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CHALLENGES AND OPPORTUNITIES OF INCREASING MATERIALS CIRCULARITY: A Focus on Critical Metal Recovery from Electronic Waste

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Editor's Note:

This article is a summary of the authors' response to the 2023 Circular Economy Request for Information: Challenges and Opportunities of Increasing Materials Circularity, a call for information issued by the U.S. Department of Energy's Advanced Materials & Manufacturing Technologies Office (AMMTO) in March 2023. Information can be found at www.energy.gov/eere/ammto/2023-circular-economy-request-information-challenges-and-opportunities-increasing.

The Urgent Need for a Secure Supply Chain for Critical Materials

The world confronts unprecedented challenges in coordinating responses to emergent conditions including global climate change, population growth, and international security. These challenges have also stimulated rapid advances in software technologies. Among them is the development of artificial intelligence (AI) designed to support predictive and responsive strategies for processing and interpreting "big data." Yet, such software advances rely on hardware technologies, for which the supply of critical materials needed to sustain their manufacture and production at scale is increasingly uncertain.

The currently unsustainable supply chain of critical materials led to the recent circular economy request for information issued by the U.S. Department of Energy's Advanced Materials and Manufacturing Technologies Office (AMMTO). In this context, critical materials are defined as high-priority metals and semimetals with specific technological applications, and the susceptibility to supply chain constraints resulting from factors such as scarcity, price volatility, declining ore grades, and environmental burden.

Critical metals have proven to be un-substitutable in various cutting-edge applications due to their unique structural and functional properties. Specifically, the innovative use of critical metals such as cobalt, lithium, nickel, and rare earth elements (REEs) dysprosium, terbium, and neodymium, have enabled technologies with enhanced electrical, mechanical, thermal, magnetic, and optical functions. Other materials that are designated as ‘critical’ include precious metals such as gold, silver, platinum, and palladium, which have broad applications across many industries.

Strategies to increase the circularity of critical materials present special opportunities for research and development to generate quantitative databases and tools, including AI for assessments of environmental life cycle and functional performance, for integrating social and ecological incentives in recycling and resource recovery, and for overcoming techno-economic barriers against the transition from a linear to a circular economy. Thus, the request from AMMTO explicitly calls for an investigation into the “potential for electronic waste (e-waste) to be a viable source of critical materials.” The trend toward circularity in the electronics industry has long been a topic of research and international regulations, but major impediments remain unresolved.[1, 2] This article focuses on this particular topic by emphasizing strategies to recover critical metals from e-waste.

The integration of critical metals in manufacturing has spurred technological breakthroughs and engendered industries such as electronics, automobiles, and energy capture, all of which have revolutionized the landscape of human societies in the 21st century. Advanced electronic products are now manufactured with a wide range of critical metals that are embedded in miniaturized components and consolidated circuitry. All electronic products rely on printed circuit boards (PCBs) and the various electronic components attached to them, which contain a wider variety and higher concentration of critical metals compared to any other electronic hardware component.[3]

At present, the electronic equipment sector is the largest consumer of critical metals, for which global resource demand is projected to double by 2030. Competition for the supply of newly mined critical metals cuts across various electronic manufacturers and industrial sectors, while potential secondary sources are routinely discarded as e-waste, which has become a notorious source of toxic environmental pollution. Recycling domestic waste printed circuit boards (WPCBs) to recover critical metals not only offers high economic value, but also facilitates the establishment of a circular supply chain that avoids fraught reliance on international sources of newly mined metals.

Limitations of Current Technologies for Resource Recovery from E-Waste

Existing technologies for recycling WPCBs do not operate at the scale necessary to ensure full circularity because of a constellation of environmental, technical, and economic limitations.[4]

The current methods, initially designed for the recovery of base metals like copper and a limited range of precious metals (such as gold), involve mechanical processing, high-temperature smelting, and chemical leaching. Unfortunately, these methods yield a low recovery rate of critical metals, while generating toxic emissions. For example, it is estimated that the pre-processing of WPCBs by mechanical size reduction and physical separation (i.e., gravity, magnetic, and electrostatic methods) results in a total dissipative loss of 30% in the initial volume of feed materials.[5] During this process, precious metals (gold, silver, palladium) and critical metals (cobalt, tantalum, nickel) are dissipated as fine dust and airborne particulates.

The extraction of metals from e-waste predominantly takes place in copper smelters, where operating temperatures often exceed 2,000°C. Although this method is effective in reducing the volume of hazardous e-waste, it has thermodynamic limitations to targeted resource recovery. For example, critical metals cobalt, gallium, germanium, yttrium, tantalum, and tungsten and REEs do not readily dissolve in liquid copper and are either gasified and lost as particulates in the fume exhaust or accumulate in the slag phase.[5]

Additionally, large volumes of sulfur dioxide emissions, mixed metal oxides, persistent organic pollutants, and particulate matter are released during the various stages of smelting and subsequent refining processes. Chemical leaching methods require large volumes of highly corrosive and volatile reagents such as cyanide and halides, which produce toxic fumes, spent solvents, and complex sludge waste. There is an urgent need to develop improved methods for extracting critical metals from WPCBs to incentivize efficient resource recovery at an industrial scale.

The Potential and Promise of Cryogenic Milling of E-Waste for Resource Recovery

Preliminary data from laboratory-scale studies support the potential viability of cryogenic milling as a more environmentally sustainable alternative to the existing-waste recycling methods. This waste beneficiation route simultaneously functions as an efficient strategy for synthesizing large quantities of nanoparticles with superior structural and functional properties, while promising to fill the gap in the increasing demand for nano-based technologies.

During cryogenic milling, materials are mechanically milled at temperatures below −150°C, which is maintained by a continuous flow of liquid nitrogen and/or liquid argon. This technique hinges on the emergent properties of materials at below-zero temperatures to promote cold embrittlement, early fracture, and rapid grain refinement.[6] Specifically, materials such as amorphous polymers, ceramics, and metals with body-centered cubic (BCC) or hexagonal close-packed (HCP) lattice structures undergo ductile to brittle phase changes as they reach specific glass transition temperatures.[7] The BCC metals of interest include lithium, tantalum, niobium, and tungsten; while HCP metals of potential interest include cadmium, titanium, and cobalt. Other metals with face-centered cubic (FCC) crystalline lattices lose substantial plasticity and form mobile dislocations that lead to grain refinement.[7, 8] Examples of metals that exhibit FCC lattice structures include copper, aluminum, silver, gold, and nickel.

Milling at cryogenic temperatures effectively suppresses recrystallization, cold welding, and agglomeration of particles, which would otherwise occur with room-temperature mechanical milling. In this regard, cryogenic milling is suitable for processing complex heterogeneous waste into recyclable elements and generates different classes of nanomaterials based on the length of milling time. Initial disassembly of electronic components should not be necessary because explosive materials can be safely milled below their ignition temperature. The consolidation of particles within a tightly closed system further reduces the risk of environmental pollution from fugitive dust.

Cryogenic milling of WPCBs aligns with safe-by-design strategies because it may be configured as a stand-alone process and does not require multiple phases and steps.[9] Thus, occupational and environmental health concerns are minimized due to suppression of the reactivity of materials at cryogenic temperatures, in comparison with current methods of e-waste management encumbered by contamination and hazardous emissions associated with the thermal degradation of polymers, halogenated flame retardants, and toxic metals.

Cryogenic milling of e-waste can be leveraged as a strategic approach to sustainable resource management by synchronizing the principles of green chemistry and materials circularity, thereby avoiding side effects that have compromised regrettable solutions to resource recovery technologies.

Next Steps

In the context of a circular economy, the mining of e-waste is a reliable opportunity to support U.S. industries with a sustainable secondary source of raw materials. The recovery of critical metals from WPCBs can unlock an untapped economic potential by producing valuable resources while reducing the environmental and social pressures of processing e-waste and extracting primary material resources. Much research and development work remains, and the necessary regulatory infrastructure needs to be implemented to support a strategic transition from the current linear economy of WPCBs to circularity.

First, existing national policies can benefit from incentives and enforcement to ensure that most if not all e-waste generated is collected from consumers, and international regulations that govern the transboundary movements of e-waste need to be strengthened. In the U.S., the Department of Justice’s contract with UNICOR (the Federal Prison Industries program), in an initiative to collect and recycle e-waste through the federal prison system, can serve as an opportunity to pilot procedures for critical metals recovery.

Second, research is needed to ensure the cost-effectiveness of relatively new approaches such as cryogenic milling of e-waste to emphasize targeted recovery of critical metals.

Third, the marketability of recycling processes should consider the optimal level of purity in recovering critical metals to incentivize implementation and scale-up by industry.[7] In the case of nanotechnology, the properties of marketable nanoparticles should be pre-defined for the intended applications.[5] Recycling and resource recovery operations also need to be monitored routinely to protect workers and the environment by eliminating or reducing potentially toxic emissions.

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