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Metals recovery from e-scrap using gravity, electrostatic and magnetic separations

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Abstract. The purpose of the work was to recover metals from e-scrap, in particular from mainboards of desktop computers, using gravity, electrostatic and magnetic separation. The article describes the method of comminution as well as the yield of size fraction after this process. In addition, the separation of the fraction of 0.32 - 0.56 mm with the use of two systems: I) electrostatic and magnetic separation, and II); gravity and magnetic separation, was presented. The feed to the magnetic separator for both systems was metals (high density products). The yield of fraction 0.32 - 0.56 mm obtained after comminution was 40.7% while the yields of the products obtained from the first system were as follows: in the case of electrostatic separation, 24.9% metals and 75.1% plastics and glass; and for magnetic separation 0.7% of ferromagnetics, 19.0% of diamagnetics and 5.3% of paramagnetics. The yields of the products in the second system were: in the case of gravity separation, fraction with a density $\rho > 2.96 \text{ g/cc} = 33.0\%$ and fraction with a density $\rho < 2.96 \text{ g/cc} = 67.0\%$; and for magnetic separation 0.8% of ferromagnetics, 25.3% of diamagnetics and 6.9% of paramagnetics.

1. Introduction

For the production of electric and electronic equipment that are used in many areas of our lives, large amounts of valuable metals are needed. After using them for several years, these products become waste. Due to the financial value of metals and in accordance with the circular economy, many researchers have undertaken to recover these metals. The presence of all metals in waste is 60.6%, of which 47.9% are iron and steel, 7.0% copper, 4.7 % aluminum, 1.0 non-ferrous [1].

Printed circuit boards (PCBs) of PC are particularly interesting due to the content of metals in them [2, 3], as well as their large amount in all waste of electric-electronic equipment. PCB can contain up to 20% Cu and 250 g/ton Au, which are very high i.e. 25-250 - fold for gold and 20-40 - fold for copper when compared with gold ores and copper ores, respectively [4]. A motherboard is the main printed circuit board found in general purpose computers and other expandable systems. They contain the following metals: copper 11-14%, iron 4.5-8%, tin 2-4%, aluminum 1.5-3%, lead 1.5-2%, nickel 1-2.5% and zinc 0.5-1%. The precious metals present in the motherboard are mainly: 0.005% gold, 0.008% silver, 0.002% palladium, 0.004% platinum and negligible content of some rare earth elements. Other materials are mainly plastics, such as polymers, polyesters, phenol formaldehyde, halogenated polymers, and nylon or polyurethane [5, 6]. It should be noted that the waste processing also has an environmental dimension in addition to financial considerations.



The methods and devices of gravity, magnetic and electrostatic separation have been presented in many works [7-12].

To summarize, technological progress and the need for more and more powerful computing units make it necessary to constantly exchange computers for new ones. This creates a large amount of electronic scrap, which contains much larger amounts of metals than in natural deposits. At the same time, they contain metals harmful to the environment. Therefore, in the work the gravity, electrostatic and magnetic separation was used to recover metals from motherboards originating from desktop computers. For this purpose, four motherboards from different manufacturers were applied.

2. Research methods

In order to recover metals from mainboards, the methodology presented in figure 1 was applied. Prior to separation, preliminary work was carried out consisting in preparing motherboard for two subsequent systems. The purpose of these systems was to separate metals from plastics and glass. Electrostatic and magnetic methods were used in the first system, while gravity and magnetic in the second (see figure 1). The preliminary work consisted of material fragmentation and their division into grains of the same size.

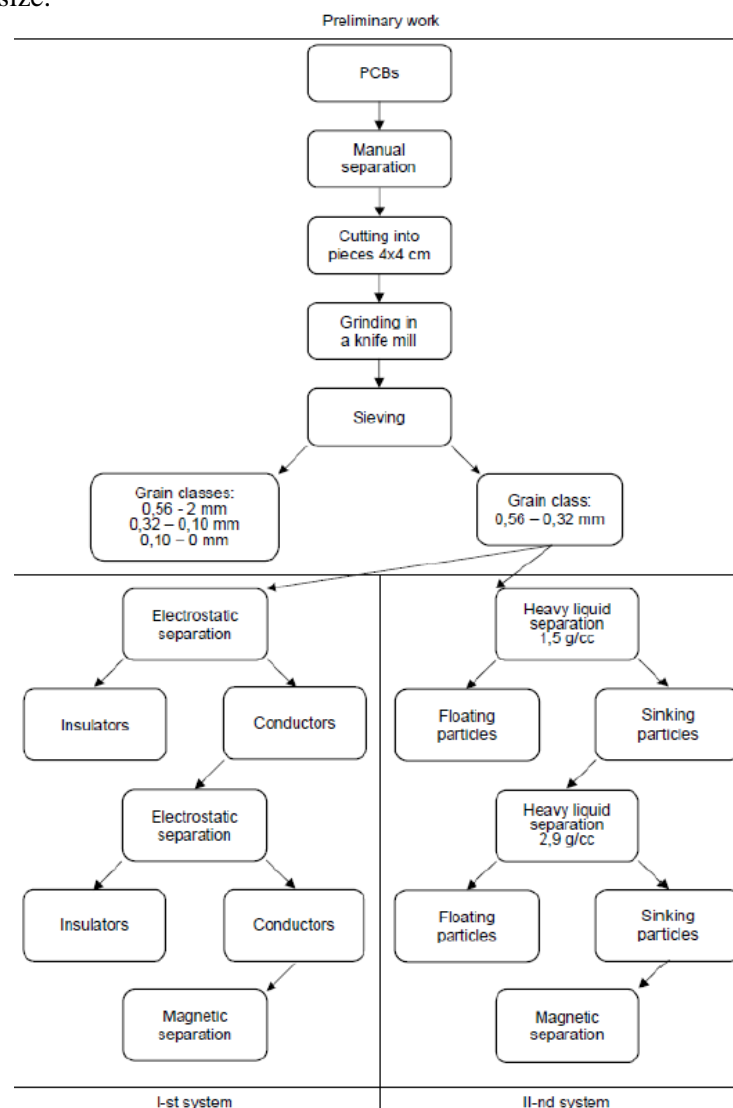


Figure 1. Research methodology.

2.1. Preparation for grinding

Printed circuits boards have many components that can cause problems when grinding or do not contain metals and at the same time can be easily removed with simple methods. Therefore, the first step was manual separation of selected parts of PCBs using basic tools such as screwdrivers and pliers. The following parts of PCB was removed: batteries, capacitor, inductors, quartz crystals, relays, resistors, transistor, integrated circuits and others (screws, connectors, switches and etc.). Then, the pre-cleaned PCBs were cut into 4x4 cm pieces due to the limitations of the knife mill.

2.2. Grinding

PCBs consist of many materials such as flexible plastic, hard glass and ceramics and various types of metals. In addition, each element has a different shape and thickness. Rotational speed, type of crushing and degree of crushing are important parameters when choosing the right type of grinding device. In the research, a knife mill was used to grind materials with hardness below 4 on the Mosh scale. Table 1 presents the parameters of this grinder. The mill is equipped with 3 sets of knives, 3 knives placed on the shaft and 3 knives on the grinding chamber.

Table 1. Parameters of the knife mill [13].

Power	2.2 (kW)
Rotation speed	2815 (rpm)
Preliminary grain	<40 (mm)
Final grain	Depending on used sieve
Standard sieve diameter	3; 2; 1; 0.425 (mm)
Efficiently	Depending on sieve approx. 10 (kg h ⁻¹)

Grinding was carried out at a rotation speed of 2815 rpm using hardened steel blades. In order to obtain the particle size suitable for the application of magnetic and electrostatic separation, a perforated sieve with a mesh size of 2 mm was used.

2.3. Screening

To prepare material for separations, four types of screens with different mesh sizes: 2.0 mm; 0.56 mm; 0.32 mm and 0.10 mm were used. The particle size 0.56 - 0.32 mm was used for the tests presented in this paper. The processing of other particles will be analyzed in subsequent studies.

2.4. Electrostatic separation

Electrostatic separation was carried out using the Boxmag-rapid Ltc separator. Electrostatic separation uses the difference in the surface conductivity of different materials. In the Boxmag separator, the material is fed to the belt of rotating shaft where it is subjected to corona discharge using a high voltage flowing through the electrode wire. This causes ionization of the air, thanks to which it is possible to charge material particles on the shaft. Particles with high surface conductivity quickly lose charge and are ejected from the rotating shaft by centrifugal force. The remaining particles that have not lost their charge are removed by a brush at the rear of the shaft. The main parameters of separation are: rotational speed of the shaft, voltage flowing through the electrode and its distance from the shaft, and the size of the material and feeding speed [14].

As a result of research conducted on the analyzed material, it was found that the most optimal parameters of separation in terms of efficiency and purity are: voltage flowing through the electrode = 20 kV, speed of shaft rotation 50 rpm and distance of electrode from the shaft of 5 cm.

2.5. Gravity separation

In subsequent works, it is planned to verify the efficiency of separation using the difference in grain density, e.g. with the use of concentrating table or cyclofluidic separator. Due to too small sample of

the analyzed material, only a simplified density analysis was carried out. Two liquids with densities of 1.5 g/cc (ZnCl₂ solution) and 2.96 g/cc (1.1.2.2-tetrabrom-ethane Br₂CHCHBr₂) were used.

2.6. Magnetic separation

The separation was made using the magnetic susceptibility of the material and the magnitude of the magnetic force. For this purpose, a disk magnetic separator was used, which ensures heterogeneity of the magnetic field. The material placed on the moving belt is affected by the ever-larger magnetic field. Grains of material with a higher magnetic susceptibility are lifted from the belt and placed in the receiver's containers by means of a chutes. The separator allowed to separate the material by means of two different magnetic forces produced by electromagnets [15]. Grains with the lowest magnetic susceptibility pass under magnetic plates and fall from the conveyor belt at the end of the separator. Additionally, at the beginning of the separator there is a permanent magnet that captures the ferromagnetic material.

The density of separated products in all tests was specified using pycnometer method in line with the PN-88/B-04481 standard. The content of ferromagnetic materials in the samples was carried out using the Satmagan 135 meter by Rapiscan Systems.

3. Results and discussion

3.1. Manual separation and grinding

Four motherboards from different manufacturers and with different masses were used in the tests. On average, about 45% of the mass of the motherboards were waste that had been manually removed (see table 2). This is a large amount of waste that also contains metals. Therefore, the recovery of metals from these wastes will be considered in subsequent tests.

Table 2. Results of manual separation of motherboards.

	Mass of the motherboards, (g)	Mass of the motherboards after manual separation, (g)	Percentage of waste, (%)
	632.4	355.0	44
	558.6	310.0	45
	497.2	269.6	46
	496.8	265.6	47
Total	2185.0	1200.2	45

During the grinding of elements with a larger content of plastics that could not be removed manually, an increase in the temperature in the material and the grinding chamber was noticed. Therefore, it is recommended to use liquid nitrogen for grinding more material.

3.2. Sieving

Table 3 shows the results of the granulometric composition after grinding. The lack of grains > 2 mm indicates good quality of grinding. During this process, in a knife mill a sieve of 2 mm was used. Two grain classes represent almost 80% of the sample. They are 0.32 - 0.56 mm and 0.10 - 0.32. The higher one was undergone to separation in the system I and II (see figure 1).

Table 3. The results of the screening tests of comminuted motherboards.

Grain class, mm	Class weight, (in % by mass)
> 2	0.0
0.56 – 2.00	7.9
0.32 – 0.56	40.7
0.10 – 0.32	38.4
< 0.10	13.0

3.3. Electrostatic separation

Electrostatic separation was carried out only for system I (see figure 1). Due to the difficulties associated with the separation of materials caused by the permanent connection of plastics and metals, a two-stage separation was carried out. In the first step, grains consisting of plastics and glass were separated from grains consisting of metals and their combinations with plastics. Then, the electrostatic separation of the metal product was again performed under the same separation conditions that allowed to separate metals from the grains in which they were combined with plastics. As a result, 25% of metals were obtained with a small amount of impurities, as evidenced by the density of this product at 11.17 g/cc (table 4).

Table 4. Results of electrostatic separation.

Electrostatic separation		Weight, (in % by mass)	Density, (g/cc)
1st	Plastics	69.7	3.86
	Metals	30.3	10.50
2nd	Plastics	5.3	7.43
	Metals	24.9	11.17

3.4. Heavy liquid separation

Density separation was performed only for system II (see figure 1). For technical reasons, it was conducted into two stages. In the first stage grain separation in ZnCl₂ solution (density 1.5 g/cc) was performed, while in the second in tetrabrom-ethane (density 2.96 g/cc). A high density value for the fraction of <1.5 g/cc indicates the difficulty of separation for fine grains resulting from the high solution viscosity. Grains with a density > 2.96 g/cc made up ca 1/3 of the total material, and their density was almost 10 g/cc.

Table 5. Density distribution results.

Separation in heavy liquid		Weight, (in % by mass)	Density, (g/cc)
1st	Fraction < 1.50 g/cc	56.9	3.16
	Fraction > 1.50 g/cc	43.1	7.25
2nd	Fraction < 2.96 g/cc	10.1	-
	Fraction > 2.96 g/cc	33.0	9.63

3.5. Magnetic separation

Magnetic separation was the last stage of research conducted in both systems. The separator parameters were the same. In the case of I system, the paramagnetic mass was sufficient to assess the density and content of ferromagnetic particles in this product, whereas in the system II the mass was

too low. Therefore, in the system II, paramagnetic products with higher and lower magnetic susceptibility have been combined.

The analysis of the results presented in table 6 shows that the I system was more efficient in separating metals from plastics, because the density of all products was higher by about 1.5 g / cm³ than in the system II. The densities of precious metals were presented among others the paper by Tuncuk et al. [4]. Analysis of the content of ferromagnetic materials confirmed the correctness of magnetic separation in both systems. F

Figure 2 shows the products after the separation processes. The shape and color of the grains indicate that the separation of plastic from metals was done precisely. Diamagnetics are also significantly different from paramagnetics, which proves the effectiveness of separation.

Table 6. Results of magnetic separation (for both systems)

Products susceptibility to magnetic fields	System I			System II		
	Weight, (in % by mass)	Density, (g/cc)	Content of ferromagnetic, (%)	Weight, (in % by mass)	Density, (g/cc)	Content of ferromagnetic, (%)
ferromagnetic	0.7	11.33	90.5	0.8	10.63	-
paramagnetic	lows magnetic force	4.0	13.38	1.0	4.8	11.61 0.2
	higher magnetic force	1.3	13.22	0.0	2.0	
diamagnetic	18.7	10.58	0.0	25.3	9.08	0.0

In terms of value and suitability, each product is important. Diamagnetics can contain such metals as: gold, silver, copper or lead, while paramagnets palladium, tin, chromium, aluminum, as well as rare earth metals. In turn, ferromagnetics can contain iron, cobalt and nickel.

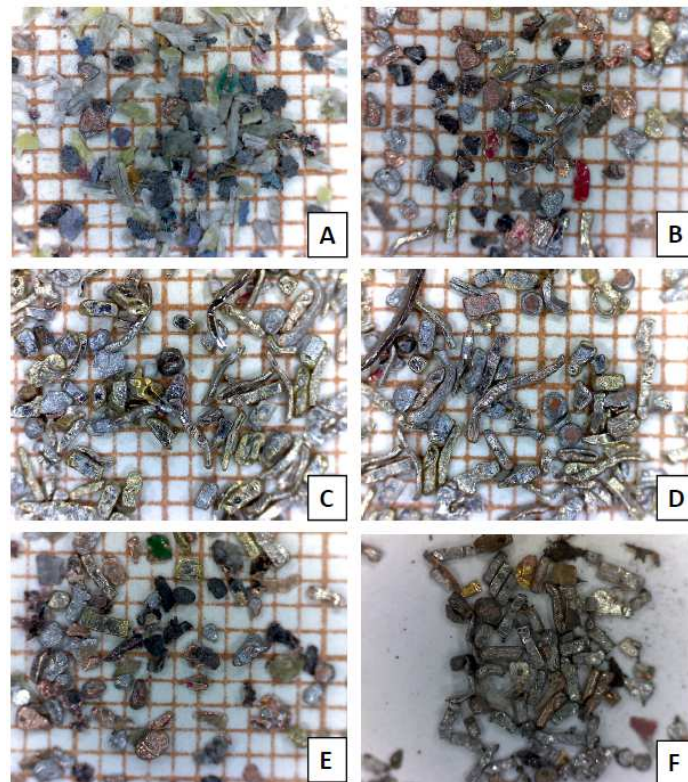


Figure 2. The grains of: A - plastics after the first electrostatic separation, B - metals after the second electrostatic separation, C - paramagnetic (low magnetic force), D - paramagnetic (high magnetic force), E – diamagnetic, F – ferromagnetic.

4. Conclusions

The following conclusions can be drawn on the basis of the research:

- the yield of fraction 0.32 - 0.56 mm obtained after grinding a motherboards in the knife mill was 40.7%,
- the separation of metals from plastics in the fraction of 0.32 - 0.56 mm is effective in both analyzed processing systems, i.e. in electrostatic and magnetic separations, as well as in gravity and magnetic separation,
- the yields of the products obtained from electrostatic and magnetic separation were as follows: in the case of electrostatic separation, 24.9% metals and 75.1% plastics and glass; and for magnetic separation 0.7% of ferromagnetics, 19.0% of diamagnetics and 5.3% of paramagnetics,
- products outputs in gravity and magnetic separation were as follows: in the case of gravity separation, the fraction with a density $\rho > 2.96$ g/cc amounted to 33.0% while the fraction with $\rho < 2.96$ g/cc 67.0%; and for magnetic separation 0.8% of ferromagnetics, 25.3% of diamagnetics and 6.9% of paramagnetics.

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