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Report No. 63528/September 27, 1985

William Rostoker Inc.
2052 W. 108th Place
Chicago, Illinois 60643

Attention: Mr. William Rostoker

SUBJECT

Chemical Analysis of Ancient Castings
Per William Rostoker.

BACKGROUND:

We were requested to investigate development of an analytical technique for analysis of ancient gray iron castings. Of particular interest were the elements phosphorus, sulfur, and silicon. Four (4) example castings identified as Nos. 120224, 120235, 120249, and 120252 were submitted as part of this development project. Other samples were submitted representing vacuum cast unknowns and various levels of phosphorus and sulfur. These other samples were prepared by William Rostoker in cooperation with Taussig Associates, Inc. to test the analytical technique.

The intention of the technique was to utilize the energy dispersive x-ray attachment on the scanning electron microscope to quantitatively determine the phosphorus, sulfur and silicon contents. In order to accomplish this, original analysis was made using standard analytical techniques.

TEST RESULTS:

Chemical Analysis:

Portions of each casting were submitted to our Chemistry Department for analysis. The results of that analysis are shown in Table I. The sample numbers are identified in Table II.

Energy Dispersive X-ray Analysis:

Attempts to correlate results obtained from energy dispersive x-ray with the results reported by the Chemistry Department were not successful. Although the instrument is capable of providing quantitative analysis with proper standards when the element detected is in excess of approximately 1%, sensitivity to the level of phosphorus, sulfur, and silicon at the percentages of interest to William Rostoker, Inc. was not adequate for quantitative analysis.

Respectfully submitted,

George M. Goodrich
Senior Metallurgical Engineer

TAUSSIG ASSOCIATES, INC.

GMG:lc

T A B L E I

CHEMICAL ANALYSIS

Sample No.	Element		
	Phosphorus	Sulfur	Silicon
1	.481%	.509%	<.05%
2	.424	.654	.223
3	.549	.607	.88
4	.590	.493	1.00
5	1.81	--	--
6	--	1.04	--
7	1.16	.320	1.61
8	1.21	.314	--
9	.523	.204	1.14
10	1.21	.348	.72
11	.354	.632	1.39

TABLE II

Sample No.	Identification
1	Rostoker Casting #120224
2	#120235
3	#120249
4	#120252
5	arc melted phosphorus standard
6	arc melted sulfur standard
7	arc melted with phosphorus, sulfur, and silicon
8	rerun on sample #7 analysis
9	arc melted unknown No. 1
10	arc melted unknown No. 2
11	arc melted unknown No. 3

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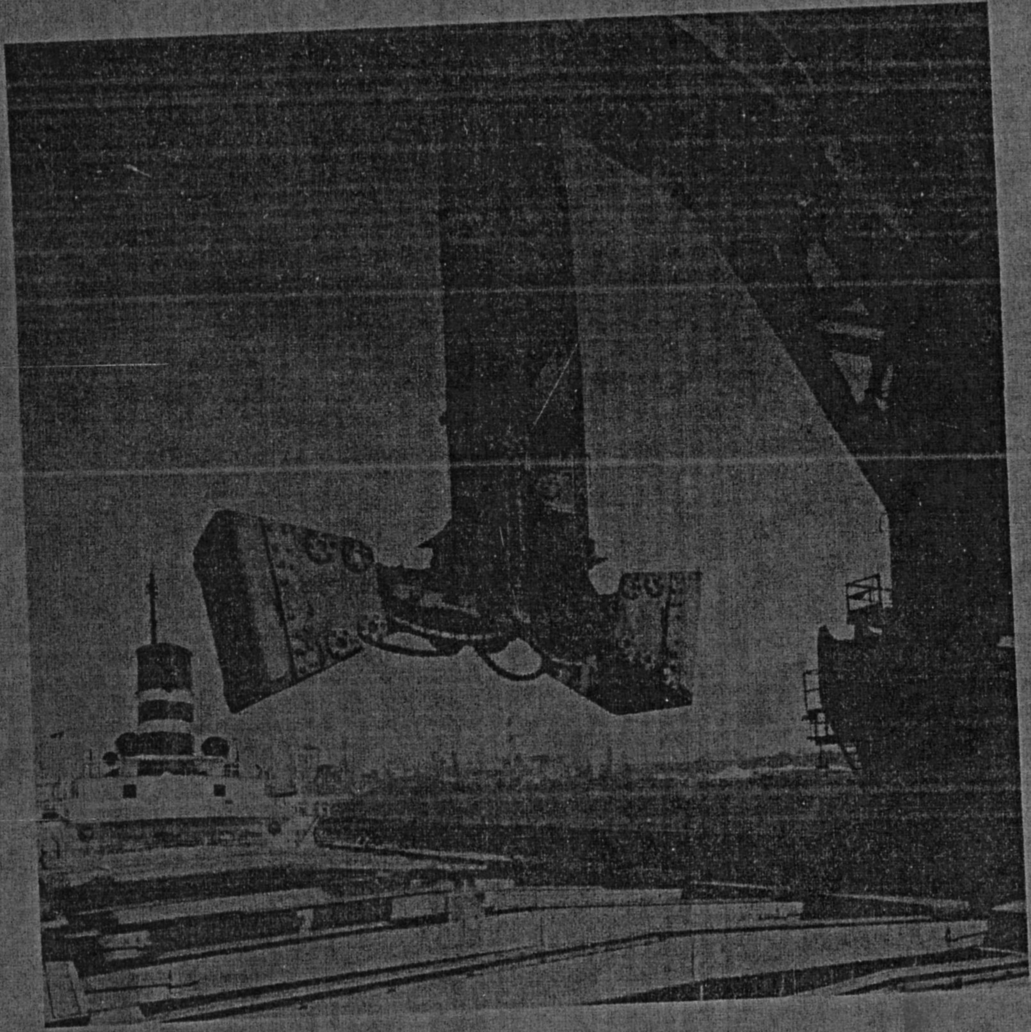

This issue: Industrial archaeology

Casting farm implements, comparable tools and hardware in Ancient China

W. Rostoker, B. Bronson, J. Dvorak and G. Shen

Population growth and the development of a nation are regulated by food supply. A meaningful food supply necessitates that farmers or farming units are able to produce a surplus of food beyond their own survival needs. The achievement of this status depends on a number of circumstances: availability of arable land, weather conditions, water supply and the use of tools. The first three of these stipulations pre-existed over much of the land mass of China. The emergence of satisfactory tools completed the requirements for national growth.

By the Shang dynasty (about 1500 BC) metal casting or foundry skills had been developed to a remarkable degree. Bronze objects of very large size and complexity of shape, even by modern standards, were produced in this period (Barnard 1961). The large objects were for ornamental, ceremonial and ritual uses and represented individual works of art. Bronze weapons also were produced in large numbers so that organized armies could engage in the conquest and subjugation of large territories. The bronze axe had a dual role both as a weapon and as a tool. The axe made from a hard metal is a special tool without which lumbering and the shaping of large pieces of structural wood are not very feasible.

The logical extension of bronze to farm tools did not occur either in China or elsewhere. This was not due to deficiency of fabrication or production technology. There were other appropriate reasons. Chief among these was metal supply. Farm tools represent a potential demand for materials far in excess of supply. Copper is the major component of the family of alloys called bronzes. Tin is usually the second component. The accessible mineral resources in ancient times were never enough to meet the needs of the agricultural sector with its millions of laborers. High cost and limited availability of bronze restricted its use to the needs of the ruling classes in ancient societies.

The key applications of farming tools involve forced contact with the soil. Topsoil is usually a very abrasive medium. Bronze does not possess a very high capacity for abrasive wear resistance. It was better in this respect as well as stronger and tougher compared to wood, bone or stone, but still not cost effective.

The 'workhorse' metal has always been iron in one form or another. Some time before the 5th century BC (Needham 1958) the Chinese developed a smelting process for iron ore that yielded a low-melting alloy of iron and carbon. In contemporary terms this metal belongs to the family of 'cast irons' of which more will be said. When the carbon content of iron is about 4.3 per cent, a very fluid, liquid metal exists above about 1130° C. Comparable fluidity in liquid bronze is attainable at only about 80° C lower. Being already sophisticated foundrymen, the Chinese learned to produce castings with this metal. It never acquired the status of bronze for decorative objects but its utilitarian value was exploited. Apart from functional attributes, the main advantage of cast iron was the almost unlimited magnitude of accessible deposits of mineral-rich iron ore (Tegengren 1923).

Iron sites for the Warring States and Han periods are mapped by Barnard (1961). There is an overlap in this distribution with the major bronze casting sites. The famous bronze casting center of Anyang, operating during the much earlier Shang period, is in Honan. The great iron casting center at Zhengzhao in Honan was also a contemporary bronze-casting center. It seems very likely that there was no geographic obstacle to the transfer of bronze foundry technology to the emerging cast iron industry.

It is apparent that the Chinese smelting process generated both temperatures in excess of 1250° C to liquefy the slag and the very high ratios of CO to CO_2 in the combustion gases necessary for the thermochemical reduction of iron ore to iron of high carbon content. However, the actual furnace design is not known. Published sketches of smelting systems are only reasonable speculations. The air supply system was probably the key factor, since the Chinese were very ingenious with air pumping machines. In Europe, other parts of Asia, and Africa, most furnaces operated at lower temperatures and with less reducing gas atmospheres. They produced 'bloom iron' which is a very different product: very high melting and, as a finished product, exceedingly forgeable and formable. The ancient Chinese smelters seem to have bypassed bloom iron production. According to Chang (1977) there is no evidence for smelting to bloom iron in early Chinese metallurgy.

While Needham (1958) supposed that bloom iron production existed at some time in China, Tylecote (1976) concluded 'there is no archeological evidence for the bloomery process in China'. The relatively few wrought iron or steel artefacts are not distinguishable from the product of a fining process applied to cast iron conversion.

Adaptation of cast iron to the production of farming tools seems to have begun (Cheng Te-k'un 1963) by the Warring States period about 500 BC. Everywhere in China excavations of sites dated to that period have yielded iron implements (Needham 1958; Cheng Te-k'un 1963). At least one author has voiced the conclusion that a 'revolutionary advance in agriculture' must have begun (Hsu 1965). This is a very reasonable perception. In default of bronze tools, farm implements must have been made of wood, bone and stone in various composite designs. Strength and wear resistance of such tools at their working tips would be poor. They would usually be made and repaired by the farmer himself. The result would be limited land usage and low productivity.

The emergence of mass production of farm tools is not an accidental event. It requires some stimulus. Cheng (1963) expresses a viewpoint in the following manner:

> The fall of Western Chou (721 BC) gave rise to the constant rivalry between the feudal states and their success depended upon not only the progress of their economy but also on an efficient government which could improve the lot of its subjects. The Chou philosophers were unanimous in advocating means to attract more population. The feudal lords and their councillors initiated economic reforms by claiming more land,

> facilitating tillage, introducing irrigation, increasing food production and developing industries and trade. It was in this atmosphere that technology was developed, iron tools and implements were introduced and bronze weapons began to be replaced by iron ones.

It is this technology of iron tool manufacture that deserves some study and analysis.

Designs of farm implements

Since the designs of cast iron tools are mostly derivative from the basic wedge (see later discussion), they represented no obvious change from what preceded in the limited use of bronze for tools. Design comparisons might be useful in the case of weapons since both bronze and cast iron spear-points and arrow-heads were used in overlapping periods. However there must have been some delay in the use of cast iron until the toughening heat treatments to produce decarburization and malleabilization were developed. Cast iron bells begin to appear in the Tang period and these seem to be directly comparable to designs in bronze.

All farm tools were castings which were fitted to wooden handles. While the existing literature on the subject focuses almost exclusively on the earliest designs, it is important to keep in mind that the manufacturing industry functioned for more than 1,500 years in much the same manner. Over that period the designs did not change much, with the exception of the plow, but the general dimensions did increase. The material of the casting was a specific type of cast iron which had been heat-treated after casting. More will be said of this in a subsequent section.

Some of the implements whose metal components have survived are identifiable as: plow, hoe, axe, adze, sickle. Diagrammatic illustrations of the tool configurations are shown in contemporary museums of the People's Republic of China. Barnard (1961) shows a grouping of such illustrations taken from a much earlier source. They are, however, modern conceptions because the wooden components have not survived and residual artistry (pottery, paintings) has not been helpful. Their actual appearance with dimensional scales as shown in Plates 19–22 helps to broaden the options in interpretation. Plate 19 shows a thin blade with a socket opening which is no more than 0.5 cm. With wood of that dimension, tolerable loading in bending would be quite small. It would be inadequate as the lifting-tip of a spade but it might be strong enough as a hoe for soil which has been plowed and turned over. It would be even stronger in a chopping application similar to the modern meat cleaver. There is no reason why it could not have served more than one use.

Plate 20 has been interpreted as a spade (Needham 1958). Again dimensions suggest this is unlikely. The width of the casting at its base is only about 11 cm. The sides give the shape a scoop-like appearance but they act more like rib strengtheners because the blade is very thin and quite weak in the bending mode which is expected of spade driven into the soil. It is also too small to be much of a spade but it would be very adequate as a hoe for cultivation around a growing plant. Plate 21 could be either a hoe or an adze but from the sturdiness of its section it is more likely to be the latter. However, it would serve equally well in breaking up hard earth or soft rock, e.g. mining a vein of ore.

Attachment to the wood handle and other wood fittings takes two forms. One represents a slipper-like fit of the metal tip over the wood. The other is the familiar projection of the shaped wood handle through a socket hole and pinning on the other side. Both of these

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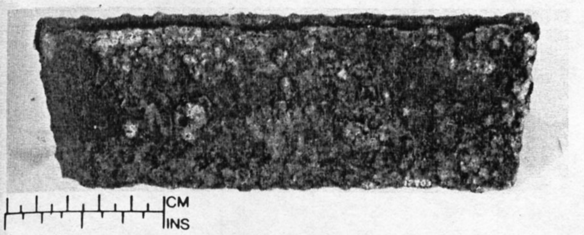

Plate 19 A hollow tool edge of unknown use, probably made sometime in the period 175 BC–AD 220. (From the Field Museum Collection: FM 127035.)

Plate 20 (*right*) A spade-like tool of rather narrow width which could also be the working end of a dipper-stirrer, probably cast sometime in the period 175 BC–AD 220. (From the Field Museum Collection: FM 127033.)

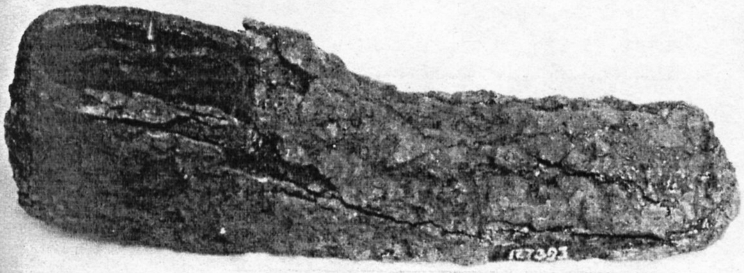

Plate 21 A heavy, socketed, adze-like tool head dating probably to about 600 BC. (From the Field Museum Collection: FM 127393.)

Plate 22 The cast iron working tip of some tool of unknown function. Both this and the spade-like tool (*Plate 20*) are very thin walled. Manufacture probably dates to 175 BC–AD 220. (From the Field Museum Collection: FM 127034.)

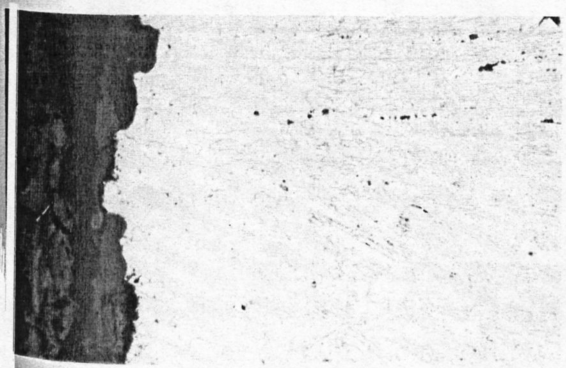

Plate 23 Microstructure illustrating the decarburized zone of an annealed white iron casting. The interior showing graphite nodules is the malleabilized cast iron product.

approaches are apparently contemporary with each other. There are advantages in each. The slipper-fit reduces the volume of metal used and thus represents a smaller unit cost. The socket attachment makes for a heavier tool and therefore a greater capacity to penetrate soil, rock or wood.

The plow tip shown diagrammatically in Figure 5 merits a special discussion. Actual photographs of excavated recoveries are shown by Barnard (1961), Zhengzhao (1978), and Beijing (1978). It represents a design that persisted with only some increase in dimensions for over 1,000 years. The metal tip provided the wear resistance to survive the break-up of virgin topsoil and, in its day, must have been responsible for a great leap in extending the land brought under cultivation. It seems, however, to be a poorly designed implement. The plow as we know it cuts the earth, raises it up and rolls it over to one side. The latter function provided by the moldboard feature not only serves to break up the lumps of earth but also diminishes the force resisting the forward motion of the plow. It performs not unlike the rake angle on a lathe cutting tool. The plow tip illustrated in Figure 5, when fitted to a sturdy wood shaft, can dig and lift but not roll-over the earth. It is possible that the roll-over profile was carved into the wood post or that the post-tip assembly was tilted to one side when set into the plow frame. In either case the exploitation of the much greater wear resistance of cast iron compared to wood was defeated. Nevertheless, this tool was produced in great numbers as can be deduced by the manufacturing methods to be discussed in the next section and the numbers found in excavations and exhibited. Although dates are not clear from museum captions, designs with an upper curved surface in the cast component did come into use. One of these later developments is shown in the Honan Provincial Museum, Zhengzhao.

A preoccupation with farm implements probably does not do justice to the scope of use of the many iron tools discovered in excavations. There were other major contemporary production activities which could have been served by similar tools modified or identical. Among these it is appropriate to consider canals and irrigation channels, road-building, mining, quarrying, wood-working, smelting and kiln operations. Quoting from Hsu (1965): 'Many irrigation systems were also built; in the early Chan Kuo (Warring States) period, the formerly useless soil of Yeh was made fertile by an irrigation system built by the governor that drew water for the territory from the Chang River. Another great engineering work is the world-renowned Tu-chiang Dam in Szechwan, built in the third century B.C. and still in use today.'

Plate 21 represents a very sturdy tool with enough weight to generate a substantial kinetic energy on the end of a long handle. With a sharpened edge it would serve well as an adze with which to cut flats on hard wood tree-trunks. The other tools to produce structural beams – axe, wedge, chisel – are all basically the same cast shape, finished somewhat differently. Added to these, the sledge-hammer and the pick provide the complement of basic tools for mining and quarrying. The tool in Plate 21, without the sharp edge and with a broader base, provides the basic tool for excavation in connection with road, canal and ditch building. All of these tools are simple castings requiring the same technology and all of these exist in the museums of the People's Republic of China.

In principle almost all of these tools are derivative from the wedge. The variants are in wedge angle, working edge breadth, weight, socket design and length-to-thickness ratio. Thus the chisel is the adze or axe without a socket hole but in all three cases with a ground edge they serve when wood is the product to be shaped. For the use of the chisel or the quarrying wedge, we must add the socketed hammer which could be a wedge geometry variant but is

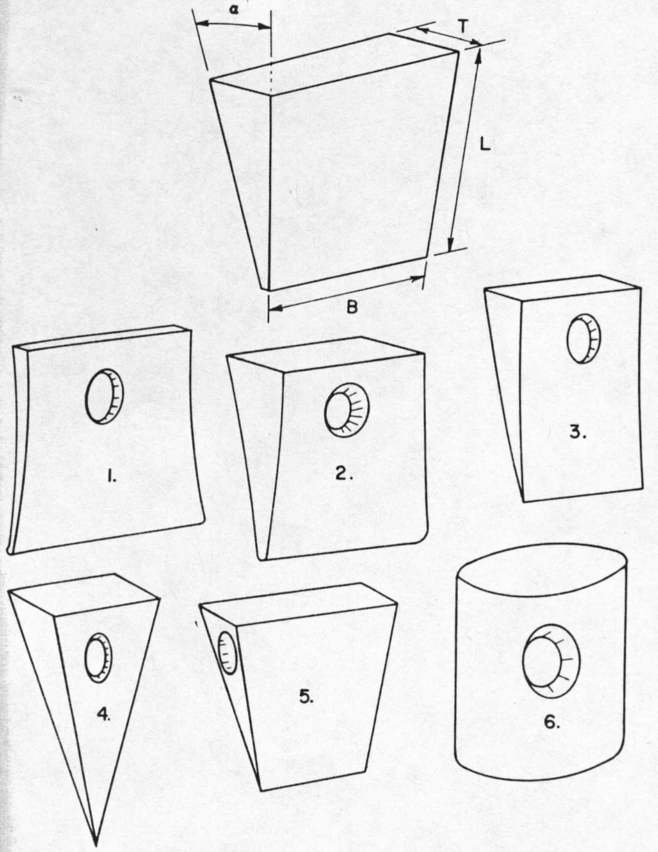

Figure 1 Diagrammatic illustration of tool designs which are variants of the wedge. The variants are described in terms of the angle α; the maximum thickness T, and the length L. Items 1–5 are intended to illustrate the socketed hoe, quarry or mining tool, wooden beam shaper, pick, and axe respectively. The cylindrical hammer is included as the companion to unsocketed versions of items 1–5.

more commonly a cylindrical shape. Figure 1 illustrates the idea of the family of wedge variants for hand-tool use. Among cast iron objects, the technology of manufacture is the same for all.

Manufacture of iron castings

While implements made from wood, bone and/or stone are likely to be hand crafted by the individual farmer, the castings under discussion require an industrial base of considerable magnitude. We must contemplate a production volume on a scale of perhaps a million units of various kinds per year.

If we assess an average casting at about 1 kg each, then one million of various kinds of tool units computes to about 1,000 metric tons of iron production per year. Presumably in periods of war the industry converted to weapons and civilian demands were set aside. Estimated annual iron production tonnages as published by Liu (1978) are shown graphically in Figure 2. These figures are for much later times. Curiously these figures are lower by more than a factor of ten compared to Hartwell (1966) whose well-documented estimates are 13,500 tons per annum (AD 806) to 125,000 tpa (AD 1078) with a sharp decline during the Jurchen and Mongol occupations. Another estimate is possible for the Western Han period (206 BC to AD 24). At that time there were three major production centers in Honan which was the center of iron smelting (Cheng 1978). On the site of one blast furnace the hearth remains.

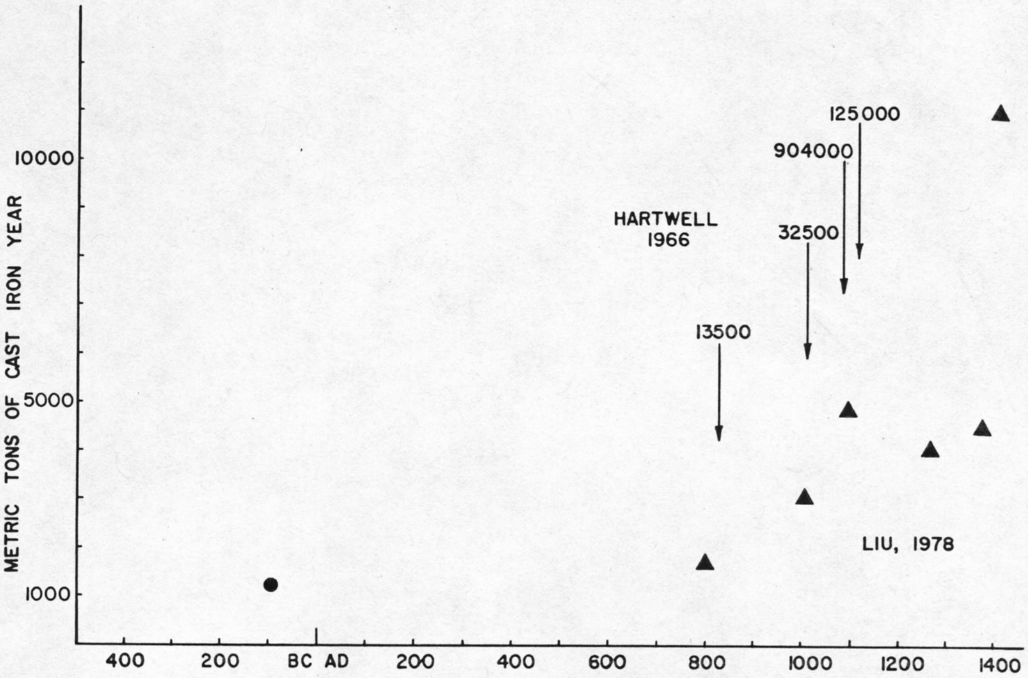

Figure 2 Graphical representation of estimated annual cast iron production rates. The crosses are taken from Liu (1978). The solid circle represents the calculation described in the text. The numbers with vertical arrows designate estimates in specific years as given by Hartwell (1966).

Its dimensions are 4 m × 2.7 m. A single piece of iron (probably a furnace that froze) of similar lateral dimensions and 0.4–1 m thick was also discovered. Using a more conservative figure of 0.3 m for the metal pool depth, the furnace could tap about 23 metric tons of iron. If this were done about 200 times per year, the production center could provide 460 metric tons per year. The three centers could therefore produce nearly 1,400 metric tons per year. This figure is not out of line with later periods considering the ebb and flow of dynamism in Chinese history. Moreover it is remarkably close to the demand estimate. Cheng (1978) also states that 'by the middle of the Western Han period, ironmaking skill and output had reached a level capable of meeting the needs of an agricultural country with a population of 60,000,000.'

This level of output clearly required some form of mass production technique. In that period there were two such methods: the stack mold and the permanent mold systems.

The stack mold system

A stacked mold involves clay shells and cores nested to one another so that multiple castings can be produced with a single metal pour using a common gate (Honan 1978; Hua 1983). The arrangement is illustrated in Figure 3, which also serves to illustrate two exceedingly important hardware items. Figure 3 (left) shows the mold cavity for a chariot or wagon-wheel bearing. The cast iron, hexagonal-shaped piece fitted into the center of the wheel. The cylindrical hole accommodated the shaft. Inserted radially into the shaft were a series of round-headed pins so that wear-resistant cast iron parts articulated with each other. The hexagonal component

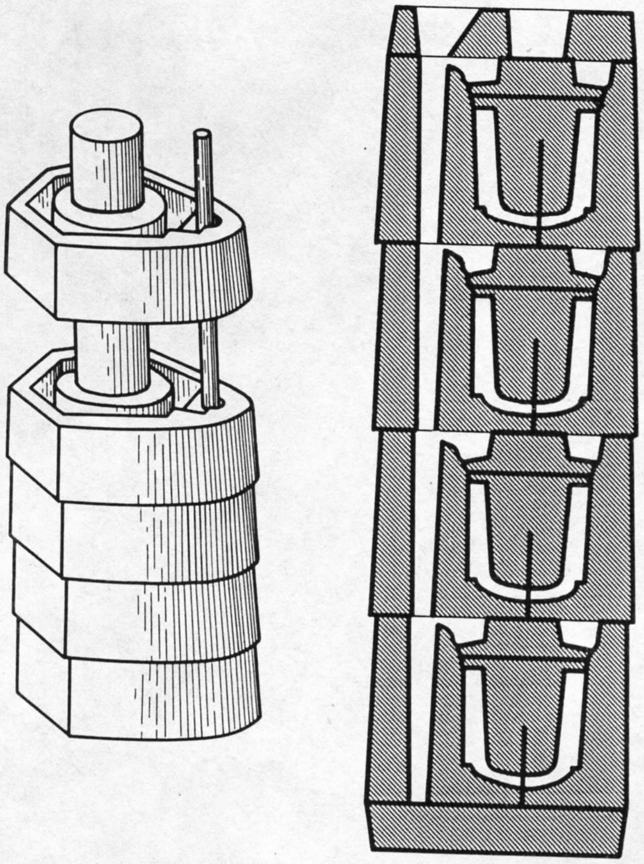

Figure 3 Diagrammatic arrangements of a stacked mold assembly for the multiple casting of a wheel bearing (left) and of a stacked mold assembly showing cores with metal chaplets for strengthening, the casting product being an axle hub (right). Source: Honan 1978.

of the wheel bearing is a Chinese design which is seen to have migrated with the Mongols since they were discovered in the excavations at Karakorum and Bolgar (Terehova 1974). The complement to the bearing was the axle hub (Figure 3 (right)). This is a special problem in molding and casting because of the fragility of the core bosses that make for the cross pin-hole in the hub. The use of chaplets or metal pins to provide structural support during mold assembly is illustrated.

The stack mold arrangement produces a number of castings with a common sprue which simplifies baking the clay and pouring the metal. It also provides a hydrostatic head of liquid metal which helps to ensure mold filling before the liquid metal freezes. Because cast iron can be either hard or strong or both, removal of the sprue can be costly of effort and time. This was reduced by using a thin runner which would be broken off much like breaking off a square of chocolate. The thin runner restrained liquid flow so that the hydrostatic pressure was useful if not mandatory.

The production of many molds required one or more patterns. The pattern is a primary replica of the intended product cut into components, each contained in a flask, into which clay negative replicas can be molded. The component divisions must be chosen so that the clay mold replicas can be lifted off the pattern and the mold replicas assembled to reproduce the whole negative of the intended casting. These ideas are illustrated in Figure 4.

The discovery of the Wenxian kiln still filled with baked clay molds (Honan 1978) establishes that all of these techniques were used by the ancient Chinese craftsmen. The variety of

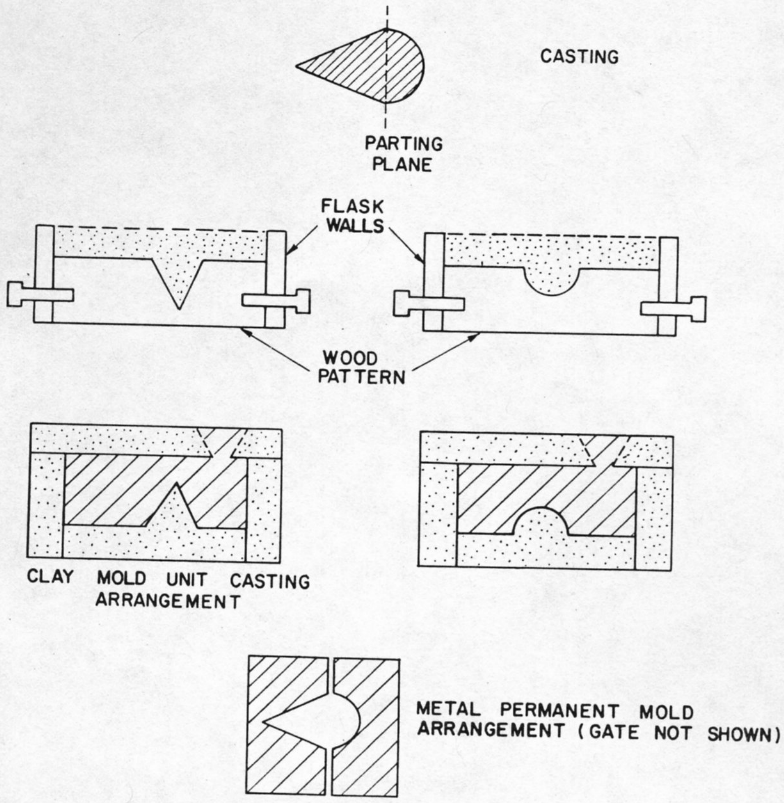

Figure 4 Diagrammatic illustration of a pattern and flask arrangement for producing clay molds. The clay molds can be used to produce castings of the desired shape (positive replica patterns) or cast molds from which castings can be produced (negative replica patterns).

other hardware objects represented by different stack molds attests to the mass production nature of the operation.

The permanent mold system

The other mass production system for castings involved the 'permanent mold' concept. The mold components themselves are metal castings. Commonly these were two or three components replicating the external surfaces and gate of the casting product and the cored hole or recess. The clamped assembly produced a gate and a cavity into which liquid metal could be poured. Liquid cast iron can be poured into a cast iron mold. Provided that the thermal capacity (mass) of the mold is sufficient, the mold itself does not melt. The liquid metal fills the cavity and freezes very rapidly because of the high thermal conductivity of the metal mold. Accordingly, if proper provision is made for rapid mold assembly, disassembly, and casting removal, a very high rate of production can be developed. Since cast iron molds have survived as well as the tools produced from them, it is clear that the permanent mold system was primarily used for the mass production of farming and other comparable tools (Honan and Shi-Ching 1978, Zhengzhao 1978). On the other hand, harness hardware, chariot and wagon

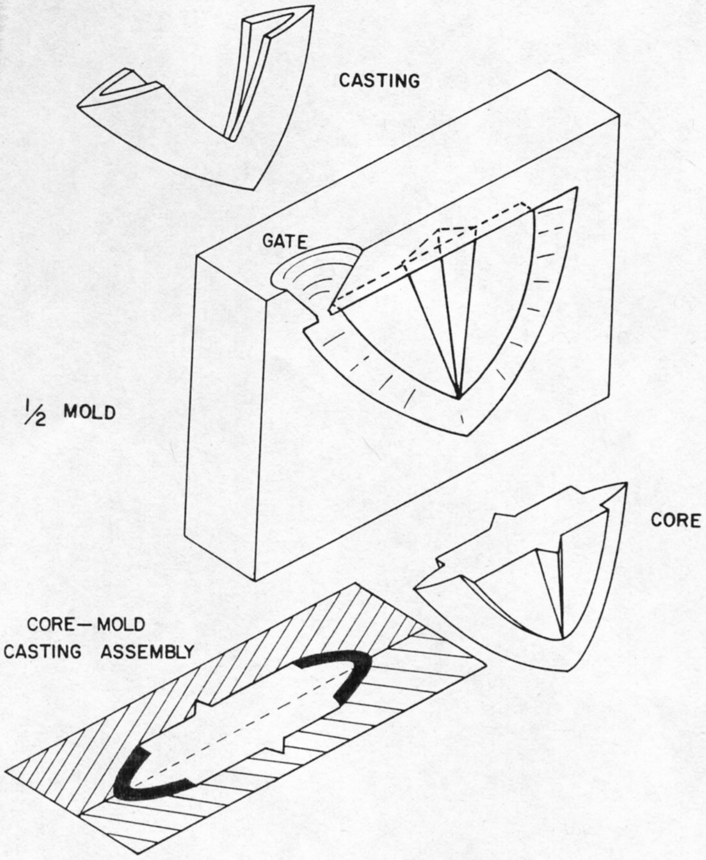

Figure 5 Diagrammatic illustration of the permanent mold components for high productivity casting.

bearings and axle caps were made with the stack mold system. A diagrammatic illustration of the probable mold components for the production of a plough tip is shown in Figure 5. When the three pieces are assembled, the core is locked by the split mold. The assembly is clamped for pouring and unclamped and disassembled to remove the casting with its gate. The permanent mold is preheated to reduce the rate of heat flow out of the liquid metal being poured into the cavity so that filling is not forestalled by premature freezing. There is a delicate balance in the maintenance of the mold preheat temperature high enough to permit mold filling and low enough to prevent corners and projections in the mold itself from melting. This correct mold preheat temperature is usually controlled by the rate of production of castings.

The permanent mold actually has a finite lifetime because of thermal fatigue. When liquid cast iron is poured into a preheated cast iron mold, the surface of the mold is immediately subjected to some substantial temperature rise and a steep temperature gradient is established from the inner surface to the outer surface of the mold. Because solid materials expand proportionately to temperature, the inner mold surface expands more than the rest of the mold. But the tendency to expand is restrained by the rest of the metal. Restraint to expansion is equivalent to the imposition of a compressive stress at the surface. This is of sufficient magnitude to generate irreversible (plastic) strains in the surface metal. When the casting is removed and the mold cools, it contracts in an opposite manner and the mold surface experiences tensile stresses and strains. Each time a casting is produced the mold surface experiences a stress cycle. Repeated stress cycles produce fatigue cracking; in this case, the phenomenon is called thermal fatigue or 'heat checking'. Cracks form on the mold surface. As they grow in depth they also yawn at the surface. At some point the liquid iron can penetrate into the cracks. When this happens the casting locks the mold parts together and disassembling to remove the casting product damages both the casting and the mold. At this point the mold must be scrapped. From studies on the thermal fatigue resistance of cast irons (Rostoker 1969), these permanent molds probably made not many more than about 500 castings before they were scrapped.

It is therefore obvious that an important feature of the permanent mold system of mass production of castings is the methodology of reproducing the molds themselves. Multiple permanent molds for any one tool product are necessary not only to replace cracked components but also to adapt to the liquid metal production characteristics of a smelting or melting furnace. The designs of both furnaces are similar. They run continuously with intermittent charging of fuel, ore and/or scrap metal. There is a steady rate of production of liquid metal which collects in a pool at the base of the furnace from which the liquid is tapped intermittently. The basin has finite capacity so that it must be tapped at intervals. Because of the aggressiveness of hot liquid cast iron, it is appropriate to tap enough liquid metal at one time for a number of castings so that the plug hole is damaged as few times as possible. Having tapped a large quantity of metal, it must be poured off before it cools too much. This scenario makes the case for a line of identical permanent molds on the casting floor at any one time. If the annual output of any individual casting type is about 100,000, there is also an annual need to produce 200 mold components over the same period. It should be realized that these calculations are reasonable orders of magnitude that serve to portray the interrelated logistics of a typical mass production industry, whether ancient or modern.

The clay molds to produce the permanent mold pieces are made by the pattern and flask method. A one-half carved replica of the outer shape of the casting is mounted on a flat plate. This is the pattern. The pattern plate is enclosed in a box with demountable sides. A water–clay mixture, as a stiff paste, is rammed over the pattern inside the box forming a block, one surface of which is indented with the profile of the half casting product item. The molded block is lifted off the pattern when the flask is disassembled. Companion flat-faced clay blocks are also produced so that when clamped together they create a cavity representing a cast block with one profiled surface. The gate is carved into one of the flat-faced blocks. These ideas are illustrated in Figure 4. The clay mold components assembled are dried, baked (fired) to about 700° C, and the permanent mold unit poured while the mold is hot. The clay mold is destroyed while recovering the cast permanent mold unit, but the pattern system allows an almost indefinite replication to close tolerances. Thus despite the manufacture of perhaps 200 permanent molds per year, the 100,000 castings of the tool are all, within good tolerances, identical.

The high production operation is visualized as working from a single blast furnace. A flat floor is constructed in front of the taphole of the furnace. About 30 kg of liquid metal is tapped from the furnace into each of two fired and preheated clay ladles supported on the outside by some form of cradle of metal bars and handles. A two-man team lifts each ladle and steps over to a line of permanent molds numbering about ten sets. The pouring time is short enough to prevent freezing in the ladle and long enough to fill each mold. While the molds are disassembled, the castings removed, and the molds reassembled, the pouring crews are tapping the furnace again.

A rough analysis of production logistics might be described as follows (Han 1979):

pouring cycle = 5 min. tap + 5 min. pour + 5 min. rest = 15 min.

mold line = 10 molds X 15 min.	= 40	castings per hour
	− 10	defective castings
	30	good castings per hr.
	X 10	working hours
	= 300	good castings per day
	X 200	working days per year
	= 60,000	castings per year
assume 3 mold lines (different products)	X 3	
	= 180,000	castings/site/year
	X 3	production sites
National Production	= 540,000	castings/year
To this we must add:	+ stack mold production	
	+ weapons production	

Note that each casting has a gate which is removed. Assume the gate is 0.3 kg for a 1 kg average casting. Reject castings and removed gates are recycled through the furnace.

Tonnage shipments from foundries as products of permanent mold casting	≅ 540,000 kg
	= 540 metric tons

Our earlier projected national tonnage output per year is easily met by the inclusion of stacked mold castings and weapons production. The latter might be stacked mold, permanent mold or individual clay mold products.

Ancient cast irons

The family of iron-carbon alloys that begin to melt at 1130° C are called cast irons. They are distinguishable from other ancient (and modern) iron products – bloom iron and steel – by being brittle, i.e. non-deformable hot or cold by hammering or bending. Being brittle does not necessarily mean weak. Cast irons can sustain stresses ranging from 20,000 to 40,000 psi, levels of strength which compare favorably to bronzes and low carbon steels. They are brittle only in the sense that they fracture at their stress limits and that they cannot tolerate notches or flaws without a very large loss of strength.

Although the common feature of all cast irons is their temperature for beginning of melting on heating, they generate many different structures by freezing on cooling. The differences lie in the crystallization of iron carbide or graphite, and in the latter case, the shape and size of the graphite crystals. From these variants come contemporary names for different kinds of cast iron: white cast iron (massive carbide in a configuration called leduburite); gray cast iron (flakes of graphite, long and short, randomly disposed in the structure); nodular or ductile cast iron (spherical nodules of graphite randomly disposed in the structure). The most common cast irons in use today are gray and nodular cast irons. The structure (and the class type) developed on freezing depends on major elements in the composition (C, Si); minor elements usually less than 1 per cent (S, P) and the rate of freezing. White cast iron is different from the rest in that the iron carbide crystals can be dissociated to graphite in nodular shapes by prolonged heating to temperatures between about 700° C and the beginning of melting. This heat treatment is called malleablizing, and the product of heat treated white iron is called malleable iron. Both malleable and ductile irons have the capacity to bend plastically to a limited extent before fracture, although the processes by which they are produced are very different and not at all related.

The mechanical properties of the various cast irons are very different. Both white and gray irons cannot tolerate more than elastic tension or bending without fracture. Gray iron is very soft (100-200 Brinell hardness number) and machinable. On the other hand white iron is exceedingly hard (350-600 BHN). Gray iron although softer is stronger in tension and bending. White iron possesses a tensile strength of only about 20,000 psi but its resistance to abrasive wear is superior to any ancient metal and is comparable to many contemporary metals.

The cast iron of ancient China for at least the first five hundred years of production was almost exclusively white iron. For the tool applications that involved forcible penetration of hard clay and soft stone it was ideal. These tools, however, would tend to spall when impacted against hard stone. White iron presented a problem in finishing the casting. It was difficult to remove the gate, vents, and flash since they would resist the penetration of chisels and saws. There are several ways by which this might have been accomplished without a high labor intensive cost. That part of the gate (runner or sprue) where the liquid metal actually entered the mold cavity could be constructed so that a notch existed at the junction with the solidified casting. The notch would permit separation of the gate from the casting simply by breaking it off as in a bar of chocolate. This method is not feasible if metal freezes in the choked entry point and prevents the filling of the mold cavity. Another approach is to remove the casting very quickly from the mold and chop off the gate while it is not completely solid. This is a very time-critical operation more appropriate to larger castings.

The third method was assuredly practiced but the full reasons are not altogether clear. Metallographic examination of a number of ancient tool artifacts disclose that they had been given a malleablizing heat treatment (Beijing 1978). The tool surface shows a thin layer (~3 mm) which is either pure ferrite (see Plate 23) or a pearlitic steel structure with a carbon content as high as 0.8 per cent. This structure could develop only by heat treatment in a decarburizing environment. Beyond the surface layer the white cast iron had transformed partially or completely to a malleablized cast iron structure, i.e. nodules of graphite in a matrix of ferrite or pearlite. This composite structure produced by protracted annealing at temperatures above about 700° C is called in modern parlance a 'white heart malleable iron.'

In this state of heat treatment the new structural state is as soft and machinable as the gray and nodular cast irons. It also has a small capacity for deformation by bending as with nodular iron. Both malleable and nodular irons have a much higher resistance to fracture or spalling, i.e. higher toughness than white or gray irons. Since this malleablizing treatment was indeed practiced in ancient China, we must conclude that it represented an acceptable trade-off between reduced wear resistance and increased spalling resistance, with the added benefit that the gates could be more easily removed from the casting. The trade-off included all states of partial malleabilization, preserving some fraction of the hard white iron structure (Liu 1960).

Summary

Through the recovery of dated objects from excavations in recent years and in combination with interpretations of ancient writings, it is increasingly clear that the development of a technology for smelting iron ore to cast iron led to a large industrial enterprise for the manufacture of farm implements, excavation tools, harness and vehicle hardware, cooking and household equipment and the many items that form the basis for a sophisticated and growing society.

These events were not abrupt. The development of furnacing to produce liquid cast iron probably occurred by 700 BC but a significant rise in casting production had evolved by 500 BC. During the Han dynasty, 206 BC to AD 220, there was a remarkable surge of technical developments and systems of mass production were organized so that useful metal objects would be available to a large part of the growing population. The permanent mold system of casting is representative of the industrial ingenuity that was operative in the climate of the time.

Although the evidence is not firm, it seems likely that the accessibility of large numbers of tools allowed major expansion in the acreage of arable land, the construction of canals both for transport and irrigation, and the development of a major road system. Since cast iron production cannot be a cottage industry, it set the precedent for large central industrial sites which served the needs of a whole nation. Combining the new concentration of specialized craftsmen, the need to collect and distribute food surpluses, and the regulation of trade that is consonant with surpluses, the urban areas became a necessary consequence.

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Abstract

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Casting farm implements, comparable tools and hardware in Ancient China

Beginning some time before the 5th century BC and continuing thereafter, the Chinese developed a process for producing molten cast iron which they applied to the manufacture in large numbers of implements, tools and hardware. Mass production techniques utilizing cast iron permanent molds and stacked clay molds are described. The tools were composites of working tips or heads of metal and wooden handles attached as a slipper fit or through a socket hole. Some degree of toughness to resist cracking or spalling was imparted by heat treatments of the cast iron. The availability of such tools for agriculture, road and canal building, mining and quarrying must have provided the bases for urbanization and national organization.