The Lost-Wax Process in the Pre-Qin Period: A Bronze Appendage with Hollow Snake Patterns from the Tomb of Duke Ning of Xu¹

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Abstract: This paper discusses the most recent case of the lost-wax process, namely, a bronze appendage with hollow snake patterns excavated in 2002 at the tomb of Duke Ning of Xu (許公寧) (a state in the Spring and Autumn period) in Ye County, Henan Province. Various physical and chemical analyses indicate that this artifact was cast as a whole in 547 BCE or slightly later in a high tin bronze alloy using the lost-wax process. No traces of cast joints or soldering were found. This research provides further proof that the lost-wax process was a significant technical development achieved by casters in the Pre-Qin period.

Keywords: lost-wax process, tomb of Duke Ning of Xu, bronze appendage, snake patterns

1 Introduction

In pre-modern China, the majority of bronze vessels were cast using clay molds. In the 1970s, a number of intricate bronze vessels were excavated from tombs of the Spring and Autumn period (770–476 BCE) such as the Chu-tomb in Xichuan, Henan, and the tomb of Marquis Yi of Zeng 曾侯乙 in Hubei. Since the 1980s, archaeologists and historians of casting technology have been conducting studies on such intricate vessels,

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as the *zun* 尊 and *jin* 禁, and it was concluded that they were cast using the lost-wax process (Hua and Guo 1979; Hua and Jia 1983; Ren and Wang 1987; Zhao 1991, 379–388).² In 1999, Li Jinghua 李京华 once again argued that the bronze *jin* vessel excavated in Xichuan was cast using the lost-wax process and predicted that “castings of this kind discovered in this tomb are not the only high-quality ones, and that more could be excavated from tombs at the same level in the territory of the Chu state and in the neighboring states” (Li 1999). This finding was not questioned until the early twenty-first century when certain scholars asserted that there was no such thing as lost-wax casting and that it was inconceivable that any bronze vessel could have been made using this process (Zhou et al. 2006). Apart from the *zun* and *jin* vessels, there are more cases of excavated bronze vessels that testify to the existence of the early lost-wax process. This paper discusses the most recent case of the lost-wax process, namely, a bronze appendage with hollow snake patterns excavated in 2002 at the tomb of Duke Ning of Xu in Ye County, Henan Province (in the following referred to as the hollow decorative casting, or casting).

2 The hollow decorative casting and the date it was cast

In the spring of 2002, a hollow decorative casting was excavated from the tomb of Duke Ning of Xu in Ye County. In early 2002, this tomb was plundered and over 350 cultural relics were unearthed through salvage excavations. Among them are over 280 bronze items, including high-quality pieces such as *shengding* 升鼎 vessels, *bianzhong* 編鐘 (set bells), *jian gu zuo* 建鼓座 (a holder for a *jian* drum, a drum stand through which a pole is run), and a hollow decorative casting. It is inferred that the hollow decorative casting was produced in the early phase of the late Spring and Autumn period (somewhere between 576 and 547 BCE or slightly later). This casting could be an accessory of a *yi* 匜 vessel or the handle of a *zhan* 盞 (cup), due to its shape and indications of how it was produced (Zhao 2006).

3 The structure of the casting

The hollow decorative casting is 58 millimeters high, 48 millimeters wide, and 2–3 millimeters thick (Figure 1). It is well-preserved with a dark green surface and is slightly rusted and corroded; there are also cracks at the top and in some of the patterns. A small amount of reddish yellow soil from the mold remained on the inside of the

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² In pre-modern China, the principle of the lost-wax process is explained as follows. First, a model is made from meltable materials such as wax. Then, it is coated with fine clay and is dried. Later, the wax model is melted to form a hollow cavity into which liquid bronze is poured. Finally, the entire casting is produced.

handle. Moreover, some dark brittle residues can be found in the upper cavity, similar to the rusted and corroded lead-tin solder commonly used for bronze wares in that era. This indicates that this casting is an appendage that was originally soldered on to the main body with the lead-tin solder.

Figure 1: The hollow decorative casting excavated from the tomb of Duke Ning of Xu (drawn by Pan Miao 潘妙).

The most complex and appealing part of this casting are the patterns grouped at the top, which feature a large quantity of hollow snakes. The patterned area is 4.8 centimeters long, 2.9 centimeters wide, and 3.6 centimeters high. The validation and discussions of the technique used to produce this are premised on the structural analyses of the casting. It is therefore vital to conduct an analysis of the composition and characteristics of this pattern group.

The analysis was carried out by means of meticulous observation and the industrial computed tomography (CT). The results showed that the pattern group is composed of 13 different types of patterns. For patterns 1, 2, 3, 4, 5, 8, 9, 10, and 11, their symmetrical patterns are named 1', 2', 3', 4', 5', 8', 9', 10', and 11'. Despite differences in size, height, direction, and composition, all of these patterns can be regarded as variants of the snake pattern and are thus generally referred to as the snake pattern (Figure 2).

Uneven in length and arranged in rows, these patterns are distributed regularly and symmetrically around an axis. With variety in uniformity, they distinctly abide by a regular mode that is complex but not chaotic, thereby constituting an intricate and complex image.

Figure 3 presents the top view of the pattern group. As shown in Figure 4, this group consists of eight types of symmetrical pattern.

Figure 2: Patterns of the hollow decorative casting (drawn by Hua Jueming).

Figure 3: The top view of the pattern group. The upper part of this top view is the front of the casting (photo by Zhang Mingwu).

Figure 4: The distribution of patterns in the top view. The middle column of this casting is beneath pattern 6 (drawn by Hua Jueming).

Figure 5 displays the front view of this casting. In the top view shown in Figure 3,

two kinds of patterns 3, 3', 8, and 8' are below the pattern group at both ends, underneath which are the patterns 9 and 9'.

Figure 5: The front of the hollow decorative casting (photo by Zhang Fangtao).

Figure 6 shows the upward view of the front of this artifact. It is thus evident that patterns 9 and 9' are supported by the slanting bronze stalks underneath.

Figure 6: The upward view of the front of the hollow decorative casting (photo by Zhang Fangtao).

Figure 7.1 shows the rear view of the artifact. As demonstrated in this figure, pattern 6 is supported by bronze stalks, and the stalks are connected to patterns 10 and 10', which are directly linked to the decorative casting. On the left and right of the lower side of patterns 10 and 10' are patterns 11 and 11'. Figure 7.2 shows an enlarged image of part of the patterns, suggesting that the surfaces of patterns 10 and 11 and so forth are concave.

Figure 7.1: The rear view of the hollow decorative casting.

Figure 7.2: An enlarged image of patterns 10 and 11 (photo by Pan Miao).

Figure 8 shows the upward view of the back of this casting, demonstrating that patterns 11 and 11' are also supported by the relatively short bronze stalks. There are four bronze stalks on both sides, respectively. Among these, apart from the two short stalks supporting patterns 11 and 11', the remaining six stalks are longer, holding patterns 12, 12', 13, and 13' on each side, respectively, as is shown in the lower part of Figure 9

(patterns on the left of the casting). Patterns 12 and 12' are therein all supported by the second bronze stalk, and patterns 13 and 13' are carried separately by the third and fourth bronze stalks.

Figure 8: The upward view of the back of the hollow decorative casting (photo by Zhang Mingwu).

A total of 13 different kinds of 24 symmetrical patterns constitute the pattern group. The majority of the patterns are held by one or two bronze stalks, and part of the stalks are intersected and interwoven (Figure 9). Such a design is doubtlessly aimed at strengthening the connections of various patterns, as well as considerably enhancing the visual effect of intricacy and convolution.

Figure 9: The left side of the hollow decorative casting (photo by Zhang Fangtao).

4 Physical and chemical analysis and technical identification

Technical identification was mainly gained through meticulous observation. A total of three groups of scholars studied this artifact: Li Xueqin 李学勤³ stated that some of the bronze wares from the tomb of Duke Ning of Xu could have been cast with the lost-wax process; Tan Derui 谭德睿,⁴ Hua Jueming and his co-authors⁵ confirmed that this artifact was made with the lost-wax process. The manufacturing procedures presented in Tan's written account of the identification are as follows:

1. Make multiple types of wax strips with patterns in advance.
2. Produce and dry the inner mold for the body of the casting, cover it with wax, and sculpt the body.
3. Weld one end of the hand-rubbed wax stalk onto the wax body. Bend the prepared wax strip, which is slightly heated, and weld it to the other end of the wax stalk, or weld the wax strips together, thereby forming a hollow pattern. Then, weld the wax sprue in the correct position so that a complete wax model is produced.
4. Coat the wax model with the specially formulated clay material (the sprue is not covered), and perform this step again after the mud has dried. Repeat this until the desired thickness is reached and cover the coated model all over with the dough-like mud, which slowly dries and turns white. Then, place the model in a kiln and heat it slowly. After the wax flows out, continue to heat the clay mold until it turns red hot (before becoming ceramic), with the temperature at approximately 800°C.
5. Take the mold out of the kiln and let it cool down to an appropriate temperature, then pour liquid bronze into it. When the liquid bronze has solidified, hammer off inner and outer molds. The sprue is then removed. Finally, after being cleaned, the artifact is finished. The whole production process, including preparation of the models and molds, takes around one month.

In a bid to obtain more substantial evidence, and to identify the structure, composition, and techniques of the casting, an industrial CT (BT-400-1) and a portable XRF were used.⁶

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³ In March 2003, Li Xueqin went to Ye County to investigate the relics from the tomb of Duke Ning of Xu.

⁴ In December 2003, Tan Derui was invited to Ye County to investigate the bronze finds from the tomb of Duke Ning of Xu, and he affirmed that the hollow decorative casting (M4-0200) was produced through the lost-wax process, as stated in his written views on the identification.

⁵ On August 14, 2006, Hua Jueming, Tan Derui, Li Yuanzhi, and Zhang Fangtao investigated the excavated bronze wares from the tomb of Duke Ning of Xu. It was once again affirmed that the hollow decorative casting found there was produced with the lost-wax process.

⁶ During September 11–13, 2006, Li Yuanzhi, Zhang Fangtao, Hua Jueming, and Zhang Mingwu went to the Beijing Institute of Aeronautical Materials, which specializes in non-destructive testing and investment casting, where tests were performed. Many experts from the third and sixth laboratories and BIAM Alloys LLC offered guidance and personally conducted tests, including Shi Yishu 史亦书, He Fangcheng 何方成, Yang Jianwei 杨建伟, He Youdu 何有都, Yang Danggang 杨党纲, Liu Qingzhen 刘庆珍, Song Xiaohui 宋晓辉, Li Hanchao 李汉超, Dong Tianxiang 董天祥, and Li Xingguo 李兴国.

In addition, samples were obtained from the lower part of the casting by means of wire-cut electrical discharge machining. SEM-EDS and metallographic examination⁷ were carried out and the following results were yielded.

4.1 Industrial CT testing

Figure 10 (No.1#-1) shows the DR image of the third bronze stalk on the right side of the casting, namely, the column in the middle. The scanned section of this stalk is shown at the left side of the figure. An industrial CT was utilized to produce the DR image. Tomographic scanning was then performed after the target was accurately located.

Figure 10: A DR image of the third bronze stalk (the middle column) on the right side of the casting and the second bronze stalk on the left (No.1#-1, tested by Yang Danggang 杨党纲 and Liu Qingzhen 刘庆珍).

Figure 11 (No.1#-2) shows a scanned image of the longitudinal section of the bronze stalk, known technically as the slice image. What has been marked with an ellipse shows that the bronze stalks and the body of the artifact were produced as a whole, with no interface or diffusion layer existing between them, which would inevitably result from casting or soldering. Likewise, there is no interface or diffusion layer at the upper end of the bronze stalk that connects pattern 12. This indicates that the bronze stalks and the patterns were also cast integrally.

Figure 12 (No.1#-3) displays the slice image of the longitudinal section of the second bronze stalk on the left side of the casting. Similar to Figure 11 (No.1#-2), Figure 12 also provides proof that the bronze stalks, the casting and patterns were cast as a whole rather than being soldered or cast together.

Figure 13 (No.1#-5) shows the DR image of the central bronze stalk beneath pattern 6 (Figures 6–7).

⁷ Yao Xiuhui 姚秀辉 and Chen Kunlong 陈坤龙 carried out the laboratory analysis.

Figure 11: A slice image of the longitudinal section of the third bronze stalk on the right side of the casting (note the section in the ellipse) (No.1#-2, tested by Yang Danggang and Liu Qingzhen).

Figure 12: A slice image of the longitudinal section of the second bronze stalk on the left side of the casting (No.1#-3, tested by Yang Danggang and Liu Qingzhen).

Figure 13: A DR image of the central bronze stalk (No.1#-5, tested by Yang Danggang and Liu Qingzhen).

Figure 14 (No. 1#-6) provides proof that the bronze stalk, the casting itself, and pattern 6 were produced integrally since there is no obvious joint between them. Thus, it can be concluded that neither soldering nor casting was used to connect them. The scanned images, mentioned earlier, of all the sections also revealed cracks in the casting, as well as in a small number of patterns.

Figure 14: A slice image of the longitudinal section of the central bronze stalk (No.1#-6, tested by Yang Danggang and Liu Qingzhen).

Figure 15 (No.1#-7) shows a DR image of the cross section of the casting when placed in an upright frontal position.

Figure 16 (No.1#-8) shows a slice image of this cross section, showing how 21 different kinds of patterns and bronze stalks are orderly and symmetrically distributed. This helps to understand the structure of this decorative casting and how it was produced.

Figure 15: A DR image of the cross section of the casting when placed in an upright frontal position (No.1#-7, tested by Yang Danggang and Liu Qingzhen).

Figure 16: A slice image of the cross section of the casting (No.1#-8, tested by Yang Danggang and Liu Qingzhen).

As demonstrated in the test report (No.2006-06-2091) of the industrial CT, the tube voltage of the DR imaging is 250KV, and that of the CT imaging is 300KV, while the tube current is 2MA.

4.2 Chemical composition analysis

After removing the corrosion from the lower part of the handle, the chemical composition of the artifact was analyzed using a portable XRF. Two tests revealed that it contained the following elements and their proportions (WT, %): copper 67.94 and 66.55, tin 20.08 and 20.98, lead 10.71 and 10.39, silver 0.15 and 0.20. The same elements of similar proportions were found in both tests, indicating that this casting is lead-tin bronze (ternary copper alloy) of high purity, with a large proportion of tin and a medium content of lead. Silver could have been introduced from ores during the smelting process.

4.3 SEM-EDS and metallographic detection

(1) Bronze sample⁸

A strip-shaped bronze sample was cut from the lower part of the casting using wire-cut electrical discharge machining (WEDM). The analysis conducted with the energy dispersive spectrometer (KEVEX) revealed the chemical composition: copper 78.4%, tin 15.0%, and lead 6.5% (Figure 17). Compared with the findings of the portable XRF, the contents of tin and lead are lower, probably resulting from different tested parts and different analytical methods. After removing the corrosion, the portable XRF was used to test the lower part of the casting, demonstrating the conditions of its surface. On the

⁸ In 2006, Yao Zhihui 姚智辉 and Chen Kunlong from the Institute for the History of Metallurgy and Materials, University of Science and Technology Beijing, conducted an analysis on this sample and provided the authors of this paper with the results and data.

other hand, in the testing performed with the SEM-EDS, the carefully polished cross section of the casting served as the sample, thus offering results with higher accuracy.

Figure 17: EDS spectrum of the sample obtained through WEDM (tested by Yao Zhihui and Chen Kunlong).

The back-scattered electron image shows that the dark surface is covered with a layer of corrosion where the black dots are copper oxides and the evenly distributed white particles throughout the section are free lead (Figure 18). The scanning electron microscope used here was No.LED-1450.

Figure 18: The back-scattered electron image of the sample obtained through WEDM from the hollow decorative casting (tested by Yao Zhihui and Chen Kunlong).

The metallographic examination indicated that the composition of the sample can be represented as $\alpha + (\alpha + \delta)$, which exemplifies the high tin bronze in as-cast state.

Dendritic segregation is obviously seen in the α solid solution, and the relatively fine and dense ($\alpha + \delta$) eutectoids form a network. In the matrix, there is a comparatively large quantity of evenly distributed lead particles, and a small amount of free copper which is the product of electrochemical corrosion during the long-term burial (Figure 19).

Figure 19: The metallographic structure of the sample gained through WEDM from the hollow decorative casting, 150 $\times$ (tested by Yao Zhihui and Chen Kunlong).

(2) Sample of solder⁹

The triangular blocky sample, which was seriously corroded, was scraped from the upper part within the cavity of the artifact. SEM-EDS area analysis indicated that tin is the primary component (Figure 20). In both the back-scattered electron image (Figure 21) and the metallographic examination (Figure 22), there are large amounts of white blocky tin oxides. Therefore, the casting, as an appendage, and the main body were soldered together by means of a solder containing high tin or pure tin.

According to the spectral qualitative analysis, the solder employed in the *shengding* vessel (M2: 34), excavated from the Chu-tomb in Xichuan in the Spring and Autumn period, contains tin at levels as high as 98.23% (Henan Provincial Institute of Cultural Relics and Archaeology et al. 1991, 390). Furthermore, *jiangu* and the Chinese dragon heads on *jian fou* 鑒缶 (a deep, wide bronze water dish and an ancient Chinese container comprising a bronze crock) excavated from the tomb of Marquis Yi of Zeng contain 93.36% and 90.92% tin, 5.88%, and 0.48% lead respectively. In addition, for the bronze loops used in the beams of *bianzhong*, and the round foot of the bronze *zun*

⁹ In 2006, Yao Zhihui and Chen Kunlong from the Institute for the History of Metallurgy and Materials, University of Science and Technology Beijing conducted the analysis on the solder, and provided the authors of this paper with the results and data.

vessel, there are 39.12% and 53.41% tin, as well as 60.05% and 41.4% lead, respectively (Hubei Provincial Museum 1989, 645). Thus, the solder utilized in the Spring and Autumn period can be seen to generally fall into two types: one consists primarily of tin or even pure tin; the other consists of tin-lead. For the latter category, the solder in the bronze loops in the beams of *bianzhong* and in the round foot of the bronze *zun* vessel is to a small degree similar to the commonly used modern solder No. 603 (39%–40% tin, 1.5%–2% antimony, and the remainder is lead).

Figure 20: EDS spectrum of the corroded solder from the upper part within the cavity of the hollow decorative casting (tested by Yao Zhihui and Chen Kunlong).

Figure 21: The back-scattered electron image of the corroded solder from the upper part within the cavity of the casting (tested by Yao Zhihui and Chen Kunlong).

Figure 22: The metallographic structure of the corroded solder from the upper part within the cavity of the casting, 150× (tested by Yao Zhihui and Chen Kunlong).

In general, the composition of solder varies greatly in different cases, and it remains to be found whether there are regular reasonable ratios, and whether more tin was applied in some solder, perhaps for the purpose of enhancing strength (Hua 1999, 181–184).

5 Conclusion

In summary, investigations on the casting techniques and the physical and chemical analyses provide sufficient proof that the bronze appendage with hollow snake patterns, which was excavated from Duke Ning of Xu's tomb, was cast as a whole. The use of piece-mold casting can be ruled out due to the fact that there are no traces of post-casting processing, such as polishing within the pattern group, and that no traces of casting marks are found on the artifact's surface, bronze stalks, or patterns. There are also no traces of cast joints, soldering,¹⁰ or forging. Therefore, there is no doubt that this artifact was produced using the lost-wax process.

There are a number of other ritual bronze wares, which are already known to have been cast through the lost-wax process in the Pre-Qin period. Produced under the reign of Xiong Shen 熊審, King Gong of Chu, the bronze *zhan* is the earliest known casting using this technique, from around 560 BCE or slightly later (Hua and Xiao 2005). In addition, the bronze *jin* vessel, excavated from the Chu-tomb in Xichuan in the Spring

¹⁰ The soldering process mentioned above, which joins the decorative casting and the bronze body together, is irrelevant to the formation of the bronze stalks, patterns, and the decorative casting.

and Autumn period, was cast no later than 552 BCE or slightly later, and the matching tray of bronze *zun* vessel from the tomb of Marquis Yi of Zeng was cast no later than 513 BCE or a little later (Henan Provincial Institute of Cultural Relics and Archaeology et al. 1991, 320–324; Hubei Provincial Museum 1989, 461–464). Furthermore, the *yun'er zhan* 愠兒盞 (*yun'er* cup) held at Hunan Provincial Museum, was cast in 530 BCE at the latest. The hollow decorative casting excavated from the tomb of Duke Ning of Xu was produced no later than 547 BCE or slightly later, approximately in parallel with the bronze *jin* in Xichuan. These two bronze items show a similar artistic style and regional characteristics. Considering their casting methods, pattern structures, and decorative techniques, the same type of process was adopted for their casting. Consequently, a series of orderly technical developments can be seen to have existed, which built upon information from their antecedents.

As a symbol of the lost-wax casting in the mid-and-late Spring and Autumn period, the hollow decorative casting excavated from Duke Ning of Xu's tomb is a perfect example of the lost-wax process in the Pre-Qin period. The excavation, research, and identification of this artifact offer further proof that the unique lost-wax process belongs intrinsically to the bronze-casting techniques of the Pre-Qin period in China.

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