GLADIUS
Estudios sobre armas antiguas, arte militar
y vida cultural en oriente y occidente
XXXIII (2013), pp. 157-192
ISSN: 0436-029X
doi: 10.3989/gladius.2013.0007

REPRODUCING CRUCIBLE STEEL: A PRACTICAL GUIDE AND A COMPARATIVE ANALYSIS TO PERSIAN MANUSCRIPTS

REPRODUCIENDO ACERO DE CRISOL: UNA GUÍA PRÁCTICA Y UN ANÁLISIS COMPARATIVO CON MANUSCRITOS PERSAS

POR

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Abstract - Resumen

Different terms are used in old Persian manuscripts, such as *Ta'id Besârat*, to define and refer to crucible or watered steel and different types of swords[1]. However, there are few manuscripts that describe the way crucible steel cakes and blades were made such as the manuscript *Gŏharnâme*[2]. The present article deals with the making of crucible steel as described in Persian manuscripts and also with a new reproduction process of making crucible steel as conducted by the Finnish smith Niko Hynninen.

Los antiguos manuscritos persas, tales como *Ta'id Besârat*[3], emplean diversos términos para definir y referirse al acero de crisol o acero de Damasco y a diversos tipos de espada. Sin embargo, existen pocos manuscritos que describan el modo en que se elaboraban los lingotes y hojas de acero de crisol, entre ellos el manuscrito *Gŏharnâme*[4]. El presente artículo describe el proceso de elaboración del acero de crisol tal y como lo refieren los manuscritos persas, así como una moderna reproducción del mismo realizada por el forjador finlandés Niko Hynninen.

Keywords - Palabras Clave

Persian Crucible Steel; Damascus Steel; Edged Weapons; Persian Manuscripts; Reproduction.

Acero Persa de Crisol; Acero de Damasco; Armas Blancas; Manuscritos Persas; Reproducción.

1. INTRODUCTION

To make watered steel blades, Persian smiths and ironworkers used a type of steel that was made in crucibles. Hence this type of steel is called crucible steel. One should note that crucible steel is not merely high carbon steel, but rather it is an ultra high carbon steel[5]. Crucible steel

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[1] See Mirzā Lotfallāh (1706–1707:1118 or 1696–1697:1108).
[2] See Mansur (1975/1354).
[3] Vea Mirzā Lotfallāh (1706–1707:1118 or 1696–1697:1108).
[4] Vea Mansur (1975/1354).
[5] One of our reviewers is of the opinion that crucible steel is a high-C% steel made in crucibles, and a subdivision or a small fraction of this crucible steel what is called crucible steel with a pattern ("Damascus steel" obtained by very slowly cooling the ingot from the crucible and carefully forging it at a low temperature. However, as mentioned above

or watered steel is called *fulâd-e jŏhardâr* فولاد جوهردار or *pulâd-e gŏhardâr* پولاد گوهردار in Persian. A sword or blade that is made of crucible steel is called *tiq-e jŏhardâr* تیغ جوهردار (blade/sword of watered steel) and *tiq-e jŏharbâr* تیغ جوهربار (blade/sword of watered steel)[6]. Not all types of steel that were produced back then were made of crucible steel: some were high carbon steel without any pattern, called *fulâd-de bijŏhar* فولاد بی‌جوهر (steel without watered pattern; high carbon steel)[7]. Upon occasion, crucible steel had failures or flaws in certain places, and these imperfect articles were called *bigŏhar* بی گوهر («without watered steel pattern»; this refers to the areas where the crucible steel pattern is not visible either due to the bad quality of the blade or poor etching)[8]. One should note that watered steel is called damascus steel in the West. The name of the city of Damešq (Damascus) دمشق is associated with this type of blade, since this city was a hub for the trading of blades and swords, and European travelers probably first came into contact with these blades in this city. Although the steel is known in the West as «damask,» Damešq (Damascus) دمشق was merely a central market place for the trade in blades and the technique presumably has its origins in India[9]. Damešq (Damascus) دمشق was a trading place where caravans from the East and West met to exchange products; amongst the products offered for sale were fine swords from Iran or India[10]. The metal for making watered steel was not made at Damascus but at Kona Samundrum near Nirma in Hyderabad[11]. In some recent Iranian publications that were based on European sources, the translated term *fulâd-e damešqi* فولاد دمشقی (steel from Damascus) is used, making the false insinuation that the steel comes from Damascus[12]. One should note that this is a recent linguistic borrowing and in historical texts the correct terms *fulâd-e jŏhardâr* فولاد جوهردار or *pulâd-e gŏhardâr* پولاد گوهردار were used. The general term for describing the pattern of the crucible steel is *gŏhar* گوهر[13]. The term is used in combinations such as *gŏhar-e šamšir* گوهر شمشیر (watered steel pattern of a sword)[14], *gŏhar-e tiq* گوهر تیغ (watered steel pattern of a blade/sword)[15], *gŏhardâr* گوهر دار (watered steel)[16] and *gŏhari hosâm* گوهری حسام (a watered-steel sword)[17].

Crucible steel is a slowly cooled type of steel with a carbon content of 1-2.1%. Thus, crucible steel can be described as an ultra high carbon steel that was left to cool down slowly after it was completely molten. The inner structure of the crucible steel is made when the molten charge starts to solidify slowly and the elements with the highest melting point begin to solidify and grow into a dendritic network. Impurity elements, such as Mn (manganese), S

patterned crucible steel is not merely high carbon steel but an ultra high carbon steel in our opinion. Further our reviewer suggests that these blades are made of "Damascus" steel not merely crucible steel. However, one should note that "damascus steel" is the term the westerners used to describe crucible steel. In Persian patterned crucible steel was and is called *fulâd-e gohardār* (precious steel or watered steel) (see Moshtagh Khorasani, 2010:163). Pattern-welded steel was not termed that way during that period. Moreover, the two steel types look absolutely different. It might clarify further to also specify folded and laminated steel. In Iran and India, swords were produced this way as well. This type is sometimes called "mechanical damask" to distinguish it from true "watered steel". Pattern welding usually refers to a cruder mechanical process of twisting and hammering rods of various compositions.

6 See *Resāle-ye Čāhrom* (1985/1374:418).

7 See *Ta'id Besārat*, Mirzā Lotfallāh (1706–1707:1118 or 1108:1696–1697:[39]).

8 See Mansur (1975/1354:286).

9 See Zakey (1965:287).

10 See Zakey (1961:23) and Grancsay (1957:249).

11 Grancsay (1957:249).

12 See Ehsāni (2003/1382).

13 See Xayyām-e Neyšāburi (2003/1382:56), Mobārak Šāh Faxr-e Modabbar (1967/1346:258) and Mansur (1975/1354:286).

14 See Onsori Balxi (1990/1369:19) and Nezāmi Ganje'i (2007/1385b:45).

15 See Attār Neyšāburi (1993/1372:22).

16 See Mobārak Šāh Faxr-e Modabbar (1967/1346:136).

17 See Sa'd Salmān (1995/1374:31).

(sulfur), Si (silicon/silicium), and P (phosphorus), begin to shape a network by separating between the austenite dendrites. The dendrites are deformed into planar arrays parallel to the blade surface during the forging procedure. The existence of cementite dendrites, together with segragated impurity elements, creates the beautiful patterns on watered steel blades[18]. There was a great deal of trading in those crucible steel cakes that were made in India and Ceylon. However, recent research shows that these crucible cakes were also made in Merv[19].

Based on historical accounts, crucible steel was considered to be the highest quality steel. The beauty of Persian crucible or watered steel has been a source of great interest and fascination for different nations over centuries. The magnificent whitish lines intertwined with each other and set in a dark background furnish a great deal of detailed information regarding the steelworking and forging process. These beautiful patterns differ from sword to sword, and although one can classify them into more general groups, each watered steel blade remains unique and individual in its own right. These patterns in watered steel blades were formed by dendrites of cementite. Thus the patterns are created due to the spheroids of cementite which is proven by metallurgical analysis. One can imagine a crucible steel blade as a soft body (ferrite/pearlite) matrix, where the hard particles (spheroidal/globular cementite) are present everywhere. Hence, the watered steel blade has qualities combining flexibility with hardness. The additional tempering for a martensite blade will decreases the hardness in exchange for added toughness and ductility. Thus, watered steel blades were not only famed for their beauty but also their durability, ductility, and edge-retention qualities. Especially, the ductility of crucible steel blades distinguished them from other types of steel[20].

Although there is not a single reliable feature that can be used to distinguish crucible steel from other types of steel, one can determine the following distinguishing characteristics of crucible steel[21]: a) crucible steel was liquid, leading to a relatively homogenous steel content with virtually no slag, b) formation of dendrites is a typical characteristic, c) segregation of elements into dendritic and interdendritic regions throughout the sample, d) the composition of any slag found in crucible steel should have an iron oxide content lower than 4% unless it is found in remnants of the crucible charge, and e) the elemental composition of the steel should reflect the dendritic segregation; under low magnification, elemental segregation can be observed as a mottled surface with elongated lighter and darker areas. Furthermore, Anosov determined four different parameters for assessing the quality of watered steel blades: a) ring: high quality steel has a clear tone —the clearer the tone, the better the quality of steel, b) sharpness of the cutting edge: watered steel must be able to cut a fine silk handkerchief in one stroke, c) strength of the blade: a watered blade should be able to slice through an iron bar without being notched, d) Elasticity: on bending, watered steel blades should not break and should not suffer a permanent set[22].

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18 Note that this part refers to the cooled down cementite dendrites.

19 See Feuerbach (2002). For a more detailed discussion of the metallurgical mechanisms behind the formation of the crucible steel pattern see Verhoeven (2002), Verhoeven, Pendray and Dauksch (1996) and *Verhoeven*, Pendray, and Gibson (1996).

20 See Feuerbach (2002b:213). Quoting Anasov, one of our reviewers suggests that the ductility of these blades is questionable. However, the ductility of a patterened crucible steel blade that is properly heat treated is similar to 1084 steel. Thus, in our opinion, the ductility of an ultra high carbon steel with a fine grain structure is not questionable. Lesuer et al. (1993) studied ultra high carbon steels with a fine grain and were able to make them superplastic.

21 See Feuerbach (2002a:228).

22 See Feuerbach (2002a:212).

2. MAKING STEEL FROM IRON

Steel is an alloy of iron, containing about 0.1 - 2% carbon. High carbon steel has a carbon content of 0.6 to 1.00% , while Ultra high carbon steel is with 1.00 to 2.1 % carbon. Because of its carbon content, a high carbon steel can be heat treated and sharpened; hence, it is excellent for making knives, swords, and other cutting weapons. A number of methods were used to obtain pre-industrial steel, such as a) direct smelting to steel, b) carburizing (adding carbon to) wrought iron (iron with virtually no carbon), a process commonly used in Europe and Asia, c) decarburizing (removing carbon from) cast iron (iron with a carbon content around 2-4%) - a method used in China and also in Europe after the introduction of the blast furnace, and d) making steel in a crucible by either carburizing or decarburizing the crucible charge (by putting some ingredients into the crucible)[23]. As far as the terms iron and steel are concerned, one should note that Persian manuscripts do not make a clear-cut distinction between the two and one needs to bear in mind that the terms «iron» and «steel» are modern terms.

Reference to various types of iron (in Persian *âhan* **آهن**) is made by Beyruni in his book *Al-Jamâhir fi Marefat al-Jawâher*[24]. There Beyruni[25] classifies *âhan-e madani* آهن معدنی (mined iron) into *narmâhan* نرمآهن (soft iron) which is soft and *moannas* مونث (feminine)[26] and the other is *šâborqân* شابرقان which is hard, has *mozakkar* مذکر (male) characteristics, can be quenched, and cannot be bent much[27]. Further, Beyruni describes that *narmâhan* نرمآهن is divided into two categories: the first is *narmâhan* نرمآهن itself and the other is its water, which comes out when it is smelted and purified from the ore, and this water resulting from the smelting of iron is called *dus/dusâ* دوصا . The latter is called *asta* استه in Persian. In Zâbolestân زابلستان, they describe this type, which is gained through smelting iron, as white, hard, and similar to silver. The *rumi* رومی (Byzantine, Anatolian) swords, *rus* روس swords (Russian swords) and *saqlâbi* صقالبی swords (Slav swords) are made from *šâborqân* شابرقان and these are also called *qal'* قلع. They say that *qal'* قلع or *qal'a* قلع has a ringing sound [when struck] and [the swords] that are not *qal'* قلع do not have this sound[28]. There is a type of sword named *qala'iye* قلعیه which is attributed to it [*qal'* قلع] and some attribute it to a special type of location by describing it as a *hendi* هندی sword, *yamâni* یمانی sword, and *mašrefiye* مشرفیه. They say that these swords [*qala'iye* قلعیه] were brought from *qala'* when tin was brought from there. Swords that are attributed to *qala'i* قلعی are wide [are broad swords] and their white color is sometimes used in the construction of literary metapohors in Arab poetry. The Rumihâ رومیها do not have any other type of swords but *šâborqân* شابرقان swords.

In the manuscript *Nŏruznâme*, Xayyâm-e Neyšâburi describes *narmâhan* نرم آهن as a type of sword[29]. In other manuscripts *narmâhan* نرم آهن is described as soft iron[30]. In the manuscript *Tansuxnâme*, Nasireldin Tusi considers *narmâhan* نرم آهن (soft iron) as a subcategory of *âhan* آهن (iron)[31]. In the manuscript *Gŏharnâme*, Mansur considers *narmâhan* نرم آهن as

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[23] See Feuerbach (2002a:13). For more details see Smith (1988) and Tylecote (1976).

[24] See Beyruni (1974/1353:43).

[25] See Beyruni (1974/1353:42–43).

[26] This is described as weak by Hoyland and Gilmour (2006:149).

[27] Note that another term for *šāborqān* is *šāvarān* شاوران, see *Tansuxnāme*, Nasireldin Tusi (1574/982 Hegira:101).

[28] According to Hoyland and Gilmour (2006:149) these swords that are not *qal'* قلع have a harsh tone.

[29] See Xayyām-e Neyšāburi (2003/1382:55).

[30] For examples see *Divān-e Mas'ud Sa'd Salmān* (Sa'd Salmān, 1995/1374:507), *Bayān al-Sanā'āt* (Taflisi, 1975/1354:31), *Tansuxnāme* (Nasireldin Tusi, 1574/982 Hegira:101), *Arāyes al-Javāher* (Kāši, 1956/1335:[80]) and *Gŏharnāme* (Mansur, 1975/1354:286).

[31] See Nasireldin Tusi (1574/982 Hegira:[101]).

one of the subcategories of *âhan* آهن, too[32]. Mansur adds that there are four different types of *narmâhan* نرم آهن: a) a type of *narmâhan* نرم آهن that can be quenched and from which many tools of different crafts are made, b) a type called *qâte'* قاطع can be quenched and is used for making *tiqhâye romi* تیغهای رومی (Byzantine/Anatolian blades/swords), *tiqhâ-ye saqlâbi* تیغهای سقلابی (Slav blades/swords), the tools of carpenters (*âlât-e najârân* آلات نجاران), and the tools of goldsmiths (*âlât-e zargarân* آلات زرگران), c) *âhan-e narm bârik-e rize* آهن نرم باریک ریزه, and d) *âhan-e sefidfâm narmandâm* آهن سفیدفام نرماندام (a soft-bodied iron with whitish color) that has the most resistance upon getting hit and can be used for making blades that can be turned/bent like paper. Mansur stresses that the *farangiân* فرنگیان (foreigners) do not allow latter type of soft iron to enter Muslim countries.

Another term used in the manuscript *Javâhernâme-ye Nezâmi* that adds to the confusion when it comes to distinguishing clearly between iron and steel in old manuscripts is *âhan-e pulâd* آهن پولاد[33] (iron of steel). Jŏhari Nezâmi states that *âhan-e pulâd* آهن پولاد is the result of heating the stone of iron (*sang-e âhan* سنگ آهن) or the stone of soft steel (*sang-e pulâd-e narm* سنگ پولاد نرم) in Herat that results in *âhan-e pulâd* آهن پولاد. The best type of *âhan-e pulâd* آهن پولاد is completely white, hard, and is homogenous. Many farmers' tools and others are made of this type [*âhan-e pulâd* آهن پولاد]. However, this type [*âhan-e pulâd* آهن پولاد] cannot be quenched. There is another type of *pulâd* پولاد which is called *šâborqân* شابرقان and again another type [of *pulâd* پولاد] which is called *qâte'* قاطع. The *šamširhâ-ye âbdâr* شمشیرهای آبدار (quenched swords), *šamširhâ-ye rusi* شمشیرهای روسی (*rusi* روسی swords), and *šamširhâ-ye saqlâbi* شمشیرهای سقلابی (*saqlâbi* سقلابی swords) are made of this [type of steel called *qâte'* قاطع]. They say that *šamšir* شمشیر should be *qala'i* قلعی (tinny) and from *pulâd âhan* پولاد آهن (steel of iron) so that when it is heated over fire and quenched in water, it can be hardened through quenching. The other types of iron do not have any effect on it, and the tools of *zargarân* زرگران (goldsmiths), *dorudgarân* درودگران (carpenters) and *šamširhâ* شمشیرها and *kârdhâ* کاردها are made of this.

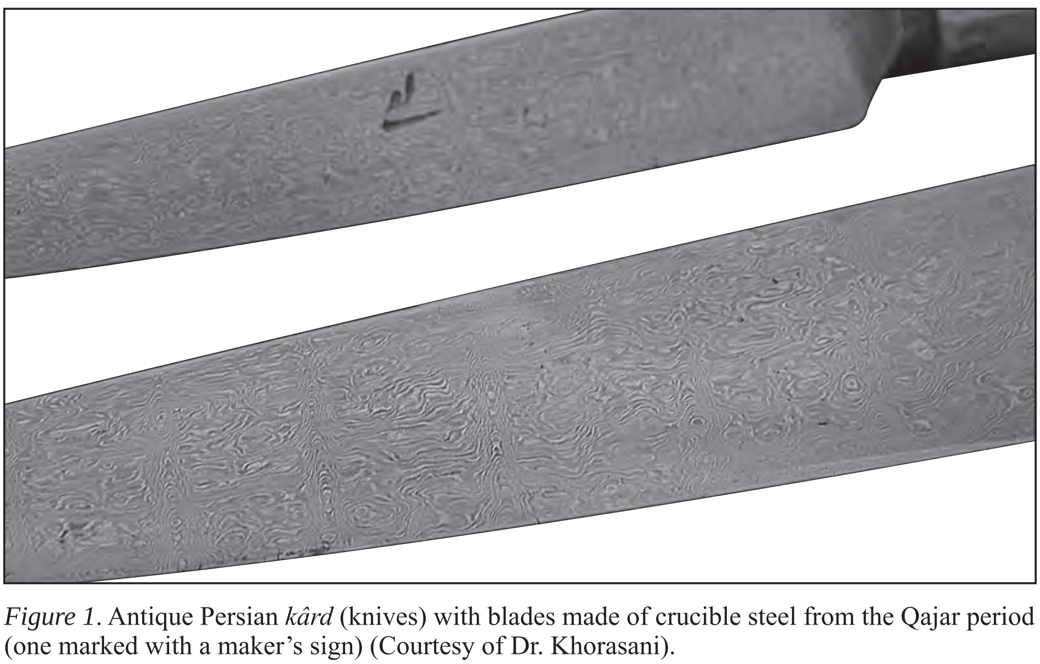

Figure 1. Antique Persian *kârd* (knives) with blades made of crucible steel from the Qajar period (one marked with a maker's sign) (Courtesy of Dr. Khorasani).

[32] See Mansur (1975/1354:286).
[33] See Jŏhari Nezāmi (2004/1383:326–327).

Figure 2. Antique Persian *šamšir* made of crucible steel from the Safavid period (Courtesy of Dr. Khorasani).

Old manuscripts also refer specifically to steel (*fulâd* فولاد or *pulâd* پولاد), for the usage of the term *pulâd* پولاد see *Gŏharnâme*[34]. The manuscript *Al-Jamâhir fi Marefat al-Jawâher* describes *fulâd* فولاد as a type of *âhan-e morakkab* آهن مرکب (mixed iron), which is made of *narmâhan* نرمآهن (soft iron) and *âb* آب (watered pattern). This is the same watered pattern that flows before the melting of *narmâhan* نرمآهن and this is known as *fulâd* فولاد. The city of Herat is famed for making it. The ingots have an oval shape and are long. At their base, the ingots are round in the shape of the crucibles that are used for melting [the iron]. The Indian swords are made from these ingots. *Fulâd* فولاد can be classified in two different categories. In the first, which the *âb* آب (watered pattern) and the *narmâhan* نرمآهن (soft iron) are melted together and cannot be distinguished from one another. This steel is suitable for those who work with it. It is assumed that *šâborqân* شابرقان is from this type of *âhan* آهن. Its essence is natural and it can be quenched. The second category is the result of the separation of the molten mass in the furnace (*âb* آب and *narmâhan* نرمآهن), and each part is obtained separately and is called *farand* فرند. The swords that are made of this are good and the blades have a green color[35]. In the manuscript *Ahsan al-Taqâsim fi Ma'refat-e al-Qâlim* [*Best Divisions for Knowledge of Regions*], Moqadasi states that the steel from Xorâsân (Khorasan) is exported to other areas and arms and armor such as mail armor and swords are exported from Xârazm to other areas as well. Swords, iron, and copper are exported from Tus (a city in Khorasan) to other areas as well. Moqadasi (1980/1361:680–681) adds that the earth in Fârs has different mines and in Tabriz there are different mines of *meqnisiyâ* مغنيسيا [manganese dioxide MnO_2][36], *sombâde* سنباده (emery), and *âhan* آهن (iron)[37].

In the *Gŏharnâme*, Mansur explains that *pulâd* پولاد is a subtype of *âhan* آهن and he differentiates between two different types of steel: a) a mined one (*kâni* کانی) that is called *šâdarân* شادران that is made by adding *narmâhan* نرمآهن with some *adviye-ye xariqe* ادویه خریقه (ingredients) and b) a second type that is made by taking small pieces of steel and melting it with the soft iron (*narmâhan* نرمآهن) resulting in *jŏhar* جوهر (damascus steel pattern)[38]. This steel is called *balârak* بلارک [a type of crucible steel pattern]. The steel is used to make *tiqhâ* تیغها (blades) and *kattârehâ* کتارهها (a type of one-edged straight sword) which are kept by Indians, and some others from *balârak* بلارک. These steel blades are covered (*talâ konand* طلا کنند) after

34 See Mansur (1975/1354:286).

35 See Beyruni (1974/1353:48–49).

36 It is a blackish clay that is extracted from the mountains of Kāšān; some say it is a very soft stone used by glassworkers, and is called *sang-e soleymāni* سنگ سلیمانی as well, and bowl makers use this to dye the bowls; there are five different types: one is black, one tends to be black, one is red, one is white, and one is yellow outside and red inside.

37 See Moqadasi (1980/1361:680-681).

38 Mansur (1975/1354:286).

a mixture of various ingredients (*adviyehâ* ادویه‌ها) has been applied to them and then the damascus pattern (*gŏhar* گوهر) appears.

3. METHODS OF MAKING CRUCIBLE STEEL BASED ON PERSIAN MANUSCRIPTS

Some Persian manuscripts report on the process on how to make crucible steel. The manuscripts presented below are all written by Persian scholars in Persian with the exception of the manuscript *Al-Jamāhir fi Marefat al-Jawāher* [*Sum of Knowledge about Precious Stones*] by Abu Reyhān Beyruni (a renowned Persian philosopher, mathematician, astronomer, chemist, historian, social scientist, geographer, and geologist) which was written in Arabic. He was born in Xārazm (Kharazm) in 362 Hegira (973 C.E.) and died in 440 Hegira (1049 C.E.)[39]. The other manuscript written in Arabic is *Ahsan al-Taqāsim fi Ma'refat-e al-Qālim* [*Best Divisions for Knowledge of Regions*] by Šamsoldin Abu Abdollāh Mohammad ben Ahmad ben Ababakr Šāmi Moqadasi which was written in 375 Hegira (986 C.E.). As a geographer, Mogadasi traveled to many countries such as Palestine, Syria, Iran, Iraq, Maghreb countries, and Spain. He used this information to write his book. Mogadasi died in 381 Hegira (991 C.E.).

The manuscripts written in Persian include: a) *Javāhernāme-ye Nezāmi* [*Nezāmi's Book of Precious Stones*] was written by Mohammad ibn Abi al-Barakāt Jŏhari Nezāmi in 592 Hegira (1196 C.E.). After *Al-Jamāhir fi Marefat al-Jawāher*, written by Abu Reyhān Beyruni in Arabic, *Javāhernāme-ye Nezāmi* is the first book in Persian dealing with precious stones, metals, alloys, and enameling. The importance of this work is due to that fact that the author and his father were both in the field of stoneworking, metals, alloys, and enameling professionally[40]. Other Persian manuscripts include b) *Nŏruznāme* [*The Book of Nŏruz*] is attributed to Omar ben Ebrāhim Xayyām-e Neyšāburi who was born in 1048 C.E. in Neyšābur and died in the same city in 1131 C.E. The book *Nŏruznāme* classifies different types of swords and crucible steels. He mastered philosophy, jurisprudence, history, mathematics, medicine, and astronomy[41]; c) *Bayān al-Sanā'āt* [*About the Crafts*] was written by Hobeyš ben Ebrāhim ben Mohammad Taflisi who was born in 515 Hegira (1121 C.E.) and died in 600 Hegira (1203 C.E.). Hobeyš ben Ebrāhim ben Mohammad Taflisi was a physician, astronmer, scientist, and literary figure from the sixth century Hegira (twelve century C.E.). He wrote many books in Persian and Arabic[42]; d) *Tansuxnāme* [*The Book of Minerals*] was written by Xāje Nasireldin Tusi who lived from 598—672 Hegira (1201–1274 C.E.). He is one of the most influential Persian scholars. His work the *Tasnuxnāme* deals with precious stones and metals; e) *Ādāb al-Harb va al-Šojā-e* [*Customs of War and Bravery*] was written by Mohammad ben Mansur ben Said Mobārak Šāh Faxr-e Modabbar. Mobārak Šāh probably wrote the *Ādāb al-Harb va al-Šojā-e* in 626 Hegira (1229 C.E.) or 627 Hegira (1230 C.E.)[43]; f) *Arāyes al-Javāher* [*Brides of Jewels*] by Abolqāsem Kāši was written in the 13th century C.E. and deals with precious stones and has one chapter on iron and steel; g) *Gŏharnāme* [*Book of Jewels*] was written by Mohammad ben Mansur in the 15th century and deals with the detailed descriptions of different precious stone and metals, among them iron and steel[44]; h) *Ta'id Besārat* [*Aid to Sight*] was written by Mirzā Lotfallāh in 1118 Hegira (1706-1707 C.E.) or in 1108 Hegira (1696-1697 C.E.).

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39 See Najafi and Xalili (1974/1353:5-7).
40 See Afšâr (2004/1383:15, 19).
41 See Moshtagh Khorasani (2007a:26).
42 See Afšâr (1975/1354:279).
43 See Soheyli Xânsari (1967/1346:10).
44 See Sotude (1975/1354:185).

Mirzā Lotfallāh wrote his treatise *Ta'id Besarat* (Aid to Sight) on the sword, swordmaking, and sword analysis (*šamširšenāsi* شمشیرشناسی) under the pseudonym Nithār with the honorary epithet of Nosratallāh Xān.

The first step in making crucible steel is to melt iron with carbonous ingredients in crucibles to obtain hemispherical crucible steel cakes. In Persian, these crucible steel cakes used to be called *beyze-ye fulâd* بیضه فولاد (lit. steel testicles) due to their shape[45]. In the next step, these steel cakes were heated to a cherry red color, and forged into blades.

In the manuscript *Al-Jamâhir fi Marefat al-Jawâher*, Beyruni describes the method of making the crucible steel[46]. He says that they [ironwokers] include five *ratl* رطل of [horse] shoes, the nails of which are made of *narmâhan* نرمآهن [in the crucible][47]. Then they add ten *derham* درهم of each [of the ingredients] *rusaxtaj* روسختج [antimony], *marqiša-ye talâ'i* مرقیشا طلائی [golden marcasite] and *meqnesiyâ* مغنسیا [*meqnisiyâ* مغنیسیا; manganese dioxide MnO_2] to the crucible, close the crucible with clay, and put it in the furnace. Then they fill the furnace with charcoal and blow air with Rumi (Roman Byzantine/Anatolian) bellows that are pumped by two men until the iron melts. Then they add a combination of *halile* هلیله (myrobalan), *pust-e anâr* پوست انار (pomegranate peel), *melh al-ajeyn* ملح‌العجین (the salt used for dough), and *sadaf-e morvarid* صدف مروارید (pearl shell). From each the same amount approaching forty *derham* درهم[48] are placed into small bags. One small bag is then added to each crucible. They keep heating vigorously without pause for one hour and then stop the heat. After it cools off, they take out the iron ingot (egg) from the crucibles. A person said that he was sitting next to a smith who was making swords in the province of *Send* سند [Sind]. He saw that the smith was using *narmâhan* نرمآهن and putting a very soft, ground mixture, which had a red color on it. Then the smith placed it in the furnace, and took it out and hammered it, and continued this process a couple of times. When asked why he did that he looked contemptuously. When he [the person sitting next to the smith] looked closely, he saw that the smith was hammering and mixing *dus* دوص with *narmâhan* نرمآهن the same way they made iron ingots (eggs) in Herat.

In the manuscript *Nŏruznâme* attributed to Xayyâm-e Neiðâburi, it is reported that another type of watered steel was made by Aristotle by taking one part *meqnesiyâ* مغنسیا (manganese dioxide MnO_2), or one part *bossad* بسد (coral), and one part *zangâr* زنگار (iron oxide), beating them into pieces, and grinding and mixing them well. Next, Xayyâm continues that 12 *ŏqiye* اوقیه (a weight measurement)[49] of this *dâru* دارو (medicament, mixture) is added to one *man* من (a weight measurement)[50] of *âhan-e narm* آهن نرم (soft iron), and all of these ingredients are

[45] See *Farhang-e Ānendrāj* (Mohammad Pādešāh, 1956/1335), *Javāhernāme-ye Nezāmi* (Jŏhari Nezāmi, 2004/1383:332) and *Digital Lexicon of Dehxodā*.

[46] See Beyruni (1974/1353:55-56).

[47] According to the *Digital Lexicon of Dehxodā*, one *ratl* is a half *man*. For the weight measurement man, see the footnote 49.

[48] Each *derham* درهم is 6 *dāng* دانگ, each *dāng* دانگ is two *qirāt* قیراط, each *qirāt* قیراط is two *tasuh* طسوح, and each *tasuh* طسوح is equal to two average barley grains in weight; a *derham* درهم is equal to the weight of 48 average barley grains. One *derham* weighs more than 3 grams (see *Digital Lexicon of Dehxodā*).

[49] Emām Šuštari (1961/1339:49) states that *ŏqiye* اوقیه is equal to 45.695 grams or in dealing with oil 42.65 grams.

[50] Based on Xārazmi's statements, Emām Šuštari (1961/1339:51-52) concludes that, at that time, one *man* من equaled 1091 grams. Based on the Lexicon of Borhān, Dehxodā states that *man* من is a weight measurement which signified different things in different locations at different times. The *man* من from Tabriz is described as 40 *estār* استار, each *estār* استار contains 15 *mesqāl* مثقال, meaning 600 *mesqāl* مثقال. Each *mesqāl* مثقال is six *dāng* دانگ, and each *dāng* دانگ is 8 *habbe* حبه, and each *habbe* حبه is the weight of one *jo* جو (barley grain). Based on Nāzem al-Otabā, Digital Lexicon of Dehxodā describes *man-e tabrizī* من تبریزی consisiting of forty *sir* سیر and each *sīr* سیر consisting of 16 *mesqāl* مثقال, so a *man* is 640 *mesqāl* مثقال. Anjoman Ārā says that *man* من is defined differently in different locations and the *man* من from Tabriz is forty *estār* استار and each *estār* استار consists of 16 *mesqāl* مثقال, resulting in 640 *mesqāl* مثقال and this was the *man* من of Tabriz which is now 1000 *mesqāl* مثقال (Digital Lexicon of Dehxodā).

put in a *bŏte* بوته (crucible), whereupon the crucible is heated well. After this, one part *harmal* حرمل (Peganum harmala), one part *mâzu* مازو (gall, oak gall), one part *balut* بلوط (oak), one part *sadaf* صدف (shell), and an equal amount of *zarârih* ذراریح (cantharide)[51] are added to the crucible. All of the ingredients are ground into small pieces. Then, two *ŏqiye* اوقیه (a weight measurement) of this mixture should be added to the crucible charge until all of them become one, meaning that the iron absorbs all of the ingredients. Xayyâm adds that the whole crucible should be left to cool off. Afterward, when blades are made from it, the blades turn out to be of high quality[52]. In the manuscript *Bayân al-Sanâ'ât*, Taflisi describes how steel is made from iron when he uses the expression *pulâd kardan narmâhan* پولاد کردن نرمآهن (to turn soft iron into steel). Taflisi explains that to turn soft iron into steel, one needs to heat up the soft iron and then add sour pomegranate (*anâr-e torš* انار ترش) and yellow myrobalane (Latin: *Terminalia chebula*) (*halile-ye zard* هلیله زرد)[53].

In the *Javâhernâme-ye Nezâmi*, Jŏhari Nezâmi describes that others say that making *balârak* بلارک (a type of crucible steel pattern) is an industry in India[54]. *Âhan* آهن (Iron) and *pulâd-e sefid* پولاد سفید [white steel][55] are filed (*borâde* براده) and cut into small pieces. Then these small pieces are mixed with soft iron (*âhan-e narm* آهن نرم) and heated up and with the blows of a heavy hammer (*zaxm-e xâyesk* زخم خایسک) and the application of water, different types of *balârak* بلارک are made. In the same manuscript, the process of polishing and etching the blade to reveal the crucible steel pattern is described in detail[56]. Jŏhari Nezâmi explains that there are types of *âhan* آهن (iron) which are ground up and rubbed with *rig-e samarqandi* برگ نی سمرقندی (gravel stone from Samarkand) and *sang-e sombâde* سنگ سنباده (emery stone) to make them soft. Then they procure *âb-e bâmiyâni* آب بامیانی [the water from Bâmiyân بامیان][57] or *zâg-e sefid-e moltâni* زاگ سفید مولتانی (white alum from Moltân)[58], or *zâj-e zard* زاج زرد [yellow alum] and they rub the blade [with it] until the *jŏhar* جوهر [crucible steel pattern] appears. All types of *fulâd* فولاد reveal this pattern, some have more of this pattern and some less. In the *Javâhernâme-ye Nezâmi*, Jŏhari Nezâmi adds that the *bandhâ* بندها (consecutive lines) that are seen on *šamširhâ* شمشیرها (swords) and *kattârehâ* کتارهها (a type of short sword) are made of *balârak* بلارک in a way that the *pulâd* پولاد is on the top. This is because the *pulâd* پولاد that can be used to make *balârak* بلارک with the watered pattern is very rare. The smiths cut the *balârak* بلارک and place the sections on top of the anvil so that they do not get separated. Then they heat and straighten them, and then they choose the parts which are still together. When they hammer it, it will necessarily break and its *jŏhar* جوهر will become consecutive, becoming one side with consecutive lines (*mosalsal* مسلسل). Then they break the parts with lines

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51 A type of insect (fly, [cantharis vesticatoria] *Cantharis vesiticatoria* or more correctly *Lytta vesicatoria* which may be right, cantharide) used in crucible steel charge.

52 See Xayyām-e Neyšāburi (2003/1382:56).

53 See Taflisi (1975/1354:317).

54 See Jŏhari Nezāmi (2004/1383:327-329).

55 It may refer to cast iron.

56 One of our reviewers opines that polishing and etching will not reveal a pattern in crucible steel alone as it has to be "Damascus" steel. However as mentioned before, there is a misconception of Damascus steel which was used by westerners to refer to the crucible steel blades. One should note that polishing the patterned crucible steel up to 800 grit, degreasing the steel and then immersing the steel in a dilute nitric acid (an acid strength that is just strong enough to oxidize the steel matrix a dark color and leave the carbide pattern bright) and this will reveal the pattern easily. Other acids can be used as well, and this is very typical process of how the pattern is revealed. The etching will show the pattern as the steel reacts differntly with the matrix and cementite. The cementite does not etch during this process (for the polishing and restoration of a crucible steel blade from the Bonyad Museum in Tehran see Moshtagh Khorasani, 2011).

57 Bāmiyān بامیان is a city of Afghanistan, or a village between Balx (Balkh) and Qazneyn.

58 Also called *zāj-e sefīd* زاج سفید which is a combination of sulfate potassium and sulfate aluminum; Mŏltan is a city between Qandhar and Lahore.

again, provided that they cut it in the middle, and then they cut it in such a way that it is close to separate from both parts. Then through sledgehammer strikes and heat they straighten it and slightly stretch it. Thus, two parts of the first part with consecutive lines are obtained that are on top of the *šamšir* شمشیر and *kattâre* کتاره. It is said that *balârak* بلارک is not heated with the fingers but with *barq-e ney* برگ نی (leaves of reed). This is because if *šamšir-e balârak* شمشیر بلارک or *kattâre-ye balârak* کتاره بلارک is not in India and they want to heat it in the fire and forge it, they will burn the *jŏhar* جوهر (pattern) completely and waste the steel, unless there is a master and an experienced artisan who knows the way of heating it. A very good *šamšir-e balârak-e šâhi* شمشیر بلارک شاهی costs 100 golden dinâr دینار. There is another type of *âhan-e hendi* آهن هندی (Indian iron) which is called *rŏhinâ* روهینا and its *jŏhar* جوهر is fine and lean, *bum* بوم (background) is green. This steel is *âhan-e harb* آهن حرب (iron for war) and is soft and made in the city of Mŏltân مولتان.

Further, Jŏhari Nezâmi reports that in Hendustân هندوستان, *beyze-ye pulâd* بیضه پولاد is heated, then reheated, and two *beyze* بیضه (crucibles) are made from it: one has a whitish nature and the other has a blackish nature. These are then cut into small parts, to which is added 10 *deram* درم of *sang-e ruy suxte* سنگ روی سوخته (stone with burnt surface; mosty probably antimony), the same amount of *merqešišâ-ye zahabi* مرقشیشا ذهبی[59], and the same amount *meqnisiyâ* مغنیسیا [manganese dioxide MnO_2] to each *bŏte* بوته (crucible), and all are heated well. Then forty *deram* درم of this mixture is added to the crucible again and heated with some bellows. Then they add identical amounts of *halile* هلیله (myrobalane), *pust-e anâr* پوست انار (the shell of pomegranate), *namak* نمک (salt) and *sadaf-e morvârid* صدف مروارید (pearl shell). Then they let it cool down and make swords from it. The half-finished [steel billet] is then placed under *sargin-e asb* سرگین اسب (horse dung) for three months, and from this they make *balârak-e šâhi* بلارک شاهی [royal *balârak*; a type of crucible steel][60].

Thus, based on manuscripts mentioned above the following types of metals were added to the charge to make crucible steel blades: a) horseshoes made of soft iron, b) soft iron, c) iron and d) white steel [possibly cast iron]. Then one added different materials (among them carbonaceous ones) to the aforementioned metals to create steel and these included: a) antimony, b) golden marcasite, c) manganse dioxide, d) myrobalan or yellow myrobalan, e) pomegranate peel, f) salt of dough, g) pearl shell or shell, h) coral, i) iron dioxide, j) Peganum harmala and k) oak gall or oak. To polish the blade, one used a) gravel stone from Samarkand and b) emery stone and to etch the blade one used a) water from Bâmiyân, b) white alum from Moltân and c) yellow alum.

4. REPRODUCTION OF CRUCIBLE STEEL

Crucible steel has been a source of fascination for many reserachers, collectors, museum curators and smiths for a long time. There have been many attampts to reproduce this type of steel, but the end results were not satisfactory in the beginning as they simply did not render the beautiful patterns of Persian crucible steel. Lately, some smiths were able to repoduce beautiful patterns of the crucible steel. One of them is the method used by one of the authors of the present article, Niko Hynninen. For years making the same quality of crucible steel, with

[59] Hard stone; it is used as eye medicament and there are different types of it: *zahabi* ذهبی (attributed to *zahab* ذهب, golden), *fezzi* فضی (white, attributed to silver), *nahāsi* نحاسی (red, attributed to copper), *hadidi* حدیدی (black, attributed to iron), and the best is *zahabi* ذهبی, and in each type of stone there is the respective mineral that can be extracted; these stones are not shiny in contrast to *meqnisiyā* مغنسیا which is shiny and the strongest type of *merqešišā* مرقشیشا is *nahāsi* نحاسی.

[60] See Jŏhari Nezāmi (2004/1383:332).

its different patterns, was considered to be a lost art. In the course of time more and more manuscripts were discovered, shedding more light on the mysterious process of making crucible steel. Neverthless, many of these manuscripts seem to be written in an arcane and difficult language. There could be different reasons for that. Possibly we do not really understand what these manuscripts are telling us due to the passage of time and semantic and syntactic shifts in the realm of linguistics. Another possibility was that the manuscript writers were trying to hide part of the information, as they considered this secretive and important technology. Another possibilty could be that the authors took lots of information for granted and assumed that their readers would understand them anyway. Yet another possibility is that the authors took for granted that the readers had access to much information that is not available now and would have understood their cryptic references. To reproduce crucible steel, one cannot ignore the important information contained in the Persian manuscripts. One needs to collect them and make a comparative analysis and then start the reproduction process. Hence a cooperation between researchers of historical texts/manuscripts and smiths is indispensable. In future, further attempts to produce crucible steel should be based on the inclusion of the ingredients mentioned before so that the crucible steel patterns which are created come closer to the original patterns. In spite of this cooperation between different disciplines, one should note that making crucible steel requires a great deal of trial and error and the failure rate can be quite high.

5. STEELMAKING AND FORGING

To melt the steel, Hynninen used a self-made gas/air furnace with a high temperature refractory cement lining and lid. He was able to create temperatures as high as + 1600º C[61]. In such a furnace, he melted charges in different crucibles, like SiC, clay graphite that have provided different steel ingots, depending on materials that are used for the melting process.

In the past Hynninen used modern, almost pure, iron that has some very low levels of alloys and impurities in it. He also used foundry cast iron to raise carbon levels to the level crucible steel typically had which means an average of 1.5%. This resulted in being able to first melt good ingots and forge out really nice steel bar stocks. But unfortunately the results were not satisfactory as only a small watered pattern was visible on the surface of the steel. Later on, Hynnien was able to obtain pure materials such as 99.8% iron and 4% cast iron with low alloy amounts in them. The assumption behind the procurement of these materials was that through this purity level, one would be able to obtain a better crucible steel pattern after the melting, forging and etching processes. Using the ingredients mentioned above resulted in making crucible steel; however, the pattern of steel was still not the desired large pattern steel typical of Persian crucible steel. Therefore, Hynninen started to rethink the whole process and to focus on how the ancients made crucible steel, and concentrated on different roasting heat treatments on the initial ingot state. His presumption was that the late smiths may have used long roast time prior to forging and this way the ingot's structural matrix could have been changed and

[61] One of our reviewers questions whether during the process of steel making with a charcoal furnace, one can reach 1600 C. The reviewer has had one up to 1400 C with a forced draft but if Hynnien's furnace is more powerful than the originals, then his experiments will be of questionable value. But one should note that a charcoal furnace can easily reach the melting temperature of pure iron at 1538 celsius and it must also exceed this temperature to melt all of the charge in a timely fashion, otherwise one uses a lot of fuel and wastes it. There is a constant loss of heat energy through the furnace walls and exhaust, therefore one must have higher than normal temperatures to melt the charge in the crucible. Hynnien used gas and air during his crucible steel making process where temperatures went over 1600 celsius. In old times, we assume that they used huge furnaces and with huge amount of fuel and reached temperatures equal to modern gas air system.

Figures 3-4. A self-made gas/air furnace with a high temperature refractory cement lining and lid.

influenced. However, keeping high temperatures for extended periods of time and the subsequent slow cooling rate led to the point where Hynninen's ingots started to crack. Additionally, the matrix of steel was more or less full of black dots and spots. This was once again quite a big setback. Hynninen continued with long and exhausting new melts and forging, but the results were not satisfactory. Since different ways of treating steel before and during forging did not produce the desired effect, therefore, something in the system needed to be changed.

Even many ingots with pure iron and almost pure cast iron ended with the same results, in spite of having tried out different methods. Hynninen hypothesized that the reason for the small weak pattern of the crucible steel was due to the level of the element phosphorus[62]. In the course of time Hynninen became more and more interested in the level of P (phosphorus) in crucible steel blades[63]. This led him to go back to the method of how he made his first ingot, which had nice a banding and pattern. There Hynninen used foundry cast iron which has a quite high purity level. Unfortunately, the problem with foundry cast iron is the presence of some alloys in steel that are not desired. Hynninen found some old bloomery iron that was made from Finnish lake ore also known as limonite. This used to be one of the biggest ore supplies in Finland more than 100 years ago. Although its Fe level was quite low, it was used to make iron and even steel (by using different methods). This lake ore had high levels of phosphorus and the amount varied by collection place, meaning that some areas are more phosphorus rich than others. One should note, however, that even phosphorus has some bad side effects in steel such as hot shortness. Hot shortness is a term used to describe forging the steel at a high temperature and having the steel react by splitting or crumbling (the crumbling is similar to the crumbling of a very dry cookie). If one forges the crucible steel at too high a temperature, it by nature will crumble like a dry cookie. It is also affected by the types and amount of alloys used. The assumption of Hynninen was that the phosphorus should have had a strong effect on the pattern of the crucible steel.

Hynninen used a self-calculated recipe that contained old bloomery iron and pure cast iron that had good levels of alloys for carbides as the following: 1155 grams of rust-free old bloomery iron plus 1079 grams of cast iron giving a total mass of 2234 grams. The mixture was placed in a clay graphite crucible of the size A6 and charge was covered with 230 grams of slag material that consisted of 42 grams of Al2O3 (aluminum oxide), 132 grams of SiO_2 (silicon dioxide), 30 grams of MnO_2 (manganese dioxide)[64], 14 grams of dolomite, 16 grams of Cornish stone and the crucible was sealed with clay paste and a high temperature refractory brick. The crucible was placed in the furnace and a 15-min preheating time was used. After this full gas air flow was used and the temperature was raised to maximum +1600º C according to infrared sensor and a total melt time of 90 minutes was applied. After this, the gas air was turned off and the crucible was left to cool in the furnace to +1000º C which took about 2 hours. After this, the crucible charge was lifted form the furnace and left to cool in the air.

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[62] Regarding the element phosphorus, Barnett et al (2009:2197) write**:** **"**the effect of phosphorus on cementite morphology can be understood best in terms of a solute drag exerted by the tendency of phosphorus to slow the rate of cementite decomposition. The phosphorus-rich bands will tend to contain more non-equilibrium cementite in the austenite that can act as sites for the growth of spheroidized cementite through the ectectoid reaction**"**.

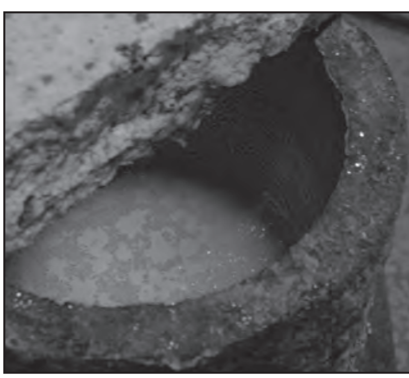
[63] As mentioned earlier in the article, the element P (phosphorus) makes up one of the impurity elements in crucible steel next to Mn (manganese), S (sulfur) and Si (silicon). For a detailed discussion on the level of P (phosphorus) in crucible steel blades see Barnett, Balasubramaniam, Kumar and MacRae (2009).

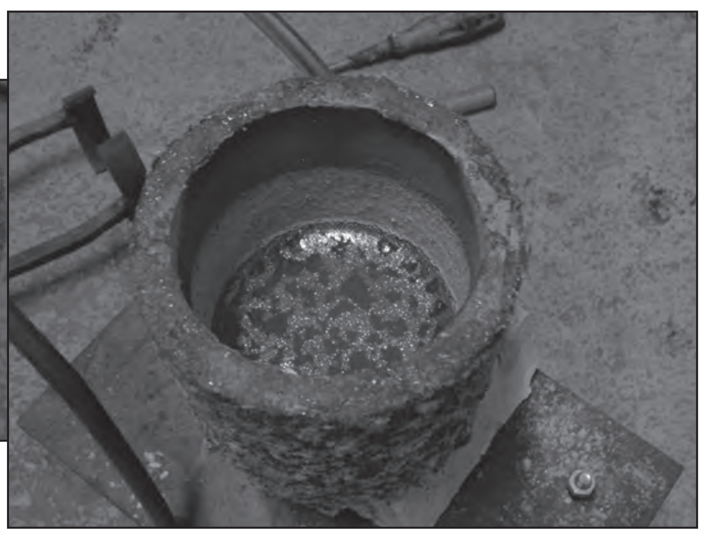
[64] This was also used in making crucible steel as mentioned in old Persian manuscripts and called *meqnisiyā* مغنيسيا.

Figure 5. The crucible charge left to cool in the air.

After cooling to +800 C, the lid was removed and the molten smooth slag could be seen inside the crucible. Using a chisel and hammer, the slag was broken and the steel ingot was released from the crucible. The top of the ingot showed a coarse dendritic pattern with a spacing almost 3 mm wide.

Since Hynninen had problems with roasting ingots by exposing them to the temperature of +1100 C varying between 2h up to 6h and 12h and then a slow cooling followed. He came to





Figures 6-7. Molten smooth slag after removing the lid.

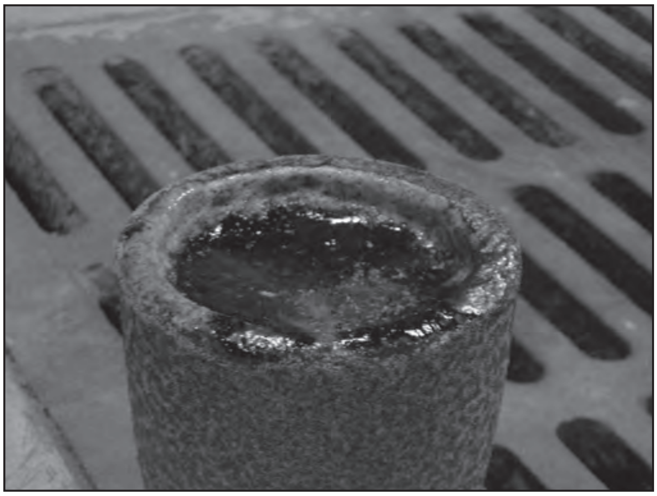
the conclusion that this method was not good for the structure and pattern of the crucible steel. Operating this way, there is a high risk of graphitisation that may occur in certain alloys that lead to the creation of micro-porosity within the ingot. The micro-porosity could happen during the solidification of molten metal. These small porous holes may act as nucleation points and C (cementite) may turn to free graphite resulting in the creation of black dots in steel within interdendritic regions. The Graphitisation means that graphite particles have grown in the steel. This happens in cast iron and is one of the reasons why cast iron is brittle and breaks easily. There are several reasons for it involving both the heat treatments and the alloy. Even with the right heat treatment, the carbide in normal steel can decay and turn into graphite particles, which is a concern with the crucible steel. Even the raw ingot contains a lot of micro porosity due to the growth of the dendrites. If these are not closed up in the beginning of forging, they potentially can be the initiation points for graphite particles to start to grow. When the liquid steel starts to solidify, it starts to nucleate at some points and from these points, as soon as the temperature is low enough, it starts to grow solid iron dendrites in the liquid steel. These tree-like solids grow in one direction and stop as soon as they hit other solids. All impurities in the molten metal are pushed between these interdendritic regions. These impurities consist of alloys and sulphides, but not carbon at this point since steel even if solid is at full austenite state and carbon is still in solution. As soon as the temperature has dropped below A_{CM} in iron-carbon or Fe-C (see phase diagrams, Diagrams 1-3 in this article)[65], it starts to nucleate there where it can find carbide forming elements. The A_{CM} temperature for a particular ingot sample is dependent on the level of carbon in the steel sample. As soon as the temperature is at A1 [A1 is at +738C] and based on its cooling rate, all carbon is in solution and the steel has a matrix that consists of pearlite and cementite in IDR (ledeburite) or pearlite and grain boundary cementite + Winmanstättens needle cementite inside the grain. In the latter type, Hynninen thinks that carbon does not have time to nucleate in those places where carbide-forming elements are and they grow inside the huge grain that is present after slow solidification[66].

When the ingots cool down, Hynninen cut small slices off for the chemical analysis as he strongly anticipated that phosphorus was already in the bloomery iron that he used and wanted to know what amount of phosphorus was in the steel. The amount of phosphorus at 0,16 % P level was close to some analyses that have been made on samples of ancient blades as the analyses show[67]. The third ingot was the same but with only two differences in that it contained slag that was green glass and the maximum temperature was higher than his first two ingots (the temperatures were as follows: ingot I and II +1550 max and III over +1600C). This is shown at Si level. All the charge materials were cleaned of rust and dirt by sandblast-

[65] Note that A_{CM} temp changes as per the level of carbon in the charge.

[66] One of our reviewers state that if the cementite present is turned into graphite, the grey cast iron is formed which is less brittle than white cast iron. Our reviewer adds that this steel is usually very low in slag and porosity in the ingot is unlikely to hold oxygen –perhaps there is confusion here with modern “killed” steel. Hynninen stresses that graphitisation is bad for the steels overall structure and if this phenomenon happens, it will turn ultra high carbon steel into a similar structure as gray cast iron. One should note that the graphite has no strength in itself and the steel will be weaker than steel that has no graphitisation in it.

[67] See Verhoeven, Pendray and Dauksch (1998:63) who write “It is well established that the ferrite/pearlite banding of hypoeutectoid steels results from microsegregation of the X element in Fe-C-X alloys, where X is generally manganese, phosphorus, or an alloy addition. For the example X = P, it is established that the microsegregation of phosphorus to the interdendritic regions (IRs) causes ferrite to nucleate preferentially in the IRs. If the cooling rate is slow enough, the ferrite grows as blocky grain boundary allotriomorphs and pushes the carbon ahead of the growth front until pearlite forms between neighboring IRs. Apparently, rolling or forging deformation is quite effective in aligning the IRs of the solidified ingots into planar arrays, because the ferrite appears as planar bands parallel to the deformation plane separated by bands of pearlite. The ferrite/pearlite bands of sword 8 were probably produced by this type of banding caused, most likely, by the microsegregation of phosphorus”.



Figures 8-10. Removing the crucible steel cakes from crucibles.

ing and compressed air to remove any sand in them. Nevertheless, Hynninen noticed that even in cast iron there are elements that lower the total C (carbon) amount in the ingot. That is the reason why a bit higher amount of carbon was calculated and added to the charge. Materials can hold the slag. The porosity in the corners can hold oxygen and other gasses that may lower the amount of carbon as well, if the temperature is as high as a maximum of +1600 carbon. There is the phenomenon of chemical reaction ($SiO2+2C=Si+2CO$) called crucible reaction that comes from a silicon (Si) reaction with carbon and during this process, the oxygen is removed but the silicon amount will increase, at the expense of C that will decrease[68].

Ingot I (2,5 kilos and all numbers are expressed in % and the analysis was done by the metallurgical mass spectrometry)

C	1.32 %
Si	0.44 %
Mn	0.11 %
P	0.33 %
S	0.07 %
Cu	< 0.003 %
Al	0.01 %
Cr	0.008 %
Mo	0.033 %
Ni	0.040 %
V	0.041 %
Ti	0.003 %
Nb	<0.002 %
Co	0.015 %
W	<0.005 %
Pb	<0.01 %
Sn	<0.003 %
B	<0.0003 %

Ingot II (2,7 kilos and all numbers are expressed in % and the analysis was done by the metallurgical mass spectrometry)

C	1.26 %
Si	0,101 %
Mn	0.16 %
P	0.16 %
S	0.116 %
Cu	< 0.003 %
Al	0.012 %
Cr	0.023 %
Mo	0.037 %
Ni	0.034 %
V	0.033 %

68 One of our reviewers asks whether the silicon reacts with carbon and removes oxygen. Hynninen stresses that the silicon removes the oxygen at the expense of carbon. Thus the carbon lowers and the silicon rises. During this process, other gases are trapped in steel such as CO.

Ti	0.005 %
Nb	<0.004 %
Co	0.018 %
W	<0.024 %
Pb	<0.01 %
Sn	<0.014 %
B	<0.007 %

Ingot III (2,1 kilos and all numbers are expressed in % and the analysis was done by the metallurgical mass spectrometry)

C	0.99 %
Si	1.3 %
Mn	<0.003 %
P	0.118 %
S	0.023 %
Cu	< 0.003 %
Al	0.008 %
Cr	0.004 %
Mo	0.032 %
Ni	0.007 %
V	0.042 %
Ti	0.001 %
Nb	<0.002 %
Co	0.019 %
W	<0.013 %
Pb	<0.01 %
Sn	<0.004 %
B	<0.0003 %

The phenomenon, hot shortness, is a major example of how phosphorus makes steel difficult to forge[69]. Many methods have been mentioned in different journals about the roasting process of the crucible steel without going into detail about this process[70]. However, many of these methods seemed to stress the necessity of roasting the ingots at a high temperature for a long time. During the thermal treatments the ingot surface is exposed to oxygen and this creates a decarburized crust over the whole ingot. In this layer there is almost no carbon and no Phosporous, and for this reason this layer acts like a buffer that takes the stress of forging better than an ingot without it, and this prevents cracking due to hot shortness. The question is why one needs to roast ingots and then to find out what is the proper way to do so. A decarburized crust [layer] should be 1 mm to 5 mm thick, and this is one of the most important features of the roasting process. Nevertheless, during the roasting at a high temperature other considerations such as diffusion are important as well. At a high temperature and over a certain amount of time, some elements move in the matrix, but some are really hard to move. The

[69] One of our reviewers opines that phosphorus is usually responsible for cold shortness, but Hynninen strongly disagrees and states that phosphorus is indeed responsible for hot shortness. He has experienced this 100 times during his forging process.

[70] See Moshtagh Khorasani (2008).

Figure 11. Prepared crucible steel cakes.es.

Figure 12. The bottom surface of the 2.7 kg ingot 10x. This ingot is number I. The figure shows when the cooling rate is faster than thefurnace cooling. Matrix here shows widmanstätten needles that are Cm (cementite). This happens when cooling rate is too fast Cm to nucleate and diffuse to those carbide-forming elements that are in interdendritic regions. Carbon gets trapped inside the very large grains and forms needle-like structures.

Figure 13. The shrink edge of 2.5 kg ingot to the central point. This ingot is number II and the figure is 10X magnification. The figure shows the matrix that is dendritic, dark matrix is pearlite and the bright white area is Cm (cementite). Surrounding this, there is a bit darker area which is P, Mn, Si and other alloys and impurities that crucible steel holds in a raw state after solidification state.

required time to move some carbide forming elements is so long that it is almost impossible to achieve. But there are some elements that will move, such as phosporous. In Hynninen's opinion, phosporous will segregate in interdendritic regions during solidification and this is also true for carbide forming elements. Under a high temperature, this Phosporous will diffuse away from those regions and if cooling rate is fast, like air cooling it doesn't have time to move back[71]. The space is now occupied by carbon since in those regions there are still carbide forming elements[72].

Hynninen is of the opinion that those ingots were cooled slowly after the roasting process. Since he had produced many bad ingots this way, he started to wonder why the ancients would have wasted the energy, time and effort first heating ingots to a high temperature and for a long time, which is a method that uses lots of energy. Hynninen did not find any benefit, nor a structural difference with this method, so he proposes a simpler way. Hynninen used a high temperature treatment for a long period of time to create decarburized crust for the ingot. To do this, he used a temperature of +1100º C and 3-5 hours. After roasting he starts to forge ingots straight away, so that he does not use a cooling off period. This way the crust makes forging easier and one can almost see no cracking. Hynninen believes that ingots can be forged quickly and easily by using the donut technique. This technique is used by forging from the top to the bottom. The ingot's thickness is about 15 mm. The ingot forged this way, is like a pancake and is about 200 mm in diameter. In the next stage, a hole is punched in middle of this pancake-shaped steel. There are different ways of making a hole, but Hynninen uses a dull hot steel punch tool. After making the hole, Hynninen uses different sizes of drifters to enlarge the hole. This is an important step since it is easier to make a hole wider with drifts than forging a hole wider with the anvil horn. The amount of steel is too big for hand hammering; in this pancake shape, the steel forging is almost 60 mm wide. As soon as the ingot turns into a big ring shape that is about 20 mm thick (the section of the ring is about 20 mm wide) and 12-15 mm thick, Hynninen cuts it open and it looks like a large «C» shape[73].

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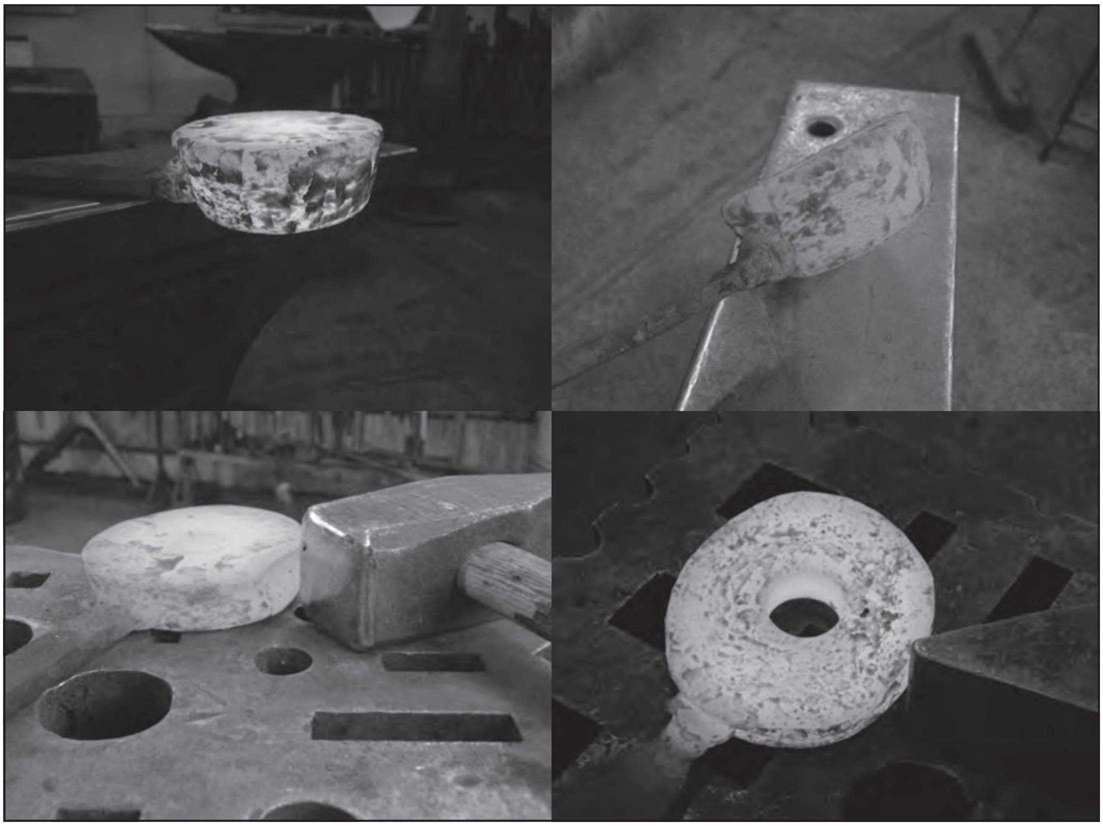
[71] One of our reviewers questions that if phosphorus has segregated why should it then diffuse away. The reviewer adds that both the dendrites and the spaces between them are full of iron carbide (not usually carbon) but in different morphologies. In our opinion, the porosity in the ingot is due to the growth of the dendrites (they are small voids during the beginning of forging). These will generally close up and the diffusion will weld them shut. However, if you thermally heat treat the ingot for long periods of time before the voids are closed up, one risks these becoming areas for graphite to nucleate and form. Therefore, it is not recommended for long hold times when producing the ductile rim on the raw ingot. Further, phosphorus will diffuse since its elements move similarly to carbon. One cannot keep it in one spot. Single heating will move phosphorus. Hynninen thinks that phosphorous provides "room" for carbon. Iron dentrite turns to pearlite after solidification when the temperature is under the A_{CM} (in carbon phase diagram). The Interdentritic region is full of left-over carbon that does not fit in the pearlite matrix and alloys /carbide-forming elements, such as V, are also pushed to interdentritic regions (IDR).

[72] For a discussion on the level of P (phosphorus) in crucible steel blades see Barnett, Balasubramaniam, Kumar and MacRae (2009) and Gahahar and Balasubramaniam (2004). One of our anonymous reviewers states that the discussion about the role of P in the process of formation of the pattern, which seems to be an important contribution of this article, lacks some clarity. Additionally, he states that it would be useful to also have the compositional analysis of the blades made from the ingots presented in the article. This would allow to see how much P is lost in the forging process, and to compare the levels of P of the actual finished product with those of the ancient blades. However Hynnien states that P is one of alloys which does not get lost during the forging process. Unfortunately, he does not have an analysis before and after the forging process.

[73] One of reviewers believes that these experiments could be very useful but deems it necessary that the ingots and sword billets need to be sectioned and then examined by microscopy at each stage of the process to find out what microconstituents are actually present. Then the phase diagrams can be invoked to explain the changes. Although no cross sections are available, we need to stress that in our opinion the micrographs are not so important, but rather what is important is that macro pictures are the evidence that the same surface patterns, as the old steel blades from Persia, have been replicated. Some studies present many micrographs, yet the patterns they show do not resemble old crucible steel patterns seen on actual Persian blades. The ingredient that moved the process forward was the addition of phosphorus and that the possible mechanism has been also referenced from a previous study on phosphorus. However, although previous studies on the element phosphorus mentioned the mechanism but it did not provide any sample or proof of principle. This study provides the proof by showing the macro pictures of the surface as seen in pictures 41-43.

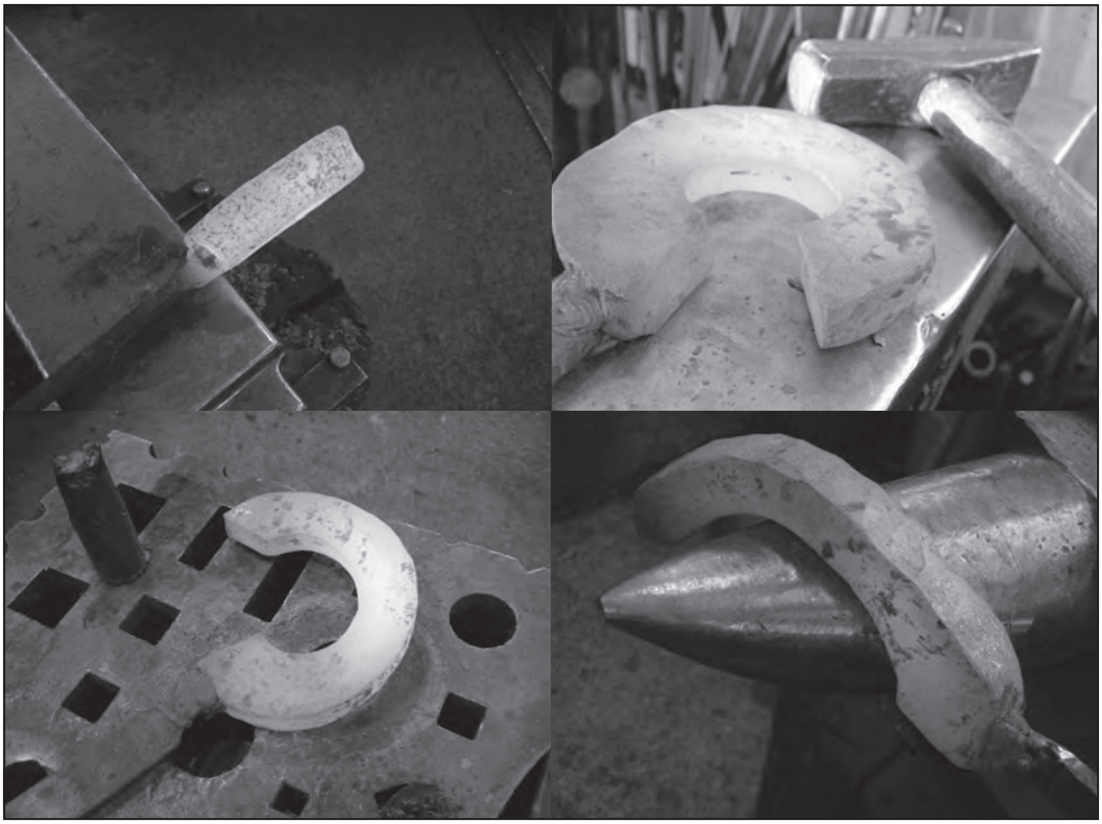


Figures 14-17. Forging the ingot in the pancake form by using the donut technique.

Hynninen continues to forge over the anvil's horn and various cone shaped tools to get the C shape open up as a straight bar. It is easier if one forges the inside of the C-form with a hammer peen or a ball peen hammer. This is due to the fact that steel tends to move more towards inside and keeps gradually expanding.

As soon as the bar is made, Hynninen starts to shape the steel. During the forging process, he hammers the surface. He peens with a hand hammer, using a ball peen hammer for the round face. At every full pass, Hynninen uses a steel scraper or file to remove steel filings, and this is done while the steel is still hot. In this state, the steel is still hot and as soon as some material is removed and the steel cools down and blackens, it is reheated in the forge and the whole process is repeated for the whole length of the blade. The pattern of crucible steel is created due to the banding of spherical clusters of cementite. The pattern is formed during the forging process from the breakdown of the raw big clusters or strings of cementite and are gradually turned to spherical form, since it is an economical shape for them. This only happens if the temperatures are right for the transfer of cementite to spheroid form, and is combined with forging so that the raw structure is broken into smaller grains[74]. If the temperature is too high, it will drive cementite into the grain boundaries, the steel will be weak, and there will be no pattern in the steel. At the same time, if the temperature is too low, the breakdown of the

[74] One of our anonymous reviewers states that it would be useful to have a value, or a range of values, for these temperatures. However, Hynnien did not record the exact temperatures.

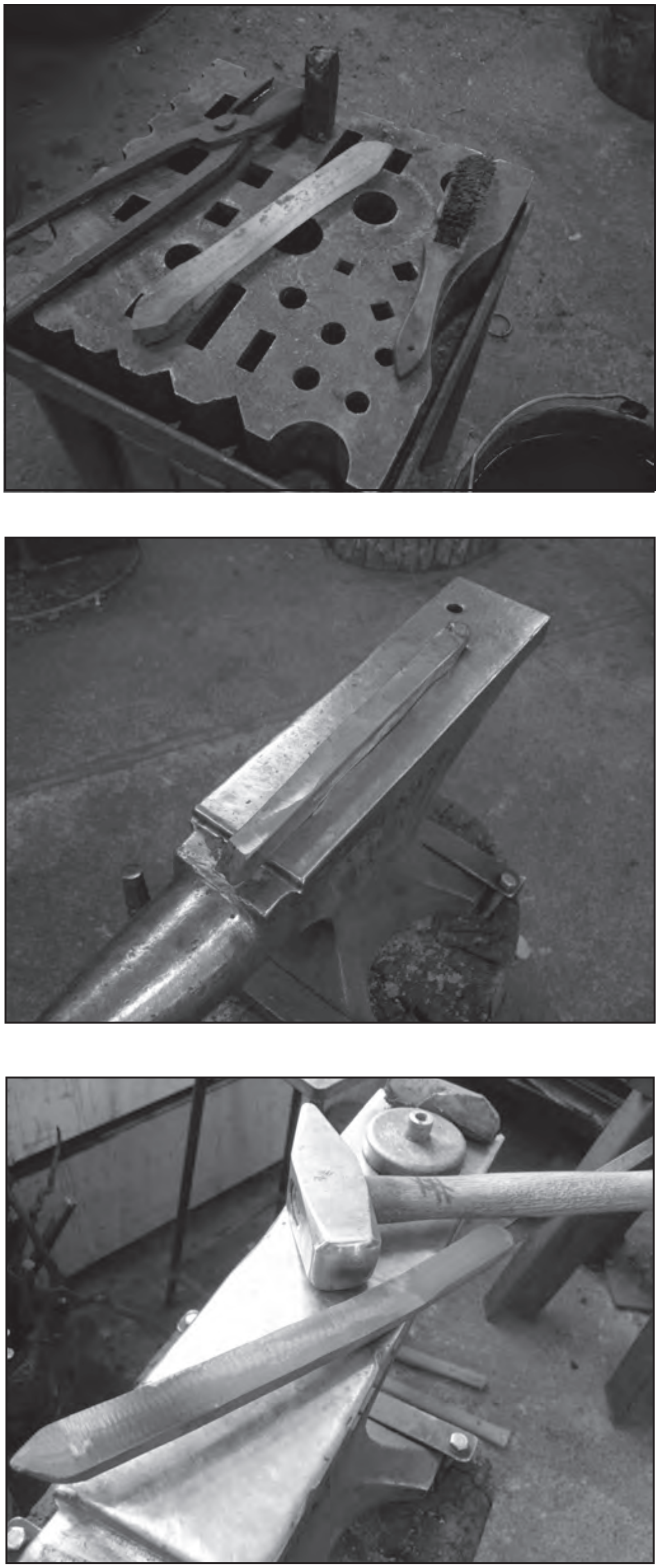


Figures 18-21. Making a C-form and a subsequent straight steel bar.

dendritic pattern does not happen as the cementite does not dissolve in austenite. The same effect is due to the reduction rate that is used for the ingot. If the reduction is small, the pattern will be raw and dendritic.

The goal of forging the barstock is also to produce a blade shape while amending the pattern to produce the famous wavy watering pattern of crucible steel. One should note that the banding in a bar of crucible steel is quite thin. Thus to get a wider pattern, some stock reduction needs to take place at low angle, and the removed amount of steel needs to be quite small. One should keep in mind that the banding space should be at 30µ -100µ and the cementite itself should be even under 10µ. If there is no surface manipulation, the pattern is more or less just simple straight lines of cementite in the surface and the real activity is missing[75]. In Hynninen's opinion, this is due to the movement of steel that comes from flat dies of a power hammer or hand-held hammer. If hammer or die surface is crowned there will be a natural move-

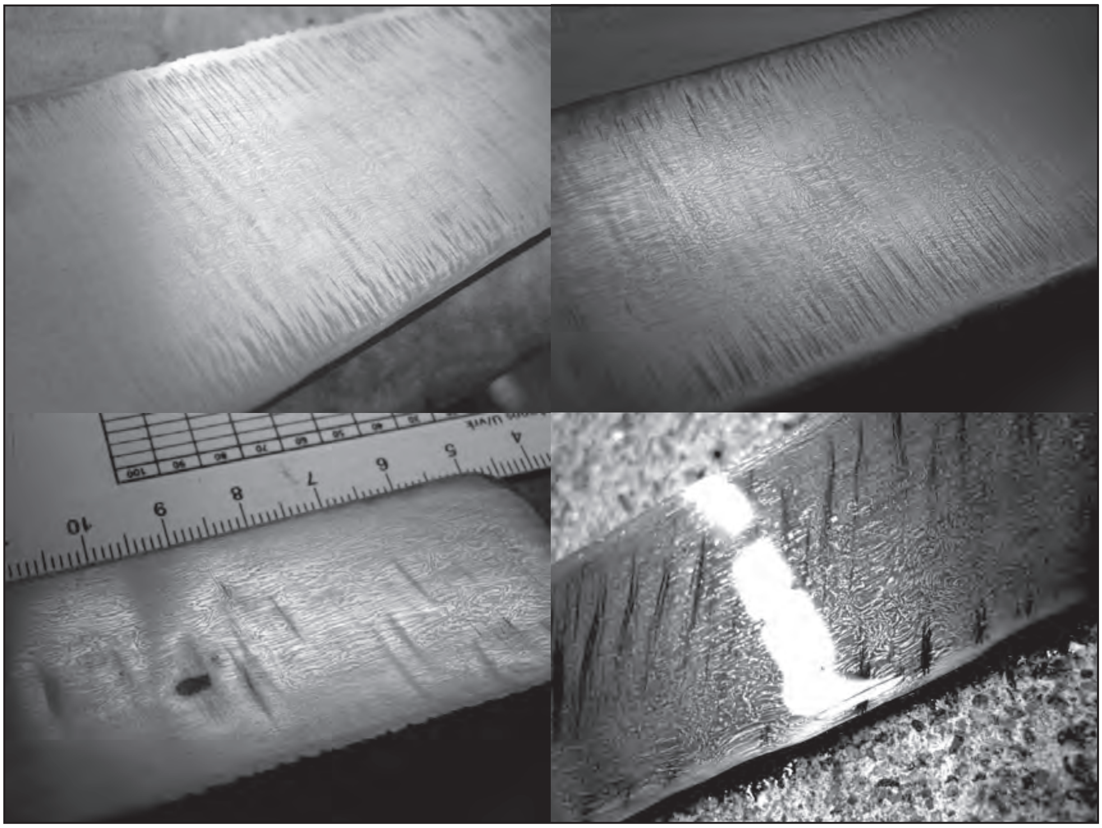
[75] One of our reviewers states that if the temperature is too high, the cementite will redissolve and it will not be driven into the grain boundaries and adds that one cannot know that the pattern is simple lines of cementite. He opines that there are other possible causes of a pattern, but if it is truly Damascus" then the pattern is not only on the surface. Therefore, he suggests that metallography is essential here. Hynninen stresses that the pattern will surely be just simple lines (these can be observed in some swords). If the pattern has not distorted or the pattern has gone through too much material removal, the cross sectional images of the spine show that the cementite is more in the shape of lines in these sections rather than at the bevels of the blade. This only happens if the pattern is developed and can be seen numerous times. If the temperature is too high all carbon elements move into austenite solution, during cooling process, this extra carbon goes to grain boundaries (GB´s).



Figures 22-24. Forging a steel bar.

ment difference in surface and this alters the high and low points of layers. When this forging method is added to the small surface material removal it enhances the pattern in the surface since high points will be removed and low points will rise to the same level. Further strikes during intensive forging will show spacing that is even bigger. Thus, if the angle is right, the depth of cut is right and the material removal is done just right, the whole cementite band will show stronger than it actually is, that's about 10ym, but this can be wide as the whole blade. As soon as the bar is forged on both sides in this way and its surface is flattened, Hynninen cleans the surface and grinds it for etching. This is just a step for the inspection to see if the pattern is good enough or whether it needs further manipulation in some places or a full pass.

Hynninen is of the opinion that the pattern is only on the surface and it is not that deep.



Figures 25-28. Grinding and test etching the blade.

Therefore, Hynninen opines that if too much material is removed at the final stage of the grinding and polishing, the pattern will change slightly. This means that it is important to forge the blade in its final shape and this needs to be done at the high forging temperature. The water forging technique[76] is appropriate to use as it pops off any forge scale that might come to the surface. This also helps the final cleaning of the steel since there is very little hard scale adhe-

[76] This technique includes adding water from a bucket to the surface of the anvil and this turns to steam as hot steel gets struck during forging by a hammer. The created steam explodes and removes the scale and leaves the steel white without any scale that is hammered inside the surface of the steel blade.

ring to the surface. Hynninen has normalized steel ranging 3 – 10 times (even more) and since the crucible steel contains carbon almost twice as much as the average modern carbon steel, there seems to be a difference between the two[77].

Hynninen does the normalizing process similar to any other steel, but the final pattern will change slightly depending on the temperature and the cooling time. He uses non magnetic point (about +770 C) and cools steel with hot forced exhaust air from the door of the propane forge. It seems that this will create finer pearlite particles than just free air cooling. Also if the steel is cooled more slowly, pearlites will turn to coarse pearlites or if the time is long enough the pearlite will spheroidize. When higher temperatures are used, more carbon will dissolve in austenite and if the cooling rate is slow it will nucleate where the carbide forming elements are positioned. In interdendritic regions, however if a higher temperature is used at a faster cooling rate, the carbon does not have time to diffuse and the pattern will be more like large grain boundary areas. This is due to the blocky cementites in those regions.

Crucible steel has a low alloy amount (other than carbon), and this fact makes this type of steel shallow hardened steel. Hynninen opines that there are two ways to quench this type of steel: light oil or really strong brine with lye. To austenitize blades, he uses a + 780 C temperature and 20 minutes of total soaking time to quench the blades in oil. However due to the thickness of the blade (5-6 mm at the spine) or the relatively low austenite temperature, only the blade edge is hardened and illustrates a strong quenched line. At the quenched line, the blade has a crucible steel pattern and shows a nice watering effect. One should note that there is a risk that too high a temperature will dissolve too much cementite and the pattern will not be as strong. The dissolving carbon that goes over the solubility of iron retains austenite. Hynninen also uses brine and lye solutions with a temperature of +760 C and a total soaking time of 15 minutes and thinks that they work even better for quenching this type of steel. The amount of salt in water in brine and the same effect of the lye help to stop the formation of a vapour jacket around the steel's surfaces and in return, speeds up the cooling rate. Even if this undercooling is fast, this type of high purity ultra high carbon steel needs it to achieve a full martensitic structure. This full martensitic structure means that if one has 1.5% C level in steel and uses only +760 C temperature, only a certain amount of carbon has dissolved in austenite and only this will turn into martensite. The rest of the carbon, that is cementite which forms the crucible steel pattern, will stay in its undissolved state and this does not change the pattern. However, this will show the pattern contrast even better since now the steel has a structure that is a dark martensite matrix with a bright cementite banding over it. The martensite turns almost bluish black and cementite obtains a silvery color after the acid etch. Hynninen stresses that at this stage the steel is really springy even after hard quenching.

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[77] One of our reviewers questions why the blade is being normalized and why Hynninen wants austenite to form. Hynninen explains that long blades are normalized since it is absolutelly impossible to forge 100% similar matrix in sword length blade. If the matrix is not similar, the quenching and tempering processes will ruin the steel. Normalizing is done at right temperatures so that the pattern does not suffer. Only some carbon will diffuse and this will create smaller grains and even spread through the whole length of the steel. One should note that Hynninen does not create austenite in steel at full austenite temperature because there is a chance of ruining the pattern if too high temperature is used in this stage.

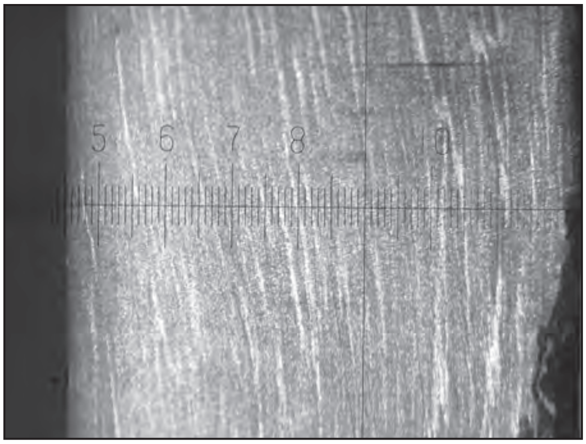
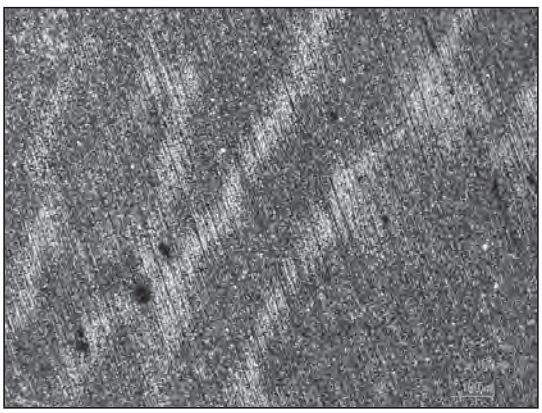
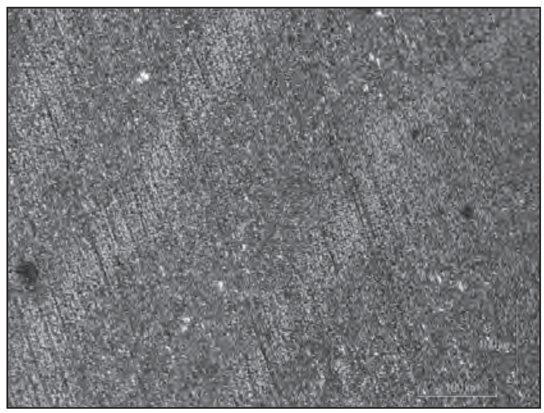


Figure 29. Close-up of the produced crucible steel at 4 mm from the forged blade spine.





Figures 30-31. Close-up figures of spheroids in crucible steel from the forged blade.

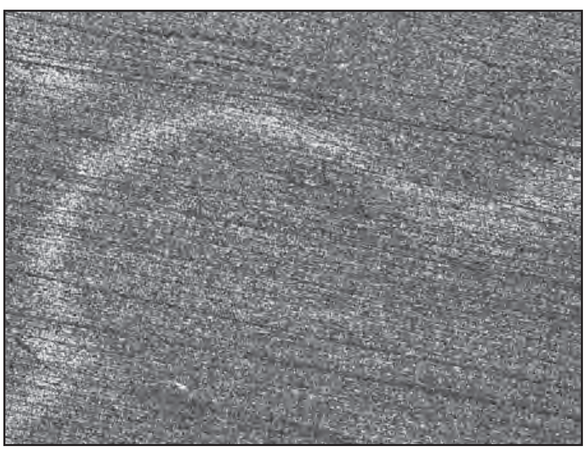


Figure 32. Close-up of the produced crucible steel at x5 from the forged blade.

Using simple tools such as fine new files and window glass, it is shown that the hardness was high[78]. New files skate over the steel, which scrapes window glass easily. However when the work is clamped between vise jaws, it shows springiness when bent with steel tubing placed over the blade and flexed. Possibly, this is due to the matrix in steel; even the martensite has a lot of spheroidal form cementite in it. However, Hynninen tempers the steel and uses +180 C and 10 hours hold time to get even more ductility and strength in it[79]. Hynninen has made forge level tests to factory steel (simple modern steel contains 0,7% C, 0,7% Mn and 0,2% Si) that shows that long time will increase ductility and decreases hardness only a small amount after the usual 1 hour that is given to steel in general. These conclusions can be extended to crucible steel as the results are even better since carbon levels are 2 times higher and the steel purer than modern steel. The longest tempering time tested by Hynninen was 24 hours.

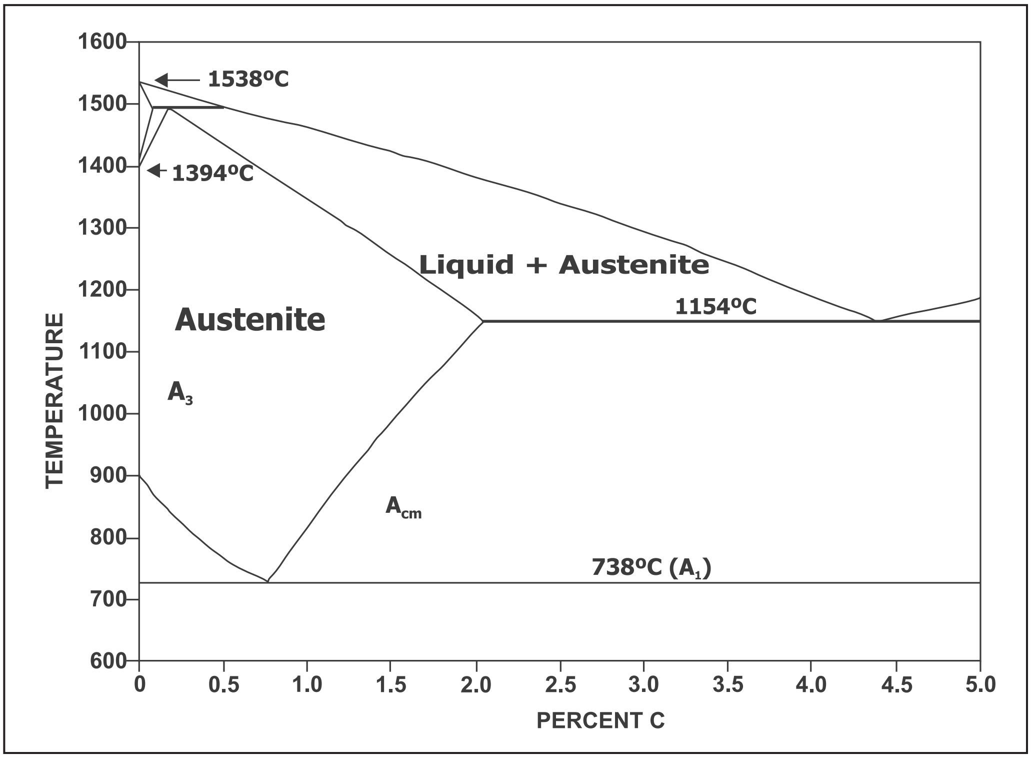


Diagram 1. Fe – C Phase diagram.

[78] One of our reviewers asked for hardness tests, but no hardness test was conducted by Hynninen.

[79] One of our reviewers asked for measurements of ductility, but Hynninen has not made any ductility measurements.

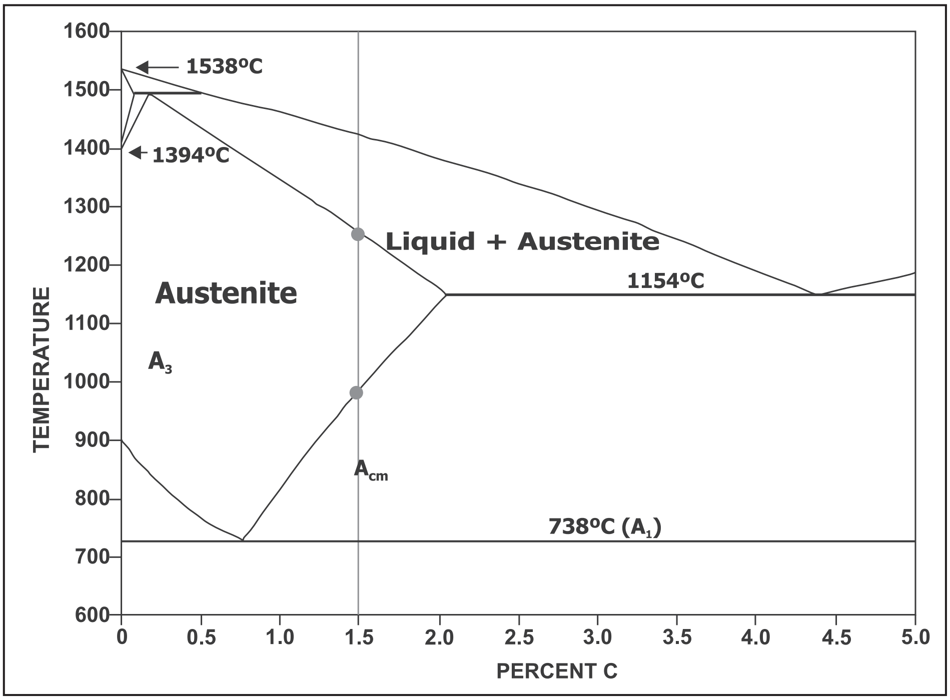


Diagram 2. Fe – C Phase diagram and example of 1.5% C steel solidification zone, the slower this zone the bigger the dendrites will grow.

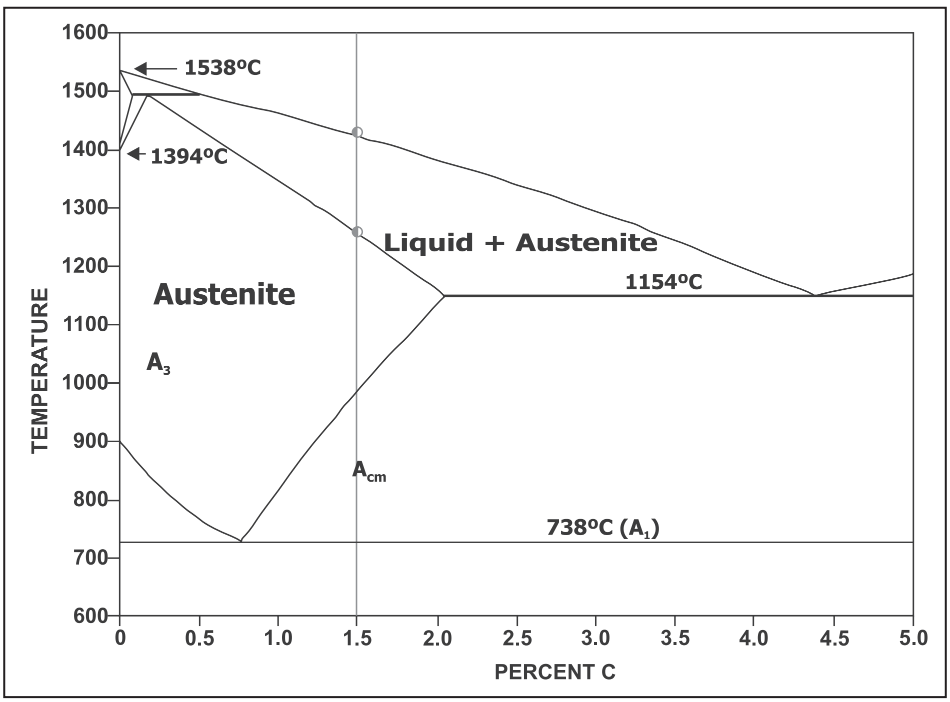


Diagram 3. Fe – C Phase diagram that shows a zone where carbon is still moving around the solidified ingot. The time of cooling within these zones will affect how and what form of carbon there is after temperature is at A_{CM} (lower red dot).

Slow cooling will affect structure between dendrites (interdendritic space); when the cooling is fast, it will stay inside the grain since there is no time for diffusion.

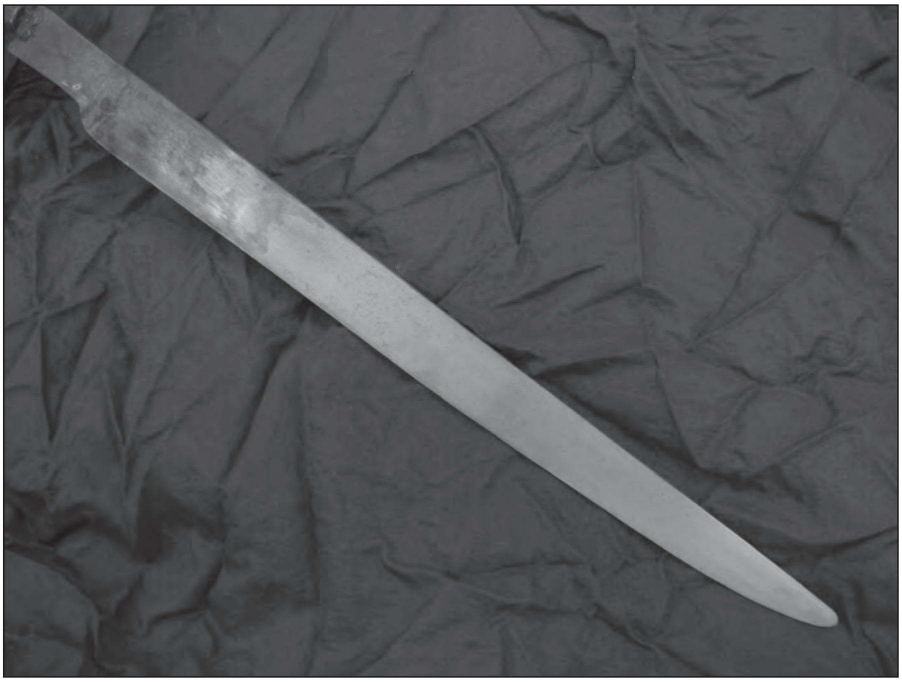


Figure 33: A ground and partially etched blade made by Hynninen.

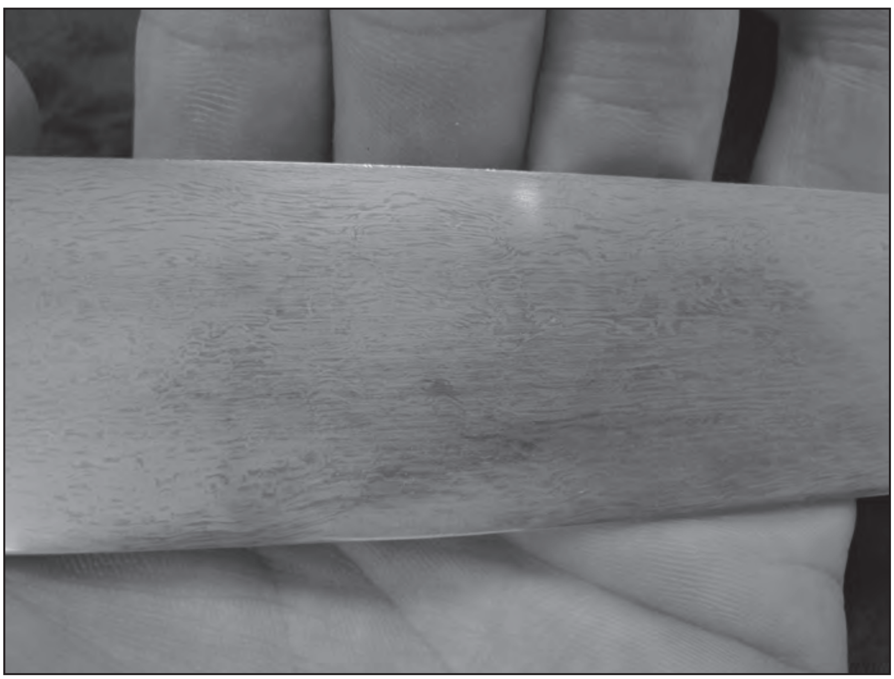
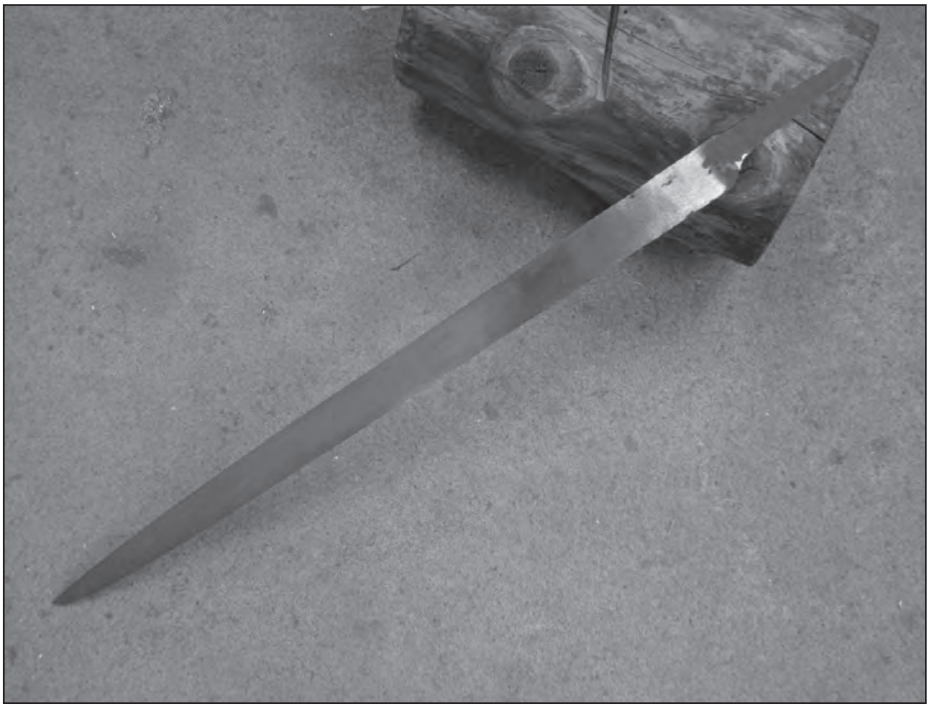
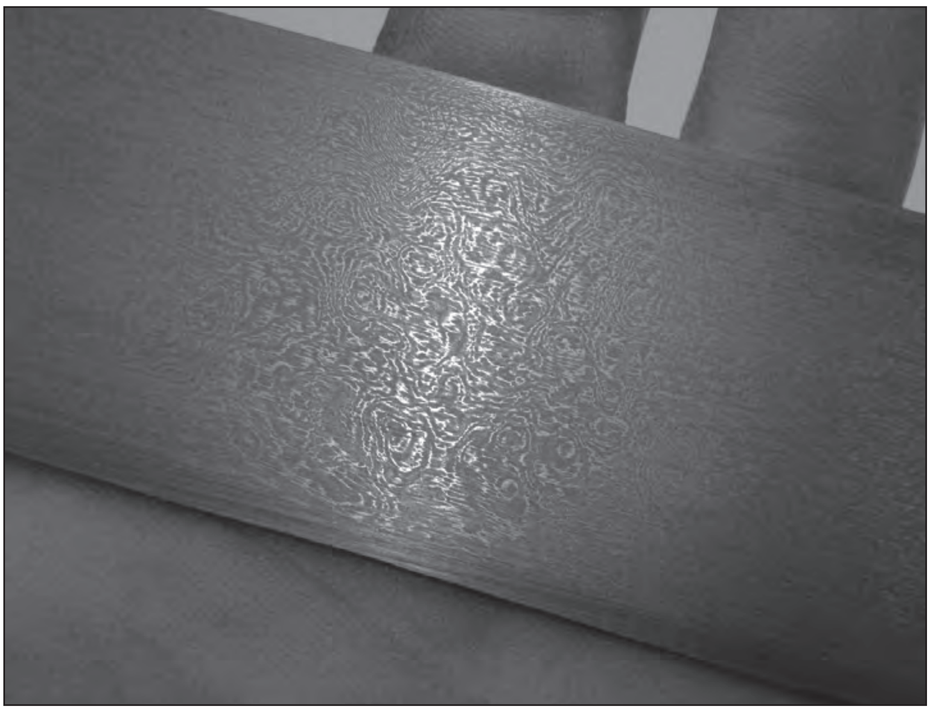


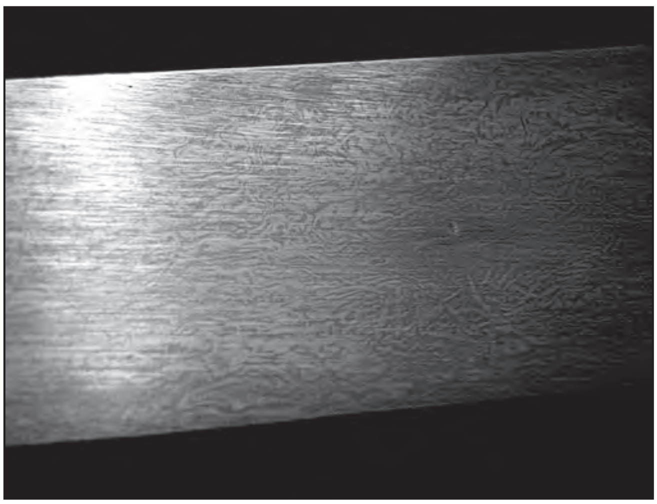
Figure 34. Blades and close-up figures of crucible steel blades made by Hynninen.

Figure 35. Blades and close-up figures of crucible steel blades made by Hynninen.

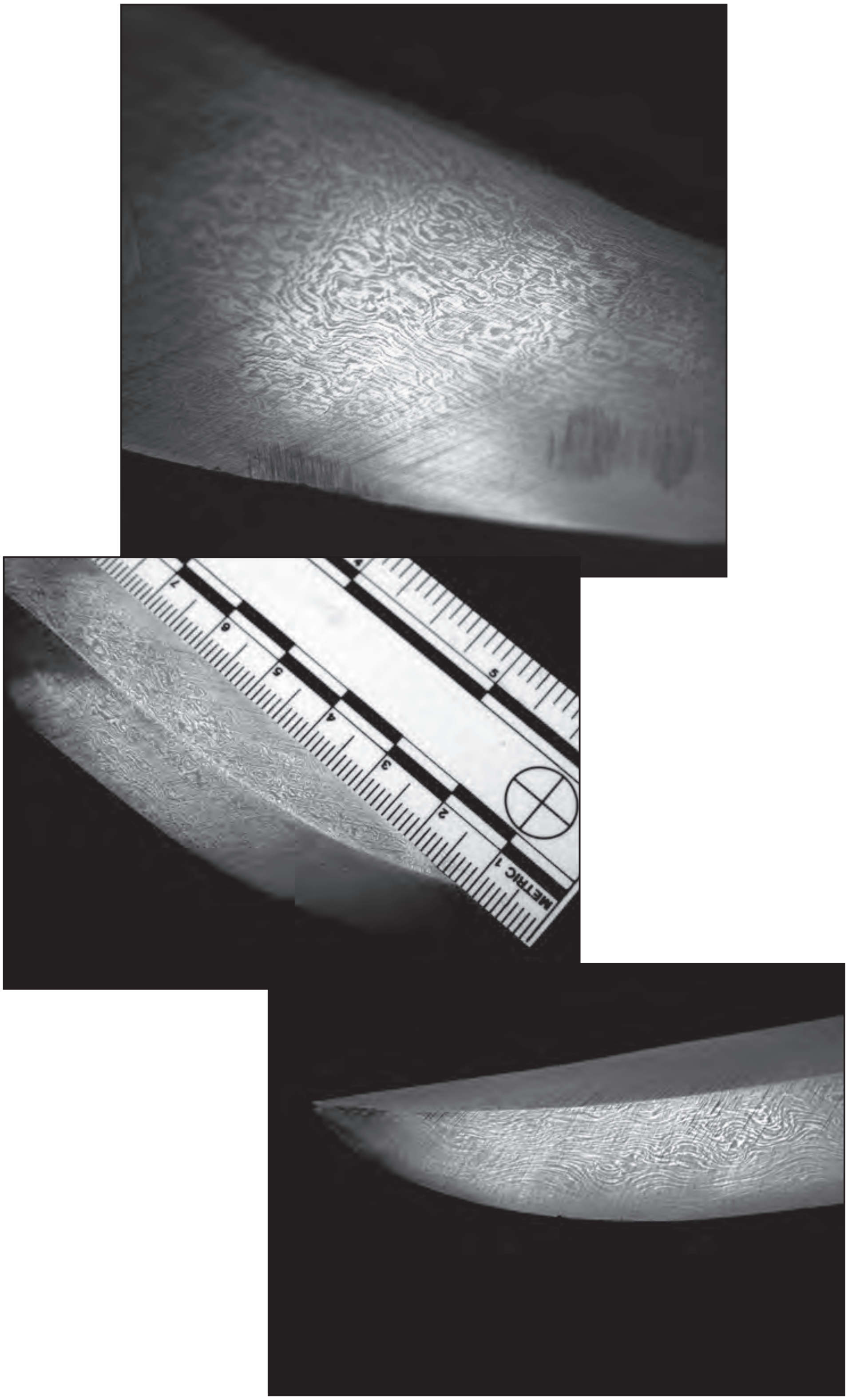




Figures 36-37. Blades and close-up figures of crucible steel blades made by Hynninen.



Figures 38-40. Blades and close-up figures of crucible steel blades made by Hynninen.



Figures 41-43: Macro figures of the pattern of the crucible steel blade made by Hynninen.

6. CONCLUSION

To reproduce modern crucible steel it is necessary to study both the alloys of ancient crucible steel blades and the Persian manuscripts decribing how to make crucible steel blades. Based on the old blades, one can try to make new crucible steel blades which are a close approximation to antique steel patterns. In future attempts to make crucible steel, modern smiths should try to add traditional ingredients to crucible steel charge such as antimony, golden marcasite, manganse dioxide, myrobalan or yellow myrobalan, pomegranate peel, salt of dough, pearl shell or shell, coral, iron dioxide, Peganum harmala and oak gall or oak. Further, Hynninen states that it is important to keep in mind how high temperatures affect the pattern of steel. Overheating causes issues that will ruin the ingot / steel totally, and it cannot be repaired at a later stage. Roasting the ingot will cause problems if it is done at high temperatures for long period of soaking time and above all, if a slow furnace cooling rate is used. This causes nucleation points in the micro-porosity and may result in cracking and delamination of steel later on during forging. Hynninen states that long roasting time creates necessary decarburized crust that helps during forging and it also prespheroidizes the cementite if faster cooling rate after solidification is used. This helps the pattern formation later during the forging that breaks down the rough cementite structure. Hynninen thinks that phosphorus has big effect in the crucible steel and a lower amount of phosphorus will change the steel structure of the crucible steel and its pattern. Phosphorus segregates more and it does tend to make the pattern stronger and bolder, similar to those ancient blades that are considered most beautiful. The strong dendritic pattern in the raw ingot will need to be broken down as well, as it determines how the pattern will look like in the end. Less forging reduction in the dendritic ingot will lead to a pattern with less distortion. An ingot with much reduction and heavy distortion has a chance to change its shape and has more movement and activity in the final pattern. To reveal a better crucible steel pattern, one should try to find out the compositions of original etchants as mentioned in Persian manuscripts such as water from Bâmiyân, white alum from Moltân and yellow alum.

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Recibido: 12/02/12
Aceptado: 21/06/13