Traditional Steelmaking in Southwestern Ethiopia: A Metallurgical Analysis

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We documented the reconstruction by local blacksmiths of obsolete traditional steelmaking methods in Dime, southwestern Ethiopia, and metallurgically analyzed the materials and products associated with this technology. The steelmaking operation was successfully recreated in 2004, including mining, furnace construction, and charcoal production. The produced sponge iron had a yield ratio of about 40%, contained 0.31~0.48 mass percent carbon, and lacked impurities. The collected slag contained typical components (iron, silicon, aluminum, potassium, phosphorous, titanium, manganese). The blacksmiths used three kinds of iron ore (*balt*, *bullo*, *gachi*) that consisted primarily of goethite [α-FeO(OH)] and kaolinite ($Al_2O_3 \cdot 2SiO_2 \cdot 2H_2O$); white inclusions in *gachi* contained calcium phosphate hydrate [$Ca_3(PO_4)_2 \cdot xH_2O$]. The local blacksmiths specifically preferred *gachi* for steelmaking; the reasons for this selection were discussed from the viewpoint of slag-forming ability. Comparison of Dime steelmaking with other traditional steelmaking methods confirmed the independent development of geographically specialized knowledge and steelmaking techniques in Dime, as in Europe and Japan.

Key words: steelmaking, Ethiopia, metallurgy, iron ore, blacksmith

1. INTRODUCTION

Steelmaking was developed in the Anatolian-Iranian region during the period of the Hittite empire (1500–1000 B.C.). The knowledge and techniques were guarded as a national secret. After the empire's decline, steelmaking spread into the surrounding countries, eventually achieving a broad distribution. By 500 B.C., it had spread northward to the United Kingdom along Danube and/or Roman routes. The technology had spread eastward along the Silk Road to India and China by 500 B.C. and 300 B.C., respectively, then diffused farther in the sixth century throughout the Korean peninsula and Japan, where the *tatara* steelmaking method was developed (Tylecote 1992: 40–52).

Steelmaking knowledge and techniques also diffused widely to the south, throughout Africa. According to Tylecote (1992), this technology spread to Nigeria, where the Iron Age Nok culture was producing iron by about 400–300 B.C. It also reached Egypt through Greek or Carian traders, where the emporium at Naukratis contains evidence of smelting. In Sudan, iron smelting began around 200 B.C. and was subsequently introduced into Ethiopia. This technology entered Central and East Africa from Nigeria around A.D. 500 with the migration of the Bantu tribes. The diffusion route terminated in South Africa about A.D. 1000.

In Ethiopia, traditional steelmaking continued in some regions until the early 19th century (Francois

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1985: 11–27; Todd 1985: 88–101). Daily necessities such as axes, harrows, and knives are still made by smitheries in many regions. However, Ethiopian steelmaking techniques gradually fell into disuse due to the availability of cheaper scrap steel in local markets, resulting in the practical obsolescence of the technology by the late 1970s (Todd & Charles 1979: 1–21).

Previous studies of traditional Ethiopian steelmaking have taken primarily archaeological and/or anthropological approaches to the material culture; metallurgical studies have been rare. Todd (1985: 88–101) metallurgically analyzed iron ore and slag from steel production in southwestern Ethiopia to clarify regional differences from Tanzanian, Sudanese, and ancient Roman products, but did not collect detailed observational data on the steelmaking process. Thus, it is academically important to reconstruct the obsolete steelmaking technology and to establish a detailed record of the production methods.

Empirical techniques that have been developed and refined for generations are usually scientifically rational. For instance, in the traditional Japanese *tatara* steelmaking method, a hollow part of the furnace's substructure (the *kobune*) plays an important role as a zone of escaping moisture (Nagata & Suzuki 2000: 63–70; Nagata et al. 2001: 665–672). The size of the *tatara* furnace was established to optimally utilize region-specific iron sand and charcoal and to produce tough and ductile Japanese swords (Yamasue et al. 2005: 1–7). In the quench-hardening process of Japanese sword making, a particular soil was painted onto the surface to increase the quench rate (Uehara & Inoue 1995: 309–315). In Ethiopian steelmaking, three kinds of iron ore were mined, and the craftspeople were clearly able to select the most appropriate ore for a given project, without explicitly understanding the scientific or metallurgical properties affecting this choice.

The aim of this study was to metallurgically document obsolete traditional steelmaking technology and knowledge in Dime, southwestern Ethiopia. Based on the results of fieldwork and analysis, Dime steelmaking is also compared to other traditional steelmaking technologies.

2. RESEARCH AREA AND FIELDWORK

2.1. The Dime

Fig. 1 shows the research area inhabited by the Dime in southwestern Ethiopia. Dime settlements are located on the rugged hillslopes and lowlands of the Omo Valley at 800–1500 m above sea level. This area acts as a buffer zone between Omotic agriculturists and Surmic agro-pastoralists. The Dime practice subsistence agriculture based on root crops (e.g., sweet potato, cassava, taro) and cereal crops (e.g., *t'ef*, maize).

The Dime maintain close relations with several neighboring ethnic groups, such as the Ch'ara across the Omo River to the north and the Me'en in the lowlands. Many of the Dime people can thus speak several languages within the Omotic language family, to which their language also belongs (Fleming 1976: 299–323).

According to Haberland (1959) and Todd (1975), modern Dime society was created through the integration of seven smaller chieftainships in the early 20th century. Traditional Dime society was hierarchical, including peasants (*nitsi*), craftspeople such as blacksmiths and potters (*gitsi*), and hide workers (*mane*). All of the Dime blacksmiths were *gitsi* men, allegedly minority craftspeople excluded from the rest of society. They had limited access to land and livestock, used segregated burial locations, and were strictly forbidden to marry peasant women, although they resided in the same settlements as peasants and produced the tools necessary for the peasants' subsistence. The designation "*gitsi*" includes more than 10 intermarrying clans. Approximately 50 men currently identify themselves as *gitsi* blacksmiths; they live and work in the Dime homeland and with the neighboring Ch'ara (Fig. 1).

The Dime political system changed profoundly after the collapse of the Ethiopian empire following the 1974 socialist revolution. The Derg socialist regime gained administrative power in 1975, reorganized the seven extant chieftainships into six local districts (*k'ebele*), and enforced a land-reform

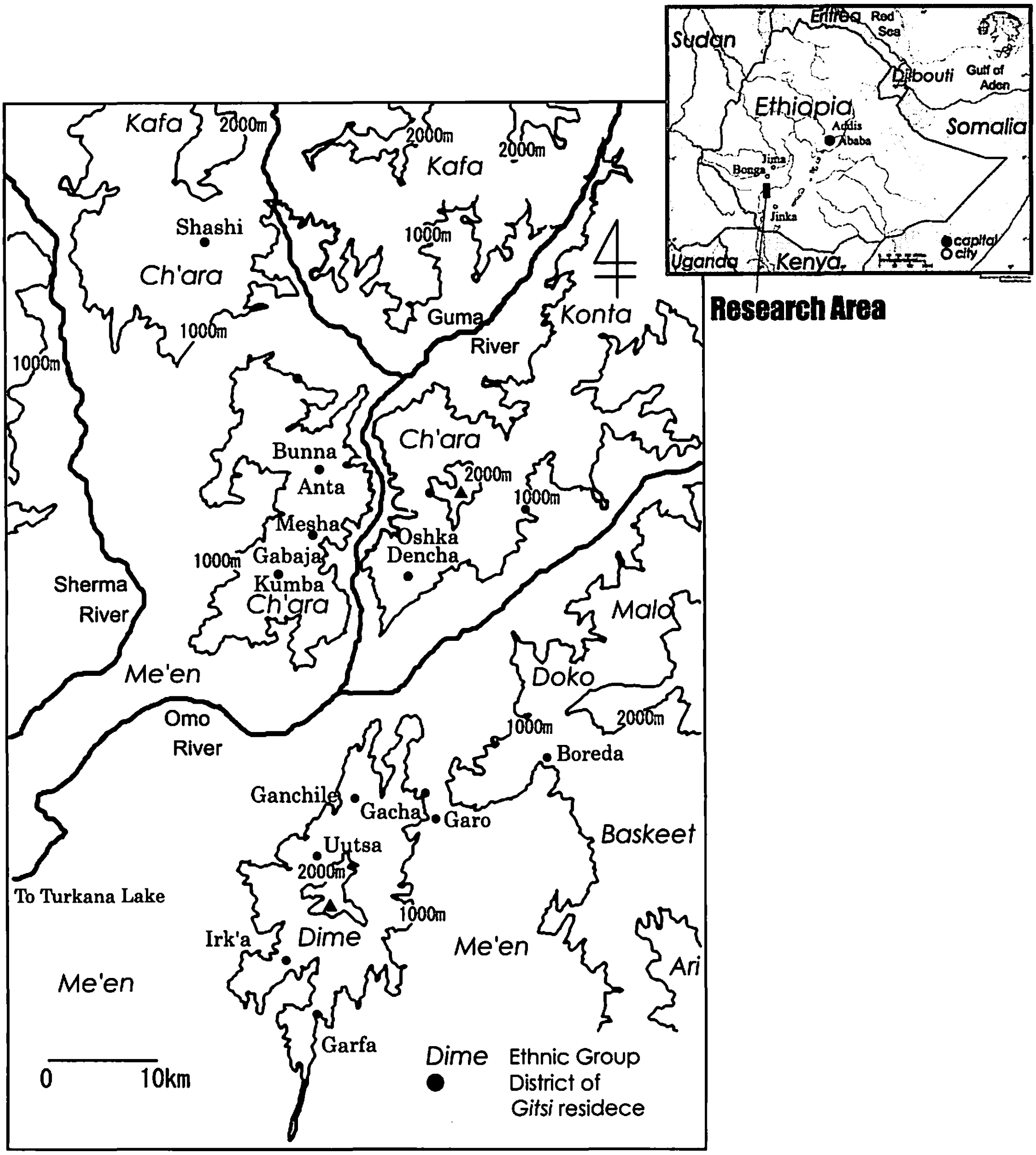

Fig. 1. Map of Ethiopia and the Dime research area.

policy that permitted craftspeople to own land and livestock. This policy, which aimed to abolish discrimination against craftspeople, fundamentally changed the hierarchical social system. Although traditional customs, such as restricted intermarriage between Dime artisans and peasants, continue to be practiced in the present day, the official equality of all Dime people is realized in most daily interactions.

The fieldwork for this study was carried out among the Dime in 2004. Nearly all traditional steelmaking furnaces are demolished or weathered, and their remains are rarely found. Although about 10 blacksmiths practice their craft in Dime settlements, they did not acquire steelmaking knowledge or skills and seldom or never use this technology. During our survey, we were fortunate to meet actively working blacksmith brothers, Major and Ketat, who were estimated to be 50 and 40 years old, respectively, and who had practiced steelmaking before its obsolescence in the 1970s. Hence, we commissioned them to recreate traditional steelmaking technology and practices in September and October 2004. The steelmaking operation consists of furnace construction, iron ore mining, charcoal production, and steel production. Each of these processes is explained in the following section.

2.2. Restoration of Traditional Steelmaking in Southwestern Ethiopia

2.2.1. Construction of the Furnace

We asked the blacksmith brothers to restore a disused furnace site to its original size, with a ground-level diameter of about 1.1 m. A schematic diagram of the restored furnace is presented in Fig. 2. An inverted cone-shaped hole was excavated into the ground to a depth of about 1 m. The hole was about 0.4 m in diameter at its base. The walls of the furnace were made from red-colored clay about

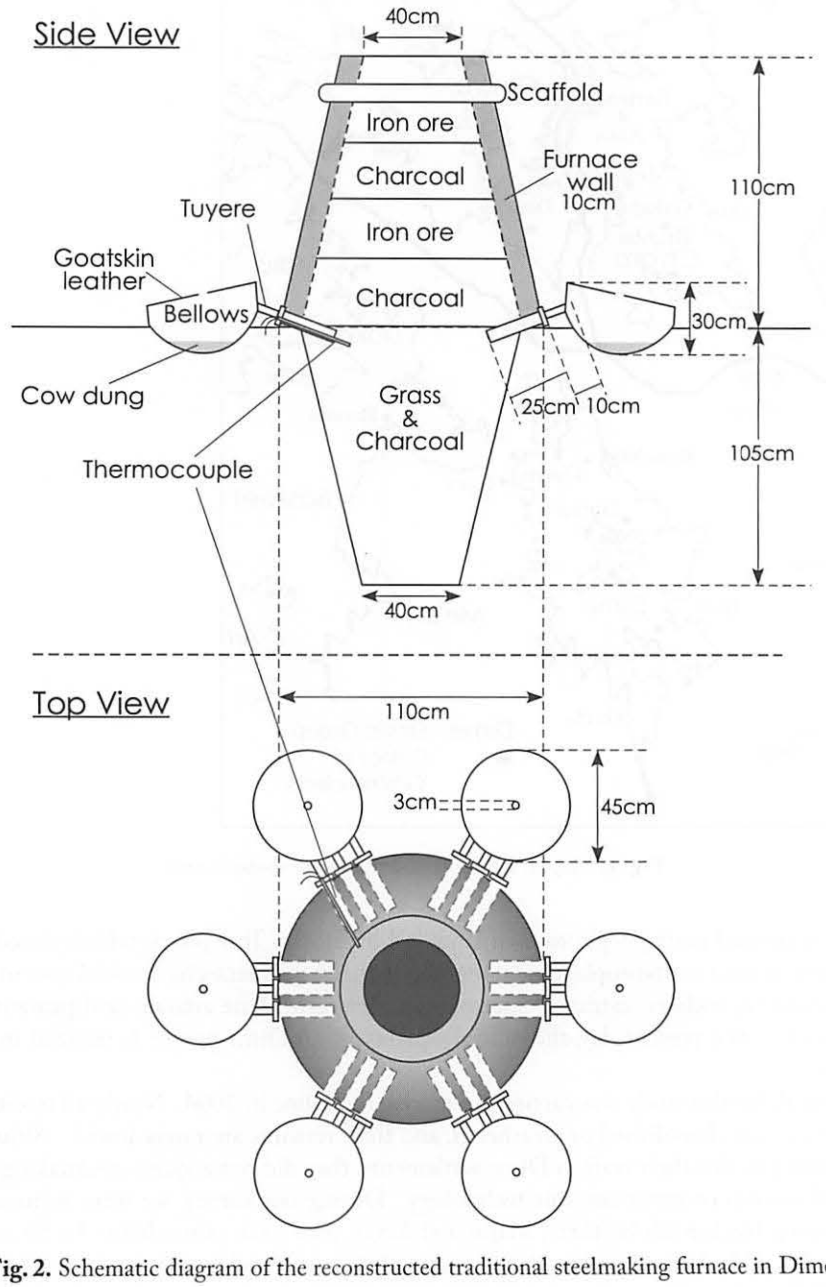

Fig. 2. Schematic diagram of the reconstructed traditional steelmaking furnace in Dime.

10 cm in thickness. X-ray analyses showed that this clay consisted primarily of kaolinite. The furnace rose about 1 m above ground level and had an upper diameter of about 0.4 m. A scaffold was placed across the upper opening of the furnace to allow access to its interior.

The outer furnace wall was coated with cow dung and allowed to sun dry. Any cracks that occurred during drying were reinforced with a second application of cow dung. After the furnace had dried completely, grass and firewood were burned within it for about 1 hour on the day before the steelmaking operation was initiated. This process ensured that the interior wall was completely dry and sintered it at high temperatures to improve durability. According to the blacksmiths, the hardening achieved with sintering and repeated steelmaking operations allowed the furnace to be used for 1 year (frequent operation) to 3 years (typical operation). Because the furnace was in an outdoor location and lacked housing, it could not be operated in rainy conditions.

Each blower consisted of a pot-shaped bellows and two sizes of tuyeres (10 cm and 25 cm in length). The large tuyeres connected the small tuyeres to the furnace. Both sizes were made by molding clay around a wooden bar, removing the bar, and sun drying the clay. They were thus fragile, although they were typically used for only one operation due to the adherence of molten slag and charcoal. The clay bellows were about 45 cm in diameter and 30 cm in depth. Three holes (ca. 3-cm diameters) were bored at even intervals into the sides of the bellows for the insertion of small tuyeres. Six bellows were placed around the furnace with their lower halves anchored in the ground. To prevent cracking, a small amount of cow dung was placed into the bellows. The small tuyeres were inserted into the bellows; the large tuyeres were then connected to them and inserted at a downward angle into the furnace. In this study, a platinum–platinum/13% rhodium thermocouple (R type) was additionally inserted through the tuyeres. After installing the blower system, the bellows rims were covered with goat leather, and a thumb-sized hole was made in the center of each skin. Blowing was accomplished by moving the leather upward and downward with the worker's thumb in the hole, thereby using the hole as a valve. During actual operation, six workers moved the bellows leather at a rate of 60–70 times per minute to produce intermittent blowing. The workers were sheltered with tree branches to protect them from the high temperatures and sparks.

2.2.2. Mining of Iron Ore

Three kinds of iron ore were mined from a dark-brown-colored lateritic deposit. *Balt* ore had a yellow zonated pattern, *bullo* ore was porous and brittle and produced a metallic clank when hammered, and *gachi* ore was hard and had white inclusions (Fig. 3). According to the blacksmiths, *gachi* was the most appropriate ore for steelmaking, and *balt* was unsuitable. For effective steel production, the mined ores were broken into small (2–4-cm) pieces with a stone or hammer and then sun dried around the furnace.

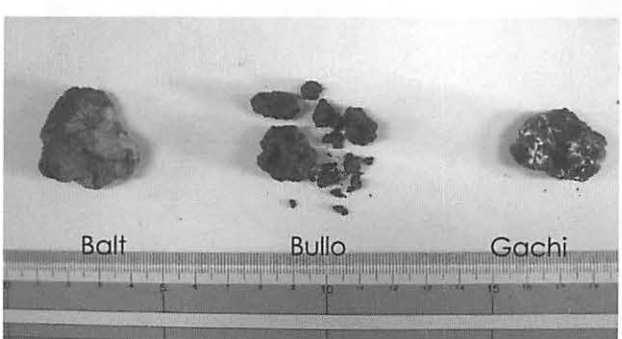

Fig. 3. Photos of three kinds of iron ore: *balt* (left), *bullo* (center), and *gachi* (right).

2.2.3. Charcoal Production

Traditional Dime steelmaking used charcoal as a source of heat and carbon and a reductant. The production method was not sophisticated. A restricted number of tree species were considered suitable for the production of charcoal; wood from *Terminalia schimperiana* Hochst of the Combretaceae family was preferred, but *T. brownie* Fresen, *Combretum* sp. (both Combretaceae family), or *Syzigium guineense* D.C. (Myrticaceae family) wood was sometimes substituted.

Fig. 4 shows a typical charcoal production scene. The wood was cut into conveniently sized pieces and burned for about 1 hour. A gourd bowl of water was splashed on the pieces and then their carbonized surfaces were chipped away with a chopper or sickle. The obtained charcoal pieces were about 3 cm in diameter and 10 cm in length. The uncarbonized cores were placed into the flames again and the procedure was repeated until the necessary amount of charcoal was obtained.

2.2.4. Steel Production

A typical steel production scene is shown in Fig. 5. As mentioned above, the operation began with the preparation of the tuyeres. Ignited grass was thrown into the furnace at the same time. When the

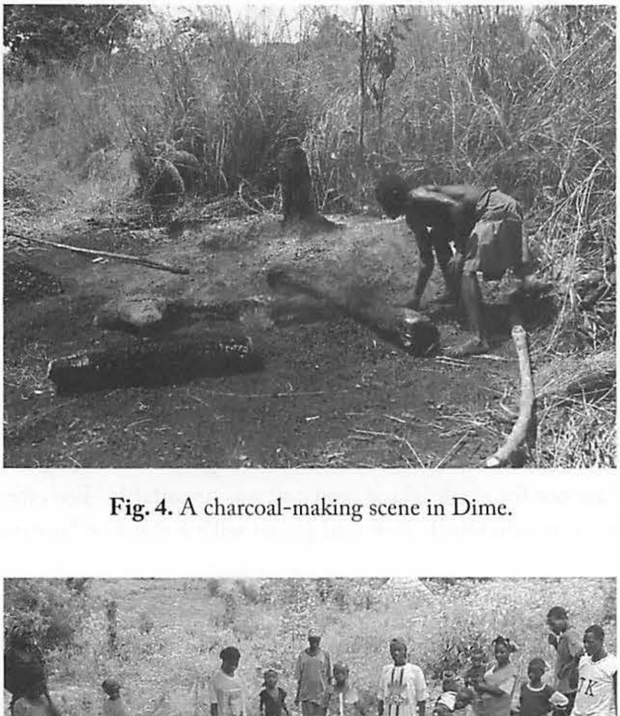

Fig. 4. A charcoal-making scene in Dime.

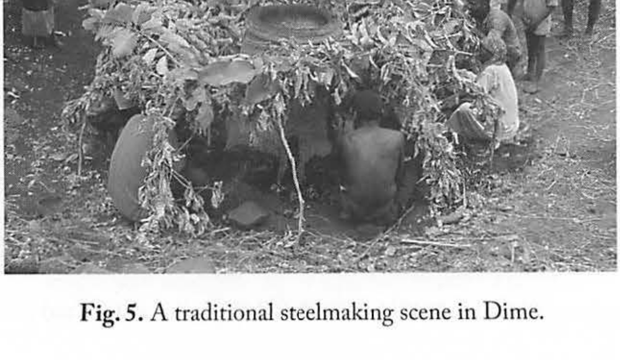

Fig. 5. A traditional steelmaking scene in Dime.

fire was burning adequately, charcoal was placed into the furnace using a wooden tray (*arch*). Fig. 6 shows an *arch* on a pile of iron-ore fragments. The tray was made by coring a half-diameter section of wood to produce a navicular shape about 140 cm in length. After about 2 hours of fire drying, blowing was initiated with the bellows. Around the same time, two *arch*-fuls of charcoal were placed in the furnace, followed by one *arch*-ful of iron ore. This procedure was repeated twice to produce a sequence of charcoal (25 kg × 2 layers) and iron ore (50 kg × 2 layers) layers (Fig. 2). No charcoal, iron ore, or other materials were added thereafter.

After 30 minutes of blowing, the temperature of the basal furnace near the tuyere outlets reached 1100–1200°C. After 2 hours, the quantity of charcoal gradually decreased, and pale reduction flames belched from the furnace opening. After 4 hours, the flames extended about 1 m above the furnace opening. At this time, the tuyeres and leather were removed from the bellows. White flames indicated the end of the operation. The furnace was allowed to cool overnight. On the following day, sufficient cooling was confirmed by showering the furnace with water, and the blacksmith entered the furnace from the top. He removed a large metallic mass from the basal furnace wall with a chipper. The thickness of the wall was nearly unchanged after the operation, indicating that no clear wastage occurred.

Fig. 6. An *arch* on the granulated iron ore.

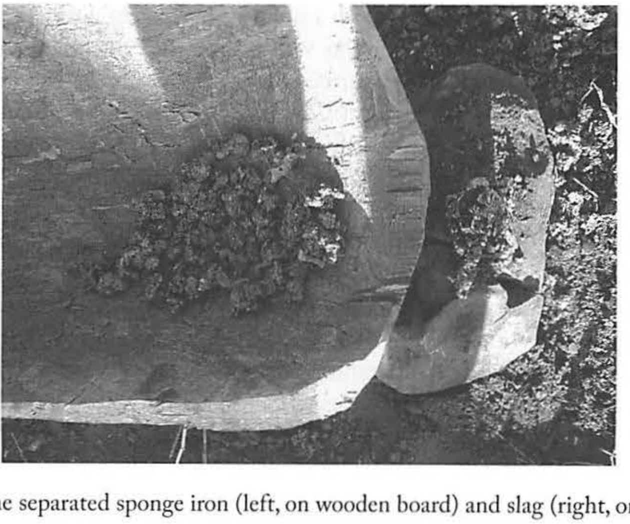

Fig. 7. The separated sponge iron (left, on wooden board) and slag (right, on stone).

The metallic mass consisted of a mixture of spongy and glassy matter. The former was considered to be sponge iron, and the latter to be slag. This matter was the "ruppe" typical of ancient and medieval steelmaking and indicated that the Dime blacksmiths produced semisolid iron. Utilizing the ductility of iron and the brittleness of slag, the materials were separated by hammering at elevated temperatures (Fig. 7), followed by smithery. The blacksmiths estimated that about five chippers (about 10 kg total, each 3 cm in diameter and 40 cm in length) could be made from the iron produced during a single operation.

3. MATERIALS ANALYSES

The following analyses were carried out on the sponge iron produced, the slag by-product, and the three kinds of iron ore. The carbon content of the samples was measured using a carbon/sulfur determinator (CS-444; LECO Japan Co., Ltd., Tokyo, Japan). Powder X-ray diffractometry (XRD) with Cu-Kα radiation was performed with a RINT-2000 diffractometer (Rigaku Corporation, Tokyo, Japan) to identify the components (phases) of the samples. Sample morphology was observed with a scanning electron microscope (SEM; JSM-5800 TYPE-C; JEOL Ltd., Tokyo, Japan). The sponge iron was observed following an etching treatment that used alcohol with 3% nitric acid. Differential thermal analysis with thermal gravity (TG-DTA; TG8120; Rigaku) was also performed.

4. RESULTS

4.1. Iron Ore

The compositions of the three iron ores are summarized in Table 1. The ore components were classified into four groups (A–D). Group A had the largest amount of iron, but variously sized gangue components. Group B, present in *bullo* and *gachi*, characteristically included segregating manganese in addition to iron. Pyrolusite (MnO_2), manganite [MnO(OH)], and rhodochrosite ($MnCO_3$) are well-known manganese ores. Groups C and D were present in the white inclusions of *gachi*, as shown in Fig. 3. These groups were both characterized by low concentrations of iron; Group C had high concentrations of aluminum and silicon, and Group D had high concentrations of phosphorous and calcium.

Fig. 8 shows the results of XRD for pulverized samples of the iron ores and the white inclusions from *gachi*. The analysis of *gachi* ore excluded the white component. The identification of the components was carefully carried out with reference to the data presented in Table 1. XRD revealed that *balt* consisted primarily of goethite [FeO(OH)], with a small amount of kaolinite ($Al_2O_3 \cdot 2SiO_2 \cdot 2H_2O$). *Bullo* contained more kaolinite than *balt* did, as well as goethite and manganite [MnO(OH)]. It should be noted, however, that the XRD pattern of manganite is similar to that of goethite, making it difficult to accurately distinguish its presence. Goethite, kaolinite, manganite, and tricalcium phosphate hydrate [$Ca_3(PO_4)_2 \cdot xH_2O$] were identified in *gachi*. The white inclusions of *gachi* consisted of kaolinite and tricalcium phosphate hydrate. Goethite and kaolinite were thus the main components of Group A; goethite, kaolinite, and manganite were the main components of Group B; kaolinite predominated in Group C; and tricalcium phosphate hydrate was the main component of Group D.

Assuming (from Table 1 data) an average iron concentration of 25 mass percent in the ores and given the 10-kg mass of the sponge iron produced, a 40% yield may be estimated.

Manganese was commonly included in *bullo* and *gachi*. Assuming that the partial pressure of oxygen (P_{O2}) in the Dime furnace at temperatures of 1100–1200°C was the same as that of a *tatara* steelmaking furnace ($P_{O2} = 10^{-14} \sim 10^{-13}$ atm; Nagata & Suzuki 2000: 63–70), manganese thermodynamically existed as manganese oxide (Mn_3O_4) (Barin & Platzki 1995: 179–181). The manganese would thus dissolve into slag or exist as manganese oxide. Accordingly, the existence of manganese in *bullo* and *gachi* did not directly affect the steelmaking operation.

Table 1. Elemental compositions (%) for three kinds of ore

Balt

Group	O	Al	Si	P	Ca	Ti	K	Mn	Fe	Total	note
A	53.4	4.7	11.3				0.5		30.1	100.0	
A	53.9	4.6	10.2				0.3		31.0	100.0	
A	54.4	4.6	10.1				0.4		30.5	100.0	
A	55.4	4.1	7.4				0.1		33.0	100.0	
A	67.7	2.5	7.6				0.3		21.9	100.0	
average	57.0	4.1	9.3				0.3		29.3	100.0	

Bullo

Group	O	Al	Si	P	Ca	Ti	K	Mn	Fe	Total	note
A	53.5	13.2	13.2			0.7			19.4	100.0	
A	54.1	13.5	10.9			0.9			20.6	100.0	
A	52.3	12.6	8.4			0.7			26.1	100.0	
average	53.3	13.1	10.8			0.8			22.0	100.0	
B	55.0	12.8	10.6			1.3		2.6	17.7	100.0	

Gachi

Group	O	Al	Si	P	Ca	Ti	K	Mn	Fe	Total	note
A	61.7	6.2	7.0	1.5					23.6	100.0	
A	60.3	5.8	6.9	2.4					24.6	100.0	
A	62.0	3.5	6.7	4.3	4.5				19.1	100.0	
A	60.9	7.2	7.1	1.3	0.7				22.9	100.0	
A	58.2	7.6	9.5			0.1			24.6	100.0	
A	58.8	7.6	8.4			0.4			24.7	100.0	
A	59.7	5.7	5.2			0.7			28.8	100.0	
average	60.2	6.2	7.3	2.4	2.6	0.4			24.0	100.0	
B	63.2	3.0	2.3	2.6	2.5	4.3		11.0	11.2	100.0	
C	57.9	17.2	18.9	2.4	2.0				1.6	100.0	white
C	70.0	10.5	9.4	3.3	5.1				1.6	100.0	white
C	59.5	15.9	16.7	3.6	4.3				0.0	100.0	white
C	61.7	17.6	17.3	1.0	1.4	0.4		0.2	0.4	100.0	white
C	60.8	13.8	20.5	1.8	1.9	0.5		0.3	0.5	100.0	white
average	62.0	15.0	16.6	2.4	2.9	0.4		0.2	0.8	100.0	
D	53.8	3.4	2.8	17.4	22.6					100.0	white

4.2. Sponge Iron

Fig. 9 shows a cross-sectional secondary electron image of the sponge iron. A typical hypoeutectoid steel texture comprised of proeutectoid ferrite (α-Fe) and lamellar pearlite (α-Fe/Fe_3C) was observed, leading to an estimated 0.1–0.7 mass percent carbon content. Quantitative analysis using the carbon/sulfur determinator determined that 0.31–0.48 mass percent of carbon was included in

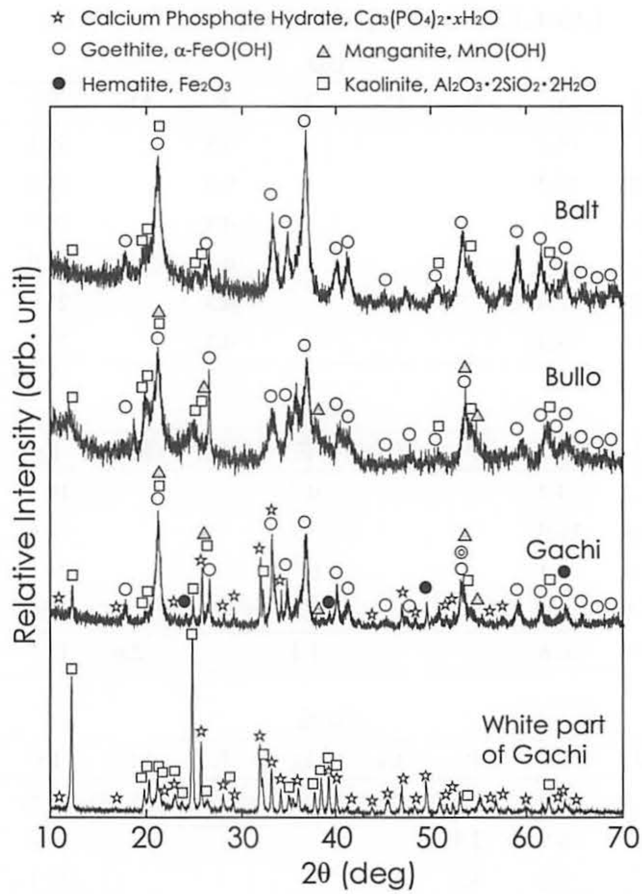

Fig. 8. X-ray diffraction patterns of *balt*, *bullo*, and *gachi* iron ores and the white inclusions from *gachi*.

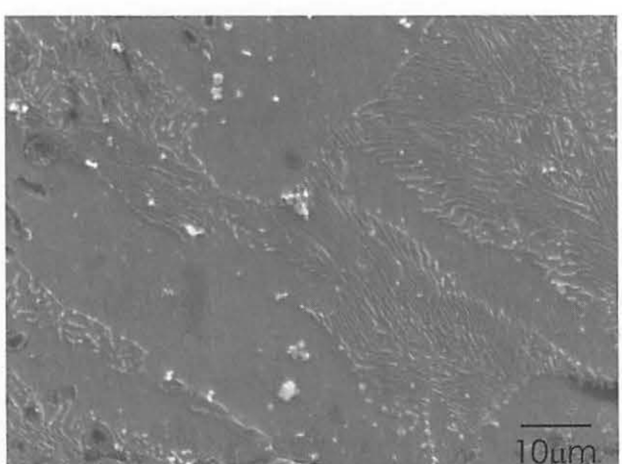

Fig. 9. Secondary electron image showing a cross-sectional view of the sponge iron produced.

the sponge iron. Thus, the sponge iron is clearly steel; hereafter, the sponge iron produced in Dime will be referred to as "Dime steel."

Elemental analyses of the sponge iron using energy-dispersive X-ray spectroscopy (EDX) detected no impurities, excluding iron and carbon, within the analytical precision limits of this method. Local consumers stated that Dime steel was more ductile, less corrosive, and more durable than steel available in the market, although the market steel was harder. Dime steel may be softer but more ductile due to its low carbon content. Its high level of purity results in corrosion resistivity.

The carbon content of a smith-forged knife made using Dime steel was 0.18–0.27 mass percent, which is lower than unmodified Dime steel because decarburization unavoidably occurs during smith forging. Dime blacksmiths forge at relatively low temperatures and do not quench, increasing the ease of working with the low-carbon and ductile steel.

4.3. Slag

Fig. 10 shows a cross-sectional secondary electron image with elemental mapping of the Dime slag by-product. Potassium (K), calcium (Ca), phosphorous (P), and titanium (Ti) showed similar distributions to aluminum (Al), whereas manganese (Mn) showed a similar distribution to iron (Fe). Oxygen (O) was homogenously distributed. EDX determined the average elemental composition of the slag to be O: 49.5 mass %, Al: 8.1 mass %, Si: 22.6 mass %, K: 1.0 mass %, Mn: 2.3 mass %, Fe:

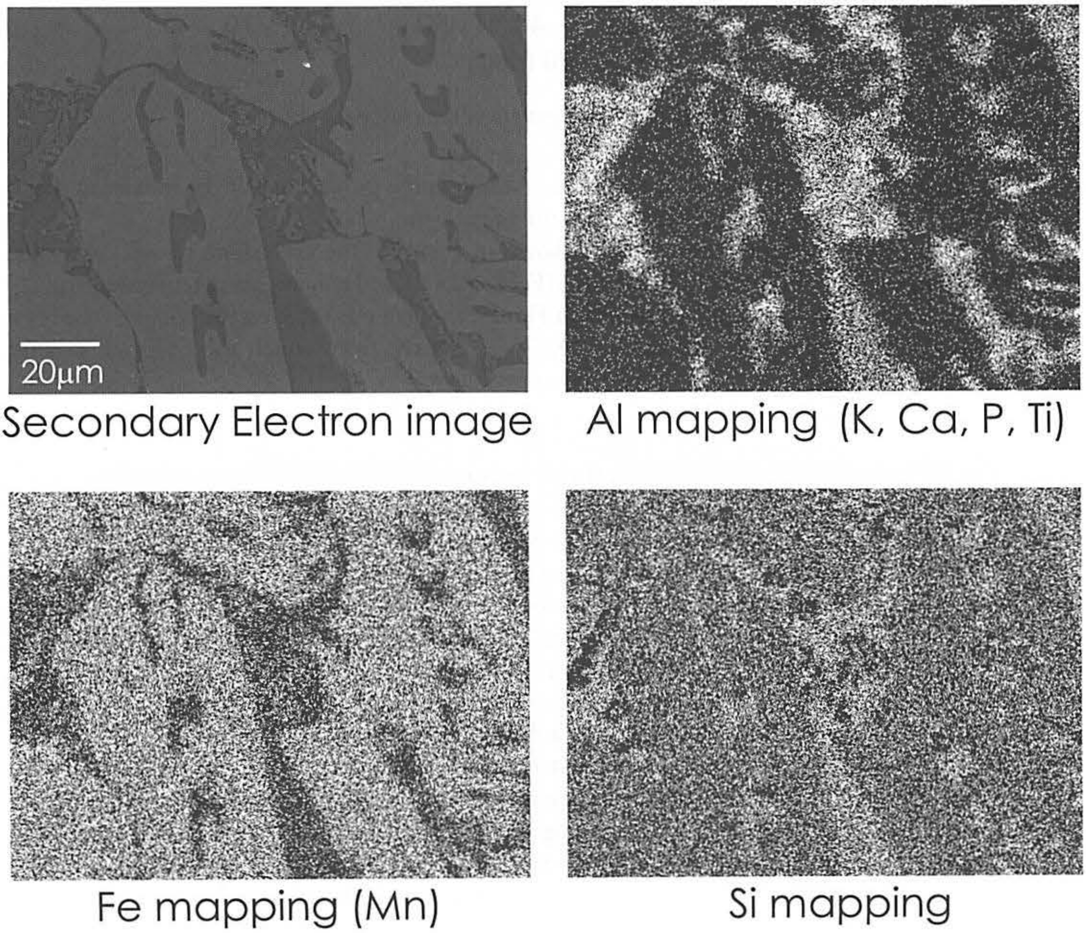

Fig. 10. Secondary electron image of the slag collected in Dime and X-ray mapping of Al (K, Ca, P, Ti), Fe (Mn), and Si.

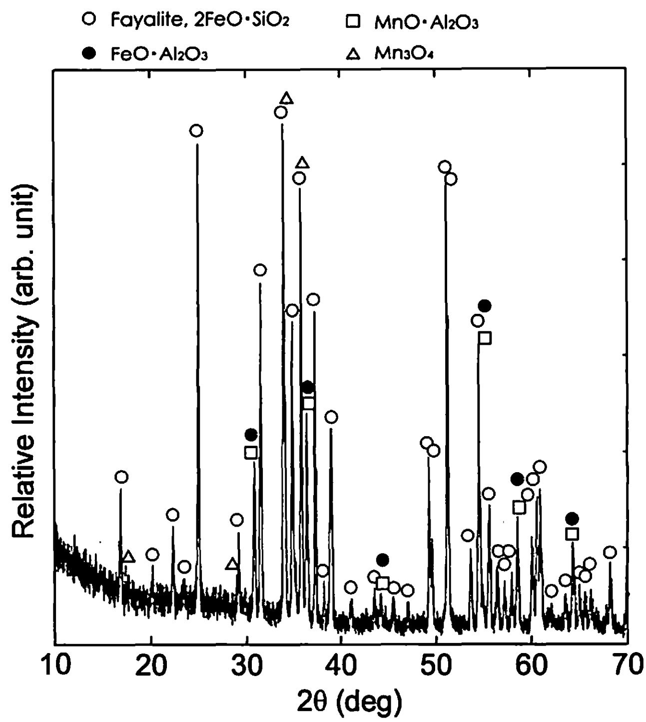

Fig. 11. X-ray diffraction pattern of the pulverized slag.

15.9 mass %, Ca: 0.3 mass %, and Ti: 0.3 mass %. Although the provenance of the measured slag is unknown, the presence of Ca and P indicate the use of *gachi* ore.

The XRD pattern of the pulverized slag is shown in Fig. 11. The crystalline phases of fayalite ($2FeO \cdot SiO_2$), galaxite ($MnO \cdot Al_2O_3$), hercynite ($FeO \cdot Al_2O_3$), and trimanganese tetroxide (Mn_3O_4) were observed. Considering the results shown in Fig. 10, the slag was inferred to consist of the non-crystalline $FeO–SiO_2–Al_2O_3–$ (CaO, K_2O, P_2O_5, TiO_2) matrix, from which the observed fayalite, galaxite, and hercynite crystallized at decreased temperatures.

5. DISCUSSION

5.1. Why is Gachi the Most Appropriate Iron Ore for Steelmaking?

According to the blacksmiths in Dime, it was easy to produce steel with *gachi* and difficult with *balt*, and *bullo* had intermediate usability. Slag formation was likely a key factor in these determinations. It is important in the steelmaking process to form "good slag" with a low viscosity and, hence, a low melting point. Good slag facilitates the separation of the produced steel from the gangue component, prevents reoxidation, and insulates the steel. In modern steelmaking operations that use a blast furnace, limestone ($CaCO_3$) is commonly added as a flux to control the quality of the slag.

Although silica (or silicon oxide) is the most important material affecting slag formation, the three ores analyzed in this study had small amounts of this material. The gangue components are expected to melt and form slag at high operating temperatures (>1600°C) such as those produced during modern steelmaking; however, the Dime steelmaking method produced maximum operating temperatures of 1200–1300°C. The tricalcium phosphate hydrate in the white inclusions of *gachi* may function as a flux and contribute to slag formation. No such potential flux materials were observed in the *bullo* and *balt* ores. We thus conducted TG-DTA to clarify the mechanism of slag formation in each of the three ores.

Fig. 12 shows the results of TG-DTA on *balt*, *bullo*, *gachi*, and the white inclusions of *gachi* from ambient temperature to 1300°C using alumina containers in an argon atmosphere. The white inclusions were removed from the *gachi* ore to the greatest possible extent for this analysis. Fig. 12 also shows the TG-DTA results for pure goethite and pure kaolin, which consist primarily of kaolinite, for comparison. The changes in each sample with increasing temperature may be explained as follows.

Weight decreases were common among the ores up to 200°C due to the dehydration of surface-absorbed water. Significant weight decreases around 300°C were due to the dehydration reaction of goethite [α-FeO(OH)], the main component of the ores, as expressed in the following equation:

$$2FeO(OH) \rightarrow Fe_2O_3 + H_2O\uparrow \qquad (1).$$

This dehydration was also confirmed by the endothermic reaction identified by TG-DTA within the same temperature range. Around 500°C, slight decreases in weight and endothermic peaks were observed. Compared with the results for kaolin, the reaction may be expressed as:

$$Al_2O_3 \cdot 2SiO_2 \cdot 2H_2O \rightarrow Al_2O_3 \cdot 2SiO_2 + 2H_2O\uparrow \qquad (2).$$

Both peaks were relatively weak for *balt*, which is consistent with its lesser kaolinite content (*vs. bullo* and *gachi*; Table 1, Fig. 8).

The significant decreases in weight and endothermic peak observed in the white *gachi* inclusions around 700°C were due to the dehydration reaction of tricalcium phosphate hydrate, resulting in the formation of tricalcium phosphate [$Ca_3(PO_4)_2$]:

$$Ca_3(PO_4)_2 \cdot xH_2O \rightarrow Ca_3(PO_4)_2 + xH_2O\uparrow \qquad (3).$$

Considering the area of the endothermic peak and the amount of decreased weight, and ignoring the difference in heat capacity between tricalcium phosphate and kaolinite, the white *gachi* inclusions may include more tricalcium phosphate hydrate than does kaolinite.

At temperatures of 900–1150°C, exothermic peaks were observed for *balt*, *bullo*, *gachi*, and the

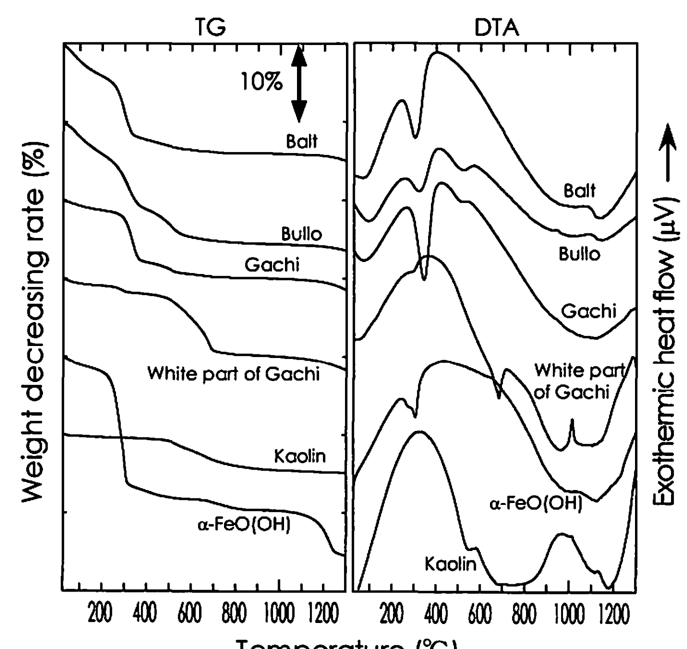

Fig. 12. Results of thermogravimetric (TG) and differential thermal analyses (DTA) from room temperature to 1300°C for *balt*, *bullo*, *gachi*, white inclusions of *gachi*, goethite, and kaolin.

white *gachi* inclusions. These peaks were due to the formation of mullite ($Al_2O_3 \cdot 2SiO_2$) and silica (SiO_2) from metakaolin ($Al_2O_3 \cdot 2SiO_2$), which had been formed by the dehydration of kaolinite (as expressed in Equation 2):

$$3(Al_2O_3 \cdot 2SiO_2) \rightarrow 3Al_2O_3 \cdot 2SiO_2 + 4SiO_2 \quad (4).$$

Some studies have reported on this reaction. For example, γ-Al_2O_3 or the spinel phase of $2Al_2O_3 \cdot 3SiO_2$ have been detected as intermediate products, and the formation of cristobalite or quartz (rather than silica) has been observed, depending on the experimental conditions (Blundley & Nakahira 1959: 311–322, Komura 1979: 459–469, Kuwahara et al. 1997: 7–17). Mullite and silica form at temperatures around 1200°C. The multiple peaks observed at key temperatures in the present analysis indicated the simultaneous occurrence of several similar reactions, as described above. The important point is that silica was formed.

The decreased weight of goethite [α-FeO(OH)] above temperatures of 1100°C was due to the reduction reaction of the produced magnetite from goethite:

$$6Fe_2O_3 \rightarrow 4Fe_3O_4 + O_2\uparrow \quad (5),$$

resulting in the formation of magnetite (Fe_3O_4). Similar weight decreases were observed in the three Dime iron ores.

The results of the TG-DTA suggest that the silica commonly formed during production using the three ores may contribute to slag formation. To confirm this hypothesis, the samples were subjected to XRD (Fig. 13). The XRD pattern of *balt* resembled that of *bullo* in the formation of mullite, silica, and various iron oxides, which is consistent with the TG-DTA results. The kaolinite content of the clay used to construct the furnace wall also contributed to slag formation.

Further investigation was carried out on *gachi*. Fig. 14 shows the XRD patterns for the white *gachi*

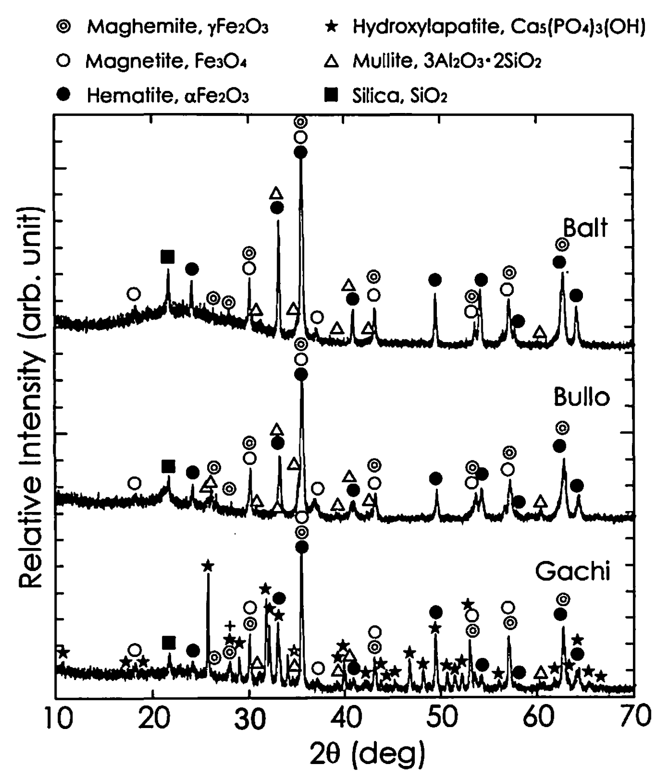

Fig. 13. X-ray diffraction patterns of *balt*, *bullo*, and *gachi* after annealing at 1300°C.

inclusions after annealing at 1100°C and 1300°C during TG-DTA. The white inclusions annealed at 1100°C consisted of silica, mullite, and hydroxyapatite [$Ca_5(PO_4)_3(OH)$]. The samples annealed at 1300°C consisted primarily of $CaO \cdot Al_2O_3 \cdot 2SiO_2$ (typical slag composition), with a small amount of hydroxyapatite. These results are consistent with the determination that the slag consisted of a non-crystalline $FeO–SiO_2–Al_2O_3–$ (CaO, K_2O, P_2O_5, TiO_2) matrix (Fig. 10). The white *gachi* inclusions became glassy and fused with the alumina (Al_2O_3) crucible at 1300°C, suggesting low-viscosity slag formation, whereas *balt*, *bullo*, and *gachi* maintained solid states at the same temperature. During Dime steelmaking, the white *gachi* inclusions additionally reacted with iron oxides, resulting in the formation of low-viscosity slag at the typically produced lower temperatures (1100–1200°C). *Balt* and *bullo* also formed slag in the same manner, but the viscosity of this slag was higher than that of *gachi* with inclusions, making it more difficult to separate the slag from the produced iron.

Consequently, *gachi* is the most appropriate ore for Dime steelmaking because the tricalcium phosphate hydrate in the white inclusions contributes to the formation of low-viscosity slag. *Bullo* is considered better than *balt* because it contains more kaolinite, the source of silica. Although the blacksmiths in Dime did not possess such scientific knowledge of the role of slag, their empirical accumulation of techniques through generations resulted in a rational choice of the most appropriate ore for their steelmaking technology.

5.2. Comparison of Dime Steelmaking with Other Traditional Steelmaking Methods

In this section, we discuss the similarities and differences between Dime steelmaking and other traditional steelmaking methods from a metallurgical perspective.

We found that Dime steelmaking resembles European steelmaking using a Renn furnace; the furnace shapes, operating procedures, and properties of the produced steel and slag are similar. We

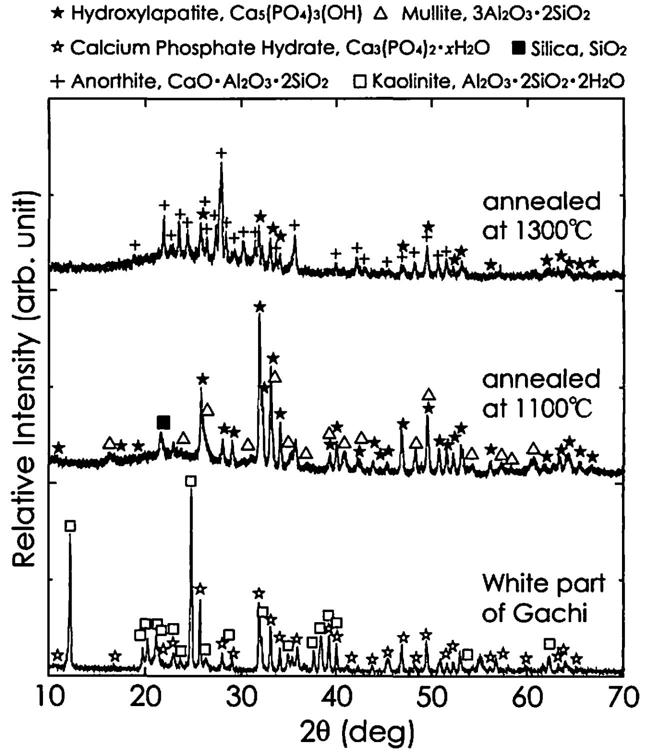

Fig. 14. X-ray diffraction patterns of the white inclusions from *gachi* without annealing and after annealing at 1100°C and 1300°C.

thus briefly explain here the features of European steelmaking, according to Beck [1897 (Nakazawa 1968: 261–328)].

In medieval Europe, Renn furnaces (German: *Rennfeuer*) used for steelmaking were about 1 m in height and 1.5 m each in width and length. Their bases contained rammed and pulverized charcoal. Charcoal and hematite (Fe_2O_3)-based iron ore were layered within the furnace, followed by firing and blowing using bellows or a water mill. Although the iron ore used in Dime steelmaking consisted primarily of goethite [FeO(OH)], it dehydrated into hematite (Fe_2O_3) at elevated temperatures (Fig. 11). The iron ores used in these two steelmaking methods were thus similar.

During Renn steelmaking, additional charcoal and iron ore were added as the materials at the base of the furnace settled. A total of two barrels of iron ore were placed in the furnace, resulting in the production of 100–150 kg of ruppe with fayalite slag after 8–12 hours of operation. This quantity is larger than that produced during Dime steelmaking because the Renn furnaces were larger.

The ore used in Renn steelmaking had a high silica content. The production of good slag is an important factor in steelmaking, whether traditional or modern. Although silica is one of the most important components in the production of good slag, its high melting point (>1730°C) inhibits the reliance on silica alone for good slag production. To overcome this problem, European steelmakers added baked lime as a flux; the same technique is used in modern steelmaking. In cryoscopic terms, the melting point of a matrix is generally depressed by the introduction of additional components (flux). In Dime steelmaking, the calcium phosphate in the *gachi* inclusions was employed as the flux.

Japanese *tatara* steelmaking used easily mined iron sand (magnetite; Fe_3O_4) rather than ore. This difference in iron sources led to methodological differences that we describe below. *Tatara* furnaces were built with clay containing silica and were 1–1.5 m in height, 0.8–1 m in width, and 2.7 m in length. Blacksmiths also occasionally used smaller furnaces that were 1.5 m in height and 0.3–0.4 m in width and length (square) or diameter (circular). The bases of *tatara* furnaces contained rammed and pulverized charcoal.

At the beginning of the operation, a *tatara* furnace was filled with charcoal, which was provided a source of heat and carbon and acted as a reductant. Firing and blowing with bellows were then performed. Charcoal and iron sand were alternately added during the operation; the powdery iron sand easily fell to the base of the furnace. Like those of Dime steelmaking, average *tatara* steelmaking temperatures were 1100–1200°C. Although no artificial flux was added, a sufficient amount of slag was produced, and the excess was discharged during the operation. The final products were fayalite slag and high-carbon steel (0.6–1.0 mass %, small furnace) or cast iron (>1 mass %, large furnace). Bloom was likely obtained rather than ruppe because the powdery iron source was easily separated from the gangue components.

The higher carbon concentration of *tatara* steel was likely due to the easily reduced and carburized powdery iron source. The yield (weight of obtained bloom: weight of elemental iron in iron sand) was about 42%, nearly identical to that of Dime steelmaking.

Tatara steelmaking was able to produce a sufficient amount of slag due to properties of the furnace and the iron source. Japanese iron sand was mined from weathered granite series. Given the poor quality of the magnetite ore (ca. 1%), it was concentrated to more than 90% (elemental iron: ca. 65%) by specific-gravity classification using water. The iron source thus contained an insufficient amount of silica. However, the clay used to construct the furnace walls contained abundant silica and likely supplied sufficient amounts of this material to the process. Although neither the wall clay or the iron source included calcium compounds, the titanium oxide in the iron sand acted as a flux to depress the melting point of slag (Nagata 2007: 693–700). This high concentration of titanium oxide is an important characteristic of Japanese iron sand. Theoretically, about 12.5 mass % would constitute an appropriate amount of titanium oxide as a flux; the *tatara* craftspeople controlled concentrations within 10–15 mass %. The kinetics of slag formation using powdery gangue and flux were also much faster than those using non-powdery materials.

Although details of the methodologies and materials differ, all steelmaking technologies have recognized the importance of slag formation and have developed innovative approaches to ensure the production of good slag. Thus, we can conclude that steelmaking knowledge and techniques spread broadly from the Hittite empire, and that geographically specialized methodical variations were independently developed in each region. In this respect, there is not much point in attempting to determine the relative merits of regional steelmaking technologies. In closing, we find it interesting that steelmaking is called *girfe* in Dime, which like *tatara* originally meant "blowing/bellows."

6. CONCLUSION

In this study, we documented the reconstruction of obsolete traditional steelmaking technology in Dime, southwestern Ethiopia, and metallurgically analyzed the materials and products associated with this technology. The steel produced by the Dime method contained 0.31~0.48 mass % carbon, had a yield ratio of about 40%, and was characteristic of ruppe, a mixture of sponge iron and slag. We detected no impurities, excluding iron and carbon, in the sponge iron.

The slag contained iron, silicon, aluminum, potassium, phosphorous, titanium, and manganese, indicating that it consisted of a FeO $FeO–SiO_2–Al_2O_3–(CaO, K_2O, P_2O_5, TiO_2)$ matrix. Goethite was the most common iron source in the *bullo*, *balt*, and *gachi* ores, and kaolinite was a common component. The white *gachi* inclusions contained kaolinite and tricalcium phosphate hydrate; the latter was found to contribute to the formation of slag at lower temperatures. Comparison of Dime steelmaking with other traditional steelmaking methods confirmed the independent development of geographically specialized knowledge and steelmaking techniques in Dime, as in Europe and Japan.

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