Міністерство освіти і науки України
Державний вищий навчальний заклад
"Національний гірничий університет"

Механіко-машинобудівний факультет
(факультет)

Кафедра Збагачення корисних копалин
(повна назва)

ПОЯСНЮВАЛЬНА ЗАПИСКА
дипломної роботи

галузь знань 18 Виробництво та технології
(шифр і назва галузі знань)
спеціальність 184 Гірництво
(код і назва спеціальності)
спеціалізація Збагачення корисних копалин
(назва спеціалізації)

освітній рівень магістр
(назва освітнього рівня)
Кваліфікація 2147.2 Інженер – технолог (гірничий)
(код і назва кваліфікації)
на тему: Стійка технологія переробки відходів електричного та електронного обладнання

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Дніпро 2018

Міністерство освіти і науки України
Державний вищий навчальний заклад
"Національний гірничий університет"

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«_____»_________________ 2018 року

ЗАВДАННЯ

на виконання кваліфікаційної роботи магістра

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(код і назва спеціальності)
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1 ПІДСТАВИ ДЛЯ ПРОВЕДЕННЯ РОБОТИ

Наказ ректора ДВНЗ "НГУ" від **22/02/18** № **266-л**

2 МЕТА ТА ВИХІДНІ ДАНІ ДЛЯ ПРОВЕДЕННЯ РОБІТ

Об’єкт досліджень: технологічні основи «переробки відходів електричного та електронного обладнання».

Предмет досліджень: механізм піролізу, отримання рідкого палива, подрібнення друкованих плат після піролізу, вібраційний млин та його сили, які впливають на подрібнення .

Мета НДР____
____
____

Вихідні дані для проведення роботи: характеристики друкованих плат та їх переробка у світі

3 ОЧІКУВАНІ НАУКОВІ РЕЗУЛЬТАТИ

Наукова новизна: відокремлення металевої фракції від наповнювачів, за рахунок ковкості металевої фракції при подрібнені та подальшому розділення при грохочені .

Практична цінність: поліпшення екологічної складової за рахунок втілення нових технологій в сектор управління відходів та рециклінгу вже добутих мінералів .

4 ВИМОГИ ДО РЕЗУЛЬТАТІВ ВИКОНАННЯ РОБОТИ

5 ЕТАПИ ВИКОНАННЯ РОБІТ

Найменування етапів робіт	Строки виконання робіт (початок-кінець)
Технологічний	20.11.17 … 19.03.18
Охорона праці	20.03.18 … 20.04.18

6 РЕАЛІЗАЦІЯ РЕЗУЛЬТАТІВ ТА ЕФЕКТИВНІСТЬ

Економічний ефект: може буду розрахований для технологічних основ «переробки відходів електричного та електронного обладнання» при виробничих масштабах під час підбору обладнання.

Соціальний ефект: зниження захоронення сміття звалищах , скорочення обсягу димових газів, поліпшення екології місцевостей .

7 ДОДАТКОВІ ВИМОГИ

Дипломна робота написана на англійській мові та подалі буде захищена в ТУ "Фрайберзька гірнича академія"

Завдання видав ____________ (підпис) Пілов П.І. (прізвище, ініціали)

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Дата видачі завдання: ________________

Термін подання дипломної роботи до ЕК 27 квітень 2018 року

TECHNISCHE UNIVERSITÄT BERGAKADEMIE FREIBERG
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Sustainable technology of waste electrical and electronic equipment (WEEE) recycling.

Master Thesis

27th April 2018

Author:

Danylo Lysenko

Supervisors:

Prof. Dr. Sc. Pilov P.I., National Mining University Dnipro

Statutory declaration

I certify, that the work presented here is original and the result of my own investigations. Utilized publications as well as special assistance and information I received are properly and duly acknowledged.

Dnipro, 27th of April 2018

Danylo Lysenko

Acknowledgements

First of all I would like to thank my supervisor Prof. Sc. Pilov P.I. Consultations during work as well as the collaboration whilst data analysis and interpretation was very supportive at any time. Further, I have to thank Prof. Bereznyak O.O. who supported my work and equipment arrangement during my stay at National Mining University in Dnipro. Special thanks goes to Levchenko K.A , who established the work in the lab of National Mining University in Department of Mineral Processing. Last but most important I would like to say thanks to all my family who supported me in such long journey.

Table of contents

List of tables

List of figures

List of abbreviations

ABS	Acrylonitrilebutadienestyrene
EEE	electrical and electronic equipment
EU	European Union
E-waste	Electronic waste
PCB's	Printed circuit boards
WEEE	waste electrical and electronic equipment

Abstract

This master thesis focuses on mechanical treatment and pyrolysis of Printed Circuits Boards PCB's for energy production and material recovery. Firstly, in the theoretical section a description of electronic waste, problems with recycling WEEE in Ukraine and the current waste management techniques, as well as example of Western countries . As more and more sustainable solutions are required for waste handling, the advantages and disadvantages of the current treatment methods are analyzed in order to compare them with the innovative technique of waste pyrolysis and mechanical treatment. The substrate used for pyrolysis in terms of this master thesis was the printed circuit boards' fraction (PCBs) and thus a particular description of this fraction is included. Furthermore, the pyrolysis as a thermal treatment method is fully described for getting an overview of the entire process.

The next section of the current master thesis includes a description of the experimental part
of grinding mass movements during mechanical treatment. The experimental part included as well the samples preparation in order to obtain a homogeneous mixture since various substances are used for PCBs manufacturing. Furthermore, the results derived from the experimental were further analyzed. The results section also includes a deep discussion of the results since the pyrolysis of electronic waste is still under research an extensive analysis is necessary. Summarizing, the results illustrates all the data, the main part was ta separate metal parts from residual after pyrolysis.

The product of pyrolysis of printed circuit boards is gases as well as fuel and metal part with ash content. Finally, the report includes several recommendations for the future work to be done and the basic directions for the research of pyrolysis process and grinding mass movements for materials and energy recovery.

1. Introduction

To secure future generations, environmental problems should be taken in consideration. Primary issue of modern society is waste management. Result of digitalization and growing economy, lead to an over-generation of waste and to an over-consumption of resources. The global use of electric and electronic equipment growing exponentially.

Frequent model change and quick progress of the growing information technology of electronic devices has resulted in a fast increase of waste electrical and electronic equipment (WEEE) around the world. It was reported that approximately 20–50 million tons of WEEE is generated annually and still growing with the increase rate of 5%each year. (Zhang and Yu 2016)

Waste of electrical and electronic equipment (WEEE) is a global concern. Modern society using more resources than nature can regenerate. Waste electrical and electronic equipment (WEEE) is one of the most critical wastes to manage. Such equipment including precious metals, and rare earth metals. The amounts of WEEE are increasing every year, due to the use of different electronic devices. Unfortunately only a small amount of WEEE are properly treated and recovered in Ukraine. Moreover, party the WEEE can be potential second-life application and prospective for business opportunity. (Marconi et al. 2018)

Different components and materials can be remanufactured and reused for sustainable purposes. Those electronic circuit boards, after end of appliance’s life, become hazardous waste that needs to be handled adequately. That is why it is important to develop new technology for effective ways of recycling and reuse of the Waste of electrical and electronic equipment (WEEE), as they become new “renewable” resource that can supply recycled metals for new production. Lack of processing capacities and suitable technologies cause by the waste management system which can utilize WEEE effectively. WEEE has to be utilized, but it also can become a source of valuable resources.

Pyrolysis is a novel approach for handling waste for recovery energy and material. Pyrolysis is a thermal treatment technology which convert the waste into fuel and in the same time helps recover valuable metals. Without access of oxygen such metals as gold (Au), copper (Cu) and palladium (Pd) can be recovered and no metals oxides are formed

Printed circuit boards (PCBs) which are reviewed in this master thesis one of the biggest issue in field of e-waste. Developing technology leads to creating more PCBs, which used in all kind of electrical equipment such as, televisions, computers and telephones. The composition of PCBs is very complex due to usage different materials during manufacturing such as metals, polymers and ceramics. This master thesis based on pyrolysis of printed circuit boards as primary treatment for further developments of technology treatment solution. The studies show importance of pyrolysis as primary treatment for easier metal recovery, also energy generation and minimization of waste. In Laboratory scale experiments showed that after pyrolysis most appropriate milling equipment is lab rot milling machine. The detail experimental part explains in thesis material. Lab result can be useful for pilot scale experiments and implication in real life, but more research is needed in order to apply on industrial scale.

1.1. Aim

The aim of this master thesis is to define experimentally and improve technology of waste electrical and electronic equipment (WEEE) treatment. Prove pyrolysis as part of process for PCB treatment and define best methods for milling and separation.

1.2. Objectives

To identify the composition of printed circuit boards

To identify problems with Ukrainian waste management system

To identify the current waste management techniques of electrical and electronic waste

To identify the principals and benefits of pyrolysis

To identify principal of separation of metal after pyrolysis process

To analyze material recovery after treatment

2. Methodology

First part of master thesis includes literature review of various related articles, publications in order to identify all the appropriate approach for pyrolysis, waste management, separation, electronic waste, printed circuit boards, and materials recovery from waste.

The second part of this thesis includes experimental research performed in the laboratory located in the department of Mineral Processing at National Mining University Dnipro (Ukraine). The work have been focused on the technology selection, based on pyrolysis of WEEE and mechanical treatment. The experiments were performed in lab scale pyrolysis tool and vibratory horizontal cylindrical milling machine.

3. Theoretical part

The theoretical part includes review information about the composition of the waste from electrical and electronic equipment. Moreover, printed circuit boards from WEEE which were used for experiments. Selection of technology in order to choose appropriate way of recycling WEEE.

3.1. Material of Electrical and Electronic Waste

The electrical and electronic equipment (EEE) is one of the fastest growing waste in EU with grow annually between 2.5 and 2.7%. The forecast for waste electric and electronic equipment (WEEE) by 2020 will be reaching a total annual tonnage of 12.3 million.(Paul T. Williams 2010) Thus, it’s necessity to estimate a right way of waste electrical and electronic equipment (WEEE) recycling for implementation of circular economy, energy recovery and reuse of critical materials. Electronic scrap roughly consists of 15-30% plastics, 40-50% ceramics and 20- 30% metals like copper, aluminum and iron.(Diaz, Florez, and Friedrich, n.d.) Metal fraction consists of copper-17%, solder-4%, iron-3% and nickel-2%. Small quantity of precious metals such as gold, silver and palladium are also includes.(R. Mankhand et al. 2013)

3.2. Why Ukraine have to recycle WEEE

Annually, waste electronica and electrical equipment which unsuitable for use of household goes to dumps dozens. This equipment based on composition materials such as phenol formaldehyde and polyvinyl chloride and almost all metals from the periodic table of Mendeleev.

Once they dump under the influence of moisture, metals contained in electronic components (arsenic, cadmium, zinc, lead), pass into soluble compounds that become poisoning. These compounds are potential dangerous for humans, exhibit high resistance and bioaccumulation potential. Plastic parts with a diverse chemical composition (polystyrene, polyvinylchloride, polyphenyl, polypropylene, etc.), including chlorine compounds, are not subject to rotting or self-destructing. For decades, they are able to provide biologically active low molecular weight chemicals (plasticizers, solvents, dyes, stabilizers, monomers).Toxic materials that are part of electronic equipment and are formed as a result of landfills, remain in groundwater, soil and air for years, fall into sources of drinking water, fields and gardens. Simply throwing electronic equipment to the landfill is to cause irreparable damage to the environment, the ecology of our cities and the health of their inhabitants.

Such equipment should not be landfilled; it must be recycled as much as possible for circular use of raw materials. In developed countries landfill band and severely punishable. Given the scale of this problem, we can’t remain indifferent and should take actions.

3.3. Requirements of legislation

First article of the Ukrainian Law "On Waste" define that waste is any substances, materials and objects formed in the process of production or consumption, as well as goods (products), which have completely or partially lost their consumer properties and have no further use in the place of their education or detection and from which their owner gets rid of, intends or should get rid of by utilization or removal.

According to Article 17 of the Ukrainian Law "On Waste", enterprises, institutions and organizations - business entities should: ensure full collection, proper storage and prevention of destruction and damage of waste, for utilization of which there is a corresponding technology in Ukraine; enter into agreements with relevant organizations for their collection and utilization; carry out organizational, scientific, technical and technological measures for the maximum utilization of waste, sale or transfer to other consumers or enterprises, establishments and organizations involved in the collection, treatment and disposal of waste, as well as at its own expense to ensure the environmentally sound disposal of waste that is not to be disposed of; prevent the storage and disposal of waste in unauthorized places or objects, etc.

Taking into account the foregoing, the enterprise, as a result of which waste is generated, must temporarily store the waste in specially designated places for further transportation to the utilization. In case the enterprise does not have its own utilization capacity, it concludes contracts for corresponding services with specialized enterprises that have a license issued by the Ministry of Ecology and Natural Resources for the conduct of economic activities in the field of hazardous waste management.

It should be noted that according to Article 42 of the Ukrainian Law "On Waste" persons who are guilty of violating waste legislation are disciplinary, administrative, civil or criminal liability for: violation of the established procedure for waste management, which has led or may lead to pollution of the environment, direct or indirect harmful effects on human health and economic damages, and the unauthorized placement or removal of waste.

3.4. WEEE in Ukraine

Across the all world people are engaged in solving a new environmental problem - utilization of technological waste, while Ukraine is still ignoring this challenge. Every year around 50 million tons of electronic waste are generated in the world, which counted by UN (United Nation) program on the environment. These include computers, electronic office equipment, electronic entertainment devices, mobile phones, televisions, and etc. The accumulation of such technological waste is three times faster than the growth of other waste. Every year the life span - not to be confused with the concept of "shelf life" - household or office equipment is shrinking: in addition to the fact that the quality of products is gradually deteriorating due to the ever larger volumes of their production, manufacturers constantly change the design and functionality of the devices in order to meet the needs of the modern user. So, a consumer often buys a new computers, cameras or washing machines before a breaking down of device that is already in use.

In Ukraine, the question of where to place an old refrigerator, TV, computer, washing machine every year becomes more and more important. Each year, Ukraine landfill 500 thousand tons of electronic waste. The exact figure of electronic waste in Ukraine is now difficult to calculate.

According to Ukrainian Ecological Public Organization "MAMA-86" about 53.6 million mobile devices used in Ukraine, 300 thousand of laptops, 277 million batteries (batteries) are imported to us annually. According to the official data of the State Customs Service, in 2012, more than 50 types of various electrical and electronic equipment were imported to Ukraine. The number of imported devices is 866.7 thousand units with a total weight of 139.4 thousand tons. After the expiration of the terms of use, these products go into trash, each year - about 500 thousand tons of waste generated.

Advertising contributes to increasing the amount of electric waste, which encourages consumers to buy newer and newer models, more often change household and other techniques, based not only on technical but purely on aesthetic reasons or on tribute to fashion. Moreover, at home there are more small and large equipment than it was 20, and even more so - 30 years ago.

In the dumps site various factors there are processes of destruction of the shell of the equipment itself, as a result chemical elements which present in their composition, evaporated and washed away into the environment. Toxic substances are transmitted by air and fall on the ground. Then through the food chain (water, plants, animals) they get into the human body, causing severe poisoning and even genetic changes.

In general, on the scale of Ukraine, more than 40 kg of mercury, 160 kg of cadmium, 400 tons of other heavy metals, 260 tons of manganese per year going in to the atmosphere and groundwater from the electronic waste.

3.5. E-waste Generation in the European Union

Current European waste policy does not mainly aim to treat waste streams but rather place in the foreground of interest the complete supply chain of a product. Recycling only takes the third place whereas recovery and disposal represent the least favorable options. The highest per inhabitant e-waste quantity (15.6 kg/inh.) was generated in Europe. However, the per inhabitant amount was nearly as high as Europe’s (15.2 kg/inh.). Basically, waste generation is a huge business and numerous stakeholders are not interested to reduce waste. More sophisticated incentives are required to decouple economic growth from waste generation .(Awasthi, Zeng, and Li 2016)

3.6. Treatment of E waste in Europe

The current techniques for handling e-waste in **Europe** are a)landfilling and incineration which is the simplest form of waste handling, b)export to low-cost regions like Africa and Asia, c) regional material recycling, and d) direct reuse (Stockholm 2014)

3.7. Who should be responsible for electronic waste: the experience of Europe

In 90's some European countries banned the placement of electronic waste at landfills. Manufacturers of electronic devices at the legislative level in the EU have been obliged to accept, free of charge utilization of waste electrical and electronic equipment that has been used or unsuitable for future use.

For example, Dell, Sony, Samsung, Nokia, Siemens have their own recyclable software, take old technology from consumers and either upgrade or reuse certain parts of it. Canon, as a manufacturer of electronic products, provides waste collection and recycling in every EU country where it has a national sales office.

In Germany, in each supermarket, special containers for receiving waste batteries are installed. When buying a new battery for a car, the buyer is obliged to hand over the old one; otherwise, he will be subject to very high fines.

In Poland, for the dumping of old electrical equipment in regularly garbage can be charge a fine of up to 1.5 thousand dollars. Old technics can be transferred free of charge to special points of reception and in stores. Special points are organized by non-governmental organizations that do not charge for this money, and private ones who can charge for disposal. The largest organization - ElektroEko - collects 60% of the old electrical engineering in Poland, and does it for free. Non-governmental organizations and private firms do not pay those who rent equipment. They collect collected garbage to special factories, which making money on it.

In terms of our closest neighbor - the Belarusians. They ahead of us on the issue of utilization of electrical equipment. Minsk has a free of charge taxi that can come to those who are not able to deliver broken old processing equipment by their own.

3.8. Urban mining areas – new source of resources

Urban mining as a new concept of mining which aims for reuse of materials which have been mined before. Normally, resources are mined processed and used in cities. And now the cities are becoming its new source. Besides the recycling of used cities infrastructure, also waste generated in the cities can be a rich resource to be "mined". New resource present more value due to high concentrations of valuable metals. New mining without mine side, thus it's benefit not only for enterprises but also for citizens who care about nature. Urban areas are the source of waste of electric and electronic equipment, it is collected in shops and collection points, and its first segregation takes place there. Also, in cities or close to them facilities for processing WEEE are located. In those plants the first step of recovery of resources from waste is carried out. First step in most cases is traditional simple WEEE processing technology: manual dismantling, milling, and segregation. Those processes allow recovery of resources like aluminum, copper, steels, glass, plastics that cover great part of the waste mass. Also, the new robotic technologies offer a new approach to WEEE dismantling decreasing human labor and energy consumption, but they are still not used widely. During every waste processing operation the secondary waste is also generated, because there is no complete neutralization and recovery process available. Examples of such "waste" that is not processed locally, and requires specialist treatment are: printed circuit boards, and the sieved part from milling of WEEE waste. Both of those categories contain Cu,Sn, Pb, some Ag, Au, Pd, and more than 60 other metals and substances . (Awasthi, Zeng, and Li 2016)

3.9. Landfill in Ukraine

Ukraine landfill the massive amount of electric and electronic equipment, which means that responsibility for environmentally friendly WEEE management at the end of EEE lifespans needs to be laid on importers. Rapid technological advances and lower product prices for more powerful machines are contributing to shorter lifespans and frequent replacement. There is a growing concern over WEEE as increased quantities are generated, coupled with toxic content and valuable materials.

3.10. Real story or how Ukraine solving the problems

Today in Ukraine, in spite of the wide network of collection and disposal of electronic waste, there are only a few attempts, mainly by the public, to carry out these tasks on their own. Let's say, mostly public organizations carry out collection and transferring to recycling. Only in recent years in cities began to appear recycling facilities, where citizens can dispose old equipment that becomes raw materials in the processing plants. Sometimes stores helping to deal with WEEE, by caring shares such as "bring old equipment and get a discount for a new one." However, not everyone has the desire and opportunity to take advantage of such actions. Another option is sell used scrap to private companies.

At the legislative level, as is the obligatory utilization of office equipment of state-owned enterprises. For example, personal computers are subject to accounting and are subject to amortization laws (depreciation period of 4-10 years, depending on the type of computer). It is possible to write down and dispose of computers only after the expiration of this term, although they are morally obsolete much earlier. In order to dispose of office equipment, a legal entity should contact one of the specialized enterprises that are engaged in this, with a request for an examination, and to conclude that this model is outdated, discarded and can’t be repaired. Only after that you can enter into an agreement with the appropriate waste management organization.

The WEEE problem can only be solved at the state level, introducing the principle of increasing producer responsibility. Manufacturers who come to the market or already have to comply with the law and be responsible for both production and disposal. Abroad, producers create appropriate funds, collect funds, which then go for recycling. Plants recycle waste and extract resource-valuable components such as: gold, silver, platinum, etc. The cost of the product includes the cost of recycling. When producers enter the market and start selling their products, they enter into contracts with the respective enterprises. It is clear that well-known multinational companies, large players in the market, have their own capacities, realizing that 90% of these wastes will be recycled and then used in future production. There are such enterprises that do not have such capacities. Then they conclude a contract and cooperate with other factories.

3.11. Waste in Ukraine - outside the legal field

The solution of the problem of electronic waste in Ukraine should also provide the "Technical regulations on waste electrical and electronic equipment", which has been developed in Ukraine since 2008. According to the drafts of these legislative acts, importers and manufacturers can both independently dispose of electricity, and sign contracts for work on the organization of collection, harvesting and utilization of the corresponding types of equipment with authorized enterprises. A draft Resolution of the Cabinet of Ministers of Ukraine "On Approval of the Technical Regulations on Waste Management of Electronic and Electrical Equipment" was also developed. This regulation provides for the establishment of electronic and electrical waste collection points that should be located in user-friendly places and provide free services to users. However, for the time being, the draft Regulation is only sent for reconciliation with the central authorities.

Another solution discussed. Ministry of Natural Resources of Ukraine, at present, the Ministry of Internal Affairs has submitted a draft amendment to the Tax Code, which provides for the central collection of funds from importers and producers of various consumer goods in order to ensure, at the expense of these funds, proper organization of collection, harvesting and utilization of waste from these goods .

However, in general, the problem with WEEE in Ukraine needs to be solved in the organizational and legal aspect - the creation of producer funds, the support of the state enterprises of waste utilization, and in the social and informational: Ukrainians understand that they can’t throw broken vacuum cleaner or laptop to regular trash.

3.12. Ukrainian law for sorting waste

From January 1st 2018, Ukraine established law for sorting all rubbish by type of material, and also to divide into three category: for recycle, disposal and dangerous waste. This is stated in Article 32 of the Law of Ukraine "On Waste", to which the relevant paragraph was added in 2012.

This item corresponds to the two EU Directives 1999/31 / EC and 2008/98 / EC, which regulate the handling of rubbish in European countries, provide a clear sequence of actions that must be carried out with waste, classify rubbish, set the strategic goal of reducing the amount of waste that taken out to polygons.

According to the Law "On Waste", "treatment (recycling) of waste is the implementation of any technological operations related to the change in the physical, chemical and biological properties of waste in order to prepare them for environmentally safe storage, transportation, utilization or disposal " According to the European rules, recyclable waste should be sent to the relevant enterprises, disposal- take away to landfills, and with dangerous will be carried out necessary to neutralize the operation. In this case, biodegradable waste should not be allowed on conventional landfills (EU Directive 1999/31 / EC).The current Law "On Waste" does not have a list and sequence of operations with garbage. Under such conditions, the clause added to Article 32 of this Law in 2012 becomes declarative. Small number of settlements separately collects rubbish and has garbage collection lines. The main problem is in absence of desire to make good for people and the environment. Even the existing capacity for recycling waste - glass, paper, plastic or metal - takes the materials selectively. Besides, Ukrainians incorrectly sort rubbish - for example, bring dirty plastic.

3.13. How does the Ministry of Regional Development intend to ban landfilled of untreated wastes?

According to the Deputy Head of the Department of Improvement and Communal Services of the Ministry of Regional Development, the issue of collecting, transporting, utilizing and disposing of household wastes belongs to the executive bodies of town and city councils. Referring to the Regulations on the Ministry of Regional Development, monitor will be according the law" On Waste "by local self-government organizations directly responsible for the transportation of garbage."The agency is actively working on the implementation of the European Union Directives 2012/19 / EC (on waste electrical and electronic equipment). Increased responsibility of manufacturers and importers, which will promote the sustainable production and consumption of electrical and electronic equipment, batteries and accumulators, create the right legal environment for their activities, and direct the costs of producers of electrical and electronic equipment, batteries and accumulators to the field of household waste management. "

As noted in the report of the Ministry of Regional Development, Construction and Housing and Communal Services of Ukraine "Status of Household Waste Management in Ukraine for 2016", last year only 5.8% of all rubbish was disposed of in Ukraine: 2.71% burned, and 3 , 09% - sent for recycling.

Today, Ukraine needs appropriate treatment equipment for the recycling garbage at existing. High investment should be inputted to make the companies environmentally friendly.

4. Circular economy in term of WEEE

In the modern world, the amount of waste produced by enterprises and the population is growing. Most countries have faced various social and environmental problems, which include a lack of resources, pollution of the environment. To cope with environmental problems and ensure sustainable development, governments of different countries are in the search for mechanisms that can not only measure the degree of pressure on nature, but also reduce it. One of these mechanisms is the simultaneous use of both the classical model of the use of primary resources in production and the use of secondary resources. Certainly, the orientation toward the recycling model is an alternative to the extraction of primary resources for production with limited availability. At the same time, the process of searching for and introducing and using technologies for waste processing by various branches of the national economy is important. The close loop economy is more than just recycling of waste. This is a philosophy of reuse and profit from what was previously unnecessary. New technology makes a life easier, but also generate impressive amount of waste. Goods are finished their life after 6 months of after their manufacture. Modern circular economy is benefit for environment as well as for economy. Even the smallest cycles - reuse, recovery, modernization and re-marketing of goods and components of industry - bring a large financial benefit. The reason for this - the minimum costs for the buyer and the maximum profit for manufacturer.

For years, a linear economy model, which is characterized as “take, make, waste” has been widely accepted, but in recent years an alternate concept has emerged. The circular model focuses on recovery of resources in a closed loop (Nowakowski and Mrówczyńska 2018). It has become a new approach in a policy of European Union (Brussels 2017).In this approach is included “zero waste strategy”. One of the groups of products with a possibility of fulfilment principles of circular economy is electrical and electronic equipment (EEE). The materials used in manufacturing of EEE can be recovered and reused and some components can be recycled. Therefore, waste management has a special role in a circular economy.

In the last two decades, the number of WEEE increased and it has become a problem for both developed and developing countries. In a circular economy approach, it is very important to keep all the materials used in the production of EEE in a closed loop to reduce negative environmental impact and improve material recovery (**Fig.1**)

Figure 1. Circular economy concept by EIT Raw Materials (https://eitrawmaterials.eu/innovation-themes/03_06_ce-draft-1/)

The first WEEE Directive was introduced in the European Union in 2003 and a second version was adopted in 2012 , which included modifications and revisions following input from policy makers, equipment producers and waste management companies responsible for collection and recycling. The Directive includes acceptable disposal methods of WEEE. The collection schemes were designed to meet these requirements. The collection companies are tasked with hauling the waste equipment from households and delivering it to recycling centers defined in the Directive as treatment facilities where the equipment undergoes dismantling, shredding into chunks, and sorting depending on the composed materials. The residents are expected to comply with the requirements of the Directive, which prohibits disposal of WEEE with household waste. Residents have many options to dispose of WEEE. Retail stores offer take back services when a consumer purchases new electronic equipment. In addition, it is also possible to bring obsolete equipment to any EEE store (floor space >400 m^2) without purchasing a new product. The main goal for collection companies is to maximize collected volume of

WEEE and at the same time minimize the operational costs. Therefore, the companies should focus on the logistics of collections: collection schedules, numbers of vehicles and employees, and numbers and locations of containers and bins. Another factor that influences the collection companies' operational costs is the distance travelled by vehicles and must be included in the collection schemes and route planning. Since some materials used in production of electronic and electrical equipment are classified as hazardous waste, in order to prevent environmental problems, it is of the utmost importance to collect large quantities of WEEE from any given area (Nowakowski and Mrówczyńska 2018).

5. Printed Circuits Boards

5.1. Composition of Printed Circuit Boards Printed

Printed circuit boards are composed of different multilayer material with ceramics, epoxides and fibers. The composition of printed circuit boards mostly depends on application. The most common type of printed circuit board is made from glass fiber reinforced epoxy resin; another very common type is cellulose paper reinforced phenolic resin. Printed circuit boards contains around 40 wt% of metals, the most common is copper, 60 wt% of fibers and ceramics. Other metals that are present in printed circuit board waste include iron, nickel, silver, gold, and palladium. The materials used in the manufacture of printed circuit boards depend on the application, the metal based components of the board are mounted on a plastic, glass fiber reinforced plastic or ceramic substrate. The substrate is non-conducting and composed of a range of materials such as acrylonitrilebutadienestyrene polymer (ABS), epoxy resins, glass fiber reinforced plastics and ceramics. The conductive printed circuit, usually composed of copper, is printed onto or inside the substrate and the components are mounted onto the substrate.

Printed circuit boards contain electrical components of a range of sizes and compositions. Larger components such as capacitors, resistors, integrated circuit chips, thermistors and transformers are mounted onto the non-conductive plastic, glass fiber reinforced plastic or ceramic substrate . Metal wires, usually composed of copper or aluminum link the components. Different components are com- posed of different materials, for example, Ta is used in capacitors, Ga, In, Ti, Si, Ge, As, Sb, Se and Te are found in integrated circuit chips and other units. Semiconductors contain Ga, Si, Se and Ge and solder joints contain, for example Pb and Cd. Table 2 shows the range of metals, ceramic and plastics found in printed circuit boards. All of the materials show a wide compositional range in the printed circuit boards, related to the range of different equipment and manufacturers.

Copper is the main metal present in printed circuit boards typically between 10 and 26.8 wt%. Recycling of printed circuit boards has been driven by the content of precious and other metals and their potential for recovery and sale into the metals markets. **Table 1** shows that gold, palladium and silver are in significant concentrations in printed circuit boards. These three precious metals represent between 80 and 90% of the intrinsic value of the boards depending on the price of the metals on the metals markets.

Table 1. Chemical composition of PCBs in the present study and values reported by other authors. (Bizzo, Figueiredo, and De Andrade 2014)

Metal content	a	b	c	d	e	f	g	h	i	j	k	l	m
Cu (%)	19	20	22	12.5	26.8	15.6	19.66	28.7	27.6	14.6	12.58	19.19	28
Al(%)	4.1	2	-	2.04	4.7	-	2.88	1.7	-	-	2.38	7.06	2.6
Pb (%)	1.9	2	1.55	2.7	-	1.35	3.93	1.3	-	2.96	2.44	1.01	-
Zn (%)	0.8	1	-	0.08	1.5	0.16	2.10	-	2.70	-	-	0.73	-
Ni (%)	0.8	2	0.32	0.7	0.47	0.28	0.38	-	0.3	1.68	0.39	5.35	0.26
Fe (%)	3.6	8	3.6	0.6	5.3	1.4	11.47	0.6	2.9	4.79	3.24	3.56	0.08
Sn (%)	1.1	4	2.6	4.0	1.0	3.24	3.68	3.8	-	5.62	1.41	2.03	-
Sb (%)	-	-	-	-	0.06	-	-	-	-	-	-	-	-
Cr (%)	-	-	-	-	-	-	0.005	-	-	0.356	-	-	-
Na (%)	-	-	-	-	-	-	-	-	-	-	-	-	-
Ca (%)	-	-	-	-	-	-	1.13	-	1.4	-	-	-	-
Ag (ppm)	5210	2000	-	300	3300	1240	500	79	-	450	-	100	135
Au (ppm)	1120	1000	350	-	80	420	300	68	-	205	-	70	29
Pt (ppm)	-	-	-	-	-	-	-	0	-	-	-	-	-
Cd (ppm)	-	-	-	-	-	-	-	-	-	-	-	-	-
K (ppm)	-	-	-	-	-	-	-	-	-	-	-	-	-
In (ppm)	-	-	-	-	-	-	500	-	-	-	-	-	-
Mn (ppm)	-	-	-	-	-	-	9700	-	4000	-	-	-	-

Se (ppm)	-	-	-	-	-	-	-	-	-	-	-	-	-
As (ppm)	-	-	-	-	-	-	-	-	-	-	-	-	-
Mg (ppm)	-	-	-	500	-	-	1000	-	-	-	-	-	-
Pd (ppm)	-	50	-	-	-	-	-	33	-	220	-	-	-
Co (ppm)	-	-	-	-	-	-	300	-	-	-	-	400	-
Ti (ppm)	-	-	-	-	-	-	-	-	-	-	-	400	-
Total Metals (%)	**31.9**	**39.3**	**30.1**	**22.6**	**40.2**	**22.2**	**46.5**	**36.1**	**35.3**	**30.1**	**22.5**	**39.1**	**31.1**

Ceramic materials used in printed circuit boards are mainly silica or alumina, but alkaline earth oxides (e.g. CaO), mica and barium titanate have also been used. The ceramic material is used as glass fiber reinforcement or reinforcement/filler material. The polymers which are mixed with the ceramic reinforcement/filler comprise a range of different plastics. **Table 2** shows that polyethylene, polypropylene, polyesters, epoxy resins and nylon have been identified in printed circuit boards. Other plastics and resins have included, polyimides, or less frequently polyethylene terephthalate. Dysfunctional epoxy resins such as bisphenol A, multifunctional epoxy resins such as phenol and creosol based epoxy novo lacs, epoxy blends, and cyanate

Table 2 Representative material compositions of printed circuit boards
(Paul T. Williams 2010)

Material	**Composition (wt%)**
Metals (typically 40 wt%)	
Cu	10–26.8
Al	1.33–4.78
Pb	0.99–4.19
Zn	0.16–2.17
Ni	0.28–2.35
Fe	1.22–8.0
Sn	1.0–5.28
Sb	0.06–0.4

Au	80–1,000 (ppm)
Pt	4.6–30 (ppm)
Ag	110–3,301(ppm)
Pd	10–294 (ppm)
Ceramic (typically 30 wt%)	
SiO2	15–41.86
Al2O3	6–6.97
Alkaline and alkaline	6–9.95
earth	
oxides	3
Titanates, mica, etc	
Plastics (typically 30 wt%)	9.9–16
Polyethylene	4.8
Polypropylene	4.8
Polyesters	4.8
Epoxies	2.4
Polyvinyl chloride	2.4
Polytetra fluoroethane	0.9
Nylon	

esters, and polyimides are amongst the most common polymers used .As well as a resin, a hardener is needed to form the cross-linking required to create a thermoset plastic, the most common hardener is dicyandiamide, but 4,40-diaminodiphenyl sulfone and 4,40-diaminodiphenyl methane are also used. (Paul T. Williams 2010)

6. Current technologies by other authors

Usually the PCBs or the PCBs' recycled residue are either incinerated or landfilled. The incineration of PCBs is much safer and controlled method, because it can be carried out through controlled combustion conditions, including an efficient flue gas treatment for minimizing the environmental impacts. The incineration of PCBs can lead to the formation of brominated compounds resulting from the brominated flame retardants, which are rather toxic . Additionally, the combustion of PCBs can also be used as a mean of recovering the energy content of plastics contained in PCBs. On the other hand, the landfill although it is also a controlled process and leachate sealed, it can lead to leaching toxic substances to the aquifer and there is also a risk of vaporization of volatile hazardous compounds. (Stockholm 2014)

There two main approaches to PCB treatment and metals recovery. Pyrometalurgical smelting of waste, and mechanical processing (milling). Currently in Europe, only few plants process electronic printed circuit boards in pyrometalurgical processes. Those plants process PCB from entire Europe. However, the waste of electric and electronic printed circuit boards, is only a part of the total input in those installations, as they prefer homogenous industrial waste over PCB waste from WEEE. Integrated pyrometalugrical smelters can process up to 300 000 Mg/year of waste, and recover up to 95% of precious metals and Cu. The facilities are located in Belgium – Umicore, Sweden – Boliden, and Germany – Aurubis. (Szałatkiewicz et al. 2013)

7. Role of microbes in recycling

It is believed that biotechnology has been one of the most promising technologies in metallurgical processing. Bioleaching has been used for recovery of precious and toxic metals from e-waste scrap. Mainly autotrophic bacteria, heterotrophic bacteria, and fungi are commonly used for the bioleaching. In this process microbial cells derive their energy needed for metabolism of itself through aerobic oxidation of reduced sulfur compounds. Several researchers reported that fungi such as Aspergillus sp. and Penicillium sp. are extremely reported as promising fungal strains could be used as bioleaching (Awasthi, Zeng, and Li 2016)

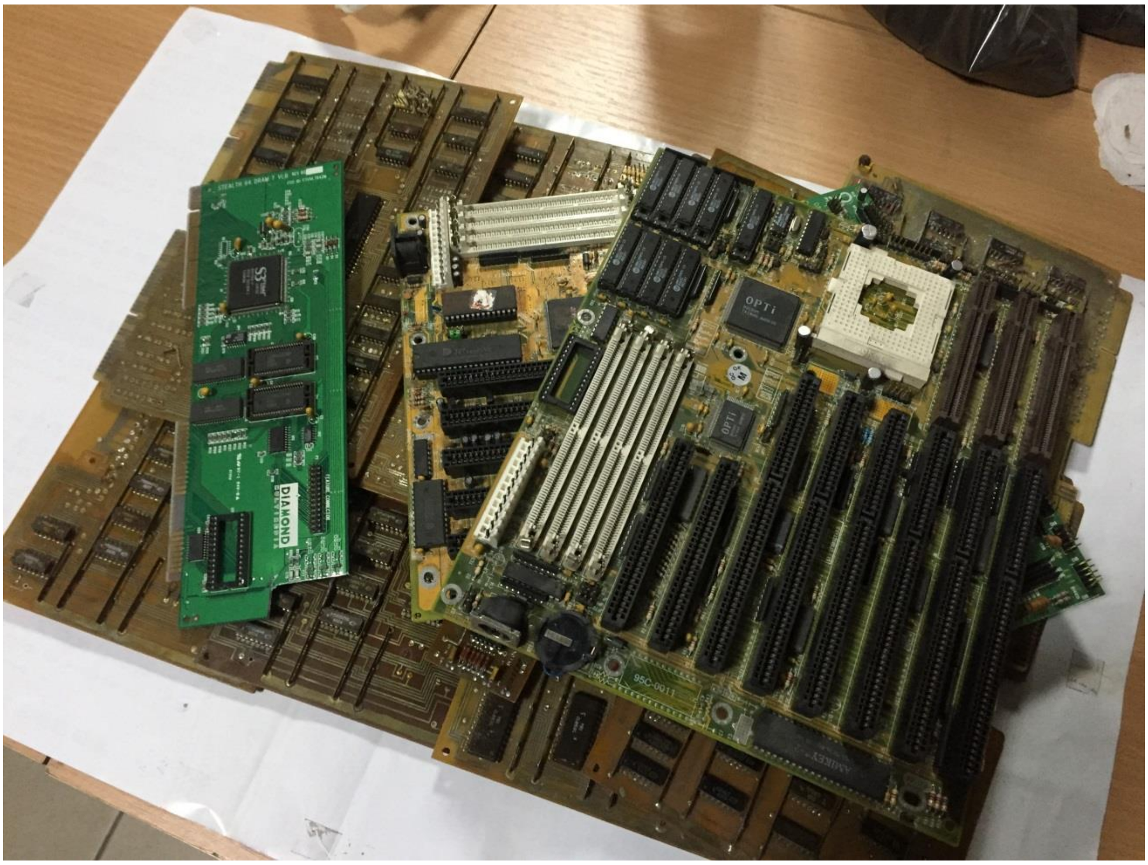


Figure 2. Donated Printed circuit boards

8. Experimental part

8.1. Material

The material for experiments was collected from old computers **Figure** , which were written-off from National Mining University. PCB's were prepared with Metal Cutting Snips to decrease size of board for further experiments. During cutting no parts were removed to guaranty validity of the experiment in real conditions After cutting PCB were ready for lab scale experiments **Figure 2** . The sizes of board were approximately 10-15 centimeter in length and 3-6 centimeter in width. All chips and plastic remain on their places. Characteristics of PCB's are present in theoretical part of thesis as well as review of composition by different authors and articles.

8.2. Pretreatment PCB

8.2.1. Jaw Crusher

First stage was to treat PCB with mechanical treatment in lab scale vibrational jaw crusher. From the first experiment was defined that such crusher is not appropriate for this material in order to perform positive result for the experiment. Mainly jaw crusher used as primary crusher in mining.

Figure 3. Cut Printed circuit boards

The mechanism of crushing is either by applying impact force, pressure or a combination of both. The jaw crusher is primarily a compression crusher while the others operate primarily by the application of impact. The faces of the plates are made of hardened steel. Both plates could be flat or the fixed plate flat and the moving plate convex. The surfaces of both plates could be plain or corrugated. The moving plate applies the force of impact on the particles held against the stationary plate. Both plates are bolted on to a heavy block. The moving plate is pivoted at the top end (Blake crusher) or at the bottom end (Dodge–type crusher) and connected to an eccentric shaft. In universal crushers the plates are pivoted in the middle so that both the top and the bottom ends can move.(Gupta et al. 2006)

8.2.2. Hammer Crusher

Hummer crusher was used to define result of applying forces. In most technologies from reviewed articles hammer crusher was used. Sarvar, Salarirad, and Shabani used hammer mill in their experiment and got product that classified into 11 fractions by manual screening: +6.3, 4.76–6.3, 3.36–4.76, 2.38–3.36, 1.68–2.38, 1.19–1.68, 0.84–1.19, 0.59–0.84, 0.42–0.59, 0.21–0.42 and −0.21 mm.(Sarvar, Salarirad, and Shabani 2015) Cayumil et al used hammer crusher followed by pulverisation to reach particles sizes of 300 lm for further leaching in a sulphuric acid solution in the presence of hydrogen peroxide for 3 h/200 rpm/- room temperature.(Cayumil et al. 2018) Zhan and Xu also used hammer crushed for waste PCBs ,than sieving and the separation of metallic and non-metallic fractions using a corona electrostatic separator.(Zhan and Xu 2011)

Our experiment showed that hammer crusher can be used for reducing size of PCB's, but is need more investigation for treatment of PCB's due to containing epoxides, fiber and cooper parts together **Figure 4**. In the next paragraphs that topic would be discussed more to choose appropriate treatment for separation copper and other metals from residual.

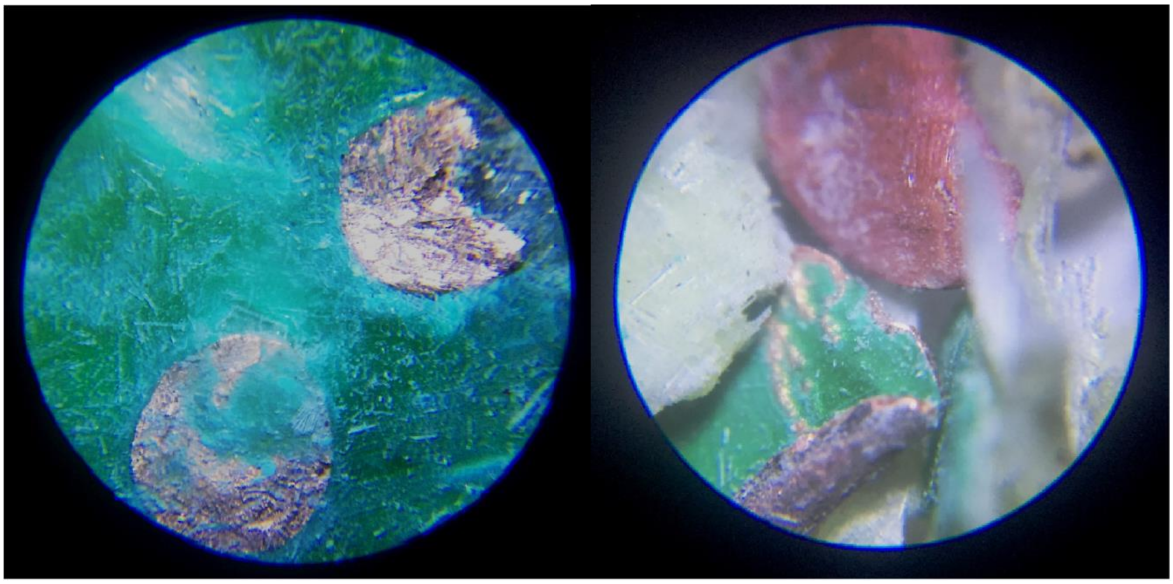


Figure 4. Crushed PCB's in hammer crusher with residuals

After experiments with jaw crusher and hammer crusher Cut Printed circuit boards **Figure 3**. were taken to perform next stage of research. To solve previous problem, where copper were bonding with residuals such as fiber, epoxied and etc. I the investigated into research of pyrolysis for develop the technology. Numbers of publications were reviewed to find appropriate pyrolysis process for PCB's.

9. Potential of pyrolysis processes in the waste management sector.

9.1. Introduction to pyrolysis

Most of waste management system based on landfill, recycling and reuse. Waste is also valuable resource of energy required proper treatment in order to minimize the waste impacts. Pyrolysis is a new promising technique for waste handling as material and energy recovery are accomplished simultaneously with waste management and minimization. This technology is a thermal treatment method which can convert the waste fraction into carbon rich fuels while on the same time the valuable substances such as metals can be easily regenerated. The fuel produced through pyrolysis is either in the form of methane rich gas or hydrocarbon rich oil in liquid form according to the process conditions. Metals recovered during pyrolysis such as gold (Au), copper (Cu) and palladium (Pd) are being regenerated in a pure form since no oxygen is present and thus no metal oxides are formed.(Stockholm 2014)

9.2. Pyrolysis

Pyrolysis is the thermal degradation of organic waste in the absence of oxygen to produce a carbonaceous char, oil and combustible gases. How much of each product is produced is dependent on the process conditions, particularly temperature and heating rate. **Figure 5**. characterizes the pyrolysis.

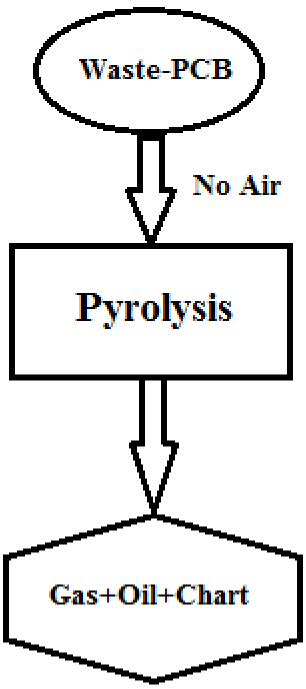


Figure 5. Process characterization pyrolysis.

The word “pyrolysis” comes from the Greek word “πυρ” (pyr) which means fire and the Greek word “λύσις” (lysis) which means breakdown and separation emphasizing the disintegration of matter due to heat. Pyrolysis is also known as thermolysis, thermal cracking, dry distillation, destructive distillation, etc.(Kantarelis n.d.)

The process of thermal degradation or pyrolysis of such materials, in the absence of oxygen, results in the long polymer chains breaking to produce shorter molecular weight chains and molecules. These shorter molecules result in the formation of the oils and gases characteristic of pyrolysis of waste. The application of pyrolysis to waste materials is a relatively recent development. In particular, the production of oils from the pyrolysis of waste has been investigated, with the aim of using the oils directly in fuel applications or, after upgrading, to produce refined fuels. The pyrolysis oils derived from a variety of wastes have also been shown to be complex in composition and contain a wide variety of chemicals which may be used as chemical feedstock. The oil has a higher energy density, that is a higher energy content per unit weight, than the raw waste. The solid char can be used as a solid fuel or as a char–oil, char–water slurry for fuel. Alternatively the char can be used as carbon black or upgraded to activated carbon. The gases generated have medium to high calorific values and may contain sufficient energy to supply the energy requirements of a pyrolysis plant (P.T. Williams 2005)

During pyrolysis, large complex hydrocarbon molecules of biomass break down into relatively smaller and simpler molecules of gas, liquid, and char.(Basu and Basu 2010) The process of pyrolysis can be used in plastics which are composed of large polymer chains, which are breaking down to lighter compounds with shorter molecular weight chains and molecules (Williams, 2005). The three main products of pyrolysis are the solid residue commonly known as char, the vapors/liquids, aromatics, water, products of low degree of polymerization, tars, etc. and the gases which is mainly CO, CO2, CH4, H2 and other light hydrocarbons (Kantarelis, et al., 2013)

9.3.Lab scale pyrolysis reactor experiments

The examined fractions of PCB were tested on a lab scale pyrolysis reactor. The reactor was charged with 2.5kg of the examined material and purged for 40-50 min with absence of oxygen and it was heated up until 700-800oC. During pyrolysis gas was produced as well as liquid. Produced gas was used in close loop to heat the reactor. In **Figure** the material after pyrolysis, where organic material was degraded.

j

Figure 6. PCB’s after pyrolysis

After process of thermal degradation or pyrolysis of such materials **Figure 6** became frangible which is easier for mechanical treatment of material.

Before and after the pyrolysis the PCB samples were weight. Weight loss was calculated. The weight loss was converted to fraction reacted (α) by the equation:

$$a = \frac{Wf * 100}{Wi}$$

$$a = \frac{1.9 * 100}{2.5} = 24\%$$

Where Wi-represents initial and Wf-final weight loss of the sample. The pyrolysis experiments were carried out in the temperature range of 700-800℃ .During thermal degradation about 24% of mass lost.

9.4.Pyrolysis of WEEE: Review of achievements and current approaches previous

In pyrolysis processes, organic compounds are degraded in an inert atmosphere. Due to this, contained metals are not oxidized during the thermo- chemical process. Pyrolysis can be operated under different conditions mainly based on temperature, heating rate or dwell time, depending on the input material and desired product quantities and qualities. A pyrolysis process could become part of a process chain to separate critical metals and to generate fuels with low yields of halogens for an energetic utilization. Products of this thermo- chemical process would be a mixture of metals, which could be treated in copper processes, as well as calorific gas and oil for an energetic utilization, e.g. in a combined heat and power plant. This energetic utilization of pyrolysis oil and gas is an appropriate option, because these products can present fuels with heating values, which are often comparable to conventional fuels like diesel fuel (41.8 MJ·kg-1) or natural gas (CH4: 35.9 MJ·m-3) (Hense et al. 2015)

Results from a review of different papers, which present heating values of pyrolysis oils and gases from WEEE plastics, PCB or other materials from WEEE. It can be seen that the ranges of this values are between 26.5 and 44.8 MJ·kg-1 for liquid products and between 12.3 and 48.6 MJ·m-3 for gaseous products. (Hense et al. 2015)

Use of pyrolysis as a means to recover valuable materials from printed circuit boards of waste electrical and electronic equipment is reviewed. The printed circuit boards consist of metals, including valuable gold, silver and palladium which can be recovered from the pyrolysis process for sale into the metals industry. Many printed circuit boards contain high concentrations of glass fiber which can also be easily separated from the solid pyrolysis residue and recycled for re-use. The plastic/resin comprising the board on pyrolysis produces a oil/wax product which can be used as fuel or recycled back into the petrochemical industry. Pyrolysis of the plastic/resin also produces a gas product with a significant calorific value sufficient to provide the energy requirements of the pyrolysis process.(Paul T. Williams 2010)

9.5.Pyrolysis Kinetics

The pyrolysis of printed circuit boards is generally a complex process and includes several steps. The level of homogeneity is relatively low compared with other waste fractions. It is extremely difficult to conduct a full kinetic analysis of such complex systems while an average kinetic description is also required. The overall kinetic reactions of printed circuit boards can be described by the following equation :

(eq-1) $$\frac{da}{dt} = k(T)f(a)$$

Where, a is the normalized conversion of the raw materials' decomposition and f(a) depends on the mechanism of the thermal decomposition.

The normalized conversion described above can be defined as:

(eq-2) $$a = \frac{m_0 - m_t}{m_0 - m_f}$$

Where,
m_0 is the initial mass of the sample
m_t is the mass of the sample at time t and ` mf is the final mass of the sample
The dependence of the rate constant is described by the Arrhenius law:

(eq-3)

$$k(T) = Ae^{(-\frac{E}{RT})}$$

Where,
E is the activation energy
A is the pre-exponential factor and
R is the gas constant

As long as the temperature is increasing through time with a constant heating rate β the temperature (T) can be expressed by the following equation:

(eq-4) $$T = \beta t + T_0$$

Differentiating the above correlation, the equation is formed:

(eq-5) $$dT = \beta dt$$

By combining the eq-1 with the eq-5 derives the following equation:

$$g(a) = \int_{T_o}^{T_{max}} \frac{A}{\beta} e^{-\frac{E}{dt}} dt$$

(eq-6) (Stockholm 2014)

Kissinger-Akahira-Sunose (KAS) Method

The Kissinger-Akahira-Sunose (KAS) Method is one of the most accepted is conventional method in the scientific community. This method describes that the relation between heating rate and the temperature is:

(eq-7) $$\ln\left(\frac{\beta}{T^2}\right) I_a = \ln\left(\frac{AE}{Rg(a)}\right) - \frac{E}{R}\frac{1}{T}$$

Where,

β is the heating rate in K/sec

T is the temperature in K

A is the pre-exponential factor

E is the activation energy in J/mol

R is the gas constant in J/molK

So, by plotting ln(β/T2) vs. 1/T at constant conversion values will produce a straight line, at which the slope is the activation energy for the specified value of conversion. By doing that on the whole range of conversion, it will produce the activation energy profile.(Stockholm 2014)

Coats – Redfern Method

The devolatilization kinetic parameters from TG data can be derived by using the Coats-Redfern Method, which is a model-fitted method.

Since iso-conventional methods are more reliable and accurate for the estimation of the activation energy of the thermal decomposition, the method of Coats-Redfern will be used in order to estimate the activation energy and determine the pre-exponential factor and the reaction order. The equations for numerical determination of the kinetic parameters of the Coats –Redfern are:

$$\ln[\frac{-\ln(1-a)}{T^2}] = \ln[\frac{AR}{\beta E}(1-\frac{2RT}{E})] - \frac{E}{RT} \qquad n = 1$$

(eq-8)

$$\ln[\frac{(1-a)^{1-n}-1}{(n-1)T^2}] = \ln[\frac{AR}{\beta E}(1-\frac{2RT}{E})] - \frac{E}{RT} \qquad n \neq 1$$

(eq-9)

Where,

n is the order of the reaction

β is the heating rate of the sample

R is the global gas constant

A is the pre-exponential

E is the activation energy.

For simplification of the eq-8 and eq-9 the $\ln[\frac{-\ln(1-a)}{T^2}]$ and the $\ln[\frac{(1-a)^{1-n}-1}{(n-1)T^2}]$, which are depending on the reaction order can be referred as $\ln B$.

Then plotting the $\ln B$ vs. 1/T will produce a straight line, which slope would be equal to $-\frac{E}{R}$, while its interception would be equal to $\ln[\frac{AR}{\beta E}(1-\frac{2RT}{E})]$.

Assuming that the $2RT << E$, the $-\frac{2RT}{E} \approx 0$, then we get this equation:

(eq-10) $$b = \ln(\frac{AR}{\beta E}) => A = \frac{\beta E}{R} e^b$$

(Stockholm 2014)

9.6.Conclusion analysis of pyrolysis

The sample used for experiment was weighted before the pyrolysis process and the weight of sample was 2,5 kg and separated for different experiments. Furthermore, the char residue after the pyrolysis was also weighted for calculations. It can be conclude that pyrolysis process is effective for material degradation and for further recovering of metals.

10. Mechanical recycling after pyrolysis

After being disassembled, the samples were processed mechanically. First, the samples were pulverized in milling machines. There were two types of milling machines used in this stage of experiment, which are **ball-milling** and **cylindrical milling** machine. Although both machines perform different function in the result of the milling process.

10.1.Ball- Milling process

During the ball milling process, e-waste particles were put together into a pot. The ball-milling machine, shown in **Figure 7** has bigger capacity and can fit more samples. The experimental milling was performing in total for 7 minutes. From that short time of experiment was conclude, that forces which applying in material during milling is not appropriate. Because influencing milling ball contacting material with hitting and perform destroying metal into small fraction. Also been conclude that friction is has positive affect on milling process. Some samples could not be pulverized uniformly and produced some residue with the larger and the time of milling should be longer.

Figure 7. Mechanical treatment in ball milling machine

10.2. Cylindrical-Vibro milling

After using of ball milling machine it was conclude that another forces should be applied to material such as friction and squeezing to achieve separation of metal part from residual. During experiment cylindrical-vibro milling machine **Figure 8-C** was used, which based in Department of Mineral Processing, National Mining University (Dnipro, Ukraine). The part of disassembled samples was cut into 30 x 30 mm by using a cutting scissors to fit into the machine. The process of milling was performed for 2 min which is enough to pulverize samples. Next paragraph tells about analysis of grinding mass movement of cylindrical-vibro mill.

11. Analysis of grinding mass movements

According to (Plescia and Tempesta 2017) analysis of grinding mass movement was implemented, in our case we used a cylindrical mill, the cups placed in direction with adjustable speed and vibration. The grinding body is placed in the jar. The rotating jar and moving grinding body and movement were analyzed. Tests performed, with four cups with grinding bodies inside, prove that the movement is that of a mechanical system of "clutch coupled wheels", where the larger wheels turn the smaller ones, faster and with less torque **(Fig. 8)**. Put simply, the acceleration caused on the jar oscillating gives the cylinder grinding body a revolution around the jar center, in the same rotation direction as the jar but faster and a rotation around its own center in the opposite direction. The rotation-revolution system doubles if we consider the jar rotation center, eccentric compared to its own center, even if just slightly. The combination of these rotations and their harmonics give rise to a highly complex revolution, rotation, sliding and translation system. The movement enabled to create a mechanical model based on the “coupled wheels” system principle. In this coupling system, couples and powers are transmitted using the action of tangential forces to the contact surfaces (sliding friction forces). In an analogy with the cylindrical mill, equipped with a jar and a cylinder, each one coaxial to the other, we have two circular wheels (that is cylindrical considering the third dimension), with $\mathbf{r_j}$ and $\mathbf{r_c}$ radii, that are in contact and are pressed against each other by equal and opposite forces applied to the respective centers. In the point of contact between jar and cylinder (**Fig. 8-A**) you have a **Njc** force (directed radially rather than to the circumference) that can produce an **Rjc** friction force (tangent to the circumference). In ideal functioning, with no friction, the drive torque is equal to the load torque:

$$M_j * \omega 1 = M_c * \omega 2 \quad (1)$$

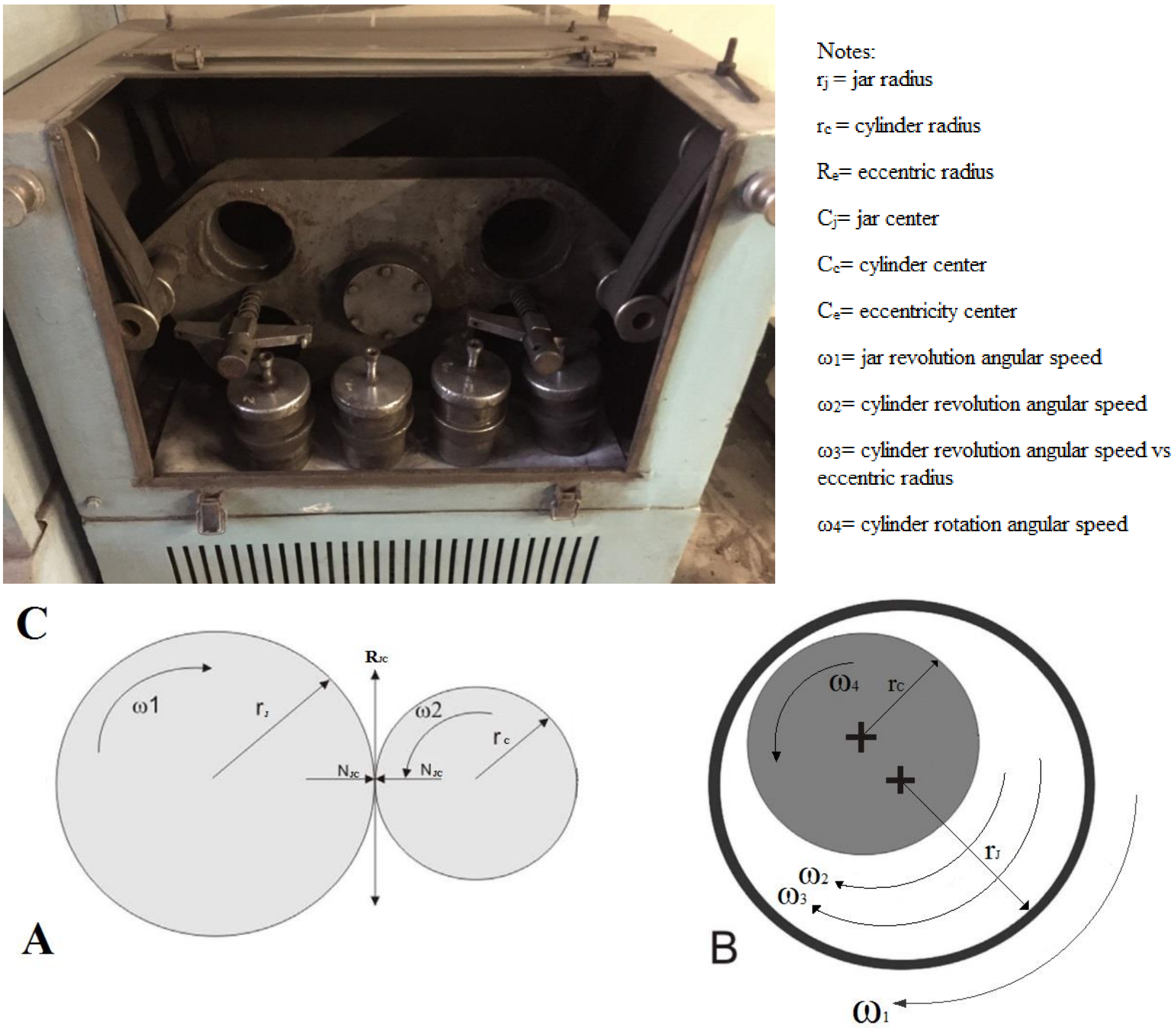
Where Mj and Mc are respectively the motor moment (jar) and the cylinder resistance moment.

In real operations the drive torque will lose power because of the friction:

$$M_j * \omega 1 * \eta_{jc} = M_c * \omega 2 \quad (2)$$

Where η_{jc} is the transmission efficiencies. During motion, so that there is no slipping, the peripheral speeds of the coupled wheels, the jar with cylinder must be equal and the friction force R must be greater or equal to the transmitted force F:

Fig. 8. Diagrams of the movements of the grinding media in a cylindrical mill. A) Simplified model of the gearing; B) ω1, ω2, pulsations (angular speed) for jar and cylinder; C) image of the grinder. The rotation center of the jar, Cj, is at once his eccentric relative to the rotation center of the system, Ce.



$$R = f * N \quad > \quad F \tag{3}$$

f is the coefficient of friction and:

$$F_j = M_j/r_j \text{ and } F_c = M_c/r_c \tag{4}$$

So if the non-slipping condition is achieved, the peripheral speeds of the contact point are equal to each other:

$$\omega 1 * r_j = \omega 2 * r_{ce} \quad (5)$$

that is the transmission ratio is

$$\tau_{jc} = \frac{\omega 2}{\omega 1} = \frac{r_j}{r_{ce}} \quad (6)$$

where r_j and r_{ce}= radius of the jar and the cylinder, ω1, ω2 =angular speed of the jar and cylinder.

As we can see in Fig. 2, the analogy between the coupling of friction wheels and the jar- cylinder pair is considerable. However, in the case of the cylindrical mill, to the coupling and resulting "wheel-on-wheel" friction we need to add friction from slipping, between the upper and lower surfaces of the jar and the cylinder. As a whole, the grinding bodies are subject to two kinds of friction:

– friction from slipping (grinding body that slip on the jar's flat surfaces)

– rolling friction (grinding body which, if coupled, roll into each other)

In the calculation model of the rotation frequencies of the cylindrical mill's grinding masses we need to consider that the rotation of cylinder come from an eccentric rotation of the jar around a center, which is moved compared to the jar center and which increases its rotation radius. This also affects the radius of coupling between jar and cylinder. For the jar - cylinder couples, coupling ratios can be expressed as:

$$\tau_{jc} = \frac{R_j}{R_{ce}} \quad (7)$$

Where R_j is the jar radius and R_{ce} is the radius of the cylinder,

$$\tau_{jce} = \frac{R_{je}}{R_{ce}} \quad (8)$$

Where R_{je} is the eccentric radius of the jar, greater than the radius of the simple jar.

Relation from (7) indicate that the transmission ratio can be expressed using just the geometrical parameters of the friction wheels. For the ring mill, the first coupling takes place between the jar, with angular speed ωl and the cylinder, which reaches an angular speed ω2, higher than ωl, equal to:

$$\omega 2 = \omega 1 * \frac{r_j}{r_{ce}} = \omega 1 * \tau_{jc} = \omega 1 * \frac{R_j}{R_{ce}} \tag{9}$$

The cylinder itself, considering the eccentric radius, 15% greater of the jar radius, generates an even greater frequency pulsation ω2ε:

$$\omega 2_e = \omega 1 * \tau_{jce} * R_{je}/R_{ce} \tag{10}$$

Where $R_{je} = R_j + R_e$

From the rotation speeds calculated you obtain a maximum value of the centrifugal force exercised by the grinding masses which, compared to the jar reference systems, take on the expression:

$$N_c = m_c * \omega 2^2 * R_{ce} \qquad [N] \tag{11}$$

Where m_c is the cylinder mass.

The normal force value:

$$N = N_c \qquad [N] \tag{12}$$

The “Total friction coefficient” f of the cylinder-jar complex will then be calculable as:

$$f = \frac{F}{N} \tag{13}$$

Where F - is the tangential force, already expressed in the ratio 4 and N- is the normal force at the sliding wall, obtainable for ratios 11. The tangential force can also be expressed as friction force; that is the force that the grinding bodies implement on the sliding walls and which in turn can be obtained from the resistance performed by the grinding masses, the cylinder on the jar wall.

The total amount of work spent in heat can be calculated by measuring the temperature of the body of the jar, which increases due to friction:

$$E_h = \Delta T * Cp * M \qquad [J] \tag{14}$$

where E_h is the energy as heat used to raise the temperature by ΔT degrees Kelvin of a mass M [kg] of steel, which has a specific heat Cp equal to 460 J*°K−1*kg−1.

From the angular speed of the grinding mass (cylinder) we obtain the peripheral speed [m/s], then the displacement L [m] over time T [s]. Therefore, the resistance work will be equal to tangential force, F:

$$F = \frac{E_h}{L} \qquad [N] \tag{15}$$

Following (Plescia and Tempesta 2017) the data obtained by applying the model can obtain the overall friction coefficients of the jar- cylinder system, both aver- aged for the entire time, and instant by instant. Naturally, the friction coefficients found are those related to the cylinder rotation movement on the internal jar wall and the sliding on the jar's lower and upper surfaces. The rolling coefficient of friction is generally a very small fraction of the sliding coefficient and is calculated as f=b/r, where b is the thickness of the contact line between the grinding mass (cylinder) and the rolling surface and r is the radius. In a two-dimensional presentation, b is in fact a surface, S. (Plescia and Tempesta 2017) found that the area crushed during grinding equals the average width of the contact point, between 50 and 100 μm, by the "effective" height of the grinding body, that is the line that is effectively parallel to the jar's internal wall during grinding, which on average corresponds to 60% of the height of the grinding body. The value of S is around 1 E−7m2. They used the same surface to calculate the pressure imposed by the grinding masses. Vice versa, the sliding friction depends on the surface conditions and on the material between surfaces so is a function of the material being ground. A last consideration on friction coefficient measurement: according to the laws of Amonton, the resistive or friction force (R) is independent of the contact area and the extent of friction is proportional to the normal force (N). Consequently, for the same material and wear conditions, the R value will depend on N, which in turn will depend on the speed of the grinding masses.

The method described is not immune to errors. In our mill the cylinder is pushed by the force of inertia generated by the eccentric rotation of the jar.

Table 3 Mechanical parameters for Jar and grinding masses.

Jar diameter	0,06	m
Jar height	0,09	m
Jar volume	28,26	cm3
Jar weight	1090	g
cylinder diameter	3,5	cm
cylinder height	8,5	cm
cylinder volume	9,6	cm3
cylinder area	112,6	cm2
cylinder perimeter	24	cm
cylinder weight	1180	g

12. Fundamentals of screening process

Screening is the process of dividing a mineral into classes by size and sifting it through one or several screens. The material entering the screen is called the original material, and the screening product is called the size classes. The remaining material on the sieve is called the oversize product, and the sieve, which has fallen through the holes, is sub lattice. Class, used in the national economy as a ready-made commodity product, is called a variety. A series of sizes of sieve holes (from large to smaller) taken during screening is called a screening scale (classification), and a constant ratio of the sizes of the holes of adjacent sieves is a module of the screening scale. Distinguish the following types of screening: auxiliary, preparatory. Ancillary screening is used to separate the finished material from the original material, entering the crushing stage, or to control the size of the crushed product. The first kind of screening is called preliminary, and the second type is called the control one. Preliminary screening is used to separate the initial material by the size into classes before subsequent enrichment operations in order to increase their efficiency. Depending on the size of the raw material and the size of the holes of the screening surface of the screen, the following types of screening are distinguished:

Table 4. Classification by size class

Class size	**Size of initial material, mm**	**Size of the screening surface, mm**
Large	-1200+0	300-100
Average	-350+0	60-25
Fine	-75+0	25-6
Thin	-10+0	5-0.5
Extra thin	-1+0	Up to 0.05

12.1. Kinetics of screening process

Between the efficiency and timing of the screening there is a relationship. At the beginning of the screening, its efficiency increases rapidly, and then its growth slows down. This is explained by the fact that the speed of the screening process depends on the number of grains that must pass through the holes of the screen. In the first moments of time, the rumbling of the grain is basically easy and the screening process proceeds quickly. Over time, their number is getting smaller and smaller. Hardly rumbling grains require much more time for their sifting. Therefore, the increase in sieving efficiency slows down over time.

12.2. Processing of sieve analysis data

The reliability of the characteristics of the initial material by size depends primarily on the mass of the sample, the method of its selection, and the accuracy of the sieve analysis. All classes are weighed and their percentage output is determined. The losses in sieving do not exceed 1% of the mass of the initial sample, distributed proportionally to the output of each class. Losses over 1% are not allowed. Sample data are recorded in the **Table 5**.

Table 5.Sieve analysis

Class size, mm	Weight m,g	Yeild γ, %	Total yield, %	
			"+"	"-"
+0,2	36,55	30,42	30,42	100,00
-0,2+0,16	1,19	0,99	31,41	69,58
-0,16+0,05	5,87	4,89	36,30	68,59
-0,05+0	76,54	63,70	100,00	63,7
Initial	120,15	100	-	-

Graphically, the results of the sieve analysis are made in the form of a summary characteristic of the fineness "by plus" (total residue of the material in the sieves) or "by minus" (total sieving). On the ordinate axis, the total yield of classes in percent is plotted, and on the abscissa - the size of the sieve holes or the diameter of the grains in millimeters.

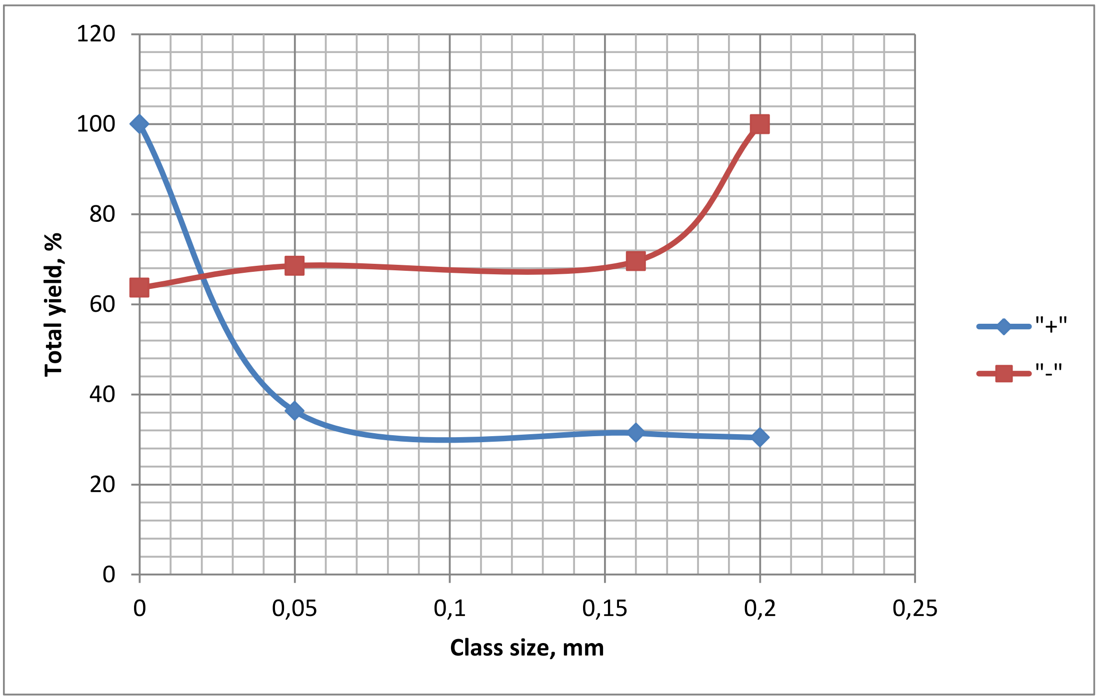


Figure 9. Results of the sieve analysis

The use of a linear scale for constructing such curves is convenient for a small number of classes and not a very sharp difference in the maximum and minimum grain sizes in the initial sample.

Photographic images of individual classes, obtained using a microscope are presented in **Fig.10**

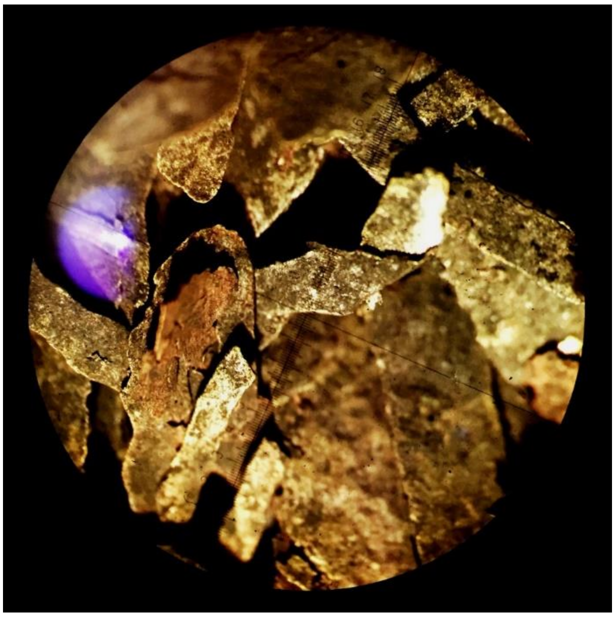


Fig.10 a The metal fraction of class +0.2 mm after screening

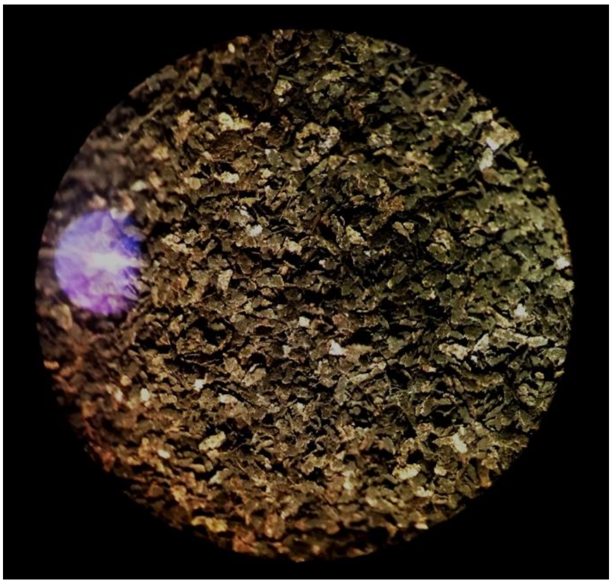


Fig. 10b The metal fraction of the class is 0.16-0.2 mm after screening

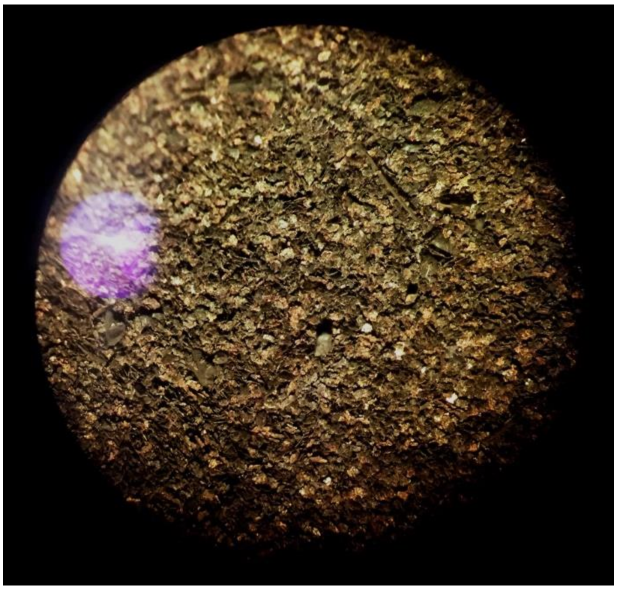


Fig.10c The metal fraction of the class 0,05-0,16 mm after screening

Fig. 10d Glass fibers and metals in the class -0.05 mm after screening

The material of class -0.05 (**Figure 10d**) after removal of metal fractions can be used as a composite filler for the production of secondary building materials. Non-metallic powder can be added as an additive to concrete, mortar, asphalt and other building materials, and greatly increases the efficiency of the use of the source material.

As a new modifier, it increases the performance of asphalt. Properties of modified asphalt with energy of non-metals powder significantly increases the same indicators as standard viscosity, penetration, softening point.

13. Proximate Analysis

Table 6 includes the proximate analysis of -0,05+0 sample that contains more residual than other samples

Table 6. Proximate Analysis

Proximate analysis	
Moisture	**0.20%**
Ash	**88.5%**
Volatile	**11.15%**
Fixed Carbon	**0.15%**

14. Magnetic separation

The magnetic separation was conducted manually by using neodymium magnet. This method only applicable to samples which were pulverized using the cylindrical-milling machine. The problem in magnetic separation was agglomeration of the particles. This agglomeration caused the magnet to also pull the nonmetal materials which agglomerate with the ferrous materials.

Table 7. Magnetic separation by classes

Class size, mm	Weight m,g	Ferrous materials, g	Nonmetal materials part, g
+0,2	36,55	4	32,55
-0,2+0,16	1,19	Less than 1	1,19
-0,16+0,05	5,87	1,87	4
-0,05+0	76,54	Impossible	76.54
Initial	120,15		

15. Protection of the environment

15.1.Human action on nature

Human’s activities always influenced nature. In modern conditions, the development of industries associated with recycling is one of the technical processes. Extraction of minerals cause on the Earth and thus changes the environment, interferes with the natural processes. Modern technology so powerful that nature in many cases gives way to it in the ability to change the landscape and relief of the surface. Small-waste storage pools in the square of several kilometers - all this is the result of human activity. In the process of drying, metallurgical and chemical processing, flue gases containing solid particles, sulfur oxides, carbon, and nitrogen are formed, moreover, they should be released into the atmosphere only after cleaning.

As a result of the burial of large volumes of waste, soil and groundwater are polluted, the surface drainage and the structure of the soil are changed, the erosion of water and wind is intensified, which in some cases causes climate change in the area of work.

A significant proportion of the state's water supplies are used for technical purposes. Huge volumes of water consumption put forward the problem of preserving the quality of water in reservoirs and rational use of water resources in a number of the most relevant. Increased water consumption leads to an increase in sewage and pollution of reservoirs. In addition, in factories as reagents are used xanthene’s, cyanides, petroleum products and other chemicals. The complexity and variability of wastewater of factories, their high toxicity, the predominant content of dissolved substances require the use of chemical, physic-chemical and biological methods of wastewater treatment.

Environmental protection is understood as a combination of state, administrative, legal, economic, political and social measures that are aimed at the rational use, reproduction and conservation of natural resources of the earth.

15.2.Harmful actions of preparatory processes on the environment

A characteristic feature of factories is the large saturation of equipment, whose work is accompanied by noise and vibration, emissions of gas and dust, contamination of adjacent lands and water sources.

Noise in the high level harmfully affects to the human body. The extent of this action depends on the characteristics of the noise and individual characteristics of the person. Noise acts not only on the hearing, but also on the nervous system, causes increase of blood pressure, weakening of attention, leads to decrease of labor productivity and increase of the level of traumatism.

Existing standards assume a maximum permissible sound level of 85 dB. The sound pressure level at frequencies 63, 125, 250, 500, 1000, 2000, 4000, 8000 Hz should not exceed 99, 92, 86, 83, 80, 78, 76, 74 dB, respectively. The vibrational speed is also normalized, which at frequencies 16, 32, 63, 250 Hz should correspond to 0.0015, 0.0022, 0.0027, 0.0035 m / s. With a vibration duration of no more than 20% of working time it is allowed to increase the vibration velocity by 1.5 times. (Smirnov et al. 2012)

The main types of pollutants emitted by the enrichment plants in the atmosphere are dust, sulfur dioxide, carbon monoxide, nitrogen, hydrogen sulfide.

The objects of emission of harmful substances are aspiration systems of crushers, robotic conveyors, boiler-houses and drying units, mineral deposits and products of enrichment, waste heaps.

The arrival of sulfur and nitrogen compounds in the atmosphere is the main cause of acid rain that damages buildings, monuments and metal structures, cause the destruction and destruction of forests, reduce the harvest of many crops, deteriorate the soil fertility that has an acid reaction, and the state of aquatic ecosystems.

Dust, which is in a damaged condition, adversely affects the health of workers and at certain concentrations may create explosive dust-air mixtures. Dusts that are emitted into the atmosphere pollute the air of adjacent settlements and also represent irreparable losses of minerals. Classification of dust and other harmful substances by degree of action on the human body are given in **Table**. **8**

Table 8. - Classification of dust and other harmful substances by degree of action on the human body

Dust	Extremely dangerous	Very Dangerous	Moderately dangerous	Light dangerous
Hazard class	1	2	3	4

The dust content in the work areas where workers are located must not exceed 3 or 4 classes of danger.

During crushing dust is forming in the places of loading and unloading of material, in screens, dry grinding and during overload of material from conveyor. In order to comply with the rules of dustiness, all these places have a suction devices for dusty air, which, after clearing dust is released into the atmosphere. Sometimes irrigation of material is used in crushers and screens.

Dust-air mixtures under certain conditions can be explosive. The dust explosion depends on their size (**Table 9**), the ash content, the content of volatile substances, the concentration in dust-gas mixtures, the presence of oxygen or other active gas in them, the content of volatile sulfur and moisture content of the mixture.

Table 9. - Classification of dust by volume

Type of dust	Large	Small	Fine	Superfine
Size, mm	100 - 500	10 – 100	0,1 - 10	Less than 0,1

The degree of dust explosion (**Table 10**) is characterized by a coefficient
Explosion:

$$Кв = 100(V^r + S_t^r) / [(NV)_c^r + W_t^r + A^r], \%,$$

where $Кв$ - coefficient of explosion,%; V^r - yield of volatile substances,%; $S^r{}_t$ - volatile sulfur content,%; $(NV)_c^r$ - non-volatile precipitate of the working mass of solid,%; W_t^r- hygroscopic moisture content of dust,%; A^r - ash content per working mass,%.

Dust explosion increases with increasing yield of volatile substances and decreases with increasing humidity and ash content.

The possibility of a blast of dust-air mixture is determined by its concentration: dust explosion hazard is 112 - 500 g / m3, at concentrations of more than 1500 g / m3 and less than 30 g / m3 carbon dust does not explode.

The smaller the size of the dust, than in the lower the concentration it may result in an explosion. The most explosive is dust with a grain size of 70-100 microns.

Table 10. - Dust explosion groups

Dust explosion class	Number of group	Кв
Safe on explosion	0	0 – 10
Not very explosive	I	10 – 25
Moderately explosive	II	25 – 35
Enhanced explosive	III	35 – 50
Especially explosive	IV	50 – 80

The action of dust on the human body is most affected by the respiratory system, especially if the size of the particles exceeds 10 - 15 microns. When inhaling this dust with the air particles are delayed in the upper respiratory tract and cause their irritation and even inflammation. The most harmful particles are the size of 1-5 microns, which, when hit in the lungs contribute to the consolidation of pulmonary tissue and the occurrence of pneumoconiosis. The most harmful in this respect is quartz dust with a SiO2 content of more than 10%. A person who works for 10 years or more in a coal dust environment can get one of the varieties of pneumoconiosis. Acutely-negative action of dust to eyes and skin: thin dust contributes to inflammation of the cornea of the eye, and large dust can cause mechanical damage to the eyes.

15.3. Control measures against harmful processes

Neutralization of noise at concentrating factories is carried out by measures of general and individual character. General measures include the replacement of machines or individual nodes with a high noise level on silent; sound insulation of noise sources; remote control of the work of machines; use of rubber for lining and for gaskets. Individual events include using stubs and headphones when working with high noise machines.

The appearance of vibrations is prevented by installing machines that cause vibration, on special foundations with vibration isolation and on foundations not related to the structure of the factory. For vibration isolation use gaskets of rubber, felt, cork, wood, as well as springs. In factories for dust control, the following measures are taken:

- reduction of dust formation in processing processes due to: reduction of overload points during transportation and height of fall, application of methods of crushing and scoring, which do not contribute to significant dust formation;

- protection of dust formation sites and the suction of air from these places;
- application of closed gutters and conveyors during transportation of minerals;
- Irrigation of dusty places or steam treatment;
- reduction of air velocity in places of dust formation;
- preliminary degradation of minerals;
- arrangement of local exhaust and general ventilation.

Protective shredders in most cases foresee the exhaustion of polluted air during loading of the raw material and unloading of the crushed product. Protective tools of the rumble assume the exhaustion of polluted air from several points: from above the suction of polluted air is carried out at the point of loading the material on the screen, from below the suction of polluted air is carried out from the pallet, and also the suction of polluted air is carried out in the place of falling material from the crank on the conveyor.

Places of loading and unloading of bunkers, where high is allocated the amount of dust, must be equipped with protective means with exhaust dust. Screws, feeders, mixers and other devices with tight coatings do not require additional protective equipment, but when loading and unloading the material, it is necessary to foresee the exhaust of the dust-air mixture.

The protection of the dressing and transport equipment is very important for the successful fight against dust formation in the industrial premises of the concentrating factories. Sealing of protective devices due to the use of rubber and felt pads in the places of joints of their individual parts guarantees 80 - 90% elimination of the possibility of penetration of dust outside the protective devices.

16. Conclusion and Prospective

The key success parameters for the WEEE are based include environmental, social, and ethical benefits. However, there still exist several forthcoming challenges and opportunities for their management. First, the huge amount of generation has brought alarming indication for limited natural resources, which could have a directly/indirectly effect on recycling sector in upcoming future. Although, the existing rules and regulation will mitigate the pollution level but not able to solve complete problem of the environmental impacts of informal recycling, e-waste regulations should be continually concerned and the alliance of e-waste recycling can be established at special regional level.

Similarly, in developed countries, e-waste is subjected to recover some materials of value and to be safely rid of the contain metals. Whereas, in developing countries, e-waste recovery is principally focused on few metals of value with primitive process. (Awasthi, Zeng, and Li 2016)

Concerning all the results and the discussions, it can be summarized that pyrolysis process of printed circuit boards can become a feasible method for energy production and material recovery.

WEEE contains a number of economically relevant metals like Cu and precious metals, and also critical metals such as Ga, Ge and a number of REE. However, the end-of-life recycling rates from WEEE are low and sometimes even less than one percent. Pyrolysis of WEEE-fractions offers the opportunity to separate valuable metals from plastic matrixes and to produce liquid and gaseous fuels at the same time. The process could represent a main part in a more comprehensive process chain to separate organic matter on the one hand and different fractions enriched with metals on the other hand. (Hense et al. 2015)

Firstly, the metals which can be recovered after the pyrolysis process have relatively high quantity in precious metals such as gold, palladium, silver and platinum and high quantity in copper and other conventional metals. Furthermore, the quality of the recovered metal should be high due to the lack of oxygen in the process which usually contributes to formation of metal oxides. Since the oxygen content of this fraction is relatively low, the produced gas and liquid fuel should expect to have high energy content.

Printed circuit boards are highly complex materials and the kinetic parameters can only be calculated through iso-conventional methods. The pyrolysis kinetic parameters founded through KAS and Coats - Redfern methods describes well the reactions occurs on this process as one apparent reaction either on one or on two stages (1st reaction and 2nd reaction). On the other hand, all these parameters are averages and should be further investigated for scaling up conditions. Finally, by summarizing the whole research, the pyrolysis of printed circuit boards can be a valuable option not only for materials and energy recovery but also as better waste management technique.(Stockholm 2014)

The process of pyrolysis can become part of the technological chain to separate critical metals and generate low-yielding halogen fuel for energy use. The products of this thermochemical process are a mixture of some metals, a mixture of ferrous metals that can be processed in various processes, as well as gas and oil for energy use, for example in the combined production of heat and electricity. The material was treated for 50 minutes at a temperature of 600 ° C to 700 ° C approximately 25% of the mass loses of material. However, the preliminary thermal treatment significantly improved the separation of fragments, including copper and other metals contained in the boards, during pyrolysis a certain amount of organic matter was removed, and the rest became more fragile. The experiment showed that the ball mill does not provide a high degree of flattening of metal particles, so a large part of them cannot be removed by screening. A higher level of flattening can be obtained by more intensively interacting the elements of the grinding medium. This is possible with the application of the cylindrical-vibro mill. Therefore, in the next experiment, the PCB were cut to size 3*4 mm and been processed in cylindrical vibration mill. This treatment allowed, due to more flattening of metal particles, to remove them by 90-96% with screening. The principle possibility of extracting a metal fraction from printed circuit boards is established in **Figure 11**.

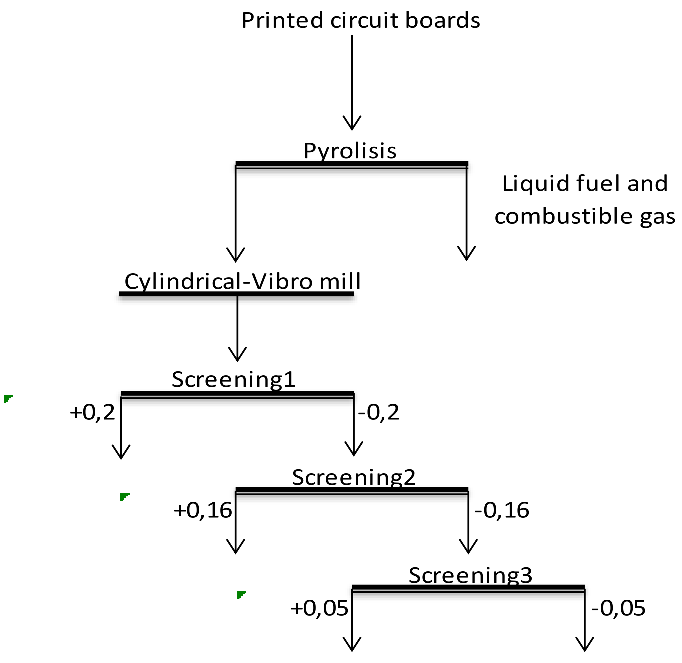


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Figure 11. Flow chart of technological process

The technology studied includes pyrolysis for 50 minutes at a temperature of 600 ° C to 700 ° C, which transmits approximately 25% of the mass of the source material into the gas and liquid phase, the treatment of the paralyzed product in vibration shredders with the production of open metal fragments, which are removed 90-96% by screening.

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РЕЦЕНЗІЯ

на магістерську роботу «Стійка технологія переробки відходів електричного та електронного обладнання» студента групи - 184М-16-3мММФ Національного гірничого університету Лисенко Данила Олександровича

Магістерська кваліфікаційна робота Лисенко Д.О., яку подано на рецензію, виконана відповідно до вимог, у повному обсязі та у встановлений термін. Тема магістерської роботи, обрана автором, заслуговує на схвалення, а її актуальність не викликає сумніву. Робота складається з наступних розділів: вступ, аналіз переробки відходів електричного та електронного обладнання в Україні, постановка задачі, розробка моделей та засобів інноваційних технологій в даній галузі та реалізації, висновки, додатки. Актуальність розробки викликана новими вимогами щодо поводження із застарілим сміттям, оскільки з 1 січня 2018 року Україна зобов'язалася сортувати все сміття за видами матеріалів. Про це йдеться у статті 32 Закону України «Про відходи», до якої був доданий відповідний пункт ще у 2012 році. Цей пункт відповідає двом Директивам ЄС – 1999/31/ЕС та 2008/98/ЕС, які врегульовують поводження зі сміттям у країнах Європи, надають чітку послідовність дій, які необхідно виконувати із відходами, класифікують сміття, ставлять стратегічну мету скоротити кількість відходів, які вивозять на полігони.

Автор опрацював певний обсяг закордонної та вітчизняної наукової літератури, що надало змогу розкрити актуальність та обґрунтувати необхідність впровадження такої інновації для Україна.

В роботі розроблено принципову новітню схему переробки друкованих електронних плат та здійснено її перевірку у лабораторних умовах. Але, до недоліку даної роботи слід віднести проведення експериментів в лабораторних пілотних установках, що не відповідають масштабам промислової переробки. Проте вказаний недолік не впливає на позитивне враження від роботи. Магістерська кваліфікаційна робота «Стійка технологія переробки відходів електричного та електронного обладнання» є самостійною, цілісною та завершеною працею. Робота виконана у відповідності із завданням з дотриманням чинних вимог та заслуговує на оцінку «відмінно», а її автор – присвоєння кваліфікації «магістра» за спеціальністю «Збагачення корисних копалин».

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