# Manufacturing techniques of Eastern Zhou bronze ding vessels with short legs: a case study of bronze ding (1949,0711.1) in the British Museum collection

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*ABSTRACT: This paper presents a detailed technical study of a Chinese bronze ding vessel with a bulging body, three short legs and a lid in the British Museum collection (1949,0711.1). It is a representative product made by the pattern-block method of the Houma foundry, the largest foundry site of the Eastern Zhou period (770-221 BC) found to date in present-day Shanxi province. The study confirms archaeologists' speculation that the legs were separately cast, and reveals that the legs were pre-cast and made of unalloyed copper rather than bronze and joined to the vessel body by the lock-on technique. This study provides scientific evidence of the construction of this type of object, raises questions for further research, and will hopefully promote the study of 30 pieces of similar ding vessels from excavations and in other collections to help determine provenance and workshop practices of this group.*

## Introduction

The Eastern Zhou period bronze *ding* vessel (1949,0711.1) (Fig 1) in the British Museum (BM) collection was acquired from General Georges Bagulesco in 1949. It has been identified as a typical Houma vessel and an addition to the 30 similar vessels mentioned below. It is 213mm high including the lid, with the body being 174mm high and 272mm maximum diameter, and weighs 3992.8g in total (body 3021.6g and lid 971.2g). In this paper we present a detailed examination of this vessel using modern analytical methods, to explore its manufacturing techniques and clarify archaeologists' and researchers' speculations about the vessel's construction. This study provides scientific information on the production of Houma bronzes and contributes to our understanding of the development of bronze technology in ancient China.

This *ding* vessel is not an isolated example but has a number of parallels from excavations, museums and private collections around the world. They all feature a bulging body and three short legs, as well as elaborate and repetitive surface decoration. Such decorations result from the use of a sophisticated 'pattern-block' method, a hallmark of the Houma foundry in present-day Shanxi province, the largest Eastern Zhou foundry site found to date. Pattern-block can be defined as a reusable baked clay block on which pattern units have been carved (Barnard and Tamotsu 1975, 58; Bagley 1995, 49). However, scientific examination of these vessels has been scarce and the casting methods of these characteristic Eastern Zhou vessels remain little understood. In the 1950s, a set of seven *ding* vessels, of similar design to the BM one, were discovered in a Warring States period (475-221 BC) tomb M2040 at Sanmenxia, Henan province, during the construction of a water reservoir (Institute of Archaeology, Chinese Academy of Social Science 1994). Visual observation of these *ding* vessels suggests at least two different manufacturing processes, integral casting and separate casting. In the latter process the 'lock-on' technique plays a key role in the construction of a vessel with separately-cast parts. The lock-on technique can be described as: 'inserting the pre-cast components into a mould assemblage that had been prepared for the vessel. The molten metal flowed into the channel and, when set, locked them securely to the vessel' (Gettens 1969, 80).


*Figure 1: The vessel measures 213mm high and 272mm wide at the maximum: a) left and right legs are labelled, the third one is referred to as the back leg, b) motif on the lower decorative band of the body, c) motif on the upper decorative band of the body.*

The seven *ding* vessels from tomb M2040 are of the same style but vary in size, measuring (height x diameter) from 298 x 296mm to 170 x 165mm. Like the BM *ding* vessel, they all feature a bulging body and three short legs. However, visual observation has suggested that the body and the legs of the smallest *ding* vessel from M2040 were integrally cast, while the other six vessels' legs were cast onto the pre-cast bodies with the 'lock-on' technique. It has, therefore, been argued that the smallest vessel may not have belonged to the original set but was a later replacement of a missing one, as it presents a different casting method to the other six. The bronze craftsmen of the integrally cast *ding* vessel may not have been aware of the application of the 'lock-on' technique applied to the other six vessels in the same set. However, scientific evidence of this assumption was not reported (Institute of Archaeology, Chinese Academy of Social Science 1994).

The use of different manufacturing processes has also been observed on a set of five *ding* vessels from the tomb of marquis Zhao of the Jin state (M251), found at the present-day Jinsheng village in Shanxi province (Shanxi Provincial Institute of Archaeology and Taiyuan Municipal Administration of Cultural Relics 1996). It has been suggested by archaeometallurgist Wu (1996) that the lids of these vessels were cast integrally, but the legs and bodies were cast separately. Again, all these speculations were based on visual observation without the aid of modern scientific investigation.

*Table 1: Eastern Zhou ding vessels with short legs recorded to date*

| | Place | No of objects | Reference (Museum No) |
|---|---|---|---|
| From excavations | Shanxi | 7 + group of 5 | |
| | Henan | 4 + group of 7 | |
| | Hebei | 2 | |
| In museum collections | Arthur M Sackler Museum | 1 | (V352) |
| | Royal Ontario Museum | 1 | (932.16.149. A-B) |
| | Princeton University Art Museum | 1 | (65-71) |
| | British Museum | 1 | (1949,0711.1) |
| Recorded in literature | ? | 1 | Umehara 1940, pl 25 |
| | Xiqinggujian | 1 | Liu 2005 |

As noted by Rongyu Su (2016), one of the authors of this paper, this type of *ding* vessel with a bulging body and short legs was prevalent from the late Spring and Autumn period to the mid-Warring States period (late 400s-300s BC) and 30 such vessels are known so far. In addition to the BM vessel and the two sets mentioned above, 13 such *ding* vessels have been found from excavations, three are in museum collections and two are recorded in the literature (Table 1). All these vessels are similar in shape, consisting of a lid, a bulging body, and three short legs, but differ subtly in decorative details, particularly on their lids. Some lids are topped with three animal figures, some attached with three loops near the rim, and the others decorated only with a loop at the centre (Su 2016, 175). Existing information on their casting methods is mostly based on visual observation. Scientific study has only been reported on the vessel in the Arthur M Sackler Museum collection (V352), which included X-radiography and compositional analysis. Based on the radiography, it was suggested that the central loop on the lid was pre-cast and the crouching leopards were solid (So 1995). It was suggested by Li and Li (2009) that the legs of this vessel were pre-cast and then attached to the body by the lock-on technique but scientific evidence was not provided.

## Analytical methods

The analytical techniques used for the examination of the BM vessel included microscopy, X-radiography and X-ray fluorescence spectroscopy (XRF). Surface examination was carried out using a Leica binocular microscope and Keyence VHX digital microscope.

Digital X-radiography and X-ray computed tomography (CT) scanning of the vessel were carried out using a custom-built YXLON Access Y.100 system. The X-ray tube was operated at 450kV and 1.55mA, with a 3.3mm brass filter placed on the tube. Images were captured by a 4 megapixel (2048 x 2048) PerkinElmer XRD 1621 AN15 ES flat panel detector. For CT scanning, 360 projections were taken throughout a 360 degree rotation of the vessel about the vertical axis, with a counting time of 10 seconds per projection. CT volume reconstruction was carried out in the VolumeGraphics Studio 2.2 software package. Computed radiography of the lid was performed with X-ray tube settings of 180kV and 3.85mA, with a 3.3mm brass filter. Images were recorded on Carestream Industrex Flex XL Blue imaging plate (240 x 300mm), and subsequently digitised with a pixel pitch of 25 microns using a Carestream Industrex HPX-1 scanner.


*Figure 2: The lid is 220mm in diameter: a) showing three crouching buffaloes and a central ring, b) the central band motif, c) the second band motif, d) the outer band motif.*

XRF was used for compositional analysis of the metals and was carried out using an Artax μXRF spectrometer with a molybdenum target X-ray tube rated up to 40W and operated at 50kV and 500μA with a counting time of 200 seconds. The alloy composition obtained by surface analysis may not represent the alloy composition of the original metal in most cases due to the presence of corrosion products and contamination from artificial patina used for repair or restoration to cover damaged areas, but can be used to determine the difference or similarity between different parts or components and help identify modern restoration. Hence, in order to determine the original alloy compositions but not to cause visible damage to the object, small areas (approximately 1mm$^2$) on the mould joins on the underside of the vessel base and on the bottom of the legs were cleaned by abrading using silicon carbide papers prior to analysis to remove corrosion products and dirt. The detection limits for each element vary, but are typically 0.1%. The relative precision (reproducibility) is *c*1-2% for main elements analysed and *c*10-30% for the other elements quoted, deteriorating to 50% as their detection limits are approached.

## Results and discussion

### The lid

The lid of the vessel is circular, slightly domed on top and everted at the edge (Fig 2a). It measures approximately 220mm in diameter, 52mm in height and 6mm in thickness at the edge. It has a bridge-shaped knob at the centre with a ring attached and three concentric decorative bands. Three crouching buffaloes sit symmetrically on the plain area between the second and outer decorative band.

The three decorative bands can be described as following: the central, circular band measures 63mm in diameter, and consists of four symmetrical units of motifs (Fig 2b). The second, ring-shaped band has an outer diameter of 160mm and an inner diameter of 85mm. It consists of three pairs of coiled dragons, of which two were interrupted with the buffalos. The dragons in each pair are interlaced and face in opposite directions, their double bodies extend toward opposite directions and are decorated with spiral scrolls and diagonal lines (Fig 2c). The outer, ring-shaped band is 12mm from the second band, decorated with interlaced motifs and filled


*Figure 3: Digital microscope image of the central ring on the lid, showing very fine design lines. The lustrous gold-coloured particles are probably redeposited copper.*

with lines, dots and spirals (Fig 2d). All the motifs in the decorative bands were made using the pattern-block technique.

The handle ring on lid has outer and inner diameters of approximately 36.3mm and 25.5mm respectively, and is decorated with spirals and triangles. The design is very fine and measures less than a third of a millimetre in both width and depth throughout, as measured by digital microscopy (Fig 3). One might assume that such a fine design was probably incised but archaeological evidence of moulds with the same design (Shanxi Provincial Institute of Archaeology 1996, P441.1109 mould IIT87H437) suggests a cast product. Lustrous gold-coloured particles (Fig 3) observed under the microscope were suspected to be gilding, however, XRF analysis showed the absence of gold and mercury, therefore, they are probably redeposited copper.

The buffalo figures attached to the lid (Fig 4) are similar in appearance, each having a ring in their mouth, a raised body decorated with hooked scrolls, cloven-hoofed feet, penis, small eyes and short round horns on the head and nape. X-radiography revealed that the buffalos are hollow with clay core remaining inside (Fig 5). They were cast as integral parts of the lid, as no joins between the figures and the lid can be seen. This was achieved by building a sub-mould for each buffalo in the mould for the lid with chaplets on the clay core to ensure its position. The rings attached to the buffalo figures are, however, solid, as revealed by X-radiography (Fig 5). They, as well as the handle ring in the centre, were pre-cast and attached to the lid. To do so, these rings were wrapped in clay (to ensure they did not attach to surrounding surface) and embedded in the mould for the lid.

*Figure 4: A crouching buffalo on the lid.*

X-radiography revealed many fractures (Fig 5), indicating that the lid has been extensively repaired with soft tin-lead solder. The skill of repair is so sophisticated that the damage is only just visible under the microscope (Fig 6). In some areas, restoration has been carried out to replace missing original fragments, as evidenced by the different texture in the radiograph (Fig 5) and the sharper motif observed under the microscope (Fig 6). XRF analysis showed a significant amount of zinc present in this piece of replacement suggesting it is a modern restoration. This is not surprising, as brass has often been found in restoration of Chinese bronzes (Wang 2012; Wang and Priewe 2016).

Spacers were reported to be present on the lid of the *ding* vessel in the Arthur M Sackler Museum collection (So 1995), but were difficult to identify in the lid studied

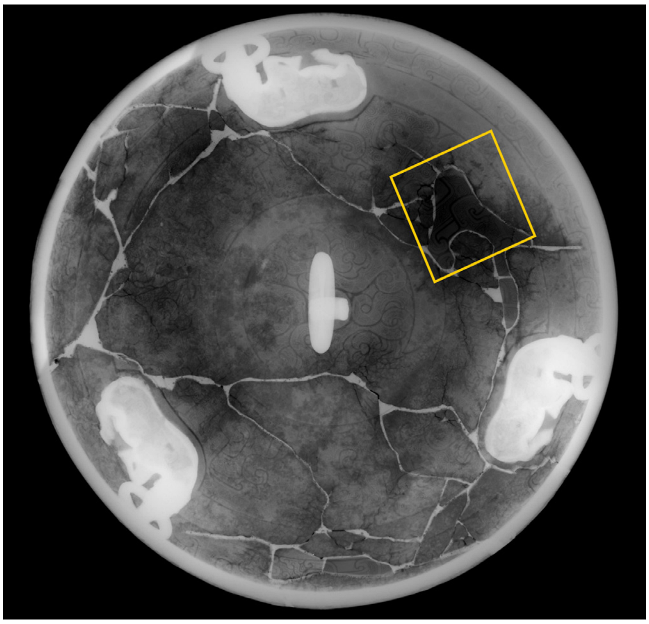

*Figure 5: X-radiograph of the lid, showing extensive repairs using tin-lead solder (the brighter lines). The yellow box surrounds an area of restoration (cf Fig 6).*

*Figure 6: Digital microscope image of the area of restoration marked on Figure 5.*

here due to the extensive repairs. The extensive repairs may also explain the absence of mould joins on the lid.

## The body

The vessel has three short legs, two escutcheon-and-ring handles in animal-head shape in slight relief just below the rim, and two horizontal bands of decoration on the body. To facilitate description, the left and right legs are labelled in Figure 1a and the third leg is referred to as the back leg. Mould-join marks are visible along the length of each leg, indicating a three-piece mould assemblage for the body. The join marks have been removed by surface finishing in the plain area of the lower legs. The vessel body has a stepped-in and everted lip, over which the lid fits.

A bow-string band, which is decorated with two twist double-ropes (Fig 1b) runs around the widest part of the vessel and divides the body into two parts. Bands of decoration running around the vessel are present both above and below the bow-string band, measuring 42mm and 26mm in height respectively. The designs in these bands are of low relief and have a linear theme consisting of lines of different thickness, dots and spirals. Like the lid, all the motifs in the decorative bands were made using the pattern-block technique. The upper band of decoration (Fig 1c) is similar in appearance to the second band on the lid, and consists of coiled interlacing dragons with double bodies, with their heads facing alternately up and down, and their bodies decorated with spirals and diagonal lines. The motifs in the lower decoration band are not recognised but they seem to be similar to the style in the upper, minus the coiled dragons (Fig 1b). The mould-join marks are more pronounced in this band.

Chinese bronzes were typically cast in clay piece moulds (Karlbeck 1935; Gettens 1969). This process usually leaves mould-join marks on outside surfaces of the vessels but often they are removed from the relief areas by the craftsman. As mentioned above, the mould assemblage for the body of this *ding* vessel consists of three sections. Section 1 begins in line with the left leg and measures 238mm long, section 2 begins in line with the right leg and measures 258mm long. The join mark between sections 2 and 3 is blurred due to corrosion of the surface. Section 3 begins in line with the back leg and measures 265mm long, starting at the body of a 'head-up' dragon at the end of section 2, and covers a 'head-down', 'head-up' and then a 'head-down' dragon, perhaps covering a complete pattern-block unit. The traditional piece-mould casting was known to be labour intensive and time consuming, as clay models cannot be reused but need to be made individually every time. This situation was revolutionised during the late 600s BC with the invention of the pattern-block technique, whereby the 'master' clay blocks responsible for the surface decoration on the objects can be reused. Clay blocks with decorative patterns were made first as the 'master' ones and fired to harden them. They can be used in two ways. One was direct employment; it was used as a stamp, impressed into the interior surface of the mould to make decorative patterns directly on the mould (Barnard and Tamotsu 1975). The second was indirect employment, where clay slabs were pressed onto the master block and impressed with the decoration, and these slabs were fitted into moulds for casting (Falkenhausen 1999).

It is interesting to find that the mould sections on the vessel being examined vary in size. Unequal sizes of mould section were also observed on some other Houma bronzes made by the pattern-block technique (Wang *et al* 2019). Could this be due to the use of pattern-blocks? This phenomenon has not been reported before, therefore is of interest with regards to the mould construction of Chinese bronzes, as it is believed that a mould assemblage was usually divided into equal sections.

The escutcheon-and-ring handles are on the upper decoration band, one in section 2 and one in section 3. There are subtle recesses on the inside of the vessel behind the escutcheons. The escutcheons appear to be solid in the X-ray CT images (Fig 7), and are thought to have been cast as an integral part of the body. No clear joins with the body wall were observed, despite the presence of traces of pressing (on clay moulds) surrounding them, presumably to make a smooth junction with the body. The rings attached through the animals' nose loops

*Figure 7: X-radiograph of the vessel wall showing many spacers present (small dark patches).*

appeared to also be solid, as revealed by X-radiography (Fig 7). They were attached to the vessel in the same way as the rings on the lid.

Numerous spacers were used in the wall of the vessel, as revealed by X-radiography (Fig 7). The overuse of a large number of spacers (which is deemed technically unnecessary) has been identified as one of the local features of southern bronze production, as opposed to bronze production in the Central Plains (Su 2015). This study marks the first time that so many spacers were found to be present in the wall of a Houma bronze, which is noteworthy with regards to the future study of bronze vessels from the Houma foundry.

The underside of the vessel has the usual triangular area outlined by mould-join marks which do not extend right to the legs (Fig 8a). In the centre of the underside there is a rectangular projection with a trace of a metal pouring gate in the middle. A small area (*c*2 x 0.5mm) of one of the mould joins was cleaned in order to obtain the alloy composition of the body. It was found by XRF analyses (Table 2) that the body is a leaded tin bronze containing 11.1% tin and 12.8% lead, a typical composition of ancient Chinese bronzes. Mould joins were not observed inside the vessel; instead, four repairing or over-flowing patches are present at the bottom (Fig 8b), which are porous and covered by green corrosion.

## The legs

The cross-sections of all three short legs of the vessel are nearly round, and their inward-facing surfaces are flat. Both the left and the right legs measure approximately 43 x 40mm, while the back leg measures 45 x 40mm in horizontal cross-section. The inner sides of the legs are curved so as to join continuously with the underside

a b

*Figure 8: The base of the vessel: a) underside showing a triangular area outlined by mould join marks and residual pouring gate in the centre, b) inside showing repairing or over-flowing patches.*

a b

*Figure 9: The interlocking flower petals on the leg: a) alternating shiny dark petals and brown petals, b) traces of abrading marks on the dark petals.*

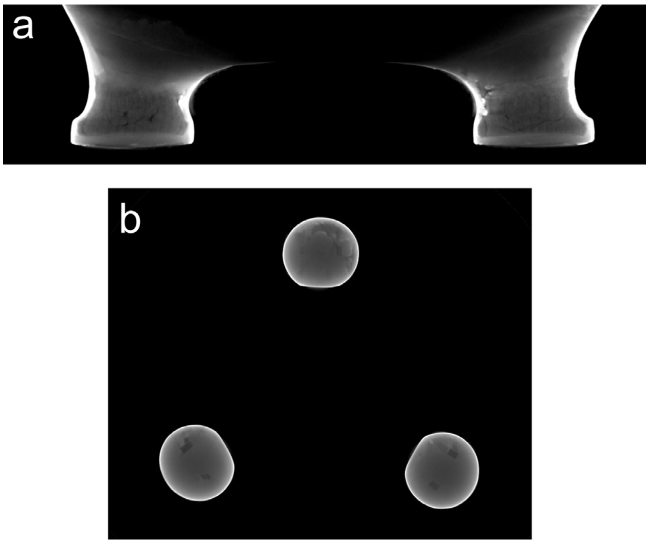


*Figure 10: X-ray CT slices of the legs: a) side view showing separately-cast legs with clay core remaining inside and the overlapping metal which can be seen on the left-hand side of the image, b) vertical view of the bottoms of the legs showing two rectangular spacers in each, thought to be part of the leg mould construction. Scatter and beam-hardening artefacts are present in the CT reconstruction, visible as thin, bright rings around the outside of the legs, and a darkening towards the centre.*

of the vessel. The legs were decorated with flower petals (Fig 9) which are in two groups of alternating appearance – shiny dark petals and brown petals. The dark petals appear to be part of the main body and the brown petals are part of the leg, which seem to have corroded more than the dark petals.

The legs were separately made as either pre-cast or post-cast and joined with the body by the lock-on technique, as revealed by X-ray CT images (Fig 10a). XRF analyses (Table 2) showed that the legs are made of unalloyed copper; the small amounts of tin and lead detected in one of the legs is attributed to corrosion products remaining after incomplete cleaning. Unalloyed copper has a higher melting point than bronzes. This indicates that the legs were made first, as a pre-cast element typically has a higher melting point than the metal of the body to be cast, to prevent the pre-cast element from melting. Archaeological evidence of pre-cast legs has been reported by Li and Li (2009).

Core material is still present inside the legs, and the junction in each leg between the core for the body and the core for the leg is evident (Fig 10a). The wall thickness at the junctions between the legs and the body is larger than throughout the rest of the body. This was probably achieved by a recess in the core for the body. CT images also showed two rectangular spacers on the bottom of each leg (Fig 10b), which were used in the mould construction to prevent the space for the bottom of the legs from shifting or closing during pouring of molten metal, ensuring a precise casting. Based on the contrast on the X-ray CT slices, the spacers used were lower density materials than the alloy of the legs, possibly non-metallic material.

The petals on the outside of the legs are almost flush with those in the vessel body (Fig 9b). Although moulds with such patterns have not been discovered, moulds with similarly interlocking zig-zag patterns were discovered from archaeological excavation in the Houma foundry

*Table 2: Alloy composition by XRF (normalised wt%).*

| Area analysed | Cu | Zn | Sn | Pb | Fe | Ni | Sb | As | Ag |
|---|---|---|---|---|---|---|---|---|---|
| BODY | | | | | | | | | |
| mould join on underside of base * | 74.9 | 0.2 | 11.1 | 12.8 | <0.1 | 0.1 | 0.2 | 0.6 | 0.1 |
| bottom of right foot * | 97.8 | 0.2 | 0.7 | 1.0 | 0.1 | 0.1 | <0.2 | 0.1 | 0.2 |
| bottom of left foot # | 91.0 | 0.2 | 2.1 | 5.9 | 0.4 | 0.1 | <0.2 | 0.2 | 0.1 |
| brown petals on left leg | 94.6 | 0.2 | <0.2 | 3.8 | 0.6 | <0.1 | 0.4 | 0.2 | 0.1 |
| dark petal on left leg | 63.8 | 0.3 | 21.4 | 11.6 | 0.1 | 0.2 | 0.2 | 2.2 | 0.3 |
| ring attached to left escutcheon | 59.9 | 0.3 | 21.9 | 15.7 | 0.1 | 0.1 | 0.4 | 1.3 | 0.2 |
| repair patch on lid | 64.3 | 11.0 | 15.5 | 6.0 | 0.3 | <0.1 | 0.8 | 2.2 | 0.1 |
| dragon head near the repair patch | 19.9 | 1.0 | 20.0 | 55.6 | 1.3 | 0.1 | 0.2 | 1.7 | 0.2 |
| LID | | | | | | | | | |
| buffalo on lid | 44.8 | <0.2 | 26.4 | 26.2 | 0.1 | 0.2 | 0.2 | 1.8 | 0.4 |
| plain band near the edge of the lid | 84.5 | 0.1 | 2.8 | 10.7 | <0.1 | 0.1 | 0.4 | 1.2 | 0.2 |
| central ring on lid | 87.0 | 0.2 | 7.4 | 4.4 | <0.1 | 0.1 | <0.2 | 0.8 | 0.1 |
| central pattern band on lid | 56.9 | 0.7 | 19.8 | 20.5 | <0.1 | 0.1 | 0.6 | 1.3 | 0.2 |
| ring attached to buffalo on lid | 51.5 | <0.2 | 32.8 | 11.9 | 0.1 | 0.1 | 1.5 | 1.7 | 0.4 |

Notes: * = Cleaned areas providing quantitative results. # = Incompletely cleaned area.
All analyses (other than the two marked *) are not quantitative and indicate alloy type rather than original composition.

site (Shanxi Provincial Institute of Archaeology 1993, pl 49, figs 5-6). The mould for the legs of this *ding* vessel could have been similar to that with a zig-zag pattern. A question is raised: why are these petals of different colours? The brown petals were found to have a similar alloy composition to that of the legs, confirming that they were part of the legs. Abrading marks were observed on the dark petals (Fig 9b), suggesting surface finishing. Could the dark petals have been produced by surface decoration techniques such as tin-enrichment decoration (Tan *et al* 2000)? The tin content of the dark petals is higher than that of the body alloy as revealed by XRF analyses (Table 2). However, the high tin content could also be a result of corrosion.

## Conclusion and further research

This is the first detailed technical study of a *ding* vessel with short legs. The combination of X-radiography and alloy compositional analysis confirmed speculations by researchers and archaeologists (Institute of Archaeology, Chinese Academy of Social Science 1994, 112; Wu 1996, 271; Su 2016, 157-160) that the legs were separately cast. Furthermore, this study has revealed that the legs were pre-cast and made of unalloyed copper rather than bronze and joined to the vessel body by the lock-on technique. The flower petals on the legs may have been of both decorative and functional to help secure the joins between the legs and the vessel body. It is, however, still unclear whether the same conclusion could be applied to *ding* vessels with a similar profile but different designs, *eg* zig-zag patterns or plain surfaces, on their legs.

Two important discoveries emerged from this study: the extensive use of spacers in the wall and the unequal sizes of mould sections for the body. These were also observed on other Houma bronzes in the British Museum collection (Wang et al 2019). Is the indiscriminate use of spacers a casting tradition of Eastern Zhou bronze production or is it limited to Houma bronze production? It has been believed that mould sections were of same sizes in a mould assemblage for a symmetrical round vessel. Are the unequal division of mould sections observed on Houma bronze vessels associated with the pattern-block method used at the Houma foundry? This is noteworthy for comparative study in the future by examining more objects, including those from other regions and periods.

This study demonstrates that multiple complementary analytical methods are often required to confirm ancient manufacturing techniques. It is hoped that this research will promote the study of bronze vessels of this type in other museums and from excavations, to help understand how these vessels were made, the similarities and differences in manufacturing techniques present in vessels from different sites, the duration of production of this type of *ding* vessels, as well as whether or not these vessels were made in the same workshop over several generations, as speculated by Su (2016). Answers to these questions will no doubt lead to further research on the impact of the bronze industry on contemporary culture and society.

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