Toward Resources and Processes Sustainability: Part I

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We are living in a time of ever-increasing demands on materials, energy, and the environment. To meet these challenges, there is a critical need for a sharp transition toward resources and processes sustainability. This special topic presents the latest work on various recycling and environmental technologies that advance sustainable resources and processes. Due to the strong response to this theme, the papers will be published in two parts, in February and April. This issue presents nine contributions covering valuable metals recovery from discarded devices or components, metals extraction from oxides, and comprehensive utilization of natural resources or industrial waste.

Rare earth elements are critical for modern technology, and their recycling will not only help mitigate global dependence on freshly mined rare earth elements but also bring economic and environmental benefits. In this special topic, Nlebedim and King have provided a review on addressing criticality in rare earth elements via recycling waste permanent magnets. The authors have discussed the market trends, the resource sustainability, the technical considerations for recycling different forms of waste permanent magnets, as well as the challenges to address to establish industrially deployable technologies.

Another paper is focused on recovering precious and base metals from waste printed circuit boards. In recent years, printed circuit boards from discarded electronics have become an important source for raw materials such as metals, ceramics, and plastics. In this special topic, Batnasan et al., have proposed recovering precious and base metals from waste printed circuit boards via a combined hydrometallurgical method consisting of high-pressure oxidative leaching and thiourea leaching. Thiourea is selected as an alternative to cyanide

that has potential environmental and human health risks. The optimized thiourea leaching process allows a more effective extraction of precious metals such as Au, Ag, and Pd than the conventional cyanidation process. This work represents a promising approach for effectively recovering valuable metals from waste printed circuit boards.

This special topic also features two papers on electrometallurgical recovery of metals. The electrochemical process is often considered as a green route for producing valuable metals, alloys, intermetallics, and composites from their respective oxides. In this topic, Hu et al., provide an overview of the Fray–Farthing–Chen (FFC) Cambridge process for the sustainable production of titanium and its alloys, focusing on two aspects: (1) resource and process sustainability and (2) advanced post-extraction processing. For example, the FFC Cambridge process can handle different lower cost feedstocks, and it can also use an inert anode (e.g. $\text{CaTiO}_3\text{-CaRuO}_3$) to replace the carbon anode to avoid CO_2 emission. In addition, the titanium powder products can be fed into 3D printers to manufacture affordable objects of complex shape or geometry. The developments of the FFC Cambridge process are promising for a sustainable titanium industry.

The solid oxide membrane electrolysis process is another promising electrometallurgical technique for directly extracting metals from their oxides and forming useful metal compounds. Zheng et al., have reported the successful production of a $\text{Ti}_5\text{Si}_3/\text{TiC}$ composite from a $\text{TiO}_2/\text{SiO}_2/\text{C}$ pellet in molten CaCl_2 by using solid oxide membrane electrolysis. $\text{Ti}_5\text{Si}_3/\text{TiC}$ composites are promising candidates for various high-temperature applications, and are traditionally synthesized by using spark plasma sintering or in situ reaction/hot-pressing methods at much higher temperatures. The solid oxide membrane electrolysis brings various advantages such as simpler design, lower energy use and lower emission, and therefore it is an attractive approach to explore for synthesizing such refractory materials in an effective and environmentally friendly way. In

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addition, the authors have also revealed the reaction steps involved in the $\text{Ti}_5\text{Si}_3/\text{TiC}$ formation process based on a series of well-designed time-dependent electrochemical experiments.

Several papers are presented on the comprehensive utilization of natural resources or industrial waste. For example, Sun et al., have reported a process for iron and phosphorus recovery from high-phosphorus refractory iron ore. The process involves a coal-based reduction of the iron ore, followed by magnetic separation of metallic iron and dephosphorization with a slag system. The iron product can be used as feedstock for steelmaking after a secondary refining, and the phosphorus can be extracted from the slag to produce phosphate fertilizer. This process represents a promising approach for transforming high-phosphorus refractory iron ore into useful products.

Another paper is focused on utilizing copper smelting slag and nickel laterite, important secondary resources, to prepare crude Fe-Ni-Cu alloys, as reported by Guo et al., During a co-reduction process, copper slag serves as an activating agent to facilitate melting phase formation and thereby accelerates metallic particles aggregation. The Fe-Ni-Cu alloy product can be used to produce weathering resistant steel by electric arc furnace to replace scrap steel and expensive electrolytic copper and nickel.

A novel ultrasound-assisted bleaching technique has been applied by Wen et al., to improve the extraction of vanadium and chromium from high-chromium vanadium slag. Compared with regular bleaching, ultrasound-assisted bleaching not only increases the bleaching rate significantly for vanadium and slightly for chromium but also decreases the reaction time and leaching temperature. This method is technically feasible and shows promise for the comprehensive utilization of high-chromium vanadium slag.

Another paper is focused on manufacturing ammonium paratungstate, which is known as the main intermediate product in industrial tungsten extraction. Shen et al., have reported manufacturing ammonium paratungstate by treating a mixed wolframite-scheelite concentrate in sulfuric acid followed by leaching in ammonium carbonate solution. Specifically, they have systematically investigated wolframite conversion, which is more difficult than scheelite conversion, and revealed the underlying mechanism. This work is useful for developing a clean technique of manufacturing ammonium paratungstate.

The last paper is on vanadium recovery from oil fly ash, which is a kind of waste generated by petroleum-based power plants. The oil fly ash has high concentrations of unburned carbon and vanadium, and therefore can be a secondary resource for vanadium. Jung and Mishra have proposed recovering vanadium from oil fly ash by carbon removal

followed by salt roasting and water leaching. A recovery rate of about 92% was achieved by water leaching after salt roasting at 650°C with sodium carbonate. This three-step process represents an effective approach for vanadium recovery.

Sustainable solutions are needed for addressing the challenges in materials supply, energy, and environment. These papers show examples from various application areas for advancing resources and processes sustainability. Continuous development of recycling and environmental technologies will be key to building a sustainable future.

The following papers are published under the topic “Toward Resources and Processes Sustainability: Part I” in the February 2018 issue (vol. 70, no. 2) of *JOM* and can be accessed via the *JOM* page at <http://link.springer.com/journal/11837/70/2/page/1>.

- “Addressing Criticality in Rare Earth Elements via Permanent Magnets Recycling” by Ikenna C. Nlebedim and Alexander H. King.
- “Recovery of Precious and Base Metals from Waste Printed Circuit Boards by Using a Sequential Leaching Procedure” by Altansukh Batnasan, Kazutoshi Haga, and Atsushi Shibayama.
- “Development of the Fray–Farthing–Chen Cambridge Process: Towards the Sustainable Production of Titanium and Its Alloys” by Di Hu, Aleksei Dolganov, Mingchan Ma, Biyash Bhat-tacharya, Matthew T. Bishop, and George Z. Zhen.
- “Electrolytic Production of $\text{Ti}_5\text{Si}_3/\text{TiC}$ Composites by Solid Oxide Membrane Technology” by Kai Zheng, Xingli Zou, Xueliang Xie, Changyuan Lu, Chaoyi Chen, Qian Xu, and Xiong-gang Lu.
- “Comprehensive Utilization of Iron and Phosphorus from High-phosphorus Refractory Ore” by Yongsheng Sun, Qi Zhang, Yuexin Han, Peng Gao, and Guofeng Li.
- “Co-reduction of Copper Smelting Slag and Nickel Laterite to Prepare Fe-Ni-Cu Alloy for Weathering Steel” by Zhengqi Guo, Jian Pan, Deqing Zhu, and Feng Zhang.
- “Comparison of Ultrasound-assisted and Regular Leaching of Vanadium and Chromium from Roasted High Chromium Vanadium Slag” by Jing Wen, Tao Jiang, Huiyang Gao, Yajing Liu, Xiaole Zheng, and Xiangxin Xue.
- “Wolframite Conversion in Treating a Mixed and Wolframite-Scheelite Concentrate by Sulfuric Acid” by Leiting Shen, Xiaobin Li, Qiusheng Zhou, Zhihong Peng, Guihua Liu, Tianguai Qi, and Pekka Tashinen.
- “Vanadium Recovery from Oil Fly Ash by Carbon Removal and Roast-Leach Process” by Myung-won Jung and Brajendra Mishra.