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Review

A critical review of material flow, recycling technologies, challenges and future strategy for scattered metals from minerals to wastes

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A B S T R A C T

Scattered metals play irreplaceable role in some clean energy technologies and advanced materials, and they will become much more important in the future. Global consumption of scattered metals has significantly grown in recent decades. However, at present, imbalances of exploitation, manufacturing and recycling of scattered metals are quite severe resulting in some uncertain supply risk. Hence, securing reliable, ordered and sustainable access to these scattered metals from minerals, functional products to wastes is necessary. This paper focuses on scattered metals in wastes and investigates minerals distribution, material flow, and current recycling technology of scattered metals from minerals to wastes. Especially, for the recycling technology, some representative methods including selective extraction, ion exchange and flotation, precipitation and vacuum metallurgical technology etc, the specific procedures, reagent, optimization and recycling situation of scattered metals were summarized in the review. Meantime, environmental and supply risk, and recycling challenges are expounded in detail. Although these technologies had obtained quite satisfactory results for recycling of a certain scattered metals in wastes, it is no deny that current technologies still have some challenges for further promotion. Overexploitation, disordered mining and the imbalance of the exploitation, production and recycling had also increased supply risk and environmental risk. For recycling technology, the shortages and defects of each technology are discussed from the perspective of technological promotion and environmental protection in the review. Furthermore, future replying strategies for scattered metals from wastes from the perspective of mining governance, environmental and supply sustainability, and technological improvement were proposed.

Contents

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1. Introduction

In 1922, the geochemist Vernadsky put forward firstly the concept of scattered metals in periodic table, which existed low content (generally 10^{-9}-10^{-6} ppm), decentralized state and rarely formed independent minerals in nature. Generally, this group of chemical elements: germanium (Ge), gallium (Ga), indium (In), selenium (Se), tellurium (Te), rhenium (Re) and thallium (Tl), have been named scattered metals (Zhai and Zhou, 2009; Zhou and Chen, 2008). In recent years, demand for some scattered metals, especially Ge, Ga and In has grown more rapidly than demand for some commodity metals (Glavinović et al., 2017; Helander et al., 2011). Growing demand for the scattered metals mainly comes from clean energy technologies as well as consumer products such as solar photovoltaic, smartphone (Liu et al., 2008), semiconductor materials (Xia et al., 2017), new functional materials and special alloys (Zweibel, 2010). For example, in the manufacture of advanced electronic and optical devices, gallium can be applied in the field of photovoltaic cells and thermal solar cells (Malaquias et al., 2017; Posthuma et al., 2005). Germanium is added into optical fiber material to promote the performance of communication. Globally, 70% indium is applied in indium tin oxide (ITO) conductive film in liquid crystal display (LCD) industry (Zhang et al., 2015b). These scattered metals are irreplaceable in these advanced materials. While the scattered metals are generally used in low volumes relative to other resources, the anticipated deployment of these advanced materials could substantially increase worldwide demand of the scattered metals.

Entering the 21st century, some metals which played important role in national security and development of industry were listed as the critical raw materials in some developed countries. The United Nations Environment Programme (UNEP) and European Union (EU) reports have identified gallium, germanium, indium and tellurium of scattered metals as critical raw materials (European Commission, 2013; Erdmann and Graedel, 2011). Forecasts indicated that demand might more than triple for germanium, gallium and indium by 2030 compared with the 2006 level. Their reports suggested that future shortages were likely for the critical raw materials, especially Ge, Ga and In. Such shortages will affect applications such as LCD, thin film photovoltaic modules (copper indium gallium selenide cells (GIGS), CdTe and GaAs), virtually all of which require one or more of the scattered metals (Amund et al., 2015; Jean et al., 2015). Germanium, gallium and indium also have been listed as strategic reserves in United States, and reserves keep in 20–40 tons per year (Zhou and Chen, 2008).

According to global primary supply of critical raw materials from survey of European Union (European Commission, 2010), China was the leading exporter of primary products of scattered metals. Worldwide, primary products of 59% germanium, 69% gallium and 58% indium were supplied from China. Supply of other scattered metals, such as tellurium and rhenium were also very prominent, which reach 24% and 4.8%, respectively. The excessive exports of primary products increased supply risk of scattered metals. More importantly, if these scattered metals have not got a sustainable exploitation and use, it is quite disadvantageous for sustainable development of China's mining resource.

On the other hand, some challenges from recycling of the wastes containing scattered metals are still growing, especially for the recycling technologies. For example, recycling of scattered metals in the high-tech products is more and more difficult because low proportion in products and complexity. In addition, the investigations on the distribution of minerals, functional products and end uses are also considerably lack. Hence, a complete recycling system throughout the life cycle of scattered metals is hard to be established. Facing on the unsustainable situation of increasing demand, increasing supply risk and low recovery for scattered metals, it is necessary for investigation to be done on mineral distribution, material flow, current recycling technologies and future strategy for scattered metals.

This review focuses on mineral distribution, material flow, supply situation and recycling technologies of scattered metals which included all seven elements. In the investigation of scattered metals from minerals to wastes, environmental risk, supply risks, recycling challenges, future strategy and recycling perspectives are expounded in detail. This review can benefit to propose scientific and effective strategies of exploitation, manufacturing, and recycling for scattered metals in the future.