Piece Mold, Lost Wax & Composite Casting Techniques of the Chinese Bronze Age

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Table of Contents

Abstract

China can claim a history rich in over 5,000 years of artistic, philosophical and political advancement. As well, it is birthplace to one of the world's oldest and most complex civilizations. By 1100 BC, a high level of artistic and technical skill in bronze casting had been achieved by the Chinese. Bronze artifacts initially were copies of clay objects, but soon evolved into shapes invoking bronze material characteristics. Essentially, the bronze alloys represented in the copper-tin-lead ternary diagram are not easily hot or cold worked and are difficult to shape by hammering, the most common techniques used by the ancient Europeans and Middle Easterners. This did not deter the Chinese, however, for they had demonstrated technical proficiency with hard, thin walled ceramics by the end of the Neolithic period and were able to use these skills to develop a most unusual casting method called the piece mold process. Advances in ceramic technology played an influential role in the progress of Chinese bronze casting where the piece mold process was more of a technological extension than a distinct innovation. Certainly, the long and specialized experience in handling clay was required to form the delicate inscriptions, to properly fit the molds together and to prevent them from cracking during the pour. This casting process expanded upon their existing divisions of labor to require implementing strict controls to manage huge quantities of bronze, clay, firewood, workers and significant logistical problems. To offer some perspective about the demand for ritual vessels, in a single tomb for the Marquis Yi of Zeng, more than 10,000 kg (10 metric tons) of bronze was unearthed. It has been estimated that 200 to 300 craftsmen were needed to produce an 800 kg vessel, not including the laborers who mined and smelted the bronze alloys.

Developments of increasing sophistication occurred together with improvements in casting technology, yet it was more than mere familiarity with the bronze material. The Chinese also had made advances in process planning, extracting, refining and experimenting with vessel form and decoration. From a metallurgical standpoint, Chinese bronzes showed huge variation when compared with the consistency of western alloys. The percentage of tin could vary significantly with other elements being randomly included. Still, the ritual bronzes, elaborately decorated vessels used by the early Chinese aristocracy in ceremonial banquets to honor their ancestors, were some of the most impressive and intriguing remains unearthed in the 20th Century. They are highly regarded for their bold exaggeration and distorted representation of ogres, dragons and other mythical beasts. By studying the casting techniques and the different molds, it is possible to see the development of the various dynastic bronze types and observe patterns that are specific to a time period and ethnic group that can offer some perspective about the culture and are crucial for authentication purposes.

Approximate Timeline

- **Neolithic Period** (8000-1700) BC
  - Yangshao culture (5000-3000) BC
  - Hongshan culture (4700-2500) BC
  - Dawenkou culture (4300-2500) BC
  - Majiayao culture (3100-2700) BC
  - Liangzhu culture (3300-2200) BC
  - Longshan (2600-2000) BC
- **Xia** (2100-1600) BC
  - Erlitou culture (1900-1600) BC
- **Bronze Age** (1766-121) BC
- **Shang** (1700-1100) BC
  - Zhengzhou phase (1600-1400) BC
  - Erligang culture (1500-1300) BC
  - Anyang phase (1300-1100) BC
  - Yinxu culture (1200-1050) BC
- **Zhou** (1100-256) BC
  - Western Zhou (1100-771) BC
  - Eastern Zhou (770-256) BC
  - Spring and Autumn period (770-476) BC
- **Warring States** (475-221) BC
- **Qin** (221-206) BC
- **Han** 206 BC - 220 AD

Chinese provinces [1]

Introduction

China can claim a history rich in over 5,000 years of artistic, philosophical and political advancement. As well, it is birthplace to one of the world's oldest and most complex civilizations. Though regional differences provide a sense of diversity, commonalities in language provide a thread of continuity binding this vast population. By 1100 BC, during the Shang dynasty, a high level of artistic and technical skill in casting bronze had been achieved [2]. The intricately decorated vessels had many shapes and sizes and were cast for the use of the early Chinese aristocracy; these vessels held food and wine in ceremonial banquets to honor their ancestors [3, 4]. Ancestors, it was believed, could intercede on behalf of the living, provided they were honored and respected. The bronze vessels were kept in ancestral halls and used during feasts and banquets. Most bronze vessels were used for food or to heat or cool a millet-based wine. Others served as water basins or jugs. Wine vessels were predominant during the Shang period, but ritual changes in the middle of the Western Zhou period resulted in a shift toward food vessels [5]. These Shang and Zhou bronze vessels were the most highly esteemed objects of their time, assuming the position held by jade in the late Neolithic period [5]. In addition to their functional and symbolic role in support of lineage rites, bronzes also demonstrated the latest technical and artistic developments.

Ritual bronzes are some of the most impressive and intriguing remains surviving from Chinese antiquity [4]. What sets most of the Chinese bronzes apart from the Western bronzes is their disregard for realism with bold exaggeration and distortion (ogres, dragons, taotie beasts and other creatures with jumbled features lurk from the bronzes). From carbon-14 dating it has been established that the Shang dynasty extended more than 500 years [6] (1700 BC -1100 BC). The Shang metallurgical tradition probably arose quickly from their long experience with pottery during the Neolithic Period (8000 BC - 1700 BC). The pottery kilns found near Xi'an could maintain temperatures at 1400 °C as early as the 6th millennium BC, more than enough to melt copper.

Two prevalent techniques for casting bronze were the piece mold technique and the lost wax method. The Chinese were a culture with much experience working pottery, and though their bronze work demonstrated great craftsmanship, their techniques sharply contrasted with the Middle Eastern and European bronze development that relied on annealing, cold working and hammering [8, 7, 4]. The Chinese bronze workers used simple and composite piece mold techniques for most of their history while the West had been using lost wax bronze casting as far back as 3500 BC [8]. It is believed that the bronze industry in China developed independently from the West because of these differing techniques [7, 9]. The Chinese, however, became more sophisticated bronze metallurgists due to this preference for casting; metallurgy became the primary means of controlling the metal’s behavior. The famous terra cotta soldiers found gripping bronze weapons at Xi’an demonstrate the deliberate alloying of copper and tin with titanium, magnesium and cobalt for superior hardness (~220 BC) [9].

Bronze is created by combining copper with tin in various proportions. Many other elements (lead, zinc, aluminum) can be added to create different kinds of bronze alloys with specific characteristics and mechanical properties [10]. Bronze alloys were used almost to the exclusion of any other alloy for nearly 1000 years in China; even after the introduction of iron, bronze was used for weapons, vessels, coinage and statuary [7]. The evolution of foundry practices and the craftwork required for ceramics, mold making, metal refining, finishing and machining lend to understanding the development of technology in China. Casting techniques and materials specific to a time period and ethnic group can offer some perspective about the culture and are often used for group classification in archaeology and are crucial for authenticating.

In most western or Middle Eastern cultures, metalworking began with sheet metal, typically in the form of native copper, gold or electrum; these were metals that were found in or could be beaten into a sheet. Smelted metal, to the contrary, had to be worked (hammered flat) into a sheet after it was cast in a billet or ingot. For the simplest type of casting, a concave depression was dug in the ground and metal was poured into it; a round, concave depression produced a bun shaped metal ingot [7]. Working sheet metal had limitations that a skilled metal smith could overcome, but still, it was not an easy task. **Figure 1** shows a copper alloy bowl that was made using the hammering technique in Persia around (550-331) BC.

Figure 1 – Phiale (libation bowl), ca. 550-331 BC, Achaemenid period, hammered copper alloy, (H: 5.4, W: 17.0 D: 17.0) cm, Iran [11].

The sheet could be bent, hammered up or down (raised or sunk) into a round shape or joined by riveting, soldering or lapping [7]. The metal thickness could be changed, but to be worked as sheet, the metal had to be somewhat malleable and ductile. Annealing techniques (softening the metal by heating to a temperature below its melting point) would have to be used for sheet working [7]. In fact, a whole series of processes had to be mastered by the ancient smith to reshape the metal into those unnatural forms. Some of these processes required a very specific series of steps, including intermediate anneals, to attain the final product. In casting, however, the metalworker treated metal not as a deformable plane, but as a liquid. It was poured into a container and then allowed to harden (cool and solidify) [7]. The actual casting, while interesting, was one of the simplest steps in the process; much more time was spent in making the molds, cleaning up, and finishing the casting after the mold was removed.

Bronze Transition from Clay

The shapes of the early Chinese bronze vessels were very similar to the forms they made with clay, yet somewhat rough and primitive [3, 4, 12]. The vessel's purpose was the same; just the material used to make it had changed. Bronze artifacts initially were copies of clay objects, but soon evolved into shapes adapted to the specific characteristics of the bronze material. In design, the uneven and unbalanced appearance of bronze vessels changed, and components of the vessel became more harmonious. The number and variety of vessel forms increased through time, as well as the complexity of decoration and manufacturing techniques [13]. It has often been pointed out that bronze casting was only possible because the bronze makers had access to highly developed ceramic technology. Certainly, long and specialized experience in the clay handling was required to form the delicate inscriptions, to properly fit the molds together and to prevent them from cracking during the pour [4]. Developments of increasing sophistication occurred alongside improvements in casting technology; it was more than mere familiarity with the bronze material, however. Several influences may have encouraged this rapid development. By the end of the Neolithic period, the Chinese already demonstrated technical skill with hard, thin walled ceramics whose creation involved many of the same techniques that bronze casting required [8]. The Chinese also had made advances in process planning, extracting, refining and experimenting with vessel form and decoration.

Elemental Analysis of Bronze Alloys

When compared with the consistency of western alloys, Chinese bronzes show huge variety. The percentage of tin could vary significantly with other elements being randomly included [14, 15]. Throughout the Bronze Age in China, both binary (copper-tin or copper-lead) and ternary (copper-tin-lead) alloys are commonly found. Elemental analyses have now been reported for a considerable number of bronzes with a provenance provided by archaeological documentation. Analyses show a wide range of compositions among objects from a single site, even from a single tomb. **Table 1** provides some idea of the composition ranges reported from the Sanxingdui pits in Sichuan province (24 bronzes, vessels excluded), from sites in Henan province at Erlitou, Erligang and three sites from Anyang, Fu Hao's tomb, a smaller tomb at Yinxu and Guojiazhuang, and the Xin'gan tomb in Jiangxi province [15]. Only the Fu Hao bronzes show any appreciable control of alloy composition. Otherwise the limits are very wide for the analyzed bronzes. This is not really surprising, even assuming an unrestricted supply of metals, alloy composition is very difficult to control, and no ancient bronze founder would bother to purify the metals and mix them in specific proportions. For weapons, where mechanical properties are important, alloy control might have been attempted (though analytical data show little evidence). For vessels and statuary, however, all that was needed was an alloy that would cast well, and this was not a severe constraint. More important was the need to recycle the valuable bronze material; the founder who recycled miscellaneous artifacts (for instance captured bronze weapons) sacrificed control of composition. It seems likely that the only control normally exercised came at the stage when the bronze was molten: if the color or viscosity of the molten metal did not seem right, the founder added copper, tin or lead to achieve a look that experience told him would pour well [15].

One reason for the prevalence of bronze may have been the color range that could be achieved by varying the amounts of copper, tin and lead in the alloy. A polished bronze surface could appear light pink to light yellow, silver-grey, grey-white, silver-white, yellow-grey-white, orange-yellow, red-yellow or copper-red just by varying the percentage of copper, tin and lead. The alloy color changes from copper-red through orange and yellow to white as tin was added to the pure copper.

Table 1 - Elemental composition of bronzes from early Bronze Age sites [15].

Site	Date (BC)	Samples analyzed (objects analyzed)	% Cu	% Sn	% Pb
Erlitou	c. 1500	32 (32)	35-99 +	0.04-23	0.03-6 1
Zhengzhou	c. 1500-1300	5 (5)	53-80	0.53-18	6-41
Sanxingdui	c. 1200	27 (24)	64-98	0.03 - 12	0.03-33
Tomb at Jiangxi Xin'gan	c. 1200	6 (6)	75-84	4.6-18.4	0-7.8
Fu Hao tomb at Anyang	c. 1200	89 (89)	72-88	9-20	<8
Guojiazhuang tomb 160 at Anyang	12th C.	19 (19)	69-99	0-19	0.41-22
Yinxu Xiqu tombs of Periods II and III at Anyang	12th C.	18 (18)	72-94	0- 20	0.5-22

Lead does not enter into the copper and tin containing phases to any great extent, but instead forms discontinuous spheres of nearly pure lead in the solid metal. The addition of lead tends to add grey to the metal color, decreasing the intensity rather than changing the hue [7]. From the available evidence it appears that the ancient Chinese formulated their alloys, at least in some cases, with color in mind. In **Figure 2**, the ternary diagram showing the three bronze group compositions are indicated. The mirrors center closely in the silver-grey color composition, evident from the mirrors seen in **Figure 3**. The composition of 71% copper, 26% tin and 3% lead is probably the lowest tin composition that can be called "white". With less than 25% tin, the metal becomes a yellow tone. The ceremonial vessels (used for **Figure 2**) were analyzed at the Freer Gallery of Art; thermo luminescence testing was performed for authentication. The vessel colors ranged from orange to light yellow. The Mingdao coinage (also analyzed at the Freer) has a very high lead content, and would have looked light pink to light yellow when newly cast and polished. These three types of bronzes form distinctly different compositional groups [7].

Figure 2 also demonstrates the variation in alloy composition for a given application. The copper-tin-lead system exhibits a great range of physical properties that depend on composition; hardness varies with tin (and lead) content. The mirror alloy seems to have been chosen for its color and the serendipitous effects of hardness tended to minimize scratching and allowed the bronze surface to achieve a high polish [7]. The quote from a sword smith in the *Lit Shi Chunqiu*, stating that copper makes a sword elastic and tin makes it hard and easily broken, shows the kind of empirical knowledge of physical properties that was known by the ancient foundry worker [7].

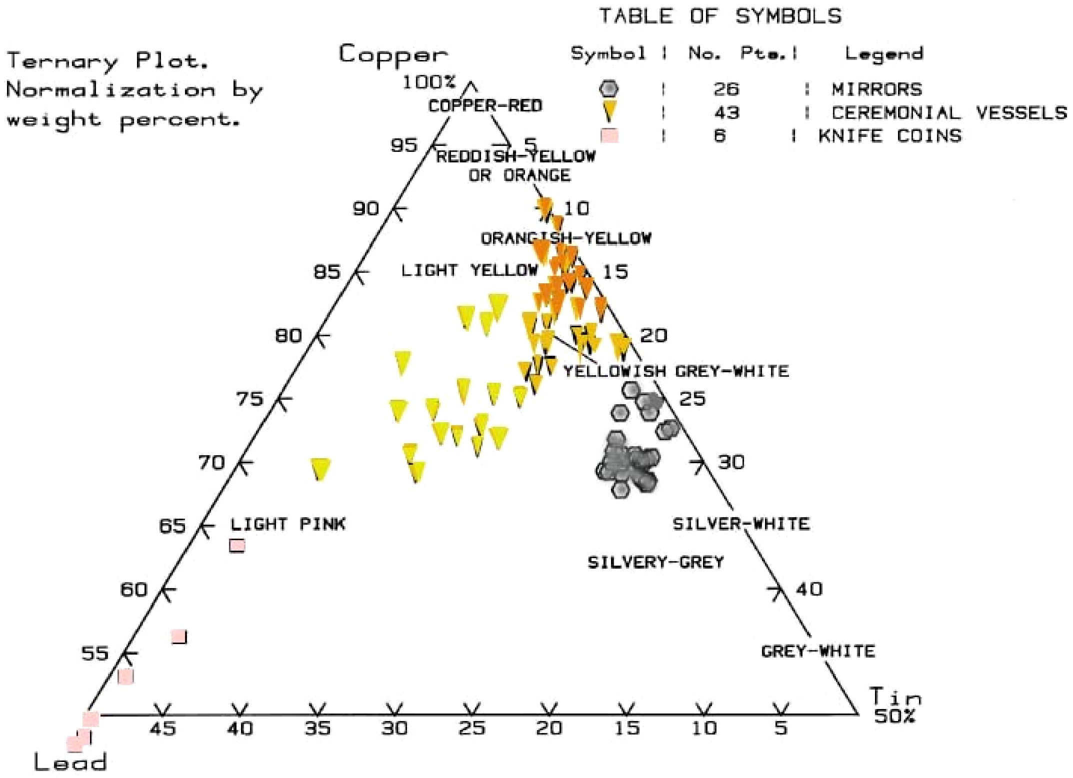


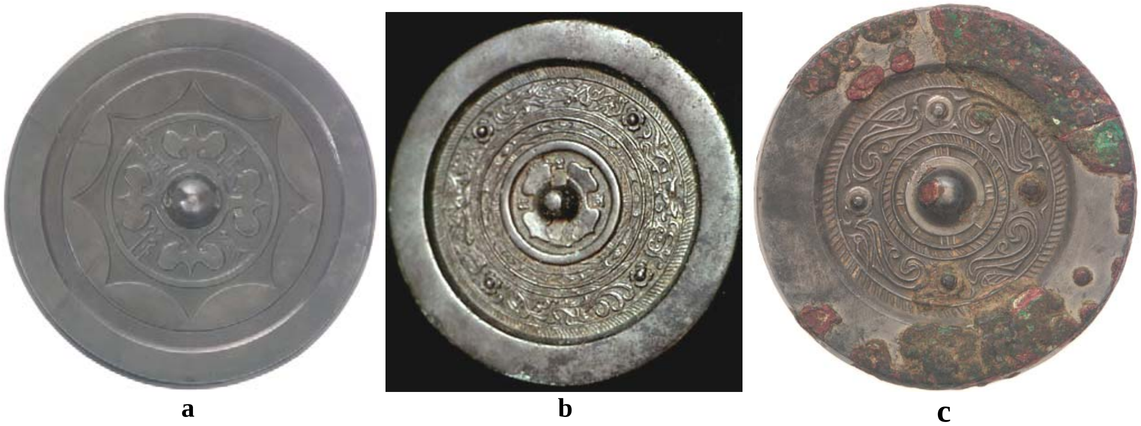
Figure 2: a ternary plot of the copper-tin-lead system showing bronze vessel colors superimposed; ceremonial vessels are indicated by the yellow-orange triangles, mirrors are the grey hexagons; mingdao knife coins are the pink squares [7].

The most useful property of the copper-tin-lead system is that it could be used for casting. Though, the highest-copper alloys (more than 97-98% copper) can be difficult to cast due to high gas absorption and medium fluidity; tin acts as a deoxidizer, decreases gas absorption, and promotes fluidity. Alloys with more than 6-7 percent tin tend to cast well, and those with 10 percent tin or more are highly fluid with very good casting properties. Lead (up to 3 percent) increases the fluidity of the melt and in any amount, improves the surface finish of the solidified casting [7].

It appears that elemental analysis cannot provide much archaeological significance due to the variable bronze compositions. Lead-isotope analysis, by contrast, does seem to reveal something useful about the trade in metals. The lead from a given mine has a distinctive isotopic composition that does not change during the smelting and casting processes. Recycling does not change the isotopic composition either, provided that all the bronzes melted together contained lead from a single mine. Therefore, if the lead has not been mixed from two or more distinct mines, the lead in a bronze artifact can in principle be matched with its source (the original lead mine) or with other bronzes whose lead came from the same mine. The isotopic analyses performed so far show patterns consistent enough to suggest that the mixing of lead from different sources did not happen so often as to make the typing of leads uninformative [15]. In fact, very interesting results have been obtained. Lead isotope analyses of Sanxingdui bronzes (imported vessels and local castings), bronzes from the Xin'gan tomb, and early bronzes from Anyang from Fu Hao's tomb show that they all contain lead of the same unusual isotopic composition, suggesting that the three foundries had the same lead source. Analysis of samples from lead mines strongly suggests that this source was in Yunnan province [15]. It seems likely that Yunnan lead was shipped north to Sichuan, eastward down the Yangzi river, and then to destinations both south (Xin'gan) and north (Anyang) of the Yangzi (after the time of Fu Hao's tomb, Anyang must have switched to another source). The trade was presumably in lead ingots, but just as likely could have been transported as a bronze artifact. Since the recycling of artifacts might be expected to mix leads from different mines, it was surprising that the lead-isotope analyses performed showed such regularity [15].

Melting Temperatures

For the most part, the alloys represented in the copper-tin-lead ternary diagram are not easily hot-worked or cold-worked in the solid state; they are difficult or impossible to shape by hammering. Two exceptions: alloys with high copper and low lead content, with tin less than 10 percent, can be hammered out to sheet, with frequent annealing. Bronzes with a tin content higher than 20%, and no lead, can be hot forged or quenched from a temperature above 550 °C and cold-worked [7]. If lead is present, these high-tin bronzes are unworkable [7]. Over the whole field of the ternary copper-tin-lead diagram, lead in amounts more than 4% makes the alloy difficult to work. The Chinese began using lead alloys early. Some of the earlier artifacts from Gansu province are lead and copper alloys with very little tin. Lead persists as an alloy constituent throughout the pre-Han period.



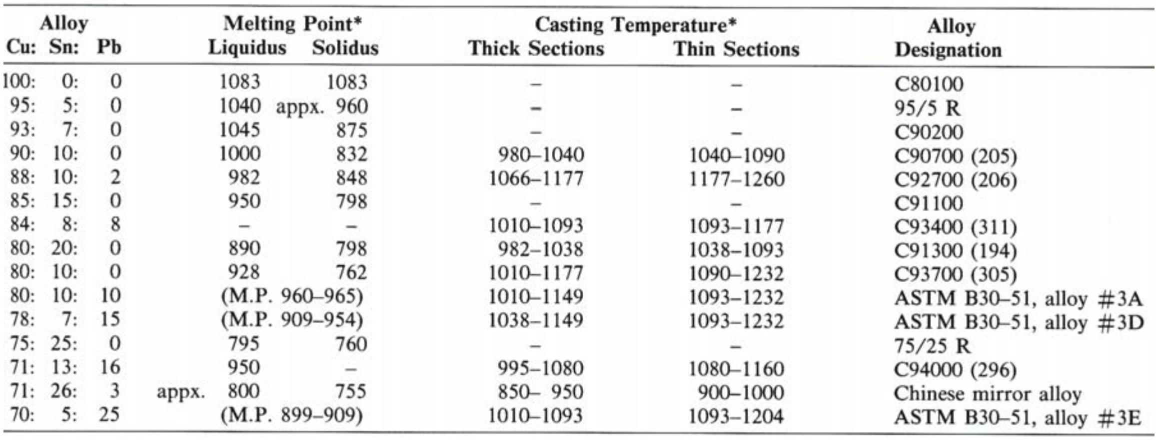
a b c

Figure 3 –Specific alloy combinations that resulted in silver-grey bronze mirrors; **a)** Eastern Han dynasty, 1st-2nd century, bronze, H: 1.1 W: 13.8 D: 13.8 cm, F1907.518 [11], **b)** Han dynasty (206 BC - 220 AD), bronze, D: 13.65 cm, Columbus, Ohio [16]; **c)** Han dynasty, bronze, H: 1.0 W: 8.2 D: 8.2 cm, F1907.520 [11].

The exclusive use of casting by the early Chinese metalworkers may have been due to the poor malleability of these alloys; in other words, they simply could not work the materials with a hammer [7]. Casting may not have only been a preference, but rather a result of pragmatism. All of the alloys in the ternary field can be cast, but some require particular attention to casting temperature. To produce metals on the scale that bronzes were produced in ancient China, copper would have had to be melted in refining or in ingot casting for transport. Pure copper melts at 1083 °C, so this would have been the absolute minimum temperature for any metal production to take place [7].

Although the melting point of pure copper is higher than any of its alloys, modern practice requires that the bronzes be given some degree of superheat when casting, so that the metal will have time to flow into the mold before it solidifies. The amount of superheat required to cast a bronze the size of the *Si Mu Wu fang ding* (1,925 pounds, 875 kilograms, the largest metal casting surviving from Chinese antiquity.) would be high. **Table 2** shows melting points and recommended casting temperatures for some of the tin bronze alloys. The degree of superheat used in normal casting practice can be seen by comparing the melting point with the casting temperature. The highly leaded bronzes require a high degree of superheat, and bronze, since it is an alloy, has a freezing or solidification range, rather than a freezing point. The beginning of freezing is shown by the liquidus temperature and the end by the solidus temperature [7]. The highly-leaded alloys that require a high degree of superheat seem to come into use for coinage only after the large scale casting of iron, when higher furnaces temperatures would have been available.

Table 2 - Melting points and casting temperatures for bronze alloys in degrees Celsius [7].



Alloy			Melting Point*		Casting Temperature*		Alloy
Cu:	Sn:	Pb	Liquidus	Solidus	Thick Sections	Thin Sections	Designation
100:	0:	0	1083	1083	–	–	C80100
95:	5:	0	1040	appx. 960	–	–	95/5 R
93:	7:	0	1045	875	–	–	C90200
90:	10:	0	1000	832	980–1040	1040–1090	C90700 (205)
88:	10:	2	982	848	1066–1177	1177–1260	C92700 (206)
85:	15:	0	950	798	–	–	C91100
84:	8:	8	–	–	1010–1093	1093–1177	C93400 (311)
80:	20:	0	890	798	982–1038	1038–1093	C91300 (194)
80:	10:	0	928	762	1010–1177	1090–1232	C93700 (305)
80:	10:	10	(M.P. 960–965)		1010–1149	1093–1232	ASTM B30–51, alloy #3A
78:	7:	15	(M.P. 909–954)		1038–1149	1093–1232	ASTM B30–51, alloy #3D
75:	25:	0	795	760	–	–	75/25 R
71:	13:	16	950	–	995–1080	1080–1160	C94000 (296)
71:	26:	3	appx. 800	755	850– 950	900–1000	Chinese mirror alloy
70:	5:	25	(M.P. 899–909)		1010–1093	1093–1204	ASTM B30–51, alloy #3E

Casting Methods

The ancient Chinese developed a most unusual casting method called the piece mold process. In the piece mold technique, surface decoration could be made by carving into the mold (for raised relief) or into the model (for recessed designs). A model of the item to be cast in bronze was sculpted out of clay and decorated with patterns and inscriptions. Early bronze vessels were cast with only one pour. The caster took pains to prepare a mold assembly, complete with decoration, that would yield a finished object with no remaining parts to be joined-on or decoration to be added. Shang bronzes rarely resemble composite pieces that were assembled from independent parts. The strong preference for single casting required that both shape and decoration emerged from the mold [8]. Composite casting is a subgroup of piece mold casting that appeared during the Shang dynasty. The technique was used to attach small appendages, such as handles, to a larger vessel. Appendages were cast first, and then placed within the mold of the uncast larger vessel. Alloys were prepared in crucibles over a charcoal fire and the molten material was then poured into the primary clay mold where it anchored the pieces in place [14]. The technique enabled the production of larger vessels and also facilitated the sculpting of more animated appendages [17]. During the Erligang period, when the Zhongyuan foundries were greatly complicating mold making with elaborate decorations, many mold part assemblies were needed. The casting that produced the bulk of the object was the main pour. A small part made before the main pour could be embedded in the mold to lock them together; this was considered precasting. Parts could also be cast on after the main mold. In rare cases, two large objects were joined together by casting a smaller piece between them called "running on" [15, 18]. From the scientific excavations at Anyang and later at Zhengzhou (both in Henan Province) where molds of grey fired clay were discovered, it was confirmed that the Shang used the direct casting (piece mold) method. The molds for weapons and agricultural implements were single casts or cast in two parts, those for ritual vessels were composite (4 or more parts) casts [19]. For the Sanxingdui, they constructed complex shapes from pieces cast separately in simple molds and later joined the components.

Large scale bronze metallurgy was seen at Erlitou in the Henan Province as early as 1500 BC [15]. Its bronze industry centered on the production of ritual vessels cast in clay section molds of two or more parts (**Figure 4)** [15]. The bronzes found at Sanxingdui looked dramatically different than the ritual vessels, yet were cast using the same techniques [15]. Heavy reliance on casting and on section mold casting in particular is a distinguishing characteristic for the bronze industry of the Erlitou, Erligang and Sanxingdui cultures.

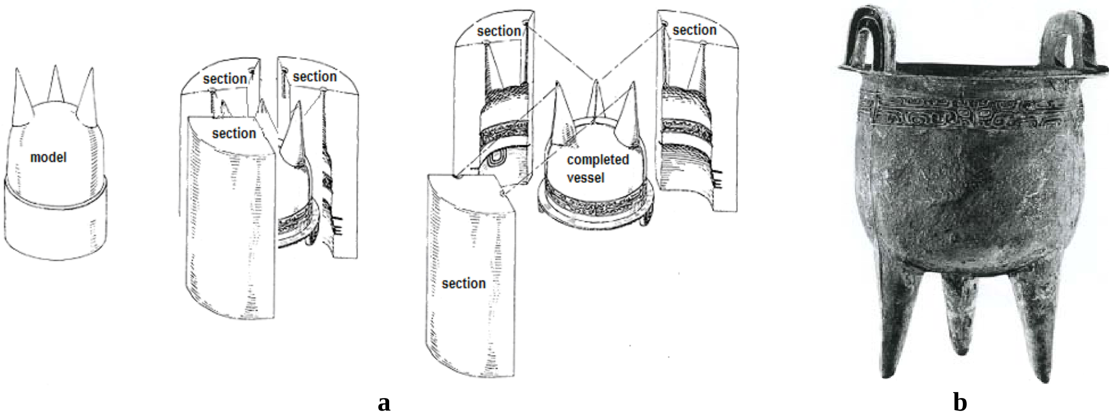


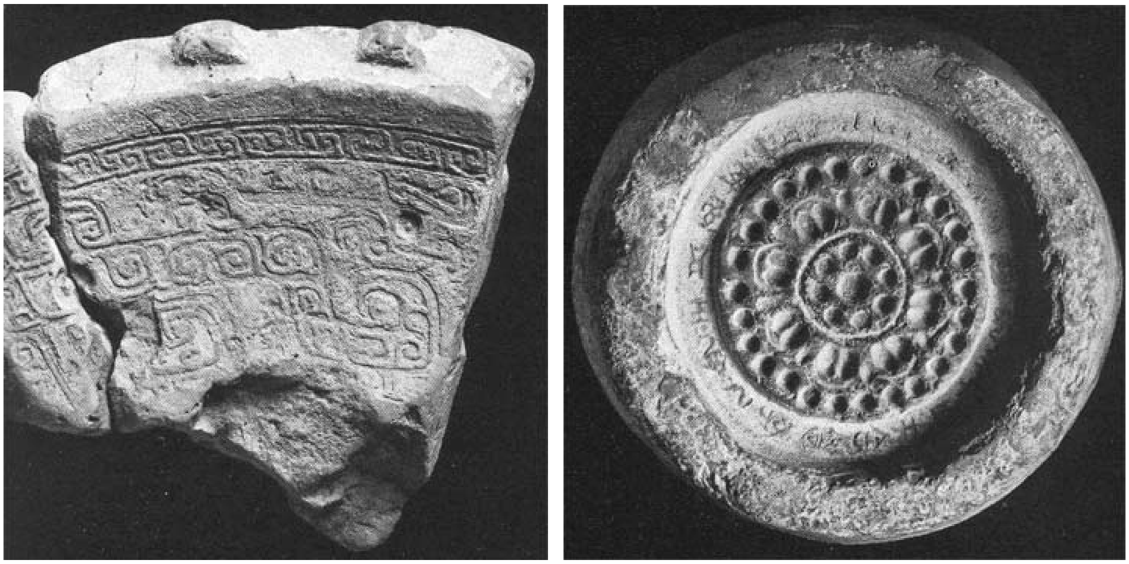
Figure 4 – **a)** Diagram shows basic components for a piece mold casting of a bronze vessel similar to a tripod *ding*; **b)** a bronze cast *ding* from 1400-1300 BC, actual dimensions are H: 54 cm, W: 9.6 kg, D: 40.7 cm [4, 8, 17].

Casting metal from molds made of two parts was a simple technique used in many places around the world. For making the molds, the casters favored fine grained, low-lime and low-clay loess because of its high porosity and its dimensional stability in drying and firing [4]. The Chinese cast great quantities of coins and blades for their weapons in this manner. **Figure 5a** shows half of a two part clay mold from the Han dynasty that was used for casting rows of coins in one pour. Chinese craftsmen during the Anyang period, however, had already developed the technical capability to make molds that were far more elaborate. Two joined parts of a mold, excavated at Anyang, used for one of the four body walls of a *Fang yi* vessel (**Figure 5b**).

a **b**

Figure 5 – **a)** Piece of clay mold used for casting coins, Han dynasty, Henan Province; **b**) Piece of clay mold used for casting a *fang yi* from c. 1100 BC [4].

The seam runs down the central axis. Each half contains 3 decorative fields, one above the other. This demonstrates that the borders of mold sections usually correspond to borders of decorative compartments and one section tends to encompass several compartments. Mold pieces are modules in a technical system; they are composite, interchangeable parts combined into units [4]. One of the best examples of a piece-mold casting foundry, the complex at Houma, dates from slightly after 500 BC, yet no evidence of lost-wax casting is seen among the thousands and thousands of piece-mold fragments [3]. The discovered remains from the Houma foundry in Shanxi province and the mine at Mount Tonglu in Hubei province have supplied considerable information regarding the development of metallurgical and mining techniques. The remains totaling more than 30,000 fragments of molds (**Figures 6-7)** and models, also included earthenware dies, bronze ingots, furnaces, crucibles, slag deposits, smelting and casting equipment [3, 4]. Excavation began in 1957, but it was not until 30 years later that systematic examination began. It became clear that the Houma foundry was the center of mass production on an industrial scale, capable of rapidly producing bronzes in large numbers [4]. Discovered at the Houma foundry were pattern blocks (**Figure 8**) that had been used to create a wide range of décor. The ancient Chinese in using these blocks as modules were able to separate mold making from its decoration [4].



a **b**

Figure 6 - a) Mold fragment for a ritual vessel with a *kui* dragon against a background of *leiwen* (spirals or thunder pattern). Grey pottery from the Shang dynasty, Anyang period, 13th -11th century BC [19]; **b)** Mold for a bronze mirror bearing an inscription and an intaglio (inscribed) pattern of nipples. Grey pottery, Han dynasty, 2nd century BC, diameter: 12 cm [19].

a **b**

Figure 7 - a) One half of a mold for a *zhong* bell decorated with bosses and geometric designs, grey pottery; Zhou dynasty, 10th -8th century BC [19]; **b)** Matrix for a *yue* axe with a *taotie* mask on the tang and a stylized owl on the blade. Grey pottery; Shang dynasty, end of the Anyang period, 12th -11th century BC, H: 23 cm [19].

Implementation of this system meant that different vessels could have the same pattern and identical vessels could have variable patterns (**Figure 9**). The modules enabled mass production with a large amount of freedom. The water basins from the Smithsonian Freer Art Gallery seen in **Figures 10 and 11** are representative of this modularity. The bronze casters had progressed to the stage where it became necessary to make more than one impression from a clay mold; for improved productivity molds would have to be reused.

Figure 8 – *Taotie* pattern block made from baked clay, excavated at the Houma Foundry in Shanxi Province, 18 x 42 cm, c. 453 BC [4].

Mechanical reproduction in large quantities (mass production) was now feasible; the casters who had duplicated décor sections mechanically with the pattern blocks could efficiently increase volume production by the year 500 BC. Creation of these vessels no longer required the painstaking carving of individual molds.

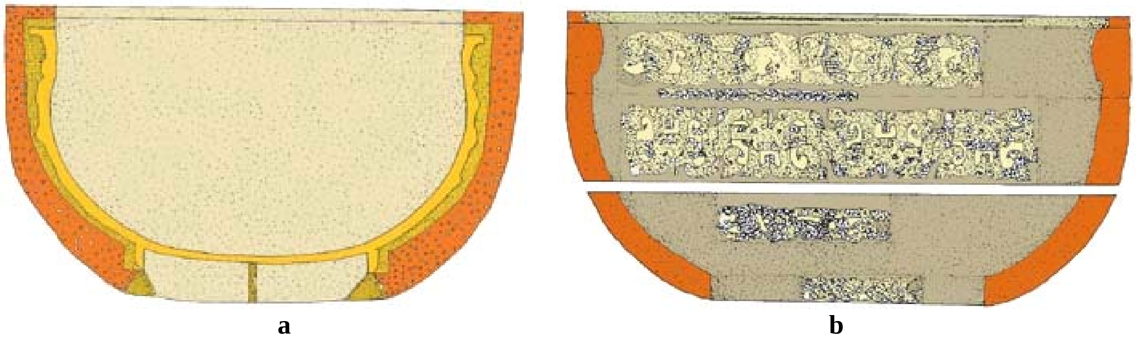


Figure 9 – **a)** An undecorated mold section for casting; **b)** Clay strips with decorative patterns are placed in a mold mantle for casting a *jian* (water basin) [4].

To provide some perspective about the demand for ritual vessels, in a single tomb for the Marquis Yi of Zeng (Zeng hou Yi) more than 10000 kg of bronze was unearthed [4]. It has been estimated that 200 to 300 craftsmen were needed to produce an 800 kg vessel, not including the laborers who mined and smelted the bronze alloys [4]. Casting bronze the complicated way involved division of labor. A subdivided production required strict control; managing huge quantities of bronze, clay, firewood and the workforce, involved great logistical problems.

Figure 10 - Ritual water basin (jian), ca. 500-450 BC, mid-late Eastern Zhou dynasty, bronze, H: 22.8 W: 51.7 cm [11].

Figure 11 - Ceremonial basin (jian), 5th century BC, Eastern Zhou dynasty, bronze, H: 28.0 cm, W: 61.4 cm [11].

The Chinese compartmentalized the process into small steps or modules. Some workers prepared the bronze, others carved the molds; carving was probably the most time consuming stage in the production process. Most of the work could be done simultaneously, because the final shape of the product had been determined before work began. One craftsman may have been responsible for carving all the mold pieces required for one vessel, but if an entire set of vessels was cast, which was the normal case, many workers could simultaneously make the necessary molds. Chinese bronze vessels were the result of a coordinated effort of several specialists. The Shang aristocracy commissioned many ritual bronze sets (thousands of vessels) for their religious and political ceremonies. Division of labor was one method to meet this large demand for bronzes and the modular systems improved efficiency.

Casting Molds

By studying the casting techniques and the different molds, it is possible to see the development of the various Shang bronze types. From the Anyang site, over the course of ten years, 176 vessels of varying kind (*gu, jue, jia, ding, lei, pan, zun, fang yi, yu*) were excavated (**Figure 12**). From the vessels and the molds, it was determined that their evolution was closely connected to the progress made in the casting technology [19]. For example, the tripod ding with Y-shaped joints was the simplest shape and the first to appear. Circular joints were developed later and were used in subsequent *dings* with bulbous legs like the *xian.* Each successive vessel progression used familiar elements and supplemented the existing design with new modifications. The *jia* incorporated the Y-shaped joints, but cast the caps in a manner similar to the way *ding* handles were cast. **Figure 13** shows the more advanced *li-ding* vessel with the simpler Y-shaped joints. The *jue*, related in style to the *jia*, was cast using four molds for the body and a special mold to cast the legs and the vessel base. The mold for the legs seems to have been influenced by the circular joint [19].

For a different perspective of the casting process, **Figure 14a** shows schematic drawings of a complete mold assembly for a *fang ding*. The vessel appears to have been cast with a 4 piece section mold. As the mold defines the shape of the bronze exterior, cores are used to define the interior. Cores were solid forms made of loess that occupied the interior spaces of the mold. The inner core was placed inside the mold to leave a space (ranging from 5 to 15 mm) between the core and the molds; this gap was later filled with the molten bronze [20]. The core material was porous and allowed gases (generated during casting) to escape, thereby reducing the possibility of casting failure. Cores can also be made by shaving down the model to create the casting space [20]. Destruction of the decorated model surface while making the core meant that each bronze made in this manner was a unique creation. Cores not made from models were probably baked, though to a lesser degree than the mold, to impart some strength yet be weak enough to break under pressure when the molten bronze shrank during cooling and to facilitate removal of the core after the vessel was cast [21].

For this specific *fang ding*, inside the vessel and between the 4 legs were 2 large cores that are separated by the vessel bottom. Exact spacing between the core and mold had to be maintained to cast the thin walled bronzes [7], so chaplets (bronze scrap material) were placed in the sides and the bottom in the undecorated areas. While the clay was leather-hard, the inside of the mold was decorated. The Chinese craftsman would have spent many hours carefully tooling with fine pointed bone needles or gouges. The intaglio lines (figures or designs carved into the surface) on the single-headed, double-bodied snakes are believed to have been sunken lines in a positive model. The intaglio lines on the flanges, handles, and the *taotie* masks on the legs may have been made the same way. It is believed that the decoration must have been incised into the mold [7].The decorative pattern on this *Fang ding* appears recessed (in the negative) in the outer slabs.

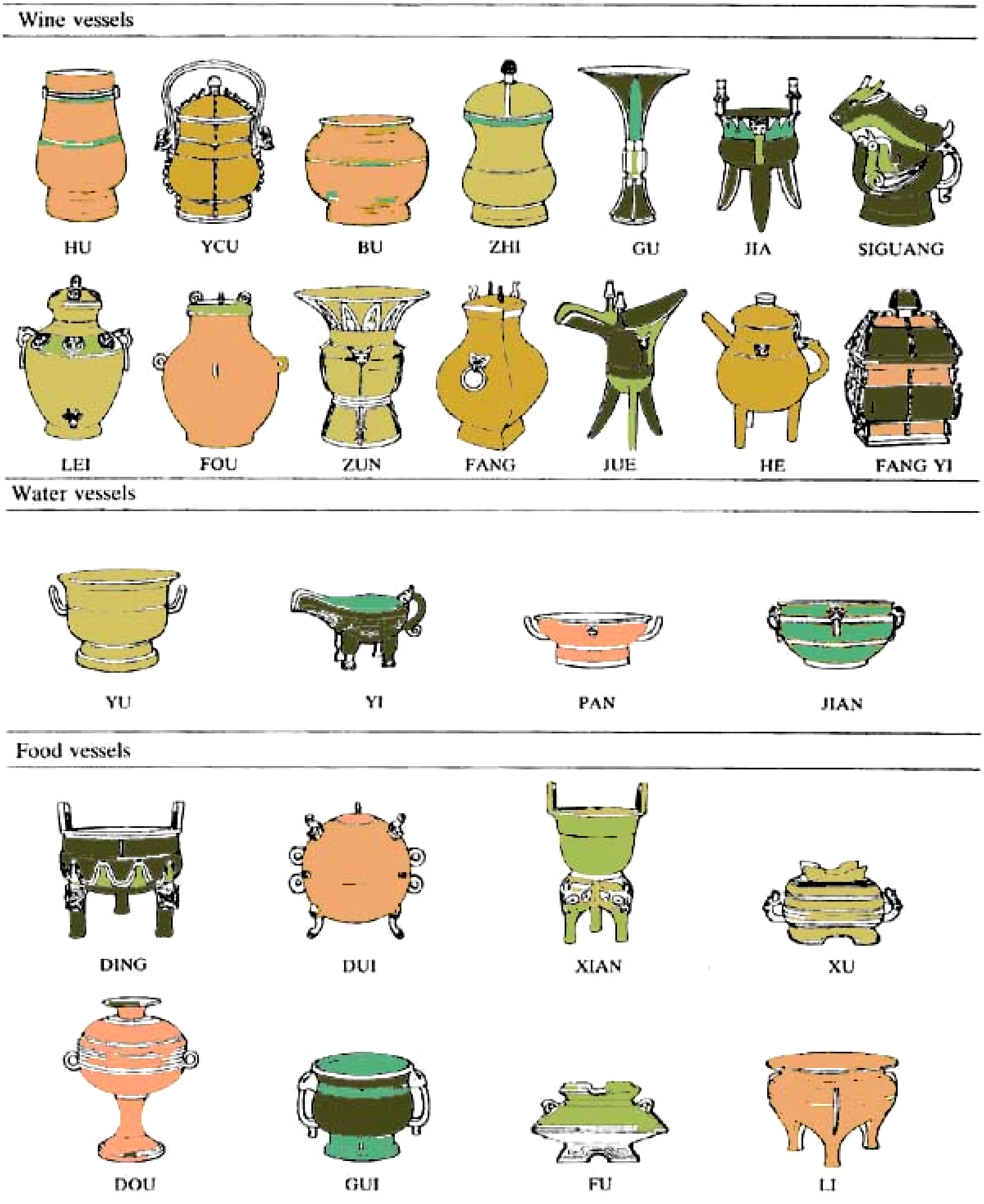


Figure 12 – bronze ritual vessels [22].

Figure 13 – a) Early Western Zhou, minimally decorated, bronze *li-ding* (3-legged cooking vessel), H: 15.5 cm; and **b)** bottom of *li-ding* showing the simpler Y-shaped joint and predominant mold marks. Also if you look closely, you can see the face of a little bird-beast formed by each leg [23].

The inscription is on the inside of the vessel wall somewhat visible in **Figure 15**. It would have been done in relief on the interior core piece, most likely taken as an impression from a positively incised inscription that had been inserted into a recess carefully cut for it in the interior core [7]. After decoration and inscriptions were completed, the mold pieces were carefully placed around the core with mortise-and-tenon joints secured for proper spacing on the mating surfaces. The leg core piece would have been carefully positioned on the top of the large chaplets (bottom of the vessel). The prepared mold was then bound with bamboo or ropes and buried for casting; several molds could be done at the same time [20].

Prior to casting, the ceramic mold was disassembled and coated, either by smoking over a fire or painting with a mixture of carbon charcoal in water [7]. The coating facilitated metal flow into the mold by reducing the surface tension of the molten metal against the mold surface and helped separate the bronze from the mold after casting [7]. Evidence of the applied mold dressing (a layer of black) has been seen in the vessel bottoms between the foot and core remnants and on mold fragments [7].

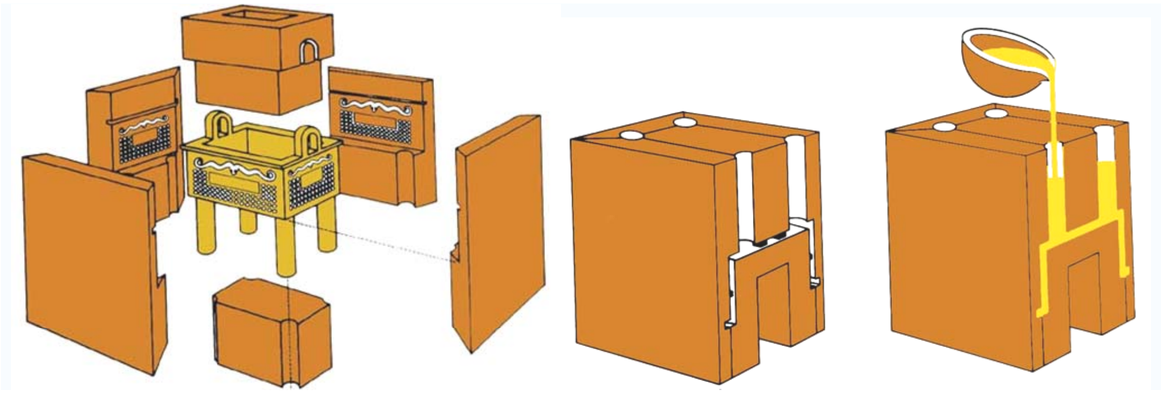

a b

Figure 14- (a) Mold assembly for casting a *fang ding* where a model (center) is surrounded by the four panels that make up the mold. The inner core and interior leg core sections are shown above and below the model; **(b)** the leg cores are kept apart with chaplets depicted as black squares. The mold is joined together and inverted for molten metal to be poured into a leg opening [7, 21].

It is not known if the molds were heated prior to casting. Some evidence indicates the molds were not preheated. Examination of the metal microstructure of the cast bronze surrounding the chaplets showed a chill zone where the molten metal was poured into molds that were not preheated [7, 21, 24]. The molten bronze would have been heated in a crucible or furnace, and then poured from the crucible, ladled, or allowed to flow by gravity through a trough into the molds. Typically, the vessels were cast upside down (**Figure 14b),** positioning the large, heavier core on the bottom [4, 20]. The molten metal was introduced into the mold through one of the open leg holes and then allowed to solidify. After a fairly short time (possibly an hour or less in the case of such a small bronze), the mold would be broken off.

Figure 15 shows an Early Zhou (roughly 10th century BC) square, four-legged *ding* that weighs 3.77 kilograms (8 pounds, 5 ounces) and stands 26.7 cm (10 ½ inches) high. It has a normal bronze composition with 77.7% Cu and 14.9% Sn that would cast well and be easy to finish [24]. From emission spectroscopy other elements were determined and are shown in **Table 3** [24].

Table 3 – Elemental analysis from wet chemical analysis and emission spectroscopy for Figure 15 (Fang Ding) [24].

Elements (%)													
Cu	Sn	Pb	Ag	As	Bi	Co	Cr	Fe	Mg	Mn	Ni	Sb	Si
77.7	14.9	5.5	0.1	0.3	<0.03	0.02	0.002	0.3	0.004	<0.001	0.04	0.3	0.04

One of the legs did not fill out in the original casting. The missing leg was cast on separately, around a core [7]. From a radiograph, more details were accessible; three of the legs were found to be solid and had been cast as one with the vessel, the fourth leg, however was clay cored. The core was tilted and off center, as if it had been carelessly tossed in the mold. No seams could be found where the three legs joined to the vessel. Mold marks were visible along the flanges, especially at each corner under the shelf-like rim. The underside of the bottom had a criss-crossed pattern with double, parallel, straight ridges that connected the legs. These ridges and the rough cast surfaces on the inside of the legs may have been caused by the inter-leg core assembly. In the rectangular undecorated area on each face was a chaplet. One of these was located midway between two characters in the inscription. This chaplet was made of metal more transparent to X-rays than the metal of the vessel. There were also three large chaplets in the bottom [24].

Figure 15 – A *fang ding* from the collection of the Freer Gallery of Art, Smithsonian Institution (FGA #50.7). The vessel stands 26.7 cm. (10 ½ in.) high, width: 19.7 cm (7 ¾ in) and weighs 3.77 kilograms (8 pounds, 5 ounces) [7, 24].

Both the openings and core extensions allowed gases to escape during casting. All of the appendages containing cores in bronzes examined for this study have some type of opening; this seems to indicate that they are necessary for successful casting, to vent gases or for proper spacing [20]. All authentic vessels are believed to have chaplets or spacers, the square bits of metal that separate the core from the mold to maintain the casting space [21]. Cores could also be used in vessel handles, feet and other appendages to make them hollow rather than solid so they would be less susceptible to shrinkage and other forms of metal stress and failure [24]. Handles and other appendages were either cast as one with the vessel or cast separately and set in the mold prior to the final casting. For the *ding* in **Figure 16**, the clay cored legs and handles were cast first and the vessel was cast to the pieces. A seam at the join of each leg and handle to the body can be seen. The precast legs were arranged in a 3-piece mold where the vessel is cast to them so that the metal flowed in and around the leg tops. The handles are clay cored and cast in a similar manner as the legs. The lid shows no evidence of mold joins; the 3 loop handles appear to be cast with the lid [25]. Wet chemical analysis and emission spectroscopy results are shown in **Table 4**.

Table 4 – Elemental analysis from wet chemical analysis and emission spectroscopy for Figure 16 (Ding ritual vessel) [24, 25].

Elements (%)													
Cu	Sn	Pb	Ag	As	Bi	Co	Cr	Fe	Mg	Mn	Ni	Sb	Si
74.8	13.7	10.0	0.01	0.05	-	0.03	-	0.2	-	<0.001	0.09	0.09	-

The hu-li-yu vessel seen in **Figure 17** was cast in one piece without the handles. The hollow tiger handles were cast separately and still retain some of the clay cores. The tiger feet provide a small area of contact with the vessel yet no solder has been detected at the joins [24]. Wet chemical analysis and emission spectroscopy results are shown in **Table 5.** The lead content was substantially higher for this vessel.

Table 5 – Elemental analysis from wet chemical analysis and emission spectroscopy for Figure 17 (hu-li-yu vessel) [24].

Elements (%)													
Cu	Sn	Pb	Ag	Al	As	Bi	Co	Fe	Mg	Mn	Ni	Sb	Si
68.8	10.5	18.3	0.02	0.001	0.5	<0.03	0.03	0.1	0.001	-	0.07	0.2	0.002

The *zun* is a generic term for wine vessels that vary in shape from a simple chalice to the more extraordinary zoomorphic forms like **Figure 18**. This *zun* resembling a bird appears to be cast in a 2-piece, four-division mold assembly with a mold join down the center of the breast and back. The bird's legs were precast with a clay core and the body was cast to them. The surface inside is smooth except for the narrow space in the tail that contains the original clay core. Join traces can be seen on the wings. There are no mold joins on the bird's head that attaches by means of an inner collar. The bird's head is removable with a locking mechanism. The curved upper beak is hinged so that it can open and close (but not remain open). The entire body is finely cast with detailed feathers; details that are believed to have been done with stamps carved with all the décor elements (similar to pattern blocks). Wet chemical analysis and emission spectroscopy results were comparable to the analysis for the ding ritual vessel.

Table 6 – Elemental analysis from wet chemical analysis and emission spectroscopy for Figure 18 (zoomorphic zun) [24].

Elements (%)													
Cu	Sn	Pb	Ag	As	Bi	Co	Cr	Fe	Mg	Mn	Ni	Sb	Si
74.1	13.6	10.8	0.02	0.2	-	0.02	-	0.007	-	-	0.07	-	-

Figure 16 - *Ding* ritual vessel (pot), Zhou dynasty, 6-5th century BC, H: 26.1 W: 30.7 D: 26.5 cm. The bronze vessel is covered with a smooth grey-green tin-oxide patina and minor crusts of malachite and azurite [11, 24, 25].

Figure 17 - *Hu-li-yu* (FGA 57.22) Zhou dynasty, 5th century BC, H: 44.8cm, W: 26.6cm, Wt: 9.38 kg. The finely cast vessel is covered with a brown and green malachite patina [24].

Figure 18 - *Zun* (FGA 61.30), Zhou dynasty, Anyang, 5th century BC, H: 26.5cm, W: 20.0 cm, Wt: 2.55 kg. The remarkable *zun* surface is covered with a fine shiny brown-grey patina [11, 24].

Casting flaws

The as-cast surface appearance of a bronze vessel is thought to be shiny with a slightly frosted appearance as if it had been sandblasted [7]. The casting would contain rough seam lines called mold marks where metal flowed into the mold joints. These would be removed through the use of gritty abrasive materials like sand. Traces of the joints can be seen if the bronze is closely examined, though sometimes they are imperceptible. The vertical flanges or ribs that occur on many vessels usually follow the joint lines [19]. Mold marks can also be found on areas of the bronze that were either difficult to polish or areas unlikely to be noticed, such as recessed areas of decorations or the undersides of flanges. Occasionally mold marks are visible where the molds slipped or were out of plane, resulting in misaligned design elements, a metal step or a ridge. Natural stones and grits were used to remove the mold marks and also to polish the bronze surfaces. Characteristically, the earliest bronzes of the Shang dynasty show the roughest surface finish, the Western to Eastern Zhou dynasties preferred more highly polished, refined surfaces [7].

Figure 19 is an ambitious display of bronze casting technology; this vessel, based on a conventional square container, is transformed into an organic, life-like form with rams at each corner. Their heads emerge as three-dimensional sculptures, while their chests and front legs appear in relief amid a dense sea of spirals, and scroll patterns. Incised birds with tall, scrolled crests cover the ram body and 3-D (snail-like) horned dragons project outward from each side of the ram's head [26]. These complex shapes exemplify the characteristically elegant Shang blending of abstract and representational animal motifs (**Figures 19** and **20)**.

In the Chinese bronzes, as casting techniques became increasingly sophisticated, flanges generally were worked into the design as abstract ornamentation where the seam lines were disguised by elaborating them into high relief flanges. In **Figures 19** and **20,** however, running under each ram chin and chest, the flanges have been used to form beards and woolly pelts. This bronze was cast in a four piece mold; the mold marks are visible on each of the flanges.

Figure 19 – Si Yang *Fang Zun*, bronze wine container with four rams [8].

Figure 20 - Shang Period (1600 -1100) BC; details of a ram ornament from the Si Yang *Fang Zun* [26].

The casting process holds many difficulties that must be overcome, such as the absorption of gases in the hot metal, shrinkage, hot tearing, cold shuts, insufficient penetration of the metal into the mold cavity and supporting the mold and core (using chaplets) to name a few. The experienced craftsman learned what to do to avoid the problems and to make the metal conform. However, many bronzes showed the scars that were encountered during the casting process due to the molten alloy degassing and the trapped air. Most vessels were cast upside down to allow for pouring channels (sprues), gates and risers to be attached to the legs; this set-up caused fewer problems than other mold orientations [20]. Vent holes were pierced in the clay to remove some of the trapped air **(Figure 21a)**. Another technique for dealing with entrapped air in porous core material was to score the foot core; this produced a fishnet or criss-cross pattern **(Figure 21b)**. Lead, it was later discovered, reduced the melting point of the alloy, could facilitate the flow of the metal during casting, eliminate the formation of bubbles, and improve the technical surface decoration. Other methods involved separate casting operations for the legs and the vessel; legs were cast on to an already completed vessel, or they were pre-cast, generally around a ceramic core, and incorporated in the mold assembly prior to the casting of the vessel. Yet another technique involved the use of copper leg cores.

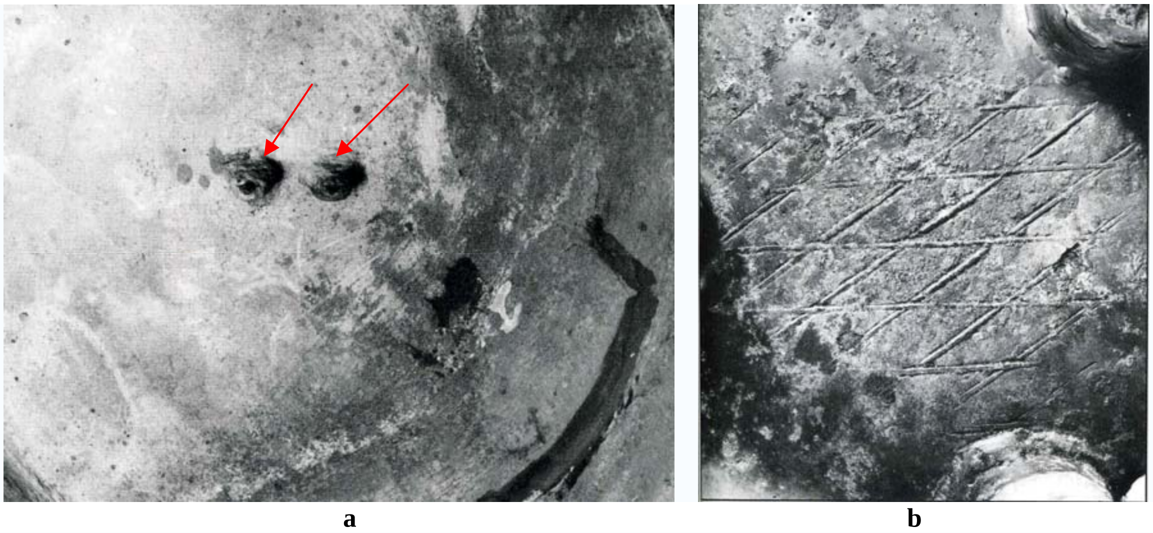


Figure 21 – a) Bottom of *zun*, holes (vents) were pierced into the casting to enable flow of entrapped gas; **b)** underside of bronze *ding* showing criss-cross pattern used to relieve entrapped gas [20].

A *ding* vessels from the Anyang period, shown in **Figure 22a**, appears to have legs cast of solid metal from the X-ray radiographs (**Figure 22b)**. However, closer examination revealed that the legs were cast around a metal core. Elemental analyses of samples from these metal cores show that the core consisted of unalloyed copper. This is the first evidence for the use of pure copper in the manufacture of Shang bronzes.

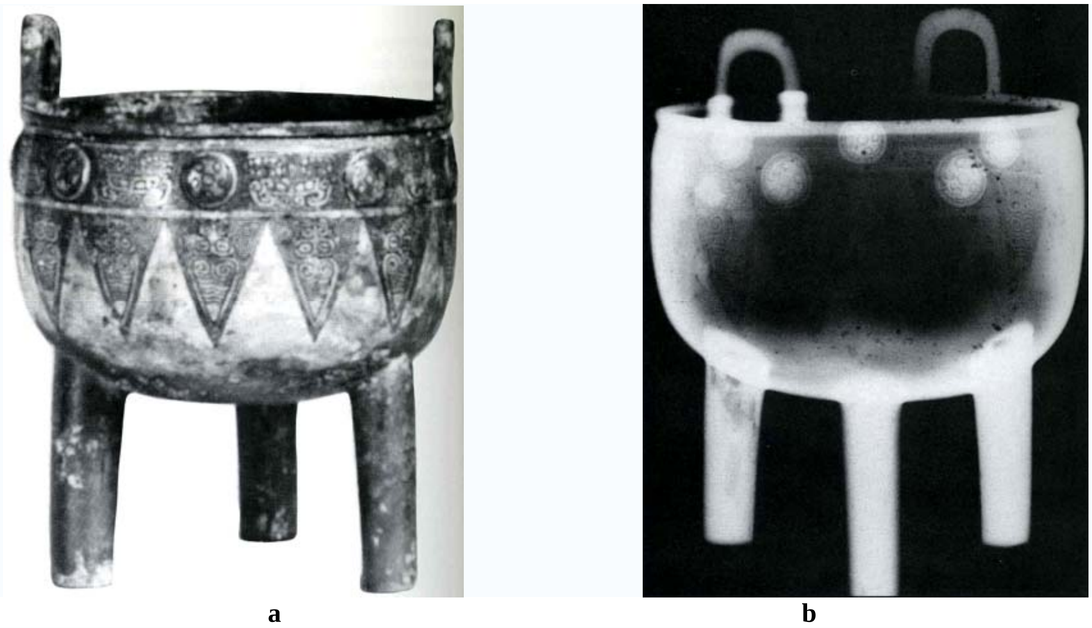


Figure 22 – a) bronze *ding* 13th – 11th century BC; **b)** X-ray radiograph of *ding* [20].

The use of copper as a casting core may indicate that the Shang bronze caster had advanced knowledge of melting points of copper and bronze alloys; a copper core has a melting point considerably higher than that of the alloy cast around it. This would significantly reduce the risk of casting failures. Whether or not the use of copper cores was limited to a specific period or to specific production centers is uncertain.

Lost Wax Method

The Chinese craftsmen may have been reluctant to change their methods; technical mastery of ceramic piece mold casting would have been the greatest barrier. It is believed that the lost wax method was available from at least 1,500 BC or earlier, but was of less interest since the same results could be obtained with more familiar techniques [7]. Small objects of irregular shape, however, could be made using the lost wax method (also known as investment casting) since wax was relatively easy to shape and great detail could be transferred to the wax. The bronze artifacts seen in **Figure 23** are believed to have been cast using the lost wax method. Their appearance is dramatically more ornate with an abundance of wispy decoration achieved through soft, pliable wax.

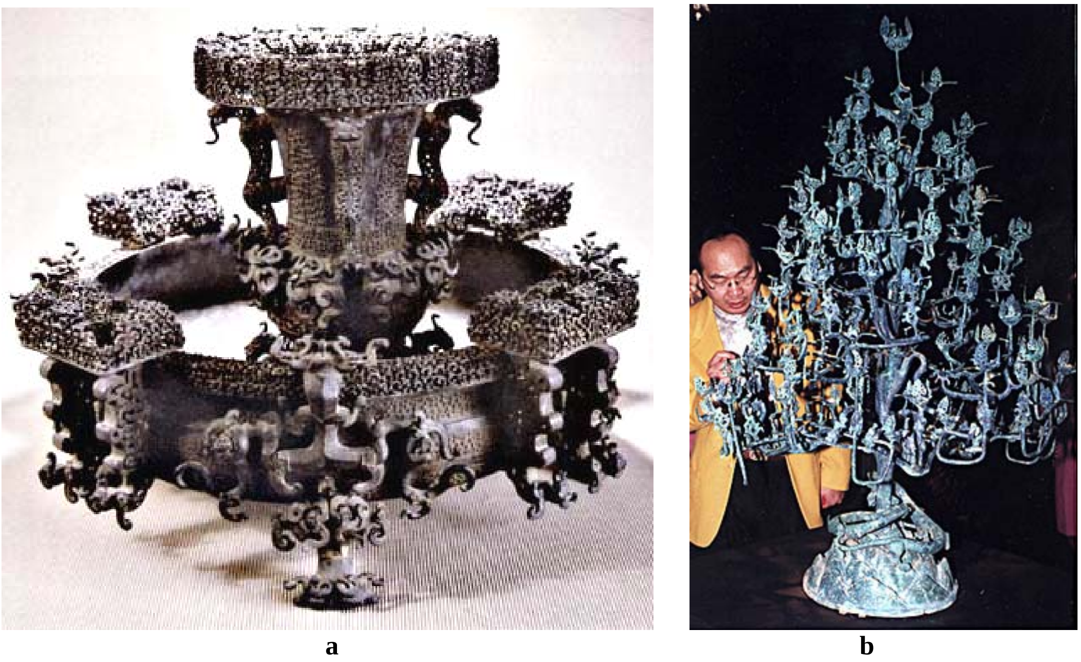


Figure 23 – **a)** To make this vessel, bronze casters combined standard section-mold casting for the body with the less frequently used lost wax method for the appendages. The appendages made using the lost wax method were later fitted into a section-mold where the main body was cast [28]; **b)** Han dynasty bronze "spirit tree" or money tree believed to have been stolen from the Three Gorges area.

The procedure for lost wax casting required a clay core in the basic shape of the object to be covered in wax and the details of the object sculpted in the wax, then covered with more clay. Once the wax copy (the positive object) resembled the original object, it was sprued with a treelike structure of wax that provided channels for molten bronze (1600°F) to flow. Wax vents were added so that hot gases could rise while the liquid bronze was being poured. The wax model with its vents and gates was painted with very thin clay to pick up the finely sculpted details. Then it was covered completely with a coarser clay mantle (the investment material). The mantle was attached to the inner core by iron or bronze pins called chaplets. The clay was dried and then slowly baked in a ceramic kiln; subsequently the wax melted, leaving a space where the molten metal could be poured. The melted wax could be recovered and reused, though often it was combusted by the burnout process.

What remained of the original object was the negative space, formerly occupied by the wax, inside the hardened ceramic shell. The clay core was removed leaving two halves that formed a container in the shape of the object. Larger or more complicated sculptures were divided into multi-section molds and cut into several pieces with molds made of each piece [10]. Once the master mold was cleaned and reassembled, a special melted wax was poured into it, flowing into every detail of the mold. When the wax was cool the mold was opened to reveal a positive object in hardened wax. The wax object was worked to remove seam lines and rejoin mold pieces to restore it to the shape of the original clay object. The liquid bronze was poured into the prepared molds and left to cool. The cooling rate was significant in that it affected the bronze microstructure, quality and its mechanical properties. The large casting with thick walls generally cooled slowly. This increased the grain size, creating a coarse microstructure that lowered the strength of the casting. Coarse grains could enable alloy elements to separate, which also weakened the casting. The more slowly cooled vessels kept the casting metal in the liquid state for a longer period of time allowing more gases and waste metal to escape, reducing the voids and inclusions that could weaken the casting. Conversely though, the vessels that cooled more quickly resulted in a fine microstructure with small grains and less alloy segregation but more trapped gases and inclusions. Like nearly all materials, metal is less dense as a liquid than a solid; a casting shrinks as it cools, mostly as it solidifies, but also as the temperature of the solid material drops. The shrinkage caused by solidification sometimes left cavities in a casting, thereby weakening it.

When the metal finally solidified, the clay investment shell was broken away, and removed, leaving a bronze cast of the object. The chaplets, vents and gates, now in bronze, were removed, and the surface of the statue was finished by various cold-working techniques [8, 10, 29-31]. **Figure 24** is a colorful diagram showing the numerous stages of the lost wax casting process beginning with the clay core and ending with the bronze casting. The diagrams in **Figure 25** shows simple examples of a cat and a Buddha’s head that have been prepared using the lost wax casting method. The limitation of this method is in losing the wax mold when it melted, so it could be used only once; it was therefore, not suitable for mass production, but was good for very detailed objects and did not leave seam or mold marks. The lost wax method was used throughout China and the Greeks used it (480-450 BC) to make statues [10].

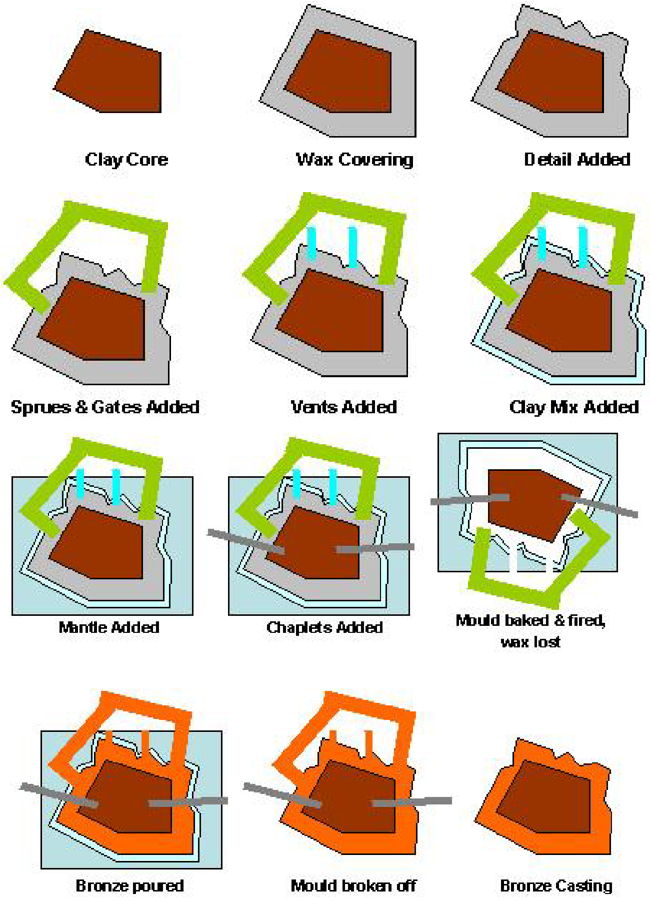
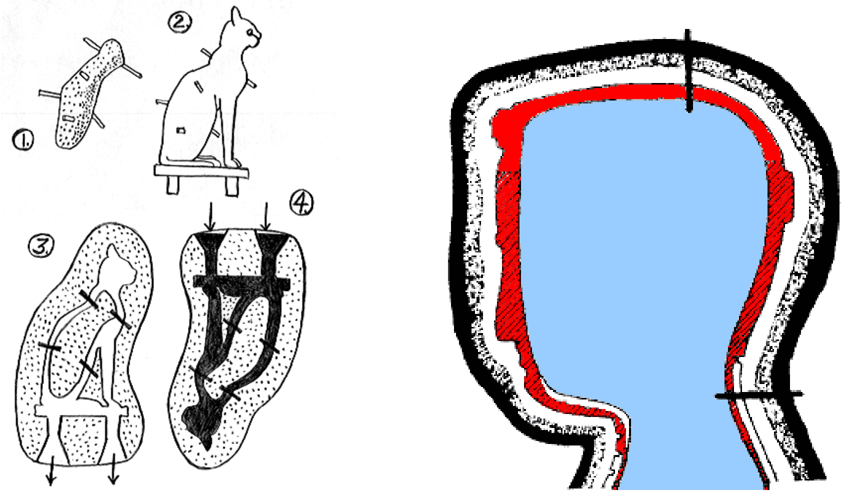


Figure 24 - Diagram of lost-wax casting; first stage: clay core (top row, left, proceed to the right), second row: sprues and gates are added, (third row, left) after a thin clay mix has been added, a thicker core mantle is deposited; (4th row, left) bronze is finally poured and left to solidify [31].



a **b**

Figure 25 – a) Lost-wax hollow-casting shows (1) core piece, (2) wax mold of cat, (3) cross section of core, wax cat and clay mantle, (4) inverted assembly ready to receive molten bronze [30]; **b)** A cross section through a Buddha head during production. The wax image (red) was modeled over an inner clay core (blue). Metal pins hold the core and outer clay casing apart [31].

Sanxingdui

The archaeological discoveries at Sanxingdui where this enormous mask was found in 1986, are among the most remarkable in recent times (**Figure 26**). This site revealed elephant tusks, jades, gold sculptures, pottery vessels, awesome life-size bronze figures, and huge, bronze masks. The form and size of these masks are unparalleled and their use is unknown. Nothing similar has been found in any other Chinese Bronze Age site. Discoveries such as this mask and smaller versions like **Figure 27** have created great surprise in the archaeological field and have initiated new directions in research, including the reexamination of ancient texts. References in these texts to a mythical people from a territory called Gushu (Shu kingdom), whose first ruler named Cancong, had protruding or bulging eyes (zongmu meant vertical eyes prevalent in Chinese myth and folklore), take on new meaning with the discoveries at Sanxingdui [26, 33].

a **b**

Figure 26 - Human mask 12, late Shang, H: 40.3 cm, W: 60.5 cm, thickness: 0.6 cm, weight: 13.4 kg, excavated from Sanxingdui Pit II; largest intact mask of this type found. Twenty masks of a similar style, characterized by the U-shaped structure when viewed from above were found in this pit. The ears are pierced for earrings. Close examination by archaeologists led to the conclusion that the mask was completed in a single casting with molds possibly divided vertically at the ears [15, 33].

Its size and the monstrous pupils make **Figure 28** one of the most weirdly supernatural of all the Sanxingdui sculptures. Twenty other masks found in Pit 2 have more human-like features. The bronze human head (**Figure 29**) has the least exaggerated features of those found in the Sanxingdui pits, yet he was definitely related to the others with his large ears, eyes and eyebrows. This head was cast in a mold divided vertically at the ears (where a molding mark can be seen) and probably at the nose too. The term “mask” is used here to describe a shell of bronze, U-shaped in horizontal section, with no top, back or neck.

Figure 27 - Human mask 13, late Shang H: 25.5 cm, W: 42.5 cm, thickness: 0.3 cm, weight 3.4 Kg, excavated from Sanxingdui Pit II. The square hole in the forehead was chiseled out with a sharp tool after casting. It is believed that the ears and the face were cast separately for this mask and joined through a subsequent casting [33].

Two other smaller masks with these more exaggerated features were also found in the pit. Thirty-three telescope-like bronze pupils were found by themselves in a pit. (Alternatively these extra pupils may represent pre-cast parts of masks that were never made. A number of objects in the two pits are incomplete or look unfinished.)

a **b**

Figure 28 – a) Front of Mask with Protruding Pupils, Late Shang period, 12th century B.C.; bronze; H. 26 in. (66 cm), width 138 cm, depth 73 cm; excavated from Sanxingdui Pit 2, Sanxingdui Museum; b) back view [15].

The opening in the forehead, which has particularly heavy scorings visible at its corners, must have held an appendage. (A trunk-like projection was found on another mask from the same pit.) The crack that runs across the mouth and chin may be damage-inflicted intentionally before burial; on the left pupil, dents are clearly visible. The mask was made in six pieces, five were pre-cast (the ears, pupils and triangular underside of the nose) and embedded in the mold for the sixth. The mold for the main pour required a core and probably two sections for the front of the mask [15, 33]. The projecting pupils for the eyes were cast first by themselves and inserted at the appropriate locations in a mold for the rest of the mask, except for the ears; when the mold was filled, the pupils were locked in place. The ears were precast and embedded in the final mold.

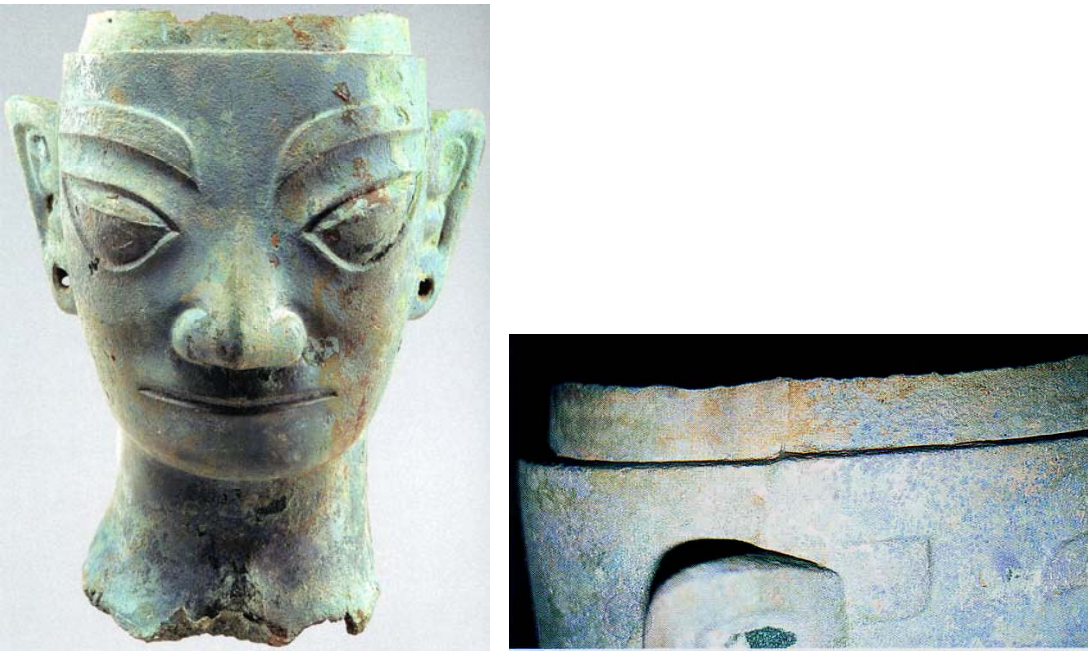

a **b**

Figure 29 – **a)** Human head, middle Shang c. 1300 BC, bronze, H: 29 cm, width: 20.6cm, weight: 4.483 kg, excavated from Sanxingdui Pit I; **b)** detail of the area above right ear [15, 26, 33].

Imagine what it was like for the archaeologists to find this life-sized statue of a human figure from Bronze Age China (Sanxingdui Pit 2). There is very sketchy information about the city or people where they were made. No texts or written information has been found. Archaeologists discovered the “standing figure” with its original casting core still inside [15, 33]; after close examination it was determined that the figure (**Figure 30)** had been cast in seven separate components. Part 1: the undecorated pedestal where mold marks along the vertical edges and top suggest that it was cast in a mold (upside down) with 5 outer sections. The pedestal was thought to be undecorated so that it could be sunk into the ground. Part 2: the pedestal portion decorated with elephant-like trunks, including the decorated block the figure stands on. This complicated shape with surface decoration was technically a very difficult piece to cast.

Figure 30 - Figure on Pedestal, Late Shang period, 12th century BC, bronze; overall H: 106 3/4 in. (260.8 cm), w: 180 Kg, Sanxingdui Museum [33].

Tenons were used to secure this piece to the undecorated slab beneath it and the plain board above it; many of the joins on this statue were soldered. Part 3: the feet of the statue, including the plain board underneath, and the lower part of the robed body. This part was probably cast with a three piece mold (1 for the back and 2 for the front). In the front, the vertical crease in the robe seems to line up with a mold separation; the horizontal mold lines are fairly close to the decoration lines. Part 4: the upper part of the body with the head and the upper portion of the crown (not the arms). This part may have been cast using a section mold for the front and one for the back, with the dividing line through the ears. There is a visible (vertical) mold mark on the headband above the left ear. Parts 5 & 6: two arms; there are traces of run-on metal where the arms are joined to the shoulders. A mold mark is visible on the left arm (from the elbow down); the arm was probably cast using 2 sections. Part 7: the decorated upper portion of the headdress [15].

Environmental Effects on Surface Appearance

The surface appearance of ancient Chinese bronzes as they exist today is a combination of the original surface finish, the deliberate damage (as seen in the Sanxingdui Pits) and corrosion products that have occurred during burial, as well as mechanical and chemical processes that have been performed by dealers, restorers and conservators after excavation. A thorough examination of the bronze using a variety of visual, technical and scientific apparatus can often reveal what has occurred over time. In looking at the range of corrosion products on bronzes, generally the corrosion mechanism varies considerably from piece to piece and even from place to place within a single vessel. This results from factors in the local environment, such as the moisture content of the soil, salts, organic matter, permeability to atmospheric oxygen and contact with other metals and materials [24, 34]. The latest theories indicate corrosion mechanisms may be driven by electrochemical processes where ion migration, transport and movement occur. The amounts of corrosion are also influenced by the degree of surface finish and alloy composition. A well finished surface can slow the rate of corrosion and affect the corrosion products formed. Tin added to the bronze makes the metal more brittle and capable of taking a higher polish, rendering it more corrosion resistant.

The combination of the extent of surface finish and alloy composition can determine the type of corrosion that occurs in the form of tin oxides on the surface, which in turn influences the protective nature of the corrosion film formed. It is thought that during burial, bronzes undergo two main types of corrosion processes: Type I (delta removal) and Type II (alpha removal) [7]. Delta and alpha refer to the different phases or crystal forms that appear in the bronze microstructure. They are selectively attacked in a corrosive environment depending on the nature of the metal, surface treatments and burial conditions [21]. Type I (delta removal) corrosion products are commonly seen on Chinese bronzes. They are mineral alterations of the bronze constituents, mostly copper (cuprite, malachite and azurite) as well as tin (cassiterite) and lead (cerussite) corrosion products [7, 21, 24]. They can appear as smooth or crusty patches of red, green, blue, gray or white material. They occupy more space than the metal from which they are derived to create thick disfiguring crusts over the original bronze, at times disguising decorative features. The crusts are not cohesive, so they allow harmful products like chlorides found in salts from the burial environment to migrate deeply into the bronze.

The chlorides react with the metal crystalline structure to promote active corrosion (bronze disease) even after the bronze has been excavated. It has been proposed that these less stable, thick, disfiguring corrosion layers are more likely to form on low-tin bronzes (that have a higher copper content), and objects that were not originally patinated where the unprotected bronze surface was more susceptible to corrosion [7]. Type II (alpha removal) corrosion products are associated with a smooth compact gray-green eggshell-like surface on the bronze, sometimes called a water patina [21]. **Figures 31-32** are examples of some unusual Chinese bronze castings and the metal interaction with its environment over the thousands of years.

Figure 31 - *Fang-yi*, Zhou dynasty, 11th century BC. H: 35.6cm, W: 24.7cm, Wt: 9.92 kg. The Fang yi first appeared as a distinctive vessel type in the Shang dynasty and continued to be made into the early Spring and Autumn period (FGA 30.54) [11, 21].

The surface of the *fang yi* in **Figure 31** is covered with a mixture of malachite and cuprite patinas; the overall appearance is grey-green with red, some areas of rough corrosion. Malachite is a copper ore mineral that forms as corrosion by product (copper carbonate) on buried bronze [34]. The vessel and lid were made by direct casting in a piece mold with 4 main sections. The primary mold marks run vertically along the corner flanges. The square post of the knob handle and the knob are both hollow cast around clay cores that can be seen clearly in radiographs. There are several concealed chaplets symmetrically placed in the sides of the vessel and lid. Wet chemical analysis and emission spectroscopy results are shown in **Table 7**. The alloy has a high percentage of tin content with a composition close to the bronze alloys used for mirrors during the Han dynasty [24].

Table 7 – Elemental analysis from wet chemical analysis and emission spectroscopy for Figure 31 (Zhou dynasty *Fang-yi*) [24].

Elements (%)													
Cu	Sn	Pb	Ag	As	Bi	Co	Cr	Fe	Mg	Mn	Ni	Sb	Si
77.3	21.5	1.2	0.02	0.2	0.04	<0.005	0.004	0.09	<0.001	-	0.03	0.2	0.01

Figure 32 - *Huo* (FGA 42.1), Shang dynasty, Anyang, 12th century BC, H: 18.5cm, W: 21.0 cm, Wt: 2.78 kg. The surface is covered with a smooth, grey-green (tin-oxide) patina and small areas of malachite and azurite encrustation. Azurite is also a bronze corrosion product similar to malachite but with a bluish hue [34].

Figure 32 is a unique vessel cast in a three-piece mold, however, due to the high finish, the mold marks are difficult to see. The mold assembly has one segment at the rear roughly 180° distance and 2 segments at the front roughly 90° apart. The spout is located along one of the mold joins. The other mold seams are just behind the lug handles. The handles appear to be cast with the vessel. Horizontal mold joins are located above and below each lug. The two horns are hollow [24]. Wet chemical analysis and emission spectroscopy results are shown in **Table 8**.

Table 8 – Elemental analysis from wet chemical analysis and emission spectroscopy for Figure 32 (Shang dynasty *huo*) [24].

Elements (%)													
Cu	Sn	Pb	Ag	As	Al	Co	Cr	Fe	Mg	Mn	Ni	Sb	Si
78.4	13.6	3.1	0.03	0.2	0.004	<0.001	-	0.01	<0.001	-	0.001	0.02	0.07

Over the centuries, bronze may come into contact with water, oxygen, carbon dioxide gas, sulfides, salts and microbes in the soil. Long term chemical and biological reactions, along with foreign elements penetrating into the metal alloy, can easily cause corrosion [13]. It is very useful to know what compounds are present to determine authenticity, as well as the proper course for conservation of the artifact. Removal of the corrosion product may destroy historical information and fine surface features [34]. Bronze articles exposed to high humidity or buried, undergo a natural change where they develop a bright coating or patina. The patina serves to protect the metal from further damage and can range in color from red to green to blue [34]. By examining tiny metallographic samples under a microscope, often intergranular corrosion can be detected, possibly confirming that an object has been buried for centuries; the vessel may also have to be x-rayed. From x-rays, spacers, flow irregularities, old repairs, precise saw cutting, and entrapped air bubbles can be seen. Pin holes, for example, are an indication that either lost wax casting has been used, and may not be consistent with the time period. Some pieces may look genuine, but when analyzed in the lab, technical inconsistencies are revealed. Often when an object has been produced with multiple castings, the separate parts have corroded differently than the main vessel, indicating that the composition of their alloys may not be uniform [8].

Conclusion

The Chinese were adept at manufacturing, creating and decorating ceramic clay vessels. It is believed that Chinese casting techniques were independently developed during the Shang dynasty or possibly as early as the late Xia. It was assumed that bronze casting was not introduced to China by foreigners since cultures outside of China relied on significantly different metal working methods like hammering sheet metal. Chinese bronzes ornamented with ogres, dragons and *taotie* beasts were distinguished by their disregard for realism in favor of bold exaggeration and distortion. The Chinese aristocracy had created a massive demand for bronze ritual vessels with their religious and cultural ceremonies. The vessels also symbolized social status and power for the owner. Initially, bronze casting using the piece mold technique was an extension of their ceramic technology. The shapes of the early Chinese bronze vessels were very similar to the forms created with clay, yet somewhat primitive. The number and variety of vessel forms increased with time, and so did the complexity of decoration and manufacturing techniques. Certainly, long and specialized experience in clay handling was required to form the delicate inscriptions, to properly fit the molds together and to prevent them from cracking during the pour.

Developments of increasing sophistication occurred alongside improvements in casting technology; it was more than mere familiarity with the bronze material, however. The Chinese had made advances in process planning, extracting, refining, casting and experimenting with vessel form and decoration.

Bronze alloys were used almost to the exclusion of any other alloy for nearly 1000 years in China; even after the introduction of iron, bronze was used for weapons, vessels, coinage and statuary. The exclusive use of casting by the early Chinese metalworkers may have been due to the poor malleability of these alloys and they simply could not work the materials with a hammer. Another reason for the prevalence of bronze may have been the color range that could be achieved by varying the amounts of copper, tin and lead in the alloy. The evolution of foundry practices and the craftwork required for ceramics, mold making, metal refining, finishing and machining are responsible for the development of casting technology and the incredible discoveries that have been excavated.

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