Microscopic and microanalytical study on Sasanian metal objects from Western Iran: A case study

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ABSTRACT
Recent archaeological excavation in western Iran discovered a Sasanian palace called Ghaleh Guri (Qela Gowri) beside of the Seimarreh River. As part of the archaeometric studies on the site, five metallic objects (a coin, a disc, a vessel, a decorated strip and some pieces with no specific function) were sampled and analysed using OM and SEM-EDS to determine alloy composition and microstructure. The results showed that strip is made of copper, disc, vessel and unidentifiable object are tin bronze and the coin is made of silver-copper alloy. Tin content in the vessel is about 30 wt% and may be classified as high-tin bronze. The microstructure of samples also revealed that the amount of working and the heat treatment was variable, most likely due to their different compositions.

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Introduction
The study of alloy composition and microstructure of ancient metallic objects has been an interesting subject for archaeological scientists to determine technology used by ancient metalworkers. Copper was the first metal used around the world, with evidence dated from the mid Neolithic period, around 7th millennium BC in the west of the Iranian Plateau (Oudbashi et al, 2012; Thornton 2009; Pigott, 2004).

The metallurgy has changed in the Iranian Plateau during the prehistoric period from the Chalcolithic period (4500–3000 BC) to the Iron Age (1500–550 BC) by developing melting and smelting processes, introducing alloys such as arsenical copper and tin bronze, developing different manufacturing processes such as forging and casting methods to produce objects with variable function, using gold and silver to make decorative objects as well as the appearance of iron metallurgy at the end of this period (Oudbashi et al, 2012; Helwing 2013; 2014; Cuénod 2012; Ross, 2001). The metallurgical activities continued during the historic period especially in the large Persian dynasties from the Achaemenid to the Sasanian empires (550 BC to 651 AD). Although copper and iron were used to manufacture the ordinary objects such as tools and weapons during historic period but most metalwork used precious metals to produce royal objects with high artistic and craftsmanship levels (Ross 2001; Gunter et al, 1992; Simpson et al, 2010; Harper et al, 1981). The ancient metalwork tradition of the area and the different developments achieved ever since, makes the Iranian Plateau pioneer in the development of the metallurgy in the region.

Western Iran has been subjected for archaeometallurgical studies due to its rich and old history and the huge archaeometallurgical activities and metal working discoveries spread in various forms in different parts of this region; that is named as Luristan in the archaeological literature. Some earliest evidence of metal use in the Iranian Plateau is discovered from Ali Kosh and Chogha Sefid in western Iran (7th millennium BC) (Pernicka, 2004; Thornton, 2009). Also earliest evidence of tin bronze metallurgy is found in Kalleh Nisar Bronze Age graveyard, the Luristan region (Fleming et al. 2005; Haerinck and Overlaet 2008; 2010; Begemann et al. 2008). The tradition of copper and bronze metallurgy was continued during the Iron Age (1500–550 BC) in the Luristan region with emerging large scale bronze metallurgy to make ritual and ceremonial bronze object found from graveyards and sanctuaries, named as Luristan Bronzes (Overlaet, 2004; Pigott, 1990; Muscarella, 1988). It shows that the Luristan (western Iran) is a pioneer region in archaeometallurgical activities in the Iranian Plateau during the prehistoric period. There are many analytical and archaeological studies about prehistoric metallurgy in western Iran showing the importance of this region in development of copper and bronze metallurgy in the Near East (Oudbashi et al, 2013; 2014; 2017; Frame, 2010; Fleming et al, 2005; 2006; Begemann et al, 2008; Pigott, 2004; Overlaet 2004; 2005; Moorey,
Nevertheless, there are no extensive available data about archaeometallurgy of western Iran during the historic period (550 BC-651 AD). There are only some case studies about analysis of archaeometallurgical materials and metalworks from different regions of Iran (Oudbashi et al., 2015; Seyedein et al., 2014, Khademi Nadooshan et al., 2011; Sodaei et al., 2013; Mortazavi et al., 2017). It shows that it is required to develop technical and analytical studies to clarify the metallurgical tradition during the historic period of Iran from Achaemenid to Sasanian eras.

The aim of the study was to obtain more details about the metallurgy during the Sasanian period (224–651 AD), by identifying the chemical nature and microstructure of some recently excavated objects from western Iran, using microscopic and microanalytical methods.

**Archaeological background**

At the autumn of 2010, a series of archaeological excavations were done around Seimarreh River to characterize and rescue archaeological sites before starting the project of Seimarreh dam. These excavations performed at the border of modern provinces of Lorestan and Ilam, western Iran. One of the rescue excavations was done in the Ghaleh Guri (Qela Gowri) site in the Ramavand region, in three excavation seasons from 2010 to 2014, that was led to discover remains of a large and ruined building located beside the beach of the Seimarreh River (Figure 1-a).

![Figure 1. a) Map of Iran and location of Ghaleh Guri archaeological site in western Iran, b) A view of excavated palace showing the stone structure, c) The map of excavated palace and place of finding of the metal objects analysed in this study.](image-url)
The building consists of four spaces or rooms (Figure 1-b). One of the spaces is a columnar hall with vaulted roof that is destroyed and remains of the vaulted roof is discovered on the floor of this hall. The walls and columns are made of stone blocks joined with gypsum mortar. Some parts of the walls are covered with gypsum plaster and in some parts are covered with stucco decoration. The floor of the spaces also covered with a thick layer of gypsum plaster. The stucco decorations show typical Sasanian stucco decorations such as geometrical patterns, figure of animals (such as hog) or figure of a man in flower in his hand. Many Sasanian buildings have stucco decorations with different pattern and figures showing a decorative tradition during this period in the Iranian Plateau (Kröger, 1982; Thompson, 1976; Keall et al, 1980; Schmidt, 1937). The layers of natural river deposits such as soil, sand and round stones (35–45 cm in some areas) suggest that the building may has been ruined in effect of river floods in different times (Hasanpour, 2014).

Architectural remains and decorations’ typology indicate that Ghaleh Guri is a local Sasanian palace dated between 300–500 AD (Hassanpur et al, 2014; Hasanpour, 2014). Some of the archaeological objects found in the site include glazed and non-glazed potteries, glass bowls and vessels and copper and iron objects. An archaemometric study was started to characterize cultural materials and historic technology in this site and some results are published previously (Holakooei et al, 2016). As a part of the archaeometric studies, a technical investigation was carried out on five metallic objects that its results are presented in this paper.

Materials and methods

Five metal objects from Ghaleh Guri of Ramavand were selected from the archaeological finds. These include fragments of a vessel (QG-None), a broken circular disc (QG-2037), a part of a decorated strip with some geometric motifs (QG-3024), a small coin (QG-2059) and some pieces with no specific function or type (QG-3019) (Figure 2, Table 1). Samples are discovered from first to third excavation seasons as ordinary objects in the area around the main building (the Sasanian palace) (Figure 1-c).

A small sample was cut from each object, mounted in epoxy resin and ground with abrasive paper of 120, 240, 400, 800, 1200, 2000, and 3000 grids; then polished with diamond paste of 3 to 0.5 microns (Scott, 1991). The prepared samples were analysed with scanning electron microscopy with energy dispersive X-ray spectroscopy (SEM-EDS) method to determine alloy composition and different phases present in the metallic structure. The SEM-EDS analyses and observations were performed in high vacuum using FE-SEM instrument model MIRA III manufactured by TESCAN Company, with a SAMx backscattered electron detector (BSE) and an energy dispersive spectrometer (EDS). The samples were inserted in the SEM

Table 1. Characteristics of the metal objects analysed in this study.

| Sample Code | Type          | Excavation Season/Year | Place of Finding (Locus) |
|-------------|---------------|------------------------|--------------------------|
| QG-None     | Vessel        | First/2010             | L:103                    |
| QG-2037     | Disc          | Second/2012            | L:204                    |
| QG-2059     | Coin          | Second/2012            | L:204                    |
| QG-3019     | Unidentifiable| Third/2014             | L:302                    |
| QG-3024     | Strip         | Third/2014             | L:302                    |
microscope and examined without any preparation procedure such as carbon or gold coating. The minimum beam size of X-ray in EDS analysis used was 750 nm. The energy used in SEM instrument was 15 kv. The bulk chemical analysis was performed by shoot the sample with a wide beam. The size of the spot analysis varied depending on the phase under examination. All EDS results are normalized automatically by the software to 100 wt%.

The microstructure was observed using an optical microscope with polarized light, model BK-POL/BK-POLR manufactured by Alltion company before and after etching by ferric chloride solution in ethanol (120 ml ethanol + 30 ml hydrochloric acid + 10 gr ferric chloride) (Scott, 1991).

Results

Chemical composition

The chemical composition of the samples is presented in Table 2. Based on EDS analysis, four objects are made of copper and its alloys and one sample is made of silver alloy.

In the first look at the cross section of five samples, it is obvious that the sample QG-2037 in completely corroded and no metallic remnant was identified in the cross section, while other four samples have significant metallic microstructure is preserved under corrosion crusts. EDS analysis shows that main components are tin, oxygen and copper, indicating that the disc was made of tin bronze. Nevertheless, it may not be possible to characterize the certain alloy composition in this samples because of changes occurred in the chemical nature due to corrosion and oxidation events in the metal. In the internal corrosion layers of archaeological single phase alpha bronzes, the amount of measured tin is significantly higher than tin content in the alloy and the Sn/Cu ratio is very high in comparison with the uncorroded part of the alloy (Robbiola et al, 1998; Robbiola et al, 1994; Oudbashi et al, 2016). Also it has been observed in completely corroded bronzes that the tin content in the internal part of the object is surprisingly high in comparison with the ancient bronze alloys (Oudbashi 2015). This phenomenon is studied carefully and referred to copper leaching from the alloy due to selective dissolution of copper and remaining tin in the metal structure with internal oxidation (Robbiola et al, 1998; Oudbashi et al, 2016; Oudbashi 2015). The result of selective dissolution of copper and internal oxidation of tin form a completely corroded alloy with high amount of tin (in comparison with tin content in ancient alpha bronzes) in sample QG-2037.

The coin (QG-2059) made of Ag-Cu alloy, contains silver (84.98 wt%) and copper (11.53 wt%). Lead and arsenic also are detected more than 1 percent in the composition of this object and tin is determined as minor element.

In unidentifiable object (QG-3019), tin, zinc and arsenic are detected as the main alloying elements as well as sulphur as major constituent. Also nickel is determined as minor element in the composition of this object (less than 1 percent). Sample QG-3024 (decorated strip) is made of impure copper with low amounts of Zn, Sn, Pb, Sb, Ag, Ni and Fe. Copper is detected as the main element with 95.88 wt%. Finally, the main elements in the composition of the vessel (QG-None) are copper (49.35 wt%) and tin (37.55 wt%). Also, lead, nickel and sulphur are detected in significant amount in the composition of this sample.

Consequently, Chemical composition of the samples show that one sample is made of impure copper with low amount of zinc (sample QG-3024), two samples are made of tin bronze alloy (QG-2037 and QG-None), one sample is made of a quaternary alloy (QG-3019) and one sample is a debased silver coin (sample QG-2059). In fact, the composition of two samples is more considerable and show that the sample QG-3019 could be considered as a Cu-Sn-As-Zn alloy while the sample QG-None should be considered as a high-tin bronze (37.55 wt% of tin) with considerable amount of lead and nickel.

Microstructure

The microstructure of samples was observed by SEM microscope in high magnifications. The sample QG-2037 is completely corroded and the corrosion crusts are visible in SEM-BSE micrograph in different greyish tonalities (Figure 3-a). Furthermore, microstructure of samples QG-3019 and QG-3024 are similar and include dark and bright fine inclusions scattered in the metallic matrix (Figure 3-b and 3-c). There is no evidence of segregations in microstructure of samples QG-3019 and QG-3024, the matrix shows an a solid solution of copper. The shape of inclusions is circular in sample QG-3024 and is elongated in sample QG-

Table 2. Results of EDS analysis of the bulk composition of samples. The sample 2037 is the chemical composition of completely corroded metal.

| Sample   | Cu   | Sn   | Pb   | Sb   | Ni   | Fe   | Zn   | As   | Ag   | S    | P    | O    |
|----------|------|------|------|------|------|------|------|------|------|------|------|------|
| QG-None  | 49.35| 37.55| 3.43 | -    | 6.24 | -    | -    | -    | -    | -    | -    | 3.42 |
| QG-2037  | 30.4 | 35.88| 0.74 | -    | 0.25 | 0.16 | 0.42 | 0.24 | -    | -    | 0.17 | 0.04 |
| QG-2059  | 11.53| 0.85 | 1.46 | -    | 0.35 | -    | 5.32 | 4.30 | -    | 1.18 | -    | 84.98|
| QG-3019  | 80.13| 4.72 | -    | 0.58 | 0.16 | 0.09 | 1.11 | -    | 0.23 | -    | -    | -    |
| QG-3024  | 95.88| 0.98 | 0.97 | 0.58 | 0.16 | 0.09 | 1.11 | -    | 0.23 | -    | -    | -    |
The EDS analysis of these phases showed that the dark inclusions are Cu-S inclusion in sample QG-3019 and Fe-rich inclusion (probably iron oxide) in sample QG-3024 (Table 3). On the other hand, the bright inclusions are lead globules that are corroded or oxidized in some cases due to presence of chlorine and oxygen in their composition (Table 3).

Microstructure of samples QG-2059 (silver coin) and QG-None (high-tin bronze) are more complicated and include a segregated and two phased structure (Figure 4). SEM-BSE micrograph of sample QG-2059 shows a dark and dendritic phase surrounded by a bright matrix. EDS analysis of these phases indicate that the dark dendrites are Cu-rich \(\alpha\) phases with 90.19 wt% of Cu and 8.29 wt% of Ag (analysis B, Table 3). Also the bright matrix is Ag-rich phase with 88.76 wt% of silver and 6.96 wt% of copper (analysis C, Table 3). In some cases, the Cu-rich phase is oxidized containing high amount of oxygen (sample QG-2059, analysis A, Table 3). On the other hand, sample QG-None presents a two-phase microstructure including some dark grey islands scattered in a pale grey matrix. EDS analysis shows that the matrix is copper-tin phase with 22.80 wt% of tin while the islands are made of copper-tin phase with about 13 wt% of tin (Table 3, analyses B and C respectively). The occurrence of corrosion in the structure of this object has led to reveal some microstructural features showing that the high-tin matrix is formed with needle-like phases (Figure 4). Corrosion phenomenon also has caused to change the composition of some needle-like phases placed in the surface of object in comparison with uncorroded needle-like phases, as is visible in EDS analysis A in this high-tin bronze object (Table 3, analysis A).

Three of copper alloy samples were observed by optical microscope after etching (Figure 5). The microstructure of samples QG-3019 and QG-3024 consist of worked and annealed grains of \(\alpha\) solid solution with twin lines. This is a typical grain microstructure in single phase copper and bronze objects showing that the object has been subjected to a thermo-mechanical operation to obtain the final shape. The microstructure of the sample QG-None shows worked and annealed grains of \(\alpha\) phase (low-tin islands) as well as high-tin needle like martensitic \(\beta\) phase grains. This microstructure that is found in \(\beta\) bronzes, usually subjected to annealing and quenching processes (Scott, 1991).

**Discussion**

Microscopic and microanalytical study on five metallic objects from Sasanian period showed that these objects are made of different alloys using impure copper to low-tin and high-tin bronze, a quaternary Cu-Sn-As-Zn composition as well as Ag-Cu alloy.

The use of copper and its alloys to make different objects has been central in the metallurgy of the Iranian Plateau from the prehistoric to the historic period. In fact, many metallic objects were made of copper alloys such as arsenical copper and tin bronze. According to
the results presented here, this tradition continued in the Sasanian period with objects made of copper and bronze. The most significant find of this study is the use of high tin bronze alloys to make vessels (such as sample QG-None). Although, high-tin bronze has been mentioned as an alloy used to make vessels during prehistoric India (Srinivasan, 2016) and historic Iran (Gunter et al, 1992, Pigott, 1990); it is rare to find high tin bronze before the Islamic period in the Iranian Plateau. In fact, high-tin bronzes began to appear towards the end of the Sasanian period becoming more common in the early Islamic Iran as an alternative for silver because of its appearance (Pigott, 1990). Late Sasanian and early Islamic high-tin bronzes have a specific tin content about 20–22 wt%, although the semi-quantitative SEM-EDS analysis of the sample QG-None shows tin amount more than 30 wt%. Cast bronze with this composition is very brittle and does

| Sample  | Phase | Cu   | Sn   | Pb   | Sb   | Ni   | Fe   | O    | P    | Zn   | As   | Ag   | S    | Cl   |
|---------|-------|------|------|------|------|------|------|------|------|------|------|------|------|------|
| QG-None | A     | 24.00| 15.12| -    | -    | 0.29 | 0.16 | 59.19| -    | 0.68 | -    | -    | 0.56 | -    |
| B       | 74.42 | 22.80| 0.35 | -    | -    | 0.46 | 0.26 | -    | -    | 1.18 | 0.51 | -    | -    | -    |
| C       | 85.90 | 12.46| 0.19 | -    | 0.35 | 0.17 | -    | -    | -    | 0.92 | -    | -    | -    | -    |
| QG-2059 | A     | 55.04| 0.07 | 0.11 | 0.12 | 0.11 | 0.09 | 42.56| -    | 0.69 | -    | 1.21 | -    | -    |
| B       | 90.19 | 0.27 | 0.32 | 0.18 | -    | -    | 0.76 | -    | 8.29 | -    | -    | -    | -    | -    |
| C       | 8.96  | 0.95 | 0.39 | 0.20 | -    | 0.53 | 0.79 | 1.06 | 88.76| 0.37 | -    | -    | -    | -    |
| QG-3019 | A     | 73.41| 1.08 | 5.93 | 0.43 | 0.38 | 0.19 | -    | 0.16 | 1.20 | 0.80 | 1.16 | 15.26| -    |
| B       | 47.33 | 0.69 | 44.37| 0.45 | 0.64 | 0.28 | -    | -    | 4.96 | -    | 1.26 | -    | -    | -    |
| C       | 9.15  | 34.43| 0.18 | 0.41 | 0.41 | 0.30 | 25.17| -    | 1.51 | -    | 0.26 | -    | 28.58| -    |
| QG-3024 | A     | 4.42 | 0.15 | 0.31 | 0.21 | 0.30 | 35.69| 57.96| 0.33 | 0.52 | -    | 0.12 | -    | -    |
| B       | 10.68 | 0.21 | 41.08| 0.28 | 0.65 | 0.38 | 6.27 | 0.20 | 0.83 | 0.32 | 0.58 | -    | 38.08| -    |

Figure 4. SEM-BSE micrograph and EDS peaks of two samples: silver coin (a) and high-tin bronze vessel (b).
not proper quality for forging operations. Based on Cu-Sn phase diagram (Figure 6), the martensitic $\beta$ phase might decompose in a eutectoid reaction to $\alpha + \gamma$ at 586°C. In turn the $\gamma$ phase undergoes eutectoid decomposition into $\alpha + \delta$ (Suri et al, 1996). Thus, the objects (usually vessels) were cast in the original shape, so the microstructure was $\delta$ phase and, in some cases, $\alpha$ islands; the $\delta$ phase is very brittle and will break during mechanical deformation (Rajpitak et al, 1979). To avoid brittleness, ancient metalworkers heated the object up to 800 °C and then immediately quenched it in water preventing the transformation of the high temperature $\beta$ phase to the brittle $\delta$ phase (Srinivasan et al, 2007; Scott, 1991). The $\beta$ phase is visible as needle like martensitic structure in the microstructure of ancient high-tin bronzes with about 20–27 wt% of tin (Saunders et al, 1992; Scott, 1991). This transformation is known as peritectic transformation where $\beta$ phase will form from the $\alpha + \text{liquid}$ at about 800 °C during solidification (Park et al, 2009). By rapid cooling via quenching, this phase will remain unchanged in the microstructure. The $\beta$ phase is less brittle than $\delta$ and it is possible to do some mechanical operations on the objects to decorate or finish them. The above explains the $\alpha$ islands with worked and annealed grains (twin lines). However tin content in QG-None is about 33 wt% while tin amount in $\beta$ bronzes is 20–22 wt%. The difference may be explained due to the corrosion process identified in this object. As noted earlier, corrosion/oxidation cause the copper dissolution in buried bronze objects leading a change in the proportion of tin/copper in the composition (Robbiola et al, 1998). As intergranular corrosion is visible in SEM-BSE micrograph of sample QG-None, it is suggested that the high amount of tin present, is because of this phenomenon. In fact, the original tin content in sample QG-None may have been about 22 wt%, and due to corrosion it has now detected as about 33 wt%.

The Ag-Cu coin also shows some considerable microstructural aspects based on its alloy composition. The Ag-Cu alloys are one of the known instances of the eutectic structure. Regarding to the Ag-Cu equilibrium phase diagram (Figure 7), the solubility of Cu in Ag and vice versa falls as the temperature drops; and there is one temperature (in a particular composition) at which the liquid metal can pass directly into solid named the eutectic point (Scott, 1991; Scott, 2010). Eutectic structure is consisting of a mixture of copper rich ($\alpha$) phase and silver rich ($\beta$) phase.

Based on EDS analysis, the coin is made of a low-copper silver alloy with about 11.5 wt% of copper. The coin’s microstructure consists in two phases: $\beta$ (high silver) and $\alpha + \beta$ (low silver) (analyses B and C in Table 3) (Scott 1991; Northover et al, 2014). Of course in high-copper silver alloys the main phase may be $\alpha + \beta$ eutectic but the main phase in the microstructure of the coin is a $\beta$ silver-rich phase that is visible as bright matrix in SEM-BSE micrograph (Figure 4-a). Based on the dendrites seen in SEM-BSE micrograph, it is possible to say that the coin was cast and no forging or annealing operation has performed on the coin afterward.

Based on the results of this study, it is worthy notable that the metallurgy of copper alloys in the Sasanian period was continuing previous metallurgical traditions, with some new innovations such as the use of $\beta$ high-tin bronze. Also, Ag-Cu alloys were used to make objects is the Sasanian period similar to previous periods (Achaemenid empire, for example) (Oudbashi et al, 2015). The addition of copper has been traditionally use to increase the hardness of silver, which pure is too soft to be worked (Scott, 2010; Oudbashi et al,
The achieved hardness in the alloy is strongly related to the copper amount intentionally added to silver (Scott, 2010). Elemental analysis of 38 silver vessels by thermal neutron activation analysis (TNAA) method dated to the Sasanian period in Metropolitan Museum of Art show that they are made of silver-copper alloy with variable amount of copper (from 1 to 38 wt%) (Harper et al., 1981). Also, analysis of different silver coins from some Sasanian sites of Iran revealed that copper concentration is variable from 1 to 10 wt% showing use of debased silver to manufacture silver coins (Khademi Nadooshan et al., 2011; Sodaei et al., 2013; Mortazavi et al., 2017). It shows that using debased silver with different amounts of copper has been a metallurgical tradition to fabricate silver coins during the Sasanian period. The microstructure of the coin showing a dendritic structure of copper-rich phase scattered in the β silver-rich phase of matrix indicates that the technology used to produce the coin was casting, showing no significant evidences of working operation to shape the coin (Northover et al., 2012; Northover et al., 2014).

Chemical composition of sample QG-3019 shows a quaternary alloy including copper, zinc, tin and arsenic. Copper alloys with tin (bronze), zinc (brass) and arsenic (arsenical copper) are observed from the prehistoric period of Iran (Thornton, 2009). The early evidences of copper-zinc alloy in the Near East may have been accidentally produced alloys from second millennium BC that contain less than 8 wt% of zinc. They may have been produced by co-smelting of copper and zinc ores (Thornton et al., 2003). The earliest examples of intentionally copper-zinc alloys from Iran are dated back to second millennium BC from Tappeh Yahya (southern Iran) with Zn amount less than 20 wt% (Thornton, 2007; Thornton et al., 2003). Nevertheless, extensive use of copper-zinc alloy is observed during the Islamic period in the Iranian plateau (Melikian-Chirvani et al., 1989). The sample QG-3019 contains three alloying elements in same concentration. There are a few examples of ternary alloys from pre-Islamic to Islamic Iran such as copper-tin-lead, copper-zinc-lead or copper-tin-arsenic objects (Craddock, 1979; Thornton, 2009). It is rare to find quaternary alloy in pre-Islamic period although some examples of quaternary copper-tin-zinc-lead alloy is observed in the Islamic period (Scott, 1991; Craddock, 1979; Allan, 1989). However,
the uncommon alloy composition of sample QG-3019 may be due to three reasons:

- Using a copper or tin ore with high impurities of As and Zn to make bronze object.
- Making brass (copper-zinc) alloy accidentally by using copper ores with high concentration of impurities such as tin and arsenic.
- Recycling by melting bronze and brass pieces to make a new object with a complex composition.

All options are probable during that period because many of copper ores in Iran contain high amounts of zinc or arsenic as impurities and the ancient metalworkers may have used impurity bearing ores to make this object. Furthermore, it is possible to make a quaternary alloy accidentally while the main aim has been produce bronze alloy. Making copper alloy object by recycling bronze (or brass) pieces may lead to a decrease the tin amount -as well as other alloying elements such as arsenic- in the final product (Figueiredo et al. 2010; Ponting et al, 2015; Mödlinger1 et al, 2017). Thus, based on low amount of three alloying elements (less than 5 percent) in sample QG-3019, it is possible to use recycling or copper (or tin) ores with high concentration of As and Zn as impurities to make this object. Producing a deliberately quaternary alloy is less possible due to concentration of this elements in the chemical composition and no quaternary alloy metallurgical tradition in the pre-Islamic period of Iran.

**Conclusion**

Five metal objects from the Sasanian palace of Ghaleh Guri (Qela Gowri) of Ramavand, western Iran were investigated by microscopic and microanalysis methods. The results showed that the samples are made of different copper alloys including impure copper, low and high tin bronze as well as silver-copper alloy. Although, the use of copper and tin bronze was commonplace from 7000 years before the Sasanian period, high-tin bronze with martensitic β structure is a significant find in this study, being one of the earliest examples of the region. This alloy has been used later in the Islamic period as an alternative for silver but there are only a few examples of martensitic β bronze objects in Sasanian period. In addition, this study has identified a low-copper silver alloy used to increase the hardness of silver by adding copper to silver, at least when making coins. Of course, using silver-copper alloys has been a metallurgical tradition during the Sasanian period to minting silver coins, although the microstructure of the analysed sample shows that it has been cast in this form with no additional working or minting. The results of this limited study well show that the metallurgy of the Sasanian period include different metalworking activities from using usual copper and bronze to cast debased silver as well as high-tin bronze. In fact, this study has revealed new and relevant evidence about copper metallurgy during the Sasanian period, although it is necessary to develop analytical study on copper alloy metallurgy in the
Sasanian period in the future to develop knowledge about this time in the Iranian Plateau.

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