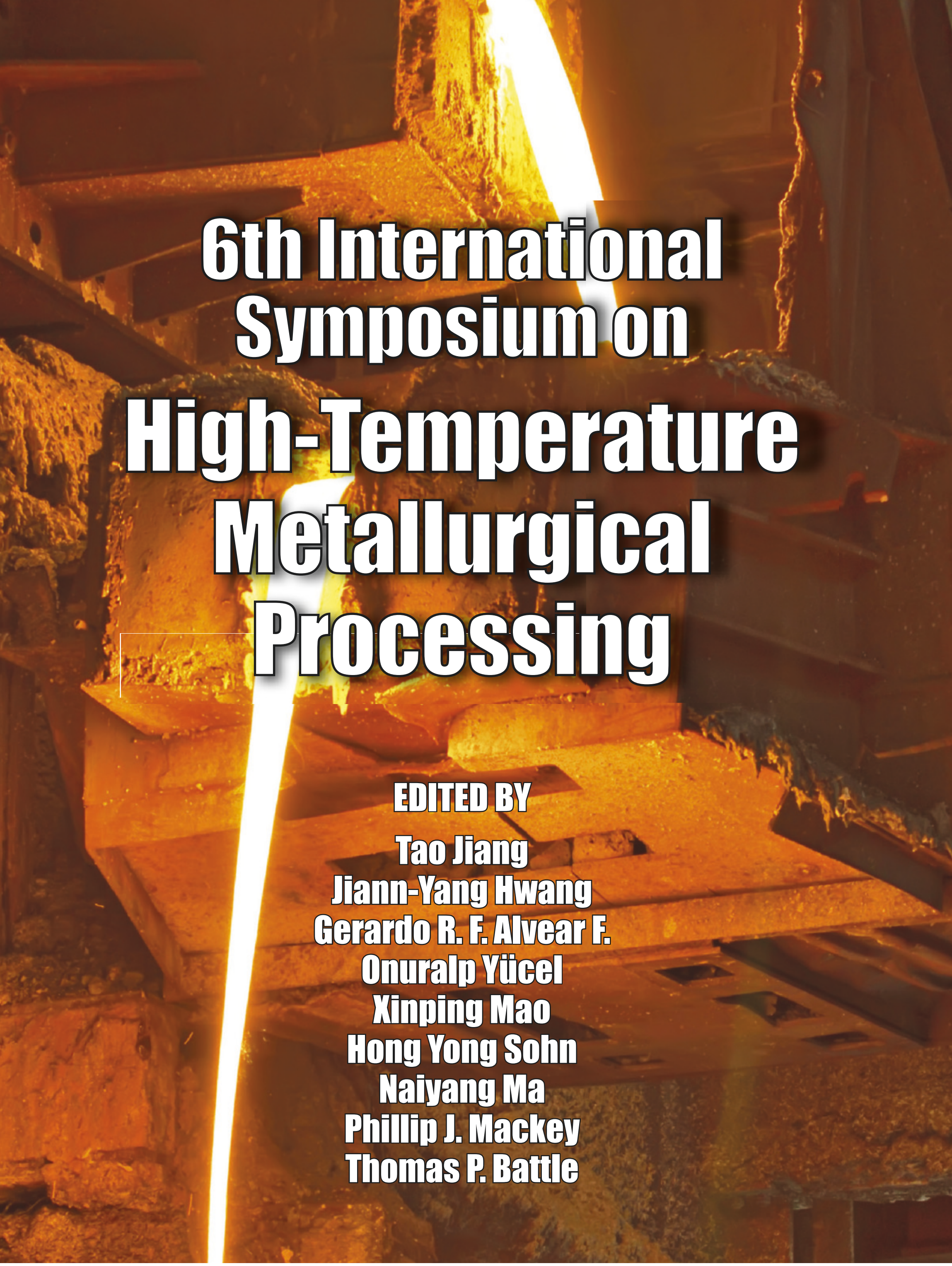

6th International Symposium on High-Temperature Metallurgical Processing

EDITED BY

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Jiann-Yang Hwang
Gerardo R. F. Alvear F.
Onuralp Yücel
Xinping Mao
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TMS

Springer

6th International Symposium on

High-Temperature Metallurgical Processing

TMS2015

144th Annual Meeting & Exhibition

March 15-19, 2015 • Walt Disney World • Orlando, Florida, USA

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Proceedings of a symposium sponsored by

The Minerals, Metals & Materials Society (TMS)

held during

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ISBN 978-3-319-48603-1 ISBN 978-3-319-48217-0 (eBook)
DOI 10.1007/978-3-319-48217-0

Chemistry and Materials Science: Professional

Published by Springer International Publishers, Switzerland, 2016
Reprint of the original edition published by John Wiley & Sons, Inc., 2015, 978-1-119-07357-4

Printed on acid-free paper

This Springer imprint is published by Springer Nature
The registered company is Springer International Publishing AG
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

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PREFACE

This book collects selected papers presented at the 6th International Symposium on High-Temperature Metallurgical Processing organized in conjunction with the TMS 2015 Annual Meeting & Exhibition in Orlando, Florida, USA.

As the title of symposium suggests, the book is on thermal processing of minerals, metals and materials and intends to promote physical and chemical transformations in the materials to enable recovery of valuable metals or produce products such as pure metals, intermediate compounds, alloys, or ceramics through various treatments. The symposium was open to participants from both industry and academia and focused on innovative high-temperature technologies including those based on non-traditional heating methods as well as their environmental aspects. Because high-temperature processes require high energy input to sustain the temperature at which the processes take place, the symposium intends to address the needs for sustainable technologies with reduced energy consumption and reduced emission of pollutants. The symposium also welcomed contributions on thermodynamics and kinetics of chemical reactions and phase transformations that take place at elevated temperature.

Over 400 authors have contributed to the symposium with a total of 149 submissions. After reviewing the submitted manuscripts, 98 papers were accepted for publication in this book, which covers the following topics: high-efficiency new metallurgical process and technology; fundamental research of metallurgical process; materials preparation; direct reduction and smelting reduction; coking, new energy; utilization of solid slag/wastes and complex ores; and characterization of high-temperature metallurgical process. Basically, these papers represent the accomplishments attained and new advances in the area of high-temperature metallurgical processing in the last few years over the world.

This is the fifth book exclusively dedicated to this important and burgeoning topic published in the 21st century. We hope this book will serve as a reference for both new and current metallurgists, particularly those who are actively engaged in exploring innovative technologies and routes that lead to more energy efficient and environmentally sustainable solutions.

We would like to thank all the authors of submitted papers, the reviewers, and the publisher. There could not be this book without their contributions, time, and efforts. We also want to thank Drs. Mingjun Rao, Youlian Zhou, Zhixiong You, and Jinghua Zeng for their assistance in collating and reviewing the submissions.

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EDITORS

Tao Jiang received his M.S. in 1986 and Ph.D. in 1990, both from Central South University of Technology. Then he joined the university and served as an assistant professor (1990-1992) and full professor (1992-2000). From 2000 to 2003, he was a visiting scientist to the Department of Metallurgical Engineering at the University of Utah. Since 2003, Dr. Jiang has been a professor in the School of Minerals Processing & Bioengineering at Central South University. He was elected as Specially Appointed Professor of Chang Jiang Scholar Program of China in 2008 and has been the dean of the school since 2010.

His research interests include agglomeration and direct reduction of iron ores, and extraction of refractory gold ores. He has accomplished more than 50 projects from the government and industry, including National Science Fund for Distinguished Young Scholars Program. He and co-workers invented the direct reduction process of composite binder pellets and three plants were set up based on the invention in China. He proposed the innovative composite agglomeration process of iron ore fines, which was put into production in Baotou Steel Company, China. He is actively involved in the areas of utilization of non-traditional ferrous resources such as complex ores and various solid wastes. Dr. Jiang has published 320 technical papers, and six books including *Direct Reduction of Composite Binder Pellets and Use of DRI*, *Principle & Technology of Agglomeration of Iron Ores, Chemistry of Extractive Metallurgy of Gold,* and *Electrochemistry and Technology of Catalytical Leaching of Gold*. He holds 35 patents and has more than 30 conference presentations. He has chaired the Pyrometallurgy Committee in TMS and has organized several symposia.

Jiann-Yang (Jim) Hwang is a Professor in the Department of Materials Science and Engineering at Michigan Technological University. He is also the Chief Energy and Environment Advisor of the Wuhan Iron and Steel Group Company. He has been the Editor-in-Chief of the *Journal of Minerals and Materials Characterization and Engineering* since 2002. Several universities have honored him as a Guest Professor, including Central South University, University of Science and Technology Beijing, Chongqing University, and Kunming University of Science and Technology. He has been recognized with a few awards, including the TMS Extractive and Processing Technology Award, Michigan Technological University Bhatta Rath Research Award, and China 1000 Talents Award.

Dr. Hwang received his B.S. degree from National Cheng Kung University 1974, M.S. in 1980 and Ph.D. in 1982, both from Purdue University. He joined Michigan Technological University in 1984 and has served as its Director of the Institute of Materials Processing from 1992 to 2011. He has been a TMS member since 1985. His research interests include the characterization and processing of materials and their applications. He has been actively involved in the areas of separation technologies, pyrometallurgy, microwaves, hydrogen storages, ceramics, recycling, water treatment, environmental protection, biomaterials, and energy and fuels. He has more than 30 patents, has published more than 200 papers, and has founded several companies. He has chaired the Materials Characterization Committee and the Pyrometallurgy Committee in TMS and has organized several symposia.

Gerardo R. F. Alvear F. received his Ph.D. in Metallurgy in 1995 from Nagoya University, Japan. After working as a post-doctoral fellow at NGK Metals, Japan and as a research associate at the Research Centre for Advanced Waste Management at Nagoya University, he joined the Chilean Institute for Innovation in Mining and Metallurgy (A Codelco-Chile Subsidiary). In 2005, after six years in Chile, Dr. Alvear moved to Australia to join the pyrometallurgy team of Glencore Technology (formerly Xstrata Technology). Dr. Alvear's industrial experience has been also balanced with academic involvement as lecturer and assistant professor in Chile, Japan, and Canada, teaching and supervising students in the non-ferrous extractive metallurgy field.

Dr. Alvear is currently chair of the Pyrometallurgy Committee of the Extractive and Processing Division of The Minerals, Metals & Materials Society (TMS) and is the TMS representative to the *ad-hoc* Copper Conference International Organizing Board in charge of coordination of the Copper Conference Series. Dr. Alvear is currently based in Vancouver, Canada.

Onuralp Yücel was born in Diyarbakir, Turkey and completed his technical education with a Ph.D. in Metallurgical Engineering from Istanbul Technical University (ITU), where he is currently holding the post of Professor since 2002. He was a visiting scientist at Berlin Technical University between1987 and 1988. He carried out post-doctoral studies at New Mexico Institute of Mining and Technology in Socorro, New Mexico, USA, between 1993 and 1994. Dr. Yücel has as many as 250 publications/ presentations to his credit, which include topics like technological developments in the production of wide range of metals, ferroalloys, advanced ceramic powders, and application of carbothermic and metalothermic processes among others. He was the vice chairman of ITU Metallurgical and Materials Engineering Department between 2004 and 2007. He has been a director of ITU Applied Research Center of Material Science & Production Technologies between 2006 and 2012.

Xinping Mao earned a Ph.D. in Materials Processing Engineering, is a Doctoral Supervisor and Professor, and holds the position of Executive Vice-President of the Research and Development Center of Wuhan Iron and Steel (Group) Corporation. He conducts the research of thin slab casting and direct rolling process as well as advanced steel material manufacturing technology. He discovered the precipitation law and strengthening mechanism of the Ti-containing precipitate in Ti-microalloyed steel, evolved a complete set of production technology, and developed the high strength and ultra-high strength steel with yield strength of 450-700MPa which are used in the sectors of automobile, container, and engineering machinery.

Hong Yong Sohn received his Ph.D. in Chemical Engineering in 1970 from the University of California-Berkeley. After working as a research engineer at DuPont's Engineering Technology Laboratory, he joined the faculty of the University of Utah in 1974. Dr. Sohn's work has been recognized through various awards: Distinguished Professor, 2014, University of Utah; 2014 Educator Award, TMS; 2012 Distinguished Scholarly and Creative Research Award, University of Utah; 2012 Billiton Gold Medal, The Institute of Materials, Minerals and Mining, U.K.; TMS 2009 Fellow Award in recognition of outstanding contribution to the practice of metallurgical/materials science and technology; 2001 James Douglas Gold Medal Award from AIME for leadership and outstanding contributions in research and education of nonferrous extractive metallurgy and for work related to the modeling of gas-solid reactors and development of novel solvent extraction systems; Fellow Award from the Korean Academy of Science and Technology, 1998; 1993 TMS Champion H. Mathewson Gold Medal Award for the most notable contribution to Metallurgical Science in the 3-year period; 1990 TMS Extractive Metallurgy Lecturer Award in recognition as an outstanding scientific leader in the field of nonferrous extraction and processing metallurgy; TMS Extraction and Processing Science Award (1990, 1994, 1999, and 2007); Fulbright

Distinguished Lecturer (1983); and Camille and Henry Dreyfus Foundation Teacher-Scholar Award (1977). In 2006 TMS honored Dr. Sohn with the “Sohn International Symposium on Advanced Processing of Metals and Materials”.

Dr. Sohn has authored or co-authored 4 monographs, 5 patents, 22 book chapters, and some 500 papers. He has delivered numerous plenary lectures. He was a DOE Fossil Energy Lecturer, 1978–81, and was appointed Advisor to LS-Nikko Copper Co., Korea in 2005.

His current research areas are Novel Flash Ironmaking Technology, Inorganic Nano-Material Synthesis, Gas-Solid Reaction Analysis, and Flash Smelting Processes.

Naiyang Ma was born in Jiangsu Province, China. He graduated with a B.S. degree in Metallurgical Engineering in 1982 from Chongqing University, China. He received his M.S. degree in Metallurgical Engineering in 1985 from the University of Science and Technology Beijing, China. After he had taught as a lecturer and later as an associate professor from 1985 to 1995 at Anhui University of Technology, China, he made an academic visit to the University of Birmingham, Britain from 1995 to 1996. He then studied at the University of Utah, USA, and received his Ph.D. degree in Metallurgical Engineering in 2000. From 2000 to 2006, he was working as a post-doctoral research associate at the University of Utah. He joined ArcelorMittal Global R&D – East Chicago Laboratories in 2006, and currently he is a lead research engineer there. Since 2011, Dr. Ma has been an adjunct associate professor at the University of Utah.

Dr. Ma has published more than 40 research papers and was awarded one U.S. patent. In 2012, he was awarded AIST Environmental Technology Award for Best Paper and Presentation. His past research experience includes pulverized coal injection into blast furnaces, optimization of blast furnace slag compositions, sintering, pelletization and cold-bonded agglomeration of iron-containing solid wastes, smelting reduction of ilmenite by carbon in molten pig iron, modeling with stochastic process and experimental testing with techniques of scanning electron microscope (SEM) imaging and automated image analysis (AIA) for understanding liberation characteristics of pyrite and other ash-forming minerals from coal, modeling and simulation of grinding ores in large ball mills with discrete element method (DEM), and modeling and simulation of nano-structured materials. At present, Dr. Ma’s main research interest is in recycling of steelmaking plant solid wastes by in-process separation of beneficial components from unwanted components in economic manners.

Phillip J. Mackey is a consulting metallurgical engineer and specialist in non-ferrous metals with over forty years of international experience in all aspects of the non-ferrous and ferrous metals business. He received his Ph.D. in metallurgical engineering from the University of New South Wales studying under Professor N.A. Warner, one of the innovative leaders of his time. Dr. Mackey was armed to take on his first challenge at Noranda Mines in Canada where he played a leading role in the development of the Noranda Process, the world's first commercial continuous copper smelting and converting process and one of the important copper technologies developed in the twentieth century. He was later responsible for the marketing of this technology to a number of other companies worldwide. His role in introducing the Noranda Converter, a new continuous converting process, was recognized by the Noranda Inc. Technology Award given in 1998. Active in the copper world, he co-founded the Copper/Cobre series of International Conferences with the first one held in Chile in 1987. Dr. Mackey also worked on nickel processing while at Noranda, including an innovative continuous nickel converting process, and later with Falconbridge he was involved in a number of nickel laterite and nickel sulphide projects around the world. He has authored and co-authored over 100 publications covering many aspects of nonferrous metallurgy. He is a Metallurgical Society of CIM Past-President (1984-1985) and a Fellow of both CIM and TMS. A recipient of several professional awards in Canada and the United States, he also received the 2007 TMS Distinguished Service Award, the Selwyn G. Blaylock Medal of the CIM in 2010, and the Airey Award of the Metallurgical Society of CIM in 2012.

Thomas P. Battle is currently a Senior Metallurgist at Midrex Technologies in Pineville, North Carolina. He has undergraduate degrees in Materials Engineering and Astronomy from The University of Michigan, a Master's in Metallurgical Engineering from the Colorado School of Mines, and a Doctorate in Materials and Metallurgical Engineering from The University of Michigan. After a time as a Post-Doctoral Research Fellow in the Centre for Numerical Modelling and Process Analysis at Thames Polytechnic, he spent 18 years at various positions with the White Pigments and Mineral Products business at DuPont (now known at DuPont Titanium Technologies). He has spent the last six years as a senior metallurgist at Midrex Technologies, focusing on iron ore pelletizing technology and the direct reduction of iron.

Dr. Battle has been active with TMS for over 25 years, holding a number of volunteer positions, both technical and administrative, mainly for the Extraction and Processing Division. This culminated in a three-year term as chair of the division and a position on the TMS Board of Directors. He is a founding member of the North American Extractive Metallurgy Council.

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TMS (The Minerals, Metals & Materials Society), 2015

RECOVERY OF IRON FROM HEMATITE-RICH DIASPORIC-TYPE BAUXITE ORE

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Keywords: Diasporic bauxite, Sodium salts, DRI, Magnetic separation, Alumina

Abstract

A technique has been proposed for recovering iron from hematite-rich diasporic-type bauxite ore in this study. Direct reduction roasting followed by low intensity wet magnetic separation process was carried out. The parameters including reduction temperature and time, sodium salts, grinding conditions and magnetic field intensity for separation of iron were determined. The optimum process parameters as follows: roasting temperature of 1050 ºC, time of 60 min, sodium salts involving sodium sulfate, borax, sodium carbonate with dosages of 10 wt%, 2 wt%, 35 wt% respectively, and magnetic field intensity of 1000 Gs with fineness of pulp reached 92.75% passing -0.074mm. Under the optimal conditions, an iron concentrate containing 88.17% total iron grade and iron recovery of 92.51% was obtained, 4.55% total iron grade in tailings. This novel technique provide a potential route for utilizing hematite-rich diasporic bauxite ore, recovering iron resource firstly, and extracting alumina from magnetic separation tailings further.

Introduction

Bauxite is considered as the main material for producing alumina. In generally, the primary beneficiation processes of bauxite is by Bayer process and this will be generated a large amount of red mud that contains considerable quantities of Fe_2O_3, Al_2O_3, Na_2O, SiO_2 and other minor valuable constituents[1]. Due to iron oxides cannot react with caustic soda solution, more residue will be generated particularly treating high iron content bauxite in Bayer process [2]. Especially, iron-rich bauxite is usually defined as Fe_2O_3 content excess 15 wt% [3]. Bauxite with high iron content resource has a huge amount worldwide, especially in Australia, Guinea, Brazil, Vietnam, Laos, etc. [4, 5]. There are also abundant high iron bauxite ores in China, which primarily distribute over Guang'xi, Yunnan, Shan'xi, He'nan provinces. Several achievements have been attained in recent years on iron-rich bauxite processing, including physical, chemical and biological methods. The physical method is straightforward with low cost, but it has some limits such as low separation efficiency and is only suitable for those with simple minerals occurring relationship [6]. Chemical method can get higher removal rate of iron and better recovery of alumina, but this method not only has a high cost but also potential environmental pollution [7, 8]. Biological method with low cost and minor environment issues is very suitable for removing iron from bauxite ores, however, the cycle of this method is extended makes it impossible to apply in industry .

In this study, a new process was proposed for treating iron-rich diasporic-type bauxite, separating and recovering iron and alumina from hematite-rich diasporic-type bauxite were achieved by direct reduction roasting followed by magnetic separation methods.

Experiments

Materials

Hematite-rich diaspore bauxite was taken from the southwest of China. The chemical compositions are presented in Table I. The results indicate that A/S ratio is as low as 2.77 in the raw material and the iron oxide is much higher than conventional bauxite ores, the microstructures are shown in Fig.1. XRD patterns and chemical analysis of the main elements in raw material demonstrate that iron oxide exists as hematite, account for 91.85% of the total iron. Aluminium and silicon mainly exist in diaspore and silicate phase. Furthermore, the bearing relationships in the raw material demonstrates that hematite, kaolinite and diaspore or aluminum silicate are complex, which leads to the full liberation of mineral impossible and a difficulty of separating each other by physical processing methods.

Sodium salts used in this research are sodium sulfate (SS), borax (B), and sodium carbonate (SC), which are all analytical reagent. Bituminous coal was used as reductant.

Table I. Chemical Compositions of the Raw Material /%

Fe_2O_3	Al_2O_3	SiO_2	FeO	CaO	MgO	TiO_2	Na_2O	K_2O	V_2O_5	LOI
24.90	41.83	15.10	0.35	0.092	0.077	3.81	0.051	0.057	0.13	13.10

LOI—loss on ignition

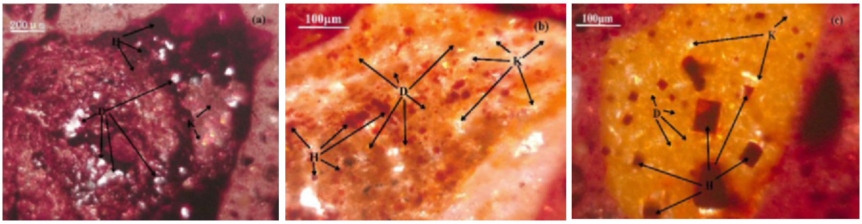

Fig.1 Microstructures of bauxite (D-Diaspore, H- Hematite, K-Kaolinite)

Methods and Evaluation Indexes

The direct reduction was conducted in a blast resistance furnace and wet magnetic separation was performed in Davis magnetic tube. The raw material was crushed and ground to certain fineness, and then mixed with the additives evenly, and agglomerated into a Φ10×10mm column briquette. The reduction was performed in Φ50×200 mm stainless pot with enough reduction agent. The reduced products were cooled to ambient temperature. Then, all the roasted products were crushed and separated via magnetic separation. The contents of the total iron, alumina and silica were measured by chemical analysis or XRF (X-ray fluorescence). The phase compositions were characterized using an X-ray diffractometer.

Total iron grade, metallization of iron and magnetic recovery of iron in concentrate were taken as evaluation indexes in this study. Whereby the grade of metallic iron and the total iron in concentrate was determined with chemical analysis, metallization and recovery of iron was calculated as following equation.

The metallization is defined as (Metallic Fe in percentage/ Total Fe in percentage) ×100.

The recovery of iron is defined as: $\vartheta = \text{yield} \times \frac{TFe(ironconcentrate)}{TFe(roastedprodcuts)}$

Results and Discussion

Effects of Sodium Salts on Recovering Iron during DR Roasting

Based on the previous researches, alkali or alkali-earth metal oxide can accelerate iron oxide reduction during high temperature roasting [9, 10]. Sodium sulfate, borax and sodium carbonate were used as additives in current research, and the effects of sodium additives on recovering iron from bauxite were investigated. To optimize the dosages of sodium additives, various salt dosages were conducted separately at first. The parameters were roasting temperature of 1100°C, time of 60 min, grinding fineness of more than 95% passing 0.074mm sieve and magnetic field intensity of 1000Gs. The results are presented in Fig.2. The results demonstrate that the metallization of iron was improved by adding salts of SS, B, and SC respectively. The Al_2O_3, SiO_2 contents in the concentrate were also decreased at some extent. Especially, the optimum result of total iron in concentrate up to 72.40% was obtained with SC dosage of 40 wt%. However, the total iron grade cannot meet the demand of raw materials for steelmaking.

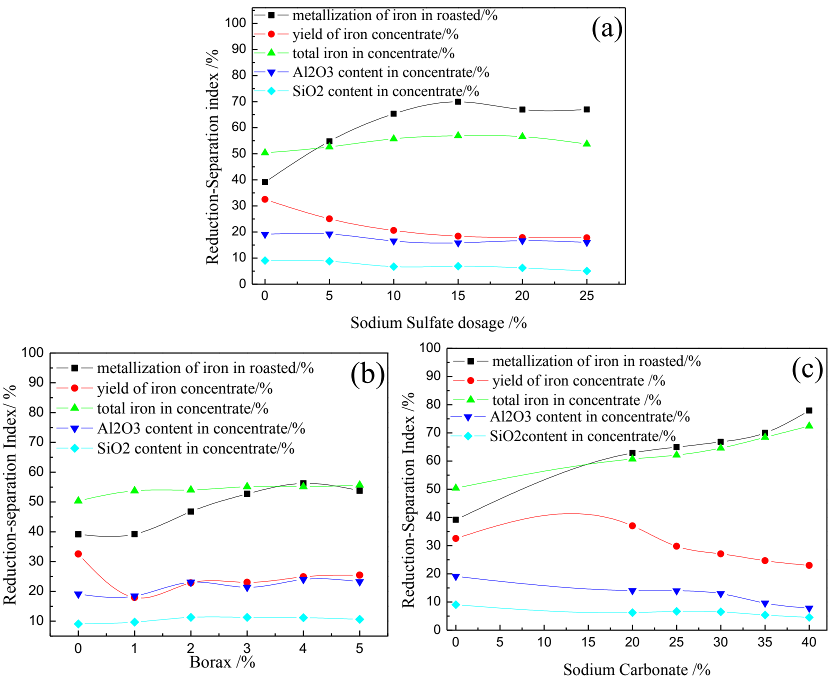

Fig.2 Effects of sodium salts on reduction and magnetic separation

Therefore, in order to realize separation and recovery of iron in hematite-rich diaspore ores effectively, further research on enriching iron and alumina by combining three additives in roasting process was conducted under optimum roasting conditions. The results are shown in Table II.

Table II. Effect of Sodium Salts Dosages on Recovering Iron / wt%

Dosages			Metallization of iron	Iron concentrate	
SS	B	SC		Grade	Recovery
10	1	30	90.51	82.48	92.21
15	1	35	86.77	81.84	78.65
15	2	30	93.47	86.91	86.25
10	2	35	94.25	82.83	91.65
10	2	40	90.93	86.40	93.42
15	2	30	81.49	80.51	77.49
15	2	35	88.48	88.49	87.00
15	2	40	86.67	87.48	81.86

The results revealed that comprehensive effect of combined additives was better than used sodium salts additives separately. In particular, with dosage of combined sodium salts additives SS, B, SC 10 wt.%, 2 wt.%, 35 wt.%, respectively, the metallization of iron in roasted products reached 94.25%, and the total iron of 82.83% and iron recovery of 91.65% can be attained in concentrate.

Effects of Roasting Temperature and Time on Recovering Iron during DR Process

The impacts of roasting temperature and time were tested with optimum dosages of sodium salts compared with no sodium salts. The results are shown in Figs.4 and 5. Reduction roasting was conducted for 60 min under various temperatures. Fig.4 shows the metallization of iron in roasted products without sodium salts increased gradually with temperature increasing from 950 °C to 1150 °C and reached the maximum of 41.31% at temperature of 1150°C. Also, the total iron in concentrate remained in the range of 50~60% with temperature increasing and the maximum recovery of iron was only 60% at 1150 °C. Further reduced with optimum dosages of sodium salts, the metallization of roasted products increased up to maximum of 94.25% (presented as Curve A). Particularly, the total iron of 86.53% with the recovery of 84.20% in concentrate was obtained at temperature of 1050°C.

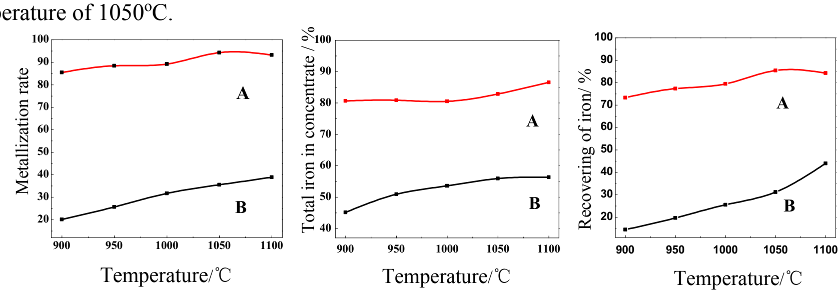

Fig.3 Effects of roasting temperature on reduction and magnetic separation
(A-with sodium salts; B-no sodium salts in direct reduction)

Meanwhile, reduction time has the same effects on the roasting process. With reduction time of 60 min, the metallization of iron in roasted products reached 93.18%, the total iron content of iron concentrate was 88.17% and the recovery of iron reached 88.55% at this point.

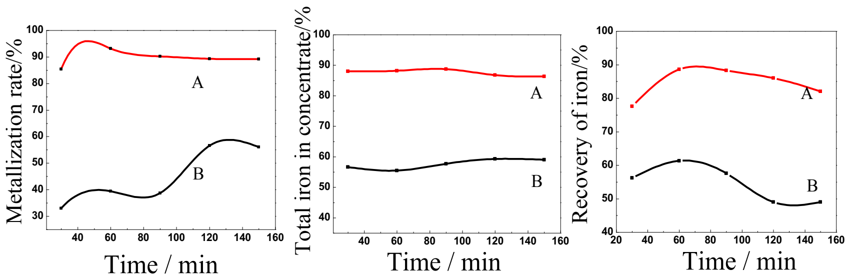

Fig.4 Effects of roasting time on reduction and magnetic separation
(A-with sodium salts; B-no sodium salts in direct reduction)

<u>Effects of Magnetic Separation on Recovery of Iron</u>

<u>Effect of Grinding.</u> The influence of grinding was also investigated in this research. Tests of grinding time and pulp concentration were conducted. The results are shown in Fig.5. The magnetic field intensity was 1000Gs in this test. The grinding concentration was 50% with various grinding time and the grinding 20min with different pulp concentration.

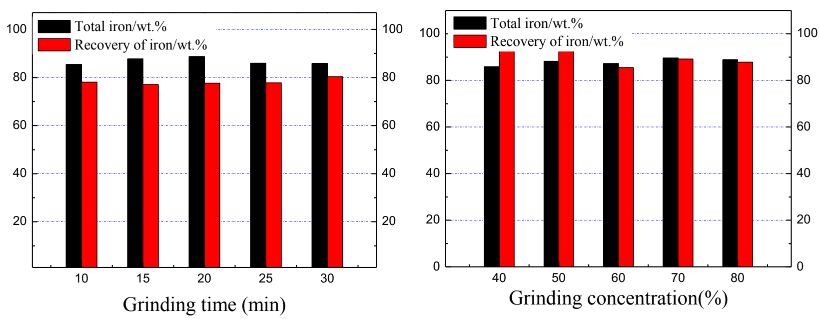

Fig.5 Effect of grinding conditions on recovery of Iron

Fig.5 revealed that the total iron grade in concentrate increased firstly, then decreased, and reached maximum at time of 20 min. The maximum iron grade of 88.72% was attained. Iron grade in concentrate increased firstly and then remained stable almost with pulp concentration increased from 50% further. In conclusion, grinding time of 20min with pulp concentration of 50% was suitable for recovering of iron in this process. The grinding fineness was more than 97.25% passing -0.074mm sieve under this condition.

Effect of Magnetic Field Intensity. Fig.6 shows the impacts of magnetic field intensity on the recovery of iron.

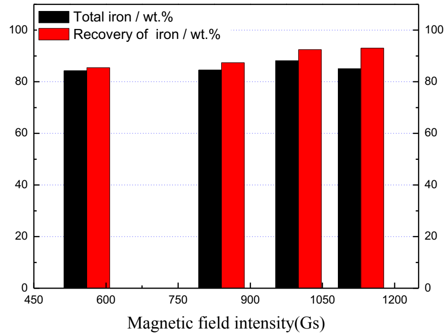

Fig.6 Effects of different magnetic field intensity on the recovery iron

With the increasing of magnetic field intensity, the total iron in the magnetic concentrate increased gradually and remained stable when the magnetic field intensity exceeded 1000Gs. Recovery of iron increased gradually in the meantime. Iron grade reached maximum of 88.17% and recovery of iron to 92.51% in concentrate when magnetic field intensity of 1000Gs. For entire process, magnetic field intensity of 1000Gs is suitable for separating iron in this process.

The Properties of Final Products

Micro image of roasting products.

As shown in Fig.7, the image revealed that larger metallic iron particles formed after reducing with optimum dosages of sodium salts, which is favorable for magnetic separation process.

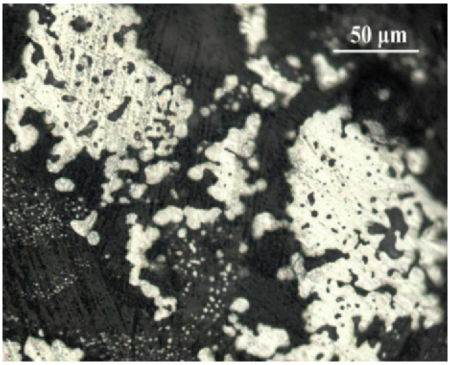

Fig.7 Image of roasted products

XRD patterns of the products. Fig.8 shows XRD patterns for iron concentrate and alumina rich residue products. From XRD results, it can be concluded that, the primary mineral in magnetic materials is metallic iron and with a little amount of sodium aluminosilicate. While the sodium aluminosilicate mainly occurring in nonmagnetic materials, contained little aluminates. Therefore, iron in the diaspore type bauxite with high iron content ores can be separated and extracted effectively. The aluminum, silica in raw material also get concentrate in residue at the end.

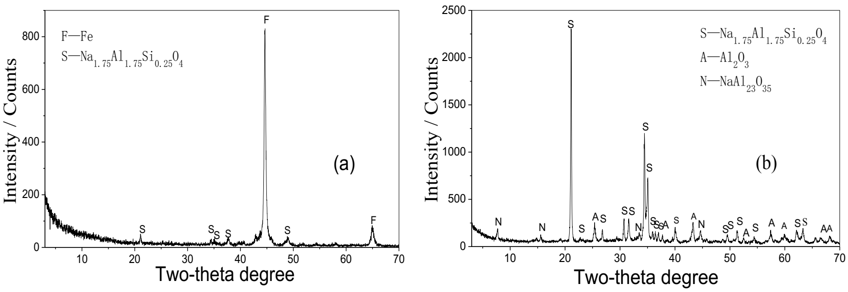

Fig.8 XRD patterns of the final products (a: Iron concentrate; b: Alumina-rich residue)

Conclusions

The results of treating hematite-rich diaspore by direct reduction followed by magnetic separation reveals that direct reduction cannot realize completely separating and recovering of iron without adding sodium salts during roasting process, metallization of iron is less than 65% and total iron in concentrate only reached maximum 56.13%. But, effects of sodium salts in roasting research reveals that the reduction and recovering of iron improved slightly using additives singly, and reached maximum of metallization of iron 77.93% in roasted products, total iron of 72.40% in concentrate with the dosage of sodium carbonate 40%. However, recovering and separating of iron are enhanced dramatically by adding three kinds sodium salts during reduction roasting. In particularly, metallization of iron over 90% in roasted products, and iron grade of 88.17% with recovery of 92.51% in concentrate were obtained, which is could take as raw material for ironmaking process. And the final products properties indicated that main phase is metallic iron in iron concentrate and aluminosilicate in alumina rich residue, respectively.

Acknowledgements

The authors would like to gratefully acknowledge the financial supports from National Science foundation of china (No 51174230, 51234008) and the Program for New Century Excellent Talents in University (NCET-11-0515).

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