Melting Indian crucible steel: experimental reconstruction of traditional production technologies

Abstract: Despite the many discoveries made in recent decades at archaeological sites in India (Kodumannal, Gatihosahali, Konasamudram, etc.), Central Asia (Merv, Aksiket, Pap, etc.), and Iran (Chahak), as well as the excellent work of archaeo-metallurgists such as A. Williams, P.T. Cradock, B. Gilmour, A. Feuerbach, and T. Rehren, some aspects of the traditional technique of producing crucible steel remain in the realm of theory. The archaeological aspects of its production have been worked out, but in practice, applying all the assumptions based on archaeological findings, it has still not been possible to carry out effective melting of this remarkable material. In order to effectively combine the findings of archaeologists, metallurgists, archaeometallurgists and blacksmiths, and to fully reconstruct the simple principles that ancient metallurgists used to successfully carry out this extremely complicated production process, it is necessary to carry out a series of experiments in the field of experimental archaeology. Only these will make it possible to answer the question of how one of the most advanced materials in history was formed in a furnace of dried clay, fired with charcoal and powered with hand bellows, at temperatures that are theoretically too low for it.

Keywords: experimental archaeology, melting crucible steel, India

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Experimental archaeology is almost always a big unknown and while the organizers of this attempt to melt crucible steel according to ancient Indian recipes may not have resolved the issue once and for all, the "hands-on" experience, shared with the participants of the Red Sea 8 Conference in Warsaw, has given both practical know-how and food for thought.

Much as the term "Damascus steel" is known to almost every enthusiast of ancient weaponry, still very few, even among historians or archaeologists, are aware of the nature of this material, its long history and the technical expertise needed to make it. Despite the efforts of generations of researchers, reenactors and master armorers, popular texts continue to lump together anything and everything that reveals a "damask pattern" on the polished and etched surface. The point is that there are several different ways of obtaining this patterned effect and the inner structure of the blades with such patterns on the flat can differ substantially (Piaskowski 1974: 7–12; Tylecote and Gilmour 1986: 252; Sachse 1993: 18–86; Verhoeven and Pendray 2001; Feuerbach 2002: 182; Thiele, Hošek, Hazamza, and Török 2015; Thiele, Hošek, Kucypera, and Dévényi 2015). This goes together with completely different technical properties, production methods and forging techniques.

TYPES OF STEEL IN THE SOURCES AND ETYMOLOGY OF NAMES

The steel that the Crusaders saw in the armorers stalls in Damascus (Sherby and Wadsworth 1985: 112), which was one of the most valued materials brought from the Islamic world, had nothing in common with the "Damascus steel" produced from welded layers of metals with different properties (Maryon 1960; Sachse 1993; Jones 1997: 5; Lang 2009; Pelsmaeker 2010: 67–75; Thiele, Hošek, Hazamza, and Török 2015; Thiele, Hošek, Kucypera, and Dévényi 2015; etc.). The "genuine" or "patterned Damascus steel" that was used most probably from about the 6th–7th centuries CE to forge the most luxurious blades of Eastern swords is a subgroup of the much older so-called crucible steel (Feuerbach 2000: 33). The extremely high carbon content (from about 1.1% to even 1.97–2.0%) (Verhoeven 1987: 146) classifies this subgroup as ultra-high-carbon steel or hypereutectoid steel (Feuerbach 2002: 196). In popular literature, this steel has been known since the 18th century as *wootz*, which is presumably a corrupted version of a local Indian name (*ukku* steel, *uchcha* steel of the highest quality in the Dravidian languages of Kannadi and Telugu, *oots*, *wootz* or *wuz* in Gujarati) (Feuerbach 2002: 163; Le Coze 2003: 120–121). The same material in Persian is called *pulad* or *fulad*, similarly as in the Arabic languages and texts. The characteristic pattern on the polished and acid-etched[1] blades of crucible steel was referred to in Arabic literature of the Islamic period as *firind* or *farand*, in Persian *jauhar* or *johar* (literally, "jewel"). The steel that has a structure allowing this pattern to form is called *fulad-e johardar* (or *pulad-e johardar*), the steel that does not generate this "Damascus pattern" is *fulad-de bijohar* (or *pulad-de bijohar*) (Le Coze 2003: 119–120; Moshtagh Khorasani and

1 The forged and polished sword blades made of patterned crucible steel were etched with mineral aluminum and iron sulphates going under the name of *zag* in general.

Hynninen 2013: 158). In an age when merchants or warriors had no other analytical tools at their disposal, the *johar/jauhar*, which is a reflection of the crystalline structure of the metal used to forge the blade, was a way to assess quality and class. Experienced users could estimate carbon content in the steel and its distribution, the quality of the raw material and technique of forging of the blade, and even the provenance of a given piece.[2]

ARCHAEOLOGICAL EVIDENCE FOR CRUCIBLE STEEL MELTING TECHNOLOGIES

Crucible steel production was invented in India to believe ancient scholars, specifically the 3rd-century AD alchemist and philosopher Zosimos from Panopolis, for example (Berthelot 1887: 332; Lang, Craddock, and Simpson 1998: 10; Craddock 2003: 10; Feuerbach 2007: 319–320). Modern archaeological research has confirmed this view, dating the invention of the older, unpatterned version of this material to 400–300 BCE (Rao, Mukherjee, and Lahiri 1970; Rajan 1991; Craddock 1998; Srinivasan 1994; 1996; Anatharamu et al. 1999; Feuerbach 2002: 166–169).

The Indian crucible steel production technology, which was developed already around the 3rd–4th century CE, was perfected in Persia and Central Asia, while Indian steel became a strategic goods on the great trade routes in the 4th and 5th centuries CE. It was held in high esteem by both Persian kings and the warrior tribes of the Great Steppe and the Arabian Peninsula as far as South Arabia. Swords of Indian steel were used by the pre-Islamic kings of the Arab kingdom of Kinda and even by the Prophet Muhammad (Woźniak 2015: 710–711, 720–722).

The most common technology, especially in the earlier phases, so-called direct carburizing, called for pieces of iron to be tightly packed in a ceramic crucible together with enough carburizer (usually organic), so in the simplest Indian–Sri Lankan recipe (Buchanan 1807: 121; Coomaraswamy 1956: 192–194; Piaskowski 1974: 284; Sherby and Wadsworth 1985: 114–115; Juleff 1990; 1998: 90–94; Wayman and Juleff 1999). Additionally, depending on the period, region and recipe, the charge for the crucibles thus prepared was mixed with several substances facilitating the purification of the alloy, its carburization, and protecting the molten metal from oxidizing etc. (the complicated Persian and Central Asian recipes often listed more than a dozen ingredients) (Feuerbach 2002: 196, 159; Alipour and Rehren 2014: 6–13, 20–22).

CRUCIBLES

The crucibles used in Central Asia were cylindrical as a rule, with flat or concave bottom, approximately 8 cm inside diameter and from 20 cm to 30 cm high [*Fig. 1:B*]. They were closed with lids,

2 The pattern and its assessment were so important that with time (e.g., in al-Biruni's works) the term *jauhar* was used to designate the inner blade structure of pattern-welded swords, not only those made of crucible steel.

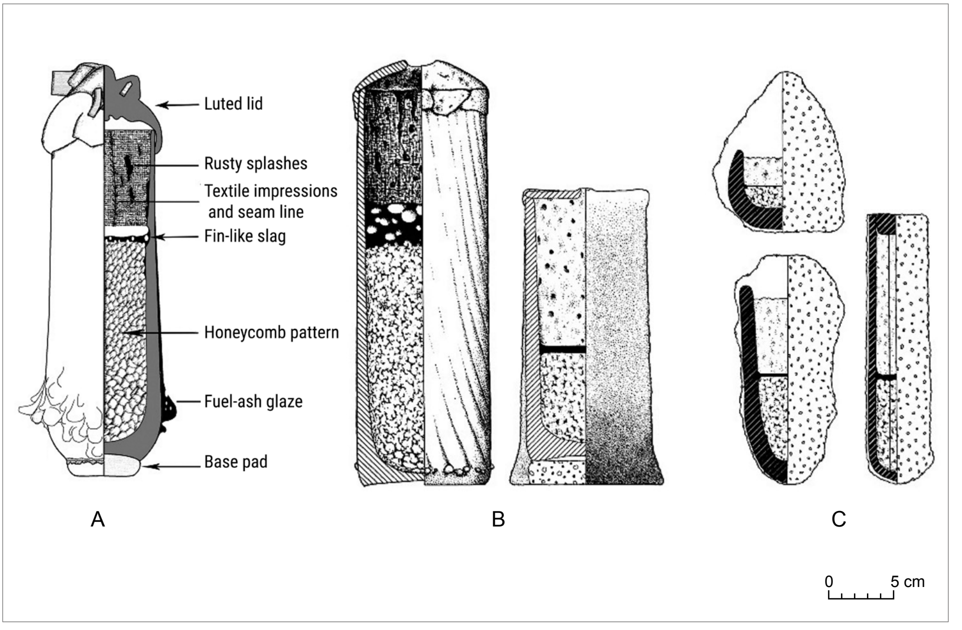

Fig. 1. Crucible types: A – crucible from Chachaku with small base; B – Central Asian; C – Indian; (C – After Alipour and Rehren 2014: Fig. 11; B, C – After Rehren 2002: 38, Fig. 3)

either flat (Merv) or slightly convex (Ferghana valley), often with one central hole, about 1 cm in diameter, or a series of a few smaller holes at the edge. Their bottoms were fitted with thick flat stands of similar or slightly smaller diameter as the bases (significantly smaller in the case of crucibles from the Chachak region in central Persia), very likely for added protection or to increase the height (without excessive use of the clay with a refractive index used for the crucibles) (Feuerbach 2002: 52–59, 131–137, 140–142, 155; Rehren 2002: 38; 2003: 210–211; Alipour and Rehren 2014: 14–20) [*Fig. 1:A*].

Indian crucibles came in a great variety of shapes and sizes, but the most common forms were pear-shaped (e.g., examples from the vicinity of Mel-Siluvalur and the Telangana region), tubular (Sri Lanka, Mawalgaha area) [*Fig. 2*] or an inverted

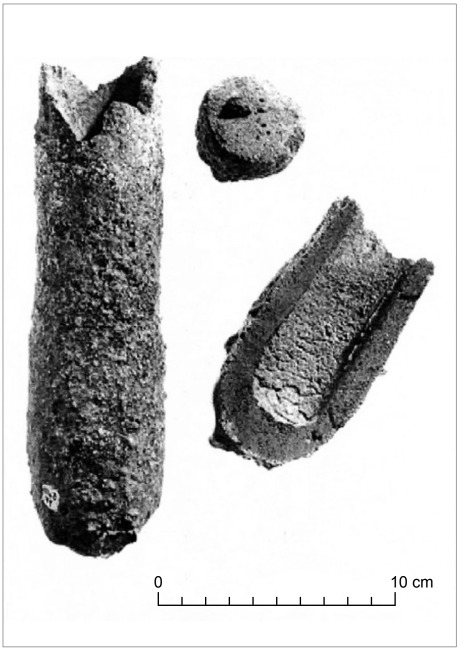

Fig. 2. Tubular crucibles from Mawalgaha, Sri Lanka (After Feuerbach 2002: 169, Fig. 90)

cone (near Gatihosahali and Mysore, where Francis Buchanan carried out his observations) (Buchanan 1807: 308; Feuerbach 2002: 168–169, 171; Solangaarachchi 2011: 85) [*Fig. 3* left]. They had a rounded base as a rule (although crucibles with almost flat bottoms occurred as well, e.g., in southwestern India in the areas of Gatihosahali and Konasamudram, and in the Telangana region) [*Fig. 3* right], which was conditioned by a specific type of furnace and a special technological process called the Hyderabad process, a cross of Central Asiatic and Indian solutions (Feuerbach 2002: 172–174). After they had been filled, they were closed with a lump of the same ferruginous clay (mixed with crushed charcoal or rice husks, sometimes also organic temper) from which they were made. After closing, they were covered for additional protection with another thin coating of clay with temper, either mineral or made of broken used crucibles (Feuerbach 2002: 166–174; Rehren 2002: 38; 2003: 210).

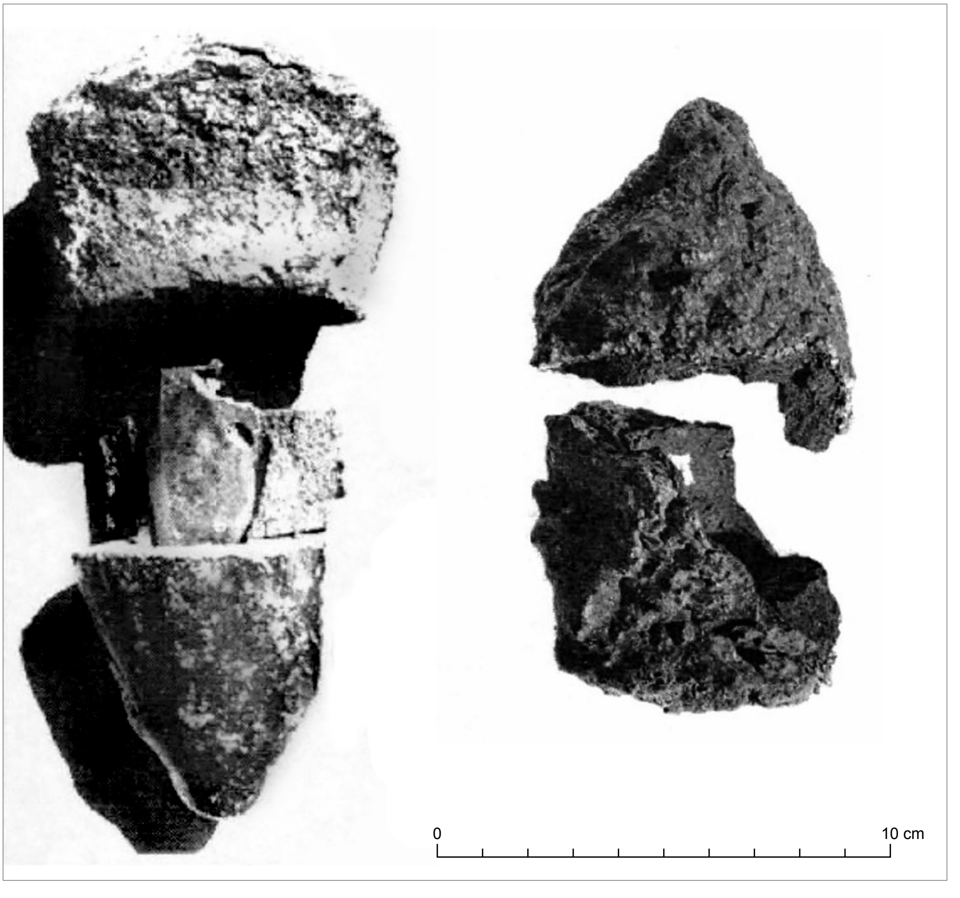

Fig. 3. Two examples of crucibles: left, inverted cone, from Gatihosahali, India; right, fitted with a flat bottom, from Konasamudram, eastern India (After Feuerbach 2002: 168, Fig. 88 and 172, Fig. 92)

RECONSTRUCTING THE FURNACE AND FURNACE PARAPHERNALIA

In order to reconstruct the crucible steel production process, one needs to know not only the right proportions of the ingredients and the time of melting, but also how to prepare furnaces and bellows to produce the required temperature of about 1500–1550°C and, of equal importance, to withstand this kind of temperatures long enough for the melting process to be completed. No other technological processes before modern times required temperatures this high nor materials capable of withstanding such conditions. The scale of the problems for ancient metallurgists producing crucible steel (in hundreds of workshops producing a dozen different kinds of this steel with different properties) is best attested by the fact that even modern metallurgists producing steel of this type in a fairly standard way use modern gas furnaces and crucibles made of the most modern refractory materials (Moshtagh Khorasani and Hynninen 2013: 166–170). To date nobody has been able to replicate the melting of crucible steel using traditional methods, equipment and materials. The Red Sea 8 Conference in Warsaw in 2017, with its theme of mineral resources, provided the opportunity for one of the first such trial in Poland.

SOURCES FOR SOUTH INDIAN FURNACES

The experimenter's own interests in this case, as well as the relatively abundant documentation, led to the choice of a furnace of the south Indian type for the planned reconstruction and experiment. This kind of furnace was described and drawn by Francis Buchanan who saw it in operation during his journey through southwestern India, especially in the district of Mysore famous for its metallurgical production (Buchanan 1807: 119–121, 305–308, Figs 40, 41; Piaskowski 1974: 282–285, Figs 185, 186) [*Fig. 5*]. Furnaces of this kind were still in operation in the beginning of the 20th century also in Sri Lanka, in the Balangoda region (Solangaarachchi 2011: 75, Figs 2, 3 E–F.) [*Fig. 4*]. These must have been some of the last furnaces for melting crucible steel,

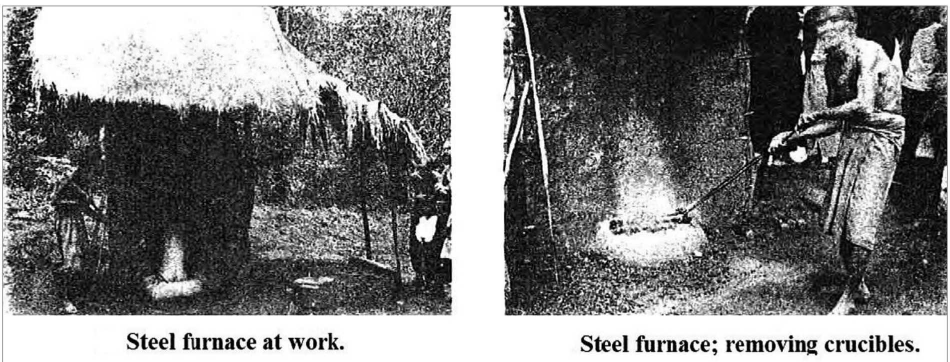

Fig. 4. Crucible steel melting furnace at Balangoda, Sri Lanka (After Solagaarachchi 2011: 75, Figs 2, 3)

shortly before its commercial production ceased, pushed out by imports of cheaper, European, mainly British steel.

Buchanan's descriptions, including the dimensions of some of the furnace elements, are sufficiently precise (even if somewhat chaotic) to be used as a base for the reconstruction of the whole furnace, especially when coupled with photographic images from the collection of Ananda K. Coomaraswamy (taken around 1908 in the neighborhood of Balangoda in Sri Lanka).

The furnace Buchanan described, from the Madhu-Giri district (most probably in Devaraja-Durga), consisted

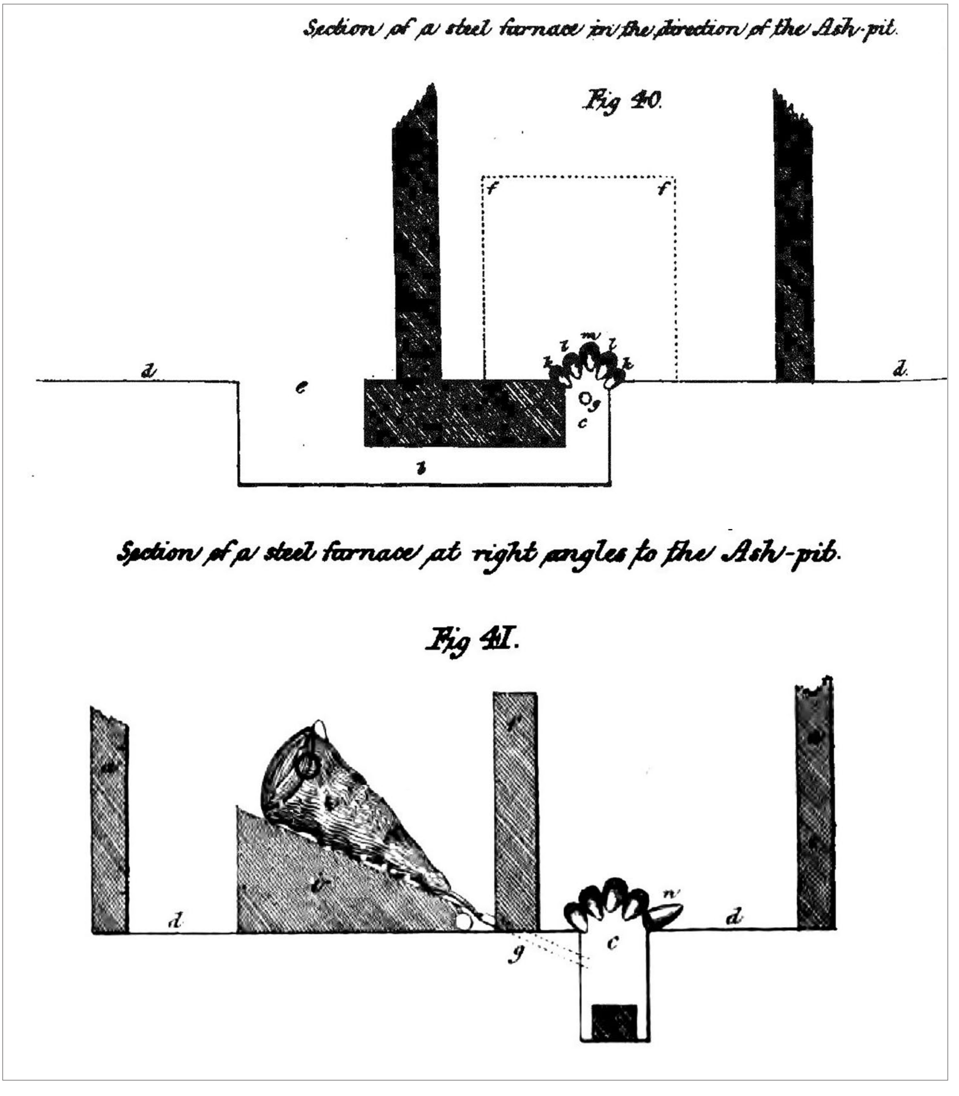

Fig. 5. South Indian crucible steel-melting furnace: top, lomg section; bottom, cross section (After Buchanan 1807: Figs 40 and 41)

of two parts, one underground and the other aboveground. The subterranean section was composed of a long ash-pit of square section, three-fourths of a cubit (34.2 cm) to the side, joining the bottom of the hearth with a cubic-shaped trench big enough for a man. The ash-pit was used to clear out the hearth either at the end of the process or during it, although the latter could have been quite dangerous because of the heat. The hearth was the main component of the underground part of the furnace. It took the shape of a circular pit one cubit in diameter (45.7 cm) and two cubits deep (91.4 cm). The upper parts of these pits flared slightly to the sides to render better support to the crucibles (Buchanan 1807: 307–308, Figs 40, 41; Piaskowski 1974: 282–284, Fig. 166).

For the experiment, the experimenters refrained from preparing an ash-pit in order to save on time and chose to make a smaller hearth (just 35 cm across and 60 cm deep) simply because of constraints of space.[3]

The underground part of the furnace at Madhu-Giri was dug almost directly by the mud-brick wall protecting the operator of the bellows from the heat and sparks, allowing the hearth practically to adjoin the face of the wall; the ash-pit ran alongside the hearth and all the way outside the shed housing the furnace. The wall was roughly 5 feet (152.4 cm) high (Buchanan 1807: 307), although this was probably discretionary; at another site, Magadi, Buchanan recorded a height of just 2 cubits, that is, 91.4 cm (Buchanan 1807: 120). The wall prepared for the experiment was lower than either of these, approximately 0.60 m, which was entirely sufficient to protect the operator of the bellows from the heat of the hearth (although it was raised by a few brick levels in the second stage of the experiment; see *Fig. 9*).

While the documentation of the Madhu-Giri furnace focuses on its underground part, it was the description

Fig. 6. First stage of the melting process; the furnace and the protective screen wall in the foreground; bellows behind (Photo J. Rądkowska)

3 The experiment was held in the central yard of the State Archaeological Museum in Warsaw as a supplementary one-day event during the Red Sea 8 Conference. The theoretical background was presented during a morning session at the Museum and conference participants could observe the proceedings while visiting the Museum exhibitions. A poster of the event is appended at the end of this article.

of the aboveground part of the furnace from the ironworks in the vicinity of Magadi that was of much greater use for the reconstruction of the experimental furnace. The hearth, which was presumably sunk into the ground, was delimited by two long, flat slabs of stone 1 cubit long (45.7 cm) and 2½ inches thick (6.8 cm), probably set parallel to the protective wall. On one side there was a low mud-brick wall roughly 23 cm high and, on the other side, a brick wall protecting the bellows operator, lower than in the other case indicated above. The distance between the hearth and the low wall delimiting the aboveground part of the furnace—and by the same the actual size of the whole furnace—is hard to determine based solely on this desription, though it seems to have been 1 foot (30.4 cm), but it is not clear whether from the stone delimiting the edge of the hearth or from the protective wall (Buchanan 1807: 121; Piaskowski 1974: 286). In the first case, the width of the furnace together with the hearth would have been 76 cm, which is fairly big considering that the furnaces from Merv had an outer diameter of roughly 70 cm on average and about 45–50 cm inner diameter (Feuerbach 2002: 60–63). The photo images from Balangoda [see *Fig. 4*] seem to show a structure that was not as wide. However, the furnaces from Merv were much higher than the Indian ones. The inner capacity of a furnace reconstructed based on Buchanan's descriptions fits the amount of charcoal that Buchanan said was used to cover each set of crucibles, which is 2 bushels (about 72.7 dm^3) (Buchanan 1807: 305).

Taking into consideration all the dimensions and calculations presented above, the furnace constructed for the purpose of the experiment was 45 cm in width and 70 cm in length (measured inside and on the ground), surrounded by an enclosure wall 30 cm high. The capacity, without the hearth and counting in the inside inclination of the furnace walls, was about 80 dm^3.

BELLOWS

The bellows—their structure, size and, above all, functioning—were the next crucial issue to be solved prior to reconstructing the production process. Buchanan's description, although fairly precise, lacks detailed drawings which would indicate air inlets, making it difficlt to reconstruct in a comprehensive way the structure of the bellows and how they were operated. For example, was the air inlet supported by a stiffer board or loose? Was it closed with a flap or was it just a fold of the leather pressed together by the operator with his hand?

Other doubts come to mind as well. Buchanan described the bellows as made of whole ox skins without a long cut and called them a pair of single-chamber bellows. Each of the bellows had an appropriately shaped earth bedding and was operated manually, the hand of the operator passing through a leather ring fixed to an outer skin fold covering the air inlet. The neck part of the skin was sewn to fit it around a wooden tube, which was attached to a ceramic tuyère (Buchanan 1807: 118–120; Piaskowski 1974: 282–284). The attached drawings are not precise enough (the bellows are shown from the side without any details of the inlet, see

Buchanan 1807: Figs 40, 41; Piaskowski 1974: 283, Fig. 166) for a fully functional reconstruction to be made on their basis. The bellows in the images from Balangoda are very primitive, cylindrical devices used in iron-smelting furnaces. The bellows used to produce crucible steel cannot be seen behind the wall protecting the operator from the heat and sparks (Solangaarachchi 2011: 75, Figs 2, 3).

An ironworks from the Orissa district in central India finally provided a model for the bellows. Their form was best rendered by Cecil Ritter von Schwarz (1901: 278; Piaskowski 1974: 279–280, Fig. 164), while the dimensions were reconstructed from the size of a pit for the bellows of furnaces 3 and 4 (the only ones where remains of bellows were preserved) in a 10th-century workshop producing crucible steel in ancient Merv (Feuerbach 2002: 63). While Buchanan gave no dimensions for his bellows, whole skins would have been too big for the pit of the Merv furnaces, which measured roughly 2 m by 1 m after the furnace (3) was installed (Feuerbach 2002: 63, Map 7). But in this case the overall shape of the bel-

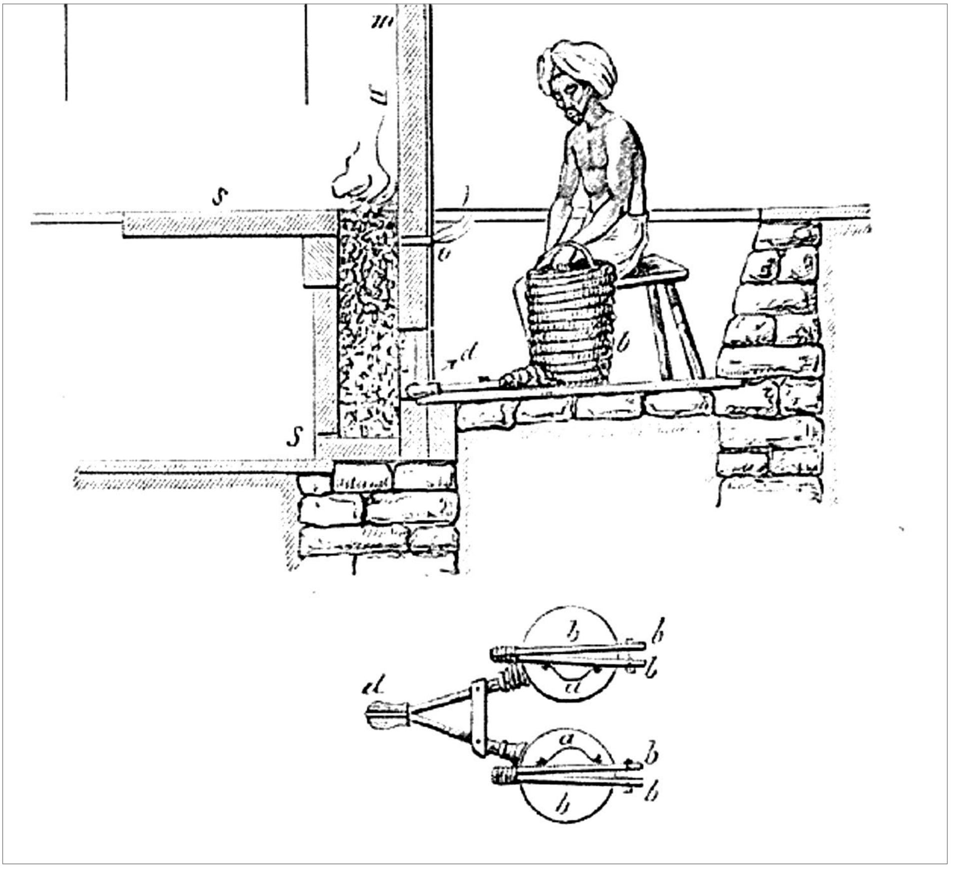

Fig. 7. Cylindrical bellows in a traditional ironworks fom the state of Orissa (After von Schwarz 1901: 278, Figs 3, 4)

lows is not known, although it is likely that they were cylindrical just like the Orissa examples and the bellows shown in old Persian miniatures.

For the purpose of the experiment a pair of cylindrical single-chamber bellows was made with full awareness of the technical risks involved. The bellows were 40 cm wide and 80 cm high, and had a volume of 100 l. The size and proportions appeared to suit von Schwarz's drawings as well as the pit of the Merv furnaces 3 and 4. They seemed not much different from the depictions in the 15th-century Persian miniatures (illustrating one of the scenes in the *Shahnameh* by Ferdowsi).

The main difference between the reconstructed bellows and those from the above minatures consisted in the preparation of the ox hide. Since modern procedures for acquiring and tanning animal hides prohibit these to be removed whole (without cutting) from the animals, it was necessary thus to double-stitch the acquired tanned ox hide so as to make a sleeve 40 cm in diameter and 90 cm long. Also the air inlet, traditionally formed from the neck part of the whole skin, needed to be formed separately and then stitched to the sleeve, next to the wooden bottom of the bellows that steadied the whole structure. The ultimate outcome of these undertakings resulted in the bellows looking—and functioning—just like the bellows from Ritter von Schwarz's illustrations [*Fig. 8*].

The air inlet of each of the bellows was sealed with a device shown in Ritter von Schwarz's illustration (1901: 278, Fig. 4). It was formed of two wooden

Fig. 8. First stage of the melting process: furnace and bellows; note the pipes from the bellows supplying air to the hearth (Photo J. Rądkowska)

slats joined at one end, closing the upper edge of the skin; the lower slat was at the same time a handle. The upper movable slat, joined with the leather loop, was moved back when the upper part of the bellows was raised to open the air inlet. Air would be pumped in when the slats were pressed together to close off more air, compressing it and pushing it out under proper pressure through a wooden pipe (replaced with a metal one in the experiment) extending from each bellow to a ceramic tuyère passing through the furnace wall at a 30° angle (von Schwarz 1901: 278; Buchanan 1807: 118, Figs 40, 41). This system of wooden slats is still common today in bag-shaped bellows used in traditional workshops in southern India.

The tuyères blowing air into the hearth of the furnace were modeled on typical pipes which are, next to slag, one of the most frequent finds at metallurgical sites in southern and southeastern India, Sri Lanka and the Malay Peninsula. These pipes measured 10 cm outer diameter and were 15 cm long; the inside tube was roughly 3–4 cm in diameter, which is midway between the diameter of tuyères from Indian Kodumanal (Srinivasan 1996: 120, Fig. 10) and the tuyères from metallurgical sites at Kiri Oya Basin in Sri Lanka (Solangaarachchi 2011: 280, 286, Figs 7-3, 7-6). They were made of a ferruginous clay similar in composition to Indian clay with a 30% crushed mineral temper of a 0.1-to-1 mm fraction, hand-formed on a wooden pole and dried two days in the shade, in temperatures around 28°C, and two days in the sun. Tuyères prepared in this way withstood well the pressure of the protective wall above it and the high temperatures operating especially on the front of the pipe (the rest of it is shielded by the wall of the hearth and by the earth which covers it).

ANCIENT RECIPES FOR CRUCIBLE STEEL

Once the hearth was covered with charcoal (in the way described by Buchanan), five crucibles were placed in it, resting on the edges of the hearth and propped up against each other. The crucibles used in the experiment were slightly bigger than the ones from India (capacity about 0.6 l), so as to avoid the need to use several pieces (15 according to Buchanan [1807: 308]) in a hearth smaller than the prototype. They had the shape of an inverted cone, the inner diameter being 12 cm at the rim and approximately 6 cm by the concave, rounded bottom, flattened on the outside. The crucibles were closed with a flat lid (in central Asian fashion rather) and covered with a thin layer of clay with fine mineral temper in order to protect them against sudden temperature change (which can be particularly big in an initial phase of the experiment.

The charge in each crucible was prepared according to a different recipe from a different period. The size of iron pieces was selected to check the effect of the temperature achieved on charges of different grade (from powder to fragments a few centimeters big), while following historical recipe recommendations.

Charge composition in the different crucibles was as follows:

1. Recipe given by Zosimos of Panopolis: (1/4 of the recommended size of the charge because of crucible size) (Berthelot 1887: 332; Feuerbach 2002: 47):
   - 450 g bloomery iron forged fragments about 2 cm × 2 cm × 1 cm,
   - 7.5 g dried fruit of *Terminalia chebula*, commonly known as black- or chebulic myrobalan (Arabic: *elileg*),
   - 2 g dried fruit of *Terminalia bellirica*, known as beleric or bastard myrobalan (Arabic: *belileg*),
   - 2 g dried fruit of *Emblica officinalis*, also known as\Indian gooseberry, *amla* from Sanskrit (Arabic: *ambileg*),
   - 1 g MnO_2.
2. Indian recipe as described by Buchanan (most probably the earliest process of melting crucible steel) (Buchanan 1807: 121, 308):
   - 430 g bloomery iron forged fragments about 2 cm × 2 cm × 1 cm,
   - about 35 g wood shavings (originally *Cassia auriculata*, here beech wood),
   - two green leaves (originally rather thick leaves, most frequently *Convolvulus laurifolius* in India, here poplar leaves by necessity.
3. Recipe of Mard Ibn Ali al-Tarsusi: (½ of the recommended size of the charge because of crucible size) (Feuerbach 2002: 159 revised following Alipour and Rehren 2014: 9 and Hoyland and Gilmour 2006: 60–61):
   - 1½ ratl (500 g; medieval Middle Eastern unit of measurement found in historical recipes) of iron consisting of small, tightly packed nails,
   - ¼ ratl (75 g) cast iron cut to pieces, about 3 cm × 2 cm × 0.5 cm,
   - small handful (about 5 g) dried pomegranate skins crushed in a mortar,
   - 12 g MnO_2.
4. According to Anosow (after Piaskowski 1974: 199):
   - 400 g iron dust,
   - 40 g graphite,
   - 10 g crushed dolomite.
5. Modern recipe for crucible iron production:
   - wrought iron cut to pieces, about 3 cm × 2 cm × 1 cm (500 g),
   - 12 g (slightly more than 2% with allowance for oxidation) crushed charcoal,
   - 15 g MnO_2,
   - 5 g steel filings CrV,
   - a few pieces of colorless glass.

RECONSTRUCTED EXPERIMENTAL MELTING PROCESS – MAIN CONCERNS

The closed crucibles, sealed with clay and dried, were stacked on a layer of charcoal in a pile shaped like a small dome and covered with more charcoal until the furnace was filled (Buchanan 1807: 121, 308). The charcoal was fired with some smoldering pieces placed at the bottom before the crucibles were introduced. The charcoal was ignited slowly for half an hour before blowing started in order the heat the crucibles and the furnace as a whole before the process proper started. Then the bellows started blowing air. Three different operators changed places in order to sustain its intensity. Every quarter of an hour the charcoal in the upper part of the furnace was supplemented to make sure that the crucibles were covered with the thickest possible layer of charcoal.

An hour into the experiment the first issue occurred: the metal pipes connecting the ceramic tuyères to the bellows started to get red-hot. This could have been caused by the position of these pipes inclined down toward the furnace (which allowed the heat to creep up along both pipes) and the fact that the bellows were worked in turns, which resulted in intermittent cooling of the pipes with air during the cycle. To deal with this issue, the pipes were covered with a wet textile, which was kept continuously wet by pouring water over it and this addressed the problem. In the ancient Indian

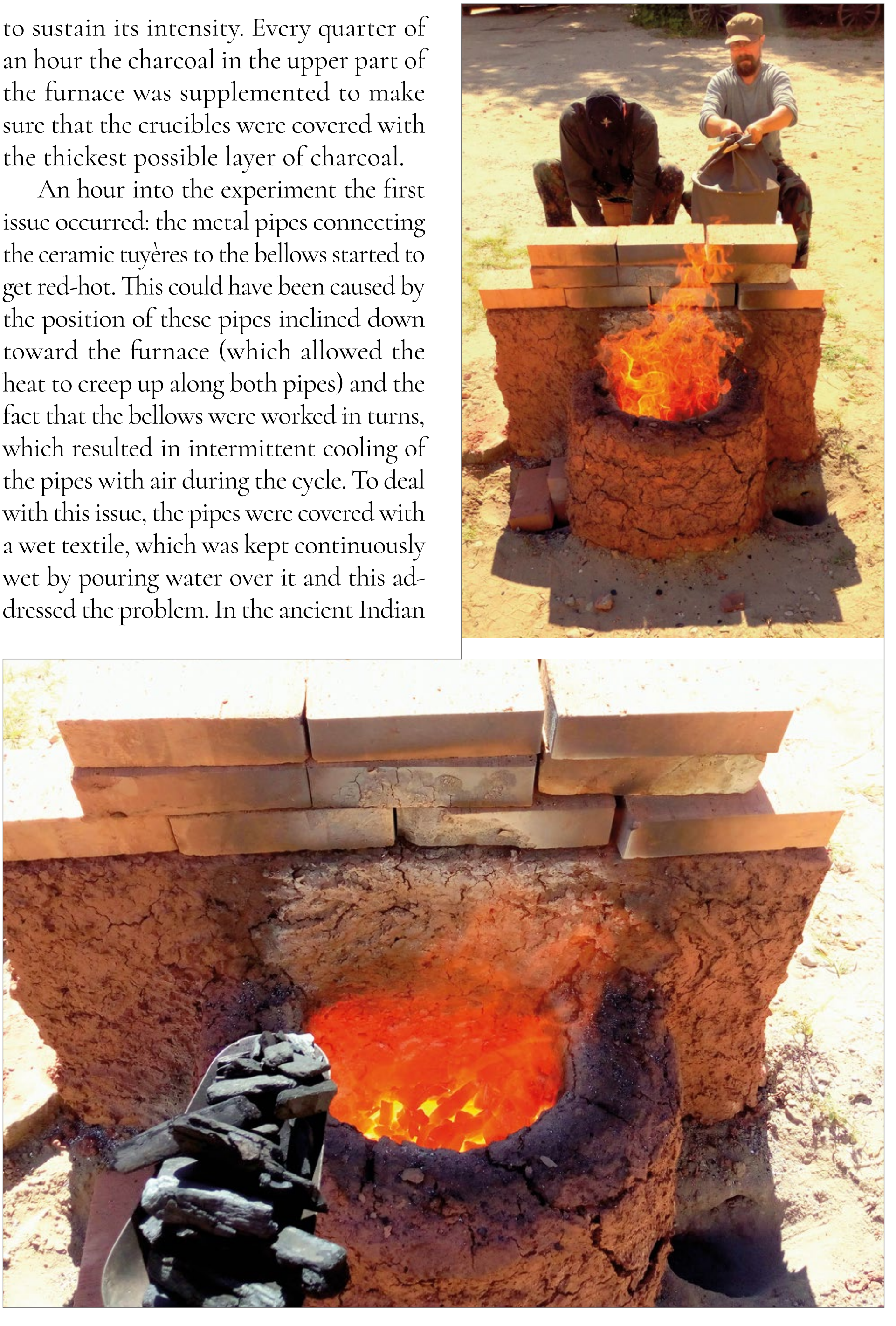

Fig. 9. Second stage of the melting process: top, the screen wall protecting from the heat is higher now; bottom, stoking the hearth with coal from the top (Photos J. Rądkowska)

furnaces, the tuyères must have been either longer or made of wood or bamboo presumably soaked in water prior to the operation and then continuously poured with water to keep them operational.

A second serious issue that was observed was that the possibility of adding more charcoal to the hearth became quite limited once the crucibles had been stacked inside the furnace [see *Fig. 9* bottom]. Buchanan noted that one of the crucibles opposite the tuyères was empty and was taken out to create an opening through which charcoal could be added (Buchanan 1807: 308). However, the opening was too small for the entire hearth to be covered evenly with charcoal through it. To make additional fueling possible, it would be necessary to make an opening in the furnace wall; such a solution was not mentioned in any of the descriptions nor can it be seen in any of the photographs from Balangoda.

The charcoal from the first fill of the hearth was quickly kindled to a high temperature due to intensive draft, but this also led to its burning out within 30–40 minutes. This left a void under the crucibles and caused the temperature in the hearth to start dropping. The draft was still heated passing over the hot cinders and ashes at the bottom of the hearth. To sustain this situation it was necessary to stoke up the hearth with more charcoal. The draft did not attain the temperature it had when the coals were still burning strong. However, it is possible that at this stage of the process all the hearth was supposed to do was to heat up the draft coming from the bellows, which passed around the crucibles to kindle the charcoal in the upper part of the furnace. The clay sealing the crucibles had melted, making them stick together; they remained in position propped up against each other and on the edges of the hearth. The supply of new charcoal to the upper part of the furnace can be replenished on a regular basis, every 10 minutes or so, to sustain the highest possible temperature.

In the original south-Indian furnace the size of the hearth must have also been determined by bellows size and the duration of the process. In the introductory part, charcoal in both parts of the furnace, at the bottom of the hearth and above the crucibles in the upper part, would have been kindled at the same time, rapidly reaching a temperature of approximately 1200–1400°C needed to a quicker carburization and melting, to a honey consistency at least of the surface (thickness of approximately 0.5–1.0 mm) of the most carburized part of the iron pieces. The highly carburized mass seeps over the lower less carburized fragments of the iron.[4] The preliminary molten conglom-

4 Many authors are, most probably, right in suggesting that iron melting in the traditional process of producing crucible steel occurred gradually due to earlier surface carburization of part of the fragments. This carburization takes place even as the charge undergoes heat treatment (after reaching an austenitizing temperature) as a result of a reaction almost identical with that taking place during modern carburizing processes. Some Islamic-age recipes mention sodium carbonate-baking soda (Alipur and Rehren 2014: 238) applied as an accelerating factor/agent in the carburization process to speed up carbon absorption by the carburized metal. The process is extremely slow (about 0.1 mm/h at about 900°C temperature) but it speeds up significantly at higher temperatures [see *Fig. 10*].

erate absorbs charcoal quickly, increasing elemental content in the liquid alloy and its diffusion to the lower, less carburized parts submerged in it (Wadsworth 1985: 115; Rehren 2002: 38). Increased carbon content continues to lower the melting temperature of the molten crucible steel, enhancing liquefaction and, consequently, facilitating even distribution of the carbon in the whole of the newly-made crucible steel ingot. Higher alloy liquefaction also helps to clean the alloy of slag intrusions characteristic of bloomery iron, which, being lighter (Feuerbach 2002: 115; Rehren 2002: 38), are transported to the surface of the molten metal forming a characteristic semi-transparent layer(often with evidence of gas bubbles of different size on the surface). Traces of this thin coat are often preserved on the inside of crucible fragments discovered at archaeological sites (Rehren and Papakhristu 2000: 58–59, Figs 6, 7; Feuerbach 2002: 45–46, Figs 9, 15; Alipour and Rehren 2014: 15 Fig. 6).

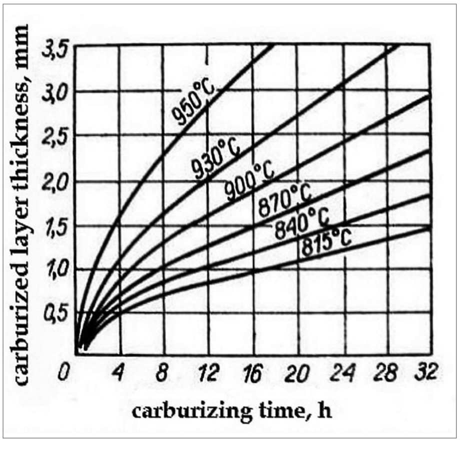

Fig. 10. Total thickness of carburized layer over time for different carburizing temperatures in an atmosphere potential corresponding to the border atmosphere for dissolving carbon in austenite (After Wasiak 2003: 15, Fig. 3)

Moreover, the characteristic structure of crucible steel crystallizes better from a well liquefied and evenly carburized alloy, which is important for its quality, especially in the case of the patterned type (Feuerbach 2002: 197–198).

This description indicates that the process speeds up continuously when maintaining appropriately high temperatures, which could threaten excessive carburization of the alloy (more than 2.1% C) and the forming of a piece of unmalleable cast iron. It is possible that heat treatment of the crucibles from above, with charcoal burning in the upper parts of the furnace, was enough to complete the melting of already carburized steel and sustained its liquid form in order to purify the crucible steel ingot being formed. In his description of the process, Buchanan speaks of only one episode of adding new fuel during the melting (Buchanan 1807: 121). This probably corresponded with the end of the preliminary melting of the charge in the crucibles and the beginning of the "additional melting" phase. According to Buchanan, the process was quite short, about four hours. Other travelers report longer durations, up to 24 hours. However, in all probability, these reports reflect the time needed, together with the gradual cooling, for making the patterned *wootz* (Feuerbach 2002: 197). Buchanan's description indicates that the workshop he observed was engaged in producing an unpatterned "tool" version of crucible steel (Gilmour 2015: 196). The production of steel of this unpatterned kind did not require "growing" a regular coarse-grained structure with properly well developed dendrites and a network of crystals of hypereutectoid cementite.

The third issue raised during the experiment and which ultimately terminated it after 2 hours and 40 minutes, was the process of the crucibles slowly dropping into the void left by the burned out charcoal in the hearth. For more than an hour the crucibles stayed in their starting position even after the charcoal had burned out, but later they started to drop gradually into the hearth (starting with those closest to the protective wall). This ultimately blocked the hole drafting air into the furnace, probably because of damage to the edge of the hearth, which was weaker in the part above the tuyères, and as a result of the deformation of the crucibles. It also appears that the hearth pit was dug too close to the protective wall, which resulted in improper shaping of the edge of the hearth.

Until this moment the process had been unfolding correctly with significantly high temperatures (at least inside the furnace) as attested by the observable vitrification of the outer surfaces of the crucibles, on the edges of the hearth and the inside walls of the furnace. However, it was impossible to continue the experiment after the crucibles had dropped into the hearth. The furnace was covered with coal just in case and, once it had been kindled, the upper hole of the furnace was closed with bricks and the furnace was left to cool down gradually before removing the crucibles.

RESULTS OF THE EXPERIMENT

The best effects, although far from what had been expected, were observed in two out of five crucibles. The metal part of the charge in crucibles 1, 2 and 5 showed practically no trace of surface melting (sporadic signs are observed on the edges of some pieces of bloomery iron in crucibles 1 and 2). The surface of the metal pieces was evenly coated with a fairly thick layer of soot from the burning of organic carburizers. It means that the carburization of the metal surface had begun, but it had not taken place with enough speed and effectiveness to induce the melting of the surface of the carburized metal. The temperature inside the crucible was probably too low for the process to unfold with proper intensity (although it must have exceeded 900°C, because the glass in crucible 5 was melted in its entirety and had flown down into the bottom of the crucible, over the metal pieces). Presumably also the experiment did not last long enough. Additionally, crucibles 1 and 2 had cracked near the bottom, probably under the influence of changes of the temperature, already after the charcoal in the hearth had burned out, when the draft reached inside the furnace almost directly under the bottom of the crucibles. One side of crucibles 1 and 2 adjoined the edge of the hearth near the protective wall, while the other side faced the inside of the hearth and the draft coming in. This must have caused differences in the temperature in different parts of the crucibles and consequently their cracking.

In crucible 3, charged according to al-Tarsusi's recipe, the cast iron fragments showed clear evidence of early melting. Some of the nails touching the cast iron had been fused to it. The nails lowest in the crucible, near the bottom, also bore signs of melting in the thinnest parts, especially at the tips. The metal in the charge was covered with a layer of black ashes from the burning of the crushed pomegranate rind. The temperature in crucible 4 was high enough for the entire iron powder to be consolidated, forming a steel cake in the shape of the bottom of the crucible. For the process to take place without additional forging, the temperature has to be about 1200°C. The graphite most probably reacted with the heated metal, but the carburization process did not terminate properly, possibly because of the small crack in the bottom of the crucible, which must have occurred when the crucible steel cake was already cooling, because the material had not seeped into the crack and was only slightly singed in the opening. After the steel cake was cut and polished, it became clear that the material had not gone through the liquefaction stage and the cake itself was slightly porous in its structure. Also, it did not present a hardness typical of appropriately carburized crucible steel cakes.

CONCLUSION

In general, while the experiment cannot be deemed a success, its results contribute to an improved understanding of the design and functioning of furnaces used for melting crucible steel in southern India.

First, the bellows used in the experiment were most probably too small for ensuring the proper draft for completing the smelting process. However, perhaps they need not have been much bigger. It might have been enough (as in the Persian bellows) to slightly change their design by adding a slab on top with appropriate air holes, ensuring greater effectiveness. Dexterity in operating the bellows could have also played a considerable role. The expertise in this regard of the operators was also of considerable importance, because it translates into appropriate work intensity and the shortest breaks between cycles.

Second, the sizes of the hearth and of the upper chamber of the furnace and their correlation with the size of the bellows were of great importance in the south Indian type of furnace, as indicated above. The need for correlation is what makes experiments with a slightly smaller examples of furnaces difficult, especially when there are less crucibles (which is important in the case of an experiment). Smaller furnaces cannot achieve appropriate effectiveness, especially in the first phase of the process, because there is less fuel; the smaller size of the hearth also shortens the duration of the first stage of melting steel, which is of key importance.

The composition of the material used to make the crucibles is also of big importance for the south Indian process. Organic temper is key to the ferrous Indian clays; it comes most often in the form of rice husks (although Buchanan also mentioned charcoal), ensuring appropriate porosity and hardness of the walls. The reaction of charred organic matter (or simply crushed charcoal) with iron oxides in the clay reduces them to metallic iron, raising considerably the melting temperature of the mass. The large porosity and appropriate composition increase the resistance of the crucibles to "temperature shock", which is extremely damaging to crucibles made of denser fabric with mineral temper (the kind used in the experiment). Moreover, the proper thickness of the coarse-grained layer coating the crucibles on the outside is important because it protects them against temperature changes. Additionally, it helps to keep the crucibles together, in position during the whole process. When it is too thick, this layer may also block the open space between the crucibles and cut off the draft to the upper parts of the furnace.

Even if not entirely successful, the experiment has contributed interesting archaeological and ethnographic information. Most importantly, it has prepare a practical foundation for further experimental research on specific issues connected with traditional methods of crucible steel melting in antiquity, much earlier than the 18th–19th century. The research should take into account with greater accuracy the results of archaeological and historical studies, which can combine into one the conclusions of archaeometallurgists, archaeologists and historians, adding details of the process once passed on only in a narrow circle of ancient masters, which have not survived in any theoretically reconstructable form.

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