Journal of Cleaner Production 127 (2016) 19–36

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Review

A review of current progress of recycling technologies for metals from waste electrical and electronic equipment

Lingen Zhang, Zhenming Xu*

School of Environmental Science and Engineering, Shanghai Jiao Tong University, 800 Dongchuan Road, Shanghai 200240, People's Republic of China

A R T I C L E I N F O

Article history:
Received 2 November 2015
Received in revised form
3 April 2016
Accepted 4 April 2016
Available online 12 April 2016

Keywords:
Recycling technology
Waste electrical and electronic equipment (WEEE)
Metals
Environmental assessment

A B S T R A C T

The development of the recycling technologies for waste electrical and electronic equipment (WEEE) has entered a new stage. The WEEE disposing technologies have evolved from simple disassembly, classification and sorting to high value-added utilization technologies. In the past decade, some modified and novel technologies have been developed to recover metals from WEEE. This paper focuses on the recycling of metals from WEEE. The recycling principle, separating process, and optimized operating parameters of existing technologies are summarized and discussed in detail. Based on traditional recycling technologies of WEEE, pyrometallurgical technology and some mild extracting reagent, such as chloride medium, ammonia–ammonium and non-cyanide lixiviants can effectively recycle metals. Compared with the conventional acid and cyanide leaching, they have vast improvements in aspect of environmental protection. More than 98% of Cu and 70% of Au can be extracted. In addition, electrochemical technology, supercritical technology, vacuum metallurgical technology, etc. are also applied to recycle WEEE. The recovery rate of Cu and Pb under optimum conditions is around 84.2% and 89.4% respectively in supercritical water oxidation (SCWO) combined with electrokinetic (EK) technology. Vacuum technology has good environmental performance due to its avoiding discharge of waste water. Other new technologies such as ultrasound technology, mechanochemical technology, and molten salt oxidation technology have also been tried to recycle metals from WEEE. Regrettably, although many endeavors to develop recycling technologies have been attempted, these technologies are still relatively single and limited because WEEE is a complex system. Hence, the shortages and defects of each technology are discussed from the perspective of technological promotion and environmental protection. Furthermore, the outlook about the further development of recycling technologies for metals from WEEE is presented.

Contents

Acronyms and abbreviations: WEEE, waste electrical and electronic equipment; BFR, bromined flame-retardant; Waste PCBs, waste printed circuit boards; PMO, precious metals operations; BMO, base metals operations; LIBs, lithium-ion batteries; SCW, supercritical water; BER, brominated epoxy resin; SCWO, supercritical water oxidation; SCM, supercritical methanol; EK, electrokinetic; XRD, X-ray diffractometer; LCD, liquid crystal display; CRTs, cathode-ray tubes; TCLP, toxicity characteristic leaching procedure; MSO, molten salt oxidation.

* Corresponding author. Tel./fax: +86 21 54747495.
E-mail address: zmxu@sjtu.edu.cn (Z. Xu).

http://dx.doi.org/10.1016/j.jclepro.2016.04.004
0959-6526/

1. Introduction

With new technological innovation, the replacement of equipment is persistently accelerating the occurrence of serious pollution problem resulting from waste electrical and electronic equipment (WEEE). The global amount of WEEE produced and disposed is sharply increasing over the past several decades. According to statistics of Kiddee et al. (2013), 500 million tons of computers were discarded between 1997 and 2007 in the United States and 610 million tons of computers became obsolete in Japan by the end of 2010. The same statistics indicate more than 1.1 million tons/year WEEE are generated in China, particularly from manufacturing industry, end-of-life appliances and imports from developed countries (Hadi et al., 2015). Every year, 20–50 million tons of WEEE are generated worldwide and this figure is growing by about 45 million tons/year (Ogunseitan, 2013).

The waste electrical and electronic products are diverse, including printed circuit boards (PCBs), television sets, refrigerators, computers, cell phones, batteries, etc. Table 1 shows the main components of typical WEEE, which were first listed in the Waste Electrical and Electronic Products Recycling Directory by Chinese government in 2011.

WEEE contains a variety of valuable materials, such as metals, glass, plastics and others. As can be seen in Fig. 1, WEEE is mainly composed of metals (~60% weight), followed by plastics (~15.21% weight), and CRT & LCD screen (11.87% weight).

Although WEEE accounts for only 3–5% in solid waste, the varieties and contents of valuable metals in it are far more than other forms of municipal waste (Li et al., 2015). As shown in Table 2, WEEE such as printed circuit boards, TV scrap has high content of base metals and the electronic devices such as personal computers and mobile phone scrap contains a large number of precious metals (Akcil et al., 2015; Cui and Zhang, 2008). Therefore, WEEE is worthy of the name of “urban mine”. According to a survey by Environmental Protection Agency, U.S., compared with primary metals production, recycling metal resources from WEEE has significant advantages, such as less secondary waste and lower energy consumption (He et al., 2006).

However, WEEE contains not only all kinds of metals, but other chemical components which are also quite complicated, such as plastics and brominated flame retardants (BFRs). If WEEE is not disposed or recovered properly, it will cause serious environmental pollution and even jeopardize human health (Wang and Xu, 2015). The main hazardous and useful materials of typical WEEE components are shown in Table 3. It has been reported that the occurrence of recycling of WEEE by environment-unfriendly, hazardous and primitive technologies in China has increased in the past decades (Ni et al., 2010). Massive amounts of dumping or open burning of WEEE took place in some cities of China.

Therefore, research on resource reutilization and safe disposal of the metals from WEEE has a great significance from the viewpoint of environmental protection. In the initial stage of WEEE recycling, simple and rough recovery processes were widely adopted. As shown in Fig. 2, ways of recycling metals from WEEE mainly include manual dismantling, hydraulic shaking bed separation, strong acid leaching, etc. The defects of these methods are huge, as they not only have low recovery efficiency, but also damage human health and environment. Facing the serious issue resulting from crude recycling of WEEE, the European Union Council passed WEEE Directive and the Restriction of Hazardous Substances (RoHS) Directive to limit the harmful composition in electronic products in January 2003. In the last decade, China has followed the same legislative trends and developed WEEE laws and directives (Gottberg et al., 2006).

Entering the 1970s, mechanical–physical separation methods began to be utilized to treat the WEEE (Zhang and Forssberg, 1998). Mechanical–physical separation steps included selectively dismantling, crushing and physical separation methods. The

Table 1
Main components of typical WEEE (He and Xu, 2014).

Typical WEEE	Main components
Refrigerator	Tubes, liners, condenser, wires, refrigerant
Air conditioner	Heat exchanger, motor, compressor, copper pipe, PCBs, wires, refrigerant
Washer	Tub, drain hose, motor, wires, salt waste
Television	Deflection yoke, demagnetized coil, speaker, PCBs, wires, CRTs, LCD
Computer	Speaker, battery, storage medium, PCBs, wires, CRTs, LCD
Cell phones	Plastic enclosure, battery, storage medium, PCBs, wires, LCD
Printer/duplicator	Roller, toner, PCBs, wires, toner cartridge

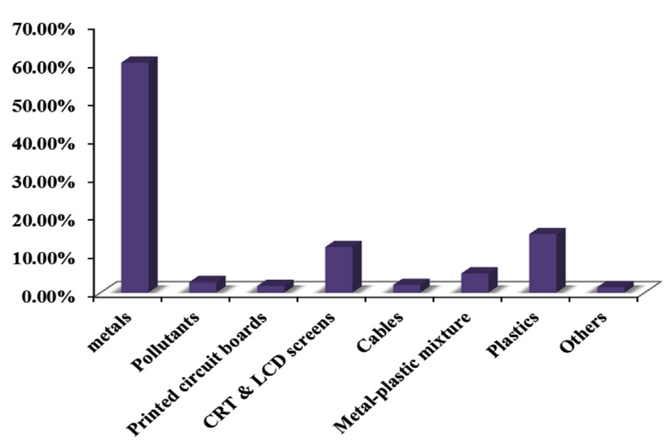

Fig. 1. Typical material fractions in WEEE (Wang and Xu, 2014).