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ORIGINAL PAPER

Study on manufacturing process of ancient Chinese bi-metallic bronze *Ge*

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Abstract
Among ancient Chinese bronze ordnances, bi-metallic weapons reflect the superb manufacturing level, and exhibit important research and historical values. Up to now, many ancient bi-metallic bronze swords have been unearthed in China, and their manufacture process has been intensively analyzed. In this paper, two bi-metallic bronze *Ges* were discovered and studied for the first time, which were identified as the *Chu Ge* dated to the Warring States Period (475 BC–221 BC), and a possible manufacturing process was proposed, regarding their morphologies, microstructures, and chemical compositions. According to excavation information and typological characteristics, we deduce that these two *Ges* belong to a halberd, called the "double-*Ge* halberd." The present work is helpful to understand the ancient metallurgical and casting technologies during the Warring States Period, and provides new technical evidences for archeology and metallurgy history.

Keywords Ancient Chinese bi-metallic bronze *Ge* · Manufacturing process · Double-*Ge* halberd · The Warring States Period · Metallurgical analysis

Introduction

Weapon played an important role in the development of human society. They were also an important part of the splendid culture of ancient China, which reflected the culture, history, science, technology, and skills of a certain period. From archeological excavation, it was found that some weapons were made of different types of metals or alloys, or the same alloy with different ratios. Some of them were gifts or ritual objects, such as a bronze sword with jade handle and iron blade (Jiang 1999) and a knife with gold handle (Tian and Lei 1993). Most weapons were for equipping army, such as bronze battle-axes with iron blade (Gettens et al. 1971; Yuan and Zhang 1977; Li 1976), bronze paring knifes with iron blade, bronze dagger-axes with iron blade (Jiang 1999), and even the bi-metallic bronze swords (Lian and Tan 2002; He 1990; Chen 1981; Ding et al. 2012).

It is well known that bronze weapons have been widely used during Chinese dynasties Xia (2146 BC–1675 BC), Shang (1675 BC–1029 BC), and Zhou (involving 1029 BC–771 BC of the West Zhou: and 770 BC–221 BC of the Spring-Autumn and Warring States Periods). In addition to regular bronze swords, up to now, several bi-metallic bronze swords have been unearthed or collected in the most area of China, which achieved the highest performance and was considered to be one representative type of the advanced technologies. The bi-metallic bronze sword was invented based on the following principle: the spine was made of low-tin (Sn) bronze with good flexibility, and the blade was made of high-Sn bronze with high mechanical strength and hardness, which consequently resulted in a stronger lethality and longer service life. This sword was usually manufactured by using a two-step casing technology, and connected by mortise and tenon joint in cross-section, which bore the rigidity and flexibility simultaneously (Lian and Tan 2002).

In general, ancient Chinese bronze *Ge* was produced in a one-step casting by using piece-mold casting technique with two pieces of mold (Chen 2010). The manufacturing process

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was as follows: (1) prepare the molds of *Ge*; (2) pour the molten bronze into the molds; (3) after solidification, move the *Ge* out of the mold and polish it, and sharpen the blade. Many researches (Zhao et al. 2012; Yang et al. 2013; Jia et al. 2011; Sun et al. 2011) revealed that the Chinese bronze *Ge* was made of Cu–Sn alloy or lead (Pb) added Cu–Sn alloys (simplified as Cu–Sn+Pb) with high Sn contents in a range of 10–20 wt%.

Due to the difference in function and usage between *Ge* and sword, few bi-metallic bronze *Ges* were discovered hitherto. And study on its manufacturing process has not been reported. In this work, two bi-metallic bronze *Ges* were occasionally discovered, which was discovered near the Longwang Mountain in Huanggang City, Hubei Province, China. According to the systematical study on the chemical compositions and microstructures, we get more acquainted with the making process of bi-metallic bronze *Ge*, and its historical background and the motive in making these objects were also discussed. It is expected to give deep understanding of the manufacturing process of bronze weapons during the Warring States Period, and provides new scientific and technical evidences for archeology and metallurgy history.

Archeological backgrounds

According to the record of the museum, these two bi-metallic bronze *Ges*, as shown in Fig. 1, were discovered from a brick factory located around Longwang Mountain at Huangzhou District of Huanggang City, Hubei province, China, in 1995, when the workers were digging soil, and now collected in the Huangzhou Museum with the record no. 74 and no. 76. Actually, they are not unearthed from a known cemetery.

Huangzhou District is located in the eastern part of Hubei Province, on the north bank of the middle reaches of the Yangtze River. It is a historical and cultural area, which belonged to the *Chu* State during the Warring States Period. There are many ancient cemeteries around the Longwang Mountain, such as Longwang Mountain Cemetery, Wangjiachong Cemetery, Guoerchong Cemetery, and Caojiagang No. 5 Tomb. Most of them are identified as the *Chu* Tombs in the middle and late times of the Warring States period (Wu and Hong 2000; Huang 2001; Wang and Wu 1983; Hubei Provincial Institute of Cultural Relics and Archaeology 1993).

In terms of appearance, the no. 74 *Ge* exhibits the following features: (1) the *Yuan* is slender, long, and slightly curved; (2) the mid-ridge is concave; (3) the *Hu* is narrow; the *Na* is wide and has hollowed-out transmuted phoenix patterns. And the no. 76 *Ge* shows the similar shape, but without *Na*. According to archeological typology, these two *Ges* meet the standard style of *Chu Ge* produced during the Warring States Period; they can be dated to the Warring States Period (475 BC–221 BC). Especially, the transmuted phoenix pattern is representative pattern prevalent during the Warring States Period. The names of different parts of *Ge* are shown in Fig. 2.

In fact, there were several similar *Ges* unearthed in the *Chu* tombs of the Warring States Period. For example, one *Ge*, called type B *Ge* (M5: 2), was from the Wangjiachong Tomb 5, which is adjacent to the brick factory where the *Ges* were found (Huang 2001). And other three *Ges* were also unearthed from *Chu* tombs in the Jiangling County of Hubei Province, which also belonged to the *Chu* State during the Warring States Period with about 300-km distance to Huangzhou District, such as one (maned I type *Ge* (M1: 288 + 295)) from the Tianxingguan Tomb 1 (The Jingzhou District Museum, Hubei Province 1982), one (M43: 21) from the Jiudian Tomb 1 (Hubei Provincial Institute of Cultural Relics and Archaeology 1995), and one (M159: 25) from the Yutaishan Tomb 1 (Hubei Provincial Institute of Cultural Relics and Archaeology 1984).

When comparing with the regular *Ges* from other *Chu* tombs, the present no. 74 *Ge* has an exquisite *Na* which shows a solid stripe molding structure, and exhibits a very high level of hollowing casting technique. In fact, this type of *Ge* with a hollow pattern is very rare, and only found in higher rank tombs, such as the Chaixu *Ge* (a king of the state of *Yue*) (Wu 2012) and the King Shiye *Ge* (Wu 2012). This suggests that the present *Ge* was made for a special person as the symbol of status or power, not for equipping the army in combat.

Fig. 1 Images of the bronze Ges. **a** No. 74; **b** no. 76

Experimental methods

The samples were cut along the edge of the broken parts, and then mounted, grounded, and polished according to standard

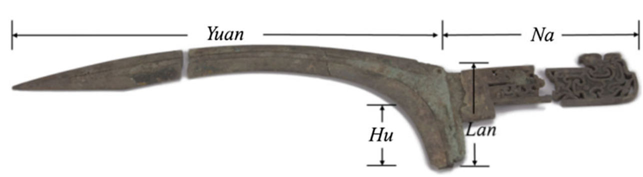

Fig. 2 The names of different parts of Ge

metallographic procedures. The main processes included the following: (1) mechanical grinding to 2000 grit, successive polishing to 0.1 μm, ultrasonic cleaning in ethanol (analytical grade ethanol) and drying; (2) the polished sections were etched with a $FeCl_3$ + HCl + C_2H_5OH solution (3% $FeCl_3$) for revealing the microstructures. Microstructural observations were carried out on the polished and etched sections by using an optical microscope (Leica DM2700, Germany), a three-dimension microscope (Leica DVM6, Germany), and a scanning electron microscope (Phenom XL, Netherlands). The chemical compositions were measured on the polished and un-etched sections in the SEM by using an energy-dispersive spectrometer (EDS) for quantitative analysis, operated at 15 kV, and the unbroken parts were measured by a portable X-ray fluorescence (p-XRF) spectroscopy (Niton XL3t 950, USA). The radiograph was obtained by using X-ray radiography (XXQ-2005, China), which is vital in understanding the internal structures. The microhardness was measured by Vickers hardness tester (HXD-1000TMB/LCD, China).

Results and discussion

Surface appearances and X-ray radiographic morphologies

Figure 3 shows the surface appearances of the bronze *Ges* by using optical microscopes in low magnifications. Obviously, they were consisted of two different metals or alloys. For the no. 74 bronze *Ge*, the concave mid-ridge and *Lan* showed jade green color and tough surface with corrosive sediments, while the other parts were smooth with gray green color, as shown in Fig. 3 b. In addition, there was an obvious seam between *Yuan* and *Na*, as shown in Fig. 3 c. The no. 76 bronze *Ge* exhibited the similar surface appearance. From the cross-section of *Yuan*, as shown in Fig. 3 g, it was found that the internal portion was reddish brown, while the external portion was gray green, which revealed the difference of alloys. The two parts were connected via a mortise and tenon joint structure.

Figure 4 shows the X-ray radiographic images of the bronze *Ges*. They also revealed the different colors for different parts of the bronze *Ges* due to the different alloys. It has been known that the attenuation of X-ray is proportional to the density of the substance, and is proportional to the cube of atomic number (Jackson and Hawkes 1981). Because of the difference of attenuation of X-ray, the bronze with higher Sn content shows a bright color, while lower Sn content shows the dim color. Therefore, it could be further confirmed that the portions of the mid-ridge and *Lan* contained higher Cu element, while the other parts contained higher Sn element. Obviously, these belonged to a kind of the bi-metallic bronze *Ge*.

Microstructures and chemical compositions

Figure 5 and Fig. 6 show the optical metallographic images and SEM morphologies of the cross-section of two bi-metallic bronze *Ges*. Obviously, they exhibited the similar characters, i.e., typical dendrites of casting. Table 1 lists the chemical compositions of different parts. The mid-ridges were made of pure copper. The blades were made of the Cu–Sn+Pb alloys with high Sn contents.

As to the mid-ridges, the structure mainly consisted of coarse dendrites. Some sulfate particles at the grain boundaries were observed, which were the residual impurities of the copper ore. The larger dendrite grain sizes indicated that this portion experienced an annealing process or other heat treatment, as shown in Fig. 5 b and Fig. 5 f.

However, for the edge and the blade, it was composed of fine α-Cu dendrites, (α+δ) eutectoid structures, and isolated Pb particles, as shown in Fig. 5 d and Fig. 5 h. Table 1 lists the corresponding point compositions. It is commonly known that Pb has no solid solution relationship with Cu and Cu–Sn alloys, and only exists in a separation or dissociation state. Our previous work demonstrated that the dispersed Pb particles exhibited functions of refining the casting microstructures and reducing the casting defects (Pan et al. 2007). In addition, according to the Cu–Sn phase diagram, the maximum Sn solid solubility in Cu–Sn binary alloy is 15.8 wt%, and when it exceeds this value, the intermetallic δ-Cu phase ($Cu_{31}Sn_8$), which contains 32.6 wt% Sn and is hard and brittle, begins to precipitate from the matrix. Therefore, these fine microstructures and numerous δ-Cu phases resulted in high strength and hardness of the bronze. The measurements showed that the hardness value of the mid-ridge of no. 74 *Ge* was 59.90 Hv, and that of the blade was 139.24 Hv, which revealed that the hardness of the blade was twice as hard as the mid-ridge. Similarly, the hardness variation of no. 76 was close to no. 74.

When the connected portion of the ridge and the blade was carefully examined, a transition zone was observed. Its chemical compositions were measured by using EDS with line scanning and point scanning modes, as shown in Fig. 6 d and Fig. 6 h. The results revealed that the transition zone showed a mechanical mixture with variant phases and chemical compositions, which meant that no new microstructure and phase were formed, and only had a short-distance elemental diffusion of Sn in the Cu matrix. Since the melting point (1083.4 °C) of Cu is higher than that of the Cu–Sn alloy, the molten Pb added Cu–Sn alloys of the second casting step could not melt the solid Cu at the interface.

Another interesting discovery was that the microstructure in the pure copper side of the transition zone was similar to that of welding fusion zone in the heat-affected zone (HAZ), as shown in Fig. 6 d and Fig. 6 h. In general, in welding metallurgy, the welding fusion zone refers to a transition zone

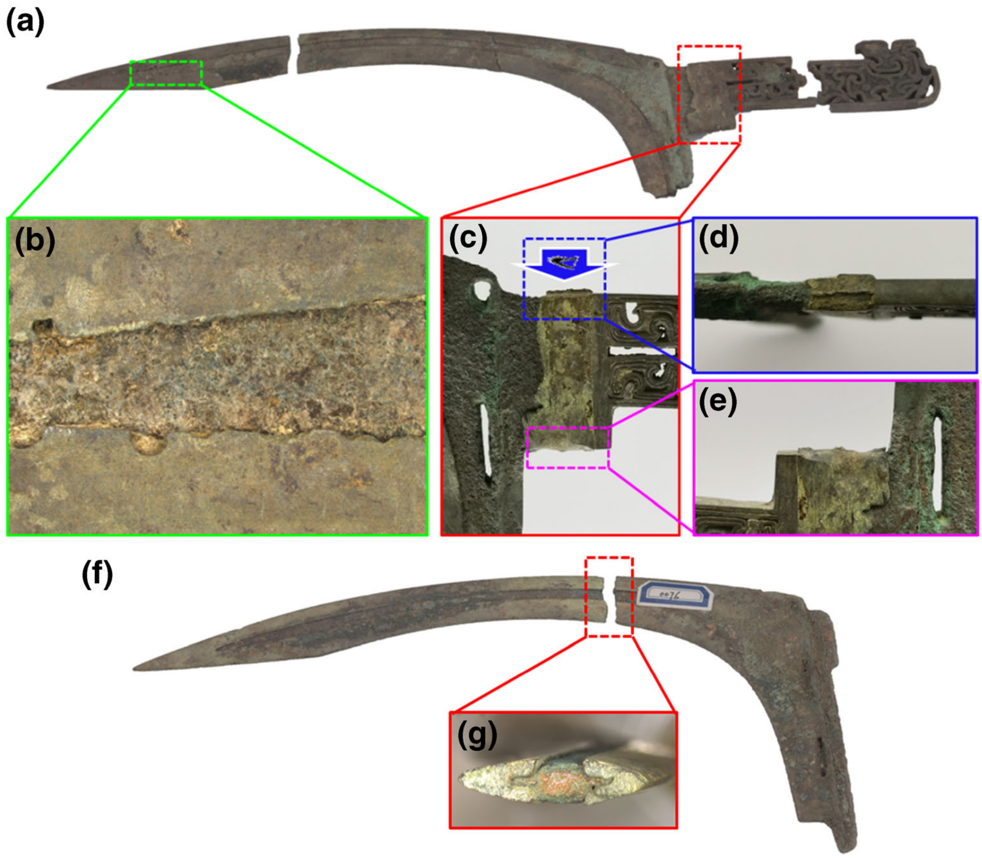

Fig. 3 Macroscopic appearances of the bronze Ges. (a) Overall image of no. 74; (b) partial image of Yuan; (c) junction of body and handle; (d) top of the junction; (e) sprue trace of the junction; (f) overall image of no. 76; (g) cross-section of Yuan

between the weld metal and HAZ in the base metal in a welded joint, which is also called the semi-melting zone. It is a narrow zone, and the local melting occurs along the grain boundaries in the area adjacent to the melted weld zone. Its heating temperature is between the solidus line and liquidus line, which results in the formation of coarse grains, the heterogeneous chemical compositions, and microstructures (Huang et al. 2013; Pan 2000).

As to the two-casting process, the thermal effect on microstructure of the mid-ridge during the second casting was similar to that of the weld fusion zone on the base metal, which also produced the similar microstructure. In addition, because the thermodynamic interface could not be formed, it was impossible to have a metallurgical connection between mid-ridge and blade. In order to solve this problem, the ancient technicians wisely designed a mortise and tenon structure to form a staggered and mutually constrained stable structure and strengthened the bonding between the mid-ridge and the blade.

To further confirm connective style of the *Yuan* and *Na* of the no.74 *Ge*, the chemical compositions of *Yuan* and *Na* and the connected portion were measured by using a portable X-ray fluorescence (XRF) spectroscopy. Five points were measured in each portion, as listed in Table 2. Obviously, they showed the different compositions. As for the microelements, the amount of Fe content in the junction was much higher. Bi content in joint part was 0.12 wt%, while there was no Bi element in the mid-ridge and *Na*. Obviously, the chemical compositions of the connection part were totally different from the other parts.

Possible manufacturing process

As the experimental examinations above, the bi-metallic bronze *Ges* exhibited the similar structures to the well-known bi-metallic bronze swords. According to the archeological discoveries, the sword-making technology was

Fig. 4 X-ray radiograph images of the bronze Ges. **a** No. 74; **b** no. 76

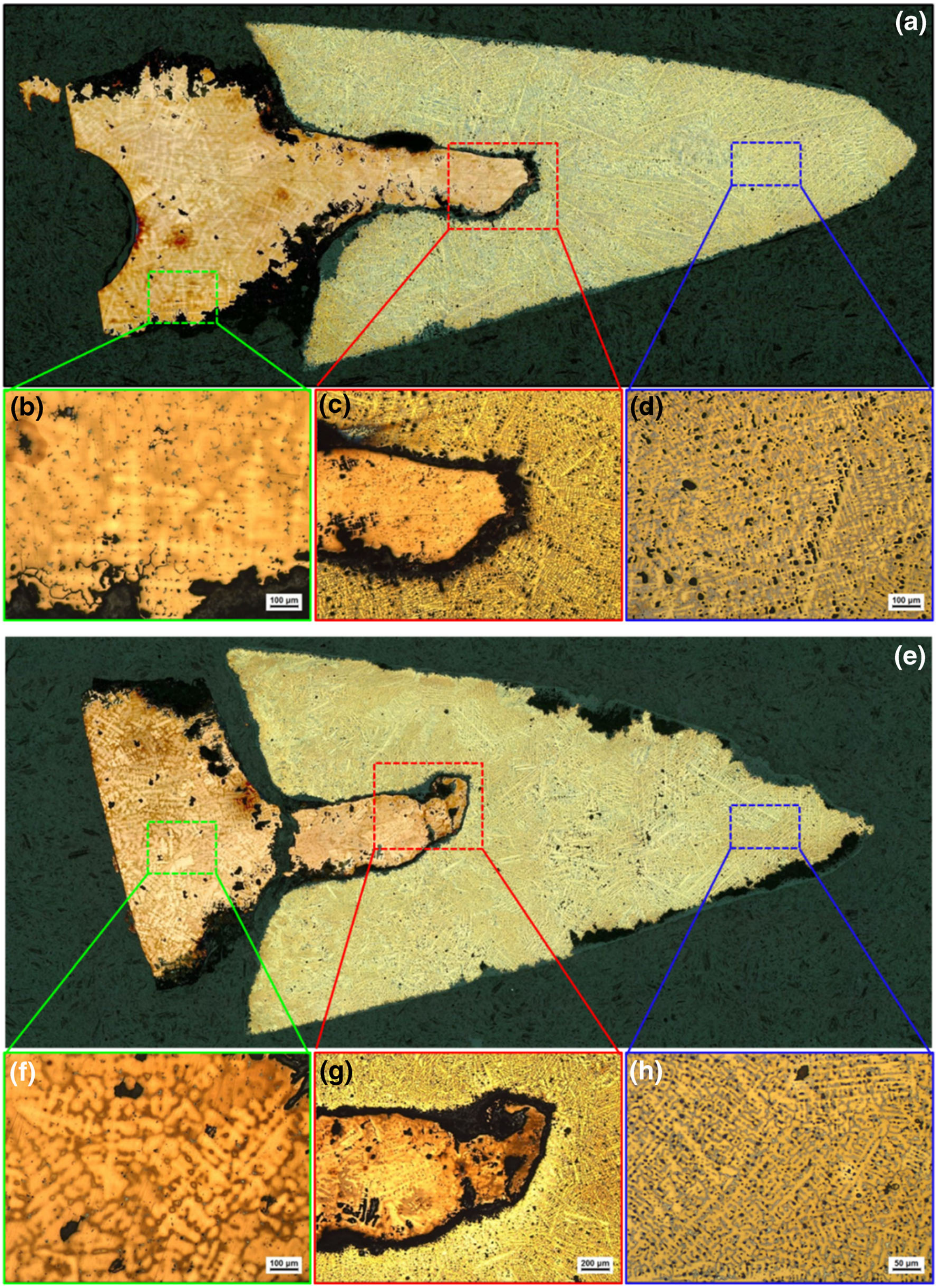

Fig. 5 Cross-section metallographic microstructures of the bronze Ges. (a) Overall image of no. 74; (b) mid-ridge; (c) junction of mortise and tenon; (d) blade; (e) overall image of no. 76; (f) mid-ridge; (g) junction of mortise and tenon; (h) blade

established and boomed in the area of the *Wu* and *Yue* State, and also exhibited the highest skill (Xiao 1991, 1996). It has been known that the bi-metallic bronze swords emerged in the areas of the early Warring States Period or earlier in the *Wu* and *Yue* State. The Huangzhou District was adjacent to the *Wu* and *Yue* State territory, so its culture and technological

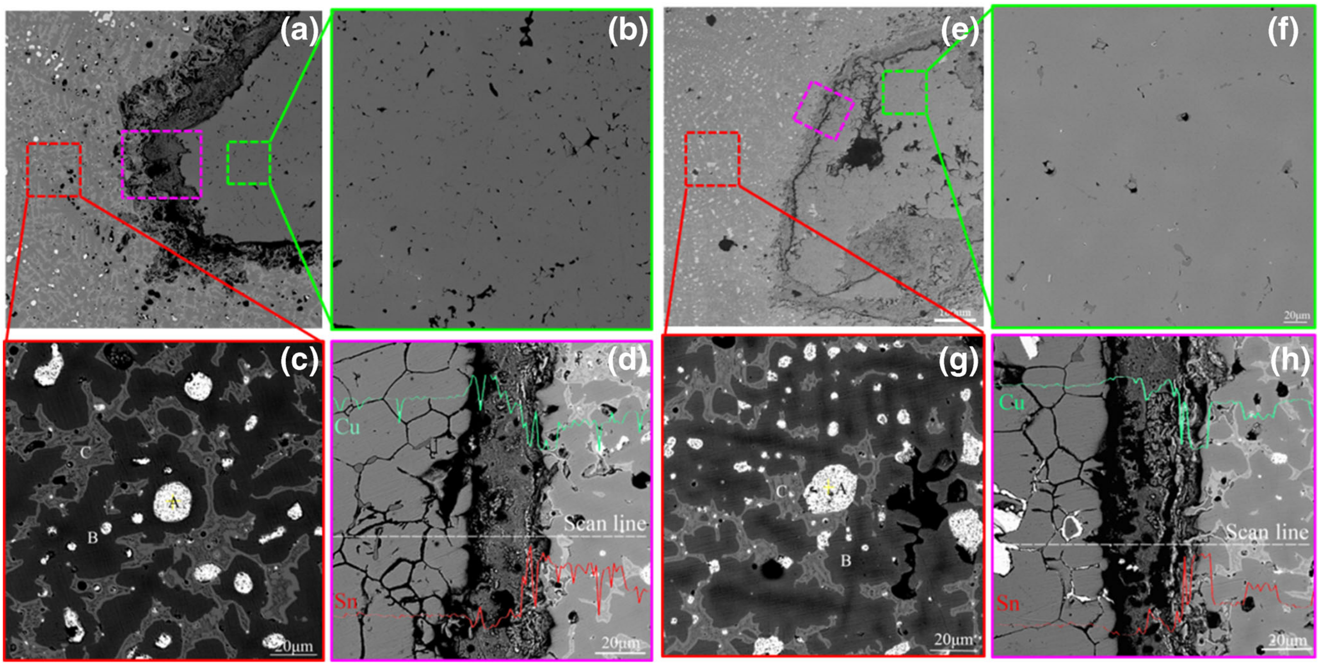

Fig. 6 Cross-section SEM morphologies of the bronze Ges. (a) Low-magnification image around the junction of no. 74; (b) mid-ridge; (c) blade; (d) junction of mortise and tenon; (e) low-magnification image around the junction of no. 76; (f) mid-ridge; (g) blade; (h) junction of mortise and tenon

development were influenced by the *Wu* and *Yue* State. Therefore, it suggested that the manufacturing technology of the bi-metallic bronze weapons was probably introduced from the *Wu* and *Yue* State.

From observation of the *Yuan* cross-section, obviously, the mid-ridge and blade were connected via a mortise and tenon joint structure. And the dendrites of the mid-ridges were coarse, indicating that the ridge was subjected to a double heat treatment, while the dendrites of the blade were fine, indicating it was a one-step casting. In addition, the microstructure in the pure copper side of the transition zone was similar to that of the welding fusion zone in the HAZ. Hence, we proposed that the bi-metallic bronze *Ges* were fabricated by a two-step casting.

In addition, the XRF results showed the chemical compositions of connection *Yuan* and *Na* were totally different from the other parts. The presence of bismuth (Bi) in the joint revealed that the joint and the other parts of the *Ge* were made of different copper mines, which demonstrated that the process of connection was in a separate step. What is more, there was a seam between the junction and *Na*, as shown in Fig. 3 c. The metal at the joint was laminated on the protruding part of *Yuan*, as shown in Fig. 3 c. Besides, there was a trace of mold seam of the separated casting with composited molds on the top of the joint, while there was no seam on the adjacent *Na* and *Yuan*, as shown in Fig. 3 d. The sprue trace of this part was observed, as shown in Fig. 3 e. These phenomena implied that this was an another casting step on the previous two parts, which was the typical soldering style (Zhang 2018). Therefore, we deduced that the two parts were connected by soldering.

Based on the above experimental analysis and observations, it could be confirmed that the manufacturing process of the bi-metallic bronze *Ges* was as follows: firstly, cast the mid-ridge and *Lan* with copper; and then, put the mid-ridge and *Lan* into the molds for making the cutting edge and blade,

Table 1 Chemical compositions of different parts of the bronze Ges (wt%)

Measurement position	No. 74			No. 76		
	Cu	Sn	Pb	Cu	Sn	Pb
Mid-ridge (average value)	100	0	0	100	0	0
Blade (average value)	70.27	17.90	11.83	70.43	17.81	11.76
A (point value)	0	0	100	0	0	100
B (point value)	84.63	15.37	0	85.17	14.83	0
C (point value)	67.63	32.37	0	66.69	33.31	0

Table 2 The XRF compositions of the mid-ridge, joint, and Na of no. 74 Ge (wt%)

	Point	Cu/ wt%	Sn/ wt%	Pb/ wt%	Fe/ wt%	Bi/ wt%
Mid-ridge	1	95.871	1.561	0.281	0.433	0
	2	93.992	1.959	0.377	0.688	0
	3	95.068	1.77	0.562	0.579	0
	4	93.692	2.125	0.91	0.822	0
	5	94.269	1.422	0.294	0.445	0
Joint	1	6.284	68.72	7.503	11.012	0.106
	2	7.887	70.091	7.793	11.768	0.103
	3	8.93	65.054	7.282	10.773	0.142
	4	8.995	64.293	7.022	11.087	0.126
	5	7.313	66.498	7.293	11.167	0.132
Na	1	41.996	40.542	4.857	5.179	0
	2	31.606	50.162	5.029	8.158	0
	3	54.793	33.773	4.561	4.503	0
	4	24.432	43.39	4.567	6.442	0
	5	33.102	47.014	4.889	8.307	0

and cast the edge and blade with Cu–Sn+Pb alloys; at last, solider the body together with *Na* by using Cu–Sn+Pb alloy.

The special choice of alloys

The above examination results revealed that the mid-ridges of *Ge* were made of pure copper, while the blades were made of Cu–Sn+Pb alloys. In contrast, most mid-ridges of the bi-metallic swords were made of Cu–Sn alloys with Sn contents in a range of 4~11 wt% (Lian and Tan 2002; He 1990; Chen 1981; Peng et al. 1994; Ding et al. 2012). For example, Chen et al. (Chen 1981) examined the chemical compositions of three bi-metallic bronze swords collected in Shanghai Museum. The data indicated that the mid-ridges were made of Cu–Sn alloy with average 10.48 wt% Sn, while the edges and blades were made of Cu–Sn alloy with higher Sn content 18.99 wt%. He et al.'s (He 1990) studies on the chemical compositions and microstructures of several bi-metallic bronze swords unearthed from Erzhou City, Hubei Province, China, revealed that the mid-ridges were made of Cu–Sn+Pb alloy with mean Sn content 10.247 wt% and Pb content 3.734 wt%, whereas the edges and blades were made of Cu–Sn alloys with higher Sn content 17.567 wt%. Compared to the bi-metallic bronze sword, the present *Ges* presented a special case by using pure Cu for the mid-ridges and *Lans*.

According to the phase diagram of Cu–Sn alloys, the melting point declines with the increase of Sn contents. Therefore, all mid-ridge, edge, and blade of the swords are made of Cu–Sn alloys with variant ratios; they would have a good metallurgical connection. That was to say, they had small differences in melting points, and were more likely to have mutual fusion and element diffusion at the joint of two-casting. Therefore, during the course of chop and collision, the bronze swords evaded the risks of cracking or separation, and their service life and quality would be greatly enhanced and prolonged.

In regard to why pure Cu was used for making the mid-ridges in these two bi-metallic bronze *Ges*, we proposed some possible reasons: (1) due to the higher melting point of pure Cu, the first-casting pure Cu mid-ridges provided a possibility to keep a rigid shape during the second-step casting, which was of advantage to have good structural integrity and the complete mortise and tenon joint; (2) as a precious metal in ancient time, to minimize use of Sn was reasonable for economic reason; (3) these two *Ges* might be made as a gift for a certain special person, rather than for equipping soldiers for battle, since they were produced carefully with hollowed-out decoration in *Na*; (4) they were probably burial objects for the dead of a special person, because lots of Pb was involved. Many researches indicated that the ancient bronze chopping and killing weapons were made of binary Cu–Sn alloys for high strength and hardness, while Pb generally reduced the strength (Chase and Thomas 1978; Liao et al. 2008).

Fig. 7 The double-*Ge* halberd picture of the *Ges* after restoration

Double-*Ge* halberd

According to archeological data, the halberds of the Eastern Zhou Dynasty (also called the Spring-autumn and Warring States Period) were assembled by separate parts. However, due to being poorly preserved in tombs, and the sticks that connected the *Ges* and spears became rotten, they were often treated as separate *Ges* and spears. In general, based on the way of combination, the halberds were divided into two categories: the first category was combined of a *Ge* and a spear; and the second type was made up of two or three *Ges*, in which the first one has *Na*, and the second and third ones have a shorter *Na* or no *Na*, and the length of *Yuan* decreased from top down (Jia et al. 2011).

When it comes to the two bi-metallic bronze *Ges* in this work, the no. 74 *Ge* had *Na*, while no. 76 *Ge* had no *Na*, and the *Yuan* of the no. 74 *Ge* was longer than that of the no. 76 *Ge*; they are 24.8 cm and 22.9 cm respectively. Besides, the contents of different corresponding parts of them were almost the same. These evidences showed these two *Ges* might be the two parts of a double-*Ge* halberd, as shown in Fig. 7. In addition, lots of multiple-*Ge* halberds were also unearthed from the nearby tombs, such as no. 5 tomb and no. 40 tomb of the Wangjiachong Cemetery, and no. 1 tomb of the Caojiagang Cemetery, which were the *Chu* tombs dated to the middle and late Warring States Period (Huang 2001). It disclosed that the multiple-*Ge* halberds were prevalent in Huangzhou District during the middle and late Warring States Period. Based on the above analysis, we confirmed that these two *Ges* belonged to the two portions of one halberd instead of as two separate *Ges*.

Conclusions

Two bi-metallic bronze *Ges*, as a kind of the *Chu Ge* dated to the Warring States Period (475 BC–221 BC), were firstly discovered and studied systematically by using optical microscope, 3-dimension microscope, SEM-EDS, pXRF, and X-ray radiography. It exhibits the same design philosophy with the well-recognized bi-metallic bronze sword, i.e., the mid-ridge is made of metal or alloy with good flexibility, and the blade is made of high-Sn bronze with high strength and hardness, which bring about a comprehensive performance in toughness and strength.

A possible manufacturing process is proposed as follows: (1) cast the mid-ridge and *Lan* with copper; (2) put the mid-ridge and *Lan* into the molds for making the cutting edge and blade, and cast the edge and blade with Cu–Sn+Pb alloys; (3) solider the body together with *Na* by using Cu–Sn+Pb alloy.

Referring to the *Ges* from the same unearthed site, similar alloys and similar typology, it is supposed that these two *Ges* were the two parts of a double-*Ge* halberd. And its special appearance and complex shape indicate that this halberd perhaps is made for a person of high position or power. This work provides a new evidence for the metallurgical level during the Warring States Period in China.

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References

Chase WT, Thomas OZ (1978) Ternary representations of ancient Chinese bronze compositions. A Chem:293–334

Chen PF (1981) Study on the composition and casting techniques of ancient bronze weapons and bronze mirrors. Shanghai Bowuguan Jikan:143–150 (in Chinese)

Chen ZT (2010) Discussion on the identification of bronzes from traditional techniques such as restoration and production. Sichuan Wenwu (Cult Relics Sichuan) 2:91–96 (in Chinese)

Ding ZM, Qu CG, Liu YC, Wu LM et al (2012) Studies on the manufacturing techniques of bimetallic bronze swords in the Eastern Zhou period excavated from Xintai, Shandong. Sci Conserv Archaeol S1:75–86 (in Chinese)

Gettens RJ, Roy SC, Chase WT (1971) Two early Chinese bronze weapons with meteoritic iron blades. J Am Orient Soc 93:639–640

He TK (1990) Preliminary analyses of bronze weapons belonged to the Warring States Period unearthed from Ezhou. Jianghan Kaogu (Archaeol Jianghan Region) 3:58–64 (in Chinese)

Huang FC (2001) Chu tombs at Huangzhou, Hubei. Kaogu Xuebao (Acta Archaeol Sin) 02:227–298 (in Chinese)

Huang YM, Wu YM, Pan CX (2013) EBSD study of solidification characteristics of austenitic stainless steel weld pool. Metal Sci J 26:750–753

Hubei Provincial Institute of Cultural Relics and Archaeology (1984) Yutaishan tombs of ancient Chu State in Jiangling. Cultural Relics Publishing House (in Chinese)

Hubei Provincial Institute of Cultural Relics and Archaeology (1993) Excavation brief of tomb no.5 at Longwangshan Brick Factory, Huangzhou. Jianghan Archaeol 01:34–39+99 (in Chinese)

Hubei Provincial Institute of Cultural Relics and Archaeology (1995) Eastern Zhou tombs at Jiudian, Jiangling. Sci Press 237 (in Chinese)

Jackson DF, Hawkes DJ (1981) X-ray attenuation coefficients of elements and mixtures. Phys Rep 70:169–233

Jia LJ, Zhao CC, Jin PJ, Yang XG et al (2011) Preliminary analysis on a group of bronze weapons of Early Qin Period. J Northwest Univ (Nat Sci Ed) 41:67–72 (in Chinese)

Jiang T (1999) Tombs of Guo state in Sanmenxia. Cultural Relics Publishing House (in Chinese)

Li Z (1976) The analysis of a bronze battle-axe with iron blade. Kaogu Xuebao (Acta Archaeol Sin) 2:17–34 (in Chinese)

Lian HP, Tan DR (2002) Study on bimetallic bronze swords in ancient China. Sci Conserv Archaeol S1:319–334 (in Chinese)

Liao LM, Huang ZY, Pan CX et al (2008) The materials science study of bronzes of Chu tomb at Jiuliandun in Zaoyang, Hubei Province. Kaogu (Archaeology) 8:68–75 (in Chinese)

Pan CX (2000) Welding of dissimilar steel and dissimilar metal: characteristics of microstructures and its transformation mechanism. China Communication Press (in Chinese)

Pan CX, Liao LM, Hu YL (2007) Functions and morphology of metal lead addition to ancient Chinese bronzes. Adv Mater Res 26-28: 523–526

Peng SF, Hua JM, Wang YZ (1994) The analysis of bronze swords unearthed from Jiangxi Province. Zhongyuan Wenwu (Cult Relics of Centl Plain) 3:101–103 (in Chinese)

Sun SY, Han RB, Li XH (2011) Metallurgical microstructures of ancient metals in China, Nonferrous Metals. Science Press. (in Chinese)

The Jingzhou District Museum, Hubei Province (1982) The Tianxingguan tomb no. 1 of ancient Chu State in Jiangling. Kaogu Xuebao (Acta Archaeol Sin) 01:71-116–143-162 (in Chinese)

Tian RX, Lei XS (1993) Excavation brief of tomb no.2 at Yinmen, Baoji of the Warring States period. Wenwu (Cult Relics) 10:1–14 (in Chinese)

Wang SC, Wu XS (1983) Excavation brief of Guoerchong tombs of Chu state at Huangzhou, Hubei Province. Jianghan Archaeol 03:13-22–108-110 (in Chinese)

Wu ZF (2012) Shang and Zhou bronze inscriptions and images integration, volume 32. Shanghai Classics Publishing House (in Chinese)

Wu XS, Hong G (2000) Two midium-sized Chu tombs in Huanggang City, Hubei. Kaogu Xuebao (Acta Archaeol Sin) 02:257-284–293-300 (in Chinese)

Xiao ML (1991) A study of bronze weapons of the Wu State. Kaogu Xuebao (Acta Archaeol Sin) 2:141–165 (in Chinese)

Xiao ML (1996) The discussion on bronze weapons of Wu State and Yue State. Kaogu yu Wenwu (Archaeol Cult Relics) 6:16–28

Yang XG, Zou HX, Jin PJ et al (2013) Metallurgical analysis of bronze weapons and bronze implements excavated from Yujiaba site at Kaixian. Wen Bo (Cult Relics Museol) 02:80–83 (in Chinese)

Yuan JJ, Zhang XD (1977) The discovery of graves of Shang Dynasty at Pinggu, Beijing. Wenwu (Cult Relics) 11:1–8 (in Chinese)

Zhang CP (2018) The use of soldering technical traditions in the process of casting bronze ritual vessels in the Shang and Zhou Dynasties. Kaogu (Archaeology) 02:88–98+2 (in Chinese)

Zhao FJ, Li XC, Zhang Y (2012) Scientific analysis of bronze wares unearthed from Kele site in Guizhou. Zhongguo Wenwu Kexue Yanjiu (Sci Anal Chin Cult Relics) 03:81–86 (in Chinese)