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CHINESE STEEL MAKING TECHNIQUES WITH A NOTE ON INDIAN WOOTZ STEEL IN CHINA

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The article[a] describes two Chinese techniques for the production of high-carbon steel: cementation and co-fusion. An imported superior type of steel called *bin tie* (or *pin t'ieh*) was an important article of commerce in ancient China, and this may have been Indian wootz steel.

Key words: *Bin tie / Pin t'ieh* (high carbon steel), China: traditional steel making processes, Co-fusion process, High carbon steel.

TRADITIONAL STEEL MAKING TECHNOLOGIES OF CHINA

Chinese fining processes produced *shu tie* 熟鐵, iron with carbon content generally in the range 0.1–0.3 per cent. In modern technical terminology this is 'mild steel' (*ruan gang* 軟鋼), but *shu tie* was used in the same applications as wrought iron (with close to zero carbon) in the pre-modern West. Therefore, the standard English practice is followed here and *shu tie* is translated as 'wrought iron'.[2] Edged weapons and tools require a higher carbon content than this, and therefore various processes have been used to make *gang* 鋼, 'steel', generally with carbon content in the range 0.5–1 per cent (in modern terminology, 'tool steel', *gongju gang* 工具鋼). Chinese traditional steel making processes have either added carbon to wrought iron by cementation or mixed wrought iron and cast iron to obtain a product with intermediate carbon content.

Chinese smiths in recent centuries seem not to have much used 'case-hardening', in which a finished weapon or tool of wrought iron is cemented to produce a hard layer of steel on a soft tough base. Instead steel is produced

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separately, most often by specialised steelmakers, and the smith forge-welds this onto a wrought-iron base. This method no doubt saves fuel, and if the smith is competent the product is as good as or better than a case-hardened weapon or tool[3]. Two examples are shown in Figs 1 and 2.

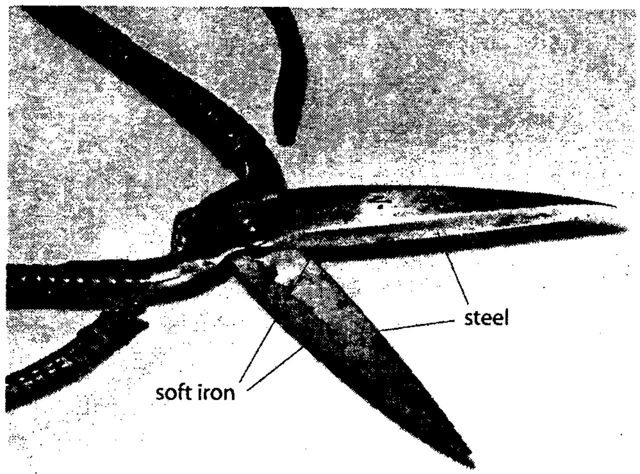

Fig. 1. Scissors made by a Chinese smith in the 1960's or 1970's, purchased in San Francisco in 1975 (photo by DBW). The blade has an edge of steel, ca. 1 mm thick, forge-welded onto a wrought-iron base. The inscription Zhang Xiaoquan 張小全 is the brand name of Zhang Xiaoquan Scissors Factory, established in Hangzhou in 1663.

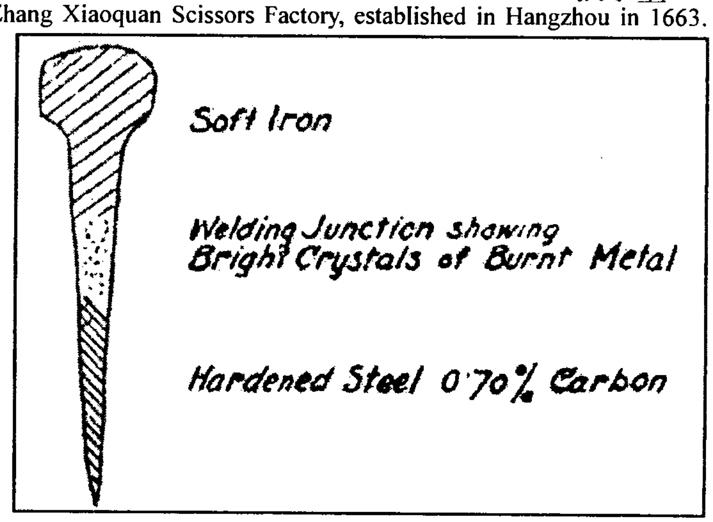

Fig. 2. Diagram of a section through a Chinese razor, reproduced from Middleton (1913). A hard steel edge was forge-welded onto a soft iron back. The dimensions are not given, but the steel edge is likely to be 1–2 mm thick.

Cementation

The term *cementation* covers a variety of ancient and modern processes in which iron in the solid state takes up carbon from an atmosphere rich in carbon monoxide. An example is *case hardening*: a smith may pack a semi-finished knife in charcoal in a sealed container and heat it to a fairly high temperature (typically about 950°C) for a period of hours in order to produce a hard steel surface layer, a few millimetres thick. Carbon is taken up at the surface of the iron and diffuses slowly into the interior. On an industrial scale essentially the same process was widely used in Europe in the 18th and 19th centuries to produce high-carbon steel bars for the cutlery trade. Large furnaces were used like the one still standing at Derwentcote near Newcastle, England. In this furnace about ten tonnes of wrought-iron bars were packed with charcoal in two sandstone chests. These were heated with a coal fire to about 1100°C for a week or more, after which the furnace was allowed to cool for about a week. The bars could then be removed and processed further[4,5].

The basic reactions involved here are:

CO_2 + C (charcoal) = 2CO

2CO = CO_2 + C (in Fe).

The conditions under which these reactions proceed to the right are shown[6] in Fig. 3. In addition an *accelerator* is normally mixed into the charcoal packing: in modern practice barium carbonate ($BaCO_3$), in earlier times usually calcium carbonate ($CaCO_3$) or sodium carbonate ($NaCO_3$). When heated the accelerator gives off carbon dioxide (e.g. $CaCO_3 = CaO + CO_2$); this replaces nitrogen in the packing atmosphere, increasing the partial pressures of both CO_2 and CO, permitting a faster uptake of carbon and also increasing the equilibrium carbon content at the surface of the iron.

The Chinese word for steelmaking by cementation is *men* 燜. Like so many other Chinese metallurgical terms, this word comes from the kitchen: its original meaning is 'to cook slowly in a sealed pot'. Not much is known about Chinese traditional methods of cementation steelmaking, but the historian Yang Kuan has some interesting information from a handbook published in connection with the Great Leap Forward[7].

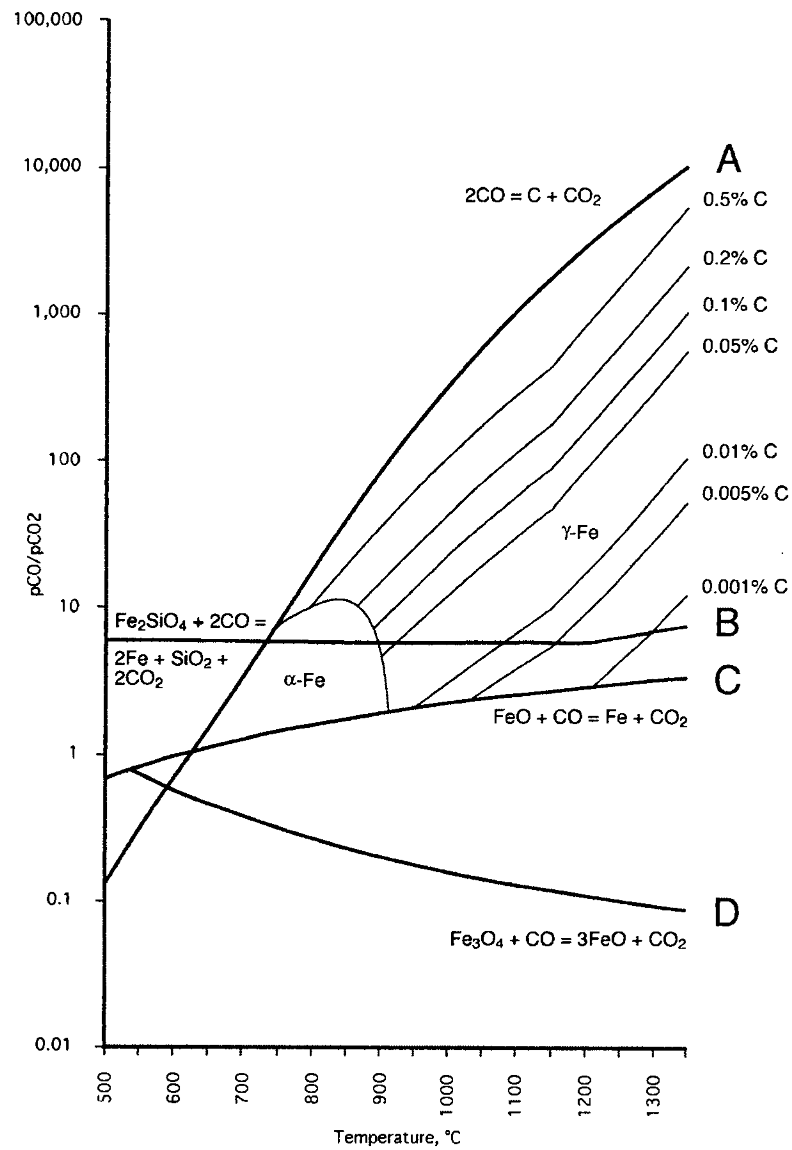

Fig. 3. Equilibrium conditions for certain reactions which are important in bloomery smelting. The vertical axis gives the ratio of partial pressures of carbon monoxide (CO) and carbon dioxide (CO_2) in the furnace atmosphere. When furnace conditions are above a particular line, the corresponding reaction goes to the right; if below, to the left. Curve A and the curves between A and C (except B) are calculated with the assumption that the atmosphere contains ca. 79% nitrogen; this is more realistic than the customary assumption[6].

The furnaces are essentially the same as those used for crucible smelting[8-12] (see e.g. Figs 4, 5 and 6). The cementation pots (crucibles) are ceramic (Fig. 7) or iron. Low temperatures are used, not over 900°C, and the annealing time ranges from 9 to 24 hours. Such low temperatures and short times would give a carburised layer of only a millimetre or two, but the steel material used by smiths, judging from artefacts I have seen, seems to have been very thin (sometimes less than a millimetre), so this was an appropriate technique.

At some works charcoal alone is used for the packing, but a bewildering variety of accelerators are also seen. At a works in Lushan County 魯山縣, Henan, for example, to make steel from 60 kg of wrought iron, the packing is 6 kg charcoal, 3.6 kg powdered ox-bone, and 2.4 kg

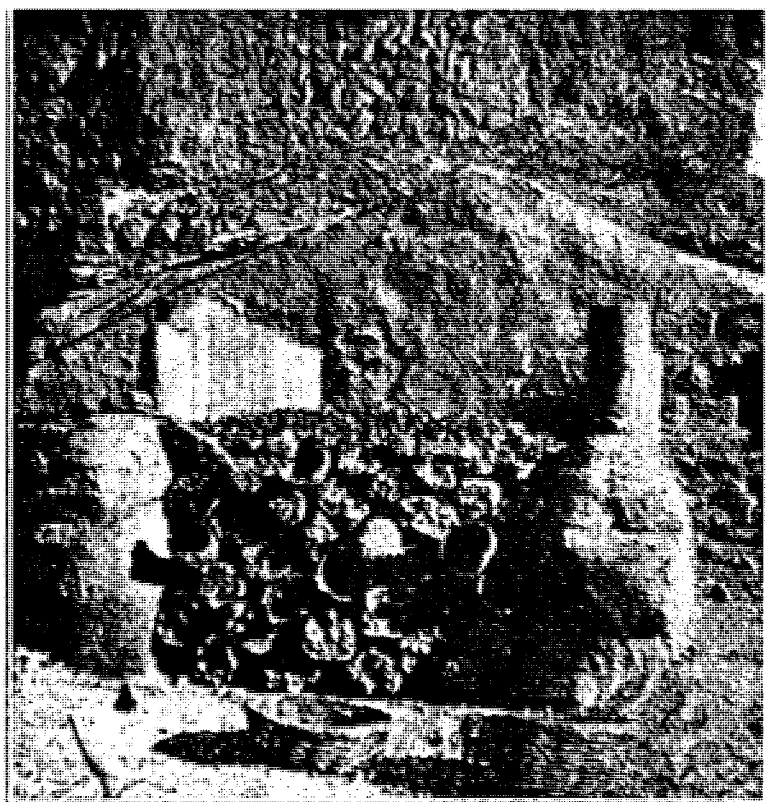

Fig. 4. Stall furnace for crucible iron smelting in southern Shanxi, photograph reproduced from Kocher[8].

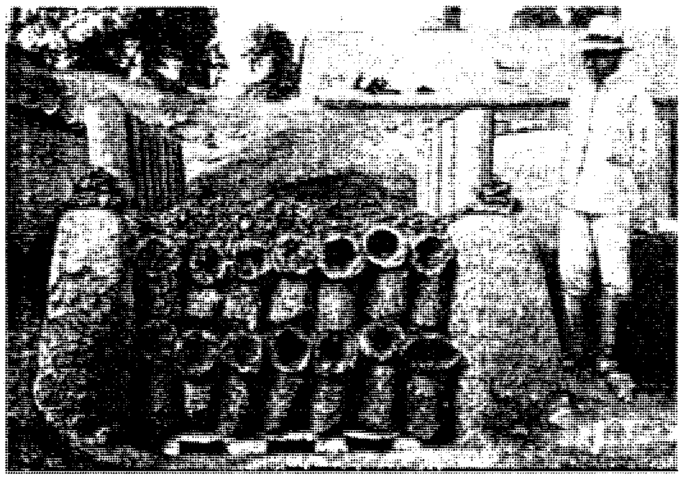

Fig. 5. Stall furnace for crucible iron smelting somewhere in Shanxi, photograph reproduced from Dickmann[9]

Fig. 6. Crucible smelting of iron in progress in Gaoping 高平 County, Shanxi, photograph reproduced from Shockley[10].

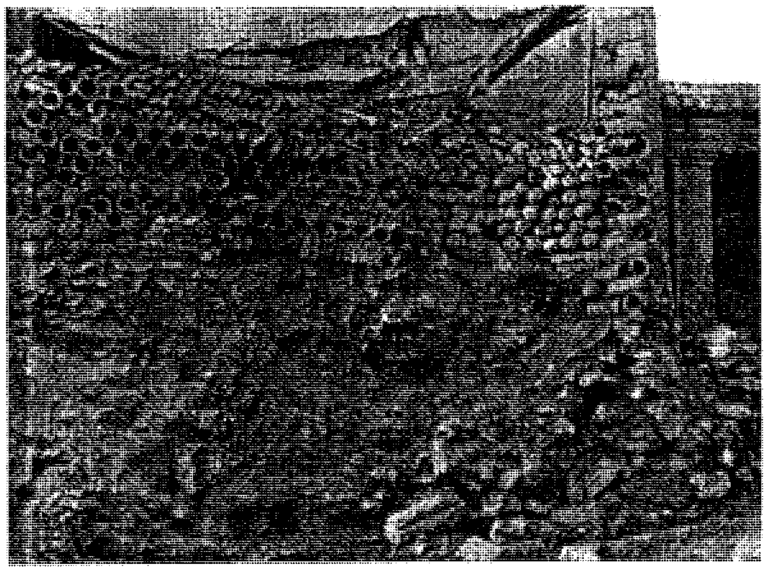

Fig. 7. Wall of old crucibles in Lanzhou, Gansu, photographed by Joseph Needham in 1943. Archives of the Needham Research Institute, Cambridge, NW/6, no. 26.

saltpetre (potassium nitrate, KNO_3). The bone supplies calcium carbonate. Saltpetre is a powerful oxidising agent; it is difficult to understand what function, real or imagined, it might have here. Still other recipes include sodium carbonate, which functions like other metal carbonates, releasing carbon dioxide when heated. One recipe includes 'salt', presumably sodium chloride; what function might this serve?

At a works in Yidu County 宜都, Hubei, the packing material is 2.4 kg charcoal, 12 kg powdered ox-bone, and 3 kg sawdust. Here the bone supplies both calcium carbonate and the greater part of the necessary carbon. The sawdust, which is also seen in several other of the recipes, supplies carbon, but what other function might it serve?

Co-fusion

The co-fusion steelmaking processes, in which wrought iron and cast iron are mixed to produce an alloy with intermediate carbon content, have a long history in China, and will be dealt with in detail further below. In recent centuries only one co-fusion process, called *Su-gang* 蘇鋼, seems to have been used, and it is rather different from the processes to be described there.

The *Su-gang* steelworks known in the 20th century have all been in Sichuan. In 1936 local legend related that the process originated in the province of Jiangsu (whence the name, 'Jiangsu steel') in the early Qing period. The Qing government, fearing that sharp weapons made of this steel could be used in popular rebellion, forbade the process and began arresting the *Su-gang* workers. They fled in all directions: one, a man named Huang •, reached Sichuan and introduced the process there[13]. If there is any factual basis to this story at all, it might be related to the decline of the iron industry of Jiangnan 江南 in the Ming period.

There are two detailed descriptions of the process, from 1936 and 1938, and they do not differ in any important way. The furnaces used are described in Figs 36–38 of Wagner's book[1]. A very spongy bloom of wrought iron is heated to a very high temperature, and molten cast iron is dripped onto it. The worker turns the bloom and moves the melting cast iron plate back and forth so as to assure that the steel is uniformly 'anointed' (*mo* 抹). Joseph Needham visited the same steelworks in 1958, and described his impressions[14]. Joseph Needham visited Chongqing again in 1972, and he was told that the *Su-gang* process had been abandoned not long after his 1958 visit.

Comparing the traditional Chinese cementation and co-fusion steelmaking methods, it is first important to note that they had different purposes. Cementation seems to have been used to produce thin edges of steel which smiths forge-welded onto soft iron backs, while co-fusion was used to produce larger billets of steel from which smiths could fabricate larger products. Cementation was a mass-production process, probably producing a relatively uniform product which was relatively cheap. Co-fusion steel seems more like a luxury product, requiring highly skilled labour and producing one billet at a time.

Costs are difficult to compare, for we do not have the necessary data. At a guess, labour costs per weight of steel were probably higher for co-fusion. Fuel costs in the two processes could have been about equal, with the low temperatures and long firing times of cementation balanced by high temperatures and short firing times in co-fusion. The fuel in cementation was mineral coal; co-fusion used charcoal fuel in the 1936 and 1938 descriptions, and mineral coal[15] in 1958.

Chinese Co-fusion Method of Making Steel

The methods used for making steel can be broadly classified as: (1) adding a controlled amount of carbon to wrought iron, (2) removing a controlled amount of carbon from cast iron, or (3) mixing cast and wrought iron to obtain a product with the desired carbon content.

It is this third category of methods which Joseph Needham called 'co-fusion', a term which has attained general acceptance[14]. The apparently simple idea of mixing irons of different carbon contents to obtain an intermediate carbon content brings with it a variety of technical complications, for which steelmakers have used different approaches.

The earliest description of a co-fusion steelmaking process occurs in the biography of Qiwu Huaiwen 綦毋懷文, who was active in the 6th century AD.[16,17]:

> Qiwu Huaiwen, whose place of origin is unknown, used Taoist techniques in the service of Shenwu-di 神武帝 [Gao Huan 高歡, 496–547, father of the first Emperor of Northern Qi 北齊].
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> . . .
>
> Huaiwen made sabres [*dao* 刀] of 'overnight iron' [*su tie* 宿鐵]. His method was to anneal [*shao* 燒] powdered cast iron [*sheng tie jing* 生鐵精] with layers of soft [iron] blanks [*ding* 鋌, presumably thin plates]. After several days the result is steel [*gang* 剛 = 鋼]. Soft iron was used for the spine of the sabre. He washed[b] it in the urine of the Five Sacrificial Animals and quench-hardened it in the fat of the Five Sacrificial Animals.[c] [Such a sabre] could penetrate thirty armour lamellae [*zha* 札] [i.e. thirty layers of armour?]
>
> The 'overnight soft blanks' [*su rou ting* 宿柔鋌] cast today [in the Sui period?] by the metallurgists of Xiangguo 襄國 represent a vestige of [Qiwu Huaiwen's] technique. The sabres which they make are still extremely sharp, but they cannot penetrate thirty lamellae.

The original source for the above description probably came from Xiangguo, a place near modern Handan, Hebei. This was a major iron-producing region in both the Tang (618–907) and the Song (960–1279) periods, and it is where Shen Gua observed a different steel making technique, in 1075. Shen Gua's account starts with a description of the making of what he calls 'false steel', which is obviously a co-fusion process similar to Qiwu Huaiwen's[18]:

> What the general run of blacksmiths call 'steel' [*gang tie* 鋼鐵] [is made as follows]. Take wrought iron [*rou tie* 柔[=鍒]鐵], bend and coil it, and insert cast iron into the interstices. Seal with clay, 'refine' [*lian* 煉] it, and hammer to cause [the soft iron and the cast iron] to interpenetrate. [The product] is called 'combination steel' or 'irrigated steel'.[d]

Shen Gua uses the word *lian* 煉\ •, which seems to have both a general meaning, 'to purify', and a large number of very specific technical meanings in particular contexts. It therefore corresponds very well to the equally vague and irritating English word 'refine', and this is the standard translation for it. In this case *lian* corresponds to *shao* 燒 in the earlier text. The basic meaning of *shao* is 'to roast', and here it clearly means 'to anneal', i.e. to subject a metal object to a high heat for an extended period.

Each of these texts describes a process in which wrought iron and cast iron are heated together. In the first the process takes several days, while the second gives no information on the time required. What happens in these processes depends on whether the annealing temperature is above or below the eutectic temperature of the iron, *c.* 1147°C. (The eutectic temperature of iron with no alloying elements other than carbon is 1147°C; alloying elements such as silicon and sulphur lower the eutectic temperature slightly.)

Lower-temperature Co-fusion

Below the eutectic temperature of the iron, the process is rather like the familiar cementation process with cast iron as the carbon donor: the basic reactions are $C + CO_2 \rightarrow 2CO$ at the surface of the cast iron and $2CO \rightarrow C + CO_2$ at the surface of the wrought iron. (In this case 'co-fusion' is strictly speaking a misnomer, since nothing actually becomes liquid, but in popular usage the English word 'fuse' has a broad semantic range, and we can think of it as meaning, 'to unite by heating together'.)

Solid-state diffusion in both materials carries carbon from the interior of the cast iron and to the interior of the wrought iron. Since this is a diffusion-limited process, the time required is determined by the thickness of the cast and wrought iron and by the temperature. Qiwu Huaiwen's process is said to require an anneal of several days, and we can therefore assume that it used a fairly low temperature.

A possible reconstruction of Qiwu Huaiwen's method was the subject of experiments in 1955 on the initiative of Joseph Needham[14]. Strips of wrought iron, 1 mm thick, were piled up and wired together with varying amounts of crushed white cast iron between layers. This faggot was heated in a non-oxidising atmosphere to a temperature between 950° and 1000°C, then immediately withdrawn from the furnace and hand-forged, welding it into a single bar. At the original welded surfaces in this bar were highly carburised zones as well as some unchanged white cast iron. A homogenising anneal of 8 hours at 900°C resulted in a uniform carbon content of 0.8 per cent throughout the bar.

At this point, it may be interesting to digress briefly to note an Indian connection. A related process was reported by al-Bīrūnī in the 10th or 11th century: he was told that in Sind, a smith had been seen sprinkling powdered cast iron on a steel sword while forging it. The passage is translated by al-Hassan & Hill in Bosworth[19] and by Allan[20]. Some scholars reject the idea that cast iron was the material used here (for example, Rāgib[21]), but this would seem to be an excellent method of producing steel.

Higher-temperature Co-fusion

If the temperature is above the eutectic, the wrought iron is annealed in a bath of liquid cast iron. Song Yingxing in the 17th century describes the higher-temperature co-fusion technique[22]. Consider the iron–carbon equilibrium diagram shown[23] in Fig. 8. The maximum carbon content of solid iron (austenite) in the relevant temperature range is given by the line JE; the minimum carbon content of liquid iron is given by the line BC. Two processes occur, the balance between them depending on the exact temperature and carbon content. If for example the temperature is 1250°C and the carbon content of the cast iron is 4.0 per cent, wrought iron (0.1–0.3 per cent carbon) will be dissolved until the bath is diluted to a carbon content of ca. 3.5 per cent. After this, carbon diffuses into the wrought iron; still at 1250°C, an equilibrium is quickly reached in which the carbon content at the surface

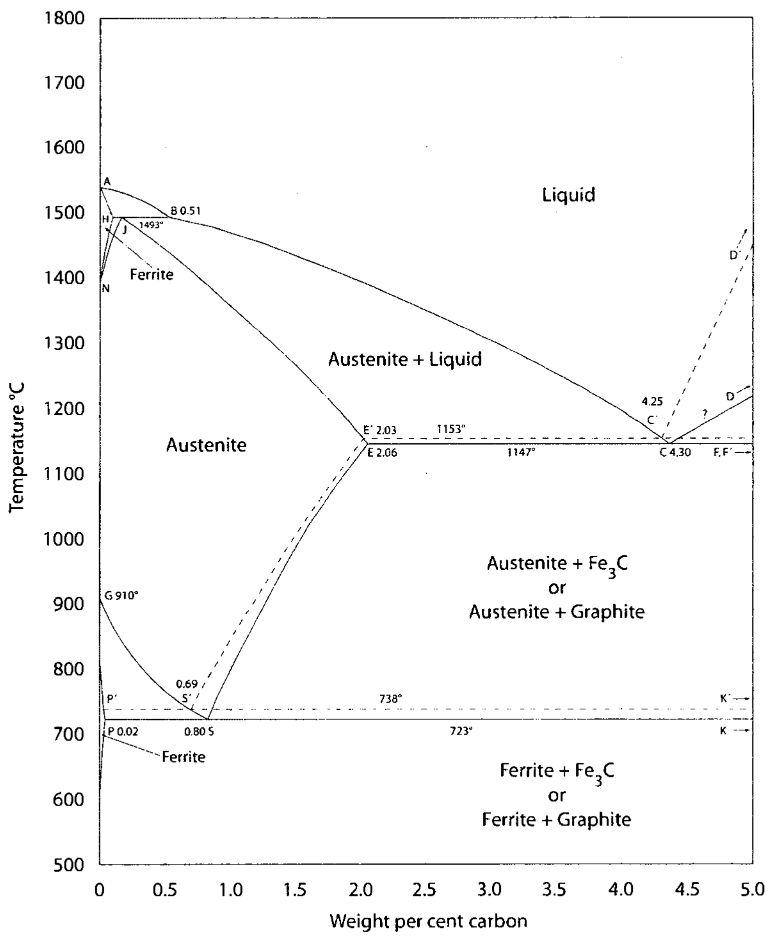

Fig. 8. Iron–carbon equilibrium diagram[23].

of the solid iron is *c.* 1.5 per cent and the carbon content of the liquid iron is *c.* 3.5 per cent. As carbon diffuses into the interior of the solid iron, using up the carbon in the liquid iron, more solid iron (with 1.5 per cent carbon) precipitates from the bath until no liquid is left. A few minutes at this temperature would result in an inhomogeneous lump of steel with carbon content varying between *c.* 0 and 1.5 per cent. Perhaps an hour at this same temperature (the time would depend on many unknown parameters), or many hours at a lower temperature, would homogenise the lump: if the original charge had been 20 per cent cast iron and 80 per cent wrought iron, the result would be a steel with 0.8 per cent carbon, excellent for many purposes.

It is not impossible that Qiwu Huaiwen[18] used a higher-temperature co-fusion process like the one I have described here, though a lower-temperature process seems more likely in his case.

What Shen Gua describes, in the second quotation above, might well have been a higher-temperature co-fusion process, and the intended result might in fact have been a non-homogeneous steel which could be used in making pattern-welded swords. The 'bending and coiling' of the wrought iron seems otherwise superfluous. Elsewhere Shen Gua refers to steel swords with the sort of pattern that might result[24]:

> Among the names of ancient swords, . . . Yuchang 魚腸 ['Fish Gut'] was what today is called a *pan gang* 蟠鋼 ['coiled steel'] or *song wen* 松文 ['fir patterned'] sword. If one takes fish, bakes them, and strips off the ribs to reveal the guts, they have a distinct resemblance to the pattern on a modern *pan gang* sword.

The possibilities of 'pattern welding' steel and soft iron to make intricate patterns have been exploited by swordsmiths in Europe and Japan as well as in China[25]. The pattern is made by variations in carbon and phosphorus content, which become visible when the sword is polished and etched. He Tangkun[26] has examined several patterned-steel swords in private Chinese collections, and gives the three photographs shown in Fig. 9.

In Shen Gua's description of a higher-temperature co-fusion technique he states that the mixture of cast and wrought iron is sealed with clay. Perhaps he meant that the material is placed in a crucible whose mouth is then sealed. On the other hand an equally plausible interpretation is that the material is plastered all over with wet clay to hold it together and protect it from the furnace atmosphere while it is heated to the necessary high temperature. When the co-fusion is complete and hammering begins, the hard-fired clay breaks up and the steel remains. The heating can easily be done in a smithy hearth.

How were such high temperatures achieved? Temperatures over 1200°C are regularly used by smiths in forge welding. In fact it appears that temperatures high enough to melt wrought iron, over 1550°C, in a non-oxidising atmosphere, were regularly used by Norwegian smiths in the 18th century. This is clear from a report[27,28] dated to 1790. It is probably important that the fuel here is charcoal and that the hearth is designed for charcoal,

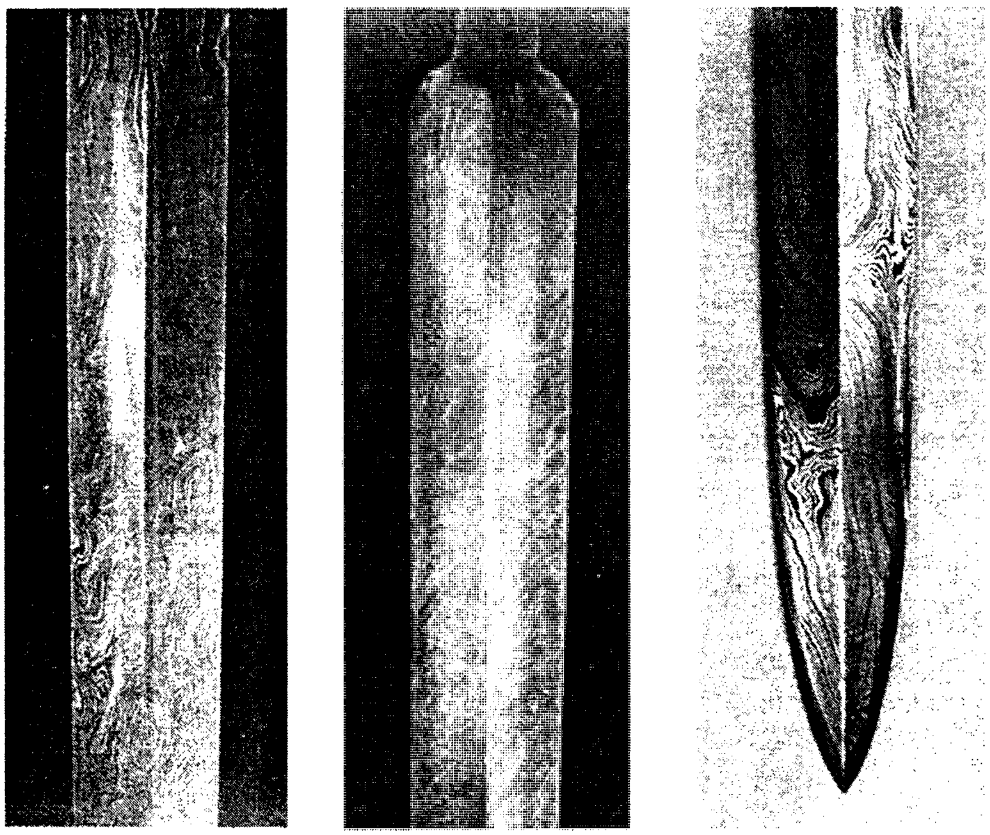

Fig. 9. Photographs of three patterned-steel swords in private Chinese collections. They are difficult to date, but are believed to be from the Yuan period. Reproduced from He Tangkun[26].

with the tuyère at the side rather than the bottom[29]; it seems unlikely that such temperatures could be maintained in a non-oxidising atmosphere with mineral coal or coke as the fuel.

Crucibles which could have been used for co-fusion steel making have been found at a few Han ironworks sites[30,31]. The only early Chinese crucibles which have been properly studied, however, are eleven which were found in a grave at Jili 吉利 in Luoyang, Henan[30,31]. The grave is believed to be from the Eastern Han period (25–220 AD), but the dating is very difficult, and it could well be a few centuries earlier or later. The important point about the Luoyang crucibles is not whether they were actually used in this way, but rather the fact that crucibles were available in Han China which would have been suitable for use in higher-temperature co-fusion steel making.

The eleven crucibles from Luoyang are made of clay tempered with a large amount of powdered coal or charcoal (14 per cent by weight). They are cylindrical, with round bottoms, diameter 14–15 cm, height 35–36 cm, wall thickness 2 cm. Both inside and outside surfaces are vitrified from exposure to high temperatures. It is not in general possible to estimate the temperature that a refractory material has actually been exposed to, but laboratory tests show that the crucibles would have been usable at temperatures as high as 1580–1610°C, high enough for any steelmaking process. Carbonaceous material adhering to the outside surfaces has been identified by geologists as mineral coal[31]: this is the most definite evidence presently available of the use of coal in metallurgy in the Han period.

In the modern archaeometallurgical literature the term *crucible steel* normally refers specifically to steel produced at temperatures high enough to melt it[32-34]. Of course a crucible is necessary when liquid steel is produced, but it is also quite useful at lower temperatures as well, so this terminology can cause considerable confusion. It will be avoided here.

The Chinese written sources give no reason to suppose that the temperatures used in steelmaking were high enough to melt the steel produced (perhaps 1400°C or higher). If the steel had been produced in liquid form, the long anneal of Qiwu Huaiwen's method would have been unnecessary, as would the 'bending and coiling' of the wrought iron noted by Shen Gua. On the other hand the Han crucibles described above could easily have been used at such high temperatures, and perhaps liquid steel was also produced in ancient China.

Other Historical Co-fusion Methods of Making Steel

The co-fusion of cast and wrought iron is of course a Chinese innovation – it was practised in China long before cast iron was known anywhere else. In later times various co-fusion techniques were used widely in Central Asia and to some extent in India, Africa, and Europe. The Medieval polymath al-Bīrūnī (973–1048) described a co-fusion method practised at Herat in Afghanistan[20,21,35-40], and al-Tarsusi (d. 1348) appears to describe something similar in Egypt[20,21,35-41]. One variant of the Indian wootz steel making process, used in Hyderabad, was in fact a co-fusion process[39,42]. Biringuccio (d. *c.* 1539) in his *Pirotechnia* described a steelmaking process with some resemblance to co-fusion (essentially a fining process in which wrought iron is added to the liquid iron as it is being fined)[43]. A similar text, presumably copied from Biringuccio, appears in Agricola's *De re metallica*[44] of 1556. This process seems to have been in use in Italy at least a century after Biringuccio[45]. In North Cameroon in the 20th century, Mafa ironmasters heated bits of cast and wrought iron, both produced in a bloomery, in an open crucible to effect both decarburisation and co-fusion[46].

Archaeology in the new states of Central Asia has revealed the remains of steel making centres which appear to have used co-fusion techniques. At the site of an important ancient city in the Merv oasis, in the southeast corner of Turkmenistan, one of the features excavated in a major cooperative project between British and Turkmen archaeologists was a steel making workshop dated to the 9th–10th century AD.[47,48]. Four furnaces and a scatter of crucible fragments were found. The crucibles seem all to have been of one type, reconstructed as having diameter *c.* 8 cm and height *c.* 20 cm. Laboratory tests indicate that the ceramic fabric could withstand temperatures as high as 1550°C. Metallic prills in the slag adhering to the crucible fragments were generally either steel, with *c.* 0.8 per cent carbon, or cast iron (carbon content not stated). Three of the furnaces appear to have been used to heat the charged crucibles. The excavators conclude that a co-fusion process was used here. They suggest that the temperature used was at least 1250°C, but do not take a stand on whether the temperature was high enough to melt the steel produced.

Further east from Merv along the Silk Road is a region praised for its iron and steel production by Greek, Islamic, and Chinese writers. The Sogdian state of Ustrûshana, a mountainous region east of Samarkand, and the Ferghana Basin have been the focus of renewed archaeological attention in recent years, and a great deal of material related to the Medieval iron and steel industry has been uncovered here. Most relevant to our present concern is a workshop excavated at a city-site of the 9th–13th century in Ferghana, at Eski Achsy, Uzbekistan. Here a large number of crucible fragments were found; the original crucible form appears to have been rather like the Merv crucibles, but higher: 7–8 cm in diameter, height 32–40 cm[49]. The excavators consider that the process used here was direct production of steel from ore, just as He Tangkun argues for the Luoyang crucibles. It is quite possible, however, that they were (also) used in co-fusion steel production as suggested by the Merv excavators.

From the early 19th century we have the excellent description of a co-fusion steel making process which is translated in Appendix 1. It was published in French by a certain Captain Massalski in a Russian mining journal[50] in 1841, and is clearly based on both direct observation and interviews with craftsmen. He describes steelmaking in 'Persia', and it is not altogether clear what a Russian of that time would have included in this term: perhaps even the region of modern Afghanistan, Turkmenistan, Tadjikistan, and Uzbekistan. Allan & Gilmour[40] suggest that Massalski observed steel making either in northern Iran or in Bukhara (in modern Uzbekistan). It seems at least possible that Massalski had seen the techniques he describes in much the same general area as the archaeological remains described above, rather than further west in modern Iran.

This is definitely a process in which the melting temperature of the steel product is reached: the contents of the crucible are stirred with a rod, and the product is a 'button' (*culot*) of steel from each crucible. It takes quite a long time, 5–6 hours, to reach the temperature at which the cast iron melts, but then things happen quickly. The wrought iron and cast iron fuse as the temperature continues to rise, and the resulting steel melts. The very long cooling time, three days, results in a microstructure with fine cementite globules at grain boundaries which is necessary for the production of some of the types of pattern found on Damascus swords[35, 51-54].

The addition of silver to the crucible charge is curious. It is unlikely to have improved the quality of the steel; if it had any function at all, this was perhaps in quality control. Silver does not alloy with iron, and in Massalski's description of the technique the silver is found adhering to the steel button. Its physical appearance would no doubt have told an experienced craftsman a good deal about the course of temperatures through which the button had passed.

Indian Wootz Steel In China

Among the exports of Western nations to China listed in sources of the 6th and 7th centuries AD is a product called '*bin* iron 鑌鐵'. There are several ancient Chinese texts which mention this term. These include *Wei shu* (ch. 102, p. 2270), *Zhou shu* (ch. 50, p. 920), *Bei shi* (ch. 97, pp. 3222, 3239) and twice in *Sui shu* (ch. 83, p. 1857). There seems to be a general scholarly consensus that the *Zhou shu* account, completed in 635 but based on earlier sources, comes closest to being a primary source. The *Wei shu* was completed in 554, but there is good evidence that the relevant parts of this book were at some time lost and later restored from the corresponding parts of one or more of the other dynastic histories[55-59]. The identifiable items in these lists are virtually all luxury raw materials rather than finished products, and clearly *bin* iron must be some highly esteemed type of iron or steel. It comes from two places, Bosi 波斯, i.e. Persia, and Cao 漕, which is identified as Jaguda, the modern province of Ghaznî in central Afghanistan.

Feng Chengjun & Lu Junling[60] note that the *Bei shi* and *Sui shu* accounts incorrectly identify Cao with the state of Jibin 罽賓 of the Han and Wei periods, which is generally identified as Kashmir[61]. Chavannes[62] identifies it as the province of Kāpisā in Afghanistan. It is not impossible that this place-name is the source of the term '*bin* iron', but there seem to be no early Chinese sources which connect Kashmir with the production of any ferrous materials. The *Han shu* (ch. 96A, p. 3885), in its description of Jibin, states specifically that it produces gold, silver, copper, and tin, and makes implements of these, but does it not mention any other metal.[e]

Bin is undoubtedly a transcription of some non-Chinese word, but scholars have considered this word unidentifiable. Berthold Laufer, in his learned *Sino-Iranica* of 1919, notes ironically that 'even the Pan-Turks have not discovered it in Turkish'. (He did suggest some possible connections: 'Iranian **spaina*, Pamir languages *spin*, Afghan *ōspinā* or *ōspana*, Ossetic *äfsän*'.) I was therefore surprised, upon consulting experts, to find that there are two quite plausible candidates, one in Sanskrit and one in Persian. These will be discussed further below.

Reports of the origins of distant imports are always subject to some suspicion, for they often give the nationality of middlemen rather than the actual producers. Arabic and Persian sources from the 5th century AD onward indicate that India and Sri Lanka produced fine steel[39,50,49,64,65]. Hanneder[66] reviews the textual and archaeological evidence on ancient Indian iron and steel. It is quite possible that the *bin* iron of the earliest Chinese sources was not produced in Persia and Jaguda, but carried to China from southern Asia by merchants of these places. On the other hand we have just seen that high-carbon steel was being produced in the eastern Iranian regions from about the 10th century at the latest, and continued into modern times. The Chinese reports may therefore support the rather skimpy evidence available for steel production here in earlier, pre-Islamic times[40].

A very curious fact is that after these reports of the early 7th century *bin* iron virtually disappears from the Chinese sources for several centuries. The dynastic histories of the Tang (618–907) and Five Dynasties (907–960) periods include accounts of Persia and other Western nations, and sometimes list their exports, but never mention any ferrous products.

From about the beginning of the 10th century to at least the 17th there are numerous mentions of *bin* iron in Chinese texts, written with either of the characters 鑌 or 賓. Some sources include it in lists of the products of places to the west of China [*Song shi*, ch. 490, pp. 14111, 14115, 14119; *Ming shi*, ch. 332, p. 8620]. There is also a report from the 12th century that *bin* iron was produced within the Chinese Empire, in Yunnei Prefecture 雲•州, near modern Hohhot, Inner Mongolia [*Jin shi*, ch. 24, p. 569].

In 1259 an embassy was sent by the Yuan to Hülegü, the Mongol conqueror of Iraq and Persia. An account of that mission by Liu Yu 劉郁 notes that the land of Yindu 印毒, i.e. India, produces *bin* iron [*Xi shi ji*, p. 11b]. Since the mission never came near India, this information no doubt came from merchants encountered along the way. It would seem to be the only real evidence we have that India produced *bin* iron.

In the above paragraph, *Yindu* presumably transcribes the Persian *Hindūstān*, which corresponds roughly to modern India[67]. A more common, but equivalent, Chinese transcription is *Yindu* 印度[60].

Perhaps from the early 10th century is a quotation by Li Shizhen 李時珍 in the 17th century from a now-lost book entitled *Xuan yuan shu Bao zang lun* 軒轅述寶藏論 (The Yellow Emperor's discourse on the hidden treasures [of the earth]) [*Ben cao gang mu*, ch. 8, pp. 48, 609.]. After some remarks about the places where iron is produced in China, Li Shizhen writes:

> *Bin* iron, which is produced by the Western Barbarians [Xi Fan 西番], is especially fine. The *Bao zang lun* states: 'There are five kinds of iron. . . .

> [The first two come from Hubei and Jiangxi.] *Bin* iron is produced in Persia [Bosi 波斯]; it is so hard and sharp that it can cut gold and jade. . . . [The last two kinds come from Shanxi and the Southwest.]

There are many more mentions of *bin* iron in contexts which indicate that it was a steel considered to be of extremely high quality [e.g. *Jin shi*, ch. 2, p. 26; ch. 43, p. 985; ch. 87, pp. 1933, 1936; *Jin shui qiao Chen Lin bao zhuang he za ju*, p. 1; *Yuan shi*, ch. 9, p. 192; ch. 78, p. 1952; ch. 120, p. 2956; ch. 203, p. 4546; *Ming shi*, ch. 247, p. 6396; ch. 332, p. 8598; *Qing shi gao*, ch. 244, p. 9612.]. An example is the story of a colourful incident of 895 in which a general declaims that if rebels arise they will have to nick (*chi* 齒) his sword of *bin* iron – apparently something very difficult to do [*Xin Wu dai shi*, ch. 63, p. 786.].

An 'Office for *bin* iron' (*Bin tie ju* 鑌鐵局), established by the Yuan dynasty in 1275, administered 'the artisans in steel and iron' (*lou tie gong* 鏤鐵工) [*Yuan shi*, ch. 85, p. 2145; note also p. 2146]. Nothing more appears to be known about this office, but its name probably reflects the idea that *bin* iron was an especially excellent steel, signalling that the office is concerned with an elite among the smiths.

In the 6th century *bin* iron appears to have been a type of fine steel, imported as a raw material rather than in finished products. One possible identification of the original word behind *bin* is Sanskrit *pínòdòa*, which some Sanskrit lexica define as 'steel', though this meaning is not attested in texts[68,69]. The usual, well-attested, meaning is 'a lump' (usually of food), and this recalls the fact that several Chinese terms for varieties of steel include characters that mean 'lump'. *Bin tie*, which I have been translating as '*bin* iron', could easily be a transcription of *pínòdòa*, with the Chinese character for the second syllable chosen not only for its sound, but also because it means 'iron'. This would also explain the odd fact that an especially admired type of *steel* was called *iron*.

The pronunciation of *bin tie* 鑌鐵 at this time would have been something like *pkgn t'iet* or *pjin* t^h*ft*. A Sanskrit–Chinese dictionary of the 8th century, *Fan yu za ming* [70], gives for *bin tie* the Sanskrit equivalent *pina* in the Sanskrit script known as *siddham*. Pelliot[71] notes that this word is not otherwise known in Sanskrit or Prakrit, so that we cannot determine whether it transcribes *bin tie*, or *bin tie* transcribes it, or both transcribe a word in some other language. The dictionary gives the pronunciation of the Sanskrit as 比笯 (*pji: ña* or *pji' nraɨ*). If my suggestion that *bin tie* transcribes *piṇḍa* or *hindia* were correct, we should expect a *t* or *d* somewhere after the *n* in *piṇa*. It is therefore interesting (though perplexing) that the Japanese edition of 1732 gives the Japanese pronunciation *hida* rather than the expected *hina* for 比笯.

There is also a possibility that *bin tie* transcribes a Persian or Arabic word meaning 'Indian steel'. Marco Polo in the 13th century states that *ondanique* (*andaine*, *andanicum*), apparently a type of steel, is produced in the Kingdom of Kerman (the province of Kerman in modern Iran). Henry Yule, in a long footnote, identifies this as Persian *hundwániy*, 'Indian steel', which shows up in Arabic sources as e.g. *hindia*, *hint*, or *al-hint* [72]. Both *bin tie* and *piṇḍa* could be transcriptions of a form, in one of the region's languages, of a form like *hindia*. Or *hindia* could be a transcription of *piṇḍa*.

'Lump steel' or 'Indian steel' might well have been what today is generally called wootz, which was produced by cementation of wrought iron in small crucibles at very high temperatures[39]. Or it might have been produced directly from ore in specialised furnaces like those recently excavated by Gill Juleff in Sri Lanka[65].

It is natural to suppose that the disappearance of *bin* iron from the Chinese sources in the 7th century AD is related to the Islamic conquest of Persia. Its reappearance in the 10th century would seem to reflect the rise of Arabic trade with China by land and sea. However we should also remember that it is precisely from this time that we have the first firm evidence of steel production in the eastern Iranian region. Steel was produced at Merv by co-fusion, which is a Chinese technique, but other techniques may also have been used in the region.

From the 10th century onward *bin* iron is well known in China, but now the term seems to mean no more than 'especially fine imported steel' (and it is not always imported), with no specific technical or geographic implication.

Of all the sources on *bin* iron from all the centuries there seems to be only one which gives any specific information about this type of steel. Cao Zhao's *Ge gu yao lun* 格古要論 ('The essential criteria of antiquities', a handbook for connoisseurs published in 1368) has [*Ge gu yao lun*, ch. 2, p. 36b]:

> *Bin iron*: It is produced by the Western Barbarians. Some [types] have a spiral self-patterning, while others have a sesame-seed or snowflake patterning. When a knife or sword is wiped clean and treated with 'gold thread' alum, [the pattern] appears. Its value is greater than silver.
>
> An ancient saying holds that 'knowing the strength of iron is like knowing gold' [i.e., the ability to judge the properties of steel is as valuable as the ability to assay the purity of gold]. Forgeries have a black patterning. One should examine [a steel object] very carefully.
>
> There are three rules for knives. The first is that in the blade there should be perfect control of fire, metal, and water [i.e., the blade should be correctly quench-hardened and tempered]. The second is that the haft should be of *xichi* wood from the Western Barbarians, and the third is that the sheath should be of Tatar birchbark.
>
> I once had a pair of scissors of *bin* iron, of exquisite workmanship. It had a raised gilt pattern on the inside, and on the outside a silver-inlaid inscription in Islamic characters.

The first paragraph may well be the earliest extant description in any language of the famous 'watered steel' blades of Persia (sometimes called 'Damascus' or 'damascened' steel). The pattern was produced by etching the finished blade to reveal the microstructure of pearlite and finely divided spherulitic cementite characteristic of wootz and other crucible steels which are allowed to cool very slowly from the liquid state. This is as far as I dare to go in discussing watered steel; it is a subject of great complexity and some controversy. For further insights, see e.g. C. S. Smith[25], Verhoeven[54], Piaskowski[58], Allan[20] and Allan & Gilmour[40]. I know of no explanation for the 'black patterning' of 'forgeries'.

The scissors of the last paragraph are directly comparable with the exquisite Persian scissors of the 18th and 19th centuries in the Tavoli Collection, described and illustrated by Allan and Gilmour[40]. But Cao Zhao's scissors are unlikely to have been of watered steel, for as far as is known this patterning technique was used only for swords and knives.

CONCLUSIONS

A kind of imported steel called *bin tie* has been related to Indian wootz steel. In addition, the traditional Chinese techniques of making steel have also been explained to show that the Chinese iron and blacksmiths were very proficient in the manufacture of steel. In spite of their proficiency, the high regard in which wootz steel was held by the Chinese attests to the ever-lasting fame of the Indian wootz steel.

Appendix 1

The preparation of Damascus steel in Persia in the early 19th century, translated from Massalski[50]; cf. Allan & Gilmour[40]. *[The illustration referred to is reproduced here as Fig. 10.]*

. . . The metals used in the preparation of Damascus steel are wrought iron, cast iron, and a small amount of silver. The former should be previously worked scrap (nails, plates, etc.), but free of rust. For the cast iron one of the best grades of white cast iron should be chosen. The silver should be extremely pure. The usual proportion is one part cast iron to three parts wrought iron by weight.

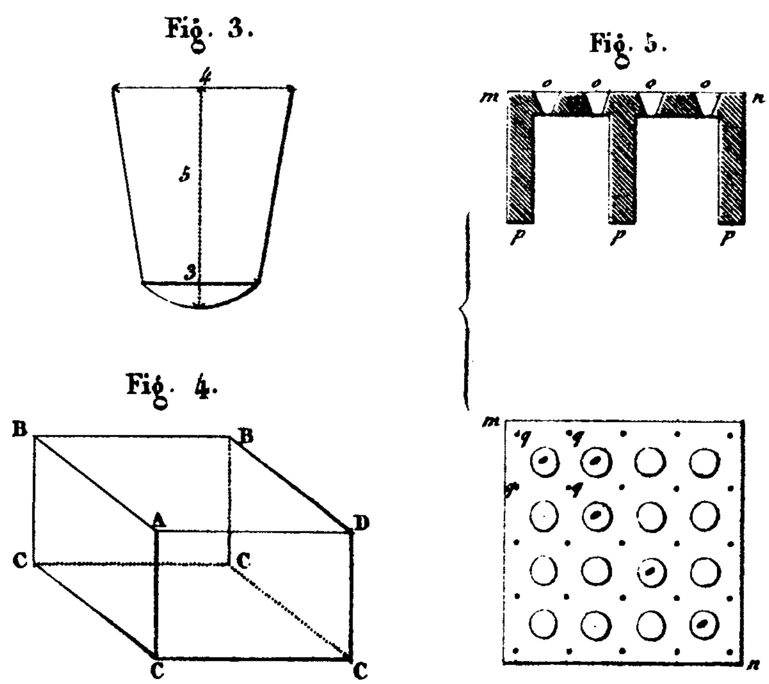

Fig. 10. Illustration accompanying Massalski's description of the preparation of watered steel in Persia (Appendix 1)[58].

The wrought iron and cast iron are broken up into small pieces, mixed as thoroughly as possible, and charged into refractory crucibles (no. 3 in the illustration) whose height, upper diameter, and lower diameter are in the ratio 5 : 4 : 3. The size of the crucibles depends on the amount of steel to be prepared. In Persia the quantity [per crucible] is usually between 1/5 and 1 *bacheman.* (One *bacheman* is equivalent to . . . 2.46 kg.) The charged mixture occupies one-third of the capacity of the crucible.

The fusion furnace (nos. 4 and 5 in the illustration) is composed of a cubical brick chamber (ABCD) with flat bottom. At each corner is an opening (C) for the nozzles of the bellows. An opening is left in one wall of the box to allow the charging of additional coal[f] if necessary during the operation. A false floor (*mn*) in the chamber has round holes with diameter equal to the diameter of the crucibles at 2/3 of their height. . . . Usually this floor is placed at 3/4 of the height of the chamber (ABCD). The holes (*o*) are arranged in such a way that the crucibles are . . . 0.051 m apart. Around each of these holes are placed four small holes (*q*) through which the flames pass and envelope the crucibles on all sides. The furnace is closed with a cover of iron or brick, plastered with clay, which is manoeuvred with the help of a simple lever. Several holes in the cover allow the passage of air out of the furnace.

The furnace is initially loaded with sufficient coal to reach the bottoms of the crucibles. These are lodged in the holes (*o*) in the floor (*mn*), positioned as nearly horizontal as possible. The space between the floor (*mn*) and the furnace cover is completely filled with coal, and the cover is carefully sealed with potter's clay. The fuel is ignited at the four corners (C), and the operation of the bellows begins. When the metal begins to melt, which occurs after 5 to 6 hours, a bubbling sound is heard which increases as the metal melts and stops when fusion is complete. As soon as the bubbling sound has stopped, the furnace cover is lifted. The crucibles are cleared of the coal which covers them and into each is introduced . . . 13–17 g of silver in small pieces. The contents are stirred briskly with a metal rod, the crucibles are again covered with coal, the furnace cover is replaced, all of the furnace openings are closed with clay, and the furnace is allowed to cool for about 3 days.

When the furnace has cooled completely, the crucibles are removed and the buttons [of steel] are collected. The buttons are cleaned, and any silver which may adhere to their surface is removed. In this state these are what is referred to as *Damascus steel.* All that remains is to test them; . . . [A detailed description of the testing process follows].

Notes

a. This article was extracted and edited by Professor R. Balasubramaniam from my forthcoming volume on Ferrous Metallurgy for Joseph Needham's *Science and Civilisation in China*[1]. I extend to him my sincere thanks.

b. *Yu* 浴, possibly a term for a hard quench, as opposed to the soft quench in animal fat.

c. The Five Sacrificial Animals (*wu sheng* 五牲) are usually identified as ox, sheep, pig, dog, and chicken.

d. *Tuan gang* 團鋼, *guan gang* 灌鋼. Another possible interpretation for *tuan gang* would be 'lump steel'

e. Laufer[63] notes that the *Tai ping huan yu ji* (ch. 182, p. 15a) (completed 981) mentions *bin* iron from Kashmir, but this mention is in fact in a direct quotation from the *Sui shu* account of Cao.

f. The fuel used in this process is referred to simply as 'coal' (*charbon*). This is surely charcoal, as the journal in which the description appears refers consistently to mineral coal as *houille.*

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