Ironware Manufacturing Techniques of Goguryeo Shown at Large Iron Swords Excavated from Hongryeong-bong Fort 1/2, Boru-gun, Achasan Area, Historic Site No 455

Seung-Jun Oh, Koang-Chul Wi

Abstract Background/Objectives: A large iron sword refers to a sword used as a weapon and in Korea, it was actually used as one of war weapons since the latter part of the 3rd Century and at the same time as a means to symbolize the status of the bearer. As research on Goguryeo period has been very limited for the scientific analysis due to the nature of the area, this study sought to deal with metallurgical analysis on large iron swords.

Methods/Statistical analysis: The study analyzed two pieces of large iron swords excavated from Mount Achasan Fort 1/2 and compared them with metallurgical analysis result of iron artifacts excavated from nearby remains of Achasan Fort 4 and Guui-dong. All of two pieces turned out to be manufactured by forging mold and heat treatment process.

Findings: Large iron sword No 1 showed the shape of ferrite crystal grain or pearlite, and given the shape of the structures, it was considered to have been pounded or exposed to heat treatment in relatively low temperatures instead of being cooled down simply by being exposed to outside air. As for Large iron sword No 2, the study found that its main parts had tempered Martensite phase, while its spine had ferrite phase - soft iron structure. So, the study believes that at the time ironware manufacturing technique was used to increase carbon content at any wanted parts through carburizing.

Improvements/Applications: Given these iron manufacturing, heat treatment techniques were used at the time, people at Achasan Fort 1/2 presumably had their own iron manufacturing ability.

Keywords: Large iron sword, Goguryeo, Manufacturing technique, Iron artifacts, Metallurgical analysis

I. INTRODUCTION

Ironware was used as a new tool following the Stone and Bronze Ages and the example in which humankind had used it for the first time was known to be during 4,000 BC when Egypt made iron beads by pounding natural irons. And in the early 3000 BC thereafter, iron daggers made from smelt iron were verified to be used in Syria and Baghdad area in the Near East[1]. In Korea's archeology, the early Iron Age means, out of its Iron Age, the period from 300 BC to around before and after BC when cast irons were distributed influenced by the Yan Dynasty, China. And the Proto-Three Kingdoms Period is meant the period to the 3rd Century AD thereafter when forged ironware was distributed in a big way influenced by the Four Commanderies of Han[2].

Form this time on, Korea used two iron manufacturing techniques: Low temperatures reduction in which low carbon iron material called 'direct reduced iron' was produced from irons in solid state; casting technique in which materials with high carbon contents were produced from melting condition[3]. And materials for irons mainly used direct reduced iron already produced or cast irons able to control carbon content, instead of refining iron ores because of technical problem[4]. In connection with iron manufacturing process, carburzing was used for irons with low carbon content, while decarburizing for cast irons[5].

Archaeometallurgy calls products made by decarburizing from cast irons 'cast iron-decarburizing iron' and research findings by China and North Korea revealed that plow blades and cast hoes - farming tools in the early years of Goguryeo around 100 BC discovered at Jian City - were white cast iron, cast iron-decarburizing iron, malleable cast iron[6]. Apart from this, typical natural-scientific research on ironware during Goguryeo period was done by Park Jang-sik, who sought to bring light to iron manufacturing techniques of Goguryeo period by analysis of microstructure and composition of ironware using excavated artifacts. He conducted research on Goguryeo's ironware manufacturing technique and its system as shown at excavated ironware from Gungnae Fortress and Hangang river basin[7].

Research on ironware manufacturing techniques of Goguryeo as such has not been conducted properly since Goguryeo's territory mostly belongs to China or North Korea, resulting in lack of remains and historical data. That said, a considerable number of iron artifacts were excavated from Goguryeo's archaeological sites at Hangang river basin before and after 2000, consequently paving the way for research on ironware techniques during Goguryeo period. For the present, investigation on Boru-gun around Achasan, - Goguryeo's archaeological site - is continuously going on, excavating a number of iron artifacts. And the study believes additional research should be carried out.

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Hongryeon-bong Fort 1/2 are situated at the most southern part of Boru-gun's archaeological sites and several other forts are learned to exist near to Hangang including Guui-dong Fort. Nevertheless, they are placed most adjacent to Hangang out of still remaining forts. As a result of investigation, Fort 1 saw excavation of 27 artifacts including Goguryeo's earthenware and small amount of Silla's earthenware, whereas Fort 2 saw excavation of 567 pieces of earthenware from Goguryeo, Silla, Joseon Dynasty and patternlessearthenwares as well as 247 pieces of Goguryeo's ironware[8]. Excavated iron artifacts included weapons such as large sword, helmet, sharp iron tool to keep spears, iron ax, iron tip, armor along with harness, iron knife, iron with shades, etc. While, complete iron flag poles were unearthed from Fort 2's storage facility.

Under the circumstances, this study conducted metallurgical analysis on two pieces of large iron swords excavated from Hongryeon-bong Fort 2, Boru-gun around Achasan area and compared them with the existing research data of artifacts excavated from archaeological sites then - Gungnae Fortress, Siru-bong, Achasan Fort 4, Guui-dong Fort. By doing so, the study would like to shed light on Goguryeo's culture during the Iron Age.

II. METHODS OF EXPERIMENT

Two pieces of targeted artifacts already experienced considerable corrosion due to the nature of excavated artifacts and so the study collected minimum amount of samples so as to maintain their original form. Large iron sword No 1 excavated near to southwest wall of water storage facility had the shape of an inverted triangle for cross-section of body part, while cross-section of scales was rectangular. The spine of the body was flat in the shape of a straight line and the blade had sharp edge[9]. The samples were collected from point A for the blade, point B for the spine and point C for the upper part (blade) as per Picture 1.

Large iron sword No 2 excavated from between walls of No 6 Chiwa had the shape of an inverted triangle for cross-section of the body, while that of the scales was trapezoidal. The spine of the body was flat in the shape of a straight line and the blade had sharp edge. The width of the body was regular and became narrower at the fore-end[10]. The samples were collected from point B for the blade, point C for the spine and point A forthe upper part (spine) as per Picture 2.

Collected samples were fixed by epoxy resins and underwent micropolishing up to 1 μm and etching so as to be used for microscopy. Etching used Nital (HNO3 + Ethyl alcohol) 3% solvent and microstructures were observed by a metallographic microscope (AxioImager A2m, ZEISS). Non-metallic inclusions existing within the microstructure were investigated by means of Scanning Electron Microscope: SEM, Energy Dispersive Spectrometer: EDS, COXEM EM-30AX.

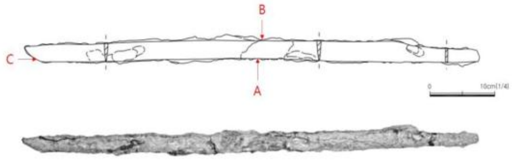

Figure 1.Large Iron Swords(No. 1) and actual drawing and sampling location

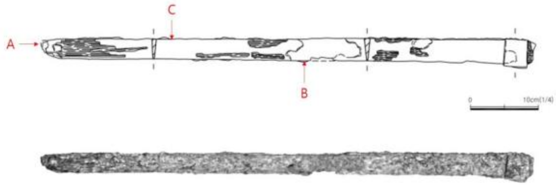

Figure 2.Large Iron Swords(No. 2) and actual drawing and sampling location

III. RESULTS AND CONSIDERATION

3.1. *Microstructure of Large iron sword No 1*

Picture 3 shows microstructure of the sample collected from blade part of Large iron sword No 1 - complete large iron sword with much lignum remain on the whole surface. Picture 3(a), the whole look of the sample, shows that all parts except corroded part had the mixed structure of ferrite and pearlite. Picture 3(b) and 3(c), enlarged photo of the top of the sample, shows typical ferrite and pearlite microstructure and seems to be within the range of 0.2-0.3%, though there might be some difference on carbon content depending on parts.

Picture 4(a) shows SEM photo of non-metallic inclusion - impurities existing at the center of the sample and EDS spectrum is shown at Picture 4(b) and Table 1. Glassy FeO, SiO_2, Al_2O_3, CaO were detected from points a-1, 2. Points a-3, 4 were confirmed to have glassy phase subject to some differences in carbon and had K_2O detected. The composition identifying the existence of Fe oxide as such is the one often seen from slags produced during smelting, telling us slags not eliminated during smelting remained partly within the iron material. Non-metallic inclusion at Picture 4(a) seems to show the occurrence of corrosion around glassy slags, presumably glassy slags and wustite formed thereon.

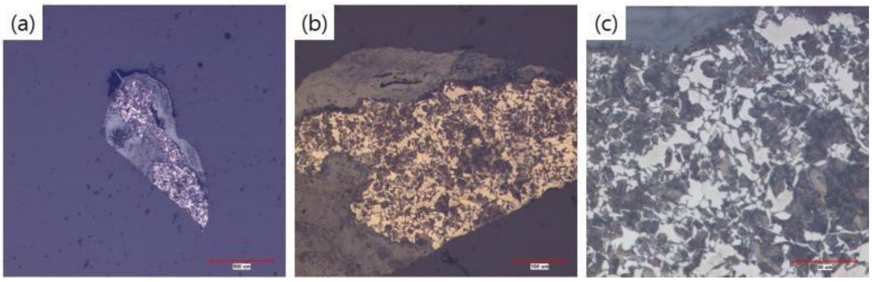

Figure 3. Microstructure of Blade part(Figure 1(A)) of Large Iron Sword(No 1). (a) Whole of Sample(×25),(b) Enlarged of the top of the Sample(×200), (c) Enlarged of the top of the Sample(×500)

Table 1: EDS Analysis Results No.1(A) Large Iron Sword

Spectrum Position	Element(wt.%)							
	FeO	Na_2O	MgO	Al_2O_3	SiO_2	K_2O	CaO	TiO_2	MnO
a-1	78.48	-	0.74	3.65	5.34	-	0.18	-	-
a-2	82.42	-	1.48	4.15	9.24	-	1.24	-	-
a-3	79.93	-	-	-	14.92	1.25	0.75	-	-
a-4	89.19	-	1.09	7.12	11.66	-	-	-	-

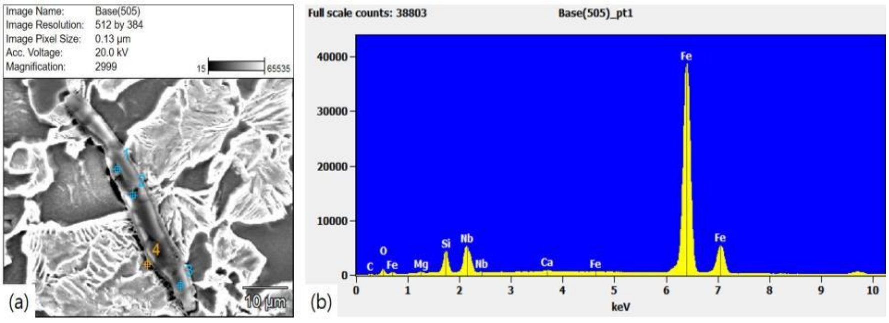

Figure 4. Non-metallic inclusion of Blade part(Figure 1(A)) of Large Iron Sword(No 1). (a) SEM photo of non-metallic inclusion, (b) EDS spectrum of non-metallic inclusion

Picture 5 shows microstructure of the sample collected from the spine. Picture 5(a), whole look of the sample, shows even distribution of micronized ferrite and pearlite on all parts except the corroded part. Picture 5(b), 5(c) that enlarged the bottom of the sample shows even distribution of dense ferrite and pearlite. So, we can presume the material of the large iron sword was hypoeutectoid iron and given the crystal grain of the spine was micronized, processed amount seems to be focused on the spine[11].

Picture 6(a) shows SEM photo of non-metallic inclusion - impurities existing at the center of the sample - and EDS spectrum is shown at Picture 6(b) and Table 2. Non-metallic inclusion at Picture 6(a) shows glassy slags. All points were confirmed to be glassy with oxides of FeO, SiO2, Al2O3, CaO. Given the study's finding that they had similar composition, it seems some of glassy slags not removed in the process of smelting remained within the iron material.

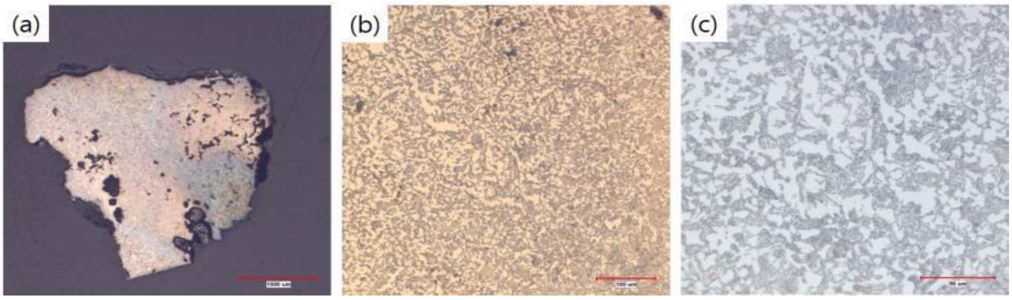

Figure 5. Microstructure of sample collected from the spine(Figure 1(B)) of Large Iron Sword(No 1). (a) Whole of Sample(×25), (b) Enlarged of the top of the Sample(×200), (c) Enlarged of the top of the Sample(×500)

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Table 2:EDS analysis results No.1(B) Large Iron Sword

Spectrum Position	Element(wt.%)								
	FeO	Na_2O	MgO	Al_2O_3	SiO_2	K_2O	CaO	TiO_2	MnO
a-1	40.04	-	0.39	2.62	14.47	3.80	5.23	0.54	1.21
a-2	13.67	0.43	0.89	6.74	32.35	5.26	5.97	0.59	1.14
a-3	48.10	0.41	0.51	4.24	16.53	1.30	1.27	0.13	-

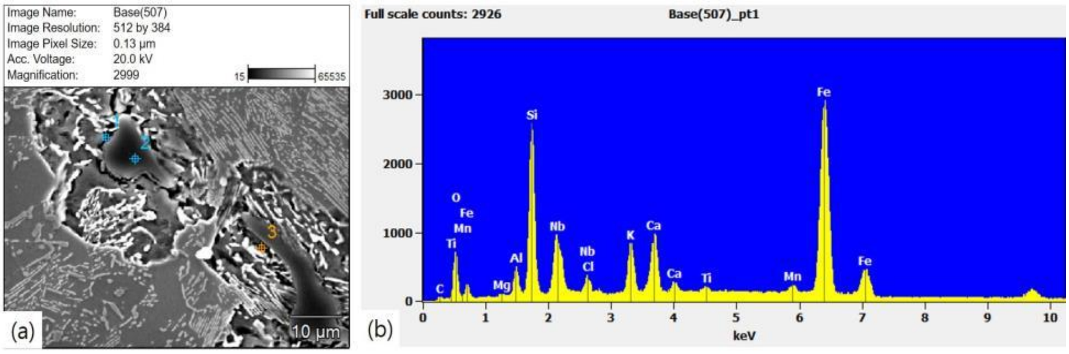

Figure 6.Non-metallic inclusion from the spine(Figure 1(B)) of Large Iron Sword(No 1). (a) SEM photo of non-metallic inclusion, (b) EDS spectrum of non-metallic inclusion

Picture 7(a), the whole look of the sample, shows that all parts except corroded part had the mixed structure of ferrite and pearlite. The more upper part, the more crystal grain, so presumably nearer to the spine. Picture 7(b) and 7(c), enlarged photos of right bottom of the sample, shows typical ferrite and pearlite microstructure and seems to be within the range of 0.2-0.3%, though there might be some difference on carbon content depending on parts[12].

Picture 8(a) shows SEM photo of non-metallic inclusion - impurities existing at the center of the sample and EDS spectrum is shown at Picture 8(b) and Table 3. Non-metallic inclusion at Picture 8(a) seems to be glassy slags that remained in the process of smelting and we can see formation of ferrite on top of glassy phase. Point a-1, 3 were found to be glassy with oxides of FeO, SiO2, Al2O3, CaO, K2O. Given the study's finding that they had similar composition, it seems some of glassy slags not removed in the process of smelting remained within the iron material.

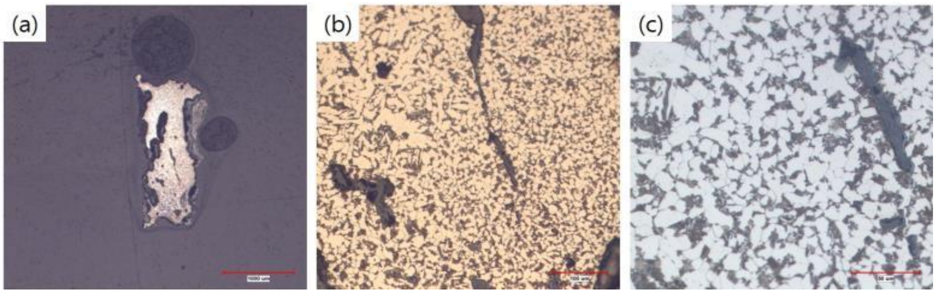

Figure 7. Microstructure of Blade part upper part(Figure 1(C)) of Large Iron Sword(No 1). (a) Whole of Sample(×25), (b) Enlarged of the top of the Sample(×200), (c) Enlarged of the top of the Sample(×500)

Table 3:EDS analysis results No.1(C) Large Iron Sword

Spectrum Position	Element(wt.%)								
	FeO	Na_2O	MgO	Al_2O_3	SiO_2	K_2O	CaO	TiO_2	MnO
a-1	20.17	0.62	0.20	6.64	25.42	2.99	3.44	0.44	0.37
a-2	84.54	-	-	0.30	2.04	0.33	0.49	-	-
a-3	32.22	0.40	0.33	4.36	21.17	2.44	3.58	0.44	0.57

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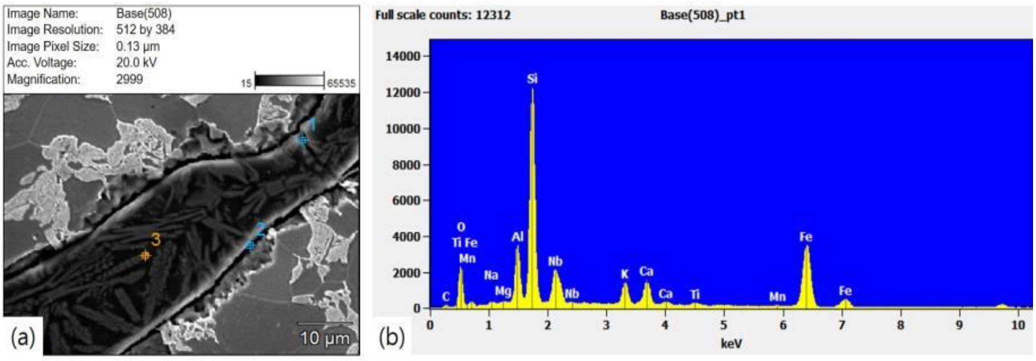

Figure 8.Non-metallic inclusion of Blade part upper part(Figure 1(C)) of Large Iron Sword(No 1). (a) SEM photo of non-metallic inclusion, (b) EDS spectrum of non-metallic inclusion

3.1. Microstructure of Large iron sword No 2

Picture 9 shows microstructure of the sample collected from top spine part of Large iron sword No 2. Picture 9(a), the whole look of the sample, shows that all parts except corroded part had ferrite structure. Picture 9(b) and 9(c), enlarged photos of the center of the sample, shows pure iron structure almost devoid of carbon content and we can observe the shape and size of ferrite crystal grain and also confirm the existence of non-metallic inclusion. Picture 10(a) shows SEM photo of non-metallic inclusion - impurities existing at the center of the sample and EDS spectrum is shown at Picture 10(b) and Table 4. Most of them had wustite structure formed on top of glassy phase.

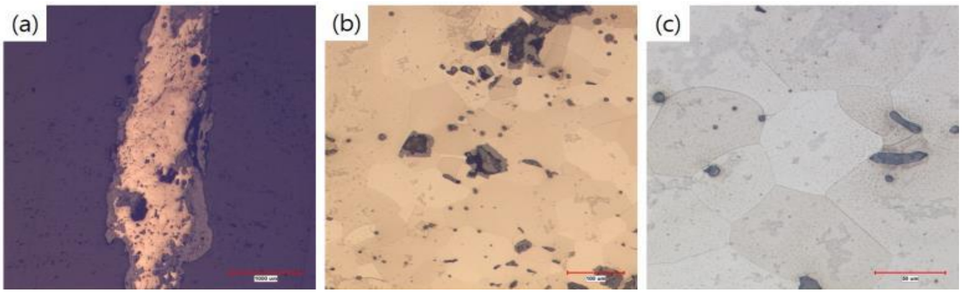

Figure 9. Microstructure of sample collected from the spine upper part(Figure 2(A)) of Large Iron Sword(No 2). (a) Whole of Sample(×25), (b) Enlarged of the top of the Sample(×200), (c) Enlarged of the top of the Sample(×500)

Table 4:EDS analysis results No.2(A) Large Iron Sword

Spectrum Position	Element(wt.%)								
	FeO	Na_2O	MgO	Al_2O_3	SiO_2	K_2O	CaO	TiO_2	MnO
a-1	67.44	-	-	0.09	15.65	0.08	1.30	-	-
a-2	76.01	-	-	0.64	11.20	0.12	-	-	-
a-3	73.06	-	-	0.57	20.15	-	-	-	-

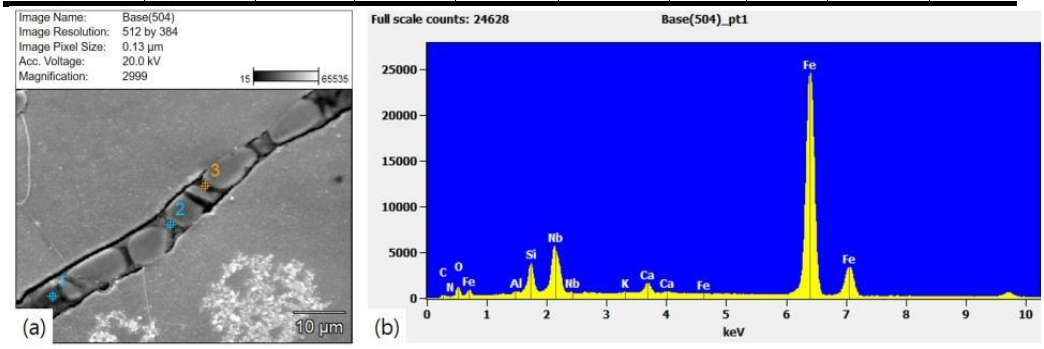

Figure 10.Non-metallic inclusion of sample collected from the spine upper part(Figure 2(A)) of Large Iron Sword(No 1). (a) SEM photo of non-metallic inclusion, (b) EDS spectrum of non-metallic inclusion

Picture 11 shows microstructure of the sample collected from the blade of Large iron sword No 2. Picture 11(a), whole look of the sample, shows distribution of Martensite structure - mixture of ferrite and pearlite structure - with almost no carbon content. Looking at manufacturing process of the blade, it seems to have gone through carburizing work of putting carbon to it to supplement its weak structure of prompted by more discharge of carbon at the blade than the spine.

Picture 12(a) shows SEM photo of non-metallic inclusion - impurities

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existing at the center of the sample and EDS spectrum is shown at Picture 12(b) and Table 5. Non-metallic inclusion at Picture 12(a) seems to be glassy slags that remained in the process of smelting and all points were confirmed to be glassy with oxides of FeO, SiO2, Al2O3, CaO, K2O. Given the study's finding that they had similar composition, it seems some of glassy slags not removed in the process of smelting remained within the iron material. Also in light of high CaO carbon content, lime material seems to have been added intentionally during the smelting process.

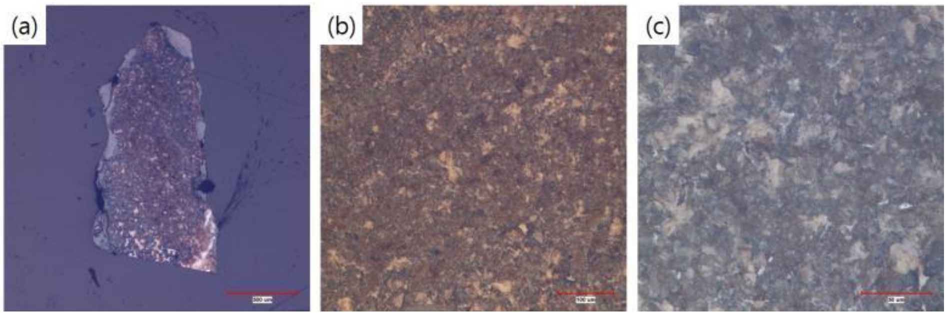

Figure 11. Microstructure of Blade part(Figure 2(B)) of Large Iron Sword(No 2). (a) Whole of Sample(×25), (b) Enlarged of the top of the Sample(×200), (c) Enlarged of the top of the Sample(×500)

Table 5:EDS analysis results No.2(B) Large Iron Sword

Spectrum Position	Element(wt.%)								
	FeO	Na_2O	MgO	Al_2O_3	SiO_2	K_2O	CaO	TiO_2	MnO
a-1	27.19	0.82	1.30	4.79	23.97	4.46	12.42	0.24	0.29
a-2	73.11	-	0.33	0.91	4.93	0.60	11.70	-	-
a-3	55.44	0.46	0.74	2.92	13.87	1.99	15.44	0.08	-

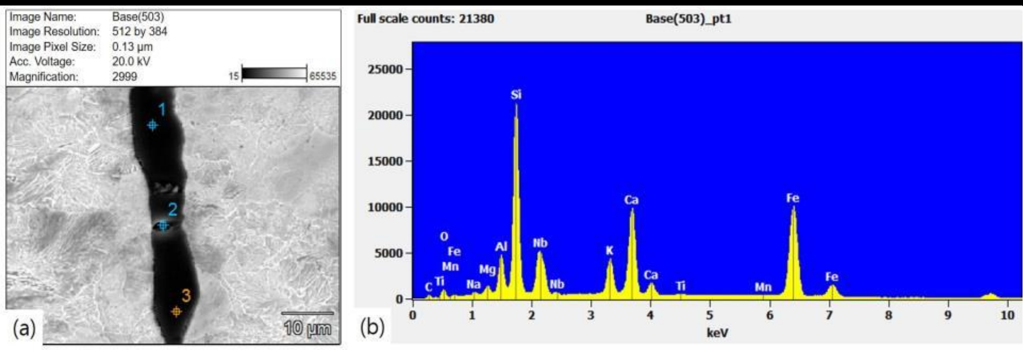

Figure 12.Non-metallic inclusion of Blade part(Figure 2(B)) of Large Iron Sword(No 1). (a) SEM photo of non-metallic inclusion, (b) EDS spectrum of non-metallic inclusion

Picture 13 shows microstructure of the sample collected from the spine of Large iron sword No 2. Picture 13(a), whole look of the sample, shows ferrite of pure iron on all parts except the corroded part with very diverse sizes of crystal grains. Picture 13(b) that enlarged the center of the sample shows the existence of annealing twins within the crystal grain. Should carbon steel be forged in high temperatures and quenched and then go through precipitation heat treatment, there were some reports of austenite being precipitated within ferrite base, which can be considered to be the form of twin crystals[13, 14].

Picture 14(a) shows SEM photo of non-metallic inclusion - impurities existing at the center of the sample and EDS spectrum is shown at Picture 14(b) and Table 6. Non-metallic inclusion at point a-1 from Picture 14(a) seems to Fe oxide, while those at point a-1, 3 to be wustite.

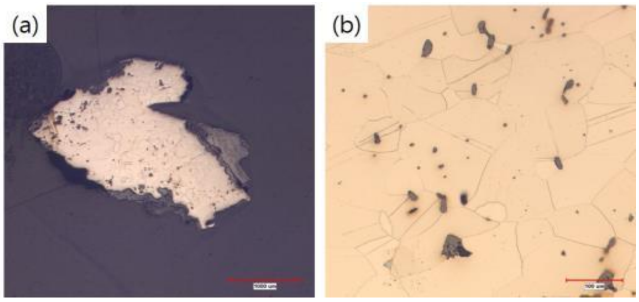

Figure 13. Microstructure of sample collected from the spine(Figure 2(C)) of Large Iron Sword(No 2). (a) Whole of Sample(×25), (b) Enlarged of the top of the Sample(×200)

Table 6:EDS analysis results No.2(C) Large Iron Sword

Spectrum Position	Element(wt.%)								
	FeO	Na_2O	MgO	Al_2O_3	SiO_2	K_2O	CaO	TiO_2	MnO
a-1	20.17	0.62	0.20	6.64	25.42	2.99	3.44	0.44	0.37
a-2	84.54	-	-	0.30	2.04	0.33	0.49	-	-
a-3	32.22	0.40	0.33	4.36	21.17	2.44	3.58	0.44	0.57

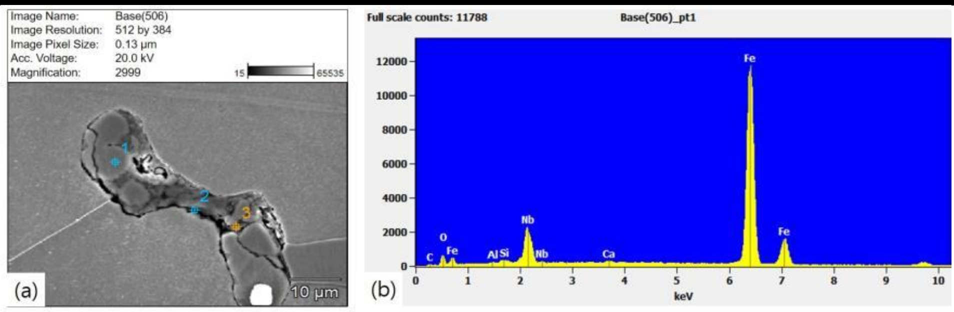

Figure 14. Non-metallic inclusion of sample collected from the spine(Figure 2(C)) of Large Iron Sword(No 1). (a) SEM photo of non-metallic inclusion, (b) EDS spectrum of non-metallic inclusion

IV. CONCLUSION

Research on ironware manufacturing techniques of Goguryeo, with its most ancient territory currently belonging to North Korea or China, has been very limited unlike that during Silla, Baekjae periods, which is going on very actively. Therefore, information of ironware manufacturing techniques during Goguryeo period has no other way but to depend on analysis on ironware excavated from Goguryeo's archeological sites around Hangang area in South Korea.

So, the study collected samples from two pieces of large iron swords from Hongryeon-bong Fort 1/2 remains and conducted metallurgical analysis. Through microstructure, the study examined iron manufacturing techniques during Goguryeo period and conducted comparative analysis with artifacts excavated from Hangang basin. By doing so, it sought to provide basic research data for ironware manufacturing techniques of Goguryeo.

Large iron sword No 1 was found to have both properties of ferrite and pearlite, and presumed to have low carbon material with around 0.2-0.3% carbon content. Large iron sword No 1 - manufactured using low carbon iron material - does not seem to have gone through extra heat treatment to increase its strength though it contained carbon more or less. And artifacts manufactured using low carbon iron as such were identical to one piece of 'sharp iron tool to keep spears' unearthed from Achasan Fort 4. However, given the shape of ferrite crystal grain or pearlite, they were considered to have been pounded or exposed to heat treatment in relatively low temperatures instead of being cooled down simply by outside air.

In case of Large iron sword No 2, analysis on the sample collected from the blade found that it had tempered Martensite phase, while its spine had ferrite phase with soft iron structure. In the aspect of applying strong iron material only to the blade and using soft iron material to the spine part, Large iron sword No 2 was identical to two axes excavated from Goguryeo's military fortress at Siru-bong and Achasan Fort 4. Large iron sword No 2 and two axes all had no trace of being folded and pounded on the blade part. This tells us they might have used ironware manufacturing technique allowing them to increase carbon content at any wanted parts using carburizing process directly taking aim at the blaze after manufacturing process of molding→manufacture→heat treatment.

This differentiated application to blade and spine parts of an identical artifact was likely to be the result of taking both functionality and economy of large iron swords into consideration. In terms of functionality, use of strong material on the blade has more advantage, also needing tempering treatment and soft iron may be used on the spine. On the other hand, in terms of economy, it may be less effective since extra manufacture process is needed. Nevertheless, their manufacturing process seems to have focused on such a high functionality as to compensate economic disadvantage.

Based on this findings, the study was able to assume that most of ironware manufacturing techniques such as molding, making and heat treatment had taken place directly within the forts. And Goguryeo might have such good manufacturing facility and techniques that they were able to make swords themselves at military forts like Achasan long away from its capital. That said, there must be limit of exact and precise assessment on the nature of manufacturing processes of iron artifacts by simple method of analysis on materials. And the study believes more intensive research must be conducted continuously using comparative analysis on shapes of used smelting hearths and slags derived during smelting process.

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