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ADVANCED EXPLOITATION OF HAGH-TIN BRONZE ALLOYS AT MEDIEVAL SETTLEMENT TALGAR IN KAZAKHSTAN

A collection of bronze artifacts, including a mirror, round plate, thick-walled container, two thick-walled bowls, a thin-walled pot, two thin-walled bowls, a dish, and a strainer, retrieved from a medieval settlement in Talgar, Kazakhstan, underwent metallographic analysis. Typological dating places these objects within the 11th to 13th centuries AD. The examination revealed the use of high-tin bronze in various household items requiring advanced functionality. Two primary techniques were identified: 1) the use of high-tin bronze alloys as spacers and binders in creating double-walled containers for enhanced thermal insulation, and 2) the application of optimized thermo-mechanical treatments within the α+β phase field of the copper-tin phase diagram to enhance impact resistance. Additionally, the presence of zinc, tin, and lead hints at an ongoing transition from bronze to brass within the Talgar region during this period. Our investigation delved into the specific engineering processes employed and the level of technological sophistication evident in the production of these artifacts.

Keywords: Kazakhstan; Medieval settlement Talgar; High-tin bronze; Material properties; Double-walled vessels

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УСОВЕРШЕНСТВОВАННОЕ ИСПОЛЬЗОВАНИЕ СПЛАВОВ ВЫСОКООЛОВЯНИСТОЙ БРОНЗЫ НА СРЕДНЕВЕКОВОМ ГОРОДИЩЕ ТАЛГАР В КАЗАХСТАНЕ

Бронзовая коллекция, состоящая из зеркала, круглой пластины, толстостенного сосуда, двух толстостенных мисок, тонкостенного горшка, двух тонкостенных мисок, блюда и ситечка, входит в состав металлических предметов, раскопанных на средневековом городище Талгар (Казахстан), подвергнута металлографическому исследованию. Хронологическая оценка, основанная на типологическом признаке, датирует исследованные предметы XI–XIII вв. н. э. Результаты анализа показали, что высокооловянистая бронза использовалась в различных бытовых предметах, требующих повышенных функциональных свойств. Две основные технологии включают 1) сплавы из высокооловянистой бронзы, используемые в качестве разделителей и связующих при изготовлении двустенных контейнеров, нуждающихся в улучшении теплоизоляции, 2) оптимизированную термомеханическую обработку, практикуемую в фазовой области α+β на фазовой диаграмме медь — олово, очевидно, с целью повышения ударопрочности. Также было замечено добавление цинка наряду с оловом и свинцом, что свидетельствует о переходе от бронзы к латуни, выплавляемой в то время в районе Талгара. Мы изучили, какие именно инженерные процессы были выполнены и каков был уровень технологической сложности.

Ключевые слова: Казахстан; средневековое городище Талгар; высокооловянистая бронза; свойства материала; двустенные сосуды.

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Introduction

The medieval period in Central Asia was faced with significant sociopolitical transformation. At the time, the region was subjected to growing power and influence from the expanding Arab Caliphate until it became one of the major sociopolitical centers representing the Islamic world [Abazov, 2008; Christian, 1998]. Meanwhile, China also exerted a significant cultural and political impact, particularly in the eastern part of Central Asia. As one of the influential aspects of material culture, copper-based technology established in Central Asia during the medieval period likely evolved under strong influence from the Islamic world as well as China.

A recent study on copper-based metal objects from one of the medieval steppe communities in the Aral Sea region [KKK in Fig. 1a] noted a bronze-to-brass transition in progress [Park and Voyakin, 2021]. Despite this transition toward a growing reliance on brass, zinc-free alloy recipes based on copper and tin were still extensively practiced. The use of these two main alloying methods, attesting to the transition from bronze to brass, hints at the existence of multiple metalworking groups with uneven rights and access to material and technological resources. It is suggested, therefore, that the particular steppe community consisted of diverse people groups with varying adherence to the ongoing sociopolitical and technological transformations as reflected in the bronze-brass transition. Significantly, a similar transition was also observed [Park et al., 2021] in another group of medieval metal objects recovered from one of the sites in the great Bukhara oasis (Fig. 1a). This observation suggests that the two roughly contemporary communities above consisted of diverse people groups embracing a bronze-to-brass transition with a different attitude. According to Craddock (1979) and Allan (1979), the transition was occurring throughout the entire Islamic world at the time and was completed by the late medieval period.

Despite the rare and valuable information derived from metallographic studies such as those mentioned above, they have usually been conducted without being specific on the benefits and technological choices involved in the addition of tin, zinc, or both to copper. Without a doubt, the substantial change in color characteristics was the main consumer-oriented incentive to use alloying elements [Mecking, 2020]. Metal workers were also interested in their effects on other material properties such as strength, ductility, melting temperatures, and flow properties in casting, some of which could be further modified through thermo-mechanical treatments subsequent to casting. However, in many cases, it is beyond the scope of metallographic analysis to assess the level and context of specific technologies locally implemented for the control of such material properties.

In this respect, the copper-based metal assemblage excavated from the medieval site at Talgar in Kazakhstan (Fig. 1a and 1b) is rather exceptional. In addition to producing evidence of the above-mentioned bronze-to-brass transition, it provided a valuable window into the technological sophistication achieved by medieval metal workers. The main achievement was found in the design of alloys appropriate for the thermo-mechanical treatments to be applied for the fabrication of objects in need of extraordinary functional properties. We present the detailed metallographic data to show that accurate thermal control coupled with a comprehensive understanding of material behaviors as determined by alloy composition and thermomechanical treatments played a major role in the production of the given assemblage.

Fig. 1. Map of the Republic of Kazakhstan: a — Kazakhstan and the neighboring countries; b — a map enlarging the rectangular area indicated in Fig. 1a. The arrow locates the medieval site at Talgar, from which the objects under investigation were excavated
Рис. 1. Карта Республики Казахстан: а — Казахстан и соседние страны; б — карта, увеличивающая прямоугольную область, указанную на рисунке 1а. Стрелкой обозначено средневековое городище в Талгаре, из которого были извлечены исследуемые объекты

Comments on the site

The archaeological site at Talgar, located approximately 25 km to the east of Almaty (Figs. 1a and 1b) in the southeastern part of Kazakhstan named Semirechye, served as a major medieval settlement for centuries. The Semirechye region is bounded by the Zailiisky Alatau Mountains to the south, the Dzunghar Alatau Mountains to the northeast, and the desert of Balkhash to the west. Its unique location at the crossroads between the desert-oasis region of Central Asia and the semi-arid and desert areas of Mongolia and western China caused Semirechye to play a key role in the establishment and operation of a branch of the Great Silk Road from around BC 130 through the 14th-15th century AD [Frachetti, 2008]. Medieval Talgar was one of the steppe towns that had developed along this Silk Road in Semirechye from the 8th century AD and thrived until the Mongol invasion at the beginning of the 13th century AD [Chang et al., 2002: 44].

The settlement was apparently established around the time the Islamic forces were coming to Central Asia, while the Chinese Tang dynasty was constantly trying to maintain hegemony over the region. The site is likely to have seen the fall of the Turkic confederacy, which led to the fragmentation of the state into its constituent tribal groups. The waning of Chinese influence following its defeat against the Islamic army at Taraz (Fig. 1a) in the year 751 placed the region under the control of the Karluk, a Turkic tribe that made a significant contribution to the victory of the Islamic army at Taraz. Subsequently, the Karluk established the Karakhanid Khaganate, the first major Islamic state of Turkic origin in Central Asia, with its capital located at Balasagun near the modern city of Tokmok (Fig. 1b) in Kyrgyzstan, approximately 167 km to the southwest of Talgar [Frye, 2004].

The medieval site at Talgar has long been under excavation, under the lead of Tamara Savelieva of the Margulan Institute of Archaeology, leading to the recovery of numerous metallic objects along with a variety of other cultural remains [Chang et al., 2002; Park and Voyakin, 2009, 2013; Park and Savelieva, 2021]. The bronze objects examined in this study were all recovered from the medieval site at Talgar. The periodization based on typological grounds placed their chronology between the 11th and 13th centuries AD.

Comments on artifacts

The external appearance of the objects examined is shown in Fig. 2, where the artifacts are illustrated approximately to scale, all at the same reduction ratio as specified by the scale bar at the lower right corner. Object № 1 is a mirror and № 2 is a round plate with an indented geometric pattern consisting of a circle and six semicircles arranged at the center and periphery, respectively. Object № 3 is a thick-walled container with its central part repaired, № 4 and 5 thick-walled bowls, № 6 a thin-walled pot, № 7 and 8 thin-walled bowls, № 9 a plate, and № 10 a strainer. It should be noted that objects № 6, 7, and 8 were double-walled containers made of a pair of thin metal plates placed by placing a group of thin spacers between them. The numbers labeled with the objects are consistent with those in Table 1.

Objects № 3, 4, and 5 were excavated in the space seemingly used as a storage room, all placed together in a single large ceramic vessel, while objects № 2 and 6 through 9 were all recovered from a single room likely used as a metalworker's area for both smithing and commercial activities.

Fig. 2. The general appearance of the bronze objects examined. The artifacts are illustrated on a reduced scale all with the same reduction ratio as specified in the scale bar at the lower right corner. Object № 1 is a mirror, № 2 a round plate with a coarse impressed geometric pattern consisting of a circular and six semicircular features arranged at the center and the periphery, respectively, № 3 a container with its central part repaired, № 4 and 5 bowls, № 6 a double-walled pot, № 7 and 8 double-walled bowls, № 9 a dish and 10 a strainer. The numbers labeling the objects are consistent with those in Table 1.

Рис. 2. Общий вид исследованных бронзовых предметов. Артефакты показаны в уменьшенном масштабе, все с тем же коэффициентом уменьшения, который указан на шкале в правом нижнем углу. Объект 1 — зеркало, 2 — круглая тарелка с грубо отпечатанным геометрическим рисунком, состоящим из круглой и шести полукруглых деталей, расположенных в центре и по периферии соответственно, 3 — контейнер с отремонтированной центральной частью, миски 4 и 5, 6 — горшок с двойными стенками, Миски 7 и 8 с двойными стенками, блюдо 9 и ситечко 10. Номера, обозначающие объекты, соответствуют номерам, указанным в таблице 1

Metallographic examination

One or more specimens were taken from each object in Fig. 2 for metallographic examination. The samples were mounted and polished following standard metallographic procedures and then etched using a solution of 100 ml of methyl alcohol, 30 ml hydrochloric acid and 10 g ferric chloride, all commercially available. An optical microscope and scanning electron microscope (SEM) were used to examine microstructures. The composition analysis was performed using an energy-dispersive X-ray spectrometer (EDS) included with the SEM instrument, with the result reported in weight fraction to within 0.1%. The approximate average composition was inferred from the EDS spectrum taken in raster mode from an area of approximately 0.65 mm by 0.45 mm, except in cases where an insufficient specimen size required a smaller area.

Alloy composition

Table 1 summarizes the data for the concentrations of tin (Sn), arsenic (As), lead (Pb) and zinc (Zn) obtained from composition analysis using EDS. Minor elements such as sulfur and iron were also detected in some objects, but their presence is not discussed here, assuming that their presence has little effect on alloy properties and is fortuitous. Table 1 shows that tin, arsenic, lead and zinc constitute the major alloying elements separately or in combination. These elements have notable effects on the alloy properties and may have been added for specific purposes. The presence of arsenic is beneficial in fabrication and use and generally results from arsenic-bearing ores used in copper smelting. Therefore, arsenic addition can frequently occur without intention, particularly in cases where its concentration is less than a few percent, as observed in objects № 1 and 3a. In addition, these two objects contain other alloying elements, so no further practical benefit is expected from adding arsenic in such a small amount. The alloy recipe in Table 1 can be understood by focusing on tin, lead, and zinc.

Table 1

Summary information of the bronze objects excavated from the medieval settlement at Talgar in Southeastern Kazakhstan, including their ID, purpose, chemical composition and structure type. The numbers labeling the objects are consistent with those in Fig. 2

Таблица 1

Краткая информация о бронзовых предметах, найденных при раскопках средневекового поселения в Талгаре на юго-востоке Казахстана, включая их идентификатор, назначение, химический состав и тип структуры. Номера, обозначающие предметы, соответствуют номерам на рисунке 2

№		ID	Artifact Sn	Composition in weight%				[a]Structure type	Comments
				As	Pb	Zn			
1		T3	Mirror	8.8	1.5	9.5	[b] —	2	Cast
2		T4	Plate	-	-	2.9	-	1	Cast
3	a	T5a	Container	2.6	1.0	23.4	10.2	2	Cast
	b	T5b	Repaired part	-	-	-	23.7	3	Forged and annealed
4		T6	Bowl	21.3	-	-	-	4	Cast, slightly forged, and quenched
5		T7	Bowl	21.4	-	-	-	4	Cast and quenched
6	a	T8a	[c]DW pot	-	-	-	-	3	Forged and annealed
	b	T8b	Binder-spacer	13.3	-	-	-	5	Cast
7	a	T9a	DW bowl	-	-	-	-	3	Forged and annealed
	b	T9b	Binder-spacer	13.1	-	-	-	5	Cast
8	a	T10a	DW bowl	-	-	-	-	3	Forged and annealed
	b	T10b	Binder-spacer	17.0	-	-	-	5	Cast
9		T11	Dish	~20.0	-	-	-	4	Cast and quenched; severely corroded
10		T1	Strainer	16.9	-	-	-	4	Cast, slightly forged, and quenched

[a]Structure type: 1) Pb particles in α, 2) Pb particles in α with variable solute segregation, 3) twinned α, 4) α and martensite background, 5) α and α-δ eutectoid background; [b]-: Not detected; [c]DW: Double-walled.

In Table 1, tin plays an important role in classifying the metal assemblage examined. According to the presence of this element, the objects are divided into those with (№ 1, 3a, 4, 5, 6b, 7b, 8b, 9, and 10) and without it (№ 2, 3b, 6a, 7a, and 8a), the former further divided by reference to the 10% tin content of 10% into high-tin (№ 4, 5, 6b, 7b, 8b, 9, and 10) and low-tin (№ 1 and 3a) bronzes. It is noted that objects № 1, 2, and 3a contain lead, while it is not observed in any of the high-tin objects. The level of lead in object № 2 is too low to have any significant effect on alloy properties, and the little lead was likely derived from lead-contaminated ores used in copper smelting.

Object № 3a is unique, as it was made of alloys containing 10.2% zinc in addition to 2.6% tin, 1.6% arsenic, and 23.4% lead. The tin level of 2.6% is too low to be a deliberate addition, as opposed to the substantial amount of lead, which must have been added in elemental form. This particular alloy composition would be readily attained in technological settings based on both bronze and brass, where recycled bronze and brass are abundantly available in scrap form. Fig. 2 shows that this object had its central part damaged and later repaired using a different material, brass. As indicated by the arrow in Fig. 2, the brass was forged into a thin plate to cover the damaged part. The sample of this plate is labeled 3b in Table 1, where its zinc level is specified at 23.7%. This concentration of zinc was characteristic of a brass-making technique named cementation, which served as the main process for producing brass alloys in the Islamic world, including Central Asia (Craddock, 1979; Allan, 1979; Park and Voyakin, 2009). In contrast to the original body, the repaired part was likely forged from fresh cementation brass without any compositional modification.

Significantly, objects № 6, 7, and 8 were made of two different materials: unalloyed copper and high-tin bronze. These objects, as mentioned earlier, were double-walled containers made of two thin copper plates separated and positioned by small, thin, high-tin bronze spacers. The spacers contain only tin as an alloying element, with the tin content determined between 13.0% and 17.0%. Within this composition range, the bronze alloys melt at temperatures lower than those of unalloyed copper 100 °C to 150 °C. Therefore, in controlled heat treatment, only the high-tin spacers could be molten and then frozen to serve as an adhesive binding to the two copper plates. The tin content of the spacers, likely determined by the accuracy of temperature control in this thermal treatment, may represent the level of technological sophistication available at the site. The arrangement of the spacers between two copper plates will be presented in the following section.

It is seen in Table 1 that objects № 4, 5, 9, and 10 are also high-tin bronzes. However, they were made exclusively of high-tin bronze alloys, with the tin content mainly determined within a narrow range around 21.0%, much higher than the spacers.

Microstructure

Structures typical of those observed in the bronze objects in Fig. 2 are presented in Fig. 3a-3g, all optical micrographs with the exception of Fig. 3b, a SEM micrograph.

Objects № 1 and 3a were similar in structure, as illustrated in Fig. 3a, a micrograph taken from object № 1, where both the dark and the bright areas are filled with the α phase. This contrast in the α areas reflects the difference in the amount of alloying elements incorporated during solidification.

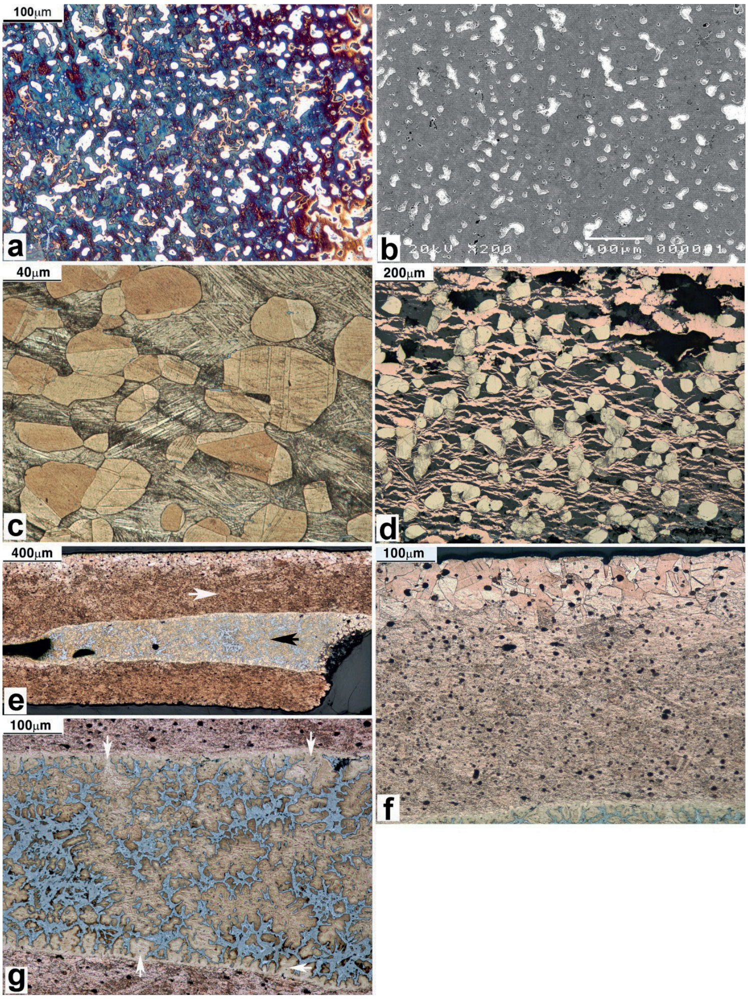

Fig. 3. Micrographs: a — Optical micrograph showing the structure at the external layer of object 7 in Fig. 2; b — optical micrograph showing the structure of object 1 in Fig. 2; c — SEM micrograph illustrating the structure of object 1 in Fig. 2; d — optical micrograph showing the structure of object 8 in Fig. 2. Note the central layer inserted between the two layers at the top and bottom; e — optical micrograph magnifying the central area of Fig. 3d; f — optical micrograph showing the structure of object 10 in Fig. 2

Рис. 3. Микрофотографии: а — оптическая микрофотография, показывающая структуру на внешнем слое объекта 7 на рисунке 2; б — оптическая микрофотография, показывающая структуру объекта № 1 на рисунке 2; в — СЭМ-микрофотография, иллюстрирующая структуру объекта № 1 на рисунке 2; г — оптическая микрофотография показывающая структуру объекта 8 на рисунке 2. Обратите внимание на центральный слой, вставленный между двумя слоями сверху и снизу; е — оптическая микрофотография, увеличивающая центральную область на рисунке 3d; f — оптическая микрофотография, показывающая структуру объекта 10 на рисунке 2

In this process, the primary α phase forms first with a lower solute content than bright areas, which solidify later with solute enrichment. The micrograph shows no indication that other phases were present in a notable amount, suggesting that the level of alloying elements was well below the solubility limit in the α phase. The composition data in Table 1 confirmed this prediction by showing that, on average, the given specimen included 8.8% tin, 1.5% arsenic, and 9.5% lead as alloying elements. It should be noted that lead is virtually insoluble in the α phase and exists in bronze as particles of almost pure lead. The presence of such lead particles, not readily identified in Fig. 3a, is clearly visible of the bright areas in Fig. 3b, an SEM micrograph taken from the same specimen as in Fig. 3a.

Fig. 3c, an optical micrograph taken from object № 10, illustrates structures typically observed in objects № 4, 5, and 10, which consist consistently of primary α areas scattered in the background of the β-martensite. This martensite phase in bronze occurs only in high-tin specimens with a tin level of 10% or higher when they are heated at temperatures around 700 °C, followed by quenching in a medium such as water. The α grains in Fig. 3c are slightly twined, indicating that the object was lightly forged at high temperatures prior to quenching. A similarly twined structure was observed in object № 4 but not in № 5.

The structure illustrated in Fig. 3d, an optical micrograph showing the structure of object № 9, appears different from that of Fig. 3c due to the corrosion-induced modification. However, a careful comparison of Figs. 3c and 3d reveals that the roughly circular areas in both micrographs are similar and represent the same primary α phase. The formation of such a unique α phase requires special thermal treatment, suggesting that object № 9 was also treated similarly. In this case, Fig. 3d should have the same phase precipitated in the background as Fig. 3c. However, corrosion completely modified the structure in the background of Fig. 3d, leading to the re-deposition of almost pure copper, as seen in the bright ribbon-like areas with the dark space between them filled with corrosion products primarily of copper and tin oxides (Wang and Merkel 2001).

The specimens from objects № 6, 7, and 8 were nearly identical in both structures and their peculiar distribution, as illustrated in Fig. 3e, an optical micrograph covering the entire thickness of the thin wall. The micrograph shows that the wall is approximately 1mm thick and consists of three layers. Fig. 3f, an optical micrograph magnifying the area marked by the white arrow in Fig. 3e, indicates that the upper layer consists exclusively of α grains, which, according to EDS analysis, were made of unalloyed copper. The twin structure seen in the α grains near the upper edge is suggestive of significant mechanical work applied during fabrication. The bottom layer in Fig. 3e was also made of unalloyed copper.

Fig. 3g, an optical micrograph enlarging the area at the dark arrow in Fig. 3e, shows high-tin bronze structures consisting of the primary α phase precipitated in the form of dendrites, with the inter-dendritic areas filled with the α-δ eutectoid. This unique microstructure occurs in the solidification reaction of high-tin alloys, followed by slow cooling as in an ambient environment. Evidently, this high-tin layer was in a molten state between the two solid copper layers at the top and bottom. It is seen in the arrows in Fig. 3g that the molten alloy began to freeze where it was in contact with the solid copper. The tin content in the middle layer was determined in the EDS analysis to be approximately 17.0%, which is within the prediction based on structure. The bronze alloys of this tin concentration melt at approximately 930 °C, which is 154.5 °C lower than the melting point of unalloyed copper), implying that the object was thermally treated within this temperature range before it was left to cool at a slow rate. In addition to serving as cement to bind two thin copper plates, high-tin alloys must have played a key role in the making of a double-walled container as spacers, allowing better control over its shape, size, and the gap between its inner and outer walls.

Discussion

Table 1 summarizes the composition and microstructure data of the fourteen samples taken from ten metal objects, revealing various alloy methods with tin, lead, and zinc serving as the main alloying elements. A little arsenic detected in some specimens is ignored for reasons mentioned earlier. Table 1 shows that five of the 14 specimens were made of copper without a deliberate addition of alloying elements. However, one of them (№ 2) is found to contain 2.9 % lead, likely as a result of inadvertent contamination. Apparently, lead-contaminated copper often circulated in the region as a raw material for the production of various copper-based alloys. Two samples in Table 1 were cast from either a copper-tin-lead alloy (no. 1) or a copper-tin-lead-zinc alloy (no. 3a). Significantly, the remaining seven were made of copper-tin alloys without lead. Their tin level was set at 13.1 % and above in the range of high-tin bronze.

During the medieval period, Central Asia, including the present site at Talgar, was undergoing a transition from brass to bronze (Park and Voyakin 2009, 2021; Park et al., 2021). As a result, recycled bronze and brass in scrap form served as the main raw materials for making copper-based alloys, and their resulting tin levels generally determined below 5.0%. Specimen № 3a from object № 3 in Table 1 is well within this range, although its lead concentration is significantly higher than normal. The other specimen (№ 3b) of the same object was also readily available as a raw material derived directly from the cementation process, the major method of brass making at the time. Apart from this particular case and five other cases of unalloyed copper, the alloys in Table 1 were all significantly different from the norm at the time in terms of chemical composition. This divergence from the contemporary standard alloying tradition evidently arose from the unique functional properties required in objects for which the given alloys served as raw materials. The seven such alloys in Table 1 were used in the fabrication of special double-walled thermal containers (objects № 6, 7, and 8) and high-tin bronze kitchen items (objects № 4, 5, 9, and 10).

As illustrated in Fig. 3e, the double-walled containers all consist of two thin copper plates forming the inner and outer walls, with an empty space positioned between them. This space was seen to maintain its shape via small spacers placed between the two copper walls. Placers were made of high-tin bronze alloys with melting temperatures than copper. The wall-spacer assembly was then thermally treated at temperatures between those of elemental copper and bronze spacers so that the latter, upon freezing, could be welded to the copper walls on both sides. The bronze spacers in objects № 6, 7, and 8 are shown in Table 1 to contain 13.3, 13.1, and 17.0% tin, respectively. Bronze alloys with these concentrations of tin melt at temperatures approximately between 930 and 980 °C. For successful thermal treatments, therefore, the temperature must be controlled between these values and 1,084.5 °C, the melting point of copper. The control of temperature within 50 °C around the target value of approximately 1,000 °C was certainly a considerable challenge at the time. This difficulty must have dictated the use of copper for the walls instead of bronze, despite the fact that bronze is better than copper in nearly every technological aspect except melting temperature.

Increasing the tin content of the spacers to lower their melting point and expand the acceptable temperature range could facilitate temperature control. However, this option causes the fraction of the fragile δ phase to increase in the spacers, making them prone to brittle fracture upon receiving impacts in service. The tin level, seen generally lower in the spacers than in the other high-tin items, hints at the possibility that this factor was taken into account, causing their tin fraction to be set approximately at the practical upper limit, 17.0%.

However, it is important to note that a proper thermal treatment can prevent the deterioration of mechanical properties resulting from high tin concentrations (Park et al., 2009). As discussed earlier with reference to Fig. 3c, this thermal process consists of heating at elevated temperatures, followed by quenching in water. During heating, the temperature is controlled so that the bronze alloys exist as a mixture of two different phases, α and β. During the subsequent quenching treatment, the β phase transforms into martensite, causing the overall microstructure to comprise both α and martensite, as illustrated in Fig. 3c. If the cooling rate is not as rapid as in quenching, the precipitation of δ, instead of martensite, is promoted. Therefore, the special thermal treatment can be considered a process to obtain ductile martensite by suppressing the formation of δ, which is too brittle to accept any impact loading, during fabrication or in service.

In fact, high-tin objects other than the spacers above were consistently given this thermal treatment, evidently to improve resistance to brittle fracture by suppressing the precipitation of δ. The recrystallized structure noted in Fig. 3c demonstrates that such a controlled microstructure could allow the given high-tin specimens to be forged without incurring brittle fracture. However, given their small size and peculiar arrangements in the double-walled containers, the application of this thermal technique to the spacers is practically impossible. Moreover, the high thermal stresses that could be induced during quenching may have negative effects on the welded joints between the spacers and the walls.

It has been established that the mechanical properties of high-tin bronze, as determined by the balance between strength and ductility, could be optimized when the alloys of near-peritectic composition, 22% tin, are heated at around 700 °C, followed by quenching (Park et al., 2009). Significantly, a recent metallographic study of Korean high-tin bronzes (Park and Joo 2017) showed that the high-tin technology in ancient Korea evolved with this condition as a target. It is intriguing to note that exactly the same condition is also confirmed in Table 1 in objects № 4 and 5, and possibly object № 9, with only one exception of object № 11, suggesting a technological development in Korea and Kazakhstan heading toward a common target. The occurrence of such a shared technological development in the two widely separated regions would not have been possible unless there was one and the same optimum condition.

Conclusion

A bronze assemblage recovered from the medieval residential site at Talgar in Kazakhstan was metallographically investigated. In addition to an object hinting at a bronze-to-brass transition in the Talgar region [Park and Voyakin, 2009], the assemblage contains high-tin bronzes employed in two innovative applications, reflecting the high level of technological achievements.

An application was observed in a group of double-walled thermal containers consisting of two thin plates joined by small spacers to form a gap between them. Given their walls made of thin copper sheets, these vessels must have been used primarily to contain liquids in need of thermal insulation. Microstructure data showed that the spacers, made of high-tin bronze, were perfectly welded to the inner and outer copper walls, indicating that they also served as binding agents. Evidently, a thermal treatment was applied to the wall-spacer assembly at temperatures between the melting points of the two different materials, copper and high-tin bronze. This technique requires a comprehensive understanding of the melting temperatures as a function of tin concentrations. The accuracy of the temperature control determines the tin levels of the spacers. The use of unalloyed copper for the walls must have been intended to maximize the difference in melting temperatures. The addition of more tin to the spacers would then widen the temperature gap and make temperature control easier. However, the tin concentration must be restricted to keep the alloy from becoming too brittle. The composition data indicate that the temperature control at medieval Talgar was practiced within 50 °C of the target temperature of 1,000 °C.

The other application was found in a group of high-tin bronze-made household items with evidence of a special thermal treatment applied, evidently for improved impact resistance. According to the composition and microstructure data, these objects were generally cast from copper-tin alloys of a nearly-peritectic composition (22% tin) and then thermally treated at around 700 °C, followed by quenching in water. These specific tin concentrations and the specific process temperatures represent conditions optimized for the best mechanical properties and noble color characteristics expected from the use of high-tin alloys [Park et al., 2009]. The successful implementation of this technique, therefore, symbolizes a significant achievement that necessitates a comprehensive understanding of the material properties as determined by the alloy composition and various phase transformations in the copper-tin system.

Early evidence of high-tin technologies practiced in Central Asia was observed, particularly in mirrors recovered from archaeological sites dating from the sixth century BC to the first century AD [Ravich, 1991]. Similar evidence was also found in high-tin Central Asian bronze vessels from Kushana-Sasanian contexts [Shemakhanskaya, 1991]. Therefore, the technology and materials evidenced in the high-tin objects under consideration were likely a continuation or revival of those long exploited in and around the region, though not in an optimized state. Little is known, however, of the history of high-tin bronze alloys used in the manufacture of double-walled vessels as spacers and binding agents.

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