Journal of Archaeological Studies
No. 2, Vol. 14, Serial No. 30 / Summer 2022
Formerly "the Journal of the Faculty of Literature and Humanities"...
University of Tehran

Re-tracing Copper Metallurgy in the Shahdad Region (3rd Millennium BCE)

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(1-17)

Received: 30, June, 2022; Accepted: 21, September, 2022

10.22059/jarcs.2022.345208.143139
Print ISSN: 2676-4288- Online ISSN: 2251-9297
https://jarcs.ut.ac.ir

Abstract
Shahdad is located on the western side of the Lut desert in the central Iranian Plateau. Shahdad has been a major focus of archaeological and archaeometallurgical research in the region due to extensive metallurgical activities documented at the site during the Bronze Age and for having the most abundant remains of copper metallurgy in southeastern Iran. The metallurgical developments at Shahdad have been well documented due to the previous studies by researchers working on the vast peripherial area of Shahdad dating to the period when the settlement was a permanently occupied city during the 3rd millennium BCE. Our latest surveys at the site have identified copper extraction metallurgy across a very large area based on significant amounts of ancient metallurgical remains on the surface including copper ores, moulds, crucibles, furnaces and complete metal tools. Pottery and slag have been observed macroscopically and microscopically in order to find particular traces of the metallurgical processes used during the EBA of Shahdad. Preliminary observations supply a new synopsis by re-tracing the ancient metallurgy at Shahdad. This research has revealed that the metal-workers of Shahdad mainly used copper sulphide (covellite) as their primary Cu-bearing ores. Three different slag types were identified according to their color, external texture and fabrication. Pottery samples were associated with copper metallurgy based on their phase characterizations, which were interpreted as the artefact of a distinct step in the metallurgical production process. This pottery is very porous and rough-textured due to the particular additives, leading to the formation of copper carbonate and copper oxide enrichments in the voids of the ceramic fabric.

Keywords: Shahdad, Archaeometallurgy, Copper Smelting, Early Bronze Age, Craft Specialization.

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Introduction

Copper extraction and copper alloying production have been at the center of archaeological and science-based research approaches for well over a century (Wertime, 1964; Muhly, 1985; Xie, P., Rehren, Th., 2009). Once archaeometallurgical studies turn to the question of the origin of alloying, the Iranian Plateau becomes an important area for examining this and related innovations (Pigott, 1999, 2004). Copper metallurgy developed on the southeastern Iranian Plateau and the neighboring Makran region during the seventh millennium BCE, less than a millennium after the earliest documented use of metal in the form of native copper at Çayönü Tepesi in Anatolia (Muhly, 1989; Maddin et al., 1998; Dardeniz and Yildirim, 2022; Chernykh, E., 1997; 2009).

On the 4th of December 1964, 58 years ago, the journal "Science" published a report about archaeometallurgical activities over an area extending from western and central Anatolia across the Taurus and Zagros mountains to the edge of the central desert of Iran by Theodore A. Wertime (Wertime, 1964). In his manuscript, "Man's first Encounters with Metallurgy", Wertime proposed that the early metalworkers had the distinctive know-how of working with ores bearing copper and other metals in the Iranian and Anatolian culture-areas (Wertime, 1964). Further research has shown that the extraction, refining, and trade of metals developed over the course of several millennia on the Iranian Plateau, in concert with regional-scale developments extending all the way to Mesopotamia (Ottaway, 2001; Pigott, 2004; Weeks, 2016).

The development of pyro-technology and metallurgy on the Iranian Plateau began with the use of native copper in the 7th mill. BCE (Wertime, 1964; Muhly, 1985). The first evidence for smelting copper ores is found at many locations dating from the late 6th mill. BCE onwards, with the first reduction of copper oxides (cuprite) and carbonates (malachite), attested during the Neolithic period (8th/7th mill. BCE). Copper from sulphitic copper ores was already being produced as early as the 6th to 4th mill. BCE (Emami and Shahsavari, 2020). The next step in technological development occurred during the Chalcolithic period, which consisted of the use of elements such Pb (lead), As (arsenic), Sn (tin), Sb (antimony), and Zn (zinc), for creating various alloys. The ore type processed during this stage is related to the size, number and type of the objects produced. This period is characterized by the use of arsenical copper and the rise of early bronze. Antimony-rich copper ores from the Chah-Messi and Toroud areas in the northern part of the central Iranian desert, employed for creating bronze objects, lead to the accidental production of Cu-Sb alloys in some parts of the Iranian plateau (Emami 2014). The metal objects and ingots from Haft Tappeh provide an important insight into the tin-bronze technology present in southwestern Iran Plateau during the Bronze Age (Rafiei-Alavi et al., 2022).

Shahdad is one of the most important cities located on the southeastern Iranian plateau, and is definitely one of the key localities based on the metallurgical activities there. Despite the cutting edge status of copper production at Shahdad, and research into the site's metallurgical industries, it is still a matter of debate from where and how the copper ores used at the site were extracted. These include the role of metal-producing communities within a larger economic setting (Meier and Vidale, 2013). Consequently, the development of metallurgy was essentially the most crucial step in the evolution of material culture during the EBA, since it represented the processing of a new class of high temperature materials, namely metals. During the Neolithic, it seems that the use of metals was largely based on selective collecting of colourful and altered ores found in the search for decorative materials. Decorative objects made of metals were first formed by cold-working native metals (e.g., copper), followed by forming them through warm-working, followed by development of true pyrotechnology. Pyrotechnological processes (e.g., metallurgy, pottery, and glass-making) required more exact information about raw materials, their behaviour at high temperatures, and their sustainability under extreme temperature conditions. It is worth mentioning that four crucial metallurgical sites in periphery of the Iranian Plateau with evidence for the smelting of copper at this early stage include the Chalcolithic site of Tal-e Iblis (Caldwell, 1967; Frame, 2004), Tappeh Qabrestan (Majidzadeh, 1979), Shahdad (Hakemi, 1992) and Tappeh Hissar (Thornton, 2009). During the Chalcolithic, the melting of copper was often performed using a variety of different types of crucibles. Such crucibles were used for the melting of copper and the smelting of copper oxides and carbonates (Rostoker et al., 1989; Hauptmann et al., 2003). In ancient copper smelting furnaces, the temperature roughly reached 1200° C and even higher (Hauptmann et al., 2003; Rehren et al., 2012). More recently, the recycling of metals and metallurgical remains has received much attention and has been the focus of scholarly debates. In addition to the metallurgical processes themselves, scholars have focused on metallurgical-related materials and objects such as specialized ceramics, crucibles, and tuyères, which were already used as relatively heat-resistant materials, each of which has a huge impact on our understanding of the evolution of pyrotechnology (Hein et al., 2013).

Metallurgical advancement on the southeastern Iranian Plateau has been considered by means of the pioneering production and use of arsenic-copper (arsenic Bronze), which has been advanced in Mesopotamia once the new alloy of Tin Bronze was commercialized in the socio-economic situation of the region (Lamberg-Karlovsky, 1967; Thornton, 2014; Weeks, 2013). Since then, archaeometallurgical studies focusing on the use of metals and alloys in southern and southeastern Iran became the focus of many studies (Maddin et al., 1977; Thornton, 2010; Wayman and Duke, 1999). Due to the wide scatter of cultural materials over a broad region, Shahdad might be considered a true centre of metal production and metallurgical ceramics. Accordingly, the area might prove to have been a commercial centre for the trade and exchange of metallurgical raw materials and goods to neighbouring areas. Our recent survey presents several new ideas based on previous (sometimes conflicting) archaeological reports on this topic and attempts to introduce insights which can settle a major debate on the nature of copper production at Shahdad.

Archaeological Highlights of the Region

The western edge of the Dasht-e Lut desert—where Shahdad is located—is situated between the eastern flanks of the heavily folded Kerman Mountain Range and the Lut desert (Fig 1). This is one of the key regions of the Iranian Plateau for studying the pathways and trajectories of early urbanization (Eskandari 2019, Eskandari et al. 2021). Previous excavations at the Bronze Age site of Shahdad in the Dasht-e Lut, with its burials containing rich and sophisticated artifacts, fully justified its definition as an advanced early urban center (Hakemi 1997, Salvatori and Tosi 1997, Hiebert and Lamberg-Karlovsky 1992). Moreover, southeastern Iran in general is known to have many ancient sites associated with early metallurgical activities, most notably Tal-i Iblis. Analysis of the data of Tal-i Iblis has confirmed the presence of copper smelting at Tal-i Iblis from at least the early fifth millennium BCE, if not earlier (Caldwell 1967, Frame 2004).

Recent investigations by one of the present authors (N.E.) at Tal-i Iblis have confirmed this early date for this innovation. Hakemi's excavations (1997) at the site of Shahdad led to discovery of more than 700 metal objects made of bronze, lead, silver and gold. 670 of them are bronze objects, including 350 vessels, 239 pins and 81 other objects, such as axes, stamp seals, rings, bracelets, instruments, plates, flag and weapons. In addition, his excavations at Workshop D in the artisan's quarter of Shahdad led to the discovery of a great complex of Bronze Age copper smelting installations. Most of the metal artifacts found at Shahdad were composed of arsenical copper and only a few have proportions of tin in their composition (Meier 2011). Found in situ in Workshop D were furnaces, crucibles, moulds and metal objects, proving that metal production occurred at the site. In this paper, we aim to highlight some of the key aspects of the ancient metallurgy documented at Shahdad and their implications for our understanding of the archaeometallurgy of southwestern Asia as a whole.

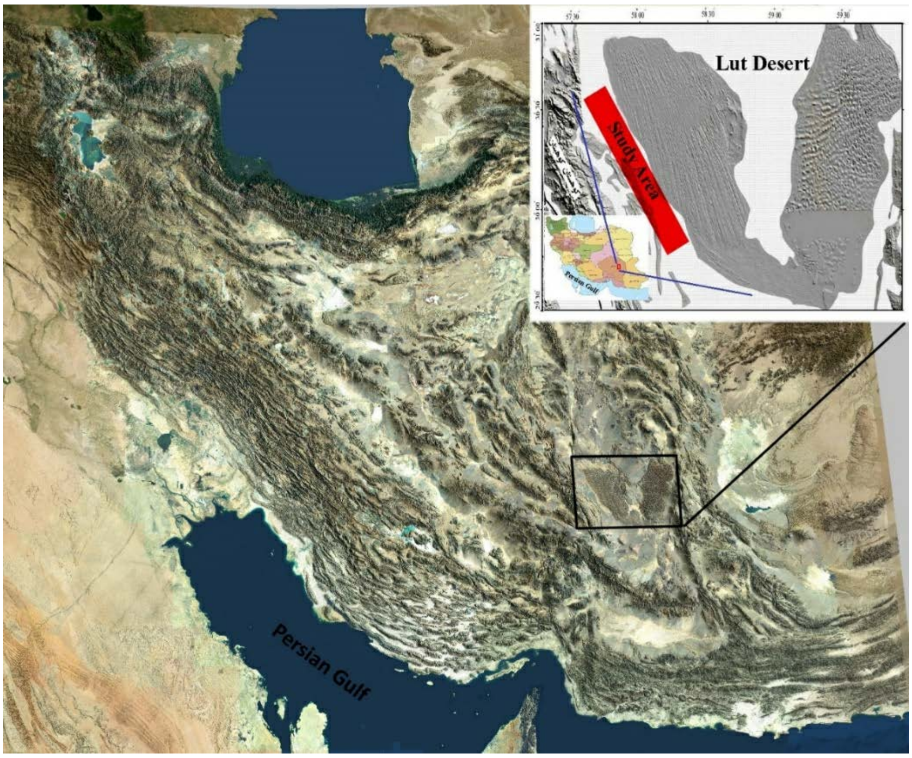

Fig 1: Map showing the study area to the west of the Lut Desert

Shahdad

The history of archaeological activities at the site of Shahdad dates back half a century. Thirteen seasons of archaeological excavations and surveys at the site have conclusively shown that it was an important urban center on the Iranian plateau during the Bronze Age. Excavations led by Ali Hakemi of the Archaeological Service of Iran began in 1969 and continued until 1978 (Hakemi 1997). Hakemi's excavations led to the discovery of many graves, altogether containing several thousand spectacular grave goods (Hakemi 1997), including impressive human statuettes, numerous stone and ceramic containers, as well as ornamental finds. As a result of the excavations, a total of 383 graves were uncovered. In the 90s, excavations at Shahdad were resumed under the direction of M. A. Kaboli (1997, 2001, 2002) for four seasons. Kaboli concentrated excavation in well preserved residential areas of the site. His important work in the northern extension of the 3rd millennium BCE settlement uncovered two architectural complexes. These two residential compounds noticeably increased our understanding of the urban fabric of Shahdad, previously only known through its graves and workshops. The finds in these newly exposed areas demonstrated the intensive involvement of Shahdad in the processing and trade of valuable raw materials.

During recent fieldwork at Shahdad (2016), one of the present authors aimed to determine the extent of the metalworking area of the site. The materials related to metalworking activities such as bits of slag are scattered across the north-eastern quadrant of the site, with an extension over more than 10 hectares (Fig 2). Workshop D, which was already excavated by H. Hakemi and Bayani (1997), is located in this area, where they found an architectural complex with five small and rather modest houses, built using pisé and a single-line of mud bricks, that appears to have been suddenly knocked down by a disastrous flood that sealed the rooms' contents (Vidale 2006-2008, Eskandari et al. 2021). Although Hakemi (1992, 1997) insisted on considering the elaborate ovens found in each house as copper-processing furnaces, they are more likely domestic fireplaces (Meier 2011; Meier 2017). Reanalysis of the distribution of the artefacts found in these excavations suggests that—notwithstanding the undeniable presence of crucibles, casting moulds, pits lined with copper slag and other less identifiable copper-smelting and/or melting indicators—the most evident activity performed in many of these rooms at the precise moment of the flood was the breaking and grinding of large amounts of copper ore on large granite slabs using pestles (Eskandari et al. 2021).

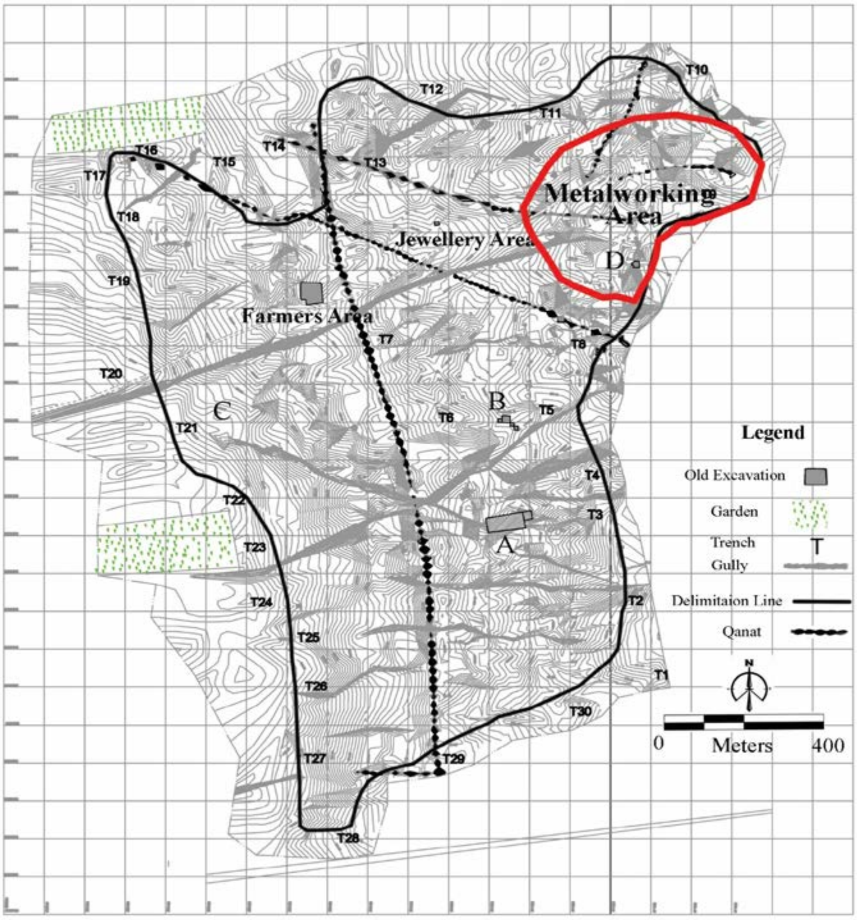

Fig 2. Topographic map of Shahdad showing the metalworking area of the site.

Materials and Methods

The distribution of ceramics and slag extents over the entire area and there is no sign of separation among the localities of enrichment (Fig. 3). Slag and ceramics under analysis here were collected from surface surveys of the area (Figs. 4 & 5). The ceramic and slag specimens were first inspected macroscopically and then examined from a mineralogical point of view. The slag pieces from Shahdad are characterized by their small size overall, ranging only from 2-4 cm. They are mostly black in colour. Numerous specific textures still remain on the surface of the slags, including from copper smelting residues such as colour-mélange structure (green-dotted copper accumulations as well as reddish bands formed due to the oxidation of iron near the surface). The shapes and external traits of the slag identify these specimens as belonging to the categories of flow-slag, herd-slag and Calotte, providing information about their process of generation (Bachmann, 1982). Unfortunately, slag has different forms and traits, even resulting from similar smelting process, or alternatively, can show similar forms from diverse smelting processes (de Rijk, 2003). Further analysis is therefore needed to reconstruct the processes used at Shahdad.

In the first stage of the research, some of samples were only analysed with optical and reflected light microscopy. Observations were carried out on the cross-section of slag and ceramics by using Zeiss Primo Star Microscope (Zeiss). The

Primo Star Microscope is well-suited for reflected light imaging and mineralogical studies on archaeological materials. The images were then studied with the Zeiss Calypso software package.

Fig 3. Shahdad; the view from the western part and the scatter of ceramics and slag on the surface.

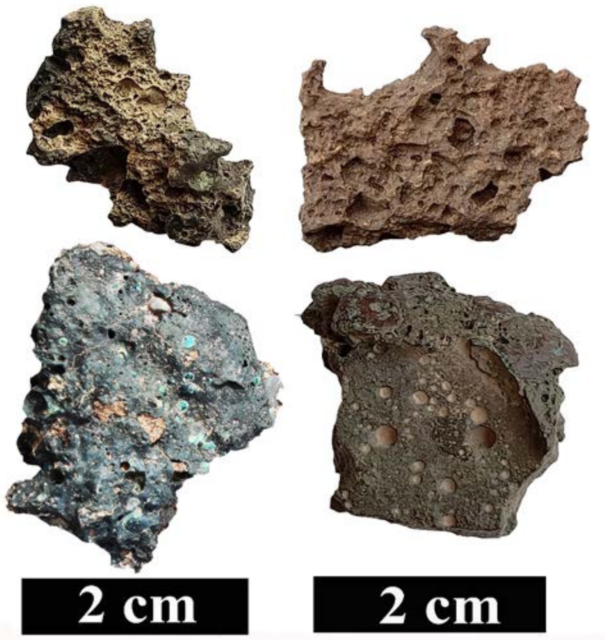

Fig 4. Diverse slag types with copper residues on the surface. They are classified as based slag and smelting slag due to their bubbly surface character.

The ceramics from Shahdad are very unique in terms of their shape, form and surface characteristics. The typical Shahdad wares are the predominant pottery type on the explored surface of the area (Fig 5). These are very coarse grained, with many dark mineral additives, which were surprisingly recognized as pyroxene. The matrix and core of the ceramics are very clayey and reddish in colour. The additives appearing on the surface are very well processed and have roughly the same size. The surface of the ceramics seems to be made very primitively with no decoration and shows that the ceramics were mostly were baked with insufficient temperature, based on the bichromy observed in cross-section (Fig 5). These ceramics are normally very light, but surprisingly have dense fabric structures with less than expected porosity.

Fig 5. Shahdad predominant pottery type with bichoromy character in section and very coarse grain fabrication.

Results from Technological Metallurgical Remains

Based on the surface character of the observed slags—such as high porosity, flow structure, low weight and dark colour—some ought to be classified as progress slags, mostly smelting and roasting slags (Fig 4) (Hauptmann 2017; Hess et al., 1998). Flow-slag is the dominant form of slag in Shahdad, however. These pieces were formed during the pouring from the furnace after smelting and contain pores on their upper surfaces due to the loss of gases through rapid cooling (Liu et al., 2015). Flow-slags are compact in structure and are grey to metallic grey in colour. Slags which were cooled within the kiln, in contrast to the flow-slag, show no flow structure on the surface and contain many heavy metal inclusions that were absorbed throughout the smelting. These mainly contain residues of copper as tiny droplets on the surface (Keesmann et al., 1983a). Slag formed at lower temperatures displays more pores due to the fast evaporation of volatiles from the top surface of the melt during solidification. In this stage the slag doesn't have a high viscosity due to the high temperature (Bourgarit, 2019). The slag that formed at the bottom of furnace contained more metallic residues, according to the specific weights of the progressively heavier metallic constituents. Heavy metals dropped down by means of specific weight (McDonnell, 1991). Calotte-form slag appears regularly in ancient iron technology. Their oval-bottomed form is generated by the shape of the base of the furnace (Keesmann et al., 1983b).

The slag from Shahdad was classified by means of their glassy matrix and specific mineralogical characterization. The slag cross sections are illustrated in Fig 6. In addition to slag samples, two pieces of ore were studied to obtain information on the industrialized ore composition in Shahdad. All of the studied slags had high porosity with many accumulations of copper, containing phases within or surrounded by them. The greenish surface of Sample I is due to the presence of pyroxenes within the glassy part of the slag. Pyroxene is an interesting phase in archaeometallurgy, because the ratio of $FeO:SiO_2$ is 1:1. Pyroxene is frequently reported in archaeometallurgy and its formation is due to low-temperature reactions; its existence provides data on the viscosity of the samples and thus the ore which has been smelted (Hauptmann, 2007; Hauptmann et al., 1999). Samples II and III present a black matrix, resulting from the high temperature of melting and production of viscous glassy fraction (Bottaini et al., 2016). The surface structure of these slags reflects high oxidation processes, which appear as reddish and yellowish zones on the surface of the samples.

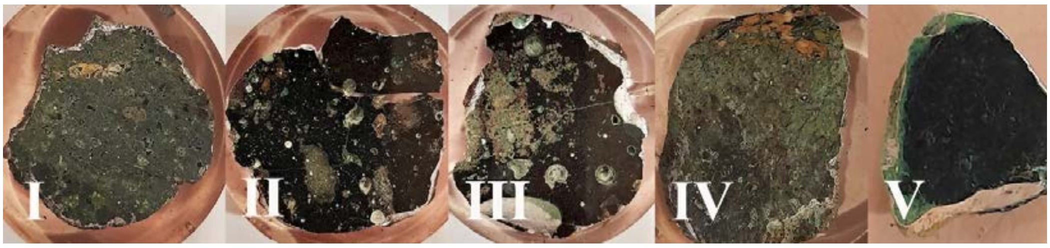

Fig 6. Studied samples by optical microscopy

For preliminary research on slag, we can consider their formation from three points of view (Emami, 2017);

- Glass forming minerals and their conditions, which provide information on the temperature and the raw material composition;
- Metals and metal droplets, which provide information on the composition of metals;
- Ore, which supplies information on the kind of ores which were smelted.

Archaeometallurgical remains usually provide evidence of metallurgical constructions and associated features such as furnaces, ceramic vases, tuyeres. They are assumed to be components of metallurgical “chaines operatoires” in a region (Thornton and Rehren, 2007). The slags studied here are mainly characterized as related to copper smelting. Copper slag mostly comprises various crystallised oxides (e.g., iron, manganese, etc.), olivines, and pyroxenes inserted in a more-or-less glassy matrix. The mineralogy of these slags is directly related to the initial charge and the working conditions predominant in the production process (Bourgarit, 2019).

It has long been assumed that the earliest types of copper ore (copper-bearing ores) that were smelted were oxides and carbonates, and that the application of sulphides was practiced later in time (Hauptmann et al., 1999; Kaniuth, 2007). As a matter of fact, the extraction of metals from sulphide bearing ores might be very complex in the past (Emami and Shahsavari, 2020). Additionally, it can be suggested that the detailed metallurgical process was influenced by the geological formations and types of ore outcrops naturally occurring in a given region. During the Chalcolithic of Iran, oxide extractive metallurgy was much easier than an industry based on sulphides. The most important copper sulphide in prehistory was chalcopyrite $CuFeS_2$. To extract copper from this structure, Fe and S should be separated, which was too complex for the earliest phases of copper-smelting. In this case, the great affinity of Fe to Si enables the separation of Cu, followed by the formation of pyroxene within the glassy matrix of slag (Figs 7). However, the great affinity of S for bonding to Cu has proven to support the separation of Cu from the slag by its high gravity as tiny droplets (Hezarkhani and Keesmann, 1996). Important phases in iron-rich silicate slags have been studied and introduced in the system of CaO–FeO–Al_2O_3–SiO_2. Based on this system, dioside and hedenbergite (i.e., clinopyroxenes) often occurred within the structure of slag samples (Keesmann 1989). Consequently, these examples have direct relevance speculation regarding the use of crucible-based sulphide for smelting processes. It is possible that the EBA metallurgical tradition was interested in surface-deposited carbonates and chlorides for co-smelting oxide/sulphide (even sulpho-arsenides) directly in the crucible. In the case of Shahdad, surprising evidence includes the existence of pyroxene as silica association to Cu-bearing ores and the sulphide droplets, which are both predominant as regards the efficiency of extraction (Fig. 8). The neo-formed copper-sulfide droplets in a composition near to chalcocite (Cu_2S) or covellite (CuS) can be removed from the silica melt due to their low melting points and viscosity, appearing within the glassy slag (Hauptmann et al., 2003; Emami 2018). The astonishing outcomes revealed that the predominant extractive ore in Shahdad was covellite (CuS) (Figs 9, 10). The only other example of extracted copper from covellite was found at Toroud in northern Iran (Emami, 2014). Covellite can be distinguished from chalcocite through its typical orange inner reflex colour in dark field microscopy (Emami, 2002).


Fig 7. Pyroxene in the slag as sign of extractive sulphide in the early stage of separation

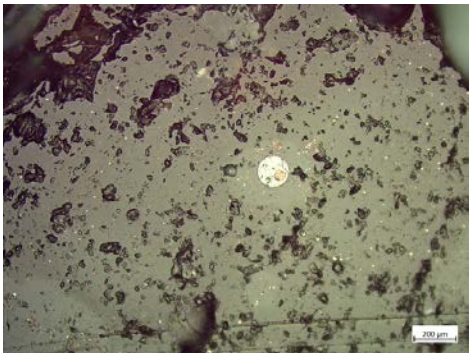
Fig 8. Copper droplet within the glassy slag. Copper enriched in the core and surrounded by sulphide.

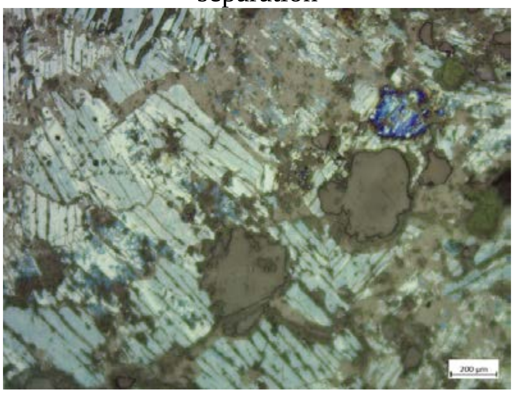
Fig 9. Covellite crystal under normal light

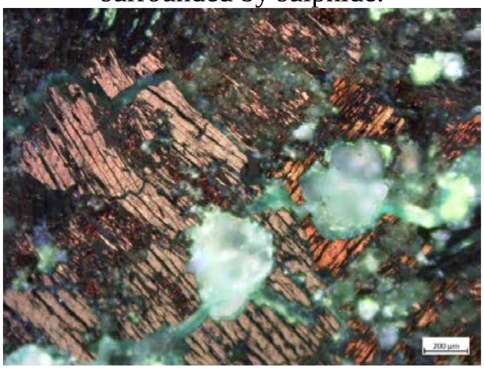
Fig 10. Covellite crystal under polarized light in dark field with oil condenser.

Pottery

The ceramics investigated at Shahdad have proven to be a very interesting aspect of metallurgy during the early Chalcolithic of Iran. In the first stage of study, we examined the ceramic matrix and temper. The matrix of pottery with dense fabrics and low porosity is similar to ceramics used for other purposes (Maggetti, 2001). The reddish colour of the matrix is caused by the high Fe content of clayey reservoirs, and/or the high temperature reaction and oxidation process of Fe embedded within the crystal structure of some clays, e.g., chlorite. This aspect will be studied in another complimentary framework in the future. The additives consist of quartz and high amounts of augite (based on the observation via geological loupe, as well as their birefringence color) that appear to have all been crushed fragments of igneous rock. According to the composition of the body, such pottery is suitable for bearing high temperatures, like other highly temperature-resistant clays used in crucibles (Rademakers and Farci, 2018).

With regard to their use-function, the cearmics from Shahdad evoked exactly the old question of “melting or smelting?” Smelting requires related devices or associated utensils, such as crucibles, which can come in the form of ceramic vessels (Craddock, 1999). It has often been difficult to discern the type of metallurgical actions that known crucibles were used for, however (Humphris et al., 2009). The ceramics used as crucibles indeed have the same characteristics as general clay-based pottery. Moreover, smelting a copper ore may affect the ceramic texture and alter the fabric through the melting process. Specifically, the cooling process may leave layered traces of copper within the inner surface of a ceramic (Fig 11). The first preliminary observation of ceramics in question should concern their design, shape and fabrication (Bayley and Rehren 2007). Secondarily, microscopic observation of the many diverse characteristics should target signatures of the metal charge within the fabric. This is difficult to discuss the multiple usages of crucibles, which may have been involved in the melting of different metals or metallic bearing rocks, due to the chemical heterogeneity of their composition. Thus, the interpretation of these suspected crucible fragments requires a strong elemental interpretation and discussion. Despite these limitations, a great deal can be learned from Shahdad by means of different designs in the side handle of the crucibles, which was routine as far east as Iran (Thornton 2009; Rehren et al., 2013).

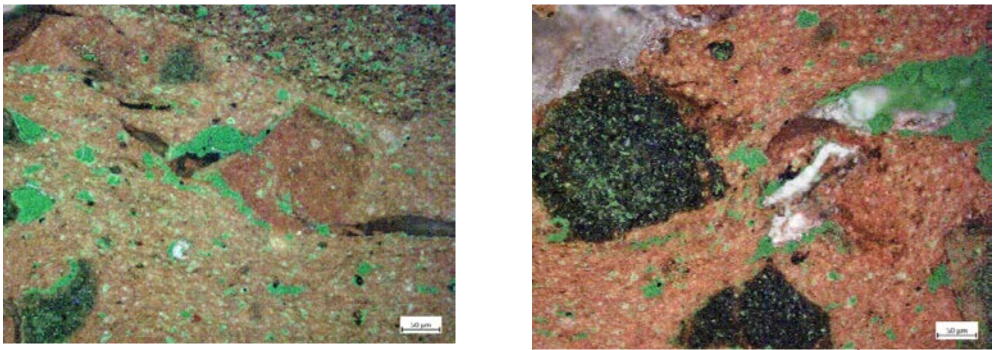

Fig 11. Shahdad coarse-grain pottery, identified as asmelting crucible of 3rd millennium BCE. Note the remains of copper carbonate and copper oxide within the ceramic fabric.

Conclusion

We have presented several slags and ceramics (crucible fragments) from Early Bronze Age contexts at Shahdad, southeastern Iran. The metal extraction process has traditionally provided the majority of the knowledge on metallurgic and pyro-technological processes on the southeastern Iranian Plateau during the Early Bronze Age. This study has revised some aspects concerning metallurgical processes performed at Shahdad and their subsequent impact on the mineralogical characterization of the remaining metallurgical objects, e.g., slag and technical ceramics. The artefacts have been investigated microscopically and mineralogically in order to identify traces that can help identify the raw ores used and their chemical compositions. Our results indicate that the presence of Cu, Sn, Fe, and S all correlate most closely to chalcosite and chalcopyrite bearing ore reservoirs, and furthermore, that these were not purely accidental choices. Additionally, the data suggests that ores belonging to the ophiolitic gangue reservoirs may possibly come from Makran orogeny.

Microscopic observation of the metallurgical remains from Shahdad has indicated that the copper ores used at the site consisted primarily of covelline bearing ores. On the basis of the information gathered in this study, three technical objectives should be highlighted for future study. How was copper production organized, and could there have been hierarchical structures in metallurgical operations occurring in the domestic periphery of Shahdad? What was the complete “chaine operatoire,” from ore processing to the final product? How were the observed technological features fitted to Shahdad socio-ecological conditions, and is it possible to reconstruct a technological lineage of any kind? As a matter of fact, the smelting strategy observed was implemented under controlled access, including the repertoires available at the time, the raw materials in use, and technological circumstances. Finally, the evident complexity of metallurgy at Shahdad—and the amount of the site’s area that remains to be explored through excavation—may eventually allow us to establish more precise knowledge of the timing of innovations and/or the adaptation of technological features which have been observed in the overburden of Shahdad and as yet have not been documented in situ.

Acknowledgments

We would like to thank Prof. M. Vidale for his helpful comments and Kyle Olson for light English-language proofreading; all remaining errors are our own.

References

Bachmann, H.-G., 1982, The identification of slags from archaeological sites, Institute of Archaeology.

Bayani M. E. (1979), *Primi risultati dello scavo nel quartiere artigiano di Shahdad (Kerman, Iran). Aspetti della produzione metallurgica alla fine del terzo millennio in Iran*. Unpublished M.A. Thesis, Università La Sapienza, Roma.

Bayley J and Rehren T., 2007, ‘Towards a functional and typological classification of crucibles’, in S La Niece, D Hook and P Craddock (eds), Metals and mines. Studies in archaeometallurgy (London), 46–55.

Bottaini, C., R. Vilaça, N. Schiavon, J. Mirão, A. Candeias, R. Bordalo, G. Paternoster, and I. Montero-Ruiz, 2016, New insights on Late Bronze Age Cu-metallurgy from

Coles de Samuel hoard (Central Portugal): A combined multi-analytical approach, *Journal of Archaeological Science: Reports*, 7, 344-357.

Bourgarit, D., 2019, Mineralogy of slags: A key approach for our understanding of ancient copper smelting processes, 203-232.

Caldwell, R. J, (ed.). 1967. *Investigations at Tal-i-Iblis* (Illinois State Museum Preliminary Reports 9). Springfield: Illinois State Museum Society.

Chernykh, E.N., 1992. Ancient metallurgy in the USSR: the early metal age, CUP Archive.

Chernykh, E., 2009. Ancient metallurgy in the Eurasian steppes and China: problems of interactions, See Mei & Rehren 2009, 3-8.

Craddock, P. T., 1999, Paradigms of metallurgical innovation in prehistoric Europe: in: The Beginnings of Metallurgy, p. 175-192.

Dardeniz, G., Yıldırım, T., 2022. Metal consumption of a middle-range society in the late 3rd millennium BC Anatolia: A new socioeconomic approach, PloS one 17, 1-38.

de Rijk, P., 2003, De scoriis. Eisenverhuttung und Eisenverarbeitung im nordwestlichen Elbe-Weser-Raum.

Emami, M., 2002, Mineralogische Untersuchungen zur Archaeometallurgie von Toroud, Iran, Deutschland-Mainz: Diplomarbeit, Fachbereich fuer Geowissenschaften der ….

Emami, M., 2014, "Toroud", the late motion for As-Sb bearing Cu prodution from 2nd millennium BC in Iran: An archaeometallurgical approach, *Mediterranean Archaeology and Archaeometry*, 14(2), 169-188.

Emami, M., 2017, A Review on Archaeometallurgy of Copper from Halil Region Based on Petrograpgical- Chemical Investigation on Ancient Copper Slags, *Parseh Journal of Archaeological Studies*, 1(1), 99-111.

Emami, S. M., and M. Shahsavari, 2020, Kahiro II: The Importance of Copper Oxide Extraction Technology in 4th Millennium BC in Halil River Basin, *Journal of Research on Archaeometry*, 6(2), 41-55. (in Persian)

Emami, M., 2018, Achaemenid Bronze! Quid Est? Archeometallurgical Investigations on Some Bronze Artefacts from Persepolis. Acta iranica 58, L'Orient est son Jardin, ed. S.G.H.H. (eds. Sebastien Gondet). 157–166.

Eskandari, N., 2019. Regional patterns of Early Bronze Age urbanization in the southeastern Iran. New discoveries on the western fringe of Dasht-e Lut. In J.-W. Meyer, E. Vila, M. Mashkour, M. Casanova and R. Vallet (eds.) *The Iranian Plateau during the Bronze Age. Development of Urbanisation, Production and Trade*. Maison de l'Orient et de la Méditerranée, Jean Pouilloux, Lyon, 201-216.

——————, 2021. Dig it up: A reconsideration of old excavations at the urban center of Shahdad. *Journal of Archaeological Studies*, Vol. 12, pp. 25-48.

Eskandari, N., K. Niknami, M. Viddale., 2021. The Bronze Age Center of Shahdad, South-East Iran: "Hollow" vs. Nucleated Early Urban Processes. *East and West*, 61, pp. 31-46.

Frame, Lesley, 2004. Investigations at Tal-I Iblis: Evidence for Copper Smelting during Chalcolithic Period, M.S Dissertation, Massachusetts Institute of Technology, (Unpublished).

Hakemi, A., 1992. The copper smelting furnaces of the Bronze Age in Shahdad. In Jarrige C. (ed.), South Asian Archaeology 1989. Papers from the Tenth International Conference of South Asia Archaeologists in Western Europe, Musée national des Arts asiatiques, Guimet, Paris, France, 3-7 July 1989. Monographs in World Archaeology no.14, Madison, Wisconsin, 119-132.

——————, 1997. Shahdad: archaeological excavations of a Bronze Age center in Iran. Istituto Italiano per il Medio ed Estremo Oriente, Centro scavi e ricerche archeologiche, Reports and Memoirs 27. Rome.

Hauptmann, A., 2007, The archaeometallurgy of copper: evidence from Faynan, Jordan, Springer Science & Business Media.

Hauptmann, A., F. Begemann, and S. Schmitt-Strecker, 1999, Copper objects from Arad: their composition and provenance, *Bulletin of the American Schools of Oriental Research*, 314(1), 1-17.

Hauptmann, A., T. Rehren, and S. Schmitt-Strecker, 2003, Early Bronze Age copper metallurgy at Shahr-i Sokhta (Iran) reconsidered: Der Anschnitt, Beiheft 16, Deutsches Bergbau-Museum.

Hezarkhani, Z., and I. Keesmann, 1996, Archäometallurgische Untersuchungen im Gebiet von Saghand-Posht-e-Badam (Zentraliran). Metalla (Forschungsberichte des Deutschen Bergbau-Museums, Bochum) 3.2 (1996), 101-125, Metalla.

Hein, A., I. Karatasios, N. S. Müller, and V. Kilikoglou, 2013, Heat transfer properties of pyrotechnical ceramics used in ancient metallurgy. Thermochimica Acta, 573: p. 87-94.

Hess, K., A. Hauptmann, H. Wright, and R. Whallon, 1998, Evidence of fourth millennium BC silver production at Fatmalı-Kalecik, East Anatolia. Metallurgica antiqua: In honour of Hans-Gert Bachmann and Robert Maddinin in Th. Rehren, A. Hauptmann, D. J. Muhly (eds) Metallurgica Antiqua, Der Anschnitt Beiheft 8, p. 57-68.

Hiebert, F. T., and C. C. Lamberg-Karlovsky., 1992. Central Asia and the Indo-Iranian Borderlands. *Iran* 30, pp 1-15.

Humphris, J., M. Martinon-Torres, T. Rehren, and A. Reid, 2009, Variability in single smelting episodes–a pilot study using iron slag from Uganda, *Journal of Archaeological Science*, 36(2), 359-369.

Kaboli, M.A. 1997. The Report of the tenth season of excavation at the ancient Shahdad, *Gozaresh-ha-ye Bastan Shenasi*, Tehran: 87–124 (In Persian).

Kaboli, M.A. 2001. The Report of the twelfth season of excavation at the ancient Shahdad, *Pajoheshnameh*, Tehran: 239–266 (In Persian).

Kaboli, M.A. 2002. The Report of the eleventh season of excavation at the ancient Shahdad, *Pajoheshnameh*, Tehran: 181–141 (In Persian).

Kaniuth, K., 2007, The Metallurgy of the Late Bronze Age Sapalli Culture (Southern Uzbekistan) and its implications for the 'tin question', *Iranica Antiqua*, 42(0), 23-40.

Keesmann, I., H. G. Niemeyer, and F. Golschani, 1983a, Schlackenfunde von Toscanos, *Madrider Mitteilungen*, (24), 65-75.

Keesmann, I., J. Preuss, and J. Endres, 1983b, Eisengewinnung aus lateritischen Erzen, Ruki-Region, Provinz Equateur/Zaaire, *Offa*, 40, 183-190.

Keesmann I. 1989, Chemische und mineralogische Detailuntersuchungen zur Interpretation eisenreicher Schlacken. In: Pleiner R (ed) Archaeometallurgy of Iron, 1967–1987. Symposium Liblice 1987, Prague, pp 17–34

Keesmann I., 1991, Rio Tinto: Die Technik der Silbergewinnung zu Beginn des Mittelalters. In: Argent, plomb et cuivre dans l'histoire. Lyon 1991, pp 1–13

Lamberg-Karlovsky, C. C., 1967, Archeology and Metallurgical Technology in Prehistoric Afghanistan, India, and Pakistan., *American Anthropologist*, Vol. 69(No. 2), 145-162.

Liu, S., Rehren, T., Pernicka, E., Hausleiter, A., 2015, Copper processing in the oases of northwest Arabia: technology, alloys and provenance. Journal of Archaeological Science, 53, p. 492-503.

Maddin, R., T. S. Wheeler, and J. D. Muhly, 1977, Tin in the Ancient Near East: Old Questions and New Finds., *Expedition*, Vol. 19(No. 2), 35-47.

Maddin, R., Muhly, J. D. and Stech, T., 1999, Early metalworking at Cayönü, In: A. Hauptmann, E. Pernicka, Th. Rehren and U. Yalcin (eds.), *The Beginnings of Metallurgy, Der Anschnitt*, Beiheft 9, Bochum, 37-44.

Majidzadeh, Y., 1979, An early prehistoric coppersmith at Tepe Ghabristan, Akten des VII Internationalen Kongresses für iranische Kunst und Archaeologie, Archaeologische Mitteilung aus Iran, Ergaenzungsband 6, 82-92.

Maggetti, M., 2001, Chemical analyses of ancient ceramics: What for?, *CHIMIA International Journal for Chemistry*, 55(11), 923-930.

Meier, D.M.P., 2011, Archaeometallurgical Investigations of Bronze Age Metal Finds from Shahdad and Tepe Yahya1. Iranian Journal of Archaeological Studies, 1(2), 25-34.

Meier, D.M.P., Kaveh´ s forefathers: Traces of protohistorical metallurgical activities during the 3 rd millennium BCE in Eastern Iran with a special focus on the case of Shahdad in the Dasht-eh Lut (Kerman province), in Geschichts- und Kulturwissenschaften Department. 2017, Dissertation, Freie Universitaet Berlin. p. 488.

Meier, D., Vidale, M., 2013. The “Man with Serpents” revisited. On a Figurated Pin from the Bronze Age Site of Shahdad (Kerman, Iran), Iranian journal of archaeological studies 3, 1-9.

McDonnell, J., 1991, A model for the formation of smithing slags, *Materialy Archeologiczne*, 26, 23-26.

Muhly, J. D., 1989, Cayönü Tepesi and the beginnings of metallurgy in the Old World, In: A. Hauptmann, E. Pernicka and G. A. Wagner (eds.), *Old World Archaeometallurgy, Der Anschnitt*, Beiheft 7, Bochum, 1-11.

Muhly, J. D., 1985, Sources of tin and the beginnings of bronze metallurgy, American Journal of Archaeology, 275-291.

Ottaway, B. S., 2001, Innovation, production and specialization in early prehistoric copper metallurgy, *European Journal of Archaeology*, 4(1), 87-112.

Pigott, V. C., 2004, On the importance of Iran in the study of prehistoric copper-base metallurgy, *Persiens Antike Pracht. Katalog der Ausstellung des Deutschen Bergbau-Museums Bochum vom*, 28, 28-43.

Pigott, V. C., 1999, A heartland of Metallurgy, Neolithic/Chalcolithic metallurgical origins on the Iranian Plateau, in; The beginning of Metallurgy, Der Anschnitt, beiheft 9, 107-120

Rademakers, F. W., and C. Farci, 2018, Reconstructing bronze production technology from ancient crucible slag: experimental perspectives on tin oxide identification, *Journal of Archaeological Science: Reports*, 18, 343-355.

Rafiei-Alavi, B., Bahrololoumi, F. & Klein, S., 2022, Three Women from Elam: A Revision of the Haft Tappeh Metal Plaque. *Bulletin of the American Society of Overseas Research*, 387(1), 171-180.

Rehren, T., L. Boscher, and Pernicka, E., 2012, Large scale smelting of speiss and arsenical copper at Early Bronze Age Arisman, Iran. Journal of Archaeological Science, 39(6): p. 1717-1727.

Rehren, T., Asderaki-Tzoumerkioti, E., Skafida, E., Karnava, A., 2013. Bronze Age crucibles from the Kastro-Palaia settlement, Volos, Greece–a contradiction of form and function?, Historical Metallurgy 47, 111-124.

Rostoker, W., Pigott, V.C., Dvorak, J.R., 1989. Direct Reduction to Copper Metal by Oxide--Sulfide Mineral Interaction, Archeomaterials 3, 69-87.

Salvatori, S., and M. Tosi., 1997. Postscriptum: Some Reflections on Shahdad and its Place in the Bronze Age of Middle Asia. in A. Hakemi. *Shahdad: Archaeological*

Investigations of a Bronze Age Center in Iran. Instituto Italiano per il Medio ed Estremo Oriente, Centro scavi e richerche archeologiche, Reports and Memoirs 27. Rome: Oxford & IBH, p. 121-138.

Thornton, C.P., 2009. The Chalcolithic and Early Bronze Age metallurgy of Tepe Hissar, Northeast Iran: A challenge to the ‘Levantine Paradigm’, University of Pennsylvania.

Thornton C. P., 2009, The emergence of complex metallurgy on the Iranian plateau: Escaping the Levantine paradigm’, Journal of World Prehistory 22, 301–327.

Thornton, C. P., 2010, The Rise of Arsenical Copper in Southeastern Iran, *Iranica Antiqua*, 45(0), 31-50.

Thornton, C. P., 2014, The Emergence of Complex Metallurgy on the Iranian Plateau, in *Archaeometallurgy in Global Perspective*, 665-696, Springer.

Thornton, C. P., and T. Rehren, 2007, Report on the first Iranian prehistoric slag workshop, *Iran*, 45, 315-318.

Vidale M. (2006-2008) Šahdad. Reallexikon der Assyriologie und Vorderasiatische Archäologie 11, Berlin, de Gruyter, 535-537.

Wayman, M. L., and M. J. M. Duke, eds., 1999, The effects of melting of native copper: Der Anschnitt-The Beginings of Metallurgy: Bochum, Zeitschrift für Kunst und Kultur im Bergbau.

Weeks, L., 2013, Iranian metallurgy of the fourth millennium BC in its wider technological and cultural contexts. , in Ancient Iran and Its Neighbours: Local Developments and Long-Range Interactions in the Fourth Millennium B.C., 278-291, C. A. Petrie, ed., Archaeological Monograph Series III. Oxford: Oxbow, British Institute of Persian Studies.

Weeks, L., 2016. Iran and the Bronze Age Metals Trade in the Persian Gulf, International Journal of the Society of Iranian Archaeologists 2, 13-25.

Wertime, T. A., 1964, Man's First Encounters with Metallurgy: Man's discovery of ores and metals helped to shape his sense of science, technology, and history, *Science*, 146(3649), 1257-1267.

Xie, P., Rehren, T., 2009. Scientific analysis of lead-silver smelting slag from two sites in China, Metallurgy and civilisation: Eurasia and beyond, 177-183.

ردیابی مجدد متالورژی مس در منطقه شهداد (هزاره سوم قبل از میلاد)

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چکیده

شهداد در حاشیه غربی بیابان لوت واقع شده است و یکی از مراکز شهرنشینی اولیه را در خود جای داده است. این منطقه تاکنون موضوع پژوهش‌های باستان شناختی و فلزشناسی متعددی بوده است. محوطه عصر مفرغی شهداد مدارک و شواهد فراوانی از فعالیت‌های فلزکاری کهن را ارائه کرده است و پژوهش‌های پیشین روند توسعه تکنولوژیکی فلزکاری و اهمیت آن در این محوطه را تا حدودی نشان داده است. طی بررسی‌ها و کاوش‌های باستان شناسی صورت گرفته در محوطه شهداد، مدارکی نظیر سنگ خام مس، قالب‌های فلزگری، بوته‌های فلزگری، کوره‌ها، سرباره‌ها و اشیای متعددی فلزی مربوط به هزاره سوم پ.م بدست آمده است. طی بررسی صورت گرفته توسط نگارندگان در محوطه شهداد، نمونه‌های سرباره فلز و همچنین قطعات سفال به منظور انجام مطالعات ساختارشناسی و ریز ساختارشناسی برداشت شد تا بتوان به اطلاعاتی از تجربیات صنعتگران ساکنان منطقه در هزاره سوم پ.م دست یافت. در محوطه شهداد، سه گونه متفاوت سرباره فلز با توجه به رنگ، بافت بیرونی و ساختارشان تشخیص داده شد. نتایج مطالعات مقدماتی انجام شده منجر شد تا اطلاعاتی جدید از فلزکاری کهن در شهداد داشته باشیم. نتایج نشان داد که فلزکاران شهداد به طور عمده از مس سولفیدی استفاده می‌کرده‌اند. از نتایج جالب توجه این پژوهش می توان به سفال‌های قرمز محوطه اشاره کرد که به نوعی در ارتباط با فلزکاری در این محوطه بوده‌اند. سفال ها حاوی ترکیبات کربانته و اکسیدی مس هستند که نشان از ارتباط با صنعت فلزکاری شهداد دارد و در فرایند استحصال مس مورد استفاده قرار گرفته اند.

واژه‌های کلیدی: شهداد، فلزکاری کهن، ذوب مس، عصر مفرغ، تخصص پذیری پیشه وری.

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