Recycling of shredded printed circuit boards (PCBs) by two-phase moving wave conveyors

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Abstract:

Introduction/purpose: The aim of this study is to demonstrate the viability of electrostatic separation of mixtures from shredded printed circuit boards (PCBs), in association with the X-ray fluorescence analysis, and simultaneously to examine how the efficiency of this method is influenced by the supply voltage, both in terms of amplitude and nature.

Methods: The electrostatic separation technique is used by means of a two-phase moving wave conveyor with characterisation analysis using X-ray fluorescence in order to justify the efficiency of the process studied.

Results: The results of this study can have practical implications for improving the recycling process of electronic waste, especially from printed circuit boards (PCBs). By optimizing the high voltage and understanding its effects on the electrostatic separation process, it may be possible to increase the efficiency and effectiveness of recycling valuable materials from electronic waste while reducing environmental impact.

Conclusion: The XRF analysis of the samples reveals their distinct compositions. The variations observed are even more marked if the influence of the voltages applied on the electrostatic separation process is considered.

Key words: recycling, environment, waste electrical and electronic equipment, two-phase moving wave conveyor, x-ray fluorescence, high voltage.

Introduction

Waste Electrical and Electronic Equipment (WEEE) is increasing rapidly globally and has become one of the most important types of solid waste (Lu et al, 2018, p.83). In the context of recycling electronic boards, it can be used to separate different components or materials based on their electrical characteristics. The separation effectiveness relies on the ability to control particle tribocharging (Iuga et al, 2005, p.937).

The triboelectric separation represents a solution for the sorting of plastics mixtures, whenever the components have a similar size, shape, magnetic permeability and electrical conductivity (Mimouni et al, 2017, p.2).

Metals represent a significant part of this waste, both in volume and in material value (UNEP, 2013). The recycling market for old electronic devices is essentially based on recovered metals, recycling chains for plastics, glass and ceramics being more limited. Printed circuit boards are among the most economically relevant waste materials in this category. Various processing units recycle Waste Printed Circuit Boards (WPCB) to capture metals of value, such as Cu, Ag, or Au (Ghosh et al, 2015, p.5).

Traveling-wave conveyors or electric curtains are generally used for the displacement of micronized insulating particles such as plastic granules and dust, among others. They consist of parallel electrodes separated by a small inter-electrodes gap of the order of 1 mm and powered by a polyphase voltage; the resulting dielectrophoretic and Coulomb forces then cause the movement of particles (Louati et al, 2020, p.2).

The study aims to investigate how the efficiency of the electrostatic separation process is influenced by high voltage. This includes variations in both the amplitude (intensity) and nature (AC or DC) of the voltage applied to the process. This variation in voltage can impact the electrostatic forces acting on particles, potentially affecting the separation efficiency. The study likely involves conducting experiments where shredded printed circuit boards (PCBs)are subjected to electrostatic separation using different high voltage settings. The separated materials are then analyzed using X-ray fluorescence to assess the effectiveness of the process in terms of sorting and recycling different components from electronic boards.

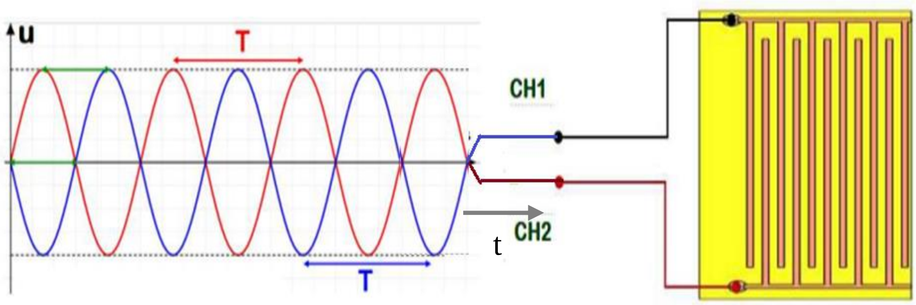
The results of this study can have practical implications for improving the recycling process of electronic waste, especially from PCBs. By optimizing high voltage and understanding its effects on the electrostatic separation process, it may be possible to increase the efficiency and effectiveness of recycling valuable materials from electronic waste while reducing environmental impact.

Experimental

Concept of moving wave conveyors

The moving wave method is an electrical phenomenon that causes particles to move by exploiting the interaction between a polarized particle and a polyphaser electric field. This electric field is generated by a set of parallel electrodes arranged in a common plane and subjected to 2, 3 or 4-phase alternating potentials as presented in Figure 1.

(a)



(b)

Figure 1
a) Experimental set-up for a sinusoidal power supply:
1) HV amplifiers, 2) Digital oscilloscope, 3) Function generator, 4) Vibrator with a regulator, 5) HV transformer,6) Two-phase, double-sided conveyor inclined at 20°, 7) Recovery tank; 8) HV connectors
b) Descriptive diagram of the two-phase conveyor feeder

When a particle is exposed to an electric field E, this induces an electric dipole moment within it. In the presence of a uniform electric field, the particle is subjected to two equal and opposite forces, which cancel out the net force, called the electrophoretic force, exerted on the particle. Unlike the polarity of the voltage, this force can be observed with AC or DC voltages. It is the dominant force in the "moving wave conveyor" type of devices.

The moving wave conveyor uses two-phase bilateral vibration excitation. This means that the conveyor electrodes are supplied with a two-phase periodic voltage, with a phase shift between them equal to π. The number of phases is denoted by "n=2". These periodic voltages generate a progressive electric field called "moving waves" in the direction perpendicular to the axes of the electrodes. This moving wave is responsible for lifting the particles deposited on the conveyor and moving them progressively.

The conveyor was mounted on an electromagnetic vibrator with the type designation "LEV2-220V-50/60HZ S3000-0.25A-37W MAX-IP66". This designation cannot be used to determine the specific type of vibratory actuator without further information.

The "220V-50/60HZ" part indicates the AC motor supply voltage, with the possibility of operating at a frequency of 50 or 60 Hz. S3000-0.25A-37W MAX" may provide information on the model or specific electrical characteristics of the motor, including rated current (0.25A), maximum power (37W), and other potential specifications. Finally, "IP66" indicates the level of protection against ingress of dust and water.

The mechanical operating frequency may be different from the mains frequency, as some vibratory conveyor systems can be designed to operate at specific frequencies depending on separation process requirements or design preferences.

For our study we varied only the material flow rate that causes the plastic granules to move and keeps the metal particles on the surface (D=0.5 g/s).

This is a set of identical parallel electrodes separated by a gap. The assembly is then coated with an insulating layer of varnish to prevent breakdown between the electrodes. Electrodes belonging to the same phase are connected together. The phases are supplied with periodic voltages with a phase shift of π, which generate a progressive field called "moving waves" in the direction perpendicular to the axes of the electrodes . The 2-phase electric field charges the deposited particles, lifts them from the substrate by electrostatic forces and propels the particle layer off the conveyor surface by a progressive wave which is none other than the moving wave. The dynamic forces of the non-uniform field wave thus generated overcome the adhesion and gravitational forces acting on the charged particles and transport them in a direction in the plane perpendicular to the electrodes in a progressive manner from one electrode to the other. The particle charging process is primarily a surface-dominated process and is described as follows: Particles on the interface of the thin insulating film above the embedded field electrodes are either triboelectrically charged by contact friction for non-conductive objects when placed on the surface, or inductively charged by the application of voltages to the electrodes for conductive objects. This particle separation device is an electronic printed circuit board measuring 200 x 165 mm^2, on which parallel copper electrodes 1 mm wide and 100 mm long have been made. The electrodes were made on both sides of the printed circuit, separated by the thickness of the printed circuit itself, equal to 1.5 mm. (Louhadj, 2021, p.52).

In this study, we used a mixture of crushed electronic boards recovered from cathode ray tube television sets, Figure 2. These boards are printed circuits that hold and electrically connect a set of electronic components together. In the whole world, more than 50 million tons of e-waste is generated yearly. PCBs represent the most economically attractive portion of e-waste and account for 3-5% by weight (Kaya, 2016, p.2). Waste PCBs constitute a heterogeneous mixture of metals, nonmetals and some toxic substances. A PCB assembly contains many electronic components (ECs) and organic plastic board. Waste PCBs have a metal content of nearly 30% (Cu: 10–20%, Pb: 1–5%, Sn: 1-6%, Ni: 1–3%, Fe:1-3%, Ag: 0.05%, Au: 0.03% and Pd: 0.01%), especially the purity of precious metals in PCBs is more than 10 times that of ore minerals (Zhou & Qui, 2010, p.823).

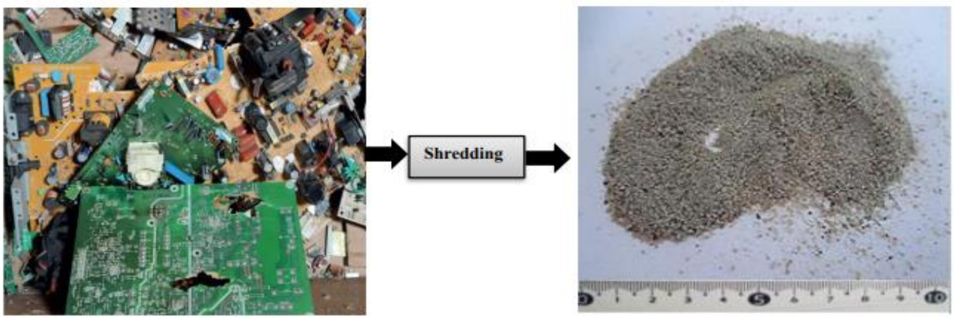


Figure 2 – Photographs of the electronic boards of a cathode ray tube before and after shredding

The experimental procedure was divided into two parts to determine the influence of the type of supply voltage and its amplitude on the attractive force applied by the moving-wave conveyors.

Experimental set-up

Sinusoidal AC high voltage:

The experimental set-up used is illustrated by the schematic description in Figure 1 .The voltage amplifier (Trek, model 2220) is one of many types in the Trek 2200 series. This series of 40 W high-voltage amplifiers offers high performance. The Model 2220 (Fig.2-7) provides precise control of output voltages in the range 0 to ± 2 kV DC or peak AC with an output current range of 0 to ± 20 mA peak AC and a wide DC bandwidth at 7.5 kHz (3 dB).

The study of variations in one quantity as a function of another requires a very rapid recording of a series of points to obtain a curve. The GDS-3000 series digital memory oscilloscope makes it possible to plot the curves corresponding to the evolution of the measurement signal directly on the screen in an experimental study with the single-sided conveyor. A mid-point transformer is used to provide a "symmetrical" voltage.

The angle of inclination of the vibrating conveyor is currently set at 20°. Parametric studies carried out by scientific researchers have shown that the optimum angle of inclination for this actuator is between 10° and 20°.

A vibrating conveyor is elastically supported by standard springs. It is designed for conveying and handling small quantities of bulk material over short distances. These feeders are ideal for applications such as dosing, mixing, weighing or continuous in-process feeding. Vibratory feeders are controlled via a 220 V - 50 Hz control box with a potentiometer in the standard configuration for precise flow rate adjustment. The chutes are made of painted sheet metal as standard.

Continuous high voltage:

For this part, a DC voltage was applied to the two-phase conveyor that varied from 0 - 30 kV with a current of 9 mA (Spellman, 30 kV, 9 mA). Using a single positive DC high voltage supply, one phase was supplied with the positive voltage and the other phase was earthed. The conveyor was attached to an electromagnetic vibrator to facilitate the movement of particles that did not stick to the conveyor surface.

Fluorescence spectrometry analysis can be used to characterize and identify the different materials present in a mixture of waste electrical and electronic equipment that has been separated using a moving wave conveyor.

Detecting breakdown voltage is usually a critical aspect of high-voltage systems to prevent failure or damage. Common methods of detecting breakdown voltage include the use of voltage sensors, monitoring devices, or predefined thresholds that trigger safety actions when voltage reaches critical levels.

To eliminate breakdowns in our system, we optimised the system parameters such as voltage, frequency and pulse duration to minimise the risk of breakdowns.

Coordination between the arrival of the material from the vibrating conveyor and the intensity of the discharge in this electrostatic separation system can be achieved by manual control.

The discharge intensity can be manually adjusted according to the material arrival. This can be done using manual controls or adjustable parameters on the electrostatic discharge device.

TORNADO M4 compact X-ray micro-fluorescence spectrometer:

For the analyses, X-ray fluorescence microscopy was used to identify and determine most of the chemical elements making up the samples (equipment available at the research technology platform (Algeria). This technique can be used for a wide variety of materials: minerals, ceramics, cements, metals, oils, water, glass, etc. in the solid or liquid form.

Bruker's M4 TORNADO is an advanced characterization tool that uses the small spot X-ray micro- fluorescence technique to analyze a variety of samples. This technique provides detailed information on the elemental composition and distribution of elements in samples, even at depths below the surface. Each separate material was placed individually in the excitation zone of the fluorescence spectrometer and the corresponding fluorescence spectra recorded. These are graphs representing the intensity of light emitted as a function of wavelength.

Results and discussion

Analysis of the results at high sinusoidal AC voltage:

It is possible to discern various constituents present in a waste mixture by examining their distinct spectral characteristics by applying a high sinusoidal AC voltage of 2kV. Fluorescence proves useful for detecting the presence of precious metals such as iron and copper, as well as other specific components of electronic devices, such as plastic and glass. We used the experimental set-up illustrated in Figure 1 to obtain two samples:

Sample 1: Separated product and adhered to the surface of the moving wave conveyor.

Sample 2: The second sample of the product is separated and analyzed also in the M4 TORNADO spectrometer.

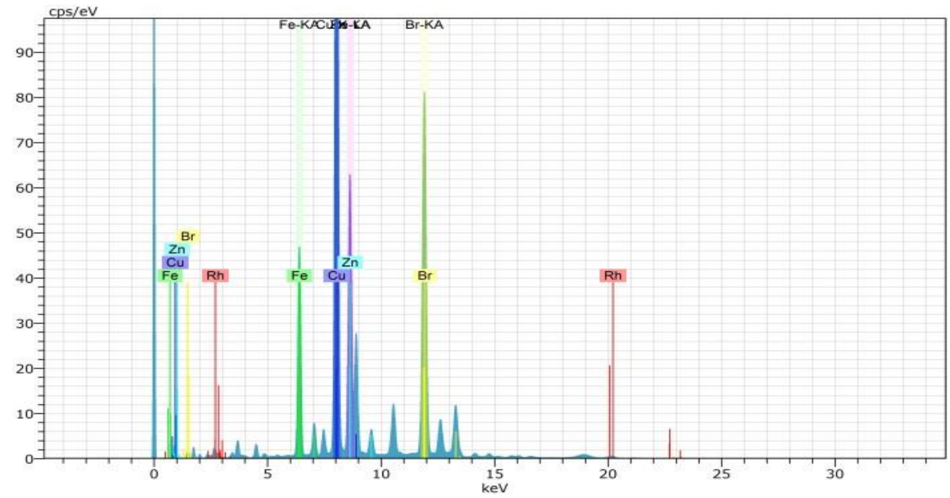


Figure 3 – X-ray fluorescence spectrum of the sample (conductor material)

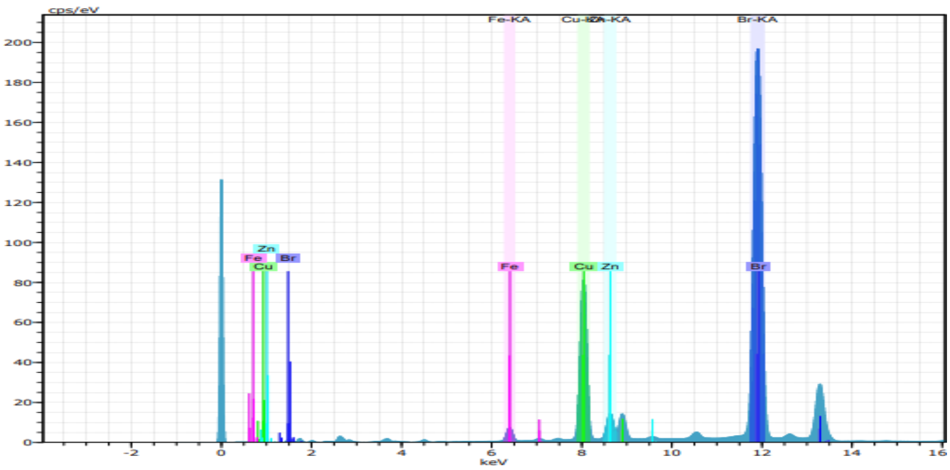


Figure 4 – X-ray fluorescence spectrum of the sample (non-conductor material)

The XRF spectra of the different samples show the elements present in each sample (Figs. 3 and 4). The intensity of the lines in the XRF spectra is associated only with the intensity of the energy, which means that the radiation is more intense for the highest lines. These lines are attributed to bromine (Br) and copper (Cu) in both samples. The elemental analysis and therefore the mass percentage of the elements present in our samples were calculated using XRF analysis software.

Table 1 – Chemical composition of samples 1 and 2 at high sinusoidal AC voltage (%)

Element	Voltage [kV]	Conductivity	Rh [%]	Fe [%]	Cu [%]	Zn [%]	Re [%]	Br [%]
Sample 1	2	Conductor	6.03	9.29	36.30	11.93	0.13	36.33
Sample 2	2	Non-conductor	<Lod	1.83	12.91	1.49	<Lod	83.77

Table 1 shows the results of the XRF analysis of the samples (1 and 2).The spectrum presented in Figure 3 shows that the sample studied is mainly composed of different chemical elements, with the following percentages: 36.30% copper (Cu), 11.93% zinc (Zn), 9.29 % iron (Fe) and 36.33% bromine (Br). It also fluoresces due to the presence of 0.34% rhodium (Rh). The spectrum shown in Figure 4 demonstrates that the sample is predominantly bromine (Br), accounting for 83.77% of its composition, while the metals copper, zinc and iron account for 15%.

In the light of the results, it appears that bromine is the predominant constituent in the chemical composition of sample 2, while sample 1 is rich in metals such as copper, zinc and iron.

Analysis of the results at high DC voltage:

By using a high DC voltage ranging from 2 kV to 8 kV, it becomes possible to distinguish different constituents present in a waste mixture by observing distinct spectral properties. To achieve this, we set up the experimental setup described in the second part, generating two samples for each test.

Further on, we present two spectra for each experiment:

Samples 3, 5, 7 and 9: of particles stuck to the conveyor surface after separation for U=2 kV, 4 kV, 6 kV and 8 kV, respectively.
Samples 4, 6, 8 and 10: of particles detached from the conveyor after vibration for U=2 kV, 4 kV, 6 kV and 8 kV, respectively.

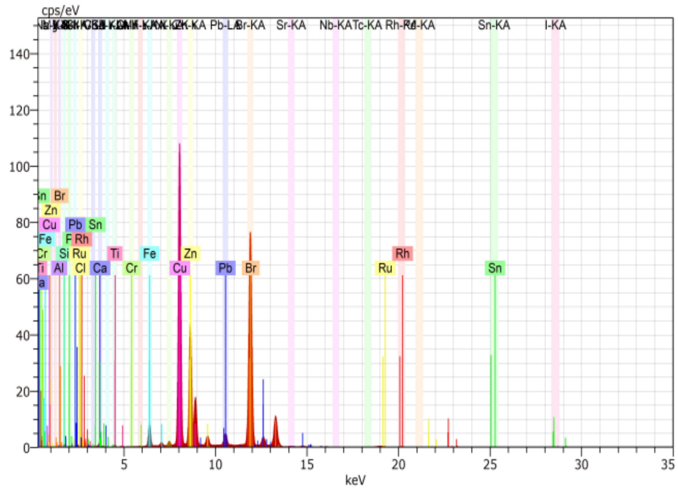


Figure 5 – X-ray fluorescence spectrum of sample 3 for U=2kV (conductor material)

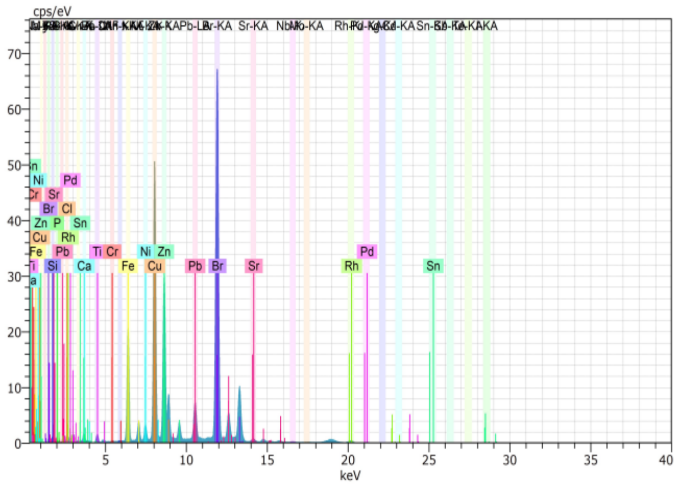


Figure 6 – X-ray fluorescence spectrum of sample 4 for U=2kV (non-conductor material)

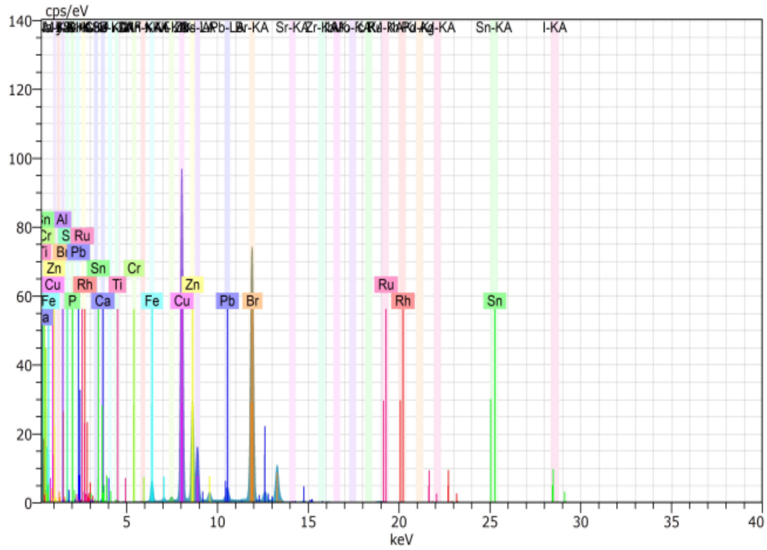


Figure 7 – X-ray fluorescence spectrum of sample 5 for U=4kV (conductor material)

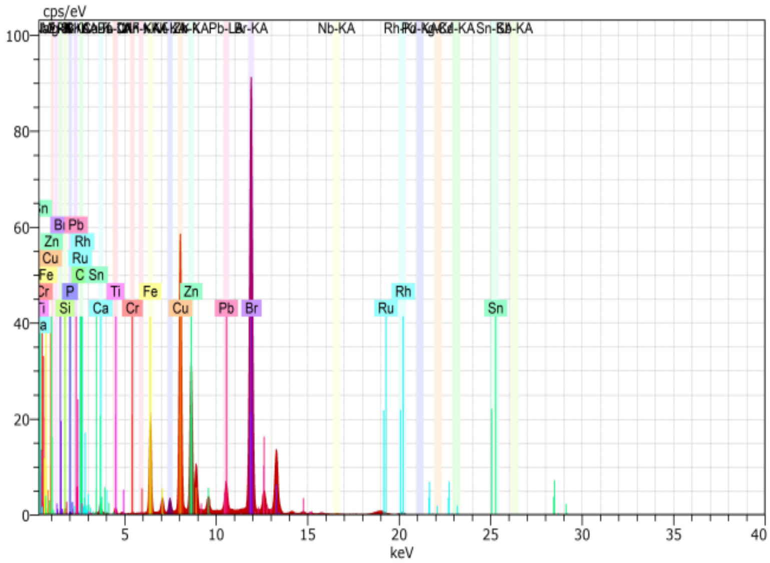


Figure 8 – X-ray fluorescence spectrum of sample 6 for U=4 kV (non-conductor material)

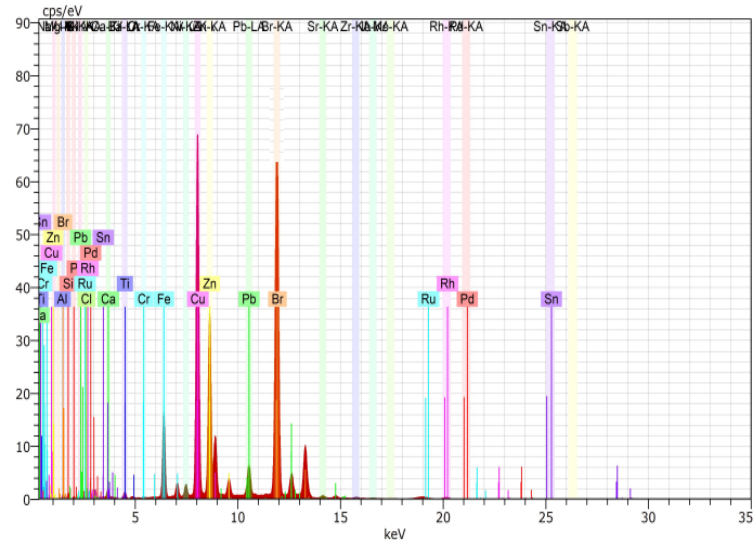


Figure 9 – X-ray fluorescence spectrum of sample 7 for U=6 kV (conductor material)

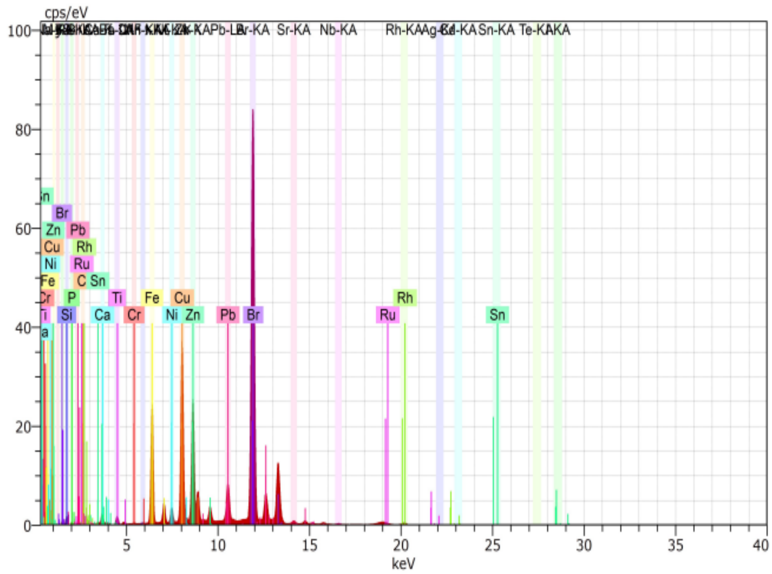


Figure 10 – X-ray fluorescence spectrum of sample 8 for U=6 kV (non-conductor material)

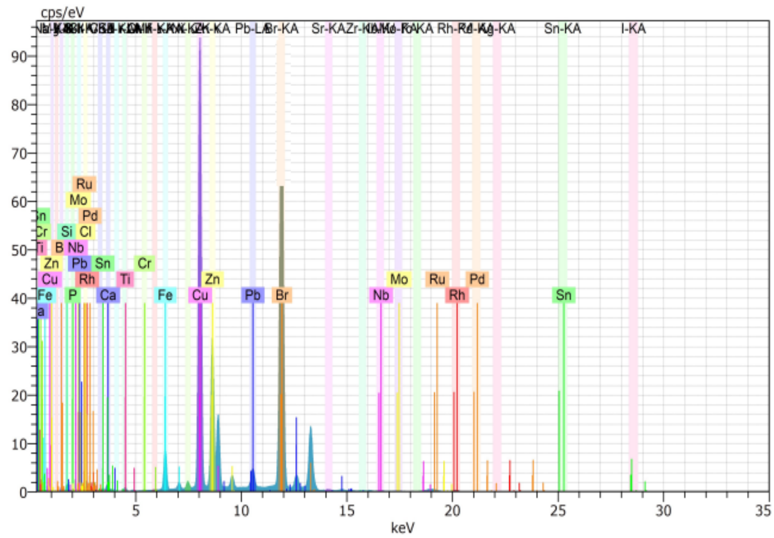


Figure 11 – X-ray fluorescence spectrum of sample 9 for U=8 kV (conductor material)

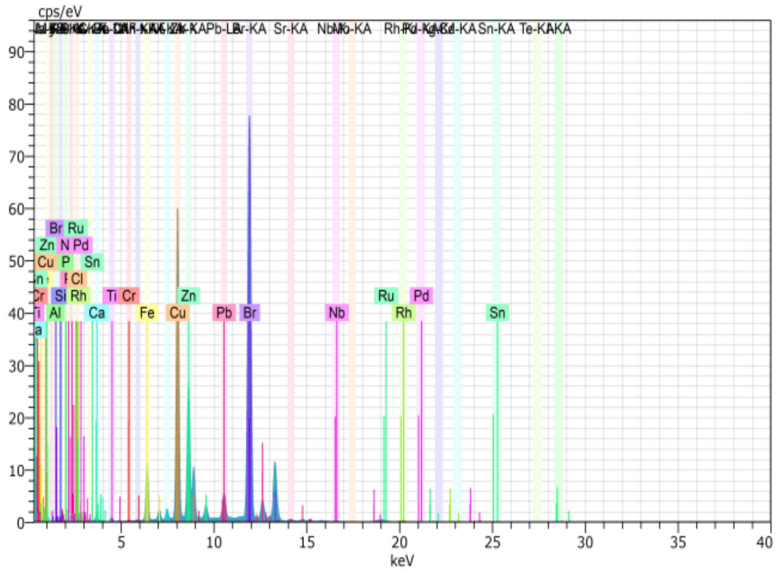


Figure 12 – X-ray fluorescence spectrum of sample for 10 for U=8 kV (non-conductor material)

The results shown in Table 2 represent the X-ray fluorescence (XRF) analyses of the samples taken after electrostatic separation of shredded TV electronic boards, followed by the application of a high DC voltage ranging from 2 to 8 kV.

The samples are divided into two categories according to their conductivity: conductive and non-conductive.Percentages indicate the relative amount of each element in the samples. Elements such as copper (Cu), iron (Fe), bromine (Br), zinc (Zn), etc., may come from electronic boards.The "<Lod" values indicate that the quantity of certain elements is below the detection limit of the analysis method used. This is due to the low concentration of these elements in the samples.

The XRF spectra of the various samples reveal the elements present in each of them. The intensity of the peaks observed in the XRF spectra is directly related to the energy emitted, meaning that the most intense lines correspond to the highest energy levels. In this context, the lines observed are attributed to copper in samples 3, 5, 7 and 9 (Figures: 5, 7, 9 and 11), while bromine is identified in samples 4, 6, 8 and 10 (Figures: 6, 8, 10 and 12).

The elemental analysis, including determination of the mass percentages of the elements present in our samples, was carried out using XRF analysis software. The results of this XRF analysis of the samples recovered from the DC electrostatic separation experiments are presented in Table 2, covering samples 3 to 10.

Table 2 – Chemical composition of samples for 3 to 10 at a high DC voltage (%)

Element	Voltage [kV]	Conductivity	Rh [%]	Fe [%]	Cu [%]	Zn [%]	Re [%]	Br [%]	Si [%]	P [%]	Pb [%]
Sample 3	2	Conductor	<Lod	13.26	57.36	6.56	0.29	19.32	3.21	<Lod	<Lod
Sample 4	2	Non-conductor	<Lod	4.02	14.61	3.25	<Lod	74.77	3.35	<Lod	<Lod
Sample 5	4	Conductor	0.33	10.98	60.55	7.28	<Lod	17.33	3.25	<Lod	0.28
Sample 6	4	Non-conductor	<Lod	4.05	10.91	3.01	<Lod	78.27	2.98	0.23	0.55
Sample 7	6	Conductor	<Lod	8.1	64.02	6.93	0.84	16.33	3.33	0.45	<Lod
Sample 8	6	Non-conductor	<Lod	3.83	10.61	2.98	<Lod	80.02	2.23	0.38	<Lod
Sample 9	8	Conductor	<Lod	7.23	68.25	6.33	<Lod	14.85	3.23	<Lod	0.11
Sample 10	8	Non-conductor	<Lod	2.95	9.91	2.03	<Lod	82.35	2.33	<Lod	0.43

The analysis of the compositions as a function of the voltages applied offers important insights into the efficiency of the electrostatic separation process applied to samples obtained from the shredding of television circuit boards. Looking at the results, significant variations in the distribution of elements are apparent. Samples subjected to higher voltages, such as those at 8 kV, show important percentages of certain conductive elements, notably copper (Cu) 68.25%, while for non-conductors there is a significant recovery of bromine which exceeds 82%.

This observation suggests that the application of a higher voltage promotes more efficient separation of conductive components from electronic boards, resulting in a higher concentration of these elements in the samples. This correlation between the applied voltage and the composition of the samples offers valuable indications for optimizing the electrostatic separation process, highlighting the possibility of adjusting the voltage to improve the specific recovery of precious metals or other valuable elements. These results provide a useful basis for refining the process parameters and maximizing the efficiency of electrostatic separation in the recycling of electronic waste.

Conclusion

In conclusion, the XRF analysis of the samples reveals distinct compositions, shedding light on the elemental makeup of shredded printed circuit boards (PCBs) subjected to electrostatic separation.

The observed variations in the composition are further emphasized when considering the influence of the applied voltages on the electrostatic separation process. Notably, higher DC voltages, such as 8 kV, result in a more efficient recovery of conductive elements, particularly copper (68.25%), while non-conductive elements, such as bromine, are significantly recovered, exceeding 82%. This correlation between voltage and composition provides crucial insights for process optimization, indicating the potential to tailor voltage parameters for enhanced recovery of precious metals and valuable elements.

The influence of the amplitude and the nature of the supply voltage to the travelling wave conveyor revealed promising results. Sinusoidal voltages of 2 kV showed superior performance compared with DC voltages, even at high values (from 2 kV to 8 kV). For example, an AC voltage of 2 kV recovered around 65% of conductors and 83% of non-conductors, exceeding the proportions obtained with a DC voltage of 8 kV. In conclusion, AC voltage appears to offer significant advantages in this context. These findings lay a solid foundation for refining electrostatic separation processes, contributing to the efficient recycling of electronic waste.

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Reciclaje de placas de circuito impreso (PCB) trituradas mediante transportadores bifásicos de ondas móviles de dos fases

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CAMPO: ingeniería mecánica, materiales, tecnología química
TIPO DE ARTÍCULO: artículo científico original

Resumen:

Introducción/objetivo: El objetivo de este estudio es demostrar la viabilidad de la separación electrostática de mezclas de placas de circuitos impresos (PCB) trituradas, en asociación con el análisis de fluorescencia de rayos X, y examinar simultáneamente cómo influye en la eficienciade este método por el suministro de voltaje, tanto en términos de amplitud como de naturaleza.

Métodos: Se utiliza la técnica de separación electrostática mediante un transportador bifásico de ondas móviles con análisis de caracterización mediante fluorescencia de rayos X para justificar la eficacia del proceso estudiado.

Resultados: Los resultados de este estudio pueden tener implicaciones prácticas para mejorar el proceso de reciclaje de desechos electrónicos, especialmente de placas de circuitos impresos (PCB). Mediante la optimización de la alta tensión y la comprensión de sus efectos en el proceso de separación electrostática, puede ser posible aumentar la eficiencia y la eficacia del reciclaje de materiales valiosos de los desechos electrónicos, reduciendo al mismo tiempo el impacto ambiental.

Conclusión: El análisis XRF de las muestras revela composiciones distintas. Las variaciones observadas son aún más marcadas si se considera la influencia de los voltajes aplicados en el proceso de separación electrostática.

Palabras claves: reciclaje, medio ambiente, residuos de aparatos eléctricos y electrónicos; transportador bifásico de ondas móviles; fluorescencia de rayos x, alta tensión.

Переработка измельченных печатных плат (ПП) с помощью двухфазных волновых конвейеров

Шахинез Мимуни

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ВИД СТАТЬИ: оригинальная научная статья

Резюме:

Введение/цель: Цель этого исследования − продемонстрировать возможность электростатической сепарации измельченных печатных плат (ПП) в сочетании с рентгенофлуоресцентным анализом а также изучить, как на эффективность этого метода влияют колебания и характер питающего напряжения.

Методы: Для подтверждения эффективности исследуемого процесса используется метод электростатической сепарации с помощью двухфазного волнового конвейера с подвижным потоком и анализ характеристик с использованием рентгеновской флуоресценции.

Результаты: Результаты данного исследования могут использоваться на практике для улучшения процесса переработки электронных отходов, особенно печатных плат (ПП). Оптимизация высокого напряжения и понимание его влияния на процесс электростатической сепарации способствуют эффективности и результативности переработки ценных материалов из электронных отходов, одновременно снижая негативное воздействие на окружающую среду.

Выводы: Рентгенофлуоресцентный анализ образцов выявил различия в их составе. Наблюдаемые различия становятся еще более заметными, если учесть влияние напряжения, используемого в процессе электростатической сепарации.

Ключевые слова: рециклинг, окружающая среда, отходы электрического и электронного оборудования, двухфазный волновой конвейер, рентгенофлуоресценция, высокое напряжение.

Рециклирање уситњених штампаних плоча (ПЦБ) помоћу двофазне таласне покретне траке

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ОБЛАСТ: машинство, материјали, хемијске технологије
КАТЕГОРИЈА (ТИП) ЧЛАНКА: оригинални научни рад

Сажетак:

Увод/циљ: Ова студија има за циљ да демонстрира изводљивост електростатичког одвајања елемената смеша насталих од уситњених штампаних плоча (ПЦБ), заједно са рендгенском *флуоресцентном анализом, као и да испита како на ефикасност ове методе утичу амплитуда и природа напона напајања.*

Методе: У техници електростатичког одвајања користи се двофазна таласна покретна трака са рендгенском флуоросцентном анализом с циљем да се образложи ефикасност проучаваног процеса.

Резултати: Резултати ове студије могу бити значајни за побољшање процеса рециклирања електронског отпада, нарочито оног насталог од штампаних плоча (ПЦБ). Оптимизација високог напона и разумевање његовог утицаја на процес електростатичког одвајања могу да повећају ефикасност и ефективност рециклирања вредних материјала из електронског отпада, уз истовремено смањивање утицаја на животну средину.

Закључак: Рендгенска флуоресцентна анализа узорака открива њихове карактеристичне саставе. Уочене варијације су још приметније ако се узме у обзир утицај напона коришћеног у процесу електростатичког одвајања.

Кључне речи: рециклирање, животна средина, опрема за електрични и електронски отпад, двофазна таласна покретна трака, рендгенска флуоресценција, високи напон.

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