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Dust in the wind : experimental casting of bronze in sand moulds

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Résumé :

Cet article nous fournit un bref tour d'horizon des témoignages archéologiques, ou de leur absence, concernant l'utilisation de moules en sable pour le travail du cuivre ou des artefacts de cuivre et des lingots en préhistoire.

Il semble que l'utilisation de moules en sable plutôt qu'en argile, en pierre ou en métal, soit beaucoup plus répandu durant le Chalcolithique et le début de l'Age du Bronze que ce qui était admis jusqu'ici.

Cette vue d'ensemble est suivie d'une discussion concernant le travail de reconstitution expérimentale portant sur le coulage dans des moules en sable mené à la fonderie de l'Université de Sheffield. Il montre quel effet peut avoir la coulée dans des moules en sable sur le refroidissement et sur la microstructure des bronzes à l'étain. Ces résultats nous conduisent à changer notre opinion sur la nature des moules à l'Age du Bronze.

Abstract :

This article gives a brief overview of the archaeological evidence, or the lack of it, in prehistoric times of the use of sand molds for copper, copper-based artifacts and ingots.

It seems that the use of sand molds, rather than those of clay, stone or metal, was far more widespread during the Chalcolithic period and the beginning of the Bronze Age than hitherto accepted.

This overview is followed by a discussion on the experimental work conducted at the foundry of the University of Sheffield on reconstituting the way casting was done in sand molds. This shows how casting in sand molds can affect the cooling and the microstructure of tin bronze. These results modify our ideas on the nature of molds in the Bronze Age.

Introduction

Research in archaeometallurgy has recently been focused on mining and smelting. Apart from Fasnacht's work (Fasnacht, 1995, 1995a, 1991), little research has been published on the methods of casting.

Mostly it is assumed that metal artefacts were cast in stone, clay or metal moulds. For the Middle Bronze Age (MBA) and later periods, archaeological evidence across Eurasia supports this. There is however, a problem when we consider the Chalcolithic and the Early Bronze Age (EBA) : there is an almost complete lack of moulds of any type for this period. And this is not because we have not looked in the right places. The evidence is simply not there. The most probable reason for this is that an alternative, non-permanent casting method was employed : that of casting in sand-moulds.

The main purpose of this paper is to show that sand-casting was used in prehistory. A further question is why was sand-casting replaced by other materials for moulds ? To this aim experimental work was carried out to investigate the effects of sand-casting on the cooling rate and on the microstructure of the cast object.

Casting in sand moulds

Many researchers, such as Brown (1976) completely dismiss the use of sand moulds, saying that « casting in a mould prepared in a sand box does not appear to have been known in antiquity ». Even Tylecote in 1986 followed this view, although he revised somewhat later (1987). Goldmann (1981) discusses theoretical possibilities of the « lost-sand forms » and Müller-Karpe (1990) concludes that casting in sand is found in the second, possibly already in the third millennium BC in Mesopotamia. Shalev suggest the use of open sand moulds for gold rings from the Chalcolithic Nahal Quanah find (Shalev 1993). Only Davey (1988) believes in the early use of sand casting, suggesting that it precedes all materials as a casting medium. Most people, however, simply omit to mention the use of sand moulds and writing as if stone, bronze and clay are the only moulding materials (Rothenberg, 1991, Rowlands, 1976, Eogan, 1979).

It is perhaps easy to understand why casting in sand is mostly ignored : stone, clay and bronze moulds are conspicuous in the archaeological record but who ever found a sand mould ? Sand moulds completely disintegrate after use and become literally « dust in the wind ».

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The Levant

Some of the best and earliest evidence comes from the Levant. During the Chalcolithic, which lies roughly in the middle fifth to fourth millennium BC, two metal working traditions seem to have been in use. One was making prestige items, such as mace heads, standards and « crowns » of copper alloyed with antimony (23 %), nickel (8 %) and arsenic (up to 8 %). Metallographic analysis showed that they were cast. The other tradition was making utilitarian items of pure copper and these were cast in open moulds and then hot worked and annealed (Shalev, 1994, Shalev *et al.* 1992, Ilan and Sebbane 1989).

Excavation of Chalcolithic settlement sites in the Levant have produced evidence for all stages of the production sequence of copper, from ores, crucible fragments to slags, but not for moulds (Adams & Genz, 1995, Shalev, 1994, Shalev *et al.* 1992, Levey & Shalev, 1989).

Only from the middle of the third millennium BC during the MBA do clay and stone mould become known (Moorey, 1985). From the late third millennium BC onwards bar ingots were found in Palestine. Although Rothenberg (1991) thinks that they were cast into stone moulds, Moorey (1985) suggests they could also have been poured into a groove carved into sand. And recently some mould fragments, made of clay, have been excavated in Jordan (Adams, pers. comm).

Southeast Asia

Here the situation is very similar to that found in the Levant. Excavations at Ban Chiang and three other sites on the Khorat plateau in north-eastern Thailand dated the earliest metalworking in the area to the third millennium B.C. (Pigott and Natapintu, 1988 ; Gormen and Chaoenwongsa, 1976). All the major steps in the process of copper production from mining, ore dressing, smelting and casting are represented. However, the earliest known moulds, made of stone do not seem to appear until about 2000 BC (Wilen, 1989 ; White, 1988) and bivalve clay moulds (as those from Non Pa Wai, which may have a « makers mark ») not until the middle of the second millennium BC (Murowchick, 1988 ; Higham, 1988). Recently, Pigott reported four burials from the basal deposits at Non Pa Wai. They were metalworker burials, and one, a 25 yr old male, had fragments of bivalve clay moulds in his hands with other fragments scattered around the body. Another had mould fragments between his legs (Piggott, in press). Work is still in progress on this interesting material and we can expect more important evidence from early Thai metallurgy sites.

Central Europe and Ireland

Examples for similar evidence from Central Europe can be found amongst the earliest copper artefact from the north alpine region (Ottaway, 1982). Numerous copper, arsenical copper and bronze artefacts have been found, but moulds for their production are absent in the archaeological record of that period. For example, flat axes, daggers and ornaments are known in the assemblages of the Mondsee cultures of the fourth millennium BC. Metallographic analysis has shown that the axes were cast (Budd and Ottaway, 1995), yet there is no evidence of any moulds from the same period. This suggests that in Austria, as in much of central Europe at this period, sand moulds may have been used for the production of the earliest copper and copper-based artefacts.

In Ireland too we have evidence pointing towards the early use of sand-casting. In the third millennium BC the earliest type of copper implements were thick butted flat axes, flat tanged daggers and awls (Harbison, 1979). Metallographic analysis of the axe found at Newgrange showed that the metal had been cast but cooled very slowly (O'Kelly and Shell, 1979). This is an indication that it was not cast in stone, which cools very quickly (Staniaszek and Northover, 1982). Stone moulds for casting these axes do not appear in Ireland until later in the EBA (Tylecote, 1986).

EBA copper ingots occur in hoards in Ireland but no moulds of these ingots have been found (Waddell, 1991). Only by the end of the EBA, when forms became more complicated, had bivalve moulds of stone come into use (Burgess, 1979, Rowlands, 1976). It seems therefore, that sand-casting is also the most likely method to have been in use in the early metal using period in Ireland.

In summary, metallographic evidence is increasingly suggesting casting as the mode of production for early copper-based artefacts. Yet actual moulds are missing in the archaeological record of these early periods. From the late EBA onwards the use of moulds other than sand seems to have become more prevalent. The authors suggest that this is strong evidence for the use of sand-casting during the early periods of metallurgy. But since the evidence has literally scattered in the wind, researchers have tended to overlook it.

Experimental work

The aims of the experimental work were :

a) to collect data on the cooling rates of the moulds,

b) to investigate the correlation between the cooling rate and the size of the mould

c) to study the crystalline structure of the bronze cast in different sized moulds and

d) to trying to understand why sand-casting was abandoned in favour of casting in stone, clay and metal moulds.

In Sheffield experiments casting a variety of bronze tools in sand moulds are regularly carried out. From the discovery of a wooden model of a flat axe in the Swiss lake side dwelling of Wetzikon Robenhausen (Strahm 1994) it is known that wooden models were used in prehistory. In this way, copies of the Iceman's axe (Spindler, 1994) socket and shafthole axes are produced. In the experiments modern metal moulding boxes, modern furnaces and crucibles are used to comply with safety regulations.

For the experiments discussed here two-piece moulding boxes of different sizes were used. The smaller one was 15.2 x 15.2 x 10 cm, the larger one 23 x 23 x 10 cm. A model made of pine wood, of 1.5 x 4 x 1-cm, was used to make the mould. The dimensions chosen were similar to the Iceman's axe. The medium for the mould was 90-95 % sand and 5-10 % clay. Temperature measurements were taken using 5 channel electronic thermocouples. Three thermocouples were placed 2 mm from the casting (channels 1,2, and 3) and 2 were placed 5 mm from the casting (channels 4 and 5). Two castings were made to ensure that results are repeatable. A 10 % tin bronze was used. After the casting, samples were taken from different locations of the casts, mounted in bakelite, ground, polished, etched in alcoholic ferric chloride and studied under the optical microscope.

The Results

An examination of the cooling curves of the smaller mould (fig. 1) shows that the sand in the mould did not reach as high a temperature as that of the larger mould (fig. 2). Thus, as can be expected, the samples from the castings done in the larger mould show signs of staying molten longer than samples from the small one : the metallographic study of the samples from the castings show that they have much larger columnar grains. Furthermore, whereas in the cast of the smaller mould delta phase (jagged, blue-black in micrograph, fig. 3) is present, this is even more pronounced in the cast from the larger mould (fig. 4). We can conclude therefore, that the size of the mould does have a noticeable effect on the cooling rate and thus on the crystalline structure of the object.

However, and more importantly, both casts from the experiment showed large grains and considerable amounts of delta phase, both indicative of slowly cooled castings. Large grains make a metal more brittle and on top of this, the delta phase has very few desirable properties. While it is harder than the alpha phase, it is also mechanically weak and very brittle (Scott, 1991). Just a small amount of cold working would begin to crack the metal, making it difficult to shape. In order to improve the working properties of the metal, the sand cast objects would have to be annealed to allow the delta phase to be absorbed by the alpha phase.

As the metal solidifies after pouring into the mould, one of the key factors is the heat transfer from the metal to the mould. Stone and metal are both denser materials than sand and have a higher heat conductivity. This means that metal cast in either stone or metal moulds will solidify quicker than in a sand mould, resulting in smaller grain size and finer delta phase. During annealing the delta phase in the stone and metal casts can be absorbed into the alpha phase relatively quickly. This has a profound affect on the mechanical properties of a cast object.

Stanianszek and Northover (1982) have shown this to be the case. When they worked tin bronzes cast into stone, metal or clay moulds, the bronze objects cast into the stone and metal moulds had better mechanical properties, i.e.where much more ductile, than the objects cast into a clay mould. This was due to the larger amount of delta phase that the clay cast object contained. Annealing for 15 minutes at 600 oC, improved the properties of the clay cast material considerably. But even six hours of annealing failed to improve the ductility of a sand-cast tin bronzes. The authors of this present paper suggest that this was probably a major contributory to why sand-casting of tools and weapons was abandoned by the end of the EBA.

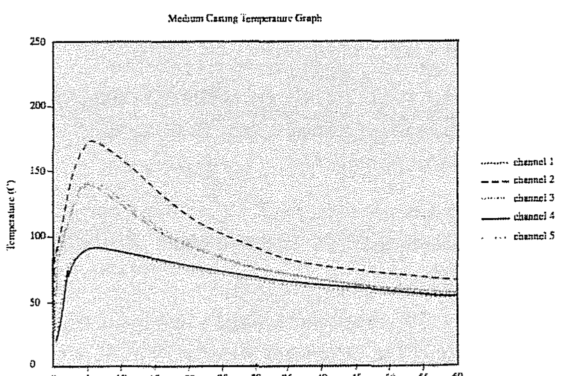

Figure 1 : Small castings temperature graph.

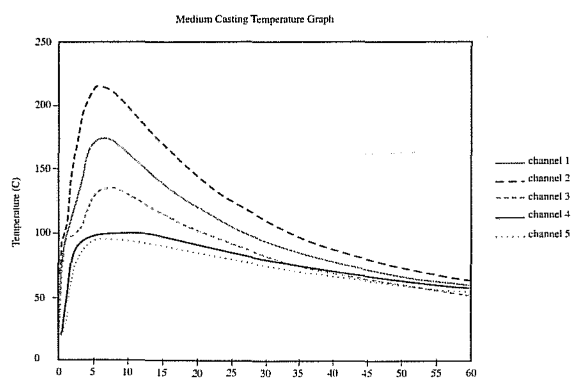

Figure 2 : Medium castings temperature graph.

Figure 3 : Sample small casting one- A. x200.

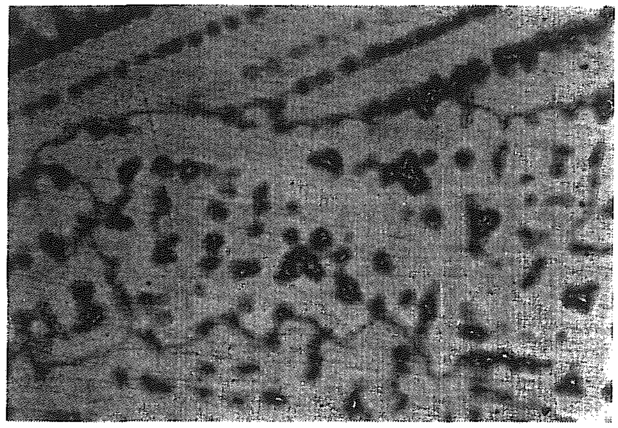

Figure 4 : Sample mediumcasting one- A. x200.

Conclusion

It has been shown that sand-casting was most probably in use to a much greater extent than is normally thought and it is suggested that sand was most likely the original casting medium.

Through experimentation, it has been shown what effects sand-casting has on the cooling rate and microstructure of tin bronzes. Of all the four moulding materials, sand is the slowest cooling. This produces the largest grain size and largest amount of delta phase in the metal. In terms of workability this is the least desirable.

It is suggested, therefore, that when tin bronzes came into use, the casting medium in use, sand, produced objects with poor mechanical properties. They were brittle and required very long anneals before improvement.

This was very wasteful in terms of energy requirements. While this may have been culturally acceptable in some regions, elsewhere different ways of casting the new alloy were sought in order to take full advantage of the properties.

How this was achieved differed from region to region, affording us an insight into the choices taken by prehistoric metal workers. In some areas stone moulds came into use, in others clay and later bronze moulds were used.

Obviously, we need to continue the series of experiments, quantifying the measurements and including work on pure copper cast in sand moulds with varying proportions of clay added to the sand. Further experiments with copper and bronze cast into lost wax moulds are also planned.

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