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Electronic scraps – Recovering of valuable materials from parallel wire cables

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Abstract

Every year, the number of discarded electro-electronic products is increasing. For this reason recycling is needed, to avoid wasting non-renewable natural resources. The objective of this work is to study the recycling of materials from parallel wire cable through unit operations of mineral processing. Parallel wire cables are basically composed of polymer and copper. The following unit operations were tested: grinding, size classification, dense medium separation, electrostatic separation, scrubbing, panning, and elutriation. It was observed that the operations used obtained copper and PVC concentrates with a low degree of cross contamination. It was concluded that total liberation of the materials was accomplished after grinding to less than 3 mm, using a cage mill. Separation using panning and elutriation presented the best results in terms of recovery and cross contamination.

1. Introduction

The increase of electro-electronic goods has grown considerably in the last decades. The variety of products and models offered to the consumer has increased. The current market offers new products and as a result of this, the changing of products happens more quickly.

Therefore, the collection and recycling of waste of electric and electronic equipment (WEEE) is a current need, not only in terms of conserving natural resources by recycling materials, but also to preserve the environment and to avoid an increasing negative environmental impact of this product type.

In the last 10 years, the recycling of electro-electronics scrap studies (Cui and Forssberg, 2003; Lee et al., 1999; Zhang and Forssberg, 1999) has intensified, although many aspects still need to be developed. The European Community Waste Electrical and Electronic Equipment Directive (Directive 2002/96/EC) has promoted even more the advance of investigation in this area. In this context, this work presents an effective contribution to wire and cable recycling, assuming that in the development of recycling processes, the wires and cables, as well as the batteries, should be segregated. In fact, many equipment pieces possess power or telephone line cables separated from the equipment body.

2. Objective

The objective of this work is to study the recycling of parallel wire cable through unit operations of mineral processing. Mineral processing is the art of separating different minerals by the exclusive use of their physical properties – specific weight, magnetic susceptibility, color, shape etc. Their unit operations are low-cost and are growing in importance in the processing of wastes.

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3. Materials and methods

In order to recover valuable materials from parallel wire cables, unit operations of mineral processing were tested. Essentially, the scrap was firstly ground to liberate the materials and secondly six different methods to separate the materials were tested. Prior to these operations, three independent samples of 250 g were used to determine the amounts of copper and PVC present in the studied waste. These amounts were determined through manual disassembling of samples using knives, scissors and a weighing scale.

All pieces of equipment used in this paper were standard laboratory ones.

3.1. Grinding

Grinding is the unit operation to reduce the size of particles from 20 to 10 mm to almost zero. The main mechanism of fines generation is attrition. It is performed in mills, which have different kinds: rod mills, ball mills, hammer mills, roller mills etc. The cage mill has knives that revolve at high speeds and cut the pieces in its interior chamber. This chamber is closed by a grid in a way that only particles smaller than the openings of this grid will pass. Attrition occurs between the hammer and the grids and in this case is effective to detach the plastic from the copper.

A sample of 9 kg of parallel wire cables was separated and processed in a cage mill. The parallel wire was chosen as it is one of the most commonly used in the market and found in appliances. Three different grate openings were used: 9, 6 and 3 mm. Thus, for each grate opening 3 kg were processed.

After grinding each sample was divided in two parts by cone and quartering. Afterwards, the samples were homogenized and obtained through the elongate pile method. Samples were extracted from piles for each separation test, e.g., size classification, dense medium separation, electrostatic separation, scrubbing, panning, and elutriation.

3.2. Size classification

The separation of particles of different sizes can be achieved in different ways. One is by sieving in screens. The particles are introduced onto a sieve, where they will or will not pass. In this research work, a laboratory screen agitator was used.

Size classification was performed using the following sieve openings: 4.76, 2.83, 1.7, 1.0, and 0.5 mm. Each sample weighed approximately 100 g and remained in the agitator for 15 min.

Afterwards, through a manual separation procedure with the aid of tweezers, the particles retained in each screen were classified into three known categories: metal, plastic and mixed material (metal + plastic). The category "mixed material" is due to the fact that in some size classes, total material liberation did not occur.

3.3. Dense medium separation

This separation method consists in preparing a liquid with a density between the specific weights of the materials to be separated. For laboratory purposes, organic chemicals such as tetra-bromo-ethane (density of 2.96 g/cm^3), bromophorm (density of 2.86 g/cm^3) were diluted with proper solvents to give the desired density. Salt solutions, as in this case, can also be used. In industry, suspensions of heavy solids finely ground, like magnetite or ferro-silicon, are used and the piece of equipment – heavy media drums, cyclones or agitated vessels – must keep them in permanent agitation.

Calcium chloride aqueous solution with a density of 1.41 g/cm^3 was used as dense medium. This density value was chosen, as long as the species to be separated possessed specific weights of 9.6 g/cm^3 (copper) and 1.21 g/cm^3 (PVC). A second separation of the floated material in the dense medium was undertaken to increase the separation output, as long as a copper contamination was observed in the first separation in the floated material, owing to the mechanical entrapment of some particles.

At the end of the test, two products were obtained, the plastic originating from the second separation stage and the copper originating from both stages.

3.4. Electrostatic separation

Electrostatic separators charge all of the particles by electron bombardment. The charged particles roll over a metallic drum and, if they are conductive, loose the electrical charge (for the metallic drum). If they are insulating, they remain charged and are attracted by a positive electrode conveniently placed, thus separating them from the conductive particles that fall vertically from the drum, and are recovered in a different vessel.

Three samples of approximately 300 g were separated for the electrostatic separation tests; the particle sizes were 9, 6 and 3 mm. The samples were added to the system in a gradual manner. At the end of each test the samples were classified in: conductor, non-conductor and intermediary.

3.5. Scrubbing

Scrubbing is the attrition of particles against particles in an effort to remove contaminants from their surfaces. The scrubbing or attrition machine is a vessel in which there is an axis with two propellers. The propeller blades are positioned in such a way that their flows have opposite directions, throwing particles one against the other. An intense surface work is achieved in these machines.

Grinding was not effective in releasing the metal and plastic for some size fractions. These samples were submitted to scrubbing tests with the intention of obtaining greater material liberation.

3.6. Panning

The pan is a very old craft to concentrate gold and other heavy minerals by the difference of their specific gravities to that of the associated minerals. It is a shallow conical vessel that is filled with water and the ore to be concentrated. The operator turns the pan in circular movements and induces a circular movement of the water inside it. The rotating water drags the particles, which acquire different speeds in function of their specific weights. The lighter particles flow quickly and remain on the borders of the pan, from where they can be poured. The heavy particles sink to the bottom of the pan, that is its apex, and remain there.

The sample was put into a pan and then the pan was halfway immersed in a basin with water. Slowly in circular movements, the PVC that fell into the basin with water was separated and the copper remained in the pan.

3.7. Elutriation

Elutriation is the separation of finer or lighter particles by vertical ascending streams. The material to be separated by sizes or sorted by specific weight is put in a cylindrical vessel. The ascending stream drags the lighter or finer particles upstream. The heavier particles have greater settling speeds and sink downstream.

Samples of approximately 200 g were used for the elutriation tests. Each test used about 100 L of water at a flow rate of approximately 85 mL/s. With the aid of a hoist, the material was placed inside of the glass elutriator. The copper settled and the PVC rose following the water current to the container where it was collected.

4. Results

The amounts of copper and PVC obtained through manual disassembling were, respectively, 45 and 55 mass %.

Material from the three different grindings (#9 mm, #6 mm and #3 mm) was size classified and the samples from each sieve were hand separated. The results of hand separation are shown in Tables 1–3.

All grinding tests presented effective liberation of copper and plastic.

Table 1
Results of hand separation and classification of material from grinding to less than 9 mm

Sieve (mm)	Accumulated (wt.%)	Cu (wt.%)	PVC (wt.%)	Cu + PVC (wt.%)	Total (wt.%)
+4	99.7	23.6	32.8	2.5	58.9
−4 +2.83	40.8	4.3	12.9	0.0	17.2
−2.83 +1.7	23.6	2.1	5.2	0.0	7.3
−1.7 +1	16.3	8.3	1.5	0.0	9.8
−1 +0.5	6.5	4.8	0.3	0.0	5.1
−0.5	1.4	0.97	0.4	0.0	1.4
Total (%)	0.0	44.1	53.1	2.5	99.7

Table 2
Results of hand separation and classification of material from grinding to less than 6 mm

Sieve (mm)	Accumulated (wt.%)	Cu (wt.%)	PVC (wt.%)	Cu + PVC (wt.%)	Total (wt.%)
+4	99.8	6.6	2.3	0.5	9.4
−4 +2.83	90.4	2.9	19.0	0.5	22.4
−2.83 +1.7	68.0	3.9	32.7	0.2	36.8
−1.7 +1.0	31.2	9.1	2.4	0.0	11.5
−1.0 +0.5	19.7	7.3	0.2	0.0	7.5
−0.5	12.2	12.0	0.2	0.0	12.2
Total (%)	0.0	41.8	56.8	1.2	99.8

Table 3
Results of hand separation and classification of material from grinding to less than 3 mm

Sieve (mm)	Accumulated (wt.%)	Cu (wt.%)	PVC (wt.%)	Cu + PVC (wt.%)	Total (wt.%)
+4	99.7	3.7	0.2	0.0	3.9
−4 +2.8	95.8	2.2	0.4	0.0	2.6
−2.8 +1.7	93.2	18.1	35.6	0.0	53.7
−1.7 +1.0	39.5	8.3	15.3	0.0	23.6
−1.0 +0.5	15.9	5.3	1.2	0.0	6.5
−0.5	9.4	8.8	0.6	0.0	9.4
Total (%)	0.0	46.4	53.3	0.0	99.7

It was observed that after grinding to less than 9 mm, the amount of non-liberated material was 2.5% (PVC + copper). The non-liberated material was concentrated on the +4 mm fraction. Consequently, non-liberated material corresponds to around 1.5% of the overall sample.

There was a decrease in the amount of PVC + copper from the sample grinded to less than 6 mm. Analogously, the overall non-liberated material was only around 0.2%.

The materials were 100% liberated when grinding to less than 3 mm.

4.1. Dense medium separation

Tables 4 and 5 show the results of the dense medium separation with the material from the three different grindings. The tables show the cross contamination, in other words, the PVC in the copper and copper in the PVC. It is seen that both the underflow and the overflow of the material ground to less than 9 and 6 mm were contaminated. The test with the less than 3 mm material gave no cross contamination. Table 4 shows that there was 1.1%

Table 4
Results of underflow composition of samples obtained after dense medium processing

Sample (mm)	Underflow (wt.%)	Cu (wt.%)	PVC (wt.%)	PVC + Cu (wt.%)
−9	45.7	98.4	0.4	1.2
−6	46.2	97.6	1.5	0.9
−3	44.5	98.9	1.1	0.0

Table 5
Results of overflow composition of samples obtained after dense medium processing

Sample (mm)	Overflow (wt.%)	Cu (wt.%)	PVC (wt.%)	PVC + Cu (wt.%)
−9	54.3	0.0	98.2	1.8
−6	53.8	0.0	99.7	0.3
−3	55.5	**0.0**	100.0	0.0

contamination of PVC in the copper sample for the less than 3 mm material.

To achieve complete material separation, the underflow material should be treated again to purify the copper more and to recover even more PVC.

4.2. Electrostatic separation

The results of electrostatic separation tests are shown in Tables 6–8.

In Table 6, it is observed that the amount of intermediate material was up to 46% of the total sample. In Table 7 the amount of mixed material continues to be high, around 36%, showing that the test did not separate the copper and PVC. It was verified in Table 8 that there was a decrease in the amount of intermediate material, 24.9%. Therefore, besides being a relatively expensive method, for parallel wire material separation electrostatic separation also was not efficient.

4.3. Scrubbing

Scrubbing tests were performed in order to release the material which was not liberated during grinding. Results of the scrubbing tests are shown in Tables 9 and 10.

Table 6
Characterization of materials obtained after grinding to less than 9 mm and electrostatic separation

Fraction	PVC (g)	Cu (g)	PVC + Cu (g)	Mass (wt.%)
Conductor	30.9	146.5	4.6	48.4
Non-conductor	19.3	0.3	0.1	5.2
Intermediate	149.1	20.3	5.1	46.4

Table 7
Characterization of materials obtained after grinding to less than 6 mm and electrostatic separation

Fraction	PVC (g)	Cu (g)	PVC + Cu (g)	Mass (wt.%)
Conductor	44.2	155.5	3.1	56.8
Non-conductor	25.4	0.3	0.0	7.2
Intermediate	117.1	10.4	0.9	36.0

Table 8
Characterization of materials obtained after grinding to less than 3 mm and electrostatic separation

Fraction	PVC (g)	Cu (g)	PVC + Cu(g)	Mass (wt.%)
Conductor	14.5	153.2	0.0	44.1
Non-conductor	116.5	1.5	0.0	31.0
Intermediate	85.3	9.3	0.0	24.9

Results demonstrate contamination both in the underflow and in the overflow materials, indicating that scrubbing cannot release the material which was not liberated during grinding.

All tests exhibit cross contamination in levels above those found with dense medium separation, even in the material ground to less than 3 mm.

4.4. Panning

The results of the panning tests are shown in Tables 11 and 12. The parallel wire cables produced 100% liberation of both PVC and copper in the tests ground to less than 3 mm. Consequently, panning was shown to be a good method to separate the material obtained after prior grinding.

The process was more selective regarding the heavy than the light material, in other words, the opposite to the effect

Table 9
Results of underflow composition of samples obtained after scrubbing processing

Sample (mm)	Underflow (wt.%)	Cu (wt.%)	PVC (wt.%)	PVC + Cu (wt.%)
−9	48.7	90.7	7.5	1.9
−6	45.0	97.5	2.2	0.4
−3	44.0	98.6	1.4	0.0

Table 10
Results of overflow composition of samples obtained after scrubbing processing

Sample (mm)	Overflow (wt.%)	Cu (wt.%)	PVC (wt.%)	PVC + Cu (wt.%)
−9	51.3	0.0	98.0	2.0
−6	55.0	0.3	98.8	0.9
−3	56.0	0.2	99.8	0.0

Table 11
Results of underflow composition of samples obtained after panning processing

Sample (mm)	Underflow (wt.%)	Cu (wt.%)	PVC (wt.%)	PVC + Cu (wt.%)
−9	46.2	95.1	1.6	3.3
−6	42.7	98.1	1.9	0.0
−3	43.1	**100.0**	**0.0**	0.0

Table 12
Results of overflow composition of samples obtained after panning processing

Sample (mm)	Overflow (wt.%)	Cu (wt.%)	PVC (wt.%)	PVC + Cu (wt.%)
−9	53.8	0.0	98.8	1.2
−6	57.3	0.0	99.9	0.1
−3	56.9	**0.9**	**99.1**	0.0

Table 13
Results of underflow composition of samples obtained after elutriation processing

Sample (mm)	Underflow (wt.%)	Cu (wt.%)	PVC (wt.%)	PVC + Cu (wt.%)
−9	45.6	97.1	0.9	2.1
−6	47.7	98.8	0.4	0.8
−3	46.0	**99.9**	**0.1**	0.0

Table 14
Results of overflow composition of samples obtained after elutriation processing

Sample (mm)	Overflow (wt.%)	Cu (wt.%)	PVC (wt.%)	PVC + Cu (wt.%)
−9	54.4	2.9	95.3	1.8
−6	52.3	1.4	97.3	1.3
−3	54.0	**0.0**	**100.0**	0.0

Table 15
Contamination levels of products obtained after grinding to less than 3 mm and treatment using different unit operations of mineral processing

Process	PVC	Cu
Size separation	Inefficient	Inefficient
Dense medium	**Not contaminated**	1% Contaminated
Electrostatic separation	Inefficient	Inefficient
Scrubbing	0.2% Contaminated	1.5% Contaminated
Panning	0.1% Contaminated	**Not contaminated**
Elutriation	**Not contaminated**	0.1% Contaminated

seen in the dense medium separation; hence, the combined use of the two techniques may lead to better results than with the two isolated techniques.

4.5. Elutriation

The results of elutriation tests are presented in Tables 13 and 14, which show a total separation of materials in the samples produced after grinding to less than 3 mm size particles.

Furthermore, elutriation is an effective method to separate PVC and copper. The cross contamination levels were the smallest of all of the processes.

5. Discussion

Contamination is a very important parameter, especially in the case of plastic recycling. Typically, very limited amounts of impurities are allowed. Metal contamination must be close to zero, so the aim of the present work is to reach such level of purity for PVC.

Besides aluminum, other kinds of plastics may be found in scrap cables for recycling. Polymer materials used to produce wire cables are PE and PVC for low voltage and rubbers and silicones for high voltage. However, other kinds of commodity plastics may be present in a recycling burden. Most commodity plastics and rubbers can be easily separated through dense medium operations using salt or alcohol to chance the aqueous medium specific weight. However, mixtures of PVC and PET, which have similar specific weights, are not easily separated (Marques and Tenório, 2000). Fortunately; PET is not expected to be found in WEEE media.

Another important feature of recycling of polymeric material from WEEE is to keep some pollutants like PCBs and flame retardants in a close circuit (Schlummer et al., 2007; Leo et al., 2007; Richter et al., 1997; Riess et al., 2000; Vehlow et al., 2000; Ebert and Bahadir, 2003).

On the other hand, polymer contamination is not a true technological problem in the recycling of metals due the high temperatures applied. In contrast, PVC contamination in most metallurgical furnaces can be a source of atmospheric pollution including production of acid gases and even dioxins and furans. Consequently, the goal of this work is to completely separate copper from PVC and PVC from copper. Thus, the evaluation of the purity of the single fractions is more important than the share of the mixed fractions.

The cross contamination between samples occurred mainly because of mechanical entrapment. The methods that presented better separation efficiency with the 3 mm size were, in terms of better separation and smaller contamination, electrostatic separation, scrubbing, dense medium, panning and elutriation in growing performance order.

A summary of the studied processes in terms of contamination of the obtained materials is presented in Table 15.

Although dry methods are classic methods to separate materials even in the recycling area, in the present study good results were not found. Size separation was not effective due to the fact that after grinding both materials presented the same behavior. Batteries after grinding liberate the fine components while plastics and ferrous alloys are just cut. The active materials present in batteries originally were present as powders before assembling. Grinding releases the active materials which can be concentrated in the fine fractions (Tenório and Espinosa, 2002; Espinosa et al., 2004; Bernardes et al., 2004). In the case of cables, a good separation could be expected since copper filaments in the cables have diameters much inferior than 3 mm. However, copper filaments tend to entrap each other or simply vibrate with their longitudinal axis parallel to the sieve face.

Based on the difference in the specific electric resistance between metals and non-metals, many research efforts have studied electrostatic separation for the recovery of copper or aluminum from cable wires (Schubert and Warlitz, 1994; Iuga et al., 1998; Dascalescu et al., 1994) and also to recover copper and precious metals from printed circuit board scrap (Schubert and Warlitz, 1994; Veit et al., 2005; Zhang and Forssberg, 1998).

Nevertheless, in the case of the present work the focus was the purity of the fractions. Consequently, electrostatic separation was not considered a good method in the present case. Also, electrostatic separation is traditionally a more expensive process in comparison to the wet process applied here.

Results of the present work are in disagreement with Schubert and Warlitz (1994) who obtained a metal-free plastic product. However, Schubert and Warlitz (1994) also pointed out that in some cases, corona electrostatic separation is difficult.

The wet methods applied are all based on the difference of specific weights of the media and the materials associated or not with the movement of the separation medium (gravity methods). The movement of particles in a medium is a function of the particles specific weight, size and shape. The effect of water movement is stronger in scrubbing but could be negligible in standard dense medium separation practice.

Scrubbing presented a strong agitation and, as a consequence, particles of both materials were present in both fractions. On the other hand, using static dense separation was not enough to release entrapped PVC from copper clusters.

Panning and elutriation use a less turbulent agitation and consequently presented the best results respectively for copper and PVC. The results indicate that a good solution could be the use of both methods to recycle parallel wire cables. One possible flow sheet is to firstly use elutriation to produce a high purity polymer concentrate and to secondly use panning to eliminate PVC from the copper fraction.

Other factors should be considered when choosing this process, such as processing capacity and operational cost. Unit operations of mineral processing were chosen because of the low operational costs involved. Panning and elutriation are extremely simple methods.

6. Conclusions

1. Liberation of materials from parallel wire cables occurs after grinding in cage mill to particles sizes inferior to 9, 6 and 3 mm. Nevertheless, total liberation was found only after grinding to less than 3 mm.
2. Electrostatic separation and attrition were not good methods for separating wire materials even after grinding to less than 3 mm.
3. Elutriation and panning presented the best selectivity result sfor PVC and copper, respectively; in other words, the cross contamination of the final separated materials was negligible.

References

Bernardes, A.M. et al., 2004. Recycling of batteries: a review of current processes and technologies. Journal of Power Sources 130, 291–298.

Cui, J., Forssberg, E., 2003. Mechanical recycling of waste electric and electronic equipment: a review. Journal of Hazardous Materials B 99, 243–263.

Dascalescu, L. et al., 1994. Charging of particulates in the corona field of roll-type electroseparators. Journal of Physics. D Applied Physics 27, 1242–1251.

Directive 2002/96/EC of the European Parliament and of the Council on Waste Electrical and Electronic Equipment. Official Journal of the European Commission, L37/24, Brussels, 2003.

Ebert, J., Bahadir, M., 2003. Formation of PBDD/F from flame-retarded plastic materials under thermal stress. Environmental International 29, 711–716.

Espinosa, D.C.R. et al., 2004. An overview on the current processes for the recycling of batteries. Journal of Power Sources 135, 311–319.

Iuga, A. et al., 1998. Optimal high-voltage energization of corona-electrostatic separators. IEEE Transactions of Industry Applications 34, 286–293.

Lee, C. et al., 1999. Management of scrap computer recycling in Taiwan. Journal of Hazardous Materials 73, 209–220.

Leo, S.M. et al., 2007. Metals, non-metals and PCB in electrical and electronic waste – actual levels in Switzerland. Waste Management 27, 1306–1316.

Marques, G.A., Tenório, J.A.S., 2000. Use of froth flotation to separate PVC/PET mixtures. Waste Management 20, 265–269.

Richter, H. et al., 1997. Examination of organic and inorganic xenobiotics in equipped printed circuits. Chemosphere 35, 169–179.

Riess, M. et al., 2000. Analysis of flame retarded polymers and recycling materials. Chemosphere 40, 937–941.

Schubert, H.G., Warlitz, G., 1994. Sorting metal/non-metal mixtures using a corona electrostatic separator. Aufbereitungs-Technik 35, 449–456.

Schlummer, M. et al., 2007. Characterisation of polymer fractions from waste electrical and electronic equipment (WEEE) and implications for waste management. Chemosphere 67, 1866–1876.

Tenório, J.A.S., Espinosa, D.C.R., 2002. Recovery of Ni-based alloys from spent NiMH batteries. Journal of Power Sources 108, 70–73.

Vehlow, J. et al., 2000. Thermal treatment of electrical and electronic waste plastics. Waste Management Research 18, 131–140.

Veit, H.M. et al., 2005. Utilization of magnetic and electrostatic separation in the recycling of printed circuit boards scrap. Waste Management 25, 67–74.

Zhang, S., Forssberg, E., 1998. Optimization of electrodynamic separation for metals recovery from electronic scrap. Resources Conservation and Recycle 22, 143–162.

Zhang, S., Forssberg, E., 1999. Intelligent liberation and classification of electronic scrap. Powder Technology 105, 295–301.