III.

THE METALLURGICAL ANALYSIS OF THREE BRONZE AGE AXES. BY LIEUTENANT-COMMANDER S. S. CRICHTON MITCHELL, R.N., AND MARGARET E. CRICHTON MITCHELL, PH.D., F.S.A.SCOT.

1. FLAT COPPER AXE FROM IRELAND.

This axe was lent for the purposes of examination by the National Museum of Ireland.

An approximate qualitative analysis showed the following chemical composition:—

Copper,	98	per cent.
Arsenic,	1·5	,,
Silver,	·1	,,
Silicon,	·1	,,

Tin was present, but less than ·05 per cent.; also traces of lead, manganese, aluminium, nickel, and zinc. The comparatively high percentage of arsenic in this ore should render easy the identification of its source. Its chemical composition, however, does not correspond with that of any of the well-known Irish copper ores.

The axe measures $4\frac{7}{16}$ inches in length, $2\frac{1}{2}$ inches across the cutting edge, and $\frac{1}{2}$ inch in greatest thickness.

A study of the microstructure leads to the following deductions:—

The axe has been cast in a moderately thick mould of clay, sand, or stone. The dendrites have none of the characteristics of the slow cooling which would take place in a very thick mould or in one sunk in the earth for support; nor are they similar to dendrites formed during the swift cooling which results from the use of a metal mould.

Some form of header has been used, as there is no collection of surface slag at the butt of the axe.

Immediately before pouring, the melt was thoroughly skimmed and was probably stirred by a wooden stick, since the oxygen content in this axe is much below normal, even assuming a reducing atmosphere around and over the crucible. A high oxygen content tends to render

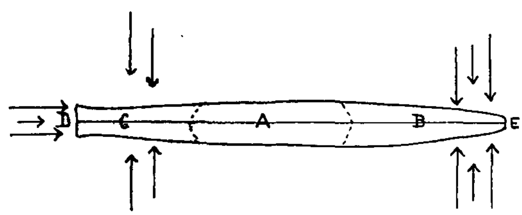

Fig. 1. Section of Irish Flat Axe of Copper.

copper brittle. It is therefore a moot point whether the use of a wooden stick was fortuitous or otherwise.

At the moment of pouring the temperature of the melt was low, probably about 1100° C.[1]

After casting, the axe was forged in the areas B and C but not in area A (fig. 1). The area C was forged at a higher temperature than the area B, thus suggesting that C was worked before B. Subsequently the axe was reheated, and thereafter the butt of the axe, edge D, was hammered. It is of interest to note that edge E had never been hammered by, or used to hammer, any hard object.

Proof of this sequence of events is afforded by the microstructure of the axe, wherein there are indications that the areas B and C have been both "hot" and "cold" forged. The direction of the forging blows is shown by the general orientation of the forged crystals. The edge E exhibits no evidence of "cold" working.

Some of these deductions are worthy of further consideration. Why was the axe forged? Hammering is generally undertaken either to alter the shape of an object or to increase its hardness, in which case it is carried out below 550° C. Since the form of this axe is so simple

[1] Pure copper solidifies at 1082° C.

that it seems incredible all the necessary shaping could not have been achieved by the mould, it follows that the forging was done to increase the hardness of the metal. But the increased hardness which would result from the "cold" forging was entirely lost by the subsequent reheating. Hardening, then, does not appear to have been the motive. But whatever the reason for the hammering may have been, it is here suggested that the reheating was due to the axe being subsequently used as a model for a clay mould, which would be baked with the model axe *in situ*.[1] This in turn argues that the open stone moulds, occurring in North-eastern Scotland [2] and presumed to be for the manufacture of flat axes, may either be moulds for the metal models of clay moulds or else the relics of an alternative but more primitive metallurgical technique. But a stone mould would be an unwieldy object in the outfit of a travelling smith. Stone moulds would be easily cracked by heat, and when lost could not be quickly replaced. The clay mould was both more economical and easier to make, while it only necessitated the possession of one or two metal models in the equipment of the early itinerant craftsmen.

2. Axe with Stop Ridge and Ornamented Flanges from St Andrews, Fife.

This early example of a palstave was only available for a very limited examination.

The axe measures $4\frac{7}{16}$ inches in length and $2\frac{11}{16}$ inches across the cutting edge.

It was impossible to make a qualitative analysis, but the character of the microstructure indicated a true bronze with 12 to 15 per cent. of tin.

The axe has been cast in a bivalve mould, and from signs in the microstructure the mould may possibly have been embedded in the earth so as to maintain an upright position. The mould has been of clay, since the appearance of the original cast surface beneath the patination was too smooth to have been in contact with stone.

The metal had been poured at the undesirably high temperature of about 1200° C.

Insufficient skimming of the melt beforehand probably accounts for the presence of a considerable amount of slag, while the header used with the mould was so short that the butt of the axe was choked with dross.

[1] Clay bakes at 600° C., which would be a sufficient temperature to produce the process of recrystallisation.

[2] *Proc. Soc. Ant. Scot.*, vol. xxxviii. pp. 487–505; vol. xl. p. 35; vol. lxiii. p. 12; vol. lxiv. p. 14.

After casting, the axe was reheated and the flanges lightly forged until the temperature had fallen below 550° C. Subsequently, the axe was reheated a second time, no doubt in order to facilitate the completion of the herring-bone pattern on the flanges.

The patination on this axe is very pronounced, and a study of this phenomenon provides the following information:—

In the patina are three differently coloured constituents. Next to the metal lies a red layer, succeeded in due rotation by a black and a green layer. The red layer is not uniformly present, and the different layers, particularly the black and the green, tend to merge into one another. A chemical analysis of the patina shows:

Sand, 43 per cent. approximately.
Copper carbonate } in considerable quantities.
Copper hydroxide }

Another constituent was probably copper sulphate.

The patina on the axe has possibly been produced by contact of the metal with carbonic acid gas (CO_2), which would most probably arise from the decomposition of vegetable matter. In such circumstances the hydroxide and carbonate are formed, and their intermediate reaction on the metal produces cuprous and cupric oxides. The carbonate is green, the cuprous oxide (Cu_2O) is red, and the cupric oxide (CuO) is black. The surface finish on the patina has perhaps resulted from water action. This conclusion is supported by the quartz grains, not fused, whose sharp angles indicate that they are water, not wind, borne.

3. A Breton Socketed Axe.

This axe was purchased at a public sale in Edinburgh. It bears the legend: "Said to be from Vale of Menteith." The form is indisputably Breton.

A qualitative analysis showed the following percentage chemical composition:—

Copper	54·64	Silenium	·02
Lead	43·3	Nickel	·02
Tin	1·46	Zinc	<·01
Sulphur	·22	Phosphorus	<·005
Iron	·12	Silver	Traces
Arsenic	·09	Magnesium	Traces
Antimony	·06		

The axe (fig. 2) measured 5 inches in length and $1\frac{3}{8}$ inch across the cutting edge. The socket measured internally $\frac{13}{16}$ inch by $\frac{11}{16}$ inch.

It is practically certain that two different ores were used in the manufacture of this axe, since no known copper ore contains all the elements present in the analysis. The lead content is the important feature. If its presence is due to its being a constituent of the ore, then "Bournonite" may have been used, since this mineral contains at least 43·0 per cent. of lead.[1] The only alternative is that the lead was specifically added to a copper-tin ore, but the presence of such a

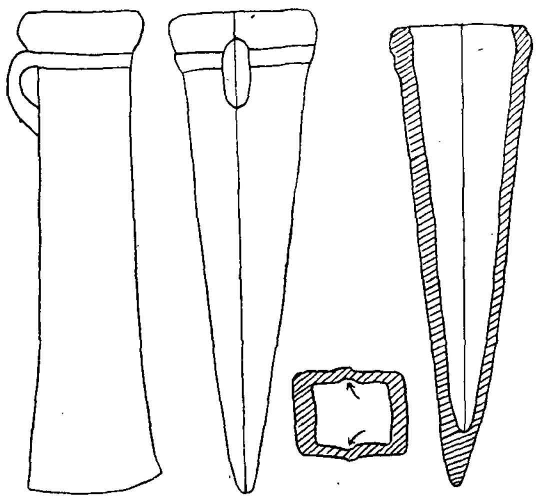

Fig. 2. Breton socketed Axe.

quantity of lead would make the bronze exceedingly brittle and render the axe quite useless for all practical purposes.[2]

A study of the microstructure shows that the axe has been cast and that no forging has been done. The fact that there is practically no slag in the axe shows careful skimming of the melt and perhaps suggests that an ingot was melted down. The oxygen content is about ·1 per cent. This indicates not only the possible stirring of the melt

[1] Chemical composition:

Lead,	42·4	per cent.
Copper,	13·0	,,
Antimony,	25·0	,,
Sulphur,	19·6	,,

"Bournonite" occurs at Alais, near Nîmes, and at Pontgibaud, north-east of Limoges.

[2] Evans, *Ancient Bronze Implements*, pp. 417, 445.

with a wooden stick, but also the presence of a reducing atmosphere formed by charcoal built around and over the crucible.

The lead is very evenly distributed throughout the axe, and this, together with certain other evidence of a purely metallurgical nature, suggests the possible conditions in the crucible. A considerable variation in temperature might be expected within the crucible. Charcoal heaped over the top would produce a higher temperature there than at the bottom, where some form of draught would naturally be introduced. Under these conditions the liquid towards the top would be relatively copper-rich, while the cooler liquid at the bottom would be relatively lead-rich. Microscopic examination of the axe provides clear evidence of the simultaneous existence of both the copper-rich and lead-rich mixtures.

Immediately prior to pouring, the melt was stirred thoroughly. This mixed the various constituents, but the time interval was too short to allow of them changing their state, as would occur if the stirring were prolonged sufficiently to produce a homogeneous temperature.[1] The mean temperature of the melt when poured was certainly low, and may have been as low as 970° C. Whether intentional or not, the almost immediate solidification resulting from this had the effect of trapping the heavy lead-rich liquid and preventing it from gravitating to one end of the axe.

The axe was then cast in a bivalve clay mould of moderate thickness. The joints of the mould are visible along the plane through the loop of the axe and there is a pronounced "fin" (fig. 2, C).

The core has been of clay, and the inner "fins" seen on fig. 2, C indicate that it had been previously fashioned in a separate bivalve mould. This deduction is further supported by the fact that the core itself is not symmetrical. If it were hand-made it would at least have been symmetrical to the eye, but if made in a bivalve mould its symmetry would depend upon the two halves of the mould being exactly similar to one another; and this is difficult to achieve.

A cross-section of the axe (fig. 2, D) shows that the core was not accurately placed, and the error of position resulted in the metal being thinner at one side than the other.

From the bottom of the socket a quantity of sand and clay was recovered. This was almost certainly from the core and not from any extraneous matter which had entered subsequently. The sand was principally quartz with some felspar, and the rounded edges of the grains indicated that they were wind borne. Iron was also present; it may have served to bind the clay.

[1] The mixing was analogous to the mechanical union of oil and water.

Several interesting features emerge from the examination of this axe. From a purely metallurgical point of view the casting exhibits a notable degree of technical skill. The oxygen content is suitably low. The axe is commendably free from slag and dross. The lead is remarkably evenly distributed throughout. In the latter connection it is of interest to observe that an alloy of comparable composition is used in modern engineering, and even to-day it is a matter of considerable difficulty to achieve the regular distribution of the lead.

The absence of forging is important, since from the nature of its composition this axe was not forgeable; the high lead content would undoubtedly have produced crumbling. This may indicate that the Late Bronze Age smiths were aware of the effects of a high lead content in a bronze alloy. This consideration reverts to the fundamental problem as to whether the lead was purposely added or not. It must be remembered, however, that where several castings are being simultaneously poured from a melt accidentally rich in lead, such as "Bournonite," the last will tend to have a higher lead content than the earlier examples owing to the tendency of the lead-rich constituents to sink to the bottom of the crucible. But it is almost certain that two ores were used in the manufacture of this axe. The evidence inclines to the conclusion that the smith who made this axe was cognisant of the amount of lead in the bronze alloy. If so, the axe constitutes one of the earliest commercial frauds, for it could never have withstood even moderate usage.

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