

Аглядны артыкул

Археаметалургічнае даследаванне медных прадметаў з ахеменідскага Персепаля

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Анотацыя. Гэта даследаванне вывучае сведчанні старажытных паразітарных захворванняў шляхам прымянення мікраскапічнага даследавання і палеагенетычнага аналізу да ўзораў, атрыманых з 59 археалагічных кантэкстаў, у тым ліку з 51 прыбіральных, звязанай з эліністычным паселішчам Дэлас у Кікладах, у Эгейскім моры. З даследаваных кантэкстаў 35 утрымлівалі яйкі страўнікава-кішачных гельмінтаў, у тым ліку прадстаўнікоў груп Ascarididae і Trichocephalida, а таксама некалькі яек тыпу Strongyle і адзін узор трэматоіды. Далейшы палеагенетычны аналіз пацвердзіў наяўнасць чалавечых паразітаў, уключаючы Ascaris sp., Trichuris trichiura і Enterobius vermicularis. Гэта даследаванне з'яўляецца адным з найбольш шырокіх вивучэнняў старажытных паразітаў у гарадскім археалагічным асяроддзі, паколькі яно ахоплівае значную частку тэрыторыі паселішча. Вынікі паказваюць, што паразітарныя інфекцыі былі шырока распаўсюджаны сярод насельніцтва, і даюць важную інфармацыю пра гігіену, грамадскае здароўе і паўсядзённыя ўмовы жыцця ў старажытным міжземнаморскім горадзе.

Ключавыя словы: старажытныя паразіты; палеапаразіталагічны аналіз; палеагенетычныя сведчанні; мікраскапічнае даследаванне; гарадская санітарыя; Старажытная Грэцыя.

Literature Review

Archaeometallurgical Study of Copper-Based Objects from Achaemenid Persepolis

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Abstract. Metallurgical production during the Achaemenid era reflects a high level of technical knowledge and artistic craftsmanship in the ancient Near East. However, the material composition and production techniques of copper-alloy objects from this period have not been fully investigated. This study analyzes fourteen copper-based artefacts discovered during early archaeological excavations at the Persepolis World Heritage Site. The assemblage includes ten arrowheads, two broken pin fragments, thin metal strips interpreted as parts of bracelets, and a rod fragment. To identify their chemical composition and manufacturing processes, the objects were examined using inductively coupled plasma optical emission spectroscopy (ICP-OES), scanning electron microscopy combined with energy dispersive X-ray spectroscopy (SEM-EDS), and metallographic observation. The analysis shows that most of the artefacts were made from tin bronze and lead-containing tin bronze, while the bracelet element was produced from brass. The technological evidence indicates that the arrowheads were mainly cast, although some were further treated through annealing. In contrast, the pins, bracelet piece, and rod were formed through repeated cycles of cold hammering and annealing. The deliberate selection of leaded tin bronze for cast utilitarian objects and brass for thin decorative components demonstrates advanced knowledge of alloy behavior and metalworking techniques. Overall, the findings enrich our understanding of Achaemenid metallurgical traditions, production skills, and craft organization at Persepolis.

Keywords: Achaemenid period; Persepolis; ancient metallurgy; copper alloys; tin bronze; leaded bronze; brass; casting technology.

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Introduction

The Persepolis World Heritage Site is one of the most important archaeological and monumental complexes in Iran and was inscribed on the UNESCO World Heritage List in 1979 (Fig. 1a). Locally known as Takht-e Jamshid, this site functioned as the ceremonial and political centre of Achaemenid royal authority and represents the monumental acropolis of ancient Parsa (Shahbazi, 2012, 2004). It is situated in the Marvdasht plain, approximately 60 km northeast of the modern city of Shiraz. Historical accounts indicate that the site has been known and described by travelers and scholars for nearly two thousand years.

The geographical location of Persepolis and the copper-based artefacts examined in this study are illustrated in Fig. 1. Figure 1a presents the position of the site within Iran, along with an aerial view of the terrace and southern architectural complex, while Fig. 1b shows the fourteen copper-alloy artefacts selected for analytical investigation.

Systematic archaeological excavations at Persepolis began in the 1930s under the direction of Ernst Herzfeld and later Erich F. Schmidt, as part of the Oriental Institute of the University of Chicago expedition. Their work resulted in the discovery of major architectural remains, inscriptions, and numerous artefacts, including administrative records preserved on clay tablets (Schmidt, 1953, 1957, 1970; Herzfeld, 1941; Shahbazi, 2012). Founded during the reign of Darius I in the late sixth century BCE, Persepolis served as an important royal centre until its destruction during the Macedonian conquest in the fourth century BCE (Shahbazi, 2004).

Archaeological findings from the site include a wide range of metal artefacts manufactured from copper alloys and iron, such as tools, vessels, weapons, and ceremonial objects (Schmidt, 1953, 1957, 1970; Herzfeld, 1941). Among the most distinctive examples are trilobate socketed arrowheads, which represent a characteristic feature of Achaemenid military equipment (Mahzounzadeh & Bortolini, 2020). These arrowheads continued to be used in later historical periods and have been discovered at several Achaemenid, Seleucid, and Parthian sites, although their technological origins date to earlier Near Eastern traditions (Stronach, 1978; Delrue, 2007; Magee, 2005; Piller et al., 2009). While many high-status Achaemenid artefacts are preserved in museum collections worldwide, numerous utilitarian objects remain stored in the Persepolis site museum, providing valuable material for archaeometallurgical analysis (Muscarella, 1988).



Figure 1. a) Map of Iran and location of the Persepolis World Heritage Site in south-western Iran, and aerial view of the site's terrace and its southern complex (Google Earth image); b) Fourteen copper-base artefacts analysed in this research.

Materials and Methods

During the reorganization of the Persepolis Museum collection in 2015, numerous copper-based artefacts were rediscovered, catalogued, and systematically classified. The assemblage comprised ornamental objects, domestic utensils, tools, and weapons. From this collection, fourteen artefacts were selected for detailed analytical investigation based on their representativeness and preservation condition, which allowed controlled sampling.

The selected materials included ten socketed trilobate arrowheads sharing identical typological characteristics (PM-01–PM-10), two fragmented pins (PM-11 and PM-12), thin metallic strips interpreted as fragments of a bracelet (PM-13), and a segment of a square-sectioned rod (PM-14) (see Fig. 1b). Although precise excavation records are unavailable, archaeological evidence suggests that these objects originated from early excavation campaigns at Persepolis. All specimens are attributed to the Achaemenid period (550–330 BCE) (Table 1). The selection aimed to represent diverse technological aspects of copper-alloy production practiced at the site.

Table 1. This stage aims to identify the problem and define the research objectives. The primary issue addressed is the high Major alloying elements of the analysed artefacts determined by ICP-OES (wt.%).

ID	Object	Cu	Sn	Pb	Zn	As	Fe
PM-01	Arrowhead	92	2.5	3.7	0.028	0.83	0.007
PM-02	Arrowhead	92	4.4	2.3	0.002	0.67	0.088
PM-03	Arrowhead	84	12	0.48	bdl	0.23	0.20
PM-04	Arrowhead	93	4.5	2.3	bdl	0.12	0.033
PM-05	Arrowhead	90	9.5	0.11	0.006	0.18	0.026
PM-06	Arrowhead	91	3.1	2.1	bdl	0.31	0.10
PM-07	Arrowhead	91	5.4	2.9	0.037	0.25	0.05
PM-08	Arrowhead	85	8.3	3.1	bdl	0.17	0.079

ID	Object	Cu	Sn	Pb	Zn	As	Fe
PM-09	Arrowhead	90	5.4	3.9	bdl	0.14	0.046
PM-10	Arrowhead	93	5.4	0.23	0.05	0.21	0.029
PM-11	Pin	89	9.7	0.048	0.033	0.18	0.071
PM-12	Pin	88	11	0.19	0.012	0.15	0.031
PM-13	Bracelet	88	0.19	0.30	9.9	0.024	0.22
PM-14	Rod	90	8.6	0.95	bdl	0.02	0.13

bdl = below detection limit.

Corrosion layers were first mechanically removed to expose metallic cores. Approximately 0.5 g of metallic filings was extracted from each artefact using a micro-drill. The samples were completely dissolved in aqua regia (HCl–HNO₃, 3:1 ratio) and subsequently diluted for quantitative analysis. Elemental compositions were determined using inductively coupled plasma–optical emission spectroscopy (ICP-OES) with a Varian 735 instrument at the Zarazma Mineral Studies Company in Tehran. The analytical detection limit for measured elements was 0.001 wt.%, enabling precise quantification of minor and trace constituents (Table 1).

Small cross-sectional samples (approximately 1 mm²) were removed using a jeweller’s saw and embedded in two-component epoxy resin. Standard metallographic preparation followed, including sequential grinding and polishing. Chemical etching was conducted using an alcoholic ferric chloride (FeCl₃) solution to reveal metallographic structures (Oudbashi et al., 2019).

Initial microstructural observations were performed using optical microscopy with a Zeiss Primotech microscope at the Central Laboratory of the Art University of Isfahan. After repolishing, the mounted sections were coated with gold and examined using scanning electron microscopy (SEM) operating in back-scattered electron (BSE) mode. Local chemical compositions were further analysed through energy-dispersive X-ray spectroscopy (EDS).

SEM-EDS investigations were carried out using a Philips XL30 microscope equipped with a BSE detector and an EDAX Silicon Drift detector under operating conditions of 20 kV accelerating voltage and spot size 5. These analyses were conducted at the SEM Laboratory, Faculty of Materials Engineering, Isfahan University of Technology.

Results

Chemical Composition of the Artefacts

The analytical investigation revealed considerable variation in alloy composition among the examined copper-based artefacts from Persepolis. Elemental analysis indicates that the majority of objects were produced using tin bronze and leaded tin bronze alloys, while a smaller group displays compositions consistent with brass production. These compositional differences suggest the coexistence of multiple metallurgical traditions and technological choices within Achaemenid metalworking practices.

Arrowheads constitute the most compositionally homogeneous group. Most samples contain copper as the principal element combined with moderate concentrations of tin, typically accompanied by small but detectable amounts of lead. The addition of lead appears to have enhanced casting performance by improving metal fluidity during mould filling, a practice widely documented in ancient Near Eastern metallurgy (Oudbashi et al., 2017; Oudbashi et al., 2016). Trace elements, including iron and arsenic, were detected in minor quantities and likely derive from ore impurities rather than intentional alloying.

In contrast, the thin metallic strips interpreted as fragments of a bracelet exhibit a distinct zinc-rich composition, identifying them as brass rather than bronze. The presence of brass is technologically significant, as zinc alloys are comparatively rare in earlier Iranian metallurgical traditions and may reflect experimentation or technological transmission during the Achaemenid period (Oudbashi & Hasanpour, 2018).

The analysed pins and rod fragments demonstrate intermediate compositions, characterized by copper–tin alloys with variable lead content. Such variability may indicate differences in functional requirements or recycling practices involving previously used metal materials.

Table 2. EDS results of different microstructural phases identified in SEM-BSE micrographs (wt.%).

Phase	Sample	Cu	Sn	Pb	Zn	S	Fe	O	Cl	Sr
A (Metallic Matrix)	PM-01	100	–	–	–	–	–	–	–	–
A	PM-06	100	–	–	–	–	–	–	–	–
A	PM-08	98	1.7	0.06	–	–	–	–	–	–
A	PM-09	99	0.89	–	–	–	–	–	–	–
A	PM-10	99	0.97	–	–	–	–	–	–	–
B (Intermetallic Phase)	PM-01	98	2.1	–	–	–	–	–	–	–
B	PM-06	99	0.84	–	–	–	–	–	–	–
B	PM-08	83	14	2.6	–	–	–	–	–	–

Phase	Sample	Cu	Sn	Pb	Zn	S	Fe	O	Cl	Sr
B	PM-09	92	5.7	2.0	–	–	–	–	–	–
B	PM-09	76	16	3.0	–	–	3.3	1.1	–	–
B	PM-10	93	6.9	–	–	–	–	–	–	–
B	PM-11	82	18	–	–	–	–	–	–	–
B	PM-11	84	16	–	–	–	–	–	–	–
B	PM-12	84	15.6	–	–	–	–	–	–	–
B	PM-12	81	19	–	–	–	–	–	–	–
C (Bright Globule)	PM-01	88	1.5	10	–	–	–	–	–	–
C	PM-02	80	1.6	19	–	–	–	–	–	–
C	PM-02	15	0.29	73	–	–	–	11	–	–
C	PM-04	89	1.9	9.3	–	–	–	0.01	–	–
C	PM-04	54	1.3	45	–	–	–	–	–	–
C	PM-06	56	1.9	40	–	–	–	–	1.9	–
C	PM-06	91	3.4	4.3	–	–	–	–	1.7	–
C	PM-07	64	1.9	34	–	–	–	–	–	–
C	PM-07	19	0.36	51	–	–	–	15	–	15

Phase	Sample	Cu	Sn	Pb	Zn	S	Fe	O	Cl	Sr
C	PM-08	54	4.9	41	–	–	–	–	–	–
C	PM-09	49	1.3	49	–	–	–	–	–	–
C	PM-10	81	11	7.4	–	–	–	–	–	–
C	PM-13	71	–	17	11	–	–	1.2	–	–
C	PM-13	5.4	–	95	–	–	–	–	–	–
C	PM-13	26	–	68	5.2	–	–	–	–	–
D (Dark-Grey Phase)	PM-01	98	1.8	–	–	0.51	–	–	–	–
D	PM-02	86	0.79	–	–	11	2.3	–	–	–
D	PM-04	92	–	–	–	6.2	–	0.72	0.64	–
D	PM-05	90	4.4	–	–	5.6	–	–	–	–
D	PM-05	89	4.3	–	–	5.6	1.1	0.27	–	–
D	PM-06	94	3.5	–	–	1.8	–	0.09	0.7	–

Phase	Sample	Cu	Sn	Pb	Zn	S	Fe	O	Cl	Sr
D	PM-07	88	0.58	–	–	10	–	–	0.66	–
D	PM-08	88	11	–	–	1.3	–	–	–	–
D	PM-09	79	15	–	–	3.2	–	–	2.6	–
D	PM-10	93	6.3	–	–	0.84	–	–	–	–
D	PM-11	87	1.5	–	–	12	–	–	–	–
D	PM-12	87	0.37	–	–	13	–	–	–	–
D	PM-13	19	–	–	62	19	–	–	–	–

– = not detected
 Values expressed in wt.%

Microstructural Characteristics

Metallographic observations reveal structural features indicative of both casting and mechanical working processes. The arrowheads show dendritic microstructures typical of cast metal objects, confirming production through mould casting techniques. In several specimens, partial homogenization of dendritic segregation suggests that post-casting heat treatment was applied to reduce internal stresses and improve mechanical performance.

By contrast, the pins, bracelet fragments, and rod display elongated grain structures and deformation bands, which indicate extensive cold-working. Evidence of recrystallized grains further suggests that deformation was periodically followed by annealing processes. These alternating cycles of mechanical deformation and thermal treatment demonstrate deliberate control over the physical properties of the metal.

Dark-grey inclusions (Phase D) are mainly composed of copper sulphides and occasionally contain iron together with alloying elements such as tin or zinc. Similar inclusions have been frequently reported in archaeological copper-based artefacts from the Iranian Plateau (Oudbashi et al., 2017; Oudbashi et al., 2016; Oudbashi & Davami, 2014; Oudbashi & Hasanpour, 2018). In some cases, copper oxide inclusions may also occur within comparable

metallurgical contexts (Oudbashi et al., 2021; Oudbashi et al., 2020). Their presence is generally associated with ore composition and smelting conditions rather than intentional technological modification.

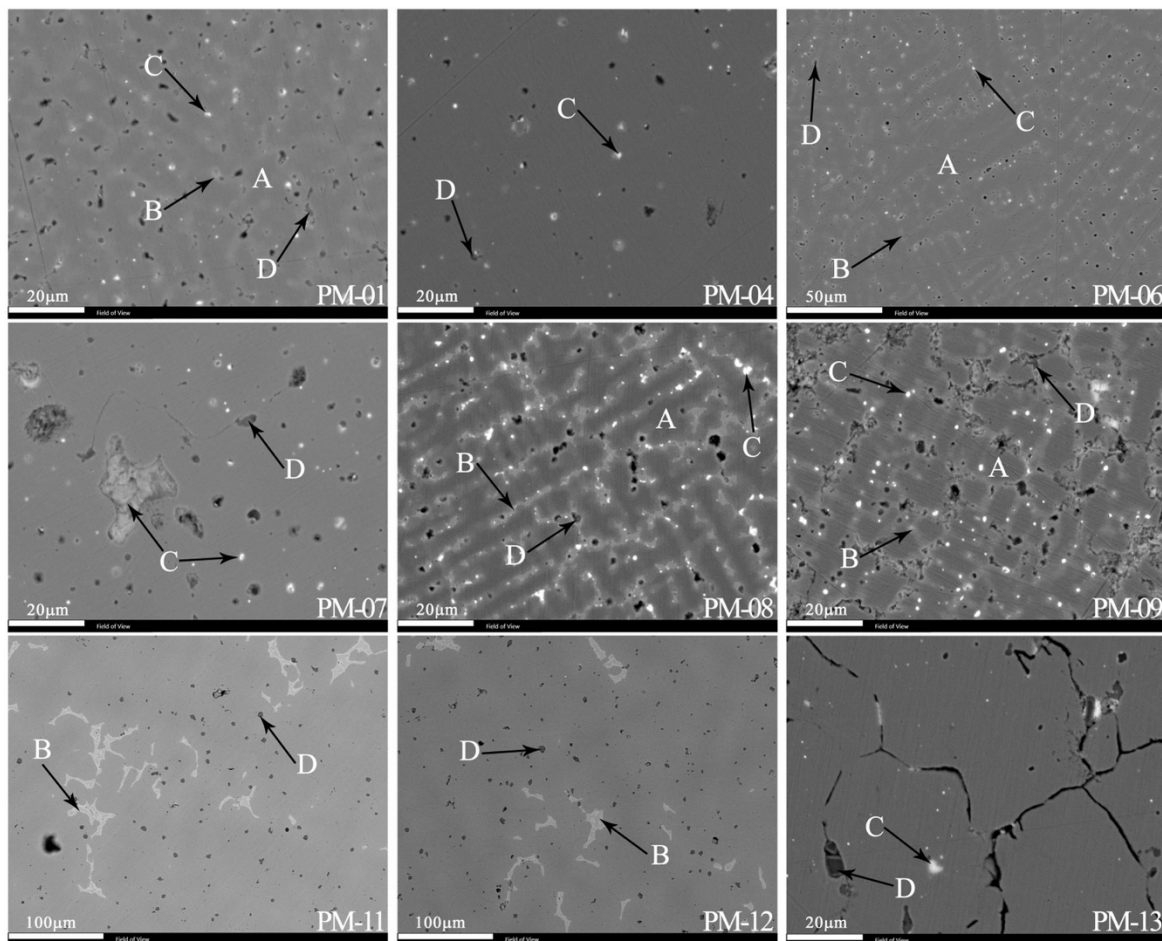


Figure 2. SEM-BSE cross-section micrographs of nine representative samples from Persepolis, showing segregated (cored) microstructures (A), segregated tin-rich phases (B), small bright globules (C), and dark-grey inclusions (D). Note the apparent intergranular corrosion in PM-13 (the brass).

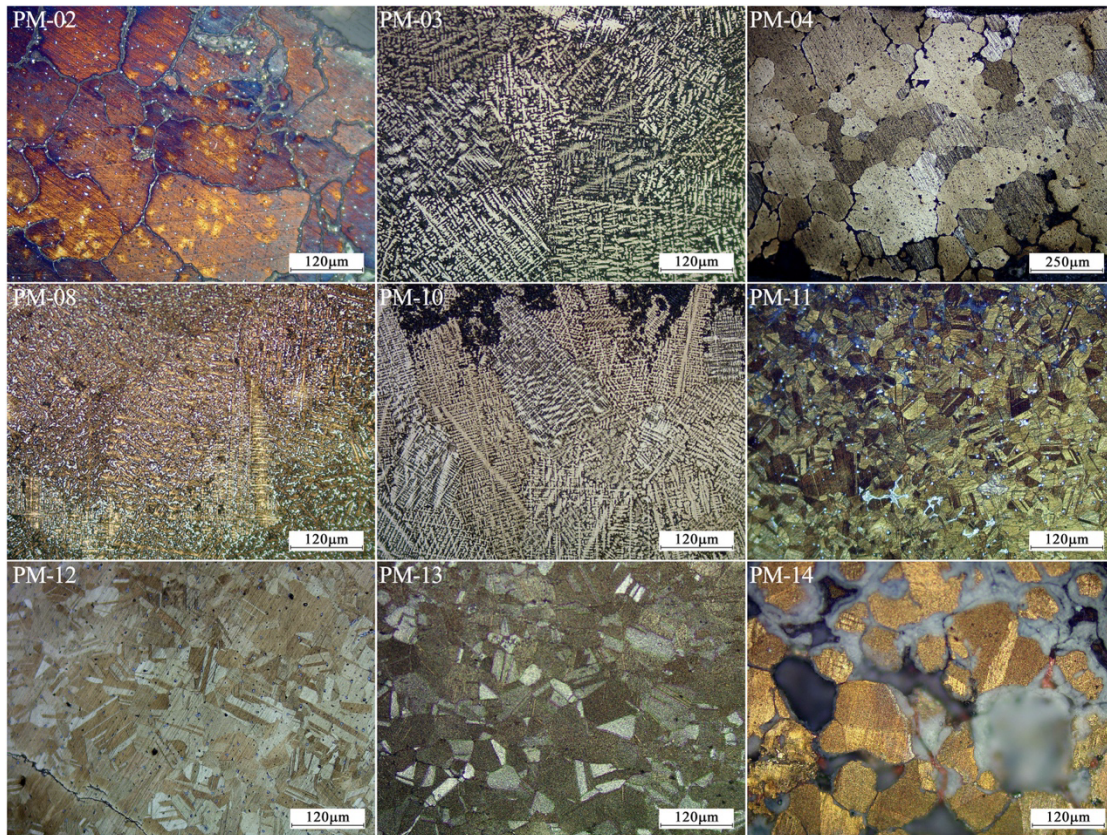


Figure 3. Etched microstructures of nine representative samples from Persepolis showing three different microstructures including: cored dendritic microstructures in arrowheads (samples PM-03, PM-08 and PM-10); equiaxed single-phase microstructures in arrowheads (samples PM-02 and PM-04); and cold-worked and annealed microstructures with small equiaxed grains and annealing twins (samples PM-11, PM-12, PM-13 and PM-14).

Manufacturing Techniques

The analytical results allow reconstruction of several manufacturing procedures employed in the production of these artefacts. Arrowheads were primarily produced through casting, a method suitable for standardized weapon manufacture. The use of leaded tin bronze would have facilitated efficient casting while maintaining adequate mechanical strength. In contrast, the bracelet fragments, pins, and rod appear to have been shaped through secondary mechanical working. Metal pieces were repeatedly hammered to achieve the desired form and thickness, followed by annealing stages that restored ductility and prevented cracking. This sequence reflects an advanced understanding of copper alloy behaviour during shaping processes.

The identification of brass in the bracelet fragment further indicates technological diversity in alloy selection. The deliberate use of zinc-containing alloys may have been motivated by aesthetic considerations, such as colour variation, or by functional requirements.

Technological Implications

Overall, the results demonstrate that copper-base metallurgy at Persepolis involved a combination of standardized production and adaptable technological strategies. Casting techniques dominated the manufacture of weaponry, whereas cold-working and annealing were applied primarily to personal or utilitarian objects. The coexistence of tin bronze, leaded bronze, and brass alloys suggests a sophisticated awareness of material properties and production requirements among Achaemenid metalworkers. These findings indicate that copper metallurgy during the Achaemenid period remained technologically active and innovative, complementing the more extensively studied traditions of precious metal craftsmanship.

Discussion

The results derived from the multi-analytical examination indicate that the arrowheads were predominantly produced through casting technologies. Among the analysed objects, three specimens correspond to tin bronze alloys, whereas seven were identified as leaded tin bronze. Metallographic evidence further reveals technological diversity: six arrowheads retained their original as-cast structure, while four experienced subsequent annealing treatment. The two pins and the rod were likewise manufactured from tin bronze, whereas the bracelet represents an exceptional case, being produced from a brass alloy.

A bivariate diagram illustrating the relationship between tin and lead concentrations is presented in Figure 4a. The compositional distribution allows the identification of three principal alloy groups distinguished by variations in tin content: (1) seven arrowheads composed of Cu–Sn–Pb (leaded tin bronze); (2) three arrowheads together with two pins and one rod made from Cu–Sn (tin bronze); and (3) a single bracelet produced from a Cu–Zn (brass) alloy.

Tin-bronze artefacts displaying varying tin concentrations were already widely produced across the Iranian Plateau prior to the Achaemenid period, particularly during the Bronze and Iron Ages (Oudbashi & Hessari, 2017; Oudbashi et al., 2016; Oudbashi & Davami, 2014; Oudbashi & Hasanpour, 2018; Oudbashi et al., 2021; Oudbashi et al., 2020; Fleming et al., 2006; Fleming et al., 2005). In contrast, leaded tin bronze appears comparatively rare in pre-Persian assemblages such as those from Luristan (Oudbashi et al., 2021; Oudbashi, 2019). The addition of lead was most probably intended to enhance alloy fluidity during casting operations, thereby improving mould filling and casting efficiency (Craddock, 1976, 1977; Srinivasan, 1998; Scott, 2002). From this perspective, Achaemenid metallurgical practices may be interpreted as a technological continuation of Iron Age bronze-working traditions. The recognition of the technological advantages of lead remains uncertain, although knowledge transfer within the multicultural structure of the Achaemenid Empire is a plausible explanation (Muscarella, 1988). Metalworkers were also familiar with lead metallurgy in architectural contexts, where lead served as a sealing material between stone blocks and iron clamps (Tilia, 1968). Nevertheless, the absence of lead in several arrowheads as well as in the pins and rod demonstrates that lead addition was selective rather than standardized.

The brass bracelet represents an anomalous element within the Persepolis assemblage. Archaeological evidence for copper–zinc alloys in Iran prior to the Achaemenid period is limited, although isolated examples have been reported from sites such as Tepe Yahya and War Kabud (Thornton, 2007; Thornton & Ehlers, 2003; Thornton et al., 2002; Rajabian et al., 2022). These early occurrences are generally interpreted as accidental products resulting from the smelting of zinc-bearing copper ores rather than intentional alloy design. This interpretation is supported by broader studies indicating that brass alloys did not become widespread across the Iranian Plateau until the Islamic period (Craddock, 1979; La Niece et al., 2012).

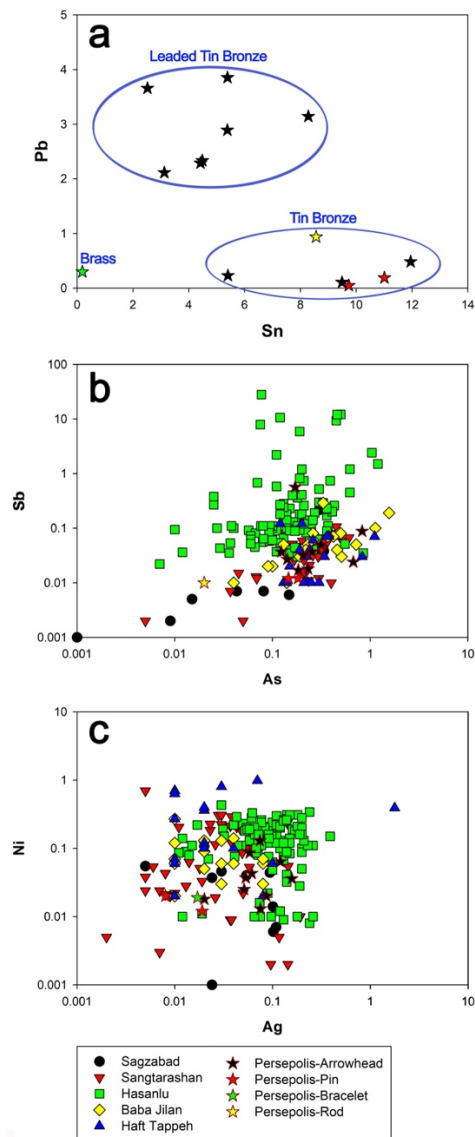


Figure 4. a) Scatter plot of Cu versus Sn, in wt.%, for the fourteen analysed artefacts from Persepolis; b, c) Two bivariate scatter plots of minor/trace elements in the compositions of Persepolitan copper-base artefacts and artefacts from some other sites dated to the second and first millennia BCE.

Figures 4b and 4c present additional bivariate scatter plots comparing minor and trace elements specifically As versus Sb and Ag versus Ni between the Persepolis artefacts and copper-based materials from other Iron Age sites on the Iranian Plateau (Oudbashi et al., 2021; Oudbashi & Hasanpour, 2018; Oudbashi et al., 2021; Fleming et al., 2011; Oudbashi & Mishmastnehi, 2020). These elemental relationships are significant because arsenic–antimony and silver–nickel ratios are commonly associated with ore provenance, while arsenic and antimony contents also reflect technological parameters of metallurgical production (Pernicka, 2014; Radivojević et al., 2019; Mehofer & Gavranović, 2021; Radivojević et al., 2010; Berger et al., 2022). The distribution observed in Figure 4b suggests partial

compositional similarities between the Persepolis artefacts and materials originating from western and southwestern Iran, including Sangtarashan, Baba Jillan, and Haft Tappeh, whereas artefacts from northern and northwestern regions such as Sagzabad and Hasanlu demonstrate weaker correspondence. Figure 4c, which considers the complete dataset, shows only limited overall correlation. Two artefacts the bracelet (PM-13) and the rod (PM-14) appear as compositional outliers and were therefore excluded from certain elemental comparisons. More definitive conclusions regarding metal provenance would likely require isotopic analysis.

Technological reconstruction based on metallographic observations indicates multiple manufacturing pathways for Persepolitan copper-based artefacts. Arrowheads were produced either by casting alone or by casting followed by annealing, whereas the pins, bracelet, and rod underwent repeated cycles of cold working and annealing. The coexistence of as-cast and annealed arrowheads, together with the selective presence of lead in several specimens, may indicate production in different workshops distributed across the Achaemenid Empire or possibly within subordinate regions. However, the available dataset remains insufficient to confirm this hypothesis. Similar uncertainty concerns the purpose of annealing certain arrowheads. Since arrowheads were likely mass-produced and relatively inexpensive, additional heat treatment would have increased production costs even when performed in batches. Moreover, the functional advantages of annealing remain unclear, aside from metallurgical effects such as reduced hardness and increased ductility. Finally, variations observed among the analysed artefacts including differences in grain size, dendritic morphology, and degrees of retained coring most plausibly reflect the empirical and experience-based character of ancient metallurgical practice rather than standardized technological regulation.

Conclusions

The multi-analytical investigation conducted on fourteen copper-based artefacts originating from early excavations at the Persepolis World Heritage Site demonstrates the extensive use of tin bronze and leaded tin bronze alloys in the manufacture of several artefact categories, including trilobate arrowheads, pins, and a rod. In contrast, the thin metallic strips likely fragments of a bracelet were produced from a brass alloy, which was probably formed unintentionally through the smelting of zinc-bearing ores rather than deliberate alloying practices. These findings indicate that Achaemenid metalworkers possessed well-established knowledge of tin bronze technology, situating their metallurgical traditions within the broader developmental trajectory of Iron Age bronze production on the Iranian Plateau. At the same time, the systematic use of leaded tin bronze with relatively consistent lead concentrations for casting objects such as arrowheads represents a technological feature not previously documented for earlier Iron Age contexts. Microstructural examination further reveals that the arrowheads were manufactured either by casting alone or by casting followed by annealing, although the specific motivations for applying additional heat treatment remain uncertain. In contrast, the pins, bracelet, and rod exhibit evidence of repeated cycles of cold working combined with annealing, suggesting different production sequences depending on artefact function and form.

A principal contribution of this study lies in clarifying previously unknown aspects of Achaemenid copper-based metallurgy and in reconstructing technological practices associated with tin bronze production during this period, particularly in relation to weapon manufacture. Variations observed in chemical composition and microstructural characteristics among the arrowheads imply production by multiple metalworkers employing slightly different techniques and possibly utilizing metals derived from diverse sources. This interpretation highlights the need for continued research focused on provenance studies, workshop organization, and raw material procurement strategies, ideally incorporating isotopic analyses to refine correlations. Finally, the study underscores the necessity of expanding research on the occurrence and technological role of brass alloys during the pre-Islamic period on the Iranian Plateau,

as currently available archaeological and analytical data remain limited and insufficient for broader historical interpretation.

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