Flotation as a Method for Metal Recovery from Printed Circuit Boards (PCBs)

Aldona KRAWCZYKOWSKA[1], Szymon MNICHOWSKI[2]

[1] Department of Environmental Engineering, Faculty of Civil Engineering and Resource Management, AGH University of Krakow, Mickiewicza 30, 30-059 Cracow, Poland; https://orcid.org/0000-0002-4150-8199; email: aldona.krawczykowska@agh.edu.pl
[2] student; mnichowski@student.agh.edu.pl

http://doi.org/10.29227/IM-2025-01-27

Submission date: 11-06-2025 | Review date: 29-06-2025

Abstract

Technological advancement and the accelerating growth of waste electrical and electronic equipment (WEEE) pose major challenges for resource recovery, particularly of metals embedded in printed circuit boards (PCBs). This study evaluates the effectiveness of flotation for the selective separation of metals from the non-metallic fractions of PCBs. Flotation experiments were conducted under various reagent regimes (different types and dosages). The investigation covered both the physicochemical properties of PCB feed material and the influence of process parameters on metal recovery. Results demonstrate that flotation can enhance the recovery of valuable metals while simultaneously minimizing material losses and mitigating environmental impacts, fully supporting circular economy principles. The work underscores the need to optimise technological parameters and to integrate flotation with other PCB recycling stages, thereby fostering more sustainable electronic waste management strategies.

Keywords: *Waste Printed Circuit Boards (WPCBs), electronic waste recycling, PCBs, flotation, circular economy*

INTRODUCTION

Technological progress and growing consumption of electronic devices mean that the stream of waste electrical and electronic equipment (WEEE) is growing faster than any other waste fraction. At the same time, e-waste is a valuable source of raw materials – over 60% of its mass consists of precious and base metals, with contaminants accounting for only about 2.7% (Widmer et al., 2005). Data indicate that between 1994 and 2003, approximately 500 million personal computers were taken out of service, containing a total of 2.9 Mt of plastics, 0.7 Mt of lead, 1.4 kt of cadmium and 0.3 kt of mercury (Kim and Overcash, 2004; Puckett et al., 2004). The shortening life cycle of devices (e.g. processors from 4–6 years in 1997 to 2 years in 2005) is driving the scale of the problem (CPU Museum). On the other hand, EU Directive 2012/19/EU defines WEEE and introduces obligations regarding its collection, recycling and recovery (Directive 2012/19; Directive 2008/98).

Printed circuit boards (PCBs) are a particularly valuable but also problematic fraction of WEEE. Although they account for only ~3% of the total weight of e-waste, they contain elevated concentrations of Cu, Sn, Au, Ag, and Pd, making them an attractive target for recycling within the framework of so-called urban mining. However, approximately 70% of PCB scrap still ends up in landfills or incinerators (Coombs, 2001; Goosey and Kellner, 2003; Grause et al., 2008; Kaya, 2016; Legarth, 2002; Li et al., 2004; Qi et al., 2005;). Therefore, it is necessary to develop efficient methods for metal recovery and minimization of environmental risks.

Due to the growing production of electronic devices and the limited availability of primary ores, the recovery of metals from PCBs has become important from both an economic and environmental point of view. Scientific literature presents numerous methods and technological approaches enabling the effective processing of this waste.

The comminution of used printed circuit boards is the first strategic step in the mechanical recycling chain, determining the efficiency of all subsequent separation operations. During the multi-stage cutting and grinding of the material, the aim is to liberate metals from their epoxy-glass matrix, reduce the volume of the load and achieve a homogeneous granulation of generally no more than 0.8 mm, which favours selective flotation. Studies by Wang et al. (2005) and Oliveira et al. (2010) showed that the use of a sequence of devices – from jaw crushers for primary crushing, through cutting mills, to vibrating or disc crushers – allows for a gradual increase in the degree of metal liberation, while reducing energy consumption and abrasive wear of tools. The finest fractions (<0.8 mm) are characterised by a higher proportion of pure copper and resin particles, which later translates into higher flotation selectivity and lower reagent consumption (Zhu et al., 2019).

The key challenges remain the heterogeneity of the material, the generation of dust containing brominated flame retardants, and the high hardness of glass fibres, which causes rapid wear of working parts. Special techniques such as cryogenic comminution, which increases the brittleness of the composite at temperatures below -100°C, or ultrasonic and hydrodynamic grinding, which uses waves or high-pressure water jets to selectively detach elements, prove helpful. The ultimate goal of all variants is to obtain a fraction of optimal size (0.074–0.25 mm) for which froth flotation or inverted flotation ensures maximum recovery of copper, tin and nickel with minimal metal losses in the froth (He and Duan, 2017).

Mechanical processes are usually the first stage of PCB recycling. Their purpose is to physically separate metallic and non-metallic fractions through grinding, size classification, magnetic, electrostatic or gravitational separation (Das et al., 2009). As a result of comminution and classification, segregation of certain components into specific grain classes can

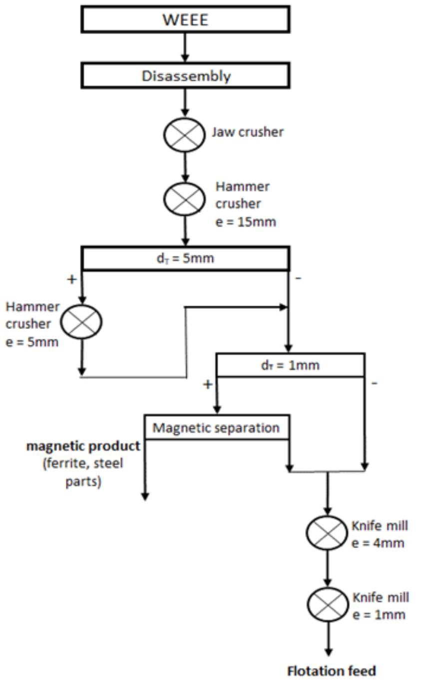

Fig. 1. Schematic diagram of feed preparation for flotation
Rys. 1. Schemat przygotowania nadawy do flotacji

be observed. Yoo et al. (2009) proposed a sequence involving piston grinding, classification into fractions <0.6 mm to >5.0 mm, followed by air and magnetic separation. The highest concentrations of copper, tin and lead were found in the smallest fractions, while nickel and iron were concentrated in particles >5.0 mm.

Veit et al. (2005) noted that ferromagnetic particles tend to agglomerate with non-metallic particles, which reduces the efficiency of separation. Nevertheless, mechanical processes effectively enrich metal concentrates, serving as a preparatory stage for further recovery.

One technology of particular interest is flotation, which, due to its selectivity, low energy consumption and ability to be integrated with other methods, is an important tool in the recycling of metals from electronic waste.

The flotation process is based on differences in particle wettability – non-metallic fractions, such as epoxies and plastics, tend to be naturally hydrophobic, which allows them to float in the foam layer. On the other hand, metals such as copper, zinc and nickel are usually hydrophilic and remain in suspension. However, research by Zhu et al. (2019) showed that the presence of organic layers on the surface of metals can significantly reduce their wettability, impairing separation efficiency. In this context, preliminary preparation of the material (grinding, cleaning) to remove these coatings becomes particularly important.

Conventional froth flotation was successfully applied by Mäkinen et al. (2015), who achieved high enrichment of the metallic fraction using shredded PCBs from mobile phones. The process was carried out without the use of collectors, which indicates the economic and ecological potential of this method. In turn, reverse flotation, described by He and Duan (2017), allowed for the removal of non-metallic fractions from the suspension using appropriate surface modifiers, which resulted in an increase in the purity of metal concentrates.

Column flotation, analysed by Syrmakezis et al. (2023), was presented as a more energy-efficient form of flotation, enabling high selectivity without the use of chemicals. Such solutions may be crucial in the context of implementing low-carbon technologies.

The effectiveness of flotation depends directly on operating parameters. Yao et al. (2020) identified significant relationships between the type and dose of collector and the quality and recovery of concentrates. The use of excessive amounts of reagents led to a decrease in process selectivity and a higher amount of metals in the froth. In addition, the optimal process temperature (around 20°C) had a positive effect on froth stability and separation efficiency.

Das et al. (2021) demonstrated that the combination of a collector and a frother allowed for a synergistic increase in flotation efficiency, particularly in the removal of silicon and bromine from non-metallic fractions. On the other hand, the absence of surfactants promoted better metal recovery (Cu, Sn), which may be desirable in conditions of limited resources or in sustainable processes.

In addition, research by Niu et al. (2018) indicated that the use of surface modifiers such as fatty acids can improve the hydrophilicity of metals, increasing the chances of separation. The work of Guo et al. (2020) investigated the effect of particle zeta potential on the flotation process, confirming that pH and surface charge control are important elements of the separation strategy. Liu et al. (2022), on the other hand, proposed the use of ultrasonic-assisted flotation, which improved the removal of organic sediments and the efficiency of the process.

MATERIALS AND METHODS

Materials

The research material included mobile phones and smartphones as well as two monitors, which was intended to in-

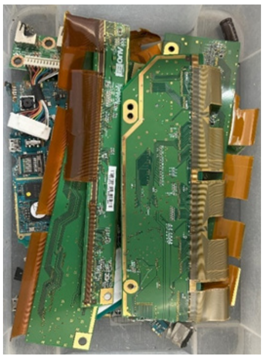

Fig. 2. Research material obtained after dismantling
Rys. 2. Materiał badawczy uzyskany w wyniku demontażu

Fig. 3. Products of two-stage comminution in a hammer crusher
Rys. 3. Produkty dwustopniowego rozdrabniania w kruszarce młotkowej

Rys. 4. Produkt mielenia w młynie nożowym Pulverisette 25
Fig. 4. Product ground in a Pulverisette 25 knife mill

crease the diversity of the samples tested. The first stage of the research involved the manual disassembly of the electrical and electronic devices obtained. This process was carried out in such a way as to extract the research material in the form of printed circuit boards.

The next stage of the research was the preliminary comminution of the material using a LAB-02-100 laboratory jaw crusher, which allowed for the obtaining of smaller fractions that could then be further processed. This was followed by multi-stage crushing in a LKM-120 laboratory hammer crusher. Magnetic separation was performed to separate ferromagnetic fractions (including ferrite and steel elements). The non-magnetic product was subjected to further comminution in a Pulverisette 25 knife mill.

The final stage of the research was the enrichment of the obtained fractions using the froth flotation method to produce metal rich concentrates of the highest possible purity. The flotation enrichment products were additionally subjected to separation on an electrostatic separator. The diagram of the experiments carried out is shown in Figure 1.

The chemical composition of all products was determined using the XRF analytical method with the Epsilon 4 analyser from Malvern Panalytical.

Preparation of PCB waste for testing – dismantling, comminution and classification

The dismantling of electrical and electronic equipment is a critical step in preparing PCB waste for testing, enabling its subsequent comminution and classification. In the context of printed circuit board recovery, it is essential to use appropriate dismantling techniques that allow for the effective separation of printed circuits from other device components (Knoth et al., 2002; Layiding et al., 2002; Stobbe et al., 2002; Xiang et al., 2014). In the case of mobile phones and monitors, this process requires the adaptation of methods depending on the type of construction and the degree of integration of electronic components.

Figure 2 shows the test material after manual disassembly.

The next step was multi-stage comminution. It is worth noting that larger steel and copper parts were separated from the product crushed in the jaw crusher. The pre-crushed ma-

Tab. 1. Designations of the experiments

Tab. 1. Oznaczenia eksperymentów

Flotation test ID	**Frother** type dosage, g/Mg	**Collector** type dosage, g/Mg
F1	–	–
F2	Pine oil 50	–
F3	NASFROTH-245B 50	Kerosene 750
F4	NASFROTH-245B 50	Industrial apolar reagent „X" 500

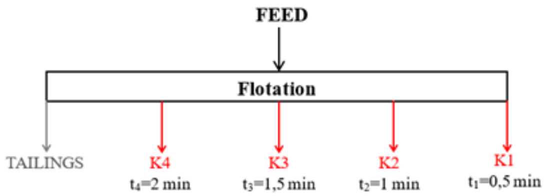

Fig. 5. Flotation test scheme

Rys. 5 Schemat badań flotacyjnych

terial was then processed in a hammer crusher with two sizes of grates: 15 and 5 mm. The multi-stage character of the comminution process is necessary to achieve the required degree of material comminution. Figure 3 illustrates the products of successive comminution stages in a hammer crusher.

The final stage of the comminution process was grinding the material using a Pulverisette 25 knife mill. Prior to this, the feed was subjected to magnetic separation in order to separate ferromagnetic material that could damage the mill knives. After this process, the appropriate particle size was obtained, enabling the material to be enriched by flotation. The grinding product is shown in Figure 4.

Flotation experiments

Flotation tests were carried out using a Denver D12 laboratory flotation machine, which is a standard device used for flotation tests to assess the flotation recoverability of material. All experiments were carried out in a 1.5 dm^3 cell at a pulp solids concentration of β =100 g/dm^3.

In the first stage, the sample was mixed with water in a flotation chamber for 10 minutes without air supply in order to thoroughly wet the material. Flotation reagents were then added and agitated for a further 5 minutes. After this conditioning step, the proper flotation process was carried out for 5 minutes.

Four experiments were performed; their identifiers together with the types and dosages of reagents used are listed in Table 1.

In the experiments performed, different reagent combinations were applied to evaluate how the reagent regime affects flotation efficiency. Using both frothers and collectors made it possible to investigate the optimal conditions for PCB beneficiation. The experimental scheme for each flotation test is shown in Figure 5.

All flotation runs were carried out under identical hydrodynamic conditions:

- impeller speed: 1 400 rpm
- air flow rate: 120 dm^3 h^{-1}

The froth product was collected in four fractions: K1, K2, K3, and K4 collected for 0.5, 1, 1.5, and 2 min, respectively.

Electrostatic separation

To improve the quality of the flotation products, additional cleaning trials were carried out in an electrostatic separator. Experiments were performed on both the tailings and the combined concentrate fractions obtained from flotation tests F1 and F3.

Electrostatic separation was conducted with a Prodecologia EBS laboratory electrostatic separator. The process yielded eight products (four conductive and four non conductive) from which weighed samples were taken for chemical analysis (XRF).

RESULTS AND DISCUSSION

From the flotation products obtained – concentrates and waste – after drying and weighing, samples were taken and prepared from the final enrichment products for analysis of the content of selected metals using X-ray fluorescence (XRF). Quantitative and qualitative calculations were then performed on the basis of the analytical results.

The varying mass fractions of froth and waste for individual experiments indicate the variable effectiveness of the flotation process depending on the reagents used.

Analysing the flotation kinetics presented in Figure 6, it can be seen that the course of the process was similar in all cases. Slight differences in the yields of individual concentrates were observed, particularly between flotation without collecting agents and with their addition. It can be seen that the addition of a collector has a positive effect on the amount of K1 concentrates, both for flotation using kerosene and industrial reagent "X". The yields of the initial concentrates (K1) in the collector assisted runs (F3 and F4) exceeded 17 %, whereas in the collector free tests (F1 and F2) they reached only about 12 %.

The efficiency of beneficiation was assessed with standard qualitative and quantitative indicators. The analysis involved determining the elemental composition of the products obtained, calculating the percentage share of each fraction (yields, γ), and computing the recoveries (ε) of selected elements in the beneficiation streams. Fractions isolated with the electrostatic separator were examined as well. Recoveries were calculated for two elements: copper and aluminium, and the results are presented in Tables 2 and 3.

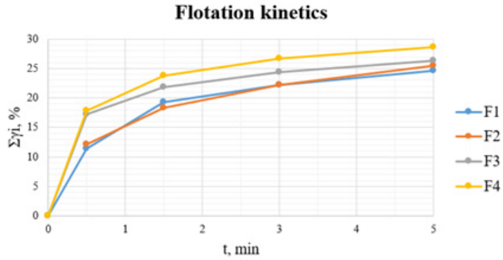

Fig. 6. Flotation kinetics curves for individual experiments
Rys. 6. Krzywe kinetyki flotacji dla poszczególnych eksperymentów

Tab. 2. Results of PCB flotation beneficiation
Tab. 2. Wyniki wzbogacania PCB metodą flotacji

Flotation ID	Product number	Al [%]	Cu [%]	γ [%]
F1	K1	6,53	7,17	11,38
	K2	7,87	9,81	7,95
	K3	8,44	10,17	2,83
	K4	9,22	9,23	2,42
	Odp	20,57	22,16	75,42
F2	K1	7,96	6,52	12,16
	K2	10,91	9,46	6,12
	K3	11,60	9,23	3,90
	K4	8,85	8,37	3,36
	Odp	21,30	20,29	74,46
F3	K1	6,50	7,81	17,22
	K2	8,99	11,37	4,58
	K3	10,01	9,73	2,62
	K4	10,91	9,03	1,97
	Odp	17,69	24,29	73,61
F4	K1	7,85	9,58	17,89
	K2	10,02	10,34	5,94
	K3	10,55	7,49	2,84
	K4	7,85	6,57	2,03
	Odp	20,28	21,04	71,30

The effectiveness of the enrichment methods was evaluated using the element recovery index in the products:

$$\varepsilon_i = \gamma_i \cdot \frac{\lambda_i}{\lambda_n}, \qquad \%$$

where: γ_i – yield of the i th product (fraction), %; λ_i – element content in the i th product, %; λ_n – element content in the feed, %.

Recoveries were calculated only for Cu and Al because these elements occur in the highest concentrations in PCB waste. Owing to the very low contents of other metals (< 1%) and the use of the chosen analytical method, the resulting calculation errors would have been excessively large. For samples with such diverse physical characteristics — including variable particle sizes, shapes, and densities — it is preferable to employ an analytical technique that requires the material to be dissolved.

An additional research stage involved electrostatic separation, which divides materials with different electrical properties by means of an electrostatic field. The conductive metal fraction was separated from the non metallic fraction in both the combined concentrates (K1–K4) and the tailings from flotation tests F1 and F3. All products were weighed, and representative samples were analysed by X ray fluorescence (XRF). The results are presented in Table 4.

Comparing the elemental contents of the conductive and non conductive fractions makes it possible to identify differences in chemical composition, which is crucial information for optimising metal recovery processes. The content of metals – both Cu and Al – is significantly higher in conductive products, but relatively large amounts of them pass into non-conductive products. This confirms the difficulties with the selectivity of waste material separation, such as PCB boards.

CONCLUSION

This study analysed the potential of applying flotation to recover metals from printed circuit boards, thereby addressing the growing challenges of e waste management and the goals of a circular economy approach. During the dismantling stage, emphasis was placed on the precise removal of electronic components, as this directly influences both the quality of the recovered raw materials and the efficiency of the downstream recycling steps.

Different separation methods demand careful feed preparation, particularly with respect to particle size. Shredded e waste displays an exceptional diversity in particle densities, sizes, and shapes. Strong inter particle interactions mean that ultra fine, hydrophilic particles can become trapped within aggregates of hydrophobic organic particles—forming “flocs” that are carried into the froth product and, in turn, reduce downstream separation efficiency. An analysis of comminution techniques shows that achieving the particle size range required for effective flotation calls for multistage grinding in equipment that employs varied breakage mechanisms, including cutting actions.

Flotation tests showed that the method can successfully separate the metallic and non metallic fractions. The results of F1 flotation without the addition of reagents prove that

Tab. 3. Element recoveries in PCB flotation products

Tab. 3. Odzysk pierwiastków w produktach flotacji PCB

Flotation ID	Product name	ε [%]	ε [%]
F1	K1	4,335	4,282
	K1-K4	11,196	10,550
	Odp	88,804	89,450
F2	K1	4,636	5,308
	K1-K4	11,758	13,074
	Odp	88,242	86,926
F3	K1	6,670	7,451
	K1-K4	11,397	13,367
	Odp	88,603	86,633
F4	K1	9,702	8,303
	K1-K4	15,134	14,531
	Odp	84,866	85,469

Tab. 4. Copper and aluminium contents in products after electrostatic separation

Tab. 4. Zawartość miedzi i aluminium w produktach po separacji elektrostatycznej

Product ID	Fraction type	γ [%]	Al [%]	Cu [%]
F1_K	Cond.	1,59	28,42	37,24
F1_K	Non-cond.	98,41	9,14	9,19
F1_Odp	Cond.	80,00	31,17	47,09
F1_Odp	Non-cond.	20,00	17,86	14,44
F3_K	Cond.	0,97	38,53	35,18
F3_K	Non-cond.	99,03	9,04	10,02
F3_Odp	Cond.	29,92	42,33	37,00
F3_Odp	Non-cond.	70,08	18,47	15,15

this process can be carried out in an environmentally friendly manner. After five minutes, the cell product achieved a copper recovery of about 89% with a Cu grade of 22%. Further trials, e.g., using different hydrodynamic conditions or a lower pulp density, could improve efficiency even more. Although the copper content in the cell products was not exceptionally high, it is noteworthy that almost all unwanted organic matter was removed to the froth stream. As a result, a subsequent upgrading stage on the cleaned cell product (for example, electrostatic separation) can be carried out far more effectively.

The electrostatic separation stage proved to be an effective way to upgrade the post flotation cell products that contain metals, raising the copper content to as much as 47%.

In summary, the results show that integrating advanced mechanical recycling routes, especially flotation, can significantly boost metal recovery from PCB waste, yielding economic benefits and lowering environmental impacts. The study highlights the need for further experimental work to refine flotation still more, thereby supporting sustainable development and the efficient use of natural resources. In particular, optimising feed preparation and identifying new, environmentally friendly reagents will be vital for maximising flotation performance.

ACKNOWLEDGEMENTS

The research was financed from a subsidy for the maintenance and development of the research potential of the AGH University of Krakow.

Literatura – References

1. Coombs, C. F. (Ed.). (2001). Printed circuit handbook (5th ed.). McGraw Hill.
2. Das, A., Kumar, P., & Bandyopadhyay, S. (2021). Influence of surfactants on flotation behavior of PCBs. Waste Management, 119, 101–110. https://doi.org/10.1016/j.wasman.2020.11.030
3. Das, A., Tiwari, A., & Panda, R. (2009). Physical separation methods for recovery of metals from waste PCBs. Resources, Conservation & Recycling, 53(9), 503–513. https://doi.org/10.1016/j.resconrec.2009.03.002
4. Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste. (2008). Official Journal of the European Union, L 312, 3–30.
5. Directive 2012/19/EU of the European Parliament and of the Council of 4 July 2012 on waste electrical and electronic equipment (WEEE). (2012). Official Journal of the European Union, L 197, 38–71.
6. Exporting Harm: The High-Tech Trashing of Asia". Dostęp: 3 grudzień 2024. [Online]. Dostępne na: https://www.researchgate.net/publication/228577617_Exporting_Harm_The_High-Tech_Trashing_of_Asia
7. Goosey, M., & Kellner, R. (2003). Recycling technologies for the treatment of end of life printed circuit boards. Circuit World, 29(3), 33–37. https://doi.org/10.1108/03056120310460801
8. Grause, G., Furusawa, M., Okuwaki, A., & Yoshioka, T. (2008). Pyrolysis of tetrabromobisphenol A containing paper laminated printed circuit boards. Chemosphere, 71(5), 872–878. https://doi.org/10.1016/j.chemosphere.2007.11.033
9. Guo, X., Mei, G., & Liang, Y. (2020). Surface charge control in flotation of metal plastic mixtures from WPCBs. Separation Science and Technology, 55(10), 1765–1774. https://doi.org/10.1080/01496395.2019.1655414
10. He, J., & Duan, G. (2017). Reverse flotation for metal enrichment from waste PCBs. Journal of Cleaner Production, 141, 1210–1218. https://doi.org/10.1016/j.jclepro.2016.09.184
11. Kaya, M. (2016). Recovery of metals and non metals from electronic waste by physical and chemical recycling processes. Waste Management, 57, 64–90. https://doi.org/10.1016/j.wasman.2016.08.004
12. Kim, S., & Overcash, M. (2004). Trends in the lifespan evolution of personal computers and implications for life cycle assessment: A case study of the U.S. higher education sector. Journal of Industrial Ecology, 8(1 2), 203–218. https://doi.org/10.1162/1088198041269414
13. Knoth, R., M. Brandstötter, B. Kopacek, i P. Kopacek, „Automated disassembly of electr(on)ic equipment", IEEE International Symposium on Electronics and the Environment, s. 290–294, 2002, doi: 10.1109/ISEE.2002.1003282.
14. Layiding, W., X. Dong, M. Peng, i D. Guanghong, „Disassembling approaches and quality assurance of electronic components mounted on PCBs", IEEE International Symposium on Electronics and the Environment, s. 116–120, 2005, doi: 10.1109/ISEE.2005.1437004.
15. Legarth, J. B. „Recycling of electronic scrap.", Technical University of Denmark, Lyngby, 2002.
16. Li, J., Shrivastava, P., Gao, Z., & Zhang, H. C. (2004). Printed circuit board recycling: A state of the art survey. IEEE Transactions on Electronics Packaging Manufacturing, 27(1), 33–42. https://doi.org/10.1109/TEPM.2004.830501
17. Liu, Y., Zhang, L., & Chen, Y. (2022). Ultrasound assisted flotation for improving copper recovery from waste PCBs. Waste and Biomass Valorization, 13, 157–168. https://doi.org/10.1007/s12649 021 01552 2
18. Mäkinen, J., Kinnunen, P., & Hämäläinen, M. (2015). Froth flotation of PCBs from mobile phones. Waste Management, 45, 347–354. https://doi.org/10.1016/j.wasman.2015.02.019
19. Niu, B., Li, Y., & Zhang, L. (2018). Surface modification to improve flotation separation of copper from non metals in PCBs. Journal of Hazardous Materials, 347, 412–419. https://doi.org/10.1016/j.jhazmat.2018.01.010
20. Oliveira, C., Amaral, M., & Ferreira, P. (2010). Characterization of waste printed circuit boards processed by shredding and milling. Waste Management, 30, 222–229. https://doi.org/10.1016/j.wasman.2009.09.018
21. Puckett, J., Byster, L., Westervelt, S., Gutierrez, R., Davis, S., Hussain, A., & Dutta, M. (2004). Exporting harm: The high tech trashing of Asia. Basel Action Network & Silicon Valley Toxics Coalition.
22. Qi H., Ganesan S., Wu J., and Pecht M., "Effects of printed circuit board materials on lead-free interconnect durability", 5th International Conference on Polymers and Adhesives in Microelectronics and Photonics, Wroclaw, Poland, pp. 140-144, October 23-26, 2005.
23. Stobbe, I., H. Griese, H. Pötter, H. Reichl, i L. Stobbe, „Quality assured disassembly of electronic components for reuse", IEEE International Symposium on Electronics and the Environment, s. 299–305, 2002, doi: 10.1109/ISEE.2002.1003284.
24. Syrmakezis, A., Athanassiou, L., & Laskaris, N. (2023). Column flotation optimization for metal recovery from e waste. Journal of Environmental Management, 348, 118425. https://doi.org/10.1016/j.jenvman.2023.118425

25. Veit, H. M., Diehl, T. R., Salami, A. P., Rodrigues, J. S., Bernardes, A. M., & Tenório, J. A. S. (2005). Utilization of magnetic and electrostatic separation in the recycling of printed circuit boards scrap. Waste Management, 25(1), 67–74. https://doi.org/10.1016/j.wasman.2004.09.009
26. Wang, G., Huang, T., & Xu, Z. (2005). Characterization and liberation of valuable materials from waste printed circuit boards. Waste Management, 25, 217–223. https://doi.org/10.1016/j.wasman.2004.12.018
27. Widmer, R., Oswald Krapf, H., Sinha Khetriwal, D., Schnellmann, M., & Böni, H. (2005). Global perspectives on e waste. Environmental Impact Assessment Review, 25(5), 436–458. https://doi.org/10.1016/j.eiar.2005.04.001
28. Xiang, D., Pang, Z. F., Long, D. F., Mou, P., Yang, J. P., & Duan, G. H. (2014). The disassembly process and apparatus of waste printed circuit board assembly for reusing the components. Applied Mechanics and Materials, 457–458, 474–485. https://doi.org/10.4028/amm.457-458.474
29. Yao, Y., Li, J., & Zhang, Q. (2020). Optimization of flotation conditions for selective metal recovery. Separation and Purification Technology, 245, 116847. https://doi.org/10.1016/j.seppur.2020.116847
30. Yoo, J. M., Jeong, J., Yoo, K., Lee, J. C., & Kim, W. (2009). Enrichment of the metallic components from waste printed circuit boards by a mechanical separation process using a stamp mill. Waste Management, 29(3), 1132–1137. https://doi.org/10.1016/j.wasman.2008.06.035
31. Zhu, P., Tian, W., Li, B., Hu, X. (2019). Copper recovery from waste PCBs by flotation after mechanical treatment. Waste Management, 85, 449–456. https://doi.org/10.1016/j.wasman.2018.12.005
32. CPU Museum. (2022, July 15). The life cycle of a CPU. https://www.cpushistory.com/life cycle cpu

Flotacja jako metoda odzyskiwania metalu z płytek drukowanych (PCB)

Postęp technologiczny i przyspieszony wzrost ilości zużytego sprzętu elektrycznego i elektronicznego (ZSEE) stanowią poważne wyzwanie dla odzysku zasobów, zwłaszcza metali wbudowanych w płytki drukowane (PCB). Niniejsze badanie ocenia skuteczność flotacji w selektywnym oddzielaniu metali od frakcji niemetalicznych PCB. Eksperymenty flotacyjne przeprowadzono z różnymi reżimami odczynników (różne rodzaje i dawki). Badania obejmowały zarówno właściwości fizykochemiczne materiału wsadowego PCB, jak i wpływ parametrów procesu na odzysk metali. Wyniki pokazują, że flotacja może zwiększyć odzysk cennych metali, jednocześnie minimalizując straty materiałowe i łagodząc wpływ na środowisko, w pełni wspierając zasady gospodarki o obiegu zamkniętym. Praca podkreśla potrzebę optymalizacji parametrów technologicznych i integracji flotacji z innymi etapami recyklingu PCB, wspierając w ten sposób bardziej zrównoważone strategie gospodarowania odpadami elektronicznymi.

Słowa kluczowe: *Zużyte płytki drukowane (WPCB), recykling odpadów elektronicznych, PCB, flotacja, gospodarka o obiegu zamkniętym*