



## Production of low-silicon molten iron from high-silica hematite using biochar

Hui-qing Tang\*, Xiu-feng Fu, Yan-qi Qin, Shi-yu Zhao, Qing-guo Xue

State Key Laboratory of Advanced Metallurgy, University of Science and Technology Beijing, Beijing 100083, China

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### ABSTRACT

A new method of utilizing high-silica hematite to produce low-silicon molten iron was proposed. In this method, FASTMELT, which comprised direct reduction and melt separation processes, was applied, with highly reactive biochar as the reductant in the direct reduction stage. The proposed method was experimentally investigated and the results show that the method is feasible. In the direct reduction stage, ore-char briquette could achieve a metallization rate of 84%–88% and residual carbon of 0.27–0.89 mass% at temperature of 1373 K, biochar mixing ratio of 0.8–0.9, and reduction time of 15 min. Some silica particles remained embedded in the iron phase after the reduction. In the melting separation stage, molten iron with a carbon content of 0.02–0.03 mass% and silicon content of 0.02–0.18 mass% could be obtained from the metallic briquettes under the above-mentioned conditions; the iron recovery rate was 83%–91% and impurities in the obtained metal were negligible.

## 1. Introduction

The average content of Fe in the abundant iron ore deposits in China is 33 mass% and many of these deposits are refractory minerals<sup>[1]</sup>. High-silica hematite is one of these iron minerals that is widely available in several provinces of China<sup>[2–4]</sup>. After conventional concentration, the high-silica hematite usually yields Fe in the range of 55–61 mass% and SiO<sub>2</sub> of 9–14 mass%, respectively. However, in the blast furnace (BF) ironmaking process, a low-silicon operation is stressed since it provides many benefits for both ironmaking<sup>[5,6]</sup> and subsequent steelmaking processes<sup>[7,8]</sup>. Therefore, silica content in the sinter must be controlled at a level of 5 mass%<sup>[9,10]</sup>. Thus, high-silica hematite cannot be considered as the main iron-bearing raw material in the BF ironmaking process. A previous study suggests that high-silica hematite could be employed in sintering by mixing it with other high-quality iron concentrates in a mixing ratio of approximately 10%<sup>[11]</sup>. Methods for further upgrading the high-silica hematite have also been proposed, including sodium roasting followed by magnetic separation<sup>[12]</sup>, stage gridding and stage separation<sup>[13]</sup>, and a combination of flotation and magnetic separation<sup>[14–16]</sup>; however, these methods require

complicated processing steps or are expensive, resulting in uneconomical BF ironmaking.

To efficiently utilize the high-silica hematite, new methods need to be developed. In addition to BF ironmaking, many non-blast-furnace ironmaking technologies have been developed since the 1980s, most of which do not have strict quality requirements on the feedstock<sup>[17,18]</sup>. The commercialized FASTMELT process developed by Kobe Steel Ltd. (Japan) and MIDREX Technologies Inc. (US) could reach an annual output of 500 kt<sup>[19]</sup>. The FASTMELT process comprises two stages: rotary hearth furnace (RHF) direct reduction and electric ironmaking furnace (EIF) melting separation. Therefore, metallized and high-temperature direct reduced iron is fed directly into a proprietary melter to produce molten iron. In FASTMELT, various iron-bearing materials and carbonaceous materials can be adopted to prepare ore-carbon composites. Moreover, FASTMELT can be tailored to precisely match the desired molten iron chemistry by controlling the reduced ore-carbon composite chemistry. In the BF ironmaking process, silicon is transferred from the slag to molten iron through the reaction between silica and carbon<sup>[20]</sup>. As the molten iron is saturated with carbon, the silicon content in the hot metal

\* Corresponding author. Assoc. Prof., Ph.D.; Tel. +86-10-82377180. E-mail address: hqtang@ustb.edu.cn (H.Q. Tang).

will become uncontrollably high if the sinter contains high-silica content. The silicon behavior in BF indicates that if the carbon content in molten iron is controlled at a low level, silicon transfer from the slag to molten iron can be inhibited. Considering the advantages of FASTMELT, a new method for applying FASTMELT to process high-silica hematite has been envisaged. Metallic briquettes with low residual carbon are produced in the RHF direct reduction stage followed by the production of low-silicon molten iron in the melting separation stage where silicon transfer is greatly reduced. In the previous study, the present authors found that by employing highly reactive biochar as a reductant, residual carbon in the metallized ore-char briquette is adjustable and could be controlled to be as low as 0.17 mass%, whereas its metallization remains high above 80% via direct reduction<sup>[21]</sup>. Thus, the present authors believe that biochar could be an excellent reductant in RHF direct reduction.

In the present study, the feasibility of the envisaged method has been examined along with its optimum process conditions.

## 2. Experimental

### 2.1. Materials

The high-silica hematite sample was supplied by a Chinese iron and steel company. The biochar was the same as the employed biochar in Ref. [21]. The hematite and biochar samples were ground to a size of less than 80  $\mu\text{m}$  and their chemical compositions are listed in Tables 1 and 2, respectively.

**Table 1**

Composition of the high-silica hematite (mass%)

TFe	FeO	SiO <sub>2</sub>	CaO	Al <sub>2</sub> O <sub>3</sub>	MgO	Mn	P	Loss
60.6	2.4	11.15	0.13	0.35	0.16	0.02	0.02	0.3

**Table 2**

Proximate analysis of the as-received biochar (mass%)

Moisture	Volatile	Fixed carbon	Ash
3.14	36.10	58.67	2.09

### 2.2. Tests

#### 2.2.1. Morphological and phase identification

Scanning electron microscopy (SEM), energy dispersive spectrometry (EDS), and X-ray diffraction (XRD) analyses were performed on the high-silica hematite sample for characterization.

#### 2.2.2. Direct reduction tests

Finely ground high-silica hematite and biochar

samples (fines) were thoroughly mixed with a prescribed biochar mixing ratio with an addition of 10% distilled water, 2% organic binder and 10% CaO. The biochar mixing ratio is defined as  $N_C/N_O$ , where  $N_C$  is the moles of fixed carbon in the biochar fines and  $N_O$  is the moles of oxygen in the iron oxide of the high-silica hematite fines. 10% CaO was added into the briquette considering that the basicity (the mass ratio of CaO to SiO<sub>2</sub>) in the blast furnace slag was approximately 1.0, and a satisfying slag/metal separation could be obtained in BF ironmaking under that basicity condition. The briquettes (mass of 6 g, diameter of 20 mm, and height of 10 mm) were made by pressing the moistened fines using a die. The briquettes were cured for 20 h, followed by drying in an electric oven at 473 K for 2 h.

Direct reduction tests were conducted in a tube furnace. The alumina reaction tube had a length of 850 mm and diameter of 40 mm. The temperature was maintained constant in the reaction zone within  $\pm 2$  K for a length of 80 mm. The reaction tube was heated from room temperature. When the temperature reached the desired value, it remained stable for 30 min under a highly pure nitrogen stream. In each run, the reaction tube was opened to load two briquettes into the reaction zone and then closed. The reduction began isothermally after nitrogen was replaced with a CO-CO<sub>2</sub> mixture at a flow rate of 200 mL/min. After a predetermined time, the briquettes were removed from the reaction zone and quenched by a nitrogen stream. The metallization ( $M$ ) and residual carbon ( $C_R$ ) of reduced briquettes were then measured, and some briquettes were examined using SEM, EDS and XRD.

#### 2.2.3. Melting separation tests

Melting separation tests were conducted using a Si-Mo high-temperature furnace. The furnace was heated to 1823 K and pure argon was introduced into the furnace chamber at a flow rate of 100 mL/min. For all individual runs, four metallic briquettes were put in an alumina crucible (height of 60 mm and diameter of 30 mm), which was protected by a graphite crucible. The sample was inserted quickly into the chamber followed by the initiation of the slag/metal separation process. Melting time was calculated when the furnace temperature returned back to 1823 K and the sample was quenched after the melting time reached 10 min. The mass of the obtained metals, the carbon content ( $w_{[C]}$ ), and the silicon content ( $w_{[Si]}$ ) were measured. The obtained slag samples were examined using X-ray fluorescence (XRF) analysis. Iron recovery rate ( $\eta$ ) was calculated by  $m_{\text{metal}}/m_{\text{iron}} \times 100\%$ , where  $m_{\text{metal}}$  is the mass of the obtained metal and  $m_{\text{iron}}$  is the mass of iron in the metallic briquette. Moreover, the cleanli-

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