

## The Mysteries of Bronze Melting: An Experimental Archaeological Study on Special-shaped Crucibles in the Bronze Casting Sites of the Shang Dynasty in China

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### Abstract

Based on the observation and analysis of a special-shaped crucible from the Shang Dynasty in China, experimental archaeology was used to reconstruct it and use it in bronze casting operations, exploring the impact of its formula and shape on the efficiency of bronze casting. The experiment found that the special-shaped crucible body formula contains coarse sand, which helps to enhance the crucible's heat shock resistance, effectively strengthen its

hardness, and improve its reusability. The function of the conical basal feet of the special-shaped crucible is to facilitate better fixation of the crucible in the furnace's charcoal pile when bronze melts in it. This reduces the possibility of the crucible tipping over due to the accumulation of bronze melting inside under high temperatures. The experiments have shown that special-shaped crucible's shape and formula are of great significance for maintaining the stability of the efficiency of bronze casting.

**Keywords:** composition, experimental archaeology, function, metallurgy, special-shaped crucibles

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## Introduction

Since the 1930s, Chinese scholars have excavated a number of Shang Dynasty bronze casting sites and found a special-shaped crucible at these sites (Liu, 1933). In terms of texture, these crucibles are generally made of pottery, and their carcasses are thick, the most common of which is sandwiched coarse sand pottery. In terms of appearance, the upper part of the crucible is similar to an open-mouthed vat, with an inwardly closed bottom that is wider at the top and narrower at the bottom. The shape resembles the inverted helmet of an ancient Chinese general, which is why they are called *jiangjunkui* or helmet-shaped vessels in China (Liu 1933; Zheng 1989). It is usually decorated with rope patterns on the outside, and is often unearthed along with bronze casting remains such as crucibles, furnaces, molds, and tuyères.

Special-shaped crucibles are commonly found in Henan, Hebei, Hubei, and other provinces in China, and a few have also been found in Jiangxi, Sichuan, Hunan, Anhui, Guangdong, and other provinces. Most of the special-shaped crucibles found so far have traces of fire, and in the vicinity of the excavated special-shaped crucible included bronze slag, models, charcoal, red-hot earth pieces, and other relics related to the bronze smelting process and bronze casting process were also unearthed. Special-shaped crucibles have been found in many sites such as the northeast of the Xiaotuncun site, the Xiaomintun site, and the Guoyuanzui site. A large number of special-shaped

crucibles of red sand-tempered pottery were excavated from the northeast of the Xiaotuncun site (Fig. 1a and 1b), most of which showed traces of fire on the object surface, and a few of which contained a thick layer of bronze slag on the interior (Zheng, 1989). The special-shaped crucible from the Guoyuanzui site (Fig. 1c) which is made of red sand-tempered pottery, with an open mouth, a square lip, a straight belly, and a small, flat, high, cup-shaped bottom that is obliquely closed at the lower belly, with a secondary bond on the lower belly, and a week's worth of rope-like clay strips secured at the bonding point (Hu, Cheng, Xie, & Lin, 2021).

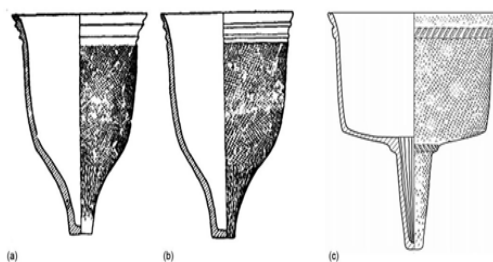


**Fig. 1** Line drawings of special-shaped crucibles (a-b) special-shaped crucibles found in the northeast of Xiaotuncun site (Zheng 1989), (c) Helmet-shaped vessel excavated from the Guoyuanzui site (Hu et al., 2021)

Most of the special-shaped crucibles found in archaeological excavations at present are made of coarse sand. Zhou et al.'s (2015) found that a special-shaped crucible excavated from the site of Xiaotuncun site contained abundant coarse sand and excessive coarse sand when testing the texture of the crucible. These sand grains are dominated by quartz and potassium feldspar with high

contents of  $\text{SiO}_2$  and  $\text{Al}_2\text{O}_3$ . This kind of special-shaped crucible with coarse sand and a thick body, its use should be mostly related to bronze casting. However, some of them were also made with fine sand, and the carcass was thinner. For example, the special-shaped crucible from Shang Dynasty Tomb No. 54 in Huayuanzhuang contains a small amount of fine sand (Xu & He, 2004). Moreover, the special-shaped crucible from the Daxinzhuang site also contains fine sand (Xu, 1995). In addition, Yue (2006) argued that this type of special-shaped crucible should not be related to the use in bronze casting.

Likewise, in the Shang Dynasty in China, pottery was mainly made using the coiling technique and the wheel-throwing technique, and the traces of the making were smoothed out (Li 2007). It can be hypothesized that the ancestors of the Shang Dynasty in China may have used the coiling and slow wheel-throwing methods to make a special-shaped crucible.

For a long time, Chinese archaeologists have proposed suggestions regarding the formula, manufacturing process, and function of special-shaped crucibles. The formula materials are mostly coarse-grained sand or fine-grained sand. The making methods may be the coiling technique or the wheel throwing technique, and the functions mainly include bronze casting crucibles or a kind of bronze holding tool (Liu, 1933; Shi, 1955; Xu & He, 2004; Yue, 2006; Zhou et al., 2015). However, these suggestions are largely based on direct observation combined with

empirical speculation and have not been tested by the experimental archaeology method. And no systematic research has been carried out, especially for the clamping part of a unique biped crucible. Given the limited knowledge of the production process and function of the special-shaped crucible among the Chinese archaeological community, it is necessary to adopt experimental archaeology to conduct systematic research on this crucible. Therefore, this research adopts the method of experimental archaeology, referring to the existing archaeological excavation data and the research of related scholars. Through a series of experiments, the making of special-shaped crucibles and the process of bronze smelting are analyzed in depth, in order to determine the material formula, making process, and function of special-shaped crucibles, and to provide practical insights for the study of crucibles used for bronze smelting in the Shang Dynasty of China.

## **Materials and Methodology**

In order to gain new insights into the special-shaped crucible, the experimental archaeology research method was utilized, with experiments; Experiment 1, Experiment 2, and Experiment 3. In these experiments, the formula materials and fabrication methods were used as variables to reconstruct the fabrication of the special-shaped crucible and the bronze smelting process, and further explore the roles they played in the bronze smelting process.

## 01. Experiment framework

Experiment 1: To explore the making method of a special-shaped crucible, we refer to the making process of Shang Dynasty pottery to design the experiment. According to the archaeological data and the research of other scholars, the making method of Shang Dynasty pottery consists of the coiling method and the slow wheel throwing method, and the archaeological data show that most of the formulas are composed of clay and coarse sand. Therefore, we used the formula composition of clay and coarse sand as a quantitative measure, and the coiling method and the slow wheel throwing method as variables to shape two control groups. In total, five pieces of special-shaped crucible were produced, which were: special-shaped crucible 'a' (coiling method, erect), special-shaped crucible 'b' (coiling method, upside down), special-shaped crucible 'c' (slow wheel throwing method, erect), and special-shaped crucible 'd' (slow wheel throwing method, upside down). In addition, a special-shaped crucible 'e' was created with a mold as a support to prevent it from collapsing during the drying process. In addition, the placement method was also taken into consideration. The placement methods of special-shaped crucible 'a' and special-shaped crucible 'b' are different, which can form a control group; the placement methods of special-shaped crucible 'c' and special-shaped crucible 'd' are also different, which also can form a control group. According to the archaeological data, it was found that a large number of sandstones were found

in the Xiaomintun site, which acted as millstones (Yue 2006; The Institute of Archaeology, Chinese Academy of Social Sciences, 2020). It is therefore speculated that it could be used to make special-shaped crucibles and other bronze smelting equipment. Therefore, the sandstone was used to modify the shape of the special-shaped crucible during the making process.

Experiment 2: To explore the performance of the formula materials for a special-shaped crucible, based on experiment 1, the fabrication method was taken as quantitative and the material formula as a variable. A total of three special-shaped crucibles were made, which were special-shaped crucible 'f' (clay, coiling method), special-shaped crucible 'g' (clay and fine sand, slow wheel throwing method), and special-shaped crucible 'h' (clay and fine sand, coiling method). The coiling method uses clay or clay and fine sand as the formula composition—the special-shaped crucible 'f', special-shaped crucible 'h', and the special-shaped crucible 'e' form a group of control experiments. Using the slow wheel throwing method, clay was used as the formula component, and the special-shaped crucible g was placed upside down with the special-shaped crucible 'd' to form a control experiment.

Experiment 3: To better understand the role played by a special-shaped crucible in the bronze smelting process, and to explore the influence of the shape of the special-shaped crucible in the Shang Dynasty of China on the bronze melting process. The four special-shaped

crucibles produced in Experiments 1 and 2 were used in the bronze smelting process. A flat-bottomed crucible commonly used in the Shang Dynasty in China was also produced for bronze smelting. It served as a control group with the special-shaped crucibles to observe the effect of the shape of the two types of crucibles on bronze smelting. The materials or equipment required for Experiments 1 and 2 included clay, coarse sand, fine sand, sandstones, kilns, bronze casting turntables, and others. The materials required for experiment 3 include a furnace, charcoal, tuyère, blower box, flat-bottomed crucible, and so on. Experimental materials or equipment, such as an infrared thermal imager, thermometer, high-temperature resistant gloves, crucible tongs, and other experimental materials or equipment are also needed in the experimental process. Except for the furnace, the tuyères, and the flat-bottomed crucible were all made by the experimenters during the preparation. The rest of the materials or equipment were purchased in advance or customized by professional craftsmen, such as the blower box.

## 02. Experiment 1: Manufacturing process for special-shaped crucible

Experiment 1 uses coarse sand and clay as the formula to make six pieces of special-shaped crucibles according to a ratio of 60% coarse sand and 40% clay. The coarse sand and clay were sifted and mixed with enough water to form several clay balls, which were repeatedly kneaded and wrestled to increase the density of the clay and make the sand content more uniform.

The balls were then sealed and aged for three days.

Special-shaped crucible 'a' and special-shaped crucible 'b' are made with coiling. The crucibles are made by rolling a well-aged clay ball into a strip and coiling it one by one. Special-shaped crucible 'a' is made in the erect position, while special-shaped crucible 'b' is made in the inverted position. The two special-shaped crucibles form a comparison group. Special-shaped crucible 'c' is made in the erect position, while special-shaped crucible 'd' is made in the inverted position. The two special-shaped crucibles form a control group. The special-shaped crucible is crafted by first making the body and then the tapered foot. Sandstone is selected to smooth its surface to make the special-shaped crucible. After the tapered foot of them is completed, it is bonded to the completed body. The joint is smoothed with a damp hand, then wrapped with a clay strip, the traces of which are smoothed out. A pattern is then scratched into the clay strip to simulate a rope-like clay strip (Fig. 2a). After it has been allowed to dry and removed, it is used a spatula to finish the inside of the vessel in a rotational motion.

Special-shaped crucible 'e' is made using the coiling method with the addition of mold support (Fig. 2b). To make it, the mold is first inverted, then the special-shaped crucible 'e' is made by coiling around it. After the object is finished, the traces of the clay strips on the outside are smoothed with water by hand. During the drying

process, small cracks appear, which are repaired in the same way. After drying, the special-shaped crucible 'e' can be easily separated from the mold using gravity. The special-shaped crucible 'e' is separated, the mouth edge is trimmed flush, and the internal trace of clay strips is smoothed with a hand dipped in water (Fig. 2c and 2d).

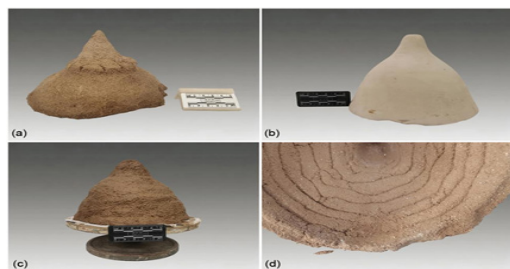


**Fig. 2** Experiment 1 making process (a) Special-shaped crucible with rope-like ornamentation (b) Mold (c) Special-shaped crucible e (d) Trace of clay strips on the inner wall of the special-shaped crucible

### 03. Experiment 2: Experimental Reconstruction of the special-shaped crucible's formula

The special-shaped crucible is made of pure clay using the coiling method and is supported by a mold. The clay has a certain degree of plasticity during the making process, and the clay strips do not break easily. After, the traces of the clay strips on the surface are smoothed out with a hand dipped in water.

Special-shaped crucible 'g' and special-shaped crucible 'h' were made with a recipe including coarse sand and clay, both in the proportion of 60% coarse sand and 40% clay. The special-shaped crucible 'g' was produced by the slow

wheel throwing method; no cracking was observed during the making process, and the walls were also trimmed with a spatula after drying (Fig. 3a and 3b). A special-shaped crucible 'h' was made by the coiling method, with molds added for support during the making process. A small amount of cracking was observed during the drying process, which could be repaired by dipping the hand in water (Fig. 3c and 3d).

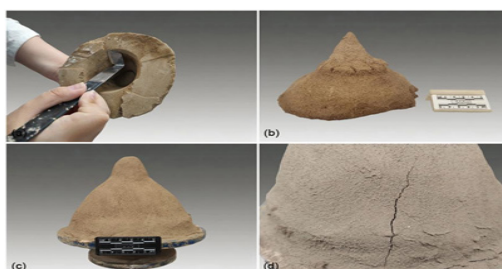


**Fig. 3** Experiment 2 making process (a) Trimming vessel wall over process (b) special-shaped crucible d (c) special-shaped crucible i (d) Cracks in special-shaped crucible i

### 04. Experiment 3: Experimental reconstruction of the function of the special-shaped crucible

The four pieces of special-shaped crucible dried in Experiment 1 and Experiment 2 were put into an electric kiln for preheating and firing (600°C), removed by natural cooling with 80% malachite and 20% tin built-in, and then placed on a cast bronze melting furnace for melting (Fig. 4a).

In order to explore the functionality of the special-shaped crucible, a flat-bottomed crucible was made to contrast with it. The flat-bottomed crucible is formed using the slow wheel-throwing method, with 60% coarse sand and 40% clay.

A flat-bottomed crucible is made and dried, filled with 80% bronze and 20% tin, and placed in a furnace on charcoal by clamping the outside of the crucible with a tong. Due to the unevenness of the charcoal pile in the bronze melting furnace, the flat-bottomed crucible is tilted when it is placed, and it is difficult to place it in the center of the charcoal or in the lower part of the charcoal where the temperature is high. During the bronze melting process, the flat-bottomed crucible cracked slightly. The crucible shook after the lower layer of charcoal was burned out (Fig. 4b). In addition, during the bronze melting operation using the special-shaped crucible, the special-shaped crucible and the melting furnace were photographed, observed and recorded by using equipment such as an infrared thermal imager and a precision pyrometer.



**Fig. 4** Experiment 3 process (a) Process of bronze melting in crucibles with a special-shaped crucible

(b) Process of bronze melting in flat-bottomed crucibles

## Results and Discussion

01. The correlation between making methods and crucibles

Terms of the making process, the results

of Experiment 1 show that special-shaped crucibles can be produced by both the slow wheel throwing method and the coiling method, and that the use of the slow wheel throwing enables the making of smooth and regular shapes due to its own highly efficient kinetic energy. In addition, the object trace or residue reflects the making process to a certain extent. Firstly, special-shaped crucible 'b' and special-shaped crucible 'e' show traces of clay strip joining as a result of the coiling method (Fig. 5a). Secondly, special-shaped crucible 'b' and special-shaped crucible 'e' show signs of hand-dipped smoothing due to the use of water to smoothen the cracks between the clay strips (Fig. 5b). Thirdly, special-shaped crucible 'h' shows traces of craking (Fig. 5e). In the meantime, it also shows wheel smoothing due to the use of wheeling (Fig. 5c). Fourthly, special-shaped crucible 'd' shows traces of spiral pulling due to the wheel throwing method. Fifthly, special-shaped crucible 'h' shows adhesion traces due to the foot bonding to the body and traces of cording due to the decoration created (Fig. 5d). In the end, special-shaped crucible 'd' shows traces of polishing due to the use of sandstone to polish the object surface.

The method of placement plays a crucial role in whether the special-shaped crucible can be formed. Experimental results show that it is easier to shape the crucible by using the inverted method. Orthotropic crucibles can deform because the edge of the mouth cannot support the weight of the billet. However, the process is also influenced by the skill of the experimenter,

particularly in controlling the thinness and thickness of the crucible. Improper control may lead to issues such as collapsing. To address this, a mold was used as a support during the formation of the special-shaped crucible, effectively solving the collapse problem.

## 02. The correlation between formula materials and crucibles

In terms of formula materials, the results of experiment 2 show that the formula of clay and coarse sand is effective. Firstly, adding coarse sand to clay can make the special-shaped crucible more plastic and have low energy consumption. The special-shaped crucible 'e' and special-shaped crucible 'h' have tiny cracks in the drying process. The special-shaped crucible 'e' is not easy to crack after repair, and the special-shaped crucible 'h' cracked again after vibration when taken down after repair. Secondly, the refractoriness of coarse sand is better. A special-shaped crucible must be melted in the casting furnace at high temperatures. The special-shaped crucible is made by adding coarse sand, which improves its refractoriness. It is not easy to crack in bronze melting at high temperatures and has muscular toughness. The special-shaped crucible 'g' formulated with fine sand is less suitable as a part of the formula because of the phenomenon of breaking into several pieces and poor toughness after the bronze melting test. However, it is noteworthy that crucibles containing fine sand have indeed been discovered at archaeological sites. However, most of them were unearthed from tombs and are decorated with patterns; they

may not have been used as crucibles for bronze casting.

The special-shaped crucible 'f', which is formulated with pure clay, is also not suitable as part of the recipe due to its fragile texture and poor refractory properties. In addition, experiment 2 was able to verify that the texture of the special-shaped crucible was clay mixed with coarse sand, as pointed out in the studies and scientific tests of past scholars (Yue, 2006; Zhou et al., 2015).



**Fig. 5** *Traces and residues of the crucible of special-shaped crucible during the making process and the bronze melting process (a) Traces of clay strips in the special-shaped crucible 'b' (b) Traces of smoothing in the special-shaped crucible 'b' (c) Traces of wheel throwing in the special-shaped crucible 'h' (d) Traces of adhesion of the bottom foot to the body and the trace of the rope pattern (e) Cracking of the crucible of special-shaped crucible 'f' (f) Clear air holes and bronze slag residues attached*

*on the inner wall of the special-shaped crucible 'h'*

### 03. The correlation between the crucible's shape and function

Experiment 3 systematically verifies the superiority of the special-shaped crucible in the bronze melting and casting process, which is mainly reflected in the fixation aspect. The experimental results show that compared with the flat-bottomed crucible, the special-shaped crucible with its unique bottom support design not only effectively avoids the tilting and shaking of the charcoal combustion process, but also significantly improves the stability and safety of the crucible through the fixing method of deepening the charcoal layer to avoid the accidental outflow of the bronze solution. The funnel-shaped internal structure promotes the circulation of airflow and concentration of heat, and the formation of an air pressure difference accelerates the melting process of the charge, shortens the melting time, and reduces the burning and suction of bronze elements.

The conical foot of special-shaped crucibles exerts a significant influence on the function and structural stability during the bronze melting operation. It facilitates rotation, allowing the crucible to move more smoothly toward the bottom of the furnace when adjusting its position or performing delicate operations. However, due to the support of the foot, it is possible to ensure enough charcoal in the lower part of the crucible to provide heat, which further enhances the flexibility of operation

and the overall efficiency of the bronze melting operation. The effect of gravity also makes the center of gravity of the crucible of special-shaped crucible fall closer to the bottom of the furnace than in the initial state, which is less susceptible to the airflow in the furnace as well as to the influence of the slight shaking caused by the air blast, such as tipping. Consequently, maintaining the fixed state and improving the efficiency of bronze melting is achieved. At the same time, in the process of outward clamping, the conical foot of the crucible with a special-shaped crucible will continuously reduce the contact surface and friction, which is more conducive to outward clamping. In addition, the special-shaped crucible also provides convenience for the bronze casters, as the foot with a specific height can increase the object's height so that the bronze casters can put in the bronze ore conveniently.

The wall thickness is critical for the crucible to withstand high melting temperatures. Crucibles with thin walls may be unable to withstand thermal and mechanical stresses at high temperatures during the melting process, resulting in crucible breakage or deformation. Therefore, crucibles with thin walls are unsuitable for melting high-temperature metals like bronze.

During placement and pouring, the conical foot area must be well secured by means of an auxiliary tool (e.g., crucible tongs). During the pouring of the bronze solution, it is important to ensure that the center of gravity of the special-shaped crucible is located

above the crucible tongs, which helps to enhance the flow rate of the bronze solution.

Through repeated bronze melting experiments, it can be found that the special-shaped crucible is mainly an externally heated crucible, which tends to show an internal temperature higher than the external temperature due to the release of a large amount of heat from the melted material inside the crucible at high temperature. It is mainly characterized by the smooth outer wall of the crucible before bronze melting; in the process of bronze melting, the crucible becomes rougher and adheres to bronze slag (Fig. 5f) due to oxidation and thermal stress under a high-temperature environment.

## Conclusion

From the perspective of experimental archaeology, we reconstructed a special-shaped crucible in the Shang Dynasty of China and explored the relationship between its shape and function. Although the current results are based on a limited number of experimental samples, which may reflect a part of the variability and standardization of actual production processes during the Shang Dynasty, we still found that the columnar or conical bottom foot of the special-shaped crucible was mainly used for fixing so that the crucible could be stood in the charcoal gap of the melting furnace in the state of being full of bronze liquid and not tilted over to lead to failure of the melting of bronze, which improved the efficiency of the melting of bronze. It also showed that

the special-shaped crucible was not only the embodiment of decorative features but also the intelligent understanding of the function of artifacts by the ancient Chinese bronze craftsmen. Regarding the formula and making method of crucibles, the experiments pointed out that the advantage of the coarse sand is that it improves the thermal shock resistance of crucibles at high temperatures, which is helpful for the reuse of crucibles. The making method of crucibles may be the coiling method or the slow wheel throwing method. The specific judgment still needs to be combined with the petrographic analysis and other scientific and technological means to assist. In the future, we could conduct further research on special-shaped crucibles, including expanding the range of experimental variables, such as size.

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