Article

Persian Pulād Production: Chāhak Tradition

Rahil Alipour[a], Thilo Rehren[a*],

[a] *UCL Qatar, Doha, Qatar*
*Corresponding author. Tel.: 00974 7777 0275.
E-mail address: th.rehren@ucl.ac.uk

Abstract

Crucible steel has fascinated scientists for over a century, but the study of its production is a fairly new field of research. Publications so far focus on archaeological sites from Central Asia (9th-12th centuries CE), India and Sri Lanka (mostly 17th century CE onwards). However, the development and spread of crucible steel making is yet to be re-constructed to its full extent. It has been long suspected that the origins of this sophisticated technology potentially are to be found in Persia, modern day Iran, yet no archaeological evidence for this has been published so far.

Several historical manuscripts provide some information on this technology and relate it to production centres in Persia. This paper reports archaeological evidence for Persian crucible steel production, based on the medieval site of Chāhak in Central Iran, in the context of selected historical documents.

The Chāhak crucible fragments have distinctive features that had not been seen elsewhere, while some similarities with Central Asian crucibles are evident. Microstructure and elemental composition of different crucible fragments and slags were determined with optical microscope and SEM-EDS, providing information on the fabric of the crucibles, the slag composition and the metal which was produced by this process. This project attempts to open a new chapter in the study of crucible steel production by introducing the Chāhak tradition, comparing it to other Central Asian traditions of production. This may pave the way to track and study the origins of crucible steel production in the broader context of Central and Western Asia.

Keywords: Crucible Steel, Technical Ceramics, Pulād, Chāhak, Carburisation, Middle-Islamic Iran

Introduction and Background

Crucible steel, also known as *pulād* in Persian or *wootz* in an Indian context, is made either from bloomery iron by carburising, that is adding one or two weight percent carbon to change the soft iron into steel, or from more carbon-rich cast iron by de-carburising, or by a fusion of the two, inside a refractory crucible to produce a high quality steel. Carburising requires a strongly reducing atmosphere to prevail in the crucible, while de-carburising requires more oxidising conditions, that is access of ambient air. The fusion of cast iron and bloomery iron to produce steel can be done under more or less neutral conditions. In pre-industrial societies, bloomery or soft iron cannot be melted and therefore always contains some slag inclusions from the smelting, which lead to weak points in the finished artefact; for blades, this can be highly detrimental, in addition to the relatively soft character of this type of low-carbon or carbon-free iron. Cast iron in contrast can be melted and is therefore slag-free, but is too brittle for use in blades, due to its high carbon content. Crucible steel combines the best of both materials – the cleanliness of cast iron and the ductility of bloomery iron, further enhanced by the intermediate carbon content to superior elasticity and sharpness of the cutting edge. To achieve this, a liquid iron alloy with less than 3 wt% carbon needs to be formed, producing a slag-free steel ingot. Since the crusades (11-13th century AD) arms and armour made from crucible steel had been known in Western and Central Asia, and from the Indian sub-continent at the latest from English rule over the region (17-19th century AD). However, the technology of crucible steel making has been kept a secret, remaining unknown to Europeans until the 19th century, and for centuries was forgotten even in its own land.

The first archaeological remains of Central Asian crucible steel production were detected in the Ferghana valley in eastern Uzbekistan, initially mistaken for glass production (Abdurazakov and Bezorodov 1966, 80-81, 158). Eventually, Papakhristu's (1985) research identified an industrial scale crucible steel production, dating to the 9th to 12th centuries AD (see also Rehren and Papakhristu 2000). Feuerbach and Merkel in a series of papers (Merkel et al. 1995; Feuerbach et al. 1998; Simpson 2001; Feuerbach et al. 2003) introduced another crucible steel industry contemporary to Uzbekistan's tradition in Merv in Turkmenistan, variously described as co-fusion (Feuerbach et al. 1998) or carburisation of bloomery iron (Merkel et al. 1995; Feuerbach et al. 2003). Other research focused on historical texts (Allan and Gilmour 2000; Hoyland and Gilmour 2006; Karlsson 2000), but struggled to find a conclusive reconstruction of the ancient technology due to semantic problems in these technical texts (see below).

Archaeological evidence for crucible steel production in Central Asia is so far limited to the Uzbek and Turkmen sites, while most of the discussion on Persian crucible steel making is based upon historical texts. Among several production centres mentioned in the historical manuscripts, one is Chāhak, situated within the heartland of Iran (Fig. 1). This paper introduces the physical evidence of a crucible steel industry from this archaeological site, the first to be found in modern Iran, and the only known one within the central provinces of the Islamic empire. The site is located in a village with the same name at the junction of the provinces of Pārs, Yazd and Kermān (Fig. 1).

Figure 1: Location of Chāhak in the southern part of Yazd province of Iran (http://d-maps.com/carte.php?num_car=14654&lang=en)

Based on historic divisions, Chāhak belongs to Neyriz city in Pārs province, while modern divisions allocate this village to Harāt, the main city of the Khātam district in Yazd province (Fig. 2). According to historical geographic texts Chāhak was a prosperous town (Ibn-Balkhi 2006; Ibn-Balkhi 1921; Mustawfi 2010); however, it is now just a modern village on top of the ruins of the historical town.

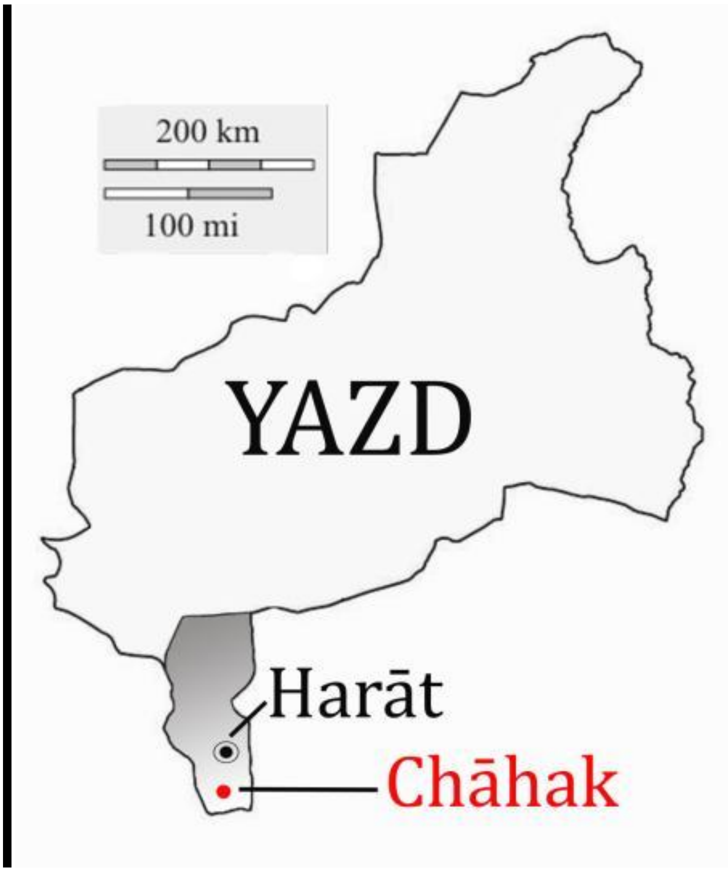

Figure 2: Location of Chāhak in Yazd province, south of Harāt city. (http://www.amar.org.ir/Default.aspx?tabid=1714)

Chāhak has so far not been excavated, but it was identified and registered by the Cultural Heritage Organisation of Iran once as a Seljuk (11th -12th century AD) and once as a Safavid (16th century AD) archaeological site. There are no significant archaeological data on this site within the national archives, and the date of the crucible steel production is not immediately clear. In contrast to the scarce archaeological information on the site, Chāhak has been mentioned in several historical geographic manuscripts from the 12th century AD (Seljuk period) onwards. Persian geographers such as Ibn-Balkhi (12th century AD) and Mustawfi (13th-14th century AD) refer to Chāhak as a town by different names such as Sāha, Sāhak, as well as Chāhak, giving information on its location, weather, vegetation, and its significant *pulād* (Persian for crucible steel) production. These records identify Chāhak as a centre of crucible steel production for the manufacture of blades and arms and armour (Mustawfi 1915; Ibn-Balkhi 1921; Ibn-Balkhi 2006, 125; Mustawfi 2010, 123). In addition, early western visitors mention Chāhak as a mediaeval site with abundant iron slags and iron smithing workshops, identifying it as an important production centre (Ibn-Balkhi 1912, 24-5; Stein 1936, 206).

One of the preserved parts of this site is protected from seasonal flooding and agricultural ploughing by a dirt road built upon a well-preserved crucible layer at the south-eastern part of the village. The stiff and compact nature of the crucible sherds provided an ideal foundation for construction of the dirt road; hence the layers remained undisturbed by farming activities (Figures 3-4). The majority of the samples for this study comprise a wide range of crucible and slag fragments collected from the upper layer where the dirt road was partially destroyed, possibly due to earlier unauthorised investigations or farming activities.

Figure 3: The location of the crucible steel deposit in the South East of Chāhak. (GoogleMap)

Figure 4: The current state of the dirt road (2012) and the crucible layer under the road.

This paper reports first results of our ongoing research, including morphological and elemental analyses of crucible and slag fragments. It also summarises the known historical documents relevant to the Chāhak crucible steel industry to aid the archaeological investigations. The manuscripts provide the historical context within which we interpret the production evidence, and provide valuable contemporary first-hand data on the crucible steel recipes and their ingredients, and on production sites and the wider cultural settings of the industry.

Historical Texts

To date at least ten Islamic manuscripts from the 8th to 15th centuries AD are known that provide substantial information on iron and crucible steel production. These historical manuscripts are categorised here in three groups: 1- Early Medieval Texts: the earliest known manuscripts mentioning iron and steel production 2- Crucible Steel Recipe Texts: manuscripts that offer recipes on the production of crucible steel 3- Later Copies and the emergence of Chāhak.

The first two groups were written during the Islamic Golden Age (8th to 13th centuries AD) providing general information on iron and steel, and on the crucible steel industry and recipes for its production, respectively. The third category exhibits a decline in the manuscript's contents, copying earlier texts. Thus, these accounts present little new information on the continuation of a crucible steel industry, but they introduce some further production sites such as Chāhak. Below, we focus on those texts which are directly relevant for the Chāhak tradition.

The translations we offer are based on earlier translations as cited in the references, and our comparison of these translations with the original Arabic texts. For texts in Persian we offer our own translation, referencing the Persian source. In the translation we keep some of the original terminology, particularly where there are words that may be ambiguous, and offer comments in square brackets.

Weight measures such as *dirham*, *ratl* and *mann* are an important part of these recipes and are essential for a reconstruction of the ancient technology; however, the actual weights of specific measures often vary from region and period, making a full quantification impossible. For a calculation of weights in gram we used data from the online version of the Dehkhoda Dictionary and Rebstock (2008), but acknowledge that other transpositions of ancient measures into modern weights are equally possible. We are also aware that over the space and time of origin of the manuscripts discussed here different values would have been understood for the measures used. For the sake of consistency, below we use an average of 3.125 g for the dirham, rounded to 3 g for convenience, and one *mithqal* as 4.5 gr. We further assume that one *mann* is 640 *mithqal* or 2880 grams, and that one *ratl* is half a *mann*, or 1440 grams.

Early Medieval Texts (8th- 9th centuries AD)

The earliest Islamic texts on iron and steel go back to the eighth century AD; they are partly cryptic and their terminology is steeped in the classical alchemical tradition. They include the 8th to 9th century AD manuscript by Jabir Ibn-Hayyān and the 14th century commentary on this text by Jildaki, as well as the much-discussed 8th to 9th century AD book by al-Kindi. We only briefly refer to them here since they have been brought by some scholars into the discussion on crucible steel. However, we do not believe that this interpretation is justified, as will be discussed elsewhere.

The first indisputable crucible steel recipe texts appear in the 10th-12th centuries AD, contemporary to the archaeological evidence from Central Asia.

<u>Biruni (10th -11th century AD – Qaznavid)</u>

Abu Rayhān Biruni (973-1048 AD) was a Persian scholar and polymath, known as the greatest scientist of Islam (Bearman 1960; Zaki 1955b, 371). He mentioned crucible steel technology in his treatise of '*al-Jamāhir fi Ma'rifat al-Jawāhir*' ('Compendium to Know the Gems'), written in Arabic. It consists of different sections and represents one of the earliest books on gemstones that later on became popular under the name '*Jawāhir-Nama*' ('Book of Gem Stones'). Biruni had a similar view on iron and steel properties as al-Kindi (Zaki 1955b, 371). Notably, he introduced certain locations of crucible steel production and provided us with the earliest crucible steel-making recipe. This manuscript played a major role as a source in recording the making of iron and steel in the next generation of *Jawāhir-Nāma or Gowhar-Nāma* by Iranian scholars.

The first crucible steel making recipe recorded by Biruni comes right at the end of his chapter on iron; any text inside [brackets] is by the authors of this paper:

> Five *ratl* رطل horseshoes with their nails, which are made of *narm-āhan,* with ten *dirham* درهم each of *rusaktaj* روسختج *[the burned], marqshisha* المرقیشا طلایی, and magnesia مغنسیا is put in a crucible, afterwards the crucible is luted [lute: clay, mud, from Latin *lutum*, mud; to lute: to seal or close a vessel with lute] with clay and put in a furnace and the furnace will be full of charcoal and blown with Roman bellows that need two men, until it [the iron] melts and whirls. Bundles are added, containing forty *dirham* ground mixture of each *halila* هلیله , pomegranate rinds, salt [used in] dough and oyster shells, and thrown into each crucible [an amount of 40 *dirham* of each ingredient]. The crucibles must be blown non-stop for an hour, then the heat must be stopped for the crucibles to cool down; and afterwards, the iron ingots are to be taken out from the furnace (Biruni 1974: 55-56; Hassan 1978: 36; Hoyland and Gilmour 2006: 155).

As it appears in this recipe, the process has two main stages. At the first stage, 5 *ratl* (about 7.2 kilograms) of soft iron (horse shoes and nails in this case) are charged into the crucible, together with 10 *dirham* each of *rusaktaj* , golden marcasite, and magnesia. The total mixture of the three ingredients would weigh about 90 grams. *Rusaktaj* is a Persian word meaning "the burned" that was used to describe black eye cosmetics or *kohl*. In this context, it could have been the black-lustrous mineral chromite, a mixed iron-chromium oxide (see below). Another ingredient of this recipe is translated as magnesia. According to medieval explanations, it is a soft stone that was mostly used in glass-making. The Dehkhodā Dictionary explains this substance as a white stone called Pargān's stone سنگ پرگان , mainly used in glass-making and other uses; the name derives from a village in the province of Pārs called Pargān that was the source of this stone. Biruni in his *Saydana* book on pharmacy explains magnesia as follows: 'it is a medicine that glass-makers and [potters] use. Some types are like soil [. . .] and some types have bigger particles and are solid. And some have red colour and some types are radiant [. . .] its characteristics are similar to *marqshisha* [marcasite] but its power is higher than *marqshisha*' (Sotudeh and Afshar 1979, 662). Other sources, such as the 19th century Persian dictionary *Anandrāj* explain magnesia as black clay coming from the Kāshān Mountains that is used for colouring glasses; it is therefore also called colouring chalk گچ رنگ. On balance, this suggests that مغنسیا is more likely manganese oxide, known in the west also as 'glassmakers' soap', rather than magnesia in its modern meaning of magnesium oxide, which is not a common additive in glass making.

The second stage introduces a different mixture. The text mentions the addition of a bag of 40 *dirham* (total of 160 *dirham*=480 grams) ground mixture of *halila* (*terminalia chebula* or myrobalan, an Asiatic prune-like fruit tree as explained in *Saydana* (Biruni 1979, 719-21)) and salt of dough (probably sodium carbonate-baking soda), oyster shell and pomegranate rinds into each crucible. The function of this mixture of organic materials and different salts will be discussed later.

<u>Khayyām (11th -12th century AD – Seljuk)</u>

A hundred years later, the second recipe of crucible steel production appears in a small chapter of the *Nowruz-Nāma* treatise "Book of the New Year", written in Persian by the polymath and poet Omar Khayyām, who died in AD 1131. This treatise contains twelve chapters on different subjects with one part "On Swords and Important Aspects about them", including a recipe for the production of crucible steel (Khayyām 1933; 2006). The editor of this treatise highlights in his introduction to the manuscript that several (minor) historical mistakes and scribal errors show that this manuscript was written in a hurry. As we will show, the crucible steel recipe also contains some scribal errors, which are perpetuated in an earlier mention of this recipe by Moshtagh-Khorasani (2007). However, this same recipe exists in another slightly later and most likely correct copy by al-Tarsusi (see below, recipe 3), which we used to identify the errors. A detailed translation and interpretation of the original manuscript together with corrections of the scribal errors is given here [text in brackets is by the authors]:

> One part *magnesia* with one part *bossad* بسد and one part *zangār* زنگار [scribal error: must be *tankār* / tincal تنکار] to be ground and mixed. Then one *mann* من *narm-āhan* نرم‌آهن [soft iron] to be constantly added and twelve *awqiya* اوقیه [scribal error: must be two *awqiya*] of that mixture to be put in a crucible and thrown to the fire to melt inside the crucible. Afterwards one part *harmal* حرمل, one part *māzu* مازو, one part *balut* بلوط, one part shell and the same amounts as the others *dharārih* ذراریح should be ground and mixed, and two *awqiya* of that mixture to be thrown to the molten iron and to be blown upon until all mix together as they become one, and the iron takes in all the mixture. Then it must cool down, and from it blades may be made (translated from Khayyām 1933, 38; 2006).

This recipe again consists of two stages:

The first stage is the preparation of a ground mixture of one part *magnesia* (MnO_2, see above), one part *bossad* (coral: its main constituent is $CaCO_3$) and one part *zangār* (iron oxide). The addition of iron oxide makes little metallurgical sense, and we believe that *zangār* is a scribal error due to its similarity in writing with the more likely ingredient *tankār*, a strong flux (تنکار tincal/borax, زنگار iron oxide). Then, it is written that an amount of 12 *awqiya* of this mixture is to be added to the soft iron. We believe that the specified amount of this mixture is the next scribal error, and that the amount must be 2 instead of 12 *awqiya*. One *awqiya* is about 40 *dirham (Dehkhoda online dictionary; Rebstock 2008, 2266)*; and 12 *awqiya* are about 1.4 kg. More likely, the weight of the mixture must be around 2 *awqiya* or 240 grams, similar to quantities in other recipes. The amount of soft iron in the recipe is indicated as one *mann;* thus, about 2.9 kilograms soft iron together with 240 grams of the mixture are thrown into each crucible.

After the iron melts inside the crucible, the second stage of the process includes the addition of another mixture, of one part *harmal* (Persian: *espand* اسپند- English: peganum harmala), one part *māzu* (apple gall), one part *balut* (acorn), one part shell and one part *dharārih* (cantharis). These ingredients must be ground and 2 *awqiya* (240 grams) of this mixture are to be added to the molten iron inside the crucible and then fire blown upon it until all mix well.

<u>Mard Ibn Ali al-Tarsusi (12th century AD- Ayyubid)</u>

Half a century later, Mard Ibn Ali al-Tarsusi (1138-1193 AD), a writer and military expert of the Ayyubid era (contemporary to Seljuk era in Iran), who was probably from Egypt or Syria, wrote military manuscripts including the *Tabṣirat arbāb al-albāb fī kayfīyat al-najāh fī al-ḥurūb min al-aswā*, about the making of arms and armour, war tactics and army orders. This treatise was written in AD 1187 for Sultan Saladin Ayyubid, and includes crucible steel making recipes. Zaki (1955b, 372) states that al-Tarsusi was in contact with an Alexandrian arms-smith named Abu al-Hassan Ibn-al-Abraki. The original text contains only four crucible steel recipes (Cahen 1947; Raqib and Fluzin 1997), contrary to some scholar's report of nine recipes (Zaki 1955a; Karlsson 2000). One of the recipes of al-Tarsusi's manuscript parallels Khayyām's recipe, but without the scribal errors identified above, suggesting that he used the same source as Khayyām for his manuscript, but copied it more carefully:

First recipe:

> Take *narm-āhan* [soft iron] from the head of old nails which is the best type, and throw on it 17 *dirham* of Kabul's *halila* [myrobalan] and the same amount of *balilaj* بليلج [bellirica]. Then put the iron pieces in a bowl and wash [moisten?] with water and salt and then mix and throw the iron and the drugs into a crucible and add one and half *dirham* crushed *magnesia* and put in a furnace and blow fire upon it so it melts and shapes egg-like [ingot]. It takes several days. Then let it cool and afterwards make swords from it, which are a deadly poison (based on the Arabic text from Cahen 1947,106, 127; Raghib and Fluzin 1997, 67).

Contrary to Biruni's and Khayyām's recipes the process is carried out in one stage; reporting melting together soft iron and plant matter such as myrobalan and bellirica (a bastard myrobalan common in Southeast Asia). These would be washed, that is possibly moistened, with salt before *magnesia* is added.

Second recipe:

> Take three *ratl narm-āhan* [soft iron] and half *ratl shāpurgān/shāburqān* شاپورگان/شابرقان [hard iron/cast iron] and put in crucible and cast on it 5 *dirham* of *magnesia* and a handful of peels of the sour pomegranate رمان حامض. And blow it in the foundry to melt and take the shape of an egg, then take it out and make a sword from it (Arabic text after Cahen 1947, 106, 127; Raghib and Fluzin 1997, 67; Zaki 1955b, 373).

This recipe is of great importance as it is the first to mention the co-fusion of soft iron and cast iron. It is again a one-stage procedure. The much lower quantity of organic carburising matter and the addition of cast iron are consistent with each other, and indicative of the introduction of another method of crucible steel making, by co-fusion.

Third recipe:

> [Take] one part of magnesia that is mentioned earlier, one part *bossad* [coral] and one part *tankār* [borax] and crush them up and put them aside; then take one *mann narm-āhan* [soft iron] of iron filings and take two *awqiya* of this mixture and fire it until it softens and takes the round shape of the crucible. Then take a share of *harmal*, *'afs* عفص *[Thuja tree of cypress family)*, *balut [acorn]*, and *sabr* صبر *[aloe]*, and the same amount as others, *dhararih*. You grind these and throw two *awqiya* of this mixture to that one *mann* iron and blow upon it until a rainbow colour rises from the crucible; when it reaches this stage let it cool down and then you make [from it] whatever you like (Arabic text from Cahen 1947, 106, 127; Raghib and Fluzin 1997, 68).

This recipe is the same as Khayyām's earlier recipe. However, at the beginning Tarsusi states *magnesia dhakara*معنيسيا ذَكَر; this means 'the magnesia that was mentioned earlier'. The word *dhakara* ذَكَر has two different meanings, one is 'mentioned' and another one is 'male'. We interpret this here to mean 'mentioned earlier', in contrast to Cahen (1947) and Raghib and Fluzin (1997) who translated this word as male and attributed it to the magnesia as 'male *magnesia*'.

Fourth recipe:

> Description of Sulaymāni Pulād of which swords are made with the same name (Cahen 1947, 107, 127; Raghib and Fluzin 1997, 68): [Take] 20 *dirham* halila murabba اهليلج مربى [myrobalan confiture], 7 *dirham* magnesia, 5 *dirham saqmunia* سقمونيا [scammony], and mix and crush these very well. Then add 3 *ratl* of *shāpurgān/shāburqān* [cast iron] and blow on it until melted in a crucible whose lid has a hole to observe [the process] from it with a rod of iron until it is melted and you take it [the crucible] out of the furnace and leave it to cool and then make what you want. For example if you hit it [a blade made of this] to a 20 *ratl* iron bar, [the sword] will cut it with the help of God (Cahen 1947, 106-7; Raghib and Fluzin 1997; Karlsson 2000, 246).

The last recipe of Tarsusi's manuscript is the only one attributed to a special type of *pulād* and the sword of Sulaymāni سليمانى. It is significant as it appears to be the first account of a decarburisation process, even though it still advises to add a substantial amount (20 *dirham* /about 60 grams) of organic matter to the charge, something that is not consistent with a de-carburisation process. It also, for the first time, mentions the use of an iron rod to check the mixture from a hole in the crucible lid, suggesting that the crucibles used for this process were different from the carburising ones.

<u>Jowhari Nishāburi (12th century AD - Seljuk)</u>

Less than a decade after al-Tarsusi's treatise, Jowhari Nishāburi wrote *Jawāhir-nāma Nazzāmi* "Nazzāmi's Book of Jewels" (AD 1195) for one of the ministers of the Khwārazm-shāh court. Jowhari Nishāburi was a prominent Persian writer and scholar in geology. This text shows an extensive use of Biruni's manuscript, providing comprehensive information on iron types and different varieties of *pulād* based on their visual differences and patterns (*gowhar*). He does not, however, copy Biruni's crucible steel making recipe, and is only relevant here as an intermediary and translator for Biruni's Arabic text into Persian.

Later Copies and the first mention of Chāhak in crucible steel making recipes

Following the Mongol invasion in the early 13th century, there seems to have been a decline in the recording of new information on crucible steel production. The surviving texts are mostly copies of the previous manuscripts with little new contribution. It is noteworthy though that the pre-Mongol manuscripts only mention India and a few other sites in Iran (such as

Harāt) as centres for crucible steel making. The appearance of Chāhak as a crucible steel production centre in the later texts is therefore of particular importance to this study to locate this technology in the heartland of Persia (Table 1).

Nasir al-Din Tusi (13th century AD- late Khwārazmian or early Ilkhānid)

The first manuscript after the Mongol invasion mentioning crucible steel is *Tansukh-Nāma,* "The Book of the Rare and Exquisite", by Nasir al-Din Tusi (1201-1274 century AD /late Khwārazmian early Ilkhānid period) (Tusi 1274, Central Library of Tehran University No: 2457/7; Tusi 1984, 220-222). The main source of this treatise is the *Jawāhir-Nāma Nazzāmi* of Nishāburi. The significance of this script for us is the introduction of Chāhak. To our knowledge, this is the first to mention this production centre in crucible steel related manuscripts. However, Chāhak had already been mentioned in Ibn-Balkhi's (12th century AD-Seljuk) historical and geographical accounts of Fars province, as a *pulād* making centre. Therefore, one could infer that Chāhak continued its crucible steel production from the Seljuk into the Ilkhānid period, even if the essence of the discussion on the types of iron goes back to al Biruni, via Nishāburi:

> There are lots of iron mines available in most of the cities. Iron has two types: پولاد *pulād*, and *narm-āhan* [soft iron]. *Pulād* has also two varieties: one is the made or worked *pulād* and the other is mined; and mined *pulād* is called *shāverān* شاوران (*shāburqān/shāpurgān*), and other *pulāds* are made of *narm-āhan* [soft iron] with some medicine in Khurāsan; a better *pulād* is made in Harāt and a variety of *palāraks* پلارک [several different natural patterns of crucible steel in the blades] are all made of iron […] the best *palārak* is *Shāhi* شاهی and is made in India, and blades are built in Pārs known as Chāhaki, have been made nearby. They look proper, white and full of patterns. At first they were thought to be Indian blades, but since they were dry and brittle they soon lost their value […] (Tusi 1274, Central Library of Tehran University No: 2457/7; Tusi 1984, 220-222. Translation by the first author).

The mentioning of the crucible steel centre of Chāhak is remarkable. It is contemporary to the *Shāhi* type of crucible steel that was made in India and the ones of Harāt. The ingots are called *palārak* based on the appearance of the crucible steel patterns in the final blades. This term was formerly introduced by Nishāburi, who in turn took it from Biruni. *Chāhaki palārak* is considered to be a very good type of crucible steel full of *gowhar* گوهر [the patterns that are visible on the crucible steel blades], and was at some point mistaken for *Shāhi* or Indian steel; although, later on, due to the brittleness of *Chāhaki* blades they were differentiated from *Shāhi palārak* and were no longer sold at the same price.

Sadr al-Din Muhammad Ibn -Mansour Dashtaki Shirāzi 15th century AD- Timurid

The final manuscript to be mentioned here was written by Dashtaki (AD 1424-1497) from Pārs province. His *Jawāhir-Nāma* "Book of Jewels" is the latest local manuscript written in Persian relevant to this paper. Dashtaki was a prominent philosopher also known as *Sayed-e Sanad* (Sayed of the Documents) by Mollāsadra (Bahārzada 1999, 139).

> *. . . Palārak* پلارک is of some types: *shāhi*, *Chāhaki* and *ruhinā* روهینا. *Shāhi palārak* have white and big *gowhar* گوهر [patterns] that are in altar shape. And *ruhinā* has even bigger patterns as if they were designed by fingertips and like this […]. And *Chāhaki palārak* has got a lot of white patterns but is dry and brittle and is sometimes as much as a fingertip or more blackish and free from pattern that is not good especially if it shows on both sides of the blade *. . . Rūhinā* and *shāhi palārak* are made in India and Chāhaki *palārak* is made in Pars [. . .]. On the prices of these, Farangi فرنگی [Frankish = foreign, European] iron that is soft and white is one of the best and a blade made of it worth one thousand Egyptian dinars*.* And *shāhi palārak* [kingship palārak] is the best of the *palāraks*; afterwards, comes *ruhinā*, and then

> Chāhaki *palārak*, which is of the best figure and pattern and in the beginning was deemed as Indian *palārak* and was sold to the same price, but when examined it was found to be dry and brittle and its glory and value decreased as it is said by the professionals of the time that good iron must have a whitish hue and does not have different or two natures (Dashtaki 15th century AD, Tehran University Library No. 3881, and No. 1285; translation by the first author).

The similarity in content and expression to Tusi's text suggests that Dashtaki based his account on Tusi's earlier manuscript, and does not necessarily report current or new information. Similarly, Dashtaki's manuscript itself was copied several times. More than seven copies of this manuscript, with minor differences, were detected during the first author's research among different archives in Iran; their composition spanning the 16th, 17th, 18th and 19th centuries AD, without adding any further information.

In summary, most of the historical texts relating to crucible steel and its production can be arranged into a lineage of copies, with little new information being added in the later versions. The main recipe consists of a two-stage process in which first a few kilograms of soft iron, often scraps such as nails or horse shoes, are placed into a sealed crucible with a bag containing a mixture of around a quarter kilogram of minerals and plant matter, and heated until molten. Then a further quarter kilogram is added of another mixture of plant and mineral matter and the content fired for another extended period, said to reach several days. After this, the resulting liquid steel is allowed to cool within the crucible, forming an egg-shaped ingot ready to be worked into artefacts. Some recipes report only the first stage and only al-Tarsusi reports in two of his four recipes the use of cast iron as the starting material instead of soft bloomery iron.

In our understanding, the role of the plant matter is to provide the carbon necessary to transform the soft iron into steel, thereby lowering its melting point to within the reach of medieval furnaces, as well as strongly improving the quality of the metal. The role of the mineral additives is less clear; they range from borax and various carbonates (baking soda, various forms of calcium carbonate such as coral and shells), possibly oxides of steel-related metals such as manganese and chromium, to sulphides (marcasite). Some of these may act as fluxes to stimulate slag formation, such as borax and the carbonates, others possibly facilitated carburisation of the iron, such as the manganese compounds or entered the alloy, such as chromium. However, the role of the sulphides is less clear, and would need further research to verify the terminology before their role can be fully discussed.

Table 1: Appearance of names of cities and countries related to crucible steel making in Persian texts.

	Biruni (10th - 11th century AD – Qaznavid)	**Khayyām** (11th -12th century AD – Seljuk)	**Jowhari Nishāburi** (12th century AD – Seljuk)	**Nasir al-Din Tusi** (13th century AD- Ilkhānid)	**Dashtaki Shirāzi** (15th century AD- Aq-Qoyunlu& Timurid)
Iron Mines	**Armania** (An Abbasid province of Iran including Azarbaijān, Armenia and Georgia)		**Khorāsan** (Tus mountains)		
***Pulād* (crucible steel)**	**Harāt**: *Āhan-e-pulād* (Iron-Steel)		**Harāt**: *pulād* ***Hindoustān***(India): *Shāhi palārak*	***Hindoustān***(India): *Shāhi palārak* **Pārs: Chāhaki** *palārak*	***Hindoustān***(India): *Shāhi palārak* **Pārs**: **Chāhaki** *palārak*
***Tāfteh* (welding)**	**Sindh** (today's Pakistan)		***Hindoustān***(India): *Sulaymāni tāfta*		
Sword types (those representing production sites)	Pulād: **India**, **Yemen**, **Khorāsān, Multān** (today's Pakistan) Shāburqān: ***Saqālabi***(Slav) and ***Rumi*** (Roman)	Among 14 sword types: **Yemen**, **India**, **Damascus**, **Egypt**, **Khorāsān** (Salmāni)	Rouhinā (Iron of war): **Multān** (today's Pakistan) Like Rouhinā: **Yemen** Combination of *pulād* and *narm-āhan*: **Bulgār** (probably Bulgarian)		Rouhinā: ***Hindoustān***(India)

Archaeological Samples

Based on the historical manuscripts, the first author identified Chāhak as a potential archaeological site of crucible steel production, the first to be known in Iran. Following intensive surveys a layer of crucible sherds was discovered eroding out of the soil near a road just south of the modern village of Chāhak. The layer is exposed over a length of about 15 meters along the side of the road, and reaches a thickness of about 15 to 40 cm at its maximum (Fig. 4). It consists predominantly of crucible fragments, seemingly of the same basic type; very little other pottery or finds are associated with this layer. Having obtained formal permission from the relevant Iranian authorities for Cultural Heritage, a preliminary investigation of the site was started and samples removed from the surface layer for detailed morphological and technological study. A full archaeological assessment of the site in general and the crucible layer in particular remains to be done. Surface finds of domestic and decorated pottery are consistent with the Seljuk-period date of the site recorded in the files of the Cultural Heritage Organisation.

Morphology

Some 300 Chāhak crucible fragments were studied to identify their common physical characteristics. Several distinct types of fragments can be identified, all relating to one basic crucible type. From the top down, these include lids, upper body fragments, body fragments with a slag line, lower body fragments, the base, and pads on which the crucibles stood. They assemble to form tall cylindrical vessels with a dark grey, nearly black and very dense, fine grained fabric. A vitrified layer has covered the outer surface of the crucibles, increasing from a thin film near the top to a thick irregular flow near the base of the vessels. Base fragments have concave interiors which would have imparted an oval shape to the ingots, reminiscent of the egg-shaped form recorded in the historical accounts. Additionally, the majority of Chāhak base-fragments have a small rounded pad adhering to their underside. These pads have a reddish colour and sometimes contain large calcareous inclusions that result in crumbling and peeling off of the ceramic (Fig. 5). The body sherds can be grouped into upper and lower fragments, separated by a distinct line of slag. The lower fragments reach from the base up to the slag line, while upper fragments reach from the slag line to the rim. Numerous fragments span across the slag line, combining upper and lower body characteristics. The slag line is typically less than a centimetre thick and solid glassy with minute metal inclusions, and sometimes developed as a thin ‘fin’ extending away from the ceramic (Fig. 6). The slag is glassy or opaque with dark or light green colour. The majority of upper body sherds retain textile impressions on their interior profile (Fig. 7; see also Alipour 2010; Alipour et al. 2011). In contrast, the inner surface of the crucibles below the slag line is covered with a thin layer of rough slag, obscuring the original ceramic surface. As discussed elsewhere (Rehren and Papakhristu 2000) this surface pattern is due to the formation of the steel ingot in the lower part of the crucibles, with any slag floating on top of the metal and forming the characteristic slag line.

Figure 5: Chāhak crucible base fragments with pads adhering to them (left: cross section; right: bottom view).

Figure 6: Slag layer inside the crucible. The fragment shows the slag-line; trapped bubbles are visible at the lower part of the slag. This slag is partly devitrified as can be seen from the *schlieren* pattern (upper centre).

Figure 7: Upper body fragment of Chāhak crucible. The interior has textile impressions and a seam-line (centre of left image); right: exterior surface of the same piece.

The lids of the Chāhak crucibles are hemispherical with a solid body, i.e. not bowl-shaped as the lids from the Uzbek crucibles (Rehren and Papakhristu 2000). They seem to consist of a lump of soft clay that was applied to cover the opening once the crucible was filled. This clay lump often took at its base impressions thought to be from bags of some ingredients that were added at the top of the original fill of the crucible. Afterwards a layer of lute would cover the lump of clay for a full coverage and sealing over the crucible rim. A peculiar feature is the presence of three or four pieces of recycled crucible wall fragments embedded radially or arranged in a cross-shape respectively on top of each lid (Fig. 8), as if to be used as handles. In contrast to the Central Asian lids, these lids do not have any holes or piercings in them.

Morphological observations and wall thickness measurements of 101 crucible body sherds reveal a tapering tendency from the base (average wall thickness of 15 mm) towards the rim (average of 3.3 mm). Based on the largest surviving fragments and a calculation of the thickness change rate per centimetre of sherd height, we calculated a tentative average crucible height of 27 cm, acknowledging that some variability may have existed. The inner diameter of the crucibles is on average 67 mm, based on 17 crucible fragments ranging from 57 mm to 79 mm in diameter. The total volume of the average crucible is in the order of 1 litre, ranging from circa 0.75 to 1.5 litres when the extreme dimensions are taken. This value is very close to the reconstructed volume of the crucibles from Uzbekistan (Rehren and Papakhristu 2000: 58), with whom the Chāhak crucibles also share the basic shape and dimensions.

Fig 8: Chāhak crucible lids (seen from above) with 4 (left) and 3 (right) ‘handles’ made of recycled crucible sherds set in the lid.

Microanalysis

Chemical analysis of the crucible itself and the slag inside the crucible was conducted to determine whether the crucibles can be linked to crucible steel production, to assess the technical suitability of the ceramic for the task, and whether the slag can be related to the historical recipes. This work is on-going, and here we present only preliminary data. A fuller data set and discussion will be published elsewhere once the analyses have been completed.

Scanning Electron Microscopy coupled with Energy-Dispersive Spectrometry analysis (SEM-EDS) of crucibles identifies the fabric as made from well processed refractory clay of high silica and alumina content with an alumina-silica ratio of 1:2.6 (Table 2).

	Composition (compound %)									
	Na2O	**MgO**	**Al2O3**	**SiO2**	**K2O**	**CaO**	**TiO2**	**MnO**	**FeO**	Information
W67s	bdl	0.7	25.4	63.0	1.4	1.3	1.5	0.5	6.6	Average of 3 analyses, MnO only in one
W92s	0.4	0.7	25.4	63.3	1.6	1.3	1.8	bdl	5.5	Average of 2 analyses
W73s	0.6	0.7	25.1	63.0	1.4	1.2	1.6	bdl	6.5	Average of 3 analyses
W85S	0.6	0.7	25.6	63.6	1.3	1.2	1.5	bdl	5.7	Average of 4 analyses, Na2O absent in one
W84S	0.6	0.7	25.7	62.9	1.4	1.1	1.5	1.1	5.7	Average of 3 analyses,

t										MnO only in one
W80S	0.2	0.9	26.8	62.6	1.5	1.4	1.8	bdl	5.1	Average of 3 analyses, Na2O only in one

Table 2: Bulk composition of crucible ceramic from Chāhak, Iran; SEM-EDS data in wt%. *The iron content of the crucibles is reported as iron oxide; due to the strongly reducing conditions in the process this has been reduced to metallic iron.

In contrast, the pads have a much more heterogeneous matrix, zones of poorly mixed clay and random occurrence of calcareous inclusions. The EDS analysis reveals significant differences in composition between pads and crucible bodies (Table 3), with the pads being made from highly calcareous clay and hence far less refractory than the crucibles.

Composition (compound %)										
Base fragment	Na2O	MgO	Al2O3	SiO2	SO3	K2O	CaO	TiO2	FeO	Information
Bulk Analysis	1.0	2.3	8.2	56.6	bdl	1.4	26.0	0.6	3.8	Average of 3 analyses
Matrix	1.1	2.7	8.7	54.1	bdl	1.6	25.9	0.6	4.8	Average of 3 analyses
Lime rich inclusions	bdl	1.7	1.7	31.9	0.8	bdl	62.8	0.1	1.1	Average of 2 analyses
Quartz inclusions	bdl	bdl	bdl	100	bdl	bdl	bdl	bdl	bdl	Average of 2 analyses

Table 3: Bulk composition of crucible pads from Chāhak, Iran; SEM-EDS data in wt%.

The fin-like slag layer is marking the upper level beneath which the metal settled before cooling down to form the ingot. The slag is in most cases a transparent dark green glass, but occasionally, it is partly opaque from having crystallised. We analysed glassy and crystalline regions separately to determine whether there is any significant difference in their composition. So far, the SEM analyses did not reveal any significant compositional difference between glassy and crystalline regions. Both areas contain about 45 wt% silica and roughly equal amounts of alumina, lime and manganese oxide, but very little iron oxide (Table 4).

Composition (compound %)												
Slag fragments	**Na2O**	**MgO**	**Al2O3**	**SiO2**	**SO3**	**K2O**	**CaO**	**TiO2**	**Cr2O3**	**MnO**	**FeO**	**Information**
Crystalline												
W67S	0.7	1.7	17.2	45.4	bdl	1.5	10.7	0.9	0.6	15.6	6.1	Average 3 analyses (Cr2O3 in two)
W92S	0.6	3.2	13.4	45.8	bdl	2.2	16.8	0.8	0.8	14.3	2.2	Average of 5 analyses and

												Na2O in four)
W73S	0.5	2.7	18.9	46.9	bdl	1.0	14.2	1.1	1.5	12.0	1.2	Average of 5 analyses
W85S	0.4	1.8	16.1	43.4	0.7	1.0	18.2	1.0	1.6	13.6	2.7	Average of 3 analyses (S in one)
Glassy												
W67S	0.6	2.4	15.0	43.5	bdl	1.5	11.3	0.8	0.9	21.0	3.1	Average of 2 analyses (Na2O in one)
W73S	0.4	2.7	17.4	48.4	bdl	1.3	14.2	1.1	0.7	13.3	0.7	Average of 2 analyses (Na2O in one)
W80S	0.4	5.5	16.8	49.0	bdl	1.3	19.8	1.2	0.3	5.7	bdl	One analysis
W84St	0.6	3.7	15.4	45.3	0.6	2.3	16.3	0.9	0.5	10.7	3.4	Average of 2 (S and Na2O in one of the two analysis)

Table 4: Bulk composition of crucible slag from Chāhak, Iran; SEM-EDS data in wt%..

Countless metal droplets or prills pervade the slags. The EDS analysis of well-preserved metal prills identified iron as the main constituent, with phosphorous, chromium and manganese as minor components (Table 5). The very high levels of chromium in some of the metallic prills are remarkable, and indicate both a strongly reducing atmosphere within the crucibles and the addition of some chromium-rich material to the original iron. One of the minerals mentioned in the recipes is named *rusakhtaj* or 'the burnt'. This descriptive term is not very specific to a particular mineral, and as in other cases may indeed have been used for a variety of minerals. In view of the analyses here, and the proximity of a modern chromite mine to Chāhak, it could be that this compound here was the black shiny mineral chromite, $FeCr_2O_4$.

Iron droplets	**Si**	**P**	**V**	**Cr**	**Mn**	**Fe**	**Ni**	Information
Glassy Slag								
W67S	bdl	bdl	bdl	0.7	0.7	98.5	bdl	Average of 2 analyses (Ca only in 1)
W73S	bdl	0.6	bdl	1.2	bdl	98.3	bdl	Average of 3 analyses
W84St	bdl	1.1	bdl	1.7	bdl	93.0	bdl	Average of 3 analyses
Crystalline Slag								
W73S	bdl	bdl	bdl	2.3	0.6	96.3	0.7	Average of 3 analyses
W85S	0.5	0.8	bdl	0.4	0.4	98.6	bdl	Average of 6 analyses (Si in 1 and Ca in 2 analysis)
W92S	bdl	0.4	bdl	0.6	bdl	99.2	bdl	Average of 2 analyses, P only in 1 analysis
Crystalline Slag-crucible Interface								
W67S	bdl	bdl	0.6	7.4	bdl	92.0	bdl	Only 1 analysis
W73S	bdl	bdl	0.7	12.1	bdl	87.2	bdl	Only 1 analysis
W80S	bdl	1.0	bdl	2.0	0.6	96.8	bdl	Average of 2 analyses (Mn only in 1)
W84S-t	0.5	4.8	bdl	3.0	0.8	91.6	bdl	Average of 2 analyses (Si in 1 analysis)
W85S	bdl	12.4	bdl	4.0	bdl	83.6	bdl	Only 1 analysis (white lines of a

								banded iron structure)
W92S	bdl	bdl	bdl	8.9	0.1	90.3	bdl	Only 1 analysis

Table 5: Composition of metal prills in crucible slag from Chāhak, Iran; SEM-EDS data in wt%.

Discussion

Historical Data

The early medieval texts provide some fundamental information related to iron and steel production in Islamic Persia. Not all of these, however, are related to crucible steel. The earliest text, Jābir's book on Iron, brings iron production under calcination which in the order of his book is much closer to iron smelting than crucible steel making.

Later, al-Kindi (8th-9th century AD) wrote a treatise exclusively on swords. He only mentions crucible steel production in a short sentence of "purifying soft iron with addition of something". This could equally refer to any carburising or co-fusion process.

Only from the Qaznavid period, 10th-11th centuries AD onwards more details appear in the relevant manuscripts. Biruni is the first to record a recipe of crucible steel making. In addition to a general use of al-Kindi's treatise as a source, Biruni's manuscript contains much new information, such as the first carburisation recipe and the mention of production sites such as Harāt.

Interestingly, Biruni's recipe reflects some of the social and cultural settings in which the technology is embedded. As in most historical crafts, the specialist's choices in conducting their processes seem to go beyond the technological purposes and exhibit influences of other cultural and social factors (Sillar and Tite 2000; Killick 2004). Pomegranate has always been a holy fruit in Iran. It is said to be the fruit of heavens, so the addition of this ingredient is likely to be a selective choice for its dual properties: one is that pomegranate rinds are dried organic materials ideal for carburising purposes and abundant in Iran; additionally they may be used in order to dignify the process or give some heavenly and super-human powers to the resulting steel. These culturally embedded technological choices are also reflected in Khayyām's recipe. '*Peganum harmala*', an ingredient mentioned in the second stage of Khayyām's recipe, has mystic applications to this day. One of these is to ward off the evil eye by throwing pieces of *peganum* into the fire. Thus, besides its technical use as a carburising agent for which any carbonaceous matter would have been suitable, *peganum harmala* might have been used specifically to ensure a successful steel-making process by protecting it from evil eyes.

Khayyām's *Nowruz-Nāma*, written during the 11th-12th centuries AD is of great importance. Khayyām is mostly famous for his scientific and poetic writings, but his accounts of crucible steel making did not receive the same attention by today's scholars as the work by Biruni or al-Kindi. This may be because the name of the treatise "Book of Nowruz [the Persian new-year]" shows no relevance to its scientific section on swords and the previously unpublished recipe of crucible steel preparation. However, Khayyām provides, after Biruni's manuscript, only the second known recipe of crucible steel making by carburisation. Half a century later, during the 12th century AD, al-Tarsusi, an Ayyubid military expert wrote a significant manuscript on arms and armour. He provided four remarkable recipes of crucible steel making, the third of which is a parallel copy of Khayyām's recipe while the first has some similarities to al-Biruni's recipe. In addition, his treatise contains two new recipes including the first co-fusion and de-carburisation recipes. After this, it seems that only copies of the existing recipes were transmitted in subsequent manuscripts, without adding any further technical information.

Chāhak is first mentioned in relation to crucible steel making in the 12th century AD, during the Seljuk Empire. Ibn-Balkhi, writing before the Mongol invasion, refers to it as a centre for *pulād* production in his geographical account of Pārs Province, while half a century later Tusi wrote a manuscript on iron and steel that for the first time discusses the quality of crucible steel from Chāhak compared to that from India and Harāt, the other production sites which are repeatedly mentioned. Thus, these two texts suggest that the tradition of crucible steel making in central Iran did not suffer the same fate as the Central Asian ones, but that the production continued after the Mongol invasion. The manuscripts and books on the history of the region clearly document that in contrast to most Northern cities in Central Asia, Pārs did not suffer the same destructive fate. During the rule of Atabaks of Pārs (1148 to 1286 AD) Mongols invaded Iran in three episodes (Sykes 1915, 127; Pigoulevskaya *et al.* 1967, 305; Gronke 2008, 43). Atabaks in turn complied with the Mongol Ilkhanate. This included becoming submissive and tributary to them in order to prevent Pārs from destruction (Shamlouie 1968, 476 and 484; Eghbal 1968, 108, 145; Bayani 1988, 200, 345-46; Rezaie 1997, 755; Sykes 1915, 128). Thus, those in Pārs were not sacked by the Mongols and continued to flourish. It is therefore not surprising to see here continuity in crucible steel production beyond the early 13th century AD.

During the 15th century AD, Dashtaki wrote the last *Jawāhir-Nāma* mentioning the production of crucible steel in Chāhak. However, the similarity of Dashtaki's treatise to earlier manuscripts makes one hesitate to conclude whether Chāhak continued an active production at that time or not, a question only full archaeological fieldwork can answer.

The technology of crucible steel production

A close study of all of the recipes shows that these were not comprehensive enough to be used as a guide to produce crucible steel; yet, they are of great importance as first-hand data for scholars for historical traces of the technology (Table 6).

		Biruni 10th -11th AD	**Khayyam and Al-Tarsusi 11th-12th AD**	**Al-Tarsusi II 12th AD**	**Al-Tarsusi III 12th AD**	**Al-Tarsusi IV 12th AD**
	Process type	Carburisation	Carburisation	Carburisation	Co-fusion	Decarburisation
First Stage Ingredients	**Iron**	5 *ratl* horseshoes and their nails (7.2 kg)	1 *mann* soft iron (iron filings) (2.9 kg)	soft iron (weight not specified) old iron nails	3 *ratl* soft iron (4.3 kg) half a *ratl shāburqān* (720 g)	3 *ratl shāburqān* (4.3 kg)
	Mixture weight	30 *dirham* (90 g) equal amount	2 awqiya (240 g) equal amount	35.5 *dirham* (106.5 g) different weight for each ingredient then wash with water and salt	different weight for each ingredient	different weight for each ingredient
	Rusakhtaj/ Chromite	Yes	-	-	-	-
	Golden Marcasite	Yes	-	-	-	-

	Magnesia	Yes	Yes	1.5 *dirham* (4.5 g)	5 *dirham* (15 g)	7 *dirham* (21 g)
	Coral	-	Yes	-	-	-
	Tincal/Borax	-	Yes	-	-	-
	Myrobalan	-	-	17 *dirham* (51 g)	-	20 *dirham* (60 g)
	Bellirica	-	-	17 *dirham* (51 g)	-	-
	Peel of sour Pomegranate	-	-	-	one handful	-
	Scammony	-	-	-	-	5 *dirham* (15 g)
	Other information			Process finished	Process finished	Process finished
Second Stage Ingredients	**Mixture weight**	a bundle of 40 *dirham* of each (480 g)	2 awqiya (240 g)			
	Myrobalan	Yes	-			
	Pomegranate rinds	Yes	-			
	Salt	Yes	-			
	Oyster shell	Yes	Yes			
	Peganum harmala	-	Yes			
	Oak apple gull	-	Yes			
	Acorn	-	Yes			
	Cantharis	-	Yes			

Table 6: Overview of technical details of crucible steel recipes from historical texts.

The table illustrates the different recipes of crucible steel-making to enable a comparative analysis of the methods and ingredients. Three recipes refer to carburisation methods, and are recorded between the 8th to 9th centuries AD until the 12th century AD. Two other methods from the 12th century AD are the co-fusion and decarburisation methods of al-Tarsusi. The carburisation recipes report a usage of about 3 to 7 kg soft iron. The additional mixture added at the first stage of firing weighs from about 90 to 240 grams. The amount of iron and mixture may differ among recipes, but all three recipes present a similar approach to the amount of iron and mixture into the crucible. The difference may be due to the availability of carburising materials. Among the mixture ingredients ‘magnesia’ is the only one that is used in all the carburisation recipes, varying from 4.5 grams (al-Tarsusi) to 80 grams (Khayyām) and seen as manganese oxide in the crucible slag. The two carburisation methods of Biruni and Khayyām state addition of some coral and oyster shell; this may be the origin of the high calcium content detected in the slag. Significantly, sulphur was not found in any of the crucible slags analysed so far, despite the mention of marcasite in some of the recipes; however, there appears to have been a source of chromium in the Chāhak recipe, possibly mentioned as *rusakhtaj* ‘the burnt’ in the historical accounts.

Overall, the carburising mixtures comprise several organic materials and minerals used for a number of reasons, such as creating strongly reducing conditions in the crucible and providing the molten iron with carbon coming from the organic materials. The indication of several two-stage processes and a one-stage process indicates that at least two different types of carburising methods existed. However, a question arises how the second mixture was added into the crucibles and whether the crucibles and furnaces for this type of two-stage process were any different from the one-stage method. Most likely the reports are incorrect when mentioning the addition of the second bag. Either, this took place during an interruption in the process when the charge had cooled and the crucible opened and re-sealed again, or no second stage existed at all.

Archaeological data

Macro-analysis and crucible re-construction

The Chāhak crucibles share their main morphological characteristics with other Central Asian crucible steel-making crucibles (Rehren and Papachristou 2003), as well as having their own peculiar features (Table 7). This mixture of similarities and contrasts may indicate possibilities to identify technological innovation, evolution and exchange of traditions within the Central and Western Asian context. It also raises a question whether the Chāhak tradition pre- or post-dates the beginning of the Turkmen and Uzbek traditions. To address this question more archaeological information and a closer dating of the Chāhak site would be necessary.

Chāhak Crucibles' Morphological Features	**Central Asian Crucibles Sharing Similar Features**
Tubular	Turkmen- Uzbek
Having Lids	Turkmen- Uzbek
Lids having handles	Exclusive of Chāhak crucibles
Lids do not have central holes	Exclusive of Chāhak crucibles
Having dark grey fabric	Turkmen
Body sherds' interior having textile impressions	Turkmen- Uzbek
Slag line is visible	Turkmen- Uzbek
Thin, dark green slag fin	Turkmen
Base fragments having clay pads	Turkmen
Body sherds' exterior covered with fuel ash glaze	Turkmen- Uzbek

Table 7: Morphological similarities and differences of Chāhak and Central Asian crucibles.

The diameter measurements of 17 Chāhak crucibles range from 57 mm and 79 mm. Such a significant scatter among the diameter size indicates a considerable variation among the crucibles. As we have argued elsewhere (Alipour et al. 2011), the Central Asian crucibles were not wheel-thrown and instead made using textile-covered templates. The same seems to have been the case here, as indicated by the textile impressions on the insides of the crucibles. However, there were probably several templates, leading to variable crucible diameters reinforced by random copying errors or different workshops and specialists. In comparison, the interior diameters of 32 crucibles from Akhsiket are ranging only from 64 to 74 mm (Alipour 2010), with an average of 69 mm. Apparently, the degree of variation in Chāhak crucible diameters is wider than that of Akhsiket samples. This is a good indication of different degrees of standardisation in crucible manufacture between Chāhak and Uzbek/Akhsiket ones (Figures 9-10).

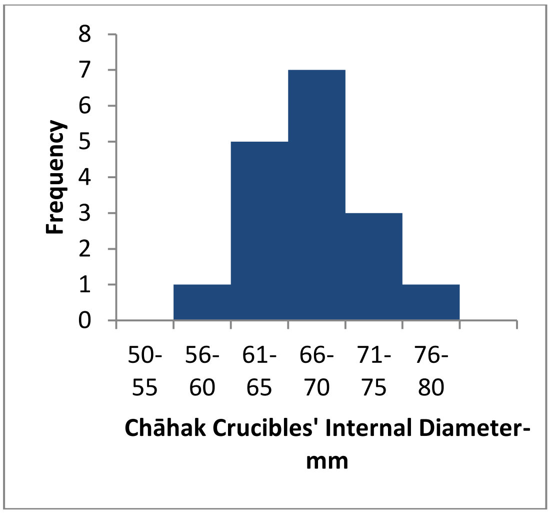

Figure 9: Frequency histogram of Chāhak crucibles’ internal diameter featuring the mean diameter and relatively widely scattered data.

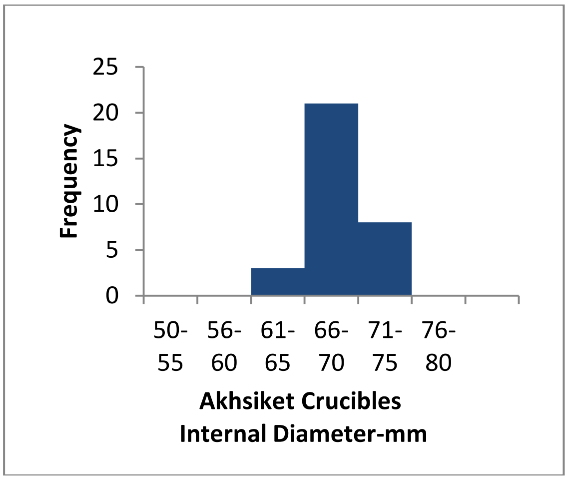

Figure 10: Frequency histogram of Akhsiket crucibles’ internal diameter featuring the mean diameter and significantly less widely scattered data.

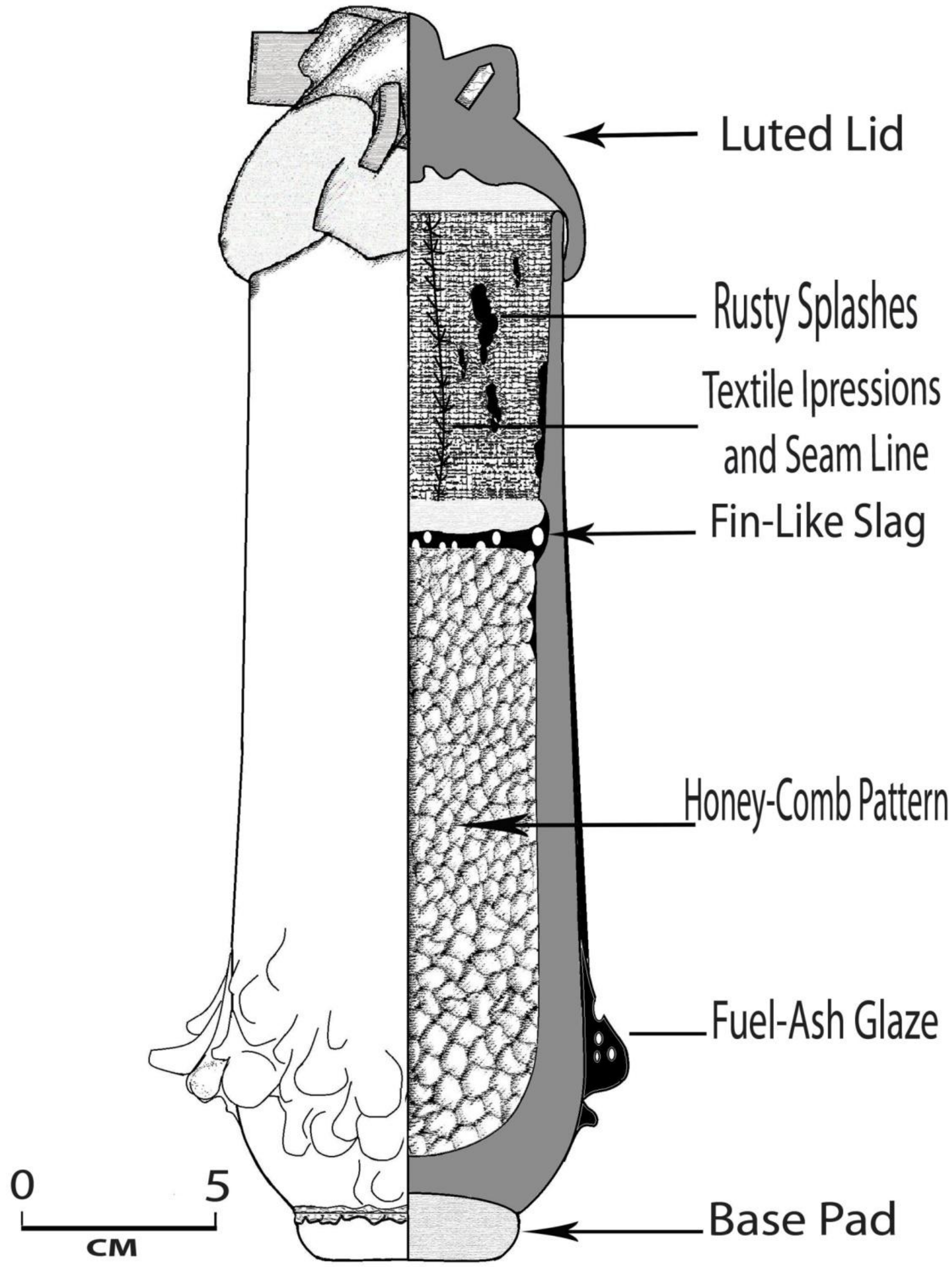

Figure 11: reconstruction of Chāhak crucibles based on archaeological fragments.

Overall, the manufacture of Chāhak crucibles is a demonstration of high craft mastery and specialisation. The well sorted homogeneous ceramic matrix of the crucibles together with its highly refractory properties shows that utmost care was taken in choosing and preparing fine refractory clay for making the crucible body. Petrographic and SEM images suggest that the entire crucible fabric has been subjected to a highly reducing environment and high temperature (Alipour and Rehren forthcoming). Most important was the reduction of the majority of the iron oxide content of the clay to iron metal. Iron oxide acts as a flux and is detrimental to use in crucibles. Its reduction to iron metal not only reflects the highly reducing conditions of the process, but strengthens the refractoriness of the clay and enhances the functionality of the crucible (Freestone and Tite 1986: 54; Bayley and Rehren 2007, 47; Martinón-Torres and Rehren 2014, 114).

Similar to the Merv crucibles (Feuerbach 2002), pads were attached to the crucibles while still leather hard. This is visible from the flexible nature of the clay that has properly filled the concave base of the crucible. They were most probably used as support for placing the crucibles in the furnace bed. The pads facilitated the removal of the crucibles after firing by preventing the fuel ash glaze fusing them to the furnace floor (Feuerbach 2002; Rehren and Papachristu 2003, 402). They are fired to a reddish colour which implies exposure to a much lower temperature in an oxidising condition. The pads' ceramic is rich in calcium carbonate which cannot withstand high temperature; its survival in most pads underlines the relatively low temperature at the base of the furnace. Given that the crucible body is entirely made of refractory clay, and that the pads and crucibles have been located in a way to receive two very different firing temperatures and atmospheres shows the amount of control, experience and knowledge that these specialists possessed regarding the clay properties and requirements for the process, and the temperatures and atmospheres needed to maintain the crucible steel production while preventing the crucibles from collapse. The simpler preparation techniques of the pads in contrast to the highly sophisticated and specialised crucibles suggest that the pads were either not made by the same specialist or just did not need much attention. As the pad's clay does not have any special properties and could be found almost anywhere it is assumed that a local clay source would have fulfilled the purpose.

The way in which the base fragments are broken is a good lead to their production technique. Almost all the base fragments exhibit step-like fractures indicating a coiling technique for the base of the crucibles. However, the body sherds reveal another technique by which the body of crucibles were made. Upper body fragments carry textile impressions (Fig. 7) similar to Uzbek/Akhsiket crucibles (Alipour *et al.* 2011). This gives a clearer vision of the making of the crucibles: firstly, wooden templates could have been made in the shape of the crucibles. Then, the template had to be covered by cloth to prevent it from sticking to the clay. Afterwards, the base that needs to be strong and stable is made by coiling, following by building the upper crucible by lifting the clay upwards and onto the template. Therefore, textile impressions are visible throughout the upper crucible body.

The crucible lids are the most peculiar fragments with no resemblance to Akhsiket or Merv lids. Once sectioned, the lids do not show any particular structure other than a lump of clay that is stacked on top of an already charged crucible. The inner profile of the lid often shows impressions reminiscent of a stitched bundle and some textile imprints. This corresponds to Biruni's description of the addition of a bag or bundle of some carburising mixture to the charge. Additionally, it shows that the crucibles were charged to the rim and then closed with a lump of clay and never opened again until the end of the procedure. As it appears from the archaeological evidence, it is likely that the crucibles were charged with the iron and then a bag of carburising agents and fluxes were stacked on top of the main charge, where it left textile imprints on the bottom of the lids.

Microanalysis

The most important identifiers of the process (Bachmann 1982; Charlton *et al.* 2013, 241) are the slag fins in the crucibles. In Chāhak, the slag fins are very thin, similar to the ones from Merv. This is indicative of the use of a refined iron source with less slag forming material that would result in a quite efficient and high-yield production, in contrast to the massive slag cakes that characterise the Ferghana Process at Ahksiket in Uzbekistan (Rehren and Papakhristu 2000; Rehren and Papachristou 2003).

The chemical analysis of the slag reveals a high degree of homogeneity, with silica around 45 wt% and alumina around 15 wt%. Higher variability is found in the concentrations of lime and manganese oxide (Table 4), each varying from c 10 to c 20 wt%. Another characteristic of the Chāhak slag fins is the presence of chromium oxide, in the order of 1 wt%. This could help identifying an iron source with high chromium concentrations and further provenancing the parent iron (Navasaitis *et al* 2010, 116), or be due to the addition of chromium-rich minerals as part of the charge recipe. The considerable levels of CaO and MnO in the slag most likely correspond to historical accounts of the addition of coral, oyster shell and 'magnesia' (most likely manganese oxide: see above) as the contributors respectively. Alternatively, some of it may originate from impurities in the bloomery iron. The addition of manganese oxide to the charge would increase the yield by substituting iron content of the slag, and facilitating the carburisation of the metal. In this case the iron content has decreased to only a few weight percent by weight, compared to around 50 to 70 wt% iron oxide in most pre-industrial iron smelting slag. The low iron content and small slag volume correspond to a more efficient process with less slag-forming than the Ferghana Process of Uzbekistan, and is more similar to the thin slag-fins of Merv in Turkmenistan. The high efficiency of the process together with the use of quite refractory material for the crucibles suggests a very specialised and standardised industry.

Metal droplets are important constituents of the Chāhak slag. These particles show an iron content ranging from 87 to 99 wt%. The concentration of chromium in the iron droplets analysed so far ranges from 0.4 to 12.1 wt%. Phosphorus and manganese are present in almost half of the samples at an average of 1.2 and 0.5 wt% respectively. The reduction of phosphorus, manganese and chromium together with iron is indicative of highly reducing conditions. The presence of phosphorus in iron is considered detrimental as it results in brittleness (Morris 2008, 1022). Therefore, the presence of phosphorus in Chāhak crucible steel may have affected the strength and hardness of their blades. It is therefore not surprising that historical accounts highlight that Chāhak blades, despite their initial popularity, suffered a bad reputation for their brittleness.

Conclusion

Crucible steel has fascinated modern researchers ever since the 19th century, but its actual production is among the least studied topics in archaeometallurgy. This paper attempts to bring together historical accounts, new archaeological and laboratory data and existing archaeometallurgical knowledge as part of our ongoing investigation of Chāhak, a newly detected crucible production site in south central Iran with large amounts of archaeological waste related to crucible steel making.

Historical manuscripts that recorded the production procedure are scarce and insufficient in their precision and coherence to track all aspects of the operation. These documents could not and do not contain enough information to preserve and transfer the technology to the following generations. Related manuscripts, however, provide some information on the time period and regions of production. The manuscripts newly introduced to the discussion here, such as Tusi's treatise, mention Chāhak as a prominent crucible steel making centre during the 13th century AD. This date, however, cannot be taken as the emergence of the Chāhak tradition because already Ibn-Balkhi, a historian and geographer of the Seljuk period (12th century AD) had mentioned Chāhak as a town in Pārs and as a *pulād* making centre. The absence of Chāhak in the 12th century AD manuscripts and its later appearance in Tusi's text is a matter of unresolved interest, and could indicate a relocation of the industry from Harāt to Chāhak, about 40 km to the South, around the time of the Mongol invasion.

Regarding the historical recipes of crucible steel making, the constant appearance of 'magnesia', coral and oyster shell among the ingredients matches the identification of high concentrations of manganese oxide and lime in the ongoing SEM-EDS analyses on Chāhak slag fins, while the presence of chromium in both the slag and the metal prills could represent a characteristic feature of Chāhak crucible steel, due to the proximity of chromite mines. In addition to technological information, historical accounts have also exposed some cultural and ritual aspects of the industry, some of which are the addition of pomegranate skin (fruit of heaven) or *peganum harmala* (when it burns it is believed to ward off evil eye) that have ancient routes in pre-Islamic Persian culture, probably to protect and secure the success of the production and further expose the steel ingot to some heavenly properties. From the 13th century AD onwards one can notice a pattern of copying earlier sources, and any potential further development of the crucible steel industry remained in the shadows. Thus, the Islamic golden age prior to the Mongol invasion provides the only significant information on crucible steel making. Although the recipes written until the 12th century AD did not serve as guides for specialists through time, they still preserve some original information to assist with the study of archaeological finds.

Studies on the archaeological finds from Chāhak facilitated a reconstruction of a typical Chāhaki crucible. However, the crucibles in which steel was produced are not as standardised as the Akhsiket crucibles. The size of around one litre and the tall cylindrical crucible shape are similar to other Central Asian examples. There are, however, also some different characteristics such as the application of a lump of refractory clay on top of the fully charged crucible to function as a lid. The application of this clay lump on top of the crucible has left some indentations that help recognising the presence of a textile bag at the top of the crucible load, probably the bundle filled with some ingredients of the charge as mentioned in the historical texts. The fact that these lids do not have any holes and that they could not be removed during the process suggests that crucible steel making in Chāhak required only one stage with no further addition of ingredients during firing. Overall, the combination of information gained from historical texts and the initial archaeometallurgical data demonstrate that the Chāhak tradition is closely related to the Central Asian processes recorded elsewhere (Rehren and Papachristou 2003). However, more investigations and excavations are needed in order to get a clear vision of the Persian *pulad* industry and its different production periods.

Acknowledgements

The authors are grateful for permission granted by the Research Centre of Archaeology Iranian Cultural Heritage Organisation for the survey and sample export at Chāhak. Advice and support from Professor Martinón-Torres is gratefully acknowledged. The research reported here forms part of the first author's doctoral research under the supervision of the second author. We are grateful for comments from two anonymous reviewers; any remaining errors are our own. This research would not have been possible without financial support from Qatar Foundation as part of the establishment of UCL Qatar, which is gratefully acknowledged.

About the authors:

Rahil Alipour is currently a doctoral student at *UCL Qatar*. She has worked previously on historical manuscripts relevant to crucible steel making and depiction of arms and armour on historical minitures while studying Museum Studies at the Cultural Heritage Institute of Iran, and on Uzbek crucible steel crucibles as part of her MA in Artefact Studies at the UCL Institute of Archaeology.

Thilo Rehren is primary supervisor of *Rahil Alipour*. He has published extensively on crucible metallurgy from the Early Bronze Age to the Early Modern period, across a range of metals and glass-making processes. He is currently based at UCL Qatar.

References:

Abdurazakov, A. and Bezborodov, M.
1966 *Medieval Glasses from Central Asia*. Tashkent.

Allan, J.W. and Gilmour, B.J.
2000 *Persian Steel: the Tanavoli collection*. Oxford: Oxford University Press.

Alipour, R.,
2010 "*The Manufacture of Steel-Making Crucibles*." Masters Dissertation, Institute of Archaeology, University College London.

Alipour, R., Gleba, M., and Rehren, Th.,
2011 "Textile templates for ceramic crucibles in early Islamic Akhsiket, Uzbekistan". *Archaeological Textile Newsletter* 53: 15-27.

Bachmann, H.
1982 *The Identification of Slags from Archaeological Sites.* London: Institute of Archaeology.

Bahārzada, P.,
1999 *sadr al-Din Mohammad Dashtaki Shirazi: Life, Works and Philosophical Ideas.* Maqalat va Barresiha 66: 139-160. Retrieved on 4 June 2014 From World Wide Web: http://www.noormags.com/view/fa/articlepage/82210

Balkhi, Ibn,
1921 *The Fārsnāma of Ibnu'l-Balkhi*, edited by G. Le Strange and R. A. Nicholson, London: Luzac.

2006 *Fārsnāma*, editted by by G. Le Strange and R. A. Nicholson. Tehran: Asatir.

Bayani, Sh.,
1988 *Religion and Government in Iran during Mongols.* Vol.1. Tehran: Markaz-e Nashr-e Daneshgahi.

Bayley, J. and Rehren, Th.,
2007 Towards a functional and typological classification of crucibles, In *Metals and Mines – Studies in Archaeometallurgy.* Edited by S. LaNiece, D. Hook and P. Craddock. London Archetype: 46-55.

Bearman, P. J., Bianquis, Th., Bosworth, C. E., Donzel, E.J. van, Heinrichs, W.,
1960 *Encyclopædia of Islam*, 2nd Ed., 1. Leiden: E. J. Brill.

Bīrūnī, Muḥammad ibn Aḥmad,
1979 *Saydanah fi al-Tibb,* translated by M. Sutūdah and I. Afshār. Tehran: Ufsit.

1974 *Al-Jamahir fi-al-Marefat al-Jawahir,* translated by M.A. Najafi and M. Khalili. Madrese āli Kakhe Danesh, 3. Tehran: Economist.

Cahen, C.,
1947 "Un traité d'armurie compose pour Saladin". *Bulletin d'Etudes Orientales* 12: 103-63.

Charlton, M. F., Shennan, S. J., Rehren, Th. and Crew, P.

2013 “Evolutionary analysis of iron making slag”, In *The World of Iron. Edited by* J. Humphris and Th. Rehren. Archetype: 288-295

Dashtaki Shirazi, Sadr al-Din,
15th century AD *Jawāhir-Nāmah*. (Held in Tehran University Library), No. 3881, and No. 1285.

Eqbal Ashtiani, A.,
1968 *A Complete History of Iran: From Mongol domination to Mashroutiat declaration.* Vol.1: from Chengiz invasion to Safavids. Tehran: Sepehr.

Feuerbach, A.M., Griffiths, D.R. and Merkel, J.F.,
1998 “An examination of crucible steel in the manufacture of Damascus steel, including evidence from Merv, Turkmenistan”. In: Th. Rehren, A. Hauptmann and J. Muhly (eds.), *Metallurgica Antiqua* , Der Anschnitt, Beiheft 8: 37-44.

Feuerbach, A. M.,
2002 “*Crucible Steel in Central Asia: Production, Use, and Origins.”* PhD dissertation, Institute of Archaeology, University College London.

Feuerbach, A.M., Griffiths, D.R., and Merkel, J.F.,
2003 “Early Islamic Crucible Steel Production at Merv, Turkmenistan”, In *Mining and Metal Production through the Ages*, edited by P.T., Craddock, J., Lang . London: The British Museum Press, 258-266.

Freestone, I. C., and Tite, M. S.,
1986 “Refractories in the ancient and preindustrial world”. In *High-Technology Ceramics: Past, Present* and *Future, Ceramics and Civilisation,* vol. III, edited by W.D. Kingery. Westerville: The American Ceramic Society.

Gronke, M.,
2008 *Iran: a short history*. Translated by S. Rendall. Princeton: Markus Wiener Publishers.

Hassan, A. Y.,
1978 “Iron and Steel Technology in Medieval Arabic Sources”. *Journal for the History of Arabic Science* 2: 31-52.

Hoyland, R. G. and Gilmour, B.,
2006 *Medieval Islamic Swords and Swordmaking: Kindi’s treatise “On swords and their kinds”*. Exeter: Short Run Press.

Karlsson, M.,
2000 “Iron and Steel Technology in Hispano-Arabic and Early Castilian Written Sources”. *Gladius XX:* 239- 250.

Khayyām Nishāburi, Omar,
1933 Nowrūz *nāmah*, edited with preface, notes and a glossary by Mojtaba Minovi. Tehran: Kaveh bookshop.

2006 Nowrūz nāmah, edited by Ali Hosouri. Tehran: Cheshmeh.

Killick, D.,

2004 “Social Constructionist Approaches to the Study of Technology”. *World Archaeology,* 36: 571-578.

Martinón-Torres, M. and Rehren, Th.,
2014 “Technical ceramics”. In *Archaeometallurgy in Global Perspective: methods and syntheses*, edited by B. W. Roberts and C. P. Thornton. Springer, pp 107-131.

Merkel, J., Feuerbach, A. and Griffith, D.,
1995 “Analytical investigation of crucible steel production at Merv”. *iams* (the Journal of the Institute for Archaeo-Metallurgical Studies) 19: 12-13.

Morris Jr., J. W.,
2008 “Stronger, Tougher Steels”. *Science*, New Series 320(5879): 1022-1023.

Moshtagh-Khorasani, M.,
2007 “Gedichte und Schwerter: Waffenklassifizierung und Tiegelstahlrezept des Omar Khayyam Neishaburi”. *Hephaistos,* 11/12: 26–27.

Mustawfī Qazvīnī, Ḥamd Allāh,
1915 *The geographical part of the Nuzhat-al-Qulub,* edited (vol.1)/translated (vol. 2) by G. Le Strange. London: Luzac.

2010 *Nuzhat-al-Qulub: Al-Maqalat al-thalithah,* edited by G. Le Strange. Tehran: Asatir.

Navasaitis, J., Selskiene, A., and Žaldarys, G.,
2010 “The study of trace elements in bloomery iron”. *Materials Science 16, 113-118.*

Papakhristu, O.,
1985 *Black metallurgy of Northern Ferghana on materials of archaeological investigation at the fort of Akhsiket of the IX to early XIII centuries*. Abstracts of the Candidate of History Dissertation, Moscow.

Pigoulevskaya, N.V., A. You. Yakoubovsky, I.P. Petrouchevski, L.V. Stroeva, and A.U. Belenitsky.,
1967 *The History of Iran: From Ancient Period to the End of the Eighteenth Century. 2 Vols,* Translated from Russian into Persian by K. Keshavarz. Tehran: Entesharat-e Moasese Motaleat va Tahqiqat-e Ejtemaie. Vol.II.

Raghib, Y., and Fluzin. Ph.,
1997 “La fabrication des lames damassées en Orient”. *Journal for the Economic and Social History of the Orient*, 40 (1): 30-71.

Rebstock, U.,
2008 “Weights and Measures in Islam” In *Encyclopaedia of the History of Science, technology, and medicine in non- Western culture,* edited by Helaine Selin. Berlin: Springer 2nd Ed: 2255-2267.

Rehren, Th.,
2003 “Crucibles as reaction vessels in ancient metallurgy”, In *Mining and Metal Production Through The Ages*, edited by Craddock, P., and Lang, J. London: The British Museum Press: 207-215.

Rehren, Th., Papachristou, O.,
2003 "Similar like white and black: a comparison of steel-making crucibles from Central Asia and the Indian subcontinent", In *Man and mining: Mensch und Bergbau: studies in honour of Gerd Weisgerber on occasion of his 65th birthday,* edited by Th, Stöllner. Bochum: Deutsches Bergbau-Museum, 393-404.

Rehren, Th., and Papakhristu, O.,
2000 "Cutting edge technology- The Ferghana Process of medieval crucible steel smelting". *Metalla,* 7 (2): 55-69.

Rezaie, A.,
1997 *Political and Social History of Iran*. Tehran: Maharat.

Shamlouie, H.A.,
1968 *History of Iran: from Medes to Pahlavids.* Tehran: Bongah-e Matbu'ati-e Safialishah.

Sillar, B., and Tite, M.S.,
2000 "The challenge of technological choices for materials science approaches in archaeology". *Archaeometry* 42: 2-20.

Simpson, St. J.
2001 The Early Islamic crucible steel industry at Merv. *iams* (the Journal of the Institute for Archaeo-Metallurgical Studies) 21, 14-15.

Stein, A.,
1936 "An Archaeological Tour in the Ancient Persis". *Iraq* 3, 2: 111-225.

Sykes, P.M.
1915 *A History of Persia*. London: Routledge and Kegnan Paul. Vol.2

Tusi, Nasir al-Din,
1984 *Tansukh-Namah.* Edited by M. Razavi., Tehran: Etela'at. Retrieved on 12 Dec 2012 from World Wide Web: http://www.noorlib.ir/View/fa/Book/BookView/Image/15568

1274 *Tansukh-Namah*. Based on a copy held in Tehran University Library, No. 2457/7.

Zaki, A. R.
1955a "Centers of Islamic Sword Making in the Middle Ages". *Bulletin de l'Institut d'Egypte*, 36: 285-95.

1955b "Islamic Swords in Middle Ages". *Bulletin de l'Institut d'Egypte*, 36: 365-94.