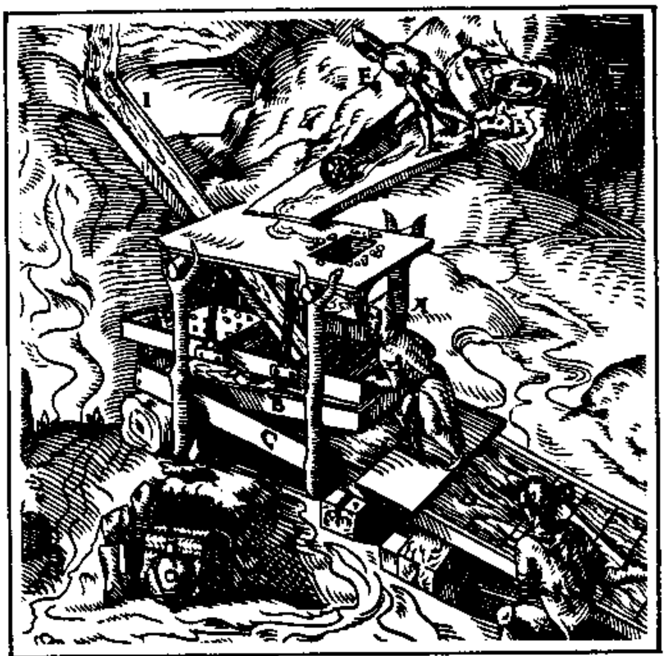
Bulletin of the Historical Metallurgy Group



Washing alluvial gold ores. Lazarus Erker, UCP translation p 99.

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The charcoal finery and chafery forge

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In 1963, Morton[1] examined the technical aspects of the charcoal finery and chafery forge, and for historical considerations he used the accounts given by Pashley,[2] Percy,[3] Bauerman,[4] and Fell.[5] The work was based on the process operated in the Lake District in the 18th century.[5] In 1964 the same author[6] examined the process used on Cannock Chase (South Staffordshire); on that occasion the work was based on the Anglesey Papers in the William Salt Library[7] and the account given by Plot.[8] The recent excavations by Davies-Shiel[9] and the work on slags being conducted at the Polytechnic, Wolverhampton, bring new light to the process and the necessity for a reappraisal.

With the introduction of the charcoal blast furnace to the Sussex Weald in c. 1490, the Midlands in 1561, and the Lake District in 1711, a method for the conversion of the pig iron produced in the blast furnace into the form of malleable bar became necessary. In the old bloomery process for producing bar direct from the ore the output was very low (in the order of 1 to 2 cwt of bar iron per furnace per day), whereas the blast furnace could produce 2 to 2½ tons of pig iron per day. In order to convert this pig iron into malleable bar, the impurities were first removed by oxidation in the finery hearth and this stage was followed by reheating in the chafery fire and by hammering into bar.

The layout of a typical finery forge based on the painting by Peer Hillestrom[10] is given in Fig. 1, and a reconstruction of a 17th century finery as given in Appendix XV of Schubert's book[2] is reproduced in Fig. 2. These can be compared with the furnace found during the excavation of Stony Hazel by Davies-Shiel (Fig. 3). In addition to the general layout, the painting gives much detail. The details reconstructed in Fig. 2 are in complete agreement with those of the excavation in Fig. 3. In the finery (on the right-hand side of the centre of Fig. 1) a pig of iron is to be seen, one end resting in the fire with the other in the pig hole. Both pig and pig hole appear much larger than the actual size, but nevertheless the position of the hole agrees with that shown in Fig. 2 and that found on excavation in Fig. 3. In the painting an iron pillar probably supported the roof, whereas Figs. 2 and 3 show the support to be of stone construction. It will also be seen that a shield is provided to protect the operator from the glare of the fire. Schubert cites this as either mortar or hard wood resting on a bar called a 'morris' bar.[11] The accounts of Cannock forge include the item:

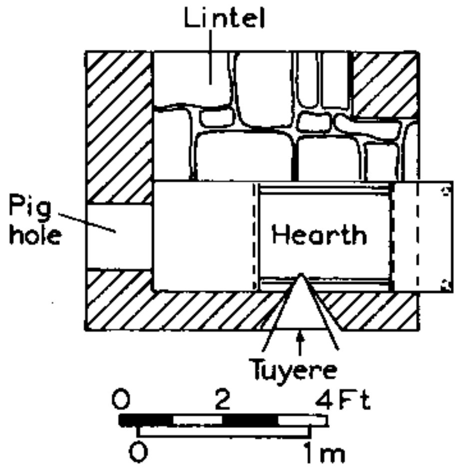

Fig. 2 — Reconstruction of a 17th century finery (after Schubert[2])

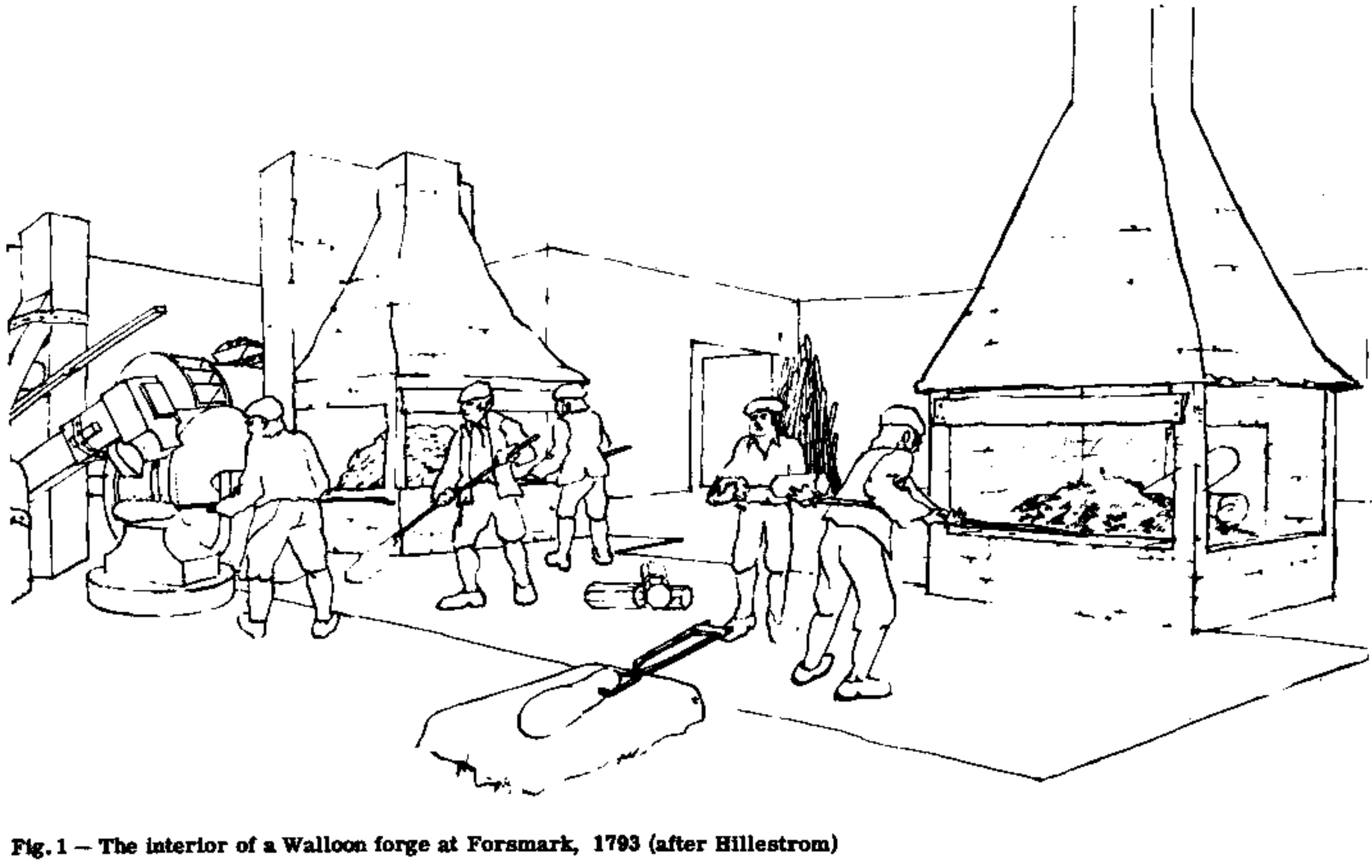

Fig. 1 — The interior of a Walloon forge at Forsmark, 1793 (after Hillestrom)

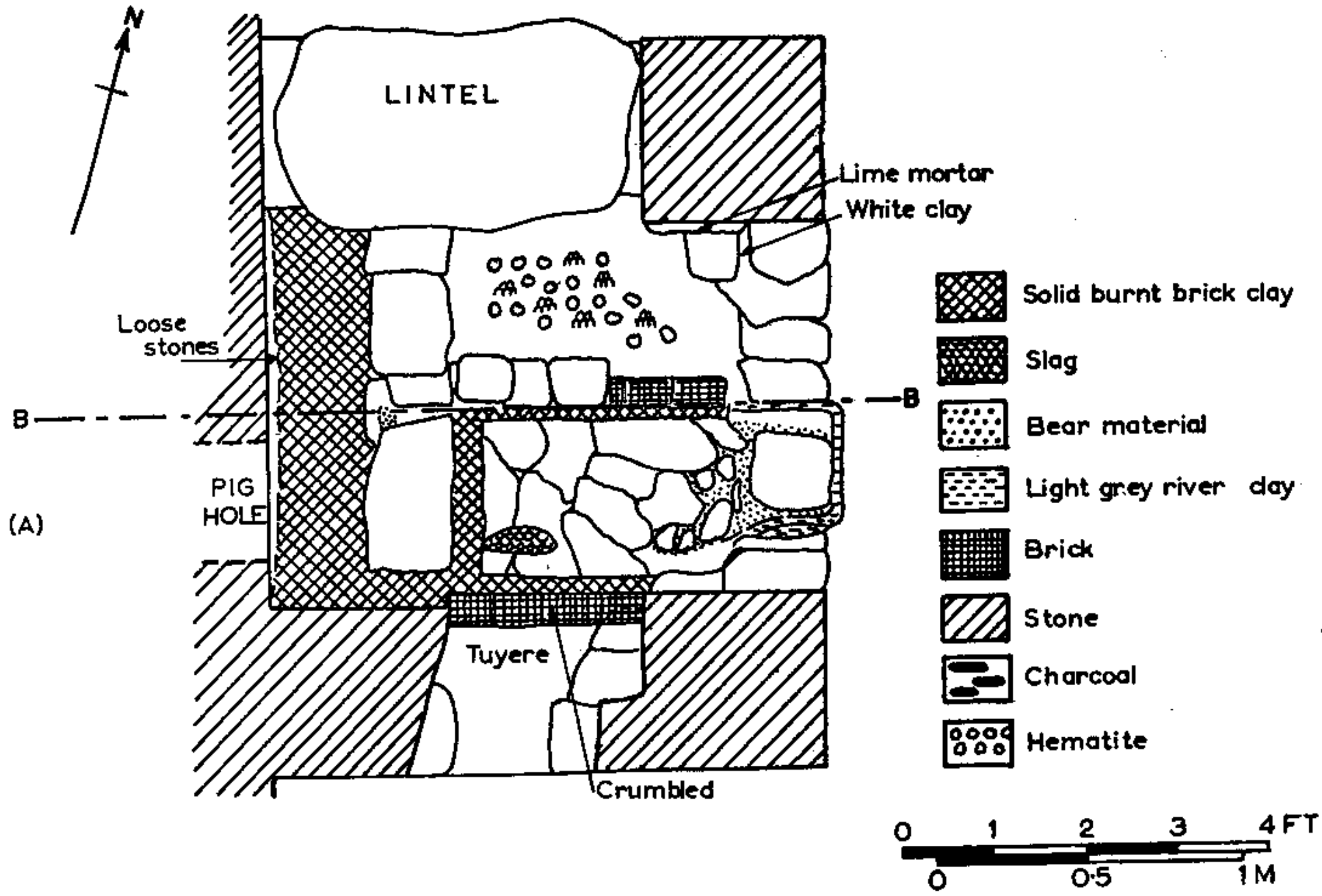

Fig. 3 — The finery at Stony Hazel

Finer	To John Mathews for fynyng the said iron	47s 4d
	to hym for mendyng his morris	7d

This confirms the use of the eyeshield in this country.

Pashley[2] describes the construction of the hearth proper and gives details of the iron plates which lined the well (Fig. 2). Prior to the commencement of the day's work, these plates were well brasqued with powdered charcoal which acted as refractory protection to the iron plates.

The chafery was essentially a reheating furnace and appears in Hillestrom's painting as a very much larger fire than that in the finery. This was due to the mode of construction, an excellent account of which is given by Fell.[5] In order to obtain a temperature suitable for forging, a muffle construction was necessary. The temperature attained in the furnace can be estimated from the appearance of the heated metal being transferred to the hammer in Hillestrom's picture. The release of masses of sparks from the hot end suggest a welding heat in the region of 1450°C. This degree of heat would be necessary to forge and weld the iron into a compact mass. According to Fell, the muffle was built in the form of a hollow beehive-shaped arrangement made from the waste material (ash, charcoal, small pieces of slag, etc.) left over in the furnace from the previous day's operation, and probably mixed with a binder such as clay. The foreplate of the chafery was in the form of a cast-iron plate, along which the blooms were skidded in and out of the fire. A simple saucer-shaped hearth sufficed the needs of the bottom, and as the slag formed it overflowed the hearth and ran through a gap between the foreplate and the hearth, and on to a sand floor where it collected in the form of the 'mossers' referred to by Fell.[5] No chafery has been found in the building excavated at Stony Hazel; it is however possible that one might exist in the building not yet cleared.

THE PROCESS

Pig Iron

Three general types of pig iron—tough, cold-short and blend metal—depending on the phosphorus content of the ore used, were produced in the charcoal blast furnaces. The analyses of tough and cold-short pig irons are given in Table I, from which it will be seen that the essential difference between them was the high phosphorus content (1.01) of the cold-short iron. This made it difficult to work in the finery and, as the name suggests, the resultant iron was cold-short. Both tough iron and blend metal were extensively used.

TABLE I Analyses of charcoal pig iron, %

	Tough		Cold-short
	Nibthwaite	Duddon	Little Aston
C	3.86	4.30	3.37
Si	0.85	0.65	0.28
Mn	0.05	0.10	0.91
S	0.11	0.124	0.081
P	0.029	0.023	1.01

Because of the low temperature at which the charcoal blast furnace worked, the pig irons produced were characterized by low silicon content. Where the phosphorus content was low, these irons were sufficiently tough in the cast condition to permit their use for such items as hammers and anvils, hence the name 'tough' pig iron.

Refining and fining

Percy[3] considered the production of malleable bar from pig iron in considerable detail, with particular emphasis on technical aspects and the processes in operation about the middle of the 19th century. Bauerman[4] also described the processes and introduced the terms 'refining' and 'fining'. Of the earlier processes, i.e. those in operation in the 17th and 18th centuries, Schubert gives a good descriptive account but does not consider technical detail. It is to these 17th and 18th century processes that the present discussion refers.

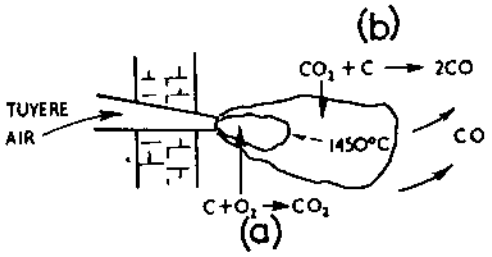

Fig. 4 — Combustion of charcoal in front of the tuyere

The burning of charcoal in front of the tuyere produced two zones, one oxidizing (a) and the other reducing (b), as shown in Fig. 4, and the maximum temperature attained was immediately in front of and above the oxidizing zone. Here the pig iron would melt readily and on entering the oxidizing zone the silicon of the pig iron would oxidize rapidly to SiO_2. In tough pig iron the major portion of the carbon was in the form of graphite (Table II). The removal of silicon from solution in the iron permitted some of the carbon to replace it as iron carbide (Fe_3C) and the remainder would be oxidized and pass up through the charcoal bed as CO. This desiliconizing operation is what Bauerman termed 'refining'.

TABLE II Analyses of pig and 'refined' iron, %

		Nibthwaite pig	Refined iron[13]
C	graphitic	2.43	0.01
C	combined	1.43	2.93
Si		0.85	0.173
Mn		0.05	0.05
S		0.029	0.037
P		0.11	0.16

When considering the reactions occurring during the refining process, Bauerman states 'The carbon, if it existed originally as graphite, first passes into the combined state, and is then converted into carbonic acid (CO_2) either by the oxygen of the blast, directly, or indirectly by the action of protoxide (FeO), peroxide (Fe_2O_3), or magnetic oxide of iron (Fe_3O_4) dissolved in the slag'. The effect of remelting Nibthwaite pig iron under oxidizing conditions can be seen in Table II, from which it will be noted that most of the silicon has been removed and some of the graphitic carbon has passed into combination with the iron.

The finery process therefore consisted of two operations following each other in the same furnace, without any marked division. The operation of refining occurred in the first melt-down. The workman then raised the pasty lump into the oxidizing zone in front of the tuyere when other impurities such as Mn and combined carbon were oxidized and the metal was said to be fined (Fig. 5). Thus the overall process consisted of a refining and a fining operation during which malleable iron was produced. The temperature in the hearth was very much lower than that in front of the tuyere (Fig. 4) and the falling molten droplets solidified and coalesced into a pasty lump with liquid slag in the interstices and around the mass.

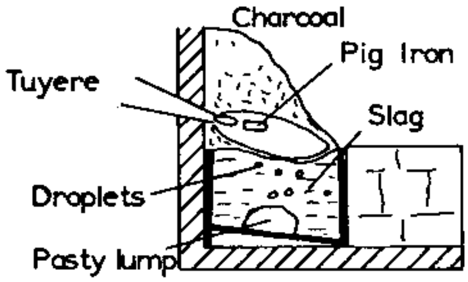

Fig. 5 — Hearth conditions during fining

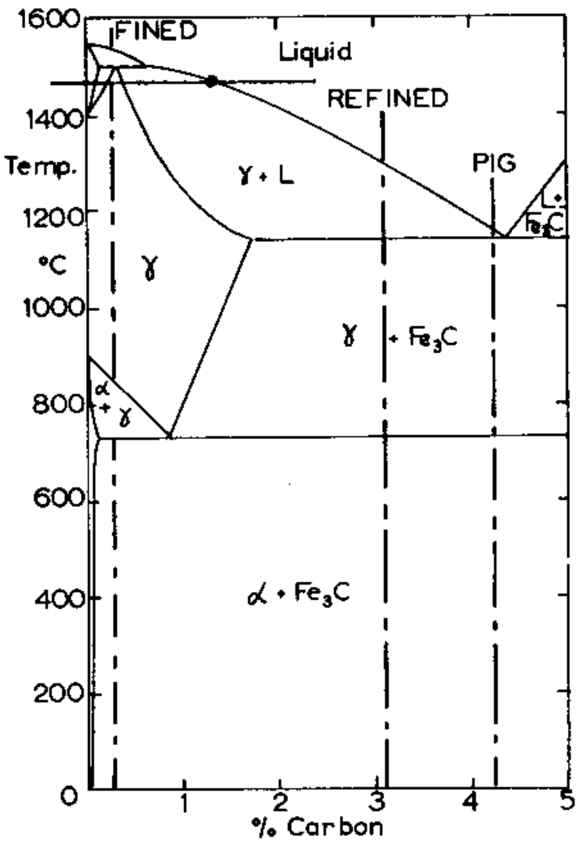

Fig. 6 — Carbon equivalents for stages of fining

The effects of refining and fining on the melting temperature of the pig iron can be seen in Fig. 6, where the carbon equivalent[14] of the iron, based on the formula:

$$C.E.\ (wt\%) = \text{Total carbon} + \frac{P}{2} + \frac{Si}{4}$$

is inserted into the iron-carbon equilibrium diagram for the various stages. Fined iron is very low in carbon and the increase in melting temperature from refining to fining can be seen in Fig. 6. During fining there would be a further gradual rise in the melting temperature of the iron, and at some stage during the operation the temperature in front of the tuyere would not be sufficiently high to keep the metal molten. Thus the finer was able to judge by the 'feel' of the metal when it was sufficiently fined, and any rabbling beyond that point would only result in excessive iron loss due to oxidation. The compositions of two typical fined irons are given in Table III.

Finery slag

The SiO_2 formed from the silicon in the metal would combine with some oxidized iron to form fayalite ($2FeO.SiO_2$) which, as slag, would descend in the molten form towards the hearth. The amount of slag formed during the refining op-

TABLE 3 Analyses of fined iron, %

	Nibthwaite	Penny Bridge
C	0.028	0.035
Si	0.23	0.14
Mn	0.13	0.09
S	0.024	0.12
P	0.31	0.209

eration was directly proportional to the silicon content of the pig iron. Thus in the case of the Nibthwaite pig iron, after initial melting and desiliconizing down to 0.17% Si, 100 lb of pig iron containing 0.85% Si would produce 5 lb of slag. This would be a very small volume compared with the metal volume. In addition, very little slag would be formed during the fining stage; any increase in slag volume would be mainly due to oxidized iron entering the slag as dissolved FeO. Thus in order to work the charge effectively, a much greater slag volume would be necessary. The majority of the oxidation of the metalloids occurred in front of the tuyere and some slag-metal reactions would take place in the hearth between the dissolved FeO in the liquid slag and the pasty metal. This would enhance the final decarburization of the metal.

In order to build up the volume of slag, hammer scale, ore, or even a little quartz or clay were sometimes added. It seems likely also that in order to maintain a suitable slag volume the main mass of liquid slag from the previous runs would be left in the furnace and only any accumulated excess over the workable level removed. Since the hearth was lined with charcoal-coated cast-iron plates which protected the furnace structure, little or no slag attack would occur, and so the slag composition was entirely dependent on the composition of the pig iron and the additives used by the finer. The constituents which would form on solidification would be similar to those found in Roman slags by Morton and Wingrove,[15] i.e. wüstite, fayalite, and a glass approximating to the composition of anorthite ($CaO.Al_2O_3.2SiO_2$).

Where hammer scale (virtually pure oxides of iron) was used to build up the slag volume, the resultant slags on fining would contain a high proportion of free wüstite, and set in a matrix of fayalite with only a small amount of glass. This is in agreement with slags found at Ipsley Forge (Worcs.) and Powick Forge (Worcs.), as shown in Table IV and Figs. 7 and 8. Percy mentions the addition of quartz or clay in the

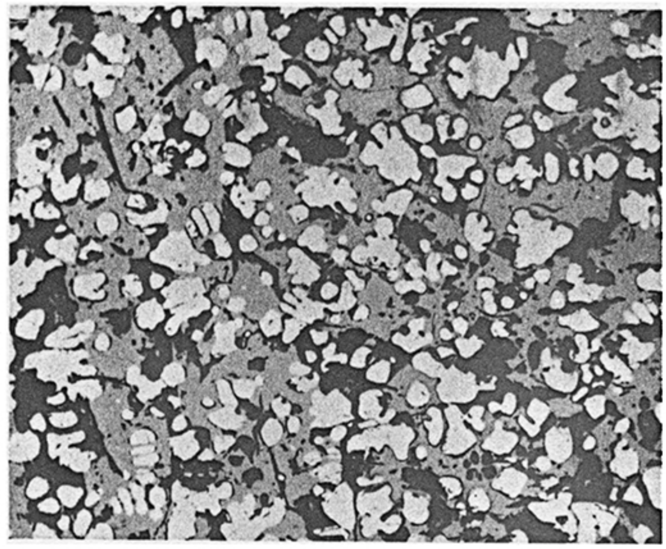

Fig. 8 — Powick forge slag (X 130)

Franche-Comté process, but no direct evidence is available to suggest such usage in this country. The pig irons used in the finery were all cast from the charcoal blast furnace into sand pig beds and siliceous material would adhere to them. This siliceous material was slagged in the finery and would influence the final composition of the slag produced.

At Stony Hazel an ore bin containing fine ore was uncovered on the site. Fine ore was also found embedded in the hammer-scale floor between the bin and the finery. In addition, ore was trapped in the slag, which is strong evidence of its use on that site. When ore was added, constituents such as FeO, SiO_2, CaO, MgO, MnO, Al_2O_3, P_2O_5, and S would affect the slag composition and volume. It is also possible that some of the Fe_2O_3 would be reduced as in the bloomery process, and the iron produced would coalesce with the pasty lump. The remainder of the Fe_2O_3 would dissolve in the molten slag where it would provide FeO for slag-metal reactions. The final slag would contain a large quantity of fayalite, glass, and wüstite in an amount dependent upon the degree of decarburization of the iron and the technique of the operator and his use of ore. The analyses and the calculated mineral phases of slags found at Stony Hazel, and New Weir (Forest of Dean) are given in Table IV, and the microstructures in Figs. 9 and 10. It will be seen that these structures agree

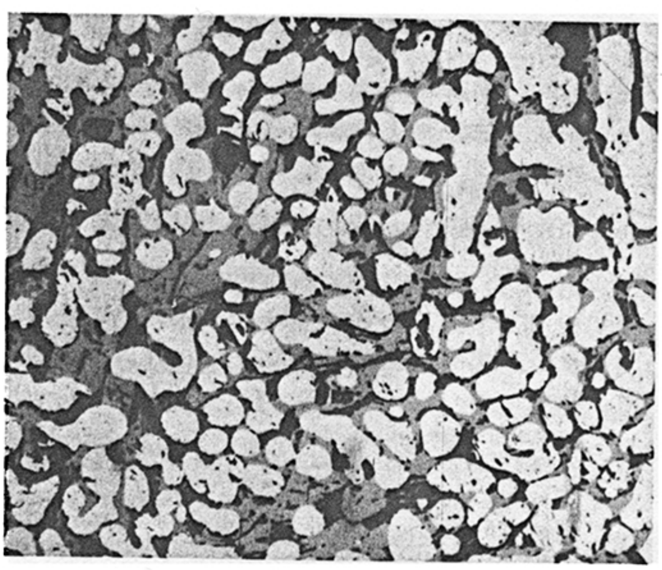

Fig. 7 — Ipsley forge slag (X 130)

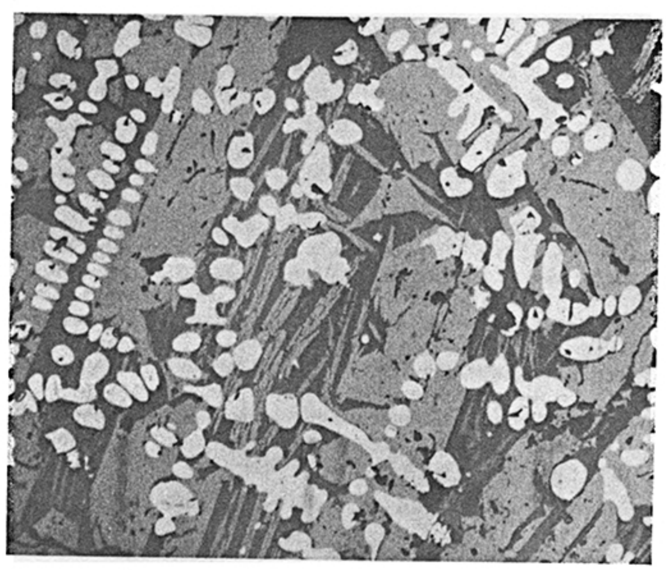

Fig. 9 — Stony Hazel slag (X 130)

Fig. 10 — New Weir forge slag (X 130)

TABLE IV Analyses and calculated phases of finery slags, %

	Stony Hazel	New Weir	Powick	Ipsley
Fe_2O_3	3.20	2.57	9.10	11.20
FeO	56.90	58.31	65.10	69.10
SiO_2	24.20	26.40	11.20	7.70
CaO	2.50	2.40	3.10	2.50
MgO	0.90	0.84	0.29	0.10
MnO	0.13	1.41	3.83	0.58
Al_2O_3	8.90	6.20	3.50	5.70
P_2O_5	0.71	1.92	2.59	1.80
S	0.22	—	0.10	0.08
TiO_2	—	—	0.23	0.10
Fe	1.90	—	0.75	0.88
	— = not determined.			
Wüstite	16.13		62.68	78.33
Fayalite	70.24		26.68	8.46
Anorthite (glass)	13.62		10.62	13.20

with those expected from the discussion. Thus differentiation between finery slags of this type, Roman bloomery slags, and some medieval slags is extremely difficult.

Chafery slags

These slags are known in various districts under such names as mossers, in Furness and the Lake District, and gits and hambones in the Midlands. They are usually found in the form of large hambone-shaped lumps weighing up to about 56 lb and comprise two distinct layers. The slag was tapped from the furnace into a hole in the forge floor and, being poured somewhat 'wild' (i.e. gassy), the top layer consists of a frothy and porous mass whereas the lower half is more dense. Frequently many pieces of charcoal are found entrapped in the upper layer. The analyses of three mossers and one hambone are given in Table V.

Many variables could affect the composition and structure of chafery slags. The use of semi-refractory culm to make up the beehive muffle meant that proportions of it would be slagged during operation, and this could cause high SiO_2, CaO, and Al_2O_3 contents in the slag. In a similar manner

TABLE V Analyses of chafery slags, %

	Mossers				Hambone
	Nibthwaite	Sparke Forge	Penny Bridge Porous	Penny Bridge Dense	Ipsley Forge, Worcs.
Fe_2O_3	9.43	27.60	31.40	9.70	9.90
FeO	65.53	33.10	29.30	40.63	58.80
SiO_2	16.16	21.32	11.04	14.58	17.80
CaO	2.10	5.68	4.34	5.16	2.60
MgO	1.20	1.77	3.14	3.00	0.22
MnO	nd	nd	nd	nd	2.50
Al_2O_3	4.30	2.52	4.30	12.45	4.90
P_2O_5	0.23	0.12	0.05	0.05	2.01
S	0.47	nd	3.69	4.67	1.50
L.O.I.	6.20 (gain)	6.50	12.90	3.95	(Fe 0.70)
	nd = not determined				

the use of mineral fuel was first applied to the chafery long before any other type of furnace and, when used, ash from the fuel would automatically be slagged. Mineral phases such as hercynite, various silicates of lime, and magnetite might appear in addition to the usual wüstite-fayalite-glass complex. The former would would result from refractory contamination, and magnetite would be formed either from detached scale formed under oxidizing conditions becoming dissolved in the slag or from rapid cooling of 'wild' slag. At the present time chafery slags can best be identified by their visual appearance in the mass and the two-layered structure rather than by analysis and microstructure. It is hoped that further work will produce distinctive features that will assist positive metallurgical identification of these slags.

ACKNOWLEDGMENTS

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