

# **The Minerals, Metals & Materials Series**

Hojong Kim · Bradford Wesstrom  
Shafiq Alam · Takanari Ouchi  
Gisele Azimi · Neale R. Neelameggham  
Shijie Wang · Xiaofei Guan  
Editors

# Rare Metal Technology 2018

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# Preface

*Rare Metal Technology 2018* is the proceedings of the symposium on Rare Metal Extraction and Processing sponsored by the Hydrometallurgy and Electrometallurgy Committee of the TMS Extraction and Processing Division. The symposium has been organized to encompass the extraction of rare metals as well as rare extraction processing techniques used in metal production and mineral processing. This is the fifth symposium since 2014, which will be held in Phoenix, Arizona, USA.

This symposium intends to cover research and developments in the extraction and processing of less common, rare metals that are not covered by other TMS symposia. These elements include antimony, bismuth, barium, beryllium, boron, calcium, chromium, gallium, germanium, hafnium, indium, manganese, molybdenum, platinum group metals, rare-earth metals, rhenium, scandium, selenium, sodium, strontium, tantalum, tellurium, and tungsten. These are rare metals of low tonnage sales compared to high tonnage metals such as iron, copper, nickel, lead, tin, zinc, or light metals such as aluminum, magnesium, or titanium and electronic metalloid silicon. Rare processing includes biometallurgy, hydrometallurgy, and electrometallurgy, as well as extraction of values from electric arc furnace (EAF) dusts, and less common waste streams not discussed in recycling symposia. Rare high-temperature processes included microwave heating, solar-thermal reaction synthesis, molten salt electrochemical processes, cold crucible synthesis of the rare metals, and the design of extraction equipment used in these processes as well as laboratory and pilot plant studies.

This volume covers extraction and processing techniques of various platinum group metals, rare earth elements as well as other less common metals such as lead, antimony, molybdenum, tungsten, chromium, titanium, and vanadium, including electrochemical processing, aqueous processing, biological separation, and microwave heating. The symposium is organized into the following sessions: (1) rare earth elements, (2) platinum group metals, (3) base and rare metals (Ni, Cu, Zn, Pb, Sb, Mn, Li, Cs, and Ga), and (4) Ti, V, Mo, and W.

We acknowledge the efforts of the symposium organizers and proceedings editors: Hojong Kim, Bradford Wesstrom, Shafiq Alam, Takamichi Ouchi, Gisele Azimi, Neale R. Neelameggham, Xiaofei Guan, and Shijie Wang. The support from

TMS staff members Carol Matty and Patricia Warren is greatly appreciated in assembling and publishing the proceedings. We sincerely thank all the authors, speakers, and participants and look forward to continued collaboration in the advancement of science and technology in the area of rare metal extraction and processing.

Hojong Kim  
Lead Organizer

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## About the Editors



**Hojong Kim** is an Assistant Professor of Materials Science and Engineering, and Norris B. McFarlane Faculty Professor at the Pennsylvania State University. Dr. Kim received his B.S from Seoul National University in South Korea in 2000 and Ph.D. degree from Massachusetts Institute of Technology (MIT) in 2004 both in Materials Science and Engineering. His doctoral research sought to identify the corrosion mechanisms of constructional alloys in high-temperature and high-pressure steam environments under Prof. Ronald Latanision in the Uhlig Corrosion Laboratory at MIT. After graduate research, he worked as a Senior Research Scientist at Samsung-Corning Precision Glass Co. Ltd. and as a project lead to improve the process yield for TFT-LCD glass melting processes. After five years of industrial experience, he returned to MIT as a post-doctoral associate to contribute to the growing need for sustainable technology. He conducted research on high-temperature electrochemical processes, including molten oxide electrolysis for carbon-free steel production with focus on developing inert anode materials in molten slags as well as molten salt liquid metal batteries for large-scale energy storage.

His current research interests embrace the development of environment-friendly electrochemical processes for resource extraction/recycling, corrosion-resistant materials, as well as energy storage systems. He was awarded The Minerals, Metals & Materials Society (TMS) Young Leaders Professional

Development Award in 2013 from the Extraction and Processing Division. In 2015, he was chosen to receive a Doctoral New Investigator Award from the American Chemical Society Petroleum Research Fund. He is currently leading efforts to separate alkali/alkaline-earth fission products from molten salt electrolytes used for recycling used nuclear fuel. He is the lead organizer of the Rare Metal Extraction and Processing Symposium at the TMS 2018 Annual Meeting and is the Chair of the Hydrometallurgy and Electrometallurgy Committee of the Extraction and Processing Division.



**Bradford Wesstrom** is the Senior Process Engineer for Freeport McMoRan at the El Paso Refinery. In 1989, he received his B.S. degree in Metallurgical Engineering from the University of Texas at El Paso. He has worked within the copper industry for over 34 years, covering areas of smelting, casting, electrorefining, electrowinning, acid purification, metal hydrolysis, metal salts production, roasting, precious metals recovery by pyrometallurgy and hydrometallurgy, pressure leaching, cementation, mechanical vapor recompression for water recovery, copper rod production, and water treatment. He has published on the above areas and given numerous talks at conferences, including TMS, ASTM, STDA, IPMI, IMM, and CANMET.



**Shafiq Alam** is Associate Professor at the University of Saskatchewan, Canada. In 1998, he received his Ph.D. degree in Chemical Engineering from Saga University, Japan. From 1999 to 2001, he was appointed as a Postdoctoral Research Fellow at the University of British Columbia and the University of Toronto, Canada.

Dr. Alam has extensive experience in industrial operations, management, engineering, design, consulting, teaching, research, and professional services. Before joining the University of Saskatchewan in 2014, he was an Assistant/Associate Professor at Memorial University of Newfoundland for about 7 years. Prior to starting his career in academia, he

worked with many different companies, such as Shell, Process Research ORTECH Inc., Fluor Canada Ltd., and the National Institute of Advanced Industrial Science and Technology (AIST), Japan. He is highly experienced in the area of mineral processing and extractive metallurgy, and he possesses 2 patents and has over 150 publications. He is the co-editor of six books and an associate editor of the *International Journal of Mining, Materials and Metallurgical Engineering* (IJMME). He is the winner of the 2014 TMS Extraction and Processing Division's Technology Award.

He is a registered professional engineer and has worked on projects with many different mining companies including Falconbridge, INCO (Vale), Barrick, Hatch, Phelps Dodge, Rambler, and Anaconda. He is an Executive Committee Member of the Hydrometallurgy Section of the Canadian Institute of Mining, Metallurgy and Petroleum (CIM). During 2015–2017, he served as the Chair on the Hydrometallurgy and Electrometallurgy Committee of the Extraction and Processing Division (EPD) of The Minerals, Metals & Materials Society (TMS). He is a co-organizer of many symposia at the international conferences through CIM and TMS. He is one of the founding organizers of the Rare Metal Extraction and Processing Symposium at TMS.



**Takamari Ouchi** is a Research Associate in the Institute of Industrial Science at the University of Tokyo. He received his Ph.D. in Nanoscience and Nanoengineering from Waseda University in 2011. He developed electrochemical deposition processes to fabricate metal nanostructures with both well-controlled crystallinity and uniformity at the single nanometer scale and demonstrated the applicability of these processes to fabrication of bit-patterned magnetic recording media for future hard disk drives. After completing his doctoral degree, Dr. Ouchi joined the Massachusetts Institute of Technology (MIT), where he developed liquid metal batteries, which is in principle a bidirectional electrolysis (electrorefining) cell, to apply for the grid-scale energy storage. As a research scientist, he led the systematic investigation of

electrochemical properties of liquid metal electrodes in molten salt electrolytes and developed novel lithium, calcium, and sodium liquid metal batteries. He authored 17 peer-reviewed papers and conference proceedings and presented 50 talks at conferences. He has constantly contributed to create the vibrant field of metal extraction by working as a Member of Hydrometallurgy and Electrometallurgy Committee at TMS, organizing technical symposiums at TMS and soliciting papers as a guest editor of *JOM*. He has earned several awards and honors, such as TMS Extraction and Processing Division (EPD) Young Leaders Professional Development Award in 2015 based on his reputation in the electrochemical metal extraction processing.



**Gisele Azimi** is an Assistant Professor cross-appointed between the Departments of Chemical Engineering and Applied Chemistry, and Materials Science and Engineering at the University of Toronto. She is an expert in the fields of materials extraction, processing, and recovery using hydrometallurgical, electrochemical, and supercritical processes. Her research program is mainly focused on the extraction and recovery of strategic materials, mainly rare earth elements, precious metals, lithium, and iron. This includes molten salt electrolysis and supercritical fluid extraction of rare earth elements as well as recovery of these elements from secondary sources. Another thrust of her research program is focused on the design and fabrication of advanced materials and surfaces with controlled properties. She has received a number of awards including the TMS Light Metals/Extraction and Processing Subject Award, CIM Gordon Ritcey Outstanding Award, and TATP Teaching Excellence Award.



**Neale R. Neelameggham** is ‘The Guru’ at IND LLC, involved in international consulting in the fields of metals and associated chemicals (boron, magnesium, titanium, and lithium and rare earth elements), thiometallurgy, energy technologies, soil biochemical reactor design, etc. He was a Visiting Expert at Beihang University of Aeronautics and Astronautics, Beijing, China. He was a Plenary Speaker at the Light Metal Symposium in South Africa—on low carbon dioxide emission processes for magnesium. Dr. Neelameggham has more than 38 years of expertise in magnesium production and was involved in process development of its start-up company NL Magnesium through to the present US Magnesium LLC, UT until 2011. Neelameggham and Brian Davis authored the ICE-JNME award-winning (2016) paper “21st Century Global Anthropogenic Warming Convective Model,” which notes that constrained air mass warming is independent of the energy conversion source—fossil or renewable energy. He is presently developing Agricoal™ and agricoalture to improve arid soils. He holds 16 patents and patent applications and has published several technical papers. He has served in the Magnesium Committee of the Light Metals Division (LMD) of TMS since its inception in 2000, chaired it in 2005, and in 2007, he was made a permanent co-organizer for the Magnesium Symposium. He has been a member of the Reactive Metals Committee, Recycling Committee, Titanium Committee, and Program Committee Representative of LMD and LMD council. He was the inaugural chair, when in 2008, LMD and EPD (Extraction & Processing Division) created the Energy Committee, and has been a co-editor of the energy technology symposium proceedings through the present. He received the LMD Distinguished Service Award in 2010. While he was the chair of Hydro- and Electrometallurgy Committee, he initiated the rare metal technology symposium in 2014. He is co-editor for the 2018 proceedings for the symposia on Magnesium Technology, Energy Technology, Rare Metal Technology, and Solar Cell Silicon.



**Shijie Wang** is a Principal Advisor at the Rio Tinto Kennecott Utah Copper in Salt Lake City. Dr. Wang has been active in extractive metallurgy and has 30 years of experience and expertise in metallurgical process development, existing operation optimization, and troubleshooting. His work interests include extractive and process metallurgy, recycling, waste treatment, metal recovery, operational efficiency, and profitability. He holds three U.S. patents and has published more than 40 journal papers including non-ferrous metals', precious metals', rare metals', and rare earth metals' resourcefulness and recoveries. He received a B.S. degree in Mineral Process from China, and an M.S. degree and a Ph.D. degree in Metallurgical Engineering from the University of Nevada, Reno. He has been very active in TMS since 1991 and is the Former Chair of the Hydrometallurgy and Electrometallurgy Committee of TMS from 2011 to 2013. He has been the lead and co-organizer of six symposia at the international conferences through TMS. He received the TMS Extraction and Processing Division (EPD) Distinguished Service Award in 2017.



**Xiaofei Guan** is an Assistant Professor in School of Physical Science and Technology at ShanghaiTech University. His primary research interest is in understanding chemical and electrochemical processes for materials synthesis and energy conversion with the goal of improving efficiency and reducing environment impact. He received his B.S. degree in Applied Physics from Nankai University in 2009 and Ph.D. degree in Materials Science and Engineering from Boston University in 2013. His Ph.D. research was on magnesium recycling and electrolytic production of energy-intensive metals from oxides. In 2014, he joined Harvard University as a Postdoctoral Fellow and led research on energy conversion and storage devices including solid oxide fuel cells, protonic ceramic fuel cells, and hydride-air batteries and later worked on synthesis of iron sulfides particularly for solar energy application, which is a joint project between materials, microbiology, and electrochemistry.

Dr. Guan received the Outstanding Ph.D. Dissertation Award in Materials Science and Engineering from Boston University in 2014 and the Young Leaders Professional Development Award from the TMS Extraction and Processing Division in 2015. He also serves as an Advisor and Guest Editor in the Recycling and Environmental Technology Committee for *JOM*.