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Archaeometallurgical studies in China: some recent developments and challenging issues

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A B S T R A C T

On the basis of a review of major research achievements over the past ten years, this paper discusses some challenging issues in current studies of ancient Chinese metallurgy, with a focus on the beginnings of bronze metallurgy in China, regional bronze technologies during the Shang dynasty, early developments of iron technology, emergence of lost-wax casting technology, manufacturing techniques of gold objects, and Qin metallurgy. It will also offer some observations on future directions for the study of ancient Chinese metallurgy.

1. Introduction

The beginning of archaeometallurgical studies in China can be traced back to the 1950s, when for the first time a metallurgical examination of dozens of iron objects of the Warring States and Han periods recovered all over China was carried out (Hua et al., 1960). The systematic application of modern analytical techniques to the examination of ancient metals from archaeological excavations only appeared in the late 1970s, in which the Archaeometallurgy Group of the Beijing University of Iron and Steel Technology (BUIST), established in 1974, played a leading role, as evidenced by the publication of both *A Brief History of Chinese Metallurgy* and *Ancient Metallurgy in China* (BUIST, 1978).

During the 1980s and 1990s, considerable progress in the study of ancient Chinese metallurgy was made both in China and abroad, with the international conference series '*Beginning of the Use of Metals and Alloys* (BUMA)' being established by Professors Tsun Ko (Ke Jun) and Bob Maddin in 1981, and becoming a significant platform for scholarly exchanges between the East and the West (Maddin, 1988). The middle and late 1990s witnessed the publication of a number of major scholarly treatises (Wagner, 1993; Li, 1994; USTB, 1994; Su et al., 1995; Hua, 1999), which demonstrated a substantial step forward in studies of ancient Chinese metallurgy.

Since 2000, there have appeared a number of new trends in the field of archaeometallurgical studies. First of all, books on the basis of postgraduate dissertations, which are mostly focused on a specific research issue, emerged to mark the arrival of a new generation of scholars in the field, some of them trained in the West (Mei, 2000; Wang, 2002; Qian, 2006; Yao, 2006; Chen and Han, 2007; Li and Han, 2011; Jia, 2011; Zhang, 2012; Huang et al., 2013). Secondly, in addition to the BUMA conferences, more international symposiums have been organized to accommodate growing interest in ancient metal technology in China and Asia (Jett, 2003; Mei and Rehren, 2009; Hanks and Linduff, 2009; Jett et al., 2012). Thirdly, the origins of metallurgy in China and the role of the Eurasian steppe continued to attract strong international interest (Linduff et al., 2000; Linduff, 2004; Linduff and Mei, 2014). Finally, some renowned scholars of the first generation in the field marked their scholarly career with massive academic contributions (Han and Ko, 2007; Wagner, 2008; He, 2009).

More than 300 research papers on ancient Chinese metallurgy have been published since 2000, demonstrating the rapid growth of this field. These papers cover a wide range of topics, including early metallurgy (Xu et al., 2010a; IHMM, 2011; Mei et al., 2012, 2013), Shang bronze technology (Chen, K. et al., 2009a; Mei et al., 2009; Ma et al., 2012; Cui and Wu, 2013), bronze casting technology (casting moulds) in the Shang and Zhou dynasties (Li, Yungti et al., 2007; Liu, 2009; Yue et al., 2012; Liu et al., 2013), early mining and smelting sites (Li, Yanxiang et al., 2011; Huang and Li, 2012; Li et al., 2012), provenance studies (Li, Q. et al., 2005; Wei et al., 2009, 2011), lead-isotopic analysis (Tian et al., 2010; Cui

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and Wu, 2011, 2013; Mu et al., 2014), iron and steel technology (Chen, J. et al., 2009, 2012; Han and Chen, 2013), lost-wax casting (Zhou et al., 2006, 2009; Tan, 2007; Dong et al., 2008; Zhou, 2009; Hua, 2010), manufacturing techniques of gold and silver objects (Shao et al., 2010; Qin et al., 2011; Huang et al., 2012), and zinc distillation (Zhou et al., 2012, 2014). It is worth mentioning that more than 30 papers among them are in English, signifying a clear trend of increasing academic exchanges between China and the outside world.

2. The six main topics

In this short review, it would be impossible to present a detailed report on all these papers. Instead, we shall only discuss the following six issues, namely early metallurgy, regional bronze technologies during the Shang dynasty, early developments of iron technology, emergence of lost-wax casting technology, manufacturing techniques of gold objects, and Qin metallurgy. At the end of this review, we shall offer some observations on future directions in the study of ancient Chinese metallurgy.

2.1. Early metallurgy

The first scientific examination of early copper and bronze objects recovered in China was published in the early 1980s (Sun and Han, 1981), indicating that copper and bronze were in use in China long before the Shang dynasty (16th–11th centuries BC). Around the mid-1990s, while the indigenous origins of bronze metallurgy in China was still a prevalent view (Barnard, 1983; Ko, 1987; Wagner, 1993: 28–33), some scholars began to argue for the introduction of bronze metallurgy from the West via the prehistoric Silk Road (An, 1993; Fitzgerald-Huber, 1995; Bunker, 1998). Since then, the beginnings and early development of copper and bronze metallurgy within the borders of present-day China have become a hot topic and attracted considerable and long-standing interest among scholars both in China and the West (Linduff et al., 2000; Linduff, 2004; Mei, 2009a; IHMM, 2011; Mei et al., 2012).

Most of the early copper and bronze objects recovered so far are from the Gansu-Qinghai region (Fig. 1) and are associated with Qijia and Siba cultures, which are roughly dated to the first half of the second millennium BC. Based on a number of new archaeological finds and metallurgical analyses (Sun and Han 1997; Sun, 1998), a fresh understanding of the early use of metals in the Gansu-Qinghai region was obtained in the late 1990s, notably the identification of arsenical copper among the Siba metals (Li and Shui, 2000; Sun et al., 2003). In recent years, new scientific examinations of copper and bronze objects from the Zongri and Gamatai sites in Qinghai (Fig. 1: 4, 5) have been carried out, and the analytical results have revealed for the first time the existence of arsenical copper among the Qijia metals (Xu et al., 2010a, 2010b). Also significant is a recent discovery of hundreds of copper and bronze objects at the Mogou site in Gansu (Fig. 1: 6), which is believed to be associated with the Qijia culture. Mei et al. (2012) report preliminary examination results of 18 Mogou metals (Fig. 2), indicating that tin bronze was the most important alloy used at the Mogou site, while unalloyed copper (Cu) and other copper alloys, such as leaded tin bronze (Cu–Sn–Pb) and arsenical tin bronze (Cu–Sn–As), were also used. These new studies further confirm the crucial role the Gansu-Qinghai region played in the development of copper and bronze metallurgy in China during the first half of the second millennium BC.

Interesting evidence for early metallurgical activities along the Hexi Corridor in Gansu has also been obtained from the analysis of sediments from Huoshiliang in northwestern Gansu (Fig. 1), which shows the geochemical measurements for Cu, As, Zn, Pb, Ni and Fe. On the basis of analysis results, Dodson et al. (2009) propose a hypothesis that first occurrence of Cu and As in the sediments arose from smelting and runoff into the site between about 2135 and 1869 BC. Li, Xiaoqiang et al. (2010) further suggested that the geochemical measurements of the Huoshiliang sediments for the period of 4200–3700 BP actually recorded the earliest bronze smelting in the region. It should also be noted that a copper smelting site has been found at the so-called Heishuigou site (now also known as 'Xichengyi') near Zhangye, in the middle of the Hexi Corridor (Fig. 1: 3), which could be dated to the early second millennium BC on the basis of the finds of painted pottery (Mei et al., 2012).

Early copper and bronze objects recovered in Xinjiang have been subjected to extensive scientific examinations since the late 1990s, revealing the predominant use of tin bronze as well as the existence of arsenical copper in eastern Xinjiang during the first half of the second millennium BC (Mei et al., 1998; Mei and Shell, 1999; Mei, 2000; IHMM, 2001; Mei et al., 2002). Recent research on metal objects recovered from the Xiaohe cemetery site in south Xinjiang (Fig. 1: 1) presents further evidence for the early use of tin bronze in Xinjiang during the early and middle second millennium BC (Mei et al., 2013).

In the northern border areas of China, early copper and bronze objects were found in contexts associated with the Zhukaigou and Lower Xiajiadian cultures, which are also dated to early and middle second millennium BC (Fig. 1: 11; Bai, 2002). An earlier examination of 13 Zhukaigou metal objects revealed that they are made of copper (5) and Cu–Sn or Cu–Sn–Pb (8) (Li and Han, 2000). Metal objects recovered from the Lower Xiajiadian culture sites are made of Cu–Sn or Cu–Sn–Pb alloys, as shown by Li et al. (2003). A recent examination of 9 metal objects excavated at the Erdaojingzi site in Chifeng, Inner Mongolia (Fig. 1: 18) indicated that they are mostly made of tin bronze (8), with only one object of unalloyed copper (Wang et al., 2013), suggesting a diversity in composition among the metals from different sites of the Lower Xiajiadian culture.

On the basis of new archaeological and archaeometallurgical evidence, more and more scholars have come to argue that bronze metallurgy was introduced into China from the Eurasian steppe through Northwest China during the third millennium BC (Li, S. 2005; Liu and Li, 2007; Roberts et al., 2009; Mei et al., 2012; Potts, 2012). However, the finds of a few early brass pieces recovered in Shaanxi and Shandong, which could be dated to the 5th–3rd millennia BC (Sun and Han, 1981), remain an unresolved issue. Fan et al. (2010, 2012) revisited the issue by performing simulation experiments as well as further examining the brass piece unearthed at the Jiangzhai site in Xi'an, Shaanxi (Fig. 1: 14), and suggested that the Jiangzhai brass piece utilized alloy produced by a solid-state reduction process. This research implies an independent invention of metallurgy in China, since the Jiangzhai brass might be much earlier than earliest metal finds known so far in Northwest China.

Another challenging issue is whether the early copper and bronze artifacts recovered in Gansu, Qinghai and Xinjiang were actually made locally or imported from other regions. The new research carried out by Dodson et al. (2009) clearly suggests the existence of local bronze production along the Hexi Corridor during the late third millennium BC. An early copper smelting site was also located at the Heishuiguo site in Zhangye, in the middle of the Hexi Corridor (Fig. 1: 3; IHMM, 2011). Obviously, further research along this line would help to clarify the position of local metallurgical production as well as its relationship with Eurasian influence during the late third and early second millennia BC.

The beginning of bronze metallurgy in the Central Plains of China is an issue that has attracted extensive attention, but remains poorly understood. Having ignored or discounted the finds of a few

Fig. 1. A map showing the distribution of major sites mentioned in this paper: 1. Xiaohe; 2. Huoshaogou; 3. Heishuigou; 4. Gamatai; 5. Zongri; 6. Mogou; 7. Majiayuan; 8. Sanxingdui; 9. Jinsha; 10. Hanzhong; 11. Zhukaigou; 12. Shilou; 13. Liangdaicun; 14. Jiangzhai; 15. Laoniupo; 16. Houma; 17. Yuanqu; 18. Erdaojingzi; 19. Dongheishan; 20. Yinxu; 21. Yexian; 22. Shuangdun; 23. Dayangzhou.

early brass pieces, many scholars are inclined to argue that metallurgy was introduced into the Central Plains of China from northwestern and northern parts of China (Li, S. 2005; Liu and Li, 2007, 2014). However, so far, evidence for supporting this argument remains weak, and further research is clearly needed in this direction. Current archaeological evidence has presented a striking contrast between Northwest–North China and the Central Plains of China in terms of the uses of early metals, with personal ornaments predominating in Northwest–North China, while ritual vessels were most significant in the Central Plains of China. The social and cultural contexts for the beginnings of bronze metallurgy in the different regions of China undoubtedly played a major role in these processes (Mei, 2009b; Zhang and Chen, 2013). This issue is definitely worthy of further research.

The recent debate on the beginning of bronze metallurgy in Southeast Asia provides an international perspective on the issue of early metallurgy in China (Ciarla, 2007; Pigott and Ciarla, 2007; White and Hamilton, 2009; Higham et al., 2011). While Ciarla, Pigott, Higham and colleagues seem to be in favour of a link between Northwest China/Eurasian Steppe, the Central Plains and Southeast Asia, White and Hamilton have proposed a route linking Northwest China/Eurasian Steppe with Southwest China and Southeast Asia – in effect, by-passing the Central Plains. The jury remains out of the paths and mechanisms of transmission, but all agree that a Steppe-based tin–bronze technology passed through ancient China en route to Southeast Asia. The argument of White and Hamilton actually suggests a route that would run from Northwest China to Southeast Asia via Sichuan and Yunnan. In light of this debate, the beginnings of bronze metallurgy in Yunnan and Sichuan will definitely attract more research interest in the years to come.

2.2. Regional bronze technologies during the Shang dynasty

Scientific analyses of copper and bronze objects aim to characterize the development of bronze technologies in different regions in terms of their chemical compositions and manufacturing techniques. Over the past ten years, steady progress has been seen in the characterization of bronze technologies in a number of regions, such as Shanxi, Henan, Shaanxi and Sichuan.

A copper smelting or foundry site of the early Shang period (16th–14th centuries BC) was found and excavated in Yuanqu, Shanxi province (Fig. 1: 17), yielding remains of copper fragments, slag and furnace walls. Cui et al. (2009) examined 7 samples of the

Fig. 2. Some copper and bronze artifacts found at the Mogou site in Gansu: 1. armband; 2, 9. knives; 3, 5, 8. earrings; 4, 12. small ornaments; 5. 6. torque; 7. tubes; 10. bracelet; 11. trumpet-earring; 13, 14. buttons; 15. beads.

metal remains from the Yuanqu site, and found that they are made of Cu–Sn–Pb (4), Cu–Sn (2) and Cu–As (1). Metallographic examination also revealed that the bronze knife containing over 22% Sn presents a microstructure of quenching, the earliest evidence for the practice of quenching recorded in archaeological metals in China. The identification of Cu–As is also significant for understanding the development of bronze metallurgy in the early Shang period.

Copper and bronze objects excavated at the Yinxu site in Anyang, Henan (Fig. 1: 20) represent the highest level of metallurgical technology developed during the late Shang period (13th–11th centuries BC). Therefore, scientific analyses of the Yinxu bronzes are of great significance. Zhao (2004) carried out compositional analysis of about 200 excavated bronze items, and found that, from Phase I to Phase IV of the Yinxu culture, the tin content in the vessels declined significantly, while the lead content increased gradually. A further analysis of bronzes excavated from the tomb M1046 at Liujiazhuang, Yinxu not just confirmed the previous finding, but also pointed out that leaded tin bronzes with a high level of lead content were the major alloys used during Phase IV of the Yinxu culture (Zhao et al., 2008).

The Hanzhong region in southwest Shaanxi (Fig. 1: 10) province has become well known among archaeologists since the 1950s because of a number of discoveries of more than 700 copper and bronze objects of the Shang dynasty (Fig. 3). Substantial discussion of these bronzes has resulted, with little scientific analysis, however, being carried out. Chen Kunlong and collaborators have recently carried out a systematic examination of more than 200 bronzes recovered in the Hanzhong region, revealing some astonishing technical characteristics of these bronzes: while bronze vessels are mostly made of Cu–Sn–Pb and Cu–Sn, the local-styled sickle-shaped and sceptre-shaped objects are mainly made of unalloyed copper and a small number of special alloys, such as Cu–As, Cu–Sb and Cu–As–Ni (Chen, K. et al., 2009a, 2009b; Mei et al., 2009). This revelation demonstrates a much more complex technological structure for Bronze Age Chinese metallurgy than was hitherto known, and is thus significant for further exploration of

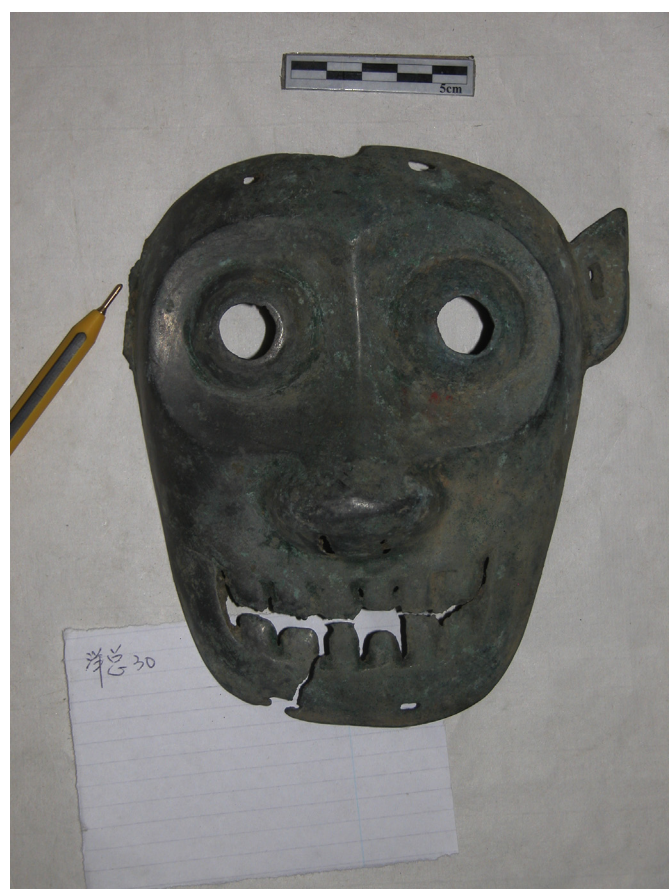

Fig. 3. A copper mask of the late Shang dynasty recovered in Yangxian, Hanzhong, Shaanxi province.

the interaction between the Shang Kingdom and peripheral regions, especially the remote areas in the southwest.

Significant new analytical work has been carried out in recent years on bronze artifacts recovered from two ceremonial pits at the Sanxingdui site, Guanghan, Sichuan (Fig. 1: 8), which are dated to the late Shang dynasty (13th–11th centuries BC) and become well known for their extraordinary typological characteristics (Fig. 4). Ma et al. (2012) reported the examination results for 30 samples taken from the Sanxingdui bronze objects, including ritual vessels as well as trees and masks, indicating that while all ritual vessels are made of Cu–Sn–Pb, objects in local style such as trees and masks are of Cu–Sn–Pb and Cu–Sn. Cui and Wu (2013) analysed 20 samples of Sanxingdui bronze objects (including vessels, trees and masks) and found that they are all made of Cu–Sn–Pb. On the basis of lead isotope analyses of these bronze samples, they further suggested that all bronze objects could have had the same provenance regardless of their typological styles, a view that is different from that proposed by Ma et al. (2012).

Another important site found in Sichuan is Jinsha, located in Chengdu, Sichuan province (Fig. 1: 9), which can be dated to the late Shang and early Zhou periods (11th–10th centuries BC), slightly later than the Sanxingdui site. Xiao et al. (2004) examined 13 bronze samples mostly taken from fragments excavated at the Jinsha site, and found that they are made of Cu–Sn–Pb (10), Cu–Sn (2) and Cu–Sn–As (1). A further examination of 22 Jinsha bronze samples was reported by Jin et al. (2004), revealing that they are made of Cu–Sn–Pb (13), Cu–Pb (4), Cu–Sn (3) and Cu (2). They also carried out lead isotope analyses of 54 Jinsha bronze samples, and found that a majority of these samples contain high radiogenic lead, similar to the Sanxingdui bronzes, while one third of them contain ordinary lead of different sources. Two flat sheets were examined by Wei et al. (2007) to show that they are made of tin bronze with tin content over 22%. Metallographic examination also indicates that these two bronze sheets were manufactured using the technology of hot-forging.

Fig. 4. A bronze figure head of the late Shang dynasty recovered at the Sanxingdui site, Guanghan, Sichuan (After EC, 1994: 7).

The above new research results have greatly advanced our understanding of regional developments of bronze metallurgy during the Shang period in the following three aspects: first, the wide use and predominance of Cu–Sn–Pb alloys among metallurgical centers during the Shang dynasty have become clear; second, the identification of special alloys such as Cu–As, Cu–Sb and Cu–As–Ni among the Shang metals has revealed the diversity of Shang bronze metallurgy and the crucial role played by regional metallurgical centres; third, the existence of high radiogenic lead among the late Shang bronzes has become significant for tracingmetal sources as well as connections among regional metallurgical centres. Many challenging issues concerning the development of Shang bronze metallurgy, however, remain to be examined further.

To find mineral resources for Shang bronze production or to locate metal smelting sites is undoubtedly a major task for future studies. While Jin and his colleagues continue to argue that southwest China (Yunnan and Sichuan) was a major source for supplying metals during the Shang dynasty (Jin, 2008), more and more scholars tend to look for mineral resources for Shang metallurgy in other regions, notably the Zhongtiao mountains in Shanxi, the Qinling mountains in Shaanxi, and the lower and middle reaches of the Yangtze River (Fig. 1; Cui et al., 2012). Although some promising signs for copper mining and smelting during the Shang dynasty have appeared in recent research, the overall picture remains obscure. Furthermore, the pattern of metal circulation revealed by the existence of high radiogenic lead remains a big challenge for future studies, as it seems to point to a common source supplying metals to several regional metallurgical centres over a long period. Smelting sites found in Laoniupo and Huaizhenfang near Xi'an in Shaanxi province (Fig. 1: 15) are really important for our understanding of Shang metallurgy. We also need to find local bronze foundries in other regional metallurgical centres.

Another major challenging issue is the patterns and mechanisms of regional interaction. As the research so far has already revealed, while the Central Plains of China, especially Zhengzhou and Anyang, played a leading role in the development of Shang metallurgy, a number of regional metallurgical centres, such as Hanzhong in Shaanxi, Sanxingdui and Jinsha in Sichuan, Xingan in Jiangxi, and the Northern Zone, also emerged and demonstrate a significant presence. There is some evidence to show that these regional centres seemed to be connected to each other, and some forms of networking may have existed too. But the general patterns and mechanisms of interaction among these regional centres are still unclear and need to be clarified further.

The third challenging issue is the social dimension of bronze production. As we all know, Shang metallurgy is characterized by its large-scale production of ritual bronze vessels using piece-mould casting technology. It would be desirable to have a clear understanding of how the whole production process was organized, such as who was responsible for the designs of vessel shapes, how the technology was passed down, and how a foundry was organized. Chang (2013a) applied production chain theory to studying the Shang foundry sites, representing a new direction of research.

2.3. Early developments of iron technology

The beginnings of iron metallurgy and early developments of iron technology in China have been a central topic in Chinese archaeometallurgical studies over the past ten years. In the late 1980s and early 1990s, scholars already began to argue that iron smelting technology was most likely introduced into the Central Plains of China from the west via Xinjiang and the Hexi Corridor in Gansu, as it seemed that the discoveries of iron objects in Xinjiang could be dated to around 1000 BC, earlier than the iron finds in the Central Plains of China (Chen, G. 1989; Tang, 1993). Guo (2009) examined early iron objects recovered in Xinjiang and argued that the earliest iron object found in Xinjiang can be dated to the 9th century BC. He further suggested that iron metallurgy may have spread to the Central Plains of China around the end of the 9th century BC. Chen, J. (2010) indicated a cautious view on the introduction of iron technology from outside and implied that the finds of iron objects in the Central Plains of China possessed their own characteristics and the technological basis for an indigenous origin, though they are later than those found in Western Asia. Chen, J. et al. (2013) further pointed out that early iron objects found in the Central Plains of China are not later than those found in Xinjiang, and their iron technologies show a marked difference: most iron objects recovered in Xinjiang are made of bloomery iron; while iron objects the Central Plains of China are mostly made of cast iron.

Fresh and interesting evidence is provided by recent scientific examinations of early iron objects unearthed from archaeological excavations in Shaanxi and Gansu. Chen, J. et al. (2009) reported examination results of a knife and a dagger-axe, both made of bronze but with an iron blade, which were excavated at the Tomb No.27 of the Liangdaicun cemetery site in Hancheng, Shaanxi province (Fig. 1: 13), and dated to the early Spring and Autumn period (8th–6th centuries BC). It was found that both blades were hammered into shape from bloomery iron. This new analytical evidence further demonstrates the region of the middle reaches of the Yellow River could have been the place where iron metallurgy first emerged in the Central Plains of China.

Two iron fragments recently excavated at the Mogou cemetery site in Lintan, Gansu (Fig. 1: 6) are of great significance, since they have been surprisingly dated to the 14th century BC. Scientific examination of one of the fragments has revealed that it is made of bloomery iron rather than meteoritic iron (Chen, J. et al., 2012). This new archaeological find and the examination result have raised a great challenge for the exploration of the origins of iron metallurgy in China. How to accommodate this new evidence into the commonly held view of outside introduction would require further research based on more archaeological discoveries of early iron objects in Gansu and Xinjiang regions.

Another important work carried out by Liu and his colleagues (2014) is the scientific study of iron objects excavated from Dongheishan site, Hebei province (Fig. 1), which throws new light on the development of iron and steel making technology in the Yan region during the Warring States period and the Han dynasty (5th century BC – 3rd century AD). The research demonstrated that cast iron technology and bloomery iron technology both existed in the Yan region, with the former being always dominant in the agricultural sector, while the latter fell out of use in military production only in the Han dynasty. It has also shown that the appearance of puddling and quenching techniques at the Dongheishan site appeared to be contemporaneous with the emergence of these techniques elsewhere in China, and the use of co-fusion processing may be the earliest documented in China. Yang et al. (2014) reported examination results of 12 iron objects excavated from the Hujiaying site in Beijing (Fig. 1), which has been dated to the late Warring States period (4th–3rd centuries BC). It has been shown that all these iron objects are made of cast iron or decarburized iron and steel.

For the studies of early iron and steel technology in China, there are three major issues requiring further research. First is the early development of bloomery iron technology in China. The archaeological and archaeometallurgical finds have demonstrated the wide use of bloomery iron technology during the early first millennium BC, especially in northwestern China, but so far no concrete evidence for bloomery iron production sites has been found in China. Second is the beginning of cast iron technology in the Central Plains of China. The current archaeological finds of cast iron seems to point to the region of south Shanxi and west Henan as a possible place for the birth of cast iron technology in China, but the mechanism and driving force behind this significant technological innovation remain poorly understood and need to be addressed further. The third issue is the dispersal and influence of iron technology from the Central Plains of China to surrounding regions since the Warring States period. Although recent research has begun to address this issue (Chen, J. et al., 2005; Chen and Han, 2007), there remain many unresolved issues, such as when and how bronze weapons were replaced by iron weapons (Han and Chen, 2013).

2.4. Emergence of lost-wax casting technology in China

Over the past ten years, there has been a fervent debate on the emergence of lost-wax casting in ancient China. Previously, it was widely held that lost-wax casting technology was already in use from the Spring and Autumn period (8th–5th centuries BC), as evidenced by the bronze vessels with complicated openwork structures unearthed from tombs of the Chu state in Henan and the Zeng state in Hubei (Fig. 5; Ren and Wang, 1987; Tan, 1996: 43; Hua and Jia, 1983). Zhou Weirong et al. (2006) claimed that those bronze vessels previously believed to be made by lost-wax casting were actually cast in piece-moulds. They believed that the lost-wax method was not a choice for the Bronze Age of China. They further argued that lost-wax casting could not develop from a

Fig. 5. A *Zun* and *Pan* vessel excavated from the tomb of Marquis Yi of Zeng (late 5th century BC) in Suizhou, Hubei province (After SACH, 2008: 136).

technological environment dominated by piece-mould casting practice (Zhou et al., 2007).

However, such a radical view failed to convince most of scholars who advocated the emergence of lost-wax casting during the Spring and Autumn period. Zhao Shigang (2006), the excavator of the Chu tomb at Xiasi in Xichuan, Henan, presented further evidence to show that the *Jin* vessel with complex openwork structure from the Xiasi tomb could only be made by using lost-wax casting technique. Tan (2007) not only insisted that the lost-wax casting technique was in use in the Spring and Autumn period, but also traced its origin to a so-called 'burn-off method' which, in his opinion, already came into use during the Shang dynasty. Li Yuanzhi et al. (2007) carried out further examination of a hollow bronze object from a tomb of the Xu state in Henan province, dated to around 547 BC, and concluded that it was cast using the lost-wax method. Some scholars provided further support by arguing for the possible use of 'lost-lead method' (Li, Zhiwei 2008) as well as by carrying out lost-wax reproduction experiment (Huang, Jinzhou 2008; Chen, Hongliang et al., 2009).

Dong et al. (2008) offered further observation evidence to support their argument for the use of piece-mould method in casting the *Zun-Pan* vessel. On the basis of examining ancient textual records on lost –wax casting, Zhou et al. (2009) pointed out that ancient lost-wax casting method would not be capable to cast such a complex object as the *Zun-Pan* vessel. However, further counter-argument can be found in Hua (2010, 2013), showing no sign of ending the debate. In his review of the debate, though he himself was obviously in favour of the early appearance of lost –wax casting, Zhang (2007) pointed out that visual examination may not be sufficient for making a judgement on the casting method, and that the application of scientific examinations would be necessary and essential.

The debate concerning the introduction of the lost-wax casting technique into China has stimulated considerable interest in bronze casting technologies in ancient China. While many previous claims or conclusions need to be re-examined in light of new scientific evidence, some attention should also be paid to the establishment of a better understanding of the development of lost-wax technique in the West, especially in the Eurasian steppe (Chen, G. et al., 2009). Considering that China closely interacted with the Eurasian steppe since the late third millennium BC, it would be necessary to investigate whether there is any possibility that the lost-wax technique was introduced into China from the steppe region (Bunker, 1983, 1988).

2.5. Manufacturing techniques of gold and silver objects

The appearance and uses of gold and silver artifacts in early China is a puzzle in the eyes of some scholars (Bunker, 1993), since it was not the supreme symbol of excellence that we see in the West. For a long period, gold did not attract much attention among scholars, because archaeological discoveries of early gold and silver items were rather limited. Now the situation has begun to change, as finds of early gold objects from archaeological excavations all over the country are increasing. Having briefly surveyed the most recent discoveries of gold objects in present-day China, Ma (2009) noted that the use of gold for personal ornaments began from the Western Zhou period (11th–8th centuries BC) and was introduced into the Central Plains of China from the northern steppe region. Mei et al. (2013) carried out an examination of 7 gold earrings excavated at the Xiaohe cemetery, which are dated to the mid-2nd millennium BC, the earliest found so far in Xinjiang. The examination reveals that these earrings are all made of natural Au–Ag alloys with Ag contents being in the range of 1.5–18%.

Fig. 6. A gold plaque in a bird and snake pattern excavated from the Majiayuan cemetery in Zhangjiachuan, Gansu Province (After GIA, 2014: 40).

In their detailed examination of gold ornaments (Fig. 6) excavated recently at the Majiayuan cemetery in Zhangjiachuan county, Gansu (Fig. 1: 6), Huang et al. (2009) have noted the employment of a series of fine-working techniques such as granulation and soldering, which, in their opinion, reveal the presence of cultural influence from the Mediterranean region via the Eurasian steppe during the Warring States period (5th–3rd centuries BC). They have also found that the Majiayuan gold objects are made of natural gold containing 5–32% silver and a small amount of copper (less than 3%), and the fabrication techniques include not just granulation and soldering, but also forging, repousse, chasing and polishing, demonstrating a relatively high level of gold manufacturing technology (Huang et al., 2012, 2013). Shao et al. (2010) also analysed 7 silver ornaments and 4 gold ornaments from the Majiayuan cemetery, and the results show that 6 silver ornaments contain a small amount of copper at the level of 1.3–3.2%, while 1 silver ornament is made of Ag–Au alloy without any copper, and 4 gold ornaments are of Au–Ag alloys. These scientific examinations have helped to characterize gold and silver technology employed at the Majiayuan site, though little information is available concerning the sources for these gold and silver ornaments.

Another interesting work carried out by Qin et al. (2011) is the examination of gold foil fragments excavated at the Shuangdun cemetery in Bengbu, Anhui (Fig. 1: 22), which has been dated to the late Spring and Autumn period (6th–5th centuries BC). 6 samples were examined and the results show they are made of Au–Ag with Ag contents between 8 and 15%, while 3 samples also show significant contents of Hg in the range of 1–13%. On the basis of the significant presence of Hg, they argued that these gold foils containing Hg are probably the earliest evidence for the use of Hg in the extraction of gold in ancient China.

Important analytical work of ancient gold objects has also been undertaken in the USA. Using newly developed method of femtosecond laser ablation-inductively coupled mass spectrometry (LA-ICP-MS), Brostoff et al. (2009) analysed a group of ancient Chinese gold objects in the Smithsonian's Freer Gallery of Art and Arthur M. Sackler Gallery. They measured major, minor and trace element concentrations in the gold fragments and found that it is possible to establish 'fingerprint' patterns based on the association of silver, palladium and platinum.

A silver box excavated from the tomb of Zhao Mao (late 2nd century BC), the King of the Nanyue state of the Western Han period, has become well known among scholars because of its obvious similarity to Iranian silverware since it was first discovered in 1983 (Rawson, 1999: 22–23). In light of recent archaeological finds of similar metal boxes in many different sites in China, Nickel (2012) proposed that the Nanyue silver box was produced most probably during the 3rd century BC, and it was not made in Western Asia or in Nanyue, but most likely in a Central China workshop. This view presents a sharp contrast with what it was previously believed.

The research undertaken so far on gold and silver finds in early China are still quite limited. However, we may make three observations as follows: first, most of early gold and silver finds come from northwestern China, especially the so-called bi-metallic objects of gold and iron, suggesting a close link with the Eurasian steppe in choosing gold and silver as personal ornament; second, gold foils are the common finds in early China, especially in the region of the Chu state in the south; third, little research has been carried out on the sources of early gold and silver. Obviously, these observations also raise some challenging issues, such as whether gold ornaments recovered in northwestern China could have come from the Eurasian steppe via trade, how manufacturing techniques for gold foils emerged and developed, and where the local sources for gold and silver were. As it has been recognized by many scholars, the uses of gold and silver items in early China involved many cultural and technological choices in different periods (Bunker, 1993). Future research needs to identify these choices and to clarify how these choices were made in a given social context.

2.6. *Qin metallurgy*

Although it only lasted for 15 years, the Qin dynasty (221–206 BC) successfully established a set of new political and cultural system, which had deep and extensive influence on the development of Chinese history. Recent research has also shed new light on hundreds of metal objects excavated from the sacrifice pits of the Mausoleum of the First Emperor of Qin (259–210 BC). Li, Xiuzhen et al. (2011) reported their significant finds through examining finishing marks present on the surfaces of the thousands of bronze weapons recovered from the Terracotta Army pits, including the use of a variety of chisels for making the inscriptions, and of files for removing excess metal from surfaces, as well as the large-scale, systematic use of rotary wheels to achieve an ideal final polish. They have also carried out a metrical and spatial analysis of weapons recovered in the Terracotta Army pits, which reveals remarkable aspects of the organization of the Qin workforce in production cells, of the standardization, efficiency and quality-control procedures employed, and of the sophisticated technical knowledge of the weapon-makers (Martinón-Torres et al., 2011; Li et al., 2014).

Liao et al. (2010) examined metal strips for stone armour excavated from a sacrifice pit of the mausoleum of the First Emperor of Qin and found that they were made of unalloyed copper. Based on metallographic observation, they suggested that the manufacturing techniques consisted of repeated cold forging combined with annealing heat treatment.

The painted bronze waterfowls unearthed from the sacrifice pit K0007 in the precinct of the mausoleum of the First Emperor of Qin are a most unusual and outstanding find in terms of their typology and manufacturing technology. Shao et al. (2014) presented preliminary technical examination results of these birds, revealing the employment of a patch-repairing technique (Fig. 7). The patches are shown to be of copper–tin binary alloy and were shaped by casting or hammering. They pointed out that such a repairing technique has not been seen on pre-Qin bronzes so far, while it was frequently found on the Egyptian and Greek bronze statues dated to the 5th–6th centuries BC. Therefore, the find of patch-repairing technique on the painted bronze waterfowls could be further evidence for the presence of western influence in China during the Qin and pre-Qin periods (Nickel, 2013).

There were many factors leading to the rise of the Qin Empire during the late third century BC. Previously it was argued that the Qin army may have been equipped with better or stronger bronze or iron weapons (Wagner, 1993). It has also been revealed recently that the Qin state developed its bronze metallurgy on the mineral resources locally available (Jia, 2011). The study of metal remains from the mausoleum of the First Emperor of Qin, as it is reviewed here, has just begun to offer new evidence for understanding the mystery surrounding the rise of the Qin Empire. Further research is, therefore, essential to clarify whether outside influence could have played a role in this remarkable historical process.

3. Future research directions

This paper does not pretend to offer a comprehensive review of all major research achievements in archaeometallurgical studies in China. Instead, it only serves to highlight some research aspects in which we are most interested. In fact, as we have pointed out in the beginning of this paper, many important research results can also be seen in other aspects, such as studies of ancient mining and smelting sites, casting technology of ritual bronze vessels, bronze technology in Yunnan and Guizhou, lead-isotopic analysis, simulation experiments of ancient metallurgical processes, and metal technology in the late periods such as zinc distillation technology.

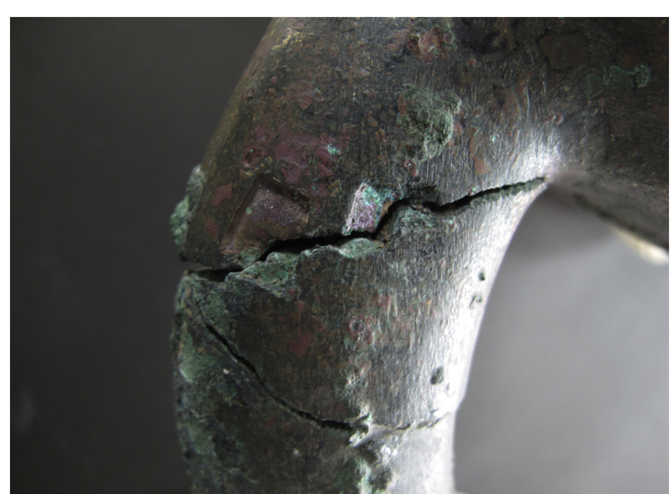

Fig. 7. The neck of a bronze waterfowl excavated from the sacrifice pit K0007 in the precinct of the mausoleum of the First Emperor of Qin showing the places where the repairing-patch may have been employed (After Shao et al., 2014: Fig. 3).

In the preceding sections, we have already offered some thoughts on the challenging issues in each specific research aspect. Now let us look at future research directions from a general perspective.

First of all, social and cultural dimensions of ancient metallurgical technologies will attract more and more research interest. As we have seen, research in the past ten years is still characterized by the heavy dominance of analysis-based work, which, to a large extent, reflected the needs of so many new archaeological finds from all over the country. Now, with the growing accumulation of research data, especially analytical ones, it is time for some scholars at least to begin to examine the developments of metallurgical technology within wider social and cultural networks, in order to have a better understanding of the relationship between technology and society. In fact, some scholars have already begun to discuss such issues as the social-cultural background for the rise of piece-mould casting in China (Mei, 2009a; 2009b), the social impact of the early use of copper objects (Li, H. 2011), as well as the relationship between metallurgy and state formation in the Central Plains of China (Zhang and Chen, 2013). Research based on the theory of *chaine operatoire* to examine the foundry sites of the Shang and Zhou dynasties also appeared and introduced a series of new ideas about the organization of bronze production in early China (Chang, 2013a; 2013b). It can, therefore, be expected that future research will put more emphasis on the social and cultural dimensions of ancient metallurgical technologies.

Secondly, an interdisciplinary approach will play an even more significant role in future research. As we have shown in the previous sections, some important research results were obtained through the application of an interdisciplinary approach, such as the analysis of sediments in Gansu (Dodson et al., 2009; Li et al., 2010), new examination of ancient casting moulds (Liu et al., 2013), provenance studies by analysing casting core materials (Wei et al., 2007, 2011), and the metrical and spatial analysis of bronze weapons from the First Emperor of Qin's Mausoleum (Martinón-Torres et al., 2011; Li et al., 2014). These studies applied research methods of other disciplines to the issues of ancient Chinese metallurgy and proved to be successful and stimulating. The results obtained from these interdisciplinary studies provide us with many promising and significant new ideas. The need for more studies of primary production sites, including slag analyses for the reconstruction of smelting processes or technologies, will become increasingly strong, because more archaeologists in China have come to realize the importance of mining and smelting sites and would like to collaborate with metallurgists to pursue an interdisciplinary target. As it has been shown briefly in previous sections, lead isotope measurements combined with trace element analysis have already shown great potential for provenance studies and will play a crucial role as a major interdisciplinary approach.

Finally, the role of outside influence in the development of metal technology in China will continue to take central position in future research. As we have pointed out, over the past ten years, this issue has already attracted considerable research interest, focussing not just on the beginnings of bronze and iron metallurgy, but also on the early uses of gold and silver, as well as the introduction of lost-wax casting. Recent archaeological finds in Northwest China and North China have presented more material evidence pointing to early cultural connections between China and the West (Rawson, 2010). More importantly, it has been increasingly recognized among scholars that early China closely interacted with the outside world throughout the whole Bronze and Iron Ages, especially with the people who lived in the eastern Eurasian steppe, and many early metallurgical innovations such as lost-wax casting, tinning, metal-sheet forging, and gold-inlaying could be traced to a steppe connection. We are, therefore, confident that early East–West interaction will definitely be a major direction for future research.

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