Original Article

Copper and metals concentration from printed circuit boards using a zig-zag classifier

Pedro Paulo Medeiros Ribeiro\textsuperscript{a,*}, Iرانildes Daniel dos Santos\textsuperscript{b}, Achilles Junqueira Bourdot Dutra\textsuperscript{a}

\textsuperscript{a} Metallurgical and Materials Engineering Department – Federal University of Rio de Janeiro – UFRJ, Rio de Janeiro, RJ, Brazil
\textsuperscript{b} Instituto Tecnológico Vale/Vale S.A., Ouro Preto, MG, Brazil

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\textbf{A B S T R A C T}

The consumption of electronic products has grown considerably in the last decades. These products become obsolete in a short period of time, generating electronic waste, which presents loads of materials harmful to health and metals of great value to industries. In this work, an innovative metal concentration technique for PCBs was applied aiming at the valuable metals recovery from ground printed circuit boards (PCBs) of computers that would be discarded. The PCBs were comminuted, classified by sieving and the metallic materials were processed in a zig-zag classifier type. The Schytîl’s phase diagram was developed to estimate the air flow rate to be used in the classifier. The product of each step was characterized. The copper content rose from 13.8\% (w/w) to 48.8\% (w/w) after the passage of the PCBs powder through the classifier. Its recovery and Newton’s efficiency were above 89.4\% and 0.91, respectively. The total content of metals was increased from 39.5\% (w/w) to 89\% (w/w) with a recovery of more than 82\% and Newton’s efficiency of 0.67 for the particle size in the range from 0.2 to 0.1 mm. The gold content has increased from 200 ppm to more than 8000 ppm after segregation by a simple manual concentration. Results shown that the use of zig-zag classifier to separate and concentrate metals was fairly effective, do not generate liquid and gaseous effluents and eliminates a number of pyrometallurgical or hydrometallurgical steps for metals obtaining.

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1. Introduction

Printed circuit boards (PCBs) are essential parts of the great majority of electric and electronic devices, which can contain more than 18% Cu, 80 g ton$^{-1}$ Au and 600 g ton$^{-1}$ Ag. The challenge of developing an efficient technology for metals recovery from discarded PCBs is due to the wide variety of materials used in the manufacture of such boards, in order to perform the necessary functions in the appliances [1–3]. The PCBs are generally composed of ceramics (−30%), polymeric (−30%) and metallic (−40%) materials [4–7]. Among the metallic materials there are gold and other precious metals besides lead, tin and antimony, nickel, aluminum, beryllium, cadmium and copper; the last one being present in larger amount [6–8].

The separation of the metallic fraction from the ceramic and polymeric materials can be achieved by air classification. Air classification is a clean separation method that does not use any polluting medium for separation [9]. The separation principle is based on the different sedimentation velocity of the particles. Smaller and lighter particles are easier to be elutriated by an air flow than the larger and heavier ones [9,10]. This separation process is widely employed in the agricultural industries for separating the valuable grains from straw, because straws are lighter than grain and can be blown away by air stream. However, the separation efficiency of this process depends on the particle shape, gas flow rate and naturally particle size [9,11].

The zig-zag air classifier is a type of pneumatic classifier where a number of sections, or stages, with rectangular cross-section are connected to each other at a fixed angle to create a zig-zag shaped channel, producing a turbulent flow which avoids the drop of irregular shaped particles, as needles, in a preferential orientation, once the specific drag force will not be parallel to the motion of the particle unless it presents certain symmetry [12]. The drag force will produce both a rotational and a translational movement of the particles. Then, at each stage, the particles are subjected to a renewed classification, through a cross flow process where the sequential stages improve the separation efficiency [10]. Due to the creation of a separation region of turbulent air, the falling particles descend along the lower section wall entering again in contact with the main air flow at the protruding edge of the next stage, where there exists a relatively high local air velocity. The lighter and smaller particles follow the upward air flow along the upper section wall [11]. The falling particles may pass over the main air flow and proceed their way down or may be deflected to such an extent that they are entrained upwards by the main air flow. The zig-zag classifier has been used to concentrate coarse particles of mica or enrichment of the metallic components of PCBs [2,13,14].

The regime in which the particles can be elutriated in the zig-zag classifier depends on a number of variables such as fluid and solids densities, fluid viscosity, particle diameter and shape, superficial gas velocity, etc. The Schütz’s diagram employs directly only two variables: particle diameter and superficial gas velocity. The Schütz’s graph is a kind of phase diagram where the X and Y axis are respectively the Reynold and Froude numbers. The diagram depicts three different regions: fixed bed, fluidized bed and pneumatic transport or elutriation. This diagram is also superposed by line functions for constant particle size and linear fluid velocity allowing the prediction whether or not particles of a given size and density will be pneumatically transported or will remain in fixed or fluidized bed regime [15,16].

For the concentration of metals from the ground PCBs, several air classifiers types have been used, such as vertical, horizontal and column. The PCBs are composed of different metals, polymeric and ceramic materials, which present very distinct physical properties and shapes after grinding, turning its separation a complex issue. In this context, the zig-zag classifier presents the advantage of minimizing the irregular particle shape effect, usually found in the ground PCBs. The zig-zag column inclination angle turn the drop of irregular particles steadier, avoiding both vertical and horizontal drops of flat, needle and other irregular shape particles, providing a more effective classification of the particles by size and density only.

This way, the objective of this work was to evaluate the pneumatic zig-zag classifier performance for the separation of a fraction rich in copper, as the more valuable non-precious metal, and other metals from a non-metallic fraction rich in polymeric and ceramic materials, contained in ground PCBs, as part of an integrated route for PCBs recycling, as shown in the flowchart of Fig. 1, where the dashed rectangle represents the present study.

2. Materials and methods

PCBs were collected from obsolete computers available in the Department of Metallurgical and Materials Engineering of the Federal University of Rio de Janeiro, Brazil. They were firstly manually disassembled for the removal of bigger components such as electric transformers, heat dissipaters, etc., that can be re-used. The slots and CPUs (Central Processing Unit), which present a much higher gold content were processed separately. Then, the clean boards were sliced to sizes around 50 × 10 mm, which were fed in a knife mill to produce a powder material smaller than 2.0 mm, with approximately 40% of metals, including about 20% of copper. This material was screen classified to generate different size fractions. The fraction above 0.8 mm was reground and returned to the fraction below 0.8 mm to be screen classified to generate five size fractions (0.8–0.6, 0.6–0.4, 0.4–0.2, 0.2–0.1, <0.1 mm) which were fed into the zig-zag classifier to separate the heavy and light materials, producing two samples each, which were partially dissolved in aqua regia and analyzed to quantify the amount of copper and other metals content in the samples. The fraction in the size range of 0.2–0.1 mm was divided into two parts in order to analyze not only the influence of the particle size but also the applied air flow rate. This classification provides the segregation of most of the polymeric and ceramic materials in the light fraction and the metals in the heavy fraction. The flowchart presented in Fig. 2 summarizes the physical processing of the PCBs. The experimental setup consisting of a zig-zag pneumatic classifier, with a cross-section of 44 × 95 mm, 780 mm height and zig-zag angle of 120°, centrifugal fan and a valve to control the air flow.
Copper and other metals analyses before and after the concentration by a zig-zag air classifier tests were carried out by atomic absorption spectroscopy (Shimadzu AA 6800).

Copper and metals recovery were determined through Eq. (1), where \( f \) is the copper or metals grade in the feed, \( c \) is the copper or metals grade in the concentrate (underflow) and \( t \) is the copper or metals grade in the tailings (overflow). The Newton’s efficiency (\( \eta \)) was determined by Eq. (2) [17]. The liberation degree of metals (LD) from non-metallic materials was calculated by the point count method expressed by Eq. (3), where, \( n \) is the number of samples, \( N_{li} \) indicates the free particles of the desired material in the \( i \)th sample and \( N_{f} \) represents the locked particles of the same sample [18].

The air flow rates used in the zig-zag classifier ranged from 8 to 19 m\(^3\) h\(^{-1}\). This air flow rates values were selected with the aid of the Schytts’s diagram, which is based in the Froude and Reynolds numbers of a fluid flowing through a bed of particles, depicting three predominance areas (fixed bed, fluidized bed and pneumatic transport) where a given particle of known density and size, should be when submitted to a certain fluid flow velocity. The diagram for the present system (PCB powder and air) was plotted with the equations (4)–(7). Eqs. (4) and (5) define, respectively, the boundaries between the fixed and fluidized bed and fluidized bed and pneumatic transport. Eq. (6) represents the straight lines of constant velocity, while Eq. (7) represents the lines of constant particle diameter. Schytts’s diagram provides useful information to select the ranges of air flow to be used in the zig-zag classifier, in order to separate base metals, with densities greater than 7 g cm\(^{-3}\), from the lightweight materials such as plastics and glass reinforced.

Fig. 1 - Flowchart proposal for an integrated route for materials recycling from PCBs.
polymers, with densities smaller than 1.8 g cm\(^{-3}\) and ceramic materials, with densities smaller than 4.0 g cm\(^{-3}\).

Recovery (%) = 100 \times \frac{c(f - t)}{(c - t)} \quad (1)

\eta = \frac{(f - t)(c - t)}{f(1 - f)(c - t)} \quad (2)

LD = \sum_{i=1}^{n} \frac{N_2/N_1 + N_1}{n} \quad (3)

Fr = \frac{\varepsilon^3 (p_s - p_g)}{p_g(150(1 - \varepsilon)/Re + 1.75)} \quad (4)

Fr = \frac{4}{3} \varepsilon^{3.65} \left( \frac{p_s - p_g}{p_s \cdot C_d} \right) \quad (5)

log Fr = - log Re + log \left( \frac{u^3 \cdot \rho_g}{\mu \cdot g} \right) \quad (6)

log Fr = 2 log Re + log \left( \frac{\mu^2}{g \cdot \rho_g \cdot d_p} \right) \quad (7)

where Fr and Re are the Froude and Reynolds numbers, respectively. \(\varepsilon\) is the void fraction, which tends to unity at the fluidized bed/pneumatic transport frontier. \(p_s\) and \(p_g\) are the solid and fluid density respectively and \(C_d\), the drag coefficient for flat particles, the most common shape of knife mill product for this material, which is a function of the Reynolds number, as shown in Table 1. \(u\), \(\mu\) and \(d_p\) are the superficial fluid (air) velocity, fluid viscosity, and particle diameter, respectively. The solid products densities were determined by picnometry.
reach 100% of the particles below 0.8 mm, increasing metals liberation. The metals liberation degree, calculated for the fraction in the size range of 0.8–0.6 mm, was of 78.8%. This indicates that metals are still associated with polymeric and ceramic materials. The interfacial bond among the materials or components are relatively weak, therefore, the size fraction in the range of 0.2–0.1 mm achieved a higher liberation degree, around 95.7%.

The copper and other metals content as a function of particle size obtained after comminution in a knife mill and dry screening classification are shown in Table 2. It can be observed that the copper content was reduced with the particle size reduction probably due to the fact that copper, as a ductile metal, is rather deformed than broken into smaller pieces; the higher copper content, 28.1% (w/w), was achieved in the 0.6–0.4 mm fraction. On the other hand, the aluminum content increased from 1.0 to 3.9% (w/w) when the particle size was reduced from 0.8 to 0.6 to <0.1 mm, indicating that most of the aluminum in the sample should be present as a non-metallic material, probably ceramics, due to its low ductility. It can be also observed that the tin and lead content was disseminated throughout all the fractions, but the finer one. This behavior can be attributed to the high ductility and malleability of the tin-lead alloys [21, 22].

The metals and copper content of the ground PCBs, for the feed, underflow, and overflow, as a function of particle size range using the zig-zag classifier and the proper air flow rate are presented in Fig. 5. An increase of the metals content, achieved with a finer grinding, can be observed. However, for copper, this increase was relatively small if compared with the whole metals content. The finer particle size range led

### Table 1 – Drag coefficient values for flat particles as a function of Reynolds number [19, 20].

<table>
<thead>
<tr>
<th>$Re$</th>
<th>$C_d$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>335.9</td>
</tr>
<tr>
<td>1</td>
<td>42.8</td>
</tr>
<tr>
<td>10</td>
<td>7.8</td>
</tr>
<tr>
<td>100</td>
<td>2.6</td>
</tr>
<tr>
<td>1000</td>
<td>0.8</td>
</tr>
<tr>
<td>10,000</td>
<td>0.4</td>
</tr>
</tbody>
</table>

### Table 2 – Percentage (w/w) of copper and other metals in the PCB powder as a function of particle size for the fractions below 0.8 mm obtained after comminution in knife mill and classification by screening.

<table>
<thead>
<tr>
<th>Particle size fraction (mm)</th>
<th>Density (g cm$^{-3}$)</th>
<th>Copper (%)</th>
<th>Zinc (%)</th>
<th>Nickel (%)</th>
<th>Aluminum (%)</th>
<th>Lead (%)</th>
<th>Tin (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.8–0.6</td>
<td>3.0</td>
<td>26.4</td>
<td>2.3</td>
<td>0.5</td>
<td>1.0</td>
<td>4.4</td>
<td>10.1</td>
</tr>
<tr>
<td>0.6–0.4</td>
<td>2.8</td>
<td>28.1</td>
<td>1.6</td>
<td>0.5</td>
<td>1.0</td>
<td>3.0</td>
<td>5.7</td>
</tr>
<tr>
<td>0.4–0.2</td>
<td>2.8</td>
<td>23.8</td>
<td>1.0</td>
<td>0.3</td>
<td>1.0</td>
<td>2.8</td>
<td>11.4</td>
</tr>
<tr>
<td>0.2–0.1</td>
<td>2.6</td>
<td>13.8</td>
<td>1.5</td>
<td>0.7</td>
<td>0.9</td>
<td>5.7</td>
<td>10.7</td>
</tr>
<tr>
<td>&lt;0.1</td>
<td>2.2</td>
<td>2.1</td>
<td>0.1</td>
<td>0.2</td>
<td>3.9</td>
<td>0.8</td>
<td>1.6</td>
</tr>
</tbody>
</table>

### Fig. 4 – Schyttil’s diagram used to estimate proper air flow rate to allow the separation of different materials from metals as a function of density for particle size range between 0.2 and 0.1 mm. (A) Materials density: 1.8 g cm$^{-3}$; (B) Materials density: 4.0 g cm$^{-3}$.
to a higher metals and copper content, around 89% (w/w), and 48.8% (w/w), respectively; associated with a total metals recovery higher than 82%. This higher metals content in the smaller size fraction can be attributed to the metals present in the ceramics, as oxides for instance, which are fragile and are pulverized even with a coarse grinding. Nevertheless, the greatest metals and copper content difference between underflow and overflow occurs in the smaller particle size range where Newton’s efficiency for the metals reached the value of 0.67.

The influence of particle size feed on the copper recovery and Newton’s efficiency of the PCBs powder from the zig-zag classifier underflow is shown in Fig. 6. It can be observed that copper recovery was increased from 36% to 89.4% when particle size feed was decreased from 0.8–0.6 mm to 0.2–0.1 mm. This behavior can be attributed to the higher liberation degree achieved for the finer grinding, which permits a better separation of the heavy and light fractions of the feed. For the particle size range of 0.2–0.1 mm Newton’s efficiency reached the highest value (0.84).

The influence of air flow rate on the copper recovery and content, along with its Newton’s efficiency, of the ground PCBs obtained in the zig-zag classifier underflow and overflow, for the particle size range between 0.2 and 0.1 mm, is presented in Fig. 7. It can be observed that copper recovery decreases from 98 to 0% as air flow rate is increased from 8 to 19 m$^3$ h$^{-1}$, while copper content in underflow was increased from 13.8% to 48.8% (w/w) approximately (air flow rate of 13 m$^3$ h$^{-1}$). The Newton’s efficiency has a peak value at 13 m$^3$ h$^{-1}$ (0.91). This behavior is associated with the copper losses to the overflow that tends to grow as the air flow rate is increased from 8 to 19 m$^3$ h$^{-1}$. Furthermore, it indicates that an air flow rate between 11 and 13 m$^3$ h$^{-1}$ should be the better choice since it renders simultaneously a high copper recovery and content associated with Newton’s efficiency in the range of 0.70–0.73 in the underflow.

It can also be observed the agreement between the air flow rate used in the zig-zag classifier and the theoretical air flow rate at the boundary between fluidized bed and pneumatic transport for materials with densities of 1.8 and of 4.0 g cm$^{-3}$ with particle size range between 0.2 and 0.1 mm as shown in Fig. 4. This behavior demonstrates the importance of Schytil’s diagram to predict the air flow rate to be applied. This kind of information can be obtained not only for zig-zag classifiers but for the majority of air classifiers that can be used to concentrate or classify metals from printed circuit boards.

The copper and metals content in the PCBs powder after concentration using the zig-zag classifier with an air flow rate of 13 m$^3$ h$^{-1}$ and particle size in the range of 0.1–0.2 mm is

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**Fig. 5** – Metals (A) and copper (B) content (w/w) in the feed, concentrate (underflow) and tailings (overflow) as function of particle size feed and air flow rate. Feed mass: 50 g.

**Fig. 6** – Copper recovery and Newton’s efficiency of the PCBs powder from the zig-zag classifier underflow as function of particle size feed. Feed mass: 50 g.
shown in Table 3. It can be observed that, besides copper, lead and tin are the metals present in larger amounts. However, silver and gold, when present, should also be concentrated with the other metals in the zig-zag underflow.

The macroscopic view of the PCBs powder underflow (A) and overflow (B) from the zig-zag classifier are presented in Fig. 8. In Fig. 8A, a clear predominance of particles with metallic luster is evident, while in Fig. 8B, the presence of a great amount of polymeric and ceramic materials is quite obvious.

4. Conclusions

The air flow rate used for metals concentration through the zig-zag classifier was estimated using the Schytil’s diagram. The agreement between the theoretical air flow rate and the used in the zig-zag classifier to elutriate materials with densities of 1.8 and of 4.0 g cm⁻³ with particle size range between 0.2 and 0.1 mm shows the effectiveness of the use of Schytil’s diagram to predict the conditions whether or not the polymeric and ceramic materials will be pneumatically transported allowing the concentration of the heavier particles rich in metals. The zig-zag design of the classifier favors the rupture of agglomerates due to the presence of intense shear stress caused by the turbulent regime. This way, a 48.8% (w/w)-copper concentrate associated with an 89.4%-recovery was achieved for the particle size range between 0.1 and 0.2 mm with an air flow rate of 13 m³ h⁻¹. The total content of metals was increased from 39.5% (w/w) to 89% (w/w) with a recovery of more than 82% for the same particle size range.
The copper recovery tends to drop when the air flow rate is increased, on the other hand, the copper content tends to increase as the air flow rate increase up to 13 m$^3$h$^{-1}$. It was observed that, soft metals, like lead and tin, tend to be deformed rather than ground so they are concentrated in the larger and intermediate size ranges.

Conflicts of interest

The authors declare no conflicts of interest.

REFERENCES


