

The use of white cast iron in ancient Korea

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Introduction

The early production of cast iron in China from the mid-1st millennium BC, and the subsequent rise of the Han Empire, led to the development of steel making technologies based on cast irons in many parts of East Asia. In Korea, iron artefacts appear as early as 400 BC, but they are considered by most to be imported from China (Barnes 1999: 215). The formation of the Han colony, Lelang, in the northern part of the Korean peninsula in 108 BC is considered as being influential on the development of iron smelting on the peninsula (Kim & Nishitani 1984: 141). Shortly after the installation of Lelang, the peninsula saw the rise, from among the many small polities, of the predecessors of the three influential states--Koguryo, Paekche and Silla. With the appearance of these three states, the Korean Three Kingdoms Period (ca. 300-668 AD) commenced.

While metallurgical studies have been conducted on numerous iron artefacts from China (Wagner 1996), studies of this nature are only beginning in Korea (Choi *et al.* 2001, Yun 1984). From a limited number of samples, Yun (1984) suggested that both bloomery and cast iron were produced in early Korea. Yun suggested that by the time of the Three Kingdoms Period, iron and steel of varying carbon content was produced from cast iron, but with little material evidence of cast iron being directly involved in the steel making. The study by Choi *et al.* (2001), examining 87 artefacts, found evidence of not only cast iron being converted to steel, but also low-carbon iron being converted to steel by carburization.

One of the purposes of this paper is to present the microstructure of four iron artefacts made on the Korean peninsula during the Three Kingdoms Period. Three were from sites in the former Koguryo state, and one from the former Paekche site. The Koguryo state covered the northern part of the Korean peninsula and extended into Manchuria. The Paekche state was located in the southwestern part of the peninsula (Figure 1), and both date from the 1st century BC to the 7th century AD. The two kingdoms were conquered by the allied forces of Silla, a kingdom located in the south-eastern part of the peninsula, and the Chinese Tang dynasty. Paekche fell in 660 AD and Koguryo in 668 AD. Their collapse marked the end of the Korean Three Kingdoms Period and the beginning of the Unified Silla, the first unified kingdom in the Korean history (Eckert *et al.* 1990: 42).

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Materials and Microstructures

Figure 2a shows an iron artefact, probably an arrowhead (KP:001), from the former Koguryo military fortress located in the modern city of Moosoon. The item was one of many excavated by Japanese archaeologists during the Japanese occupation of the Korean peninsula; a report on the excavations is in preparation. The artefact has been stored in the Seoul National University Museum of Korea (Choi *et al.* 2001: 279).

A metallographic sample was taken from the region noted in Figure 2a.¹ The microstructures are shown in Figure 2b and c.

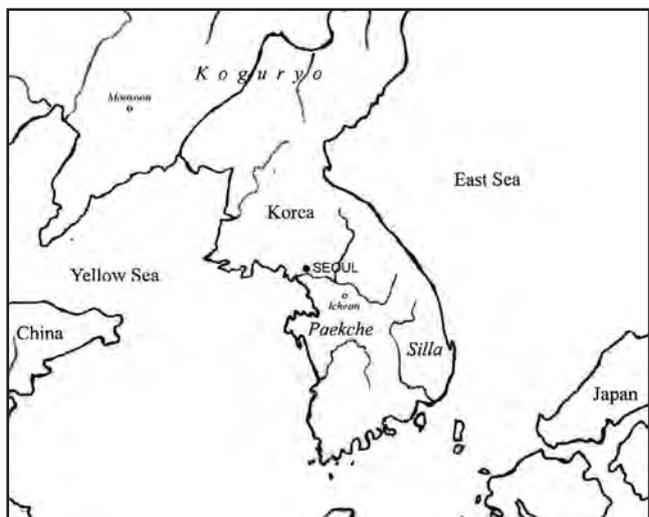
The interior region consists of white cast iron, and is surrounded by a layer of pearlite. The steel layer corresponds to the exterior of the artefact. Figure 2c shows the Vickers indentations at 500 g load. The hardness values (see Table 1, page 12) increase as one goes from the exterior to the interior of the steel layer. The hardness increases due to the increasing carbon content. Additional evidence for an increasing carbon content is the decreasing amount of ferrite in the steel layer. The hardness shows a sharp increase upon crossing the boundary from the steel layer to the white cast iron region, and keeps increasing into the core before it levels off.

It is interesting to see that the steel layer has no hint of graphitization, another reaction that may occur during such a thermal treatment. The absence of graphitization may be because of the negligible silicon content in this sample. No silicon was detected in the energy dispersive X-ray spectrum (EDS) of the steel layer as shown in Figure 2d.² The spec-

1 This specimen, as well as those that follow, were mounted and polished following standard metallographic practice. After polishing, the metallographic samples were etched with a solution of 2% (volumetric) nitric acid in methanol.

2 The gold (Au) peaks are due to gold coating the specimen for examination in the scanning electron microscope (SEM).

Figure 1: The cities of Moosoon and Icheon within the territorial boundary of the former Koguryo and Paekche state, respectively.



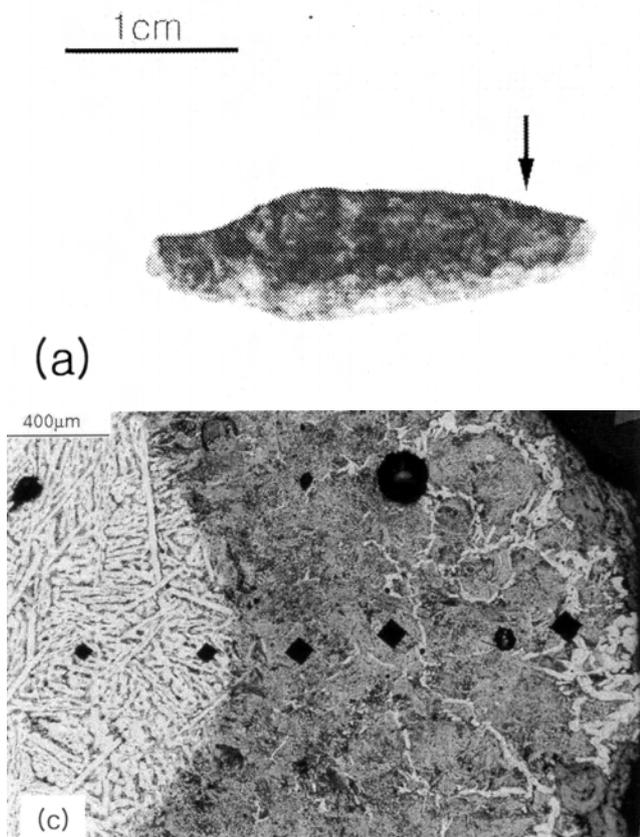
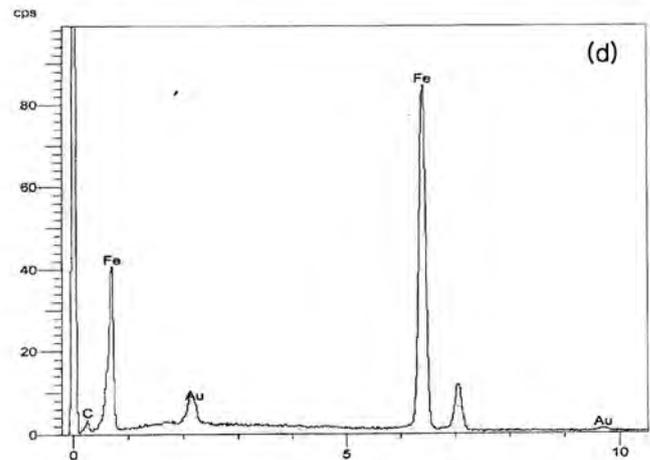
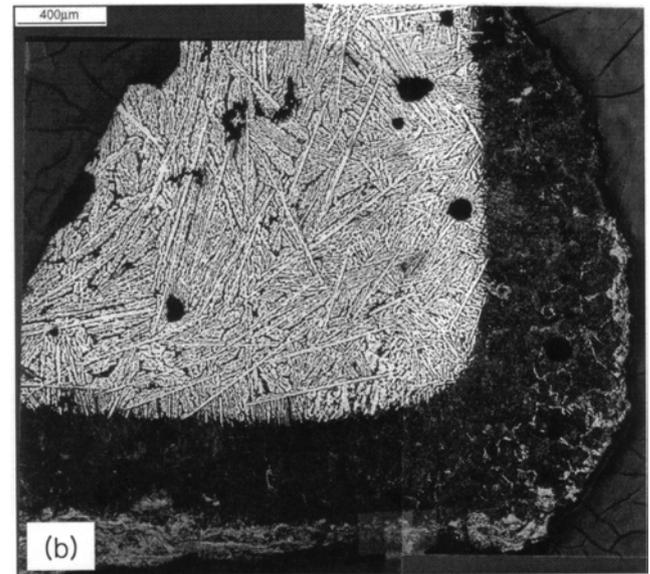


Figure 2:
 (a) General appearance of a cast iron artifact (KP:001) from the Koguryo fortress in the city of Moosoon.
 (b) Optical micrograph showing microstructure at the region noted in Figure (a).
 (c) Optical micrograph showing the Vickers indentations at 500 g load. Hv = 640, 500, 290, 260, 220 from left.
 (d) EDS spectrum from the pearlite part of (b).



trum from the white iron region was found to be similar to that in Figure 2d. Without silicon, graphitization in white cast iron is suppressed.

Figure 3a is another iron arrowhead (KP:002) recovered from the same fortress (Choi *et al.* 2001: 282). The microstructure of a metallographic sample is shown in Figure 3b. The area near the bottom center, which corresponds to the core of the arrowhead, consists of pearlite and is surrounded by a layer consisting of both ferrite and pearlite. The fraction of ferrite increases in the outer layer as one goes towards the surface of the artefact.

Figure 3c and 3d are higher magnification SEM photographs of the outer ferrite and inner pearlite region, respectively. Two things are apparent; the morphology of cementite is significantly modified compared with that in ordinary pearlite, and there are no ferrite grain boundaries completely free from the presence of the modified cementite phase. Like the previous specimen, the EDS spectra contained no hint of silicon, and graphitization could have been easily avoided.

Figure 4a is an iron armor scale from a private collection. The piece is claimed to be from a region of Manchuria that would have been within the territorial boundary of Koguryo. On typological grounds, the iron scale is similar to examples of Koguryo iron scales dating to the Three Kingdoms Period (Jeng & Sun 1993: 215).

A metallurgical specimen was taken from the area noted in Figure 4a. The microstructure distribution over the entire thickness is presented in Figure 4b. The Vickers hardness data indicates that the hardness value at the center is higher by 5 to 10% than those at the surface regions (see Table 1). Figures 4c, 4d and 4e are higher magnification SEM pictures taken near the indentation at the left, center and right, respectively. It is evident that the microstructure of the specimen consists primarily of cementite in the shape of particles or ribbons in a matrix of ferrite. The cementite phase is almost completely spheroidized, suggesting that the specimen was forged at temperatures near 727 °C. The higher hardness at the center may be associated with the higher carbon content there. The amount of carbon is estimated from the cementite fraction to be around 2 wt%.

Figure 5a is a farming implement from a military fortress constructed by the Paekche kingdom in the modern city of Icheon (Son *et al.* 1999: 341). Figure 5b shows the microstructure found along the entire thickness of the region noted in Figure 5a. The structure consists of cementite that is partly spheroidized and coarsened in a matrix of pearlite.

The Vickers indentations in Figure 5c, a magnified view of Figure 5b, correspond to the relatively low hardness of Hv 240, despite the high carbon content. The low hardness is expected based on the shape of cementite.

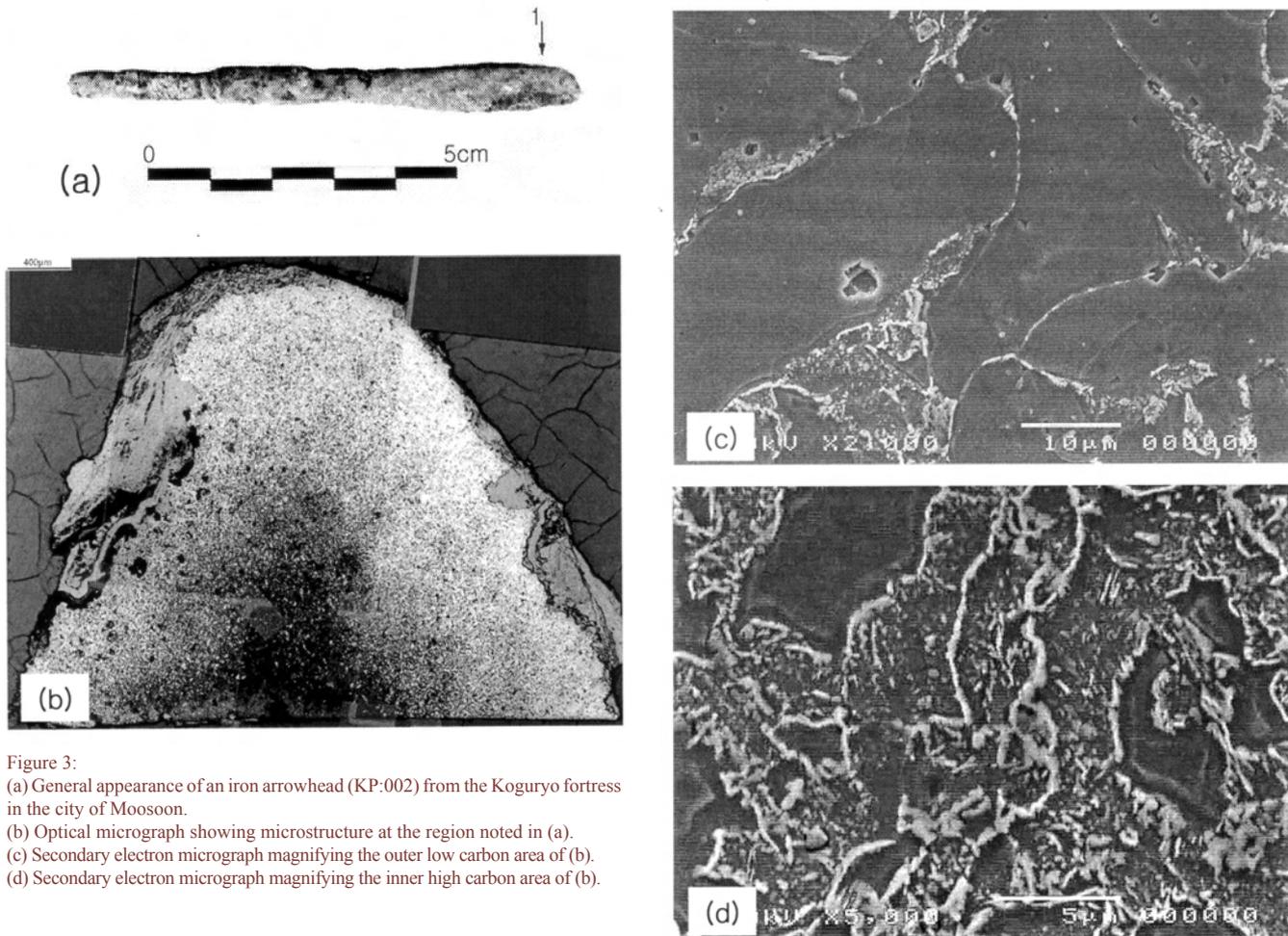


Figure 3:
 (a) General appearance of an iron arrowhead (KP:002) from the Koguryo fortress in the city of Moosoon.
 (b) Optical micrograph showing microstructure at the region noted in (a).
 (c) Secondary electron micrograph magnifying the outer low carbon area of (b).
 (d) Secondary electron micrograph magnifying the inner high carbon area of (b).

Discussion

The microstructures of the four artefacts examined in the present work all point to the ancient use of white cast iron in the production of iron and steel implements. Of all of them, the arrowhead (KP:001) in Figure 2 presents the most direct evidence of white cast iron turning into steel by decarburization on the surface. This kind of microstructure can be obtained when the article is first cast in a pre-formed mould, and then given a decarburization treatment at elevated temperatures for a prolonged period.

The manufacture of the arrowhead KP:001 from cast iron raises some questions though. It is rare to find weapons made out of cast iron, and it is not clear whether or not this artefact was intended as an ordinary arrowhead as has been proposed. The shape implies it could be used as some sort of projectile though. White cast iron, being relatively brittle, may be the wrong choice for making items that are subjected to high impact loading. The surface steel layer may be an indication by the smith(s) to overcome the problem and thereby achieve an easy mass production of such items. The steel layer may act as a ductile container to keep, even for a brief moment, the brittle white iron core from breaking apart upon impact. The relatively small fraction of the layer indicates that the decarburization reaction was never completed, but stopped either on purpose or by chance.

The microstructure of KP:002 has similarities to that of the previous arrowhead--the core has a higher carbon content than the surrounding exterior layer. Although there is more than one route to reach the structure distribution as in

Figure 3b, the decarburization of white cast iron is a probable choice. In that case the difference between this and the previous artefact is a matter of heat-treating conditions, such as the time, temperature and atmosphere of the thermal treatment. Other things being equal, KP:002 would have been decarburized longer after being cast in a pre-formed mold.

Some might suggest that the arrowhead in Figure 3 was forged from high carbon steel and its exterior was decarburized during forging. If this was the case though, the ferrite grains emerging with the decreasing carbon content have to undergo recrystallization in the annealing process to release strain energy built up by deformation. No ferrite regions (Figure 3c), however, have grain boundaries suggesting this occurrence, even though they were found in a fully annealed state ($H_v = 160$). Furthermore, as mentioned above, most of the grain boundaries between ferrite grains are covered with a cementite phase that is significantly coarsened, a phenomenon hard to occur in ordinary annealing after deformation. On this basis, it is suspected that the arrowhead was made from white cast iron and then decarburized.

Depending on the raw material, the microstructure found in the armor scale could have been produced in one of two ways. Before discussing the possibilities for the raw material, one must inquire if such a high carbon content was intended and required in the artefact. Spheroidized carbides are the least effective means of hardening steel. The spheroidized carbide particles do impart ductility to ultra-high carbon steel, which would otherwise be too brittle to deform.

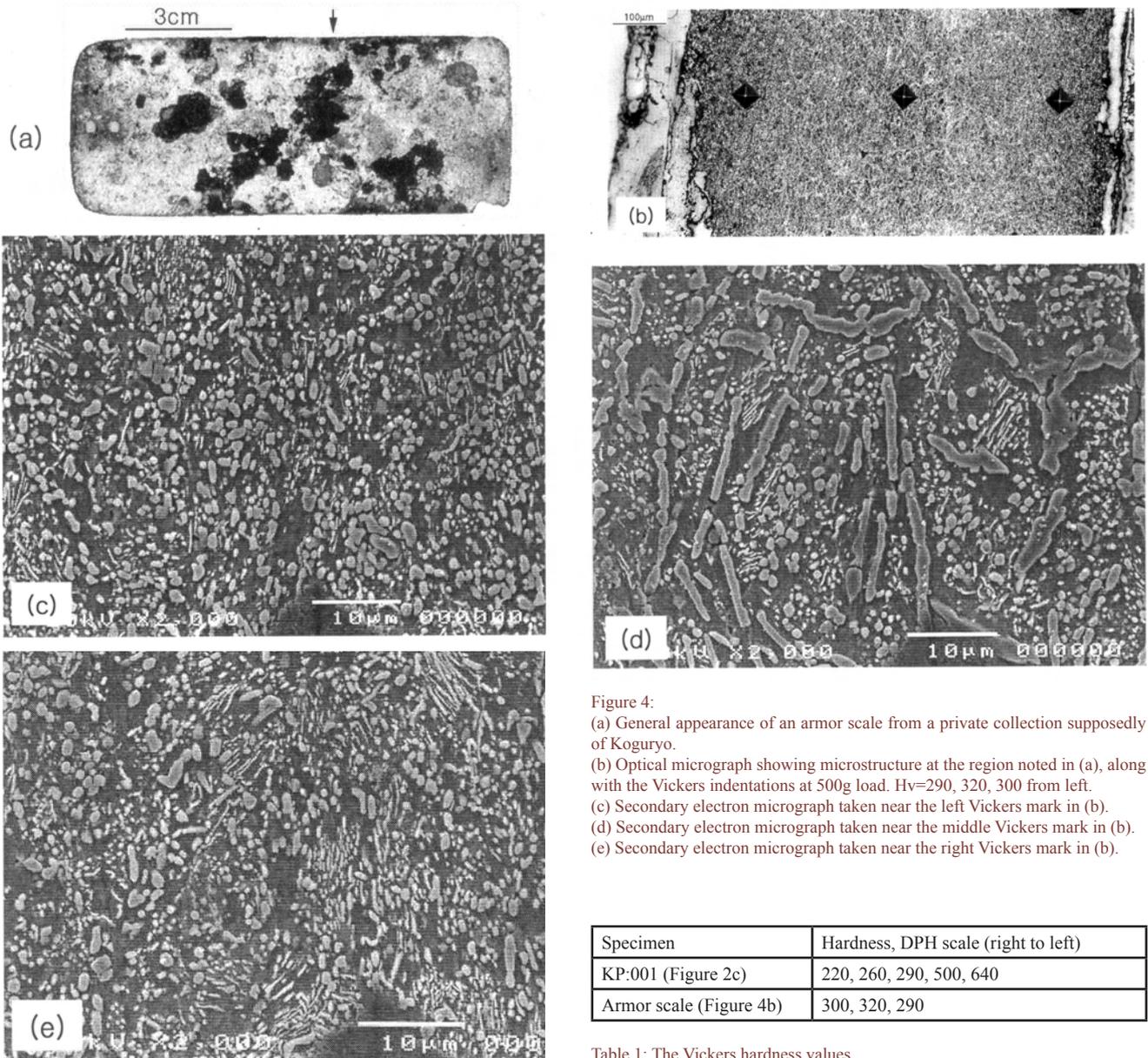


Figure 4:
 (a) General appearance of an armor scale from a private collection supposedly of Koguryo.
 (b) Optical micrograph showing microstructure at the region noted in (a), along with the Vickers indentations at 500g load. Hv=290, 320, 300 from left.
 (c) Secondary electron micrograph taken near the left Vickers mark in (b).
 (d) Secondary electron micrograph taken near the middle Vickers mark in (b).
 (e) Secondary electron micrograph taken near the right Vickers mark in (b).

| Specimen | Hardness, DPH scale (right to left) |
|-------------------------|-------------------------------------|
| KP:001 (Figure 2c) | 220, 260, 290, 500, 640 |
| Armor scale (Figure 4b) | 300, 320, 290 |

Table 1: The Vickers hardness values

If hardness was important, it could have readily been attained with a much lower carbon content combined with the proper thermal treatment.

Three scales recovered from another Koguryo site (Choi *et al.* 2001 45-50) were made out of bloomery iron. Their microstructures consisted primarily of low carbon steel, except at a localized region of a scale having around 0.4-0.5 % carbon, which might have been achieved by pack carburization. For the scale examined in this study, it would have been technically difficult and inefficient to produce the high carbon content through secondary carburization. It is probable that the starting material supplied for making the scale was white cast iron.

It is unlikely that this scale was cast in a pre-formed mold and then decarburized though. Decarburization is slow and takes time. The process can be significantly accelerated if the object has a high surface area, and is forged. Studies by the author demonstrate that forging increases the rate of decar-

burization substantially (Park forthcoming). Unlike the two arrowheads, steel items produced by such a thermo-mechanical treatment would naturally take the form of a thin plate.

The farming implement is similar to the armor scale in two aspects. First, in its present condition, it has a high carbon content. Second, the high carbon content was not intended for the purpose of hardening, but is probably due to the raw material that was used. By contrast, such a high carbon microstructure may simply result if white cast iron is decarburized and forged. Tools and weapons, especially those in the form of thin plates like this implement, would then be shaped from the decarburized plate with little effort. The high carbon, if in spheroidized form, would help with the plastic deformation occurring during forging.

There is also documentary evidence that decarburization was done with forging. The Chinese account translated by Needham (1980) indicates that forging of cast iron was done in the decarburization process.

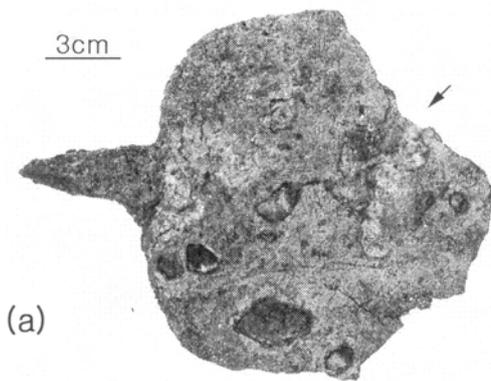
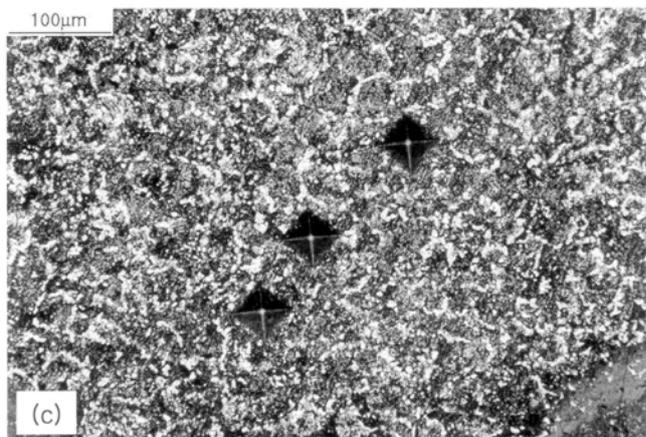
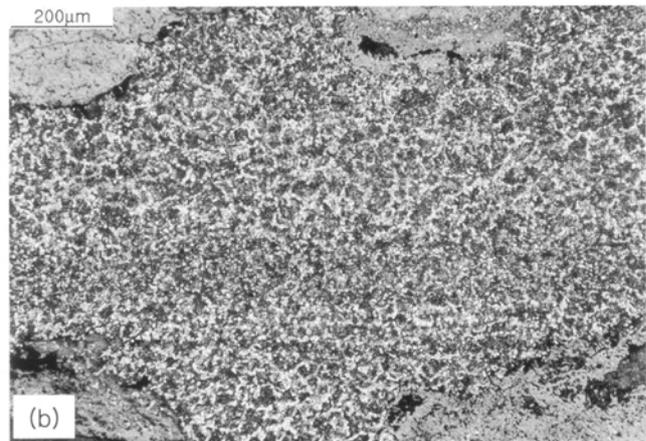


Figure 5:
 (a) General appearance of a farming implement from the Paekche fortress in the city of Icheon.
 (b) Optical micrograph showing microstructure at the region noted in (a).
 (c) Optical micrograph showing the Vickers indentations at 500g load. Hv = 240.



Conclusions

The results here suggest that cast iron was used to make iron and steel on the Korean peninsula by the time of the Korean Three Kingdoms Period (ca. 300-668 AD). The evidence suggests this occurred in both the north and the south of the peninsula. The microstructural evidence indicates that the iron and steel could be made from white cast iron in one of two ways. One way, the items were cast with white cast iron in a pre-formed mould and subjected to a simple thermal treatment for decarburization. The two arrowheads are examples of this method. This manufacturing method would allow mass production of the items.

In the second case, white cast iron is decarburized and converted to iron and steel under the combined action of heating and forging. In this method, forging is used to accelerate decarburization. The armor scale and farming implement were made by this method.

It is apparent from the present work that, from the early 1st millennium AD, inhabitants of the Korean peninsula practiced a complex ferrous metal technology that incorporated the use of white cast iron. Considering the geographical proximity, the influence to and from China cannot be underestimated, especially in the Koguryo state whose territorial boundary extended to Manchuria. While a Chinese text mentions the use of forging to assist in decarburizing, the metallography of contemporary Chinese artefacts shows little evidence of forging being utilized (see Wagner 1993: 291-295, 480). Whether this technology was developed in Han China or in the kingdoms of the Korean peninsula requires further research.

Acknowledgements

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