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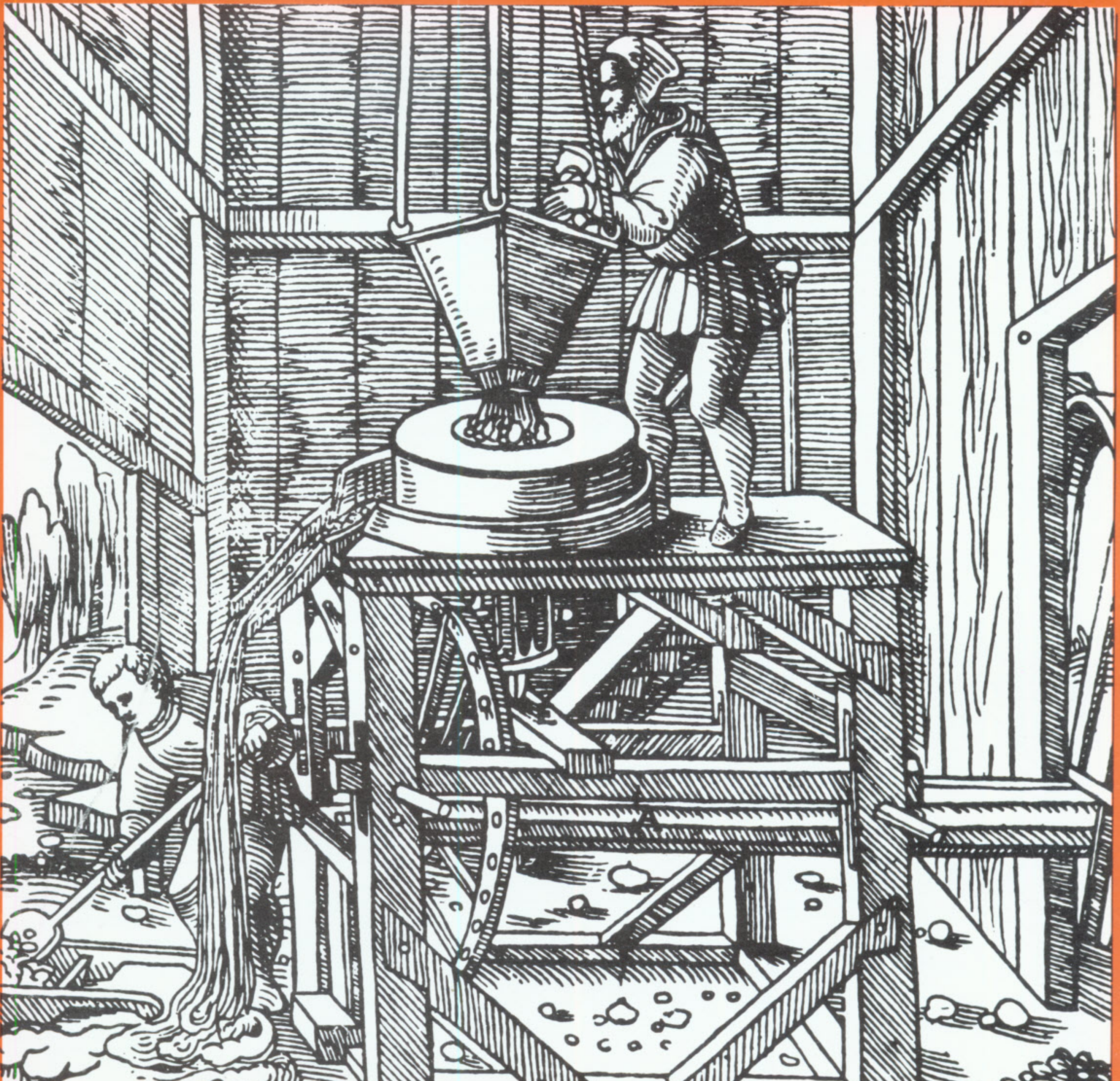

# Journal of the Historical Metallurgy Society

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# Historic blast furnace slags: Archaeological and metallurgical analysis

*John R White*

**ABSTRACT**

Blast furnace slags, the most ubiquitous of furnace by-products, can be analyzed and evaluated as to their ability to fulfill four principal criteria ie. fusibility, fluidity, optimum composition, and desulphurizing capacity. In addition to these chemical characteristics, slags have visual attributes such as colour, texture, and porosity which likewise provide clues to their use, temperature, effectiveness, etc. The effectiveness of the slag is a primary indicator of the efficiency of the furnace operation and the ironmaking process. Furnaces may fail to match up to minimum standards either because they are historically early, technologically sub par for their time, or because they employed inferior raw materials. Twenty-seven slag samples from twelve American and European pre-1850 blast furnaces were collected, analysed, and compared. None of the slags were particularly effective with regard to any of the criteria but only in the case of the innovative Eaton, where coal was mixed with charcoal and a relatively high level of sulfur added to the charge, did a failure to meet minimum standards appear to make any significant difference.

**KEYWORDS**

a) UNITED STATES, AMERICA, EUROPE, EATON FURNACE; JOANNA FURNACE, SAUGUS FURNACE, HOPEWELL FURNACE, TRUMBULL FURNACE, WILLROY FURNACE,
b) 1802–1808, INDUSTRIAL REVOLUTION, 16th–9th CENTURY,
c) ARCHAEOLOGY, CHEMISTRY, SPECTROGRAPHY, METALLURGY, X–RAY FLUORESCENT ANALYSIS,
d) SLAG, BITUMINOUS COAL, CHARCOAL, CAST IRON, SULPHUR, ALUMINA
e) IRONMAKING, BLAST FURNACE, SMELTING, SLAG EFFICIENCY, DESULPHURIZATION REFRACTORY INDEX, PHASE RELATIONS

In the summers of 1975, 1976 and 1977 archaeological excavations were carried out at the Eaton (Hopewell) Furnace near Struthers, Ohio. These excavations were conducted primarily to recover information specifically on the operation of the Eaton, a National Register site and more generally on early (pre-1850) ironmaking in the Western Reserve. The Eaton Furnace, considered to be the earliest blast furnace west of the Allegheny Mountains was erected in 1802-03 and probably went out of blast around 1808. Subsequent post-seasonal analyses of the recovered material led to the discovery of several significant facts of both local and worldwide interest; among them the fact that the Eaton represented the as yet earliest evidence (archaeological and chemical) of the use, for any length of time, of the combination of bituminous coal and charcoal as a reduction fuel in American ironmaking.[1]

Analyses of the various materials from the Eaton site (33 MH 9) led to the ready realization that slag, the most ubiquitous of cultural remains from a blast furnace, was a singularly informative blast furnace by-product. From it can be determined, with a certain degree of accuracy, the furnace firing temperature; too, the slag can be analyzed and evaluated in terms of its efficiency, ie. how well it performed its duties in purifying the cast iron. By extension, the slag effectiveness (or noneffectiveness) can supply us with insights into the overall efficiency of the furnace operation. These are determinations that would not have been readily known to the Eaton ironmasters, but which, because of the technological and analytical developments since 1808, are available to us only in hindsight.

## Slag Criteria and Characteristics

The slag phase in ironmaking has always been a critical one as indicated by the maximum "Take care of the slag, and the steel will take care of itself". Whereas today's steel-maker is a highly trained technologist well steeped in slag chemistry, his antecedent, the 19th century ironmaster was more an artisan guided by that elusive quality that we refer to as a 'feel' for his trade. Then, as now, the slag characteristics of primary concern to the ironmaker were a) fusibility, ie, the slag should be completely liquid at ironmaking temperatures; and b) its fluidity, ie, the liquidus should have relatively low viscosity, that is, favourable diffusion properties. To these, Muan and Osborn[2] add the properties of c) optimum composition, ie, the slag should be such that uncontrollable variation in its composition is tolerated without a troublesome slag developing; and d) a high sulphur-removing capacity.

The requirements of fusibility and optimum composition are perhaps the easiest to meet. Furnace charge materials which fall above the 1500°C isotherm are all liquid. Early blast furnaces had little difficulty satisfying this temperature minimum even minus the hot blast, though some, the Eaton for instance, created difficulties for themselves by having a weak (it was propelled by a relatively small bellows some twenty-plus feet up a 50° slope), damp, and cold blast. Chemically the various oxides present in the charge have a mutual affect on the melting temperatures of each other, the temperature of the formation of slag is generally higher than its melting point. As a rule, the melting point of a slag is influenced by its degree of basicity, ie, the most fusible slags have acid constituents somewhat, but not overwhelmingly, in excess of the basic.

One very important ratio governing the slag temperature has to do with the alumina-silica-lime sequence. Slag which is high in alumina compared to lime and silica will take on a refractory character[3] and require a higher furnace temperature. This tendency is much more critical in cold blast furnaces where minimal temperatures are not met with a great deal of leeway. A refractory index (RI) can be devised by dividing the percentage of alumina by the combined percentages of lime and silica:

$$\frac{Al_2O_3}{CaO+SiO_2} = \text{Refractory Index (RI)}$$

The lower the index, the less refractory the slag.

As to the requirement of optimum composition, it was of prime importance that the ironmaker avoid close approach to composition areas where a crystalline phase would start to separate out. The measure of efficiency in a slag has much to do with its ability to take up and retain the gangue material not desired in the finished iron. This ability depends on the essentially relative basicity of the slag. Silica ($SiO_2$) and alumina ($Al_2O_3$) are the principal acid constituents in a furnace charge; together they constitute invariably more than 40–50% of the gangue. By controlling the percentages of these acids the necessary level of slag basicity is maintained, as whatever is not acid must be base. Such knowledge and ability was considered to be part of the experienced ironmaker's intellectual wherewithal. It was this perhaps more than any other skill, which separated the first-rate furnaceman from the mediocre.

The desulphurizing capacity of slags increases in the order $SiO_2 < Al_2O_3 < MgO < CaO$. The optimum compositional ratio for desulphurization will have a low $SiO_2$–$Al_2O_3$ content and a high CaO – MgO content.[4] A desulphurization index can be determined by dividing the combined percentages of CaO and MgO by the combined percentages of $SiO_2$ and $Al_2O_3$:

$$\frac{CaO+MgO}{SiO_2+Al_2O_3} = \text{Desulphurisation Index (DI)}$$

To a point, at least, the higher the index the greater the sulphur-removing capacity.

Potassium oxide ($K_2O$) and sodium oxide $Na_2O$) are the best desulphurizers but because of their high vapour pressures and the severe way in which they attack the furnace inwall, they are not acceptable slag components.[2]

The fourth requirement, low viscosity, is met by the same set of circumstances that provide a high sulphur-removing capacity. The viscosity or fluidity of most basic slags is a function of the degree of polymerization of the silicon-aluminum-oxygen tetrahedra. The lime (CaO) and periclase (MgO) act as 'breakers' and promote this desirable polymerization.

To a point, the viscosity decreases with the increased ratio of lime (CaO) and periclase (MgO) to silica ($SiO_2$) and alumina ($Al_2O_3$). But there is a limit to this. When the $SiO_2$ level gets too low, either absolutely or relative to the CaO and MgO, the vicosity will begin to increase with the formation of merwinite ($Ca_2MgSi_2O_8$) and periclasic crystals in the liquidus.[4]

The optimum slag compositions for a temperature of 1500°C are presented in Table 1. According to Muan and Osborn[2] it is more likely that rather than there being an ideal $Al_2O_3$ percentage – 10% as suggested by Holbrook and Joseph[5] and Holbrook[6] – it makes little difference what the $Al_2O_3$ level is as long as it ranges between 0–30% and as long as the desulphurization is maintained near the optimum value of 1.41. Of course, the desulphurization index becomes more critical the more sulphur present in the raw materials.

Slags, as well as having measurable chemical compositions, have visual characteristics which can provide clues to their use, effectiveness, etc. Colour, texture, and porosity are three such slag characteristics.

Slag colour ranges from very light or milky grey to a deep black, and includes different tones of green, blue and turquoise. The colour of the slag is due to any of a combination of factors including chemical constituents, temperature of formation and rate of cooling; with slags that are high in earthy bases (especially MgO and CaO) tending to be light grey to blue and with high silica slags generally having a darker colour than basic ones. Colour is dependent on so many subtle combinations of variables that, by itself, it is not sufficient in any but the most superficial comparisons.

Texture refers to such traits as vitreosity, hardness, and homogeneity. Slags may range from glassy to dull and stony in appearance, and when scratched may be rock hard to chalky in hardness. Slags tapped from cold blast charcoal furnaces may be texturally homogeneous throughout or they may be bisque-like, containing small fragments (sometimes not so small) of charcoal, 'rust spots' or prills of iron, and under certain conditions (slow cooling) crystallized minerals.

To a point – a high percentage of alumina to silica opposes the tendency – as the proportion of bases to acids decreases, slag becomes more vitreous or glassy throughout[7]. The type

**TABLE 1**

**OPTIMUM SLAG COMPOSITION WITH VARIOUS PERCENTAGES OF $Al_2O_3$**

| $Al_2O_3$% | CaO% | MgO% | $SiO_2$% | Desulphurization Index |
|---|---|---|---|---|
| 5 | 43 | 16 | 36 | 1.44 |
| 10 | 44 | 14 | 32 | 1.38 |
| 15 | 44 | 12.5 | 28.5 | 1.30 |
| 20 | 45 | 11 | 24 | 1.27 |
| 25 | 48 | 8 | 19 | 1.27 |
| 30 | 56 | 5 | 9 | 1.56 |
| 35 | 54 | 4 | 7 | 1.38 |

of blast (cold or hot) and rate of cooling (slow or fast) will also affect the vitreosity of the slag. All things being equal, cold blast slags are glassier than hot blast ones[8]; and rapidly cooled ones retain a vitreosity whereas those slow-cooled are dull and stony in appearance.[7] Stated in temporal or evolutionary terms, early blast furnace slags will generally be glassier than later ones.

The hardness of the slags varies, at least with the passage of time and attendant weathering, from talc-like soft and slaked to something just less than the hardness of quartz. As a general rule, the slaking, soft, slags are those which are high in lime. MgO tends to retard this 'softening' process. The average slag has a hardness of 5 or 6 on the Moh's scale.[9]

The degree of homogeneity of blast furnace slags is a function of its composition, firing temperature, and cooling rate. Slags when cooled slowly tend to crystallize into definite mineralogical forms, depending on their chemical compositions. Enstatite, augite, wollastonite are common crystal forms as are olivine, pyrozene, and melilite. Fast cooling prohibits the alignment of such forms. Charcoal slags which have not been heated to the proper temperature, often as a result of their location within the furnace, will sometimes contain small to medium-sized charcoal and/or prills or beads of iron (Fig. 1). The iron is often noticeable in the form of rust.

**Porosity** refers to the minute to medium-sized holes or vesicles which may interrupt the smooth surface and internal consistency of the slag. Molten slag is charged with gas while under the extreme pressures of the blast furnace; when released from the pressure of the furnace, these dissolved gases (of which CO is a principal one) escape forming vesicles in the cooling slag. Porosity will vary from slag to slag depending on the chemical composition of the furnace charge. Morton and Wingrove[7] observe two things going hand-in-hand with an increased porosity: a glassy appearance will decrease and the colour will lighten.

The amount of slag produced is a function of the composition of the ore being smelted. A high grade ore inevitably leads to the production of a moderate amount of slag while a low grade ore produced more slag.[10] Depending on the ore grade, a blast furnace might be expected to produce upwards of half a ton of slag for each ton of iron produced.

### The Historic Slags

A total of thirteen slag specimens were selected for analysis from the Eaton (Hopewell) Furnace (Table 2). These slags were chosen on the basis of their provenience (horizontal and vertical) and their colour and texture. An attempt was made to test a wide variety of colour-texture-porosity-location combinations. Nine of these Eaton samples were examined by x-ray fluorescent analysis and titrimetric analysis at the Youngstown Sheet and Tube Company, the remainder were sent out to four independent industrial research laboratories for similar testing. The specimens were analyzed using a Vaccum X-ray Quantometer. The instrument was calibrated using slag samples of known constituency. The critical calibration for the Eaton slags (and for the eight other historic American slags analyzed) was for $SiO_2$ where the range was in the 50 percentile. Modern test samples, though available, are not common in this high silica range.

Note was made during the excavation of the Eaton Furnace slag heap that black-glassy-nonporous was specifically the most predominant colour-texture-porosity slag combination. Generally speaking, dark-coloured slags, whether black, deep blue, or greenish black, were much more common than light-coloured ones. Glassy texture was the only noted for the Eaton slags. Nonporous slag was far more predominant than porous or vesicular. Even those specimens categorized as porous are only so in a relative sense. No Eaton slag samples were very porous.

It was also noted that the greater the depth within the slag pile the smaller the fragments of slag. It is difficult to determine whether this fragment size difference is a function of cultural or natural processes; or more plainly, whether the slag on the bottom is smaller because of the Eaton smelting techniques and the nature of the slag produced in the early years, or because of taphonomic, geological, and/or climatic processes operating on the slag heap in the 170 years since the site's abandonment.

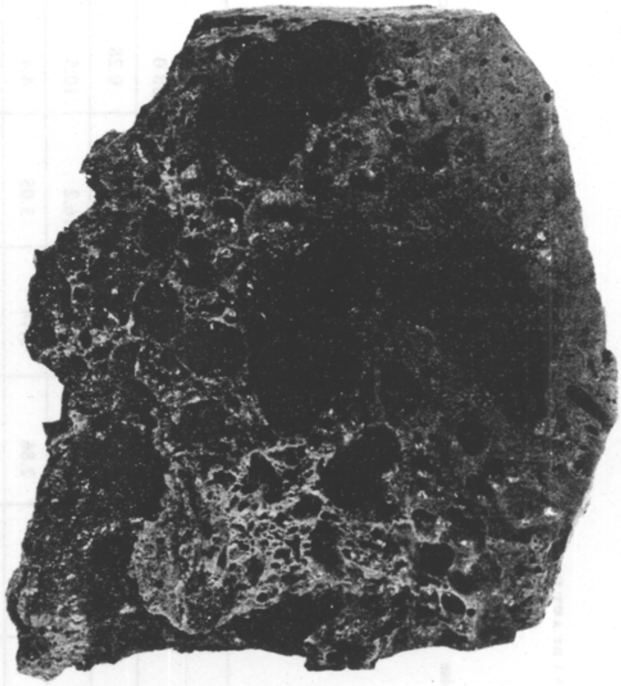

*Fig. 1 Large fragment of Eaton slag showing inclusions of charcoal and vesicles formed by escaping gases.*

Using the 15% $Al_2O_3$ plane of the $CaO$-$MgO$-$Al_2O_3$-$SiO_2$ tetrahedron designed by Osborn and his co-investigators[11], the Eaton slags were found to fall within the 1300°C isotherms (Fig. 2). This is about as 'cool' a blast as it is possible to use in the iron smelting process.

The refractory indices (Table 2) for the Eaton slags ranged between 0.18 and 0.24 with a mean of 0.21. The reasonably low indices bespeak a not-too-refractory slag and this fact probably allowed the furnace to operate at such a low temperature.

The desulphurization index for Eaton slags (Table 2) varied between a low 0.20 and 0.42 with a mean of 0.33. For comparison, slags from eight other early American blast furnaces dating from 1650 to 1850, were collected and analyzed (Table 3). The desulphurizing indices ranged from a low of 0.28 (from Hammersmith-on-the-Saugus, the earliest blast furnace in the New World) to a high of 0.54 (from the upper levels at the original Hopewell Furnace in Berks County, Pennsylvania). It is plain that the Eaton acid slags would not be considered particularly effective,

TABLE 2

COLOUR, TEXTURE, POROSITY AND ANALYSES OF EATON (HOPEWELL) BLAST FURNACE SLAGS, %

| Specimen* | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Colour | Deep Blue | Green | Black | Turquoise | Green-Turquoise | Green | Black | Grey-Black | Green-Black | Dark Grey | Light Blue-Green | Grey-Black | Blue-Black |
| Texture | Glassy | Glassy | Glassy | Glassy | Glassy | Glassy | Glassy | Glassy | Glassy | Glassy | Glassy | Glassy | Glassy |
| Porosity** | NP | NP | NP | NP | NP | NP | NP | P | P | NP | P | P | NP |
| Constituents | | | | | | | | | | | | | |
| Mg0 | 6.1 | 6.1 | 5.1 | 6.2 | 3.3 | 2.7 | 2.9 | 2.4 | 4.3 | 3.47 | 4.5 | 6.68 | 4.4 |
| $A1_20_3$ | 15.3 | 16.2 | 14.8 | 16.3 | 14.5 | 15.0 | 13.1 | 14.4 | 16.3 | 13.9 | 14.8 | 14.36 | 15.2 |
| $Si0_2$ | 51.6 | 51.8 | 53.5 | 53.2 | 55.3 | 55.8 | 55.0 | 56.0 | 58.0 | 56.86 | 50.4 | 51.12 | 54.21 |
| S | 0.4 | 0.5 | 0.3 | 0.4 | 0.4 | 0.35 | 0.28 | 0.38 | 0.28 | 0.23 | 0.31 | 0.31 | 0.55 |
| Ca0 | 18.2 | 16.6 | 20.2 | 15.4 | 19.0 | 17.8 | 19.3 | 16.2 | 10.5 | 19.8 | 19.4 | 20.69 | 20.6 |
| Mn0 | 3.2 | 4.1 | 2.6 | 4.1 | 2.9 | 2.86 | 3.74 | 3.05 | 4.4 | 2.3 | 2.4 | 3.44 | 3.2 |
| $T_10_2$ | 0.7 | 0.7 | 0.5 | 0.7 | 0.6 | 0.61 | 0.6 | 0.6 | 0.7 | 0.7 | 0.58 | 0.98 | – |
| Fe0 | 0.5 | 1.0 | 0.4 | 0.6 | 0.6 | 0.66 | 1.94 | 2.32 | 1.75 | 0.86 | 3.2 | 1.46 | 0.9 |
| $\frac{(Ca0+Mg0)}{(Si0_2+A1_20)}$ = D.I. | 0.36 | 0.33 | 0.37 | 0.31 | 0.32 | 0.29 | 0.33 | 0.26 | 0.20 | 0.33 | 0.37 | 0.42 | 0.36 |
| $\frac{(A1_20_3}{(Si0_2+Ca0)}$ = R.I. | 0.22 | 0.24 | 0.20 | 0.20 | 0.20 | 0.20 | 0.18 | 0.20 | 0.24 | 0.18 | 0.21 | 0.20 | 0.20 |

*Specimen Proveniences: 1,2,3,4, –surface of the slag heap; 5–tipple zone at 20cm; 6–86,8 – casting floor at 25cm; 7 – slag pile at 75cm; 9 – slag pile at 120cm; 10 – slag pile at 200 + cm; 13 – slag pile at 10cm; 11,12 – slag pile at 50-60cm.

**Those specimens categorized as porous are only such in a relative way as compared to other Eaton samples. No Eaton sample was very porous or vesicular.

at least in terms of their sulphur-retaining abilities, even for their time.

The need for an effective sulphur retention increases with the amount of sulphur being added to the furnace. Where very little or but a trace of sulphur was being introduced into the furnace charge, iron-masters would not have to concern themselves with removal, however such a neglect would have to be rectified when an appreciable amount of sulphur was added (as it would be with the substitution of raw coal or coke as a fuel). Such a need was called for at the Eaton Furnace. Archaeological and chemical evidence indicates that part way through the furnace's operation period the ironmakers switched from a charcoal fuel alone to a combination of bituminous coal and charcoal. This innovative step was taken some thirty years before it is historically attested to anywhere else in the New World.[1] Ironically it was this charcoal-saving measure that ultimately led to the furnace going out of blast; for while the innovation forestalled the eventual shortage of hardwood needed for charcoal, it upped the sulphur content of the furnace charge to a level that was beyond the capacity of the slag. This created a two-fold disadvantage with a) cast iron having higher sulphur content than desirable and b) the furnace being 'choked up' by the bituminous coal which becomes tarry when heated. This latter condition was especially serious when primitive blowing equipment provided only a weak and cold blast. When the Eaton Furnace blew out, a section of inwall and spilled out onto the casting floor in the form of a huge multi-lobed salamander, the Eatons did not bother to repair and refire – a task which the archaeological evidence indicates the ironmakers found the need and incentive to perform on at least one previous occasion. The Eaton 'camel' had obviously encountered its bituminous 'straw'.

It is significant that the three slag specimens (10, 9, 7; Table 2) having the lowest sulphur content were from the lower strata of the slag pile ie, presumably before bituminous coal was added as a substitute fuel; and those having the highest (2 and 13) were recovered in the upper stratum or surface to –10 cm.

A comparison of the Eaton slags in terms of their Ca0, Mg0, and $Si0_2$ percentages with the figures considered optimum for a 15% $A1_20_3$ composition (Table 1) demonstrates that the Eaton slags were certainly below the optimum overall. There was far more $Si0_2$ than desirable; far too little Mg0; and far too little Ca0. Such a poor slag composition was ultimately the result of utilizing a less than ideal combination of flux (limestone), fuel, and reniform ore in a relatively primitive cold blast furnace.

In addition to the thirteen slags selected for analysis from the Eaton Furnace site, the author either collected himself, or had sent to him by others, eight slag specimens from various other pre-1860 American charcoal blast furnaces. These were subjected to the same series of spectroanalytic and wet chemical tests as the original Eaton samples and the results compared.

All eight pieces of slag were non-porous or at least relatively so. None were what would be termed vesicular. All of the specimens save the Trumbull one were either semi-glassy or glassy in texture. The semi-glassy appearance may have been due to a dullness imparted to the otherwise glassy material by rolling or battering. The Trumbull Furnace specimen was decidedly stony and dull in texture.

It was noted while collecting the slag specimens, that the Trumbull slag chunks had a far bigger maximum size than any of the slag from the Willroy or Eaton Furnaces. Several pieces weighed in excess of fifteen pounds. We are not sure of the significance of this observation, if any, however it does seem to have something to do with the process of its creation that in some way increased its toughness and inhibited its fragmentation.

Analysis of the slag specimens demonstrated that the various furnaces produced irons at temperatures ranging between approximately 1260° and 1315°C; the mean being approximately 1278°C (Figs. 3, 4 and 5). Even the least hot of these furnaces operated at temperatures measurably higher than those at the Eaton Furnace. All obviously were more efficient than the Eaton, at least in this regard.

The refractory indices for these slags ranged from a low 0.15 to a high 0.28, with a mean of 0.22 (Table 3). This is just one point higher than the Eaton slags and indicates a not-too-refractory slag, a definitely positive trait in cold blast furnaces.

The desulphurization indices ranged between 0.28 and 0.54 with a mean of 0.40 (Table 3). None of these indices begin to approach the ideal. While these acid slags on the average were better in this respect than the Eaton slags, none are what one could call a good desulphurizing slag. As none of these furnaces is known to have used anything but charcoal as a fuel (which was not the case with the Eaton), the poor sulphur-retaining capacity was not critical.

On comparison, and with but one exception-the Trumbull – none of the Eaton slags, even those collected from stratigraphic levels representing a pre-coal time period, approached the low sulphur content of these other specimens. This undoubtedly, relates to the quality, vis-a-vis low sulphur content, of the raw materials being converted rather than the desulphurizing capacity of the slag itself, as, with few exceptions, the capacity for sulphur-retention was superior, at least relatively so, in these other historic slags. In short, in addition to having slags with a better desulphurizing capacity, the other historic furnaces in this study made cast iron from materials with less sulphur to begin with.

Only one slag, that from the Trumbull Furnace operated by Isaac Heaton the older brother of Danial Eaton (Daniel had the 'H' legally dropped from his name as "no one pronounced it anyway'), had an appreciable amount of sulphur. Is it possible that the use of coal in combination with charcoal that ultimately caused his brother's 'Hopewell' Furnace to fail, may have been employed by Isaac at the Trumbull Furnace? Only the archaeological collection and chemical analysis of Trumbull raw materials and furnace products can verify this. The author is presently at work on this project.

A comparison of these historic American slags in terms of their Ca0, Mg0, and $Si0_2$ percentages with the figures (Table 1) considered optimum for the various levels of alumina, e.g. 10%, 15%, and 20%, demonstrates that the two 10% alumina slags (later Hopewell and Joanna) were far too low in Ca0, too high in $Si0_2$, and just about right (maybe a bit high) for Mg0; the four 15% alumina slags (the two Willroy, Trumbull, and early original Hopewell specimens) were far too low in Ca0 (all less than half the desired amount), far too high in $Si0_2$, and in three out of four cases (the two Willroy and single Trumbull specimens) far too low in Mg0 content; and the two 20% alumina slags (early Saugus and Willroy specimens) were again far too low in Ca0 (less than half the desirable), far too high in $Si0_2$ (more than twice the desirable), and far too low in Mg0 (less than half the desirable percentage). As with the Eaton slags, these specimens were not up to optimum even for their time.

**TABLE 3 – COLOUR, TEXTURE, AND ANALYSES OF EARLY AMERICAN BLAST FURNACE SLAGS, %**

| **Specimen:** | **Saugus*<br>Hopewell (Early)** | **Original*<br>Hopewell (Slightly later)** | **Original*** | **Joanna*** | **Willroy** 1** | **Willroy** 2** | **Willroy** 3** | **Trumbull** |
|---|---|---|---|---|---|---|---|---|
| **Colour:** | **Grey** | **Grey** | **Grey** | **Blue-Green** | **Black** | **Blue-Black** | **Dark Green** | **Green** |
| **Texture:** | **Semi-Glassy** | **Semi-Glassy** | **Semi-Glassy** | **Glassy** | **Glassy** | **Glassy** | **Glassy** | **Stony** |
| **Porosity:** | **NP** | **NP** | **NP** | **NP** | **NP** | **NP** | **NP** | **NP** |
| **Constituents:** | | | | | | | | |
| $MgO$ | 4.8 | 15.3 | 17.3 | 14.9 | 1.9 | 1.6 | 2.0 | 3.7 |
| $Al_2O_3$ | 18.2 | 14.7 | 9.9 | 12.0 | 18.2 | 16.2 | 15.4 | 16.0 |
| $SiO_2$ | 49.7 | 50.1 | 51.3 | 52.0 | 54.7 | 53.2 | 54.3 | 48.5 |
| S | 0.2 | 0.15 | 0.2 | 0.2 | 0.15 | 0.15 | 0.15 | 0.7 |
| $CaO$ | 14.2 | 15.0 | 16.0 | 18.0 | 19.0 | 21.5 | 20.2 | 26.5 |
| $MnO$ | 4.8 | 0.9 | 0.6 | 0.6 | 1.9 | 2.5 | 2.3 | 1.7 |
| $TiO_2$ | 2.4 | 0.9 | 0.7 | 0.6 | 0.6 | 0.5 | 0.5 | 0.5 |
| $FeO$ | 6.1 | 4.0 | 4.0 | 3.0 | 3.1 | 6.3 | 2.6 | 1.0 |
| $\frac{(CaO+MgO)}{(SiO_2+Al_2O_3)}$ = D.I. | 0.28 | 0.47 | 0.54 | 0.51 | 0.29 | 0.33 | 0.29 | 0.47 |
| $\frac{Al_2O_3}{(SiO_2+CaO)}$ = R.I. | 0.28 | 0.23 | 0.15 | 0.17 | 0.25 | 0.22 | 0.21 | 0.21 |

*Specimens analyzed by author but collected and sent to him by others. Exact proveniences unknown.

**Willroy (also Willieroy) specimens taken from surface and selected on basis of colour.

The twenty-one slags collected and/or analyzed by the author, were compared with six European charcoal furnace specimens (Table 4) analyzed and reported on by Morton and Wingrove.[7] None of the slags in the American sample, with the exception of the Saugus specimen, were from furnaces as old in the extreme as the European ones.

The desulphurization indices ranged between 0.26 and 0.57, with a mean of 0.37. None of the figures were even close to the ideal 1.41, and while the mean was less that of the seven other American slags, it was above that of the Eaton specimens. A good desulphurizing capacity would be irrelevant to early furnaces such as these unless undue amounts of sulphur were being introduced into the furnace in some vehicle other than the fuel, which was charcoal. However, the sulphur levels in these acid slags is appreciably lower than in the American slags other than the coal using Eaton ones; indicating that this was likely not the case.

The refractory indices ranged between a low 0.16 and a high 0.38, with a mean of 0.27 (Table 4). These figures include both the lowest (0.16) and the highest (0.38) in the sample and are perhaps reflective of a greater range of raw materials than with the Eaton, where all the raw materials came from a confined area; or the other American slags, where again there is a tighter areal concentration, 3 samples coming from the Willroy and 2 from the original Hopewell.

A comparison of these European charcoal slags in terms of their $CaO$, $MgO$, and $SiO_2$ contents with the optimum figures for 10%, 20% and 25% alumina levels (Table 1), demonstrates that the two 10% alumina slags (Sharpley Pool and Duddon) were far too low in $CaO$, far too high in $SiO_2$, and in the case of Duddon, at least, far too low in $MgO$; the three 20% alumina slags (Rievaulx, Rockley, and Charlcot) were far too low in $CaO$, far too high in $SiO_2$, and in the case of the Rievaulx and Charlcot slags, too low in $MgO$; the single 25% alumina slag (Cannock) was far too low in $CaO$, far too high in $SiO_2$, and just about right in $MgO$. So, like their American counterparts, these early slags were not close to optimum compositional levels.

## Summary and Conclusions

The slag characteristics of primary concern to the ironmaker, now as well as historically, are 1) its fusibility at a reasonable temperature; 2) its fluidity; 3) its optimum composition so that it does not become troublesome in any regard; and 4) its desulphurizing capacity. Certain combinations of materials can constitute what might be deemed an ideal slag, that is, a slag which scores high in the above stated properties. If the study sample is any indication, and there is no reason to suspect it is not, most historic slags fell short of the ideal on at least one or two of these characteristics. However, it is necessary to consider other factors before coming to any

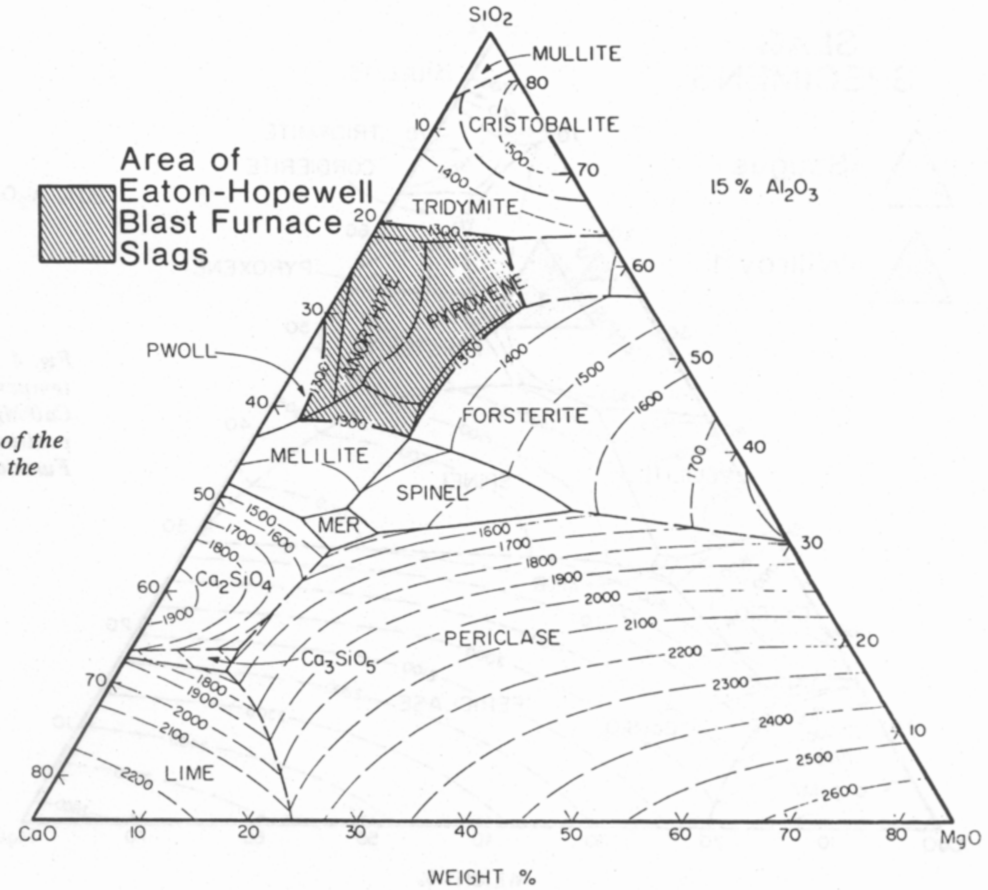

*Fig. 2 Phase relations at liquidus temperatures in the 15% $Al_2O_3$ plane of the $CaO$-$MgO$-$Al_2O_3$-$SiO_2$ system, showing the position of the Eaton Furnace slags. Temperature in degrees Celsius.*

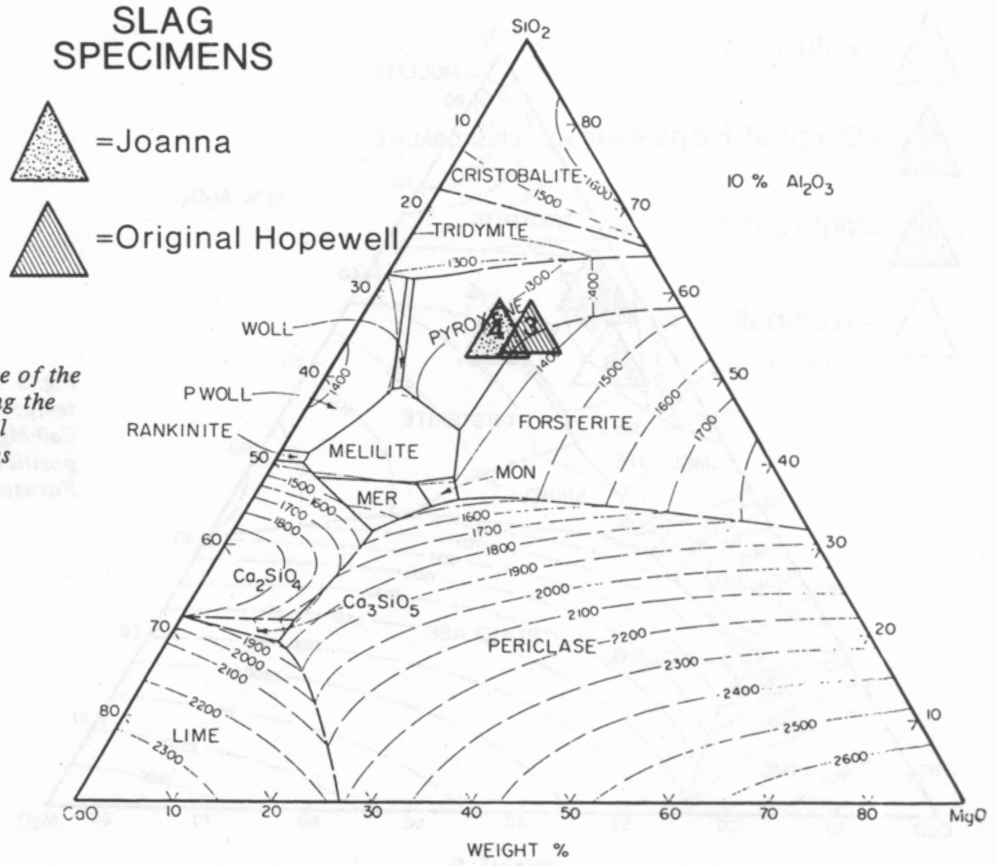

*Fig. 3 Phase relations at liquidus temperatures in the 10% $Al_2O_3$ plane of the $CaO$-$MgO$-$Al_2O_3$-$SiO_2$ system, showing the position of the Joanna and Hopewell Furnace slags. Temperature in degrees Celsius.*

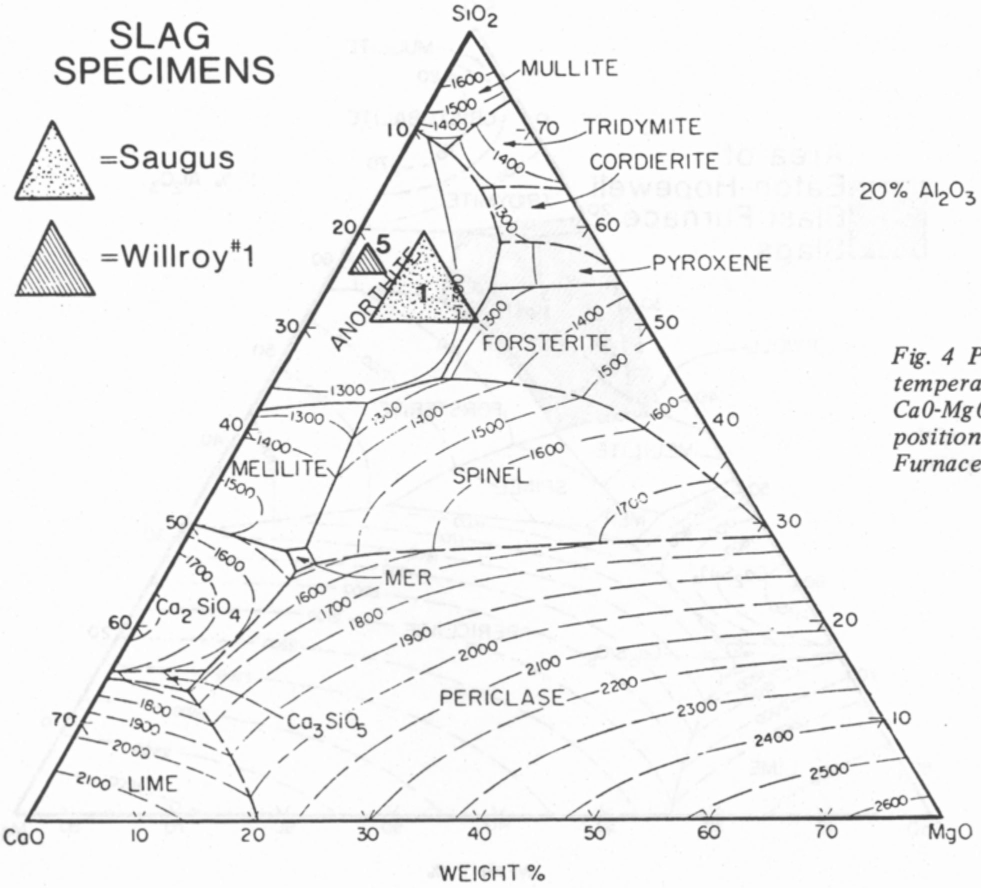

*Fig. 4 Phase relations at liquidus temperatures in the 20% $Al_2O_3$ plane of the $CaO$-$MgO$-$Al_2O_3$-$SiO_2$ system, showing the position of the Saugus and one Willroy Furnace slags. Temperature in degrees Celsius.*

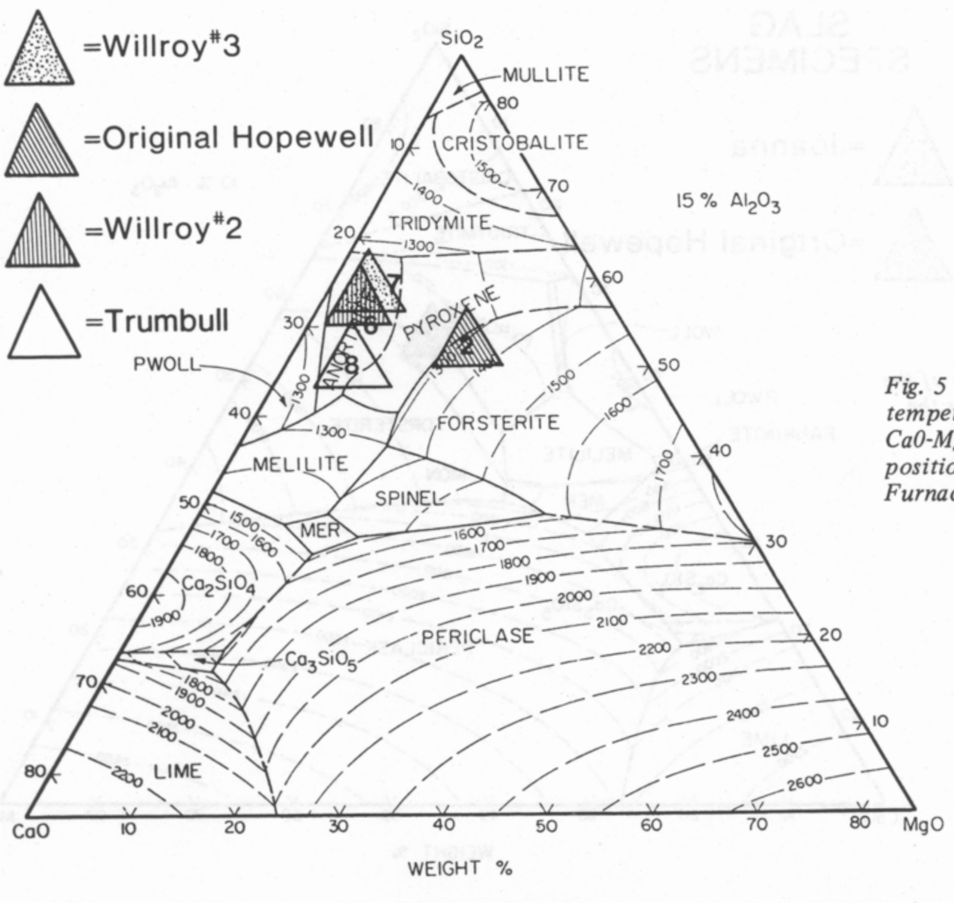

*Fig. 5 Phase relations at liquidus temperatures in the 15% $Al_2O_3$ plane of the $CaO$-$MgO$-$Al_2O_3$-$SiO_2$ system, showing the position of Trumbull, Willroy, and Hopewell Furnace slags. Temperature in degrees Celsius.*

**TABLE 4 – ANALYSES OF EUROPEAN CHARCOAL BLAST FURNACE SLAGS, %**

| Specimen: | Cannock | Rievaulx | Sharpley Pool | Rockley | Charlcot | Duddon |
|---|---|---|---|---|---|---|
| Date(s): | 1561-1650 | 1577-1790 | 1652 | 1652-1736 | 1700-1763 | 1736-1866 |
| Constituents: | | | | | | |
| Mg0 | 7.16 | 3.69 | 12.0 | 9.19 | 4.57 | 3.6 |
| $A1_20_3$ | 23.16 | 22.48 | 11.4 | 19.07 | 20.17 | 12.4 |
| $Si0_2$ | 49.66 | 45.3 | 49.3 | 45.9 | 52.5 | 56.4 |
| S | 0.1 | 0.22* | trace | 0.16* | 0.01 | – |
| Ca0 | 11.92 | 22.8 | 22.8 | 18.4 | 17.0 | 14.6 |
| Mn0 | 3.29 | 1.17 | 0.84 | 2.95 | 1.86 | 9.8 |
| Fe0 | 4.37 | – | 2.7 | – | – | 2.6 |
| $\frac{(Ca0+Mg0)}{Si0_2 \quad A1_20_3)}$ = D.I. | 0.26 | 0.39 | 0.57 | 0.42 | 0.32 | 0.26 |
| $\frac{A1_20_3}{(Si0_2+Ca0)}$ = R.I. | 0.38 | 0.33 | 0.16 | 0.30 | 0.29 | 0.17 |

*Sulphur percentage is total of sulphide and sulphate

final judgment on the efficiency of the slags produced. The temporal position of the furnace producing the slag is certainly an important consideration. Clearly, a furnace representing an era that used only charcoal as a fuel would not have, as a principal concern, the failure to maintain a good sulphur-retaining capacity. A good desulphurizing capability would be, in itself, irrelevant. Likewise, a furnace equipped with primitive blast equpment, either because of being historically early or technologically sub par, will suffer more from a failure to meet fusibility standards than will one that is capable of maintaining a temperature well above the minimum. As to optimum composition, the slag's success in this regard largely depends on its ability to absorb the gangue ingredients (aside from sulphur) not desired in the finished iron. If a furnace was situated so as to be able to utilize high quality raw materials, especially ore, then it could afford less than an optimum composition, as the volume of slag ultimately depends on the quality of the ore – high grade ore leads to a moderate slag volume, low grade to a greater one. Hence, a blast furnace's efficiency will depend on at least three factors: 1) the date of its operation in an absolute sense; 2) its technological level for its time; and 3) the quality of the materials being used.

Twenty-seven specimens of slag collected from or reported on from twelve pre-1860 blast furnaces in the United States and Europe were compared with regard to their physical and chemical properties and several observations made.

The Eaton slags were the coolest of the slags tested, produced at minimum temperatures between 1180°C – 1240°C. This was a function of having an inefficient technology rather than being early historically as ten of the twelve furnaces from which slag was tested were older than the Eaton. Archaeology has shown that the Eaton blast equipment and its arrangement were quite primitive even for 1803. The relatively non-refractory nature of their slag was undoubtedly a blessing unbenownst to the Eaton ironmakers and one that provided the narrow edge that they surely needed.

One thing should be noted. Having a low furnace temperature is not entirely disadvantageous. Providing of course, that the proper fluidity of the slag can be maintained, a lower temperature will normally produce a purer cast iron. This occurs because the gangue material in the charge is not reducible at such low temperatures and hence does not enter the iron but will remain in the slag.

The remaining five American blast furnaces from which eight slag specimens were taken were all measurably hotter than the Eaton. None of the sampled furnaces utilized a hot blast, an innovation first used in Scotland in 1829[10] and in the New World at the Oxford Furnace in New Jersey in 1834[12], so that differences are accounted for by the levels of blast equipment efficiency and the refractory nature of the material.

In terms of desulphurizing capacity, none of the twenty-seven specimens came anywhere close to being effective. However, only in the case of the Eaton, where archaeological and chemical evidence indicates bituminous coal was used in conjunction with charcoal, did this fact make any difference. Pre-coal era furnaces generally could afford the luxury of a poor desulphurizing capacity.

As to meeting the requirement of optimum composition, none of the historic slags scored at all well overall. In fact, only in the area of Mg0 were any of the specimens (Early and Later Hopewell, Joanna, and Cannock) able to maintain near the optimum amount. Such a slag composition is likely due to the use of a somewhat imperfect combination of furnace raw materials.

Examination of the American specimens, at least, supports the hypothesis that earlier (and cold) blast furnaces have a glassier texture than latter (and hotter) ones; all but the Trumbull specimen being semi-glassy or glassy.

Morton and Wingrove's observation[7] concerning the correlation between increased porosity and decreased glassiness and lightened colour, while perhaps to be expected, was not substantiated in the study. Of the four Eaton specimens that were porous (or relatively so) all were glassy and three were dark in colour, and the single Trumbull Furnace specimen was non-porous but stony and light in colour (Tables 2 and 3).

In those early times, just as today, furnaces produced far more slag than ironmakers could, in their wildest imagination, preferably find a market or, at least, a use for. Slag was thought of as an unfortunate and cumbersome byproduct of ironmaking and slag heaps, along with furnace stacks, became the most easily recognizable landmarks of the blast furnace. With the older furnaces, or those that due to some other process, either environmental or cultural, lay buried or in ruins, slag piles remained as the single most visible landmark. The archaeologist or industrial historian who collects and analyzes samples from these unsightly heaps soon comes to appreciate how valuable they can be. No single product or by-product of ironmaking is as informative of the reduction process as is slag. Certainly none is as ubiquitous. Archaeologists with the help of chemists and metallurgists may eventually develop new ways of wringing even more information out of slag. When they do, they may reverse their opinion of this debris and come to realise that perhaps Forsythe[8] knew of what he was about when he said that "the proper mental attitude towards a slag is to consider it a reagent divinely appointed for the purification of metal". To the archaeologist always anxious to fill the lacunae in the historical record, the accent is on **divinely**.

**Acknowledgments.** The author wishes to thank Daniel Mamula and Dominic Russo for the opportunity to dig the Eaton Furnace site from which many of the slag specimens were taken; Frank Galletla for his time and spectroanalytical expertise; Youngstown Sheet and Tube Co for the use of their facilities; and the Graduate Research Council of Youngstown State University for its monetary support throughout. The author himself, of course, is solely responsible for any shortcomings herein.

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# The operation of Charcoal Blast Furnaces in Sussex in the early Eighteenth Century

*R V Saville*

The manuscript transcribed below is a fascinating account of the working up of a charcoal blast furnace in the early eighteenth century based largely on Sussex practice. The document was written by John Fuller, the ironfounder, of Rose Hill (now Brightling) Park in Sussex, whose family owned Heathfield furnace.

The family connection with the iron trade went back at least to the early seventeenth century. In 1692 Fuller started selling cannon to the English Board of Ordnance, though he was selling guns to merchants from Stream furnace, Chiddingly, before then. The family continued selling guns at home and abroad until the 1760's, and Heathfield furnace continued to make pig-iron and iron goods until blown out in 1788. The wider economic interests of the family included slaves and estates in Jamaica, sugar production and sales, landowning and farming in Sussex, in addition to owning and managing the furnace and forges.

We know from other surviving records that Fuller was informed about developments in the iron industry in the British Isles. One of the surviving letter books of the family contains the 1717 list of ironworks which has been referred to by writers in **Historical Metallurgy**[1]. In another document he mentions the **Natural History of Staffordshire** by Robert Plot[2] and the family library contained at least some volumes of **The Philosophical Transactions of the Royal Society of London.** In the early eighteenth century the Fullers were able to improve the output and efficiency of the furnace. The available figures show that the furnace produced a little over 7.03 tons per founday (6 days) in 1708–11; rebuilding in 1723 led to a higher rate of 9.33 tons per founday for the years 1723–26. The nearest comparison by product mix with the 1708–11 figures comes in 1730–1 when output reached 9.43 tons per founday.[3] The document published here shows Fuller's detailed concern for eliminating unnecessary consumption of raw materials and for achieving a smooth run of production. Concern over working arrangements, supplies of water and the attainment of a high average output are frequent themes in the Fuller papers.

This document is most important. It gives a very detailed explanation of how a blast furnace was worked up from the cold, with the problems the founders could expect to encounter and examines the ways a skilful founder could assess the progress of the smelting. It is altogether more detailed than Robert Plot's work mentioned before, or for that matter the notes by John Ray in **A collection of English Words not generally used;** the **Diary of Sir James Hope;** or the pieces by Henry Powle, 'Account of the Iron Works in the Forest of Dean', and John Sturdy, 'On the Iron Works in Lancashire' published in **The Philosophical Transactions** in 1677 and 1693 respectively.

The printing of the document here is thus an important contribution to our knowledge of the management of charcoal furnaces in the last phase of production. It is not possible at this stage to be more precise about the date. The manuscript was found among a set of papers originally in the possession of the May family of Sussex. The manuscript is now in the East Sussex Record Office, Pelham House, Lewes, no A.2449.[4]

The document is transcribed as it appears in the original. No changes have been made in the spelling. A restrained attempt has been made to add some punctuation for clarity.

**References**

1 Barbican House, Lewes, Ms. RF 15/25 f.9, 9v.

2 B M Sloan 4020 f 189. For the reprinting of the second half of this document see the Bulletin of the Wealden Iron Research Group 1980.

3 It is hardly necessary to add that this was a low output compared with, for example, some of the Forest of Dean furnaces at this time.

4 I wish to take this opportunity to thank Christopher Whittick of the ESRO for his discovery of this and other manuscripts relating to the Fuller interest in Sussex. I also wish to thank Dr A S Gratwick of St Andrews University, and Judith Brent of the ESRO for their help with the Latin phrases. I am further indebted to the help and advice of David Crossley of Sheffield University.

# John Fuller's account:

John Fuller **How the melting worke is begun and How the Furnace is filled with Coales from the Bottom to the Top and for some dayes shut up Close**

When the Furnace is new Built and the Loamy Joints are yet moist, and the Bricks which make the Inner walls are yet Raw and Wett, They Burne some Trunks of Trees or peices of Timber, which Burning for some dayes dissipates the Rawness and moisture and prepares the walls for a more lasting use. As often as the worke of making Iron care must be taken that the Bottom stone be drye if not it must be dried with ashes and coales strowed upon it, which being done the Furnace must be filled with Coales, a modern Furnace holds about holds from 12 to 8 Lasts of Coales.* Formerly they used to fire the coales immediately, and without Blowing for some dayes, very weakly made Iron. Now they doe not put fire to them immediately, but stop every Hole in the Furnace, and then Light them at the Bottom that the Heat may get up by degrees, The opening att the Top, is shutt up close with Iron Plates, covered over

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*A Last of Coales about 12 Bushels.
*(Inserted in the margin of the MS)*

with Coal dust, that all the cracks may be stopped that the Included Heat being dissipated may be closely shutt up. If they have not Iron Plates, they stop it with Bords and Leaves and coal dust, by which means every Breath of Heat is kept in. But that naked coales only should not fill the Furnace a little parcell of mine is put on the Top 3 or 4 Boshes, which the common people say is that the coales may have somewhat to feed on, but I believe it signifyes nothing whither the coales are destitute of this nourishment or have it, in this degree of Heat in which they are kept for some dayes the coales have no power upon the mine nor the mine upon the coales. The Living Fire being thus suffocated by its being shut up, And a black Heat being in the coales, the Furnace is left in this condition for eight dayes and nights and in some places fourteen dayes. If in the mean time in a little Hole is left in the Iron Plates which lever the Top, you put in an Iron Rod you may know to what depth the coales have subsided, for the coales are diminished by little and little, by the Heat consuming them, which after Twelve dayes may subside six or seven foot. But if the openings are not well stopped, for all the joints are to be well stopped with Loame, or if the Furnace thro age be full of cracks, or from other causes be open, that there is Vent for the air, the mass of coales will consume faster to the depth of eight or Ten foot.

It does not signify whither the coales are well coaled which the Furnace is filled with, or the Brands be put in with them, for they are as well imbued with the Heat, and are turned into coales, for it has been experienced, with cleft wood instead of coales, that in Ten or Twelve dayes the wood has been Turned into coales, for the fire is digestive and coaling so that Trees half burnt and drye may be mixed with them.

In the mean time the Heat from the coales has been found to Penetrate in the walls to the space of half or three quarters of a foot which is sensible to the Touch, but this Heat is of the second degree but not the melting heat, this not only Heats the Bricks, and draws away the noxious Humors; but prepares the Bricks for the reception of the greatest and the melting Heat. For if the Quick and Vehement Heat should come att once upon the Inner Walls; then it would be unequally forced upon the walls, or it would include the water here and there* in small quantityes or breake the structure in to parts, but by a Gentle Heat, the Pores are opened and shutt, and the Veines capable of Receiving a stronger fire.

When the stopping up and suffocation affords the aforesaid Life and the Furnace is opened you may put in a greater quantity of mine than if you put in the fire all att once. It is not many years agoe since this method was found out and is received in most places with more gaine and a much less consumption of coales. Formerly when the Furnace was open the First dayes they could not carry above Two Boshes of mine att a charge, destroying in the mean time without any profit, a great quantity of coales, but here when the Furnace is opened att the first charge they might put up 5 or 6 Boshes of mine, which are melted with the same quantity of coales, as the former 2 or 3 Boshes.

It is also to be observed that the Included Heat is indued with a very Elastick and Extensive force, for when a little dust or ashes is thrown upon the Hole in the Plates that cover the Furnace they are thrown up a great hight like chaff or straw, three or four foot High which showeth that the Included air is very much expanded by the Heat, and by its extensive force, throws up what it meets with but I have not yet found out in what proportion this Included Heat operates in respect to the weight or Lightness of the air.

**How the mine and coales should be put on, or the Furnace charged that the melting may be duly performed**

When the Inner walls are properly Heated, and rightly fitted for the [ ] of the melting Heat, then the fire is to be encreased by degrees, so that when the Furnace is first opened, the Bellows should not Blow for Ten or Twelve Hours, so that no wind may Blow the fire or the Kindled coales. After which time you must draw a Little water, that the Bellows may have but a small motion, that they may as it were Fann and Enliven the coales, so that when the wind and Heat are Increased by degrees in about Ten or fourteen dayes. For unless the time of the degrees and augmentation of the Heat be not rightly observed, the Furnace will contract a mischief at the beginning which in time will redound to the melting part at the Last. The mischeifs which happen from a too quick Heating of the walls shall be explained in another place.

As to what belongeth to the Charging of the Furnace the first day after the opening, we doe not put up above four or five Boshes of mine with a due quantity of coales, the Bosh which we use is made of wood or Iron and made Hollow, so as to hold about fourty or fifty pounds of mine, by the number of them one knows what quantity of mine is used. As to the measure of coales they are put in Basketts which may Hold about four Bushels, three or four of these Baskets to a charge, three of them make Twelve Bushels or a Last which is the Swedish measure. These coales are put in first att the Top of the Furnace, and raked Level, then they put as much mine as the Furnace will digest. They put on afresh more coales and mine, when the coales and mine are sunk to a certain depth, but of this more following.

The first day there may be four or five Boshes: The next day when the Heat has sufficiently penetrated the wall and the fire seven or eight Boshes, the Third day yet more nine or Ten Boshes, the Fourth from eleven to Twelve the 5th.14. 6th. 15, and in the like order to the 12 or fourteenth day, 16, 17-18-19, till att Length till you come to the number of Boshes of mine that the Furnace will carry. The Reason is because the Heat, as has been said before, is to be encreased gently and by degrees, for unless it doe so in the walls of the Furnace, the cold and damp that is in them will not be expelled in due order and measure. Of the Influx of Heat in Hard Bodyes it seemeth to be proved by the aforementioned experiments, that the force of fire in a wall or in Hard Bodies is inceased in a duplicate proportion, the quantity of mine being increased from the first day to the Tenth in the following order to witt the first 5. the second 7. the third 9 the fourth 10. the Fifth eleven the fourteenth 20 or thereabouts, or in one series 5,7, 9, 10, 11, 11½, 12, 20 the squares of these are 25, 49 or 50, 75 or 81, 100, 125. 150, 175, 200, 400, the difference is always 25, so that since the times are equall,the Force of the fire is augmented in a Parabolicall or quadrat Ratio, as it is called.

When Nature exactly keeps this rule, it appeareth by experience that if the augmentations should be Hastened to get up the Furnace in Less time, as suppose four the first day the next eight the third twelve and so on, this would be with a great Loss in melting afterwards: for if the fire be forced to penetrate the walls sooner it must be restored in the process of the melting. If the Blowing be continued for a longer time, that is if you have a great stock of mine and coale then the augmentations must be slower, and not brought to their Hight before the fourteenth day, on the contrary if you have

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*volumation

but a small stock: so that If you blow for 30 or 40 weeks you must not get up in Less than 14 or 15 dayes but if you Blow but 4 or 5 weeks you may get up in 9 or Ten dayes some people despising this Rule for covetousness sake, have not observed this Rule, but get up their Furnace to the utmost in 10 or 11 dayes, that is have put up 24 or more Boshes of Veines, which they should not have done till the fourteenth or fifteenth day, but have experienced after some weeks, with a great Loss of coales, that the Furnace began to sicken, and its digesting force began to fail, and would not take its portion of mine, and as it were satiated or glutted refuseth it dayly Task. As soon as the Founder finds out this, endeavouring to help his sick Furnace, he presently lessens the quantity of mine from 24 Boshes to 20 or 18, and continueth this for severall dayes, till she groweth well again and will take the former quantity of mine, but sometimes Labours in vaine that her lost appetite may be restored. This disease oweth its Rise to the Heat being to suddenly compelled into the walls and stones, for if the Heat acts with much force upon the Hard wall, all the moisture and cold which lieth in the walls cannot be duly Exhaled; but a sudden Heat shuts up partly the moistures and cold and acts Partly upon the Inner parts and sides, and conglomerates them so that the walls being not yet freed of their moisture and coldness, Labours continually with the fire, which breaketh out into an open flame, or forceth it into another place where it continually worketh against the fire, and endeavoureth to restraine its force, as being an obnoxious Enemy. It also happens that the mine by reason of its quantity not being well melted, but as it were Raw hangeth to the wall, and covereth the Hot wall as it were a Veil or curtain which being so covered cannot duly exert itself upon the mine flowing upon it. But if the Blowing will last but four or five weeks, then the Furnace may be gotten up in 10 or 11 dayes, for a Furnace does not begin to be, as it were feavourish till 4 or 5 weeks be past, If it were fed to fast att the first.

The same thing also used to happen in the middle of the Blowing for if you make your fire Heavy with too much mine, and fill the devourer with a superflous quantity of aliments that part of it lyeth in the fire altogether crude and uncocted then the Furnace will contract a disorder that the following days she will not take half the mine, and so by going Backward returne to her former foot steps with a great Loss of coales.

By how much the Larger the Furnace is, it will require the greater quantity of mine. A large Furnace may take 20 to or 28 Boshes of mine, and a Lesser from 12 to 15, In some I have heard they have taken 30.

It often happens that a large Furnace will not take above 15 or 17 Boshes of mine, when another of the same dimensions will take 24 or 28. Many causes are given, whither in the beginning of the Blowing you over whelm your furnace with too much mine, so that the Faeces are crude and incocted. or att the Bottom of the fire, there is a watery vapour, which cannot get away other wise, but is turned towards and against the fire. Or the Bottom stone is broken by the Heat of the fire and the metall runneth out att the crack or the Furnace thro' age may be full of Vents, and so may cool in divers places or the coales may be to wet, and the moisture in the mine and walls is everywhere spread about, or theri be not a sufficient menstruum, that is Plenty of mine stone or Grayes, by the help of which the mine is fluxed or made fluid, or the sort of mine being mixed with other sorts brings a sluggishness or Heaviness upon it.

When the melting of Iron is so slowly performed in the Furnace a great part of the coales is lost, for the same quantity of coales is always used, if the number of Boshes of mine be more or less viz. 15 or 28, and consequently the Less quantity of Iron which is a great Loss.

The charges use to be 14 or 18 in 24 Hours. Att the beginning of the Blowing the charges are less, not above Ten or Twelve in 24 Hours, for when the Bellows blow softly, the mine and the coales are melted and consume slower. As soon as the Furnace is Low, which is when it subsides to about 5 foot or thereabouts then they fill it againe.

**But that the process of Iron may be better understood, it is necessary that I should expound it in the series that it is performed**

The mine being first Burnt is broken partly in peices partly into dust, by an Hammer which goeth with a waterwheel. Its stony Part is as it were reduced into Lime by the fire, and the Humor is thereby expelled which causeth its Tenacity so that it is easily Broken. It is better the mine should be broken into Little peices for if it were broken into Powder or dust, it would stop up the Cavities between coales and stop the Passage of the fire and hinder the flame from breaking out. For the minerall sand easily gets thro' the Interstices of the coales, and will fall into the Harth.

The first dayes the cavity being filled with coales, the mine is put in the middle not next the walles, the reason is because the wall being yet cold instead of Heat throws out a sort of cold or something Less Hott, and in some measure restraines the Living fire in the coales that it cannot melt the mine att a certain distance from the walls, and because now the greatest degree of Heat is in the centre. Hence the mine being broke small Flowing down toward the centre is mettled which cannot be done if it lye near the walls, nor if a greater quantity of mine were put up.

After some time when the walls grow Hotter, the mine is spread Broader and farther from the centre, and after 7 or 8 dayes upon the walls, to witt when the Heat comeing from the wall is equal to the Heat of the coales, then this Irony or metallick Gravell is spread all over the opening, att length when the wall is Hotter than the coales, the greater part of the mine is laid upon the walls. For the walls being once duly Heated they require a greater quantity, and attract as they call it, in proportion to the Heat conteined in the walls. From whence it may seem to be, that the walls at first exhale a Heat cooler than the rest, so that the matter which is nearest to it is Heavy and dull, that after the walls are imbued with a greater Heat, grow as Hott as the coales, for the Heat is greater and more intense in Hard Bodies then in softer, as is also the cold. The same thing also Happens in the* Harth, att the first the Iron sticks to the walls, whilst they have any coolness or moisture belongs to them, then it Heats more and more of which Hereafter.

When again the coales subside to the depth of four or five foot, which used to be in an hour and half, an hour and three quarters or Two Hours, more coales are put up, which are raked Levell that the mine may be equaly spread upon it, this being done. 4. 5, 10. 15. 24. or 30 Boshes of mine are put upon it according as the Furnace will take it and the whole superficies of the coal is covered with the mine, and the Reverberating flame is forced to the walls. But it will be observed, where the Heat is greatest, whither in the middle or att the sides, att the first the Heat is greatest in the middle, and afterwards att the sides, and where the Heat is most Intense, there the greater peices should be put, for the Larger they are, there is required the greater Heat for their solution and melting.

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*The word 'fire' is here partly erased, and appears to have been altered to 'fore'.

If there be diverse sorts of mine they are to mixt, in some there are Ten or Twenty sorts, In others only Two or Three, but an Industrious workman will know the nature of every sort, and so knows where to place every sort in its proper place upon the coales, That which hath the most sulphur in it, should be placed on the side directly opposite to the Tweir, for the Flame of the sulphur being melted corrodes the walls and the Iron, and consequently, enlarges the opening of the Furnace. The sort of mine in which the Lime stone abounds should be placed just over the Twier.

The skill of the Founder doth very much consist, in knowing the Certain quantity of each sort, that he may make good Iron. For if the mine be full of sulphur it should be mixed in a proper proportion with the mine that wants it. For if there be Twenty sorts, he ought to know the nature of each of them, and how much of one sort should be mixed with the other, that Genuine metal and a Good sort may be made with it.

Iron mine does not easily melt of itself, unless it be well burnt and have been passed thro' the calcining fire; for the more it is burnt, it melts the easier, for all the Bonds whither of sulphur water or salt are broken and loosed, by which its Texture is better penetrated an easier Broken.

But because it is not easily melted by itself, especially if it be rich and have not much Lime in it, Hence it is necessary that they add some Lime stone or quick Lime att every charge, and this agreeth better with the mine, if it be put in the middle or the centre of the coales on the Top of the mine. In some places they use three or four Boshes of Lime stone as the Vein requireth more or less. Quick Lime is like a menstruum in drye solutions and unless there be such a menstruum or solving matter, the metallick parts will not be separated from the stony parts, this is the Iron from its dros; The Liquor of the Iron if there be no Lime, groweth more and more sluggish, nor will the Cinders which swim on the Top of it Leave the Iron, which the Iron holds in its Bosom. In some places as att Roslage they doe not want any Lime because the Lime stone is in the mine itself, and every where showes itself in the mine like Veines of blood. It has been Tryed that Flint stones calcined, will serve instead of Lime stone and succeeded; for Flint stones being Burnt turned into a sort of Lime: otherwise Flint stones used to impart a fluidity to Brass and Copper by whose help their business is well performed.

In what manner the Heat Penetrates Hard Bodies, and the Inner walls, even to the sight it maketh a sort of sphere, which you may see from the watery vapour, which cometh thro' the Iron canals or Pipes, att the beginning when the Heat has not fully penetrated the Bottom, att first cometh forth a cool vapour, but afterwards after a few dayes, the vapour or watery breath is perceived Hotter, and att Length when it is come to the Highest degree is most Hott; so that one cannot move either ones Hands or mouth to it for it is evaporated thicker then water, and like a thick smoake, which is a sign that the Heat has penetrated to the Bottom, even to the Hollow under it.

In the first dayes the Iron sticks to the walls, and the Bottom being yet cold, which thickens more and more, but in the succeeding time, that slow matter, is Loosened and growes soft, but according to the Lenght of the Harth, so that the bottom groweth naked in the middle, then att the walls, and by how much the more this droggy matter, is separated from the walls, they know how much the Force of the Fire has penetrated the walls.

**Of the signs by which the Founder may Judge whither a greater Quantity of mine or coales, may be put into the Furnace**

The knowledge and duty of a Founder to In the first place consist that he may know how to put in a Genuine quantity of mine and coales and that he may judge by signes, which mine or coales be to be added, for if a greater quantity of coales be put in, and consumed without use and Effect upon the mine, besides that the Iron is as it were burnt up with too much fire, and is not of that nature, as if it were duly mixd. If there be too much mine the Iron will be crude and Raw, and not free of its sulphury and stony droggishness, and beingas it were unripe, shineth with Great Crumbs, besides that the Furnace being Loaded to too much mine Looseth its appetite and Hunger, that it will not take so much mine as before; but refuseth part of it. From hence it appeareth how much art there is, that a founder should know the due proportion between his coales and mine.

In like manner att the beginning he should carefully observe, in what proportion the quantity of mine is to be encreased: From what hath been said before, the quantity must be dayly increased to a certain day, and the number of Boshes, which he will judge by the signes.

But before the skillfull Founder trusts to his Indications and signes, he must consider the quality of his Furnace and Harth, that is the faults and Virtues of his Furnace and its construction, whither its bottom be moist, or the Hollow place under the bottom be of a proper dimension? whither there be a Free Passage for the Vapours thro' the Vent Pipes? Whither the ground about it be moist or drye? Whither the stones of the Harth be Green, or not so? Whither the bricks of the Inner walls are Good? Whither being old, it refuseth to take a proper degree of Heat? Whither in the upper part it be too open, and Gaping? Whither in the Belly it be too Large or as it were too fat? and many tother things which a Founder ought to know, before he can make a certain Judgement.

He ought also to know the quality of the mine, whither it be rich or Poor in Iron, Whither it be full of sulphur assnick or other Heterogenious Contrary Qualityes? or whither it have none of them? What sort of stone is in it? Whither it easily part from the Iron by fire, or doe long resist the force of it? Whither it have a great deal of Lime stone or none? What sort of cynders come from it? What its colour* in the Harth? What its motion and concoction, and what its Fluidity.

He must also consider what sort of coales he has, of what wood they are made whither hard or soft, drye or moist.

A skilfull and prudent Founder will always take care, that a Lesser quantity of mine be put up, than the appetite of the Fire requireth, that is may always rather want more, the reason is that the Hurtfull Rubbish of the metall may be the better separated and to make better Iron; but rather for this cause, that the danger may be avoided of choaking her up, and that she will not digest half the mine she did before.

**The signs whither a greater or lesser quantity of mine or coales are to be put up are these that follow.**

1. If there appear some Crumbs or scales sticking in the Cynders or dross, especially in those which come out of the Harth with the cast Iron, sometimes such crumbs lye

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*'colour' is the most likely word.

upon the Iron itself; as often therefore as the Cynders are scaly, or the Iron itself, is a sign that the Furnace wants more mine, as to desire or thirst for it, or that there are to many coales in respect of the mine. The crumbs are like to......* (fu.1).

From the first day to the 12th they are always upon the Cynder and Iron, but when there is no more occasion for augmenting the charge, they suddenly disappear; but when the Harth or Furnace requireth more, and as it were thirsts for mine, the Bright scales appear in the middle of the fusion or melting; which as soon as the Founder perceiveth, he presently orders one or two more Boshes of mine, and so the charge is augmented. These shining crumbs or scales also stick upon the Ringars; but if the mine be very Rich, then doth not appear any great quantity of it.

2. If the If the Rerements comeing out of the Fire are of a white Colour, especially in the Extremityes, or be white and Green, tis a sign more mine should be put up. The first day the Cynders are white, which seemeth to arise from the Lime, stone, for the same quantity of this stone is put up att first, as att last, tho in the first dayes there be put up, but from 4 Boshes to 12, the Last 24 Boshes; But if the mine be poor, and full of Lime stone or other stone, the white cynders are apt to grow Green, The Reason is, that if there be less than a just quantity of mine, and all the metall in it plainly sweat out, so that there is nothing left in the Cynders unless the stony part turned into Glass; altho' the Green Colour indicate that that some particles of Iron are Included in it. It would be otherwise If there were less Heat, if there were a greater quantity of mine.

3. If the Cynders are very light and Limpid like water, and will not run out in strings, and harden immediately in the air, tis a sign the Heat is to Intense and should be Tempered with more mine.

4. By the Twier, which the Founders very carefully look into. This orifice is deservedly called the Founders Eye. By that he seeth the condition of his melting, they are always walking Towards it, and there misseth not a quarter of an hour; but they looke into it, they see the Volumn of the fire stirred about, the cynder swimming att Top, and the drops of the melted Iron falling into the Harth: There appear little drops, which may rather be called sparkes, partly white a snow, partly black, falling like a slow raine, into the Body of Iron, or the most fiery white coales: If this raine consist of more white drops than Black ones, it is a sign of too much Heat, and of a Two great a quantity of coales, and that more mine should be added. If the Black drops are more in number, it is a sign that the mine is not throughly solved; but that coales are wanting, and a more Intense fire. The most convenient state of Liquefaction or melting is, If the aforesaid Raine consists of an equall quantity of Black and white drops.

5thly. It is known by the Cynders looked upon att the Twier what quantity of mine or coales is wanted. If the cynders appear of a Brown or Black colour, it is a sign of a weake Heat, which that it may be restored more coales must be added: but if the cynder appear too bright, or shining, it is a sign they want a more Intense degree of Heat, and more coales to be put up. If the colour of the drop be Green, and the fluidity everywhere equall, tis a sign the quantity of coal and mine is as it should be.

6thly. If the Iron be let out and cold, showeth a Limestony shining, tis a sign of too much mine being put up; but if the Iron being broke looketh like Ice, it is sign of to little mine in respect of the quantity of coales, the reason of each of them is just the like. If the Iron being broke, showeth shining Graines but of a Gray colour mixed, with Brown Graines: But from the Iron and its colour the signs are not certain; for the mine itself, causeth that Variety of colour and shining, whither a greater or a Lesser quantity be put up, so that from the shining or Blueness of the Crumbs or graines in broken Iron a certain Judgement cannot be formed, of the middle proportion of coal and mine; but it is certain, If there is not a sufficient degree of Heat, or quantity of coales, that it shineth like silver, and looketh Like the mine when Broken.

7thly If next the Twier the Iron seemeth to congeal in the Harth, that orifice seemeth to be shutt up, tis a sign the coales consume to much, and that the mine does not melt as it should doe but of this Hereafter.

8thly. If the Cynders fall immediately upon Iron when it is Lett out and appear Fistulous or Pipy, and of an Irony and Black Colour; but very light, it is a sign of a just quantity of mine and coales, The contrary If the Cynders be Heavy to Compact, and too Irony.

9thly. The smoke and Flame which is forced thro the Furnace into the open air, and which in Evening appeareth spread abroad, shows How the mine is concocted in the Harth. For if the flame riseth Higher than ordinary, being mixed with smoke, it is a sign that the body of the metall Boils and swells, that the metall is not well separated from the Cynders, In which case the coales are consumed without effect.

10thly The state of the melting is known not only by the colour and Vibration of the Flame, but by the Colour of the Walls, which the Flame continually Licketh. For If the Breast wall be Green by the Flame and smoake, it showes there wants more mine, in like manner if the upper wall be Green. But if it be Black it wants more coales.

11thly If the mass of Raw Iron be as it were polished and smooth, it signifieth the want of more mine: If the Iron sparkle when it breaketh forth of the Harth, there wants more coales. I shall speak of more things hereafter, when I treat of Guessing att the Coction in the Harth.

## Of the Heat and Ebullition of the Irony Liquer in the Harth

Iron flowing more slowly and cooly then other metalls into the Harth, in some measure filled with the Hotest Metall, affords a cause of great struggling, an action with it, By and By it Leapeth like water in Brasen Vessels, it behaves furiously, swells, Black froths are ejected, and small waves Pointed, and terminated in darts, and so the mass in this fury and fervour, boils and is expanded, above the Brims of the Harth, not otherwise than Boiling water in caldrons. This Heat and struggling of the parts, useth to returne att a certain time, like an ague, For as soon as a certain quantity of Iron is collected in the Hollow wall, and by its own weight, falls down into the Harth; this Impure Iron falling down, is like a Ferment or yeast, and unless the Founder knoweth How to compose these waves, to witt this swelling drossy matter, now as it were Tired with its to much contention and strife, and almost exanimated to draw it out of the Harth, and then stir up the swelling mass with Ringers and Rakes, and continually stir it and subdue it, and to take away the dregs consolidated about the Twier, and to skim the superficies of the Harth. The Harth would be stopped up with the slow and Tenacious matter, the Tweir would be

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*'nibido sterili Glacici marias'. approximate meaning 'snowy pure ice droplets'

*(Inserted in the margin of the MS)*

stopped, and must blow out. Besides the Cynders, would be full of Iron, so that the Greatest part of the Iron would be lost.

As to what belongeth to the Cause of this Effervescence, it is the same as in other Lighter fluids, in new wine must or Liquids concreted whilst they ferment. For if Alcalies or other things be mixed with acids which are instead of a ferment, are put into a Liquor which has not fermented, when the particles are dissolved, and the Lesser ones are set free, the Liquer Boils, and raiseth a froth on the superficies the parts being forced upwards. The same thing Happens among these Liquers of Iron, tho they are Heavier, If the mine be as yet undisolved and full of Heterogeneous particles, falls into the Harth, and the Iron already melted; presently raises a motion, and moves and Expandeth the Liquer into Bubbles, swellings, and seum. For the mine being yet crude and not separated is instead of a Ferment, nor does the Ferment cease, till the Fermenting matter whatever it is, is drawn out of the fire, or divided or seperated: The aforesaid Ferment or Heating Fury, as often as a great quantity of mine, as yet crude, and not free from strange particles slides down or the collected Liquid hangs in some Hollow of the wall, and being in some measure cooled, does not come down slowly and like Raine; but in a Lump all at once by its own weight into the Fluid Iron in the Harth; I have seen this case, the Iron swell and behave Ill and madly; not otherwise than like to spirits in a Bottle of a contrary nature. It is not easy to give the Genuine causes of this Phenomenon, or this Batell and fluctuation may be occasioned by the mixture of cold with Heat, and consequently that, which is more fluid and Hotter, begin to Leape and to Foame. Or it may arise from thence, that the mine or Iron so collected in the Hollow of the Wall, or Blown up and arising in the middle of the Funnel; and not yet deprived of its Exteraneous parts, may bear Heavy upon the Cynders and the Iron. So that it cannot have any consort, with the Body of more metall, nor with Cynders, att the Top of it because they are lighter, but is mingled with both of them in the middle which is intercepted, so that the Liquer being moved, those cruder parts being countermined, now being as it were drowned in the Iron are Hid, now lift up their Head and Invade the Cynder, and so wandring confound both Liquor and distat their confines, sink the Cynders in the Iron, and the Iron in the Cynder, and mingle the whole volumn, with the settlement and drogs in the Bottom, like thick water. In this case a fight may arise, for the Iron as Heavier, must always endeavour to throw of the Lighter particles, and consequently a motion and conflict must follow in the metall. Or some sulphury Humor or Vapour is included in the crude parts which fall down in a Lump from the declivity, which by a too sudden and too much Heat, is expended like air and water, and swelleth into Bubbles and froth. Or some other cause is given, which is hidden from us which produceth this Fermenting Head For the same thing happens in the Heaviest Liquer or Hard Bodies, as in a watery, oleose Liquer, or lightest spirituous Liquer, so that they are all fluid, for the particles of the Hardest Bodies, may have struggles and conflicts among themselves in the same mannour as the Light and the fluid ones. What has been said are confirmed by experiments which follow.

1st If the coales and too wet and old, and consequently weake, that the mine is not duly melted, in in part cannot be turned to a pure fluidity. We see the aforesaid Fermentation arise, for the coales being Heavy with moistur, do not obtaine in the first or second degree of Fire, a white Heat, or If they doe Hidden moisture is hardly expelled, and the particles of the Vapour, doe sensibly breake out with the sparkes, upon the fire and mine to be melted, and so breake the force of the fire and restraine it force, so that the mine not being well melted and crude, with its Herterogeneous particles falls into the Harth, and raises the aforesaid Ferment. We see same thing Happen If the quantity of coales be to small in respect of the mine.

2dly This Heat in the Harth is occasioned, If there be not a sufficient quantity of Lime stone, or the Limestone be bad; For the Lime as has been said before, is as a menstruum in drye solutions, If the solutions are made with Bad Lime, the Light parts are not separated from the Heavy, the stone from the Metallick, the soft from the Hard, the mixt from the pure, but presently make as it were a fight, and have no peace, till the Battel is Ended, and they unite in the fire.

3rdly Such strifes happen most times from the obliquity of the Boshes, upon which the upper fire cheifly lyeth, If they be so oblique, that the Rivulets of the mine cannot flow perpendicular enough, but stay and are stopt, as it were in Rods or couches and in time, a Body of it is got together, and in the mean time groweth sluggish, and hangeth in the wall, Like moss or Glue, and doth not drop into the Harth, unless there be such a quantity of it, as by it own waight falleth down att once, or slides down by the wall in a slow stream like Pitch, From hence it follows that this metall being slower colder; than that already in the Harth, and falling into it, immediately causeth an Ebullition and strife: and that such a slow, derivation, or fall of the Liquid matter, is the occasion of it, Experience wittnesseth. For if you looke into the Tweier, a little before the motion ariseth, or when it seemeth to arise, you will see a slow and Pitchy matter fall before the hole, in Lumps as it were, and then be merged in the Iron, so that you may be an Eye wittness of the cause and originall of it. This distemper is not unlike to a cold Feavour, which returns alternately att stated times, and affects the Harth every 6th or 12th Hour, which first groweth cold, then trembles, then Heats then revives. For if there be no Black or shining drops, it is a sign, that the cold and Feavour are coming.

The Blowing also being ended that part of the wall, where the collected matter used to rest, appeareth very much Hollowed, and as it were eaten, These sort of Holes, and Hollows used to be made and Hollowed, by the continuall attrition of the wind: For if the direction wind be so, that it is not thrown up spiraly; but lickes and strikes always upon one part, then being helped by the fire, it easily forms a cavity, and perforates and Bores through the very joints of the walls, and so maketh resting places for the melting Iron.

For when the Harth is built in a moist place, and when all the water, sliding under it, is not exhaled by the Vent Pipes; but part of it insinuates itself, into the Bottom of the Harth, stoppeth the melting Power, and stoppeth the the fluidity of the Iron, and then usually appeareth the Pointed, or cuspidated of the Iron: all these are evidences, that these motions and enmityes arise, from the crude mines not being well melted which that it may be more confirmed, they say may be also occasioned from the mines not being well Burnt: For by how much the better the mine is Burnt, so much the better, the metallick and stony particles are separated, which it Bound, are very hardly disjoined, not without a Ferment going before, and the aforesaid reaction in the fire. They also say if the mine be Broke to small, as it were meal, for this gets easily into the Harth, and fills the Interstices of the coals.

**The signs of an Ebullition comeing on are as followeth.**

1st If the dross breake thick out of the Harth, and swelling strive to get out, or are Roled about for a long time, tis a sign the Iron has swelled a long time, or the cynders swimming on the Top of the Iron, and that Formenting matter, stoppeth the eruption from the metall, and the cynders appear to be four times as many in quantity, not otherwise than Barly Corn mixed with water, or a ferment of Beer and sarvives or Chequers mixed together.

2ndly The Cynders out of the Harth may show the motion that is a going to rise; for If they appear swelling att the first, and as soon as out of the Harth fall down, and as it were return to themselves, tis a sign of the Fermentations being arisen, and of a Violent fluctuation to follow; and when att length the Cynders are cold, they are light, Fishilous Like sponge or Pumice stone.

3rdly The colour in the Cynders when cold, used to show a too great coction in the Harth. To witt, If they have not their usuall colour which is Blue or Green, But a darke Brown and Blackish; as soon as they Grow thick, and appear obscure and Cloudy; tis a sign the mine is not yet solved, but is Heavy, with the Iron and Cynders intermixed, for if the stony parts are not free from the metall, or the metall from the stony, the Cynders are darkened, with a crude minerall dust, that the stony Part, cannot Turn into a Glass of its proper colour, nor the Iron parts seperate from it, and because so great a part of uncocted mine, remains in the Rerements flowing out, Here and there, bright sparks are continually thrown out, like Red Hott Iron struck with an Hammer, which all are a sign there is much Iron in the Rerements, which not being seperated, moveth all the Liquid Iron in the Harth.

4thly A skillfull Founder a far of, may Guess from the Flame what condition the Harth is in, whither there be a disturbance or Rest. So that a stranger att some miles distance, may tell his Freind how the melting goes on in the Harth. Whither it be disturbed, or the motion of the parts be quiet and easy, and whither the be any other faults, but this must be only in a darke night, when the Flame from the Furnace Vibrates very Broad. For if the Flame Roll high above the Furnace, and as it were undulates very thick, that is, If the volumes of Flame, are thrown out, and Glomerate downwards, which are broken in the air, and disappear, as it were with a thickness, it is a sign the Harth is troubled, and that the Iron in the Bottom of the Furnace is ejected or Troubled; like the flame att the Top. The colour of the Fire and Flame, is an Index of the motion or Tranquillity in the Harth. If the Flame be too Red, and filled as it were with dirt and smoke, if it be thickened with a dark coaly dust, If the sparks breake the Flame, and flow plentifully in the air: It is a sign of a Tempest coming into the Harth.

For the Flame which continually floweth out att the dam, and beats the Timp, used to be a forerunner of the motion about to come; for if it appear unequal and breake out in different places, and shine acutely, and fly out* and suddenly die, and shine againe, it is a sign of the Fervour already begun in the Harth.

For the Tympe stone which is, continually likked by the Flame which Reverberates upon it and as it were covered with a Fuliginous matter, showeth that the melting of the Iron in the Harth goeth on quietly or Turbulently. The wall being of a Brown and smoaky colour, showeth the effervescence and Heat, and in like manner that the mine is not melted, and that the Light and Ignoble particles, doe not forsake the Heavy and more noble but fight one with the other. This smoak or Black colouring ariseth from the Flame, which being mixed * with sulphury and coaly particles, Blackens the Tymp and the stones above. But if the wall or Tympe be between white and Green, it is a sign all goeth well. The wall over the Tweier, used to be Tinged with the same colour. In like manner the walls over the Tweier, used to be of the same colour, for the smokey vapour alwayes exhales out of the Harth covereth the walls.

6thly You may see plainly the beginning and Progress of this Efforvescense, If you looke in att theTwier and thoroughly Inspect it. First the Rising Cynders appear, behind Orifice, towards the mouth and against the Blast itself, they strike the wall with frequent strookes, like as waves strike the shores. These waves are Terminated in points att the Top, not with a round and fluid Body, as they are att other times: For it is a sign that the Liquer swells, and is expanded into Bubbles: The Cynders grow Blacker and Blacker, and show the mine Black and crude upon the superficies. The superficies beginneth to stagnate, and then being immersed in the Irony Liquer, forceth it upwards, and all the Liquer, into waves, Froths and Bubbles, nor does it stop its motion or anger, till it is drawn out of the fire, and the Liquer is seumd. In the mean time a black shower falls down, parts of the mine not dissolved hang upon the Tweier, and the Rills of Iron being tenacious, flow so softly, that they Hang over it like drops att the nose, and fall into it like Pitch into the Hott fire, and because the cold and thick Bodies, are thrown into the Hottest, and most Liquid matter, it is no wonder that a great Conflict is raised, and because the aforesaid Froths may easily contract and Hardne(t) from/cool** and perhaps watery ones, thence they are allwayes to be thrust away from the Tweier, with some wooden stake, or a sharpe Ringer, otherwise they will easily stop up the Twieier, which is as it were the soul of the Furnace. When this Liquer is so Intractable, a great part of it is cast out att the Tweier in the form of sparkes, by which the Orifice becomes sensibly stopped, or its mouth narrowed, which must always be kept open. These and more things may be observed by Looking into the Tweier.

The Worke and Labour is that these unpeacable motions, may be stopped and quieted, for unless you help it quickly, you will Labour or sweat in Vaine; the Remedy is too late, If the Tweier be stopped, and the metall be stagnated, I shall now tell you by what methods, it is to be helped.

When they find the Harth in this condition, they continually stir the Fermenting mass, with a Ringer and subdue it, for when the fermented Liquer is distended into Tumours, when it is stirred about it ceaseth its swelling, and as it were ceaseth being angry, as Hot water doeth in a Pott just ready to Boil over, when an handfull of salt is put into it, or the selling Liquer being stirred about with a spoon, the Boiling ceaseth, and the water becometh quiet, so this Liquer by a continuall stirring, Lets fall its crests, and sensibly falls down, By this motion and artificiall undulation, the freindly and animicous particles are mingled together, and by the

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*'striatum'. scratches, (claw marks(?).)
*(Inserted in the margin of the MS)*

* 'mixed' is the most likely word.

** 'Flabris', bellows, by means of.
*(Inserted in the margin of the MS)*

success of the agitation, the Light parts are seperated from the Heavy, the stony from the metallick parts, and every one chuseth its place, according to its specifick Gravity.

2ndly Still the People Labour Hard, and pull out the Cynders with their Ringers: for the Cynders now swelling very much are rolled about in a long Tract out of the Harth, and because they are expanded into smalled an Bubled superfices, hence appeareth the Great Plenty of them, as If two or three Harths were fitted with them, not otherwise then meal milk and water, with yeast mixed with them; but as soon as they are brought out to the air, immediately subside.

3rdly The Recrements which Hang about the Tweier, must be carefully shooke of with a Ringer, and the Hole kept open, for if they doe not take Especial care of this, the Hole will easily stop up, and the whole Heat of the fire extinguished.

4thly They have experienced that this evill may be avoided. If the mine be well Burnt, and If it be not broke to small, so that the Interstices between the coals be not stopped, If the coales be not too wett or that drye coales be mixed with them: In like In the in cavity of the Furnace the Boshes are to sloping, or if the under Tweier stone be too sloping, or too levell, or if the Cavity under Bottom stone be cleaned of it Rubbish or sediment and If more things are observed, which as the skilfull founders know

**It follows that the losses and ditriments arising from such an Heat of the Irony matter should be Treated of**

First, If the Heat be but middling nor too much, that If the Feavor come but once in a day, or two daies, It does not doe any damage; but by its Intestine motion, rather occasions a separation and solution of the parts, not otherwise when a Liquer has worked, it groweth clear and fine; from whence the Harth is purged of its dregs and sediments, and it melts better in the Harth, so that the Fire, as it were restored to its, gets its stomach again, and desires more mine.

2dly But If it happens three or four times in a day, and rages with an ungovernable Fury, the masters suffer a great Losse, for the metall does not separate from the cynder, but Hanging in them, is pulld out with them, so that the cynders appear full of Iron, which is kown by the Colour and weight of them.

3rdly Unless the Industrious Founder, keep the Tweier open, it will be stopped up, and the Inclosed fire suffocated.

4thly in the aforesaid case the greatest part of the Iron being lost, the coales and mine are consumed to a great Loss.

5thly The Fervor having done all the mischeif it can, the Iron will be fistulous, and of a Bad sort; for the strife of the Liquors being ended, to witt of the cynders and Iron, the superficies of the Iron being cold, will be full of Holes and Little Hollows which are a sign of the swellings and Tumescenses.

**The Externall signs of the Inward state or melting in the Furnace taken Principally from the Flame**

1st If the Flame be skin coloured it is a sign the Furnace goeth well

2 So it is if it be white

3 If the Flame be too blue it is a sign, tis a sign the ore is crude, and full of a thicker sulphur, so that if it be well burnt, this colour will grow faint and disappear

4. A yellow flame showeth the melting in the Harth, too drye

5. A Red Flame showeth that the coales being lately put in are not throughly fired: otherwise it is a sign of strugle and disorder in the Harth, which has been Treated of before, and much more so when sparkes with smoke breake out of the flame, and If the wall be blacked as it were with soot

6 A small Flame not spreading itself showeth that the way of its eruption is precluded, by the mine or the dust of the coales.

7. From the Hight and Broad disperson of the flame, you may judge the mine, goes into the Harth crude and indigested, which foretells the Heat and fury that is to come. Through the Rare and empty Interstices the fire runneth freely, and Rolls as it were in Globes: whence the bosh Flame does not rise very high

8 The Flame is almost the same, in the first and the following dayes, tho it may differ by reason of the quantity of the mine, besides that att first it is whiter, and afterwards groweth Bleuer

9. The Flame being reverberated and flying out of the upper part of the Furnace, shineth only about the walls, and not in the middle, by reason that the mine lying in the middle, throweth it out against the walls. Att two sides of the Tunnel, it always appeareth Higher, to witt immediately over the dam wall, and the wall opposite to it; but not over the Twire wall.

From the Body of the Iron itself you may judge of the mine and coal, and the nature of the Iron. For when the Iron is Let out, heat and Brown sparkes, breake out as it were out of a little Furnace it is a sign the Iron is hard, and the more it sparkles the more hard. In which there ought to be more coales and Less mine. But when Hard Iron is wanted for Forge anvills, or other Hard ware, then should be more then ordinary mine put up, especially att the Latter end of a blowing, for then it cannot doe much damage because you may blow out. But if you would make Goods of a softer metall then more coales may be put to it, and that also att the latter end of a blowing, for the Furnace will still endeavour to keep the Heat which she hath obteined, therefore if the quantity of coales be encreased or diminished it signifyeth not much, whither the Furnace contract a distemper, then If a dying man should be wounded.

**How the Cynders are, and are taken of from the Metall**

A great part of the ore goeth into Cynders, The cynders consist of the stony part seperated from the metallick part of the ore, and swim att the Top of the Iron being Lighter than it. From hence the moment the Iron sweats out, it passeth through the lighter parts and immeryeth itself among the Heavier parts. From hence the Cynders are for the most part, stony and sulphury and not alwayes Free from metall; but there are some little parcells of Iron, which appear in round and ovall Globules, or being disported in the stone looke Greenish, or Tinge the Glass with a Green or Black substance. Then we see that the Recrements or dross is full of Iron. Besides the quantity of Cynders is Larger and encreaseth more than the Iron.

The Founder seeth att Tweier to what highth the dregs and cynder riseth, and the time of pulling them out. He hath a certain hight, which when they come to he pulleth them out with a Ringer, leaving those behind which are not come to a proper hight, where the Blast keepeth them down, and will not Let them rise higher.

It is experienced that the cynders contribute very much to the easyness of melting and seperating the metall from the stone, so that if the Cynder be wanting, which keep the upper part over the Iron and hide as it were with a cover, may be easily Burnt and make the Iron Hard, and lo[ ]* Tenacity, so that it lieth safe under its cloake or skin or Cynders, not otherwise than water under oil which will not stink in the middle of summer, nor congeal in winter; It has been often observed that If the Iron has been naked and all the Cynders taken of, a Violent Heat and motion ensueth by the mine falling into the most Hot and Heavy Liquor, doth not presently agree with it, so that then is a motion stirred up in the Iron, which doeth not cease, till the Fermentation is finished, and the Lighter parts are seperated from the Heavier and the cooler from the Hotter parts.

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# The Mamora Iron Works in Upper Canada: The first Phase, 1819 to 1826

*Arthur D Dunn*

It was only with the development of the process of handling molten iron that industry as we know it today became possible. For many centuries man had forged items of iron, first from meteoric materials, and then as he learned to produce crude iron 'blooms' from the ores that he had by that time identified. By about 1450 AD in Europe, earlier in China, man had learned to cast iron into complex forms from which ultimately they were able to produce the machines that made the Industrial Revolution possible.

Thus as language and communications is fundamental to the society of man, so also is the working of iron fundamental to man's industrialized society.

The history of ironworking in North America might be said to have started around the year 1607 when members of the early settlers of Virginia discovered iron ore there. A shipload was despatched to England and its importance duly determined. Shortly afterward a company of men were sent out ot Virginia with the intent of setting up a furnace near to the site where the ore had been found, but the key workmen died shortly afterward of some unrecorded disease.

In an attempt to ensure continuity of the effort John Berkeley, of Beverstone Castle near Tetbury, Gloucester, was sent out with his son, and all seemed to be going well when in 1622 the site of the ironworks was attacked by the Indians, and all of the workers there at the time were massacred.[1] The Indians destroyed all the buildings and no further attempt was made to continue. The actual location of this site at Falling Creek, Virginia, is not accurately known and it is suspected that it was located on a site now occupied by a marina.[2]

We should say, however, that while this is the first recorded attempt to work iron in North America, there were even earlier attempts known from archaeological investigations notably at the site in Newfoundland known as L'Anse aux Meadows where it is believed that Norse visitors worked iron, but as far as we know did not reduce iron from the ore, about the year 1000 AD[3].

The next, and first successful attempt to set up an ironworks in North America, took place at a location now known as being near Boston, Massachusetts((1645). The Company

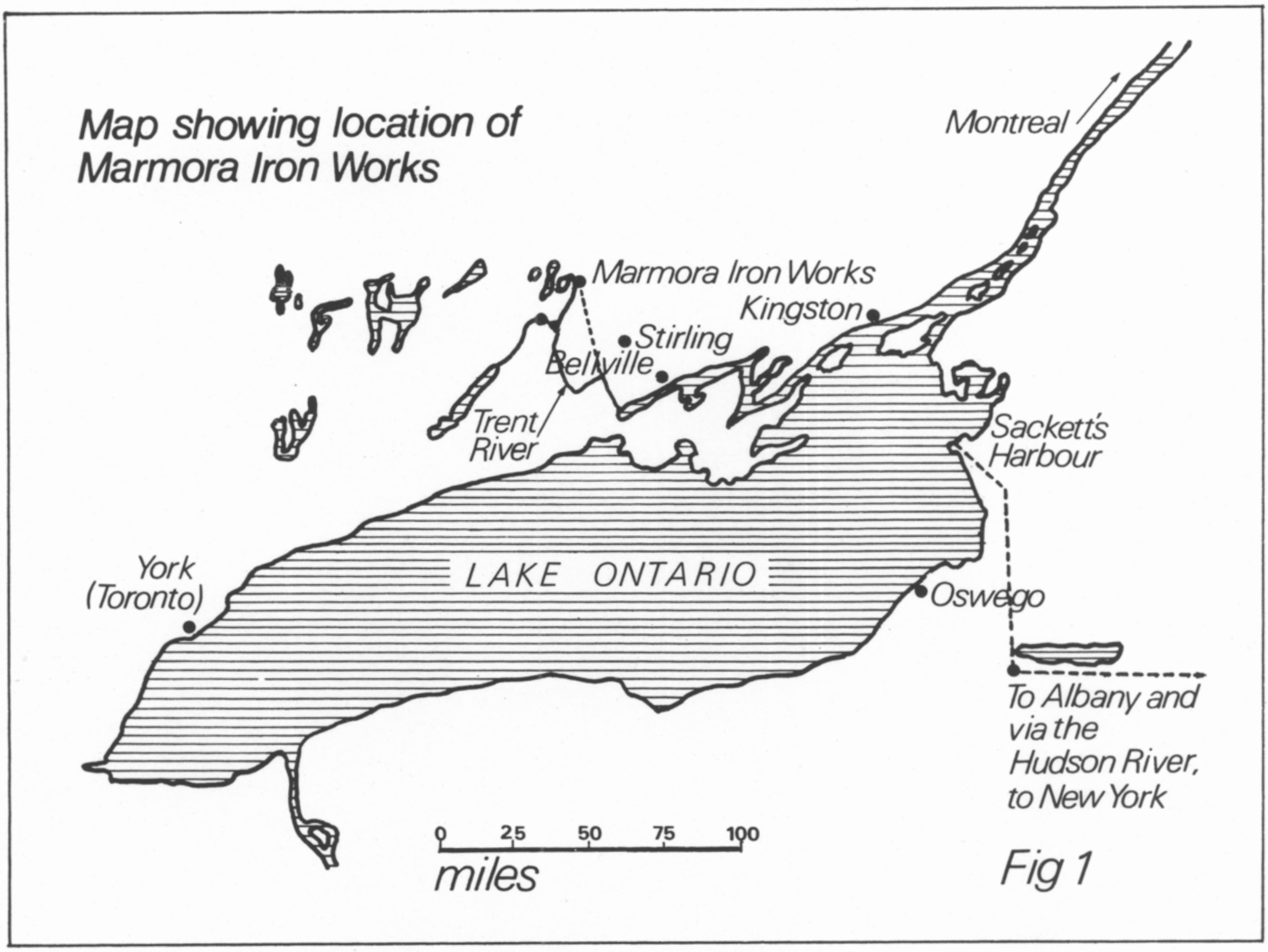

Map showing location of Marmora Iron Works

Fig 1

which was involved in the setting up of the colony on Massachusetts Bay was very much more concerned with a well managed settlement than were those who were involved with the attempts in Virginia which seems largely to have been been a very poorly organised expedition.

This attempt at setting up an ironworks[4] was a limited success although the company of which it was formed was constantly racked with dissention until its dissolution some twenty years later in about 1665.

About this time there was recognition that iron ore (limonite) existed in fairly large quantities in the area just north of Trois Rivieres, and various suggestions were made over the years to the French Government that it should be exploited.

Eventually, about the year 1750 the French Government agreed to financially support an ironworks in this vicinity and the Forges de Ste Maurice came into being. It, however, was never a very serious productive unit until well after the defeat of the French at Quebec when Les Forges were taken over by an Englishman[5] by the name of Bell who very successfully operated the ironworks until the iron ore began to run out and he lost his licence to operate the works. Various attempts were made thereafter to continue the ironworks in operation but eventually due to the lack of suitable ore the operation had to be closed.[6]

We have now reached to close to the end of the 18th century, and about this time the Province of Upper Canada was very sparsely settled. Some 20,000, or so, only were new settlers in that area and they, largely settling close to the banks of the St Lawrence,[7] and the shores of Lakes Ontario and Erie, comprised a very tenuous and widely spread group of people at no greater density than 20 to 30 persons per average mile of waterfront. There was therefore little reason, or need for, ironmaking facilities and most of the supplies came from iron forged in Montreal or more likely from English sources.

About the year 1798 there appears to have been two attempts to start ironworks in Upper Canada, both of which were by persons of American origin, one on the Niagara River at Chippawa,[8] and the other at a place called Furnace Falls, now known as Lyndhurst, just north of Gananoque.[9]

Although much has been claimed for the former ironworks so far we have not found any significant records to show that any iron was reduced or worked at this site, while the latter seems to have been solely a 'bloomery' furnace that was in operation for some two years before being destroyed by fire. Enough has been found to indicate that it was a productive operation but the site was later occupied by a grist mill and all traces of the ironworks have disappeared.

In 1815, or 1816, we learn of an Englishman by the name of John, or Samuel, Mason[10] seeking permission to erect a furnace to make iron at a location known as Turkey Point on Lake Erie. Mason eventually did build a furnace, and so must have received some form of permission, but it is evident from his letters that he was a neurotic type of person and, after his furnace failed shortly after it had been put into blast, he died.

This site and its remains were later sold to a group of Americans sometime about 1823 headed by a man by the name of Hiram Capron,[11] who rebuilt the furnace and commenced a period of operation that was to prove to be very productive, although not for Capron. By outlining the early history of ironworking in Canada it will be seen that during the critical years of the early settlement of Upper Canada the only reliable source of iron products, other than those products brought from England was the Forges de Ste. Maurice, either directly or via subsidiary forges in Montreal. The long journey up the St Lawrence to the few customers who could affort these materials is indicative of one of the problems that the settlers in Upper Canada had to contend with, as well as the possibility that these supplies might well fall into the hands of those Americans who occupied the south bank of the river and who took a delight in denying those loyal to England the means and products with which they might eke out their precarious existence.

It is fairly evident that the provision of local supplies of iron commodities was one of the primary reasons for the consideration by the Lieut. Governor, Sir Peregrine Maitland in establishing an ironworks in Upper Canada when he was appointed.

This was not only a necessity for a growing population, and it was growing at a very rapid rate at that point, but also a military necessity, since at the time of Maitland's appointment, the possibility of war with the Americans still existed and the war of 1812 had just taken place.

These conditions also determined other factors regarding the proposed ironworks; (a) it could not be permitted to be operated by persons of American origin, and (b) the ironworks had to be some distance from the border to prevent capture by possible American invasion forces.

At the same time it was clearly recognised that reliance on the use of bog ores (limonite) was not desirable, and that more use of mined ores (magnetite and haematite) was desirable. Up until this time the use of bog ores had been almost universal in Canada as it was also in many other locations in North America.

Finally, the need for iron products was becoming especially evident as the needs of agriculture grew; but an even greater emphasis was indicated of the need for iron products, but especially stoves, when the year of 1816 – the year without a Summer – occurred;[12] and when a similar year of very cold temperatures occurred in 1818, conditions were such that the need for an ironworks of considerable size was clearly indicated. At this point it should be noted that the Laws of England as they stood at that time did little to assist the Colonies, and this included the United States, in the setting up of basic industries such as the iron industry.[13] Indeed, the laws bluntly forbade the export of any products, or parts of products, that would contribute to the creation of an industry in the Colonies. Furthermore, it also precluded the emigration of any skilled ironworkers out of England, even to the continent of Europe, although the ironmasters of the time fondly hoped that America would send to England as much pig iron as possible to obviate the need to use British fuel for the primary reduction of the ores.

So drastic were these laws that it has been suggested that one of the main reasons for the Declaration of Independence of the United States was due to these restrictions, and it is significant to note that many of the signees of that Declaration were directly or indirectly involved with ironworking at that time.

There is evidence to suggest, as previously indicated, that Sir Peregrine Maitland, on assuming the Lieut. Governorship of Upper Canada, had had his attention drawn to these particular problems and had made some efforts to have the laws relaxed. They were relaxed, in part, in 1824.[14]

With such new freedom it would be possible for Maitland to provide for an easing of the sources of supply of iron products to the settlers, provide a source of munitions should there be further difficulties with the United States, and provide for the expansion of the economy with the introduction of a large scale industry.

Maitland appears to have made it known that offers from those persons that had the means to construct an ironworks would be welcomed, and promised a very large contract for military supplies, as well as general assistance in the provision of appropriate Land Grants to ensure that the practicability of the project was possible.

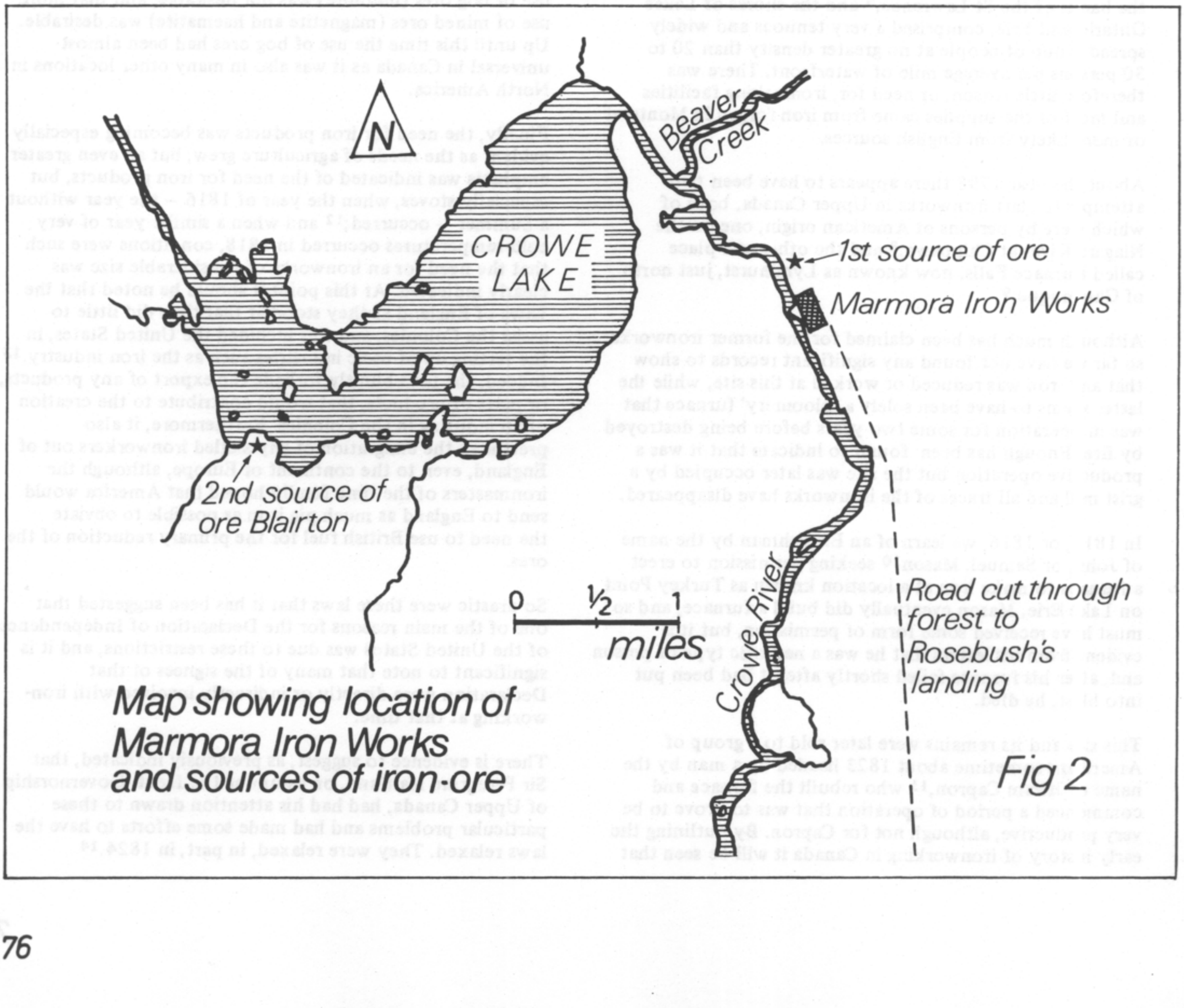
As far as we are at present aware the only person to respond to this offer was a person by the name of Charles Hayes, of Dublin, in Ireland. He seems to have been a business man and had become quite wealthy as a linen merchant, and in 1819 Hayes visited Upper Canada[15] to discuss the whole project with Sir Peregrine Maitland himself, and it is possible that at this time he first visited the site of the town that was later to be called Marmora.

Upon Hayes' return to England he appears to have satisified himself as to his legal situation, and to have received government sanction to proceed. At the same time he sought advice from someone whom he refers to as a 'miner' and in another context as a 'man of science'. Whom this person could have been we do not have any information at the present, but suspect that it could well have been Richard Smith, later to make a name for himself in a somewhat similar way in Nova Scotia, and still later to become the impressive manager of the Earl of Dudley's properties in the Midlands.

By the middle of 1820 Hayes, accompanied by his wife, had made his way once again to North America, travelling via New York, the Hudson River, the Mohawk valley and Sackett's Harbour to Kingston in Upper Canada. From this point he made a detour to Montreal, leaving his wife in Kingston, possibly to requisition materials for the project or to make arrangements for the forwarding of equipment and materials that had been shipped from England,[16] returning to Kingston and then proceeding to locate himself in Sydney Township, on the River Trent, possibly at Louis Rosebush's Landing a few miles west of the present day Stirling from where he commenced the construction of a road (Fig. 1).

From here the line of the road ran almost in a straight line to the site on the Crowe, or Marmora, River where the ironworks were to be constructed.[17] (Fig. 2). Work continued throughout the ensuing Winter to achieve this end since Hayes wanted to get his 'works' completed as quickly as possible so that his Land Grants could be confirmed and the military contracts issued.

After some difficulties with the Indians the road was completed and work commenced on the buildings necessary for a community situated so far from any major civilized centre as it was, being then some 100 miles from Kingston



Map showing location of Marmora Iron Works and sources of iron-ore

Fig 2

the nearest source of supplies.[18] The main buildings shown in Fig. 3 appear to have been completed quite rapidly, which indicates that he had in some manner acquired the services of a number of good competent workers, as well as the necessary materials to construct the specialised buildings and equipment that we know were in production by the middle of 1822.[19]

At the time some one hundred tons of cast iron products had been produced at the new ironworks, and they had even attempted to cast, and bore a couple of guns one of which being bored was found to have 'imbibed too much air'. Despite this fault Hayes was very confident that should the Government of Upper Canada have demands for munitions they, at Marmora, would have no difficulties in supplying their needs.

By this time Hayes had also found that the originally indicated source of ore had not proven to be of a significant size, and from existing records it would seem to have been largely in the form of an 'ochre'. Some of this ore was used, and some of it shipped out for the manufacture of paint, and Hayes set off in search of a better source of supply of ore which he found some three miles away at a site now known as Blairton. (Fig. 2). This site contained an excellent source of magnetite, and since it was not within the Land Grants already made available to him Hayes[20] made an agreement with the Government of Upper Canada at York (Toronto) that he survey the whole area around the site at Marmora and as his payment for so doing he would be able to select and obtain as a part of his Land Grant any lots that might appear to him to be of use to him up to the limit prescribed to him as his allocation.

Such an agreement was concluded, and a sketch map of these lots is in existence.

While doing these surveys Hayes was also conscious of the need for supplying materials to his 'works', and also for the movement of the finished goods to market, and seized on the occasion to try and determine methods whereby these problems, for problems they were, could be solved. Later he was to make suggestions where potentials for canalization of the rivers and interconnection of lakes and rivers could be made to advantage to the government, and while there is little doubt that his suggestions had little effect on the government they may well have been used by later surveyors.

There is little doubt that for the period when the Marmora Iron Works were constructed they were for North America a quite advanced community arranged as it was to be as far as possible self-supporting.[21] To provide for the main materials of construction – wood – a saw mill had been installed and this was probably the first piece of equipment constructed. The type of mill installed is generally referred to as a 'muley' saw (German – muhle) and with the exception of the cutting blade and the feed wheel was almost wholly constructed of timber available locally. Some 10 miles away to the east near the village is a reconstructed 'muley' saw, which in all probability was one of the original saws installed at Marmora, but now sadly in need of a total rebuild. Associated with the saw mill was a bark mill which provided hard wood bark for a tannery which was presumably used to prepare leather for protective clothing for the workers at the furnaces and at the forges.

For the community at large there was also a grist mill,[22] a bake house, a general store, a dry goods store, a potashery (for the manufacture of crude soap), and a blacksmith's shop. For the younger members of the community there was a schoolhouse, as well as some twenty six or more dwelling houses for the workers and their families, and for Charles Hayes, himself, a very carefully constructed log house which still exists as one of the better houses in the community.

The main buildings of the Ironworks proper consisted of two furnaces facing on to a common Casting House which appears also to have been provided with some accommodation for the furnacemen. Both furnaces were of an overall height of 36 feet and the No 1 Furnace had a bosh diameter of 8½ feet and was blown by what is referred to as a pair of German Bellows. This we would presume to mean were bellows constructed entirely out of wood and in a similar fashion to the Steffen Bellows used in Sweden. Plot, in his Natural History of Staffordshire,[23] shows a diagrams of similar units. In the case of the No 1 Furnace the bellows were each 28 feet long and 15 feet wide and worked into a receiver, the whole being driven by a waterwheel 27 feet diameter and 6 feet wide. From the water levels at the site it is presumed that the water wheel was most probably a breast wheel.

The No 2 Furnace was as noted earlier of the same height as No 1 but this one had a bosh diameter of 9 feet and was blown by a blowing engine that is described as a Three cylinder Blowing Engine having cylinders of 5 ft 7½ in diameter and 3¼ ft stroke, and it was driven by a waterwheel of 25 feet diameter and 7 feet wide. It is interesting to speculate the type of construction that was used in this engine and one is led to believe that the only possible form that it might have taken would have been similar to that designed by Smeaton.[24] Such a device might have been quite easily manufactured in Canada, with the cylinders and pistons in Montreal.

Since there is no coal in Upper Canada, the fuel used was charcoal obtained from the hardwood forests which once dominated the area but are now almost replaced by softwoods. Charcoal was the major fuel used for reducing iron in North America until quite late in the 19th century, although some furnaces did use anthracite with some success. The Marmora Ironworks had three houses for storing charcoal for the furnaces and these were capable of storing some two hundred thousand bushels.

There was also a smaller Coal House provided for the Forge. The furnace shafts were constructed of stone quarried locally although some difficulty was experienced with the hearthstones in the early days and it was later decided to procure future stones from the United States, probably Potsdam, New York, whose hearthstones were used by several furnaces in that State. That hearthstones were procured from this source is recorded in letters sent by Hayes to the Customs officers, and also to York, to obtain clearance of these items through the Customs as it seems that, acting in haste, he had ordered them to be shipped in American ships instead of Canadian.[25] A rather serious delay resulted, with some possible political interactions which might have caused Hayes the trouble that he experienced later.

Some fifty yards, or so upstream from the furnaces was the Forge. This was the normal second portion of the 'indirect' process, and produced bar iron from the iron pig produced in the Casting House.[26] The Forge had two complete sets of 'finery' hearths, 'chauffery' hearths, and hammers. So far there is little known of the construction of the Forge or its equipment, but should we be correct in suggesting that the three cylinder blowing engine be attributed to the design of John Smeaton, then it is very possible that the various hearths and hammers could well have been constructed to his designs also. At least for the time being we are making that assumption.

The several blowing engines (4), and the two hammers in the Forge were each driven separately by a waterwheel, and a power take-off from one such unit was used to power machinery, which included a lathe, in the Carpenter's shop. Probably in the first instance this shop was used for general carpentering work but later seems to have become the Pattern Shop, and the accounts available had made quite a number of patterns which were stored in the second floor of one of the buildings.

To complete the community there was a farm of some 150 acres, but where this was located we have little idea at this juncture. We know that Hayes drove roads east and west from the village of Marmora, as well as a short one north to the Beaver Creek Settlement about a mile away, and although locally the site of the village is very rocky and unfit for cultivation good cultivatible land is available within the radius of ten miles.

The subsequent history has shown that the selection of the site at Marmora was an ideal one for that period. Vast quantities of hardwood abounded on the surrounding lands, the falls of the Marmora, now the Crowe, River could supply abundant power, the head being about nine feet at that time, and the river about 100 feet wide just above the falls, with a constant supply provided by the Marmora, now Crowe, Lake about half a mile away. Vast amounts of magnetite have already been mined, not only from the originally used mine at Blairton, but also at the Marmoraton mining site just south-east of Marmora, and enormous deposits remain, much under the present Crowe Lake.

The site was therefore a very sound selection, but why did it fail as did Hayes in 1826, and all of his successors? Hayes was the first to offer to manufacture castings of all types, and bar iron for sale, but he was continually in difficulty in maintaining the roads to get his products to market, which was basically a government responsibility to organise and pay for. But for Hayes no such support was forthcoming and this transportation problem is often cited as the reason for his failure.[27] But there is evidence that Hayes was promised vastly larger orders for the naval dockyards than he actually received, and it seems possible, in retrospect, that Sir Peregrine Maitland, or his officers had not the authority to make such large contractual arrangements so that the support that had been promised did not arrive and Hayes was left to bear the consequences.

At this point Hayes and his wife left Upper Canada and returned to England hoping to find financial support there, leaving his 'works' largely in the hands of the Hon Peter McGill, of Montreal.[28] Unfortunately, Hayes arrived in England just after the end of the Napoleonic wars, when industry was at a low ebb in England, and many of the banks had been forced to close.

For many years he tried to raise money on his, and his wife's, other holdings, and applied many times to the British Government for assistance without any success.

During this time he lived for some years in London, and later in Bristol, and the repeated frustrations together with the loss of his wife caused him to return to Dublin, where he eventually remarried[37] and was able to regain much of his former position although he had apparently always had a wish to return to 'his' works in Upper Canada.

From the little information that is available to us at present it appears that he moved from his home in Dublin, (he hadstill retained possession evidentally ) to another on the outskirts of Dublin and there he died in 1844.

We have no knowledge of his age at death so that we cannot determine his age when he came to Upper Canada, but he seems to have been a remarkably able person, an excellent organiser, a good employer and a strong supporter of the Irish immigrants whom he appears to have helped to emigrate. From being a linen draper to becoming an owner of ironworks Hayes shows himself in his letters to have been a dedicated person albeit a retiring person, not quite the type that would have used his political powers to the best advantage if indeed he had any appreciation of his political power that was so necessary during that frontier time.

After Hayes had left for England McGill, later to be the founder of the Bank of Montreal, and of the well known McGill University, continued to operate the iron works but finding difficulties with his manager put the works up for sale.

For the next fifty years or so Marmora Iron Works continued to operate in a sporadic way then,with the rising demand for timber in the United States,the site was cleared and replaced by saw milling operations, the mine at Blairton supplying ore to furnaces in the United States.

Aeromagnetic surveys[30] have shown that there still is vast amounts of iron ore deposits still in the area, as well as lead, gold, silver, copper and many other valuable minerals.

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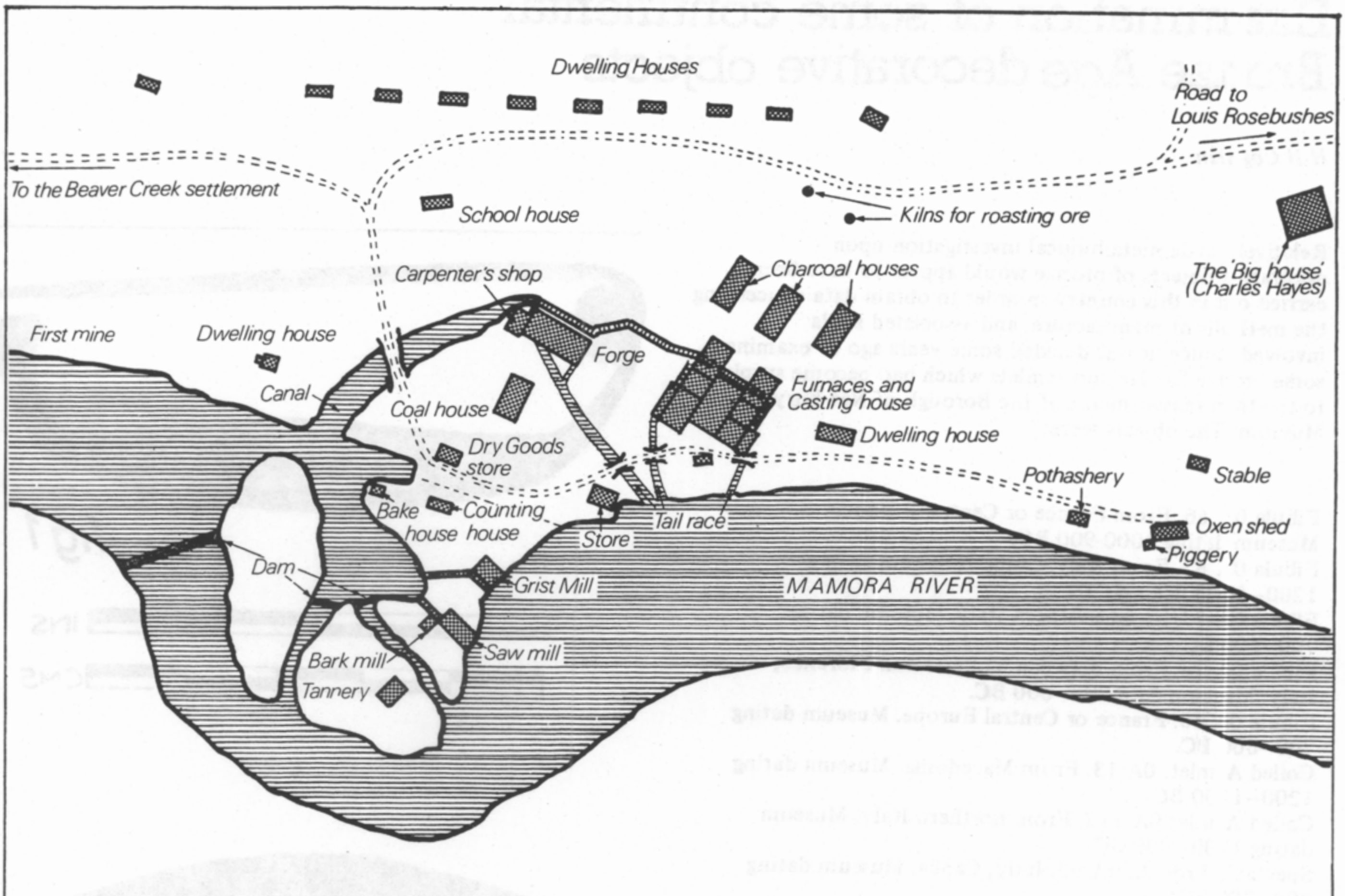

Plan of the Marmora Iron Works and Village in Upper Canada: 1824/1826

From original maps of Charles Hayes

Fig 3

feet
0 50 100

Map after AD Dunn 1979

15 P A C Upper Canada Sundries pp 22388-91.

16 Ibid. pp 24535-6.

17 Ibid. pp 25477-80.

18 PRO Treasury Records No 14120.

19 P A C Upper Canada Sundries pp 30529-32.

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22 Ibid.

23 Plot – Natural History of Staffordshire, 1686.

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27 P A C Upper Canada Sundries pp 22388-91.

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Public Archives of Canada (PAC).

# Examination of some continental Bronze Age decorative objects

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Relatively little metallurgical investigation upon decorative objects of bronze would appear to have been carried out in this country in order to obtain data concerning the methods of manufacture, and associated skills involved. Hence, it was decided some years ago to examine some bronze fibulae and armlets which had become surplus to the then requirements of the Borough of Newbury Museum. The objects were:

Fibula 0A 66. From France or Central Europe. Museum dating 1000-900 BC.
Fibula 0A 67. From Italy. Chiusi. Museum dating 1200–1100 BC
Fibula 0A 77. From southern Italy. Museum dating 700–600 BC
Fibula 0A 78. From between Volterra and Florence, Italy. Museum date 700–600 BC.
Fibula 0A 80. France or Central Europe. Museum dating 700–600 BC.
Coiled Armlet. 0A 13. From Macedonia. Museum dating 1200–1100 BC
Coiled Armlet 0A 112. From northern Italy. Museum dating 1000–900 BC
Spectacle Brooch. 0A 99. Italy, Capua. Museum dating 800–700 BC
Spectacle Brooch S 309. From Macedonia. Museum dating Second millennium BC
Bracelet 0A 69. From Hungary. Museum dating 1300–1200 BC

The chemical composition of the objects is given in Table 1.

## EXAMINATION OF THE ARTEFACTS

### 1. The Fibulae

*Bow Fibula 0A 66*

This Fibula is relatively simple and the bow is formed by a flat elliptically shaped piece of cast bronze which has a pronounced central strengthening rib (Figs 1–3). The helical spring is neatly wound with three coils, and the point of the pin seats into a clip which is formed by bending round one end of the bow. For metallographic examination the following sections were removed. A section through one coil of the spring including also part of the pin. Transverse and longitudinal sections taken through the bow near to the spring, and a longitudinal one from the rib of the bow adjacent to the clip. Sections were also taken from the point and centre of the pin, and a transverse section through the clip for the pin. Weight as received, 16.2 grams. (See Table 1 for composition).

Upon viewing the various sections in the unetched state the metal was seen to be relatively sound except for some general microporosity. For an ancient bronze, it may be said that corrosion attack from the environment has been relatively slight. However, in the case of the slender pin, corrosion attack has been quite severe in places. Upon etching the section taken from the spring, twinned crystals of medium grain size were seen, the spring has been worked and annealed

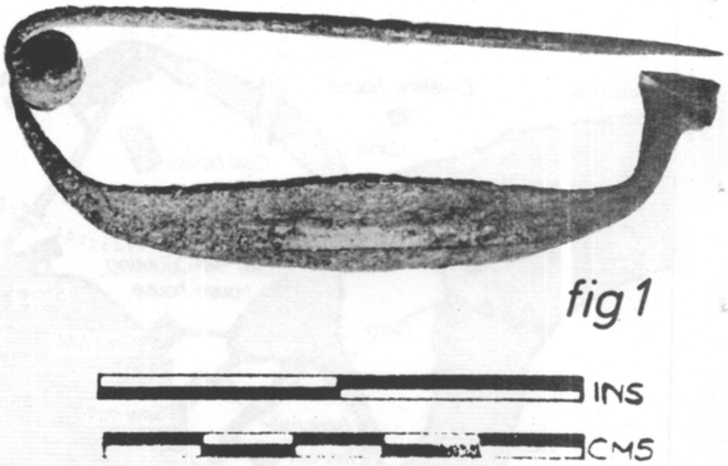


fig 1

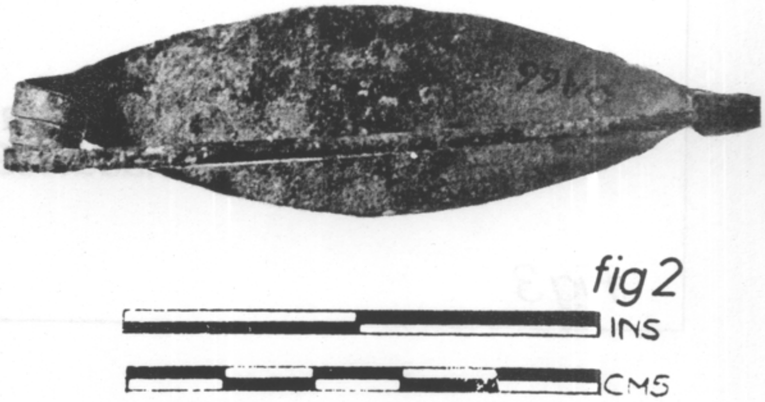


fig 2


fig 3

probably at moderate temperature. In the wire of the pin, near to the spring, an imperfectly made joint was detected showing that the pin had been made from a separate piece of bronze wire, cast-on or run-on to the material of the spring. While the joint was not perfect, it was satisfactory since the pin did not fail in use. (Fig 4).

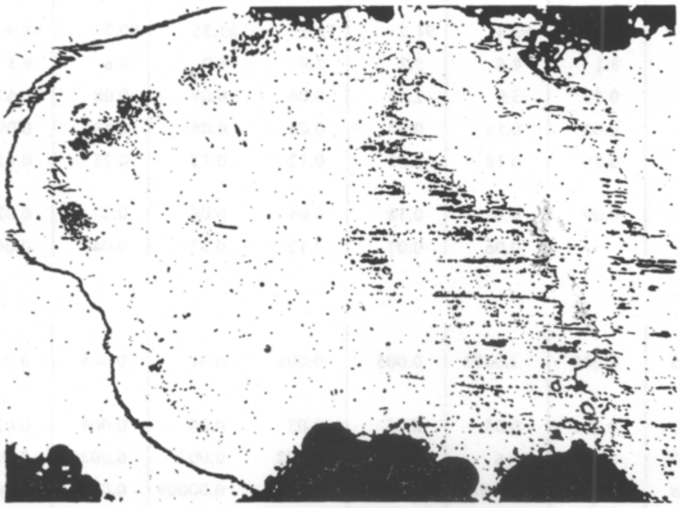


fig 4

The part of the pin near to the spring showed very little hardening, the average hardness being only 100 HV. Hardness was measured at three different positions upon the coil of the spring. Unexpectedly, it was found that the spring had not been wound in a soft annealed state but had been work hardened to some extent. Average hardnesses are shown in Table 2.

The coils of the spring are unusual in being of approximately rectangular cross section rather than of the more normal circular section. In view of the light transverse section, of but 1.5 to 2 mm in thickness, it should not have been difficult to wind the spring even in a somewhat hardened state. Some of the work hardening may be due to the operation of coiling the spring in the cold state, but probably most of the hardening occurred before the spring was actually wound, since it would be all but impossible to work harden this small spring after it was wound.

Upon etching the sections containing the point and centre of the pin, the structures showed equiaxed twinned crystals of fine grain size. The extreme point of the pin has been appreciably hardened, 160 and 165 HV. The remainder of the section was hardly work hardened, 97 HV. Again, the centre of the pin was only very slightly hardened, the average hardness being only 109 HV. Upon etching the various sections taken from the bow of the fibula it was seen that the metal had been annealed, but not homogenised. In places, twinned crystals appear with a limited amount of slip banding, the general structures are consistent with that of a partially annealed casting which has been subjected to some slight mechanical working. Determinations from three sections in the bow showed very moderate hardness of 121, 125 and 132 HV. As expected, the thin metal forming the clip has been annealed, forged, and bent round to receive the pin. Remote from the clip, the partially annealed structure of the cast bow is entered. The metal of the end of the bow showed an average hardness of 137 HV, while that of the thin metal of the clip was 146 HV. Hence, the forged end of the bow and clip have only been work hardened to a very moderate extent.

### *Bow Fibula 0A 67*

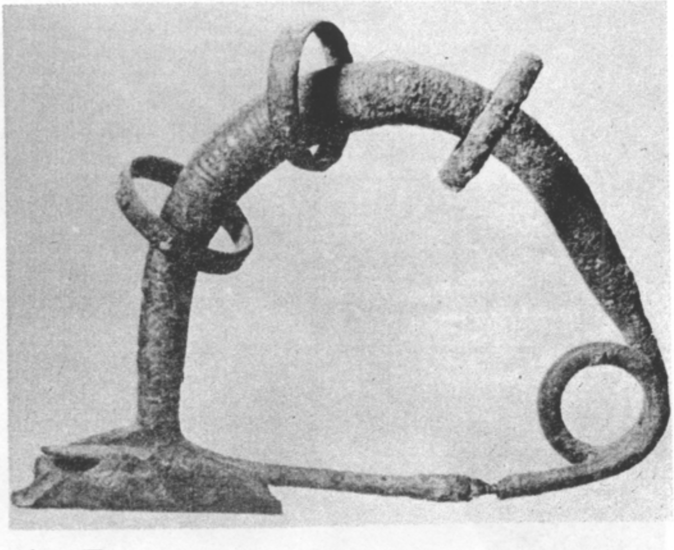
This is a somewhat unusual fibula which has three bronze rings threaded loosely on the bow. Figs 5–8. These rings could have been placed upon the bow before the spring was formed. The patination is of dark green colour with a somewhat rough surface, the bow is in good condition and visual inspection suggests that it has not suffered much from corrosion attack. On the other hand, it can be seen that corrosion has been severe in the case of both the pin and the rings. Along its length the bow has a number of decorative zones of annular grooves with intervals of undecorated metal between the grooved zones. These grooves are very well executed but of very shallow depth, they strongly suggest that the decoration was graved in. If this is so, the graving and chasing was a highly skilled piece of work. The bow is a substantial one of nearly 10 mm in diameter at its central portion, but tapered towards the spring and clip ends. Weight as received 78 grams.

The major constituents of the bow metal are 5.7 per cent of tin, and 1.15 per cent of lead. The rings threaded upon the bow are of different composition containing 6 per cent of tin and 1.05 per cent of antimony. The spring is a simple one, consisting of little more than one coil. The spring is substantial, and it is clear that most of the flexing in use would have occurred in the relatively slender pin which is only about 2.5 mm in diameter rather than in the so-called spring. For metallographic examination sections were removed from the bow, and from one of the rings threaded upon it, a transverse section through the bow, and also a section from the coil of the spring. Another section was taken from the clip for the pin, the pin itself was sectioned throughout its length.

Examination in the unetched state showed that the metal of the bow is relatively sound and without serious corrosion attack. The same may be said of the bow and clip section, although at the thin point of the clip corrosion is severe in places. Plastically deformed and elongated non-metallic inclusions show that the clip has been formed by hot forging down, and bending round, from the thick metal of the bow. The metal of the spring appears to be sound and corrosion attack is not severe. The spring has been longitudinally hot forged during fabrication. In the metal of the pin corrosion has been severe, at one place almost cutting the pin in two Fig 9. The worst area of corrosion occurs quite near to the spring. It is possible that here the pin was cast-on, as in the case of fibula number 0A 66. The pin has also been hot forged during fabrication. The ring, which was inserted on the bow, is highly corroded and in places corrosion penetrates completely through the metal. No evidence for a joint could be detected.

Hardness measurements show that again the spring has not been wound in the fully soft state (Table 2).

The metal in the transverse section of the bow has been subjected to working and heating, probably at low temperature, and the metal has not been homogenised. Here, the bow has been moderately work hardened, average hardness being 147 HV. At another place in the bow there was considerable work hardening, upon one edge of the section average hardness was 158 HV, while upon the other edge the average hardness was as high as 237 HV. Concerning the section taken through the end of the bow and clip, as expected in an extensively forged section the bronze has been hot worked and the structures show equi-axed twinned crystals of medium grain size. Hardness tests in various places showed that the end of the bow had been irregularly work hardened by cold hammering, the maximum hardness was 246 HV, and the minimum 117 HV. The thin metal of the clip was softer, the average value being 123 HV.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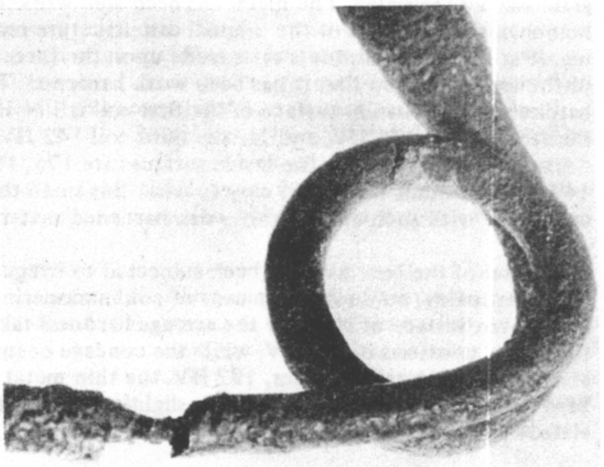
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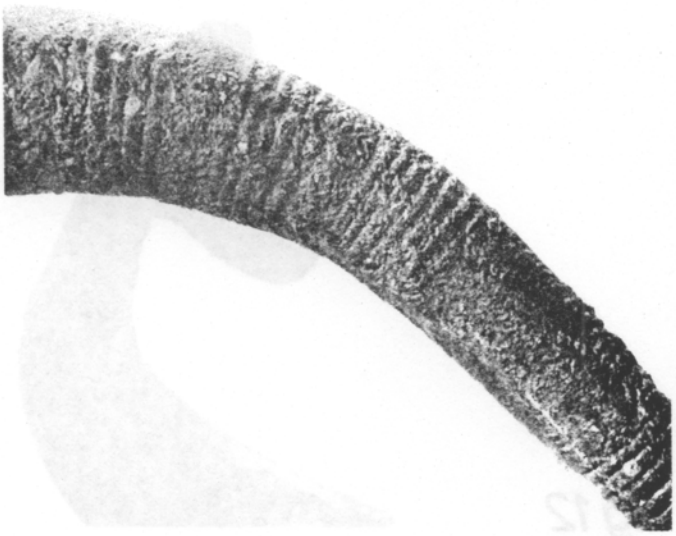
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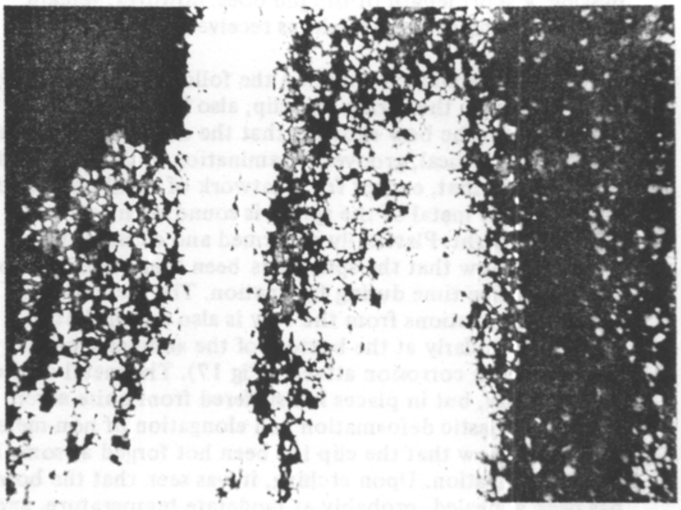
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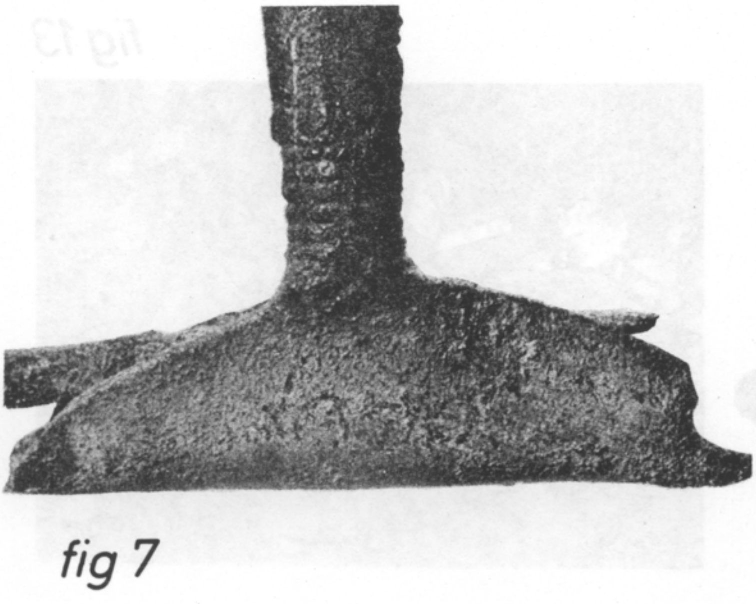
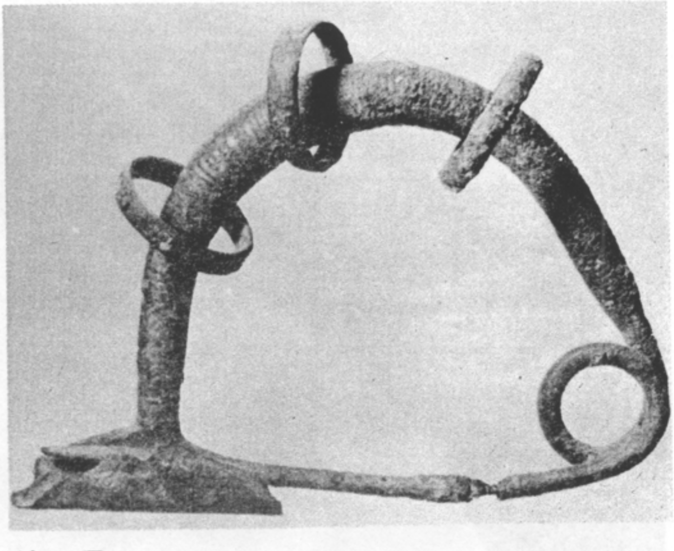


fig 7

*Bow Fibula 0A 77*

This bow fibula comes from the south of Italy, or Sicily, and is of relatively simple type but with an unusually long clip. (Fig. 10). Upon the bow is a certain amount of decoration, but not of the annular grooved type. This decoration will have been applied by means of graving and chasing. (Fig. 11). The spring consists of three closely wound coils, and the diameter of the wire in the spring is 3 to 3.3 mm, the diameter inside the coils of the spring is only 3 to 3.5 mm. The pin has broken off and is missing. (Fig 12). The clip to receive a pin is an unusually long one, about 25 mm in length with a small ornamental coil at the non-working end. Weight as received 16.5 grams.

For metallographic examination sections were taken from the bow, the spring, and the clip for the pin. Examination of these sections in unetched state showed the bronze to be relatively sound. Corrosion attack upon the exterior surfaces is slight, but the thin metal of the clip has suffered severe corrosion in places. Upon etching the specimens a structure of equiaxed twinned crystals of medium to somewhat small



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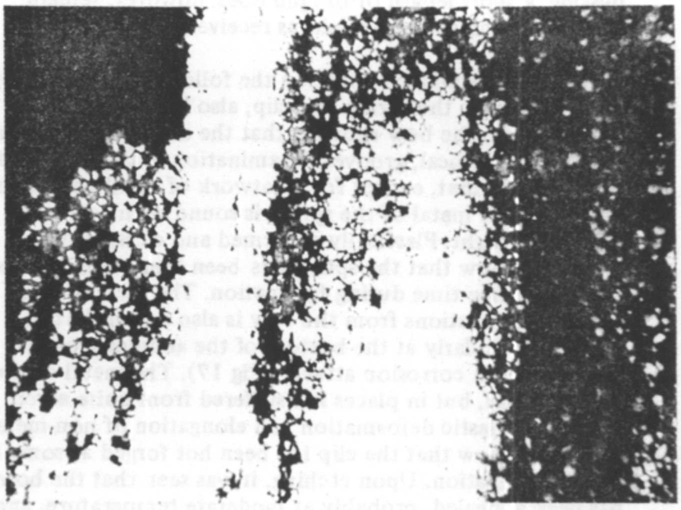

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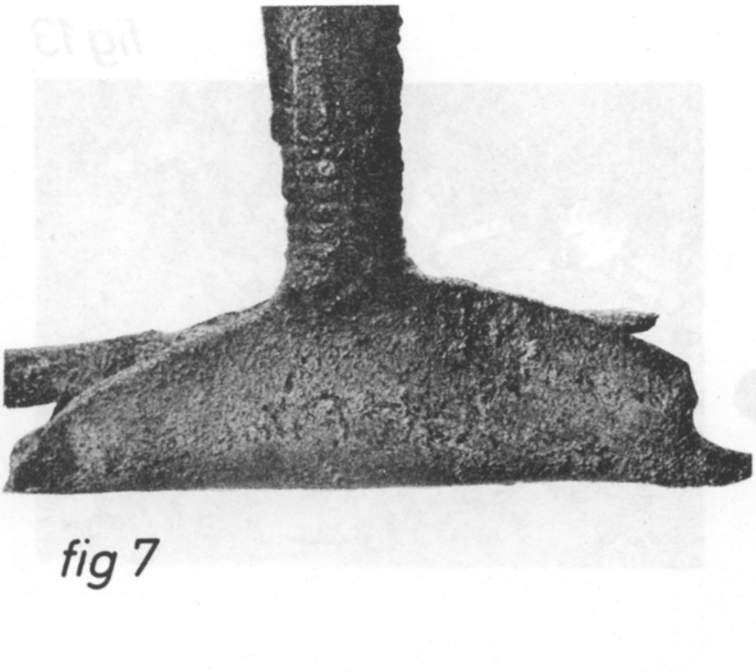

fig 7

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For metallographic examination sections were taken from the bow, the spring, and the clip for the pin. Examination of these sections in unetched state showed the bronze to be relatively sound. Corrosion attack upon the exterior surfaces is slight, but the thin metal of the clip has suffered severe corrosion in places. Upon etching the specimens a structure of equiaxed twinned crystals of medium to somewhat small grain size was revealed. The metal has been well worked and homogenised, no relics of the original cast structure remaining. (Fig 13). Microhardness tests made upon the three coils of the spring showed that it has been work hardened. The hardness at the outside surface of the first coil is 174 HV, at the second coil, 175 HV, and for the third coil 142 HV. Corresponding values for the inside surfaces are 175, 199, and 149 HV. It cannot have been easy to wind this small three-coil spring with such appreciably work hardened material.

The metal of the bow has also been subjected to irregular work hardening, no doubt by means of cold hammering. At the convex surface of the bow the average hardness taken from four positions is 150 HV, while the concave or inner surface is considerably harder, 192 HV. the thin metal of the bent round clip itself has been left in slightly work hardened state, the average hardness being 150 HV.

*Bow Fibula 0A 78*

This fibula comes from between Volterra and Florence in Italy, and may be dated to the Etruscan period. Practically the whole length of the bow carries very clearly defined annular grooved decoration (Fig 14). One end of the bow is bent round to form the clip for the pointed end of a pin, (Fig 16), at the other end of the bow a simple spring of three coils has been wound (Fig 15). The pin has broken off and is missing, a short length of the pin does, however, remain adjacent to the spring. Weight as received 26.7 grams.

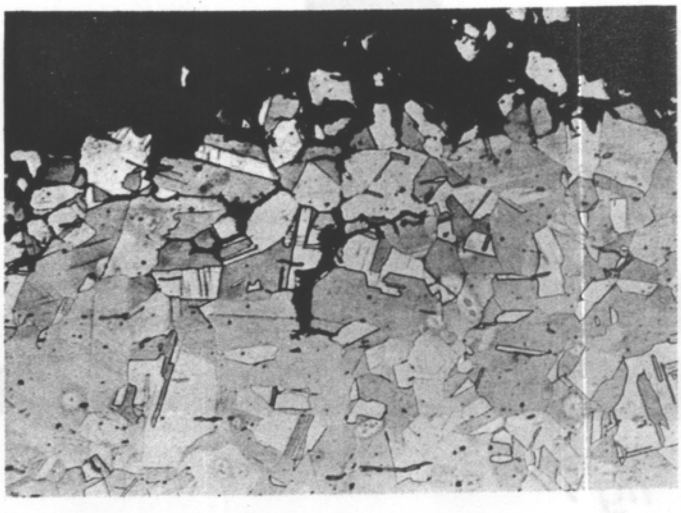
For metallographic examination the following sections were removed: From the spring and clip, also longitudinal sections from the bow showing that the decoration consists of annular, not helical, grooves. Examination in the unetched state showed that, except for a network of small non-metallic inclusions the metal of the spring is sound with corrosion attack but slight. Plastically deformed and elongated inclusions show that the spring has been longitudinally hot forged at some time during fabrication. The metal of the longitudinal sections from the bow is also sound, but in places, particularly at the bottom of the annular grooves, there has been corrosion attack. (Fig 17). The metal of the clip is similar, but in places has suffered from quite severe corrosion. Plastic deformation and elongation of non-metallic inclusions show that the clip has been hot forged at some time during fabrication. Upon etching, it was seen that the bow has been annealed, probably at moderate temperature, and slightly mechanically worked. Twinned crystals could be seen throughout the section. While heated and worked, the metal in general does not appear to have been fully homogenised.

fig 11

fig 12

fig 10

fig 13



Alpha-delta eutectoid was not observed. Definite evidence to decide whether the annular grooves cut into the structure of the metal could not be obtained owing to thick corrosion products upon the surface of the grooves.

A micro hardness plot was made of a number of the annular grooves and it was found that the average hardness at the apex of the grooves was 169 HV, the average at the sides was 175 HV, and at the bottom of the grooves 181 HV. These figures show that the annular grooves in the bow have been appreciably work hardened. The metal of the clip, and the adjacent end of the bow, shows a somewhat similar structure to that of the rest of the bow. Hot working is indicated by plastically deformed inclusions drawn out in the direction of forging. It was found that the metal had been appreciably work hardened by cold hammering. This hardening is fairly uniform, the average value from six positions taken along the end of the bow and clip is 196 HV.

Upon etching the section of the spring a structure of equiaxed twinned crystals was revealed, the crystals tending to be of somewhat small grain size, the metal does not appear to be fully homogenised and to have been worked at relatively low temperature. Unexpectedly, the spring was found to have been appreciably hardened as the figures in Table 2 show.

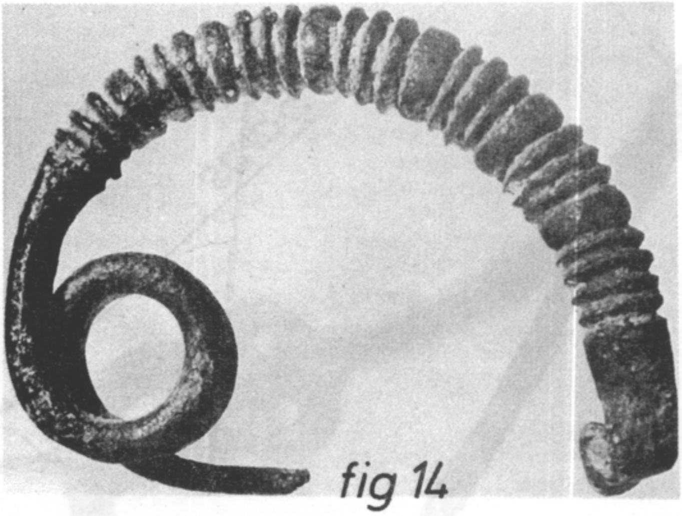
The so-called spring consists of three coils of quite substantial wire some 3.5 mm in diameter. The bend is an easy one, the diameter at the inside of the coils being approximately 10mm. Again, the conclusion is that winding was carried out with the wire in the hardened state.

*Fibular 0A 80*

In this fibula, or inverted brooch, of Late Hallstatt period, the arrangement of the spring is complex and unusual. (Fig 18–20). Instead of the normal helical coil arrangement,the spring is formed in effect by a number of S bends. A spring of this nature must have been difficult to wind and there would appear to be no advantage in the design. Adjacent to the spring there is a circular disc on the bow which may have had some functional purpose. The weight as received was 8.59. Analysis of the bronze gave 8.1% of tin in the composition. For metallographic examination, sections were taken from the spring-end, the spring and body wire, the circular disc, clip, and along the length of the pin.

Examination of the various sections in unetched state showed the metal to be sound and relatively free from inclusions with corrision attack but slight. In the case of the clip there has been inter-granular corrosion in places, otherwise the metal is sound. (Fig 21). The metal in the pin is generally sound, but in places it has suffered from corrosion. Upon etching, the section taken from the spring revealed structures of equiaxed twinned crystals of medium to small grain size. (Fig 22). The metal has been well worked and homogenised and slip bands were detected. In fact, the so-called spring has been slightly hardened as the figures in Table 2 show.

The slight hardening probably occurred during the preparation of the wire since it could not have been hardened once the winding of the spring had been completed (unless the slgiht hardening may be ascribed to mechanical strain originating during coiling of the spring). The coils are not closely wound, and with wire of 2.5 to 3 mm in diameter it would have been possible to coil the spring, even in cold condition, with the small hardness recorded. It is difficult to suggest what form of tool or fixture would have been used to enable the complex winding to have been carried out.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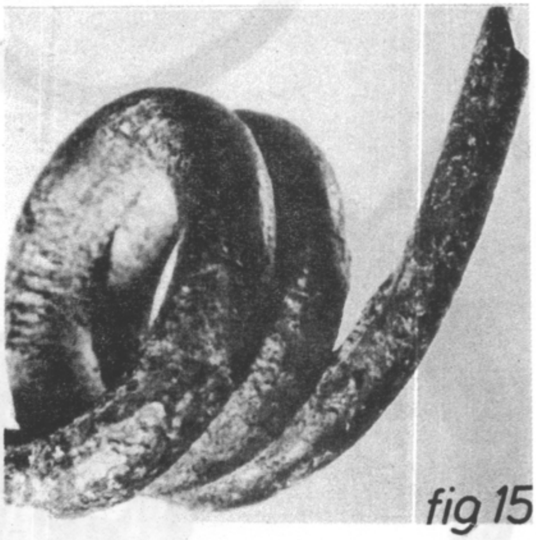
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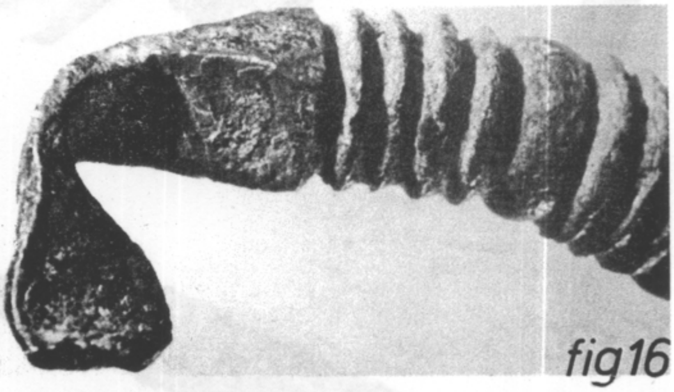
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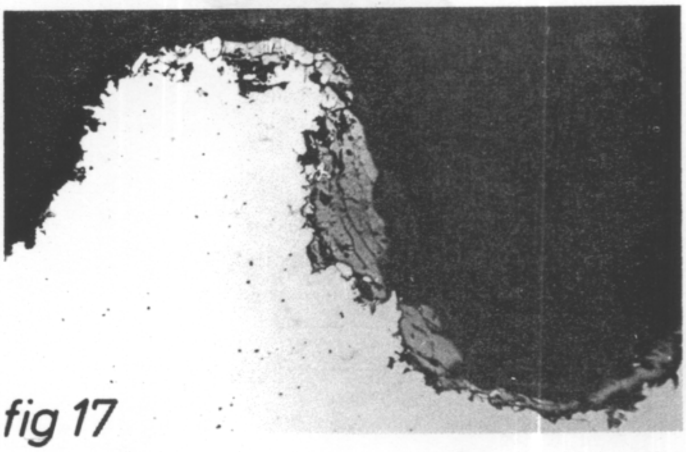
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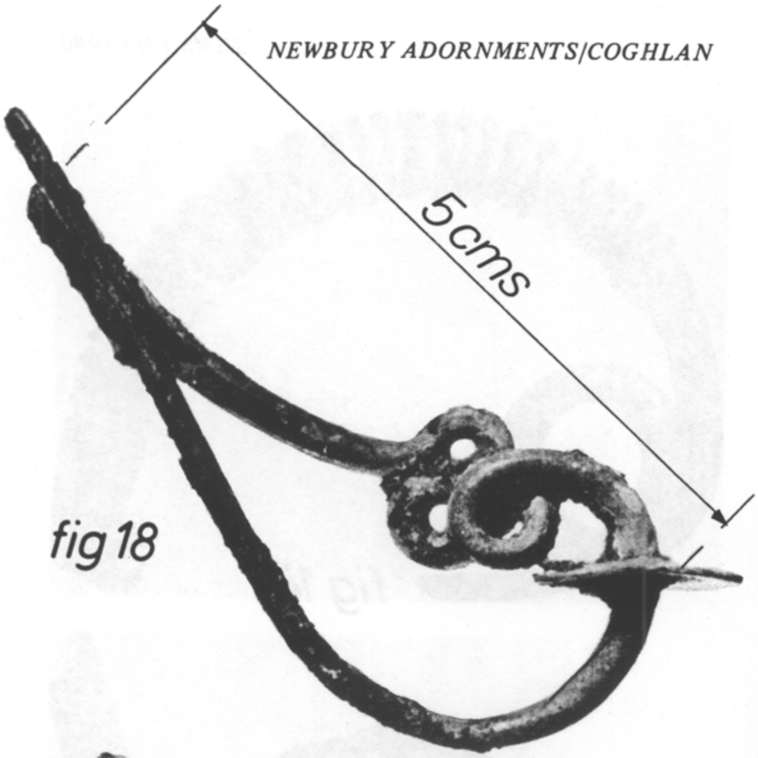

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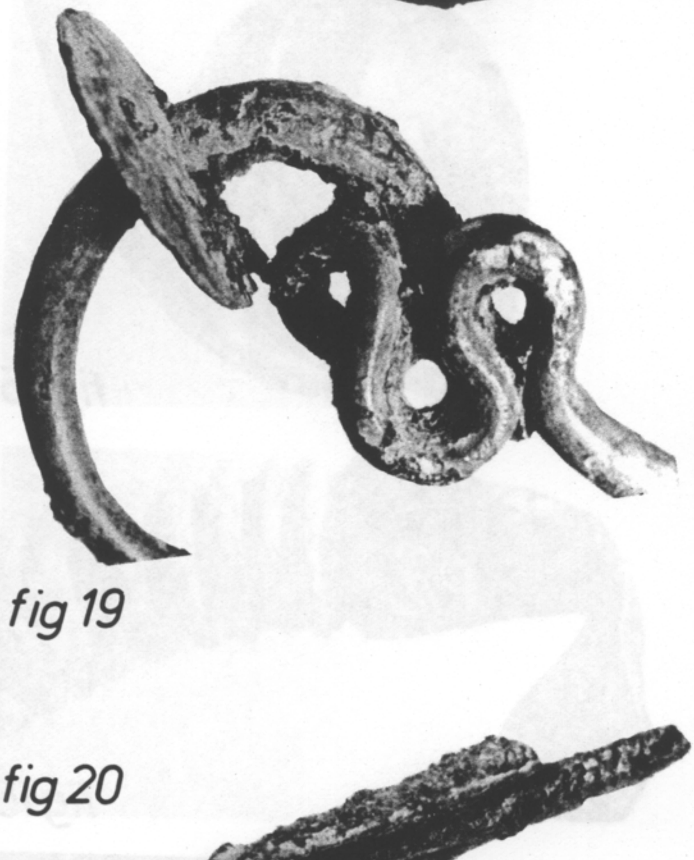


fig 19

fig 20

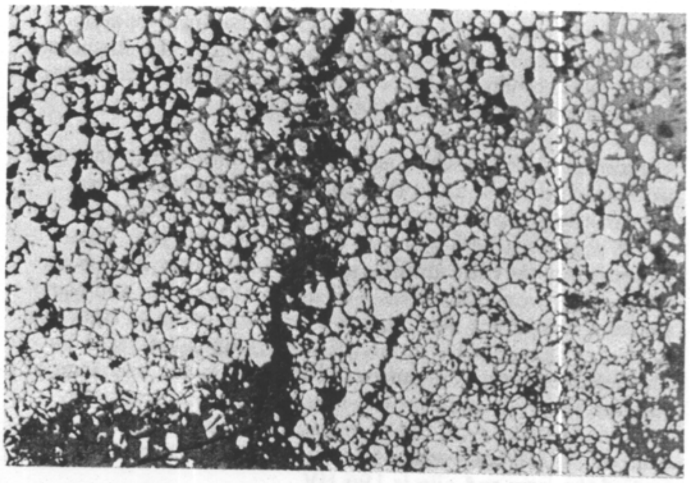
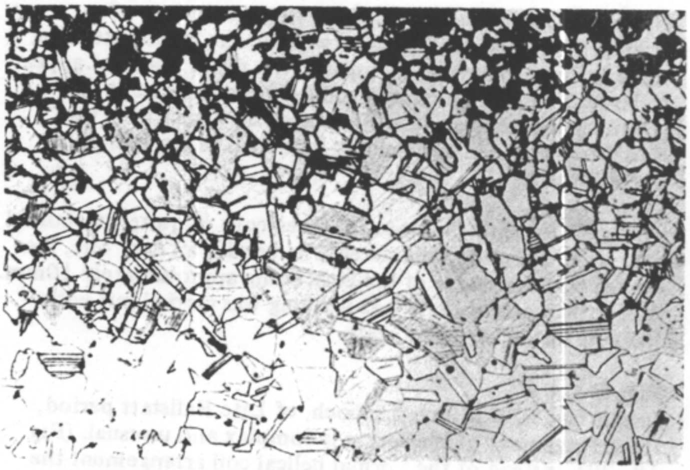


fig 21



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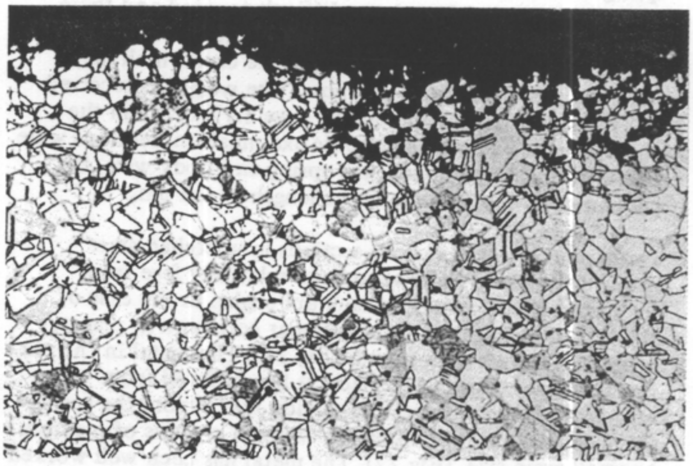


fig 23

In the case of the circular disc,the structure seen was also that of equiaxed twinned crystals of medium to fine grain size, the metal has been well worked and at least partially homogenised. Unexpectedly, no evidence for any joint between the disc and the wire could be detected, and the disc, unlikely though it may seem, was apparently cast solid with the wire. In general, the structure of the clip is similar to that of the other sections examined, it has been formed by forging and bending round metal left at the end of the bow for this purpose. The structure of the pin exhibits equiaxed twinned crystals of very fine grain size. (Fig. 23). The metal has the appearance of having been extensively worked at a low temperature. Alpha-delta eutectoid was not seen in any of the sections examined.

Concerning the hardness of the various parts of the fibula, microhardness tests showed that the extreme point of the pin had been highly work hardened to 236 HV, while the rest of the pin was not nearly so highly hardened. For instance, the average hardness of the curved part of the pin is only approximately 150 HV. The body wire from which the fibula is made varies from a soft state, 112 HV, to a slightly work hardened one, 132 HV. At and around the decorative disc there has been a certain amount of irregular but moderate cold working, giving an average of approximately 135 HV in this area.

*Coiled Armlet 0A 13*
In appearance, this armlet resembles a helical spring which is slightly tapered throughout its length. (Fig 24). The approximate maximum diameter of the coils is 75 mm at one end, tapering to about 55 mm at the other end. As received, the length of the armlet is about 100 mm. The armlet is quite flexible and springy in its length, and to a lesser extent in diameter. In cross section the coils are flat internally, and slightly rounded externally. They are of light section, quite well made without much variation from a maximum width of 7.8 mm at one end of the armlet to 6.8 mm at the opposite end. The average thickness of the metal is about 2.2 mm. There are eight coils, and the total length of bronze wire in the armlet is approximately 1.5 metres. Weight as received 145 grams.

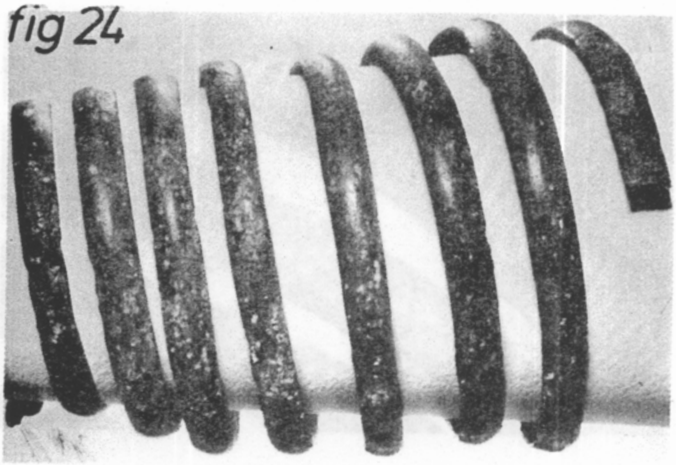
Superficially, the armlet appears to be in good condition and is covered with a light greenish patination, much of which still retains a polished surface. Visually, the metal does not appear to have been badly attacked by corrosion. However, in three places severe local attack can be seen (Fig. 25). In view of the considerable length of wire involved it was thought possible that these pieces may denote joints in the coils made by casting-on or running-on. Four longitudinal sections were removed for metallographic examination.

In the unetched state the metal in the sections taken was seen to be sound apart from some micro-porosity and, except at the local areas mentioned above, there has been relativley little corrosion attack. Upon etching, the structures revealed equiaxed twinned crystals of medium grain size. The metal has been homogenised, and alpha-delta eutectoid was not observed. Microhardness tests were carried out on the various sections, the average hardness being as shown in Table 2.

The figures show that the internal and external surfaces of the coils have been moderately hardened. In general, the work hardening has been well carried out, and without excessive variation in hardness.

*Coiled Armlet 0A 112*
As received, this armlet consists of eight open coils wound cylindrically (Fig 26). The outside diameter of the armlet is approximately 80 mm, and the length of wire in the coils is around 1.8 metres. The bronze wire used is substantial, being of approximately circular cross section of 5 to 6 mm in diameter. At both ends of the helix are terminals, and here there is an increase in diameter over a length of about 50 mm. The terminals carry shallow decoration as annular grooves. (Fig 27). There is also some evidence of grooving over a short distance in the wire beyond the terminals, otherwise, the coils do not appear to have any decoration applied. The decoration, was probably formed by graving and chasing before the helix was wound. It was noted that any

fig 24



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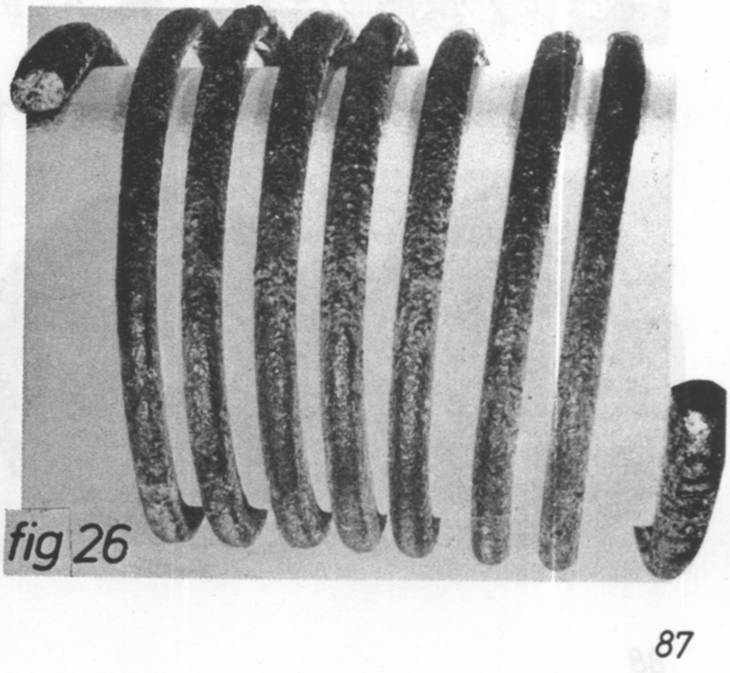
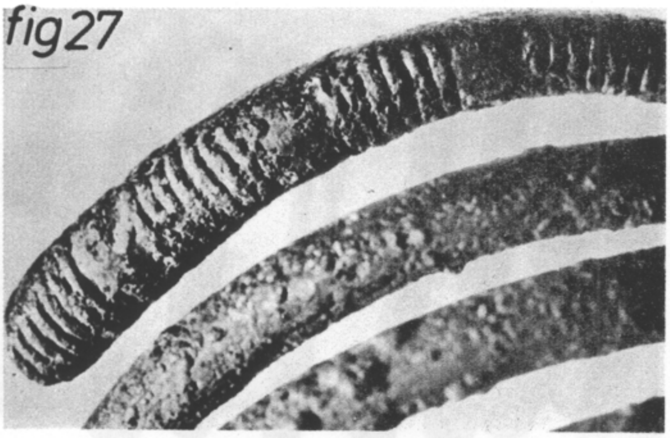


fig 26



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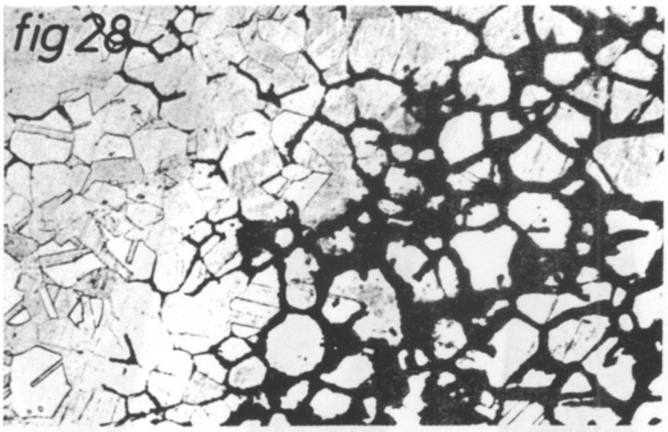

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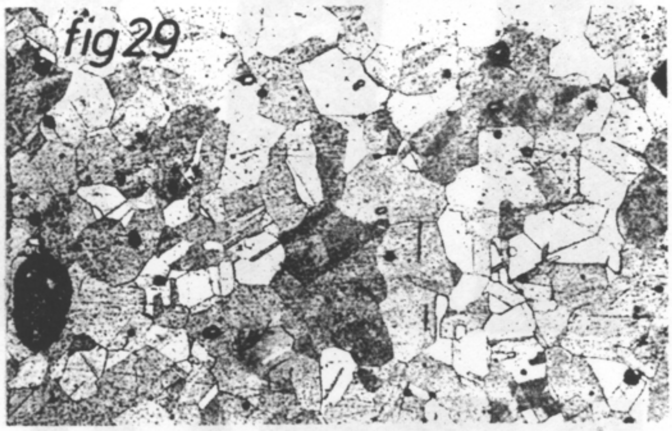

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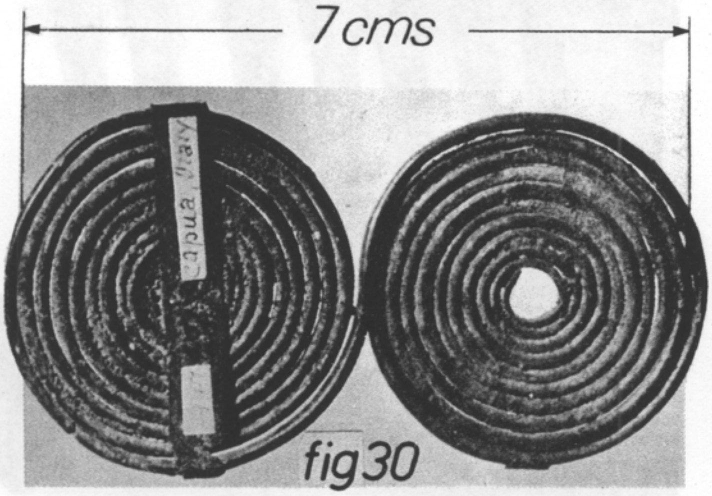


fig30

decoration only appears upon the outside of the armlet where it would have been seen. Weight as received 390 grams.

Owing to environmental conditions the patination is rough, but in places a smooth dark greenish polished patination can still be seen on the inside of the coils. Visual inspection suggests that there has been a certain amount of corrosion attack, and at two positions in the wire corrosion has been so severe upon a small area that an imperfect joint in the wire may be suspected. For examination a section was removed from the wire where the presence of a joint was suspected, and also two longitudinal sections were taken through the remains of annular grooving upon one of the enlarged terminals. In the unetched state in the section where a joint was suspected the bronze was seen to be clean and free from non-metallic inclusions. In places upon the edges of the specimens there has been severe inter-granular corrosion, (Fig 28), but no evidence for any joint in the metal could be detected. In the case of the sections through the annular grooves upon the terminals, the metal is sound with but little corrosion upon the surfaces. It may be said that, for an ancient specimen, corrosion attack has been remarkably slight. Although the armlet contained 8 per cent of tin, alpha-delta eutectoid could not be seen in any of the sections.

Upon etching the sections taken through the shallow annular grooves a structure of equiaxed twinned crystals of medium grain size was revealed, and the metal has been homogenised. Precise evidence that the shallow annular grooves were cut into the structure of the metal was difficult to establish because of slight surface corrosion but no doubt they were; the grooves being formed by graving and chasing. The structures in the sections taken through the wire are very similar (Fig 29).

Twelve microhardness determinations were made at various places upon the circumference of one of the end terminals, and it was found that the metal is in a moderately work hardened state, the average hardness being 158 HV. However, the hardening operation was highly irregular, in a hard spot a value of 220 HV was observed, while in a soft spot a value so low as 118 HV was recorded. The wire of the coils has been slightly hardened by cold hammering, or possibly by drawing. The average hardness from a number of indents taken at the circumference of the wire is 149 HV, but the work hardening is irregular, in places, it can rise to a maximum of 170 HV, and descend to a minimum of about 120 HV. there is little difference in hardness at the circumference, and in the centre or mass of the metal.

*Spectacle Brooch 0A 99*

As received this brooch was intact. (Figs 30-32). Either a joint was made in the wires between the two coils of the spectacle, or one of the coils has been reverse wound. One of the spectacles has a central boss and a bronze clip over the coils. The purpose of the clip was apparently to hold the coils tightly together, it has no connection with the central boss which would appear to have been held in place by some non-metallic substance such as bitumen. Under visual examination the coils appear to be in fair condition. Patination is of greenish colour, and in places, shows a polished surface.

The spectacle without a central boss and clip is about 33 mm in external diameter, and the coils are very tightly wound. The wire is of small diameter, and reasonably uniform in transverse section. There is a slight but regular reduction in the diameter of the wires from about 1.5 mm to about 1.25 mm, measured from the circumference of the spectacle to its centre. The total length of wire comprising the

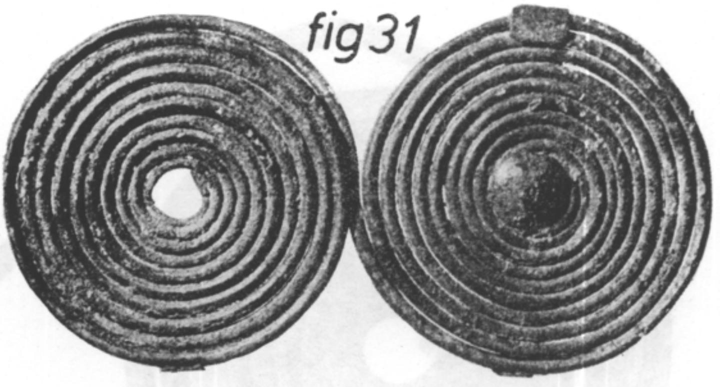


fig 31

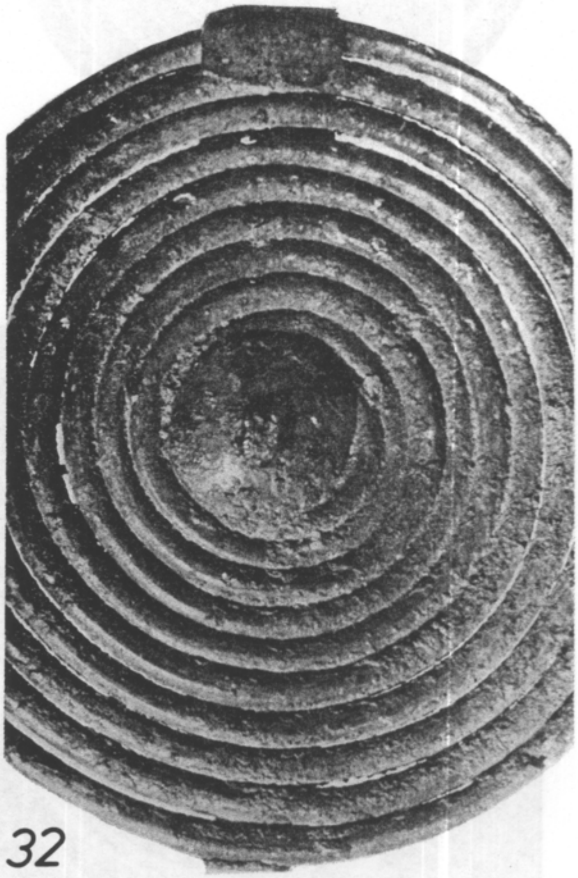


fig 32

complete brooch must be around one metre, a considerable length unless a joint was made between the two spectacles. Weight as received 25.5 grams.

For examination complete transverse sections were taken through the numerous small wires in both spectacles, also through the central boss and retaining clip. Examination in the unetched state showed the bronze to be fairly sound apart from micro-porosity, but some of the wires have been rather severely attacked by intergranular corrosion. In the central boss and retaining clip the metal was found to be dirty with porosity and inclusions. Here, the bronze has been severely corroded and in places corrosion has penetrated completely through the metal. Upon etching, the structures showed equiaxed twinned crystals of very small grain size, and the metal appears to have been at least partially homogenised. Microhardness tests were made at the circumference of the small wires and the average hardness was found to be 140 HV. Hence, the wires are in a slightly work hardened state. This work hardening is probably due to drawing the wire through a vee-shaped notched die. The material of the thin retaining clip has also been very slightly work hardened to around an average of 115 HV, but slightly harder where the ends of the clip have been bent round to retain the coils.

*Spectacle Brooch S 309*

Number S 309 is a large and heavy spectacle brooch with two tightly wound coils of bronze wire. (Figs 33-35). The connecting wire between the two coils has been broken in antiquity. In one of the spectacles there is a central boss which has no metallic connection with the wires, it was retained in place with the aid of some substance such as bitumen. The external diameter of the spectacles is approximately 85 mm, and superficially the bronze would appear to be in fair condition although in places there has been some corrosion attack. Patination is of a dark green colour, originally polished, and considerable areas of polished surface still remain. The total length of wire in the two coils is estimated to be around 8 feet (2.43 metres), and in such a length one would suspect one, if not more, joints to have been made. Weight as received 394 grams.

The bronze wire comprising the coils is approximately circular in cross section, the wire of the exterior coils is 5 mm in diameter, and there is a reduction to 4 mm in the centre turns of the coils. This perhaps suggests that the wire was finished by pulling through a Vee notch rather than drawing through a closed circular die. As may be seen from the illustrations, the spectacle coils are very accurately and tightly wound. With the bronze in appreciably hardened state it is remarkable that the smith achieved such close and accurate winding. In transverse section the spectacles are not flat, but slightly coned, and this may have helped in attaining close winding, the coils may have been wound over a slightly conical former. The following sections were removed for metallographic examination: S 309 (A) is a transverse section through six of the wires. S 309 (B) shows the central boss and also some of the wires comprising the central part of the coil, S 309 is a longitudinal section through four of the coil wires.

Examination in the unetched state showed the metal of section S 309 (A) to be sound. Hardly any corrosion was seen upon the wires, in fact, they are practically uncorroded. In the case of section S 309 (B) the same remarks apply, but the central boss has suffered some corrosion attack. ( Fig 36). In the case of the wires, the structures revealed upon etching is of equiaxed twinned crystals of medium grain size. The bronze has been homogenised, and any alpha-delta eutectoid absorbed. No evidence for a joint could be detected in the sections of wire examined. Microhardness tests showed that the wires have been appreciably and fairly uniformly hardened. The average from six indents gave a hardness of around 180 HV. The central boss has been slightly heated but remains substantially in the 'as cast' state, relics of the original cast dendritic structure being clearly seen. However, in the region adjacent to the wires the metal has been worked, a structure of small twinned crystals appearing. The lower end of the boss has been cold hammered, the structure crushed, and inclusions flattened. Most of the boss has been slightly but irregularly hardened, an average figure being about 135 HV. At the lower part of the boss, where it has been extensively hammered the metal is of course much harder, 240 HV in places.

## FABRICATION

Although the coils of this spectacle brooch are of substantial transverse section, fabrication should not have presented serious difficulty to a competent smith, the most difficult

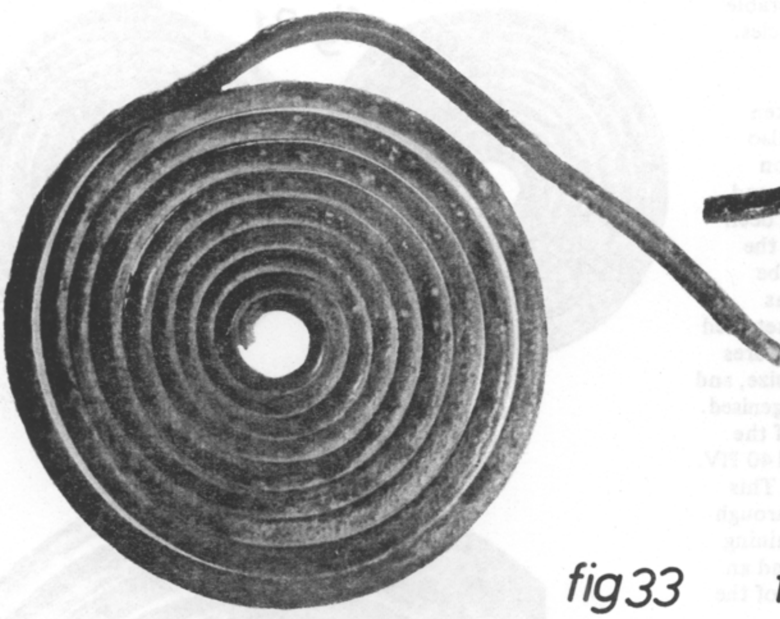


fig 33

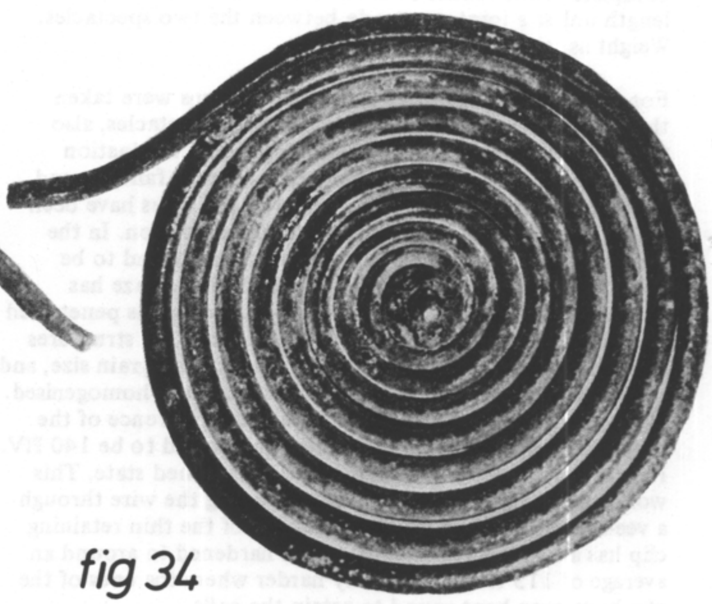


fig 34

fig 35

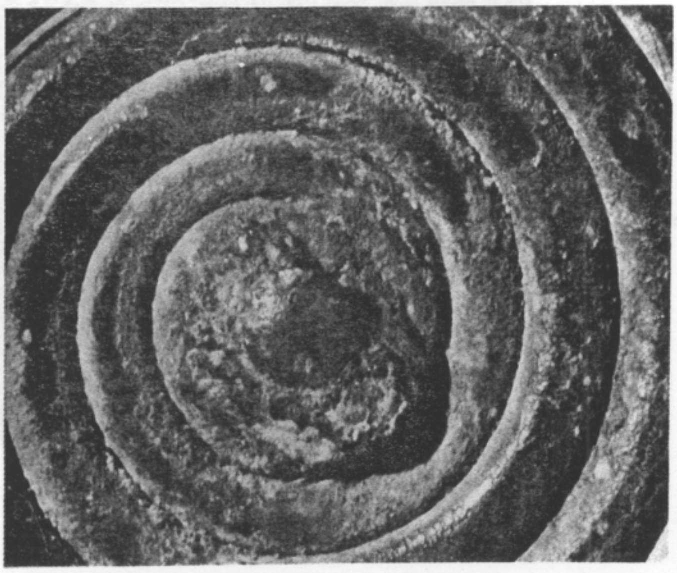


fig 36

operation would be to get the coils so accurately and closely wound. No doubt some sort of fixture would have been necessary.

As an experiment a piece of the original wire, of sufficient length to make about three of the inner coils, was taken from the connecting link between the two spectacles. This length of wire was found to be hard and stiff so that it was necessary to anneal it thoroughly before commencing operations. The wire was wound round a steel plug of the diameter of the central hole in the spectacle. Owing to the stiffness of the wire, even in the fully annealed state, it was not possible to bend it by hand to the small radius desired. To coil the wire, and also to obtain the required close coiling, it was found necessary to resort to hammering upon the outside of the coils to bend and close them. Naturally, the large radius bends of the outer coils would be easier to form, and it is possibe that the outer coils could have been wound by hand without the aid of hammering. After completion of the experimentally wound coils hardness tests showed the hardness at the circumference of the wires to be 185 HV. Hence, the annealed wire has been hardened by the action of bending and hammering during fabrication of the coils. The figure of 185 HV compares very well with that of 180 HV obtained from the original coils, and suggests that a similar fabrication technique was used in antiquity.

The above experiment was of course made with the aid of modern tools, even so, the work was not very easy, nor was the result so good as that of the original. Given the composition and heavy gauge of the wire it is remarkable that the smith should achieve such a high standard with the relatively simple tools available to him. Perhaps we have tended to underrate the ancient skills.

*Bracelet 0A 69*

This is from Hungary and is a nicely made bracelet with decorated terminal ends which perhaps are intended to represent a snake's head. (Figs 37-39). A somewhat similar snake's head motive appears on gold jewellery from Teke, near Knossos, of the 9th century BC.[1] The central part of the bracelet is of rectangular cross section measuring about 8 x 2 mm, and is also decorated with a twisted cord motive.

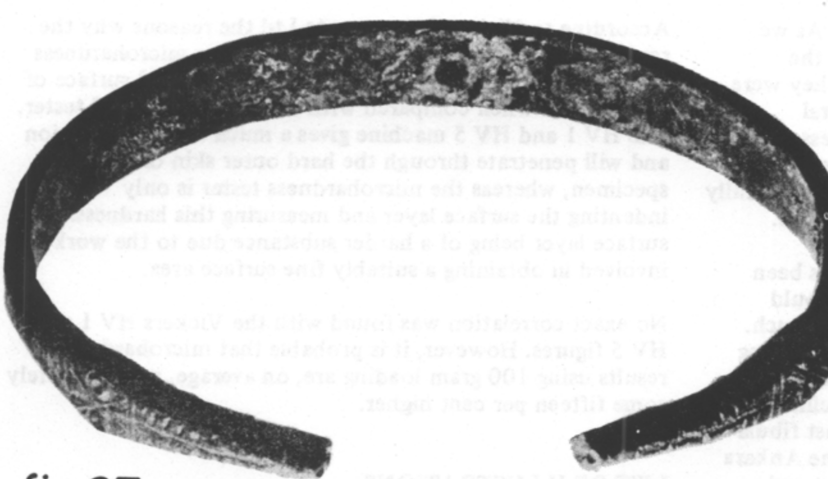


fig 37

fig 38

fig39

The superficial condition of the object is quite good, with a greenish patination which in places still retains a polished surface. What may be termed the internal diameter, or space for the wrist, is approximately 65 mm. Weight as received 21.98 grams. Analysis showed the bronze to contain 4.6 per cent of tin, and 5.9 per cent of lead. That is, quite a heavily leaded low-tin bronze. For metallographic examination longitudinal sections were taken from the centre part of the bracelet cutting through the 'twisted cord' decoration (Section A), and also from the tip and eye of the snake's head terminal (Fig 40).

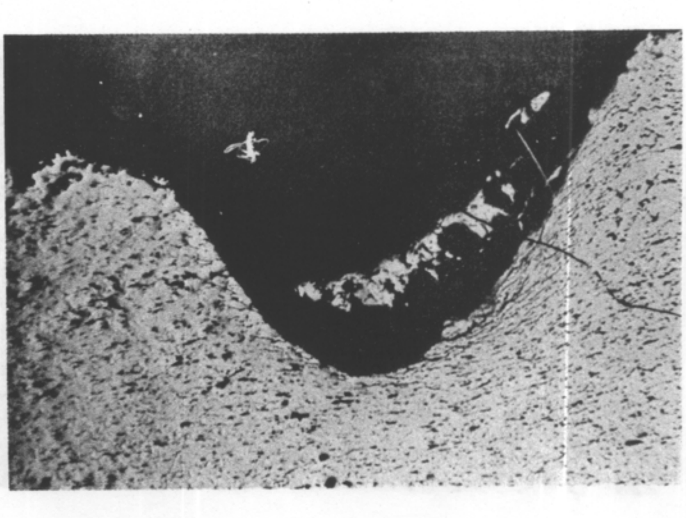
Examination in the unetched state showed the metal to be sound and free from gross defects. Throughout the sections a network of lead particles is seen, in places elongated as if in a direction of forging. Corrosion attack upon the exterior surfaces has, in general, been remarkably slight. Upon etching the various sections a structure of equiaxed twinned crystals of very small grain size was revealed. Throughout the sections examined the metal appears to have been extensively worked, annealed at moderate temperature, and homogenised. (Fig 41).

Microhardness tests carried out upon two sections, one containing the eye, etc, of the so-called snake's head and the other including the tip of the terminal, showed the average hardness to be between 128 and 145 HV. Hence, the leaded bronze has been slightly work hardened by cold hammering, in each case the interior or mass of the metal is softer with hardness of about 117 HV. For two longitudinal sections taken through the rectangular central portion of the bracelet the average hardness is approximately 135–140 HV. This hardening is slight but irregular, and to impart springiness to the bracelet such moderate work hardening would appear to be on the low side for a leaded bronze with such low tin content.

Except for the application of the decoration this bracelet is a simple piece of work, and while well made, its fabrication would have presented no difficulty to a Late Bronze Age smith. Essentially it may be regarded as a wrought product. The structural evidence shows that the decoration was applied by means of chasing and punching. This is shown by the compression and displacement of inclusions, some of non-metallic origin, around the areas where the decoration has been applied.

*Conclusions*

In the case of the five fibulae certain variations in fabrication technique may be observed. For example, in the case of numbers 0A 66, 0A 67 and 0A 78, the bow will have been cast by conventional methods, or by the cire perdu process; while numbers 0A 77 and 0A 80 are essentially wrought



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products in which the metal has been homogenised. As we should expect from consideration of the objects, all the fibulae have been heated and worked all over after they were cast, but unexpectedly, it appears that it was a general practice to work harden the fibulae to a greater or less extent as a final operation. Why this should have been done is not clear. It will also be noticed that a low-tin bronze was generally selected, that is, a forging alloy rather than a casting one.

In each case it was found that the so-called spring has been work hardened by means of cold hammering. This would have been good practice had the spring really acted as such. However, any spring action would have occurred in the long and slender pins so that the springs could just as well have been left in the annealed state which would have facilitated the coiling operation. As an exception to this is a cast fibula from the Midas Mound tumulus, Gordion, now in the Ankara Museum.[2] Here, the pin is strong and relatively short and increases in diameter towards the spring so that there was probably appreciable working action in the coils of the spring.

The spectacle brooches, numbers 0A 99 and S 309, and indeed the coiled armlets numbers 0A 13 and 0A 112, are much more simple artefacts than the fibulae, and fabrication would have been a relatively easy matter. Points of interest are the production of the wire, and the quality of workmanship attained in coiling the wire. Owing to their large diameter and wide spacing of the coils, the armlets 0A 13 and 0A 112 would present even less difficulty in fabrication that the spectacle brooches.

Although the technique of jointing bronze wire was known, for the fabrication of spirals long pieces of wire can be made without joints. In the course of experimental work Hans Drescher[3] forged a spiral 67.5 cm in length from a copper bar of about 8 x 10 x 66 mm with, of course, intermediate anneals. To obtain the correct profile for the wire Drescher used a shaped groove in hard wood, stone, or metal. This operation increased the length of the wire to 80 cm. No doubt the same, or a similar process could be applied to a soft well annealed bronze, although it would not be so easy as in the case of a copper spiral. Much would depend upon the transverse profile required for the wire.

### *Appendix*

Owing to the number of extremely thin sections which are present in the objects, hardness determinations were made with a Vickers microhardness tester. On average, it was found that the results obtained from the microhardness tests were higher than those from a Vickers HV 1 or HV 5 machine.

fig 41

According to Vickers Instruments Ltd the reasons why the results with 100 gram load are higher on the microhardness tester is most probably due to the work hardened surface of the material when compared with the HV 1 and HV 5 tester. The HV 1 and HV 5 machine gives a much larger impression and will penetrate through the hard outer skin of the specimen, whereas the microhardness tester is only indenting the surface layer and measuring this hardness. The surface layer being of a harder substance due to the work involved in obtaining a suitably fine surface area.

No exact correlation was found with the Vickers HV 1 and HV 5 figures. However, it is probable that microhardness results using 100 gram loading are, on average, approximately some fifteen per cent higher.

## LIST OF ILLUSTRATIONS

*Bow Fibula 0A 66*

| | |
|---|---|
| Fig 1 | A general view of the fibula. |
| Fig 2 | Underneath of the bow, spring, pin, and clip. |
| Fig 3 | Enlarged view of the spring |
| Fig 4 | The imperfect joint at the position where the pin has been cast-on to the metal of the spring. Unetched. X 20. |

*Bow Fibula 0A 67*

| | |
|---|---|
| Fig 5 | The fibula with the three rings in position on the bow. |
| Fig 6 | Detail of the decoration upon the bow. Enlarged. |
| Fig 7 | Detail of end of bow, and clip for the pin. Enlarged. |
| Fig 8 | Enlarged view of the spring. Very severe corrosion of the pin in one place is seen adjacent to the spring. |
| Fig 9 | An area of very severe corrosion in the pin. Only a very thin strip of metal remains. Unetched. X 20. |

*Bow Fibula 0A 77*

| | |
|---|---|
| Fig 10 | Side view of the fibula. The pin is missing. |
| Fig 11 | Enlarged view of decoration on the bow. |
| Fig 12 | Enlarged detail of the spring. The pin has broken off short. |
| Fig 13 | Recrystallisation at the surface of one of the coils of the spring. Etched. X 100. |

*Bow Fibula 0A 78*

| | |
|---|---|
| Fig 14 | The fibula, with annular grooved decoration upon the bow. |
| Fig 15 | Enlarged detail of the spring. |
| Fig 16 | Enlarged detail of end of bow and clip. |
| Fig 17 | One of the annular grooves in the bow. Showing corrosion attack. Unetched. X 20. |

*Fibula (or inverted brooch) 0A 80*

| | |
|---|---|
| Fig 18 | A general side view of the fibula |
| Fig 19 | Detail of the spring and circular disc. Enlarged. |
| Fig 20 | Enlarged detail of the clip, and end of the pin. |
| Fig 21 | One of the areas of severe intergranular corrosion in the clip. Unetched. X 100. |
| Fig 22 | Recrystallisation at the circumference of the spring. Here, there has been surface intergranular corrosion. Etched. X 100. |
| Fig 23 | Typical recrystallisation of low grain size near to the point of the pin. Etched. X 100. |

*Coiled Armlet 0A 13*

| | |
|---|---|
| Fig 24 | A general view showing open winding of the coils, and tapering in the length of the armlet. |
| Fig 25 | Showing corrosion attack at the exterior of a coil. Enlarged. |

*Coiled Armlet 0A 112*

| | |
|---|---|
| Fig 26 | A general view of the armlet |
| Fig 27 | Shallow annular grooves upon a terminal |
| Fig 28 | A field showing severe intergranular corrosion at the circumference of the wire. Etched. X 100. |
| Fig 29 | Typical recrystallisation in the wire of the coils Etched. X 100. |

*Spectacle Brooch. 0A 99*

| | |
|---|---|
| Fig 30 | Side view of the brooch showing the clip. |
| Fig 31 | Reverse side, showing the central boss. |
| Fig 32 | Enlarged view of the central boss and bent over end of the clip. |

*Spectacle Brooch S 309*

| | |
|---|---|
| Fig 33 | One spectacle of the brooch. |
| Fig 34 | The other spectacle with central boss |
| Fig 35 | Enlarged view of the closely wound inner coils and the central boss. |
| Fig 36 | An area of severe local corrosion in the central boss adjacent to the wires. Unetched. X 50. |

*Bracelet 0A 69*

| | |
|---|---|
| Fig 37 | The bracelet. As received. |
| Fig 38 | Decorated snake's head terminal. |
| Fig 39 | Twisted cord decoration on the bracelet |
| Fig 40 | A section taken through the eye of the snake's head terminal. Inclusions have been deformed and compressed by punching of the eye. Unetched. X 30. |
| Fig 41 | Equi-axed twinned crystals of low grain size and inclusions of lead. Typical of the structure in the terminals. Etched. X 100. |

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1 Jacquetta Hawkes. Dawn of the Gods. London, 1968. plate on p.279.

2 Arthur Steinberg. Technology and Culture; Technological styles in the bronzes of Shang China, Phrygia and Urnfield Central Europe. Proc. Amer Ethnog Soc. 1975.

3 Werner Lorenzen. Helgoland und das Fruheste Kupfer des Nordens. Niederelbe Verlag. 1965, p 57.

**Acknowledgement**

It is with great pleasure that I acknowledge my indebtedness to Dr George Parker who gave invaluable help with the preparation of this paper. The mounting of the specimens and the photography are due to his kindness.

# Reconstruction of techniques used to produce prehistoric nickel rich iron artifacts

*Erik Tholander and Stig Blomgren*

## 1. Introduction

In the previous report on a prehistoric iron axe[1] it is shown that a stripy structure appears in the axe blade. The structure consists of several martensitic, nickel rich streaks in a soft iron matrix. In the report it is also described how this structure could be formed. Two different materials, a hardenable one rich in carbon and nickel, and a low carbon one are forge-welded together and then folded and forge welded six times in repeated cycles. In order to verify the described method, a reconstruction experiment was made at the Rinman Laboratory in Eskilstuna.

## 2. Performance and result of the experiment

The materials available were a specially manufactured steel[2] and a low carbon steel having the chemical compositions according to Table 1.

**Table 1 Chemical composition of the materials used (percent)**

| | C | Si | Mn | P | S | Cr | Ni | Mo | Cu |
|---|---|---|---|---|---|---|---|---|---|
| Nickel steel | 1.00 | 0.0 | 0.01 | 0.030 | 0.013 | 0.01 | 5.7 | – | 0.01 |
| Low carbon steel | 0.09 | 0.21 | 0.29 | 0.003 | 0.014 | 0.03 | 0.05 | 0.01 | 0.06 |

The materials were in the shape of bars having the transverse sections 3.5 x 23 mm, and 10 x 50 mm for the nickel steel and low carbon steel respectively

From the soft material a piece of almost 400 mm length was cut. At one of its ends a tong hold was forged so that the rest of the bar was about 300 mm. In the middle of one flat side a notch of a few mm depth was made perpendicular to the longitudinal direction. The middle of the bar was heated by a gas burner and then double-folded to receive a 130 mm piece of the nickel steel between the two shanks. In this way a blank of 150 mm length was made, see Fig 1, having a 3.5 mm thick core of the nickel rich steel surrounded on both sides by 10 mm of the soft material. In order to prevent scaling on the inside surfaces during the heating, the space between the shanks was sealed by arc welding so that the air could not enter.

The blank was heated to 1230°C in an electric resistance furnace and forged under a pneumatic hammer to a thickness of 7 mm and a length of 340 mm. (Fig 2). A cross section of a sample cut from the forged bar, ground, polished and etched in 2% Nital, showed the nickel rich material as a central streak of about 0.9 mm thickness, see Fig 3a. The micrograph in Fig 3b shows the welded seam between the nickel rich and the soft material. Slag occurs in the seam. The structure of the streak near the seam consists of pearlite and grain-boundary ferrite, which means that the carbon content in this area has been somewhat reduced from the original one (1.0%C), because carbon has diffused into the soft material.

A notch was made in the middle of the bar which was heated locally and folded to half of its length. The furrow around the bar was filled by arc welding followed by heating and forging to 5.5 mm thickness. The cross section of a sample cut out from the bar shows two streaks of the nickel rich

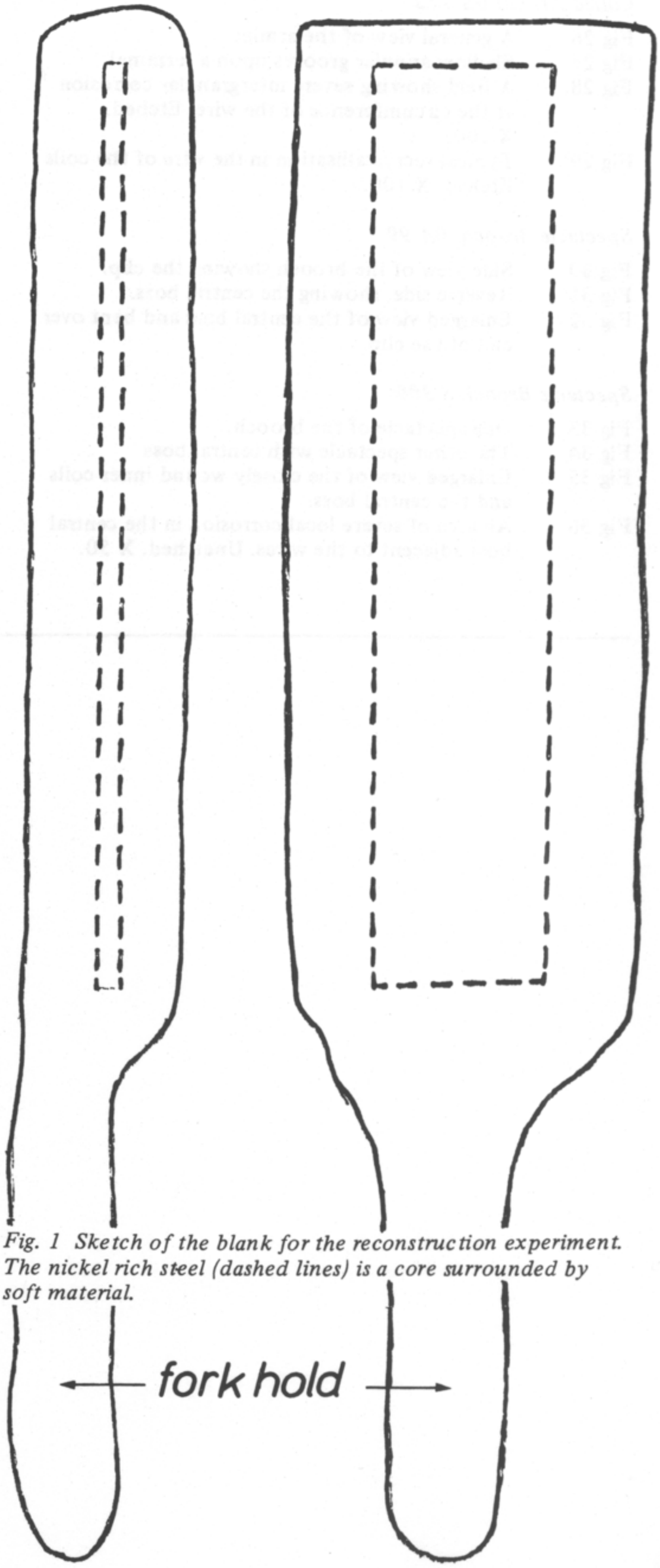


*Fig. 1 Sketch of the blank for the reconstruction experiment. The nickel rich steel (dashed lines) is a core surrounded by soft material.*

material, each of them being about 0.45 mm thick (see Fig 4).

After repeating the same cycle again, ie. notching, folding, arc welding, heating and forging the bar contained four layers of the nickel rich steel. The sketch in Fig 5 shows how a sample was cut out from the bar in order to examine a longditudinal section. This section appears in Fig 6. The 'hair pin' appearance emanates of course from the folding. The notch made before the folding has obviously cut off one of the streaks, thus preventing the formation of an outer 'hair pin' curve. In the figure, therefore, the two outermost streaks suddenly end near the surface. The average thickness of the streaks is now 0.22 mm.

*Fig. 2 The forging operations were made under a pneumatic hammer.*

After the third cycle, eight streaks appear in the longitudinal section which is shown in Fig 7. The average thickness of the streaks is 0.14 mm.

An interesting detail is seen in this figure. In the 'hair pin' an ''offshoot' is directed opposite to the 'hair pin' This formation can be explained as a result of a poor joint between the nickel rich and the soft material leading during folding to separation and buckling of the nickel rich material like the buckling of a strut built-in at both ends. After the above three folding and forge welding operations the bar had the dimensions 6.5 x 95 x 145 mm.

The tong-hold was now moved to a new position at right angles to the earlier one. This meant that as the forging continued the bar was stretched perpendicular to the earlier stretch direction.

The work continued with three more folding and forge welding operations. The first two of these were made about a central axis in the new longditudinal direction, and the last folded about a central axis perpendicular to that direction. (Compare Fig 63 in the axe report[1]). The final dimensions of the bar were 5 x 75 x 110 mm and its appearance is shown in Fig 8.

After cooling in still air several specimens were out out. The microhardness of the streaks was found to be HV 215-240.

Two samples were heated at 825°C and quenched in water. In Fig 10a from a cross section of one of these samples (see Fig 9) two groups of 'hair pins' occur, which both come from the 5th folding (compare the principal sketch Fig 51:4 in the axe report[1]). The microstructure of two 'hair pins' is shown in Fig 10b.

The structure of the section is stripy throughout, from many nickel-containing martensitic streaks embedded in a low carbon matrix, see Fig 11 (compare Fig 7 in the axe report[1]). Fig 12 shows the appearance of a streak at high magnification (to be compared with Fig 10 in the axe report[1]). Often thin ribbons of pearlite occur in the boundaries between streak and matrix, see Fig 13. The number of streaks varies between 44 and 48, over the whole section, their average thickness being about 16 mm and their microhardness HV 425-450. Elongated slag inclusions occur (see Figs 14 and 15) containing wüstite as the dominant phase.

## 3. Comparison of the experimental bar and the ancient axe blade

### The materials

According to Table1, the nickel rich steel has an original carbon content of 1.0%, while the corresponding value for the axe blade was estimated to about 0.4%. The nickel content of the streak material in the bar, 5.7%, is evenly

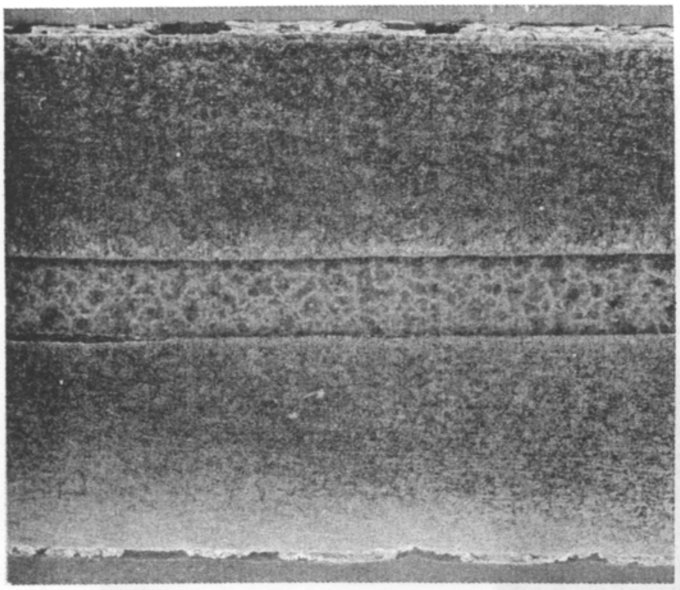


*Fig. 3a Macrostructure. Cross section of the blank after thickness reduction from 23 to 7 mm. The nickel rich steel appears as a streak in the middle. 10x.*

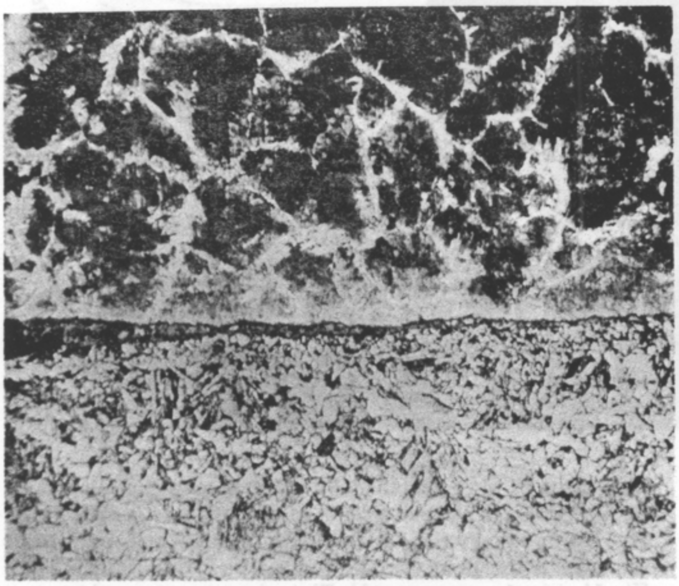


*Fig. 3b Microstructure of part of Fig. 3a. The phases in the nickel rich steel (at the top) are pearlite and grain boundary ferrite, and in the soft material (at the bottom) ferrite and pearlite. To the left an elongated slag inclusion is seen in the seam. 80x.*

distributed while the nickel content in the streaks of the axe blade varies between 1.3 and 6.9%. This circumstance explains why the structure of the streaks in the bar is rather uniform, while the streaks in the axe blade have a more variable appearance.

In the soft material of the bar some elements are present, eg. silicon and manganese, which in primitively produced iron usually occur in very low concentrations only.

The thickness of the nickel steel at the beginning of the experimental blade was about 3.5 mm, while the corresponding thickness of the nickel rich material in the axe blade was assumed to have been 2 mm. Another difference is the width of the original components, which for the axe blade were assumed to have been the same, while in the reconstruction experiment the soft iron was about double the width of the nickel steel bar.

In spite of this there is no essential difference between the manufacturing procedure assumed for the ancient axe blade and that for the experimental bar.

### The heating

When the original axe was produced heating took place in a blacksmith's hearth giving temperatures about 1250°C. In the Rinman Laboratory the available hearth, however, was considered to be too small for such an experiment; it would have been difficult to keep temperature constant. For this reason an electric furnace was used.

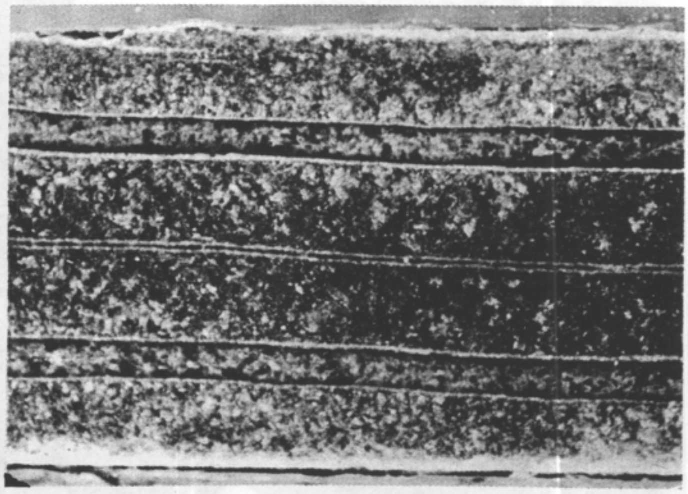


*Fig. 4 Macrostructure. Cross section of the bar after cycle No 1 (ie. one folding and forge welding operation). Two streaks of nickel rich steel appear. The seam from the last forge welding separates the soft material in the middle into two halves. 10x.*

Owing to the relatively high carbon content (1.0%) of the nickel rich steel it was decided to keep a moderate heating temperature (1230°C) to be sure to avoid the formation of liquid phases in the streaks. Because the corresponding nickel rich streaks of the axe blade had a lower carbon content (0.4%C) it was assumed that they had been submitted to a higher temperature, which was a favourable factor when welding together the two materials.

As mentioned in the axe report[1] it is impossible to forge weld two iron bars if their surfaces are oxidised.

In the practice known in antiquity this drawback was eliminated by adding sand ($SiO_2$) which, with the solid scale, forms an eutectic molten phase of iron silicate at about 1180°C. This liquid was mainly forced out of the joint during the forging, but some of it remains as slag in the welding seams. This method must have been used when fabricating the axe blade.

In the experimental work, however, sand protection was not used for several reasons, such as lack of equipment for reaching the desired temperature (above 1250°C) and shortness of time. Instead the air was kept out by arc weld welding and in this way scaling was prevented.

In the bar, however, elongated slag inclusions occur in the welding joints formed after each forge welding operation. Most of them are lying in the matrix marking the joint between two soft iron layers (Fig 14), but some are located in the boundaries between matrix and streaks (Fig 15). The inclusions are dominated by wüstite, but also contain some silicate glass (compare Figs 18, 19 and 20 in the axe report). This slag emanates from scale residua containing $FeO$ and $SiO_2$ which will be described below.

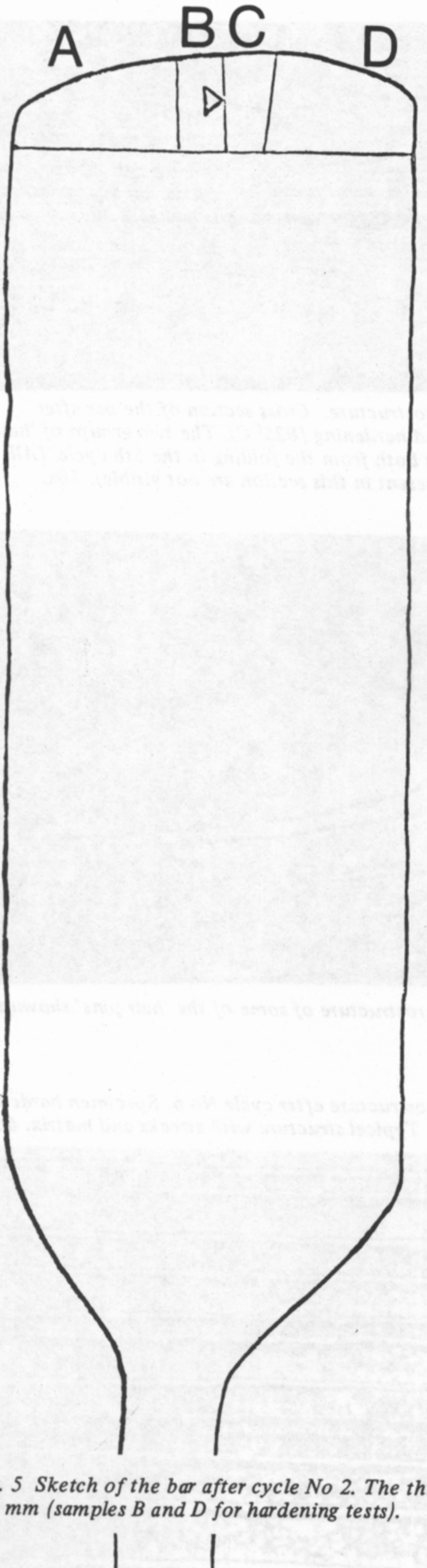


*Fig. 5 Sketch of the bar after cycle No 2. The thickness is 5.5 mm (samples B and D for hardening tests).*

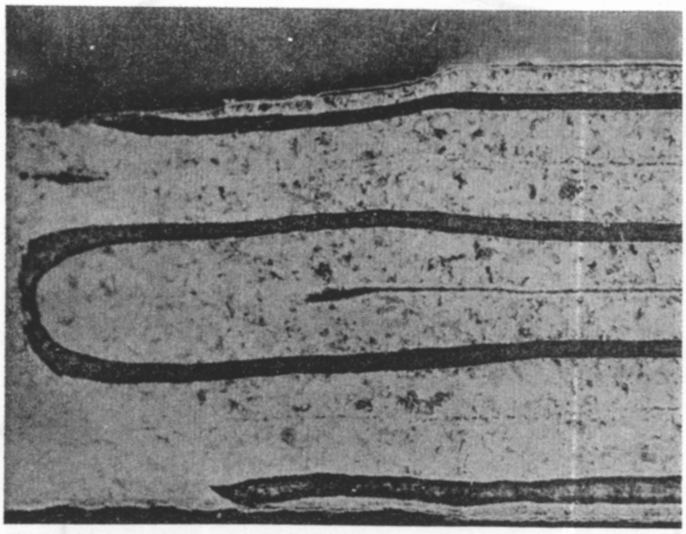
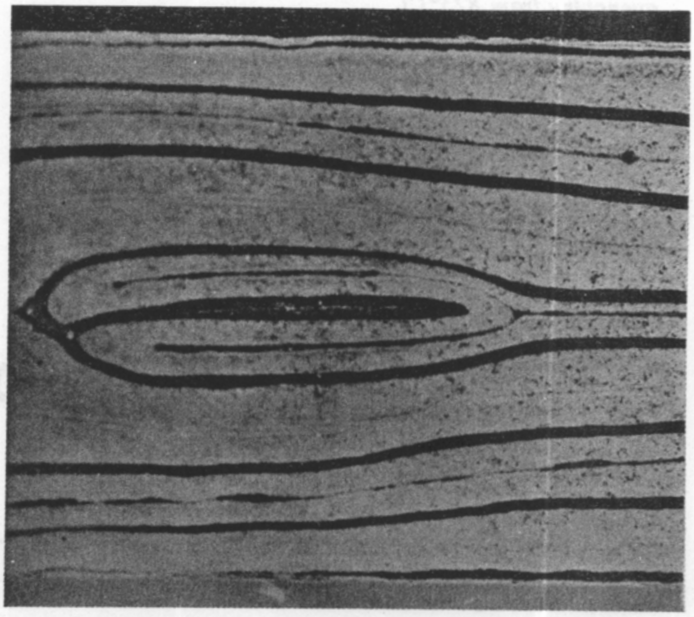


*Fig. 6 Macrostructure. Longitudinal section of the bar after cycle No 2. Four streaks of nickel rich steel appear. The 'hair pin' appearance is formed by the folding. The two outermost streaks suddenly end to the left, because the notching made before the folding has cut off one of the streaks. 10x.*

In a study of scale formation, the authors[3] have found that on a steel containing silicon (according to Table 1 the soft material has 0.21% Si), the scale at a temperature above about 1100°C consists of a heavy outer part with solid iron oxides and a thin inner part being liquid iron silicate. The outer scale can be removed mechanically without difficulty but the inner scale sticks to the surface and cannot, in general, be removed easily.

After each heating operation the oxide scale was roughly removed by drawing the bar between two steel wire brushes. But a silicate film must have been left on the surface, and later on that film remained in the fold so that it came to be included in the central seam as well as traces of solid oxide. At the next heating the silicate fused and thus formed the slag lenses included in the welding joints

*Fig. 7 Macrostructure. Longitudinal section of the bar after cycle No 3. Eight streaks of the nickel rich steel appear. In the 'hair pin' an 'outshoot' directed to the right is seen, which is caused by a buckling phenomenon. 10x.*



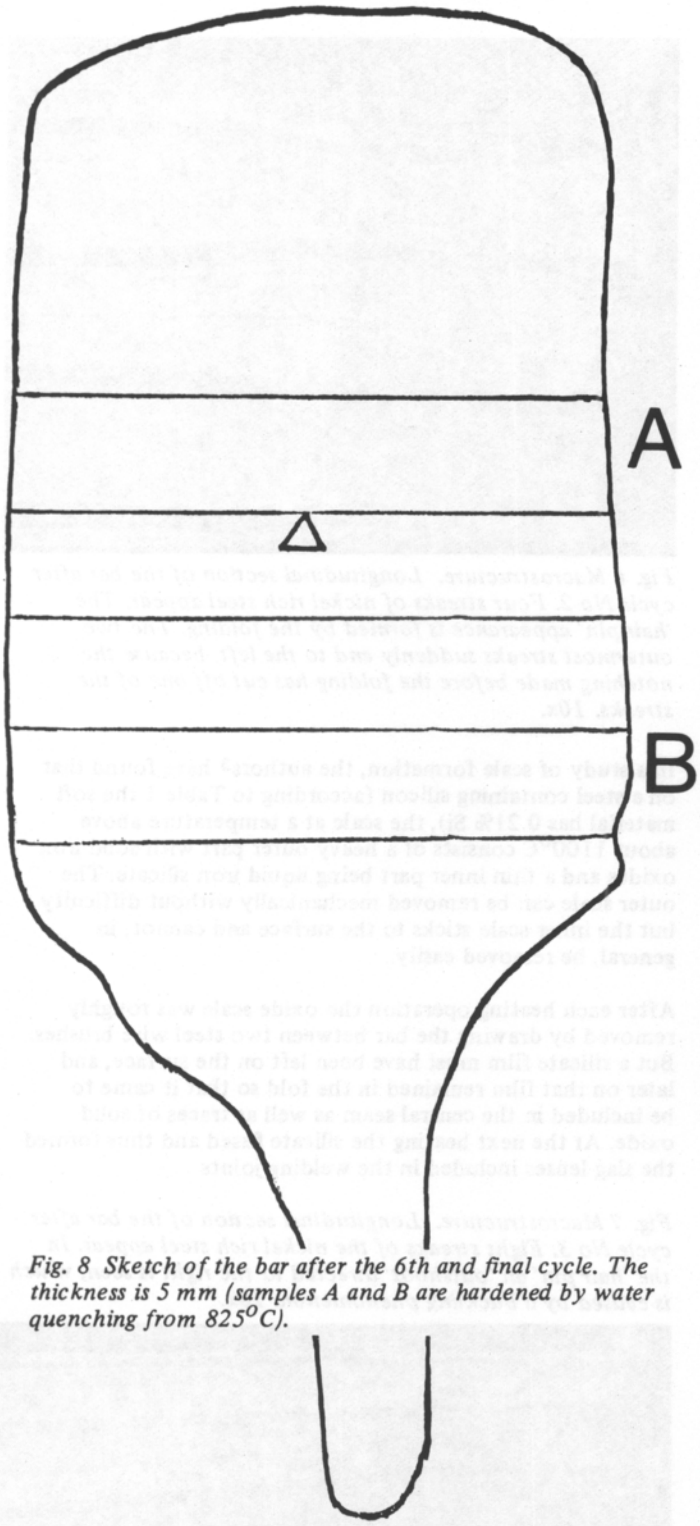


*Fig. 8 Sketch of the bar after the 6th and final cycle. The thickness is 5 mm (samples A and B are hardened by water quenching from 825°C).*

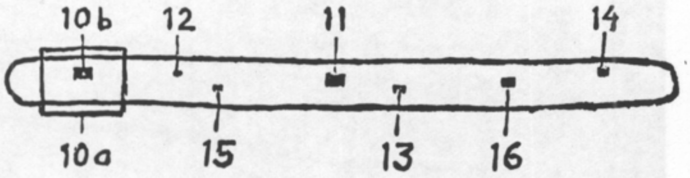


*Fig. 9 Sketch of the cross section of the bar after cycle No 6. Position of macrograph and the micrographs with corresponding figure numbers.*

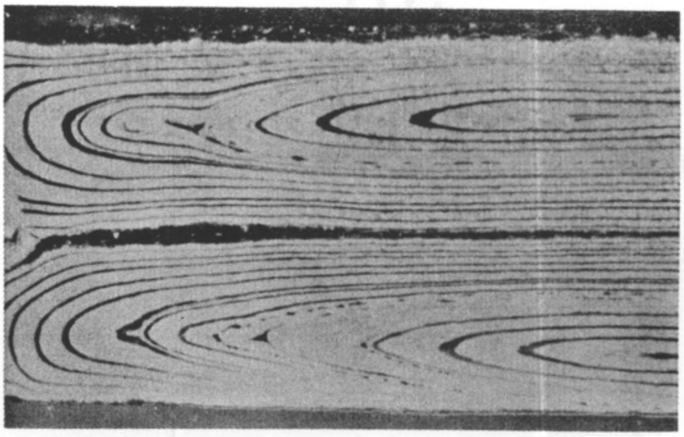


*Fig. 10a Macrostructure. Cross section of the bar after cycle No 6 and hardening (825°C). The two groups of 'hair pins' emanate both from the folding in the 5th cycle. (All the streaks present in this section are not visible). 10x.*

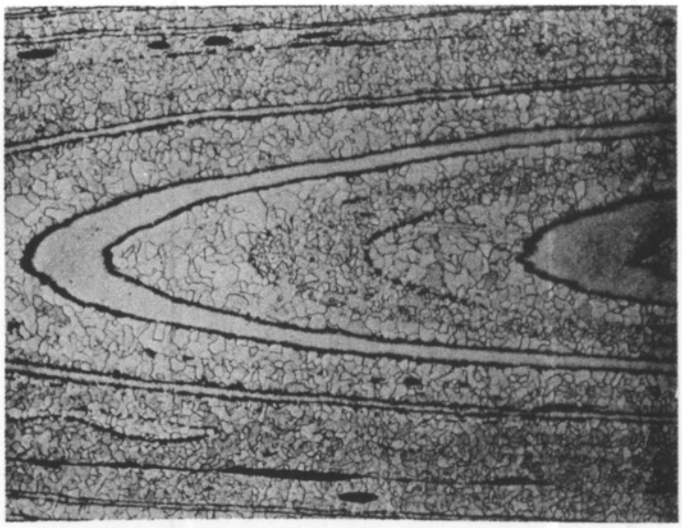
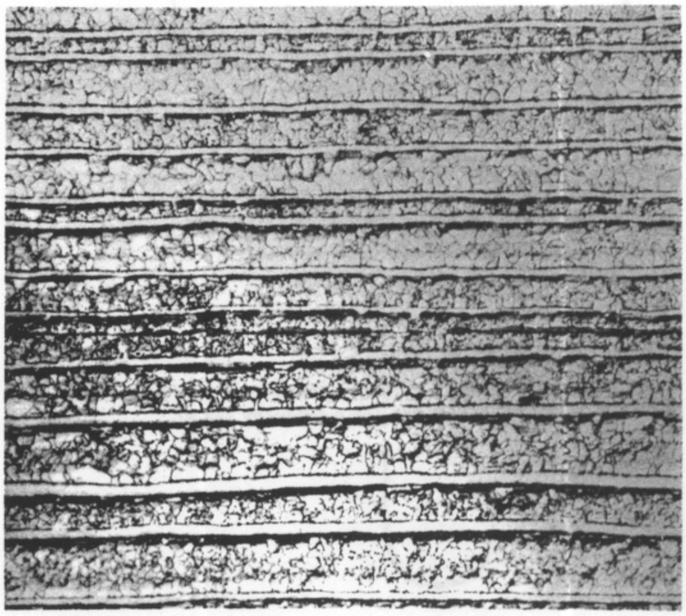


*Fig. 10b Microstructure of some of the 'hair pins' shown in Fig 10a. 60x.*

*Fig. 11 Microstructure after cycle No 6. Specimen hardened from 825°C. Typical structure with streaks and matrix. 60x.*



So the silicon content of the welding joint inclusions has a different origin in the bar and in the axe blade. In the first case it comes from the low carbon steel and in the last one it emanates from the added sand.

During the heating the surfaces of the bar were exposed to oxidation. In spite of placing some pieces of charcoal inside the furnace door the scaling was much greater than in a hearth. Thus, soft iron at the outer surface was lost as scale, and the outer layers became still thinner as can be seen in Fig Figs 6 and 7. This has caused the distance between the two nickel rich streaks on both sides of the middle seam to decrease successively (see Fig 7) until the soft iron disappears causing two nickel rich layers to be laid against each other, (see Fig 16).

During continued heating, the nickel steel at the surface was also lost as scale. This influenced the number of nickel rich layers in the bar during the process, which is shown by the following calculation.

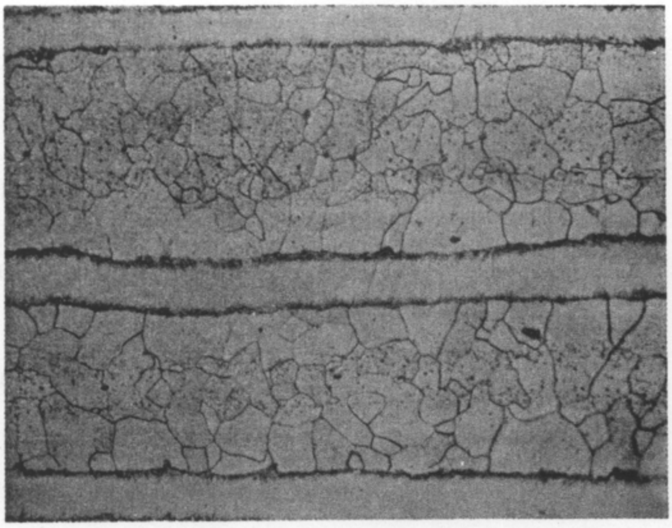


*Fig. 13 Microstructure after cycle No 6. Specimen hardened from 825°C. Martensitic streaks with thin pearlitic borders to the ferritic matrix. 220x.*

Assuming that no oxidation of the nickel rich material takes place, the number of layers of this material during the 6 folding and forge welding operations follows the series (see page 87 in the axe report[1]):–

2 , 4 , 8 , 16 , 32 , 64

Assuming that the scaling during the heating from the 3rd folding on includes the outermost nickel rich layer on both the flat sides of the bar the series will be:

2 , 4 , (8–2=) 6 , (12–2=) 10 , (20–2=) 18, (36–2=) 34

Assuming instead that the loss of nickel rich layers occurs only from the 4th folding on, the series will be:

2 , 4 , 8 , (16–2=) 14 , (28–2=) 26 , (52–2=) 50

In practice this 'loss of streaks' of course may have happened more irregularly. For instance the outermost nickel rich layer on only one of the two flat sides of the bar may have been lost during heating, or the disappearance of the nickel steel into scale may have happened locally only on certain spots.

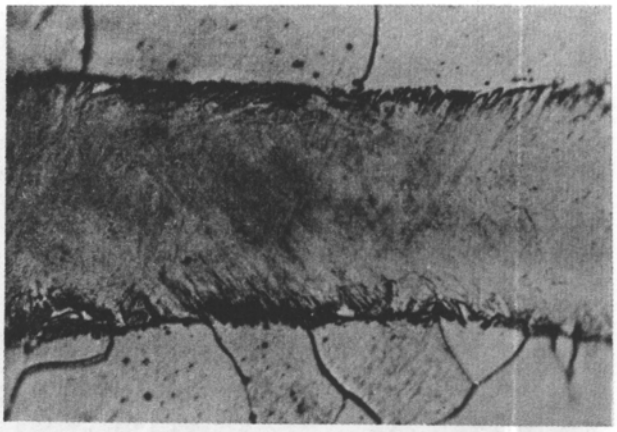


*Fig. 12 Microstructure after cycle no 6. Specimen hardened from 825°C. Streak of martensite surrounded by ferrite. Microhardness of the martensite, HV 425–450. 1000x.*

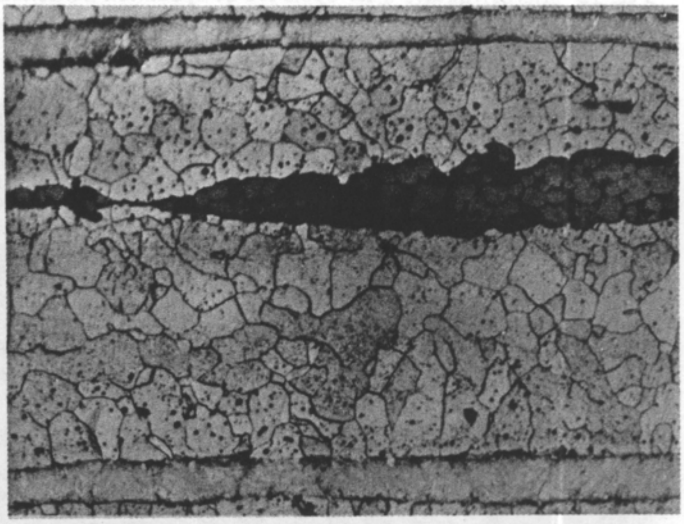


*Fig 14 Microstructure after cycle No 6. Specimen hardened from 825°C. Large elongated slag inclusion with wustite (light grey) and silica glass (dark grey) in the matrix between two streaks. The slag emanates from surface scale. 220x.*

Such scaling of the nickel rich layers explains why the real number of streaks in the bar, 44 to 48, is less than the theoretical value of $2^6 = 64$ streaks. The axe blade certainly has been heated in a charcoal hearth; this is why the scaling and therefore also the 'loss of streaks' has been less than that of the experimental bar.

## The forging

In the reconstruction experiment a pneumatic hammer was used for practical reasons. In principle it would have been possible to use manual forging for this experiment if only the necessary equipment and time had been available. The part of the forging work requiring the most energy would be the initial reduction of the thickness from 23 to 7 mm. This, however, could have been made by two blacksmiths, who were working alternately. Repeated heating would have been necessary, and this is normal in forging workpieces of small thickness.

The hammer machine used in the Eskilstuna experiment was equipped with round-faced tools ('fullers') in cycle 1 but in the cycles 2 to 6 it had plane 'set-tools'. The narrow-faced hammer called a 'fuller' gives a good elongation effect but

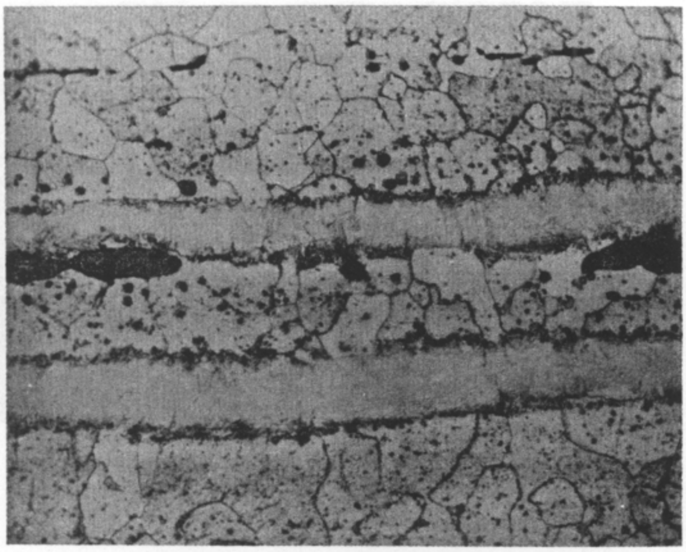


*Fig. 15 Microstructure after cycle No 6. Specimen hardened from 825°C. Slag inclusions in the border between streak and matrix. 400x.*

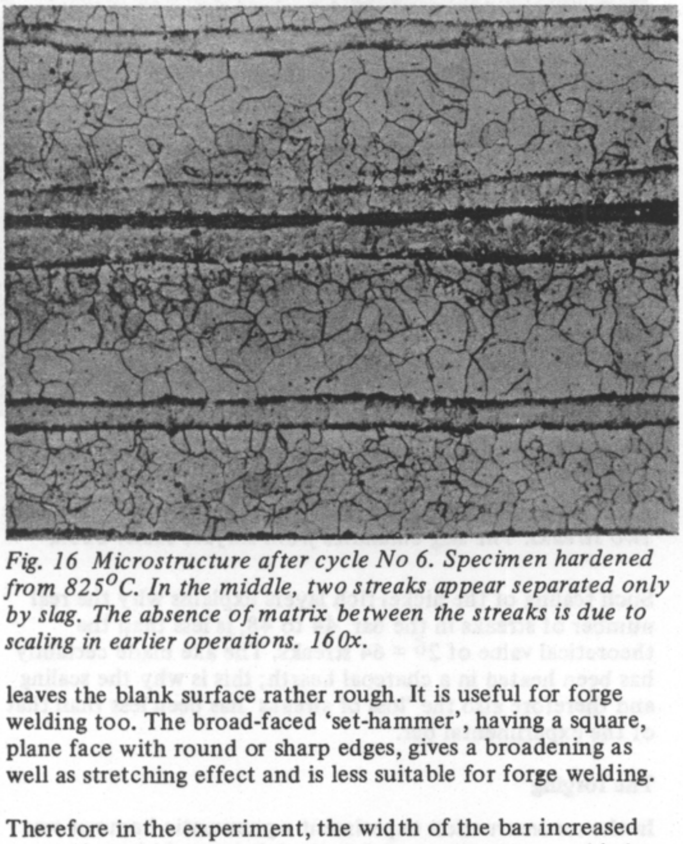


*Fig. 16 Microstructure after cycle No 6. Specimen hardened from 825°C. In the middle, two streaks appear separated only by slag. The absence of matrix between the streaks is due to scaling in earlier operations. 160x.*

leaves the blank surface rather rough. It is useful for forge welding too. The broad-faced 'set-hammer', having a square, plane face with round or sharp edges, gives a broadening as well as stretching effect and is less suitable for forge welding.

Therefore in the experiment, the width of the bar increased by 20 to 25% in each of the cycles. Regarding the axe blade, there are reasons to think that it was made by a manual forging method using 'fullers' giving a spread much less than the above figures.

**The hardening operation**

Hardening of the two bar specimens after six folding and forge welding cycles was made, as mentioned earlier, by water quenching from 825°C. This temperature was chosen after a series of hardening tests on six small pieces measuring 5 x 15 x 15 mm, also cut from the bar after the 6th cycle.

The temperatures used were 650, 700, 750, 800, 850 and 950°C; then quenching in water. The microhardness values of the streaks are shown in the diagram in Fig 17. A maximum hardness of about HV 700 occurs at about 700°C. In the Figs 18-20 are shown the microstructures representing the hardening temperatures 700, 800 and 850°C. All the streaks in Figs 18-20 contain martensite. In Fig 19, at 800°C there are borders of pearlite between streak and matrix. In Fig 20 at 850°C the boundary between streak and matrix is rather diffuse. On the basis of the diagram and the microstructures it was considered that a hardening temperature of 825°C would give the streaks in the bar a hardness and a structure most like those in the axe blade.

The hardness values of the streaks according to the diagram in Fig 17 led to the following two questions:–

Why is the hardness considerably less than what is usual for martensite containing 1% C, namely about HV 1000?

What causes the great reduction of the hardness when the austenitizing temperature increases from 700°C and upwards?

In order to get a broader basis for answering these questions two more hardening tests were made.

Firstly, two pieces, cut out from the bar after the second cycle, containing four streaks of 220 microns average thickness were subjected to hardening from 700 and 825°C.

Secondly, small pieces of 3.5 x 10 x 25 mm from the nickel steel alone were heated to the temperatures, 650, 700, 750, 800, 850 and 950°C and quenched in water. The streaks from the first test gave the hardness of HV 770 and HV 520 for the hardening temperatures of 700 and 825°C respectively.

For the nickel steel alone the highest average hardness value, HV 990, was obtained for the piece heated at 700°C. The temperature 650°C gave HV 540, while all the other temperatures gave HV 750 to 950. The values are considerably higher than those shown in the diagram in Fig 17.

The hardening tests show that for each temperature except for 650°C the hardness is greatest for the nickel steel alone, then follows the thick streaks (220 microns) from the 2nd cycle and at last the thin streaks (16 microns) from the 6th cycle. This is probably caused by the different carbon content of the martensite, which will be discussed below.

Carbon diffused from the streaks into the matrix during each heating operation when the whole bar was austenitic. Thus the carbon content of the streaks decreased gradually during the whole manufacturing procedure.

In general, the reduction of the average carbon content of a thin streak must be greater than that of a thick streak with the same original carbon content when heated at the same temperature during the same time. As the thickness of the streaks was reduced with the number of folding and forge welding operations, the reduction of their carbon content was promoted.

For the same reason the original carbon content of the nickel rich material used in the axe blade ought to have been higher than the estimated value of 0.4% of the streaks. How much higher is not possible to say.

It is not impossible that a few more than the six folding and forge welding operations would have made the carbon content of the nickel rich layers in the axe blade so low that the hardenability would have got lost.

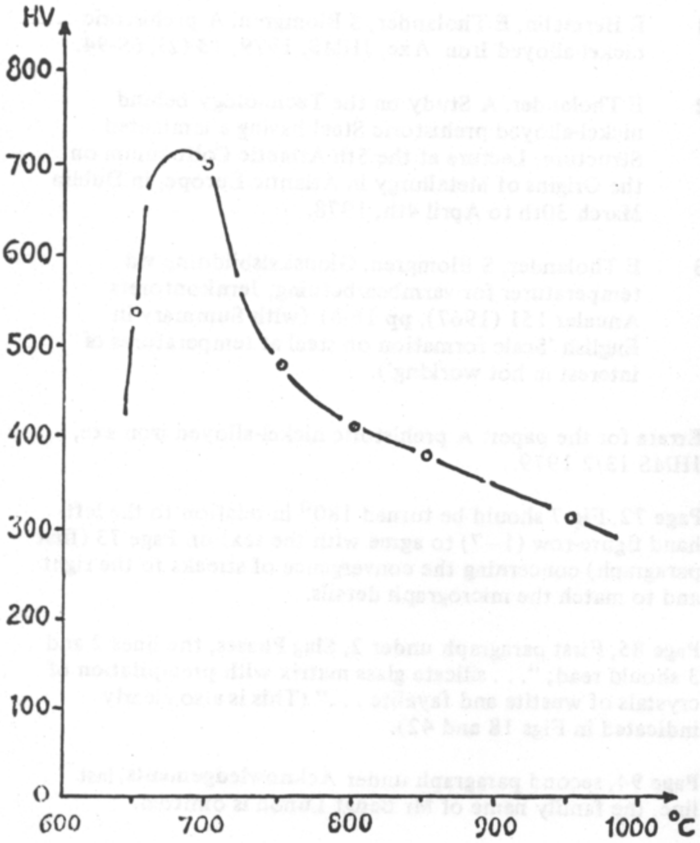


*Fig. 17 The hardness of streaks in hardened samples from the final cycle plotted against austenizing temperature. Each point for the curve is an average of about ten impressions.*

Obviously it seems to be necessary that the nickel rich material to be used has a sufficient carbon content. Too high carbon concentration, however, provides as mentioned earlier, the risk of fusion. Signs of such fusing were in fact observed in the axe socket, as mentioned in the axe report[1] (Fig 36).

As already reported, the hardness of the nickel steel alone has a maximum after austenitizing at about 700°C, but it is much less pronounced than the corresponding maximum for the streak material in the experimental bar after the 6th cycle (Fig 17). For the samples from the 2nd cycle the hardness of the streaks is greater after hardening from 700 than from 825°C. Therefore, it is obvious that the austenitizing temperature affects the hardness obtained on the nickel rich material especially when it occurs as streaks in the bar. In this case too, a possible explanation may be diffusion of carbon from the streaks into the matrix, but this time during austenitizing before hardening.

At 700°C the matrix contains no austenite, this is why diffusion of carbon hardly occurs at all from the streaks. At higher temperature the matrix contains austenite which promotes the diffusion of carbon from the streaks. Thanks to the small thickness of the streaks such a great reduction of the carbon content may happen so that the hardness of the resulting martensite may be influenced. This influence will of course increase the higher the austenitizing temperature.

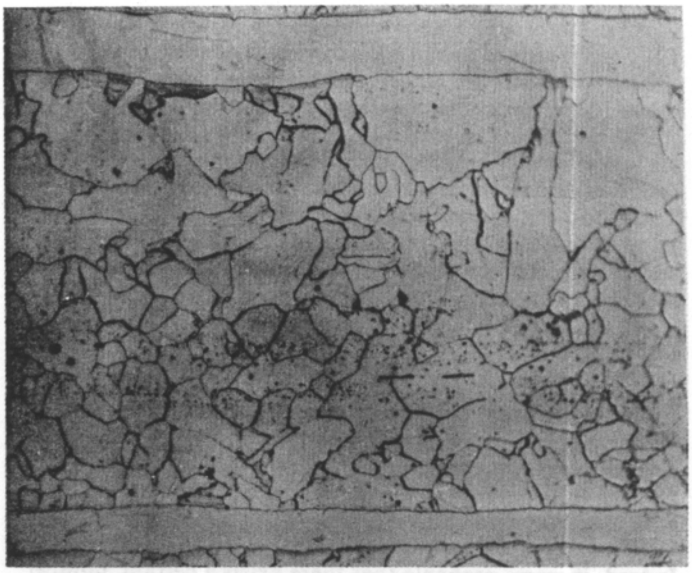


*Fig. 18 Microstructure after 6 cycles and water quenching from 700°C. Two streaks containing martensite determined to a hardness of HV 700. 400x.*

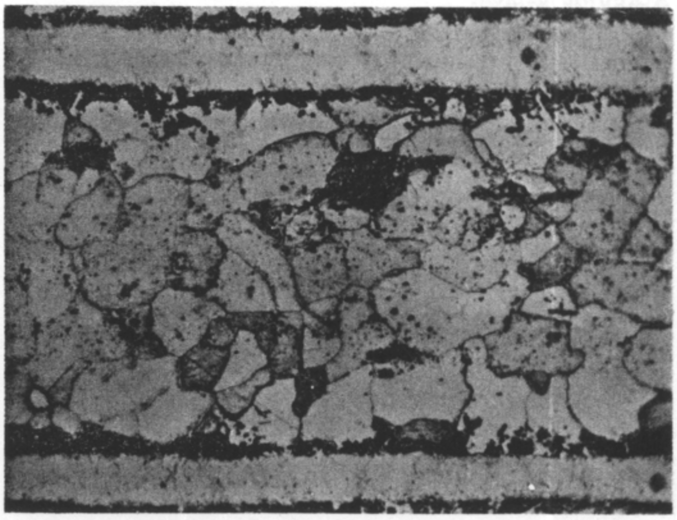


*Fig. 19 Microstructure after 6 cycles and water quenching from 800°C. Two streaks containing martensite with pearlite as borders to the matrix. The martensite hardness determined to HV 410. 400x.*

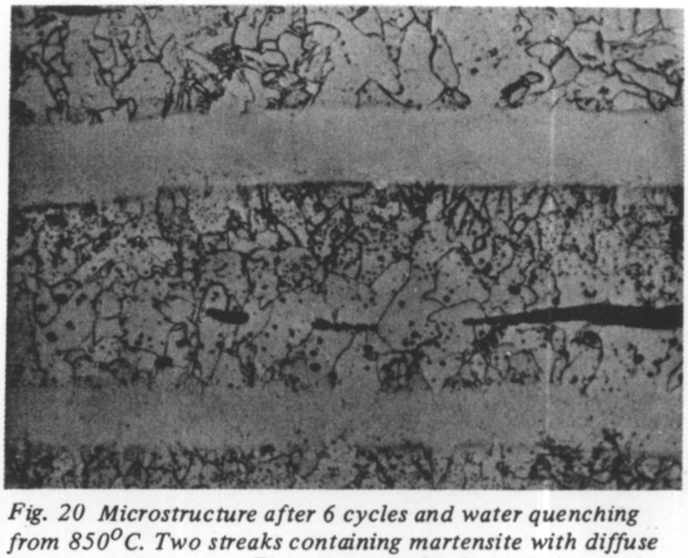


*Fig. 20 Microstructure after 6 cycles and water quenching from 850°C. Two streaks containing martensite with diffuse borders to the matrix. The martensite hardness determined to HV 380. 400x.*

Another factor which may influence the hardness would be if the martensite is mixed with some soft phases. In the microstructure of the nickel steel hardened from temperatures above 700°C some austenite also can be seen. This would probably explain the variations in hardness values as well as the lower level of hardness obtained at temperatures above 700°C in this test series. It is therefore possible that the streaks too can contain some austenite, but in too small amounts to be recognized under the microscope. The interpretation of microstructures in Fe-Ni-C-alloys is, however, quite complicated.

## 4. Conclusions

This reconstruction experiment shows that it is possible to apply in practice the manufacturing method described in the axe report, and that it gives a stripy structure of the same type as in the axe blade. In the opinion of the authors, this method is the only possible way to get this type of laminated structure containing nickel.

Indeed, it seems probable that there exists a certain number of manufacturing cycles – perhaps about six – giving the optimal properties of hardness and toughness of tools and weapons produced by this type of technology.

## 5. Acknowledgement

The authors are grateful to Mr Thure Sundqvist for his skilful performance of the practical work which made this experiment possible.

Eskilstuna, March 11th, 1978

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**Errata** for the paper: A prehistoric nickel-alloyed iron axe, JHMS 13/2 1979.

**Page 72,** Fig 7 should be turned 180° in relation to the left-hand figure-row (1–7) to agree with the text on Page 73 (first paragraph) concerning the convergence of streaks to the right and to match the micrograph details.

**Page 85,** First paragraph under 2, **Slag Phases,** the lines 2 and 3 should read; "... silicate glass matrix **with precipitation** of crystals of wustite and fayalite ..." (This is also clearly indicated in Figs 18 and 42).

**Page 94,** second paragraph under **Acknowledgements,** last line, the family name of Mr Bengt Lundh is omitted.

# The possibilities of producing iron nickel alloys in prehistoric times

*Stig Blomgren*

## Introduction

Prehistoric iron artefacts have in some cases proved to contain nickel in high concentrations which is hard to explain[1,2,3]. Always, there have been local areas with high Ni-concentrations (often in combination with some Co) in a surrounding matrix containing little or no nickel. Because these artefacts were obviously manufactured from material extracted in the solid state, the nickel concentration cannot be an effect of segregation. In sections, examined microscopically, the Ni-containing areas appear in such a way that it must be a question of two quite different materials, 'the matrix' and the Ni-containing one. These have had different origins and are in some way welded together and forged into the actual artefact.

## General conditions

Material containing iron and nickel is often considered to be meteoric iron, which certainly is a possibility which cannot be excluded. The question is, however, whether it is possible, using a primitive technique, to produce iron-nickel-alloys from the ore. Piaskowski[4] considers, for example, that the production of such alloys could have occurred during antiquity.

That an iron-nickel-alloy could be produced from the two elements is excluded, because the extraction of pure nickel was first made as late as in 1751.[5] It was the Swede, Cronstedt, who then obtained nickel from the mineral nickel-arsenide-pyrite.

Therefore a metallurgical reduction process must have been used which directly gave ferro nickel, and so we must consider the question of the possibility of producing an iron-nickel-alloy from available nickel ores.

## Suitability of nickel ores for the production of ferro nickel

Considering bog ore it seems that no such ores with considerable nickel content have been reported, at least from Sweden. The theoretical conditions for the precipitation of nickel in such ores are in fact unfavourable. Because of this, only rock ores containing nickel remain as possible raw materials.

Nickel deposits occur in three types of rock ore[6,7,8]:

1. Magmatic sulphide ores containing the nickel mineral pentlandite, $(Ni,Fe)S$.
2. Weathering products with the nickel mineral garnierite, a hydrous Ni-Mg-silicate, or the iron rich deposit laterite.
3. Hydrothermal veins with nickel as sulphides and arsenides.

In the first type of ore copper almost always occurs in considerable amounts as copper pyrite[5,6,7,8,9]. For extraction, the sulphide ores must be melted to a so called 'primary matte', which then is converted into 'concentration matte'. In this procedure the iron is fluxed into slag, because the iron has a considerably less affinity to sulphur than the nickel and the copper, which both come before iron in the so called Fournet's series.[8] So the iron is removed before the copper and therefore no ferro nickel can be formed.

If the sulphide ore was free from copper, the matte with the sulphides of nickel and iron could possibly be roasted into axides and then reduced by carbon to an iron-nickel-alloy.

Concerning the second type of ore, the extraction of ferro nickel from garnierite ore is possible. In modern times it has been done industrially by reduction in an electric furnace and by the so called 'Krupp-Renn-process'[10,11]. In the last method the reduction takes place in a very long rotary furnace at a temperature so low that the metallic product does not melt, e.g. in Magdeburg this process was used to reduce a garnierite ore from Frankenstein (Silesia). As an example it can be mentioned that an ore with the composition 2.1% Ni, 18.3% Fe, 33.1% $SiO_2$, 1.3% $Al_2O_3$, 0.2% CaO, 21.0% MgO and the rest moisture, gave an iron-nickel-alloy with 9.2% Ni. This was in the form of grains embedded in the furnace slag. This information indicates that it might be possible to produce ferrous nickel from garnierite ore using a primitive technique. As is well known, iron was extracted in the solid state (only the slag was molten) during prehistoric times.

No production from laterite ore is reported in the literature[6]. The third type of ore with sulphides and arsenides always contains copper and some intert metals[6,8]; and for the same reason as with the first type of ore the production of ferro nickel is impossible.

## Conclusions

Summarizing the possibilities of producing iron-nickel-alloys in prehistoric times, the garnierite ore would be the only possible raw material. In Sweden, however, there are no weathering products of garnierite to be found because of the geologically short time, about 10,000 years, which has passed since the last ice age.[7] Such weathering products formed earlier have been removed by the ice and new ones have not had time to form. The known Swedish nickel deposits, such as Kleva, all contain pentlandite together with copper pyrite.[6]

It does not seem probable that the iron-nickel material in the early Ni-containing iron artefacts found in Sweden could have been produced in this country.

An inventory of World garnierite deposits would therefore be of interest, as well as a reconstruction experiment using such ore in primitive furnaces.

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# Excavation Reports

## INTERIM REPORT ON THE EXCAVATION OF A TIN MILL ON BODMIN MOOR, CORNWALL IN 1979 (SX 177 713)

### Background

The upper St Neot valley will be flooded in the early 1980s by the South West Water Authority, to produce a large reservoir which will cover a number of archaeological sites, mostly preserved in open moorland. In 1979, two medieval sites came under consideration and were funded for rescue excavation by the Department of the Environment through the Cornwall Committee for Rescue Archaeology. The first of these sites was a tin mill, potentially belonging to an approximate date range of 1300 to 1700. The site will be excavated in two seasons under the general direction of David Austin of St David's Unversity College, Lampeter.

Work in 1979 under the direction of Tom Greeves and David Austin showed that the earthworks of the mill were cut into a slight terrace above the flat valley floor. The outline of the mill structure itself was clear, showing a single rectangular room and a narrow depression at the north end which could be identified as a wheel pit. At the southern end of the room and set vertically was a characteristic mortar stone, clearly out of position. Serving the wheel pit was one well-defined channel for a leat which was cut into the slope of the valley side and could be followed upstream for a distance of 600 m from the mill, by a spoil heap from a later, small shaft. Other earthworks associated with the milling process covered the valley floor between the mill and the river, notably a straight bank running eastwards from the wheel pit.

Approximately 25 m south of the mill was the lower end of an openwork, the remains of the opencast extraction of tin ore. Its full length of 325 m had been dug south-westwards into the side of the valley. Essentially a single trench, 25 m wide on average, it had several branch trenches and broadened at the western end where spoil tips from contemporary and later activities confused the interpretation. On the hill side above the western end was a breached concave earthwork, probably a dam 35 m across.

### The excavation

The main area of excavation uncovered the mill, wheel pit, an associated terrace to the west and several leats. In the mill the basal courses of the drystone granite walls survived to a maximum height of 0.72m. On the west side the wall was terraced into the natural slope and also retained later deposits which were banked against it. In the wheel pit the walls, including the north gable of the mill, were internally founded on the granite bedrock retaining the natural growans and peats on all sides.

The interior of the mill was filled with a large quantity of stone tumble in a matrix of heavy loams and clays formed during the destruction and decay of the building. These sealed two distinct areas within the mill, the southern where evidence of floors remained and the northern where removal of the mill machinery had clearly destroyed all contemporary surfaces. The southern portion, the smaller of the two, consisted of a possible hearth area against the gable with surrounding charcoal spreads and an entrance passage (2.40m x 1.20m wide) in the south east corner. To the north were a substantial pit and stone-covered drain. The pit (3.20m x 1.40m) and steep sides (0.83m deep), but was otherwise featureless, suggesting strongly that its original contents had been removed, probably the stamping machinery particularly the mortar stone found in the rubble to the south.

Leading southwards from this pit, along the central axis of the mill was a channel cut in the subsoil, approximately 0.80m wide and 0.50m deep. After 1.60m it turned eastwards, becoming stone-faced with a granite slab capping and continued up to the east wall of the mill. Beyond the east wall was a channel which appeared to be a continuation of the internal one, although the connection remains to be confirmed by excavation. It is thought that the purpose of this channel was to carry crushed ore material to settling pits, deposits in both contained large quantities of very fine sand. Another channel (approximately 0.60m wide x 0.66m deep) again filled with sand was discovered running parallel with the east wall of the mill, through the entrance. This will need further investigation in 1980. The sands and fine gravels in the channels were also found in large quantities in the pit and on the surrounding surfaces in the northern portion of the mill and were the residue of the tin dressing process.

The relatively well-preserved wheel pit lay next to the north gable of the mill. A 6.80m length of the pit and its tail race were excavated in the 1979 season down to bedrock. Next to the gable wall the width of the pit was 0.80m, but it splayed outwards after 5m to a width of 1.40m. The north gable of the mill was thicker having borne the weight of the wheel and the axle operating the stamps. A small drain through this wall allowed water to pass from the stamp pit to the wheel pit.

**Finds**

i) The pottery from the mill was surprisingly abundant, including one or two near-complete vessels. The interim dating places them between the early 14th and mid-16th century with the bulk belonging to the latter parts of that range. Most vessels were unglazed domestic wares although one internally green glazed bowl was represented. No post-medieval pottery was found.

ii) The principal stone artefact from the mill was the mortar stone which had 2 sets of three relatively shallow hollows on one face only. A probable bearing-stone for the axle of the waterwheel was found discarded a short distance north of the wheel pit, in a position suggesting that it had been deliberately pulled aside to remove the wheel. Some flint was also found on the mill site in superficial contexts.

iii) Metalwork on both sites was almost entirely absent due to the high acidity of the soil, and what did survive was usually in very bad condition. From the mill, however, came one small piece of bronze sheeting, scored with a grid and perforated with round holes which may be a fragment of the 'grate' through which ore passed after being crushed by the stamps. From the drain in the mill's north gable wall came a tin or pewter object like a spoon or small shallow bowl. In the farm building was a length of iron chain.

iv) A few fragments of wood were recovered from the basal, waterlogged deposits of the wheel pit. They were, however, largely unidentifiable in form and function.

**Conclusion**

The mill and openwork probably functioned throughout the later medieval period with some evidence to suggest that this use was periodic, if not seasonal. It is also already clear that the site produced only the dressed ore and was not involved in the smelting process since slag, mouldstones and furnaces were not found. Detailed analysis of the spoil from the dressing process is already beginning to yield valuable information about the techniques and efficiency of late medieval tinworking.

*Tom Greeves*

# Conferences and Reports

**The Earliest Iron in Europe** (24th–26th October 1979) was the title of the 3rd International Symposium organized by the Comité pour la siderurgie ancienne, this time under the magnificent sponsorship of the Emil Vogt Gedachtnis–Fonds in Zurich. The conference took place at the Klostergut Paradies where the well-known Eisenbibliotek of the +GF+ Foundation is housed. The symposium which was attended by 16 participants from 10 European countries dealt with the earliest occurrence of iron objects in the Bronze Age of Europe, ie. up to the 8th century BC. *W Kimmig* (Tubingen) read a paper on an iron blade from the Urnfield cemetery at Singen; *T H Erismann* (Dubendorf) made the participants acquainted with the complex examination of the same blade; *G Sperl* (Loeben) offered two contributions: one of them was concerned with two Hallstatt Period iron fibulae which were believed to be of cast iron, the second treated the typology of bloomery slags. *B G Scott* (Belfast) presented a survey of the earliest iron working on the territory of Ireland. *J Alexander* (Cambridge), before discussing the first appearance of iron in England, presented some models of spreading and acquiring iron among different civilizations. *G Varoufakis* (Athens) lectured on twenty recently acquired iron objects of the Mycanaean civilization (17th–12th centuries BC), the majority of which has been chemically analyzed (elevated nickel contents in the earlier artifacts). *V B Trbuhovic* (Beograd) went into the problems of the Late Bronze Age and Early Iron Age in the central and western Balkans, *Z Bukowski* (Warsaw) examined the earliest iron objects occurring in the area of the Lusatian cultures between the Odra and Vistula rivers. *H Hingst* (Schleswig) presented a survey of recent field work on bloomery sites in Schleswig-Holstein, *E Nylen* (Visby) analysed the situation of the transitory period from the Bronze to Iron Ages in Sweden. *J–P Mohen* (St Germain-en-Laye) desecrated his paper to progressive cultural groups in France having existed on the threshold of the Iron Age.

On Friday, October 26th, the symposium was transferred to the University of Zurich. There was held a special evening session where numerous scholars and representatives of scientific and economic spheresin Switzerland were present. The addresses by Prof Dr W U Guyan, President of the Symposium and by His Magnificence the rector of the University, Prof Dr G Wester, were followed by two closing lectures: *R F Tylecote* (London) paid his attention to the earliest iron in Europe and Africa, and *R Pleiner* (Praha) to the comingof iron to Europe.

Thanks to the contributions (to be edited in a special volume) and to the friendly discussion, favourable conditions for further research relating to the economy and technology of the Late Bronze Age in Europe have been secured. As Prof. Kimmig proposed, a corpus of the earliest European iron objects will be prepared by means of broad inquiries. The Comité pour la siderurgie ancienne de l UISPP wishes to express their deep gratitude to the Emil Vogt Gedachtnis–Fonds for having organised the symposium on the highest level.

*R Pleiner, Prague*

**Examination of a Late Bronze Age Iron Sword from Singen, Federal Germany.** Through the courtesy of Prof Kimmig, Tubingen, the Swiss Federal Laboratories for Materials Testing (EMPA), Bubendorf, Switzerland, carried out a complex examination of a Late Bronze Age flange-hilted iron sword blade (early 8th century BC). The investigation was initiated by Prof T H Erismann, president of EMPA. Two specimens were taken from the centre of the blade by electro-erosion, the third could be broken out from the edge. Metallographical, micro-chemical, electron-microprobe, plasma-spectrometric, and structural (Quantimet) analyses as well as microhardness tests enabled to look into the manufacturing technology and properties of that artifact, which is one of the most ancient European iron blades. Heterogeneous piled structure with welding seams is to be seen on polished blocks, where ferritic and pearlitic laminations with traces of Widmannstatten structure occur. Globular cementite indicates long forging below 700°C. Numerous slag inclusions were relatively rich in Si and Mn and extremely poor in P. Structures at the surface are harder than the core but they do not exceed 200 HV. The use of comparatively hard steel sheets welded upon the core to form edges is not out of the question but it would be necessary to take larger portions of metal from those parts in order to verify this possibility. The sword belongs to the equipment of a rich grave of the Late Urnfield period in southwest Germany.

*After T H Erismann, Dubendorf*

**A Surprising Find of Iron Currency Bars at Cracow, Poland.** On May 15th, 1979 there had been made a surprising discovery in the subteranean rooms of the house No 13, Kanonicza Street, Cracow. In a rectangular timbered pit there were deposited three piles of axe shaped iron bars. Their average weight was 0.75-1 kg, the heaviest specimens weighed 1.6–1.7 kgs. The total number covered 4212 bars representing the weight of about 3620–3630 kgs, ie. more than 3.5 tons of iron.

Within the piles some groups of bars seemed once to have been tightened with a rope in bundles. No other objects were added. The excavation of this extraordinary find took five months, since each layer of bars had to be carefully photogrammetically documented. The separation of specimens rusted together was in itself subject to the utmost care. The operation had been directed by E Zaitz, Archaeological Museum, Cracow.

The stratigraphical position of the hoard (under the destruction of a fortification wall of the former Okol suburb near the Wawel castle) indicates that the stock of iron must have been buried somewhere between 800–950 AD, possibly during the second half of the 9th and at the beginning of the 10th centuries. A complex metallographical investigation of what is probably the largest hoard uncovered in the 20th century, has been proposed by Mrs E Nosek and Dr K Bielenin, of the Archaeological Museum, under cooperation with the Mining and Metallurgy Academy at Cracow (Prof Dr W Rozanski). The existence of several sites in southern Poland, where recently axe-shaped bars came to light (Zawada, Nowa Huta, Stradow, Radymno, Piotrawin), throws an interesting light on relations with the contemporary cultures of the southern neighbours, since axe-shaped bars – evidently used as a certain kind of premonetary currency in the period of the Great Moravian realm, 9th century – were found in many hoards, hillfort layers, even in graves in Moravia and SW Slovakia.

*E Zaitz (Cracow) – R Pleiner (Prague)*

# Letters to the Editor

### On the age of the nickel-alloyed axe from Kjula, Eskilstuna

*Reply to Professor J Piaskowski*

Dear Sir

In our report in JHMS 13:2, 1979, on the socketed axe having a hardened, laminated structure of thin nickel-rich steel-streaks embedded in a soft iron matrix we gave the dating already made by Swedish archaeologists after the axe had been discovered 50 years ago, the period 0–400 AD. Now, Professor Piaskowski has asked for our opinion on that dating with regard to the situation in Poland where he points at two regions showing finds of similar axes, one South-Western district belonging to the Lusatian Culture in the Hallstatt period (800–500 BC) and one North-Eastern district inhabited half a millenium later by Baltic tribes (0–100 AD) *

Basically, the dating problem can be said to be an archaeological one and not a technical. For the history of technology, however, also the chronology must be considered in our efforts to obtain a good understanding of context details leading to a correct survey of the technical development. Therefore, a few remarks should be of interest here.

Firstly, according to Piaskowski, it is apparent that in Poland the laminated nickel-steel has been in use during at least about 900 years, the last of those centuries being contemporary with the first one mentioned for the Kjula axe.

Secondly, it is well known that trade connections have been established between Sweden and the continent of Europe during prehistoric time since the Bronze Age, which supports the assumption that the axe was imported by boat from the continent of Europe.

Therefore, a somewhat later use in Scandinavia than in Poland of products connected with a certain sort of technology, would not necessarily be something anachronistic. Craftsmen did move, and thus clever individuals may have brought handicraft traditions to other places where they could survive for long periods of time.

In order to check actual personal opinion on the age of socketed axes similar in shape to the Kjula axe and found in Sweden, we have discussed the case with two archaeologist friends of ours. **Dr Andreas Oldeberg**, who has specialized in ancient metal-working techniques, says:

"We like to consider those axes as pre-christian, but I can well believe them to have lasted long into later times."

**Dr David Damell**, The Central Board of National Antiquities, says:

"Concerning the dating, there is not much to add to Hermelin's figures. No new finds or find-combinations have given rise to any change in this connection. But, self-evidently, an axe of this type might be older, at least from the centuries just before the birth of Christ, especially in a Swedish find-environment. However, we don't have any evidence for that, yet."

Finally, it may be of interest here, that another artefact consisting of nickel-alloyed, laminated steel with a microstructure very similar to that of the Kjula axe was found recently at Tandla, Eskilstuna, on an excavation by Mr O Lorin, Eskilstuna. It is a small double-pointed rod of maximum cross-section 0.9 x 0.25 cm and maximum length 10.4 cm, hardened to about 400 Vickers. One cross-section at low magnification is shown in Figure 1 and a micrograph from the same section at higher magnification is seen in Figure 2. There are martensitic streaks in a ferritic matrix which also contains some pearlite. The thickness of the streaks varies between 5 and 30 microns, the average being about 10 microns, or half the corresponding size in the structure of the axe.

The Tandla rod has been determined as an engraving tool because of the conformity with modern engraving tools in the dimensions and the point angle. Five radio-carbon tests for the excavation site gave the mean dating of 355 AD. This figure is in good accordance with the original dating of the

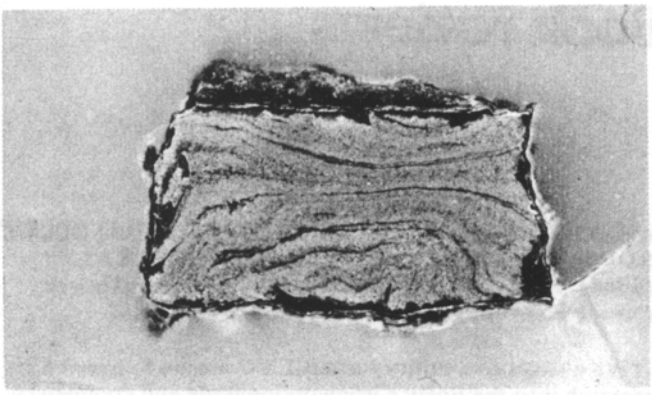


*fig 1*

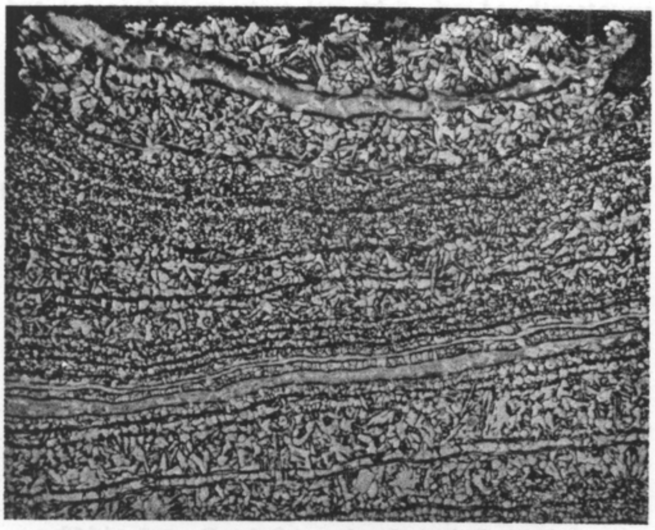


*fig 2*

Kjula axe. Further details are published in the Proceedings of The Fifth Atlantic Colloquium held in Dublin 30th March to 4th April 1978 as: 'A study of the Technology behind Nickel-alloyed Prehistoric Steel having a Laminated Structure", by E Tholander.

Eskilstuna and Ronninge in April 1980.

*Elias Hermelin Erik Tholander Stig Blomgren*

## A Herefordshire Monastic Mill and its Bibulco

Dear Sir

In 'White Monks in Gwent and The Border' (1976) David H Williams states: "Dore had at least four or five water mills – King John allowed the monks in 1216 to enlarge and raise a millpond they had in Trivel Wood, and adjacent to one of their mills (at Puseyton) was a **bibulco**. What this was is unknown, but similarly in Herefordshire in 1232 the **Med. Latin Word List** records a **bifultum** as being adjacent to a mill".

French Cistercians founded Abbey Dore (1147) in a disturbed region abandoned by the Romans but long fought over by the Welsh, English and Normans. The language became very mixed where thesfighting men spoke French, the churchmen and scholars Latin and the commonfolk English and this affects wording. A T Bannister's 'Place names of Herefordshire' records a Dore Charter (undated) mentioning a Puscyton which is probably the present Poston.(Courtesy Reference Librarian, Hereford Library). As for **bifultum** the L Fulcire means prop up, support lit. porticum and a fulcrum is a beneficial appendage to a structure whilst **bi** signifies 'having two', 'double'. The **L bibulus** is 'freely drinking' which with a co-mplementary auxiliary structure might make a water wheel more available and productive thanks to its having a **bibulco.**

The Hoovers' 1950 translation of Agricola's 'De Re Metallica' (1556) gives information about medieval Germanic water machines. On p 187 there is an engraving of double water wheels, one overshot and above an intermediate 'broad race' supplying its undershot companion, together with auxiliary vertical feed pumps worked by the lightweight (primary) upper wheel for drought conditions. On p 319 concerning water-driven crushing stamps 'in this case the machines are constructed' (at different levels) 'and generally placed in one building'. Surely this would constitute a **bibulco** or **bifultum** adjacent to a mill?

Incidentally Keynsham Abbey on (Bristol) Avon had one mill before the Dissolution but from 1703 the zinc industry developed nearby and the expanding Warmley Works had several mills but only a meagre water supply. Champion 'solved' his energy crisis by using altogether two horsemills, one windmill and finally a steam engine to pump back water to the mill pond. Some **bibulco!**

Examination of the site at Whitfield in Trivel (Treville) Wood reveals the (1216?) millpond. At Poston Mill between Turnastone and Peterchurch to the west side of B4348 on a tributary of R Dore is a pond with a disused 40 hp water turbine which is perhaps the descendant of the Puseyton **bibulco.**

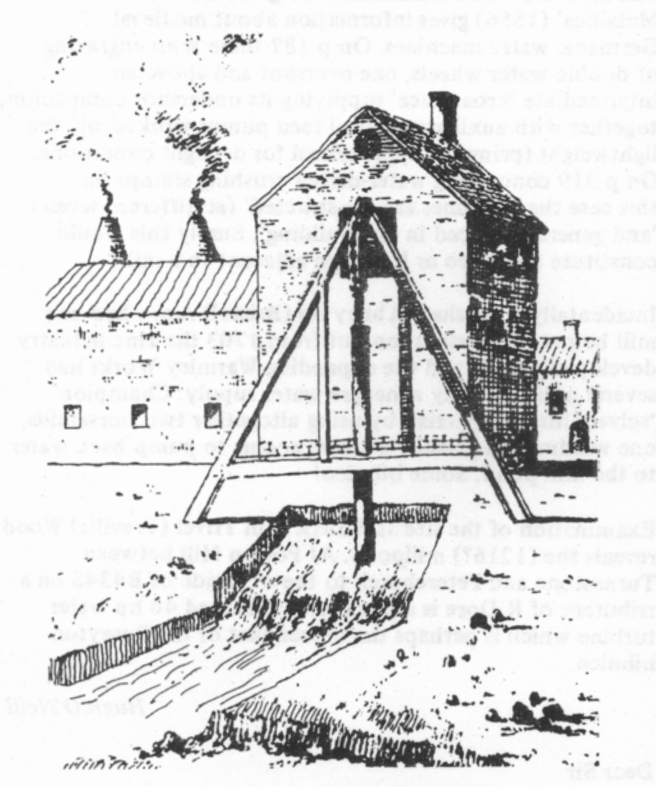
*Hugh O'Neill*

Dear Sir

Intrigued as I am with obscure Latin terms in references to medieval watermills, particularly fulling mills, which have come to my notice recently I regret I am not enough of a scholar to add to Professor O'Neill's discussion about his *bibulco.* Keynsham watermills and Champion's works at Warmley are quite another matter and I cannot let his incidental asides pass without comment.

Keynsham Abbey had not just one but three mills in Keynsham before the Dissolution, Avon Mill, Down Mill later known as Chew Mill, and South Mill which became the Logwood Mill or Albert Mill. All three sites were subsequently involved in some way with the brass company established in 1702, at Baptist Mills on the River Frome, some five miles away in Bristol. Keynsham's Avon Mill eventually became the headquarters of the company and remained so until it closed in 1927.

The quite separate enterprise of William Champion was initiated particularly to exploit his Patent 564 of 1738 for the production of metallic zinc, although also intended to encompass coppersmelting, brassmaking and the manufacture of wares in these metals. Established in 1746, in an area well-stocked with cheap coal, the problems of inadequate waterpower available from the Warmley Brook must have been recognised and tackled from the outset. The earliest accounts of manufacturing processes at the site date from 1748, the year that parts of a 36 ins cylinder engine were delivered. Probably erected and found to be too small, it was replaced by a 48 ins cylinder in the following year. A local newspaper reported this engine installed by Joseph Hornblower of Birmingham and other references reveal that it pumped tailwater from water-wheels driving rotative processes, returning it to a specially-constructed ornamental reservoir for recycling This, of course, was just a few years after a similar installation of a Newcomen engine at Coalbrookdale. An even larger engine was installed at Warmley in 1761 with a cylinder of 74½ ins which at the time was said to have been the largest built.



*Reinhold Angerstein's drawing of the Warmley pumping engine, c1754*

In the same year an inventory of the site was compiled in preparation of large-scale expansion to further premises. Clearly, by then, Warmley was outgrowing its potential energy resources. It is at this stage that references were made to the horsemills and the ore-crushing windmill, suggesting that these ancillary forms of power may well have employed in the final effort. I feel that Champion would not have been amused to find his progressive ideas for Warmley compared with a medieval *bibulco,* whatever the meaning of the term.

Bankruptcy prevented Champion's expansion being fully realised and the old Bristol brass company took over the site and did little to develop it. The tower of the windmill still stands close to some buildings which probably housed the horsemill. Champion's house and his clock-towered headquarters remain and the bed of his lake can still be recognised, though now drained, adorned with his copper-slag statue of Neptune. Similarly, the sites at Keynsham survive and can be compared with the more complete brassmill at nearby Saltford. They are some of the features which can be visited during the HMS Conference at Bath in 1981.

*Joan Day*

# Book reviews

**A SELECTION FROM THE RECORDS OF PHILIP FOLEY'S STOUR VALLEY IRON WORKS 1668–74, PART I, (edited by) R G Schafer, Worcestershire Historical Society (New Series, Vol 9), 1978, 128pp, no price quoted.**

It is a quarter of a century since B L C Johnson followed his research into the Foley's ironworking trade and commercial activities by a series of publications about varied aspects of that trade. Historical metallurgists, economic historians and geographers have found much of interest about the seventeenth and early eighteenth centuries trade in iron, and indeed in technical details about its manufacture, from the Foley papers which were generously placed on public deposit in Hereford County Record Office in 1963. Yet it has not been easy to use these papers in spite of the skill and care with which they have been classified and arranged.

Professor Schafer, in the first of two volumes, has performed a valuable service in transcribing some very illuminating and important parts of the Foley papers, which relate in fact to a wider area by far than is implied by the title. Similarly, the period covered is wider than merely the six years in the title, although the accounts presented do cover those years. There can be no doubt that to anyone with interests in the English iron industry, this will be a most useful sourcebook.

The Stour Valley Iron Works were but part of the Foley's interests. Schafer gives a brief introduction, valuable for its coverage of the activities, places and persons mentioned in the accounts. The present selection includes a range of sources; Philip Foley's Stock and Debts Book for 1669, a summary of all his works for 1668 and 1669, accounts of the Bustleholme Slitting Mill and some family and commercial agreements. Chosen to illustrate the state of the Foley's key Stour works when Philip took over from his father, these documents enable one to follow the complex and comprehensive accounting procedures, to see the geographical and technical interactions, and to collate a variety of outputs for furnaces, forges and mills. (The next volume promises some far more detailed accounts of yields and outputs, incidentally.)

The extremely tedious form of the original accounts has, by some judicious departures and ingenious arrangement, been printed in a form which is not only clear but enables the exact location of every item to be found in the originals should that be needed. The overall arrangement is clear and concisely indicated; a general introduction leads on to the three main sets of documents, each of which has a brief specific introduction. There are two sketch maps of locations, and a comprehensive index.

A reviewer, faced with a book of this sort, essentially a record society publication making available to many what few have the time or opportunity to study in the original, can only admire the labour expended on it. He can also be grateful it is here at all. Equally, as it is here, he has the unkind duty to point out its imperfections and infelicities. Truly they are few in number. The maps of the West Midlands and of the area within ten miles of Dudley Castle are not really adequate to illustrate the activities described by the accounts. Newport is not in Montgomeryshire, at least not the Newport of the accounts, where the evidence points to Newport Monmouthshire. Hampton Loade and Hampton have been lumped together on the map, and in the index, but I am sure that 'Hampton' must refer in almost every case to Wolverhampton, and not to Hampton Loade on the Severn below Bridgnorth. The maps omit Hubbals Mill, one of the works mentioned from time to time, which lies two miles west of Bridgnorth. I should have liked to have seen an attempt made to provide a glossary of some of the less common technical terms, notwithstanding the difficulties of providing satisfactory definitions. Lastly I have noticed one error in the index, where there is an entry for Kinlet, page 21, but a perusal of that page shows no mention.

The last thing on which I wish to comment is Schafer's view that these accounts show an essentially modern form of accounting. They do not, they ignore numerous items, like depreciation, which a modern accountant would insist on having. They are very business-like, that I agree, but it is still not a modern business. I am looking forward to seeing volume II, and that is a good enough recommendation for volume I, I am sure.

*Norman Mutton*

### W A ODDY (EDITOR). SCIENTIFIC STUDIES IN NUMISMATICS. British Museum Occasional Paper No 18 1980. Published by the Trustees of the British Museum. Price £3.75. ISBN 0 86159 017 1

This group of papers forms part of the Proceedings of the 19th Symposium on Archaeometry held in London in March 1979. The rest of these proceedings are planned to appear in BM OP 19–21.

The editorial mentions that the Royal Numismatic Society has set up a Scientific Research Committee which expects to publish a new occasional publication called 'Metallurgy in Numismatics'. This is clearly a red letter year which marks the coming of age of one of the most important users of metals over the ages – coins are now something like 2600 years old, and paper does not seem likely to take their place.

The papers in this number cover a wide field from the statistics of Ashanti gold weights by A D Hewson to the tin distribution in Coriosolite coins (Cu–Ag) by Bernard et al. In the latter, experiments showed that 4–20% tin was added to lower the melting point and ease the striking of the blanks. Striking was found to cause surface enrichment of Sn and Ag.

Craddock and his colleagues show that the use of zinc in Hellenistic copper-base coins dates from the 1st century BC and therefore dates the first use of brass to the area of Phrygia and Bothynia for the coinage of Mithradates of Pontus. The low iron content is said to justify the view that the zinc was made from sulphide ores rather than the more usual carbonate ores. But there is no reason why the carbonates should not be reduced to pure zinc oxide by volatilisation and condensation in the sort of hearth described later by Marco Polo and others. Earlier objects which contain appreciable zinc (6-12%) are noted going back to the 6th century BC but these may be made from copper ores containing zinc.

Carter and Theodory give the analysis of 28 2nd to 3rd century AD copper coins from Caesarea (Kayseri). These are leaded gunmetals of variable tin and zinc content made from scrap metal. No doubt the zinc originated from the same source as Craddock's. Oddy's contribution deals with the interesting cases of medieval silver forgeries using embossed silver foils. Finally, there is a paper by Gilmour on the actual composition of the silver token coinage of 1811–12.

The papers are presented in A4 format with unjustified typescript, a common type of presentation today and one which manages to keep the costs down. This has resulted in a very clear and readable booklet of 100 pages. While there has been photographic reduction of the tables one is grateful that this has not been overdone.

*R F Tylecote*

### ARCHAEOLOGISCHE EISENFORSCHUNG IN EUROPA (Archaeological research on iron in Europe). Symposium Eisenstadt 1975. Wissenschaftliche Arbeiten aus dem Burgenland, Heft 59, Eisenstadt (Austria) 1977, 183 pp, photographs, figures.

With considerable delay there has now appeared (1979) in one volume papers read by European scholars at the 2nd symposium of the Comité pour la siderurgie ancienne de l'UISPP which had been organised in cooperation and under the sponsorship of the Burgenlandisches Landesmusem at Eisenstadt, 1975. H Schmid: Die montangeologischen Voraussetzungen des Ur- und fruhgeschichtlichen Eisenhuttenwesens im Gebiet des mittleren Burgenlandes (Geological conditions of the ancient and early metallurgy of iron in central Burgenland), 11-23. The amount of early mining of spathic ores and limonites suggests that about 200.000 smelts and about 2000 tons of iron were produced in the area of the Djela-Wald alone. W Mayer: Bestandaufnahme von Pingenfeldern im Bezirk Oberpullendorf, Bgld. (The documentation of early mining fields in the district of Oberpullendorf), 25–48. Plans and charts relating to mining pits of Zerwald, Herrschaftswald, Djela-Wald, etc. K Bielenin: Einige Bemerkungen uber das altertumliche Eisenhuttenwesen im Burgenland (Some remarks on the ancient iron metallurgy in Burgenland), 49-62. Results of excavations on bloomery sites at Unterpullendorf, Weppersdorf, Klostermarienburg, Harmisch, Langfeld, Oberpullendorf (La Tene period), Unterpullendorf-Sportplatz (Early Middle Ages), Dorfl; different types of furnaces: dome, slag-pit, shaft. K Kaus: Zur Zeitstellung von ur- und fruhgeschichtlichen Eisenverhuttungsanlagen Burgenlands auf Grund der Kleinfunde (On the chronology of bloomeries in Burgenland in the light of minor objects), 63-70. Typological analysis of pottery and radiocarbon dates from the sites of Raiding and Kostermarienburg (La Téne). E Nosek (Mrs): The investigation of the iron-sponge fragments from Burgenland, 71-82, Chemical and metallographical investigation of small iron nodules from Unterpullendorf, containing carbon-free and hypereutectoid structures. They represent particles separated in course of the bloom-removal from furnaces. J Gomori: Archaeologische Eisenforschung in Westungarn (Excavations on iron producing sites in West Hungary), 83-99. Bloomeries of the early medieval period discovered at Sopron-Banfalvi ut, Tarjanpusxta, Nemesker, shaft furnaces, tuyeres, charcoal burning piles. G Vastagh: Einige Eigentumlichkeiten der ungarischen Rennfeuerverhuttung (Some specific features in the Hungarian bloomery process), 101-105. The author suggests the practice of open-hearth smelting in furnaces of the Imola type. R Pleiner: Neue Grabungen fruhgeschichtlicher.

Eisenhuttenplatze in der Tschechoslowakei und die Bedeutung des Schachtofens fur die Entwicklung des Schemelzvorganges (Recent excavations of early bloomery sites in Czechoslovakia and the role of the shaft furnace in the development of the bloomery process), 107-117. A La Tene period bloomery at Msec, Roman period bloomeries at Kadan, Sudice, Labska Chrcice, Krepice and Mlekojedy, Slav furnaces at Olomucany; the development of the shaft furnace from the bowl hearth is considered decisive both from the technological and economic points of view. K Bielenin: Ubersicht der Typen von altertumlichen Rennofen auf dem Gebiet Polens (A Survey of types of bloomery furnaces discovered on Polish territory), 127-145. Excavation in Lizawice, Dobrzen May, Kowalkowice, etc (Heiligenkreuz–Gebirge), Milanowek, mainly Roman period. I Martens (Mrs): Vor- und fruhgeschichtliche Eisenverhuttung in sudnorwegischen Gebirgsgegenden (Ancient and early iron smelting in the highlands of South Norway), 147-155. Early medieval iron smelting at Fet and Mosstrond with its smelting pits and later clay-walled furnaces. R F Tylecote: Iron Working at Meroe, Sudan 157-171. Walled buildings with multi-tuyere furnaces, slag heaps, tuyeres, forging hearths, 1st half of the 1st millennium AD. P–L Pelet: L'architecture des fourneaux a fer primitifs, evolutions autonomes et tendances generales (The architecture of primitive bloomery furnaces, their specific development and general trends), 173-180. A special attempt in order to classify the early bloomery furnace types according to thermal insulation properties, air-blowing system, and building technology. G Sperl: technologische Beziehungen zwischen der fruh-geschichtlichen Kupfer- und Eisenmetallurgie (Technological relations between prehistoric metallurgy of copper and iron), 181-183. The role of siliceous and iron fluxes in the smelting of copper sulfides.

*R Pleiner*

**JERN OG JERNVINNE SOM KULTURHISTORISK FAKTOR I JERNALDER OG MIDDELALDER I NORGE**
**Iron and iron making as a historical and cultural factor in the Iron Age and Medieval Norway. Stavanger 1979. 118 pp. photographs, figures.**

The research programme of the ancient and early iron industry in Norway culminated just when editing the present book, which in fact represents the acta of a special symposium held at Bryne, Rogaland, 1979. All papers are accompanied with summaries in German. B Nakkerund – E Schaller: Slaggroper pa Eg, Kristiansand, Vest Agder – Schlackengruben in Eg, Kristiansand, Vest Agder (Slag-pits at Eg), 8–18, 105. Seven hearths of slag pit furnaces from the later Roman period; wooden post construction; I O Solvberg: Jernvinne i Kaupanger i Sogn – Eisenverhuttung in Kaupanger on Sogn? (Iron smelting at Kaupanger in Sogn?) 19-25, 106. A battery or six hearths serving for wood-tar burning. The adjacent older iron slag layer indicates that the original purpose of the hearths might have been connected with iron making. A E Christensen: Forhistorisk Smiteknik – Vorhistorische Schmiedetechnik (Protohistoric blacksmith's technique), 26–36, 107. The author calls for recording technological survivals in the contemporary peasant blacksmith's work A M Rosenquist (Mrs): Utvikling av effektivitet av jervinner som en funksjon av tida – Entwicklung und Effektivitat als eine Funktion der Zeit (Developement and Effectivity of iron production as a time function), 37–49, 108. According to analytical results the technology of the older phase of the Mosstrond bloomeries (6th–8th centuries AD) was more primitive than in the later phase, dated to the 9th–12th centuries. It concerns the type of furnaces, melting temperatures and composition of slags and, consequently, the productivity itself. O Farbregd: Jernvinne og jernalders buselning i Trondelag, – ei problemstilling – Die Beziehung zwischen der Eisenproduktion und der eisenzeitlichen Siedlung in Trondelag (Relation between iron production and Iron Age settlement in Trondelag), 59–64, 109. Research of various bloomery sites of the Roman Age uncovered in the above region is postulated. I Martens (Mrs): Jerndepotene – noen aktuelle probmstillinger – Eisendepots – einige aktuelle Fragenstellungen (Iron hoards – some actual problems), 59-64, 110. There are about 150 iron hoards dating from the Migration period up to the 14th century AD. Their study is to be conceived in Norway on a complex basis. A A Bagien (Mrs): Introduksjon av jern i Skandinavien – Die Einfuhrung des Eisens in Skandinavien) The introduction of iron to Scandinavia), 68-72, 111. Little information is available from the summary. The mentioning of the Late Bronze Age bloomeries in Denmark seems to be misunderstood. E H Hofseth (Mrs): Jernvinna – spontant eller organiser opptak? – Die Eisengewinnung – spontane oder organisierte Entstehung? (Iron production – a spontaneous feature or an organised introduction?), 73–81 112. In spite of A B Johansen's theses the iron making in the area of Hardangervidda must have been introduced by agricultural population which had connections with the outer world and not by the native hunters. A B Johansen: Livberigmater i Fjelldalene – Vorhistorische Wirtschaft in den sudnorwegischen Gebirgstalern (Prehistoric economy in the valleys of South Norway), 82-92, 113. It were decidedly native hunters who were involved in the iron smelting activity of the region in question. The date occurring in the summary (1300-600 BC by radiochronology) seems to be an error Chr. Keller: Jernet som teknologisk nodvendig ressurs – Eisen als technologisch notwendiger Rohstoff (Iron as an unavoidable material in technology), 91-98, 114. Short notes on pp 50-53, 65-66, 99-101. A strictly selective bibliography section appears on pp 115-118.

*R Pleiner*

# Abstracts

## GENERAL

**E D Nicholson: The ancient craft of gold beating.** *Gold Bull. 1979,* 12 *(4), 161-166.*

History of the process together with the modernised process now used to produce gold leaf by a firm in Scotland. Gives some compositions of Egyptian gold of 1 micron thickness. Claims that it is possible today to produce thicknesses of 0.05 micron. The fineness is not the maximum (it contains some Ag and Cu). Intermediate annealing is used after reduction by rolling to 25 micron.

RFT

**W A Oddy: Coin forgers at work.** *Masca Journal, 1979,* 1 *(3), 80-81.*

Forgeries may be of modern coins made in modern times, of ancient coins made in ancient times, or of ancient coins made in modern times. Proving that a coin is forged may be simple – for example, specific gravity measurements will reveal the 'gold' coin that is only 'gilded', and metallography will reveal the forging made by casting when the original coins were made by striking. By far the most deceptive of modern forgeries of ancient coins are those made by striking. Struck forgeries also exist from the past, but in this case they can be detected from the alloy, which must be deficient in quality or quantity if the forger is to make a profit. For example, thirteenth century silver pennies were forged by placing a genuine coin between two pieces of silver foil with a sheet of soft lead on either side. The pile is then struck leaving the impressions of the genuine coin in the foil, which are then cut out and soldered together with a low melting-point solder. APG

**Vittori Ottavio: Pliny the elder on gilding: a new interpretation of his comments.** *Gold Bulletin, 1979,* **12,** *No. 1 pp 35-39.*

The *Natural History* of Pliny the elder is usually regarded as one of the first references to the process of fire or mercury gilding. This paper reinterprets Pliny's remarks and shows that the process was most probably not fire-gilding as it is understood today, but a process in which mercury was used as a simple adhesive. The secret of the process was to use as little mercury as possible. Accompanied by a useful bibliography. WAO

**Francois Schweizer and Pieter Meyers: Structural changes in ancient silver alloys: the discontinuous precipitation of copper.** *ICOM Committee for Conservation, 5th, Zagreb, 1978, 78/23/5/1-16.*

The age embrittlement of ancient silver could be due to discontinuous precipitation of copper from the super-saturated silver-rich silver-copper solid solution during the long sojourn at ambient temperatures. Microstructures of a number of ancient silver samples (500 BC to 600 AD) have been examined with the optical microscope and by microhardness measurements. The microstructures are compared with the precipitation behaviour of modern, artificially aged silver-copper alloys. Based on kinetic data the growth-rate of the precipitating cell at 25 C is estimated to approximate 10 m/year. The temperature-dependence of the interlameller distance of the segregated copper in the precipitated cell could be used to distinguish between ancient objects (aged at ambient temperatures) and artificially aged modern objects (aged at elevated temperatures). AA

**G P Smedley: Design of Large Steel Structures.** *Metallurgist and Mats. Tch., Nov 1979,* **11** *(11) 627-631.*

The author, who is Head of Offshore Services Groups, Lloyd's Register of Shipping, examines the inter-relationship between evolution in steelmaking practice and design experience in the 19th and 20th centuries. Amongst the topics considered are corrosion of ships plates, rivetted points, boiler and bridge construction, welded construction, and brittle fracture of storage tanks and ships. APG

**A Williams: The metallurgy of Muslim Armour.** *Seminar on Early Islamic Science Monographs No 3, May, 1978 (Manchester).*

According to some results of metallographical research carried out on museum specimens, Muslim armour seems to have been made rather of soft wrought iron sheet, except for a Persian vambrace (19th century) made of wootz steel. (CPSA)

**T S Wheeler, R Maddin & J D Muhly: Ancient Metallurgy: Materials and Techniques.** *J Metals, Sept 1979,* **31** *(9) 16-18.*

The authors quote John Coles, who pointed out that a stone artefact of the third millenium BC in Britain or Ireland required of its maker knowledge of the precise properties of the parent rock, careful quarrying, flaking, smoothing and occasional drilling. Pretreatment by heat was well known. To produce a metal object involved exactly the same requirements, an intimate understanding of the available materials, careful preparations, the use of percussion and grinding, and, in this case, more heat.

Lack of clear diagnostic criteria for distinguishing worked and annealed native copper from worked and annealed smelted copper makes it difficult to speak with authority about the history of native copper use, but the use of copper seems to date from the late 7th/early 6th millenium BC. Silver first appears in the Near East in significant quantities in the second half of the 4th millenium at Byblos and other sites in Anatolia, in Palestine, Egypt and Mesopotamia. It seems unlikely that this is all native silver since cupels have been found at Byblos and in Egypt. Gold objects in relatively large numbers appear at about the same time, but it appears to have been used for its aesthetic value, and for the case with which it would be made into intricate shapes, since it is normally too soft for utilitarian purposes.

Alloying probably began with the smelting of a conglomerate copper and arsenic ore, which gave a metal which looked like copper, but which was harder and more easily cast. Subsequently both arsenic and tin ores would be sought for the manufacture of bronze. Iron production gradually increased after the 12th century BC and by the 10th century BC and largely replaced bronze for making tools. The discovery of the hardening of iron by the addition of carbon to produce steel and the further hardening obtained by quenching the steel must have played an important part in this development. APG

**E J Lenik: A study of cast iron nails.** *Hist Archaeol, 1977,* **11,** *45-7, pl.*

Presents information on the microstructure of a sample of cast iron nails together with a short history of the malleable iron making process in 18th century. The nails concerned are from three late 18th/early 19th century sites in USA, and were likely to have been imported from England in limited numbers for highly specialized functions (for nailing lath or for decorative purposes). Author (abridged) (BAA)

**J E Harris and I G Crossland: Mechanical Effects of corrosion: an old problem in a new setting.** *Endeavour, (New Series), 1979,* **3** *(1), 15-26.*

This paper brings together seemingly unrelated failures. and successes, all involving expansion due to oxide film formation and rusting. Examples include oxide 'jacking' or cracking by expansion of the railings around St Paul's, deformation of components of the Tower Bridge, and rusting of recent steel reinforcement in buildings on the Acropolis — a failure of the type that the original builders avoided by lead encasement of iron.

On the credit side is cited the invention by William Murdock of 'rusting' cement used during the construction of the British Museum Reading Room. RFT

**A R Williams: A technical note on some of the armour of King Henry VIII and his contemporaries.** *Archaeologia, 1979,* **106,** *157-165.*

The standard of 15th-16th century iron armour was examined by polishing the cut edges of the plates themselves without the usual removal of metallurgical sections. The 20 pieces of armour cannot be taken as typical because of their royal provenance but represent the most advanced levels of

**the time. They are mostly steel in the range 0.5-0.8% C. And while some have been hardened to 600-700 HV, most are in the unhardened condition. The plates themselves were probably produced by case carburizing and made more homogeneous by folding over several times. Then quenching and tempering, or slack quenching, to give hardnesses of 400 HV was carried out in some cases. In the majority, air cooling gave hardnesses in the range 200-250 HV.**

**Some quantitative spectrographic analyses are given. The photomicrographs show that the chosen technique can be made to give acceptable results. Some pieces have been mercury gilded.** RFT

## BRITISH ISLES

**S M Linsley: Hareshaw and Ridsdale Ironworks.** *Northumbria, Spring, 1978, No. 12, pp 15-17; Summer No 13, pp 11-14.*

**Vicissitudes of two Northumbrian iron making plants of the early 19th century. Their background, plans, proximity of coal, ore and limestone. But no rail at outset.** RFT

**Colin J M Martin: La Trinidad Valencera: an Armada invasion transport lost off Donegal, Interim site report, 1971-6.** *Int J Naut Archaeol Underwater Explor, 1979,* **8,** *13-38, pls, figs, refs.*

**Gives the historical background to the wreck (a former Venetian merchantman requisitioned by the Spaniards for a troopship) and describes the site and the excavation of the much-scattered remains. Timbers, anchors, cables, rigging fittings, and gun-carriage wheels are among items raised so far, and the exclusive use of iron in the fittings is noted.** (BAA)

**B G Scott: Iron 'slave-collars' from Lagore Crannog, Co Meath.** *Proc Roy Ir Acad C, 1978,* **78,** *213-30, pls, figs, refs.*

**Technical examination suggests that the fine two-piece collar recovered from the lowest occupation level was assembled from two pieces, a new half being copied from the old by a different smith. The long chain attached to it is of a late RB type, and the collar decoration appears inspired by Anglo-Saxon work. Date: no later than early 7th century AD. The one-piece collar is of a type with a long currency in Britain, late PRIA to late Roman. There is also a part of a previously unrecognized third collar. Consideration is given to the way in which these metalworking techniques reached Ireland. Hostages – or else favourite dogs – seem more likely than slaves to wear such fine work.** (BAA)

**R Bradley: The interpretation of later Bronze Age metalwork from British rivers.** *Int J Naut Archaeol Underwater Explor, 1979,* **8,** *3-6 figs.*

**It is likely that not all the weaponry and other objects found in rivers was placed there for ritual purposes; riverside settlements, or even pile structures, of high status may have been the source for many of these bronzes. Underwater research might help resolve the ambiguities.** (BAA)

**T H McK Clough & Charles Green: The first Late Bronze Age founder's hoard from Gorleston, Great Yarmouth, Norfolk.** *Norfolk Archaeol, 1978,* **37,** *1-18, figs, refs.*

**TG 519036. The 1952 hoard is published and discussed in its geographical, environmental and chronological setting. About 80 implements were found including socketed axes (plain, decorated, and faceted), fragments of sword and rapier, spearheads, and metal waste. The hoard is transitional between Wilburton and Carp's Tongue phases and dates to 7th century BC.** (BAA)

**Anon: Famous Waterwheels retain Nineteenth-century Patterns.** *Foundry Trade Journal, 1979,* **147** *(3176) 1099–1100.*

**Coupled cast-iron breast-shot water wheels, designed by John Rennie, each 17.5 ft diameter and nearly 12 ft wide, drive a pair of massive pumps at Claverton near Bath which raise water 48 ft from the river Avon to the Kennet & Avon Canal. Hanging in the gear-room wall is a waterwheel section pattern which probably dates from the modification of the equipment carried out by Harvey and Sons of Hayle in 1844. Illustrated.** APG

**C R Blick: Two Centuries of Blast-furnace Development.** *Metals and Materials, Dec 1979, 19-20.*

**This article summaries five papers given to the seminar on 14th July, 1979 jointly organised by the Historical Metallurgy Society and the Ironbridge Gorge Museum Trust on the development of the blast furnace: R F Tylecote on the development of the bloomery process; D Crossley on the post-medieval development of the blast furnace; S Linsley on the 17th century blast furnace; J R Hume on the 18th century blast furnace and K Gale on the 19th century blast furnace.** APG

**Anon: Portsmouth No 3 Ship Shops.** *Foundry Trade Journal, 1979,* **147** *(3175) 1006-1007.*

**Built in 1843, the earliest surviving arched iron building in the world has now become redundant in Portsmouth Naval Base. The trustees of the Southern Industrial History Centre are attempting to raise £100,000 to transfer the entire building to the new Industrial Museum of the South at Amberley, Sussex. The construction of the building is briefly described and illustrated, and an etching is reproduced from the Illustrated London News of 1859 showing the launching of HMS Victoria from the building.** APG

**P T Craddock: Deliberate alloying in the Atlantic Bronze Age.** *Proc 5th Atlantic Colloq Dublin, 1978 (ed M Ryan) 1979, pp 369-385.*

**Bush-barrow metal is both Cu-As, Cu-Sn and Cu-Sn-As suggesting the ready availability of As copper scrap. By the EBA tin bronze of regular composition (10%Sn) became common and there is no doubt that it was made with cassiterite or tin metal (tin slag from Caerloggas – RFT). Some artifacts show a rather higher level in the MBA. Pb was occasionally added to give more than 3%.**

**By the LBA, tin content was back to 10% for all artifacts. Some Sb alloys with more than 2.0% Sb probably from fahlerz. There was considerable lead addition during this period – random but about 5%. For this all the usual reasons are given with the addition of a new one – the excess lead arising from the cupellation of silver-lead.** RFT

**S M Smith: The construction of the Blists Hill ironworks.** *Industrial Archaeology Rev Spring 1979, 3, 170-178.*

**Describes the proposed works for the manufacture of wrought iron to be built at the open air museum of the Ironbridge Gorge Museum Trust at Blists Hill, Shropshire.**

The main building will be the former Woolwich Smithery, constructed in 1814 by John Rennie, and the equipment will mostly come from the works of Thomas Walmsley and Sons, Ltd, of Bolton – the last makers of wrought iron in the world, whose commercial production ceased in 1976. The process of production and its proposed operation, staffing and marketing at Blists Hill, are described.
DGT

**J G D Elvin: Cannon Founders.** *Foundry Trade Journal, 1979,* **147** *(3172) 619. Letter.*

The author has been tracing the origin of founders initials on the cannon aboard HMS Victory and has been successful in every case except one. He asks the help of readers in the case of a 24 pounder which bears the letters CAB in a triangular format on the trunnion face.
APG

**J S Jackson: Metallic ores in Irish prehistory: copper and tin.** *Proc 5th Atlantic Colloq Dublin, 1978, Ed M Ryan, 1979, 107–125.*

Estimates that ore equivalent to 1400 t copper was mined in BA. Assume 50% efficiency of conversion = 700 t Cu. As this is far in excess of the estimated production of artifacts used in Ireland at this time much of it must have been exported.

Not more than 14% of the objects dated to the EBA are bronze, the rest being copper. This amounts to 1.72 t and is equivalent to 0.18 t of tin, all of which could have been panned from the Gold Mines River area of Co Wicklow.
RFT

**S M Linsley: Excavations at the Allensford Blast Furnace, Northumberland, NZ 079503.** *Industrial Archaeology Rev, Spring 1979,* **3**, *193 and 195-8.*

Less detailed account of the excavations described in *J Hist Met Soc, 1979,* **13**, *42,* but with the advantage of four photographs.
DGT

**B G Scott: Notes on the introduction of non-ferrous metal technology to Ireland, and the transition from stone use to indigenous non-ferrous metal use.** *Ir Archaeol Res Forum, 1977,* **4** *(2), 7-15, figs, refs.*

It may have been seasonal movements that led to the discovery of Ireland's exploitable resources – whether flint, or metal ores, or fertile land – and thence to fuller penetration and settlement. The Beaker peoples may have been responsible for the introduction of metal, but the evidence is slim. The mechanisms by which a complex new technique is first introduced, then passed on to the indigenous population are discussed; the stone-users have difficulty keeping their skills topped up after separation from their homeland, so the process of acculturation is lengthy and complex.
(BAA)

**K Muckelroy and P Baker: The Bronze Age site off Moor Sand, near Salcombe, Devon. An interim report on the 1978 season.** *Int J Naut Archaeol Underwater Explor, 1979,* **8**, *189-210, pls, figs, tables, refs.*

The finding of a third bronze blade on the seabed prompted a systematic survey of the area. This resulted in the recovery of the three more bronzes – a featureless blade and two palstaves of Portrieux type. The degree of seabed scour found at this site, and the different states of preservation of the six items, may put some difficulties in the way of postulating a BA wreck as their source. Appended are analyses of the original three bronzes and a biological assessment of the conditions at the site.
(BAA)

**B Trinder: The first iron bridges.** *Industrial Archaeology Rev., Spring 1979,* **3**, *112-121.*

Reviews recent new evidence on the origins of the Iron Bridge in the Severn Gorge and in particular the role of T F Prichard, a Shrewsbury architect who prepared the original design for the bridge. Then discusses a large number of subsequent early iron bridges and their designers. Little discussion of engineering, and none of metallurgical matters.
DGT

**G J Wainwright et al: Gussage All Saints: an Iron Age settlement in Dorset.** *London, HMSO (=Dept Environment Archaeol Rep,* **10***), 1979, xi + 202 pp, pls, figs, tables, refs, index. Price £18 (paper).*

ST 998101. A 3-acre settlement was completely excavated and most of the archaeological deposit removed so as to provide a basis for broader interpretations, especially in view of the long rule of the 'Little Woodbury model' which derived from a partial excavation by Bersu in 1938-9. Post-holes for buildings, numerous pits, gullies, and internal enclosures provided evidence for settlement throughout the second half of 1st millennium BC: its environment, development, material culture, economy, and population are discussed. Bronze-founder's debris represented about 50 sets of pony harness and chariot fittings.
(BAA)

**Owen Bedwin: The excavation of a late 16th/early 17th century gun-casting furnace at Maynard's Gate. Crowborough, East Sussex, 1975-6.** *Sussex Archaeol Collect, 1978,* **116**, *163-78, pls, figs, refs.*

TQ 539298. Excavation of the remains of a gun-casting blast furnace revealed the base, a working floor, and the wheel-pit, though extensively robbed. Masonry was of sandstone throughout; the floor of the wheel-pit consisted of well preserved wooden planks. The circular gun-casting pit, 3m deep, had also suffered from robbing. Documents give dates from 1562 to 1667; finds were few. *Author (abridged)*
(BAA)

**R Le Cheminant: Antique lead merchants' weights from the City of London.** *London Archaeol, 1979,* **3**, *289-91, pl.*

Discusses the few (less than 30) weights so far known, ranging from Anglo-Saxon times to George I, and mostly made in the City of London.
(BAA)

**P Rahtz et al: The Saxon and medieval palaces at Cheddar: excavations 1960-62.** *Oxford, Brit Archaeol Rep Brit Ser 1979,* **65**, *411 pp, pls, figs, refs, Price £10 (paper).*

ST 457531. At Cheddar, site of the palace of late Saxon and early medieval kings of England, 0.8ha were excavated to reveal buildings of mainly 9th to 14th century date. Residual Roman material was present in some quantity, but the earliest complex of structures (hall and ancillaries) may date to 9th century. The next phase (hall, chapel, ?fowl-house, elaborate approach) is confidently identified with 10th century documentary references. In 11th century the hall was modified and the chapel rebuilt on a larger scale. Rebuildings followed for Henry I and II, John, and the eventual episcopal owners. Many specialist contributions: coins, Roman, Saxon and medieval pottery (including petrographic analysis) metalwork, soils/silting, medieval bell-casting pit, human and animal bones, and mollusca. Author (adapted).
(BAA)

**P R Sealey: The later history of Icenian electrum torcs:** *Proc Prehist Soc, 1979,* **45**, *165-78, pl, fig, table, refs.*

The Snettisham torcs were probably, the Ipswich ones possibly, made locally, but the type went out of manufacture in early 1st century AD, and indeed the three hoards with coins (Snettisham, Weybourne, and Netherurd) should have been deposited no later than Caesar's Gallic Wars. Cessation is ascribed to the Roman world's demand for gold, and Belgic appetite for Roman luxuries, diverting British gold supplies from Icenian smiths and mints. The practice of gilding in the Late Iron Age may stem from these difficulties in obtaining gold. (BAA)

**J F Cave: A Note on Roman metal turning.** *Hist Technol, 1977, 2, 77-94, figs. refs.*

Roman craftsmen indisputably used turning techniques in making a wide range of metal vessels: criteria for detecting these are visual, dimensional and metallurgical. Spinning was also used. Mutz assumes and reconstructs an unindirectional lathe, but the less advanced reciprocating lathe could have been made to produce continuous rotary motion by means of a flywheel. Some techniques for mounting the work are discussed. (BAA)

**R A Hall et al: A Viking age grave at Donnybrook, Co Dublin.** *Medieval Archaeol, 1978, 22, 64-83, pls, figs, refs.*

Recognition in the Castle Museum, Nottingham, of a 'lost' sword from a Viking age warrior's grave excavated at Donnybrook in 1879 has prompted a reassessment of the burial in relation to other Viking age burials in the 'Irish Sea province'. Detailed metallurigcal analysis of the sword, undertaken during conservation, has provided important information about the techniques of its construction and demonstrated the potential of a variety of analytical approaches. The elaborate hilt had brass and silver inlaid into a network forged in the iron, forming one of the finest Viking age weapons from these islands. Authors (amplified). (BAA)

**C J Lynn: Trial excavations at the King's Stables, Tray Townland, Co Armagh.** *Ulster J Archaeol, 1977,* **40**, *42-62, pl, figs, tables, refs.*

J 838455. A partial section across a waterlogged hollow showed it was an artificially constructed flat-bottomed basin measuring about 25 m across and up to 4 m below ground level. Finds included fragments of moulds for bronze leaf-shaped swords, an unusual collection of animal bones, and a portion of human skull. 14C dates in the 1st millennium BC were obtained, and the best available parallels are the Celtic ritual shafts of similar date. Appendices deal with the bones, petrology of a sherd, and palaeoecology. (BAA)

**C A Smith: Early hot galvanizing – Part 3.** *Finish Ind, 1978. 2, No 12, pp 12, 15. In Eng.*

A history of the development of hot galvanizing in England from about 1850-1900. The early galvanization of wire and development of a galvanizing company are described.

**Charles K Hyde: Technological change and the British iron industry 1700-1870.** *Book. Princeton U Press, New Jersey, 283 pp, 1977. Tables, charts extensive bibliography, index.*

Charts the diffusion of new techniques in the iron industry, during 1700-1870, which changed the type and amount of the industry's output. There are chapters on: charcoal iron; coke smelting; wrought iron; the hot blast furnace; the advent of steel. CGA

**J Andrews and F Celoria: A 19th century smith's leg vice from Staffordshire, England, with a metallographic analysis of parts of its screw.** *Science and Archaeology, 1976,* **17**, *pp 21-34. In Eng. 25 figs, 7 refs.*

A blacksmith's leg or staple vice of suggested 19th century date, in use in Staffordshire till the 1970's is examined with regard to 17th century and later descriptions relating to use and manufacture; and with regard to a scientific examination made of the box or nut to ascertain methods and materials of construction. X-ray examination together with optical metallography, as well as boroscopic and electron beam microprobe analysis methods were used in the examination. The wrought iron consisted of a ferritic matrix with many elongated silicate and oxide inclusions. A copper zinc brazing spelter had been used throughout. The nut, fabricated from three metal rings, two keys, an end cap, a main tube, thread and spacer, all brazed together, shows evidence of impressive craftsmanship. AA

**Mary Tucker: The system of watercourses to lead mines from the river Leri.** *Ceredigion, 1977, 8, 217-33, pls, figs, refs.*

The historical evidence for the construction of 19th century watercourses to power ore preparation equipment at lead mines in north Cardiganshire is outlined, and the streams and leats mapped. DWC(BAA)

**A Hartmann and B G Scott: [Interpretation of spectranalyses of Irish gold]** *Ir Archaeol Res Forum, 1977, 4 (2), 35-8, refs.*

The two protagonists continue the debate about the origins of PC gold. Hartmann, refuting Scott's attack on his interpretations, maintains the likelihood of a non-Irish origin for La Téne gold objects of this type; Scott reasserts his methodological objections to Hartmann's conclusions. (BAA)

## EUROPE

**J Dunin-Karwicki: Analiza bronioznawczo-metalograficzna trzech mieozy wczesnosredniowiecznych ze zbiorow Panstwowego Muzeum Archaeologicznego w Warszawie.** *Summary. Metallographic and weapon-expert analysis concerning three Early Medieval swords in the collection of the State Archaeological Museum in Warsaw. Wiadomisci Archeologiczne 1978, 42 (2), 165-172.*

Swords of the 10th-12th centuries AD bear steel edges or shells welded-on to wrought iron blades. Heat treatment in the case of the specimen from Warszawa-Krolikarnia.

**J Piaskowski: Rozwoj metaloznawczych badan starpzytnych i wczesnosredniowiecznych przedmiotow zelaznych w krahu i za granica (Summary: Development of metallographical studies on ancient and early-medieval objects made of iron in Poland and abroad).** *Kwartalnik Historii Nauki i Techniki 1978, 23 (3-4), 715-731.*

The author tries to sum up the present state of metallographical research on ancient iron objects. In his view three aspects have been followed up to now: 1) the reconstruction of early technology, 2) the type of technology of different assemblages ascribed to various ethnic complexes; in our view the ethnic interpretation ranges into another field of study, 3) the third aspect is related to attempts to recognize the origin of archaeological iron. Piaskowski claims the latter trend as the highest stage of research. It may be useful if the author discusses more thoroughly some metallurgical aspects of this problem simultaneously considering new applications of microprobe analysis on slag inclusions, slag, ore from forged objects, blooms, waste and raw materials from a single bloomery site.

**Z Glowacki – H Przygodska (Mrs): Badania metaloznawcze zabytkow zelaznych ze Styrmen.** *Summary: Recherches concernant les objets en fer der Starmen, Bulgarie (Metallographic investigations of iron objects from Styrmen, Bulgaria). Slavia Antiqua 1978,* **25** *245-295.*

Results of examination of 127 iron weapons as daggers, swords, arrow heads and the like, without comments. The paper should be connected with that by H Mamzer.

**S Martin-Kilcher (Mrs), H Maus and W Werth: Roman mining at Sulzburg 'Muhlematt'.** *Fundberichte aus Baden-Wurttemberg 1979,* **4**, *170-203.*

Investigations of Roman period mining debris. Argentiferous lead-ores were the main subject of the activity (ca 180-380 AD, according to the radiocarbon dates). Occasionally limonitic ores were exploited as fayalitic slags and small blooms of hard steel indicate.

**A S Ostroverkhov: Pro cornu metalurhiyu na Yahorlys komu poselenni. (The metallurgy of iron at the site of Yahorlyk).** *Archeolohiya (Kyiv) 1978,* **28**, *26-36. (In Ukranian).*

Traces of iron making at the Black Sea coast near Olbia, hearth-like features explained as bloomery furnace bottoms (6th century BC). Greek colonists obtained hematite and magnetite ores in the areas of Krivoy Rog and Azov while exporting iron on behalf of Scythian tribes.

**K Leciejewicz (Mrs): Rudy darniowe Mazowsza.(Bog Iron ores of the Masowia).** *Z Otchlani Wiekoa 1978, (2)* **44**, *109-110. (In Polish).*

The bog iron ore resources west of Warsaw are estimated at about 7700 tons. The shallow deposits, presently of a very low iron content (about 20-25% $Fe_2O_3$), could have supplied with the raw material of the bloomeries described in the article by S Woyda.

**H Mamzer: Technologia produkcji przedmiotow zelanznych ze Styrmen nad Jantra w Bulgarii. Summary: Technologie de la production d objets de fer provenant de Starmen sur la Yantra, Bulgarie (Technology of iron objects from Styrmen upon Yantra river in Bulgaria).** *Slavia Antiqua 1978,* **25**, *225–243. (In Bulgarian).*

127 iron objects (weapons) were investigated originating from the Slav site at Styrmen. The mostly applied technology was faggoting of iron and steel strips. Two slag agglomerations and hearth-like features. See Z Glowacki, above.

**J Wigfors: Jarnet og smideskonsten (Iron and the blacksmith's art).** *In: Vis alven. Bygd och viking. Goteborg 1978, 36-48. (In Swedish).*

A chapter on iron working in a popular book. In the north of Europe iron appeared at about 400 BC. According to the author's estimate 200 kg of charcoal and 200 kg of ore consumed during a bloomery smelt would have produced 100 kg of slag and 15-20 kg of wrought iron.

**H Schonberger: Kastell Oberstimm.** *Die Grabungen von 1968 bis 1971. Berlin 1978.*

The catalogue of finds of the above Roman castellum, compiled by Mrs A Bohne, contains a blacksmith's hammer and tongs (p.191). An appendix entitled Eisenschlacken und Gusstiegel (Iron slags and melting crucibles), by H–G Bachmann, is devoted to metal working waste in the form of limited quantities of fayalitic slag, interpreted as bloomery slag containing up to 10-20% of CaO, which possibly had its origin in the ore used. Dating: ca 69 AD.

**St Otletanu: Roumains, Slaves et nomads dans le processus de valorisation du minerai de fer du territoire roumain aux $IV^e$–$XI^e$ siecles de NE (Roumanians, Slavs and nomads and the smelting of iron ore on the Roumanian territory during the 4th–11th centuries AD).** *Dacia N S 1978, 22, 299-303.*

Remarks on the metallurgy of iron in the Roumanian territory in the Early Middle Ages. Indication of crucible smelting at Udesti near Suceava (6th–7th centuries). The period of nomadic invasion involved the decline of industrial activity.

**Christiane Eluere: The Maintenon hoard and rib-decorated socketed axes of British types.** *Bull Soc Prehist Francaise, 1979,* **76**, *119-27, figs, tables., refs.*

The eight-piece hoard of carp's tongue facies included one example of a ribbed axe of E English type, which prompts a review of all such finds in France. Although these axes are not often associated with carp's tongue complex material in England, they are almost invariably so in France. Features and mechanisms of their distribution (? redistribution) in France are discussed, and spectranalytical results for the Maintenon hoard provided. (BAA)

**C Reimann and G Sperl: Structural investigations of the bloomery slags.** *Sonderbande der praktischen Metallographie 1979,* **10** *349-358. (In German).*

Analyses of ancient and medieval slags from six sites. Too high a smelting temperatures as a limiting factor in the total yield; the presence of wustite and magnetite indicates poor reducing conditions in the furnace.

**G Sperl: Comparative studies in early iron slags.** *Berg- und Huttenmannische Monatshefte 1979,* **124** *74-84. (In German).*

Chemical and mineralogical analyses of bloomery slags offer various kinds of evidence as to intimate knowledge of the temperature regime in the furnace, of reducing effects of the furnace atmosphere and of the type of the original ore. Six classes of slags were found in bloomery sites.

**E Nylen: (Iron and Silver).** *Zeitschrift fur Archaeologie 1978,* **12**, *211-224. (In German).*

The regions of central and north Sweden started their production of iron just about BC but a rapid development is to be registered between 600 and 1100 AD. Rich families settling around the Maleren lake system profited by the iron transit trade in the 9th-10th centuries. At that time Gotland represented a great iron working centre where iron and steel imported from the mainland used to be worked. It played an important role in the far distance trade (eg in the known eastern trade route called 'Iz Varyag v Greki'). Imitations of the Renish Ulfberht sword blades.

**P Paulsen – H Schah-Dorges (Mrs): Das alamannische Graberfeld von Giengen an der Brenz (The Alammanic cemetery of Giengen).** *(Kreis Heidenheim). Stuttgart 1978. (In German).*

In the richly equipped equestrian grave no. 26 there was a pattern-welded sword. Among the seven swords uncovered at the cemetery another example bore a pattern-welded blade (grave No 50). 7th century AD.

**J Stankus: Juodoji metalurgia. Summary: Die schwarze Metallurgie (The black metallurgy).** *In: The material culture of Lithuania in the 9th–13th centuries AD. Vilnius 1978, 73-88, 140-142.*

Iron bloom of Petresiuna. Metallographic investigations of iron objects (results of 203 analyses, proportions of different construction techniques of blades.)

**P Burdova, F Obr, K Ludikovsky and V Souchopova: The discovery of and research on the metallurgical centre at Sudice, distr. of Blansko.** *Hutnicke listy, 1977/8, 32 605-608.*

Some results of chemical and structural analyses of slag waste found in the bloomeries of Sudice, Moravia. The composition of slags corresponds with the local iron ore of the Pametice deposit. Some interpretations of the slaggy materials suggest that the authors are not familiar with the bloomery process.

**Jean-Rene Jannot: Tin production in Amorica in ancient times.** *Les Pays de 'Ouest: etudes archeologques, = Actes du 97e Congres National des Societes Savantes (Nantes, 1972), Paris, Bibl Nat, 1977, 97-109, figs, table, refs.*

Gives the geological data for tin distribution, discusses bronze as an index of tin production, and considers the data obtainable from literary and archaeological sources.
(BAA)

**Zoltan Hegedus: Some remarks on the foundry technology of bronze baptismal fonts of the 14th to 16th centuries.** *Banyasz. Kohasz. Lapok, Ontode, 1978, 29, No 6, 122-130. (In Eng. and Hung.)*

A brief description of the shape and execution of the baptismal fonts of the 14th-16th centuries is given, and some fonts cast in Hungary are presented. From Hungarian and foreign contemporary records, the probable foundry technology of these fonts is discussed.
(AATA)

**Gusztav Heckenast: Our medieval ironmaking based on archive sources.** *Bangasz. Kohasz. Lapok, Kohasz, 1978,* **111,** *No 3 97-105. (In Hung.)*

A historic account of iron metallurgy in Hungary up to the end of the 16th century.
(AATA)

**W W Phelps, G J Varoufakis and R E Jones: Five copper axes from Greece.** *The Annual of the British School of Archaeology at Athens, 1979,* **74,** *175-184, plates 22-25.*

Chemical analysis shows that the axes contain between 97.8 and 99.6% copper, the least pure containing 1.5% lead, 0.4% zinc and 0.15% tin. The maximum arsenic content reported is 0.4%. One axe is in the 'as cast' condition with hardness in the range 32-57HB, and no sign of the use of hammering to form the blade. The main bodies of two were 'as cast', but metallography shows that the edge of the blade had been cold worked, increasing the hardness from 76HB in the main body to 101 HB at the cutting edge in one axe, and 101 HB to 160 HB in the other. In one case the entire axe had been heavily hammered, with hardness in the range 95 HB to 107 HB, and in the last case the whole body appeared to have been hammered hot, or hammered cold with subsequent reheating, and the blade additionally hardened by cold hammering. (There appears to be discrepancy between reported chemical analysis and the general level of hardness – for example, axe 1 should be the hardest, on the basis of chemical composition, but it is reported as being by far the softest axe of the group).

The discussion is mainly concerned with the origin and dating of the axes, but no definite conclusions are drawn.
APG

**Hensel Zdzislaw: Metal examination of iron objects from 9-12 c from Wolin.** *Materialy Zachodnio-Pomorskie, 1975,* **XXI,** *61-93. Tables, diagrams, drawings, illus, German summary. (In Polish).*

Spectrographic analyses (qualitative and quantitative), metallographic examinations and microhardness tests on 86 objects from archaeological excavations in the north-western part of Poland led to the classification of the finds into several characteristic technological groups. The results are discussed in detail, from the technological as well as the historical point of view.
HJ

**Ernst Hoke: Microanalysis of metal threads in Graye I of the parish church Traismauer.** *Fundberichte aus Oesterreich, 1978,* **16,** *255-259. 1 table, 6 illus. (In German).*

Early textile fragments with gilded silver threads from an entombment dating 8-9 centuries AD were analyzed microchemically and with a microprobe. Two groups were selected: one with gilding on a silver-copper-base, of oriental origin, and a second set of German origin, with a majority of lead.
MK

**G A Voznesenskaya and L S Homutova: The technology of blacksmith's production at the fortified settlement of Maritsa.** *Soc Ark 1979 (4), 180-188. (In Russian).*

Scythian-like site of 6-5th century BC in Seim basin. Metallography of 38 artifacts mostly knives and axes. No hardness nor compositions. Varying carbon levels; welding of iron tosteel; piling; carburizing but no heat-treatment.
RFT

**S I Tatarinov: The Late Bronze Age metal work of the Middle Donetz.** *Sov. Ark. 1979 (4), 258-265. (In Russian).*

A metal working site. Stone moulds for socketed axes and other artifacts. Copper-base tanged, dagger/knives and socketed axes. Gives about 40 analyses which show some Sn bronzes but at least half are impure coppers all with low lead and most with low As.
RFT

**B Jovanovic. The technology of primary copper mining in southeast Europe.** *Proc Prehist Soc, 1979,* **45,** *103-10, pls, fig, refs.*

Summarizes recent work on Early Eneolithic mines in Bulgaria and Yugoslavia (4th millennium BC), outlines their basic characteristics, and points out the advanced nature of the mining techniques used even at an early stage. The copper needs of Early Eneolithic groups were evidently much greater than had been supposed.
(BAA)

**Carol C Mattusch: Corinthian metalworking: The Forum Area.** *Hesperia. 1977,* **46,** *No 4, pp 380-389*

Small metal fragments (c 100) found in the Forum Area in Corinth indicate large-scale production here of small-scale figures. Techniques of lost-wax casting, used in each case, are illuminated: in some instances, the brush strokes resulting from the application of wax remain imprinted in the cast metal. Fragments date from Late Protocorinthian to 5th c BC, and after a break, start again in the early Roman Period. Large-scale figures were probably cast outside of the city's centre.

RDZ

**Lothar Suhling: Technological developments in Middle Age copper metallurgy.** *Erzmetall 1978,* **31,** *Nos 7-8, 348-353. (In German).*

The history of Cu liquation and smelting processes in the Middle Ages, especially the 12th to 16th centuries, is discussed, including the separation of Ag from crude Cu. The introduction and spreading of the techniques in Europe, the literature records of the techniques, and the intermediate stages in their development are discussed. (AATA)

**J–P Mohen: Bronze moulds in the Bronze Age.** *Antiq. Nationales. 1978, (10), 23-32. (In French).*

Discusses the usual types of bronze moulds for palstaves, socketed axes etc, with seven analyses showing the majority to be tin bronzes with 0.7 to 8.5% Pb. One is however an impure copper rather than a bronze and another has 2% Sn and 1% Pb. The trunnion and clamp cores are also made of bronze unlike the British equivalent.

Also shows a fragment of a thin-walled mould for the point of a dagger from the Larnaud hoard. The 2 parts seem to be held together by pins only 1 mm diameter. The author is quite certain that all these moulds were used for the direct casting of bronze. RFT

**Ulf Qvarfort: The cultivation influence in Lake Tisken and the opening of the Falun copper mine.** *Jernkontorets Forsk 1980, Series H, No 19, 1-13. (In Swedish).*

By sampling the silts from the lake bottom for Cu, Zn, Pb, Mn, Ag and Cd it is shown that large scale smelting started about 700 AD. The ore is now 21% Fe, 3% Zn, 1% Pb, and 0.5% Cu. In the 18th century Cu was 7%. The maximum silt metal contents are: Fe 150, Mn 0.5, Cu 5, Zn 5, Pb 1 (mg/g) and Ag 25 and Cd 10 (microg/g).

RFT

**Ulf Qvarfort: Prehistoric iron smelting near Kolnsjon.** *Jerkont. Forsk. 1980, Series H, No 19, 1-9. (In Swedish).*

Results show the existence of a submerged iron smelting site in lake. Slags typical and similar to those from Dalerna. Chemical and micro examination. RFT

**Claude Domergue and G Herail: Roman gold-mines in Spain: Valduerna District. Geomorphological and archaeological study.** *Toulouse, Univ de Toulouse – Le Mirail, 1978, 305, + separate map-case, pls (some in colour), figs, refs, glossary. (= Serie B tome 4).*

A detailed study of the remains of the Roman gold-mines in the valley of the Rio Duerna, south of Astorga in North-West Spain. Examination of the geomorphology of the river valley, with special attention given to the different types of gold-bearing deposit and their comparative auriferous content, is set against a consideration of the areas actually worked by the Romans and by what techniques. It seems that the type of deposit did not matter: where gold was found it was worked. Mostly, however, the quaternary alluvial deposits were exploited. The different workings are examined in detail on the basis of aerial photographs, ground survey and selective excavation. Various different working methods are then identified, involving a complex variety of sluicing techniques. The mines are thought to have been in action continuously from early 1st to late 2nd century AD. DGB (BAA)

**S C Bakhuizen. Greek Steel.** *World Archaeology, 1977,* **9,** *221-234.*

The hypothesis is put forward that effective steel metallurgy originated in Greece, and that steel technology was a major factor in shaping Greek economy and society from the ninth and eighth centuries BC on. It is argued that the leading region of Greek iron and steel metallurgy of the opening period was central Euboea. Here Xeropolis-near Levkandi and Chalcis became prosperous towns. It is held that iron metallurgists of central Euboea constituted the nuclei of the early Chalcidian colonization enterprises to the Bay of Naples. When a concerted attempt at the analysis of iron objects, blooms, slags and ores has been made, the hypotheses can be tested. ECJT

**Miriam S Balmuth: Sardinian Bronzetti in American Museums.** *Studi Sardi, 1975-77,* **24,** *145-156.*

The four small bronze figurines are described in detail and can be roughly dated to the first half of the first millennium BC. The question of their authenticity and dating is discussed and reference is made to Lilliu's catalogue of bronzetti and it is suggested that it should form the basis of a comprehensive program for analysis. The result of these four figurines does not allow us to draw detailed conclusions about the nature or origins of Sardinian metal technology. All four figurines are true bronzes, containing between 80 and 90% copper and 5-10% tin as the major components. They all contain a detectable amount of arsenic and are low in zinc. The lead content is much lower than that of Roman bronzes.

ECJT

**R A Hebbert: The Horses of San Marco: A metallurgical detective story.** *Metals and Materials Dec 1979, 27-30.*

Four gilded 'bronze' horse statues have stood above the facade of the Basilica of St Mark in Venice since the 13th century. Their origin is obscure, but it is known that they were pillaged from the Hippodrome of Constantinople in 1204. Internal evidence indicates that the several parts of each statue were cast by the indirect lost wax casting technique, in which a sectional mould is made from the original solid model (the countermould) and a wax shell made by pouring wax into this countermould. An investment mould is then built up around the wax, and the metal is poured in after the wax has been removed by melting. Considerable areas of porosity on the surface, as well as apertures left by removing the spacers and core supports, have been repaired by chiselling out and then hammering in a section of plate of the same composition as the casting. The plate is held in position by dovetailing into the sides of the hole.

Chemical analysis of the metal shows that it contains 0.39 to

1.31% tin, 0.11 to 1.16% lead, very small amounts of antimony, silver and iron, remainder copper. Metallography indicated that the 0.008 mm thick gilding was applied by covering the castings with a mercury-gold amalgam and then applying gold leaf. Radiography indicates extensive porosity in all the wall areas, and particularly near the gates through which the metal entered the mould.

At some time the gilt has been deliberately scored with a network of fine lines, using a specially shaped tool. Corrosion has taken place so that the gold leaf is no longer joined to the copper, but rests on corrosion products. The scored lines have become covered with oxides, basic carbonates, basic chlorides and basic sulphates. For centuries this patina protected the metal due to its adhesion, but in recent years combustion of coal and petroleum products has radically changed the environment so that a new group of corrosive processes is attacking the products formed over the centuries.

The cleaning of the horse which was recently exhibited at Burlington House, London is described. APG

**P T Craddock: Europe's earliest brasses.** ***MASCAJ, 1978,*** **1,** ***4-5, pl.***

Current investigations at the British Museum of the main copper alloys used in the classical world have now covered some 1200 Greek and Etruscan 'bronzes' and established that at least three Etruscan pieces were of brass. This helps to reduce the isolation of the Athenian Agora find of zinc metal. However, even if both zinc and brass were known in Europe before the Roman Empire, the powerful contribution of the Romans in making full scale use of the cementation process by end of 1st century BC must not be overlooked. (BAA)

**Judith Swadling: The British Museum Hoard from Paramythia, NW Greece; Classical trends revived in the 1st and 2nd Centuries AD.** ***Cahiers D'Arch. Romande. No 17, Lausanne, 1979 103-106. (In English).***

Found in 1791-2 but dispersed. Hellenistic and Roman styles but all probably of the Roman period. Analyses of 11 out of 12 show a marked similarity of composition apart from lead. Sn 9-13, Pb 0.5-13%. The 12th has 30% Pb and 3.0% Sn. RFT

**Christiane Eluére: The earliest gold objects in France.** ***Bull de la Soc Prehist Franc 1977,*** **74,** ***Etudes et Travaux. Fasc 1, 390-419. (In French).***

A very comprehensive report with the usual archaeological treatment of Chalcolithic and EBA artifacts with 17 analyses grouped according to Hartmann.

The earliest Chalcolithic objects have affinities with the Aegean and SE Europe and are probably based on the metallurgy of the Carpathians and Anatolia. These fall into Hartmann's Group B. Some French copper objects of this period also have an E Mediterranean origin. Other objects also come from outside France; some are Iberian, some N European and some from the British Isles.

The golds belonging to the beginning of the EBA are clearly connected with the British Isles and lunulae type material. At the end of the EBA one sees a partial return to the connection with the Aegean in the Atlantic zone of France but the east has contacts with the central Europe, Germany and Switzerland. With one or two exceptions the Cu contents are all less than 1.0% and we are clearly dealing with natural gold. Tin may be high (0.23–0.15%), Group S or L, ie. lunulae metal, or low, less than 0.043%. Naturally the high Cu golds have high silver as well, so the copper addition was clearly intentional although one high silver lunula (35–40%) was not alloyed with Cu and may be a natural white gold or electrum. RFT

## TECHNIQUES

**16–874. Jacques Francaix: L'apport de la spectrometric d'emission a plasma dans l'analyse des objets metalliques anciens. The contribution of plasma emission spectrometry in the analysis of ancient metallic objects.** *ICOM Committee for Conservation, 5th, Zagreb, 1978, 78/23/11/1–3.*

New sources of plasma excitation for emission spectroscopy have solved the principal technical problems (standardisation, third-element and matrix effects), and offered new possibilities for archaeological material analysis, such as analysis of any element including main elements in the most varied alloys without preparation of solid standards, and analysis of non-conducting samples: corrosions and especially ore and scoria whose study is important in the investigation of the object's origin. Normalisation of the operation conditions are facilitated by the fact that standardisation and dosages are done in solutions. AA (Trans MB)

**16–922. B M Tejam and B C Haldar: Neutron activation analysis of metal bangles of archaeological importance.** *Natl. Acad. Sci. Lett. (India),* **1,** *No 2, pp 67–69 (1978). (In English).*

Neutron activation analysis was used to study bronze bangles excavated from various sites in India and estimated to be 3500–4000 years old. The Cu content of the bronze ornaments ranged 84.2–92.7%; Sn contents were about 6% with small amounts of Sb, Zn, and Fe. (AATA)

**16–924. R F Tylecote: Better hydrogen reduction of iron.** *Museums Bulletin,* **18,** *No 11, p 216 (Feb 1979).*

The author laments the revival of the hydrogen reduction method for treating archaeological iron artifacts, because it is totally destructive of metallurgical structures, whatever temperatures used, precluding possible future research into the visible internal structures of ferrous metal artifacts which can prove in detail how well thestechniques were understood and executed. Advocates improved storage conditions and non-destructive conservation methods. HOH

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