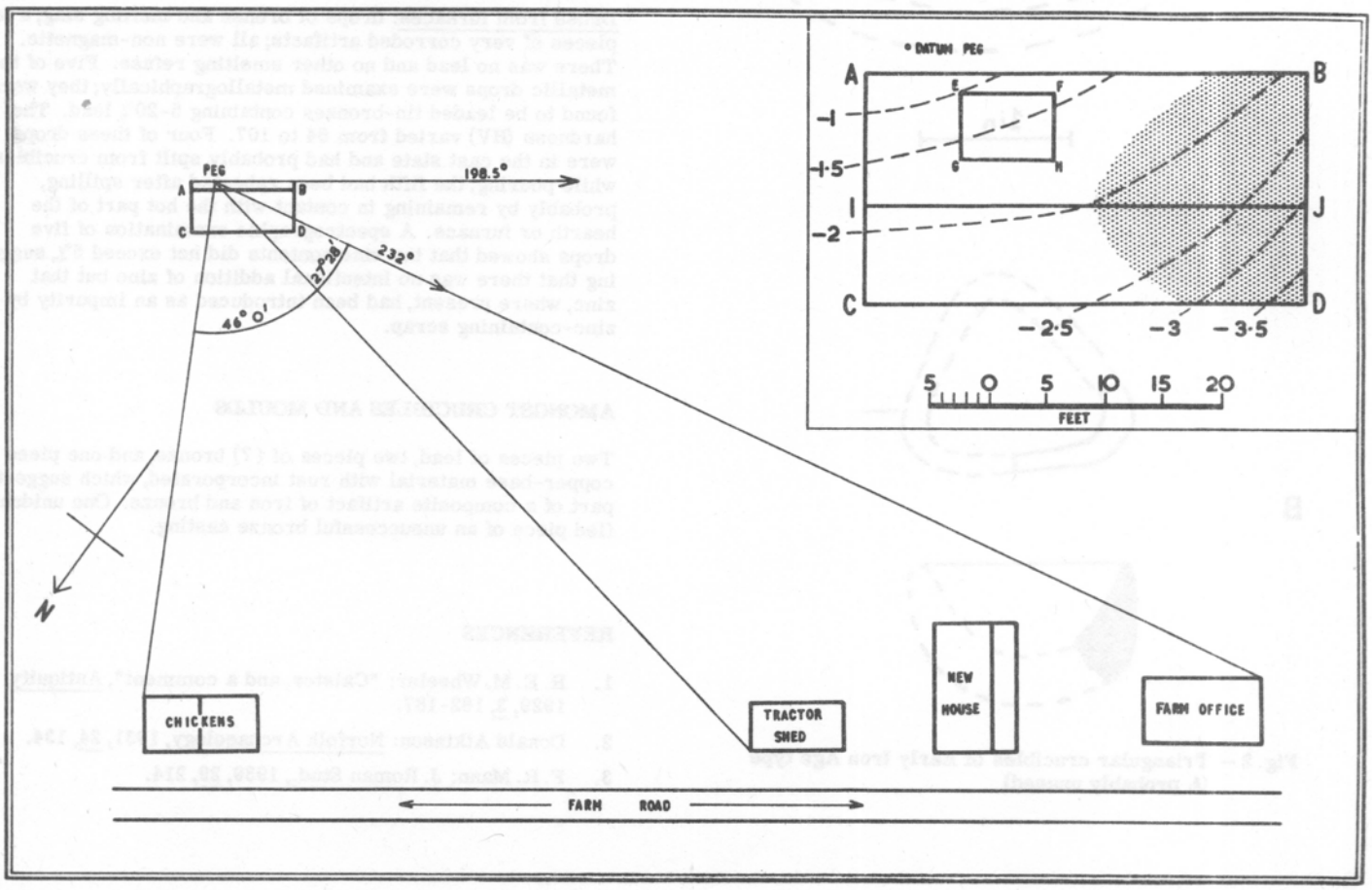

Fig. 1 — Achimota College Farm: ABCD indicates the area excavated. Directions by prismatic compass, included angles by box sextant (after C. S. Deakin). Not to scale. The inset shows the dump area stippled; EFGH is the area shown in Fig. 4

The author is Research Professor of Archaeology, University of Ibadan, Nigeria.

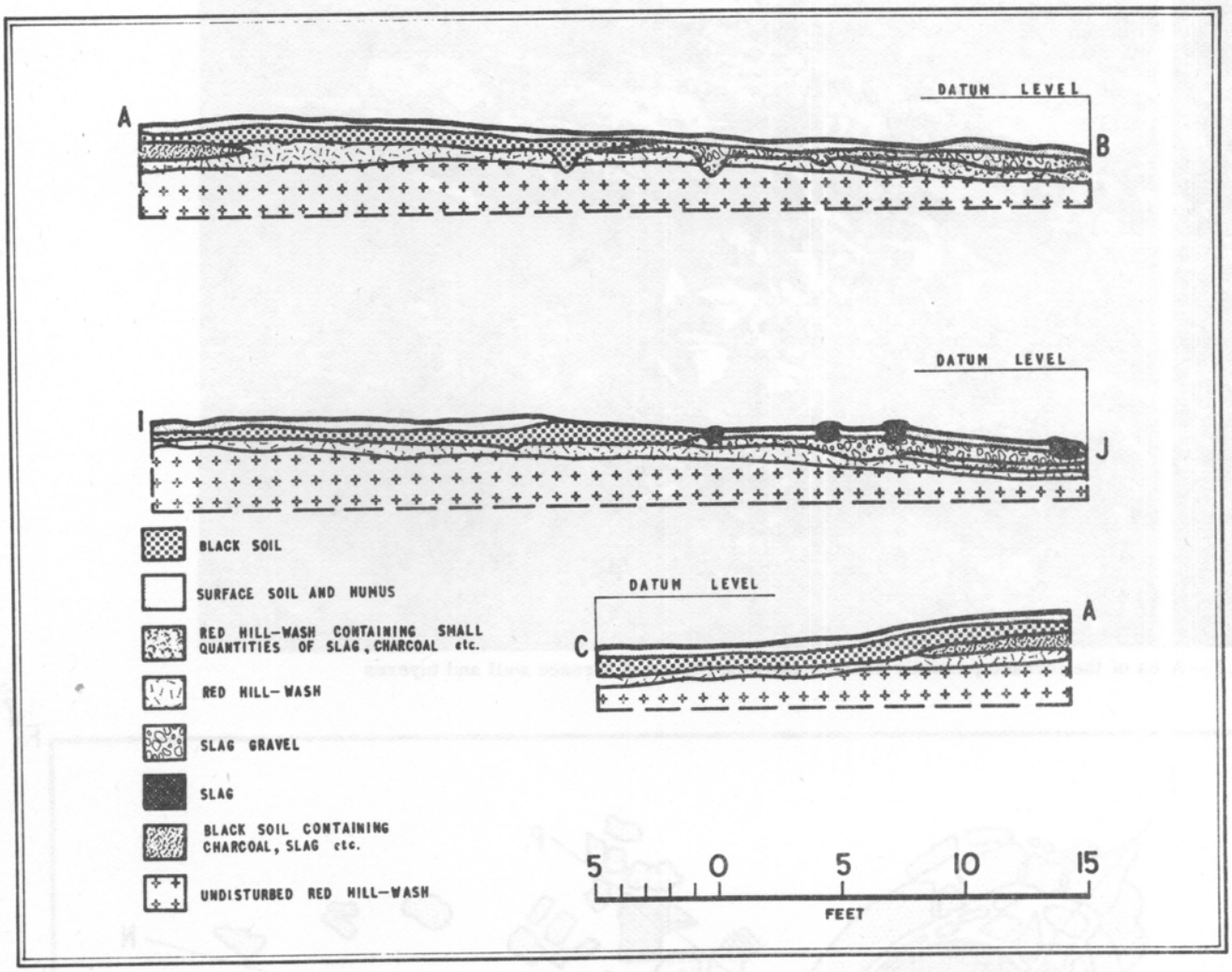

Fig. 2 — Sections along AB, AC and IJ shown in the inset in Fig. 1

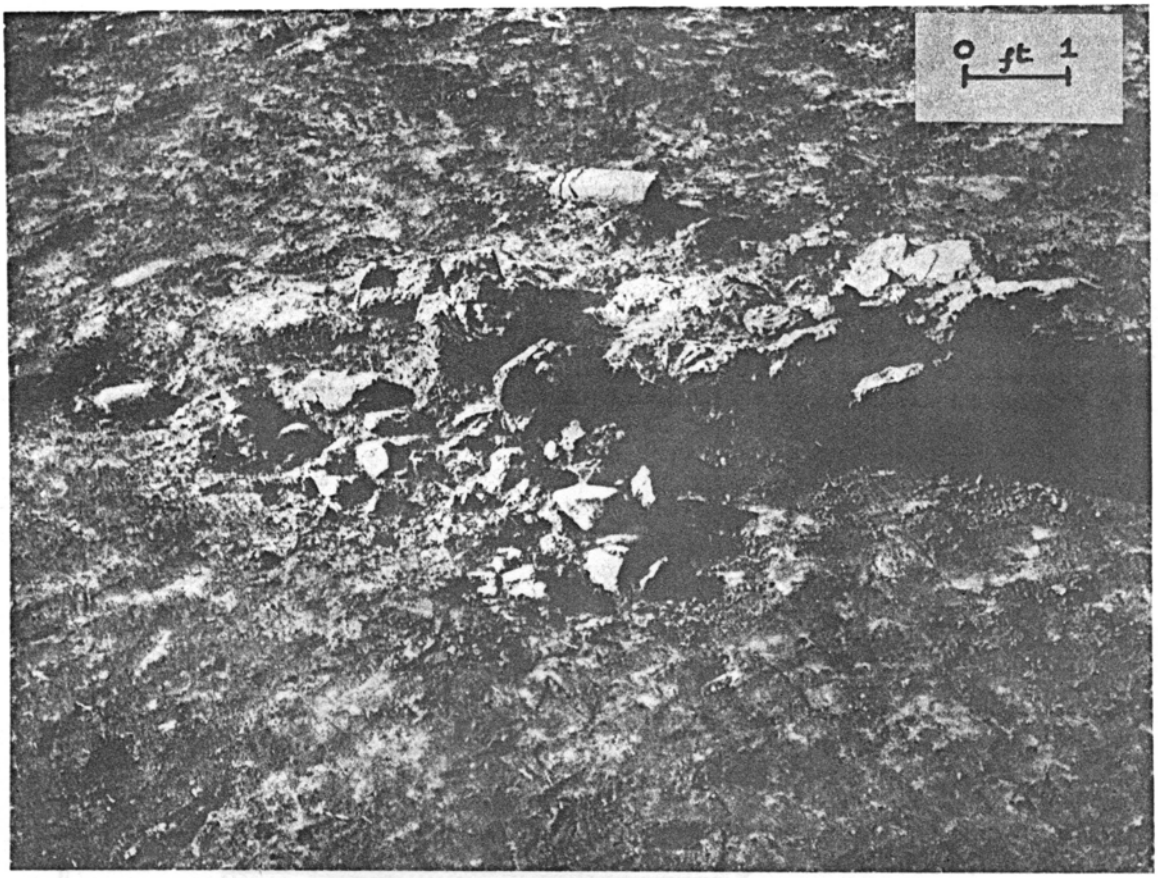

Fig. 3 — Area of the furnace partially cleared, showing pieces of furnace wall and tuyeres

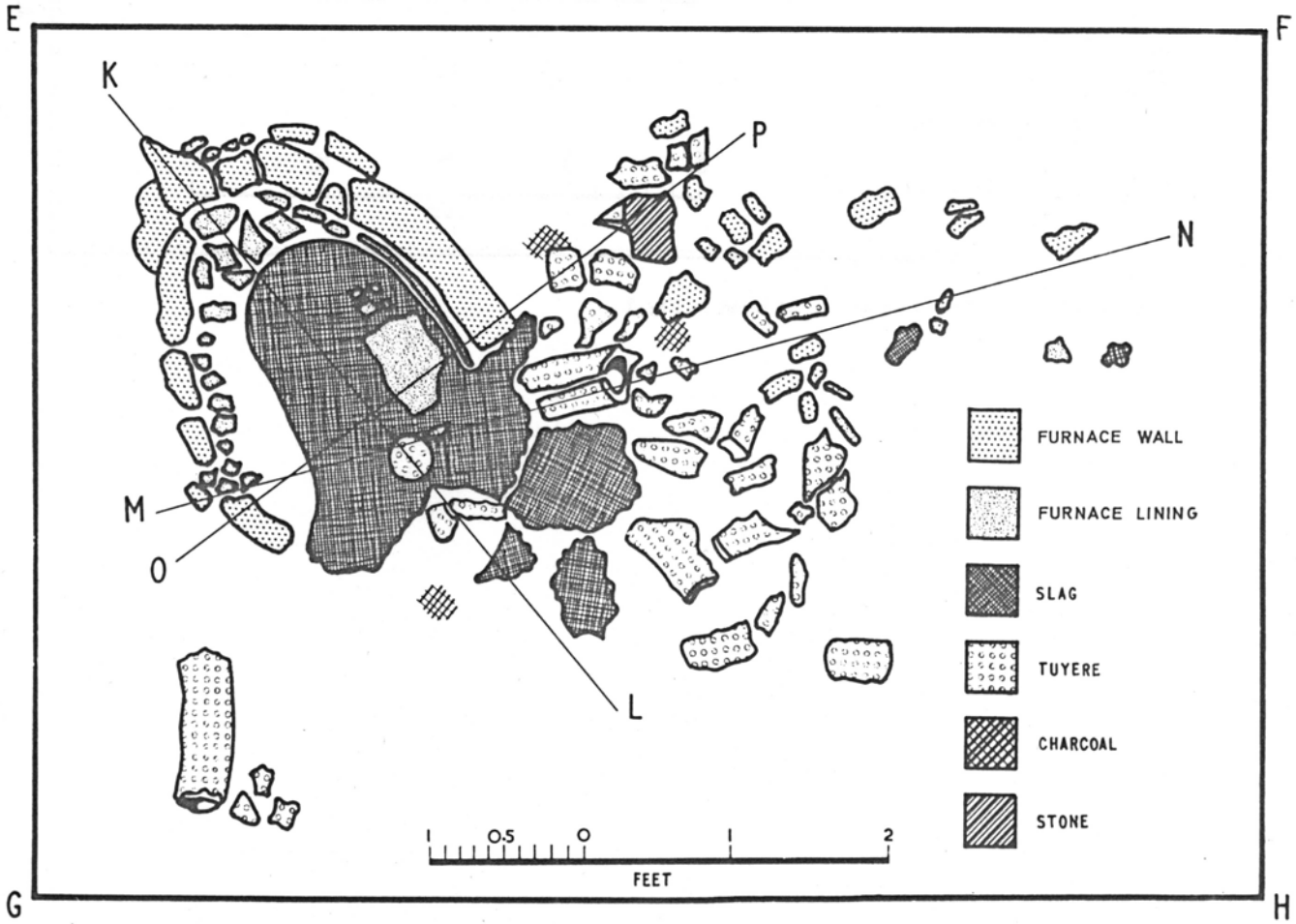

Fig. 4 — Plan of the furnace in the area shown as EFGH in the inset in Fig. 1

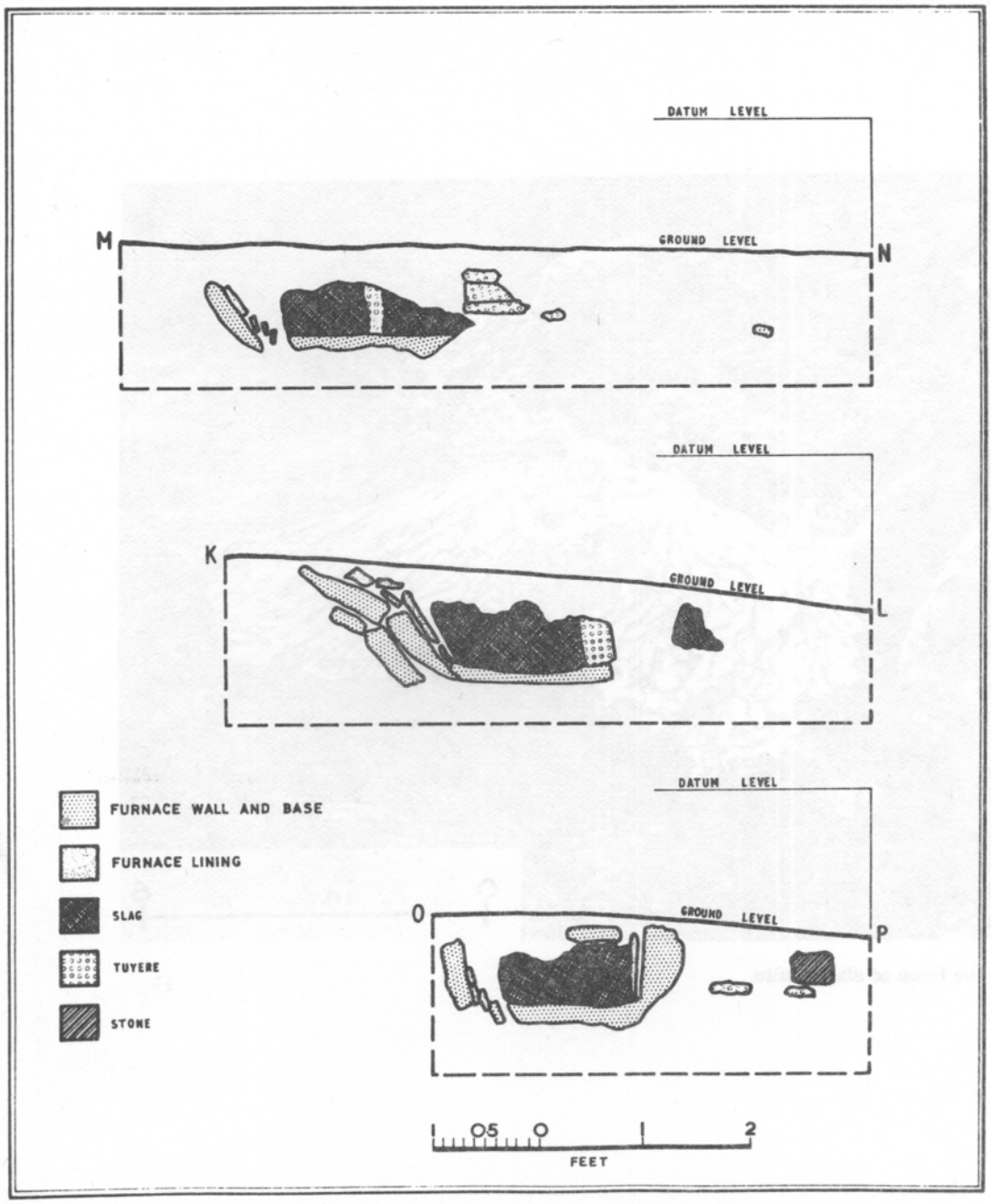

Fig. 5 — Sections through the furnace along the lines KL, MN and OP shown in Fig. 4

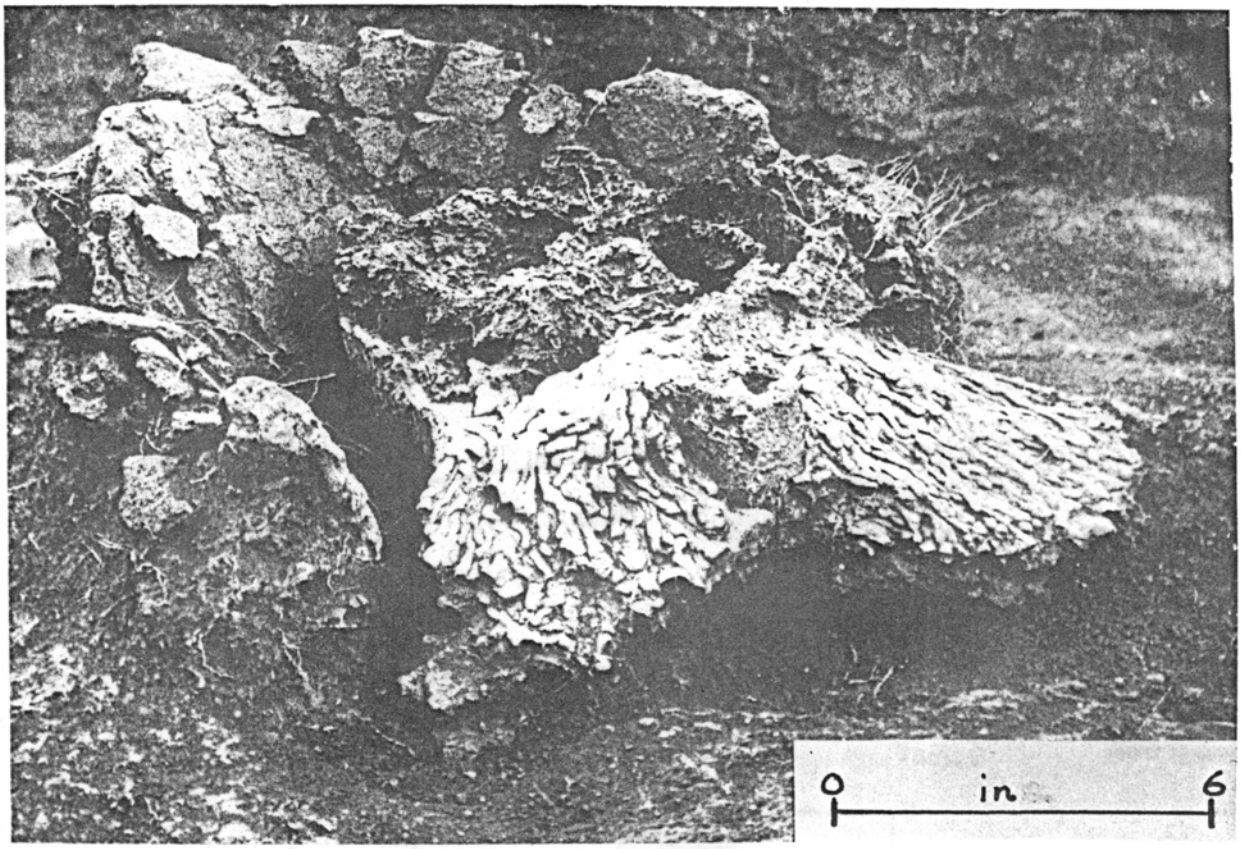

Fig. 6 — The furnace with the lump of slag in situ

Fig. 7 — The furnace after the lump of slag had been removed

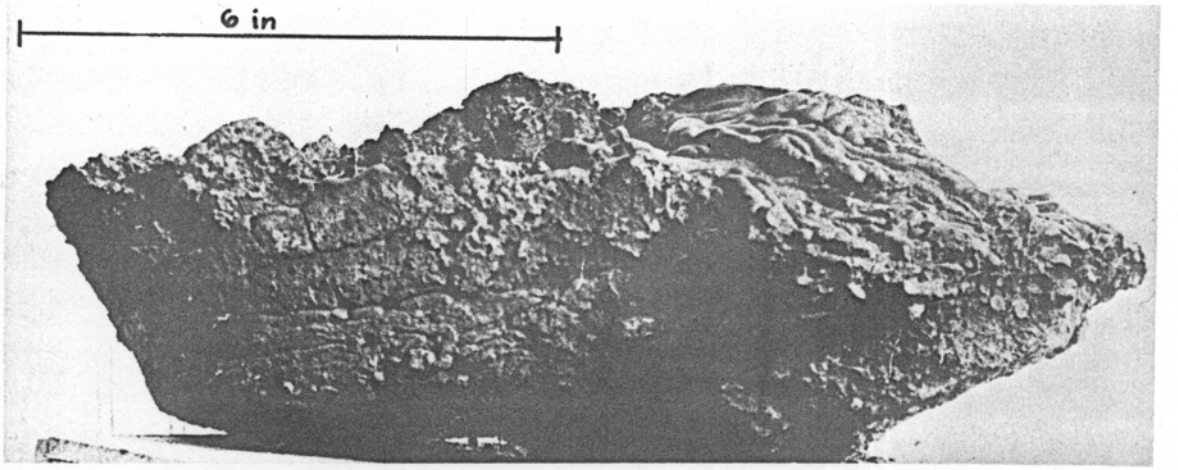

Fig. 8 — The lump of slag after removal (weight 146 lb)

the slag broke out at this end when the furnace was opened at the end of smelting. On this basis the maximum external length is estimated at 2 ft 9 in and the internal at about 1 ft 8 in.

It is impossible to estimate the original height of the furnace, but it is interesting to note that the internal measurements are smaller than in any of the African induced-draught furnaces of which Tylecote gives particulars.[2] The dimensions at ground level are comparable to the Sukur furnaces, but these are of the forced-draught type; the weight of product recovered from them is not given.[4]

There were no assoicated finds with the Achimota furnace to give any indication of date.

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Slag, cinder, and bear

G. R. MORTON AND JOYCE WINGROVE

In archaeology, and indeed in modern ironmaking terminology, the terms "slag" and "cinder" are used in a somewhat loose manner and the two terms are frequently used in the same context. In addition, the term "bear" appears to be restricted to coke blast-furnace practice only, although in the authors' opinions bear material was present in charcoal blast-furnaces and to a lesser extent in bloomery hearths.

The object of this paper is to consider the properties and structures of some of these products, to relate them to the processes, and to make recommendations for future terminology.

In iron-smelting operations, slag can be considered as the molten silicate complex formed by the combination of impurities and earthy matter agglomerated with the ore, fuel, and fluxes either in or added to the charge. Slags are formed from molten silicates which act as carriers for other impurities, either in solution or suspension. All slags are in the molten condition when in the furnace hearth. Slags are also formed in refining operations, in which case some of the metal from the charge, or fluxes specially added for the purpose, combine with the impurities in the charge, fuel, and fluxes to form a silicate slag complex.

In many metallurgical operations, drossy solid material collects on the top of the molten slag or metal, and when removed it resembles a mass of infusible or partially fused material, often intermixed with slag. Since this material has never reached a molten nor free-flowing condition in the furnace, it should be termed cinder.

Stead[1] defines a blast-furnace bear as "a solidified mass of metal or conglomerate below the hearth or floor level of a blast furnace, found after the furnace has been blown out after long service". When a blast furnace is blown out, the whole of the liquid mass below the level of the tapping hole eventually becomes solid and constitutes the bear, which is also known by other names, such as "old horse", "sow" and "salamander". In furnaces where the product is molten pig iron it is only when the furnace is being blown in that molten slag can come into contact with the refractory material of the hearth. When a well of metal has formed it must be the iron and not the slag which is responsible for the attack on the brickwork, and as a result of this attack bear is formed. Details of slag, cinder, and bear in relation to the furnace hearth are shown in Fig. 1.

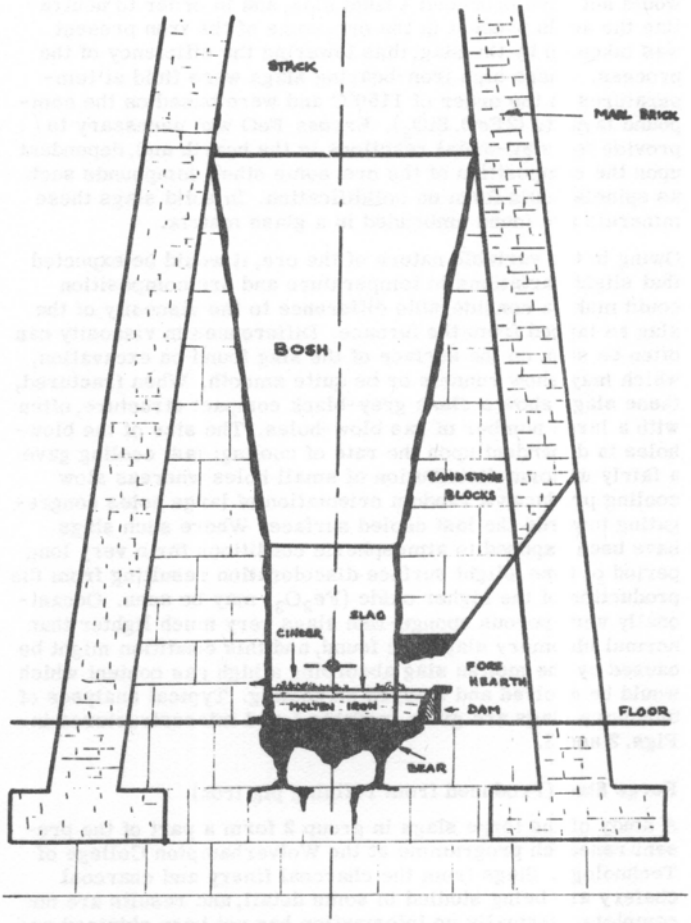

Fig. 1 — Sketch showing sites of formations of slag, cinder, and bear in the blast-furnace

TYPES OF SLAG

The main types of slag found as a result of ironmaking operations can be conveniently classified according to the amount of iron lost to the slag. In the early bloomery process and in slag produced by the conversion of pig iron to the form of bar, the iron loss was generally high and the slag contained in the order of 30-50% Fe, whereas in early blast-furnace slags the iron loss to the slag was as low as 2-4%. In modern blast-furnace slag this iron loss is less than 1%. It is therefore convenient to classify slags by consideration of the iron lost to the slag, and in the following manner:

1. Bloomery slags, in which the iron acted as a flux to the gangue material of the ore, thus causing high iron loss to the slag. The bloomery process was the only smelting operation in which some of the iron contained in the charge acted as a flux, and the iron content of the slag was in the order of 40-50% of the slag.

2. Slags from processes relating to the production of malleable bar by refining pig iron in the forge, where the iron loss was high. Little is known of several of these processes, but they have been considered in some detail by Morton and Mutton[2]. These are subdivided as follows:

(i) Charcoal finery
(ii) Charcoal chafery
(iii) Coke/coal refinery
(iv) Coke/coal finery
(v) Coke/coal chafery
(vi) Puddling furnace (usually known as tap cinder)
(vii) Balling and reheating furnace

3. Blast-furnace slags, where the iron loss was low.

(i) Charcoal furnace
  (a) where sufficient Al_2O_3 was present in the ore to act as a flux
  (b) where a small quantity of lime was added to the charge.
(ii) Slag from blast-furnaces where coke or coal, or a mixture of coke and coal, was the fuel used and where the air blast was not preheated (cold-blast slag)
(iii) Slag from blast-furnaces where coke or coal, or a mixture of coke and coal, was the fuel used and the air blast was preheated (hot-blast slags).
(iv) Modern blast-furnace slags.

The authors are at the College of Technology, Wolverhampton.

Bloomery slags (smelting processes where iron loss is high)

Morton and Wingrove[3,4] have considered the bloomery process and the slags produced during the Roman era in detail, and later bloomery slags are now under consideration. Since the operating temperatures of the bloomery were low, little or no special flux such as lime could be added, since this would not have produced a fluid slag, and in order to neutralize the acids present in the ore, some of the iron present was taken up by the slag, thus lowering the efficiency of the process. These high iron-bearing slags were fluid at temperatures in the order of 1150°C and were based on the compound fayalite ($2FeO.SiO_2$). Excess FeO was necessary to provide for slag-metal reactions in the hearth and, dependent upon the composition of the ore, some other compounds such as spinels could form on solidification. In solid slags these minerals are found embedded in a glass matrix.

Owing to the variable nature of the ore, it would be expected that slight variations in temperature and ore composition could make a considerable difference to the viscosity of the slag as tapped from the furnace. Differences in viscosity can often be seen on the surface of the slag found on excavation, which may show runnels or be quite smooth. When fractured, these slags show a clean grey-black compact structure, often with a large number of gas blow-holes. The size of the blow-holes is dependent upon the rate of cooling: fast cooling gave a fairly uniform distribution of small holes whereas slow cooling produces a random orientation of large holes congregating towards the last cooled surface. Where such slags have been exposed to atmospheric conditions for a very long period of time, slight surface discoloration resulting from the production of the higher oxide (Fe_2O_3) may be seen. Occasionally very porous sponge-like slags very much lighter than normal bloomery slags are found, and this condition might be caused by the molten slag absorbing a high gas content which would be evolved and trapped on cooling. Typical analyses of bloomery slags are given in Table I, and microstructures in Figs. 2 and 3.

Forge Slag (Produced from refining pig iron)

A study of the forge slags in group 2 form a part of the present research programme at the Wolverhampton College of Technology. Slags from the charcoal finery and charcoal chafery are being studied in some detail, and results are not complete. Virtually no information has yet been obtained on slags from groups (iii), (iv), and (v). These are related to processes where attempts were made to use mineral coal or coke for heating purposes. All slags in this group were fluid at furnace operating temperatures and were tapped as a molten magma.

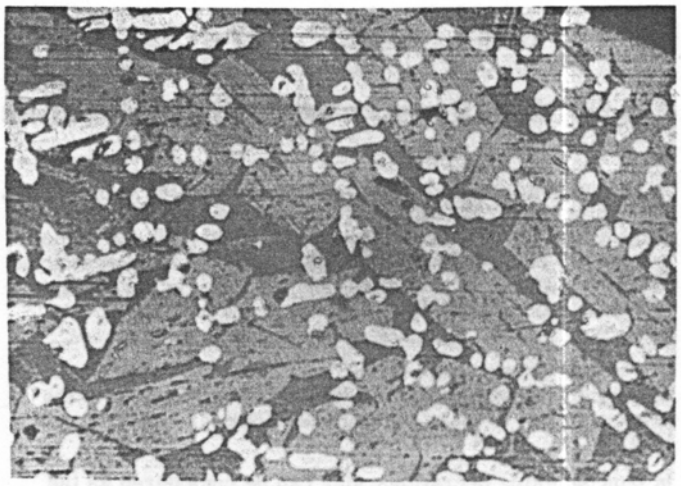

Fig. 3 — Microstructure of Stoney Hazel slag
Magnification × 100

The conversion of pig iron into the form of malleable bar (wrought iron) in the charcoal finery and chafery has been considered in detail by Morton[7], and the fuel transition from charcoal to coal by Morton[8] and Morton and Mutton[9]. From the variety of processes covered by this group it would be expected that the characteristics of the slags would also vary. Nevertheless, those examined to date appear to contain the compound fayalite, which in itself is high iron-bearing. As with bloomery slags, the fayalite is associated with a glass phase, but in these slags oxides of iron other than wüstite could be present, and the iron in the slag can be in the order of 50% of the slag. It follows therefore that slags in this group are likely to be somewhat similar in appearance to bloomery slags, but perhaps more compact. Other differences may be found, and these will be the subject of a further paper on completion of the section of the work now being undertaken. Typical analyses of slags in this group are given in Table II.

BLAST-FURNACE SLAG (Low iron loss)

The higher temperatures attained in the blast-furnace permitted the formation of slags containing silicates of lime and alumina instead of silicates of iron as in the bloomery process, thus leaving more iron available for reduction and providing slags low in iron.

TABLE I Analyses of Bloomery Slags, %

	Roman			Medieval		
	1[5] Ashwicken	2 Worcester	3[6] Gt. Casterton	4 Nun's Well	5 Rushall	6 Stoney Hazel
Fe_2O_3	7.70	10.57	3.20	6.90	4.30	3.20
FeO	62.10	61.85	46.10	47.50	45.50	56.90
SiO_2	21.20	16.15	26.20	24.20	24.70	24.20
CaO	0.40	3.05	7.00	1.10	5.60	2.50
MgO	1.40	1.25	1.10	0.30	2.60	0.90
MnO	0.50	0.24	0.70	2.50	0.80	0.13
Al_2O_3	3.20	5.86	9.50	14.50	13.60	8.90
P_2O_5	1.72	0.03	2.30	1.60	0.60	0.71
S		n.d.		n.d.	n.d.	0.22
TiO_2			0.45			
Fe				1.20	1.40	1.90
Total	98.22	99.00	96.55	99.80	99.10	99.56

TABLE II Analyses of Forge Slags, %

Group	(i)	(i)	(ii)	(ii)	(iii)	(iv)	(vi)
	Powick	Ipsley	Back-barrow	Ipsley	Little Aston[10]	Little Aston	Staffs.
FeO	65.10	69.10	33.20	58.80	56.59	45.20	58.67
Fe_2O_3	9.10	11.20	8.60	9.90			17.00
SiO_2	11.20	7.70	20.02	17.80	12.50	22.62	11.76
CaO	3.10	2.50	4.20	2.60	3.20	nil	2.88
MgO	0.29	0.10	1.94	0.22	0.54	0.15	0.29
MnO	3.83	0.58	0.74	2.50	0.24	0.06	0.57
Al_2O_3	3.50	5.70	10.60	4.90	7.92	13.38	2.84
P_2O_5	2.59	1.80	1.00	2.01	0.51	n.d.	4.27
S	0.10	0.08	1.83	1.05	2.47	0.08	3.11 FeS
TiO_2	0.23	0.10					
Fe	0.75	0.88	17.20	0.70			
C					13.89		
H_2O					1.40		
Alkali					0.74		

The development of blast-furnace slags over the years can be directly related to this ability to obtain higher and higher air blast volumes and pressures. The effect of increasing blast on the operating temperature made possible a change in the fuel used from charcoal to coke, and to coke-coal mixtures, which led to the ability to use lime in greater quantities as a flux. Blast-furnace slags can therefore be divided into groups according to the nature of the blast, the fuel used, and the quantity of lime added as flux (Table III). This ability to use more lime as a flux also allowed more sulphur to be taken up by the slag, which meant that poorer-quality ores (i.e. those with higher sulphur content) could be successfully smelted.

All these slags have definite identifiable visual, chemical, and mineralogical characteristics. Early blast-furnace slags are glassy and, as the lime content increases, the slag takes on a more stony appearance, even to the point of slaking after many years of exposure to atmospheric conditions. The visual characteristics of these slags are given in Table IV.

It is to be expected that the chemical analyses of the slags will vary according to the nature of the gangue material associated with the ore, but in the charcoal blast-furnaces the ratio of the sum of the bases to acids is always such that the resultant slag has a glassy appearance. Table V shows the analyses of charcoal blast-furnace slags. The appearance of cold-blast coke furnace slags, on the other hand, is markedly affected by the rate of cooling; rapid cooling retains a glass whereas slow cooling produces a calcium silicate stony mass. Thus cold-blast slags tapped from the furnace into cast-iron slag bogies will show a glassy surface where the melt was in contact with the bogie, and this turning to stone a short distance from the surface. Hot-blast slags are generally stony and unless very rapidly cooled show little glass.

Cinder

The definition of cinder suggests that drossy material insoluble in the molten slag at a particular temperature might be taken into solution with progressive increase in temperature. It therefore follows that bloomery cinder will differ in constitution from that found on the top of charcoal blast-furnace slags, and this again will differ from that found on slag from later blast-furnace processes where still higher temperatures were obtained. In the bloomery process the slag was either tapped off into a slag pit via a runner from the hearth taphole (i.e., tap slag[15]) or left in the hearth and removed

TABLE III Analyses of Blast-Furnace Slags, %

	Charcoal blast-furnace			Coke/coal blast-furnace	
	Cannock 1561-1650	Charlcot 1700-1792	Duddon 1736-1866	Tipton[11] c1850 coke cold-blast	Ebbw Vale[12] c1850 hot-blast
SiO_2	47.90	52.50	56.40	39.52	43.55
Al_2O_3	23.20	20.17	12.40	15.11	20.40
CaO	11.90	17.00	14.60	32.52	28.85
MgO	7.20	4.57	3.60	3.49	1.10
MnO	3.30	1.86	9.80	2.89	0.25
FeO	4.40		2.60	2.02	3.74
Fe_2O_3		4.30			
P_2O_5	0.10	0.32			0.35
S	0.10	0.01		2.15 (CaS)	0.65

TABLE VI Visual examination of representative samples of slag

Group	A	B	C	D	E
Colour	Mainly light to dark grey. Some opaque milky green and some bottle-green patches	Lightish milky grey-green	Milky grey-green to turquoise	Greyish-white chalky appearance.	Light to medium grey.
Texture	All pieces show glaze. Some patches completely vitrified. Some pieces of unburnt charcoal present.	All pieces highly glazed. Many completely vitrified patches. Some pieces of unburnt charcoal present.	Outer (top) surfaces cement-like. Large proportion of striated glass. Some outer separation of clear green-brown glass.	Mostly rather soft and slaked, due to weathering.	Hard, concrete-like.
				No glassy phase visible	
Porosity	Variable, gas holes mainly small, though some up to 1 cm dia. Well distributed.	Greater than A, with average pore size larger. Well distributed.	Outer (top) surfaces pin-pointed with many mainly small holes.	Gas holes largely invisible, but in places medium-sized, even, and closely spaced.	Low, except in darker pieces, where there are closely spaced small to medium-sized holes.
Rust	Present in fair quantity on the most porous pieces.	Present in fair quantity in many porous pieces.	None visible.	Infrequently visible	Infrequently visible.
Smell (on fresh break)	None	None	H_2S	Strong smell of H_2S	Sulphur.

General remarks: For all glassy slags the glassy appearances decrease with increasing porosity, and the colour lightens in most cases.

The diameters of the gas holes are stated: very small—pin-head to 1mm; small—1-3mm; medium—3mm-1cm.

TABLE V Analyses of charcoal blast-furnace slags, %

	Cannock	Rievaulx[13]	Sharpley Pool	Rockley[14]	Charlcot	Duddon
	1561-1650	1577-1790	1652	1652-1736	1700-1763	1736-1866
SiO_2	49.66	45.30	49.30	45.90	52.50	56.40
Al_2O_3	23.16	22.48	11.40	19.07	20.17	12.40
CaO	11.92	22.80	22.80	18.40	17.00	14.60
MgO	7.16	3.69	12.00	9.19	4.57	3.60
MnO	3.29	1.17	0.84	2.95	1.86	9.80
FeO	4.37		2.70			2.60
Fe_2O_3		3.72		2.43	4.30	
P_2O_5	0.073	0.055	trace	0.50	0.32	
S	0.10		trace		0.01	
Sulphide		0.032		0.102		
Sulphate		0.19		0.058		

when cold as "furnace bottoms". The upper surface of these furnace bottoms might well include drossy material which is, in effect, cinder and the two terms "cinder" and "slag" should not be confused. They are structurally different and also differ in chemical and mineralogical composition. Cinder found on the top of slags tapped from the blast-furnace, particularly from those of the charcoal era, includes many readily identifiable constituents such as charcoal, prills of iron, glassy slag, oxides and sulphides of iron, and many other insoluble phases. Details of cinder found on the top of pieces of slag taken from the Cannock site are shown in Fig. 4.

Blast-Furnace Bear

At the site of Cannock charcoal blast-furnace, Morton[16] found a number of slagged hearthstones and a mass of bear approximately 18 in dia. and 3 in thick. The bear material was heavy and had the appearance of slag produced in the charcoal finery forge rather than the bottle-green slag usually made at Cannock and other charcoal blast-furnaces. It was apparent that the bear was formed by contact of molten iron and slag with the silica stone of the furnace hearth, and that its structure would be related to the reactions occurring between the metal, slag, and refractory, and the tramp materials held in suspension in the molten mass. A section through this sample of bear (Fig. 5) shows the high iron-bearing mass with entrapped charcoal, metallic iron prills, and other materials. Adhering to the underside were larger pieces of pig iron and partially slagged refractory material from the hearth. On fresh fracture the colour appeared a lighter grey than that of forge slags, and x-ray analysis confirmed the matrix to be a mixture of crystalline anorthite ($CaO.Al_2O_3.2SiO_2$) and cristobalite. The presence of anorthite in its crystalline form confirms the slow rate of cooling to which the bear would have been subjected on the

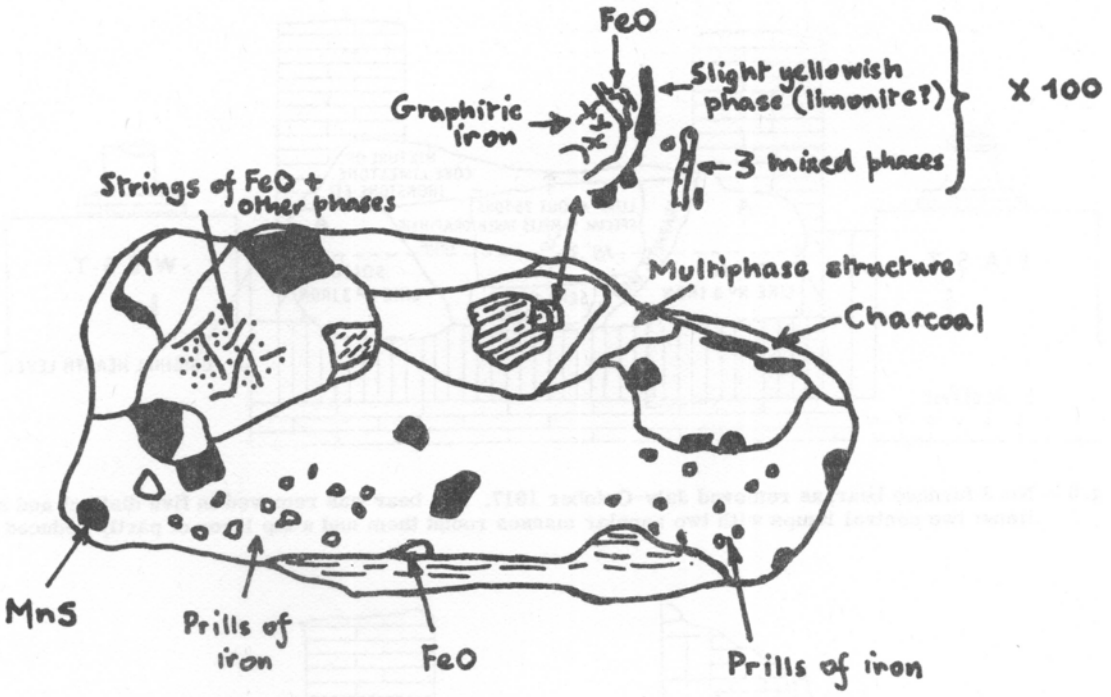

Fig. 4 — Cannock cinder

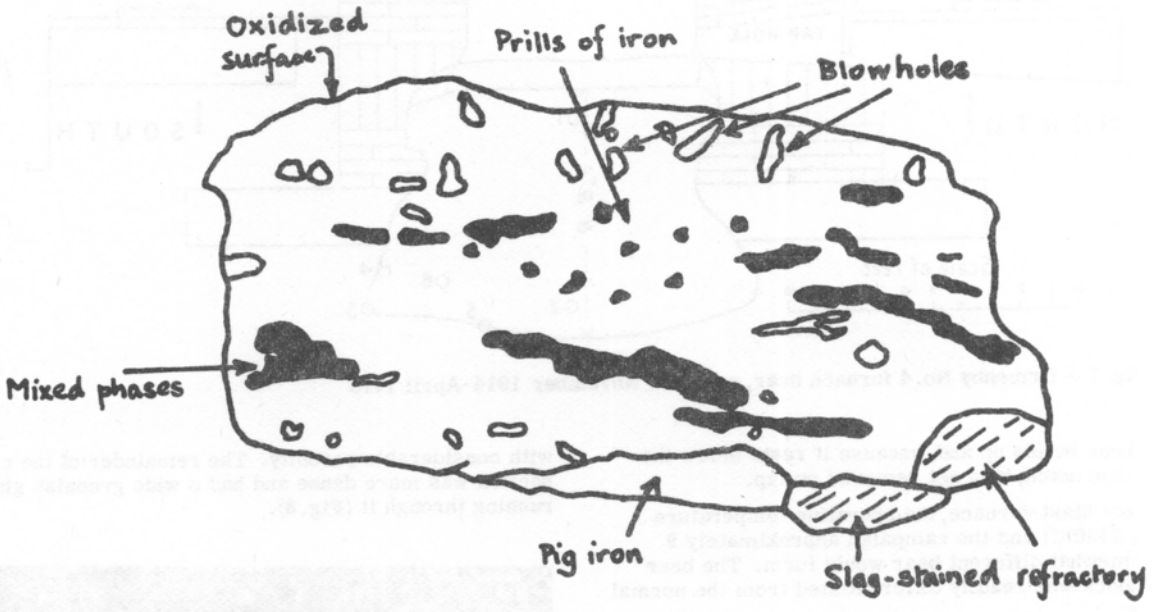

Fig. 5 — Section through Cannock cinder

blowing out of the furnace. The other material has become entrapped in this matrix.

The type of bear from coke blast-furnaces considered by Stead was formed over a long period of years, during which time the bottom linings were more or less fluxed away and replaced by a metallic agglomerate in which a large and varied number of substances collected. This mass contained a mixture of metal, kish, and partially fused brickwork, in which sulphides of iron and manganese, masses of oxides and silicates of iron, and other compounds were present. Details of typical bears are given in Figs. 6 and 7, each of which would weigh many hundreds of tons[17]. Bear of this type were common in coke blast-furnaces where the operating temperature was high (> 1500°C) and the campaign lasted many years (4-5 years +).

Since the melting temperature of the refractory material in the hearth was far above that of the liquid iron, it follows that the main action on silica and firebricks was due to chemical attack and not by simple fusion. In addition it must be noted that, when a furnace is blown in at the beginning of a new campaign, the only time that molten slag is in contact with the hearth is prior to the first tap. It is therefore the metal which is mainly responsible for the attack on the brickwork, and every class of silica brick and firebrick gives way to the action of the liquid iron. Stead also points out that all pig irons contain manganese, which is highly reactive with silica, and produces a fusible manganese silicate, green in colour. He gives the reactions:

$$2Mn + SiO_2 \rightarrow 2MnO + Si$$

$$2MnO + SiO_2 \rightarrow 2MnSiO_3$$

This green discoloration is frequently seen on the side walls of early charcoal furnaces. Alumina in the refractory materials will be fluxed away with the manganese silicates and iron will also form the silicate fayalite ($2FeO.SiO_2$). In this

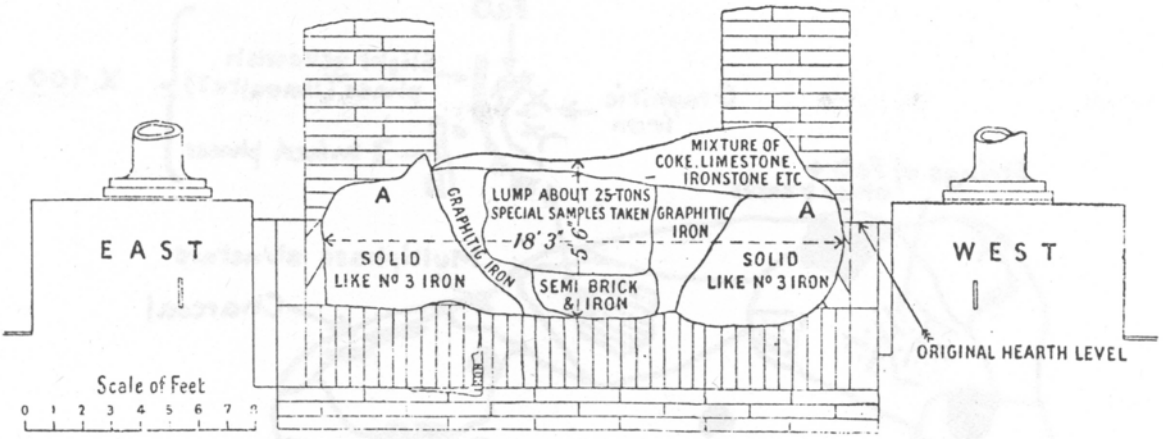

Fig. 6 — No. 3 furnace bear, as removed July-October 1917. The bear was removed in five distinct and separate formations: two central lumps with two annular masses round them and a top layer of partly reduced material

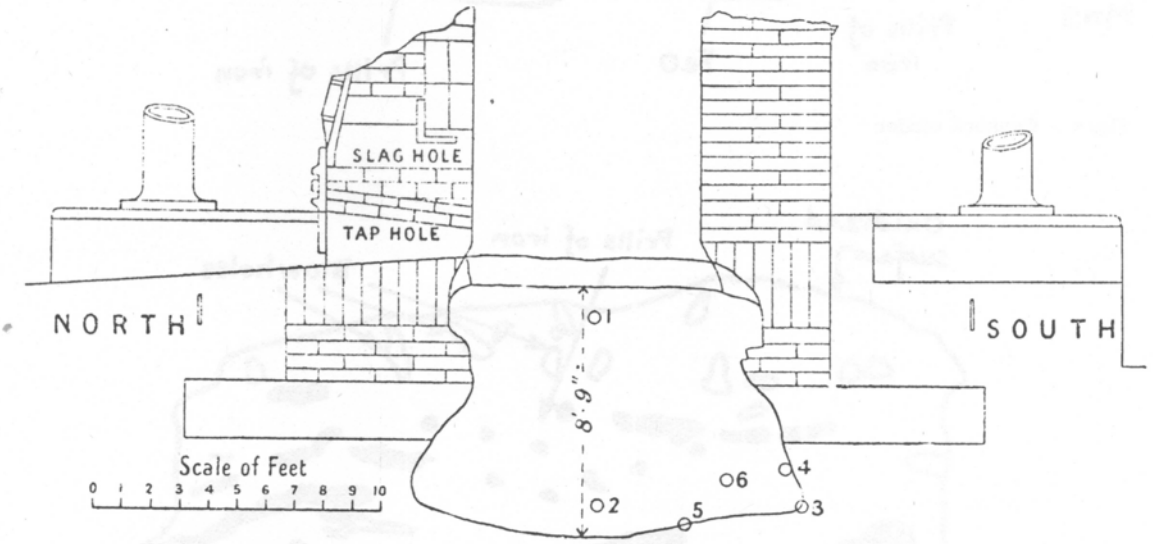

Fig. 7 — Ormesby No. 4 furnace bear, removed November 1914-April 1918

manner the bear builds up and, because it rests below the level of the iron notch, it is not removed on tap.

In the charcoal blast-furnace, the operating temperature being low (< 1450°C) and the campaign approximately 9 months, a somewhat different bear would form. The bear found at Cannock was readily differentiated from the normal working slag.

Bear material from bloomery hearths

With the still lower operating temperature of the bloomery hearth (< 1350°C) and the working cycle of approximately 12 h, it follows that the bear material might be limited only to the attack of the slag on the refractory material in the region of the hearth and sidewalls. Since in the bloomery furnace the reduced iron was never molten in the hearth, virtually all the attack on the lining must have come from the molten slag, at temperatures in the order of 1100-1250°C. Bloomery furnace linings were usually made from clay minerals, probably in the form of an agglomerate of kaolinite and free quartz grains. At about 500°C, water of crystallization would be driven off from the clay, leaving amorphous SiO_2 and Al_2O_3, and it would be with these that slag reactions would occur.

A sample of bear material 2-3 in thick was obtained from Rockley bloomery, and examined visually, microscopically, and subjected to x-ray analysis. The appearance of the working surface was rough and eroded. Immediately below the surface the structure was quite hard and the colour dark grey, with considerable porosity. The remainder of the cross-section was more dense and had a wide greenish glassy band running through it (Fig. 8).

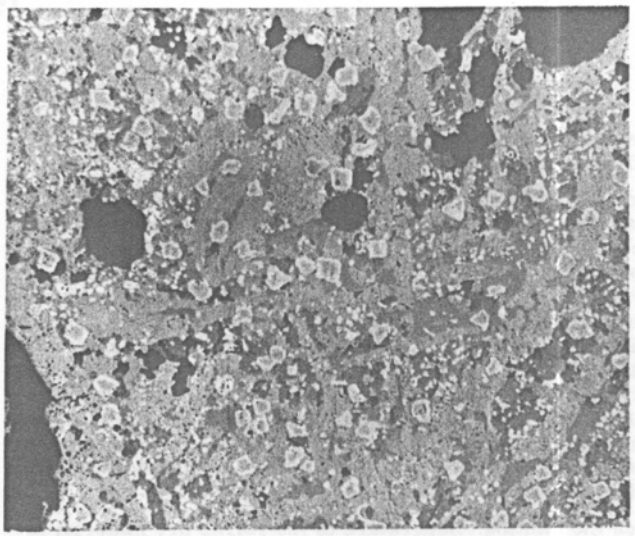

Fig. 8 — Section of Rockley lining

The microsection near the working surface showed a structure varying from one very similar to slag from the same furnace (Fig. 9) to one containing large laths of fayalite in a refractory background. A section from the centre of the sample showed a few large laths of fayalite in a refractory matrix. Thin sections showed, in addition, many feathery dendrites of mullite, and near the working face there were areas opaque to polarized light. X-ray analysis confirmed the presence of fayalite, mullite and probably some anorthite. Spectrographic analysis showed Al, Ca, Fe, Mg, and Mn as major elements, with only traces of the alkalis Na and K.

Fig. 9 — Rockley bloomery slag
Magnification × 100

It is therefore clear that when the clay lining of a bloomery furnace is fired at 1000°C, FeO from the slag penetrates the lining to form fayalite with the amorphous silica. The depth of penetration of fayalite continues for a distance of at least $1\frac{1}{2}$-2 in. The presence of glass away from the working surface may be due to the small amount of alkali present in the clay acting as a flux for the formation of low-melting glasses. Nearer the working surface these would dissolve into the slag. Thus it can be seen that bear material in bloomery furnaces is confined to a very narrow region near the actual working face.

SUMMARY AND RECOMMENDATIONS

Slag, cinder, and bear are three distinct and identifiable materials. Slag is a molten product of smelting, cinder an infusible or partially fused mass produced at a particular temperature of furnace operation, and bear a material resulting from reaction of molten smelting products with the refractory lining of the furnace hearth. These terms should not be confused, and attempts have been made in the paper to clarify the present uncertain state. It is therefore recommended that terms for each material should be put forward for national and international acceptance, and towards this end members of the Historical Metallurgy Group should be requested to criticize constructively the suggestions made.

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Reports of work in progress

The chemical composition of the bronze coinage of Maxentius, AD 306–312

LAWRENCE H. COPE AND HARRY N. BILLINGHAM

In Rome, on 28 October AD 306, Maxentius, the son of the retired Senior Emperor Maximianus Herculius, took advantage of the strong public resentment of the enforcement of severe tax-assessment measures and rose in rebellion against the absent legitimate rulers. He was immediately acclaimed Emperor, and became accepted throughout most of Severus's territory.

When news of the rising was brought to Galerius, he ordered Severus, based at Milan, to besiege Maxentius in Rome, and to recover his lost territories and restore his own rule; but in the ensuing campaign Severus was forced to lift his siege and return. Just before the spring of 307 his line of retreat was successfully cut by Herculius, and Severus was driven into refuge in Ravenna, where he surrendered and was taken captive to Rome. As expected, Galerius then invaded Italy himself, but he in turn failed to recover Rome. Probably later in April 307 he retreated to Illyricum, leaving a wake of devastation. Thus Maxentius became firmly established as the ruler of both Italy and North Africa.

In consequence he came into possession and full control of the four central imperial mints of Rome, Aquileia, Ticinum, and Carthage, but in 307, he decided to close the mint of Carthage (it was seized later, in 308, by the usurper L. Domitius Alexander, whom Maxentius finally defeated in 311), and to open a new mint at Ostia, the port of Rome, thus contracting the sphere of his minting activities[1].

In November 308 the Carnuntum Conference of the imperial rulers of the Roman Empire totally denied Maxentius's claims and officially declared him to be a public enemy. Maxentius then took further steps to consolidate his position, and to further concentrate his bullion resources and minting facilities close to the centre of his administration. So, in c. 309/310, he closed the more vulnerable northerly mints of Ticinum and Aquileia, which he rightly regarded as a military risk in the event of a landward invasion of his territories, and centred the bulk of his coinage output at the mints of Rome and Ostia. These two mints continued to coin for Maxentius until his eventual defeat, by Constantine, at the battle of the Milvian Bridge, on 28 October 312, the sixth anniversary of his seizure of power. Almost immediately, the Maxentian mints of Italy were brought into use by Constantine to meet the needs of his heavy military and civil expenditure in Rome in the winter of 312/313.

Maxentius exercised a profound influence on the outputs of the central mints in his control; their previous dull uniformity gave way to a much greater variety of types, and to considerable differences between the individual mints in their coinage issues and in the recognition accorded to the various rulers of the Empire. And Rome itself acquired a renewed status.

The assays[2] of the Maxentian coins which are listed in the accompanying Table show other distinctive features which have been hitherto unknown: a remarkable strict and uniform control of the fineness of the argentiferous bronze alloys, at a level which is clearly evident as being standardized at four scrupula of silver per libra; the use of copper from a wide variety of sources having different characteristic impurities; and the tendency for a marked increase in the proportions of lead in the alloys minted in the later years of his rule. The substantial proportions of tin which were employed give no indication of any shortage resulting from Maxentius's apparent isolation from the rest of the Empire. Apart from the decreed fineness, the alloying practices of the mints when under Constantine's subsequent rule seem to have continued unchanged. Indeed, when Constantine later transferred the mint personnel of Ostia to Arles (later in 313)[3] it is obvious that they took their familiar metallurgical practices with them, for the early folles coinage of Arles is distinguished by a much higher lead content than is to be found in the contemporaneous coinage of the other follic mints of Trier and Lyons[4].

The Constantinian coinage issued shortly after Maxentius's defeat seems to have been issued with a lower fineness standard, of 3 scrupula of silver per libra (see section B of the Table). This is difficult to explain, at present, because the Constantinian mints themselves appear to have worked to a 4-scrupula standard both before and after the Italian campaign[5]. It is possible that Maxentius became short of bullion towards the end of his reign, and that the coinage fineness standard had to be reduced some time before Constantine's victory. Until Constantine could have reorganized the bullion supplies he might have had to adopt an existing local standard as a temporary expedient when meeting his own urgent requirements of coin.

It will be necessary to perform further assays of other carefully selected datable pieces before it will be possible to determine the most probable course of events affecting the coinage fineness. The situation is complicated by the pronounced segregation effects which can occur in the more highly leaded bronzes, whereby the silver can be most unevenly distributed[6]. When analysing the weight-reduced folles of this period we take half-coin samples, but we have found a difference of as much as 0.34% silver between two separate halves of a coin of this era[7]. This could make all the difference between identifying the fineness standard as one of 3 scrupula per libra instead of 4 scrupula per libra. Perhaps whole coin assays should be performed when the lead-content is suspected of being in excess of about 10%, but even this precaution cannot obviate any segregation effects which occurred in the original coinage alloy melt—as distinct from those within each individual coin. Results are really required on a more statistically significant basis than that at present available.

Maxentius's isolation from, the independence of, the rest of the Roman Empire is manifest by the persistence of the weight-standards of all his coinage issues, as well as by the bronze alloy developments. By the middle of 307 Maxentius effected a weight-reduction in his follis coinage at Carthage, Rome, and Aquileia, almost immediately after Constantine had initiated the identical adjustments at Trier. The new "6.5" g follis (perhaps indicative of deliberate minting at 48 pieces per libra) became the revised standard-weight follis throughout the Empire, during 308 and 309[8]. Thereafter, Maxentius made no further definite change, although the issues of Rome and Ostia show a slight fall-off in weight during 311 and 312. Constantine, however, made a precipitate weight-reduction, to a "4.5" g (72 per libra) standard, early in 310[4]; and when he captured the Maxentian mints in the autumn of 312 he enforced, immediately, the "4.5" g standard follis which was then in vogue at his Gallic mints and in Britain. The Balkan and Eastern mints were also coining at this standard in the latter part of 312.

Thus Maxentius remained independently out of phase with the financial adjustments which became necessary in the rest of the Empire between 310 and 312. Therefore, the consistency of his minting policy, with respect to both coin weight and fineness, enables us now to make a fairly precise assessment of the intrinsic value of his folles in terms of equivalent silver.

TABLE Chemical analyses of folles issued from the central mints of the Roman Empire, under Maxentius and then under Constantine

Item No.	Code No.	Emperor	Date of issue (A.D.)	Coin Weight (g.)	Reverse Type	Mint.	Chemical analysis, weight per cent									Coin reference in R.I.C. VI
							Copper	Tin	Silver	Lead	Iron	Nickel	Cobalt	Zinc	TOTAL	
A. Maxentian issues																
1	L.H.C. 3	Maxentius	Autumn 307 to Spring 308	4.48	CONSERV/VRB SVAE (Hexastyle temple)	Ticinum	86.00	4.97	1.43	7.26	0.01	0.01	0.04	Trace	99.72	Ticinum 95
2	B.M. 80	Maxentius	c. May 308 to 309/10	5.15	CONSERV/VRB SVAE (Hexastyle temple)	Ticinum	87.04	5.89	1.35	5.55	Nil	0.01	0.03	0.01	99.88	Ticinum 100
3	B.M. 54	Divus Constantius	Autumn 307 to c. 309/10	7.90	MEMORIA DI/VI CONSTANTI	Aquileia	88.69	3.91	1.27	5.68	0.05	0.04	0.06	0.07	99.77	Aquileia 127
4	Ca. 8	Maxentius	308 to 310	5.71	CONSERV/VRB SUAE (Hexastyle temple)	Rome	85.55	6.32	1.44	6.45	0.08	0.04	0.01	0.01	99.90	Rome 208
5	N.M.W. 28	Maxentius	308 to 310	7.24+	[CONSERV]/VRB SUAE (Hexastyle temple)	Rome	83.51	5.56	1.39	9.29	0.04	0.02	0.07	0.02	99.90	Rome 208 or 210
6	Ca. 7	Maxentius	308 to 310	6.45	CONSERV/VRB SVAE (Hexastyle temple)	Rome	81.96	6.06	1.59	9.82	0.04	0.06	0.01	0.04	99.58	Rome 212
7	N.M.W. 24	Maxentius	Late 309 to Oct. 312	6.19	FIDES MI/L/IT/VM AVG N	Ostia	88.06	3.97	1.49	6.46	0.02	0.02	Trace	0.02	100.04	Ostia 45
8	N.M.W. 25	Maxentius	Late 309 to Oct. 312	4.80	[F] IDES MI/L/IT/VM AVG N	Ostia	87.16	5.65	1.28	5.58	0.03	0.04	0.01	0.04	99.79	Ostia 45
B. Constantinian issues from the captured Maxentian mints																
9	B.M. 87	Maximinus Daza	Oct. 312 to May 313	4.03	GENIO A/V/GVST1	Aquileia	85.04	6.89	1.08	6.59	0.14	0.10	0.07	0.04	99.95	Aquileia 130
10	N.M.W. 29	Licinius I	Oct. 312 to May 313	3.72+	GENIO P/OP ROM	Ostia	84.98	5.53	0.91	8.26	0.09	0.04	0.01	0.05	99.87	Ostia 77 b
11	C.J.O. 4	Constantine I	Oct. 312 to May 313	3.44	SOLI IN/VI/CTO COMITI	Ostia	80.85	5.82	1.01	12.34	0.06	0.02	0.01	0.03	100.14	Ostia 89

The theoretical weight of a one-fortyeighth libra follis piece is 6.88 g. Of this, 4 scrupula of silver added per libra would represent 1.37% silver; this is equivalent to a nominal weight of 0.0942 g silver in each Maxentian follis. Taking the remainder of the alloy as being worth one-hundredth of its weight in silver results in an estimation of the follis as having been worth the quivalent of 0.162 g silver. On this basis twenty folles would have equated with the metal-worth of one contemporaneous silver argenteus. There was thus a three-fold reduction in worth from the inception of the follis coinage c. 294[9]. Since the weight-reduced folles would have had an official tariff rate of less than 20 to each silver argenteus it is not surprising that the latter coinage disappeared during Maxentius' reign in Italy, as it did, earlier, in Constantine's western territories. The minting of silver is known to have steadily diminished at the Maxentian mints which produced it, until it eventually ceased at Ostia after 309, and at Rome after 310.

The analyses shown in the Table do not shed any direct light on the knotty problem of the sequence of certain issues at the Maxentian mints[10]. It is possible, however, that if the chronological increases in lead content (which have been observed to apply at the mints of Rome and Ostia) applied also to the products of the mint of Ticinum, further determinations of the lead contents of the coinage might enable the sequence of some issues to be more positively arranged then is possible at present.

ACKNOWLEDGMENTS

We extend again our grateful thanks to the Governors, the Principal, and the Head of the Department of Metallurgy (Dr G. J. T. Hume), of the Wednesbury College of Technology, for continued encouragement and for the provision of facilities for metallurgical analysis.

We are also deeply indebted to the following for their generous provision of disposable coins for analysis: Mr. G. C. Boon, National Museum of Wales (Coins coded N.M.W.); Mr. R. A. G. Carson, The British Museum (Coins coded B.M.); Mr. Robert Hogg, The City Museum and Art Gallery, Carlisle (Coins coded Ca.); and an anonymous donor (coin coded C.J.O.). One of us donated the coin coded L.M.C. 3.

NOTES AND REFERENCES

1. For the history, as it affects the coinage of the period, see C. H. V. Sutherland: "The Roman Imperial Coinage", Vol. VI, (1967).
2. Each coin analysis recorded in section A in the Table was based on a quarter-coin sample; for the analyses in section B a half-coin section was taken.
3. See P. Bruun: "The Roman Imperial Coinage", Vol. VII, (1966), for a review of the details and timing of the transfer of mint-personnel from Ostia to Arles.
4. L. H. Cope: Work to be published.
5. L. H. Cope and H. N. Billingham: Assays of weight-reduced folles awaiting publication.
6. Usually found in association with the microstructural lead phase, for which it has a marked affinity.
7. An unpublished coin analysis (B.M. 93). This follis was minted in Rome, later (A.D. 314-315). One half assayed 1.08% silver; the other half assayed 1.42% silver. The lead content is in the region of 12%, and rather heterogeneously distributed within the coin.
8. One of the few short periods of universal coinage weight stability between 306 and 318.
9. For the metal-worth of the largest and finest folles see L. H. Cope: "The argentiferous bronze alloys of the large tetrarchic folles of A.D. 294-307", The Numismatic Chronicle, 1968, p. 148.
10. Discussed thoroughly by Cathy E. King: "The Maxentian Mints", The Numismatic Chronicle, 1959, reviewed later by C. H. V. Sutherland (op. cit. above).

Iron-smelting experiments at Varde, Denmark, April, 1968

R. F. TYLECOTE

Robert Thomsen of Varde Steelworks, Jutland, has been experimenting with the Scharmbeck-Drengsted type of shaft furnace which was in use in North Germany and Jutland during the period AD 300-500. His experiments are based on material found in the course of excavations at Drengsted by Dr Olfert Voss of Copenhagen University. It is not known whether this type of furnace was blown by induced draught or forced draught. Thomsen believes the former, whilst Dr Pleiner of Prague, who has been doing similar experiments, believes the latter. In any event the clay shaft was built over a pit and the slag ran down forming a furnace bottom or "schlackenklotz" of which we have one example from East Anglia in the museum at Norwich. These experiments are likely therefore to be of great interest in the study of early ferrous metallurgy in this country.

Mr Thomsen kindly invited Dr Pleiner, Dr Schweitzel of Schleswig, and myself to witness his experiments in April 1968.

The furnace (see Fig. 1) was based on those found at Drengsted and had the dimensions shown in the figure. It was made by taking ordinary yellow and pottery clay, tempering it with chaff, making a coil, and winding this. Due to the plasticity and low strength only 1 ft could be made at a time, as time had to be allowed for it to dry in order to take the weight of more wet clay. Thus, four furnaces had been started but only two completed.

The pit was dug in the rubbish of the foundry yard (mainly moulding sand) with the aid of a specially shaped spade. A cylinder of straw, tightly wound, was then placed in the pit so as to leave an annular space all round. Some dilute clay (lute) was applied to the upper surfaces of this plug to prevent premature burning.

The furnace was filled at 07.00 with large (4in × 4in × 5in) pine charcoal and ignited. The level was kept 8-12 in from the top. The normal CO_2% was 2.0 with all four tuyeres

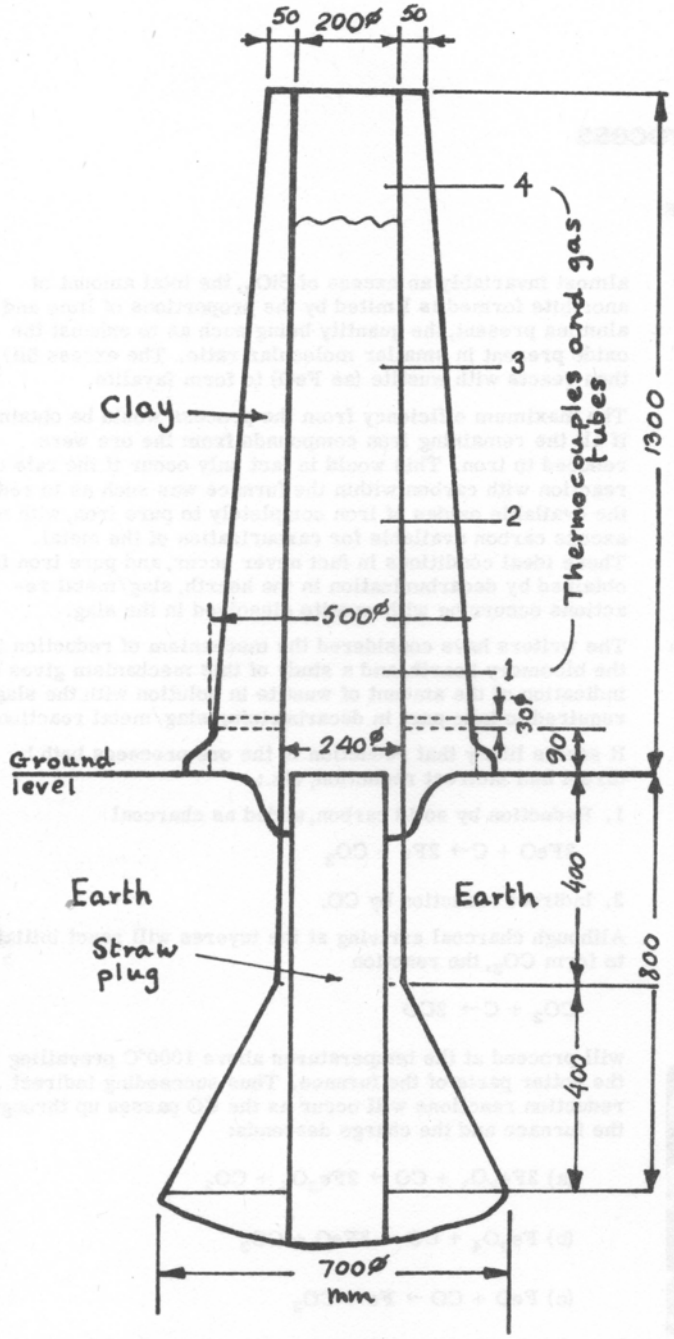

Fig. 1 — Diagram of experimental smelting furnace at Varde

open. The tuyeres were 3 cm dia. and 4 in from the bottom (ground level).

At 10.45 charging of ore and started and the temperature in the thermocouple tubes (1 to 4) was 1292°, 1000°, 872°, and 640°C respectively. This shows a remarkably good distribution for such a slender furnace with such a thin lining, and must be done to the very high permeability conferred by the large charcoal.

The ore charged was bog ore and had previously been roasted according to the method described by Evenstad. Originally it was brown, but on roasting had gone slightly indigo-brown. Its analysis was 82% FeO, 1.74% Si, 1.94% P, 0.84% Mn remainder H_2O, before roasting. It was broken to a very fine size (< 1/8 in).

The charge was 2 kg charcoal to 1 kg of ore, and the rate of burning of charcoal was 19 kg in 3 h 20 min, i.e. a rate of 5.75 kg (12.6 lb) per hour. This was found to depend on wind direction and intensity to some extent.

At 14.10 with the wind in the west the temperatures were much the same as at 10.00. Some liquid slag was present near the tuyeres. The CO_2 content was 9.0% at hole 3.

From 13.00 to 15.10 the ore/charcoal ratio was 1/1. Charging stopped at 15.30 and the temperature in hole 1 was 1195°C. No more charcoal was added and slag tended to block the tuyeres. Temperature could be maintained at 1200°C but only with difficulty. It was never allowed to cool for the night.

Total consumption after the first charge of ore would seem to be 65 lb of charcoal and 46 lb of ore. No charcoal was added during the night. The burning rate of 12.6 lb/h compares very well with the rate of 16 lb/h for a forced draught of 300 l/min, and suggests that the effective flow is of the order of 240 l/min.

Next morning the furnace was sectioned down the axis and it could be seen that a very compact slag lump occupied the bottom and that some of it had tried to drip into the pit. For the most part the straw was unchanged, no doubt owing to the thin coating of clay on its top surface (this will be omitted in future). At least 1 in of lining had been dissolved from both sides by the slag. The lining was red from top to bottom throughout its section except for the outer surface layer (c. 1 mm), which was still yellow. The inside of the shaft was black up to hole 3, which indicated that reducing conditions were continuing down to 870°C. Some metal was present in the slag but probably not much.

I would like to thank Olaf Bülow, Director of Varde Staalvaerk, and Robert Thomsen for arranging this interesting visit and for their kind hospitality.

Technical note

The efficiency of the bloomery process

G. R. MORTON AND JOYCE WINGROVE

The efficiency of iron extraction in the bloomery is generally defined as the proportion of the iron content of the prepared ore charged into the furnace which is extracted as metallic iron; thus

$$E\% = \frac{e}{T} \times 100$$

when e = weight of iron extracted,

T = total weight of iron in ore.

In practice various considerations affect the iron yield of the operation. Since in the bloomery process there is no added flux, some iron is used to flux the gangue material in the ore and this iron cannot be extracted as metal. In addition, some iron is lost by reaction with the clay lining, and this iron also cannot be extracted. The operator has no control over such losses.

Some iron enters the slag as wustite (FeO), which then takes part in decarburizing slag-metal reactions, and the quantity of this dissolved FeO may be considerably controlled by the worker in order to obtain a good yield of iron.

The maximum theoretical efficiency would be achieved if all the iron were extracted excepting for that used in fluxing the gangue material of the ore.

The writers have shown that bloomery slags comprise three main phases: fayalite ($2FeO.SiO_2$), glass, and wustite (approximately FeO)—see Fig. 1. Other phases may be present in small amounts, but can be neglected for the purposes of this note. The authors further showed that the quantities

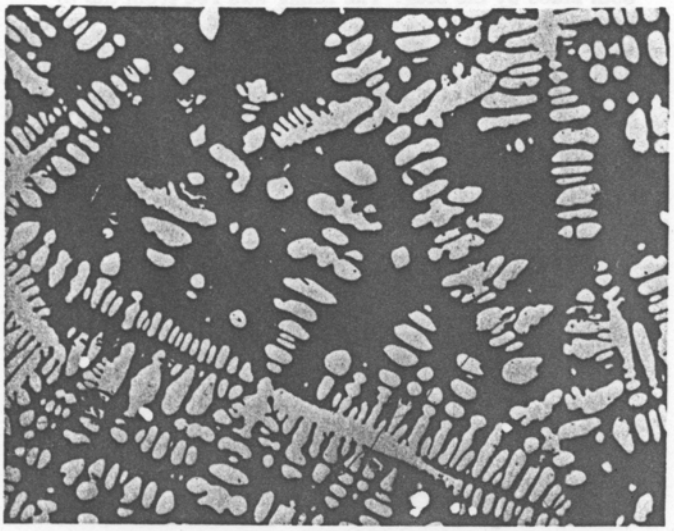

Fig. 1 — Bloomery slag: dark = glass, grey = fayalite, light = wustite Magnification × 100

of the main phases can be calculated from the chemical analysis of the slag, using the simplified argument set out below.

The composition of the glass phase approximates to the mineral anorthite ($CaO.Al_2O_3.2SiO_2$) and, since there is almost invariably an excess of SiO_2, the total amount of anorthite formed is limited by the proportions of lime and alumina present, the quantity being such as to exhaust the oxide present in smaller molecular ratio. The excess SiO_2 then reacts with wustite (as FeO) to form fayalite.

The maximum efficiency from the process would be obtained if all the remaining iron compounds from the ore were reduced to iron. This would in fact only occur if the rate of reaction with carbon within the furnace was such as to reduce the available oxides of iron completely to pure iron, with no excess carbon available for carburization of the metal. These ideal conditions in fact never occur, and pure iron is obtained by decarburization in the hearth, slag/metal reactions occurring with wustite dissolved in the slag.

The writers have considered the mechanism of reduction in the bloomery hearth, and a study of this mechanism gives an indication of the amount of wustite in solution with the slag required to take part in decarburizing slag/metal reactions.

It seems likely that reduction of the ore proceeds both by direct and indirect reduction, viz.:

1. Reduction by solid carbon, added as charcoal

$$2FeO + C \rightarrow 2Fe + CO_2$$

2. Indirect reduction by CO.

Although charcoal arriving at the tuyeres will react initially to form CO_2, the reaction

$$CO_2 + C \rightarrow 2CO$$

will proceed at the temperatures above 1000°C prevailing in the hotter parts of the furnace. Thus succeeding indirect reduction reactions will occur as the CO passes up through the furnace and the charge descends:

(a) $3Fe_2O_3 + CO \rightarrow 2Fe_3O_4 + CO_2$

(b) $Fe_3O_4 + CO \rightarrow 3FeO + CO_2$

(c) $FeO + CO \rightarrow Fe + CO_2$

In order for these reactions to proceed excess CO must be present. At temperatures below about 500°C, the reaction

$$2CO \rightarrow C + CO_2$$

take place rapidly, depositing carbon as finely divided lampblack, which coats and impregnates the partially reduced ore and leads to direct reduction reactions:

(a) $6Fe_2O_3 + C \rightarrow 4Fe_3O_4 + CO_2$

(b) $2Fe_3O_4 + C \rightarrow 6FeO + CO_2$

(c) $2FeO + C \rightarrow 2Fe + CO_2$

Visual evidence of the occurrence of solid-state reduction can be seen in Figs. 2 and 3.

The operation will be most efficient when the reduction rates (both direct and indirect) are such that the amount of excess CO, and therefore the carburization of the iron, is a minimum. In practice some CO will always pass out with the waste gas, and the CO/CO_2 ratio of this gas will thus give an indication of the reduction efficiency.

The authors are at the College of Technology, Wolverhampton.

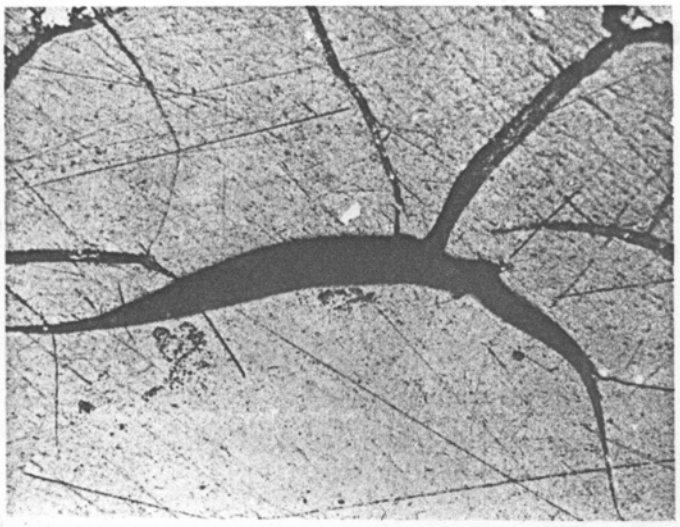

Fig. 2 — Internal fissures in ore

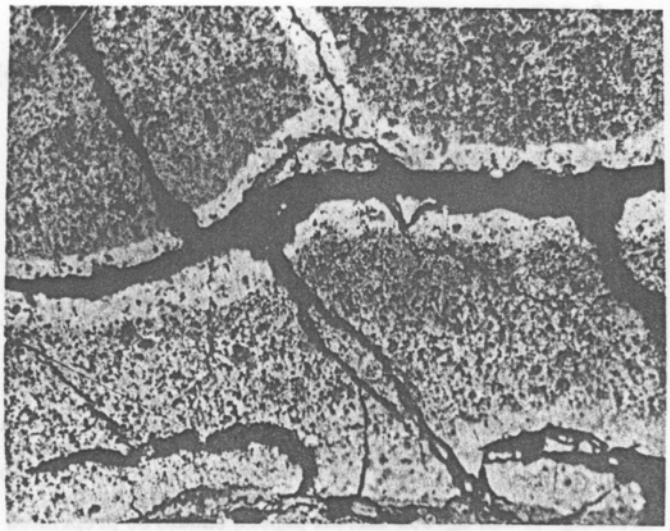

Fig. 3 — Internal reduction

It can be seen from the above outline of the complex reduction mechanism that the skill of the operator in controlling the course of the reaction had an important bearing on the efficiency of extraction. The main aim was to produce slag containing a minimum amount of wustite consistent with the production of pure decarburized iron, thus minimizing the iron loss to the slag. The control of temperature, rate of addition of charcoal and of ore, and estimation of slag composition and iron purity by personal skill were all matters gained through long experience of working the process.

An unavoidable lowering of yield from the bloomery occurs as a result of slag attack on the furnace lining. These were generally of clay mineral, probably in the form of an agglomerate of kaolinite and free quartz grains. At about 500°C water of crystallization would be driven off, leaving amorphous SiO_2 and Al_2O_3. During the running of the furnace, wustite in the slag would readily attack the refractory, forming fayalite with the amorphous silica. Thus, according to the physical form of the attack, extra slag could be formed by this means, or iron could be lost by the penetration of fayalite into the refractory. This latter has in fact been observed, as the typical fayalite lathes penetrating the furnace lining show (Fig. 4).

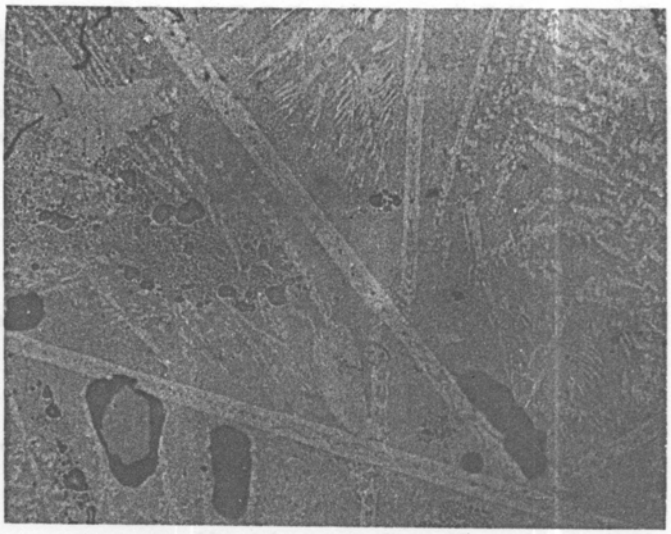

Fig. 4 — Fayalite laths in clay lining

SUMMARY

The efficiency of a bloomery reduction process may be defined as the proportion, expressed as a percentage, of the iron content of the ore (including gangue) which is extracted as metallic iron. This is governed by a number of factors which control the iron loss. These are (i) the amount of iron needed to flux the gangue material of the ore; (ii) the amount of wustite in the slag, some of which is needed for slag/metal reactions in order to produce pure iron; and (iii) refractory attack of the furnace lining by the slag. The iron loss can be reduced by skilful working of the furnace to produce a slag containing a minimum of wustite at the end of the operation. Thus a study of the mineralogical constitution of any given slag will give an indication of the efficiency of operation during the corresponding furnace run.

Report of the Annual General Meeting 1969

Minutes of the Annual General Meeting of the Historical Metallurgy Group, held in the Royal Mint, Tower Hill, London EC 3, at 2.00 p.m. on 17 April, 1969.

[The meeting was preceded by a tour of the Mint followed by a talk on the Metallurgical History of Coining given by Mr E. G. V. Newman, Chemist and Assayer. After this the Chairman gave a vote of thanks to Mr Newman and the staff of the Mint, which was heartily endorsed by all those present.]

Present: H. T. Angus, L. Biek, E. B. Babler, K. C. Barraclough, C. R. Blick, H. N. Bowen, J. W. Butler, D. W. Crossley, C. W. Brewer, D. W. O. Dawson, R. C. Dyer, M. M. Hallett, P. L. Nice, J. Reynolds, D. G. Ryder, J. G. Rollins, H. H. Smith, E. D. Mackerness, B. H. Tripp, and R. F. Tylecote, with the Chairman, W. K. V. Gale, in the Chair.

Apologies: were received from The President, N. S. Angus, H. F. Cleere, G. J. Cox, Professor Beaver, Professor M. W. Flinn, J. H. Flux, D. H. Houseman, J. W. Jenkin, D. E. Jordan, B. M. Hardman, D. Newton, G. R. Morton, W. I. Pumphrey, D. M. Headworth, G. A. Redfern, S. H. Russell, Professor W. Minchinton, A. J. Shore, S. J. Woolridge, N. Swindells and Sir Frederick Scopes.

Minutes: The minutes of the last A.G.M. held on 25 April 1968, having been circulated with the Vol. 3, No. 1, issue of the Bulletin, were taken as read and signed by the Chairman as a correct record.

Matters Arising: No matters were brought up.

Officers' reports: In view of the shortage of time these were given very briefly. It was reported that the membership was about 450 and that the provisional accounts showed a balance of about £240, after carrying forward £140 from 1967. It was agreed that grants of £20 should be given to two H.M.G. members: H. F. Cleere for iron-smelting work in the Weald, and to M. Davies-Shiel for an excavation in the Lake District. Subject to the final satisfaction of the auditor, the accounts were accepted unanimously.

Election of Officers and Committee for 1969-70

There were no further nominations and those listed below were proposed from the Chair, seconded by B. H. Tripp and elected unanimously. The new President, M. M. Hallett, thanked the retiring President for the work he had put into the affairs of the Group and also paid tribute to the efforts and enthusiasm of the Chairman and Honorary Secretary.

Officers:

President: M. M. Hallett
Chairman: W. K. V. Gale
Hon. Secretary: R. F. Tylecote
Asst. Hon. Sec: D. W. Crossley
Hon. Treasurer: C. R. Blick

Committee

K. C. Barraclough
Professor M. W. Flinn
B. H. Hardman
N. Swindells
H. F. Cleere, G. R. Morton } (representing The Iron and Steel Institute)
Professor H. O'Neill (representing The Institute of Metals)
W. I. Pumphrey (Hon. Auditor)

Annual Conference in Cornwall

It was agreed that this would be held during the week-end 26-28 September 1969 at Newquay, Falmouth, or Penzance. Talks would be given by an archaeologist on the prehistory, J. H. Trounson on mining and smelting, and F. B. Mitchell on mineral dressing. The talks would be on Friday evening and Sunday morning and the whole of Saturday would be devoted to tours. It was reported that attempts had been made to interest air charter companies in flying members down from Luton but this had been unsuccessful. Mr Butler asked that the emphasis should be on ancient techniques and that not too much time, if any, should be spent in modern mining and dressing. It was agreed that all papers should be preprinted and made available before the meeting.

Other business

Mr L. Biek agreed to represent the Group on the Standing Conference for Local History.

Abstracts and book notices

British Isles

Early steelmaking in the Sheffield area. K. C. Barraclough. (Steel Times Ann. Review, 1968, Oct., 161-173). An illustrated account of steelmaking in the area from the 16th to 19th centuries.

Cupola lead smelting sites in Derbyshire, 1737-1900. L. Willies. (Bull. Peak Dist. Mines Hist. Soc. 1969, 4, (1) 97-114). Notes, with map, on 36 smelters with slag still lying on many of them.

The quest for a lost lead mine in Leicestershire. R. J. King and B. A. Ludlam. (Bull. P. D. Mines Hist. Soc. 1969, 4, (1) 3-28). At Tickow Lane, Shepshed, west of Loughborough (SK 46161865). Opened in 1865. Minerals, cerussite, and galena in Lower Keuper Sandstone. No signs of earlier working and probably merely a prospect. But this is the most South-easterly deposit in the British Isles and may have archaeological significance.

Stone Edge Cupola. C. J. Williams and L. Willies. (Bull. P. D. Mines Hist. Soc. 1968, 3, (6) 315-322) NW of Ashover (NGR. 334670). Describes the remains now to be seen at this site and gives some of the history of the plant. Compares finds with Farey's furnace of 1807. It is hoped to excavate the site.

James Foster and tinplate manufacture in Shropshire. N. Mutton. (Iron Steel, 1969, 42). An illustrated article on the construction of a tinworks at Hampton Loade in Shropshire and its operation from 1822 to 1826. It is the only tinworks known in that county and has not previously been noted (e.g. in Brooke or Minchinton). It was built at a time when it had been thought that the Midlands tin industry was quiescent, but after only four years it was abandoned and the forge site was then used for the manufacture of charcoal iron.

Europe

The development of iron furnaces and the introduction of the Walloon blast furnace into Bohemia. Ivo Krulis-Randa. (Rev. Hist Sidér, 1967, 8(4), 245, 275) [In Fr.]. Describes the development of European blast-furnaces from the 13th century, in particular those of Czechoslovakia. Finds that the relationship of the internal dimensions agrees with the Pavlov formula of 1952-53.

Creusot on the eve of the 1830 revolution. B. Dureault. (Rev. Hist. Sidér., 1968, 9, (3), 201-216) [In Fr.]. The statistics of production, finance, costs and the installations of the Creusot works, the first iron works in France to use coke in the blast-furnace, in 1828-9, are reviewed.

The beginnings of the Compagnie des Mines, Fonderies et Forges de l'Aveyron. B. Gille. (Rev. Hist. Sidér., 1968, 9, (3), 217-248) [In Fr.]. A detailed record is given of the 16th meeting of the company in 1833 with full financial reports, production statistics and details of products.

Manufacture of iron in Burgenland and western Hungary during the 10th to 13th centuries. G. Heckenast. (Rev. Hist. Sidér., 1968, 9, (3), 181-192) [In Fr.]. The records of the region are reviewed and it is established that Eisenburg was known in these times as a centre of ironmaking and the existence of analogous contemporary organizations is demonstrated.

Asia

To-Ken. An exhibition of Japanese Swords and other items representing the martial arts from the fourth to the twentieth centuries. (To-Ken Society of Great Britain) Ashmolean, Oxford 1968, 96 pp.

America

Iron furnaces of the Confederation in Virginia. J. D. Capron. (Rev. Hist. Sidér., 1968, 9, (3), 193-200) [In Fr.]. The Virginian manufacture of iron with wood charcoal during the civil war and the succeeding period of reconstruction (to 1870) is reviewed. [A translation of an article in "Virginia Cavalcade", 1967, 17, (2)].

Metallurgical Examination

Studies on the structural properties of rust from ancient iron. J. K. Mukherjee, A. K. Lahiri and T. Banerjee. (NML Techn. J., 1968, 10, Feb., 25-29). Physical and chemical tests were performed on rust collected from the ancient iron beam of the thousand year old temple at Konarak. These tests indicated that the rust consists mainly of Fe_3O_4, γ–Fe_2O_3 and α and γ hydrates of iron.

Metallanalyse Kupferzeitlicher und frühbronzezeitlicher Bodenfunde. S. Junghans, E. Sangmeister, and M. Schröder. Vol. II in Studien zu den Anfängen der Metallurgie (in 3 parts).

Biography

An engineer at work in the West Midlands: the diary of John Urpeth Rastrick for 1820. N. Mutton. (Spec. Pub. No. 1 of the J. West Midland Reg. Studies, 1968). A transcript of John U. Rastrick's diary for 1820, with an introductory essay and some ninety notes relating to the subject matter of the diary. Rastrick had kept in his earlier years manuscript journals in which he had written at length. By 1820 when he was managing partner of the Stourbridge Ironworks he was too busy to do more than keep a printed diary in which he made cryptic entries of only one or two lines. Nevertheless these indicate clearly the sort of activities he was engaged upon, and his social life and also give odd glimpses of his family life. The notes do not claim to be exhaustive, but help to elucidate details of people and places mentioned, and the editor asks for any further amplification of entries.

Book Notice

Heckenast-Novaki-Vastagh-Zoltay:

"The History of Iron-Working in Early Medieval Times" [in Hungarian]: Budapest 1968: 253 pages.

Two medieval iron-working sites have been investigated and partly excavated. The largest of these is in the Borsod mountains north of Miskolc; the other is in the west, close to the Austrian border.

From Borsod 30 smelting sites are known. The ore was mined nearby at Rudabanya. This was established by the analysis of slag from the site, which contained Ba and Cu, elements which are usually rare. The source of the ore from

the western site is now known. This site had been completely levelled and filled in. But since the sites are all in a forested area and useless for agriculture, the reason is not known. This has, however, helped to preserve the furnaces, nine of which were found in situ and have been transported to various museums.

Sherds found established a date of 10th-11th and perhaps 13th century for the furnaces at Borsod. The dating for the west is more problematic, and one of the furnaces might be Roman; the rest are dated to the 11th-12th century.

All furnaces were of the shaft type, but there are differences between the two areas. The Borsod furnaces had an "open breast" and are known from other areas, i.e. Germany, Bohemia etc. According to Krasa and Gilles, many breast walls which had been broken out of the furnaces after smelting had been found amongst the slag-heaps. In Borsod, however, not a single piece of the breast has been found. But hundreds of tuyeres were found, even round one furnace, and they appeared to have been used only once. As many as 4500 tuyeres were found altogether and it seems that smelting must have taken place with an "open breast". This is called the Imola type furnace. The number of tuyeres fixed in the opening is not known.

Furnaces were built into a slope, and one had a pit which had what was probably a seat for the smith who worked the bellows. The tuyeres indicate that artificial draught was used. In one of the pits they found crushed ore in little heaps, ready for the next smelt. Ore was scattered everywhere. About 50 kg of ore could be collected without difficulty at Imola.

Furnaces in the West are of a different type than at Borsod and also show varying methods of construction on the site itself. Many seem to have had a breast wall and a few tuyeres were found; some were built into the wall of the furnace.

Slags from Borsod differ from all other slags in having higher Fe_2O_3 contents. It is possible that the higher degree of oxidation is connected with smelting with an "open breast" Gilles first drew attention to the fact that slags with high silica contents have lower iron contents and experiment agrees with this. Many of the medieval ores have a high silica content, in contrast to today's ankerite ores, which consist of siderite and dolomite.

As regards the question of cinder, which according to various authors is due to incomplete smelting, in one area there was found large heaps of cinder which could not be the product of misfired smelting.

Another question discussed is, in what part of the hearth does the metallic iron and slag collect? Some authorities think that it collects at the bottom. The furnace bottoms that have been found on many sites show that most collects inside the furnace. At Trizs the authors found on a slag heap an almost round lump, the diameter of which corresponded to that of the "rast" or furnace bottom. It contained 80 to 70% Fe, including pearlite, cementite, and ledeburite. This indicates that the iron collects just above the hearth.

A small bloom weighing 2.75 kg is of interest; it was found near one of the smelting sites. The relatively high C content is remarkable and may be due to inhomogeneity, since metallographic examination showed only ferrite and no pearlite.

Slags from West Hungary clearly differ from those from Borsod. They are much more homogeneous and did not have such a high Fe_2O_3 content.

The third chapter deals with the economic and social history and the feudal society of the "smith-kings" which in AD 896 were probably in charge of all mining operations and of iron production. A study has been made of place names in the relevant areas, including documents of which only a few exist. Iron production in West Hungary seemed to have ceased in the 12th and 13th centuries, and this is thought to be due to the better quality of iron produced and exported from Styria in Austria.

Iron working seems to have ceased also at Borsod, and it is suspected that the reason is deforestation. At this time iron production shifted towards the north of Hungary at Zips and Gomor.

Then follows an account of the authors' smelting experiments. These were carried out with the help of the Lenin Iron Works at Miskolc-Diösgyör. The furnace was a reconstruction of the Imola type. Draught was produced with a compressor. Temperatures, gas analysis, etc. are given and the results of the experiments are discussed. They reject the contention that the ores, as prepared for smelting, contained additions of SiO_2; they found no evidence of any such additions. Practical conclusions were as follows: Smelting in furnaces with a closed breast using ankerite ores was unsuccessful. Success was obtained only when the ore was sufficiently acid (some medieval ore was used), and well mixed with charcoal before smelting. Putting ore and charcoal in alternate layers did not lead to success. This is confirmed by metallographic examination and slag analysis. The last successful smelt yielded 310 g of iron in the form of small particles from 10.5 kg ore (with 50% Fe) and 24.0 kg charcoal. The iron could be smithed into plate and wire.