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ORIGINAL PAPER

The implication of the metallurgical traditions associated with Chinese style wagons from the royal Xiongnu tomb at Golmod 2 in Mongolia

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Abstract Lavishly decorated wagons excavated from royal Xiongnu burials are generally regarded as tribute items from China offered to Xiongnu elites, symbolizing important political and economic interactions between the Xiongnu state (209 BC–155 AD) and the Han dynasty (206 BC–220 AD). This theory views such vehicles as having no relation to indigenous Xiongnu craftsmanship. Furthermore, specialized products delivered to the northern nomadic peoples from the Han state are often cited in support of the notion of Xiongnu dependency on foreign states for technological and political development. Expecting to find evidence of China's traditional iron and bronze technology, we examined a number of key metallic components of these wagons excavated from the royal Xiongnu burial at Golmod 2 in central Mongolia, radiocarbon dated to 109 BC–AD 75. Surprisingly, the iron metallurgy in question was based primarily on the bloomery process while low tin bronze and arsenical copper alloys dominated the pertinent bronze production. These respective technological traditions are typical of Xiongnu manufacture but significantly different from traditional Han metallurgy. We interpret this evidence as suggesting the need for a more balanced evaluation of foreign influence on the rise and development of the Xiongnu state.

Keywords Mongolia · Xiongnu · Chinese style wagons · Metallurgical traditions · Dependency

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Introduction

The emergence of the Xiongnu state in Mongolia marks the beginning of notable changes in material cultures as well as in social and political organization. Influential theoretical models proposed to explain the evolution of these changes focus on the nomadic pastoral lifestyle of steppe communities and highlight the role of external influences, especially from China, as the major element responsible for those changes (Barfield 2001; Khazanov 1994; Kradin 2002). In this theory of economic and political dependency, heavy investment in animals, marginal environments, and dispersed and mobile herding peoples with a penchant for autonomy serve as key limiting factors in the political consolidation of steppe peoples. Accordingly, state formation among northern nomadic groups is attributed to influence from and dependency upon more stable agrarian states as a way to explain the emergence of eastern Eurasian complex societies. Recently, however, some scholars (e.g., Eregzen 2011; Honeychurch 2013, 2014; Rogers 2012) have reviewed these limitations, drawing primarily on the growing body of material evidence from well-documented archeological expeditions. Their results reveal that the Xiongnu state emerged from indigenous political and economic traditions based on aspects unique to steppe communities including diverse forms of pastoralism, investment in transportation and spatial networking, and power sharing. It is important to note that animals and movement play a core role in all these aspects, practices which could hardly have been borrowed from the contemporary sedentary states in China.

One of the factors in support of the dependency theory is associated with difficulties in acquiring agricultural and craft products from nomadic pastoral environments seemingly inappropriate for effective farming as well as for achieving high degrees of technological sophistication. As for the issue on grain supplement, a competing theory and body of evidence propose multiresource and multipurpose pastoralism (Honeychurch 2014; Svyatko et al. 2013; Spengler et al. 2014) as an alternative. Excavated botanical and faunal evidence from the Bronze Age through the Iron Age of eastern Eurasia has provided substantial evidence for integrated pastoral and agricultural subsistence systems. Evidence for testing the proposed theoretical models in terms of specialized craft goods, however, is relatively sparse due to a lack of information required to distinguish between objects of domestic and foreign origin. It is not surprising therefore that the provenance of most craft items, especially metal products, from excavations has been determined based on stylistic characteristics. Recent collaborative research projects have begun to address this long-standing lack of pertinent data. Extensive archeometallurgical work on Mongolian bronze and iron objects of the Xiongnu and pre-Xiongnu periods (Park et al. 2010, 2011) has established a basis for the discussion of indigenous technological traditions, which were different from those practiced in China. These prior studies have special significance for the numerous metallic objects recovered from the royal Xiongnu tomb at Golmod 2 (Fig. 1) (Erdenebaatar et al. 2015), an elite mortuary site located in what is thought to be the heartland of the Xiongnu state (Honeychurch 2013). Because metalwork played a prominent role in constituting Xiongnu material culture, we expect that the analysis of these objects will serve to test the degree of nomadic dependence on external metallurgical traditions. To this end, we initiated an archeometallurgical project focusing on groups of bronze and iron objects used as key functional components of the Golmod 2 wagons (Fig. 2).

Horse-drawn wagons were part of a long-standing tradition among steppe people that included the earliest chariots and spoked wheel technology in the Old World (Anthony 2007). This technology was transferred to the Central Plain of China during the late Shang dynasty (Wu 2013) and, from that time on, became a significant part of Chinese material culture. Given this history, the technology and manufacture of impressive lightweight wheeled vehicles was not unfamiliar to steppe peoples, as the highly ornamented and well-preserved wagons from Pazyryk burials in the Altai Mountains clearly attest (Rudenko 1970). Based on the style of wagons recovered from Xiongnu elite burials, their universal attribution as the products of Han dynasty workshops has not generated any debate (Honeychurch 2014; Miller 2012; Polosmak et al. 2007, 2008), but nor has this proposition been tested by direct material analyses. In this article, we will present a detailed account of the microstructure and chemical composition of the objects examined for the evaluation of pertinent technological traditions. The resulting outcome will then be employed to test the traditional view on the origin of Chinese style wagons interred in Xiongnu elite burials, which is frequently used to underscore economic and political dependence of this early nomadic state.

Comments on metallurgical traditions

A recent study on iron technology practiced in ancient Mongolia (Park et al. 2010) demonstrated that the Xiongnu had established their own iron industry drawing on the smelting of bloomery iron and steelmaking through solid-state carburization. This particular iron tradition is in strong

Fig. 1 Map of Mongolia showing provinces and archeological sites mentioned in the text, with *arrows A* and *B* locating the Xiongnu burial sites at Golmod 1 and Golmod 2, respectively, in the North Khangai (Arkhangai) province

Fig. 2 Photos showing excavation contexts. **a** Photo taken while the wheel of an interred wagon was being excavated. **b** Photo showing two undisturbed areas from which the respective metal objects displayed were excavated. **c** Photo enlarging the area marked by the *arrow* in **b**

contrast to that typical of the Han dynasty where iron production was based on the smelting of cast iron, which could subsequently be decarburized into iron and steel in the solid or liquid state (Rostoker and Bronson 1990). Cast iron was also used in the Xiongnu state, but not very frequently and only as wheel components for horse-drawn wagons such as bushings and axle caps (Park et al. 2010). It is important to note that the unique Xiongnu iron tradition was maintained with no significant modification for more than a millennium and was still dominating the iron industry of the Mongol empire (Park and Reichert 2015). The only difference was found in the substantially increased use of cast iron in varied applications primarily for making less critical items such as large-scale agricultural and domestic implements.

The early and continuing implementation in Mongolia of bloomery-based iron technology, which is fundamentally different from China's cast iron-based tradition, is unexpected from a scholarly viewpoint emphasizing relations of political and economic dependency between states in Mongolia and China. The mobile and independent life style of dispersed herding populations in Mongolia must have been responsible for such a persistent selection of bloomery-based iron tradition, which is best suited for small-scale production with a minimal initial investment (Wagner 1996). Ironically, the factors considered critical in theorizing nomads' political and economic dependence on neighboring agrarian state communities are seen to have promoted their technological independence in iron production.

Technological tradition established for Mongolian bronze production constitutes another area in which one may test the extent to which Xiongnu material culture depended on foreign influence, as proposed by Park et al. (2011) in their study on bronze objects from Xiongnu and pre-Xiongnu contexts. It was shown that the nomadic communities at the site of Baga Gazariin Chuluu (BGC) in the northern reaches of the Gobi Desert established a bronze tradition where arsenic was a major alloying element and the addition of lead was rarely practiced. This specific alloy recipe was confirmed in the absolute majority of objects from pre-Xiongnu contexts and continued in general use during the Xiongnu period. With the dawn of the Xiongnu state, however, they observed the implementation of another bronze formula based on the profuse use of both lead and tin. Given this particular alloy recipe representing the traditional bronze technology of ancient China (Bagley 1987; Barnard 1961; Rawson 1990; So 1995), they posited the introduction of a new bronze tradition in Mongolia, driven apparently by increased Xiongnu contact with Han communities. In fact, the new alloys were primarily associated with Xiongnu sites from which items typical of Han material culture were excavated, indicating that they were produced under strong Chinese influence, whether in the Xiongnu or Han territory.

The transition in Mongolian bronze technology evident in the use of lead was also noticed in the numerous Xiongnu bronze artifacts excavated from the royal tomb at Golmod 2 (Fig. 1). In our previous study on the alloy chemistry of a group of bronze ornaments, almost identical in shape and size (Park et al. 2015), we found that they were products under a unique technological environment where arsenic played an important role as the major alloying element. This alloy recipe is almost identical to that of the BGC communities as well as a continuation of the steppe bronze tradition drawing on the copper-arsenic system, with the exception of lead observed in the majority of those examined. The amount of added lead, however, was insignificant due, evidently, to a limited access to tin, indicating that the use of lead could have only a limited impact in such a tin-lacking environment. It is intriguing to see that in Xiongnu communities, restriction in material resources enforced most key features of the earlier bronze tradition to be maintained while their unique lifestyle was instrumental in their persistent adherence to bloomery-based iron technology.

Comments on site

The tomb from which the bronze and iron objects of interest here were recovered constitutes the major structure within the large-scale Xiongnu burial complex named Golmod 2. This site, located in the Arkhangai Province of Mongolia, was so named following another important Xiongnu burial complex in the same province named Golmod 1. The sites at Golmod 1 and Golmod 2, marked respectively by arrows A and B on the map (Fig. 1), share substantial commonalities in both construction and layout, as well as in artifact assemblages. The royal tomb under consideration is the greatest in scale of those known to date from Xiongnu contexts and is accompanied by 27 satellite tombs arranged in an arc along its eastern flank in addition to a single satellite burial exclusively for a horse positioned to its north (see Fig. 5 in Park et al. 2015). Following the discovery of the site in 2001 (Erdenebaatar et al. 2011), archeological excavation was first conducted for the satellite structures (Miller et al. 2006) and then for the main tomb (Erdenebaatar et al. 2015). A more detailed account of site contexts may be found in our previous publication (Park et al. 2015).

Radiocarbon analysis carried out on a piece of leather attached to the surface of a bronze object yielded a 1σ ^{14}C age of 2008 ± 37 radiocarbon years (Park et al. 2015). This age, when calibrated within 2σ probability range, gives a date span of 109 BC–AD 75, which is in fair agreement with the periodization proposed for other large-scale Xiongnu burials at Golmod 1, Tsaram, Duurlig Nars, and Noyon Uul (Brosseder 2009).

Comments on artifacts

The volume of bronze and iron objects recovered from the main tomb described above was of almost an industrial scale, the absolute majority of them being functional or decorative items associated with horse-drawn wagons (Erdenebaatar et al. 2015). Estimation based on the number of recovered metal parts showed that they could represent at least a dozen of two-wheeled carriages. Of these vehicles, only one was buried in its entirety while the others had apparently been dismantled prior to the interment, making it impossible to reconstruct their general shape and appearance based on the various metallic and nonmetallic components that were excavated. The numerous decorative items, which could be classified into groups based on their shape and size (see Fig. 3 in Park et al. 2015 and Plate 92 in Umehara 1937), and the particular interred wagon were all considered stylistically of Chinese origin.

Figure 2a is a snapshot taken during the excavation of one of the two wheels of the wagon, showing a bronze axle cap still assembled at the position marked by the arrow. There was clear evidence of looting in the excavated tomb, which may explain why the other wheel was missing. Substantial portions of the carriage, however, survived the pillage, showing that the wagon was two wheeled and drawn by two horses. The wheel in Fig. 2a was placed on a layer of charcoal about 1 m in thickness, beginning at approximately 16 m below the ground surface. This layer, presumably associated with a Xiongnu burial ceremony where metal objects were often broken and burned (Park and Eregzen 2015), was initially positioned about 1 m above the main wooden burial chamber with the space between them filled with gravel. The remains of the wagon, including the wheel, were discovered within the depression created when the infrastructure supporting the charcoal-covered area collapsed near its center. Excavation context, however, showed that the deposition of the wagon occurred subsequently to the formation of the charcoal layer.

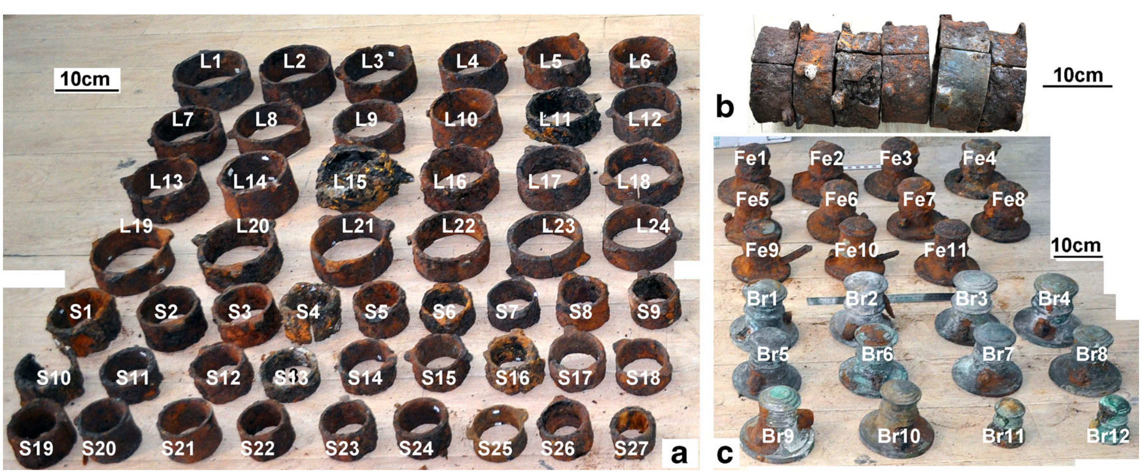

Fig. 3 General appearance of the iron and bronze objects examined. **a** Large (*L1–L24*) and small (*S1–S27*) iron bushings. **b** Photo showing the presence of split lines in some of the large iron bushings in **a**. **c** Cast iron (*Fe1–Fe11*) and bronze (*Br1–Br12*) axle caps. Each of the photos in **a**–**c** was photographed in a single shot. The magnification bars in **a** and **c** were drawn in reference to objects *L21* and *Fe11*, respectively. The *labels of the objects* in **a** and **c** are consistent with the IDs given in Tables 1, 2, and 3

Most metal parts of such vehicles, however, were deposited in two other areas located within the large burial pit to the north of the spot for the wagon. Figure 2b presents two large metal collections recovered from the two respective areas, remaining undisturbed until the formal excavation. The collection on the left hand side is seen to consist of iron strips for the rim of a wheel with spokes still attached to them, iron bushings and caps, a number of bronze decorations in the form of a flower (see Park et al. 2015), and others. Figure 2c, providing a magnified view of the other area near the upper right corner of Fig. 2b, also shows a variety of bronze and iron objects including iron bushings and bronze caps. Of the total amount of 28 bronze and iron caps excavated, most were recovered from this particular area with the notable exception of four smaller bronze caps, which were found within the eastern space between the inner and outer compartments of the main burial chamber. The deposition of metal objects in the two areas mentioned above occurred after the construction of the charcoal layer was completed, indicating that they were disassembled before being collected for deposition. It is not clear whether there was any connection between the formation of the charcoal layer and the separation of metal objects from vehicles. Some of them, however, displayed strong evidence of a thermal treatment given near or slightly above the melting temperatures.

The artifact assemblage of interest here consists of metallic bushings and caps that were used in the wheel-axle assembly, the most crucial part for the intended purpose of the vehicles. The bushings must have provided a bearing surface for rotary motion of the wheels, while the caps functioned to keep the wheels in the correct position. The bushings shown in Fig. 3a, a photo taken in a single shot, may be classified into two groups based on their size: one with relatively large objects (L1 through L24) and the other with smaller objects (S1 through S27). The outer diameter of the larger and smaller objects is approximately 140 and 80 mm, respectively, as represented by the magnification mark, drawn in reference to L22. The bushings were all made of iron and had a cut along their length, which can be verified in Fig. 3b, a photo showing the cylindrical surface (sleeve) of some objects. Such a split sleeve is an unmistakable sign of fabrication by forging rather than by casting. Only one exception, however, was found in S13 of Fig. 3a, which has a solid sleeve without a split, indicating that it was cast to shape.

In contrast to the bushings above, the axle caps were cast from either iron or bronze. The photo (Fig. 3c) presents the iron caps (Fe1 through Fe11) at the top and the bronze caps (Br1 through Br12) at the bottom, with the magnification mark drawn relative to Fe11. They are similar in size, with their height and the outside diameter of their bottom being approximately in the range of 105–125 and 130–160 mm, respectively, except Br11 and Br12, which are about half the size of the large ones. An iron pin, a component used to fix the axle cap in the set position of an axle, was found left in some of the iron (Fe5 and Fe7–Fe10) and bronze (Br1–10) caps.

Parting lines indicative of the bivalve molding process employed in casting were observed in the iron caps. No such features were found, however, in those cast from bronze alloys, suggesting that a lost-wax or investment casting technique was applied for their manufacture. Also found in some of the iron caps was the presence of bronze patches, which were applied to fill empty spaces that came to exist due to pouring defects. For instance, the top surface of Fe9 had a large through hole sealed with such a patch where a clear sign of the solidification reaction is still visible on its back surface exposed toward the inner space of the cap. In strong contrast, no pouring defects were identified in any of the bronze axle caps. This observation demonstrates that the caps were manufactured in a technological environment with only limited experience in iron casting as opposed to its excellent command of bronze casting.

Analytical results

For metallographic examination small specimens were taken from some of the iron bushings presented in Fig. 3a and all the iron and bronze caps in Fig. 3c. They were mounted and then prepared following the standard metallographic procedures of polishing and etching. A solution of 2% nitric acid by volume in methanol was used to etch the iron specimens while a solution of 100 ml methyl alcohol, 30 ml hydrochloric acid, and 10 g ferric chloride was used as an etchant for the bronze specimens. The microstructures were examined using an optical microscope and a scanning electron microscope (SEM). The carbon level of iron specimens was inferred from the microstructures observed and reported according to weight fraction. The chemical composition of bronze samples was measured using the energy-dispersive X-ray spectrometer (EDS) included with the SEM instrument and specified also in weight fraction to within 0.1%. Their average composition was inferred from the EDS spectrum taken in a raster mode from an area of approximately 0.65 × 0.45 mm, except in cases where restrictions on the specimen size necessitated a smaller area.

Bushings

Of the 24 large and 27 small bushings presented in Fig. 3a, 15 were selected for metallographic investigation. Table 1 specifies the identification (ID) and weight of the objects examined along with the experimental data obtained from the analytical procedures discussed below. The IDs are consistent with the labels given in Fig. 3a. Note that S13 is the only object with a

Table 1 Summary information on ID, weight, carbon concentration and microstructure of the large and small iron bushings examined from the royal Xiongnu tomb at Golmod 2, Mongolia. The IDs are consistent with the labels of the objects shown in Fig. 2a

#	ID	Weight (kg)	C level (wt%)	Microstructure	Comments
Large bushings					
1	L1	1.37	1.0	Numerous large cementite particles in ferrite or pearlite background; slag particles	Split sleeve
2	L2	1.43	0.4	Ferrite grains in pearlite background; slag particles	Split sleeve
3	L3	1.33	0.8	Pearlite; slag particles	Split sleeve
4	L8	0.94	0.5	Ferrite grains in pearlite background; slag particles	Split sleeve
5	L9	0.96	0.1	Mostly ferrite grains with a little pearlite; slag particles	Split sleeve
6	L23	0.83	1.0	Some cementite particles in pearlite background; slag particles	Split sleeve
7	L24	0.79	0.5	Ferrite grains in pearlite background; slag particles	Split sleeve
Small bushings					
8	S7	0.33	0.5	Ferrite grains in pearlite background	Split sleeve
9	S11	0.40	0.4	Ferrite grains in pearlite background; slag particles	Split sleeve
10	S13	0.30	4.3	Numerous graphite flakes in white cast iron eutectic	Cast iron Solid sleeve
11	S14	0.33	1.0	Numerous cementite particles in ferrite background; slag particles	Split sleeve
12	S18	0.33	0.1–0.8	Pearlite gradually turning to ferrite; slag particles	Carburization Split sleeve
13	S20	0.53	1.0	Some cementite particles in pearlite background	Split sleeve
14	S24	0.50	1.0	Some cementite particles in pearlite background	Split sleeve
15	S25	0.25	0.6	Ferrite grains in pearlite background; slag particles	Split sleeve

solid sleeve and expected to have been shaped by casting as opposed to the others that were all forged to shape and consequently have a split sleeve.

The optical micrograph (Fig. 4a), showing the structure of S18, illustrates the gradual change in brightness from bottom to top. This difference is associated with the varying fraction

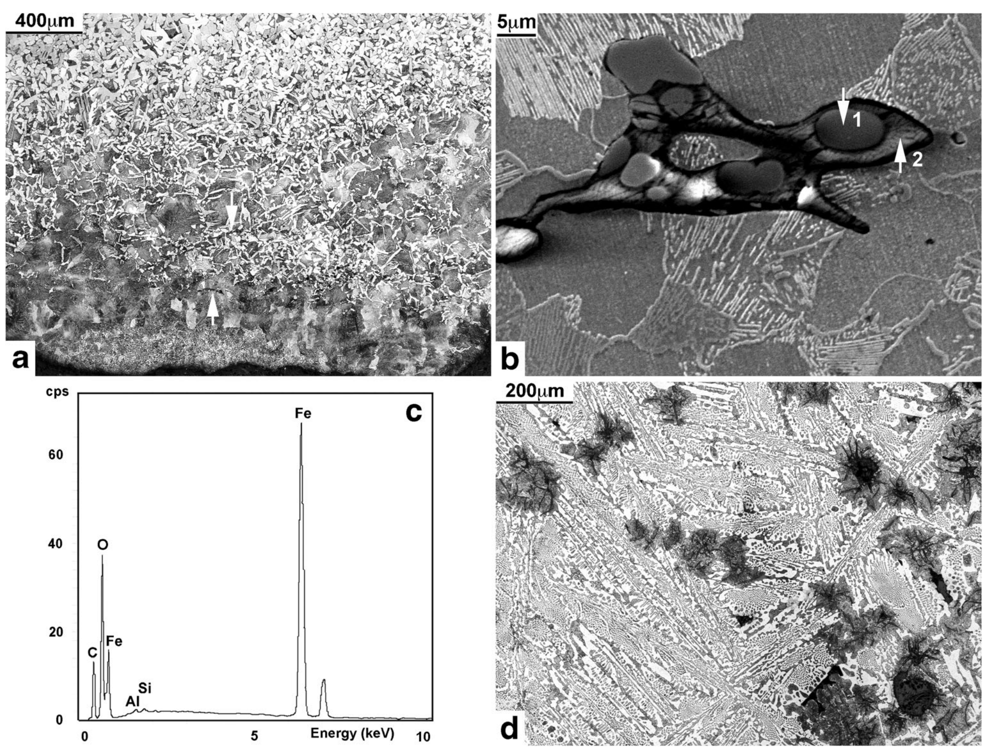

Fig. 4 Micrographs and EDS spectrum. **a** Optical micrograph showing the structure of Fe6. **b** SEM micrograph magnifying the area near the *upper arrow* in **a**. **c** EDS spectrum taken from the spot at *arrow 1* in **b**. **d** Optical micrograph showing the structure of S13

of two micro constituents covering a given area of the micrograph. One of them termed pearlite, which etches dark, dominates the dark area near the bottom while the bright area near the top is mostly covered with the other constituent termed ferrite, which appears bright against pearlite. Pearlite and ferrite generally coexist in iron and steel specimens, but in varying proportions depending on their overall carbon concentration. Ferrite, dissolving approximately 0.02% carbon or less, is the major constituent of a low carbon area while the fraction of pearlite, whose carbon level is 0.77%, increases with the increase in carbon level until it becomes 100% at the specific carbon content of 0.77% termed eutectoid. Beyond this value, another constituent termed cementite, which is a compound of 93.33% iron and 6.67% carbon, starts to form and exist together with pearlite. The increase in brightness toward the top of Fig. 4a, therefore, corresponds to the variation in carbon levels from approximately 0.8 to 0.1%. This kind of carbon distribution is typically obtained when an iron specimen is carburized. In this treatment, carbon atoms penetrate the specimen from the surface, thereby establishing a negative concentration gradient toward its interior. This is exactly the pattern that is observed in Fig. 4a where the high carbon level near the bottom, which was exposed on the surface during carburization, decreases toward the inner area.

In addition to ferrite or pearlite, the micrograph (Fig. 4a) is seen to contain nonmetallic inclusions at the areas marked by the white arrows. The SEM micrograph (Fig. 4b), magnifying the area near the upper arrow, visualizes two major constituents of the inclusion. It was inferred from EDS analysis that one of them at arrow 1 was basically made of iron oxide termed wüstite (FeO; Fig. 4c) while the chemistry of the other at arrow 2 approximated that of fayalite (Fe_2SiO_4). Such inclusions are suggestive of the bloomery process employed for the smelting of the raw material used in S18 while the microstructural distribution of Fig. 4a implies the application of a carburization treatment to raise its carbon level. Note in Fig. 4b the presence of thin cementite plates in the bright areas of pearlite, which is responsible for the contrast between the areas of pearlite and ferrite.

The optical micrograph (Fig. 4d), taken from the specimen of S13 the only cast object, shows the precipitation of white cast iron eutectic called ledeburite in the bright area where a number of small gray regions are scattered. Ledeburite forms when cast iron alloys of near-eutectic composition (4.3% carbon) are solidified. The gray regions, however, are diagnostic of a thermal treatment that was applied subsequently in the solid state to transform brittle white cast iron into more ductile structure termed malleable cast iron. In this treatment, graphite is precipitated in the form of flakes at the expense of white cast iron structure, as is confirmed in the gray regions, which consist of dark flakes embedded in the metal matrix. Note that the reaction was terminated prematurely while they were still growing.

Table 1 summarizes the carbon concentration and microstructural characteristics of the specimens taken from the bushings examined. Microstructures in most specimens were fairly uniform and consisted of varying fractions of pearlite and ferrite regions, allowing the carbon content to be

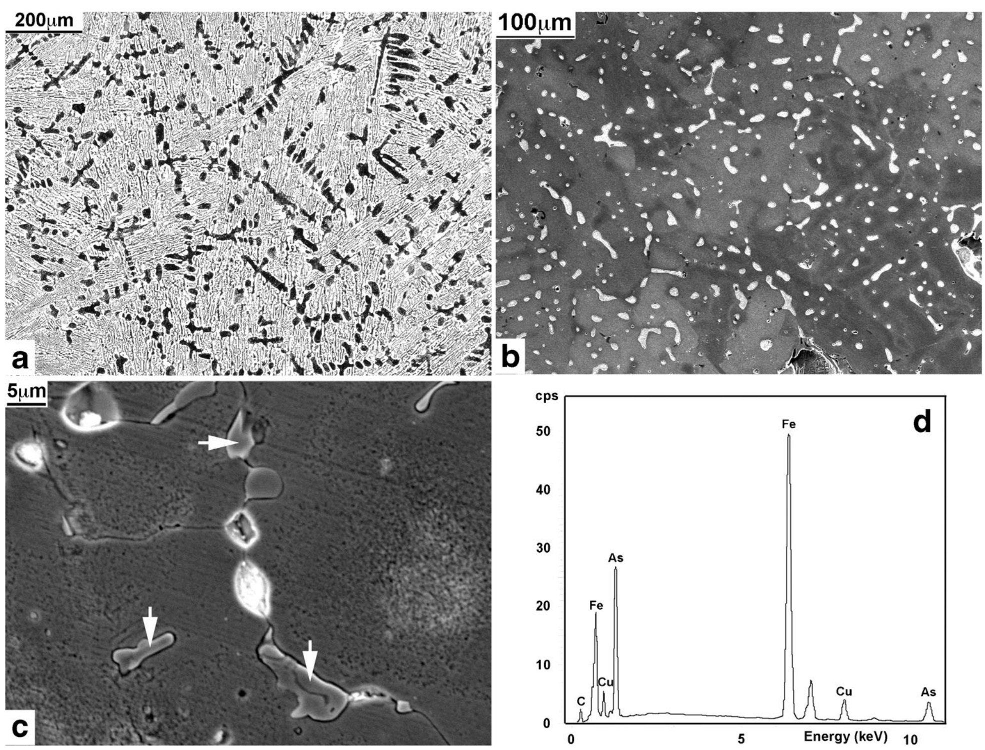

Fig. 5 Micrographs and EDS spectrum. **a** Optical micrograph showing the structure of S18. **b**, **c** SEM micrographs showing the structure of Br2 and Br8, respectively. **d** EDS spectrum taken from the spot marked by the *bottom left arrow* in **c**

determined at approximately 0.8% and below. In some of them (L1, L23, S14, S20, S24), however, relatively large particles of cementite were precipitated in pearlite background, indicating that the overall carbon concentration is above the eutectoid composition (0.77%). It should be noted that all specimens were small in scale and taken from near the surface of associated objects. As such, they only represent the near-surface areas and give no information on their interior. The evidence of carburization applied to S18 as shown in Fig. 4a, however, may allow one to presume that a similar treatment was given to others. We tested this possibility with a small bushing, not shown in Fig. 3a, which was heavily corroded and had the inner part almost exposed, where we found a microstructure mostly of ferrite. Note that some nonmetallic inclusions were consistently observed in most specimens examined.

Axle caps

Iron caps

The iron axle caps (Fig. 3c) were similar in structure to those presented in the optical micrograph (Fig. 5a) taken from Fe6, which consists of dark tree-like regions (dendrite) of pearlite scattered in the bright background of white cast iron eutectic. This structure is typically obtained from the solidification of cast iron whose carbon content is less than eutectic (4.3%). If the carbon level of pearlite (0.77%) is taken into account, the average carbon concentration of the structure in Fig. 5a is determined from the relative amounts of pearlite and white cast iron to be approximately 4.0%. Note that the carbon level of the cast iron structure in Fig. 4d without dendrites was determined to be 4.3%. The carbon concentration thus determined is summarized in Table 2 along with the microstructural characteristics, ID, and weight of the associated objects. The IDs are consistent with the labels given in Fig. 3c. In Table 2, the presence of spherical particles of cementite in many objects was interpreted as evidence of significant thermal treatments applied in the solid state. Table 2 also lists the analytical data on the carbon content and microstructure of the pins associated with Fe9 and Fe10. The results reveal that both pins were forged out of bloomery iron, with a clear sign of carburization identified in one of them.

Another fact to be noted in Table 2 is the comments on bronze patches applied to repair large-scale cavities that had been introduced in Fe4, Fe7, Fe9, and Fe11 as casting defects. Specimens were taken from some of them for metallographic examination with the results reported in the following section.

Bronze caps

The axle caps cast from bronze alloys had structures similar to those illustrated in the SEM micrograph (Fig. 5b), which was taken from Br2. In the micrograph, the gray background corresponds to the copper-rich α phase dissolving varying amounts of tin or arsenic or both while the bright regions are filled with almost pure lead. Though not clearly visible, a number of tiny particles of dark copper sulfide are also scattered in the background. In addition to these particles, the specimens from Br8, Br9, and Br10 had another kind of

Table 2 Summary information on ID, weight, carbon concentration, and microstructure of the iron axle caps examined from the royal Xiongnu tomb at Golmod 2, Mongolia. The IDs are consistent with the labels of the objects shown in Fig. 2c

#	ID	Weight (kg)	Part	C level (wt%)	Microstructure	Comments
1	Fe1	2.13	Cap	3.2	White cast iron eutectic containing pearlite (formerly austenite) dendrites	
2	Fe2	2.12	Cap	3.2	Similar to #1	
3	Fe3	2.00	Cap	4.0	White cast iron eutectic containing (formerly austenite) dendrites filled with cementite particles and ferrite	Heat treated
4	Fe4	1.52	Cap	3.2	Similar to #1	Cavities repaired using bronze
5	Fe5	1.92	Cap	4.0	Similar to #3	Heat treated
6	Fe6	1.50	Cap	4.0	Similar to #3	Heat treated
7	Fe7	1.76	Cap	4.0	Similar to #3	Heat treated Cavities repaired using bronze
8	Fe8	1.51	Cap	4.0	Similar to #3	Heat treated
9	Fe9	1.53	Cap	4.0	Similar to #3	Heat treated Cavities repaired using bronze
			Pin	0.02–0.8	Pearlite layers enclosing the ferrite interior; slag particles	Carburized steel
10	Fe10	1.76	Cap	4.0	Similar to #3	Cavities repaired using bronze
			Pin	0.1	A little pearlite in ferrite background; slag particles	Low carbon steel
11	Fe11	1.30	Cap	4.0	Similar to #3	Heat treated Cavities repaired using bronze

particles precipitated as shown in the SEM micrograph (Fig. 5c) from Br8, where some such precipitates were marked by the arrows. The EDS spectrum (Fig. 5d), taken from the top arrow, reveals that the particle is made of iron (Fe) and arsenic (As) containing a notable amount of copper (Cu). These iron arsenide particles named speiss are observed only in copper alloys of high arsenic contents (Park et al. 2015) and suggestive of a certain technique employed in the preparation of such specific alloys (see Lechtman 1999; Park and Eregzen 2015).

The compositional and microstructural data summarized in Table 3 according to the same artifact IDs specified in Fig. 3c make it clear that the objects examined were products of a bronze tradition where arsenic played a key role as the major alloying element. The low tin level, which is mostly below 3.0% with the average being approximately 1.9%, strongly suggests that the arsenic-based tradition was a choice enforced by restriction in tin supply. Given the fraction of lead in bronze being strictly dependent on its tin level, the low lead content of 3.0% or below found in some objects could be another indication of a tin-lacking environment. Such low levels of tin and lead could result inadvertently from the use of tin- or lead-contaminated ores or bronze scraps in either smelting or alloy making. In contrast, the high arsenic concentration of Br8, 9Br, and Br10 set at around 3.6–4.7% signifies a special technique in practice at the time for the control of arsenic levels. This technique, yet to be uncovered, is well known for the precipitation of speiss in the resulting alloys. This fact is also confirmed in Table 3, which shows the presence of speiss only in the high arsenic objects. Another fact to be noted in Table 3 is the substantial amount of lead added in some objects, particularly Br2, Br3, Br12, and Br13. The use of lead in such a tin-lacking and arsenic-based bronze industry may signify the beginning of a subtle transition in the local bronze tradition.

The data in the last two rows of Table 3 came from the bronze patches applied to fix casting defects in the iron caps labeled Fe9 and Fe11. They are almost identical in alloy composition to Br1, Br2, and Br12, suggesting that the repair was made in the same technological environment where the bronze caps were cast. It is likely therefore that the producers of the iron and bronze caps were in close association.

Discussion

The iron and steel technology as inferred from the data outlined in Table 1 and Fig. 4a–d may be characterized by the use of iron-carbon alloys with varying carbon contents from 0.1 to 1.0% and the use of forging as the primary fabrication technique. Strong evidence was found that the objects were given a carburization treatment to raise the carbon contents in near-surface areas, suggesting that the raw materials supplied for shaping contained little carbon. Given the role of

Table 3 Summary information on ID, weight, alloy composition, and microstructure of the bronze axle caps examined from the royal Xiongnu tomb at Golmod 2, Mongolia. The IDs are consistent with the labels of the objects shown in Fig. 2c

#	ID	Weight (kg)	Chemical composition (wt%)			Microstructure	Comments
			Sn	Pb	As		
1	Br1	1.64	2.7	5.0	–	Particles of lead or copper sulfide scattered over the α phase background	0.3% S–1.2% Fe
2	Br2	1.44	2.0	6.4	–		
3	Br3	1.50	2.5	8.9	–		
4	Br4	1.53	2.5	3.7	–		0.2% S–0.3Fe
5	Br5	1.00	1.3	2.8	0.6		
6	Br6	1.26	0.9	2.7	–		
7	Br7	0.99	1.3	4.8	0.6		
8	Br8	1.10	1.6	2.8	3.6	Particles of speiss, lead, or copper sulfide scattered over the α phase background	0.2% S–2.2% Fe
9	Br9	1.17	1.4	3.0	4.7		0.2% S–3.7% Fe
10	Br10	1.15	1.5	2.6	4.6		0.4% S–3.0% Fe
11	Br11	0.66	2.3	3.1	–	Particles of lead or copper sulfide scattered over the α phase background	0.3% Fe
12	Br12	0.69	3.2	6.0	–		0.9% Fe
Average			1.9	4.3			
Samples taken from the bronze portions applied to fix the poring defects of some cast iron caps							
13	Fe9	1.53	2.0	6.0	–	Particles of lead or copper sulfide scattered over the α phase background	
14	Fe11	1.30	2.7	5.0	–		0.4% S
Average			2.4	5.5	–		

bushings as providing a bearing surface for relative motion, higher surface hardness must have been necessary for the sake of abrasion resistance. It is then evident that they were manufactured in a process where low carbon iron was first forged to shape and then carburized for hardening. Since this process was characteristic of an iron tradition based on the bloomery process, the artifacts (Fig. 3a) must have been manufactured under such a unique iron-making environment. This conclusion is further supported by the presence of non-metallic slag inclusions in most specimens examined.

Bloomery-based iron technology was widely practiced in Korea (Park 2012), India (Park and Shinde 2013), and Europe (Rostoker and Bronson 1990) in antiquity as well as in Mongolia up to the Mongol period (Park et al. 2010; Park and Reichert 2015). It is distinctly different from cast iron-based technology that had long been established in China by the time the objects concerned were made (Rostoker and Bronson 1990; Wagner 1996). The cast iron artifact, S13, suggests that cast iron was also used, though on a much smaller scale, in Mongolia during the Xiongnu period. The evidence of a thermal treatment observed in it (see Fig. 4d) may be interpreted as an effort to improve material properties by reducing the fraction of brittle white cast iron. The low resistance of white cast iron to brittle fracture is well attested in objects similar to S13, which have been recovered, mostly in fragmented pieces, from sites in Mongolia of Xiongnu (Park et al. 2010) as well as of Khitan and Mongol (Park et al. 2008; Chunag et al. 2006) contexts. As such, cast iron may not be ideal for making moving parts, such as bushings that are frequently exposed to impact loading in service. It is well suited, however, for mass production and provides an excellent abrasion resistance, another key property to be considered in the design of bearings. In contrast, bloomery iron is ductile and good at absorbing impact, yet it is not appropriate for mass production and has poor abrasion resistance unless the surface is hardened through a complicated treatment. Bloomery iron may then be the best choice for small-scale production of quality items, as opposed to cast iron, which is optimal for large-scale production of relatively low product integrity. The former employed in the absolute majority of the artifacts (Fig. 3a), therefore, is another indication that they were indeed products of bloomery-based iron tradition with only limited expertise in handling cast iron.

In contrast to the bushings (Fig. 3a) that were forged to shape, the axle caps (Fig. 3c) were all fabricated by casting, apparently because of their complex shape. The selection of either cast iron or copper alloys for them indicates that both materials could meet the functional requirements. The presence of large defects observed only in some of the cast iron objects, however, implies that there was a significant gap between the two materials in terms of the technological sophistication achieved for their casting. This difference, which must have been associated with the high melting points and high oxidation rates of cast iron, signifies a lack of required technological experiences. With these difficulties expected, cast iron would not have been recommended for use in making objects such as axle caps unless it was readily available. However, the availability of cast iron and pertinent technological ideas does not seem to have been fully exploited, apparently due to bronze casting available as an alternative approach.

The compositional data presented in Table 3 highlight the key role of arsenic as an alloying element, a limited access to tin and the addition of lead intended in some objects. This particular alloy formula is characteristic of the steppe bronze technology that dominated Mongolia during the pre-Xiongnu period and continued in use as a major tradition of the Xiongnu state (Park et al. 2011, 2015). It should be noted that the arsenic-based or low-tin recipe with a limited use of lead is clearly distinguished from the major bronze tradition long established in the Han dynasty based on the copper-tin-lead alloy system.

Conclusion

The visual and metallographic examination of the metallic objects from the royal Xiongnu burial at Golmod 2 of the fist century BC and the fist century AD provides some important insights. The evidence suggests that these artifacts were products of a metallurgical tradition based on the use of bloomery iron- and arsenic-based bronze technologies. This tradition, established in Mongolia long before the emergence of the Xiongnu polity, continued to be the primary means for Xiongnu metal production (Park et al. 2010, 2011, 2015). If indeed the objects under consideration were functional components of Han dynasty style wagons interred in this burial context, an important question emerges about the cultural and political identities of their producers. According to theories regarding such vehicles as symbols of Xiongnu dependency on China (Miller 2012; Polosmak et al. 2008; Yü 1967, p. 209), the vehicles as well as their metal components should be products of Han workshops with little connection to contemporary Xiongnu industries. The evidence presented here does not support that idea and instead argues for a high degree of local manufacture using traditional Xiongnu metal technologies. Given the clear differences between Han and Xiongnu methods of working iron and bronze, the present study demonstrates that such political and cultural theories should be reconsidered.

Nevertheless, there is little doubt that the cast iron technology used in some of these objects likely reflects Han influence on Xiongnu material culture. It is seen that cast iron was employed primarily for wheel caps, which were shaped exclusively by casting, a process not practiced in the bloomery-based iron tradition. Its use was apparently limited due to a lack of technological experience with cast iron, as inferred from defects observed in some cast iron objects but not the ones cast from bronze. Such serious defects would not have occurred in a technological environment with sufficient expertise with cast iron, as was the case in China. This lack of proficiency, however, does not diminish Xiongnu achievements in iron metallurgy. Rather, it has to be understood as reflecting a Xiongnu propensity to seek flexibility by making the most of available resources and practices, whether domestic or foreign. With a high level of technological capability already achieved in bronze casting, some of the iron components could have been rendered in bronze. Very likely, bronze would have been chosen had not cast iron been readily available and its availability encouraged experimentation in the manufacture of the particular items. In the case of bushings, bloomery iron manufacture sufficed and therefore no additional use of cast iron was required. Even in this case, however, some evidence suggests that experimentation was carried out to test the possibility of exploiting cast iron.

Our results have shown that Xiongnu crafts specialists had in their possession the full capacity to manufacture the most important functional components of Han style horse-drawn wagons. Given the long-standing importance of wheeled vehicles in traditional steppe life, there is no compelling reason to deny that some or most of such vehicles excavated from royal Xiongnu graves may have been constructed domestically. Apart from the stylistic characteristics, Xiongnu workshops would apparently have had nothing to borrow from the Han dynasty to this end. It is ironic that an impressive artifact supposedly highlighting nomadic cultural dependency on sedentary neighbors turns out to confirm just the opposite, the self-sufficient status of the Xiongnu nomads in establishing and practicing their own metallurgical traditions. The Xiongnu success in assimilating such exotic high-tech craft products as these stylized horse-drawn wagons into their own material culture is a significant departure from explanations emphasizing economic and political dependency of the Xiongnu state. Such dependency theories depend upon the somewhat biased assumption that a pastoral nomadic economy and the marginal steppe environments would make specialized craft production improbable and, therefore, dependency would be an inevitable outcome (e.g., Khazanov 2001). Ironically, the present discovery found that these same features were in fact instrumental in the establishment and implementation of unique steppe-oriented metallurgical traditions in Mongolia.

We come to the conclusion that Xiongnu achievements in material culture were not dependent on foreign models as they were once supposed to be but, in fact, were relatively resistant to external cultural and technological influences. This resistance along with culturally governed selection of external ideas and practices is best understood as the result of a conscious effort to maintain Xiongnu identity and lifeway as developed within the natural, cultural, and political contexts of the northern steppe. There is no doubt that success in this effort was facilitated by the indigenous technological infrastructures that had long been tailored to meet the specific needs of steppe peoples. It may not be fortuitous therefore that similar conclusions have been drawn with regard to the development of nomadic political systems and unique forms of statehood among the northern steppe nomads, with the Xiongnu state as a primary case in point (Honeychurch 2014; Rogers 2012).

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