Resources, Conservation and Recycling xxx (2017) xxx–xxx

Contents lists available at ScienceDirect

Resources, Conservation and Recycling

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

Full length article

Analysis of the metal content of small-size Waste Electric and Electronic Equipment (WEEE) printed circuit boards—part 1: Internet routers, mobile phones and smartphones

Stellan Holgersson[a,*], Britt-Marie Steenari[a], Max Björkman[b], Klas Cullbrand[b]

[a] Chalmers University of Technology, Department of Chemical Engineering, Industrial Materials Recycling, Kemivägen 4, SE-41296 Göteborg, Sweden
[b] Chalmers Industriteknik, Chalmers Teknikpark, SE-41288 Göteborg, Sweden

ARTICLE INFO

Article history:
Received 25 August 2016
Received in revised form 9 December 2016
Accepted 16 February 2017
Available online xxx

Keywords:
Waste Electric and Electronic Equipment
Aqua regia leaching
Metal concentration
Printed circuit boards

ABSTRACT

The metal content of printed circuit boards from three types of Waste Electric and Electronic Equipment (WEEE) products were analysed. The products disassembled to retrieve the printed circuit boards (PCBs) were 10 Internet routers, modems and hubs; 30 mobile phones; and 30 smartphones. The collected boards of each product type were milled to 2–3 mm fractions, cryo-milled further and then leached with aqua regia. Leaching solutions were analysed for Ag, Al, As, Au, Be, Bi, Cd, Cr, Cu, Fe, Hg, Ni, Pb, Pd, Pt, Rh, Sb, Sn and Zn. The leaching residues were pyrolysed, fused with $LiBO_2$ and analysed for Al, Ba, Be, Ca, Co, Cr, Fe, K, Mg, Mn, Mo, Na, Nb, P, Sc, Si, Sr, Ti, V, W, Y, Zr and Zn. The results gave a PCB weight of the total product weight of 43% for the routers and 21% for the two phone types. The main constituents of the PCBs were carbon polymers with a concentration of 34%, 30% and 25% for routers, mobile phones and smartphones, respectively and Cu, with a concentration of 22%, 34% and 40% for routers, mobile phones and smartphones, respectively. The concentrations of precious metals, Ag, Au and Pd, in PCBs were found to be 1213 ppm, 199 ppm and 20 ppm for the routers; 2640 ppm, 1051 ppm and 119 ppm for mobile phones; and 2773 ppm, 1083 ppm and 55 ppm for the smartphones, respectively. The concentrations of toxic metals, As, Be, Cr and Pb, in the PCBs were <70 ppm, 0.3 ppm, 506 ppm and 3413 ppm for routers; 93 ppm, 99 ppm, 953 ppm and 3747 ppm for mobile phones; and 141 ppm, 115 ppm, 1306 ppm and 260 ppm for smartphones, respectively. The results demonstrate that for toxic metals, the Pb content is lower in more modern smartphones compared with older mobile phones while the content of other toxic metals are fairly constant. For the routers, the Pb content was similar to the mobile phones, despite the later production year span (2004–2010) compared with the mobile phones (1999–2010). Regarding precious metals the contents of Ag and Au remain at same level when comparing older mobile phones with newer smartphones. Internet routers, modems and hubs are shown to also be a potential source for precious metals, with comparable concentrations to the two phone types if the total product weight is considered.

1. Introduction

The worldwide generation of Waste Electric and Electronic Equipment (WEEE) is increasing each year and has now become a major environmental issue in industrially developed countries. The average life span of Personal Computers (PC) decreased from 5 to 3 years between 1992 and 2005 (Kang and Schoenung, 2005), and in 2009, mobile phones only had a 2-year life span (Robinson, 2009). A recent study on the German market confirms the decreasing life-span of electronic household products (Prakash et al., 2016). The waste generation is also multiplied by the increasing world-wide demand for electronic products. A recent review on the recycling of waste printed circuit boards (PCBs), estimates the PCB production for the world-wide market for the years 1980–2016 and shows a steadily increasing trend with a doubling of the market value about every 8 years, but forecasts for 2012–2016 an accelerated growth (Ghosh et al., 2015). Toxic metals, such as Pb, Cd and Hg, are known to be present in the PCBs of PCs (Hall and Williams, 2007). In addition, most electronic equipment that contains plastics is treated with brominated flame-retardants that generate toxic substances upon incineration (Menad et al., 1998). On the other hand, WEEE also contains significant enough amounts of precious

* Corresponding author.
E-mail address: stehol@chalmers.se (S. Holgersson).

http://dx.doi.org/10.1016/j.resconrec.2017.02.011
0921-3449/

Table 1
EU classification of WEEE categories and statistics on the mass percentage (%) of each category of total waste collected from households. Boldface figures with category 1 excluded.

Class	Category	EU + Norway 2007 Huisman et al. (2007)	*	EU + Norway 2013 Eurostat (2016)	*	Sweden 2013 El-kretsen (2015) **
1	Large household appliances	49	–	50	–	–
2	Small household appliances	7	**14**	8	**17**	**17**
3	IT and telecommunication equipment	16	**32**	16	**32**	**39**
4	Consumer equipment	21	**41**	21	**42**	**21**
5	Lighting equipment	2	**5**	1	**2**	**16**
6	Moveable electric/electronic tools	4	**7**	3	**5**	**3**
7	Toys, leisure and sports equipment	0.1	**0.2**	0.4	**1**	**3**
8	Medical devices	0.1	**0.2**	0.1	**0.3**	**0.3**
9	Monitoring and control instruments	0.2	**0.4**	0.3	**1**	**0.9**
10	Automatic dispensers	0.2	**0.4**	0.1	**0.1**	–

* Recalculated without category 1.
** The Swedish statistics do not include category 1.

or semi-precious metals that it can be considered to be an alternative source to high-grade ore. The cost in energy consumption for acquiring metals from WEEE is only 10–15% of the cost of mining pristine ore (ISRI, 2003). In 2009, the Cu and precious metals (PM) concentrations of PCBs were ten times higher than the concentrations found in high-grade ores[1] (Robinson, 2009). Consequently, there should be interest in facilitating the development of efficient processes for WEEE recycling, both from environmental and the economical perspectives.

Legislative actions have now been taken in many countries to force producers and importers of electric and electronic equipment to recycle end-of–use products. In WEEE recycling there is a front-end business that collects and initially takes care of WEEE and then sells it as a raw material to back-end business, which refine the material. Although the back-end business is profitable, with large energy savings when recycling metals from WEEE instead of mining fresh ore, the front-end business is still mainly legislation driven. In the worst case, WEEE is exported, legally or illegally, to underdeveloped countries, often with severe consequences for both human health and the environment (Awashti et al., 2016; Wang et al., 2016). The importance of economic incentives for the adaption of sound methods for the WEEE recycling in countries with weak environmental-legislative authorities have been pointed out (Williams et al., 2013). One obstacle to attain good profit margins in the front-end business may be the relatively low-grade material that is produced, with respect to the material mixture. One aim of this work was to investigate the potential for improving the front-end WEEE product quality by manual and/or automated sorting and upgrading procedures. An upgrading process for WEEE must be based on detailed knowledge of the WEEE metal composition of individual products that appear in the waste stream.

Today, manual handling and sorting of WEEE is common, if it is done at all. This is mostly due to the technological limitations of sorting materials into the corresponding product categories by the automatic identification of individual WEEE items from complex waste streams. Manual removal of PCBs from the casings can also be employed, at least for certain valuable product types. This will, of course, require detailed knowledge of the value of the products in order for their selection to be manually disassembled.

Upgrading by sorting WEEE should be feasible if the diverse products in the waste stream also contain very different amounts of metals. Most of the precious metals in WEEE are found in PCBs and, according to the literature review by Chancerel et al. (2009), the amount of PCB weight to product weight varies between 2% and 22% of the investigated product types and the amount of PM content in the PCBs varies by several orders of magnitude.

This may, for example, initiate a sorting procedure where the WEEE stream is separated into, at least, one PM-rich fraction, which may be dismantled manually to retrieve valuable PCBs, and one PM-poor fraction, which may be shredded and fractioned into the constituent materials, where the eventual loss of minor amounts is not of concern. Since most PMs are found in PCBs, it is of interest to perform a thorough analysis of the contents of both PMs and toxic metals (TMs) in PCBs of some of the major WEEE product categories. The EU classification system of WEEE is shown in Table 1, together with statistics on the relative amounts found in a waste stream collected from households (taken from Huisman et al., 2007; Eurostat, 2016 and El-kretsen statistics, 2015).

The statistics in Table 1 show that the mass-percentage of WEEE is not only dominated by category 1 “Large household appliances” but also by categories 3 “IT and telecommunication equipment” and 4 “Consumer equipment”. Contrary to Category 1, Categories 2–10 are mostly of medium to small size and therefore are often collected together, with the exception of CRT and LED screens and LED lamps, which are collected separately because of their known high content of Pb or Hg.

After the exclusion of these pre-sorted products with a high TM content and of the bulky products of category 1, what remains is a waste stream composed of categories 2–10 consisting of small to medium-sized WEEE, with a relatively low content of TMs, but, at least for some product types, a relatively high content of PM. In addition, this waste contains large amounts of other metals and mixed plastics, including flame-retardants, from their casing material.

It is the purpose of this work to identify some specific but common product types from this particular waste stream, to analyse the content of PMs and TMs in the PCBs of the products and to measure the relative amount of PCB weight to product weight. This is done for a relatively large number of items (10–30 items) to provide a statistical foundation for the results. We plan to present the results in a series of articles, where different product types are investigated. In this first paper, we present data for the following products: 1) internet routers, modems and hubs; 2) mobile phones; and 3) smartphones, which were analysed as three distinct product types. All of these products appear in EU WEEE classification Category 3.

The main foci of the analyses described herein were: 1) PMs (Ag, Au, Pd, Pt, Rh), 2) other valuable metals usually found in considerable amounts (Cu, Ni) and 3) TMs (As, Be, Cd, Cr, Hg, Pb).

2. Literature review

To our knowledge, for the first time, data are presented for the metal contents of PCBs in Internet routers and smartphones, at

[1] For example, WEEE PCBs typically contain approximately 25% Cu, while copper ores that are today worth mining contain approximately 2% Cu.