Comparison of mineral processing methods for metal recycling from waste printed circuit board

Bedeković, Gordan; Premur, Vitomir; Ivić, Anđela

Source / Izvornik: **Inzynieria Mineralna : Journal of the Polish Mineral Engineering Society, 2020, 2, 7 - 12**

Journal article, Published version
Rad u časopisu, Objavljena verzija rada (izdavačev PDF)

https://doi.org/10.29227/IM-2020-01-29

Comparison of Mineral Processing Methods for Metal Recycling from Waste Printed Circuit Board

Gordan BEDEKOVIĆ[1)], Vitomir PREMUR[2)], Anđela IVIĆ[3)]

[1)] University of Zagreb, Faculty of Mining, Geology and Petroleum Engineering, Pierottijeva 6, 10000 Zagreb, Croatia; email: gordan.bedekovic@rgn.hr
[2)] University of Zagreb, Faculty of Geotehnical Engineering, Hallerova aleja 7, 42000 Varaždin, Croatia; email: vitomir.premur@gfv.hr
[3)] University of Iceland, Faculty of Life and Environmental Sciences, Tæknigarður - Dunhagi 5, 107 Reykjavík, Iceland; email: aivic1@hotmail.com

http://doi.org/10.29227/IM-2020-01-29

Submission date: 10-01-2020 | Review date: 02-04-2020

Abstract

Faster technology development, increasing of living standard and market availability are the main causes of faster obsolescence of electronic devices. Each electronic device contains printed circuit boards that are a valuable source of metal. The paper presents the results of preliminary research of the possibility for using various mineral processing methods in recycling of waste printed circuit boards. The gravity concentration (concentration table and Humphreys spiral concentrator), electrostatic separation and wet magnetic separation were used in this preliminary research and the obtained results were presented in the article.

Keywords: *waste printed circuit boards, recycling, metals, separation*

Introduction

Faster growth of the population and technology development, an increase in the standard of living and market availability have resulted in the waste electric and electronic equipment (WEEE) being one of the largest waste streams globally (Tanskanen, 2013) and more than 50 million tons generated yearly (Wang et al., 2013).

WEEE contains a large amount of metal, sometimes 30 to 40 times more than the primary raw material (minerals) from which certain metals are obtained (Robinson 2009), so it is an excellent secondary raw material for metals production. For example, copper content in ores today is approximately 0.4% (Freeport-Mcmoran 2013), while the content of copper in electronic components can be 18% (Veit, 2006), even more than 30% (Monal et al. 2011).

Today, almost every electrical or electronic device has a printed circuit board (PCB), and PCB constitutes about 3% of WEEE (Marques et al., 2013). The PCBs contain many valuable metals such as Cu, Al, Ag, Au, Pb, etc. (Bedeković, 2015).

PCB consists of a base (a thin insulating board that serves as a base for conductors and electronic components) and a conductive layer (usually copper in the form of thin lines tightly glued to the base).

The structure of the supporting insulating base is layered and is made by mixing the basic material with fillers. The base usually consists of cellulose fibres impregnated with phenol resin (pertinax) or glass fibres impregnated with epoxide resin (vitroplast). For higher frequencies, fluoropolymers and ceramics are used which are selected only in case when there is a price justification or when a different solution is not possible. Depending on the required thickness of the PCB, the desired number of layers of glass cloth is applied.

The conductive copper layer can be applied in several ways: depending on the desired quality of the finished PCBs, the quantity and the price vary between silk screen printing, photo printing, printing methods such as lithotis and lithofecta printing, and mechanical methods of molding and shaping copper figures.

On average, the PCBs consist of over 70% nonmetals (plastic, epoxy resin and glass fiber), 16% copper, 4% solder, 3% iron, ferrites, 2% nickel, 0.05%, silver, 0.03% of gold, 0.01% palladium and others (bismuth, antimony, tantalum etc.) with a share of less than 0.01% (Eswaraiah, C., et al., 2008).

The most common classification of the PCBs is one-sided, two-sided and multiple although they can be classified according to different criteria. Single-sided have electronic components on one side (top side), and conductive connections on the other (bottom side). This type of PCBs is simple, the cost of production is low, which is advantageous, but with lower component density and poorer high-frequency properties.

Double-sided PCBs have conductive links on both sides of the PCB while the components are most commonly on one side. They have higher component density packing, better high-frequency properties, and easier component connectivity, but are more expensive than one-sided. They have weaker electrical properties and the possibility of realization very complex assemblies in relation to multilayer PCBs.

Multilayer PCBs are used in case when the density of conductive links is greater than is possible with double-sided PCBs or where precision data is required. It consists of several double-sided tiles between which is a thin layer of so-called pre-impregnated material and thus makes a multilayer PCB. This type of printed circuit board is characterized by very high component density, excellent high-frequency properties and the ability to control line impedance, but the production cost can be very high.

The previously described PCBs are solid PCBs (Fig.1 left), and except them there are flexible PCBs (Fig.1 right) which are also divided into single, double and multilayer. They

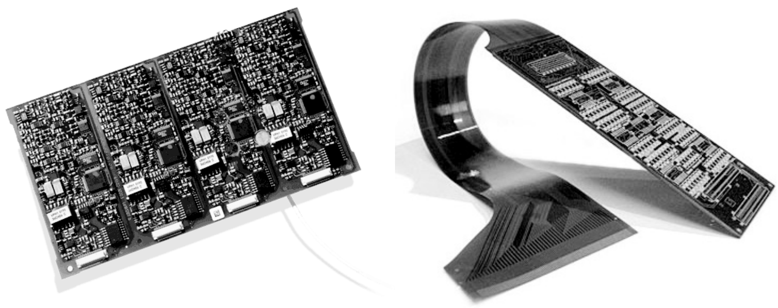

Fig. 1. Solid (left) and flexible (right) PCBs
Rys. 1. Stałe (lewe) i elastyczne (prawe) płytki drukowane

are used as a replacement for multi-wire cables to achieve high-level complexity in small volumes, in mobile phones, video and photo cameras, calculators, etc. Their advantages are flexibility, 3D bending flexibility, low mass and dimensions, high density in small volumes, cheaper and more reliable connection of multiple PCBs. On the other hand, the design and manufacturing process is very complex and the production price is high. Solid PCBs have the advantage of flexible in most applications, and flexible ones are only selected when there is either a price justification or where it is not possible to implement a solution for a particular application.

Materials and methods

The aim of this study was to compare different methods for separating metals from solid waste PCBs.

A sample of 3.88 kg was delivered from Spectra Media d.o.o. which deals with the recycling of electronic waste. The electronic components have been previously removed from the PCBs, and the PCBs are cut to smaller dimensions for easier handling. The average size of the PCB in the sample was 5×5×0.2 cm.

The PCBs are made of glass fibers impregnated with epoxy resin (vitroplast). The metal (in this research valuable component) is attached to the PCB with the insulating base (non-valuable component). The precondition of separation is to interrupt the bonding of the metal with the base. Therefore, the first step in the research was comminution in order to achieve the liberation of metal from the insulating base. The metal mass content of the feed sample (PCB) was 33% and is determined by firing at a temperature of 400° to 600°C. PCBs were crushed in an impact crusher with an exit opening of 18 mm. However, crushing in the impact crusher did not satisfactory results due to small masses and small grits. Subsequently, the sample was crushed in a hammer crusher with a grid openings of 8 mm. After crushing, a granulometric analysis was carried out. Previous researching has found that by crushing the sample below the particle size of 2 mm almost completely liberate the metal from the base (Zhang and Forssberg, 1997). Therefore, the sieving was used to obtain samples of grain sizes 2/1 mm and 1/0.5 mm for further testing by gravity, magnetic and electrostatic concentration. Wilfley concentrating table and Humphreys spiral concentrator were used in gravity concentration. On the concentration table, two size classes (2/1 mm and 1/0.5 mm) were tested on three different slopes of the table (3°, 6° and 9°). The mass of each sample was 30 grams. The wash water flow was 4 l/min. The same size class (2/1 mm and 1/0.5 mm) were also tested on the Humphreys spiral concentrator, with the heavy component exits completely closed on the first five bends and at the last one, sixth fully opened. The mass of the samples was 200 g. After the tests in these two devices, all the obtained products were dried and weighed. The electrostatic separator tests were conducted only in the size class 1/0.5 mm since the manufacturer prescribes an optimum particle size from 0.65 mm to 1.6 mm. In the first phase of the testing the drum speed was changed (40, 50, 60, 70 m/min), in the second ionization electrode voltage (17, 20 and 25 kV) and finally the influence of the ionization electrode distance from the drum (25 and 40 mm). The obtained products are weighed after the test. Tests in a wet low intensity magnetic separator were also performed in two classes (2/1 mm and 1/0.5 mm).

After each individual test, obtained products were dried and its composition were determined by hand sorting and weighing. Separation efficiency were estimated by two parameters: recovery (of metals) and grade of concentrate. The recovery represents the percentage of the total metal contained in the feed that is recovered into the concentrate. The recovery R can be expressed by follow equation:

$$R = 100 \cdot \frac{C \cdot c}{F \cdot f} \qquad (\%)$$

where R is recovery in percentage, C is a mass of the concentrate in grams, c is a mass content of metal in concentrate in percentage, F is a mass of feed in grams and f is a mass content of metal in the feed material in percentage. Grade of concentrate represents the percentage of the metal contained in the concentrate as a final product and can be expressed by follow equation:

$$G_C = 100 \cdot \frac{m_m}{m_C} \qquad (\%)$$

where G_C is grade of concentrate in percentage, mm is mass of metal in concentrate in grams and m_C is mass of concentrate in grams.

Results and discussion

The results of the granulometric analysis of the crushed sample in hammer crusher were shown in Table 1. Since a grid with a 8 mm openings size was used during crushing, it is not surprising that almost half of the mass sample (49.23%) is larger

Tab. 1. Grain size distribution after crushing
Tab. 1. Rozkład wielkości ziarna po kruszeniu

Grain size	Screen retain		
(mm)	(g)	(%)	(cum. %)
8/2	21.66	49.23	49.23
2/1	5.58	12.68	61.91
1/0.5	5.56	12.64	74.55
0.5/0.1	8.28	18.82	93.36
- 0.1	2.92	6.64	100.00
Σ	44.00	100.00	-

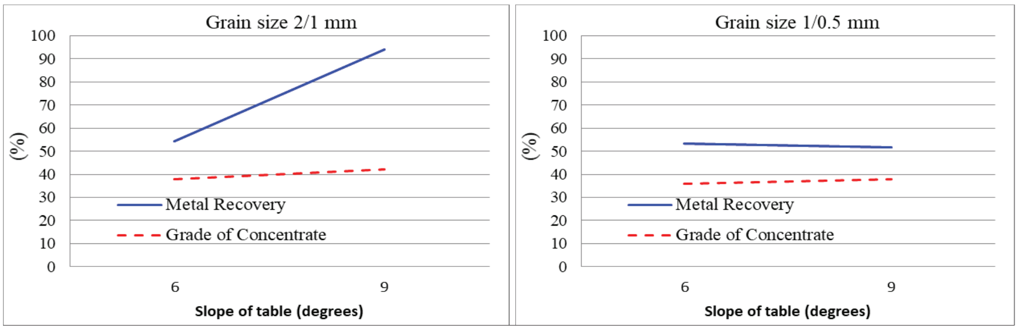

Fig. 2. Results of separation in Wilfley concentration table
Rys. 2. Wyniki rozdziału w tabeli stężeń Wilfleya

than 2 mm. When the particles less than 2 mm are considered, the most common class is 0.5/0.1 mm (18.82%), and the lowest represented class is -0.1 mm (6.64%). The mass fraction of these two smaller classes together amounts to 25.46%, which is approximately half of the mass in the size class of -2 mm. The other half (25.32%) makes size classes 2/1 mm and 1/0.5 mm with approximately equal masses (12.68 and 12.82%), and separation tests were performed on those size classes.

Figure 2 shows the separation results of coarser size class 2/1 mm on the Wilfley concentration table. Although separation tests were carried out at three different slopes of the table (3°, 6°, 9°), only the results of tests performed at slopes of 6° and 9° were shown, as in the slope of 3° test results were far from satisfactory. From Figure 2 (left) it can be seen that with increasing slope there was also an increase in recovery and quality of concentrate (Grade) of grain size 2/1 mm. Thus, metal recovery grew by 40% (from 54.23 to 94.18%) and concentrate quality by 4% (from 38.08 to 42.12%).

The finer size class 1/0.5 mm did not show any significant changes with a change of table slope (Fig. 1 right). The recovery of the metal was somewhat over 50%, and the concentrate quality was slightly below 40%, which was worse than the results obtained by testing the size class 2/1 mm (Fig. 1 left).

In addition to the concentration table, the Humphreys spiral concentrator as well as at the concentration table for both size classes were used in gravity concentration. From the results (Fig. 3) it can be seen that in the spiral concentrator a better result is achieved with a coarser size class of 2/1 mm. In the coarser size class 2/1 mm test, the metal recovery was 56.95% with the concentrate quality of 78.12%. The finer size class 1/0.5 mm gave worse results in terms of metal recovery of 19.89% and concentrate quality of 50.98%.

When comparing the results of both devices used in the gravity concentration method, it can be seen that significantly higher metal recovery (up to 94.18%) can be achieved on the table than the spiral concentrator (56.95%) but with a significantly lower concentrate quality of 42.12% (78.12% in a spiral concentrator). Based on these results, it would be recommended to use the concentration table in the first stage of separation when high recovery is desired, and then concentrate quality can be improved in the second stage by using a spiral concentrator to cleaning concentrate obtained in the first stage. In addition to the gravity concentration, the study was conducted using electrostatic concentration, and the results are shown in Figures 4 and 5. The electrostatic concentration tests was performed in three phases.

In the first phase of the testing the influence of drum speed on the separation (Figure 4 left) was researched. The first series of tests was performed by varying the drum speed from 40 to 70 m/min at the 25 kV electrode voltage and its distance from the drum of 25 mm. The figure shows recovery increasing up to 65.05% and concentrate quality up to 71.03% with drum speed up to 60 m/min. With a further increase in speed to 70 m/min, both parameters, recovery and quality of the concentrate decreased. The speed of 60 m/min was selected as the best, and a second phase of the tests was performed in which the influence of the electrode voltage was tested and the results are shown in Figure 4 (right).

In Figure 4 (right), it can be seen that by increasing the voltage from 15 to 20 kV practically hasn't influence on the separation parameters. With a further increase in the voltage of up to 25 kV, a slight increase in the quality of the concentrate and a significant increase in metal recovery are obtained. After testing the drum speed and the electrodes voltage, it was to be determined whether the electrode distance from the drum had a separation effect. For this purpose, tests with two different distances from drum (25 and 40 mm) at 25 kV and drum speed of 60 m/min were performed and the results are shown in Figure 5.

From Figure 5 it can be seen that with the increase of the electrode distance from the drum there is a significant reduc-

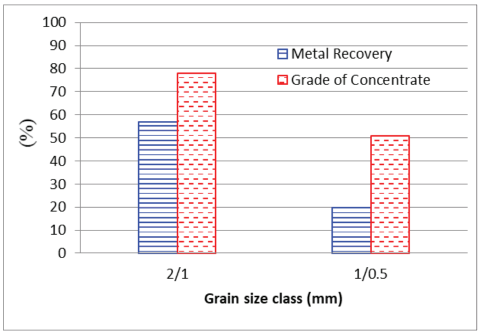

Fig. 3. Results of separation in Humphreys spiral concentrator (grain sizes 2/1 and 1/0.5 mm)
Rys. 3. Wyniki separacji w koncentratorze spiralnym Humphreysa (wielkość ziaren 2/1 i 1/0,5 mm)

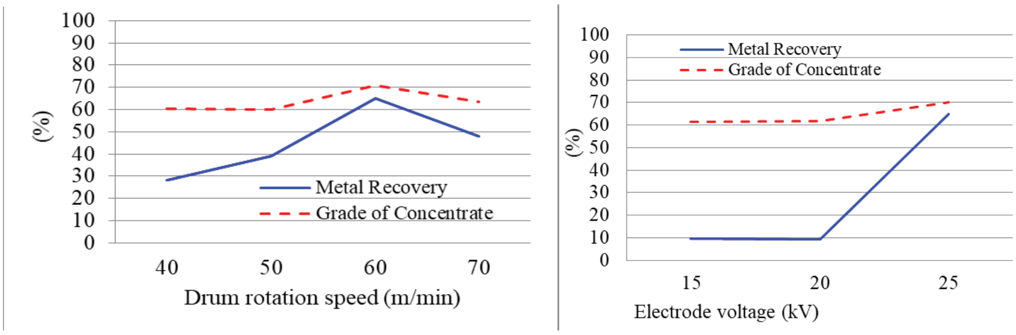

Fig. 4. Results of separation grain size 1/0.5 mm in Electrostatic separator at different drum speeds (left) and electrode voltage (right)
Rys. 4. Wyniki wielkości ziarna separacji 1/0,5 mm w separatorze elektrostatycznym przy różnych prędkościach bębna (po lewej) i napięciu elektrody (po prawej)

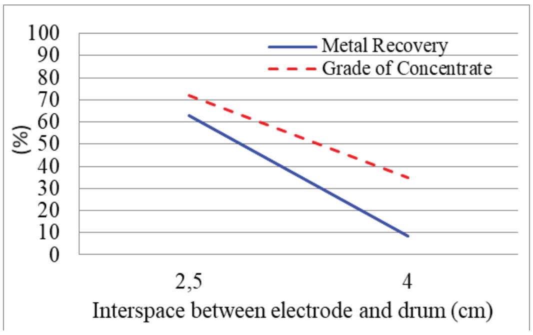

Fig. 5. Results of separation in Electrostatic separator at different distance between drum and electrode (grain size 1/0.5 mm)
Rys. 5. Wyniki separacji w separatorze elektrostatycznym w różnej odległości między bębnem a elektrodą (wielkość ziarna 1/0,5 mm)

tion of both observed parameters. Concentrate quality decreased from 72.11 to 35.03%, and metal recovery from 62.75 to 8.49%. Based on the results of the three-phase testing, it can be said that each of the tested independent variables can have a significant effect on the separation results. To determine the optimum separation conditions, a more detailed set of tests should be performed in the area of the value of the individual independent variables in which the greatest changes were observed (drum speed in the range from 55 to 65 m/min, electrode voltage from 25 to 30 kV and electrode distance of about 2.5 cm).

In a wet magnetic separator, the test was performed at a voltage of 57.5 V and a current of 10 A to generate a magnetic field. Two size classes were tested (2/1 mm and 1/0.5 mm), as well as gravity concentration. When testing the size class 2/1 mm, 10.5% of the mass of the sample was separated as a magnetic component, while in the finer size class 1/0.5 mm it was significantly less (5.4%).

Conclusion

This test compared several methods for separating metals from waste PCBs. Two crushers were used during comminution. It has been shown that due to the small weight and grit of the PCBs, hammer crusher is an incomparably better solution than the impact crusher. Gravitation concentrations on the Wilfley concentration table and Humphreys spiral concentrator were studied in two size classes (2/1 mm and 1/0.5 mm). On both devices, better results were obtained by separating the coarser grain size (2/1 mm). Comparison of the device showed that better results in terms of recovery were achieved at the concentration table and the concentrate quality with the spiral concentrator. Therefore, it may be recommended to use a concentration table to achieve higher recovery in the first separation stage, and in the second use a Humphreys spiral concentrator for concentrate cleaning. The electrostatic separation tests were performed with the purpose of testing the influence of three independent variables (drum speed, electrode voltage and drum electrode distance). The results have shown that all three variables can have a significant effect on separation, depending on their values. Given the manufacturer's recommendations, a finer size class 1/0.5 mm was tested. It has been shown that recovery could be obtained somewhat over 60% (Humphreys spiral concentrator about 20%, Wilfley concentration table slightly more than 50%) and concentrate quality can be achieved, depending on separation conditions up to 70% (Humphreys spiral concentrator about 50%, concentration table Wilfley below 50%), which are better results than those in gravity concentration. With a wet magnetic concentration, about 5% of the magnetic component in the finer size class 1/0.5 mm and about 10% in the coarser size class 2/1 mm were obtained, which were worse than the first two methods. However, it should be kept in mind that the first two methods can practically separate all of metals, and a magnetic concentration just iron.

Acknowledgements

Dissemination process is supported by the Development Fund of the Faculty of Mining, Geology and Petroleum Engineering, University of Zagreb.

Literatura – References

1. BEDEKOVIĆ, G. E-waste recycling by electrostatic separation. Handbook of research on advancements in environmental engineering. Hershey : IGI Global, 2015, p. 285-317, ISBN 978-1-4666-7336-6.
2. ESWARAIAH, C., KAVITHA, T., VIDYASAGAR, S., NARAYANAN, S.S. Classification of metals and plastics from printed circuit boards (PCB) using air classifier. Chemical Engineering and Processing, 47(4), 2008, p. 565-576, ISSN 0255-2701.
3. FREEPORT-MCMORAN Copper & Gold Inc.,. Annual report pursuant to section 13 or 15(d) of the securities exchange act of 1934 [online]. Phoenix Arizona 2013 [cit. 2019-02-21]. URL: < https://catalog.hathitrust.org/Record/101582359>.
4. MARQUES, André Canal, CABRERA MARRERO, José-María, MALFATTI, Célia de Fraga. A review of the recycling of non-metallic fractionsof printed circuit boards. Springer Plus a Springer Open Journal [online]. 2013, vol. 2, no. 521, April [cit. 2019-03-27]. Accessible from URL: < https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3930799/ >. ISSN 2193-1801.
5. MONAL, B., Shah, DEVAYANI, R., Tipre, SHAILLESH, R. Dave. Chemical and biological processes for multi-metal extraction from waste printed circuit boards of computers and mobile phones. Waste management & Research, 32(11), 2014, p. 1134-1141, ISSN 0734-242X.
6. ROBINSON, Brett H. E waste: An assessment of global production and environmental impacts. Science of the Total Environment, 408, 2009, p. 183-191, ISSN 0048-9697.
7. TANSKANEN, Pia. Management and recycling of electronic waste. Acta Materialia, 61(3), 2013, p. 1001-1011, ISSN 1359-6454.
8. VEIT, Hugo Marcelo, BERNARDES, Andréa Moura, FERREIRA, Jane Zoppas, SOARES TENORIO Jorge Alberto, MALFATTI, Célia de Fraga. Recovery of copper from printed circuit boards scraps by mechanical processing and electrometallurgy. Journal of Hazardous Materials, 137(3), 2006, p. 1704-1709, ISSN 0304-3894.
9. WANG, Feng, HUISMAN, Jaco, STEVELS, Ab, BALDE, Cornelis Peter. Enhancing e-waste estimates: Improving data quality by multivariate Input-Output Analysis. Waste management, 33(11), 2013, p. 2397-2407, ISSN 0956-053X.
10. ZHANG, Shunli, FORSSBERG, Eric. Mechanical separation-oriented characterization of electronic scrap. Resources, Conservation and Recycling, 21 (4), 1997, p. 247-269, ISSN 0921-3449.

Porównanie różnych metod odzysku metali z odpadowych płytek drukowanych

Szybki rozwój technologii, podwyższenie standardu życia i dostępność na rynku to główne przyczyny szybszego starzenia się urządzeń elektronicznych. Każde urządzenie elektroniczne zawiera płytki drukowane, które są cennym źródłem metalu. W pracy przedstawiono wyniki wstępnych badań możliwości zastosowania różnych metod przeróbki surowców w recyklingu zużytych obwodów drukowanych. W tych wstępnych badaniach wykorzystano wzbogacalnik grawitacyjne (stół wstrząsany i wzbogacalnik spiralny Humphreya), separację elektrostatyczną i separację magnetyczną na mokro, uzyskane wyniki przedstawiono w artykule.

Słowa kluczowe: *odpady obwodów drukowanych, recykling, metale, separacja*