Some Chinese steelmaking techniques

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Steelmaking by cementation in China

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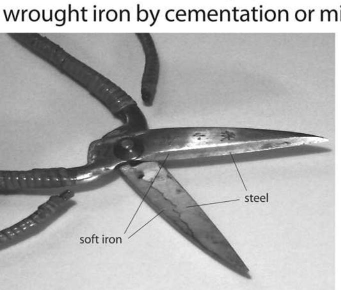
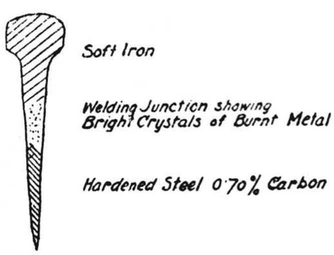
Chinese fining processes produce *shu tie* 熟鐵, iron with carbon content generally in the range 0.1–0.3 per cent. In modern technical terminology this is 'mild steel' (*ruan gang* 軟鋼), but *shu tie* was used in the same applications as wrought iron (with close to zero carbon) in the pre-modern West, so I follow standard English practice and translate *shu tie* as 'wrought iron'.

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 steelmaking 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 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 or better than a case-hardened weapon or tool. Two examples are shown here.

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.

In modern practice an *accelerator* is normally mixed into the charcoal packing: in modern practice typically 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 at the surface of the iron.

In China, steelmaking by cementation is traditionally called *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.

The furnaces are essentially the same as those used for crucible smelting (one example is shown here, photographed in Shanxi in 1904). The cementation pots (crucibles) are ceramic 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 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?

Sources

These four posters are taken from a forthcoming book of mine on the iron industry of ancient and traditional China. The following is a brief list of the sources used in the posters.

Bei shi 北史 (Standard history of the Northern Dynasties [+386–618]). Critical ed., 10 vols., Zhonghua Shuju, Beijing, 1974.

He Tangkun 何堂坤. 'Ji mei chuanshi huawen gang jian de chubu kaocha 幾枚傳世花紋鋼劍的初步考察' (Preliminary investigation of several patterned-steel swords handed down from ancient times). *Wenwu* 2001 (no. 1), 68–73.

He Tangkun (et al.) 何堂坤. 'Luoyang gan-guo fu-zhuo gang de chubu yanjiu 洛陽坩堝附着鋼的初步研究' (Preliminary investigation of steel adhering to a crucible found in Luoyang, Henan). By —, Lin Yulian 林育煉, Ye Wansong 葉萬松, & Yu Fuwei 余扶危). *Zhongguo kexue shi yanjiu* 1985, 4 (no. 1), 59–63 + 1 plate.

Joseph Needham. [Unpublished MS, 1961, in the archives of the Needham Research Institute, Cambridge].

Luo Mian 羅冕. *Gang tie* 鋼鐵 (Iron and steel). Report no. 15 in *Zhongguo Gongchengshi Xuehui Sichuan Kaochatuan baogao* 中國工程師學會四川考?團報告 (Reports of the Sichuan Investigation Group, Chinese Engineering Society). N.p., n.d., preface dated 1936.

Meng xi bi tan 夢溪筆談 (Jottings from Dream Brook, by Shen Gua 沈括 [+1031–95]).

Tian gong kai wu 天工開物 (The products of Heaven and Man, by Song Yingxing 宋應星, d. ca. +1660).

Ye Wansong 葉萬松, Yu Fuwei 余扶危, & Zeng Yidan 曾意丹. 'Luoyang Jili faxian Xi Han yetie gongjiang muzang 洛陽吉利發現西漢冶鐵工匠墓葬' (A grave of an iron craftsman discovered at Jili in Luoyang, Henan). *Kaogu yu wenwu* 1982 (no. 3), 23 + 39.

Zhou Zhihong 周志宏. 'Zhongguo zaoqi gangtie yelian jishu shang chuangzaoxing de chengjiu 中國早期鋼鐵冶煉技術上創造性的成就'. (Creative accomplishments in early Chinese iron and steel metallurgy). *Kexue tongbao* 科學通報 (Science bulletin), 1955 (no. 2), 25–30.

Co-fusion steelmaking

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Each of the ancient Chinese texts translated on the accompanying poster describes a process in which wrought iron and cast iron are heated together. Qiwu Huaiwen's process takes several days, while Shen Gua and Song Yingxing give no information on the time required. What happens in these processes depends very much on whether the annealing temperature is above or below the eutectic temperature of the cast iron, ca. 1147°C.

Lower-temperature co-fusion

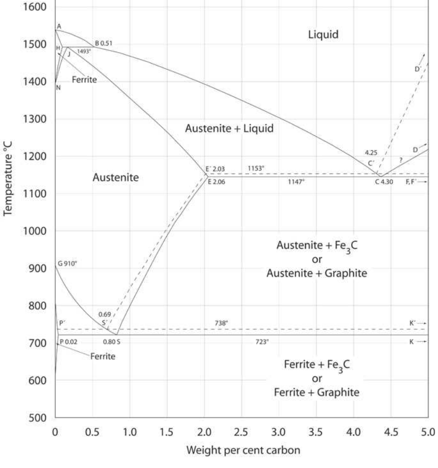
Below the eutectic, the process is essentially the familiar cementation process, with cast iron as the carbon donor. Since this is a diffusion-limited process, the time required is determined by the thickness of the cast and wrought iron and by the temperature. Qiwu Huaiwen's process is said to require 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, by Mr P. Whitaker of Stewarts & Lloyds, Ltd., Corby. 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.

This proposal fits reasonably well with the little we know of Qiwu Huaiwen's method, though the original description includes no mention of forging the faggot into a bar at the beginning of the anneal. The forging undoubtedly speeds up the process considerably, but is unlikely to be a strict necessity. Another aspect is that the wrought iron strips were very thin in these experiments; an ancient smith would certainly have been capable of producing wrought-iron strips which were only 1 mm thick, but this would have been time-consuming, and would have involved the loss of a considerable amount of iron through oxidation. The 'wrought iron blanks' of the description would no doubt have been thicker, perhaps 2–3 mm, necessitating a longer annealing time.

Higher-temperature co-fusion

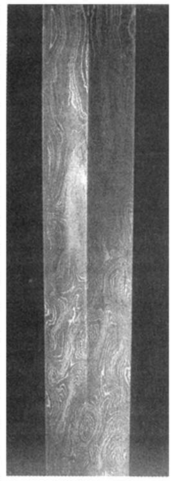
If the temperature is above the eutectic, the wrought iron is annealed in a bath of liquid cast iron. Song Yingxing in the +17th century describes what is clearly a higher-temperature co-fusion technique. Two processes occur, the balance between them depending on the exact temperature and carbon content. 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 % C) 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 of the solid iron is ca. 1.5 per cent and the carbon content of the liquid iron is ca. 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 ca. 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.

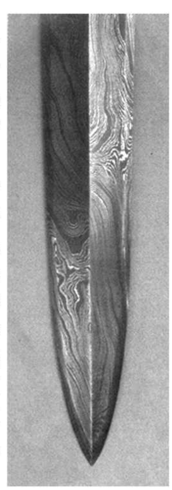


It is not impossible that Qiwu Huaiwen used a higher-temperature co-fusion process like the one I have described here, though a lower-temperature process seems more likely in his case.

What Shen Gua describes 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.

He Tangkun has examined several patterned-steel swords in private Chinese collections, and gives the three photographs reproduced here .





What sort of furnaces were used in these processes, and how was the metal held together while it was heated? Were crucibles used? We have seen from the experiments by P. Whitaker reported above that a lower-temperature co-fusion process can be carried out without a crucible or other container for the material. In those experiments a modern electric furnace was used, but the same conditions – a temperature in the range 950–1000°C in a non-oxidising atmosphere – is regularly attained and held for long periods in a charcoal-fuelled smithy hearth. A furnace specifically designed for heating crucibles would be easier to control and much more fuel- and labour-efficient, but would not, strictly speaking, be necessary.

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 could easily be done in a smithy hearth.

Steelmaking in ancient China 1st, 6th, 11th, and 17th centuries AD

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Some Han-dynasty steelmaking crucibles

Crucibles which perhaps could have been used for co-fusion steelmaking have been found at a few Han ironworks sites. 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. The grave is believed to be from the Eastern Han period, but the dating is very difficult, and it could well be a few centuries earlier or later.

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: this is the most definite evidence presently available of the use of coal in metallurgy in the Han period.

A piece of steel adhering to the inside of one of the crucibles has been studied by He Tangkun and his associates. Both form and microstructure indicate that the object has been molten, and the investigators also state that it is obvious from the object's appearance that before solidification it had flowed toward the mouth of the crucible; that is, it solidified while the contents of the crucible were being poured or dumped out.

Wet chemical analysis shows a carbon content of 1.21 per cent. Other element percentages were determined by scanning electron microscope (energy spectrum):

Fe 98.637%   P 0.277%   S 0.584%   Si 0.117%   Al 0.383%

The high sulphur content is strange: if steel produced in the crucible had this much sulphur throughout, it would have been so hot-short (brittle at high temperatures) as to be almost unusable.

The first of many questions raised by this find of crucibles is why they should have been placed in a grave at all. Perhaps, as the excavators suggest, the person buried was a steelmaker, and the crucibles symbolise his mastery of the craft. On the other hand it is not impossible that he had nothing to do with metallurgy, but his family could not afford any other ceramic objects for his grave. In any case the place where the crucibles were used would have been nearby.

Removed as they are from their use-context the crucibles are difficult to interpret. He Tangkun et al. argue that they were used for direct production of steel from ore by a version of the crucible smelting technique known in later times. It seems that the crucibles were heated with mineral coal. If this was also used as the reducing agent inside the crucibles, as in the early modern process, then the high sulphur content of the product would be explained. What would not be explained is what this extremely hot-short steel could have been used for.

Further possibilities become apparent if we drop the assumption that the material left behind in the crucible is directly representative of the product which was made in it. In particular, it is quite possible that the piece of steel left in the crucible was the incidental result of partial decarburisation of a liquid iron with a much higher carbon content. If molten cast iron were poured out of the crucible, the tail end of the pour could lose enough carbon to solidify, adhere to the side of the crucible, and lose more carbon while cooling slowly from a temperature over 1150°C.

Excerpt from the biography of Qiwu Huaiwen, 6th century AD

Qiwu Huaiwen, whose place of origin is unknown, used Taoist techniques in the service of Shen-wu-di 神武帝 [Gao Huan 高歡, +496-547, father of the first Emperor of Northern Qi 北齊].

. . .

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 it in the urine of the Five Sacrificial Animals and quench-hardened it in the fat of the Five Sacrificial Animals. [Such a sabre] could penetrate thirty armour lamellae [*zha* 扎] [i.e. thirty layers of armour?]

Shen Gua on steelmaking, AD 1075

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 *tuan gang* 團鋼 or *guan gang* 灌鋼 ['combination steel' or 'irrigated steel'].

But this is nothing but false steel. It temporarily borrows the cast iron to provide hardness, but in two or three 'refinings' [*lian* 煉] the cast iron becomes 'cooked' [*shu* 熟, i.e. it becomes wrought iron, shu tie 熟鐵], and [the steel] is again soft iron. But if no one considers it false, this is only because they have never known true steel.

On an inspection tour I went to a smithy in Cizhou 磁州 [near modern Handan 邯鄲, Hebei], and there I knew true steel for the first time. The presence of steel in iron is like that of gluten in flour. When 'soft' flour [*rou mian* 柔麵] is thoroughly washed, the gluten appears. 'Refining' steel is similar. One merely takes excellent iron [jing tie 精鐵] and hammers it for a hundred or more heats [*huo* 火]. After each hammering it is weighed; with each hammering it becomes lighter. When the point is reached at which repeated hammering does not cause the weight to decrease, it is pure steel. This may be 'refined' a hundred times with no loss.

This [true steel] is the essence of iron [*tie zhi jing chun* 鐵之精淳]. Its colour is pure and bright, and when polished it is dark blue-black, unlike ordinary iron.

There are also [irons] which, 'refined' to completion, contain no steel at all. These are always associated with the products of [particular] regions.

Description of steelmaking by Song Yingxing in 1637

The method of 'refining' steel [*gang tie* 鋼鐵]: Wrought iron is beaten into thin strips as broad as a finger and about 1 *cun* 寸 [5 cm] long. The wrought iron strips are tightly tied together in a bundle, and cast iron is placed on this. (In Guangnan 廣南 [south China] there is [a type of cast iron] called 'lump raw steel' [*duo zi sheng gang* 墮子生鋼] which is especially suitable.) The top [of the bundle] is covered with old straw sandals (plastered with clay so that they do not quickly decompose), and the bottom is plastered with clay. [This package] is lowered into a fiery furnace, and the strength of the fire is blown with the bellows. After a certain interval the raw steel first melts and then soaks into the wrought iron, and the two natures [*qing* 情, of the cast and wrought iron] commingle. It is then removed and hammered. It must be 'refined' many times over; once is not enough.

This [steel] is popularly called *tuan gang* 團鋼, but it is more correct to call it *guan gang* 灌鋼.

Steelmaking in Chongqing 1938 and 1958

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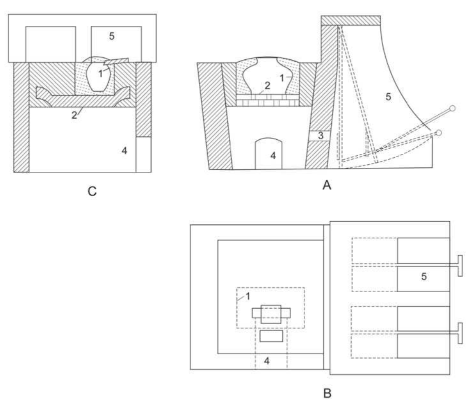
Joseph Needham's description of *Su gang* 蘇鋼 steelmaking in 1958

In the summer of 1958 I had the good fortune to be able to spend an afternoon at a steel-works of traditional type making *Su gang* at Beibei 北碚 near Chongqing. Here cast pig iron (C 3.05%) is first converted in small wood-fired finery hearths (*chao tie lu* 炒鐵爐) to a low-carbon iron (*liao tie* 料鐵) not quite as pure as wrought iron (C about 0.4%). In the next shop, this iron, having been formed into billets of markedly porous structure is heated strongly in coal-fired hearths where it is repeatedly subjected to the dripping of molten cast iron. This can be seen through blue glasses melting like candle wax. The steel so formed is called *gang tuan* 鋼團 – a noteworthy use of a Song technical term – and repeatedly forged into bars with a C content of about 0.9%. The hearths in which the sprinkling is done are known as *mo gang lu* 抹鋼爐 (steel-anointing furnaces), and the forges of the last stage are the *chou tiao lu* 抽條爐 (drawing-out furnaces). This factory, which has been working in an amphitheatre of hills overlooking the Jialing river [嘉陵江] and backed by Jinyunshan [縉雲山] for more than a hundred years, has always produced billet and bar steel, the method of dripping cast iron on to already formed wrought-iron tools not being practised in this part of Sichuan. At the time of my visit, the future seemed to lie wholly with giant steel plants of modern type, but immediately afterwards there came the great movement for decentralisation of industry in China, and for the revaluation of traditional techniques, so perhaps the Beibei plant is now safe for another hundred years.

↑*Photograph by Joseph Needham of the operation of a steel-anointing furnace (mo gang lu 抹鋼爐) at Beibei 北碚 in Chongqing, 1958.*

↑*Photograph of a steel-anointing furnace (mo gang lu 抹鋼爐) in Sichuan, ca. 1936.*



←*Diagram of a steel-anointing furnace (mo gang lu 抹鋼爐) at Beibei 北碚 in Chongqing, 1938.* ***A:*** *front;* ***B:*** *top;* ***C:*** *side.*

1: *furnace chamber and furnace lining of sandy clay.* ***2:*** *grate.* ***3:*** *blast channel.* ***4:*** *opening for removal of ashes and slag.* ***5:*** *blowing apparatus.*

'The furnace bottom consists of four wrought-iron bars laid in parallel to form a grate. This is covered on both sides with sandstone and clay, so that there are only three openings, ca. 2.5 cm wide, which must occasionally be bored out to allow the free passage of air and slag up and down.'

Zhou Zhihong's description of *Su gang* 蘇鋼 steelmaking at Beibei in 1938.

First the furnace is filled with charcoal, and two bars of raw wrought iron are placed outside the furnace next to the furnace mouth. The cover is put in place and the blast is started, so that the charcoal burns with a red flame.

Then some charcoal is removed from the upper part of the furnace, the two pre-heated bars of raw wrought iron are placed inside, charcoal is added up to the furnace mouth, the cover is replaced, and charcoal is piled up on all sides of the furnace mouth.

Now the blower is operated energetically, and after 2 minutes the furnace interior is red hot. The cover is removed, and two plates of cast iron (rectangular, weighing 0.75 kg) are prepared. One is placed beside the furnace mouth and the other is inserted into the furnace with tongs. Energetic blower operation continues, and the temperature inside the furnace rises to ca. 1000°C.

After 3 minutes the cast iron plate inserted in the furnace begins to melt, and sparks from the iron plate appear in the flames from the furnace mouth. At this time the temperature is ca. 1300°C.

The steel-anointing worker now takes over at the furnace. With his left hand he holds the cast iron plate in a large pair of tongs, moving it left and right so that the drops of molten cast iron drip down uniformly over the raw wrought iron and there is an intense oxidising action [?!]. Meanwhile, in his right hand he holds a steel hook with which he constantly turns the raw wrought iron, so that all parts absorb as much of the molten cast iron as possible.

This is the most important step in the process, requiring practised skill as well as the ability to regulate the anointing according to the temperature-colour of the raw wrought iron bar. Most of the steel-anointing workers are able to regulate the speed of the blower judging from the colour of the furnace interior.

After 6 minutes the first cast-iron plate has been used up and the charcoal in the furnace has burned out. The furnace is then filled half-full of charcoal and the remaining cast-iron plate at the side of the furnace is brought to the furnace mouth, held as before with tongs, the cover is closed, and the blower is operated.

After 4 minutes the cast-iron plate begins to melt and the second anointing of iron is performed. When this plate is used up the process is finished and the blowing is stopped. The raw wrought iron bar is removed, hammered on an anvil to remove slag and make a steel billet, which is popularly called a *gang tuan* 鋼團 ['steel lump'].