Apprehension of material distribution of complex components in end-of-life electrical and electronic equipment

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Abstract:

During the pre-treatment process of WEEE, certain types of electronic components are released, which due to their diversity in shape, size, and material composition, cannot be attributed to one particular material fraction, e.g. ferrous metals, aluminium or similar, and are sorted out as mixed material stream. These components can generally be classified under an umbrella term as “complex components” and include Printed Circuit Boards, Power Supply Units, Hard Disk, etc. Although complex components are interesting from both economic and environmental point of view, the results of material composition analyses in the scientific literature tend to be highly scattered so that their practicality for further use is significantly diminished. Within the scope of this research, complex components have been analysed through a series simple analytical methods, e.g. nickel test, aluminium/magnesium test, etc., and ICP-OES in order to provide a new approach for the material analysis of complex components. The research provides an assessment of more than 40 different papers published in high impact scientific journals and results of material composition analysis of more than 60 components classified into seven types of complex components. Conclusively, a guideline for material analysis of complex components arising from end-of-life electrical and electronic equipment has been developed.

Keywords: ICP-OES, complex components, waste analysis, recycling, precious metals

1. Introduction

Amount of Waste Electronic and Electric Equipment (WEEE), also referred to as e-waste, in the year 2014 exceeded 40 million t globally with an annual growth rate ranging between 4-5 % (Baldé *et al*., 2015). Since the global population in 2014 was app. 7,3 billion people (Worldometers, 2017), the annual average of e-waste generation was 5,5 kg per capita. In order to be able to optimize the recycling process of waste electronic and electric equipment (WEEE), pre-processing companies need accurate material composition databases for their target WEEE and, if possible, reliable and cheap analytical methods in order to close the data gaps. In this way, simpler assessment of the full potential of the material input stream would simultaneously allow more flexibility for the pre-processing companies resulting in an overall increase of the recycling efficiency.

The focus of this research is on components from electrical and electronic equipment (EEE), which have significant recycling potential, but cannot be associated with any single (homogenous) material output stream like ferrous metals, aluminium, or similar due to their complex construction. For practical purposes, recycling companies usually refer to such components just as “complex components”. In the recycling of end-of-life electrical and electronic equipment, the material stream containing complex components emerges primarily during the dismantling process or during the mechanical de-pollution process. Complex components emerge also in the subsequent process steps as part of a shredder output stream. As these components get fragmented and deformed during the shredding process, it is considerably harder to analyse them. Therefore, the complex components originating after the shredding process have not been included in the focus of this research up to now.

2. Materials and methodologies

2.1 In-depth manual disassembly

Manual separation analysis is a simple analysis method requiring only basic tools for a successful conduct of analysis. The aim of the analysis is to disassemble and separate target components into single materials, so that they can be identified and allocated to homogenous material groups, e.g. plastics, copper, ferrous metals, etc. The complex components that are included within the scope of this research were first disassembled into component parts. Those parts were further separated or broken apart mechanically so that the share of material assemblies (material composites) was kept as low as possible (see Figure 1). After the in-depth disassembly, the parts have been analysed for materials following the simple analytical procedure including magnet test, nickel test, swim/sink test, and similar. Identified parts have been then weighed and organised into two levels. First level constitute functional components: housing, voice coil assembly, mechanical components, etc.

Figure 1: (from left to right): Hard Disk Drive (3.5”), Power supply unit, CD-ROM Drive

Second level constitute parts made of, if possible, a single or of only few materials. The second level is created in order to associate homogenous materials to the functional elements. By following this procedure, it is possible to accurately locate the potential changes in material composition between models of complex components produced by different manufacturers or to follow the change in the material composition over the years.

2.2 Inductively Coupled Plasma – Optic Emission Spectroscopy

The goal of the Inductively Coupled Plasma – Optic Emission Spectroscopy (ICP-OES) analysis was to determine a trace metal composition of aluminium capacitors (< 15 mm) originating from a “mainboard” type of Printed Circuit Boards (PCB). The detachment of the aluminium capacitors was carried out with a soldering gun and a flat-blade screwdriver in order to keep the connectors from detaching from the capacitor. The detached capacitors (weighed in average 0.67 g) were than organised into two sample sets. Each sample set contained five capacitors originating from different mainboard PCBs manufactured in the years 1999 and 2004. After detachment from the PCBs, the capacitors were cut in at least four pieces using simple pliers for cutting metal and subsequently brought to the acid digestion. Both samples sets 1 and 2 containing capacitors with an average weight of 0.83 g for the sample set 1 and 0.55 g for the sample set 2 were digested via aqua regia extraction procedure. Each sample (an entire, mechanically fragmented aluminium capacitor) was placed in a polyethylene 50 mL digestion tube and additionally the 8 mL acid mixture of 70%HCl:30% HNO_3 (3:1) was added to each digestion tube (+ process blank (PB) sample) and were left at the room temperature for 2 h. Then, the samples were digested at 80° C for 4 hours in the SC100 HotBlock heater. The obtained suspension was then filtered through FilterMate 45 µm via on tube direct filtration and subsequently it was diluted to 50 mL with Ultra-High Purity (UHP) water. The resulting solution was stored in the new set of polyethylene tubes at 4° C for ICP-OES analyses. Following this procedure, the complete dissolution of the samples was achieved.

3. Results of in depth-disassembly analysis

As part of this research, several components have been identified as “complex components” and have been analysed via in-depth disassembly analysis. An overview of material compositions is available at the end of the chapter (Figure 2-Figure 4)

3.1 Hard Disk Drive

Within the scope of this research, there were 10 HDDs analysed, manufactured between the years 1996 and 2012. The samples were obtained at the local recycling company. An average mass per HDD is 578 ± 62 g. Although there was a dramatic increase in the storage capacity of HDDs since the mid-1990s, the average weight per HDD did not change significantly due to the similar increase in the data storing efficiency. The analysed HDDs were composed mainly of metals and approximately 3-5 wt.% of PCBs, assemblies, and plastics. The analysed HDDs have an average mass of 578 ± 62 g. Housing, also the largest component of the HDD, is made of cast aluminium and a ferrous metal cover. Other components made of Aluminium are also: actuator arm, spacers between magnetic plates, and spindle cover. Total aluminium content makes in average approximately 55 ± 6 wt.% of a HDD. Copper contents are contained in the induction coils of the electric motors, as part of the circuit board and in the wires. The copper containing components make in average approximately 10 ± 2 wt.% of a HDD. Besides housing cover, the components containing ferrous metals are mainly mechanical components. The total mass share of ferrous is in average approximately 30 ± 8 wt.% (c.f. (Ueberschaar and Rotter, 2015)

3.2 Power Supply Unit

As part of the research, 10 different Power Supply Units (PSU) originating from desktop computers were randomly sampled at the local recycling company and brought to the further analyses. The analysed PSUs have an average mass of 1446 ± 286 g. Components composing a PSU are: casing, a PCB with very massive components mounted, cables, passive (aluminium) cooler, active (plastic) fan, and a series of different components, such as transformer, switches, etc. In terms of material composition, the PSU are composed mostly of material assemblies. Mainly due to PCB and cables, which make in average approximately 50 wt.%. The ferrous metal fraction makes in average 32.8 ± 5.2 wt.%. Components made of ferrous metals are: casing, screws, and various other mechanical components. Aluminium fraction comprises in average 5.7 ± 0.9 wt.%. Components made of aluminium are mostly passive coolers mounted on the PCB. In general, there are two coolers per PSU, which are fixed to a PCB with ferrous metals retainers. PSU contain, in general, one or two active, plastic fans, which are significant from the recycling point of view, since they contain two permanent magnets per fan. The larger of the two magnets comprises in average 5.7 g (0.4 ± 0.1 wt.%). The smaller magnet is much smaller in size and was not further analysed within the scope of this research.

3.3 CD-ROM Drive

Within the scope of the research, 10 CD-ROM Drives were randomly collected at the local recycling company and analysed via in-depth dismantling analysis. The average mass per CD-ROM Drive is 823 ± 174 g. The CD-ROM Drives are fairly simple in terms of component complexity and material composition compared to the other complex components. Parts and components comprising CD-ROM Drives are: casing, three different electrical motors, laser assembly, PCB, and cables. CD-ROM Drives are mainly composed of ferrous metals, plastics, and material assemblies. The ferrous metal fraction makes in average 57.7 ± 9.4 wt.%, mainly comprising the casing of the drive. The plastic fraction makes in average 19.7 ± 7.2 wt.%. The PCB makes in average 9.9 ± 2.0 wt.% of CD-ROM. The laser assembly is relatively small, but highly complex component made of plastics, ferrous metals, glass, and other materials, and makes in average 3.7 ± 1.4 wt.%. In the CD-ROM Drive, there are three different electric motors. The 9/10 CD-ROM Drives contained two DC motors and one micro stepping motor. In the one remaining case, the CD-ROM Drive all three motors were DC motors. Similarly, as it was the case with the other complex components, the motors represent material assemblies, but are interesting from the recycling point of view, since they contain Cu in the coils and small permanent magnets. The DC motor 1 makes 4.7 ± 0.9 wt.%, DC motor 2 makes 2.6 ± 0.5 wt.%, and micro stepping motor makes 1.9 ± 0.8 wt.%.

4. Results of ICP-OES analysis

The analysis of Al-capacitors via ICP-OES included 10 different capacitors (< 15 mm) originating from a “mainboard” type of PCB. The capacitors were subdivided into two groups. First group consisting of capacitors from the mainboard PCBs originating from the year 1999 and the second group consisting of capacitors from the mainboard PCBs manufactured in the year 2004.

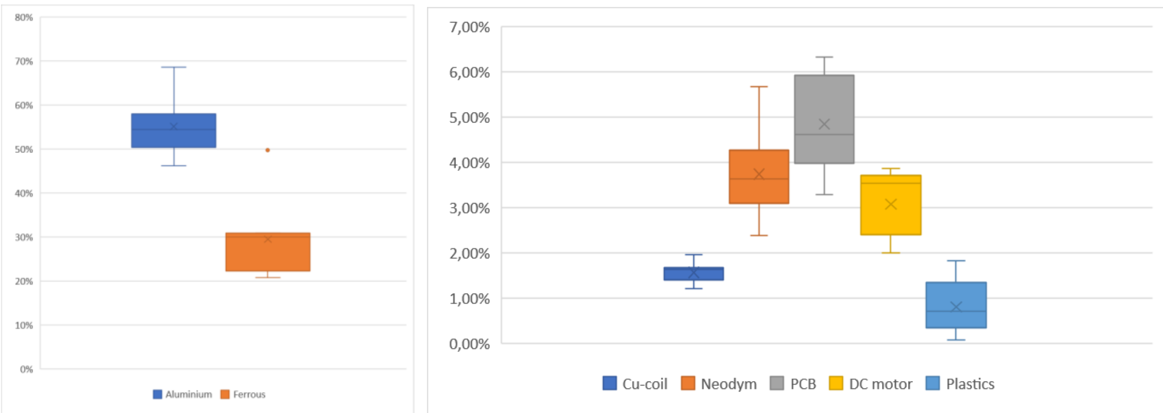

Figure 2: Average material composition of HDDs (n=10)

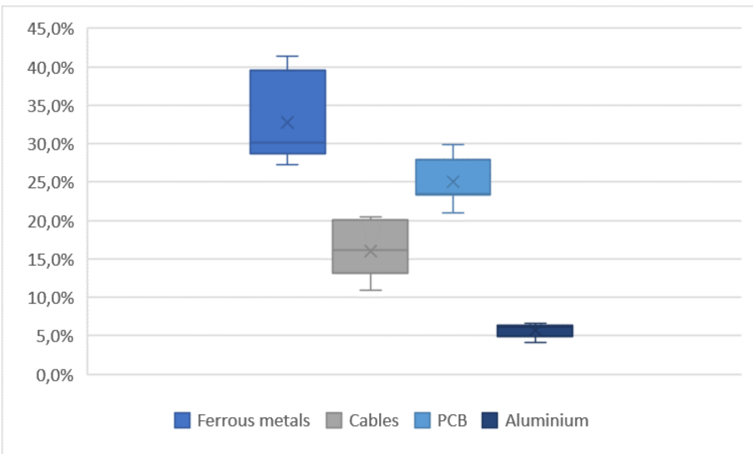

Figure 3: Average material composition of Power Supply Unit (n=10)

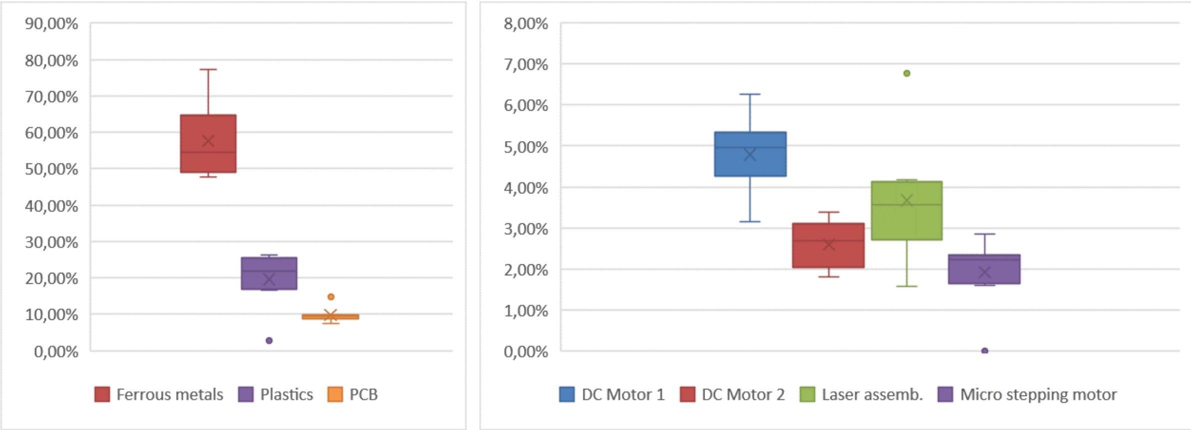

Figure 4: Average material composition of CD-ROM Drive (n=10)

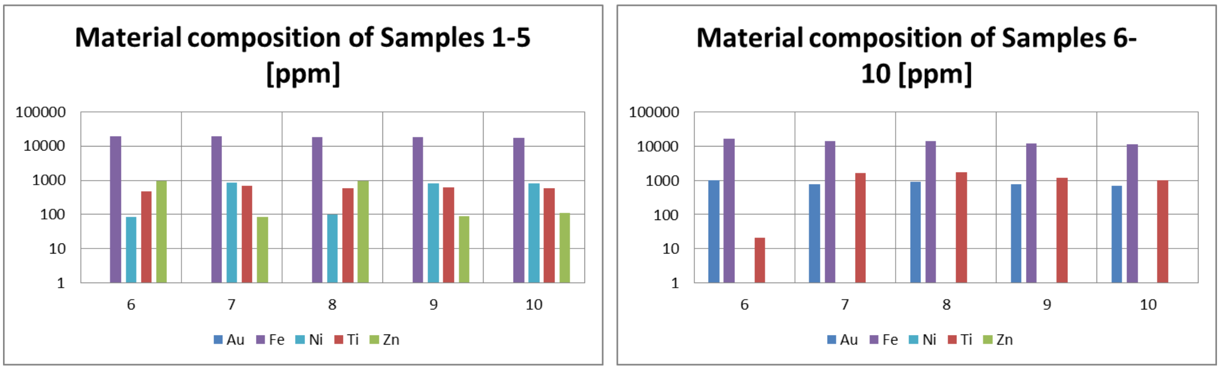

Figure 5: Material composition of Al-capacitors with focus on trace elements

The analysis focused on the trace metals, so besides aluminium, the fractions detected by the ICP-OES were: iron (Fe), nickel (Ni), titanium (Ti), zinc (Zn) for the first set of samples, and Fe, Ti, and gold (Au) for the second set of samples. While the Fe fraction has relatively constant mass share, approximately 10000 ppm for both sample sets, the other fractions show much higher fluctuation. Especially interesting is the presence of relatively high concentration of Au with approximately 800 ppm in the samples 6-10. Which is higher than the average concentration of gold for the whole mainboard PCB (c.f. Chancerel et al., 2013; Cui and Zhang, 2008). However, the in the samples 1-5, ICP metadata did not provide reliable results, so for this sample set, the Au fraction could not be determined.

5. Conclusions

The analysis of end-of-life electrical and electronic equipment is a complex and challenging endeavour due to high complexity of the material composition of analysed samples. Furthermore, the technology has been developing very dynamically and the results conducted analyses become very quickly obsolete. For these reasons, the results published so far in the high impact scientific papers are often very scattered and the determination of the material composition trends is near impossible. Within the scope of this research, there have been compared two different methods for determining material composition of complex components of end-of-life electrical and electronic equipment, namely in-depth disassembly and ICP-OES. For in-depth disassembly, a set of simple analytical procedures has been developed in order to identify the base metals, such as ferrous metals, aluminium, copper, etc. As it can be observed in the results above by means of in-depth disassembly, very large share of the component or electronic device can be analysed. Since the preparation of the samples and carrying out the ICP-OES analysis is a complex procedure and the outcomes of the analysis depend on various different parameters, e.g. sample particle size, acid matrices, type and composition of standardised solution, etc., the results also tend also to be very scattered.Therefore, in order to reduce the variability of the data, we suggest that the samples introduced for the ICP analyses should first undergo the in-depth dismantling analysis. Those parts, containing complex metal alloys, precious metals, rare earth elements, or similar, which cannot be analysed to a satisfying extend by the simple analytical procedures, should be subsequently analysed via ICP analytical technologies. By following this procedure, the data dispersion could be reduced and the interconnectedness of studies published by different authors would also increase too.

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