Beneficiation of Oolitic Iron Ore Sourced from Gara Djebilet using Coal-Based Direct Reduction prior to Magnetic Separation

Farid Aghilasse Mansour, Malek Ould Hamou, Amira Merchichi, and Nabil Babahoum

Abstract−A process involving coal-based direct reduction followed by wet low-intensity magnetic separation is presented in this paper with the objective of promoting the Fe content and reducing the P assay of phosphorus-rich oolitic iron ore. A final direct reduced iron powder assaying 92.5 wt% Fe and 0.2 wt% P at a recovery rate of 95.9% was obtained when a mixture of ore-coal-CaO was reduced at 1200°C during 60 min in the presence of 7.5% sodium sulfate. In addition, microscopic analyses reported that the oolitic texture was completely destroyed, and most of the iron occurred in the metallic state. These findings suggest the ease utilisation of the ore mined from Gara Djebilet in the steelmaking industry as a substitute to scrap steel in electric arc furnace.

***Keywords*− Direct reduction, Gara Djebilet, magnetic separation, oolitic iron ore.**

NOMENCLATURE

AAS	Absorption atomic spectroscopy
BT	Billion Tones.
CBDR	Coal-based direct reduction.
DRI	Direct reduced iron
EAF	Electric Arc Furnace.
EDS	Energy dispersive spectroscopy
SEM	Scanning electron microscopy.
WLIMS	Wet low-intensity magnetic separation.
XRF	X-ray fluorescence.

I. INTRODUCTION

Owing to the depletion of easy-to-process iron resources and the rapid increase in need for iron in steelmaking industry, the iron extraction from various refractory iron ores has become a focus of research [1]. One of the most important occurrences of refractory iron ores is the oolitic iron ore [2]. This type distributes in Algeria as plentiful deposits of huge reserves such Gara Djebilet (5 Bt) and Mecheri Abdelaziz (3 Bt) [3]. Gara Djebilet has not yet been commercially exploited since its processing has run into the inability of iron oxides beneficiation by the conventional routes due to many problems related to its complex texture resulted from the finely dissemination of iron minerals in those of gangue and the presence of phosphorus in excessive content [4]. Therefore, current attentions are turned towards the pyrometallurgical methods as an alternative to the hydrometallurgical ones for iron extraction and phosphorus removal. The coal-based direct reduction (CBDR) prior to EAF is a promising route for iron recovery by using coal as reductant at temperatures below the melting point of iron [5]. During this process, the iron oxides are reduced to metallic iron with grain growth and then recovered by subsequent grinding and wet low-intensity magnetic separation (WLIMS) [6]. In this study, ironstone samples sourced from Gara Djebilet underwent various treatment experiments including WLIMS, CBDR-WLIMS without any additives, and CBDR-WLIMS in the presence of Na_2SO_4. The concentrate product of each experiment is subjected to chemical analyses to assay their iron and phosphorus content. In addition, SEM-EDS were performed to study the morphology and microstructure of the DRI as well as identify local composition.

II. MATERIALS

The ironstone samples were collected from Gara Djebilet field which is located in the Tindouf province of Algeria. Chemical composition and Phase of a homogenized sample from Gara Djebilet West is presented in Table I and Fig. 1, respectively.

Table I.
CHEMICAL COMPOSITION OF THE RAW ORE (WT%)

SiO_2	6.45	FeO	13.0
Al_2O_3	4.90	P_2O_5	1.80
Fe_2O_3	64.5	Loss On Ignition (LOI)	7.35

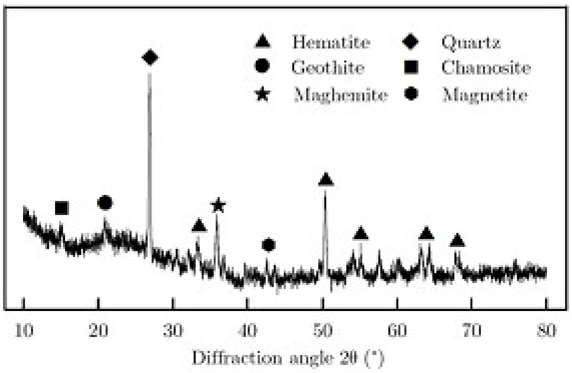

Fig. 1: XRD pattern of raw ore

The total iron grade amounts to 55.30 wt%. However, the P content is as high as 0.8 wt%. Fig. 2 presents the microstructure of selected ironstone observed under a reflected light microscope. Obviously, the typical oolitic texture is generated of ooids with alternating hematite, goethite, and chamosite

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laminae that are embedded in chamositic matrix.

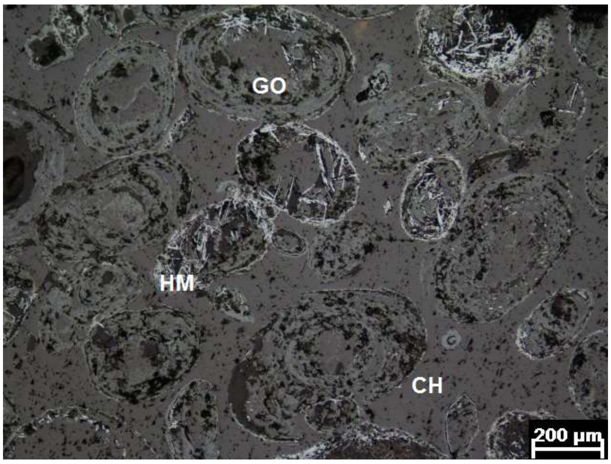

Fig. 2: Photomicrograph of the raw ore
CH—Chamosite; GO—Goethite; HM—Hematite

The bituminous coal used as reductant is taken from Bechar province of Algeria. Its components are reported in Table. II. The burnt lime (CaO) used as flux, and the additive of sodium sulfate (Na_2SO_4), are of reagent grade (AR) and their particle size is less than 74 µm.

Table II.
PROXIMATE ANALYSIS OF COAL (%)

Fixed carbon	Ash	Volatile matter	Moisture
49.5	6.20	45.3	14.9

III. METHODS

Three experiments were designed to investigate the efficiency of each route in iron recovery and phosphorus removal. The iron ore and coal were crushed separately to 100% less than 1 mm using a laboratory jaw crusher. For requirement to the first experiment, a certain amount (60 g) was taken from the crushed raw ore and milled to 80% less than 74 µm using a planetary ball mill (Retsch pm100). Then, a sample weighting 20 g was subsequently slurried to 20wt% solids by weight (20 g powder by 100 mL distilled water) and subjected to WLIMS through a Davis tube (KHD Humboldt Wedag International AG GmbH, Germany) under a magnetic field intensity of 0.14 T. The main operating variables are the wash-water flowrate which is set at 2.5 $L \cdot min^{-1}$ and the running period of time which is set to be 10 minutes. While the conception variables are the glass tube slop which is set at 45° from the horizontal and the agitation cycles which is set at 60 cycles per minute. Regarding the remaining trials, the rest of the raw ore was mixed with coal and CaO according to specific proportions. Each experiment requires 20 g iron ore, 15 g coal, and 1 g CaO. An additional amount of 1.5 g Na_2SO_4 was added to the mixture during the last experiment. Next, the mixtures were charged into heat-resistance graphite crucibles, and then reduced inside a high-temperature electric resistance muffle furnace at 1200°C for 60 min. Once the reduction achieved, the mixtures were withdrawn from the furnace and cooled down to room temperature under an air-isolated environment. After that, the samples were milled to 80% less than 74 µm using a vibratory disc mill. Then, a representative sample weighting 20 g taken from each milled product was slurried to 20 wt% solids by weight and subjected to WLIMS through the aforementioned device under the same conditions. The concentrate produced from each experiment was subjected to chemical analyses to assay their iron and phosphorus content using both XRF and AAS methods. Moreover, both reduced powder and DRI were subjected to SEM-EDS analyses to investigate their microstructure and identify their local composition.

IV. RESULTS AND DISCUSSION

The outputs of WLIMS and the chemical composition of the magnetic material are summarised in the Table III. The Fe Content (TFe) amounts to 72.80wt% whereas the P content is as high as 0.5wt%. Despite the efficiency of WLIMS in recovery of iron, its uncompetitive in dephosphorisation is evident.

Table III.
RESULTS OF WLIMS FOR THE FIRST TEST

Product	Yield (%)	Fe content (wt%)	Fe recovery (%)
Concentrate	51.35	72.80	67.60
Tailing	48.65	36.82	32.40
Total	100	-	100

For the experiment involving CBDR-WLIMS without any additives, the outputs of the WLIMS are reported in Table. IV. The chemical analyses of the DRI using AAS reported that the TFe amounts to 79.20 wt% whereas the P content reaches a value as high as 1.25 wt%. Obviously, subsequent grinding and WLIMS obtain a phosphorus-rich DRI. This is because the reduction, at this high temperature and for a long period, causes the dissolution of the elemental phosphorus into the hot metallic iron (Fe), rather than emitting to the atmosphere and generating the Fe_xP alloy. The latter is then turned towards the concentrates during WLIMS [7].

Table IV.
RESULTS OF WLIMS FOR THE SECOND TEST

Product	Yield (%)	Fe content (wt%)	Fe recovery (%)
Concentrate	68.35	81.20	92.5
Tailing	31.65	14.21	07.5
Total	100	-	100

For the experiment involving CBDR-WLIMS in the presence of 7.5% Na_2SO_4, the outputs are presented in Table. V. The TFe amounts to 93.5wt% while the P content is 0.2wt%.

Table V.
RESULTS OF WLIMS FOR THE THIRD TEST

Product	Yield (%)	Fe content (wt%)	Fe recovery (%)
Concentrate	78.65	93.50	97.40
Tailing	21.35	09.19	02.60
Total	100	-	100

It is clear that the Fe-P separation is intensified in the presence of Na_2SO_4. The microstructure and composition of the DRI produced during the presence of 7.5% Na_2SO_4 was investigated using SEM-EDS analysis and the result is presented in Fig. 3. The EDS analysis of the spot indicated in the figure reported that iron is the main element present in the DRI suggesting that a nearly monophased material has been acquired through the third test.

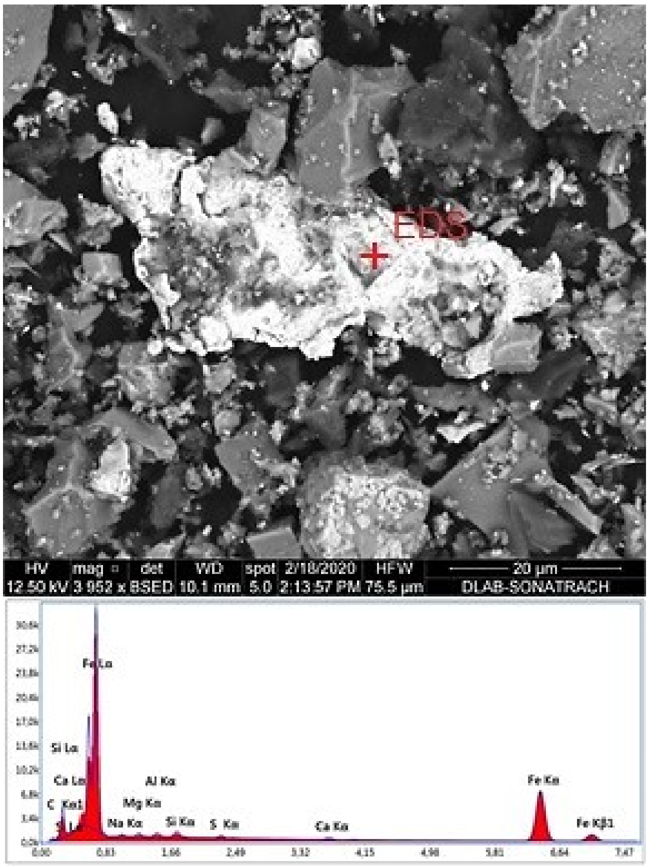

Fig. 3. Microstructure and EDS measurement of the magnetic material output of the third experiment

However, there was found few amounts of Al, Ca, Mg, Si, and S which are part of some fine size impurities such as fayalite Fe_2SiO_4, hercynite $FeAl_2O_4$, and troïlite FeS, which are turned into, concentrates along with iron grains via the magnetic reunion phenomena (Table. VI) [8].

Table VI.
EDS QUANTITATIVE ANALYSIS DATA OF THE SELECTED SPOT FROM THE MAGNETIC MATERIAL OUTPUT OF THE THIRD TEST

Elt.	%mass	%atomic	Elt.	%mass	%atomic
C	1.57	6.43	Si	0.75	1.71
O	1.62	5.08	P	0.21	0.33
Na	0.33	0.18	S	0.62	0.98
Mg	0.27	0.14	Ca	0.35	0.11
Al	0.69	1.50	Fe	93.59	84.15

V. CONCLUSION

Throughout this study, a series of experiments were carried out for iron enrichment and phosphorus removal from Gara Djebilet ironstone samples. A magnetic product assaying 72.5 wt% Fe and 0.5 wt% P was acquired by WLIMS of -74 µm raw ore. This material is not suitable for steelmaking industry via the blast furnace route due to its high phosphorus content. Without any dephosphorisation agent, a DRI assaying 81.2 wt% Fe and 0.25 wt% P was obtained by WLIMS of a reduced ore-coal-CaO mixture at 1200°C for 60 min. This high phosphorus-containing metallic iron powder could then be converted to steel by a steelmaking duplex process, and the phosphorus-rich steelmaking slag containing more than 10wt% P_2O_5 could be used as phosphate fertilizer [9]. In the presence of a dephosphorisation agent, a DRI assaying 93.5 wt% Fe and 0.2 wt% P was acquired via WLIMS of a reduced ore-coal-CaO-Na_2SO_4 mixture at 1200°C for 60 min. This product is suitable for steelmaking industry as substitute to scrap steel in EAF.

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