

***UNIVNET* 2022**

Innovative Machines, Technologies and Materials
in Circular Economy Environment

PROCEEDINGS



September 26 - 28, 2022
Hotel Kaskada Brno, Czech Republic

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TABLE OF CONTENTS

Research Into the Possibilities of Recovering Headlights from End-of-life Cars	8
M. Badida, T. Dzuro, M. Moravec, L. Sobotová, M. Piňosová	
Development of Sound Insulating Materials and Products on the Basis of Waste from the Automotive Industry	13
M. Badida, M. Moravec, T. Dzuro, M. Piňosová, L. Sobotová	
Experimental research of material properties in Additive Manufacturing.....	20
J. Beniak, P. Križan, Ľ. Šooš, M. Matúš	
Design of a recycling device for the processing of old car bodies	24
V. Čačko, I. Čáčková, Ľ. Šooš	
Processing of spent automotive lithium batteries.....	31
T. Havlik, J. Klimko	
Environmental assessment of the particle boards with content rubber waste from the automotive industry	38
H. Hybská, M. Lobotková, D. Samešová, I. Čabalová	
The evaluation of pellet production with an admixture of FFP2 masks formed by a small pellet press	43
J. Jandačka, N. Č. Kantová, M. Holubčík, A. Čaja	
Lithium slag leach solution refining by hydroxide precipitation.....	47
J. Klimko, T. Havlik, D. Oráč, J. Pirošková, Z. Takáčová, V. Marcinov	
Production conditions for 3D printing of recycled material based waste HDPE.....	52
P. Križan, J. Bábics, J. Beniak, M. Matúš	
Mechanical and Physical Properties of New Particleboards Containing Recycled Plastics from Automobiles.....	58
V. Mancel, J. Krilek, I. Čabalová, R. Réh, M. Osvaldová	
Theoretical and practical aspects of the application of semiconductor ferroelectrics as energy-generating and energy-saving elements	62
A. Molnar, V. Gerasimov, D. Gal, M. Badida	
Hydrometallurgical treatment of slags from steel industry	68
D. Orac, J. Piroškova, V. Marcinov, J. Klimko, T. Vindt, P. Liptai	
An innovative approach to cost calculation using machine hour rates at product of circular economy principles	74
M. Osvaldová, M. Potkány, J. Krilek	
Pyrolytic Processing of Waste from the Automotive Industry	79
M. Patsch, P. Pilát	

Information Platform for the Recycling Technologies Innovation – SmartWaste	84
M. Pokusová, L. Šooš	
Financial Support of Progressive Technologies and Innovations in the field of Waste Management in Automotive Industry	88
R. Sivak, K. Belanova	
Recycling and New Joining Technologies in Automotive	93
L. Sobotova, M. Badida, M. Badidova	
Bicycle transport – an original solution for building cycle paths also on unused railway tracks	99
L. Šooš, V. Čačko, I. Čačková, O. Chlebo, R. Szabo	
Development and design of a line for the decomposition of waste laminated glass ...	103
L. Šooš, M. Pokusová, V. Čačko, I. Čačková, J. Babics	
Application of PM Mitigation Measures on Construction Sites in Novi Sad during 2022.....	109
M. Šunjević, B. Obrovski, V. Rajs, M. Šunjević, M. V. Miloradov	

Research Into the Possibilities of Recovering Headlights from End-of-life Cars

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Abstract — The paper deals with the analysis of the possibility of a recovery of the reflectors (luminaires) from the cars that have ended their life. The lamps are components that have not been addressed yet in terms of a recovery of material used to produce them. The authors present their own research work related to the dismantling of car lights. There are two approaches to the dismantling: a reverse assembly and a destructive dismantling. The aim of both approaches is to get the most amount of a homogeneous plastic and of other types of the materials used. The paper includes the results of the analysis of components, materials, time trials dismantling headlamps, as well as the technical and economic analysis of the different alternatives proposed dismantling. There are 3D simulations of the proposed workplaces presented.

I. INTRODUCTION

The automotive industry is today a sector that significantly influences and at the same time develops other sectors of the national economy such as engineering, metallurgical, electrical, chemical or construction industries [10]. Over the past decade, the car production has been steadily rising, with the SR not relegating. There are about a billion cars in the world, of which about 200 million cars drive on the European roads and more than 2 million cars drive in the Slovak Republic.

The Slovak car makers produced a record number of cars in 2016, while PSA Group Slovakia produced 315 050 vehicles, KIA Motors produced 339 500 vehicles, and Volkswagen produced 345 540 vehicles. In total 1 000 900 cars were produced [1]. In 2014, there was around 80 million cars produced worldwide, with the average passenger car weight of 1,25 tons representing 100 million tons of the clean processed material [11, 14]. It is clear that, in addition to „pure material”, the car production also generates waste, which producers have to take care of and at the same time after the end of its life cycle, the car itself becomes the hazardous waste that needs to be taken care of [2]. The basic legal regulation is the Directive of the European Parliament and of the Council no. 2000/53 / EC of 18 September 2000 on end-of-life vehicles (ELV) [3]. This Directive establishes the measures whose the primary objective is to prevent the generation of waste from vehicles as well as reuse, recycling and other forms of recovery of durable vehicles and their components in order to reduce the amount of waste disposed of and to improve the protection of the environment by engaging all economic operators, involved in the life cycle of vehicles, but especially those involved in the after-sales process of

vehicles [12]. The Directive includes, inter alia, the limits on the reuse and recovery of components [3].

The authors of the paper focused on the issue of the automobile reflectors dismantling over their lifetime [2, 4, 5]. The reflector itself consists of several materials such as: plats, glass, metals, rubber, and so on. Reflector structures start to dominate over plastic [7, 8, 9]. Of the total amount of plastics in the automobile (approximately 143,4 kg / car [2, 15]), the reflectors (lighting) represent about 5,6 % [2] of the total amount of used plastics.

II. THE ANALYSIS OF COMPONENTS AND MATERIAL COMPOSITION OF VEHICLE REFLECTORS

For the purpose of the experimental dismantling, the authors chose the Skoda Octavia of the 2nd generation car. The experimental disassembly and decomposition of the Skoda Octavia automobile lights was done for the following purposes [2]:

- the analysis of components of individual types of luminaires and their material composition,
- the detection of the mass proportions of the individual materials used in the luminaires,
- to assess the possibilities and difficulty of disassembling the lights (analysis of joints, use of tools and tools, etc.),
- to design an optimal dismantling procedure to evaluate the effectiveness of the entire dismantling process.

The variety of types of car lights are very large Table I.

TABLE I. TYPES OF HEADLAMPS

Front lights	Rear group lights	Front fog lights	Side direction lights
			
			
			Branding light
			
			

For the purpose of dismantling and decomposition, the following external lights were selected from the Skoda Octavia of the 2nd generation (Figure 1.):

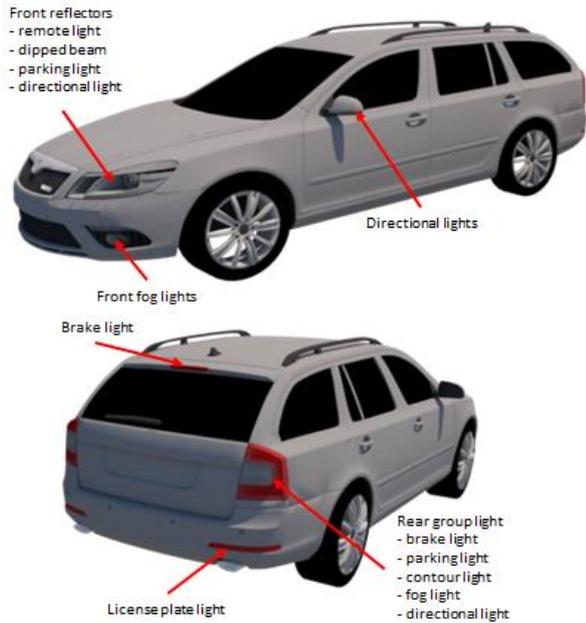


Figure 1. Exterior view of car and lights

The authors of the post performed consistent decomposition of the selected lighting an example is the decomposition of the front light Skoda Octavia of the 2nd generation (Figure 2.).



Figure 2. Decomposition of the front light of the Skoda Octavia of the 2nd generation

Table II. below includes the material and weight composition of the Skoda Octavia of the 2nd generation car headlamp.

TABLE II. MATERIAL AND MASS COMPOSITION OF THE HEADLAMP COMPONENTS

No.	Component	Material	Labeling of material	Weight [g]
1.	Front cover	polycarbonate	PC	565
2.	Back cover	polypropylene	PP	1025
3.	Frame	high temperature polycarbonate	PC-HT	560
4.	Reflector	unsteamed polystyrene with glass fibers	UP-GF	125
5.	Electrocomponents and motorbike	copper, rubber, plastic	-	130
6.	Frame of lens	polybutylen terephthalate	PBT	80
7.	Lens	glass	G	145
8.	Body of the lens	Fe metal	Fe	210
9.	Plastic handles	Plastic mix	-	40
10.	Screws	Fe metal	-	10
Total				2890

Analogously, there was the decomposition of other lamps carried out [2]. Based on this analysis, the weight of the materials in the lights of one Skoda Octavia of 2nd generation was determined (Table III.).

TABLE III. MASS WEIGHT OF MATERIALS IN THE LIGHTS OF SKODA OCTAVIA OF 2ND GENERATION CAR

No.	Material	Labeling of material	Weight [kg]
1.	Polypropylene	PP	1,025
2.	Polypropylene + 20 % filled with talc	PP+TD 20	0,105
3.	Polycarbonate	PC	0,855
4.	Acrylonitrile Butadiene Styrene - Polycarbonate	ABS-PC	0,480
5.	Acrylonitrile Butadiene Styrene - Polycarbonate	ABS-PC	0,480
6.	Acrylonitrile Butadiene Styrene	ABS	0,016
7.	Acrylonitrile Styrene Acrylate	ASA	0,025
8.	Polymethyl methacrylate	PMMA	0,295
9.	Polybutylen terephthalate	PBT	0,08
10.	Unsaturated polyester with glass fibers	UP-GF	0,125
11.	Polyamide with fiberglass	PA66-GT14	0,025
12.	Polyamide with fiberglass	PA66-GF30	0,002
13.	Mixed plastic		0,04
14.	Glass		0,145
15.	Electrocomponents		0,13
16.	Gum		0,028
17.	Ferrous meta		0,022
Total			4,008
Total weight of individual materials			8,016

III. THE TIME STUDY OF THE AUTOMOBILE REFLECTORS REMOVAL

The following part of the paper deals with the time studies, which include the time consumption of two options of the automobile reflectors dismantling:

- the time study of the automobile reflectors dismantling (a reversed assembly),
- the time study of the automobile reflectors dismantling (by so-called destructive dismantling).

The example of the time study of the front reflector by the reversed assembly is shown in Table IV.

TABLE IV. THE TIMING OF THE REVERSIBLE DISASSEMBLY OF THE FRONT REFLECTOR

Operation:	Remova of the front light	
	Tool	Time (min:sec)
Remova the outer cover	manually	00:12,2
Removal of seals	manually	00:10,5
Breaking the body of light	screwdriver	00:17,5
Light bulb	manually	00:15,5
Separation of the metal plate and small parts	manually, screwdriver	00:28,6
Removal of cables	manually	01:24,6
Dismantling the motorcycle	manually, screwdriver	00:24,5
Σ		02:24,4
Total time (2 pcs)		04:48,8
Total time (decadic) min.		4,82

The example of the time study of the destructive disassembly of the front reflector is given in Table V.

TABLE V. THE TIMING OF THE DESTRUCTIVE DISASSEMBLY OF THE FRONT REFLECTOR

Operation	Removal front reflector - destructive	
	Tool	Time (min:sec)
Light bulb fitting as needed	manually	00:12,2
Fragmentation by dividing lines	breaker	00:10,5
Split front cover	manually	00:11,3
Fold the rear cover	manually	00:12,4
Frame separation	clamp, screwdriver	00:07,3
Removal of the reflector	manually	00:08,3

Unscrew the motorbike	manually, screwdriver	00:11,2
Removal of the cables	tool 3	00:10,0
Removal of the Body of Lenses and Lenses	tool 1	00:05,3
Removal of the handles	pliers	00:04,7
Friction of screws	tool 2	00:10,0
Σ		01:43,2
Total time (2 pcs)		03:26,4
Total time (decadic) min		3,44

On the basis of the time analyzes [4, 5] that have been carried out, the time required for the reserve installation and dismantling of the car lights (front reflector, rear group light, fog light, side direction light and state license plate light) per a vehicle was determined below (Table VI).

TABLE VI. THE REVERSE ASSEMBLY AND DISASSEMBLY COMPARISON

	Reverse assembly	Disruptive dismantling
Front reflectors (2 pcs)	4,82 min./ vehicle	3,44 min./ vehicle
Rear group lights (2 pcs)	6,47 min./ vehicle	4,56 min./ vehicle
Fog Lights (2 pcs)	4,02 min./ vehicle	3,58 min./ vehicle
Side direction lights (2 pcs)	4,84 min./ vehicle	2,24 min./ vehicle
Shields (2 pcs)	2,48 min./ vehicle	2,48 min./ vehicle
Crush		2,68 min./ vehicle
Total	22,63 min./ vehicle	18,98 min./ vehicle

The material and mass composition of the lamps (only external) of the analyzed car are shown in Table VII.

TABLE VII. THE MATERIAL AND MASS COMPOSITION OF THE LAMPS

Skoda Octavia of the 2 nd generation vehicle [1 PSC]	Material	Weight [kg]	Representation [%]
Car Lighting components (exterior)	Plastics	7,366	91,9
	Glass	0,29	3,6
	Electro	0,26	3,2
	Gum	0,056	0,7
	Fe metals	0,044	0,6
	Total	8,016	100

The resulting calculations of the total amount of the waste generated from the automobile lamps were based on the statistical data the includes the number of processed vehicles in Slovakia (Table VIII. - Source: Recycling Fund). For the calculations, we considered data for 2015. We have not been able to get any new data.

TABLE VIII. THE VEHICLE PROCESSING STATISTICS FOR 2004 TO 2015 [2]

Year	2004	2005	2006	2007	2008	2009
Pieces	723	3929	19 449	28 413	37 209	72 508

Year	2010	2011	2012	2013	2014	2015
Pieces	37 889	34 915	32 795	34 408	28 052	26 642

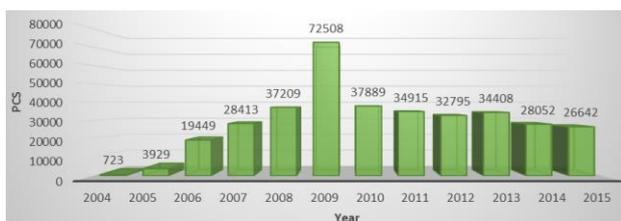


Figure 3. Vehicle processing developments for 2004 to 2015

Based on information about the type of material, the available quantity of material and the available purchase

prices of the material obtained, it was possible to complete the data in Table IX.

TABLE IX. THE AMOUNT OF WASTE OF THE LANTERNS AND REVENUE FROM SALE PROCESSING OF 26 642 PCS OLD VEHICLES (2015) [4]

Material	Weight [kg]	Representation [%]	Pieces [kg/year]	Purchase price [€/kg]	Revenue from the sale [€/year]
Plastics	7,366	91,9	196 245	0,1 - 0,5	196 24,5 - 98 122,5
Glass	0,29	3,6	7 726,18	-	-
Electro	0,26	3,2	6 926,92	0,53 - 0,87	3 671,27 - 6 026,42
Gum	0,056	0,7	1 491,95	-	-
Fe metals	0,044	0,6	1 172,25	0,10 - 0,15	117,23 - 175,84
Total	8,016	100	213 562,30	-	23 413 - 104 324,76

Copper cables - the price of 1 kg

Cu content from 20 % (Ø below 1 mm)0,1 - 0,3 €

Cu content 21 % - 30 % (Ø below 1 mm)0,4 - 1,0 €

Cu content from 31 % - 40% (Ø below 1mm) 1,10 - 1,30 €

Ø 0,53 - 0,87 €

The largest percentage of the materials in the automobile luminaire are plastics, up to about 91,9 % of the weight of the lamp. There are very diverse types of plastics [4, 6, 8, 9]. It should also be borne in mind that plastics used to produce automobile reflectors account for only about 5,6 % of the mass of the plastics used in the automobile (Table X.) of the total material.

TABLE X. THE PLASTICS IN AN AUTOMOBILE

Parts	Main types of plastics	Weight in average car [kg]
Bumpers	PP	10,4
Seats	PUR, PP, PA, PVC, ABS	18,4
Interior of a car	PP, SMA, ABS, PC, PVC, PUR	21,3
Fuel system	PE, POM, PA	8,6
Bodywork (including body panels)	PP, PPE, UP	10,8
Components under the hood	PA, PP, PBT	13,8
Interior trim	PP, ABS, POM, PVC, PUR	31
Electrical and electronic components	PP, PVC, PA, PBT, PE	10,3
External cladding	ABS, PA, PP, PBT, ASA	5,1
lighting	PP, PC, ABS, PMMA, UP	5,6
Upholstery	PUR, PP, PVC	6,8
Other reservoirs	PP, PE, PA	1,5
Total		143,4

The composition of the car is shown in Table XI.

TABLE XI. THE MATERIAL COMPOSITION OF CARS

Materials used in the automotive industry	
Steel	41 %
Unalloyed steel	18 %
Aluminium	8 %
Alloy	6,4 %
Zinc, copper, magnesium	2 %
Gum	5,6 %
Plastics	9,3 %
Other materials	9,7 %

A high percentage of use of plastic materials (or components) is also expected in the future due to the growing demand from consumers, therefore the both, a weight reduction and, low consumption vice versa is important [4, 5].

IV. THE DESIGN OF A LAYOUT SOLUTION FOR THE DISASSEMBLY OF REFLECTORS

The authors of the paper suggest two options of the reflectors dismantling from vehicles after their lifetime:

- reverse mounting (in 2D - view Figure 4., in 3D - view Figure 5.),
- destructive dismantling (in 2D - view Figure 6., in 3D - view Figure 7.).

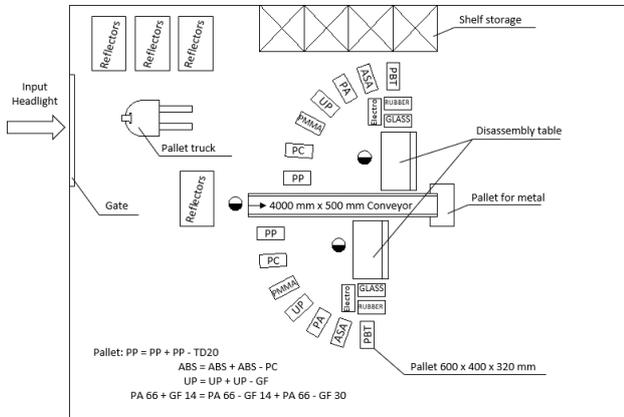


Figure 4. A workplace layout (2D - view) of the reverse installation

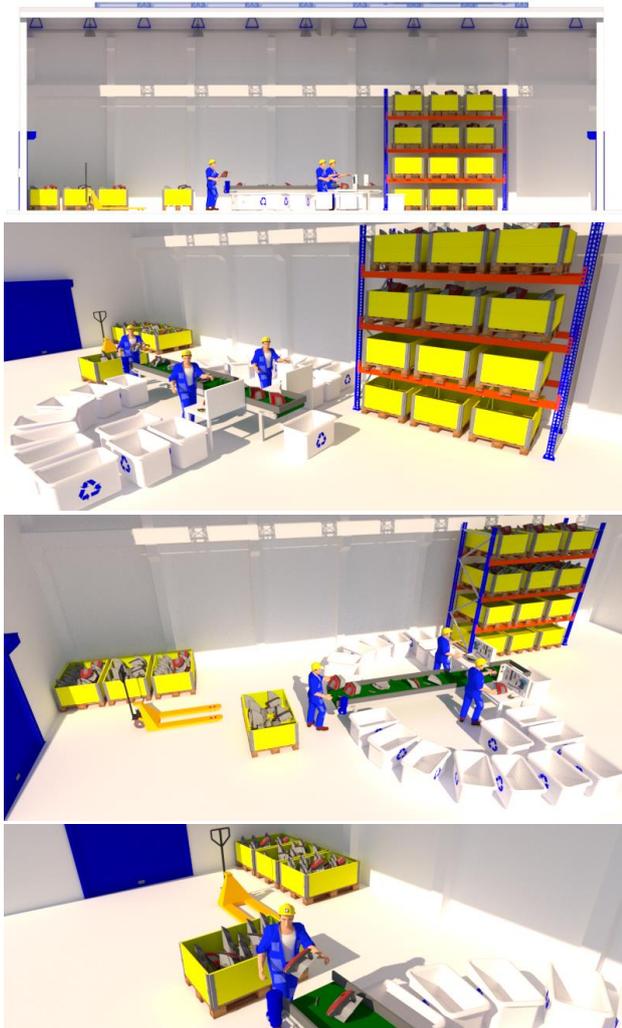


Figure 5. A workplace layout (3D - view) of the reverse installation

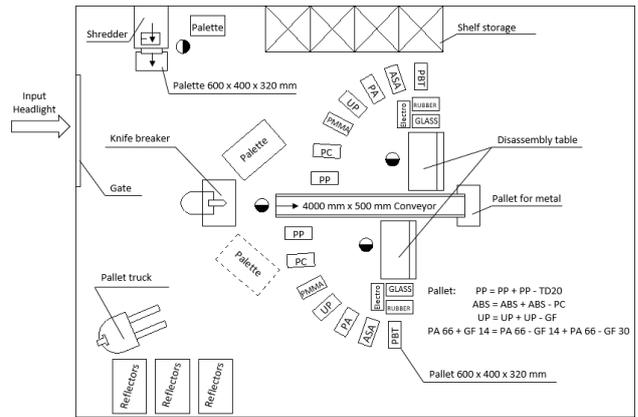


Figure 6. A dispositional layout (2D - view) of the destructive dismantling

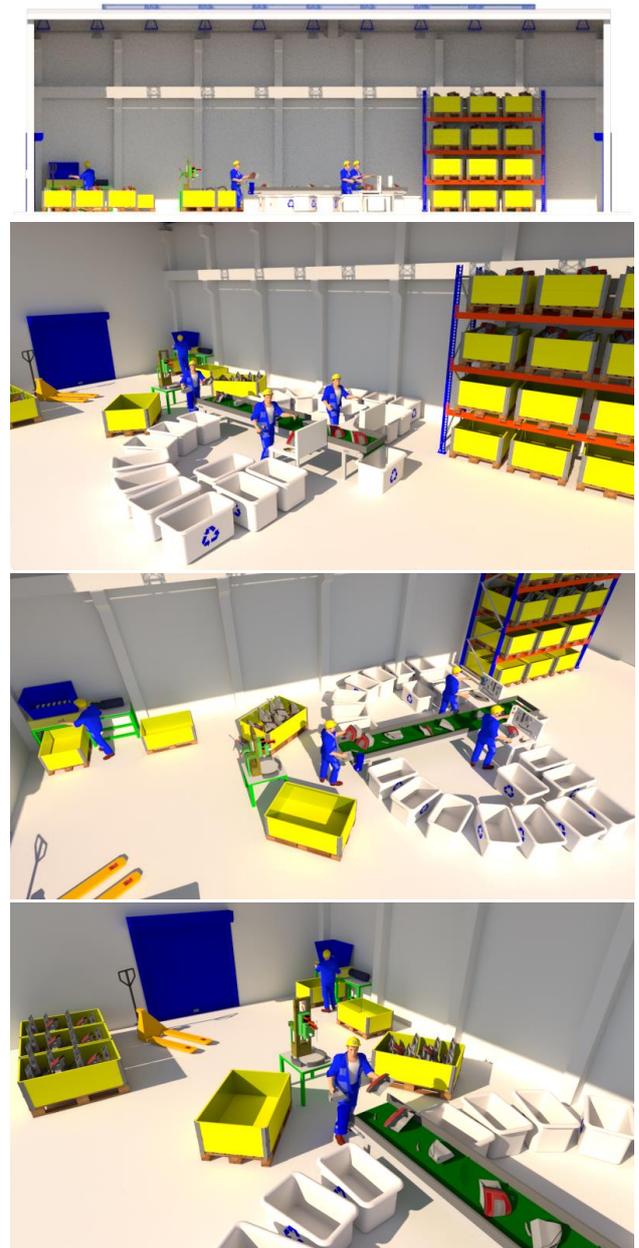


Figure 7. A dispositional layout (3D - view) of the destructive dismantling

The goal of both solutions for light dismantling is to obtain the most efficient individual types of plastics and other types of materials that can be subsequently evaluated. A detailed design of the workplaces is mentioned in the report [5].

V. CONCLUSION

The research team, in solving the partial role of the project, „Integrated research platform for the recovery of individual waste streams, especially from the automotive industry”, focused on the component of the automobile - a reflector (exterior car lights). The lamps from cars are, at present, the waste that can be labeled problematic. Recycling companies and services dispose of this waste in a variety of ways (landfill, incinerator, etc.). The authors solved the problem of a valorization of automobile luminaires in two ways: by retrofitting and destructive dismantling in the study [2, 4, 6] capacitive conversions related to the dismantling process were performed. It came to the following conclusions:

According to the preliminary experience of dismantling of different types of reflectors by the method of reversing assembly, it is reasonable to establish in the conditions of the Slovak Republic 4 dislocated workplaces in the recycling centers of cars in two-shift operation of 2 + 2 workers.

According to the time studies of destructive dismantling of individual species, it is rational, under the conditions of the Slovak Republic, to establish 3 dislocated workplaces in the recycling centers of cars in a one-shift operation with 3 + (1) workers (temporary worker). The workshop could be additionally equipped with a plastic shredder and the plastic shredder, which reduces the transport costs and reaches the higher purchase unit price of the plastic crush.

Receiving workstations from disassembled reflectors is assumed as follows:

- **Reception from one vehicle:** 3,04 EUR / vehicle (reversed assembly).
- **Intake from one vehicle (separate pulp):** 3,12 EUR / vehicle (destructive dismantling)
- **Capacity 4 work places:** 7 360 Nh / year (Reverse Mounting).
- **Capacity of workplace 3 + (1):** 6 440 Nh / year (destructive dismantling).
- **Required standard vehicle hours:** 22,63 min/vehicle = 0,3772 h/vehicle (installation).
- **The necessary man-hours for the vehicle:** 18,98 min / 0,3162 h = vehicle / vehicle (d. Rep.).
- **Number of vehicles dismantled:** 19,512 vehicles / year (reversed assembly).
- **Number of dismantled vehicles:** 20,363 vehicles / year (destructive dismantling).

The payback period of the reversing assembly is assumed to be 3 years, and the recovery time of the dismantling plant is assumed to be 2,63 years. In connection with the concept of a closed loop economy, according to Duflo et al [13]. Still, it is not clear in academic and industrial circles whether systematic dismantling of the product in the context of used products is viable to its achievement and it seems that the contradiction of economic and environmental priorities

results in a downward trend in non-destructive dismantling as a target scenario for in-use products. This is also the opinion of the authors.

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Development of Sound Insulating Materials and Products on the Basis of Waste from the Automotive Industry

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Abstract— The research was focused on the selection of suitable materials from the components in the end-of-life vehicles. For the further detailed research, the research of sound insulating materials were selected materials such as various fractions of recycled waste tires and various fractions of textile materials from the automotive industry. The basic objective of the research is the idea to use bulk materials, that is, those specified fraction types of the selected materials for use as sound insulating products. The study was focused on the comparison of the same fractions of materials in compact form and in bulk form. For the purpose of the research of bulk materials, we have developed and produced special testing cartridges and special test cartridge filling equipment. Attention was given to a wide range of scientific experiments which were analysed and evaluated. The research was also focused on the specific products characterized by good sound insulating properties.

I. INTRODUCTION

The acoustic properties of materials are playing an increasingly important role today. This is the reason why a number of new acoustically suitable materials with different sound-insulating properties appear and develop almost every day. Recycled components from automobiles over their lifetime are often used to develop such materials. These materials are used for passive sound control in the interior design of automobiles, factories, workshops, residential buildings, noise barriers, etc., to prevent unwanted noise. The determination of acoustic properties is therefore extremely important [1–3].

End-of-life vehicles represent a range of components (wastes) of different material composition that should be further recovered. Attention is focused mainly on problematic materials such as tires, car seats, carpets, upholstery, airbags, glass, etc., and on the development of technologies and techniques for waste recovery for acoustic, thermal insulation and other products [3].

Peng C., et al. [4] and Tan K.N. [5] described using an impedance tube with two microphones. The impedance tube was used by Suhanek M., et al. in his experimental studies [6], Pierre J., et al. [7] Koruk H. [8], Tan W.H., et al. [9]. Neto B.N., et al. [10] all carried out experimental analysis of the variation in the sound absorption coefficient for measurements on the impedance tube.

Xinwu X., et al. studied the possibilities of using recycled natural or synthetic polymers from waste rubber

in the production of acoustic materials for their good acoustic properties [11]. Bhingare N.H., et al. [12] described the characteristics of natural fibres and waste (recycled) material. Akiwate D., et al. [13] examined the acoustic properties of porous materials produced by 3D printing. Labašová E., Duriša R. [14] evaluated the sound absorption coefficient for various single-layer and two-layer materials (cork, felt, polyethylene). Gumanová V., et al. [15] and Moravec M., et al. [16,17] also devoted themselves to similar research.

This article focuses on analyzing the results of measurements of acoustic properties of bulk recycled materials and comparing them with compact materials of the same material composition. The aim of the article is to assess the suitability of recycled bulk materials for sound-insulating applications and products. There is great potential for the creation of suitable materials usable in sound-insulating applications in the automotive industry (production waste, or end of life vehicle waste).

II. MATERIAL AND METHODS

Within the research of acoustic and heat insulating properties of materials from end-of-life vehicles, we have studied the issue of recycling of the selected types of materials from cars that are suitable and available for re-use in practice. The selection of materials was conditional on the possibilities and the laboratory equipment available in the experimental workplace, as well as on its use in practice as the insulating and sound-absorbing material.

Based on the material's physical and mechanical properties, we have selected the following materials for the experiments:

- tires and rubber from cars and rubber granules recycled from them,
- textiles from the interior of cars and textile material recycled from them.

Tires belong among consumables within the operation and maintenance of vehicles. Their consumption grows each year together with the increasing number of vehicles at home and worldwide. In terms of safety and running characteristics of tires, this number grows even more since car owners are obliged to use special tires according to the seasons in our latitudes, which increases the number of used tires. Technical textiles in a car fulfill the intensive needs of the automotive industry and their life highly exceeds the period determined by the car itself. It is used

in a car, on average, for 10 years. When we say technological waste, we mean the original, production of textile waste.

A. Measurement Equipment

For the measurement of selected types of recycled materials, the BSWA SW433 impedance tube was used in a configuration with two microphones; it had a length of 500 mm, an internal diameter of 60 mm, and a frequency range from 100–2500 Hz (Figure 1) [6,13,18].

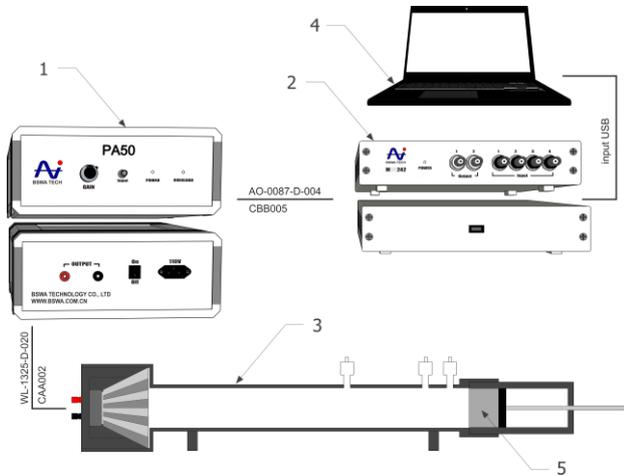


Figure 1. Diagram for measuring equipment. Explanatory note: 1–metering power amplifier PA50 (50 W) for powering the speaker in the impedance tube; 2–MC3242 data collection analyzer with 4 input ICP and 2 output channels (0~20 kHz); 3–impedance tube BSWA SW433; 4–PC with VA-Lab4 software; 5–test sample.

Five repeated measurements were carried out for each sample and the average values were evaluated. The other components of the measurement technique were a 4-channel MC3242 data collection analyzer (0~20 kHz), a PA50 (50 W) metering power amplifier for powering the speaker in the impedance tube, a PC with VA-Lab4 software, the necessary cabling, an impedance tube (100 Hz–6.4 kHz; model SW433), and their connections. Acoustic parameters, namely the sound absorption coefficient α (dimensionless) and sound reduction index R (dB) [8,10,13,14,19], were measured using the transformation function method in accordance with STN EN ISO 10534-2 (730537) [20].

B. Development and production of test cartridges

For the purposes of this research, the team of researchers designed and developed test cartridges (Capsule1, Capsule2) to measure the acoustic properties of materials obtained by recycling from scrapped cars. The test cartridges are designed in such a way to be applicable for measuring the acoustic properties of bulk, granulate and compact materials in the BSWA SW433 impedance tube with the length of 500 mm and inside diameter of 60 mm.

The test cartridges besides other things, they serve for the filling (compression) of the required bulk material, such as rubber granulate, glass, textile fractions, etc., in order to get a compact block for the measurement of sound and heat insulation with verified properties. Their production enabled us to conduct measurements in the

impedance tube which is structurally limited for solid materials.

The design of the cartridges was important for several reasons. The first reason is that the sample of bulk or granulated materials cannot be placed into the measuring device – impedance tube. Another one is that the resulting product (anti-noise barrier) will consist of multiple layers, a so-called sandwich (bulk and compact layers). It is equally important that the examined bulk material obtained by the recycling of end-of-life vehicles will be examined and tested with the use of the filling equipment at various pressures, and in this way, we will change the porosity of the measured sample which is either glass, crushed rubber or textile components. In this case, the test cartridge will not only serve for the measurement itself, but also as auxiliary filling equipment.

Two options for test cartridges were developed using a CNC machining device (Capsule1; see Figure 2), or 3D printing (Capsule2; see Figure 3).

Both test cartridges are designed to expand the possibilities of laboratory measurements of the selected acoustic descriptors, namely sound absorption coefficient (α) and sound transmission loss (R).

Since this research focuses on measuring and designing new materials from selected recycled parts from scrapped vehicles, namely used tires (ground rubber), glass (fractions $\geq 1\text{mm}$), textiles (fibrous materials), etc., it was necessary to design and manufacture suitable auxiliary equipment to meet our requirements.

Production of the test cartridge using a CNC machine (Capsule1)

The test cartridge (Capsule1) is manufactured in five lengths of 20, 50, 75, 100, and 120 mm, modifiable for use in different dimensions (Figure 2). The body of the cartridge is made of aluminum with its subsequent finish (anodic oxidation). An important part of the production of test cartridges are the perforated sieves, which prevent the emptying of bulk material.

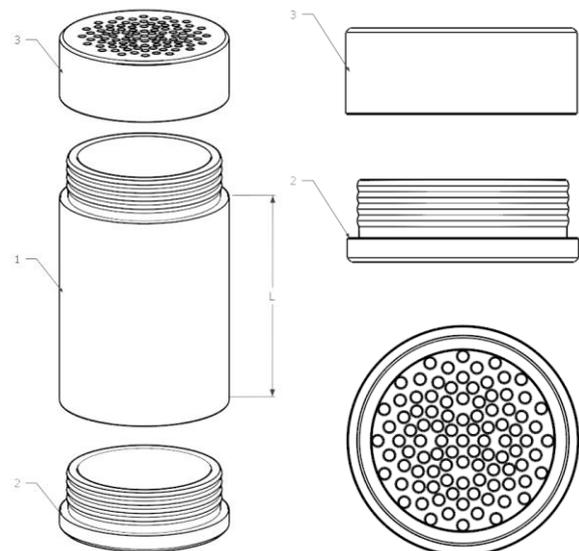


Figure 2. Test cartridge (Capsule1) – CNC machining. Explanatory note: 1–cartridge housing; 2–lower perforated bottom (sieve); 3–top perforated lid (sieve); L–modifiable length.

Production of the test cartridge (Capsule2) by 3D printing

The test cartridges of this type were manufactured using a PRUSA i3 MK3 3D printer. PLA and PETG filaments were used for printing. PLA is one of the most versatile materials and is a biodegradable material that is increasingly used in industry. PETG is more durable, stronger and can handle larger impacts. PLA was used for the production of the internal sieves and outer joins. PETG was used for the other parts of the test cartridge.

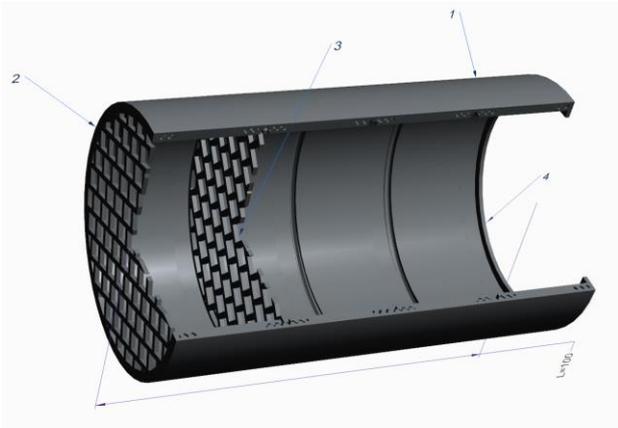


Figure 3. Test cartridge (Capsule1) – CNC machining. Explanatory note: 1–cartridge housing; 2–lower perforated bottom (sieve); 3–top perforated lid (sieve); L–modifiable length.

C. Development and production of the device for the filling of test cartridges

The device for filling of test cartridges with bulk and compact materials was developed at the Department of environmental engineering of the Faculty of Mechanical Engineering of the Technical University of Košice. An application for the utility model, as well as a patent application, which are granted by the Industrial Property Office of the Slovak Republic in Banská Bystrica, have been currently filed for the device. The following Figure 4 and Figure 5 shows the model of the designed filling device.

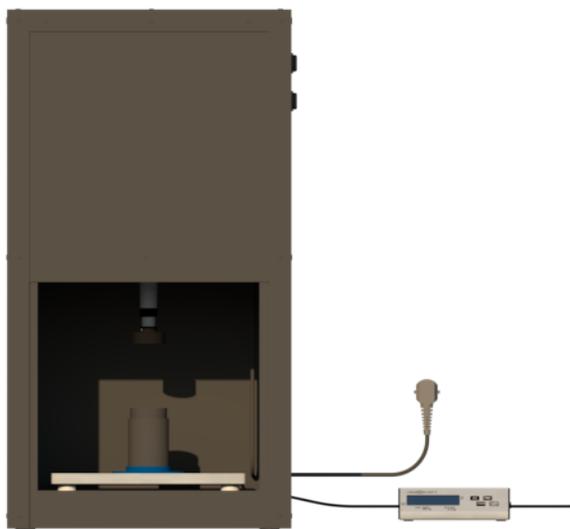


Figure 4. Model of the designed filling device in 3D view.

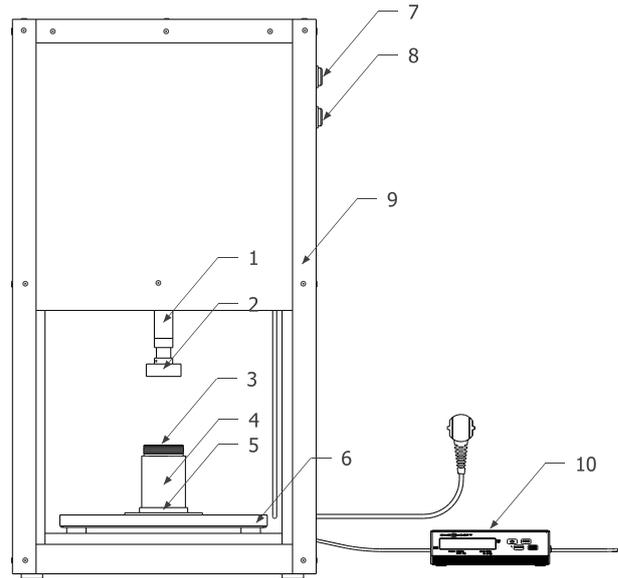


Figure 5. Model of the designed filling device – 2D scheme. Explanatory note: 1–electric linear piston; 2–pressure ring; 3–bulk material; 4–cartridge; 5–centering ring; 6–scales base; 7–button switch – upwards; 8–button switch – downwards; 9–frame; 10–control element of the scales.

After the removal of the upper perforated lid from the cartridge, the bulk material is poured into the cartridge and the cartridge with material is then placed into the centering ring which is located at the scales base. By pressing the button switch “downward” the electric linear piston starts to extend and when the pressure ring touches the bulk material, the material is compacted or compressed inside the cartridge. After the completion of material compression, the resulting value is displayed in kilograms on the display of the control element of the scales. After reading the measured value and pressing the “upward” switch, the electric linear piston starts to retract into its original position. After that, the test cartridge with the compressed material is removed from the centering ring, the upper perforated lid is screwed on, and the sample is prepared for further measurements in the impedance tube.

D. Description of the Tested Material Samples

The measurement of acoustic properties of the bulk materials from the end-of-life vehicles was carried out with the use of aluminum test cartridges designed (Capsule1) at our workplace.

The measurements were carried out on 3 size fractions of the recycled rubber granulate (Fraction1, Fraction2, Fraction3) and a mixture of textile material, the same as used for the production of Stered insulation board. In order to compare the acoustic properties of bulk materials, we have used the standard available products (a compact panel from recycled rubber from the company AVE and insulation board Stered made from recycled textiles). From these commonly available panels, we have made samples with the diameter of 60 mm applicable for the measurement of acoustic properties in the impedance tube.

The list and characteristics of individual samples are specified in Table 1.

TABLE I.
LIST OF TESTED MATERIALS

Material	Sample	Test cartridge (use)	Material thickness (mm)	Density (kg.m ⁻³)
Recycled rubber panel AVE (compact)		no	40	812
Recycled rubber granules (Fraction1)		yes	55	464
Recycled rubber granules (Fraction2)		yes	55	470
Recycled rubber granules (Fraction3)		yes	55	377
Recycled textile material STERED (compact)		no	50	276
Recycled textile material STERED (chopped)		no	50	91

During the measurement, the cartridges were filled with bulk material (recycled rubber granulate and textiles), while the material was poured into the cartridges without any additional compression of the bulk material.

The following acoustic parameters were evaluated during the measurement:

- sound absorption coefficient (α),
- sound reduction index (R).

Measurements of each sample were repeated five times and the results were then averaged. In order to evaluate the effect of the test cartridge on the measurement results, we have also carried out measurements of an empty test cartridge. Based on these measurements, it is possible to correct the results of measurements of bulk materials located in the test cartridge.

III. RESULT AND DISCUSSION

This article evaluates the possibilities of using recycled and granular materials in sound insulation applications in terms of their acoustic properties. Several authors have addressed this issue. The research by authors Borelli D., Schenone C. [21] was focused on the experimental analysis of the acoustic properties of vulcanized rubber

crumbs, obtained by the shredding of used tires. In the paper by authors [22] two types of recycled insulating panels were investigated: they are composed of waste paper and textile fibers, joined by glue, with a total thickness of 12 mm and 20 mm respectively. Svoboda J., et al. in 2021 [23] conducted research focused on lightening the concrete mixture, which was achieved by replacing aggregate with rubber granulate from waste tires in cement composites, which places this mixture in the category of lightweight concrete.

A. Measurement results of materials on the basis of recycled rubber granulates

Measurement of acoustic properties (frequency range from 100–2500 Hz) was carried out on 4 samples on the basis of rubber granulate (Figure 6, 7). One sample was made of a compact panel from recycled rubber material. Another 3 samples were made from bulk recycled rubber of various fraction sizes.

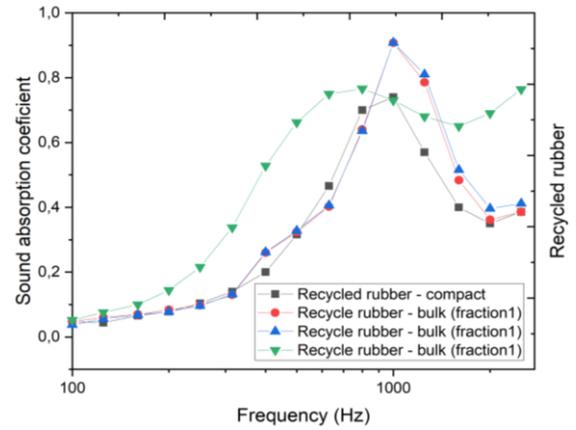


Figure 6. Sound absorption coefficient α (-) – rubber materials.

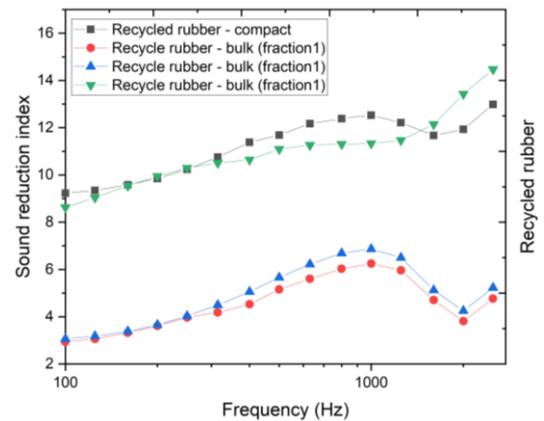


Figure 7. Sound reduction index R (dB) – rubber materials.

Rubber material is generally characterized by its good absorptivity and lower attenuation. This is also confirmed by the executed measurements. The main aim of the measurements was to compare the properties of bulk rubber recycled materials with a compact rubber panel, which is normally commercially manufactured. Based on the measurements conducted, we can state that the sound absorption coefficient of bulk materials reaches higher values than that of the compact rubber sample. This is caused mainly by the fact that the sound in bulk materials

is absorbed not only by the material itself, but also by the air gaps between individual rubber particles.

As expected, the best values in measuring the attenuation index are achieved with the compact rubber sample. Almost equal values are reached with the bulk rubber granulate having the lowest fraction size. The bulk materials with bigger fractions reach lower attenuation index values than the compact rubber and bulk rubber with the smallest fraction. In this case, the lower attenuation index values are caused mainly by the compactness of bulk rubber granulates with larger fractions.

B. Measurement results of recycled textile materials

Measurement of acoustic properties (frequency range from 100–2500 Hz) of recycled textile materials was carried out on two samples. One sample was made of compact recycled textile material STERED (Figure 8, 9). The second sample was prepared from the same recycled bulk textile material which was not compacted.

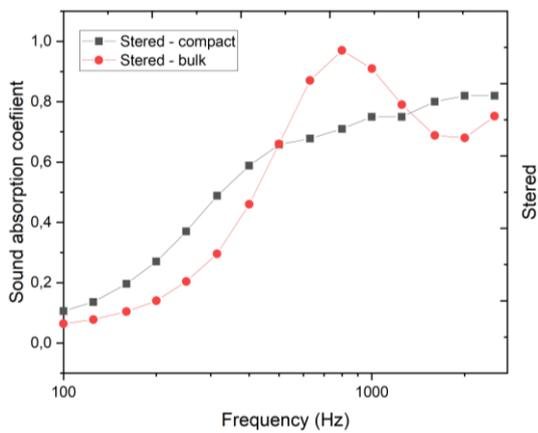


Figure 8. Sound absorption coefficient α (-) – textile materials.

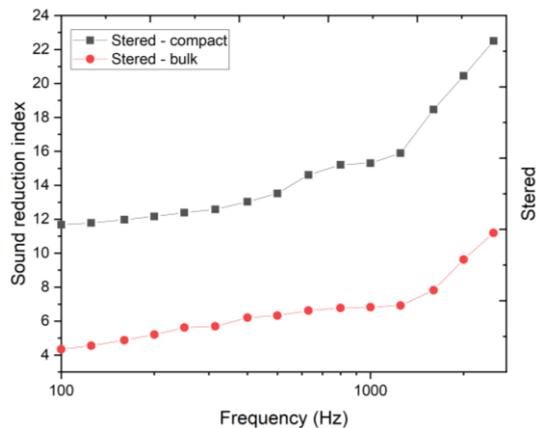


Figure 9. Sound reduction index R (dB) – textile materials.

On the basis of the conducted measurements of sound absorption coefficient, we can state that the compact textile material reaches better parameters in the frequency band 100–500 Hz and 1600–2500 Hz. The bulk textile material reaches better absorptivity parameters within the frequency band 500–1250 Hz. Based on the results of attenuation index measurements, it is clear that the compact textile material has better properties in the entire

frequency band. This result was expected since the bulk density of the compact material is 4 times higher than the bulk density of the bulk textile material.

C. Development and manufacture of the product based on bulk materials

The objective of the authors was to search for application possibilities of the recycled bulk materials from the components of end-of-life cars. They have specifically selected the recycled rubber, recycled textile material and crushed glass from cars. The application of the specified materials is foreseen in the implementation of noise barrier structures (Figure 10–13), or other sound and heat insulating products. Noise barriers are currently used to reduce traffic and industrial noise directly in the production process. The structures of noise barriers can be very varied. Many materials included in the end-of-life vehicles which are problematic in terms of their further recovery (textiles, airbags, glass, tires, etc.) could be suitable for the production of sound-absorbing elements. The production of compact materials from these recycled materials requires the application of a certain amount of binder. The addition of binders will eventually make the production of these materials more expensive, and they are often harmful to the environment. One of the possible solutions for the use of recycled granulated (but also chopped, cut, torn and crushed) materials in acoustic applications without the use of binders is the application of these materials in noise barriers in the form of bulk material.

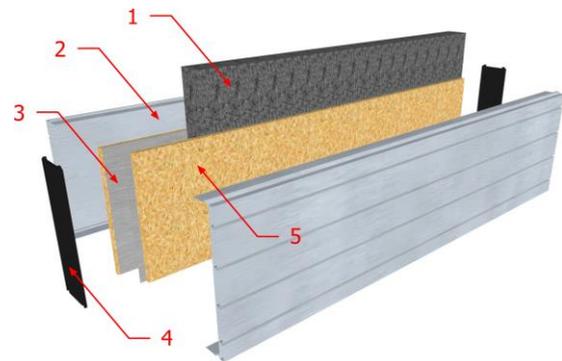


Figure 10. Individual parts of the noise barrier panel (recycled rubber fraction). Explanatory note: 1–recycled rubber fraction; 2–external aluminum cover; 3–aluminum layer; 4–side rubber cover; 5–layer Nobasil.

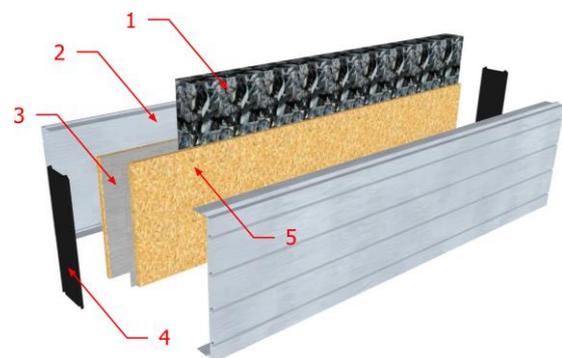


Figure 11. Individual parts of the noise barrier panel (recycled bulk textile material). Explanatory note: 1–loose recycled textile material; 2–external aluminum cover; 3–aluminum layer; 4–side rubber cover; 5–layer Nobasil.

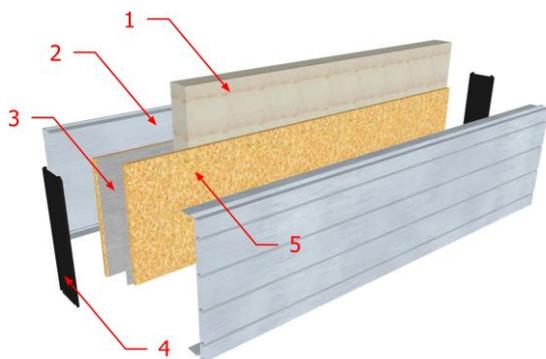


Figure 12. Individual parts of the noise barrier panel (bulk crushed glass fraction). Explanatory note: 1–fraction of loose glass crumb; 2–external aluminum cover; 3–aluminum layer; 4–side rubber cover; 5–layer Nobasil.

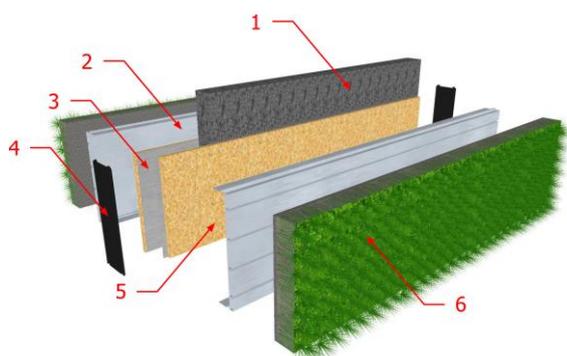


Figure 13. Noise barrier panel with green wall. Explanatory note: 1–recycled rubber fraction; 2–external aluminum cover; 3–aluminum layer; 4–side rubber cover; 5–layer Nobasil; 6–vegetation.

In the development of these noise barriers, the authors have cooperated with the firm FORSTER The advantages to using these so-called “green” materials in acoustic (and also thermal) applications, such as noise barriers, in comparison with the commercial material, are the combination of a very light substance, high physical and chemical stability, low costs and high sound absorption values.

IV. CONCLUSIONS

This article evaluates the possibilities of using recycled and granular materials in sound insulation applications in terms of their acoustic properties.

Determining the acoustic properties of granular recycled materials was one of the basic bases for the implementation of this research. A special test cartridge was developed to determine the acoustic properties. A filling tool was developed for filling test cartridges.

Based on the results of research on the acoustic properties of bulk recycled materials and comparing them with compact materials, we can conclude that the acoustic properties of bulk recycled rubber and textile materials achieve very good values, which enables them to be used in a wide range of applications. The acoustic properties of bulk materials can be further improved by increasing their bulk mass by using additional pressure when filling these materials into specific applications. The assessment of the impact of bulk mass and pressure increase in filling these materials into test cartridges will be the subject of further research.

One possible solution for the use of recycled granular materials in acoustic applications without the use of binders is the application of these materials to noise walls in the form of bulk material. A prerequisite for such an application is the suitable structure of the noise panel and suitable application of bulk material with subsequent compaction. Advantage of the application of bulk recycled materials is their price. The production of acoustic panels with recycled materials is costly and time consuming. To combine individual grains and pieces of materials, different types of binders are required, and process of compaction and pressing at high temperature. The price of these binders greatly increases the price of the final product [24].

Recycled bulk materials have wide industrial applications in in the cores in the noise barriers and prefabricated dividing constructions, as filling in building walls in assembled houses, and in the cores of sound-insulating panels.

ACKNOWLEDGMENT

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Experimental research of material properties in Additive Manufacturing

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Abstract—The aim of using additive manufacturing technologies is to be able to produce a wide range of component designs on a single device, using a wide range of materials and minimizing material consumption. There are several technologies that work on different principles. The present article is focused on Fused Deposition Modeling (FDM) technology, which is focused on the application of layers of semi-molten polymer. The advantage is the lower cost for obtaining of FDM device, but also the low operation cost. The output of production are complex components designed for prototyping, but also for final use. Due to the fact that there is requirement to produce parts also for final use, it is necessary to know the strength properties of the parts after production. Because the structure of parts volume is not homogeneous, it is not possible to subject it to conventional calculations and simulations, but it is necessary to take into account the specifics that are produced during production by FDM technology.

I. INTRODUCTION

Topological optimization processes are used not only in mechanical, but also in other industries in order to reduce the amount of material used and the deformation energy of construction details, while maintaining mechanical strength. It is a mathematical method that spatially optimizes the distribution of structured elements within predetermined boundary conditions. Boundary conditions can be understood as, for example, the incoming loading forces of the system, the physical and mechanical properties of the material used, the safety coefficients etc. The result of such optimization is a targeted shape, as the most optimal for a given construction detail.

There are a number of topological optimization methods in the scientific literature. The two most popular methods are the solid isotropic material (SIMP) technique and the structural optimization (ESO) technique. Solid Isotropic Material with Penalization (SIMP) technique The SIMP method was defined by Bendsoe - Kikuchi (1988) and Rozvany - Zhou (1992).

The method performs the optimal distribution of the material within the basic proposed space within the boundary conditions. According to Bendsoe (1989): "Optimizing a shape in the most general setting should create a shape at every point, whether or not the material is in it." Traditionally, topology optimization is solved by discretizing the domain into a finite element network, the so-called isotropic solid microstructures. Each element is then either filled with material in the areas required by the material or stripped of material in those areas where removal is possible (cavities). The material density

distribution within the design domain ρ is discrete, each element is assigned a binary value:

$\rho(e) = 1$ where material is mandatory (black)

$\rho(e) = 0$ where material is removed (white)

The following figure shows the optimal distribution of the embedded beam material under load. Solid particles with densities $\rho(e) = 1$ are clearly visible as black, empty particles with densities $\rho(e) = 0$ are collected particles.

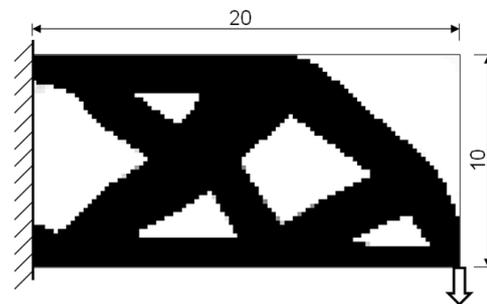


Figure 2 Example of an embedded beam

For each element, the assigned relative density can be between the minimum value of ρ_{min} and 1, which allows the addition of intermediate element densities, also referred to as porous elements. ρ_{min} - is the minimum allowable value of relative density, for empty elements, which is greater than zero. This density value ensures the numerical stability of the finite element analysis (FEM).

II. METHODOLOGY AND MATERIALS

In the next part of the article, the results of the software analysis and experimental measurements on the manufactured samples will be presented. A component was designed, which was subsequently subjected to strength analysis and topological optimization. The basic part can be seen in picture number 2.

By means of specialized software, the part was subjected to topological optimization. With a known value of the load, a strength recalculation was carried out and then a topological optimization was carried out, through which the mass of the material was removed. Each subsequent iteration removed more material from the part. In this way, we want to monitor the effect of the amount of

material removed on the strength of the manufactured part. The shape of the residual material is determined by software for topological optimization. All iterations can be seen in Figures 3 and 4.

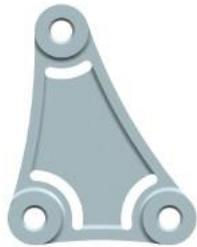


Figure 2. Design of original testing specimen



Figure 3. Design of testing specimens with iteration 1 and 2

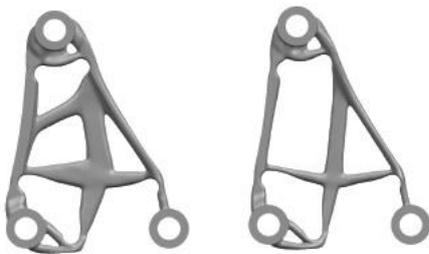


Figure 4. Design of testing specimens with iteration 3 and 4

In figures 5 and 6 we can see the result of strength calculations of individual iterations of parts. The results of these strength calculations are subsequently used for comparison with the measured data.



Figure 5. Results of stress analysis for specimens with iteration 1 and 2



Figure 6. Results of stress analysis for specimens with iteration 3 and 4

III. MEASUREMENT AND RESULTS

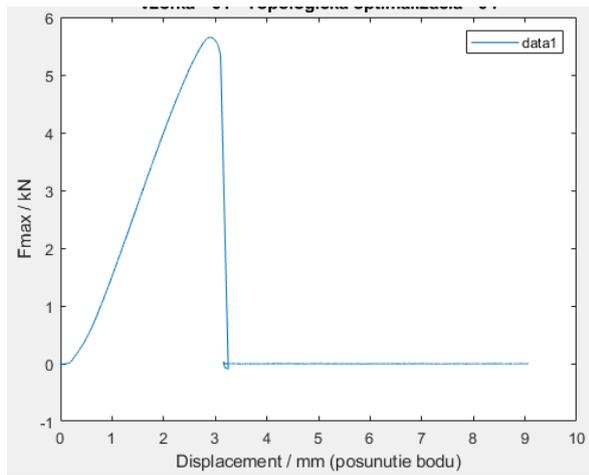
The parts designed in this way were produced using FDM additive manufacturing technology. PET-G plastic was used. The same material was also used in all software simulations, so that the measured and simulated values could be compared.

The following figures show the results of experimental measurements for individual iterations.



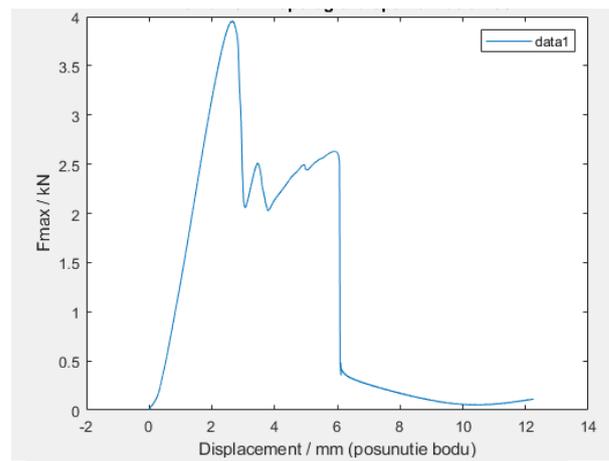
Figure 7. Testing device MTS Bionix

All the measured data are summarized in table number 1, where you can see the individual iterations of the manufactured parts, the corresponding weight of the manufactured part and the tensile force that was measured during the experimental testing. The MTS Bionix device was used for testing (Figure 7). The parts were tensile tested.



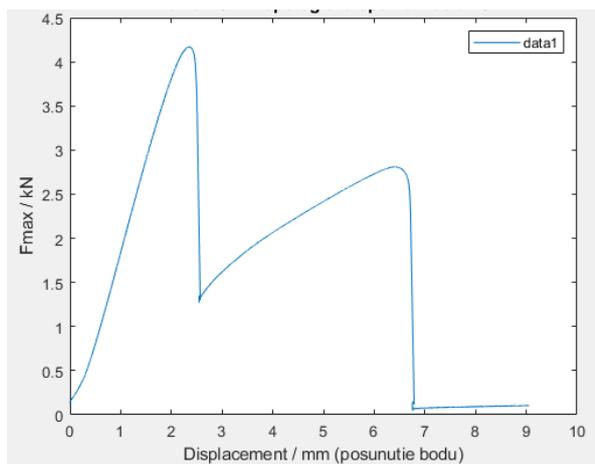
	X Displacement (E+00 mm)	Y VonMisses MAX (Mpa)
min	7.898e-05	-0.09026
max	9.063	5.655
mean	4.529	0.9739
median	4.528	0.001228
mode	7.898e-05	-0.09026
std	2.62	1.77
range	9.063	5.745

Figure 8 Testing development of specimen with design iteration 1



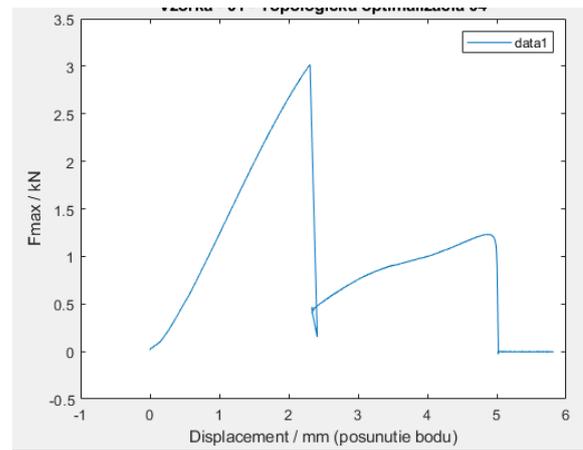
	X Displacement (E+00 mm)	Y VonMisses MAX (Mpa)
min	-0.001406	0.004917
max	12.24	3.959
mean	6.119	1.183
median	6.139	0.3118
mode	-0.001406	0.004917
std	3.535	1.247
range	12.24	3.954

Figure 10 Testing development of specimen with design iteration 3



	X Displacement (E+00 mm)	Y VonMisses MAX (Mpa)
min	7.898e-05	-0.09026
max	9.063	5.655
mean	4.529	0.9739
median	4.528	0.001228
mode	7.898e-05	-0.09026
std	2.62	1.77
range	9.063	5.745

Figure 9 Testing development of specimen with design iteration 2



	X Displacement (E+00 mm)	Y VonMisses MAX (Mpa)
min	-0.00138	-0.03021
max	5.817	3.018
mean	2.907	1.003
median	2.907	0.9228
mode	-0.00138	-0.03021
std	1.681	0.7762
range	5.818	3.048

Figure 11 Testing development of specimen with design iteration 4

TABLE I
TABLE OF BASIC PARAMETERS AND RESULTS

Part	Weight (kg)	Tensile force (kN)
Iteration 0	0,0478	6,221
Iteration 1	0,0457	5,655
Iteration 2	0,0440	4,172
Iteration 3	0,0330	3,959
Iteration 4	0,0220	3,018

The tables below (Table II and Table III) also show a comparison of weights and measured tensile forces. In this way, it is possible to compare the effect of material loss on the strength of manufactured parts.

TABLE II
DIFFERENCE BETWEEN PARTS WEIGHT

Part	Weight (kg)	Difference (kg)	Difference (%)
Iteration 0	0,0478	-	-
Iteration 1	0,0457	0,0021	4,39
Iteration 2	0,044	0,0038	7,95
Iteration 3	0,033	0,0148	30,96
Iteration 4	0,022	0,0258	53,97

TABLE III
DIFFERENCE BETWEEN TENSILE FORCES

Part	Tensile force (kN)	Difference (kN)	Difference (%)
Iteration 0	5,861	-	-
Iteration 1	5,655	0,206	3,55
Iteration 2	4,172	1,689	29,12
Iteration 3	3,959	1,902	32,79
Iteration 4	3,018	2,843	49,02

IV. RESULTS

Before performing the experiments, we expected that the topological optimization would contribute in a fundamental way to the saving of the material while maintaining its strength properties, or at least with its minimal loss. However, as can be seen from the results and comparisons shown in the tables above, it largely copies the loss of material and the loss of strength of the manufactured parts. Such a result was not expected, so in further research it will be necessary to reevaluate the used software equipment for the purpose of topological optimization and find a more suitable solution in order to achieve the desired result.

ACKNOWLEDGMENT

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Design of a recycling device for the processing of old car bodies

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Abstract — The paper focuses on the design and development of equipment for bodywork from old vehicles. It is a design of a cutting device for the body of old vehicles, car wrecks. For the correct sizing of the cutting device, it was necessary to know the size of the cutting force, which also depends on the strength of the cut material. The subject of the research was the experimental determination of the ultimate strength of bodies from old vehicles. To more specifically determine the ultimate strength, we chose to divide the experimental samples (old car bodies) into three categories. The criterion of distribution was the engine capacity, and we assumed that cars with a larger engine capacity have bodies made of sheets of greater strength. The results of the ultimate cutting force measurement for each category were analyzed and statistically processed. The results of the experimental determination of ultimate cutting force and strength were applied to the design of a new cutting device.

75% by weight of ELV. [1]

Five EU Member States reported reuse and recycling rates of 95.0% or more in 2019, these countries included Poland (118.8%), Luxembourg (96.7%), Croatia (96.3%), Bulgaria (95.8%) and Slovakia (95.5%) another five reported rates in the range of 90.0% to 94.9%. Twelve reported rates in the range of 85.0% to 89.9%, and two Member States reporting rates falling in the range of 84.2% to 84.7%; for missing reporting countries the EU aggregates are calculated from available years applying trend or median estimates. [3]

The portfolio of discarded vehicles is wide. However, they can be divided into categories such as buses, motorcycles, trucks, trailers, semi-trailers, special vehicles, agricultural machinery such as tractors and others. Table 1 lists the types of ELVs excluded from the vehicle register for 2021 in the Slovak Republic (KDIBB - Regional Transport Inspectorate Banská Bystrica, KDIKE - Regional Transport Inspectorate Košice, KDINR - Regional Transport Inspectorate Nitra, KDIPPO - Regional Transport Inspectorate Prešov, KDITN - Regional Transport Inspectorate Trenčín, KDITT - Regional Transport Inspectorate Trnava, KDIZA - Regional Transport Inspectorate Žilina). Most passenger cars are registered in the Bratislava region.

I. INTRODUCTION

EU Member States have set "reuse and recovery" and "reuse and recycling" targets of 95% and 85%. The weight of ELV processed in EU countries in 2019 is shown in fig. 1. When recycling old vehicles using shredders, 15-25% of the weight of the ELV, classified as hazardous waste, usually remains. For recycling usually remains

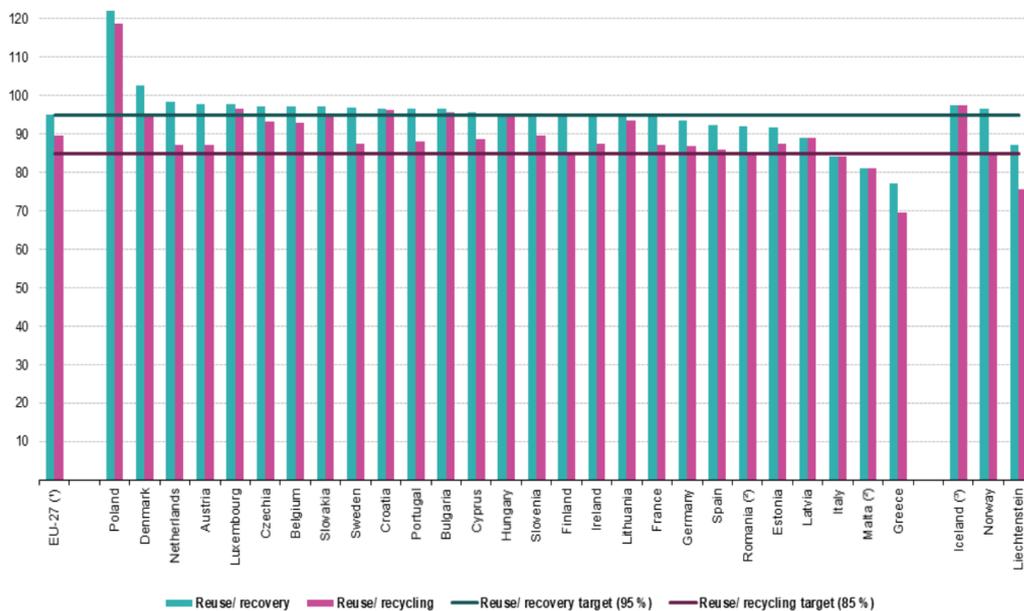


Figure 1. ELV – reuse, recycling and recovery, 2019 (% of weight of vehicles) [2]

TABLE I.
TYPES OF ELVS EXCLUDED FROM THE VEHICLE REGISTER FOR 2021 IN THE SLOVAK REPUBLIC

TYPE OF VEHICLES	KDIBB	KDIBA	KDIKE	KDINR	KDIPO	KDITN	KDITT	KDIZA	Together
BUS	29	40	47	63	89	73	49	56	440
MOTORCYCLE	115	176	103	177	79	153	134	147	1080
TRUCKS	852	1924	734	1225	682	672	819	1057	7960
SEMITRAILER	73	129	38	328	72	60	56	80	830
CARS	6525	11237	5555	7251	5213	6225	6125	7048	55170
CARGO TRAILER	204	218	156	347	161	168	298	187	1730
SPECIAL VEHICLE	37	42	47	45	29	33	33	44	310
TRACTOR	200	70	115	237	277	122	264	265	1550
Together	8035	13836	6795	9673	6602	7506	7778	8884	69100

It can be noted that the total number of discarded passenger cars represents the largest share, approximately 80% of all discarded vehicles.

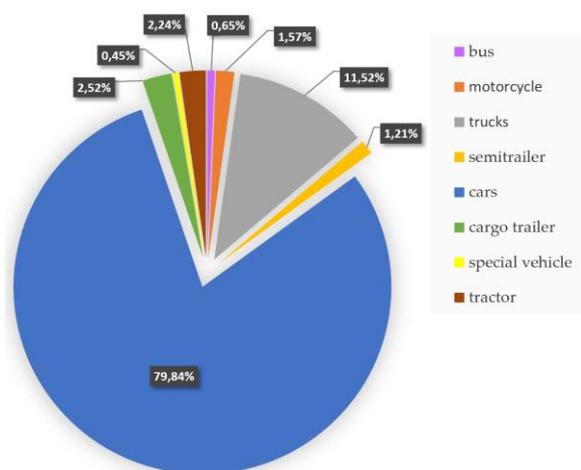


Figure 2. Percentage of individual ELV categories discarded in 2021, SR [9]

The materials used in the manufacture of automobiles are diverse and their percentage is published [4], [5], [6]. In order to achieve the set recycling targets, the ELV materials used must be sorted efficiently. According to study [4], the recyclable metals such as iron, aluminum and platinum are the main renewable resources in the total weight of ELV approximately 72%. During the last decades there were very intense developments concerning the applied materials in car body manufacturing. Among steel developments the various generations of high strength steels should be mentioned. [15]

A significant part consists of steel and aluminum. For the correct design of the recycling equipment, it is necessary to know the strength of the processed material. The study [10] compares the strength of steel and aluminum car parts. For a specific design of the shearing device, it is necessary to know the magnitude of the shearing force. Current trends in bodywork development are increasing the proportion of aluminum. Al-Mg alloys are widely used in transport and vehicle industries due to their good combined properties such as excellent corrosion resistance, weld ability, formability, and high

strength to weight ratio [11] For the increase in application of aluminum alloy and high strength steel sheets to automobiles, it is desirable to develop not only new forming processes. [12] The impact of car body material is significant both in recycling and in vehicle operation. It directly affects, for example, fuel consumption. To improve the fuel consumption of cars, the reduction in the weight of cars is intensively required in the automobile industry. The strength of high strength steel sheets remarkably increases, and ultra-high strength steel sheets more than 1 GPa in tensile strength have been developed. [13] Car bodies, as well as other car structures such as the doors and the main part of the car seat structures, are built by assembling many components. The latter components are most commonly manufactured by deep drawing metal sheets. Other processes, such as the hot forming of metal sheets, or processes specific to composite materials, are also used. A wide range of steel grades, mostly fabricated in the form of 0.8 to 1.5 mm thick sheets, are most commonly used for car-bodies. [14]

The initial assumptions focused on manual disassembly. However, a major disadvantage of manual disassembly was economic inefficiency. The study [7] concludes that the traditional manual dismantling method increased the recycling rate effectively. ELV commodities need to be separated manually to achieve a set recycling rate. Such separation can only be achieved by removing the ELV by manual disassembly so that the body sheets, which are determined for further processing, remain clean. Machines for cutting steel scrap from old vehicles are designed for high cutting forces. Which has an adverse effect on energy consumption and thus the economy of processing. The present study deals with the optimization of cutting force and the design of a cutting device for cutting the bodies of old vehicles. The cutting force was investigated during the processing of cleaned sheets of old vehicle bodies.

II. MATERIALS AND METHODS

The principle of the experiment is to find real cutting forces when cutting pressed body of old vehicles.

The observed variable of the experiment is the pressure in the hydraulic cylinders needed to derive a force that is able to cut the pressed inhomogeneous material. Another monitored value was the thickness of the pressed sheets. In order to be able to determine the cutting force from the

read parameters, it was necessary to perform the following transformations of quantities into SI system units:

- conversion of pressure to force by determining the area of the hydraulic cylinders in which the pressure acts. This is a basic conversion of force pressure,
- the pressed thickness was determined from the value of the maximum stroke of the hydraulic cylinders and the reading, which was measured using an interferometer.

Another parameter that influences the process of cutting inhomogeneous sheets from the pressed bodies of old vehicles is the cross section of the pressed body, which varies depending on the place of cutting the body. It is possible to assume that the strength of this inhomogeneous material will vary depending on the place of the cut, when we can assume that the place of the reinforced body will also be stronger. In order to achieve the most accurate values for statistical evaluation, a cutting cycle of 100 mm along the entire body was set, which is the smallest possible displacement for a given experimental device.

A machine from Acros-Henschel, CIV 600, (figure 3.) was chosen to carry out the experiment. The main criterion for selecting this device was its design, which corresponds to the selected cutting technology with inclined knives.



Figure 3. The experimental device Acros-Henschel, CIV 600

Old vehicle bodies were used as experimental samples. The sample corresponded to a real portfolio of vehicles removed from the register and intended for processing in Slovakia. 34 experimental samples were prepared, with approximately 30 cuts made on each sample according to the experimental design, as the cycle was set at 100 mm, fig. 4. The number of cuts is directly dependent on the type of ELV.



Figure 4. The Schematic illustration of the cut ELV

The whole experiment was performed in order to determine the real cutting forces when cutting the dismantled compact body and thus when cutting inhomogeneous material. As it was not possible to immediately read the magnitude of the cutting force from the experimental equipment, the monitored quantities were:

- pressure in hydraulic motors by the cutting stated in bars,
- the thickness of the cut material in millimeters.

III. EVALUATION OF THE MEASUREMENT

To determine the real cutting force, a recalculation was performed from the results of the monitored pressure. The input parameters for the conversion of the area on which the pressure acts were the design dimensions of the hydraulic motors, namely:

- cylinder inner diameter of the hydraulic motor 300 mm,
- cylinder outer diameter of the hydraulic motor 380 mm,
- piston rod diameter 250 mm.

The calculated active area of the hydraulic motor (S_H) is 0.1413 m². And the cutting force was calculated from the relationship:

$$F = p \times S_H \text{ (kN)} \quad (1)$$

where: F is the cutting force (kN), p is the pressure (Pa) and S_H is the area (m²).

To correctly determine the size of the optimal cutting force, it was necessary to divide the experimental samples into three categories according to the engine capacity:

- engine capacity up to 1300 cm³, designation A1300,
- engine capacity category from 1300 cm³ to 1900 cm³, designation A1300-1900,
- engine capacity category above 1900 cm³, designation A1900.

Each category contains 6 experimental samples. At the time of cutting, 34 cuts were made on each sample. In table 1 is shows the calculated shear averages for each of the shears.

TABLE II.
MEAN F (10⁴N) IN EACH CATEGORY

Cut number	A 1300	A 1300-1900	A 1900
1	66,04	75,64	67,51
2	74,92	67,58	74,72
3	74,20	74,92	73,48
4	74,44	75,07	72,45
5	69,40	74,92	77,39
6	75,40	73,91	75,34
7	107,10	80,97	90,36
8	87,65	85,44	124,74
...
34	133,13	163,90	175,21

Cumulative relative abundance, Gubbs and outliers test methods were used for statistical evaluation. The cumulative frequency is obtained by adding (cumulating) frequency values. Indicates how many elements of the statistics file have a character value less than or equal to a given value. When determining the cumulative abundance, the individual abundance councils must have the character of a variation council. The determination of

the critical value $KH = T_n$, α is determined from the Grubbs test tables for the processed range of values of n and the selected level of significance α . Comparison of the test criterion TK with the critical value KH , if $TK < KH$ hypothesis is not rejected (agreement with H_0), if $TK > KH$ hypothesis is rejected (disagreement from H_0). In this case, the corresponding value x_{\max} (x_{\min}) must be excluded from the sample data set. Calculate new numerical characteristics and repeat the test for new pairs of extreme values of the variation series. [8]

A. Statistical evaluation of category A1300

The number of cutting forces in the individual cuts for category A1300 is shown in Figure 3. In the individual histograms, the cutting force value of 200 tons is highlighted in red. This value was used as an assumption resp. estimation of cutting force for optimization of equipment used for processing dismantled bodies from old vehicles. It can be seen that of all the measured cutting forces, the value is up to 200 tons approx. 95 - 97% of the values of cutting forces.

The resulting mathematical function for the engine capacity category up to 1300 cm³ is in the form of a Weibull function:

$$F(x) = a_1 + a_2 \left(1 - e^{-\left(\frac{x}{a_3}\right)^{a_4}} \right) \quad (2)$$

where: a_1 - estimate of minimum force; $a_1 + a_2$ - estimate of maximum force; a_3, a_4 - an estimate determining the position of the inflection point and the slope of the curve; μ_A - uncertainty of the result.

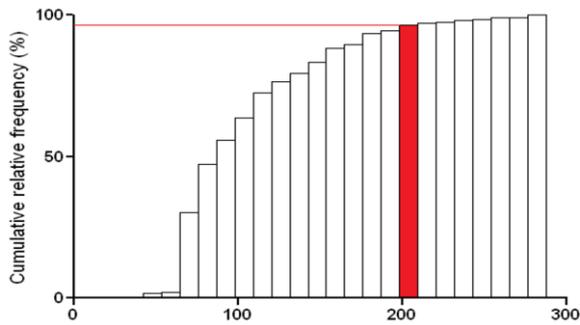


Figure 5. Cumulative abundance cutting force in tones for category A1300.

The resulting course of average cutting forces for category A1300 with engine capacity up to 1300 cm³ is shown in Figure 6.

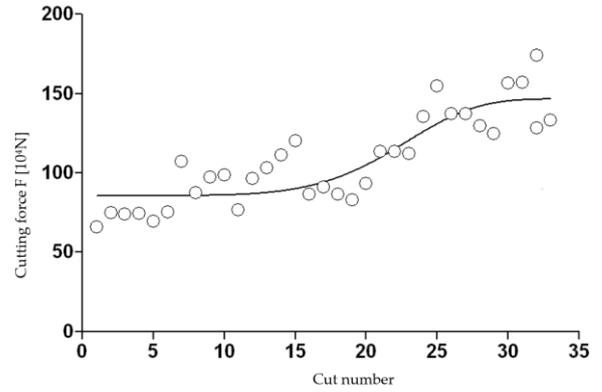


Figure 6. Course of the cutting force in category A1300.

The function represents the course of the average cutting forces in this volume category. After substituting the values of individual parameters of the function, it is possible to determine the range of the average cutting force in a given category.

B. Statistical evaluation of category A1300-1900

The number of cutting forces in individual cuts for category A1300-1900 is shown in fig. 7.

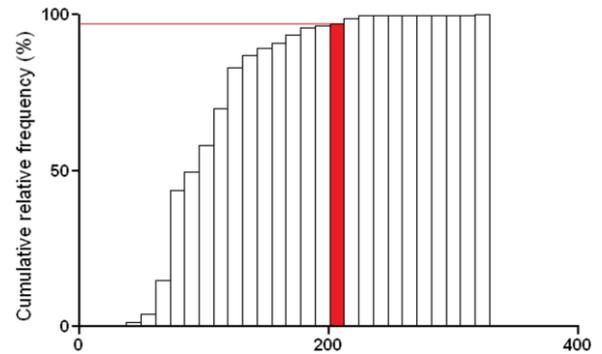


Figure 7. Cumulative abundance cutting force in tones for category A1300-1900.

The resulting mathematical function for cutting force for the engine capacity category from 1300 cm³ to 1900 cm³ is in the form of an exponential function:

$$F(x) = a_1 e^{x a_2} \quad (3)$$

where: a_1 - minimum force estimation, a_2 - rate of increase of cutting force depending on the order of cut x , μ_A - uncertainty of the result.

TABLE III.
WEIBULL FUNCTION PARAMETERS FOR CATEGORY A1300

Engine capacity (cm ³)	a_1 (10 ⁴ N)	a_2 (10 ⁴ N)	a_3 (10 ⁴ N)	a_4 (10 ⁴ N)
A1300	86,11	57,69	23,52	6,29
μ_A	4,3	8,5	1,5	2,8

TABLE IV.
EXPONENTIAL FUNCTION PARAMETERS FOR CATEGORY A1300-1900

Engine capacity (cm ³)	a_1 (10 ⁴ N)	a_2 (10 ⁴ N)
A1300-1900	67,84	0,022
μ_A	3,4	0,002

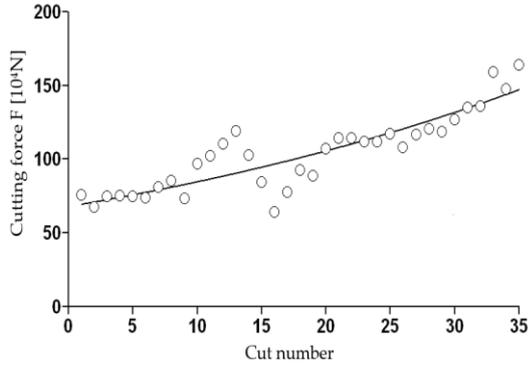


Figure 8. Cumulative abundance cutting force in tones for category A1300-1900.

C. Statistical evaluation of category A1900

The resulting mathematical function for the engine capacity category over 1900 cm³ and more is in the form of a Weibull function:

$$F(x) = a_1 + a_2 \left(1 - e^{-\left(\frac{x}{a_3}\right)^{a_4}} \right) \quad (3)$$

where: a_1 - estimate of minimum force; $a_1 + a_2$ - estimate of maximum force; a_3, a_4 - an estimate determining the position of the inflection point and the slope of the curve; μ_A - uncertainty of the result.

The parameters of the Weibull function for cutting force for the engine capacity category above 1900 cm³ and more are given in table 5.

TABLE V.
WEIBULL FUNCTION PARAMETERS FOR CATEGORY A1900

Engine capacity (cm ³)	a_1 (10 ⁴ N)	a_2 (10 ⁴ N)	a_3 (10 ⁴ N)	a_4 (10 ⁴ N)
A1900	81,2	98,24	21,07	3,63
μ_A	4,8	8,7	1,2	2,8

D. Statistical evaluation of results for all categories

The resulting mathematical function of the cutting force profile (figure 8) for all samples is in the form of an exponential function:

$$F(x) = a_1 e^{x a_2} \quad (4)$$

Where: a_1 - minimum force estimation, a_2 - rate of increase of cutting force depending on the order of cut x , μ_A - uncertainty of the result. The function parameters valid for all sample categories are listed in the following tab. 6.

TABLE VI.
EXPONENTIAL FUNCTION PARAMETERS FOR ALL CATEGORIES

Engine capacity (cm ³)	a_1 (10 ⁴ N)	a_2 (10 ⁴ N)
All cars	72,76	0,068
μ_A	1,9	0,03

The maximum average cutting force in this volume category can be estimated according to the relationship:

$$T_{\max} = F(35) \quad (5)$$

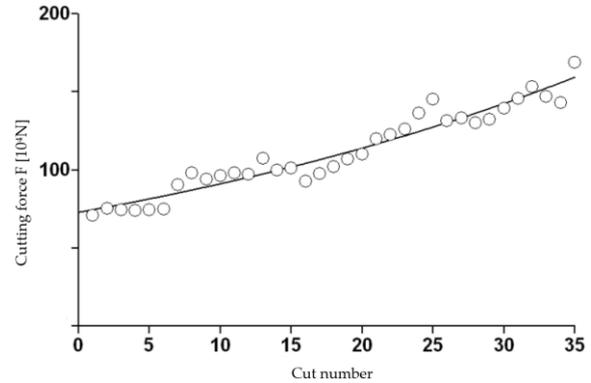


Figure 9. . Resulting graph of average cutting forces for all categories.

E. Design of cutting equipment for optimal cutting force

Theoretical knowledge as well as the output from experimental measurements were fully used in the structural design of the entire cutting equipment (fig. 10). The result of the experiment and its evaluation served as the input optimization parameter. It follows that a cutting force of 200 tons was therefore chosen.

The cutting force of 200 tons is significantly less than the cutting forces used for dimensioning current equipment in practice. This fact affects the proposed design parameters of the machine:

- weight (possibility of mobility),
- machine size,
- machine power consumption (economic efficiency).

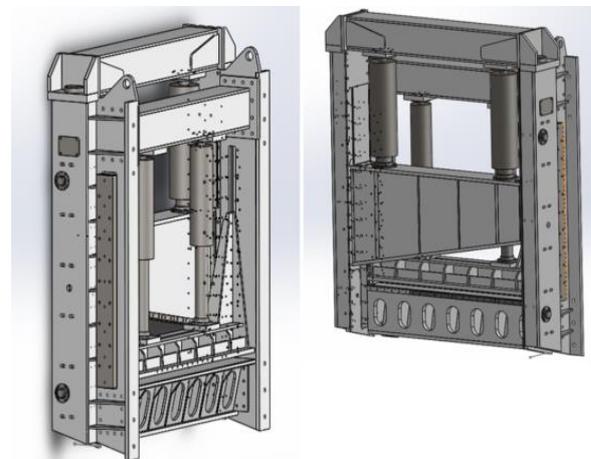


Figure 10. Designed cutting equipment

For the purpose of simulation, a complex FEM assembly of a shearing device was created (fig. 11 and fig.12). The assembly includes complete material and shape characteristics of components, ties, contacts, friction, press

loads, shear loads. Bolt preload was not considered as it does not have a significant effect on the simulation result.

Input parameters of cutting equipment construction:

- pressing force: FL = 1000 kN
- cutting force: FS = 2000 kN

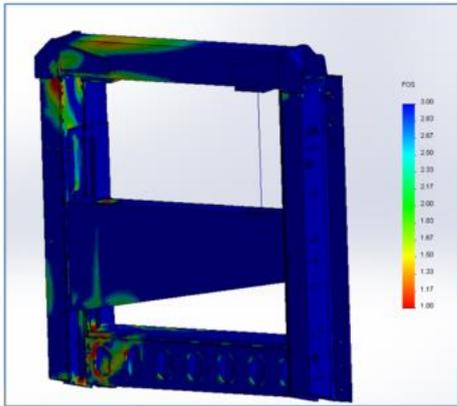


Figure 11. Linear FEM analysis of the cutting device - safety factor

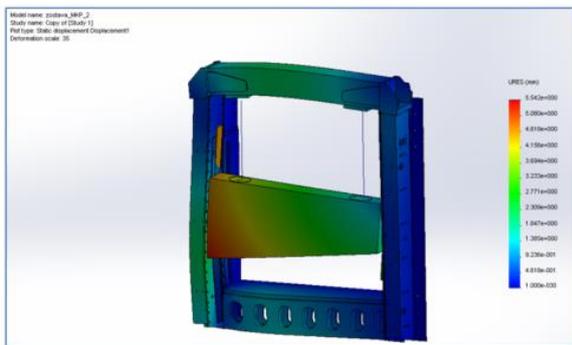


Figure 12. Linear FEM analysis of the cutting device - deformation (mm)

IV. DISCUSSION

The issue of processing old vehicles is currently a very complicated process. The complexity of the whole process is influenced by several factors. *In the fulfilment of these requirements, the weight reduction has an important role. Concerning the overall weight of an automobile the car body has a decisive role. In the production of car body elements – often termed as body-in-white production – sheet metal forming is regarded as one of the most important manufacturing processes* [16]. Among the most important factors influencing the process of processing old vehicles is the legislation of the European Union, which places more and more demanding and greater emphasis on the ecological course of the entire processing of vehicles. In order to achieve a sufficient degree of recycling, the ELV needs to be thoroughly dismantled. Precise dismantling is currently possible mainly by manual disassembly. This form of disassembly is economically demanding. Therefore, it is important to pay attention to other economic impacts. One of them is the energy consumption of cutting equipment for cutting sheet metal parts ELV. Research has clearly shown that in the case of

cutting clean sheets, it is possible to significantly reduce the cutting force. By reducing the cutting force, it is possible to consider the design of a cutting device with lower power input. The question remains to what extent manual dismantling can be automated. The design of the cutting machine for recycling ELV is possible in two ways, namely, by experimentally determining the shear force, as in the present study, or on the basis of the ultimate strength of drawn sheets (280MPa) [17].

V. CONCLUSIONS

The advantage of the proposed cutting device is its smaller dimensions. It is also possible to easily integrate this device into a complex line for processing car bodies from old vehicles, fig. 13. The main advantage of the modular arrangement of the individual machines is their independence from each other. And so it can be said with certainty that each module is able to work both in the whole assembly and separately. The fact is that it is possible to assemble several combinations according to the requirements of the customer or the manufacturer of the old vehicles.

Combination options::

- each module separately,
- pressing in combination with cutting,
- pressing in combination with cutting and crushing,
- pressing in combination with shearing and crushing and final compaction.



Figure 13. Modular set of equipment for processing the body of old vehicles.

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Processing of spent automotive lithium batteries

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Abstract— One of the most important challenges of the waste industry within the dynamically developing sector of electric vehicles is the management of discarded traction lithium batteries. They represent a potentially very dangerous waste, but, on the other hand, they are the source of very important materials that must be recycled with regard to their price and scarcity. It is not negligible that some components, such as cobalt, graphite, and lithium, contained in Li batteries belong among the critical raw materials for the European Union. Recycling of these is an important way to gain these critical raw materials, but, on the other hand, it is a complicated and demanding process, since it is a complex composite material and its characters as well as electrical and chemical properties pose a serious risk in terms of safety and the protection of health.

This paper is focused on the experimental study of processing of spent automotive lithium batteries with aim to recover of copper, aluminum, black mass and plastics as well. The recycling process consist from such operations as discharge of residual voltage, separation and extraction of metals Cu, Al, then separation and extraction of active material (black mass), then separation and extraction of plastic and separation and extraction of metals from the solution, especially Li, Co, Ni, Mn, etc.

In order to achieve specified aims physico-mechanical methods were used based on gravitation methods. Relatively high purity copper, aluminum, black mass and plastics were obtained in results of this work.

I. INTRODUCTION

As a result of increasing demands to reduce carbon footprint of the transportation sector, electro-mobility is being implemented on a global scale. Lithium batteries (LiA) are currently the main energy source for this sector, mainly due to their high capacity and electrical performance, long lifetime and low failure rate. This results in an exponential increase in the production of LiA, which of course has increased the demand for their components, especially lithium, cobalt, nickel and similar materials. From the perspective of the European Union, the shortage of such materials in EU countries is a problem and therefore at least cobalt, graphite and lithium contained in LiA belong to critical raw materials for the European Union. Renewal of these components is an important way to recovery, but, on the other hand, it is a complicated and challenging process, since this secondary raw material is very complex.

A lithium battery is a fairly complex system made up of different materials and operating at different levels as shown in Figure 1.

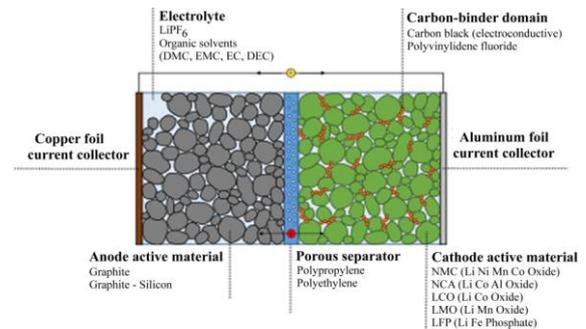


Figure 1 Schematic view of the main LiA components [1]

The basic LiA unit is a body consisting of a copper foil representing the current collector, on which a porous anode material consisting of graphite or silicon particles fixed with a binder is placed. Space between the anode and the cathode is separated by a polypropylene or polyethylene separator. The porous cathode is made from an active material mixed with conductive carbon and the polymer polyvinylidene fluoride PVDF binder. The cathodic conductive collector is made of aluminium foil.

The porous electrodes and the separator are soaked with an electrolyte consisting of LiPF₆ salt dissolved in a mixture of organic solvents such as dimethyl carbonate DMC, ethyl methyl carbonate EMC, ethylene carbonate EC, cyclohexylbenzene CHB, diethyl carbonate DEC [2]. These listed are placed in layers which are hundreds of microns thick or less, they are many times interleaved and placed in a steel or aluminum casing or in a flexible casing wrapped with an aluminium-coated foil [3,4].

The composition of the anode is essentially uniform and consists of graphite allowing intercalation of lithium. [5]. The active anode material is bonded with a PVDF binder, allowing good adhesion to the current collector film. [3]

In contrast to the anode, the composition of the cathode is more complicated due to conductive components such as soot and PVDF binder, the different chemical composition of the cathode active material which is caused by manufacturing processes and materials of different manufacturers. Lithium cobalt oxide LiCoO₂ (LCO), lithium manganese oxide LiMn₂O₄ (LMO), lithium nickel manganese cobalt oxide

$\text{LiNi}_x\text{MnyCo}_{1-x-y}\text{O}_2$ (NMC), lithium nickel cobalt aluminium oxide $\text{LiNi}_x\text{CoyAl}_{1-x-y}\text{O}_2$ (NCA) and lithium ferrum phosphate LiFePO_4 (LFP) are active cathode materials [6]. These differences usually arise from the use of individual cells in individual devices, such as smartphones, laptops, cameras, etc., hence their characteristics and, in turn, production costs.

For the EV and HEV segment, NMC cathodes are usually specified. They have varying stoichiometry, ranging from $\text{LiNi}_{0.33}\text{Co}_{0.33}\text{Mn}_{0.33}\text{O}_2$ and $\text{LiNi}_{0.5}\text{Co}_{0.3}\text{Mn}_{0.2}\text{O}_2$ to $\text{LiNi}_{0.6}\text{Co}_{0.2}\text{Mn}_{0.2}\text{O}_2$ and $\text{LiNi}_{0.8}\text{Co}_{0.1}\text{Mn}_{0.1}\text{O}_2$ in order to achieve different LiA properties [7].

The composition of LiA suggests the possibility of obtaining valuable components by recycling this secondary raw material [8 – 10]. Recycling enables us to obtain valuable scarce metals, thus saving primary raw materials [11].

Based on published experimental studies, it appears that recycling processes of discarded LiA start with pre-processing using physical-mechanical treatment procedures. These include the discharge of residual voltages, disassembly, reduction and sorting of mainly pure components found in LiA as part of the composite structure. The next step is the application of physical-chemical processes such as thermal or hydrometallurgical processes [12 – 13].

Figure 2 schematically shows the general processing sequence of discarded LiA [12].

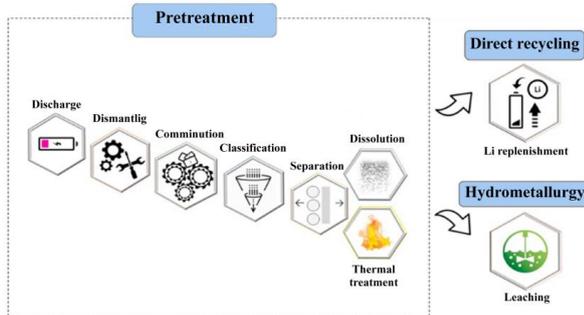


Figure 2 Processing sequence of discarded LiA [12]

Historically, LiA recycling methods were initially developed through mechanical processing, where the results were an attempt to recover elementary copper, elementary aluminium and possibly plastics. From this point of view, these were relatively simple processes, with copper and aluminium obtained by high-temperature melting processes. However, it was obvious that particularly valuable components such as lithium, cobalt, nickel also need to be extracted, especially as their price is rising dramatically, as shown in Table 1, which shows that metal prices have recently risen dramatically, on average by up to 100 percent or more compared to 2020 [13], and their price is rising continuously, which implies that the price of LiA waste is rising as well, Figure 3.

Table I Material composition of LiA with respect to prices of individual components

COMPOUND	Compound content [%]	2020		2021		2022	
		Compound price /t [US\$]	Compound price in LiBs [US\$/t]	Compound price /t [US\$]	Compound price in LiBs [US\$/t]	Compound price /t [US\$]	Compound price in LiBs [US\$/t]
lithium (Li ₂ CO ₃)	1(5.32)	8000	426	24800	1319	80250	4269
cobalt	3	33965	1019	55755	1673	82000	2460
copper	9	6810	613	9860	887	10200	918
aluminum	35	1744	610	3076	1077	3214	1125
nickel	3	14554	437	19825	595	32445	973
manganese	3	1667	50	7520	226	7039	211
graphite	8	500	40	970	78	1310	105
steel	9	295	27	445	40	510	46
plastics	11						
volatile compounds	8						
electronics	3						
cables	2						
		#	3222		5895		10107

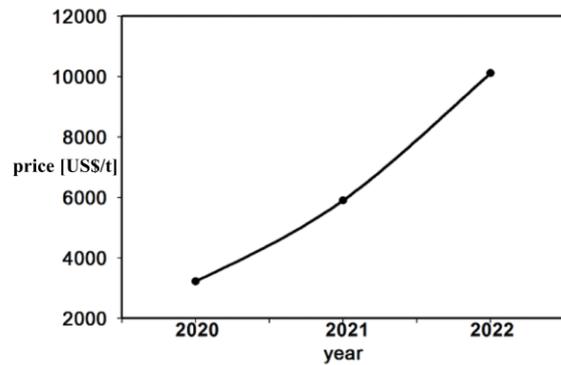


Figure 3 LiA waste price development

Due to the continuous dynamic development in LiA design and composition, recycling methods for LiA processing are quite difficult to optimise. Therefore, the possibilities of pyrometallurgical as well as hydrometallurgical recycling of LiA in a laboratory as well as semi-operational and industrial scale are being continuously investigated [14 – 16]. In both cases, physical-mechanical pretreatment of discarded LiA is included in the process [15].

Although discarded LiA is formally classified as other waste in the Waste Catalogue [17], it is potentially a hazardous waste due to its explosivity, flammability, small particle size and toxicity of some components. A new Regulation of the European Parliament and of the Council concerning batteries and waste batteries, repealing Directive 2006/66/EC and amending Regulation (EU) No 2019/1020 [18] is currently in the process of draft and approval and should address some disputable issues.

In any case, recycling of discarded LiA is a potentially environmentally hazardous as well as financially demanding process [19].

II. EXPERIMENTAL

Prior to the actual recycling procedure, it is necessary to consider the fact that the electric cells in an EV or HEV are designed in three groups as an individual

electric cell, the battery module and the battery pack, as described in Table 2.

Table 2 Classification of automobile drive unit batteries

Classification	Definition	View
battery cell	Basic LiBs unit generating of electrical energy by charging and discharging. Constructed from cathode, anode, separators and electrolyte inserted into aluminum cover.	
battery module	Battery complete inserted in frame in exact amount due to save of cells from outer shocks, vibrations or thermal shocks	
battery pack	Final form of battery systems installed into EV/HEV cars. It is clustered from modules and various operating and protective systems involving electrical control, cooling, etc. It usually contains 8 modules; each contains 12 cells in one accumulator.	

It follows that the representation of individual materials in individual battery segments will vary, as the more robust an individual segment, the more it contains other systems, as shown in Table 2.

Table 3 provides a list of content items of basic components in an electric cell and an electric module, while the module contains the same electric cells.

Table 3 Content comparison of basic components in an electric cell and an LiA electric module

	Cu	Al	active mass	plastics	electrolyte
	mass %				
cell	15.8	5	60	5	15
module	10	13	48	13	11.5

Table 3 lists average values. The differences result from the fact that the cells are placed in housings, casings, etc., and other electronic control and protection devices are present at the same time. The composition of the entire battery pack is not available due to the design diversity of individual EV/HEV manufacturers.

This fact significantly affects economic calculations of recyclers both in terms of investment and operating costs in relation to the size of the processed units and in terms of the expected yields and efficiencies of the recycling processes.

Considering the material composition and design of LiA, the following procedures, or a combination thereof, are generally used:

- physical-mechanical pretreatment
- pyrometallurgical processing
- pyrohydrometallurgical processing
- hydrometallurgical processing

This order is valid also historically – at the beginning there was an interest in obtaining pure metals such as copper, aluminium and iron, and since these metals are found in LiA in their elementary form, it was enough to apply physical-mechanical treatment procedures and then to remelt the pure metals after a slight treatment (pressing, briquetting). The rest, however, disappeared as waste. However, it contains very valuable components (Li, Co, Cr, etc.) which are usually hazardous due to the form in which they are present. Therefore, hand in hand with the progress of scientific research, more sophisticated pyrohydrometallurgical and hydrometallurgical methods of processing, or the processing of residues after physical-mechanical treatment, gradually began to be applied in order to obtain these valuable components.

In this case, the following research procedure for the processing of discarded automotive LiA was considered:

- discharging of the residual electric charges with regard to the danger of its burning or explosion during mechanical processing
- material and structural analysis of the individual LiA with regard to the fact that there are many various designs
- physical-mechanical processing since it is a complex composite material of metal, inorganic, plastic and organic components
- possibilities of separation and extraction of metals in their elementary form as Cu, Al, Fe
- possibilities of separation and extraction of active mass
- possibilities of separation and extraction of plastics
- possibilities of separation and extraction of metals from the solution, especially Li, Co, Ni,
- waste management

A. Discharging of residual electric LiA charges

The discarded LiAs always show a certain value of residual voltage. During improper handling or mechanical processing this voltage can cause a short connection and subsequent ignition or explosion of the cell. Therefore, it is automatically assumed, that the discarded electric cells enter the process of material recycling with minimum or no residual voltage.

The stabilisation processes of the discarded LiA processing generally aim to reduce the residual voltage (depending on the type of the electric cell) to 2.5 V and less. Residual voltage in a cell should stay at the level below 2%. This will eliminate the risk of ignition or explosion by mechanical damage during processing. Of course, it all depends on the chemical composition and structure of the individual cells.

Table 4 compares the investigated techniques for discharging or pre-processing of discarded LiAs, highlighting their most significant advantages and disadvantages.

Table 4 Comparison of various pre-processing methods of the discarded LiA with the aim to discharge them

Process	Advantages	Disadvantages
Electric discharging	Potential energy recovery	Difficult setting of the energy recovery
Discharging in saline solutions	Low price	Energy cannot be recovered, necessity to process waste solutions
Cryogenic processes	Safe process, possibility to recover metallic Li	High energy, investment and operating costs
Thermal processes	Total discharge of the cells, easy handling	Possible degradation of materials, impossibility to extract electrolyte, formation of volatile components
Milling in an inert atmosphere	Necessity to use dry materials	Possible ignition not excluded, necessity to process volatile components
Wet milling	Very simple and cheap, work in a closed cycle	Theoretical necessity of cleaning of the waste water

In this case, the possibilities of discharging the discarded LiAs in salt solutions and by wet milling were investigated.

In the case of discharge in salt solutions, NaCl solutions of different concentrations were prepared and the time dependence of LiA discharge in these solutions was monitored. The graphical representation of residual voltage time dependence from the density of the saline solution is shown in Figure 4.

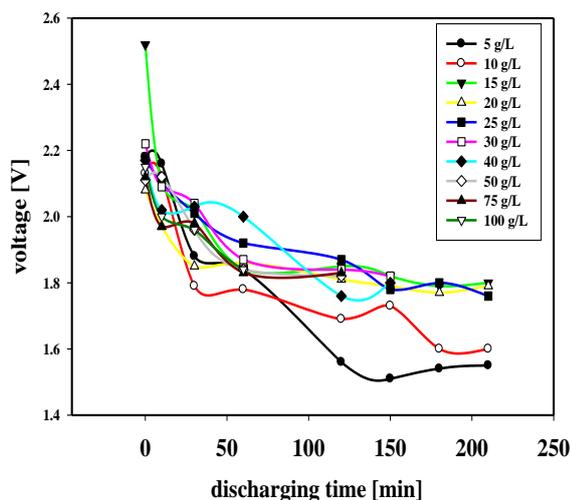


Figure 4 Time dependence of LiA discharging depending on the density of the saline solution

Discharging of LiA in an aqueous NaCl solution will lead to certain reduction of the residual voltage, but the electrodes corrode and the process slows down. It does not depend on the NaCl concentrations, on the contrary, it seems that lower concentrations at the level of 5 or 10 g/l

are more effective. However, it is certain that some residual voltage remains even in thus treated cells since some sparking, although moderate, still occurred during disassembly.

The wet milling of discarded LiAs proved to be an effective method where the LiA was thrown into the rotor crusher and the crushed parts fell directly into the water, so that even if burning occurred, the process was terminated by the fall into water. For this method, however, it is necessary to accurately track the performance of the crusher against the amount of LiAs being crushed, because when trying to crush excessive amounts of LiA, it will actually result in overheating or even explosion. A separate part of this process step is the treatment of the leaking volatile organic electrolyte. This electrolyte is extracted and disposed of separately.

B. LiA material analysis

The average quantitative LiA material analysis is a rather challenging task, as LiA cells exhibit a high diversity with respect to the manufacturer as well as the actual components of which they are composed, as LiAs on the market have varying quality and performance, which is determined by their composition.

In this case, one sample cell was analysed which included a copper anode and an aluminum collector and had dimensions $32 \times 14 \times 1$ cm. The result is shown graphically in Figure 5.

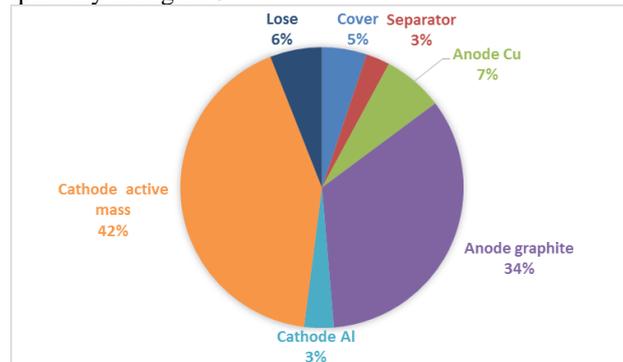


Figure 5 Material analyses of a chosen LiA cell

C. Physical-mechanical processing of LiA

In terms of the treatment processes the material streams were directed at future recovery of required metals, graphite, black material, organic components and plastics. With regard to the possible risks and complexity of the material composition and, at the same time, differences in the structure and composition of the individual LiA, the disassembly is very expensive and inefficient and, therefore, shredding of the entire cells is applied with subsequent sorting and extraction of individual components of the LiA.

In the first mechanical processing step, the discharged batteries were crushed in a rotor crusher. The process was set up so that the crushed mixture fell from the crusher directly into the water tank. The resulting water slurry did

not hinder further processing, since the following hydrometallurgical steps were considered. This procedure completely eliminated the risk of ignition or explosion and significantly reduced the evaporation of volatile electrolytes. In addition, a very important finding arose that controlled input for crushing also resulted in smooth destruction of undischarged cells. A mixture of slurry containing active mass, imperfectly separated electrode materials and separators, and a high pH (+10) solution was present in the water collection tank after crushing.

The components contained in the slurry have a different specific weight. The separators that are made up of a fine plastic film have a smaller specific weight than water and therefore float on the water surface. From there they are easily collected and after washing they give a product of relatively high purity. Subsequently, the remaining mixture was re-screened to separate the mixture of electrode materials and active mass from the original solution. This resulted in three separate components: separators, a mixture of electrodes and an active mass, and a relatively dirty solution with high pH.

The mixture of electrodes and active mass obtained in the previous step was flushed on a fine sieve. This process separated the active mass from the mixture underneath the sieve and formed another slurry containing the unsettled active mass. The remaining electrodes still contained a small amount of active mass that did not separate from the surface during mechanical pre-treatment. Therefore, the mixture was re-crushed, which caused sufficient separation of individual components of the composite from each other.

The presence of copper and aluminium particles as well as plastics and black matter can be detected with naked eye in the resulting mixture above the sieve after crushing. In order to determine the granulometric composition, sieve analysis was carried out in a standard way according to STN ISO 44 1313. This resulted in a cumulative and distribution arrangement of the LiA crumb as shown in Figure 6.

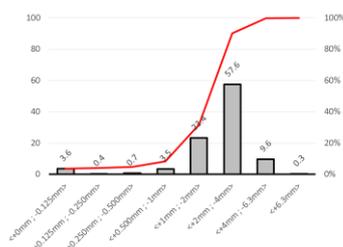


Figure 6 Cumulative grain size distribution (red dependence) and particle distribution (bar graph)

The results show that about 60% of particles are in the range of 2 – 4 mm. Optical observation may imply the presence of golden-red particles, which are represented by copper, grey to black particles, which are represented by either aluminium or plastics from separators, both contaminated with black mass, and black mass itself, which is concentrated into small grains. At the same time,

the distribution of these particles into different grain size classes can be seen. Copper was predominantly concentrated in the +1 -2 mm grain size class, aluminium in the +2 -4 mm grain size class and separators in the +4 mm grain size class. However, aluminium and separators are probably mixed, and towards the larger particles there are more separators in the mixture. The finest particles are made up of optically black mass and it was not possible to clearly determine their form. Therefore, they were subjected to a diffraction phase analysis. The results have shown that the black mass is not a uniform material, since the phase analysis in this case indicated the presence of at least two phases, namely carbon phase and LiNiO₂ phase.

The LiA crumb showed the presence of main components of copper, aluminium, black mass and plastic separators. These components differ significantly from each other in their specific weight. Therefore, gravity sorting was chosen for the experimental tasks. The results have shown that the relatively light aluminium was concentrated into a light fraction and the heavier copper into heavier fractions. The mutual separation of aluminium and copper can be achieved with high efficiency. Separators are very light and separated into the lightest fractions.

The active black mass is of two types, anodic and cathodic. During separation, it was found that the anode mass, represented by graphite, separates easily from the metal carrier, whereas the cathode mass, represented by complex lithium oxides, sticks very tightly to the aluminium cathode and separates very hardly, or not at all. The result was that in the first stage, a mixture of aluminium with active mass and copper was separated. Further chemical procedures more thoroughly separated the active mass from the aluminium and the copper residue from this semi-finished product.

An overall view of all the products of LiA crumb sorting by gravity crushing is shown in Figure 7.



Figure 7 Products of experimental LiA crumb sorting

The material balance of the implemented procedure is shown in Table 5

Table 5 Material balance of the implemented procedure

Component	Copper	Aluminium	Active mass	Separator	Return material
amount [%]	36.47	10.12	14.87	19.05	19.6

The return material is a mixture of electrode collectors, active mass and plastics. It goes back into the process for re-sorting.

III. CONCLUSIONS AND RECOMMENDATIONS

The results so far have shown the possibility of material recycling of discarded traction batteries of electric vehicles. Through a suitably adjusted procedure and by observing the tracked parameters, the sorted materials obtained are metallic copper, metallic aluminium, black active mass consisting of both cathode and anode mass, and plastic separators. Prior to actual processing, the discarded LiA must be treated to discharge the residual voltages.

The procedure was studied experimentally under laboratory conditions in which several routes have been studied in which either the maximum amount of active black mass can be obtained with a minimum of aluminium, or metallic aluminium mixed with active mass and possibly with copper. The approach to be acceptable with a high benefit must be decided by a thorough economic analysis, not only in terms of price of final saleable products, but also in terms of investment and operating costs.

The products obtained are currently of most interest to the recycling industry. However, lithium batteries contain other components that are very interesting with respect to price. Such components are organic components, for instance PVDF, etc., other non-ferrous metals (due to LiA design) such as nickel, cobalt, manganese, etc., but especially lithium.

In future, the focus of this project will be on the recovery of these components in the material recycling of discarded LiAs. At the same time, the focus will be on semi-operational and operational validation of the proposed procedures. In this respect, the cooperation with SAKER, s.r.o. in Horný Hričov is an invaluable help.

Based on the theoretical and experimental research into the processing of discarded automotive LiAs, a block scheme for the processing of this secondary raw material was proposed as shown in Figure 8.

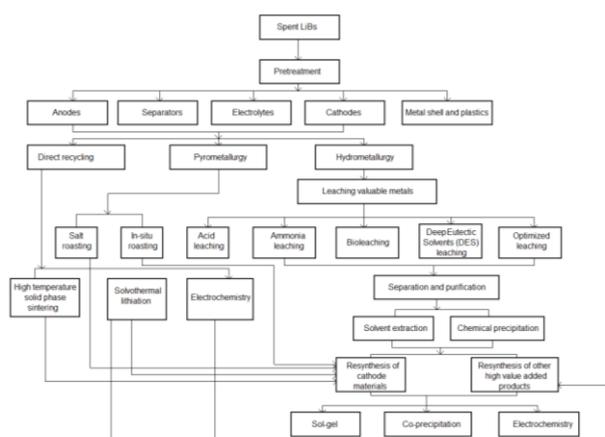


Figure 8 Block scheme for the processing of discarded automotive LiAs

The specific agents, individual procedures and qualitative as well as quantitative parameters will be determined according to the specific type of processed LiAs.

Figure 9 shows the proposed method of material recycling of discarded automotive batteries in the context of circular economy.

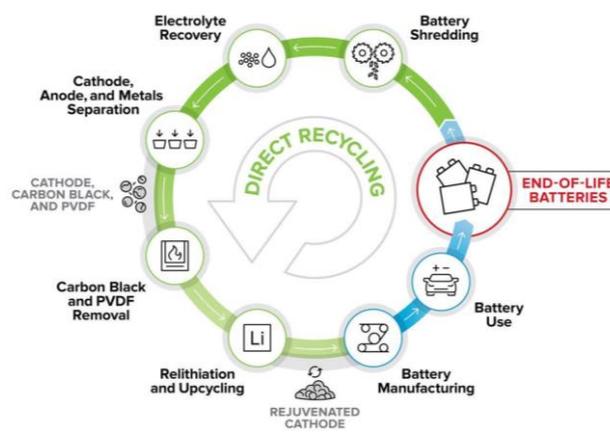


Figure 9 Material recycling of LiAs in the context of circular economy

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Environmental assessment of the particle boards with content rubber waste from the automotive industry

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Abstract—The automotive industry is a sector with a significant impact on the economies of many countries. Around the world, a lot of rubber waste from the automotive industry has become a problem for many countries. It is a significant environmental problem. The article deals with the possibility of the recycling waste from the automotive industry by using it in wood composites and their impact on the aquatic and terrestrial environment. Aqueous extracts were prepared from the experimental samples (wooden composites with various additions of the waste rubber from tires and waste seals). The pH value and organic pollution (by COD) were determined in the aqueous extracts. The effect on the environmental components (aquatic and terrestrial) was tested using ecotoxicological tests using the test organisms *Sinapis alba*, *Lemna minor* and *Daphnia magna*. Preliminary acute ecotoxicity tests were performed.

Key words: plastic, rubber, waste, wood composites, ecotoxicity, automotive industry

I. INTRODUCTION

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Every year, a large number of the cars end their useful life and become waste. One of the many wastes generated by the automotive industry is waste tires and waste seals. Waste tires and their accumulation in the environment represent a global environmental problem. One possibility of the using waste tires is the creation of the granulate from them, which is used for playgrounds with synthetic turf. The company became interested in whether the chemical substances found in this granulate could have a negative impact on human health. More than 100 scientific studies have been developed on this topic. Many of these studies are academic research and government reports produced by the European Chemicals Agency (ECHA) and the Environmental Protection Agency (EPA). In 2016, the EPA and the Centers for Disease Control began a research project which represents one of the largest studies of the synthetic turf and rubber granules derived from waste tires. They found that, despite the high

proportion of the chemical substances found in rubber granulate, human exposure to these substances during activities on the playground is quite limited. The problem with waste tires is that they contain heavy metals and various chemicals that are potentially mutagens and carcinogens. Through gradual decomposition, these substances reach the environment. Toxins from these substances can contaminate the soil or water environment. Contaminated soils have a negative effect on the flora, fauna and on people. A significant risk is represented by rubber microparticles, which are present in the environment. The main contaminants of the rubber microparticles include zinc, PAHs and 6ppd-quinone derived from the 6PPD compound contained in tires. Zinc in tires represents up to 1-2% of the total weight. The solubility of zinc from rubber microparticles is influenced by UV radiation, pH value and microparticle size. In the case of increasing pH values, the solubility of zinc decreases considerably. The solubility of zinc from the particles of the waste tires increases in the presence of UV radiation and, on the contrary, decreases in the dark. The solubility of zinc is also influenced by the size of the particles coming from the tires, because with a smaller particle size more zinc is leached due to an increase in surface area and mass transfer rate with smaller particles. A higher amount of zinc in the aquatic environment can cause a toxic effect for aquatic organisms. However, PAHs are also present in aqueous extracts, which may be largely responsible for the overall toxicity. PAHs represent substances, which are immunotoxic, mutagenic and carcinogenic to many different types of aquatic organisms. Rubber microparticles can present varying degrees of the chemical toxicity because it depends on the chemical composition, particle type and size or other factors. Particles which come from waste road tires may contain certain chemicals compared to tires which are created in laboratory conditions. The cause is possible chemical entrapment which come from the road or other abiotic factors [1, 2, 3]. Recycling represents an important solution in reducing waste tires and waste seals from landfills. The processing of the waste tires and seals into granules with subsequent incorporation into various building materials is one of the ways of their reuse.

II. MATERIAL AND METHODS

The work experiment is aimed at assessing the impact of the wood composites prepared with waste from the automotive industry on the aquatic and terrestrial environment.

A. Experimental samples

Particle boards were made by replacing wood with 10, 15 and 20 % waste rubber/seals or with 10, 15 and 20 % waste tires. The used granulate in the waste rubber composites consisted of the seals with a size fraction of 1.0 - 3.0 mm. Granulate from the waste tires had a fraction size of 1.0 – 30 mm. Granules from the waste seals and waste tires from automobiles were obtained from the company AVE SK-Kechnec plant Slovakia. Particle boards without added waste was also used for testing. Wood composites were prepared in the laboratories of the Technical University in Zvolen, Faculty of Wood Sciences and Technology, Department of Furniture and Wood Products.

B. Preparation of aqueous extracts.

Aqueous extracts were prepared from the each sample by leaching for 24 hours and 48 hours with a leaching agent - demineralized water with pH adjusted to a value of 3. The volume of the leaching agent was calculated based on the size of the surface of the wood composites, which had the shape of a cuboid. In order to maintain the ratio of the values of the surface of the sample and the used demineralized water in the ratio of 1:5, the volume of the treated demineralized water was calculated according to the calculated surface, which was 2950 ml. The dimensions of the composites were the same. Each sample was placed separately in a glass container and a volume of 2950 ml of extracts was added. After the leaching, samples of the aqueous extracts were taken and used for testing [4, 5].

C. Determination of selected indicators: pH, COD_{Cr}

The pH value was determined using the WTW Ino Lab pH Level 3. SenTix 81® electrode [4, 6].

By determining the COD_{Cr}, the amount of the substances of the organic origin present in the sample is estimated. The process of this method consists in the oxidation of the organic substances found in water by means of potassium dichromate in a strongly acidic environment, which is formed by sulfuric acid during two hours of boiling [4, 7].

D. Ecotoxicological tests

Tests were used to assess the harmful effects of substances released into water extracts: growth inhibition test with *Lemna minor* (Table 1), acute toxicity test on *Daphnia magna* (Table 2) and *Sinapis alba* (Table 3). Preliminary tests were carried out in all tests [8, 9]. Test conditions are listed in the following tables.

TABLE 1 THE TEST CONDITIONS FOR LEMNA MINOR [10, 11]

Test organism	<i>Lemna minor</i>
Biotest conditions	25°C ± 2°C, day and night simulation; continuous lighting with min. intensity 6,500 lux, thermostat ST FOT (Eko Pol Poland)
Control sample	Z-medium (nutrient solution prepared according to the instructions of the supplier CCALA, Třeboň, Czech Republic)
Reference substance	3,5-dichlórfenosl, EC ₅₀ = 2.9 mg/l (limit 2.2 – 3.8 mg/l)
Test duration	7 days
Preliminary test	15 leaf/sample
Validity of the test	mean number of leaflets in the control after the end of the test > than eight times at the beginning of the test, pH at the end of the test < than 1.5 compared to the input pH
Monitored response	growth rate (inhibition)

TABLE 2 THE TEST CONDITIONS FOR DAPHNIA MAGNA [12,13]

Test organism	<i>Daphnia magna</i> Straus, individuals younger than 24 hours
Biotest conditions	21°C ± 2°C; 7.8 ± 0.2; laboratory conditions
Control sample	diluting water prepared from the solutions of CaCl ₂ ·2H ₂ O (1), p.a., MgSO ₄ ·7H ₂ O (2), p.a., NaHCO ₃ (3), p.a., KCl (4), p.a.; by the addition of solutions (1) - (4) per 10 ml and adding demineralised water into a volume of 1 liter
Reference substance	K ₂ Cr ₂ O ₇ , EC ₅₀ = 0.82 mg/l (limit 0.3 – 1.5 mg/l)
Test duration	48 hours
Preliminary test	20 daphnia/sample (10 ml), same conditions for a control
Validity of the test	immobilisation ≤ 10 %, change of concentration of dissolved oxygen O ₂ ≤ 2 mg/l
Monitored response	% of immobilised individuals

TABLE 3 THE TEST CONDITIONS FOR SINAPIS ALBA [14].

Test organism	<i>Sinapis alba</i>
Biotest conditions	20 °C ± 1 °C, thermostat TS 606 CZ/2-Var (WTW, Germany).
Control sample	Reconstituted water
Reference substance	K ₂ Cr ₂ O ₇ , IC ₅₀ , 72 h = 28.5 mg/L (limit 4.1 to 85 mg/L)
Test duration	72 hours
Preliminary test	per 30 seeds of <i>S. alba</i> L. in Petri dishes/10 ml sample
Monitored response	Inhibition of growth of root from <i>S. alba</i> compared with the control

III. RESULTS AND DISCUSSION

A. Growth inhibition test with *Lemna minor*

The signs of the necrosis or chlorosis were not observed on the leaves of *Lemna minor* during the test. The growth rate μ and its inhibition $I\mu$ was calculated from the recorded number of the leaves (Table 4 - 5).

TABLE 4 BASIC CHARACTERISTICS OF THE TEST USING LEMNA MINOR IN AQUEOUS EXTRACTS AFTER 24 HOURS

Sample Composition	I μ (%)	
	Average	Standard deviation
Particle board (PB)	79.18	2.13
Particle board + 10% sealing	75.14	1.91
Particleboard + 15% sealing	75.55	2.33
Particleboard + 20% sealing	70.15	1.73
Particle board + 10% tire	78.91	0.71
Particle board + 15% tire	71.55	2.26
Particle board + 20% tire	67.31	1.59

TABLE 5 BASIC CHARACTERISTICS OF THE TEST USING LEMNA MINOR IN AQUEOUS EXTRACTS AFTER 48 HOURS

Sample Composition	I μ (%)	
	Average	Standard Deviation
Particle board (PB)	91.41	2.73
Particle board + 10% sealing	90.96	1.22
Particleboard + 15% sealing	79.66	2.72
Particleboard + 20% sealing	73.15	2.85
Particle board + 10% tire	90.96	1.22
Particle board + 15% tire	79.66	2.72
Particle board + 20% tire	74.91	2.34

The results of the preliminary test are positive because the growth rate inhibition was $\geq 30\%$. The values of I μ in extracts from the wood composites with the addition of the granulate from waste rubber/seals are lower compared to the wood composite without the addition of the waste, but there is no significant difference between them. With increasing addition of the waste to the wood composites, I μ decreases [10, 11]. The authors Fořt et al. [15], Hybská et al. [16] also dealt with the effect of the tire extracts on the aquatic environment and confirmed the inhibitory effect on growth rate.

B. Inhibition test of *Sinapis alba* root growth

The root growth inhibition (IC) was calculated from the measured lengths of *Sinapis alba* roots compared to the control. The values are in Tab. 6.-7.

TABLE 6 BASIC CHARACTERISTICS OF THE BIOASSAY USING SINAPIS ALBA IN AQUEOUS EXTRACTS AFTER 24 HOURS

Sample Composition	IC (%)
Particle board (PB)	76.23
Particle board + 10% sealing	61.07
Particleboard + 15% sealing	54.46
Particleboard + 20% sealing	43.74
Particle board + 10% tire	56.24
Particle board + 15% tire	43.58
Particle board + 20% tire	23.09

	Average	Standard Deviation
Particle board (PB)	58.77	5.99
Particle board + 10% sealing	46.26	2.75
Particleboard + 15% sealing	40.25	1.42
Particleboard + 20% sealing	31.25	0.74
Particle board + 10% tire	51.21	5.82
Particle board + 15% tire	44.26	3.46
Particle board + 20% tire	41.87	6.84

TABLE 7 BASIC CHARACTERISTICS OF THE BIOASSAY USING SINAPIS ALBA IN AQUEOUS EXTRACTS AFTER 48 HOURS

Sample Composition	IC (%)	
	Average	Standard Deviation
Particle board (PB)	76.23	5.21
Particle board + 10% sealing	61.07	2.10
Particleboard + 15% sealing	54.46	2.86
Particleboard + 20% sealing	43.74	1.65
Particle board + 10% tire	56.24	2.89
Particle board + 15% tire	43.58	1.92
Particle board + 20% tire	23.09	3.38

The preliminary test shows that the inhibitions of the root growth (compared to the control) with the addition of the wastes are lower than in the samples without the addition of the automotive waste. Also in this test, the influence of the wastes on the reduction of the inhibitory effect on the test organisms was recorded. We assume that a higher addition of the waste to the wood composites causes changes in the composition of the aqueous extracts. The wood content is lower and less water-soluble substances dissolve in the extracts. This is evidenced by the determined COD_{Cr} values (Table 9), which the concentration decreases with the increasing proportion of the waste in wood composites compared to the sample without the addition of the waste. Changes in the content of the organic pollution in extracts due to time have also been recorded. The samples with root growth inhibition $\geq 30\%$ compared to the control are positive, except for the sample with 20% granulate from the waste tires. Authors Fořt et al. [15] determined a terrestrial test with *Sinapis alba* to inhibit the aqueous extracts from tires by 31%. Our determined IC values (%) are higher and we assume that the higher inhibition is caused by the substances dissolved in the water extract from the wood [14].

C. Acute toxicity test on *Daphnia magna*

The result of the preliminary test is positive (Tab. 8). During the test, death or immobilization was $\geq 50\%$ [9, 12, 13].

TABLE 8 IMMOBILIZATION OF DAPHNIA MAGNA IN 24 HOURS AND 48 HOURS AQUEOUS EXTRACTS

Sample Composition	Imobilisation (%)	
	for 24 hours	for 48 hours
Particle board (PB)	100	100
Particle board + 10% sealing	70	98
Particleboard + 15% sealing	93	100
Particleboard + 20% sealing	100	100
Particle board + 10% tire	90	100
Particle board + 15% tire	100	100
Particle board + 20% tire	87	100

There are several studies [17, 18] in which the authors also used the test organism *Daphnia magna* in testing the toxicity of tire extracts. Similar to our testing, these organisms were very sensitive to the composition of the aqueous extracts. These studies recommend using the results from such testing as a basis for the eco-labeling of the automotive tires.

D. Determination of pH and COD_{Cr}

From Table 9 shows that the pH value in all extracts was acidic. Due to the influence of the addition of the waste to the wood composites and also the influence of the leaching time, a slight decrease in acidity was noted. We assume that the higher acidity in the extracts from the particle boards samples is caused by the degradation of acetylated hemicelluloses [19].

TAB. 9 SELECTED PHYSICO-CHEMICAL INDICATORS IN IN AQUEOUS EXTRACTS AFTER 24 HOURS AND 48 HOURS

Sample Composition	pH		COD _{Cr} (mg.l ⁻¹)	
	for 24 hours	for 48 hours	for 24 hours.	for 48 hours.
Particle board (PB)	3.66	5.11	1655.28	1993.86
PB+ 10% sealing	4.24	4.87	1053.36	1956.24
PB + 15% sealing	4.22	4.69	978.12	1918.62
PB+ 20% sealing	4.52	4.97	902.88	1918.62
PB + 10% tire	4.33	4.57	902.88	1580.04
PB + 15% tire	4.42	4.58	865.26	790.02
PB + 20% tire	4.12	4.95	865.26	639.54

The highest average COD_{Cr} value is in the wood composites without the addition of the waste (particle boards). The addition of the seals and tires in PB caused a reduced content of the substances of the organic origin without the influence of the type of the waste used compared to PB. In the case of PB with the addition of the

waste tires after 24 hours of leaching, there are up to about 50 % less organic substances in the extracts compared to pure PB. In these samples, on the basis of the determined COD_{Cr}, the effect of the percentage replacement of the wood with the tire waste in the production of the wood composites was noted.

The solubility of any metals contained in the samples containing tires is also affected by the size of the particles, because with a smaller particle size, a greater amount of the elements are leached due to an increase in the surface area. Their higher amount in the aquatic environment can cause a toxic effect for aquatic organisms [2]

IV. CONCLUSION

During the test with the test organism *Lemna minor*, no signs of necrosis or chlorosis were recorded on its leaves. The preliminary test results were positive and were higher in the 48-hour extracts. With increasing addition of the waste to the wood composites, I_u decreased. A terrestrial test using *Sinapis alba* revealed an inhibitory effect of the waste on the plant root growth (compared to the control).

We assume that a higher addition of the waste to the wood composites causes changes in the composition of the aqueous extracts. The wood content is lower and thus less water-soluble substances are leached into the extracts. From a chemical point of the view, wood is composed of the biopolymers of a lignin, cellulose, hemicellulose as the majority organic components. There is more wood in the samples without the addition of the waste, so the values were set higher.

Aquatic organisms *Daphnia magna* reacted most sensitively to the composition of the aqueous extracts. All the results were positive and 100% immobilization was noted in almost all samples.

The pH value was acidic in all extracts. Due to the influence of the addition of the waste to the wood composites and also the influence of the leaching time, a slight decrease in acidity was noted. We expect that the higher acidity in the extracts from the PB samples was due to the degradation of acetylated hemicelluloses. The highest average value of COD_{Cr} was in the wood composites without the addition of the waste (pure PB). The addition of the seals and also the tires in PB reduced the content of the substances of the organic origin without the influence of the type of waste used, compared to pure PB.

In conclusion, we can conclude that the addition of the waste rubber from tires and seals from the automotive industry to the wood composites, despite the fact that the test results were positive in most cases, shows in these samples more acceptable results in terms of the impacts on the aquatic and terrestrial environment than wood composites without the addition waste.

Because the wood composites have been used in practice for a long time and have the prospect of further use as building materials, the use of such waste from the automotive industry represents a suitable opportunity for their valorization.

Wood-based composites are a substitute for solid wood. Their production can contribute significantly to waste recovery, as they usually contain wood waste. Wood

composites are not only economically suitable, but also represent a high-quality building material.

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The evaluation of pellet production with an admixture of FFP2 masks formed by a small pellet press

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Abstract— The reuse of waste materials or their recycling is an important issue due to environmental protection. Nowadays, the world has faced a new environmental challenge due to a worldwide shortage, production, and following consumption of protective face masks. This article deals with the reuse of FFP2 masks as an admixture in wood pellets and observes their mechanical properties and also emission and performance characteristics for the potential optimal sample. However, emission and performance measurements are still realized at the present. Based on the results achieved in this work and also discussed results from other works, it can be concluded that the optimal sample could be the spruce pellets with 10% FFP2 masks. This sample met limit values for bulk density and also mechanical durability according to STN EN ISO 17225-2: 2021. Moreover, a higher percentage of FFP2 masks increases also the net calorific value. However, it is important to realize other measurements with regard to the emerging emissions.

I. INTRODUCTION

The use of face masks, also FFP2 masks as one of the preventive measures to slow down the COVID-19 transmission has resulted in a worldwide shortage of face masks, then increased their worldwide production, and also consumption and the increasing amount of medical waste [1]. Nowadays, the world has faced a new environmental challenge.

The disposition of waste can be realized by landfill, combustion, or pyrolysis. However, the toxins can penetrate into the soil during their landfilling. The combustion can lead to the increase of various emissions [2]. Therefore, it is necessary to reuse already used materials or realize their recycling [3].

This article focuses on the reuse of FFP2 masks as an admixture in wood pellets. These masks were added to spruce or beech sawdust with a weight proportion of 5% or 10%. Afterward, they were compressed into pellets by a small pellet press. Their bulk density was determined and their other mechanical properties were discussed. Nowadays, emissions measurements are still realized, but resulting gas emission and performance characteristics for the potential optimal sample have been also stated in this article.

Rezaei et al. dealt with the energy waste utilization from paper, plastics, household organic, and wood by

using palletization [2]. The combustible fraction of municipal solid waste is a blend of heterogeneous materials, which is the reason for difficult handling. Pelletization is an effective treatment to minimize heterogeneity. In the research of Rezaei et al., the individual components were ground, wetted to 20% moisture content, and subsequently pelletized. Increasing the content of plastics from 20% to 40% led to a reduction in energy consumption for their production and to an increase in the calorific value of pellets. Increasing the content of paper from 30% to 50% has increased the durability of the pellets, but more energy has been used to produce them [2].

The pellets should meet the mechanical and energy requirements. Mainly the use of alternative pellets brings together other problems, such as low bulk density, high ash content, low ash melting temperatures, low calorific values, and so on. Low bulk density means low energy density of pellets and then high transport and storage costs. High ash content and low ash melting temperatures cause the creation of deposit formation, slagging, and sintering [4, 5]. Except for this, emissions and environmental requirements are also necessary [6].

Lukáč et al. investigated the influence of various factors on emissions of nitrogen oxides (NO_x) and carbon monoxide (CO) and created a mathematical model based on the regression analysis [7]. Except it, the significant harmful emissions are particulate matter. Poláčik et al. found out that the decreasing oxygen content in the atmosphere can cause a higher production of particulate matter (PM) [8].

II. MATERIAL AND METHOD

Input materials were compressed by a small pellet press shown in Figure 1 with its power of 7.5 kW and theoretical efficiency of 150–200 kg/h. As input materials were used spruce sawdust, beech sawdust, and disintegrated FFP2 masks. Sawdust was supplied from local sawmills as waste material and further air-dried in a laboratory. FFP2 masks were used as a waste product from production. These masks were first crushed in small elements and then added to sawdust as an admixture. Also, pure sawdust pellets were created and compared with pellets with 5% and 10% of the weight proportion of FFP2 masks.



Figure 1. Used small pellet press.

Used materials were pressed outside and during different weather conditions, which affected mainly the spruce samples with 5% of the weight proportion of FFP2 masks. However, small pellet presses operate at a lower pressure than larger ones in general. Water had to be added to input materials before the pelletization process due to better connection. Despite it, samples were not being granulated after the first compression yet. The optimal moisture content was up to 20%. The produced connected pellets had a diameter of 6 mm. Afterward, pellets were air-dried in a laboratory again.

At least two weeks after their production, pellets were tested for bulk density, because low bulk density means low energy density of pellets and then high transport and storage costs [4]. The bulk density was calculated from the net weight per defined volume [9]. The individual samples were freely fallen into a container with a defined volume and then were weighted. Other realized measurements were described in the article of Čajová Kantová et al. [10] and here discussed in the Results and discussion section.

Nowadays, emissions measurements are still realized, but resulting gas emission and performance characteristic for the potential optimal sample are stated in the Results and discussion section. Gas emissions were measured by ABB AO 2020 flue gas analyzer with sensor modules Uras 26 shown in Figure 2 and the heat output was calculated based on the calorimetric equation.



Figure 2. Used flue gas analyzer

III. RESULTS AND DISCUSSION

Despite a theoretical efficiency of 150-200 kg/h, the real efficiency was at most 40 kg/h. The pellet production in a small pellet press was affected by many impacts such as weather conditions, the moisture of input materials, the pelleting phase, the setting of the pressure of the pellet roller to the die, and so on. During the production of FFP2 masks, the weather was cold which caused a long time to warm up to operating temperature. The high moisture of input materials could cause wet and disintegrated pellets and on the other way, low moisture could cause the repetition of the pelletization process due to their failure to connect together. The pelleting phase also influenced the process, because the pellet press first has to be heated to an operative temperature.

The results from the measurement and the calculation of bulk density are shown in Figure 3. Wood pellets for commercial and residential applications should have a bulk density in the range from 600 kg.m⁻³ to 750 kg.m⁻³ according to STN EN ISO 17225-2: 2021 [11]. Only two tested samples had a bulk density higher than 600 kg.m⁻³, namely pure spruce pellets and spruce pellets with 10% FFP2 masks. In general, spruce sawdust is better connected than beech sawdust due to higher lignin content. However, the sample of spruce pellets with 5% FFP2 masks was affected by cold weather conditions.

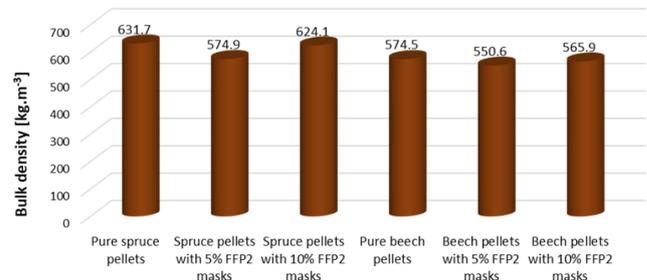


Figure 3. Bulk density of produced pellets.

In Table 1 are stated values of particle density described in more detail in the article of Čajová Kantová et al. [10]. The particle density of wood pellets should be ranging from 1000 kg.m⁻³ to 1400 kg.m⁻³ [12]. All values of individual samples had a particle density in this range.

TABLE I.
PARTICLE DENSITY OF INDIVIDUAL SAMPLES [10]

Sample	Particle density [kg.m ⁻³]
Pure spruce pellets	1186.5
Spruce pellets with 5% FFP2 masks	1132.3
Spruce pellets with 10% FFP2 masks	1129.2
Pure beech pellets	1199.6
Beech pellets with 5% FFP2 masks	1078.4
Beech pellets with 10% FFP2 masks	1163.4

According to the data stated in the article of Čajová Kantová et al. [10], the measured energy consumption was

in the range from 180.78 kWh to 872.63 kWh. The use of FFP2 masks in the pellets consumed more energy than during the production of pure spruce or beech pellets. The lowest energy consumption was measured for sample of pure spruce pellets. The highest energy consumed the sample of spruce pellets with 5% FFP2 masks, which was affected by cold weather conditions [10]. The energy consumption is then reflected in the price of the produced pellets. Except for the pelletization process, it is also necessary to include the preparation of input materials (crushing and drying), transport and storage costs in the price of pellet production.

Mechanical durability was also described in the article of Čajová Kantová et al. [10]. Only two samples, namely spruce pellets with 10% FFP2 masks and beech pellets with 5% FFP2 masks, met the limit value according to STN EN ISO 17225-2: 2021[11]. However, these samples also consumed more energy than the remaining samples with lower values of durability [10].

The production of pellets formed by a small pellet press required more manual work and the created pellets have worse quality in general than pellets made by an automatic pellet line.

Based on the all mentioned results, the potential optimal sample could be the spruce pellets with 10% FFP2 masks. Therefore, gas emissions are stated for this sample in Figure 4 during the combustion in a small heat source USPOR 18 AUTOMAT with a retort burner.

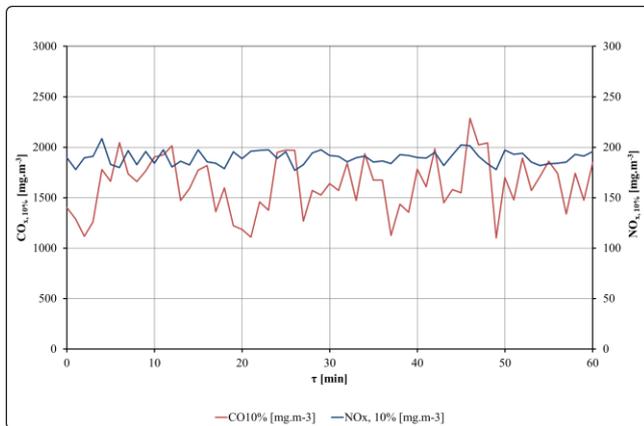


Figure 4. Gas emissions for spruce sample with 10% of FFP2 masks

Figure 5 represents the performance characteristic of used heat source during the combustion.

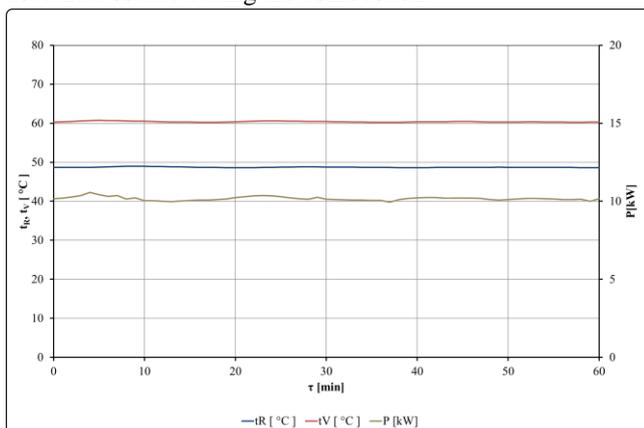


Figure 5. Performance characteristic for spruce sample with 10% of FFP2 masks

During one-hour measurement, the highest value of carbon monoxide ($CO_{10\%}$) was 2287 mg.m^{-3} and nitrogen oxides ($NO_{x,10\%}$) was 208 mg.m^{-3} . The heat output (P) was still approximately about 10 kW. Nowadays, emission and performance measurements are still realized.

The combustion of produced pellets in a small heat source USPOR 18 AUTOMAT with a retort burner is shown in Figure 6.



Figure 6. Pellet combustion in a small heat source

IV. CONCLUSION

The reuse of waste materials or their recycling is an important issue due to environmental protection. This article deals with the reuse of FFP2 masks as an admixture in wood pellets and observes their mechanical properties and also emission and performance characteristics for the potential optimal sample. However, emission and performance measurements are still realized at the present. Based on the results from determined bulk density and other properties investigated in the article of Čajová Kantová et al. [10], it can be concluded that the optimal sample could be the spruce pellets with 10% FFP2 masks. This sample met limit values for bulk density and also mechanical durability according to STN EN ISO 17225-2: 2021 [8]. Moreover, a higher percentage of FFP2 masks increases also the net calorific value. Spruce pellets were better connected than beech pellets due to higher lignin content. It can be also summarized that the reuse of FFP2 masks into pellets represents an interesting area of research and it is important to realize other measurements with regard to the emerging emissions.

ACKNOWLEDGMENT

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Lithium slag leach solution refining by hydroxide precipitation

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Abstract— Lithium-ion batteries (LIBs) contain many of critically important metals and their effective recycling after end-of-life is key for the sustainable development of the EU. The recycling process can be divided into pre-treatment of accumulators, which includes disassembly and possibly discharge, then into mechanical recycling, the goal of which is to separate Cu and Al current collectors and black mass from other components, and the last step is the recycling of the black mass itself. In the past, only metals such as Co, Ni, and Cu were recycled from black mass by pyrometallurgy, Li and Al were concentrated in the slags and further processing of the slags was not possible. Novel approach of a black mass pyrometallurgical treatment propose possibility of further hydrometallurgical recycling of slags. In this paper, refining of solution obtained by leaching of slag in sulfuric acid is studied. Solution most valuable dissolved element is Li, but in addition it also contains Al, Si, Co, Mn, Ni and Cu, which removal is essential before high purity Li recovery is possible. Refining is performed by pH adjustment by addition of NaOH, which confirm the possibility of 100 % removal of Al, Cu, Mn, 93.56 % removal of Si and 61.75% removal of Co. Results also confirmed that removal of Li was not suitable by this method and addition of NaOH caused 8.75% Li loses at the optimal conditions.

I. INTRODUCTION

The use of new technologies requires variety of different materials, and countries in the EU have a particularly high consumption. In order to ensure high demand, in addition to the extraction from primary raw sources by EU countries, it is necessary to import raw materials from other countries, which represents a significant risk for our sustainable development. Reducing the shortage risk of raw materials is possible through their production from secondary raw materials, which is the main goal of the circular economy implementation into strategic sectors of the EU [1].

Lithium-ion batteries (LIBs) are used in the key sectors such as renewable energy, e-mobility, communications, and many others. LIBs work as simple electrochemical rechargeable cells that can be use as single cell or are connected in series or parallel. This makes batteries suitable for wide use of applications. From the material point of view, they contain Al cathode with black mass layer on its surface, mostly Cu anode with graphite layer, but some LIBs use Al as anode as well, semi-permeable separator, electrolytes, binders and housing cover made

of Al and plastic composite foil. Battery packs made from multiple LIBs cells also contain wirings, electronics and additional plastic or Al cover. Black mass of currently used LIBs are oxide mixtures such as LCO (LiCoO₂), LMO (LiMnO₄), NMC (LiNiMnCoO₂), NCA (LiNiAlO₂), LFP (LiFePO₄) and LTO (Li₂TiO₃).

Spent LIBs represent important secondary material suitable for recycling, since we don't have access to all primary raw material deposits in the EU for the production of new LIBs and import in unreliable. Success at implementation of circular economy in the EU can be evaluated by end-of-life recycling input rate (EOL-RIR), from which its known, that recycling of LIBs is not sufficient compared to our consumption. Only 30-40% of Co, Ni and Mn comes from secondary raw sources and EOL-RIR for Li was under 1% in the year 2020 [2].

LIBs recycling methods can be mechanical, which focuses on crushing, milling, and sorting, pyrometallurgical, which use evaluated temperature to separate different phases, and hydrometallurgical, which use solvents to separate LIBs materials by selective dissolution and selective recovery from solutions [3-8].

Mechanical pre-treatment methods in LIBs recycling are used to recover Cu and Al current collectors and black mass. Further recycling of black mass needs to use more sophisticated methods, since chemical reactions have to be implemented in order to selectively recover products or by-products.

Hydrometallurgical treatment offers good selectivity, high purity of obtainable products and it also enable to recover graphite [9-11], which reduce carbon footprint of whole process. On the other hand, these methods are sensitive to changes in the chemical composition of the waste input, consume large volume of chemicals and overall capacity is not sufficient for the volume of LIBs waste generated. Therefore, the more robust pyrometallurgical recycling methods are current more suitable for LIBs at state of the art [12,13].

Pyrometallurgical methods does not need disassembly into smaller units and mechanical pretreatment, does not require discharge step and the risk of fire can be neglected. On the other hand, carbon present as anode active mass cannot be recovered, since this material is oxidized into CO₂. Slag forming additives causes oxidation of Li, Al and Mn into slag and other metals

such as Co, Ni, Cu and Fe are reduced into alloy. Further recycling or metal alloy is possible, but slag recycling is complicated, since slag forming additives in hydrometallurgical leaching steps forms dense gels in case of SiO₂ additive and gypsum which adsorb metal ions in case of CaO additive.

This scientific article builds on the results of the authors' previous research in the processing of black mass using the combined pyrometallurgical and hydrometallurgical method. Pellets of lithium-ion battery black mass generated from Accurec Recycling GmbH black mass were processed in the Electric Arc furnace (EAF) at the IME Process Metallurgy and Metal Recycling, Institute of RWTH Aachen University, Germany with the addition of SiO₂ used as flux and CuO used to react with excess carbon from pyrolyzed battery black mass [14]. Output of EAF treatment were Co, Cu alloy and Li-Al slag. Obtained slag was then crushed, sieved and metal particles impurities were separated by magnetic separation. The chemical and phase analysis of slag confirmed high content of Li (6.8%), Al (16.52%), Si (48.62%) and minor composition of Co, Cu, Ni and Fe. Phase analysis confirmed LiAlSiO₄ and Li₂SiO₃. Results of chemical composition before and after treatment of the lithium slag are shown in Table 1.

TABLE 1
CHEMICAL COMPOSITION OF LITHIUM SLAG BEFORE AND AFTER
MAGNETIC SEPARATION

Sample	Li	Co	Cu	Al	Fe	Si	Ca	Ni	Mn
Li slag [%]	6.80	1.17	1.53	16.52	0.51	48.62	1.16	0.15	0.65
Demetallized Li slag [%]	6.96	0.00	0.11	16.40	0.20	51.10	1.26	0.01	0.88

Obtained Li slag powder was leached in sulfuric acid achieving high Li and Al leaching efficiency, but also high Si leaching efficiency, which caused gelation of solution by oligomerization of orthosilicic acid. Therefore, novel approach of leaching was studied, in which Li slag powder was firstly mixed with concentrated sulfuric acid and small amount of water, which resulted in exothermic reaction and caused silicon from LiAlSiO₄ and Li₂SiO₄ phases to precipitate as insoluble SiO₂. After reaction of this Dry Digestion experiment ended, mixture was dissolved in water. This

process maintained high Li and Al leaching efficiency and significantly reduced Si leaching from 50% to 1.25% at optimal conditions [15]. This paper further study possibility of recover marketable products from obtained leach solution. Overall lithium-ion battery process by proposed combined pyrometallurgical and hydrometallurgical method with the aim to recover lithium from slags is shown in figure 1. The aim of this paper is to study optimal conditions for impurity removal from the leach solutions.

II. MATERIAL AND METHODS

A. Sample Preparation

Lithium leach solution was obtained by dry digestion and leaching of lithium slag from EAF smelting of black mass pellets with the addition of SiO₂ and CuO according to process shown in Figure 1. In dry digestion experiment with the duration of 1 hour, 50 g of lithium slags was mixed with 50 ml of concentrated H₂SO₄ and 120 ml of deionized H₂O. Another 500 ml of deionized H₂O was added to the mixture and dry digestion and solution was stirred for next 15 minutes at room temperature. Leach solution used for this study was obtained by filtration of solid residues by vacuum filtration.

B. Analytical Method

The chemical composition of the solutions before and after refining was analyzed by atomic absorption spectrometry (AAS) using spectrAA20+ spectrometer (Varian, Australia). The pH of the solutions was measured with pH-meter (Inolab, WTW 3710, Germany).

C. Solution Refining Methodology

Thermodynamic calculations used as background for solution refining were performed by MEDUSA software (Make Equilibrium Diagrams Using Sophisticated Algorithms, 32-bit version 2010, Royal Institute of Technology, Stockholm, Sweden).

Three parallel refining experiments were carried out simultaneously in 200 ml glass beaker with continuous pH measurement and magnetic stirring of 200 rpm. Input material for the experiments was 100 ml of leach solution. 10 ml liquid samples were taken at the beginning of the experiment and after each pH

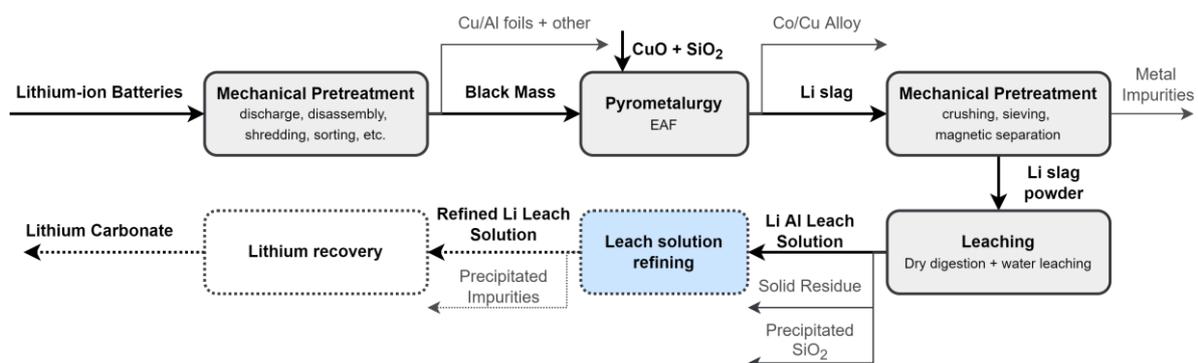


Figure 1 Proposed combined pyrometallurgical and hydrometallurgical lithium-ion battery recycling process with the aim of extracting lithium.

adjustment. The pH value was adjusted from initial 0.48 to 1, 1.5, 2, 2.5, 3, 3.5, 4, 4.5, 5, 6, 7, 8, 9, 11 and 12. For each 10 ml of sample taken, specific amount of 2M NaOH solution was added until next pH value was reached. Remaining volume (until 100 ml mark of glass beaker) was filled with deionized water.

Each sampling and filling up to volume 100 ml resulted in dilution of solution by 10%, which was taken into account and concentration values in the results were corrected by number of dilutions.

III. RESULTS AND DISCUSSIONS

A. Input Leach Solution Analysis

The results of atomic absorption spectrometry of the input solution obtained by slag leaching are shown in Table 2. Leach solution contains Al and Li in relatively high concentration and Si, Mn, Co, Cu and Ni in minor concentration. Although Al has the highest concentration, the highest value in solution is represented by Li (2367 \$/m³). Apart from Al, all other metals in the solution have a negligible value due to their low concentration and therefore we consider them as impurities. Impurities reduce the quality of the obtained Li, and for that reason, they have to be removed from the solution before obtaining Li itself.

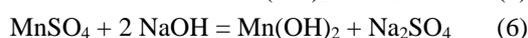
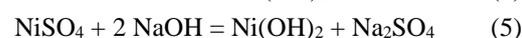
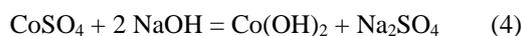
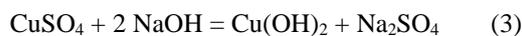
TABLE II
THE CHEMICAL ANALYSIS OF THE INPUT LEACH SOLUTION AND SPECIFIC MATERIAL VALUE OF INDIVIDUAL METAL IONS IN SOLUTION

Input Leach Solution	Li	Al	Si	Co	Ni	Cu	Mn
[μg/ml]	5 606	11 870	244.3	56.0	4.8	17.3	136.2
[mol/dm ³]	0.81	0.44	0.01	0	0	0	0
[mmol/dm ³]	808	439.96	8.7	4.15	0.09	0.31	2.48
[\$/m ³]	\$2 367	\$27.25	\$-	\$2.91	\$0.10	\$0.13	\$4.32

B. Theoretical Study of Precipitation

The aim of this study is to verify solution refining by precipitation of the impurities. Precipitation can be defined as a process where metal ions react with other compounds to form a low solubility product and metal hydroxide precipitation (by addition of NaOH) is the most common example of this process [16].

Reactions 1 – 6 shows potential reactions of metal sulfates present in leach solution with NaOH and table 3 shows the ΔG° values between 20°C and 80°C.



Figures 2-7 shows fraction diagrams of Li, Al, Co, Ni, Cu and Mn respectively. The fraction diagram for Li (Figure 2) shows presence of Li⁺ and LiSO₄⁻ ions in

TABLE III
ΔG° VALUES OF HYDROXIDE PRECIPITATION REACTIONS 1 – 6.

Temp.	ΔG° [kJ]					
	(1)	(2)	(3)	(4)	(5)	(6)
20 °C	-55.40	-595.81	-201.68	-167.05	-164.97	-147.65
40 °C	-56.33	-610.73	-205.58	-170.72	-169.05	-150.66
60 °C	-57.17	-625.09	-209.32	-174.24	-172.97	-153.52
80 °C	-57.93	-638.91	-212.89	-177.60	-176.73	-156.23

solution at calculated molarity in all pH under 12. According to the diagram, small portion of LiOH should start to precipitate at pH 12. Solubility of LiOH is 12.8 grams per 100 ml which represents Li concentration of 3699 μg/ml. Hydroxide precipitation method is not suitable for recovery of Li from solution since Li concentration is only slightly greater than the Li

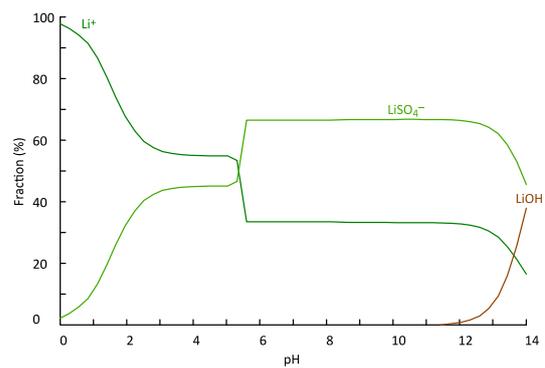


Figure 2 Predicted fraction diagram of lithium: [Li] = 808 mM

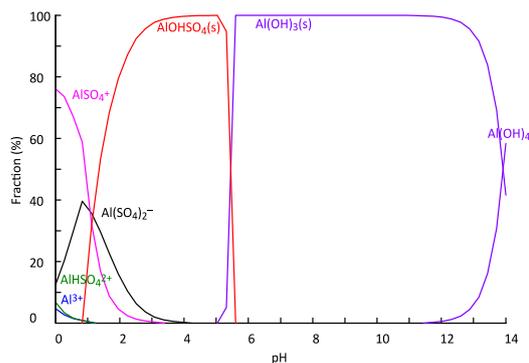


Figure 3 Predicted fraction diagram of aluminum: [Al] = 439.96 mM

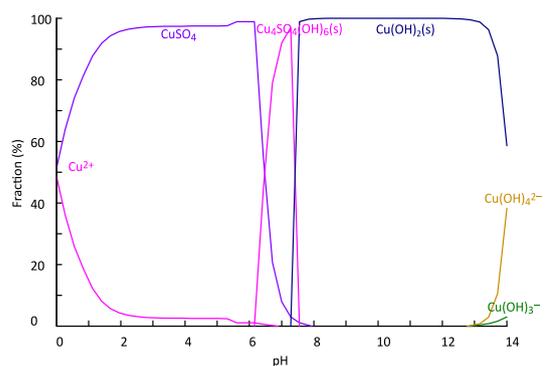


Figure 4 Predicted fraction diagram of copper: [Cu] = 0.31 mM

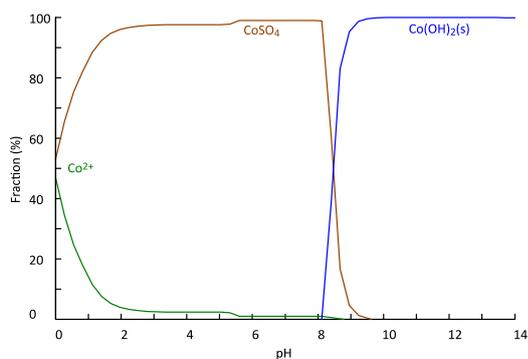


Figure 5 Predicted fraction diagram of cobalt: [Co] = 4.15 mM

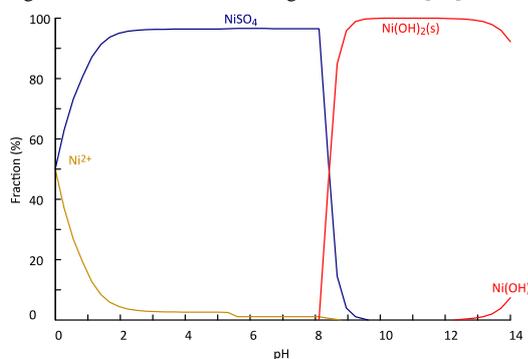


Figure 6 Predicted fraction diagram of nickel: [Ni] = 0.09 mM

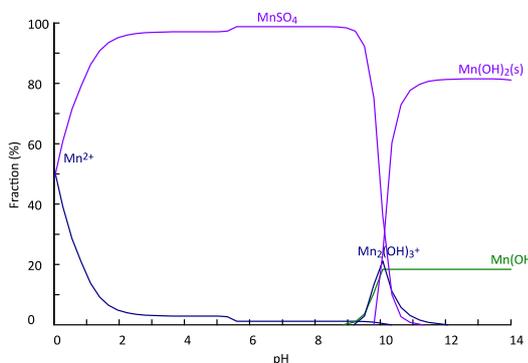


Figure 7 Predicted fraction diagram of manganese: [Mn] = 2.48 mM solubility and precipitation occur only at high pH, but removal of impurities from the leach solution should be possible at pH below 12 without loss of Li. Losses of Li may occur due to adsorption on the surface of the precipitated phases, which needs to be verified experimentally.

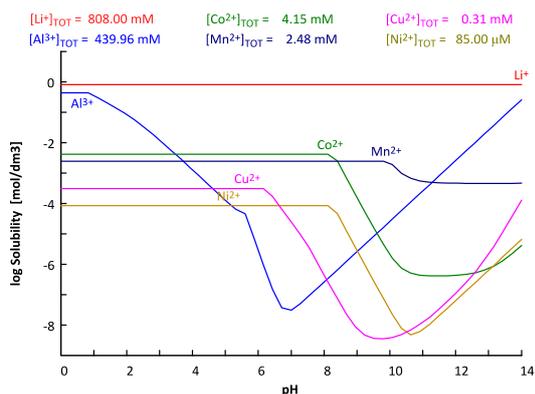


Figure 8 Molar solubility of elements present in lithium slag leach solution as function of pH

According to the fraction diagrams of Al (Figure 3), AlOHSO_4 complex, which solubility is unknown, should start to precipitate at pH 1. From pH 5 to 5.5, insoluble $\text{Al}(\text{OH})_3$ should precipitate. Cu hydroxide should start to precipitate from solution at pH 6 (Figure 4), Co and Ni hydroxides at pH from 8 to 9 (Figure 5 and 6) and Mn from pH 10 to 11 (Figure 7).

Figure 8 was constructed from the outputs of the fractional diagrams and the concentration of individual components in the thermodynamic system. Straight lines represent pH range, where metal should be soluble and curves represent pH ranges, where metal solubility is lower than concentration in solution and therefore - precipitation should occur.

C. Solution Refining Experiment

Metals concentration change as function of pH is shown in Figure 9. No significant concentration changes were measured between initial pH 0.48 of input Li leach solution and 3.5. The first changes have appeared between pH 3.5 and 6, where 99.37% of Al and 85.91% of Si precipitated out of solution. Cu precipitated out at pH 6. Li losses at pH 6 were around 10%. Further increase in pH above 6 resulted in precipitation of Co and previously precipitated Cu phases started to partially dissolve again. Maximum 60% of Co was precipitated at pH 8. The concentration of Ni was not changed during the experiments. Mn precipitation was observed above

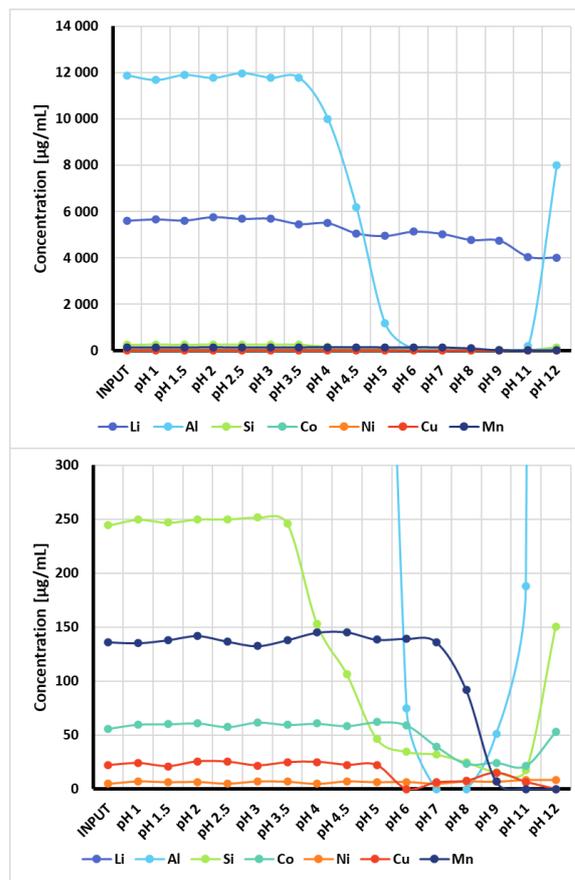


Figure 9 Results of lithium slag leach solution refining by pH adjustment: a) High concentration elements b) low concentration elements

pH 8 and 95.06% efficiency were achieved at pH 9. Li losses at pH above 8 were 14.86% and at pH 11 27.81%. Precipitated Al phases started to dissolve again significantly at pH above 11 and Si with Co phases started to dissolve at pH 12.

IV. CONCLUSION

Hydroxide precipitation is a simple and effective method for removal of some partially soluble ions from solutions. In this study, hydroxide precipitation was used on LiBs leach solution with the high concentrations of Al (11870 µg/ml), Li (5606 µg/ml) and with other elements such as Si, Mn, Co, Cu and Ni in concentrations below 250 µg/ml. The aim was to conduct thermodynamical study of hydroxide precipitation and compare conclusions with the results of the experiments.

Theoretical order of hydroxide precipitation was Al, at pH 5-5.5, Cu at pH 6-7, Co and Ni at pH 8-9 and Mn at pH 10-11.

The results of the experiments partially coincided with the thermodynamic study, but in some cases, it was possible to observe different intervals of elements precipitation. Precipitation is suitable for removing the most concentrated Al by adjusting the pH to 7. Si and Cu also precipitate together with Al, at pH 7. Li is adsorbed on the surface of the precipitated phases, which cause a loss of 8.75%.

At this point, it is proposed to filter the solution and, according to the analysis, the residual leach solution should contain 5034.9 µg/ml of Li, Al, and Cu should be below level of detection, 31.9 µg/ml of Si, 39.5 µg/ml of Co, 4.8 µg/ml of Ni and 136.1 µg/ml of Mn. Further increase of pH will remove other impurities, but also cause another 5% loss of Li.

Recovery of Li from solution by LiOH precipitation is not suitable for this specific leach solution, since large volume of NaOH solution is required to reach high pH. Therefore, it is proposed to combine pH 7 hydroxide precipitation with other more suitable selective solution refining methods to remove other impurities with small concentration below 100 µg/ml.

Recovery of Li from refined Li leach solution should be possible by precipitation of Li_2CO_3 , which is also marketable product for production of new LIBs.

ACKNOWLEDGMENT

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Production conditions for 3D printing of recycled material based waste HDPE

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Abstract— The main aim of this paper is to present the research findings which come out from the experimental investigation of the 3D printing conditions for material based waste materials (recycled HDPE). In this research study, the first step was to produce filament for 3D printer from recycled HDPE of an acceptable and competitive level of quality which could be used for 3D printing. Another steps was intended to an investigation of type of bed layer which should be used for 3D printing of such recycled HDPE material. The paper deals with the investigation of the impact and the relationship between the initial recycled HDPE material properties and production processes – filament producing and 3D printing. As the input raw material, two types of recycled HDPE material, represented by lids from PET bottles and waste from HDPE injection moulding, was used. The main aim of this research study was to determine the effect of 3D printing parameters (bed temperature, extruder temperature) with interaction of two types of recycled HDPE on the final printing's shrinkage.

I. INTRODUCTION

Plastic is an important and ubiquitous material in our economy and daily lives. Over the past 50 years, the role and importance of plastics in our economy has consistently grown. It has multiple functions that help tackle a number of the challenges facing our society. Light and innovative materials in cars or planes save fuel and cut CO₂ emissions [1]. In recent years, the global demand for plastic-based products has risen considerably. According to PEMRG [2], global plastic production reached 359 million tons in 2019, with Asian countries accounting for 51% and Europe accounting for 17%. The supply of virgin plastics consumes 4% of global demand (1.3 billion barrels a year) [3]. The polymers used in manufacturing are often non-degradable and can last for several years in the environment [4]. As a result, environmental contamination caused by this type of waste may be a big issue.

However, too often the way plastics are currently produced, used and discarded fails to capture the economic benefits of a more 'circular' approach and harms the environment [1]. There is an urgent need to tackle the environmental problems that today cast a long shadow over the production, use and consumption of plastics. The plastics industry is very important to the European economy, and increasing its sustainability can bring new opportunities for innovation, competitiveness and job creation, in line with the objectives pursued by the renewed EU Industrial Policy Strategy [5]. In December 2015, the Commission adopted an EU Action Plan for a circular economy [1]. There, it identified plastics as a key priority and committed itself to 'prepare a strategy addressing the

challenges posed by plastics throughout the value chain and taking into account their entire life-cycle'.

According to statistics, up to 90% of plastics can be reused. Currently, 80 percent of plastic waste is disposed of in landfills, with just a small percentage recycled [6]. The most serious issue is HDPE, LDPE, PP, and PVC plastics, which are widely used by factories and pollute the environment with gas emissions [7]. PLA-related pollution, which has a much smaller global effect due to its natural roots, is a much smaller global concern. Unfortunately, products made of this material are less physically stable, discouraging future producers from using it more often. The most significant drawback associated with fabric reuse is the issue of properties being lost following several recycling cycles. Furthermore, there is a lack of equilibrium, which can harm public wellbeing [8]. One of the possibilities for the production companies to ensure the EU strategic plan is implementation of the circular economy. The circular economy, also called "green economy", is a new economic model that is the opposite of the current model - the linear economy [9]. The essence of the profit of the current system of "take-produce-throw away" is above all the high consumption of renewable and also non-renewable raw materials, which logically cannot work in the long run. The effect of recycled or waste thermoplastics, on the other hand, is still unknown, leaving research possibilities for improving product properties available. When we add other negative factors to this, such as the use of cheap manpower from developing countries, the population explosion, increasing consumption and the devastating human impact on the environment, we can rightly consider the current system to be unsustainable [9]. Economically, ecologically and socially. On the contrary, the circular model is intended to ensure the competitiveness of countries, their stable economic growth and a healthy environment. The yield in the circular economy is based on the efficient use of natural resources achieved by the efficient recovery of the materials, products and components used. Their constant return to the technical and biological cycle represents the closure of material flows. This radically minimizes waste and the costs of material inputs and energy required for the production of new products. The main features of this concept are the use of renewable energy sources, eco-innovation, rental, sharing or support of local trade. The rising concern towards environmental issues and, on the other hand, the need for more polymer-based materials has led to increasing interest about polymer based waste materials [10].

Moving decisively towards a more prosperous and sustainable plastics economy could deliver considerable benefits. To reap these, Europe needs a strategic vision,

setting out what a ‘circular’ plastics economy could look like in the decades ahead [1]. This vision needs to promote investment in innovative solutions and turn today’s challenges into opportunities. While the EU will propose concrete measures to achieve this vision, making it a reality will require action from all players in the plastic value chain, from plastic producers and designers, through brands and retailers, to recyclers. Similarly, civil society, the scientific community, businesses and local authorities will have a decisive role to play in making a difference, working together with regional and national governments to bring about positive change.

A smart, innovative and sustainable plastics industry, where design and production fully respects the needs of reuse, repair, and recycling should be a solution for EU’s plastic circular economy [1, 2]. Reuse and recycling of waste based plastics integrated by 3D printing can save human lives, can decrease the negative effect of plastic waste and can decrease amounts of new plastic products [5].

The general purpose of this paper is to present the research findings regarding the investigated conditions for 3D printing when using a waste based materials. Effect of recycled HDPE based waste, 3D printing conditions and technology set-up is very significant and in this paper this effect on final printing’s quality were determined. Authors would like to present the possibility and way for usage of waste based plastic material for 3Dprinting. Such of results are very important and interesting from the production possibilities and applications of HDPE waste material point of view. Obtained research findings can be very helpful at production using 3D printers and shown the possibility of using also waste raw materials this technology, and thus increase the environmental responsibility with the environment protection.

II. MATERIALS AND METHODS

In general, the aim of our experiment is to investigate the possible application and usage of waste HDPE for 3D printing. Take in mind this aim and according to the review, the experiment procedure had to be divided into several phases. First phase was intended to a processing of HDPE waste into a form which is suitable for 3D printing. This phase was followed by investigation of 3D printing conditions which is represented mainly by type of bed layer. The main aim of this research is determination of 3D printing parameters effect on the final printing’s shrinkage. Most influencing parameters are type of material, bed temperature and extruder temperature [11].

A. Raw material processing

For purposes of above mentioned investigation, the basic raw materials were chosen and prepared. HDPE 1 (waste from high-density polyethylene named TIPELIN 1108J which is intended for injection moulding, with the melt index 8.0 g / 10 min), HDPE 2 (high-density polyethylene originating from lids of PET bottles) were used as plastic matrices. The whole treatment and samples preparation consisted of following steps:

- basic mechanical treatment (separation, disintegration),
- filament production (filament for 3D printer),
- samples production (FDM 3D printing).



Figure 1. Disintegration of PET bottles and Retsch cutting mill

Because the proper shape of material suitable for 3D printing should be prepared by Filament Maker, the input raw waste material was disintegrated into a smaller particles. So for obtaining the given particle sizes of HDPE waste the disintegration and separation processes were used. For disintegration of PET bottle lids (Fig. 1) and also for HDPE waste, the cutting mill Retsch SM 300 was used. The moisture content of chosen HDPE waste, before extrusion were measured with the aid of a Kern MRS 120-3 balance. This measurement consisted of heating the raw material (gravimetric method of moisture content measuring) [12] at $105 \pm 2^\circ\text{C}$ until a constant weight was achieved. The moisture content of HDPE 1 on the level of 0.2 %, and HDPE 2 on the level of 0.2 % was determined.

B. Filament production

For the 3D printing purposes, the proper shape of filament needed to be produced. Filament for 3D printer from recycled HDPE of an acceptable and competitive level of quality, with the Filament Maker Composer (Fig. 2) was produced. We tried do our best and we were able to produce the filament from both samples of waste based HDPE. On the base of different material properties, it was necessary to set up the filament maker extrusion parameters separately for each material sample. HDPE 1 filament (Fig. 3) and also HDPE 2 filament (Fig. 4) had proper output parameters for printing and stable shape and surface of filament. These seem to be used for 3D printing. The settings of filament maker kept during extrusion the filament are shown in Table 1. According to the properties of filament maker but mainly according to the properties of 3D printer (the output diameter of printing nozzle is 1.0 mm), the diameter of filament was stated on value 1.76 mm. Lonely extrusion process was should be investigated, filament maker has its own limitations where the extruder speed was not able to increase as required. Its maximum speed was 15 Rpm. We have adjusted the extruder speed according to the requirements of the filament. So that the filament can be produced without any damage and in the required quality.



Figure 2. Filament Maker Composer 3devo

Also, the fan output power of the filament maker was adjusted according to the requirement of the filament quality. During production of the filaments the temperature at the beginning of the screw (T1) was constant for both samples of the filaments. But at the end of the screw (T2), it was changing as shown in the below Table 1.

TABLE I.
FILAMENT PRODUCTION PARAMETERS ACCORDING TO THE SAMPLE

Sample	HDPE 1	HDPE 2
Extruder speed (rpm)	4.60	7.10
Filament fan power (%)	55	40
T1 (°C)	240	240
T2 (°C)	230	230
T3 (°C)	230	230
T4 (°C)	220	220
Puller speed (rpm)	automatic	14.37



Figure 3. Filament produced from waste based HDPE 1



Figure 4. Filament produced from waste based HDPE 2

Where we have compared the different temperature at different point. The puller speed influences the output shape and quality of filament, and thus also the filament maker productivity. This parameter of filament maker was also necessary to adjust according to the final filament quality. In some cases, the filament maker was able to automatically control the puller speed, and no operator intervention was required.

C. FDM 3D printing process

For plastic parts production by FDM technology are used as standard plastic materials ABS (Acrylonitrile Butadiene Styrene), PC (Polycarbonate) or PLA (Polylactic acid). In our case was used waste based HDPE, which is in general not intended for 3D printing [11]. They have different processing requirements as for example required temperature, but also very important material properties. Selection of printing device type for produced specimen depends mostly from used input material to be printed because not all FDM devices are able to process all available materials [13]. Temperature is necessary for plastic material melting and layer thickness. Each producer of filaments states just range of suitable temperatures, not the exact temperature [14]. This is because different 3D printers work with different software and have different technical design, so there could be necessary different temperature setting, but also settings of many other parameters.



Figure 5. FDM 3D printer used for the experiment

The temperature affects the consistency or the flow of semi-melted thermoplastic what will affect the diffidence of deposited fibres [14, 15]. Layer thickness is affecting the dimensional accuracy, so we try to figure out if there is also influence to shape and positional tolerances [15]. Each 3D printer allows to set layer thickness and it is easy to change and affect the final quality of produced parts. In our experiment, we are planning to print specimens with standardized dimensions. A set number of specimens for testing were produced by FDM 3D printer Prusa i3 (Fig.5).

D. Type of bed layer

After preparing the filaments we tried to print the samples within the 3D printer. But during printing we faced another troubles. Because the input material composition was not proper, the basic questions was which 3D printing parameters should be adjusted? This significantly influences the printing process and a shrinkage of printings. Shrinkage of printings can cause due to many reasons, but the main 2 reasons were bed temperature and bed layer. Our 3D printer have limitations regarding the printing temperature, because during the printing can be adjusted only up to 120 °C. Other problem was the adhesion of printings on the bed layer. So we decide to investigate the optimal solution as bed layer for such an investigated material compositions. The general aim was to increase the adhesion forces between printing surface and bed layer. This can be done with right combination of bed temperature, extruder temperature and type of bed. Material composition of bed layer should be as close as possible to the printed material. Due to the many options and for obtained clear results dealing with influence of bed type on adhesion, only one setting was chosen. The 3D printer was adjusted on following technological parameters, extruder temperature 190 °C, bed temperature 120 °C and printing speed 18 mm/s. As a bed layer the different types were used:

- PP base material without additional layer,
- PVC base material without additional layer,
- PVC base material with additional 2nd textile layer (rectangle structure),
- LDPE base material with additional 2nd textile layer (line structure),
- LDPE base material with additional 2nd textile layer (square structure).

In this phase of investigation only mentioned types of bed layers were used due to availability. As we can see on following Fig. 6–8, most of bed layers were not suitable for printing. Except of LDPE tape with second squared textile structure (Fig. 9) was suitable for printing during both types of printing materials. On the following Fig. 6 we can see that during printing in PP bed layer, even if we used HDPE 1 or HDPE 2 as filament, problem was in the corners of printings, were getting shrink and the sample was not able to stick to the bed. The same results were achieved also during printing using PVC bed layer (Fig. 7) and also during printing using LDPE (grey) bed layer (Fig. 8). The corners of printings were getting shrink and the sample was not able to stick to the bed due to the small adhesion. However it looked like the LDPE tape was better than both previous tapes. The improvement can be attributed to the presence of second (textile) layer of this tape. This textile layer has lined structure.



Figure 6. Polypropylene (PP) transparent bed layer



Figure 7. Polyvinyl chloride (PVC) black bed layer



Figure 8. Low-density polyethylene (LDPE) grey bed layer

We decided to use another tape based LDPE but with different structure of second layer. Second (textile) structure of this tape (green neon) was squared. Using this type of bed layer we were able to print stable samples (Fig. 9). For the main experimental phase we will use bed layer with LDPE base material with additional 2nd textile layer which is square structured.

3D printer has variable parameter setting options. As a constant variables are given below. With the given variables we can compare the difference in the shrinkage of samples.

III. RESULTS AND DISCUSSION

The main aim of experimental stage is to investigate the effect of bed temperature, extruder temperature with interaction of type of waste HDPE on the final printing's shrinkage.

- length of the printing sample: 100 mm,
- printing nozzle diameter: 1.0 mm,
- extrusion coefficient "e", which means amount of material between the starting point and ending point: 7,
- printing speed: 20 mm/s.

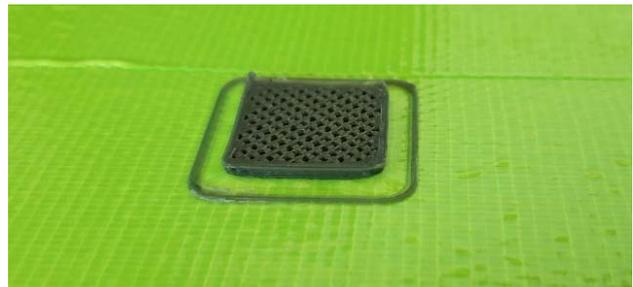


Figure 9. Low-density polyethylene (LDPE) green-neon bed layer

The influencing parameters (bed temperature and extruder temperature) were changing within the following values:

- bed temperature: 60 °C, 90 °C and 120°C,
- extruder temperature: 180 °C, 200 °C, 220 °C and 240 °C.

After the 3D printing was realized, and the final shrinkage of the samples – printed lines from two types of waste HDPE was compared. Each experimental setting was repeated 6times, to avoid measurement inaccuracy. The final value of printing’s shrinkage was evaluated by mean value from these 6 repetition. On the following Fig. 10 we can see samples of HDPE 1, printed at different extruder temperatures with a constant bed temperature at 60°C. By the change in length of the printed lines the shrinkage was evaluated. Similar, on the following Fig. 11 we can see samples of HDPE 2, printed at different extruder temperatures with a constant bed temperature at 60°C. By the change in length of the printed lines the shrinkage was evaluated.

The final graphical results can be seen on Fig. 12 and Fig. 13. On these figures the dependence of printing’s shrinkage on extruder temperature at various levels of bed temperature for both waste HDPE samples can be compared. Fig. 12 represents the result for waste HDPE 1 samples. We can see that with increasing the extruder temperature the shrinkage is decreasing. The decrease of shrinkage can be achieved also by increasing the bed temperature.



Figure 10. Printed samples-lines from the HDPE 1 material at different extruder temperature

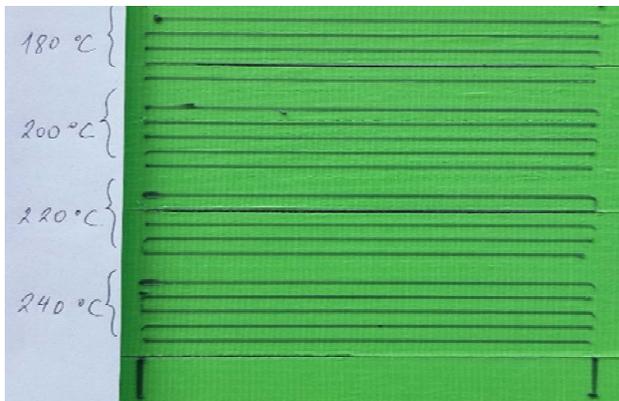


Figure 11. Printed samples-lines from the HDPE 2 material at different extruder temperature

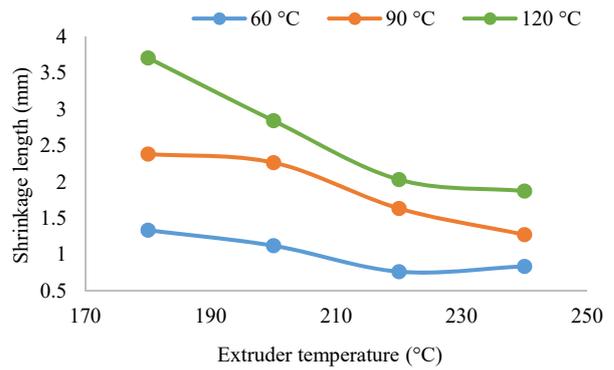


Figure 12. Dependence of printing’s shrinkage on extruder temperature at various levels of bed temperatures for HDPE 1

On the Fig. 13, shown the dependence of printing’s shrinkage on extruder temperature at various levels of bed temperature for waste HDPE 2 samples. We can see that with increasing the extruder temperature the shrinkage is decreasing. The decrease of shrinkage can be achieved also by increasing the bed temperature. However, the dependencies have a course with a local maximum, the results are very similar comparing with the results of DPE 1. Difference is only with the dependence of 90°C and 120°C, where the dependence character is changing after when it exceeds the value of 200°C extruder temperature.

If we would like to look closer on the comparison of results between HDPE 1 and HDPE 2, we have to investigate separately each level of bed temperature. At level of 60°C bed temperature smaller shrinkage by waste HDPE 1 sample was reached. At level of 90°C bed temperature had smaller shrinkage HDPE 2 sample till the extruder temperature exceeds the value of 200°C extruder temperature. From this moment the HDPE 1 noted smaller printing’s shrinkage. At level of 120°C bed temperature had smaller shrinkage HDPE 2 sample till the extruder temperature exceeds the value of 210°C extruder temperature. From this moment the HDPE 1 noted smaller printing’s shrinkage.

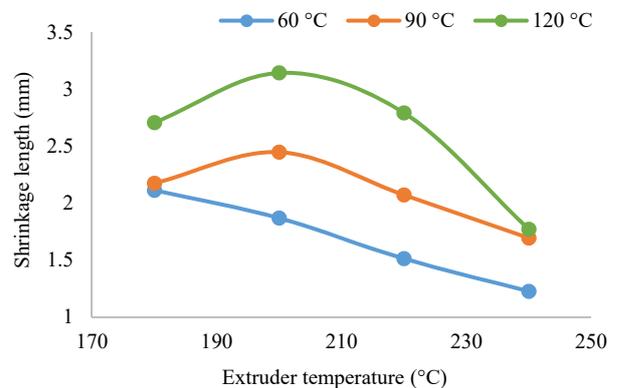


Figure 13. Dependence of printing’s shrinkage on extruder temperature at various levels of bed temperatures for HDPE 2

IV. CONCLUSION

Investigation of filament production and 3D printing conditions using wasted plastic (HDPE) materials was presented in this research. Presented results of preliminary phase relates to the effect of waste based materials on the 3D printing conditions and printing's shrinkage.

The main conclusions that can be withdrawn from this study are as follows:

- Waste based HDPE recycled material can be used for filament production,
- Waste based HDPE recycled material can be used for 3D printing under special conditions,
- Tape based LDPE with second textile squared structure can be used for printing using recycled HDPE material,
- Shrinkage of printing's can be affected by bed temperature and extruder temperature,
- Comparing two samples of waste based HDPE we can say that printing's originating lids from PET bottles noted smaller shrinkage.

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Mechanical and Physical Properties of New Particleboards Containing Recycled Plastics from Automobiles

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Abstract – This article is focused on the research of new composites - particleboards (PB) composed of waste spruce wood particles and recycled crushed plastic granulate. Crushed plastic granulate (size from 1.0-4.0 mm) was obtained from worn automobiles, specifically from painted and unpainted bumpers. In the production of PB, urea-formaldehyde resin and paraffin emulsion were used as binder. The proportion of plastic granulate represented 10%, 15% and 20% of the total weight of the composites. The aim of the article was to compare selected properties of new PBs containing plastic waste with commercial PB. From the point of view of the mechanical properties, tensile and bending strength, and from the physical properties, water absorption and thickness swelling were evaluated according to valid technical STN EN standards. Based on the results, it can be stated that the bending strength and physical properties of PBs containing recycled plastics were significantly better compared to commercial PB. In contrast, the tensile strength values were lower in most cases. New PBs containing waste plastics could be used in practice as part of furniture, floors, insulation, or noise barriers.

Key words – mechanical properties, physical properties, plastic recycling, wood composites, worn automobiles

I. INTRODUCTION

Approximately 90 million automobiles are produced worldwide annually. The average weight of an automobile is about 1.2 tons, which represents 108 million tons of refined processed material. The types of materials used in the automobile are ferrous metals; plastics; tires; non-ferrous metals; glass; foam; car batteries; textiles; and insulation materials. Currently, in the automotive industry, there is a growing trend to replace metals with plastic components, which leads to a reduction in the weight of automobiles and thus to a reduction in fuel consumption. The worldwide problem of hard-to-remove waste is related to the increasing number of automobiles, and thus also to the growth of plastic waste [1]. Large plastic parts of an automobiles

include bumpers, seats, or dashboards. Bumpers are most often made of polypropylene, but they can be reinforced with glass fibers [2]. There are also other plastics in automobiles such as door and roof linings, fuel tanks, spoilers, washer tanks, covers, etc. [3]. Currently, the production of plastic waste is a big problem.

As of 2015, approximately 6,300 Mt of plastic waste had been generated in the World, around 9% of which had been recycled, 12% was incinerated, and 79% was accumulated in landfills or the natural environment. It is assumed that roughly 12,000 Mt of plastic waste will be in landfills or in the natural environment by 2050 if current production and waste management trends, continue [4]. Around 25 million tons of waste plastics are produced in Europe every year, of which only 30% is recycled. The aim of many scientists is to develop new methods for recycling some of the most produced plastic polymers.

One way to utilize plastic waste is to use it as part of composites. Wood composites are a key material for a several structural and non-structural application for interior and exterior purposes, such as furniture, structural elements, floors, windows, or doors, and have wide applications in construction, infrastructure, and transport [5, 6]. To produce wood composites, urea formaldehyde (UF) resin is most often used due to good adhesion, cohesion, and low price. One kind of the composites is particleboard (PB). PB has many advantages, but the most important disadvantages include water absorption, flammability, and formaldehyde emissions. The mechanical and physical properties of wood composites depend on several factors, for example the mass proportion of materials, amount of resin, pressing temperature, pressing pressures, and time [7, 8]. In the preparation of wood composites, wood is mixed with other polymer materials at a high temperature. High temperature can cause instability of the composite, leading to reduced mechanical properties [9].

Gozdecki et al. [10] deal with wood-plastic composites with a new polypropylene content (more than 20%), which were produced and pressed at the temperature of

180°C. The results showed better mechanical (tensile strength, bending strength, impact strength) and physical (water absorption, thickness swelling) properties of wood-plastic composites compared to PB. According to Lopez et al. [11] wood composites with recycled thermoplastics in a proportion of 30% and more, also indicated better favorable mechanical (tensile strength, bending strength) and physical (water absorption, thickness swelling) properties.

The aim of this work was to evaluate the mechanical (tensile strength, bending strength) and physical (water absorption, thickness swelling) properties of PBs containing waste plastics (painted and unpainted bumpers) from automobiles in the proportion of 10%, 15% and 20% and to compare the results with commercial PB.

II. MATERIAL AND METHODS

A. Used Material

In the experiment, wood particles prepared from the fresh spruce logs were processed in the company Kronospan s.r.o. (Zvolen, Slovakia) and obtained from them. The dimensions of particles commonly used for the core layer and selected for the single-layer PB production were from 0.25 to 4.0 mm. Particles were dried to a moisture content of 5%.

Granulates made from the mixture of waste painted bumpers (WPB) and the mixture of waste unpainted bumpers (WUB) were used as a plastic additive. Granulates of fraction 1.0-4.0 mm were produced in the laboratories of the Technical University in Zvolen (Zvolen, Slovakia). Waste painted and unpainted bumpers were primarily made of polypropylene.

Commercially available UF resin Kronores CB 1100 F was used for pressing single-layer PB with the addition of crushed plastic (solids content: 67.1%, viscosity: 460 mPa.s, condensation time: 55 seconds, pH value: 8.6). The resin mixture contained ammonium nitrate NH_4NO_3 (47%) as hardener and paraffin emulsion (30%).

B. Production of Wood Composites

Single-layer PBs with the addition of crushed plastics with dimensions of 360 mm x 280 mm x 15 mm were prepared in the laboratories of the Technical University in Zvolen (Tab.1). PBs were prepared by the common technology, i.e., firstly cold pre-pressing of particle mats under the pressure of 1 MPa, followed by hot pressing

under the pressure by using the laboratory pressing machine CBJ 100–11, TOS (Rakovník, former Czechoslovakia).

Wood particles, crushed granulate, and resin mixture were mixed in a laboratory application drum. After mixing, 971 grams were weighed into the mold for one wood composite. The mixture was placed in a hydraulic

pre-pressing machine for approximately 2 minutes. Pre-pressing was followed by hot pressing under the pressing pressures of 30 MPa, 15 MPa and 7.5 MPa in different time intervals. The total pressing time was approximately 6 minutes at the temperature of 240°C.

C. Mechanical Properties

From the point of view of mechanical properties, the tensile strength and bending strength were evaluated.

The tensile strength was determined according to STN EN 319 [12] standard. Measurements were made on six samples per composite. The principle is to pull the sample with subsequent recording of the tensile stress at disruption. The laboratory equipment TIRA test 2200 (Thüringer Industrierwerk Rauenstein, Germany) was used for the measurements. The tensile stress σ is calculated according to the equation (1):

$$\sigma = \frac{F_{\max}}{S} \quad (1)$$

- σ - tensile stress (MPa),
- F_{\max} - maximum tensile force (N),
- S - surface area of the sample (mm^2).

The bending strength was determined according to STN EN 310 [13] standard. Measurements were made on eight samples per composite. The principle is to load the sample with subsequent recording of the bending stress at break. The laboratory equipment TIRA test 2200 (Thüringer Industrierwerk Rauenstein, Germany) was used for the measurements. The bending stress σ_{\max} is calculated according to the equation (2):

$$\sigma_{\max} = \frac{3 \cdot F \cdot L_0}{2 \cdot b \cdot h^2} \quad (2)$$

- σ_{\max} - maximum bending stress (MPa),
- F - bending force (N),
- L_0 - spacing (mm),
- b - width of material (mm),
- h - thickness of material (mm).

D. Physical Properties

Water absorption and thickness swelling after 2 and 24 hours were determined according to STN EN 317 [14] standard. Measurements were carried out on six samples per composites. The principle is to input samples into the water, and to record the thickness and weight after 2 and 24 hours.

III. RESULTS AND DISCUSSION

A. Mechanical Properties

The results of the mechanical properties of PB and wood composites containing recycled plastics are shown in Table 2.

TABLE I
COMPOSITES SIGNIFICATION

Signification	Composite characterization
PB	Particleboard
P10	Particleboard containing 10% of WPB
P15	Particleboard containing 15% of WPB
P20	Particleboard containing 20% of WPB
U10	Particleboard containing 10% of WUB
U15	Particleboard containing 15% of WUB
U20	Particleboard containing 20% of WUB

TABLE II.
MECHANICAL PROPERTIES OF WOOD COMPOSITES

Sample	Average tensile strength (MPa)	Average bending strength (MPa)
PB	0.294±0.05	3.807±0.85
P10	0.330±0.03	5.582±0.91
P15	0.253±0.02	5.540±1.30
P20	0.274±0.04	5.429±1.06
U10	0.228±0.03	5.380±0.60
U15	0.275±0.04	5.605±0.60
U20	0.274±0.09	6.746±1.44

From the results of the mechanical tests, it can be concluded that the bending strength of the produced wood composites containing recycled plastics was higher compared to the PB. In contrast, the tensile strength was lower in most cases. The results of P10 samples evaluation showed better tensile strength, namely 0.330 MPa. The highest bending strength was recorded for U20 samples, namely 6,746 MPa. Buyuksari et al. [15] investigated the mechanical (tensile strength, bending strength) properties of PB, composed of two different wood materials. The bending strength results were comparable to our PB. The mechanical properties of wood-plastic composites were discussed by Chaharmahali et al. [16]. The composites were made from wood particles combined with recycled high-density polyethylene from waste bottles. Tests of mechanical properties, bending strength, showed the best values for composites containing 40% of waste plastics. Basalp et al. [17] investigated PBs in combination with polypropylene from waste garden furniture in a ratio of 50:50. The observed mechanical (tensile strength, bending strength) properties compared to our results, were much better probably due to the use of plastic in a larger proportion.

B. Physical Properties

The results of the PB, and wood-plastic composites physical properties are shown in Table 3.

From the point of the results of physical tests, it can be concluding that all composites containing recycled plastics have better properties compared to commercial

PB. By adding the larger proportion of plastic granulate into the composite become to the reduction of the water absorption and thickness swelling. The best values of water absorption and thickness swelling were reached for U20 samples, where the water absorption was reduced of 67.29% and thickness swelling of 40.51% compared to commercial PB. Buyuksari et al. [15] and Kord et al. [18] deal with the PB composed of two wood materials. They evaluated the water absorption and thickness swelling of a PBs. The results showed better properties compared to our PBs. The physical properties of composites made from wood flour and waste polyethylene terephthalate from bottles were investigated by Dotun et al. [19]. The best results of water absorption and thickness swelling were obtained in composites containing 50% of waste plastics. From the point of view of our results, some of the samples physical properties were comparable to the results of above-mentioned authors.

Based on our results, as well as the results obtained of other authors, it follows that the physical properties (water absorption and thickness swelling) of wood-plastic composites improve with the amount of added plastic filler.

IV. CONCLUSION

Particleboard (PB) is commonly used as an interior cladding material in residential or commercial buildings, as part of furniture, floors, or roofs. Nowadays, automobile waste is a big problem. The preparation of wood-plastic composites using waste wood chips in combination with waste plastic material from the automotive industry is one way to use waste material and to create a new product with advantageous properties.

In this paper, we performed tests of the mechanical (tensile strength, bending strength) and physical (water absorption, thickness swelling) properties of new wooden composites containing waste plastics (painted-P and unpainted bumpers-U) from automobiles in proportions of 10%, 15% and 20%. Based on the analyses of the mechanical properties of wood-plastic composites, it can be concluded that the bending strength of the produced composites was better compared to PB. In contrast, the tensile strength was worse in many cases. However, the physical properties are significantly better. The most favorable properties were obtained for U20 samples, whose average tensile strength was 0.274 MPa, average

TABLE III.
PHYSICAL PROPERTIES OF WOOD COMPOSITES

Sample	Average weight (g)	Average water absorption (%)		Average thickness (mm)	Average thickness swelling (%)	
		2 hours	24 hours		2 hours	24 hours
PB	22.00±0.88	141.41±8.61	166.16±5.29	15.41±0.08	59.87±5.50	70.28±6.62
P10	21.81±0.81	110.85±8.53	131.87±8.47	15.25±0.08	38.19±4.12	46.78±4.14
P15	21.95±0.71	97.38±11.72	116.37±10.49	15.32±0.07	30.44±4.24	37.62±5.12
P20	21.88±0.69	84.46±6.19	105.58±9.05	15.31±0.10	28.38±5.42	33.66±5.72
U10	21.58±0.74	105.70±4.24	124.49±2.13	15.24±0.07	39.85±1.31	48.77±1.63
U15	21.98±1.54	103.67±11.16	113.00±7.97	15.29±0.03	38.12±5.17	45.28±6.49
U20	22.03±1.58	89.19±15.71	98.87±15.02	15.19±0.09	25.34±7.72	29.77±9.38

bending strength of 6.746 MPa, average water absorption after 24 hours of 98.87% and average thickness swelling after 24 hours of 29.77%. The stated values of wood-plastic composites are a good prerequisite for replacing commercial PBs in practice.

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Theoretical and practical aspects of the application of semiconductor ferroelectrics as energy-generating and energy-saving elements

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Abstract — The article deals with the results of a study of 2D and 3D ferroelectrics as multifunctional converters of light, heat, motion, and deformation into electricity with their subsequent accumulation. A description of a prototype of a multifunctional generator based on CuInP_2S_6 and $\text{Sn}_2\text{P}_2\text{S}_6$ crystals has been presented. A study of the parameters of crystals was carried out, as well as the results of their optimization to improve their characteristics.

I. INTRODUCTION

Recently, in connection with the crisis of classical energy and the development of alternative one, developers of electronic devices are increasingly attaching importance to reducing the power consumption of modern electronic devices. Thanks to this trend, the power consumption of modern devices, such as microprocessors and microcontrollers, memory devices, analog microcircuits, etc. has decreased tenfold compared to a decade ago. This has led to the possibility of developing alternative micro-energy devices that allow the creation of self-powered ones with virtually unlimited service life. This has become especially relevant with the introduction of the so-called Internet of things (IoT), smart toothbrushes, wheels, clothes, etc. into our daily lives. They can be powered by mechanical movement, deformation, heat or lighting. These devices use different physical effects, such as photovoltaic, piezoelectric, pyroelectric or triboelectric effects. Most micro converters are based on one of the above phenomena, however, functional devices that are capable of using several effects simultaneously are more promising. One of the most interesting materials for modern functional electronics is ferroelectrics [1] which can simultaneously use at least 3-4 of the listed physical effects (Figure. 1). Many articles and books have recently been devoted to the prospects and possibilities of their application in the field of alternative micro-energy [2-10]. However, before real serial devices, there is still a lot of work to be done on the choice of suitable materials, engineering of complete solutions with low cost and a wide range of applicable parameters. We have developed an alternative microgenerator based on CuInP_2S_6 layered crystals and $\text{Sn}_2\text{P}_2\text{S}_6$ 3D crystal which is capable of simultaneously converting deformation, movement or vibration as well as changes in heat and lighting into electric current and with wide scaling capabilities (from tenths of millimeters to square meters).

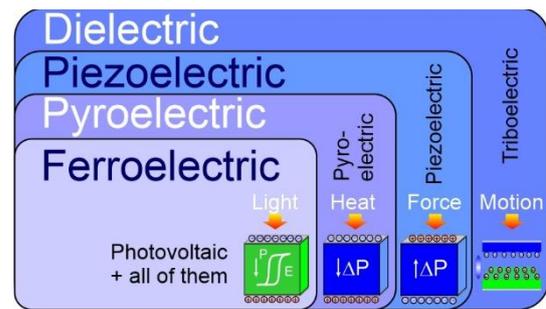


Figure 1. Dielectric, piezoelectric, pyroelectric, and ferroelectric material relationships and physical effects in them that can be used to generate electricity.

II. TRANSDUCER MATERIAL SELECTION

In most practical developments based on ferroelectrics, oxide crystals, ceramics or composites are used. This is due to their manufacturability, wide operating temperature range and good stability. However, as devices are reduced in size, there is a limitation due to the size effect which complicates the creation of devices smaller than 50 microns. Interface problems also arise when it is necessary to combine them with other materials of electronic engineering, especially two-dimensional ones, such as graphene. Therefore, in recent years, it has become relevant to use materials of the type $\text{Me}^1\text{Me}^2\text{P}_2\text{S}(\text{Se})_6$ or $\text{Me}_2\text{P}_2\text{S}(\text{Se})_6$ [11], Figure 2. This class includes both 3D crystals of the type $(\text{Pb}_y\text{Sn}_{1-y})_2\text{P}_2(\text{Se}_x\text{S}_{1-x})_6$ [13], layered 2D crystals $\text{CuInP}_2(\text{Se}_x\text{S}_{1-x})_6$, CuCrP_2S_6 , $\text{CuBiP}_2\text{Se}_6$ and others, as well as 1D needle crystals $\text{Cs}_2\text{Ag}_2\text{P}_2\text{Se}_6$. From a practical point of view, sulfides are of greater interest, because of the phase transition temperatures in selenide compounds are in the low-temperature region. 3D crystals $\text{Sn}_2\text{P}_2\text{S}_6$ can be used as an active medium in nonlinear optical devices [14], in piezoelectric transducers and sensors [15,16], in pyroelectric devices [17,18], as a matrix for solid electrolytes [19], and others. Based on layered CuInP_2S_6 crystals, the main components of electronic devices have already been created, starting with diodes and transistors [20] and ending with memory cells [21]. To date, this material is the only ferroelectric in which, at room temperature, it was possible to observe stable polarization switching in a sample with a thickness of 4 nm [22]. In addition, similar crystals (for example, $\text{Li}_2\text{FeP}_2\text{S}_6$,

$\text{Li}_2\text{NiP}_2\text{S}_6$) are candidates for creating solid-state batteries with ultra-high capacity [23,24].

Among them, the most interesting are layered van-der-Waals crystals, for which there is the possibility of easy delamination by both mechanical and chemical methods, with the prospect of creating nanometer-sized devices consisting of one or two structural layers of the material. In addition, intercalation, the introduction of various chemical compounds into the van-der-Waals interlayer space, can be easily implemented in such crystals, which allows them to be used as a matrix for creating batteries or supercapacitors to store the generated electricity. In addition, the layered structure of such crystals makes it easy to combine them both, to create heterostructures and with existing and promising functional materials of modern electronics such as graphene, MoS_2 , silicon, etc.

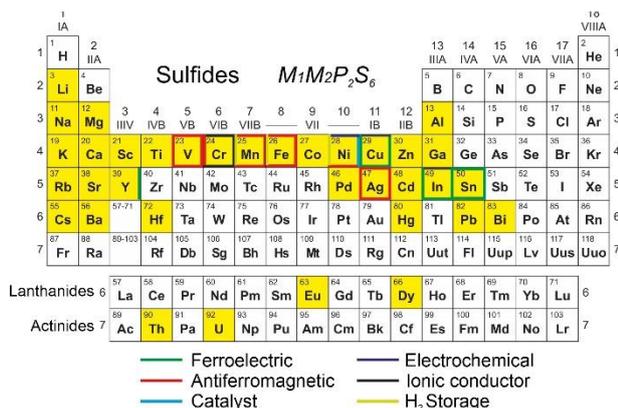


Figure 2. Functional properties of compounds in metal-phosphorus-chalcogen systems. Filled blocks represent elements for which the $\text{M}^1\text{M}^2\text{P}_2\text{S}_6$ structure has been reported to form (based on [11, 12] and our data).

CuInP_2S_6 crystals are an unusual example of a collinear ferroelectric system and illustrate the general features of cooperative dipole effects in layered chalcogen phosphates [25]. CuInP_2S_6 is a ferroelectric at $T < T_c = 315$ K (monoclinic spatial group Cc) because it contains polar lattices of Cu^{I} and In^{III} that are shifted in antiparallel directions relative to the median plane and detects spontaneous polarization $P_s = 3.5 - 4 \mu\text{C}/\text{cm}^2$ in the direction, perpendicular to the layer. The latter circumstance is very important for practical use since it does not require orientation of the samples before use (as in the case of 3D ferroelectrics $\text{Sn}_2\text{P}_2\text{S}_6$, as shown in our previous work [1], where the orientation of crystallites in an external electric field is required) and it is enough only to apply electrodes to its upper and lower planes, and the converter of illumination, temperature changes and deformation into electric current is ready. This crystal belongs to the group of "weak" ferroelectrics, the so-called ferroelectrics with the value of the coercive being 70 kV/cm. Besides, CuInP_2S_6 crystals are wide-gap semiconductors with a band gap $E_g=2.8$ eV, which has a positive effect on its photovoltaic properties and as shown in [25], they have an ionic component of the conductivity.

To create the generator, we used single crystals of CuInP_2S_6 obtained by the method of directed crystallization from the melt according to the method described in the

work [26]. The resulting crystals were large, from which plates with an area of 1 cm^2 and a thickness of 0.5 mm were cut. As can be seen in the Figure 3, depending on the cooling rate and the purity of the initial components, the quality of the obtained crystals can differ significantly.

TABLE 1.
PARAMETERS FOR OBTAINING CuInP_2S_6 SINGLE CRYSTALS

Parameter	Value
The temperature of the melting zone	1150 K
The temperature of the annealing zone	870 K
Temperature gradient in the crystallization zone	3 K/mm
The crystallization front movement speed	2.5 mm/day
Cooling rate of the obtained crystal	200 K/day

The process was carried out in two-zone furnaces, and the temperature of the zones was regulated by using RIF-101 devices. The main technological parameters of the production process are given in Table 1.

The synthesis of the starting material was carried out by a two-temperature method from elementary components of high purity, taken in stoichiometric quantities directly in growth quartz ampoules, and pumped up to 0.013 Pa. The ampoule had a cylindrical "spout" with a length of 20 mm and an inner diameter of 4 mm for the formation of a monocrystalline seed.

As a result, monolithic CuInP_2S_6 boules with a diameter of 14 mm and a length of 20-25 mm (cylindrical part) with a well-developed cleavage were obtained, which makes it possible to easily manufacture samples of different thicknesses (Fig. 3). It should be noted that the optical characteristics of the obtained crystals slightly changed along the length.

Compared to crystals obtained from the gas phase, these samples are much larger (both in area and thickness), which provides an easier and cheaper way to create large-size transducers.



Figure 3. Single crystals of CuInP_2S_6 grown from a melt of different quality

The chemical composition of all grown and further investigated crystals was confirmed using TESCAN MIRA 3 Scanning Electron Microscope with EDAX EDS.

III. EXPERIMENTAL SETUP

The photovoltaic characteristics of the studied samples were measured using LED light sources produced by Thorlabs: M505L3 (505 nm), M660L4 (660 nm), M810L3 (810 nm), and M940L3 (940 nm). The Thorlabs PM100 High Sensitivity Optical Power Meter was used to measure the illumination level with the S120B (Si) sensor, which works in the wavelength range of 400-1100 nm and power range of 50 nW to 50 mW. The output photovoltage level was fixed using OWON XDM 3041 digital multimeter.

The temperature dependence of permittivity and losses were measured using an automated measuring system [27] based on an LCR-819 impedance meter. To measure the temperature, we used the LabVIEW controlled Measurement Computing USB-TEMP-AI data acquisition device. As a temperature sensor, the PT100/1509A platinum thermistor of TDI Ltd. company (England) was applied. The temperature measurement accuracy was ± 0.01 K. The heater power was changed using a Linear Programmable DC Power Supply OWON ODP3033.

IV. PHOTOELECTRIC PROPERTIES

To study the photovoltaic characteristics, we used a CuInP_2S_6 crystal, obtained from the melt by the method of directed crystallization, with a size of 10×10 mm² and a thickness of 0.5 mm.

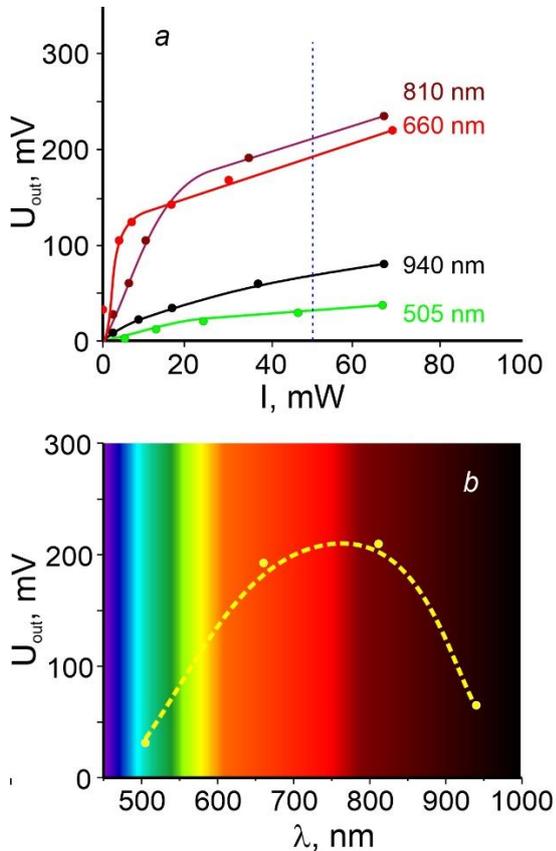


Figure 4. The dependence of the output voltage of the converter on the intensity of illumination - *a*. *b* - spectral sensitivity of the transducer at an illumination power of 50 mW.

An aluminum plate was used as the lower electrode to which the crystal was glued with a silver paste. We used a

semitransparent vacuum deposited SnO electrode as the top electrode.

As we can see in Figure 4(a), with an increase in the illumination level, the initial, highly non-linear dependence of the output voltage, above 20 mW, goes into a more linear mode. The initial nonlinearity may be due to the presence of blocking space charges in the near-electrode regions.

As for the spectral characteristics of the photosensitivity (Figure 4(b)), it strongly resembles the behavior of CuInP_2S_6 crystals, which is not surprising, based on the close values of the band gap of both crystals (for CuInP_2S_6 , $E_g \approx 2.8$ eV, and $E_g = 2.5$ eV for $\text{Sn}_2\text{P}_2\text{S}_6$). True, it should be noted the higher photosensitivity of CuInP_2S_6 crystals, which is two to three times higher than in the case of $\text{Sn}_2\text{P}_2\text{S}_6$ [1]. The maximum photosensitivity falls in the near-infrared range with a wavelength of 800 nm, which is most likely due to the depth of penetration of radiation into the bulk of the crystal. Based on this, it is possible to experimentally find the optimal thickness of the photosensitive layer for each wavelength.

V. INCREASING THE PHASE TRANSITION TEMPERATURE OF CuInP_2S_6 CRYSTALS

One of the significant drawbacks of the CuInP_2S_6 crystal is the relatively low phase transition temperature, which as noted earlier, is slightly more than 40 degrees Celsius. In the case of practical application this parameter is a significant limiting factor. For example, when using them as photoconverters or pyroelectric converters, due to heating, the crystal can easily overheat, passing into the paraelectric phase, and losing its ferroelectric properties. In this regard, the search for ways to increase the phase transition temperature of CuInP_2S_6 crystals remains very relevant. At the moment, there are two ways to increase the phase transition temperature of CuInP_2S_6 samples. This is a uniaxial or hydrostatic compression of crystals (which is very difficult to implement in practice) [29] or a change in the chemical composition of the material [30]. We went the second way.

When studying the dielectric properties of CuInP_2S_6 crystals, it was established that both the phase transition temperature and some properties of the crystals change significantly from batch to batch. This is obviously due to the deviation from stoichiometry. The most likely reason for this phenomenon is probably to be a large difference in the rate of mass transfer of copper and indium. Therefore, in order to optimize the properties of these crystals, we studied samples that were grown by the chemical transport reaction (CTR) method, both from a charge with a stoichiometric composition and a composition of $0.9 \cdot \text{CuInP}_2\text{S}_6 - 0.1 \cdot \text{Cu}_2\text{S}$ with a deviation from stoichiometry in the direction of Cu_2S and $0.9 \cdot \text{CuInP}_2\text{S}_6 - 0.1 \cdot \text{In}_2\text{S}_3$ in the In_2S_3 side, which involves the enrichment of the resulting crystals with copper and indium, respectively. The degree of perfection of the studied crystals can be judged by the shape and maximum value of the dielectric anomaly during the ferroelectric phase transition. We conducted studies of the dielectric properties of crystals obtained by the Bridgman method in comparison with those ones obtained by CTR from the charge of the above-mentioned compositions.

The studied samples were in the form of thin plates with a thickness from 0.05 mm to 0.3 mm and an area of $S \sim 3 \times 3$ mm² for crystals grown by the CTR method and a

thickness of about 1 mm and an area of $S \sim 5 \times 5 \text{ mm}^2$ for crystals obtained by directed crystallization from the melt. For dielectric measurements, electrodes made of indium-gallium amalgam were applied to large sample planes (perpendicular to the layers), obtained by mechanical chipping. In the frequency range of 100 Hz - 10 kHz, measurements were made by using an LCR-819 LCR-meter.

A sharp jump in ϵ' upon heating, due to a phase transition of the first kind, in a crystal that was obtained by the CTR method from a charge of stoichiometric composition, is observed at a temperature of 311.3 K, which is very close to the value of T_c , in a crystal grown by the Bridgman method at 312.0 K (Figure 5(a)). The peaks of $\epsilon'(T)$ practically coincide in temperature in both types of crystals. The temperature hysteresis of the phase transition for both samples was $\sim 1 \text{ K}$.

In the entire temperature range, a dielectric dispersion is observed, which stretches in a very wide frequency range - from 10^5 Hz to the lowest measured frequencies. Obviously, this dispersion continues even at lower frequencies, since there is a steady tendency to increase ϵ' and ϵ'' with decreasing frequency. After application to a "fresh" sample of the measured field, its capacitance and dielectric losses have a long-term relaxation. In addition, at temperatures above the $\epsilon'(T)$ jump, the measured dielectric parameters at frequencies below 1 kHz depend significantly on the magnitude of the measured field: they increase with the increase of the measured field. At the same time, a sudden increase in the measured field is accompanied by a long-term increase in the measured values of the capacity and $\text{tg} \delta$ of the sample. These facts indicate the contribution to the low-frequency dielectric response of the volume-charged polarization mechanism due to the presence of electrodes or macroscopic inhomogeneities of the sample. Another explanation for this phenomenon can be due to the ionic contribution to the conductivity of the sample, which increases with increasing temperature. During long-term application of a constant electric field to the CuInP_2S_6 sample, one of the electrodes peels off, and copper oxide is observed on its surface. The ionic conductivity of CuInP_2S_6 , and CuCrP_2S_6 crystals was studied in detail in work [31], and is explained by the jump conductivity of Cu^+ ions.

The temperature dependences of the real ϵ' and imaginary ϵ'' parts of the dielectric constant for crystals obtained from a charge with different degrees of stoichiometry are shown in Figure 5. The measurements were performed at a frequency of 100 kHz, at which the low-frequency dielectric response associated with conductivity is practically unaffected by the measurement results in the vicinity of the phase transition. In the crystals obtained from the charge enriched with indium sulfide, the phase transition is shifted to the region of higher temperatures ($T_c = 319.8 \text{ K}$) in relation to the crystal obtained from the charge of stoichiometric composition. At the same time, in a crystal grown from a charge with an excess of copper sulfide, the phase transition is observed at lower temperatures $T_c = 305.3 \text{ K}$. The maximum dielectric constant in this crystal is much higher and the shape of the anomaly is "sharper". In the sample obtained at a high concentration of the CuJ carrier, the phase transition occurs at almost the same temperature as in the crystals grown from the Cu_2S -enriched charge. However, it should be noted that the $\epsilon'(T)$ peak in this sample is more blurred.

The degree of blurring of the dielectric constant anomaly can be seen more clearly from the temperature dependences of $1/\epsilon'(T)$ (Figure 5(b)). For samples obtained from a stoichiometric charge and enriched with Cu_2S , the dependence $1/\epsilon'(T)$ in a wide temperature range obeys a linear law with the Curie-Weiss constant $C \approx 6.6 \times 10^3 \text{ K}^{-1}$. Deviation from the Curie-Weiss law occurs in the range of several K above T_c . In a sample obtained from a charge with an excess of indium sulfide, the Curie-Weiss constant is $C \approx 4.5 \times 10^3 \text{ K}^{-1}$. This value is close to the value $C \approx 4.7 \times 10^3 \text{ K}^{-1}$ obtained for these crystals in [32]. Judging by the degree of blurring of the dielectric anomaly, its temperature position, and the maximum value of ϵ in the CuInP_2S_6 crystal grown from the melt, it can be concluded that these crystals can be compared in terms of quality with crystals obtained from the gas phase from a charge of stoichiometric composition.

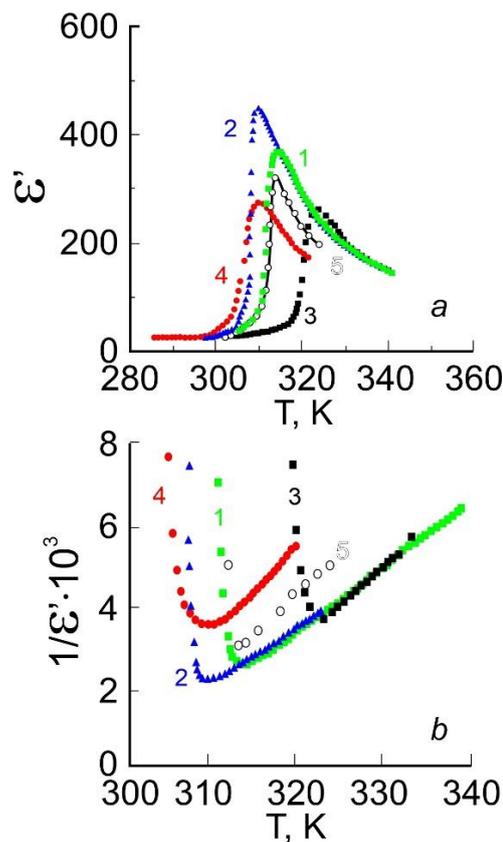


Figure 5. Temperature dependences of ϵ' and $1/\epsilon'$ for crystals grown: 1 - from a stoichiometric composition, 2 - from a composition $0.9\text{-CuInP}_2\text{S}_6\text{-}0.1\text{-Cu}_2\text{S}$; 3 - from a composition of $0.9\text{-CuInP}_2\text{S}_6\text{-}0.1\text{-In}_2\text{S}_3$; 4 - from a stoichiometric composition at a concentration of the transport agent CuJ of 20 mg/cm^3 ; 5 - by the method of directed crystallization (heating).

Based on the above results, it is possible to qualitatively explain the dependence of the temperature of the phase transition in CuInP_2S_6 crystals on the degree of their stoichiometry. The fact that the phase transition occurs at higher temperatures and the dielectric constant anomaly is greater in crystals obtained with an excess of Cu_2S indicates that, most likely, there are copper vacancies in the crystals grown from the stoichiometric composition. In the crystals obtained from the charge with an excess of In_2S_3 , apparently, the degree of non-stoichiometry with respect to copper increases even more. Thus, it can be assumed that

with an excess of copper sulfide in the initial raw material for crystal growth, the obtained crystals have a more perfect structure. Conversely, an increase in the content of indium sulfide in the charge leads to an increase in the concentration of crystal lattice defects, namely copper vacancies. As for the case of crystals obtained at high concentrations of the transporting agent (curves 4 in Figure 5(a)), it is obvious that the situation here is the same as in the case of samples obtained from a charge enriched with Cu_2S : due to the excess copper contained in the transporting agent, "healing" of copper vacancies takes place. The blurring of the phase transition is probably associated with the introduction of iodine into the interlayer space. As a result, the crystals take on an orange color.

Based on the fact that the occurrence of ferroelectric polarization in CuInP_2S_6 is mainly caused by the difference in the occupancy of two non-equivalent non-central positions in the crystal lattice by copper ions [33], copper vacancies can be considered as soft defects that can reorient, and which, as is known [34], shift the phase transition to the region of higher temperatures. Such a qualitative conclusion is well consistent with the situation observed in the experiment.

VI. MULTITYPE ENERGY CONVERTER

We propose to use layered CuInP_2S_6 crystals as an active substance for the transducer of deformation, lighting, and heat into electric current. In contrast to the converter, which we implemented earlier [1] based on a composite using 3D ferroelectrics $\text{Sn}_2\text{P}_2\text{S}_6$, the use of layered CuInP_2S_6 crystals provides many advantages. First, its photoelectric sensitivity, as shown earlier, is two to three times higher than in the case of $\text{Sn}_2\text{P}_2\text{S}_6$. In addition, there is no need to orient the crystals when applied to the supporting electrode, due to the spontaneous polarization in them is directed perpendicular to the layers. By reason of the layered vander-Waals nature of CuInP_2S_6 crystals, it is much easier to create thin-layer and ultra-thin-layer converters. In the case of $\text{Sn}_2\text{P}_2\text{S}_6$, the layer thickness was limited by the minimum size of microcrystals ($\sim 50 \mu\text{m}$), below which the ferroelectricity phenomenon disappears in them.

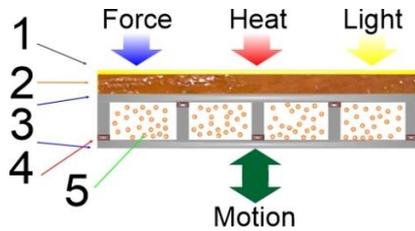


Figure 6. Schematic section of the converter of deformation, lighting, heat and motion into electric current.

The design of the converter proposed by us is very simple and is shown in Figure 6. The active single-crystal layer 2 of the CuInP_2S_6 crystal is placed between the translucent electrode 1 (sputtered thin layer of gold or stanum oxide) and the main carrier electrode 3 made of thin (1 mm) aluminum. This sandwich structure, due to the ferroelectric properties of the active material, converts deformation or compression (due to the piezoelectric effect), illumination (due to the photovoltaic effect), and temperature change (due to the pyroelectric effect) into an electric current, all at the same time.

The lower part of the transducer, consisting of aluminum electrodes 3, flexible rubber insulators 4, and active substance ($\text{Sn}_2\text{P}_2\text{S}_6$ powder) 5, remained practically unchanged [1], not counting the shape of electrodes 3, which, due to 3D architecture, were able to use movement not only in vertical but also in the horizontal direction. This part of the transducer uses the triboelectric [35] and piezoelectric effects to convert motion or vibration into electrical current.

TABLE 2.
COMPARISON OF THE MAIN CHARACTERISTICS OF CuInP_2S_6 AND $\text{Sn}_2\text{P}_2\text{S}_6$ SINGLE CRYSTALS

Parameter	CuInP_2S_6	$\text{Sn}_2\text{P}_2\text{S}_6$
$T_c, ^\circ\text{C}$	42	65
E_g, eV	2.85	2.5
Spontaneous polarization, $P_s, \mu\text{C}/\text{cm}^2$	4	14
ϵ at 300K	30	280
Piezoelectric coefficient, $d_{33}, \text{pm}/\text{V}$	17.4	28.2 ± 1.2
Pyroelectric coefficient, $\gamma, \mu\text{C}/\text{K m}^2$	735	750

The operation of this cascade is based on the movement of particles of the active powder (as in a liquid) [1], its friction on the electrodes and particles on each other, and the formation of a charge on the particles of the active substance due to the triboelectric and piezoelectric effect, and its transfer between the electrodes. In this cascade, it is better to use 3D $\text{Sn}_2\text{P}_2\text{S}_6$ crystals as an active substance, in which both the dielectric constant and the piezoelectric coefficient are higher compared to CuInP_2S_6 . The effect of rapid destruction of active particles with the formation of a parasitic blocking layer on the electrodes described in [28] is proposed to be eliminated by applying a solid protective Al_2O_3 [36] layer on the $\text{Sn}_2\text{P}_2\text{S}_6$ micro crystallites. The parameters of this layer are given in the work [1] and has an output voltage of 180-200V.

With a slight modification of this design, namely by adding a multilayer structure based on $\text{Li}_2\text{FeP}_2\text{S}_6$, $\text{Li}_2\text{NiP}_2\text{S}_6$ [23,24] or SnP_2S_6 [37], we can also add an energy storage device or battery which will make it possible not only to generate but also to store the created energy.

Because different cascades of this converter have different output voltages, namely, the upper cascade is hundreds of millivolts and the triboelectric cascade is hundreds of volts, it is necessary to use special energy harvesting circuits, for example, Analog Devices LTC3330, ADP5092, STMicroelectronics SPV1050 and others [35].

VII. CONCLUSION

Based on the studies carried out, we can conclude that using 2D and 3D ferroelectric and superionic crystals it is possible to create multilayer structures capable of simultaneously converting illumination, deformation, heat, and motion into electricity with its subsequent accumulation. Using layered ferroelectric crystals CuInP_2S_6 we can easily create multifunctional transducers of submicron thickness. To increase the operating temperature range, crystals obtained with a stoichiometry deviation, namely, those enriched with indium are most suitable.

ACKNOWLEDGMENT

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Hydrometallurgical treatment of slags from steel industry

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Abstract— This paper deals with the processing of slag from steel production in a high-frequency field. The slags represent an important raw material that can be used in several areas and have also content material potential in the form of metals. The leaching experiments were carried out on two types of slags from steel production in an electric arc furnace. The experiments were carried out using as received slags and thermally pretreated with NaOH. The aim of thermal pretreatment was to convert of hardly soluble compounds of chromium to more soluble forms. From the results of classical leaching follow that the highest recoveries of Cr (70%) after thermal pretreatment of the mixtures in 2M HCl were achieved. The results of leaching using high-frequency field showed that it is possible to leach out about 70% of chromium after heat pretreatment. In the case of iron recovery, recoveries above 90% from as received samples were achieved.

I. INTRODUCTION

The consumption of materials in the European Union is currently higher than the extraction of primary raw materials, so countries depend on imports from other countries of the world. Reducing dependence on imports from other countries is possible by increasing the rate of recycling of generated waste. The content of metals in secondary raw materials is significantly higher compared to primary raw materials, while other advantages of their recovery are the conservation of natural resources and energy, the reduction of their carbon footprint and the creation of new jobs.

In 2008, the European Commission launched the "Raw materials" initiative to address the growing concerns of securing valuable raw materials for EU countries. The initiative resulted in lists of critical raw materials from 2011, 2014, 2017, and 2020. In the current report from 2020, there are 30 critical raw materials from the EU viewpoint, including up to 21 raw materials of metals. Another important document that the European Commission started implementing in December 2015 is the Circular Economy Action Plan. The goal is to maximize the use of the material potential of wastes and effective substitution of primary raw materials with secondary materials. The goal of the action plan is also to support the production of environmentally friendly products with the minimization of waste generation in individual parts of the circular economy diagram [1, 2].

The most used construction material is steel, of which approximately 1.9 billion tons are produced annually in the world (year 2021). The steel is produced in oxygen

converters (67.7%), followed by a production in electric furnaces (27.9%). The largest producer is China with an annual production of more than 1 billion tons, the second largest producer is India with a production of more than 100 million tons (Fig. 1). During the production of steel, slag is created to capture impurities from the steel. Slag is a by-product and needs to be processed, not only for legislative reasons, but also because of the decreasing capacity of landfills and for the saving of primary raw materials [3].

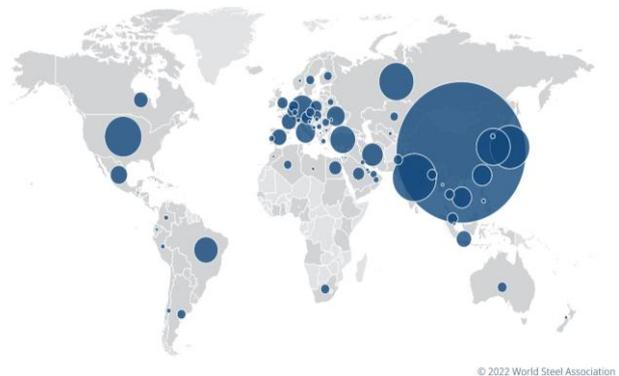


Figure 1. Production of steel in 2021 [3]

During the production of 1 ton of steel, approximately 100 – 200 kg of slag is produced. With a total annual production of 1.9 billion tons, approximately 190 to 380 million tons of slag is generated annually.

From a legislative point of view, slag from the metallurgical industry is defined as other waste, therefore it is used quite commonly in construction, mainly because of its large amount and similar properties to natural aggregates. One example is blast furnace slag, which is used in the production of cement as an additive in the final mixing and grinding of cement mixtures. Slag from steel production is also used as input material for the production of cement clinker.

Steel slag is produced in the process of transforming pig iron in a basic oxygen converter (BOF), in the remelting of scrap in an electric arc furnace (EAF) and in the off-furnace processing of steel in ladle furnaces (LF). Slag from the production of alloy steels and ferrochrome production is still mostly landfilled, and their material potential is not sufficiently used. Slags from steel production may contain high concentrations of metals, such as Cr, Ni, Mn, Ti, V, Nb and Mo. However, due to the higher Cr content and unsatisfactory physical

properties, the slag from the production of alloy steel is landfilled almost without use. The slag from high-alloy, stainless, or special steels and ferrochrome production could have the greatest importance for metal recovery, mainly due to the content of V and Nb, whose raw materials belong to the group of critical raw materials. From the perspective of the content of a significant number of metals and materials and the constantly increasing consumption of primary raw materials, it is necessary to pay attention to the recycling and material recovery of slags.

The chemical composition of the EAF slag is various and can be as follows: CaO 22-60%; CaO_{Free} 0-4%; SiO_2 6-34%; Al_2O_3 3-14%; MgO 3-13%; Fe_{total} of 20-30%; Mn_{total} 2-5%, FeO 10-40% while not stating the content of S, Na_2O , K_2O . Other sources state: 40-60% CaO; 10-30% SiO_2 ; 2-9% Al_2O_3 ; 10-30% FeO; 3-8% MgO; 2-5% MnO; 0.1-0.6% SO_3 ; up to 1.2% P_2O_5 [6-9].

From a mineralogical perspective, it can be concluded that the slag from the EOP process contains CaO (lime) in the majority. The slag can also contain: $3\text{CaO}\cdot\text{MgO}\cdot\text{SiO}_2$ (merwinite), FeO - solid solution (wüstite), solid solution FeO-MnO-MgO, M_2SiO_4 (olivine; M=Fe, Mg, Ni, Mn), $3\text{CaO}\cdot\text{SiO}_2$ (tricalcium silicate, C_3S), $2\text{CaO}\cdot\text{SiO}_2$ (dicalcium silicate, C_2S), CaCO_3 , Ca_3SiO_5 , CaAl_2O_4 , MgO, Fe_2O_3 (magnetite), Fe_3O_4 , $\text{Ca}_2\text{Al}(\text{AlSiO}_7)$ (gehlenite), Ca_2SiO_5 (belite), $\text{Ca}_{14}\text{Mg}_2(\text{SiO}_4)_8$, MgFe_2O_4 (magnesioferrite), Mn_3O_4 , MnO_2 , MnO, $\beta\text{-Ca}_2\text{SiO}_4$, $\gamma\text{-Ca}_2\text{SiO}_4$, spinel solid solution $(\text{Mg},\text{Mn})(\text{Cr},\text{Al})_2\text{O}_4$, $\text{Ca}_2(\text{Al},\text{Fe})_2\text{O}_5$, Fe_2SiO_4 , $\text{Fe}_7\text{SiO}_{10}$, MgCr_2O_4 [8-13]. According to the authors [10], the dominant mineral in the slag is spinel containing Mg-Fe: MgFe_2O_4 (17 wt.%), Fe_3O_4 (magnetite up to 5 wt.%), MgCr_2O_4 (magnesiochrome up to 3 wt.%), then SiO_2 , MgO (periclase), Ca_2SiO_4 (larnite), $\text{Ca}_2\text{FeAlO}_5$ (brownmillerite). The presence of Cr in the slags was confirmed by the authors in the FeCr_2O_4 phase. It follows from the technological step of steel production and thus also from the chemical point of view that EOP slag may contain Nb, Mo and V, but their concentrations are too low for mineralogical identification [7, 12].

Currently, EAF slag is processed with the aim of obtaining metal potential from the slag using various processing methods, such as physical-mechanical processing methods, e.g.: magnetic separation with the aim of obtaining metallic iron [14-17], pyrometallurgical processing methods with the aim of reducing metal oxides and the gain of metals such as Cr and V [18-20], but also the use of hydrometallurgical and combined processing methods with the gain of the mentioned metals. Currently, biological leaching with the use of bacteria is also applied to the recycling of EAF slags [24, 25].

Leaching with the use of a high-frequency field belongs to the intensification methods and enables rapid heating of the leaching solutions. The advantages of this method include that the high-frequency field attacks the structure of the material, no mechanical parts are needed when mixing the sample with the solution, the process operates at boiling temperature and requires smaller volumes of the leaching solution.

This work focuses on the hydrometallurgical recovery of metals from steelmaking slag by leaching using a high-frequency field. The main goal is to leach chromium and

iron and the use of the remaining material in another industry.

II. EXPERIMENTAL PART

A. Material and methods

Two samples of slag from steelmaking in electric arc furnaces were used for leaching experiments in the high frequency field. The slags were crushed, milled and sieved to fraction -125 +90 μm . From homogenization and quartering, representative samples were obtained, which were subjected to input analysis. The chemical analysis was carried out by the AAS method using a ContrAA 700 spectrophotometer (Table 1). Phase analysis was carried out using Philips X'Pert PRO MRD (Co-K α), the measurement range (10 – 120° 2 θ), scan step (0.0170°). With the help of X'Per HighScore plus software, the phases present in the slags were identified.

TABLE I.
CHEMICAL ANALYSIS OF SLAGS

Sample	Content [%]						
	Cr	Fe	Mg	Al	Ca	V	Si
CHR1	3,33	35,8	2,99	3,63	21,14	0,067	4,88
ZP1	1,39	30,48	4,94	2,76	19,42	0,0624	5,8

X-ray diffraction phase analysis identified phases in sample CHR1: magnesioferrite, $\text{Ca}_2(\text{Al}_{0,92}\text{Mg}_{0,08})(\text{Al}_{0,02}\text{Si}_{1,08})\text{O}_7$, calcium silicate, Fe, Mg and SiO_2 oxides. Chromium was identified in the Cr_2SiO_4 phase. The following phases were identified in the ZP1 sample: magnesioferrite, calcium silicate, $\text{Ca}_2\text{Fe}_2\text{O}_{5,12}$, $\text{Ca}_2(\text{Al}_2\text{SiO}_7)$ and FeO. Chromium was identified in $\text{Fe}(\text{Cr}_2\text{O}_4)$ and Fe_2CrO_4 phase. Vanadium could not be identified in the X-ray diffraction phase analysis of samples, it may be present in phases together with Fe and Mg.

The leaching experiments were realized carried out using two processes: classical leaching and leaching using high-frequency field. For the leaching were used original slags and samples after thermal pretreatment.

A thermal pretreatment process was realized with NaOH at a temperature of 500 °C for 120 min in the composition: 12 g sample + 16 ml H_2O + 8 g/16 g NaOH. Chemical analysis of thermally treated slags is shown in Table 2.

TABLE II.
CHEMICAL ANALYSIS OF SLAGS

Sample	Content [%]		
	Cr	V	Fe
CHR1 + 16g NaOH	1,03	0,033	15,99
CHR1 + 8g NaOH	1,10	0,041	23,94
ZP1 + 16g NaOH	0,37	0,032	15,38
ZP1 + 8g NaOH	0,48	0,039	20,77

Classical leaching was realized in a glass reactor with constant stirring (300 rpm), which was placed in a water

bath to ensure heating. The experiments occurred at temperatures of 20, 40, 60, and 80 °C for 60 min., at a constant ratio of L:S = 40 (400ml, 10g). Concentrations of 0.1; 0.5; 1 and 2M H₂SO₄ and 2M HCl were applied for leaching. The leaching was also carried out with the addition of the oxidizing agent H₂O₂ in a volume of 40 ml.

The leaching experiments in a high-frequency field were carried out in the apparatus shown in Fig. 2. A solution of sulfuric or hydrochloric acid with a concentration of 2M and a volume of 400 ml was first poured into the glass reactor. The reactor was closed and the solution was allowed to heat to boiling point. After reaching the boiling temperature, 10 g of a sample or a sample after heat treatment with NaOH was added to the solution. At time intervals of 5, 10, 15, 30 and 60 minutes, a liquid sample was taken for chemical analysis by the AAS method, where the content of chromium and iron was analyzed. After the experiment, the remaining solution was filtered and the volume was measured.

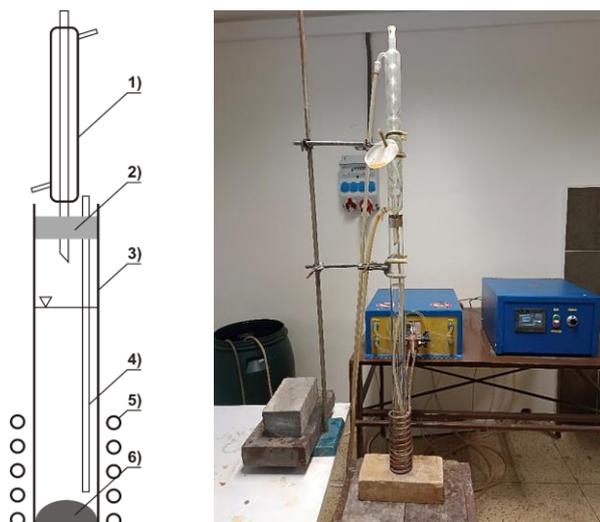


Figure 2. Scheme of the apparatus for leaching using high-frequency field, 1) cooler; 2) sealing; 3) reactor 4) liquid sample take off; 5) high-frequency field; 6) sample

B. Results and discussion

1) Classical leaching

a) Leaching of slags without thermal pretreatment

The best recoveries of Cr and Fe were achieved in 2M H₂SO₄ and 2M HCl at a temperature of 80 °C (Fig. 3 and Fig. 4). The highest extractions of Cr from both slags were under 10% and the addition of hydrogen peroxide does not have a significant effect. The leaching efficiencies of iron is higher than that of chromium. Maximal extractions of 60 % Fe were achieved. From the results follow that chromium is bound in stable compounds in contrast to iron, which is present in more soluble forms. From this reason, thermal pretreatment was realized to disrupt the stable spinel phase containing Cr, which could result in a higher efficiency of metal transfer into the solution.

a) Leaching of slags after thermal pretreatment

Slag mixtures after thermal pretreatment with NaOH were leached in water and acid solutions (sulfuric and hydrochloric acid). Fig. 5 shows leaching curves of chromium in water. The highest Cr extraction (42%) was

achieved from the slag mixture CHR1/16g NaOH. From the results follow that insoluble chromium compounds were changed to soluble and chromium was leached out. The thermal pretreatment has positive effect on chromium leaching.

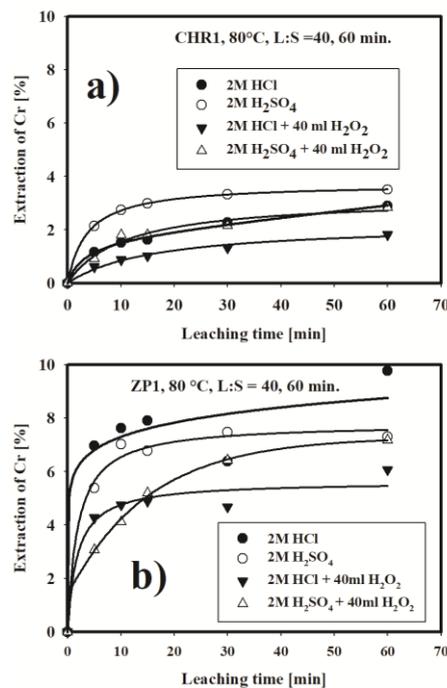


Figure 3. Extraction of chromium for classical leaching of slags without thermal pretreatment

The chromium extractions increased (Fig. 6) when slag mixtures were leached in acid solutions of sulfuric and hydrochloric acid. The highest chromium extraction in sulfuric acid around 60% was achieved. In hydrochloric acid it represented around 70%. It is known that leaching in hydrochloric acid is accompanied with the creation of several species and that's why extractions are higher than using sulfuric acid.

The leaching mechanism of iron is different from that chromium. If the iron extractions from untreated and thermally treated samples are compared, the extractions are very similar, the differences are around 10%. It is possible to conclude that thermal pretreatment does not have an effect on iron leaching and iron is present in soluble compounds (Fe oxides). The small increase in extractions is caused by leaching of compounds which are connected to chromium and, which disrupted during thermal pretreatment. Higher iron extractions were observed by leaching the sample ZP1. Sample CHR1 contains more chromium which bound more iron in the compounds. Therefore, based on the results, it follows that more iron is present in compounds, which are easier leachable than compounds with chromium.

2) Leaching using high-frequency field

a) Behavior of chromium

Fig. 8 and 9 show chromium leaching curves for two types of slag samples, including heat-treated slag with NaOH. Leaching of the as received sample did not result in a significant transfer of chromium to the solution, in contrast to the leaching of the heat-treated samples. Heat pretreatment was implemented because chromium is

bound in stable compounds that are resistant to leaching in common acids. By thermal pretreatment, it is possible to convert chromium into compounds from which it will be leached. The results show that by leaching the samples in hydrochloric acid, higher recoveries were achieved (around 70% Cr) compared to leaching in sulfuric acid, where the recoveries were around 60% Cr. Complete leaching of chromium was not achieved either due to incomplete conversion to soluble chromium compounds or the closed structure preventing the access of the leaching agent, as the chromium content of the samples is relatively low.

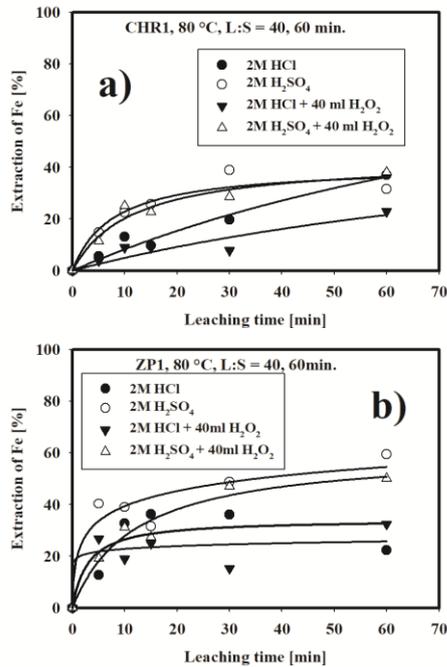


Figure 4. Extraction of iron for classical leaching of slags without thermal pretreatment

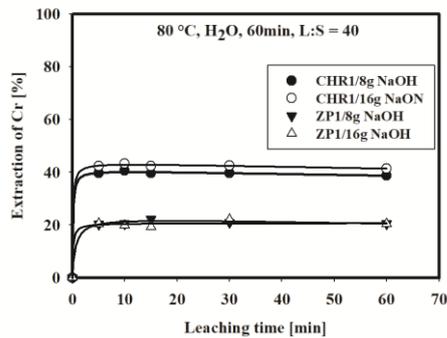


Figure 5. Leaching of chromium in water of slags after thermal pretreatment

The behavior of chromium using high-frequency field led to similar results with classical leaching experiments. It follows that thermal pretreatment has the most significant effect on chromium leaching and high-frequency field did not work to attack and disrupt the compounds.

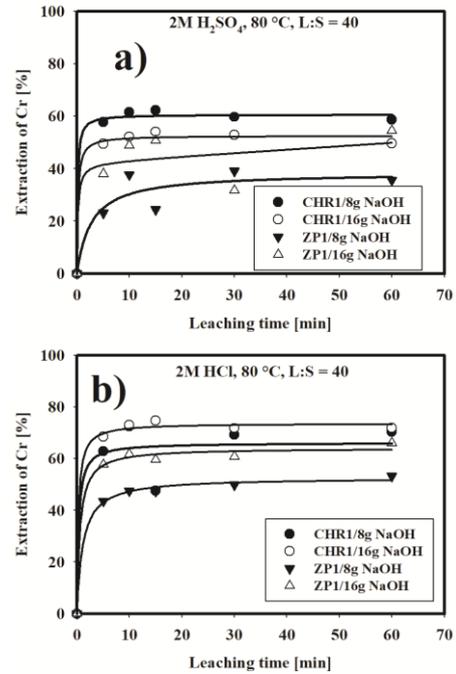


Figure 6. Leaching of chromium in sulfuric acid and hydrochloric acid of slags after thermal pretreatment

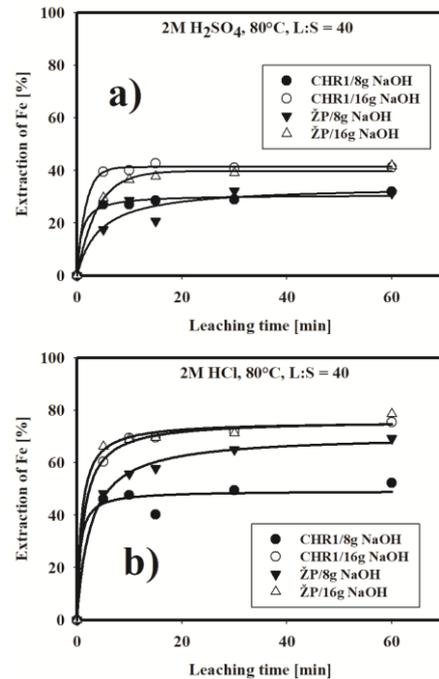


Figure 7. Leaching of iron in sulfuric acid and hydrochloric acid of slags after thermal pretreatment

b) Behavior of iron

Figs. 10 and 11 show iron leaching curves from two types of slag samples, including heat-treated slag with NaOH. In the case of iron leaching, thermal pretreatment did not have a significant effect what points to the fact that iron compounds are more leachable than chromium. The highest iron extractions around 90% were achieved. Higher leaching efficiencies were achieved using hydrochloric acid. This is due to the formation of several

anionic chloride species of iron, which allow the transfer of iron into the solution in contrast to sulfuric acid.

compounds and interaction of iron compounds with high-frequency field.

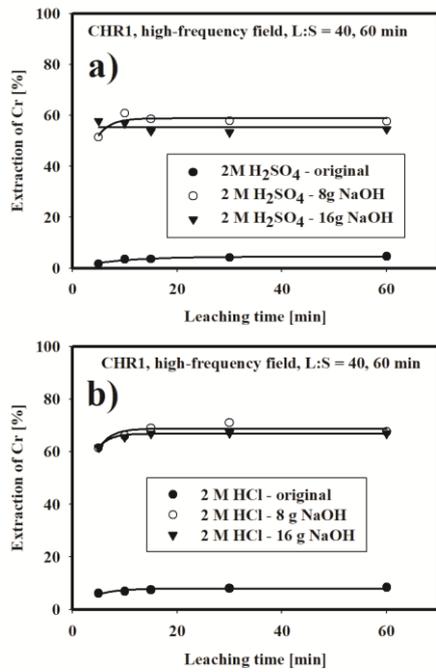


Figure 8. Leaching curves of chromium using a high-frequency field for sample CHR1

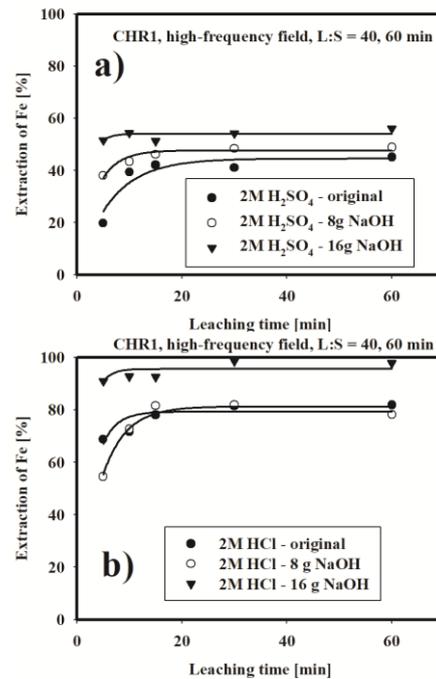


Figure 10. Leaching curves of iron using a high-frequency field for sample CHR1

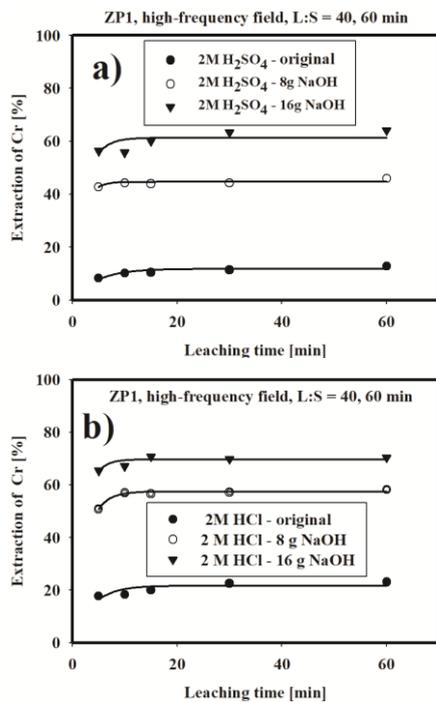


Figure 9. Leaching curves of chromium using a high-frequency field for sample ZP

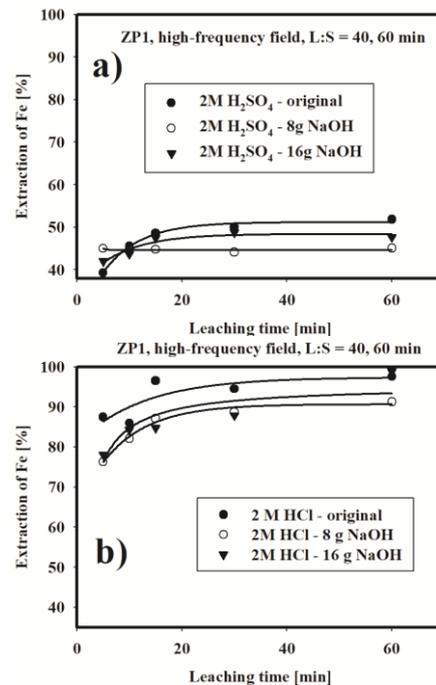


Figure 11. Leaching curves of iron using a high-frequency field for sample ZP

From the comparison of the results of classical leaching and high-frequency field follows that high-frequency field has a positive effect on iron leaching. The iron compounds are conductive and high-frequency field interact with them in comparison to chromium compounds. The iron extractions for the sample CHR1 increased in compare with classical leaching of thermally pretreated samples, which indicates the release of chromium/iron from stable

III. CONCLUSION

This paper dealt with the hydrometallurgical treatment of slags from steel production by classical leaching and leaching using a high-frequency field.

From the leaching experiments of samples without thermal pretreatment follows that the chromium

extractions only 10% were achieved from the ZP1 sample in a 2M HCl solution after 60 min and no significant influence of H₂O₂ addition on increasing Cr extraction was observed.

From the results of slag leaching after thermal pretreatment can be concluded that the heat pretreatment of the samples has a positive effect on increasing of chromium extraction. This was valid for classical leaching and also for leaching using high-frequency field. The highest Cr recovery of approximately 70% was achieved by leaching in 2M HCl using both methods. Higher extractions of chromium were not achieved either due to incomplete conversion of chromium compounds or a closed structure that prevented the access of the leaching solution.

The leaching of iron was different. From the results follows that iron compounds are better leachable and thermal pretreatment is not needed to leach out iron. Higher extractions were observed by leaching sample ZP1 what is connected to a lower content of chromium i.e., less stable chromium-iron compounds. High-frequency field has a positive effect on iron leaching because of the fact that iron compounds are conductive. The increase of iron extractions for sample CHR1 confirmed that stable iron-chromium compounds were decomposed during thermal pretreatment and subsequently iron was easier to be leached.

In future research, it is necessary to study the maximization of chromium extraction into the solution and the possibility of applying the solid residue after leaching in industry.

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An innovative approach to cost calculation using machine hour rates at product of circular economy principles

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Abstract— Increasing plastic waste from the automotive industry combined with wood waste creates a good potential for circular economy production to have a positive environmental impact. Example of an application is wood plastic composite. This article presents an innovative methodical procedure, based on the calculation of machine hour rates for a product based on the use of recycled wood plastic raw materials. A selected group of direct and overhead costs may be more accurately allocated to determine a product's final price via the presented calculation procedure.

Key words – calculation, circular economy, machinery hours, cost, wood plastic composite

I. INTRODUCTION

Environment-wise, the situation is getting increasingly unfavourable with current approaches. Human abilities and actions on earth have disturbed the environment's balance in recent century. Environmental problems are becoming more global in many instances, and they are growing deeper. A companies that demonstrate environmental responsibility implements eco-friendly practices [18]. Over the last several years, the circular economy (CE) has gained traction both on the political and industrial levels [5]. CE has become an important concept in sustainable economies in recent years. Several researchers and institutions are investigating CE as a means of enhancing economic sustainability [14]. In a nutshell, CE is an organizational principle aimed at evolving from traditional linear economics – resources are mined, produced, consumed and wasted – in other words, this economic model values resource efficiency across the entire value chain, protects biodiversity, and enables sustainable development that benefits individuals' well-being. In order to support decision-making in the CE, processes, indicators, and tools are necessary to develop CE strategies, action plans, and business models. It is essential to involve the public, private, and third sectors. [5]. Technology, operational efficiency, financial structures, and governance expertise can help companies transition to CE. Sustainability in economics, environmental protection, and social development can only be achieved through holistic thinking. For the CE model, wood is an ideal choice. Why is that so? There is no better raw material than wood, which is a natural,

renewable resource. A wood product is one of the few that tends not to pollute the environment, since it has a negative carbon footprint [10]. Using technological procedures, wood can be produced into a product that, after reaching the end of its useful life, can be re-used (recycled) or used as a source of bioenergy. This cycle is natural and works as intended. The development of the woodworking industry in Slovakia should be boosted by CE and innovative technologies. There is a need for new investment projects due to the shortage of wood raw materials, the search for new sources, and increased efficiency and added value through wood processing. Utilizing wood waste and recycled materials is a great example of focusing on CE and extending the lifetime of inputs that have already been used in production. This allows new added value to be created in new products, and input from the primary wood raw material can be saved. Furthermore, marketing approaches should also consider issues such as target groups, sales support, and an acceptable selling price level. This article presents an innovative approach to pricing products using CE principles by allocating machine hour rates.

A. Circular economy

During the 1960s, interest in environmental protection began to increase significantly, which led to the early ideas of CE. Ecologists, economists, and experts from various fields began to address the issue. Following 1990, CE development increased significantly on an international scale. A full definition of CE was provided by Pearce and Turner, 1990 in their work *Economics of Natural Resources and the Environment* [13]. The circular model of the economy described by Pearce and Turner is based on the assumption that everything in the economy is an input for something else, while the economy is interdependent with the environment. According to CE, the environment performs four economic functions: preserving resources, capturing waste and emissions, and providing for life [4]. Compared to linear economies, CE thinking represents an alternative to sustainable production and consumption. Linear economy is characterized by the extraction of raw materials, their use in the production of goods, and then their disposal after a short period of time. This means that their economic value is lost. As far as the economy is

concerned, the linear model is not sustainable. Consequently, CE aims to maintain the value of products and materials for as long as possible [6]. As [8] argue, the CE key idea is that it is an economic system aimed at the life cycle of waste, which includes reduction, reuse, recycling, and material recovery. As a concept, CE can be divided into three levels: micro (products, companies, consumers), meso (eco-industrial parks), and macro (cities, regions, nations, and other). The objectives of CE are economic prosperity and social justice, the preservation of the climate system and the biosphere, and the sustainable growth of the economies. As one of the largest charitable organizations focused on CE, the Ellen MacArthur Foundation works with Also, companies, public investors, and the general public are interested in it, government, academia and others towards building a regenerative and restorative economy [17]. As defined by Ellen MacArthur Foundation, CE is a framework for solving global challenges such as climate change, biodiversity loss, waste disposal, and pollution. The process of system change involves companies, governments, individuals, cities, products, and jobs. It is possible to re-design waste and pollution, keep products and materials in use, and regenerate natural systems with the right design approach [15]. Economic growth, environmental conservation, and human health are driving low-carbon development and resource use [9]. Several major economies, such as The European Union, Japan, and China consider CE as one of the pillars of sustainable development. They have incorporated CE into their environmental and economic growth policies [2]. According to the World Economic Forum, CE will provide an economic benefit of up to \$4.5 trillion by 2030. To make this transition successful, there needs to be a complex collaboration. At present, only 8.6 % of the world economy is circular [16]. The European Commission and other EU institutions, as well as cities and countries throughout the EU, strongly support CE. Also, companies, public investors, and the general public are interested in it. CE is viewed by the EU not only as a tool for reducing waste, but also as a means of ensuring a stable economic environment. In March 2020, the European Commission adopted a new CE action plan. It is one of the main component of the European Green Deal. By converting to CE, the EU intends to reduce pressure on natural resources, to create sustainable growth and employment, as well as achieving climate neutrality by 2050 and to protect biodiversity [7].

B. Calculation procedures

Despite the wide range of application options offered by conventional calculation methods, they are limited in terms of their accuracy because of the changing conditions of the cost structure and automation of production. In actual practice, overhead cost calculation is one of the traditional methods for calculating costs. As mechanization and automation increase, human work is increasingly replaced by machines. As a matter of fact, this is clearly seen in the sphere of production. Evidence of this can be found in the changes in the cost structure of production enterprises. It is important to note that, while

the share of production labour costs as direct costs is declining, the overhead costs associated with the machines required to produce outputs are increasing significantly. There is evidence to support this claim in the research of many authors [19], [22], [3], [25]. There is a question regarding the use of overhead cost calculations. Are labour costs of production still an appropriate basis for allocating production overhead costs? Based on the assumption that most of the output will be produced by machines, it is no longer functional to redistribute costs through direct wages [22]. Due to the changed circumstances, two fundamental problems need to be solved. In order to preserve the causal principles as much as possible, how can we do so? And what can we do to improve accuracy if we want to continue to use the overhead cost rate method of calculation? There is solution that could help solve the problems mentioned above, and that is to calculate using machine hour rates. The calculation of machine hour rates is a specific form of overhead cost rate calculation with attempting to better allocate overhead costs.

The tradition calculation formula	The modified calculation formula
Direct Material Cost + Direct Labor Cost (DLC) + Other direct cost = Total Direct Cost (TDC) + Overhead Production Cost = Total Own Cost (TOC) + Profit = Price without VAT = Price with VAT	Material cost of wood substance (sawdust) + Material cost –plastic components (HDPE + additions) + Labour calculation rate of machinery hour (LCR/MH) + Energy calculation rate of machinery hour (ECR/MH) + Depreciation calculation rate of mach. hour (DCR/MH) = Total production cost + Other overhead cost = Total cost of product + Profit margin = Price without VAT = VAT = Price with VAT

Figure 1 The tradition and modified calculation formula

II. MATERIALS AND METHODS

As part of the analysed investment plan of the company, which was presented in more detail in the article: The concept of a business plan for the production of wood plastic boards in the context of the circular economy principle [11], the subject of investigation is a product based on the use of recycled wood plastic raw materials, a non-absorbent construction large-scale wood plastic board with dimensions: height 2,500 mm – width 1,250 mm – thickness 20 mm and weight 48.5 kg. The product is produced on a WPC profile extrusion line (Figure 2) consisting of a twin-screw extruder, mold, stereotypes, traction, cutting machine and loading and cooling table. The output of WPC extrusion line is 1,600 kg per hour with a yield of 87.5 %. This means that during an 8-hour shift, the line produces approximately 11,200 kg output.



Figure 2 Wood Plastic Composite profile extrusion line

Source: <https://www.plastech.pl>

Various types of plastic can be used in the manufacture of wood plastic boards. Currently, most Wood Plastic Composite (WPC) produced and sold are made of polyethylene (PE), polypropylene (PP), or polyvinyl chloride (PVC) [1]. We are considering a WPC product made of a thermoplastic polymer made from ethylene monomer – HDPE (high density polyethylene). To calculate costs, we recommend using a modified calculation formula based on the standard calculation formula. [3], [12]. Our procedure involves calculating the cost of one calculation unit by using a modified formula, in our case, the cost of one kilogram of the wood plastic composite output. The calculation formula contains the rates of induced costs (labour, energy, and depreciation) determined per machinery hour (MH) presented in Table 3. The modified calculation formula consists of the following steps:

Material cost of wood substance (sawdust)
 + Material cost –plastic components (HDPE + additions)
 + Labour calculation rate of machinery hour (LCR/MH)
 + Energy calculation rate of machinery hour (ECR/MH)
 + Depreciation calculation rate of mach. hour (DCR/MH)
 = Total production cost
 + Other overhead cost
 = Total cost of product
 + Profit margin
 = Price without VAT
 = VAT
 = Price with VAT

Table 1 presents structure of overheads cost of company for calculation of other overheads cost margin.

TABLE 1
STRUCTURE OF OVERHEADS COST OF COMPANY PER YEAR

Type of cost	monthly amount of costs (without VAT)	Numbers of months	Cost per year
lease	4,500 €	12	54,000.00 €
fixed energy	300 €	12	4,754.00 €
administration	1,850 €	12	24,900.00 €
Σ other overhead cost			83,654.30 €

TABLE 2
DETAILED INFORMATION ON THE QUANTIFICATION OF SELECTED CALCULATION ITEMS

Margin of other overheads cost	= other overhead cost/direct labour cost*100 (%)
Energy cost rates/ Machinery hour – ECR/MH	= machine power rating × Ø % electrical capacity utilization rate per unit of energy (€/MH)
Depreciation cost rates/ Machinery hour – DCR/MH	= machine acquisition price / machine lifetime × the planned time fund of the machine (€/MH)
Labour cost rates/ Machinery hour – LCR/MH	= direct labour cost / the planned time fund of the machine (€/MH)

III. RESULTS AND DISCUSSION

To determine the final selling price, we use a modified standard calculation formula along with overhead cost principles. The final price of the product includes: other induced production costs (includes input materials like wood waste from own production and HDPE (+ additions)); labour costs (includes the labour costs and levies of technology service employees and sales managers converted to machinery hour); energy costs (represents the conversion of direct costs for driving machine technology to machinery hour) and depreciation calculated by machine hour rates. Based on the calculations, overhead costs are part of the company's indirect costs, and are covered in the sales price through overhead cost rates. In order to calculate the growth in profits, it is possible to use the average cost profitability level of the industry at 20 %.

Subsequently it was possible to quantify of selected calculation items from the table 2.

a) Other overhead cost rate
 = $83,654.30 \text{ €} / 149,909.76 \text{ €} * 100 = 55.80 \%$

b) Energy cost rates/ Machinery hour – ECR/MH
 = $105 \text{ kW} * 0.9 * 0.18 \text{ €/kWh} = 17.1 \text{ €/MH}$

c) Depreciation cost rates/ Machinery hour – DCR/MH
 = $1,032,000.00 \text{ €} / (6*2,000 \text{ MH}) = 86.00 \text{ €/MH}$

d) Labour cost rates/ Machinery hour – LCR/MH
 = $149,909.76 \text{ €} / 8*7/2,000 \text{ MH} = 65.59 \text{ €/MH}$

As a result of quantifying the calculation rates for selected groups of costs, it is possible to see Table 3 present the final calculation procedure of the product. The calculation unit was determined to be 1 ton of output mixture, 1 kilo of output and 1 piece a non-absorbent construction large-scale wood plastic board with dimensions: height 2,500mm – width 1,250 mm – thickness 20 mm and weight 48.5 kg.

TABLE 3
FINAL INNOVATIVE CALCULATION PROCEDURES OF PRODUCT

Calculation item	Notes for calculation	1 ton of output	1 kg of output	1 board
Material cost sawdust	Own production	22.00 €	0.02 €	1.07 €
+ Material cost HDPE + addit.	620 €/ton	372.00 €	0.37 €	18.04 €
+ LCR/MH	rate 65.59 €/MH	40.99 €	0.04 €	1.99 €
+ ECR/MH	rate 17.01 €/MH	10.63 €	0.01 €	0.52 €
+ DCR/MH	rate 86.00 €/MH	53.75 €	0.05 €	2.61 €
= Total Production Cost		499.37 €	0.50 €	24.22 €
+ Other Overhead Cost	Margin 55.8 %	22.87 €	0.02 €	1.11 €
= Total Cost of Product		522.25 €	0.52 €	25.33 €
+ Profit	20 %	104.45 €	0.10 €	5.07 €
= Price without VAT		626.70 €	0.63 €	30.39 €

=VAT	20 %	125.34 €	0.13 €	6.08 €
= Price with VAT		752.03 €	0.75 €	36.47 €

IV. CONCLUSION

Woodworking enterprises in Slovakia frequently use overhead cost rates in their calculations so as to redistribute direct and indirect costs among the units of calculation. In the presented work, to calculate the final price of the product, we used an innovative methodology for calculating machine hour rate based on the recycled wood plastic raw material. A technologically oriented production with the use of machinery against the decline of manual labour is one way to allocate production costs. A key advantage of using overhead rates is that it eliminates the so-called principle of averaging. Thus, problematic cost items can be calculated more accurately per machine hour. We have practically allocated the overhead costs of the production WPC profile extrusion line (summary rate 168.60 € per machinery hour). Using the principles calculation of overhead cost rates, we determined the selling price 30.39 € without VAT per 1 piece of board with dimensions: height 2,500 mm – width 1,250 mm – thickness 20 mm and weight 48.5 kg resp. 702.56 € without VAT per 1 ton of output, which can compete with alternative products.

There is also the possibility of considering the Activity Based Costing methodology as an alternative method for calculating costs. The basic concept behind it is the assignment of costs to the individual activities. To implement this approach, would be required a detailed classification of business activities and possible cost divers. Due to this, its practical application is greatly hampered. There is also another method that can be used, calculation of variable costing. In this method, the market-acceptable selling price should be reduced by the maximum level of direct and variable costs. In this case, all groups of machine hour rates may be used in order to establish a specific level of contribution margin. The following approach is more appropriate for calculating the prices of different variants of the product to obtain a faster orientation in pricing.

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Pyrolytic Processing of Waste from the Automotive Industry

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Abstract—Human life is inextricably linked to the creation of waste, whether in the municipal or industrial sphere. Waste is an important source of secondary raw materials and stored energy, which nowadays is advantageous to use. If we leave aside the possibility of not creating waste at all, the most appropriate way of valorizing waste is its recycling and its reuse. In practice, however, there are cases when wastes are not suitable for recycling for various reasons, their share is currently relatively high, it exceeds the processing capacity of the Slovak Republic, and therefore these wastes are mostly deposited in landfills. Waste stored in this way can be a great source of energy, and their use would help not only in the area of waste management rationalization, but also in the area of energetics and chemical industry, especially in today's energy and raw material crisis. The EU is gradually prohibiting its member states from landfilling waste that can be used for energy, which is why new innovations are needed in this area [11]. The simplest way of energy recovery of waste is its direct incineration or co-incineration with a other fuels, more complex technologies are its gasification and pyrolysis. All these technologies are collectively called Waste to Energy processes. Incineration or co-incineration of waste releases stored chemical energy, which is converted into heat, which is used to produce electricity and heat. The products of gasification and pyrolysis are gaseous and liquid fuels that can be directly used in heat devices for the production of electricity and heat for heating, but also as input material for the production of high-quality fuels and for the chemical industry, for example for the re-production of plastics. In the field of gasification and pyrolysis, research is carried out worldwide, but it mainly focuses on the processing of single-type waste (for example, old tires, biomass, single-type plastics, etc.). The processing of waste mixtures, for example several types of plastics, is problematic, especially due to the ambiguity of the composition and the resulting uncertainty in the chemical composition of the output products and in the correct setting of the entire technological process. For the above, it is necessary to carry out systematic research in this issue, which would determine the operating parameters of the entire technological process of waste treatment with the given technologies.

The article deals with energy utilization of waste by pyrolysis technology, especially plastics from the automotive industry and sorted municipal waste. The article summarizes the previous knowledge from experimental research in the field of preparation of input material, technological methods of its use by pyrolysis and the possibilities of using the resulting products of processing plastic waste. The article contains the results of laboratory pyrolysis processing of mixed plastic waste and the properties of the resulting products.

I. INTRODUCTION

The current lifestyle produces a large amount of municipal and industrial waste, which contains a large amount of plastics of various kinds. Due to the insufficient network of processing facilities in SR, this waste is largely deposited in landfills. According to the regulation of the European Commission, the disposal of waste of this type in landfills will be limited in the near future (recyclable or energy usable) [11], so nowadays we are faced with the question of how to deal with it and process it. If we ignore the fact that the most appropriate solution is not to produce plastic waste, plastic recycling is the optimal solution to the given problem. Not all plastic waste is suitable for recycling and subsequent use (either from the point of view of the impossibility of sorting plastics by type, its gradual degradation or contamination with other substances, etc.). Another possible solution is its incineration, or co-incineration with other fuel and obtaining heat for the production of electricity, heating or technological processes. Incineration, or co-incineration of plastic waste and its energy use is a solution, unfortunately there are relatively few facilities in SR and they are unevenly distributed throughout the territory. An ecologically and energetically more appropriate solution is the use of new plastic waste processing technologies, e.g. gasification or pyrolysis, which transform this waste back into the starting raw material – gas and liquid phase, which can be used either directly as fuel or as input raw material for the petrochemical and chemical industry [1]. The construction of such facilities in the territory of SR is not yet widespread, the reason may be the financial difficulty or the almost non-existent market where the products of decomposition of plastic waste could be used. Existing operations, e.g. for the gasification and pyrolysis processing of plastic waste are rather pilot projects in SR, they have limited capacity, they are unevenly distributed, which also implies the need to transport suitable waste over long distances from a wide area. Transporting waste over long distances can hardly be called as economic and ecological. Large gasification and pyrolysis processing facilities are available in the world and on the market, which are investment-intensive and unsuitable for the conditions of SR. The starting point for this situation is the construction of smaller gasification and pyrolysis processing facilities, capacity-dimensioned according to the amount of waste in the immediate vicinity, evenly distributed throughout the territory of SR, support for their construction by the state, e.g. appropriate legislation, subsidies, etc., and also the creation of a market for gasification or pyrolysis products - synthesis gas, oil, etc. Such smaller processing plants of non-recyclable plastic

industrial and municipal waste could be located near larger sources of plastic waste, e.g. near processing facilities for discarded cars, or for associations of municipalities, or in areas for sorting municipal waste. Such an operation could be a modular system, e.g. placed in containers and could be adapted to specific requirements, types and quantities of processed waste.

Gasification or pyrolysis processing of single-type sorted plastic waste (e.g. PET bottles, HDPE, LDPE, PP) is technologically manageable, the technology of processing mixed plastic waste, which can be contaminated with various impurities, such as waste from the automotive industry, is problematic [1]. The disparity of this input material for energy recovery increases the technological complexity of the entire process. This waste is specific mainly due to its state (solid and liquid), species composition and various fractions (depending on the method of previous processing). Plastics, rubber, operating fluids (fuels, engine and transmission oils, cooling and brake fluids,...), leather, synthetic textiles, upholstery, etc., can be considered energetically usable waste from the automotive industry and car recycling. The largest share of energy-usable waste from scrapped cars is made up of plastics, which can generally be divided into polypropylene 35% of the total weight of plastics in a car wreck, polyurethane 20%, PVC 11%, ABS 10%, polyamide 9%, polyethylene 5% and other unspecified 10%. In the category of plastic waste, it is also possible to include the remains of cable scrap, they are made up of cable insulation, terminals, connectors, etc., they are mainly made of PVC and ABS and are no longer recycled, and they are intended primarily for energy recovery. The biggest problems in the energy recovery of plastics are with PVC, whose presence in the fuel is limited due to the resulting emissions (if PVC in the fuel is above 1%, an increased temperature in the combustion chamber and an increase in the residence time are necessary). The composition of the input fuel for the process of energy recovery of plastics is given by the technology of processing the car wreck. The crushed plastic portion after shredding is already very difficult to separate and this plastic portion is primarily intended for energy recovery, the input fuel has unspecified properties and composition. The most accurate chemical and physical properties and composition of the input fuel are achieved when the car wreck is completely detachable.

II. PYROLYSIS

Pyrolysis is the heat treatment of waste substances in a pyrolysis furnace or reactor at a temperature of 250 to 1650 °C without air access, or with limited air access and at reduced atmospheric pressure. The result of pyrolysis decomposition is liquid substances (pyrolysis oil) and gaseous substances (pyrolysis gas – syngas).

The principle of this method of energy recovery of plastic waste is polymer degradation, which can take place with the participation of a catalyst, the reaction takes place in a closed reactor under the influence of heat. The reaction takes place either in the presence of a small amount of air or without the presence of an oxidizing reagent, which is most often replaced by an inert gas, most often nitrogen and most often at normal atmospheric pressure. The batched mixture of plastic waste is depolymerized in the reactor, split into lower hydrocarbon chains

(decomposition of long chains of plastic materials into a fluid mixture of saturated hydrocarbons). The waste plastic material is converted into gas, and by its subsequent cooling, it turns into oil fractions, the raw material from which it was originally made, and synthesis gas, which contains non-condensable molecules. By cooling the resulting fluid mixture of saturated hydrocarbons, the process of fractional distillation begins, i.e. the separation of individual oil fractions, when the plastic waste is converted back into the basic raw material. The resulting product of the process, which is called catalytic cracking, is a mixture of petroleum fractions, containing diesel, gasoline and oil components, paraffin, wax and other parts.

Depolymerization most often takes place in the presence of a catalyst. When adding a catalyst, plastic waste acquires elasticity already at low temperatures (around 200 °C). The advantage of the catalytic depolymerization process at lower working temperatures is also the lower fuel consumption needed to heat the reactor. The catalyst is continuously added to the reactor, which ensures its continuous and stable activity and thus balanced working i.e. temperature conditions with a favorable effect on uniform product quality.

III. INPUT RAW MATERIALS AND OUTPUT PRODUCTS

With the described technologies, it is possible to process various types of waste, municipal and industrial, biomass, plastics, old tires, etc. From plastic waste, waste polyolefins (polyalkenes) such as HDPE, LDPE and LLDPE are most often processed using the given technologies, i.e. polyethylenes of different specific weights and PP – polypropylene. The suitability of these polymers results from the fact that they are composed exclusively of carbon and hydrogen and their basic structural units are ethylene $\text{CH}_2=\text{CH}_2$ and propylene $\text{CH}_3-\text{CH}=\text{CH}_2$ [4, 10].

Depolymerization using the methods described above produces synthesis gas from the input materials, which can be divided into condensable and non-condensable molecules by cooling (tab.1 shows an example of the composition of the synthesis gas depending on the input raw material). Depending on the input raw material, if it is plastic, after cooling it contains mainly liquid depolymerization products – crackers, which, depending on the conditions of the decomposition process, and especially depending on the height of the decomposition temperature, have an oily, waxy or diesel character. These emerging products have a similar fractional composition to those produced primarily from petroleum. The remaining part after depolymerization is water and solid residue in the form of carbon, foreign residues from the original waste plastic raw material, in the form of e.g. metal residues, glass, stones, earth and other mechanical impurities. The resulting liquid and gaseous fractions do not contain a significant amount of halogens, sulfur, nitrogen or metals, as the original raw material does not contain them either. Therefore, from the point of view of the chemical composition, there are practically only C_1 to C_5 hydrocarbons in the gaseous portion, and the output

product of the entire technology is a mixture of liquid carbon and hydrogen, in a mass ratio of 86:14 %, which are structurally predominantly unsaturated hydrocarbons without a significant content of aromatic compounds. The output product corresponds to the fractional composition of light heating oil, diesel fuel and wax, that is, raw materials that can be further processed in the petrochemical industry as a valuable raw material or can be directly used for the production of heat and electricity. [10]

Application of the given technologies to other types of plastic waste, e.g. from the automotive industry is particularly problematic due to the diversity of the input material, which has a fundamental impact on the choice of depolymerization temperature, the length of the depolymerization period, the use of catalysts, the final product and the residues after depolymerization. [10]

TABLE I
EXAMPLE OF SYNTHESIS GAS COMPOSITION DEPENDING ON THE TYPE OF INPUT RAW MATERIAL [3, 7, 9]

	H ₂ [%]	CH ₄ [%]	C ₂ -C ₄ [%]	CO [%]	CO ₂ [%]	N ₂ [%]	Density [kg.Nm ⁻³]	Thermal capacity [MJ.Nm ⁻³]
biomass	15	26	3	35	17	4	1,10	17,10
plastics	25	38	18	9	5	5	0,80	28,00
old tyres	19	40	28	3,5	6,5	3	0,90	36,00

IV. GASIFICATION AND PYROLYSIS EQUIPMENT

For gasification and pyrolysis, reactors are used, most often cylindrical, depending on the amount of processed waste, they are constructed either as continuous or discontinuous. Both technological processes require the supply of a certain amount of heat, its amount depends on the working temperature, amount and type of processed waste. Heat to the process is supplied either by burning gaseous and liquid fuels or by electric heating. Heating with electric energy is realized directly, through an electric spiral, which can be placed in the feed screw. For safety reasons, heating by burning liquid or gaseous fuels in burners is most often realized through an intermediate medium located in the double wall of the reactor. The reactor has thermal insulation due to the economy of operation. [6] Reactor capacities range from several hundred kilograms to several tons of processed waste per hour. The retention time of the batch in the reactor and the operating parameters depend on the reactor design and the type of waste being processed, an example of operating parameters is shown in tab.2. The solid residue after the technological process is removed through the bottom of the reactor by a cooled screw conveyor. The amount of solid residue depends on the type of processed waste, technology and operating parameters. [5, 8]

V. PREPARATION OF RAW MATERIAL

Plastics after the selective dismantling of car wrecks were chosen as the input raw material for the pyrolysis processing of waste. It mainly consisted of plastics from bumpers (painted and also without surface treatment), plastics from the engine area (engine covers, plastic parts of the air intake, etc.) and parts of the interior. Typically, the plastics consisted mainly of PE, PP and ABS. Their percentage in the created mixture of plastic debris corresponded to their percentage by weight in the car wreck. Plastics were selectively crushed according to the

type of plastic on a rotary device (fig.1) and then a working mixture was created by mixing individual types of plastic (fig.2). The fractional composition of the plastics in the mixture was heterogeneous, the characteristic size was from a few millimeters to 5 centimeters, mostly in the form of strips (the shape results from the method of crushing with the knife head of the

TABLE II
EXAMPLES OF OPERATING PARAMETERS OF PYROLYSIS REACTORS [9, 2]

	Biomass ¹	Polymer plastics ²	Old tires
Working temperatures	250 – 700 °C	650 – 800 °C	650 – 800 °C
Holding period	5 – 15 min	15 – 25 min	15 – 25 min
Amount of syngas	15 – 80 %	60 – 95 %	30 – 60 %
Amount of synthesis oil (after cooling)	5 – 40 %	5 – 30 %	20 – 40 %
Solid residue ³	15 – 90 %	2 – 30 %	35 – 45 %

¹ Wood chip, agricultural dendromass, sawdust,...

² Plastics, energetically significant components of municipal and industrial waste

³ changes depending on operating conditions (torrification / pyrolysis / high temperature pyrolysis) grinding device used).



Figure 1. Used shredding device



Figure 2. Mixture of plastic waste

VI. LABORATORY PYROLYSIS

The laboratory discontinuous pyrolysis reactor was filled with a mixture of prepared plastic waste, one working batch weighed 3.5 to 4 kg. The reactor was filled in a cold state (at ambient temperature), the condensation exchanger was cooled to an average temperature of 13.5 °C. Different working temperatures in the range of 300 to 600 °C were chosen for pyrolysis [2]. The course of working temperatures during the selected cycle of pyrolysis is shown in fig.3. The pyrolysis process took place without added catalyst. In fig.3, four phases of the pyrolysis process can be observed:

- Preheating phase – the working space is filled with an inert atmosphere, the temperature of the pyrolysis reactor and the charge rise from the ambient temperature, the phase is completed when the first vapors are released.
- Phase of vapor formation – the first vapors began to be released at a temperature of 62 °C, the supply of inert atmosphere from the pressure bottle was stopped, the start of the pyrolysis process no longer allows the entry of atmospheric oxygen, the vapors flow through the condensation exchanger but are non-condensable.
- Condensate formation phase – condensate began to form at a working temperature of 240 °C, at temperatures below 350 °C the condensate is oily, after complete cooling it has a waxy character with high viscosity, at higher working temperatures the viscosity of the product decreased.
- Cooling – after the end of the pyrolysis process (minimum amount of condensate formed), the reactor is cooled to ambient temperature so that it can be opened and solid residues can be removed.

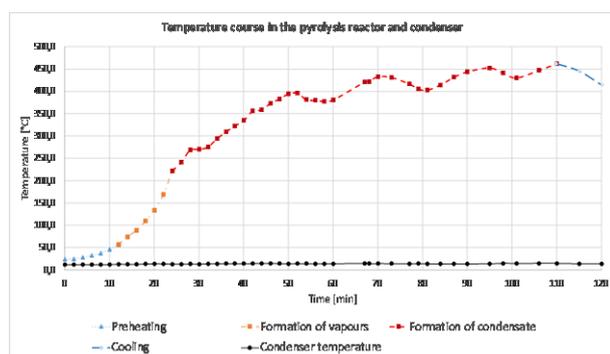


Figure 3. Working temperatures during pyrolysis

The resulting products of the pyrolysis processing of plastics were pyrolysis oil and syngas, the by-product was a solid residue. Table 3 shows their representation in selected pyrolysis cycles. The average mass fraction of pyrolysis oil was 60.44 %, pyrolysis gas 29.74 % and solid residue 9.81 %. Crude pyrolysis oil was made up of all condensable hydrocarbons that were formed during pyrolysis, it was represented by fractions with low viscosity (consisting of gasoline and diesel fractions, fig.4) to high viscosity fractions (oily and waxy, resembling fuel oil, fig.5). The pyrolysis oil was dark brown to black in color, with a strong odor. The low-viscosity fractions were filtered (fig.6), the treated samples were subsequently weighed again. An example of the results of the sample processing after the pyrolysis process is shown in Table 4. The filtering took place at room temperature, which had an impact on the permeability of the sample through the filter, all the part of the sample that did not pass through the filter was included as waste from the process. The light fraction constituted about 40% of the weight of the obtained pyrolysis oil, the heavy about 33% and about 26.5% of the weight was removed by filtration. This amount of waste could be reduced if the filtering was carried out in a heated state of pyrolysis oil, the waste separated in this way is still highly flammable, which was confirmed by a combustion test.

After opening the pyrolysis reactor, the solid residue was removed (fig.7), which, in addition to carbon, probably contains other components (metal pieces from the input material, heavy metals from surface coatings and adhesives, etc.). The solid residue can be used in the following pyrolysis cycle as a catalyst because it contains a high proportion of active carbon.



Figure 4. Low viscosity fraction

TABLE III
WEIGHTS AND PERCENTAGE BY WEIGHT IN SELECTED SAMPLES

	1. sample		2. sample		3. sample		4. sample		5. sample		Average
	Weight [g]	%									
Oil	2140.0	59.3	2459.0	61.5	2118.4	60.1	2218.7	57.4	2534.8	63.9	60.44
Syngas	1139.8	31.6	1186.8	29.7	998.2	28.3	1196.6	31.0	1115.2	28.1	29.74
Solid residue	329.1	9.1	345.2	8.9	406.2	11.5	446.8	11.60	317.0	8.0	9.81
Batch	3608.9	100.0	4000.0	100.0	3522.8	100.0	3859.1	100.0	3967.0	100.0	



Figure 5. High viscosity fraction



Figure 6. Filtering

TABLE IV
EXAMPLE OF SAMPLE PROCESSING BY FILTRATION AFTER PYROLYSIS

Pyrolytic oil	2140.0	g	100.00	%
Light fraction	873.7	g	40.83	%
Heavy fraction	699.2	g	32.67	%
Waste	567.1	g	26.50	%

VII. CONCLUSION

In the future, pyrolytic processing of waste will play an important role in the use of waste, not only for direct energy use, but also as a source of input material for the production of noble fuels and lubricants and also for the chemical industry for the re-production of new materials. Prospective research in this area shows that it is also possible to process mixed multi-species plastic waste, with an average gain of approximately 90% of the original mass usable for energy and other purposes (liquid and gaseous phase of pyrolysis products). The solid residue is suitable as a catalyst for the next cycle of pyrolysis, due to its increased content of harmful substances it is then suitable to be deposited in a landfill.

Such waste treatment requires further research in the field of the influence of the operating temperature of the pyrolysis reactor, the length of the residence time, the use of various catalysts to improve the economics of the



Figure 7. The solid residue after pyrolysis process

operation of the pyrolysis reactor, and also in the field of pyrolysis oil and gas processing.

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Information Platform for the Recycling Technologies Innovation – SmartWaste

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Abstract— The paper deal with the information platform “SmartWaste” intended for sustainable waste recovery, which has supported the transformation of Slovak waste management in line with the circular economy objectives and the opportunities offered by Industry 4.0. It considers current and future EU requirements around the waste management. Using the intelligent specialization and modern information technologies, the main aims of “SmartWaste” are (1) to collect the information about the waste treating technologies in operations, and (2) to carry out research in the field of material and energy recovery of waste which cannot be treated by the conventional technologies. Moreover, it gives the emphasis on innovative solutions with new added value, the optimization of relevant logistics processes based on the analysis and forecasting of trends in industrial production, and their impact on the economy and waste management development.

I. INTRODUCTION

The European Union's waste management policy has been developed for more than 30 years through several environmental action plans and framework directives. Their main goals are focused on continual reducing the negative effect of waste on the environment and human health while at the same time increasing the efficient and effective use of resources. In the Thematic Strategy for waste prevention and recycling which is one of seven strategies of the EU Environmental Action Plan [1], the EU defined not only its priority goals but also introduced key concepts such as a recycling society, thinking in the dimensions of the life cycle, the extended producer responsibility, the hierarchy of waste management, prevention of waste generation, and using the waste as a resource. They express the approaches applied when creating the EU concepts of waste management policies.

Today, waste management is faced with several significant trends that have significantly influenced the business model used so far. The implications of the health pandemics and other serious uncertainties in the form of disruptions in supply chains and the growth of energy prices have increased the attention towards the circular economy. Implementing the circular economy strategy moves waste management closer to resource management concepts and makes it an integral part of global markets with limited resources. The precondition for increasing the efficiency in resource use and closing the cycle within the circular economy is the transition of waste into a resource [2]. Switching to the circular economy requires implementing the changes in the entire value chains, from product design to new business models, from new

methods of transforming waste into resources to new modes of consumer behaviour, including systemic changes and innovations in the technologies. The intensive development of Industry 4.0 digital technologies is redefining what we call waste management. Digital technologies - robotics, the Internet of Things, autonomous vehicles, the intelligent sensors, and artificial intelligence will be the core of the waste management transformation in the 21st century [3, 4, 5].

The EU's intention to move towards carbon neutrality is the strong impulse to develop clean waste treatment technologies throughout the whole product life cycle and, gradually, to replace the old product designs with new technological elements that will contribute to improving the quality of the environment. These changes are only possible with a transition to the high technologies designed for photovoltaics, fuel cells, microelectronics, LED technologies, optical fibres, laser technologies, etc., which are demanded in the so-called critical strategic raw materials [6]. Therefore, it is crucial to mobilize and separate the waste containing such strategic raw materials, while their significant source in the Slovak Republic is e.g. waste from electrical and electronic equipment or the processing of old vehicles, etc. [7].

Today, the automotive industry is a sector that significantly influences and, as well, promotes other sectors of the national economy, such as the engineering, metallurgical, electrotechnical or chemical industries. There are approximately one billion cars in the world, of which about 200 million drive on European roads and more than 2 million drive in Slovakia [8]. Moreover, the progress in the material structure of current cars reflects the EU's strategy to produce energy-saving vehicles when introducing breakthrough technologies in vehicle design with extremely low carbon emissions. The various requirements, such as reducing fuel consumption and emissions and increasing safety and comfort of operation, involve the application of complex functional materials - composites, which are hardly recyclable so far [9, 10]. The notable increase of electronics in car design and starting the mass production of electric vehicles and vehicles with other alternative drives bring new challenges for recycling technologies.

Currently, in the Slovak Republic, systematic attention is paid neither to the research in economically effective processes for critical strategic raw materials recycling nor to statistical evaluation of the yield of these sources in available waste [8]. Due to their specific properties, new materials are increasingly promoted in practice, which puts technological pressure on existing recycling facilities inevitably. It is an open question how developed markets

and infrastructure are for recycling the specific waste, which is much more vulnerable and sensitive to fluctuations in demand than markets for metallic materials. The waste recovery facilities are confronted with the fact that in the case of waste based on advanced multi-component materials, the traditionally used technologies become ineffective or even unusable [11].

One of the ways to support the innovation in recycling technologies, regardless of the waste category (industrial or municipal) in Slovakia, was to design the integrated information and innovation platform for recycling technologies.

The paper presents the conceptual starting points and results of the digital platform "SmartWaste" development in the environment of the automotive industry.

II. DEVELOPMENT OF "SMARTWASTE" INFORMATION PLATFORM

The idea to create the integrated information platform "SmartWaste" did not arise by chance but passed through development associated with searching for the system's optimal internal structure and its functionalities, the structure of the provided information and data, and the user interface.

The first thoughts about the need for a modern and efficient information system in the field of waste management appeared during the economic crisis of years 2009 to 2010. Then, in the waste sector, crisis management required urgently to work with correct and consistent data on the quantity and quality of material streams of waste, and available processing and logistics capacities, not only with historical data but also with data obtained in real-time. As a result of extensive discussions on the state of information systems in waste management, the conceptual proposal is presented in Fig. 1.

The proposed integrated system was supposed to map all information, material and financial flows in the waste management sector and to ensure the information in the scope and quality necessary for effective control and development of modern waste management. The core of the system consisted of three interconnected subsystems, which were supposed to collect information on entities operating in the entire chain of waste management processes (registers), on issued permits for waste managing (permitting processes) and on the amounts of generated and processed waste (waste records and reporting).

The adoption of the Circular Economy Action Plan and new goals for waste recycling by the European

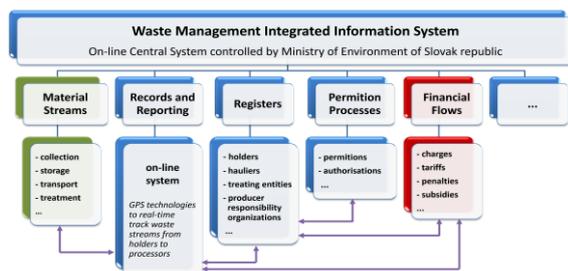


Figure 1. A concept of on-line integrated waste management information system (model 2011)

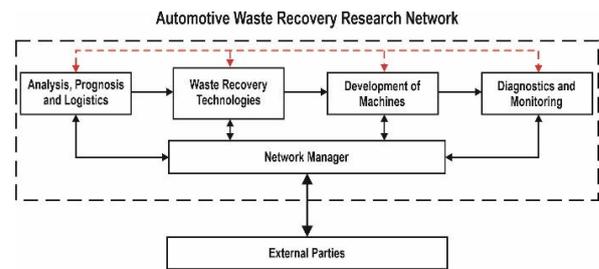


Figure 2. Functional diagram of a research platform (model 2015)

Commission in 2015 caused the cooperation between the Slovak Automotive Industry Association and the Slovak universities to research and develop advanced technologies for waste recovery from end-of-life vehicles and the automotive industry, which has become the dominant industry in Slovakia. This cooperation brought about the design of the research platform, the structure of which is shown in Fig. 2.

It was based on the concept of modern distributed production systems and digital technologies of Industry 4.0, specifically, PLM (Product Lifecycle Management) systems which support fast and robust innovations carried out in a virtual environment where new ideas about technology, equipment, or products are assessed with customer requirements. In the environment of the research platform set up in this way, the research teams of the Slovak universities should collaborate on the implementation of research projects, while each one should contribute their unique knowledge and experience, as well as equipment [12, 13]. Functioning applications were supposed to ensure effective communication and reliable exchange of information with suppliers and customers about the projects' progress. The open digital environment of the PLM system was supposed to enable real-time collaboration and information sharing between the project teams using diverse data sources. A characteristic feature of the considered concept was its modularity and openness. After verifying the functionality of the proposed platform concept, the authors assumed enhancing it with other services, e.g. searching for partners for cooperation to ensure the implementation of research and development results in small and medium enterprises.

The expansion of Industry 4.0 digital technologies, the adoption of a circular economy strategy, and the evaluation of their impacts in the field of waste management regarding the effect on technologies, management processes, analysis of data on waste streams and business models caused that universities and the Slovak Automotive Industry Association conceived a new system - an integrated information and innovation platform for recycling technologies "SmartWaste" (Fig. 3). Its main goal is to enable based on the intelligent specialization and advanced information and communication technologies to collect systematically the information on waste management technologies in the territory of the Slovak Republic, and to carry out effective research and development in the field of material and energy recovery of waste, especially, from the automotive industry and the end-of-life vehicles processing.

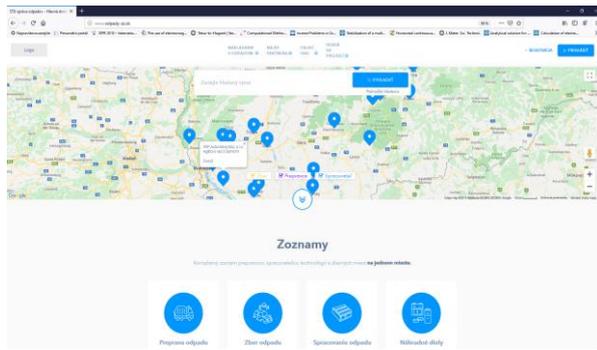


Figure 3. “SmartWaste” platform with an interactive map and searching

The priority is the waste unprocessable by conventional technologies when innovative solutions with new added value are emphasised. Furthermore, it focuses on optimizing the relevant logistics processes via forecasting the trends in automotive production and its effect on the national economy.

III. FUNCTIONALITIES OF INFORMATION PLATFORM

The platform is built as a virtual space intended for the communication of entities involved in the waste management chain to provide users with up-to-date and transparent information on the available collection, transport and treatment capacities, qualitative information on the installed technologies for waste processing, on the one hand, and to develop business activities on the other hand, especially at the level of small and medium-sized enterprises in cooperation with universities, in the field of research and development of new innovative technologies for waste processing.

The platform provides users with two basic functionalities. Based on various criteria, it enables the waste producers or holder to search for the optimal waste transports (shipments), the most suitable recovery technology for his waste – its availability (GPS location), the quality level of technology (BAT, quality management systems, material balance, certification of output products, equipment capacity, etc.). It allows the waste processor to communicate with waste holders about their spare recovery capacities (proximity principle) and to establish contact and communicate in one place with research centres or technology suppliers about the possibilities of developing or supplying specialized technologies for recycling and recovery of specific wastes.

IV. PLATFORM INTERNAL DESIGN

The architecture of the platform, presented in Fig. 4, is built as the client-server model. Users access the application through the user interface via a web browser. This access design allows other e-services can be incorporated into the system according to evolving needs in the future. To ensure the economic sustainability of the system, the platform considers two categories of users, the public with free access and users with paid registration, who differ in the scope of information available. The portal's graphic interface is designed to be responsive for mobile phones, tablets, and desktops and is uniform for the entire platform.

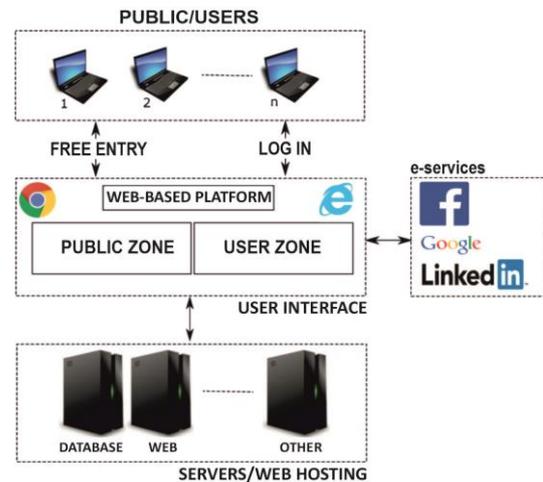


Figure 4. The technical architecture of “SmartWaste” platform with an interactive map and searching

The internal structure reflects the specified requirements for its functionalities and goals (Fig. 5) and consists of two zones. The first one is the information subsystem "collection - transport - processing", where the waste holder can search for the most environmentally and economically acceptable way of handing over the waste, e.g. regarding the output of the applied technology, which can be waste, secondary raw material or a certified product.

The second zone is the innovation subsystem, where the subjects of the waste management chain can in a virtual environment search for new commercially available technologies or partners to research, develop or produce the new procedures, technologies, and equipment according to the current need in waste management through projects and the offer of contracts. The authors perceive this functionality as a chance to create and support business opportunities for domestic small and medium-sized enterprises. In the innovation subsystem, a stack for offers of new technologies and devices that have already been developed or implemented is created.

The application "Waste Catalogue" (Fig. 6) was designed in the user-friendly interactive form in order to the user could filter and search the waste in the full text either according to its number, the catalogue or its slang

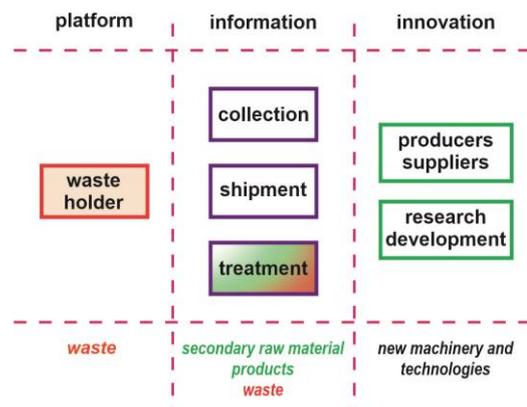


Figure 5. The philosophy of internal structure of the platform “SmartWaste”

name in real-time. It is simultaneously linked to the registers of entities providing waste collection, shipments, and treatment. The searching results are displayed on the interactive map (Fig. 3).

When making the decision on the quality and structure of data collected and processed by the platform, the authors kept in mind its main goal to provide objective and transparent information about technologies and their capacities operated in the waste management system and their location so that to simplify the informed decision-making of subjects in waste management. At the same time, it provides relevant data for identifying the critical areas of waste processing, planning the development activities in waste management, or creating new business opportunities.

The basic data structure consists of the specialized registers which collect and store the individual data records of registered entities. The internal data structure of the registration record of the waste processing facility is given in Fig. 6. From the point of principles applied in the circular and green economy view, the set of qualitative and quantitative information about the crucial characteristics of technologies allows the person interested in waste processing to make a qualified decision whether to hand over the waste to the given facility or to look for another one.

V. CONCLUSIONS

Launching the platform “SmartWaste” (www.odpady-az.sk), it supports the fulfilment of recycling and other goals listed in the key EU directives and the strategic documents of the Slovak Republic, which regulate our waste management. Its effective functioning encourages the design and use of new innovative technologies for the collection, shipment, and recovery of waste, and that is why it will act not only upon preventing waste generation but also to reduce the amount of disposed waste. It can be a tool for strengthening the research and innovation capacity in the area of cleaner products and environmental technologies.

The platform's functionalities enable to identify the current and future critical areas and bottlenecks in waste processing technologies, which can be the basis for

Registers	
Register of facilities for waste collection	
Register of facilities for waste treatment	
Register of waste shipment operators	
Register of waste holders	
Register of research organisations	
Register of producers/suppliers of technologies	
Register of the project calls	
Register of projects	
Source tables (under the applicable waste legislation)	
Catalogue of waste (European waste catalogue)	
Catalogue of technologies	
Catalogue of recovery operations	
Catalogue of disposal operations	
Catalogue of equipment (mobile/stationary)	
Catalogue of permissions	
Catalogue of authorisations	

Figure 6. Registers and source tables for platform “SmartWaste”

defining research, development, and innovation projects on environmentally friendly waste recovery technologies. The active use of platform by the interested parties will support the rate of yield the waste as a source of secondary raw materials and energy, saving of primary sources of raw materials, the use of recycled materials in the production of eco-innovative products, and the acquisition of critical strategic raw materials through waste processing.

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Financial Support of Progressive Technologies and Innovations in the field of Waste Management in Automotive Industry

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Abstract— The contribution points out to the fact that when old vehicles are processed, it is very important for manufacturers to focus not only on the disposal of waste itself, but especially on their reuse, i.e. recycling. In addition, meeting the strict environmental obligations for the production, operation and disposal of automobiles will call for a number of specific innovations in the near future. It will require the creation of adequate conditions. The priority is to support the financing of research and development, as well as the implementation of new waste management technologies, especially when it comes to problematic waste (e.g. plastics, composite materials, windshields with foils, etc.) and hazardous waste.

The subject of the contribution is also an overview of the possibilities from which companies can obtain external financial resources for financing innovations in waste management in the automotive industry.

As for resources from the state, in the past companies could get resources from the Recycling Fund. Currently, it is possible to obtain support in the form of a subsidy or loan from the Environmental Fund. Good and green intentions that meet the standards of sustainable business can also be co-financed with the support of structural funds. The paper presents the possibilities of obtaining financing from the European structural funds in chronological order according to individual program periods. We are currently at the beginning of the 2021-2027 program period. Slovakia still has approximately 8 billion euros available from the previous program period, which must be used up by 2023. Until the same year, it also has 780 million euros available from the REACT package to mitigate the effects of the corona crisis. So, until 2023, there should be more calls for subsidies from both the previous and the current program period. Within the new program period, Slovakia should receive 6.3 billion from the Recovery Plan focused on investments and reforms until 2026. In addition to grants and standard financial instruments, alternative financing options, including crowdfunding, can be used to finance innovative projects in the field of waste management.

I. INTRODUCTION

The automotive industry is a key branch of Slovak industry. Within this industry, the processing of old vehicles generates waste that can be described as

"problematic" (e.g. upholstery, composite materials, windshields with foils, etc.).

The issue of waste disposal is not only a question of the present, but also of the future. Storing waste in landfills seriously damages the environment, and therefore it is very important to focus not only on the disposal of waste itself, but especially on its reuse, i.e. recycling.

Many legislative standards have been adopted within the EU, which set guidelines for car manufacturers on the recycling of end-of-life vehicles. Fulfilling strict environmental obligations for the production, operation and disposal of cars will require a number of specific innovations in the near future. An obvious consequence should be the creation of adequate conditions, so the companies involved would be motivated to do so. The priority is to support the financing of research and development, as well as the implementation of new waste management technologies, especially when it comes to problematic and dangerous waste.

In connection with the lifespan of cars, the European Commission's guideline no. 2000/53/EC (hereinafter referred to as the Directive) was adopted [1]. Its purpose is to increase the environmental aspect of the dismantling and recycling of end-of-life vehicles (ELVs, End-of-Life Vehicles). [1] is also used to regulate the recycling process and determine the proportion of how much material should be recycled.

[1] requires the car manufacturer to take responsibility for the disposal of its product, thereby encouraging him to increase the sustainability of its products. [1] states that no more than 5% of the vehicle can be sent to the landfill, the remaining part should be recycled or reused.

The overall impact of [1] has naturally resulted in the modification of the assembly process of car production (in connection with possible disassembly), in the use of materials that are recyclable, further in the search for new alternative materials and finally in new recycling technologies that will be able to restore today's non-recyclable materials.

The aim of the contribution is to provide an overview of the possibilities from which companies can obtain external financial resources for financing innovations in waste management in the automotive industry.

II. DEVELOPMENT OF RECYCLING OF OLD CARS IN SLOVAKIA

In the case of Slovakia, companies operating in the field of recycling old cars gradually began to emerge in the nineties of the last century.

The vehicle fleet at that time consisted of vehicles, the main part of which was manufactured back in the 1970s. These cars were mostly made of metal. After removing dangerous substances such as oils or batteries, they did not contain any more complex components, so their processing was relatively simple. With the then "non-legislative" also low-cost.

The development of the processing industry of old vehicles began its boom only at the beginning of the first decade of this century. In this period, legislation on the recovery of old vehicles also began to develop. In 2001, Act No. 223/2001 Coll. on waste [2], which replaced the first ever law on waste from 1991, was adopted. The law was valid until 2015, when there were significant changes that affect waste management to this day.

Act no. 79/2015 Coll. on waste [3], effective from 1 January 2016, defined the concept of extended producer responsibility (EPR) and its content. The EPR is a summary of the obligations of the manufacturer of the reserved product, applicable to the product during all phases of its life cycle, the aim of which is to prevent the generation of waste from the reserved product and to strengthen the reuse, recycling or other recovery of this waste stream. The term "reserved product" refers to all products to which EPR applies according to this law, i.e. j. electrical equipment, batteries and accumulators, packaging, vehicles, tires and non-packaged products.

An important strategic document in the waste management of the Slovak Republic (SR) for the years 2021-2025 is the Waste Management Programme of the Slovak Republic (WMP SR) [4].

As for the automotive industry, the aim is to maintain the binding limits for the extent of reuse of old vehicle parts and the recovery of waste from the processing of old vehicles at at least 95% and the reuse and recycling of old vehicles at least at 85%. Within the [4], this was reflected through the establishment of two measures:

- Support the financing of research and development of new waste management technologies, especially when it comes to problematic waste (eg plastics, composite materials, windshields with foils, etc.) and hazardous waste.

- Support funding of

- a) implementation of progressive technologies for the recovery of problematic waste from the processing of old vehicles (e.g. plastics, composite materials, windshields with foils, liquid hazardous waste, components from electric vehicles, etc.), which are in accordance with BAT,

- b) building new facilities for the processing of old vehicles that are in accordance with the requirements for BAT in those parts of the Slovak Republic where they are not located,

- c) modernization of existing recovery facilities for the processing of old vehicles that are in accordance with the requirements for BAT.

In the management of waste tires, long-term material recovery prevails. In 2018, the level of their material evaluation reached 89.8%, 9.15% of them were evaluated energetically.

TABLE I.
RATE OF RECOVERY AND RECYCLING OF WASTE TIRES

Year	Collection (t)	Achieved % of appreciation	Achieved % of recycling
2016	12,235	97.99	88.93
2017	24,294	99.32	86.04
2018	28,036	92.84	83.36

Source: Ministry of the Environment of the SR

In connection with the continuous development in the field of waste tires, a goal was set for the period until December 31, 2025 to achieve a waste tire recycling rate of at least 75% and a waste tire energy recovery rate of a maximum of 24% of the total weight of the listed tires on the market. The possibility of other handling of waste tires was set at a maximum of 1%.

III. RESOURCES FROM STATE

A. Recycling fund

The Recycling fund was a non-state special-purpose fund that, since January 1, 2002, served to collect financial resources from importers and producers of commodities stipulated by the Waste Act and consequently provide them to support projects establishing and developing separate collection, evaluation and processing of used batteries and accumulators, waste oils, worn tires, multi-layer combined materials, electrical and electronic equipment, plastics, paper, glass, vehicles, metal packaging. Funds for projects could be obtained in the form of subsidies and loans.

On the basis of [3], the Recycling Fund was canceled on December 31, 2016.

With the support of the Recycling Fund, Slovakia managed to build an efficiently functioning system of complex collection and processing of old vehicles. In the course of its operation, the fund significantly participated in creating the necessary technical and system prerequisites for the efficient processing of old vehicles.

B. Environmental fund

The Environmental Fund was established by Act 587/2004 Coll. on the Environmental Fund [5] as a state fund for the implementation of state support for environmental care. The Environmental Fund is an independent legal entity with its seat in Bratislava. The fund is managed by the Ministry of the Environment of the Slovak Republic. The provision and use of the funds of the fund must be in accordance with the priorities and objectives of the state environmental policy strategy approved by the Government of the Slovak Republic.

The following can apply for support:

- a natural person who is a citizen of the Slovak Republic and has a permanent residence in the territory of the Slovak Republic and who has reached the age of 18 and has his own regular income, or
- legal entity and natural person-entrepreneur with registered office in the territory of the Slovak Republic.

The environmental fund provides support in the form of a subsidy or loan (to cities and municipalities). The maximum amount of the subsidy is 200,000 euros, co-financing of the applicant min. 5% (of eligible project costs).

The amendment to the Act on the Environmental Fund [6] stipulates the obligation to publish by March 31 the list of activities that the fund will support in a given year. The amendment changes the way individual specifications are published. While until now one document was published for all activities that can be supported from the Environmental Fund, now individual specifications will be published separately. The list will also include the date of making a specific specification available. In this way, applicants will always know at the beginning of the year when they can expect the specification to be made available, within which they will want to apply for support.

The development of waste and circular economy (C) was made available in June 2022.

Table II. shows the average amounts of support in individual areas based on allocations in accordance with the approved budget of the Environmental Fund in previous periods.

TABLE II.
SUPPORT FROM THE ENVIRONMENTAL FUND (2017-2020)

Area	Average number of supported projects per year (2017–2020) (in pcs)	The total amount of support in euros per year (2017-2020)	Share of successful applications per year in %
Air protection (A)	26	2,325,809	26
Water protection and use (B)	168	20,471,090	29
Development of waste and circular economy (C)	81	4,773,664	30

Source: Ministry of the Environment of the Slovak Republic

IV. EUROPEAN UNION FUNDS

A number of good and at the same time green intentions that meet the standards of sustainable business can be co-financed with the support of structural funds.

As a new member state of the EU, Slovakia first used European funds in the area of cohesion policy in the years 2004–2006 in the so-called shortened program period.

The 2007–2013 program period was the first program period for Slovakia in which it had the opportunity to use resources from EU funds during its entire duration. To a greater extent, resources for waste management in the period from 2007–2013 were managed by the Ministry of Economy of the Slovak Republic (Operational Program Competitiveness and Economic Growth), but support could also be obtained from programs administered by the Ministry of the Environment of the Slovak Republic (Operational Program Environment).

On October 28, 2014, the European Commission approved the Operational Program Environmental Quality (OP EQ), which represents the basic strategic document for the years 2014–2020 through which projects in the field of environmental protection are supported.

The main goal of the operational program is environmental protection, efficient use of natural resources, flood protection and adaptation to climate change, as well as the support of a low-carbon economy.

Support is focused on all key areas of the environment.

In the field of waste management, the support focuses mainly on the loading, recovery and processing of waste, thereby contributing to the reduction of waste disposal in landfills.

The managing body for the Environmental Quality Operational Program is the Ministry of the Environment of the Slovak Republic.

TABLE III.
ENVIRONMENTAL QUALITY OPERATIONAL PROGRAM ALLOCATIONS (EUR)

Operational program Environmental quality	3,885,811,623
From that	
The Cohesion Fund	1,861,112,261
The European Regional Development Fund	1,276,787,849
National co-financing	747,911,513

Source: Ministry of the Environment of the Slovak Republic

The Cohesion Fund will support activities within priority axes 1 and 2 in a total amount of more than 1.861 billion €, which means that for almost 60% of the allocation of EU funds within the OP EQ, the eligible territory will be the entire territory of the Slovak Republic. The European Regional Development Fund will support activities within priority axes 3, 4 and 5 in a total amount of almost 1.277 billion. €, the territory of the Slovak Republic except the Bratislava region is eligible. Public and private sector entities will be able to apply for financial assistance, i.e. not only municipalities, higher territorial units and state administration bodies, but also a wide range of associations and non-profit organizations operating in the areas of operational program support, as

well as physical and legal persons authorized to do business in defined areas.

TABLE IV.
DIVISION INTO PRIORITY AXES AND CORRESPONDING ALLOCATIONS
FROM EUROPEAN STRUCTURAL INVESTMENT FUNDS

Priority axis	Allocation within OP EQ (EUR)	Fund
Priority axis 1: Sustainable use of natural resources through the development of environmental infrastructure	1,441,766,000	CF
Priority axis 2: Adaptation to adverse consequences of change climate with a focus on flood protection	419,346,261	CF
Priority axis 3: Support for risk management, emergency management events and resilience against extraordinary events affected by climate change	260,901,369	ERDF
Priority axis 4: Energy-efficient, low-carbon economy in all sectors	938,886,480	ERDF
Priority axis 5: Technical assistance	77,000,000	ERDF
Total allocation from European structural investment funds	3,137,900,110	CF+ERDF

Source: Ministry of the Environment of the Slovak Republic

Priority axis 1 has 4 investment priorities.

INVESTMENT PRIORITY 1 of Priority Axis 1: 1.1 Investing in the waste management sector in order to meet the requirements of the environmental acquis of the Union and to cover the needs specified by the Member States in

connection with investments beyond the stated requirements

In the area of waste management, OP EQ is focused in terms of the hierarchy of waste management on preventing the generation of biodegradable municipal waste, supporting the sorted collection of municipal waste and recovery with a focus on preparation for reuse and recycling of waste.

On October 28, 2014, the European Commission approved the Research and Innovation operational program (OP RI) for the program period 2014-2020. This operational program is covered by the Ministry of Economy of the Slovak Republic.

The total allocation of OP RI from EU resources amounts to 2.26 billion €, of which more than three quarters of all funds are intended to strengthen research, technological development and innovation, and the remaining part is allocated to support the increase in the competitiveness of small and medium-sized enterprises. The authorized territory is the entire territory of the Slovak Republic.

We are currently at the beginning of the 2021-2027 program period. Slovakia still has approximately 8 billion € available from the previous program period, which must be used up by 2023. Until the same year, we also have 780 million € available from the REACT package to mitigate the effects of the corona crisis. So, until 2023, there should be more calls for subsidies from both the previous and the current program period. Within the new program period, Slovakia should receive 6.3 billion € from the Recovery Plan focused on investments and reforms until 2026.

In the period 2021-2027, a large part of the investment from European funds will go to innovations, support of small and medium-sized enterprises, digital technologies and modernization of industry. Among other things, their goal is to motivate countries to transition to a low-carbon, circular economy and fight against climate change and to fulfill the Paris Agreement.

V. INNOVATIVE FORMS OF FINANCING

In addition to grants and standard financial instruments, alternative financing options, crowdfunding, can also be used to finance innovative projects, including the field of waste management. Types of crowdfunding for innovation:

- Peer – to peer consumer lending
- Equity – based crowdfunding
- Reward – based crowdfunding
- Donation – based crowdfunding.

VI. CONCLUSION

Recycling the average end-of-life vehicle today takes about 5 hours. During this demanding process, operating fluids must be drained, units must be dismantled, materials sorted into individual categories and prepared for later recycling. With the increasing complexity and material diversity of new cars, the demands for their recycling are also increasing. Recycling of deregistered vehicles is becoming increasingly difficult and less

profitable. In the case of textiles, plastics, foam or glass, the company must ensure transport to the final processor, to whom it pays for the recovery or disposal of these wastes. With the modernization of automobile production, there are fewer and fewer metals in vehicles. Special attention should be focused on the evaluation of electrical, or hybrid cars. For financing innovations in waste management, companies can use resources from the state, the EU, as well as innovative forms of financing, e.g. crowdfunding.

ACKNOWLEDGMENT

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the context of addressing the coronavirus consequences and No. VEGA 1/0688/20 Financial risks and their impact on the credit cycle and financial stability of the Slovak economy.

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- [1] Directive 2000/53/EC of the European Parliament and of the Council of 18 September 2000 on end-of life vehicles
- [2] Act No. 223/2001 Coll. on waste
- [3] Act no. 79/2015 Coll. on Waste
- [4] Waste management programme of the Slovak Republic 2021 – 2025
- [5] Act 587/2004 Coll. on the Environmental Fund
- [6] Act no. 66/2022 Coll., amending Act no. 587/2004 Coll. on the Environmental Fund and on the amendment of certain laws, as amended.

Recycling and New Joining Technologies in Automotive

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Abstract—These The paper presents the results of the scientific-research activities of the authors in the field of recycling and research of new joining systems, enabling quick and effective disassembly of components and knots used in automotive industry. There are presented the new types of joinings and the results of own research in joining technology using thermal drilling by method Flowdrill.

I. INTRODUCTION

The EU (European Union) Directive increases the requirements for recycling of cars after their life-service. It is required that 95% of weight of cars must be recycled or reused. In this context, there are arisen the questions of comfortable dismantling of car components and knots for recycling requirements, respectively their further recovery.

II. JOINING PROCESS FOR DISSIMILAR/SIMILAR METAL JOINTS

The considerable attention is paid to the **Product Lifecycle Management (PLM)**. Designers are constantly aware of this problem and are using techniques that allow them to design with greater responsibility. It involves designing a product to be disassembled for easier maintenance, repair, recovery and reuse of components or materials. As part of **Design for the Environment (DFE)** and sustainable product design, **Design for Disassembly (DFD)** is becoming increasingly recognised as an effective tool by designers, manufacturers and legislative boards alike [1,2,3,4].

Reducing waste in the manufacturing and recovery processes using DFD techniques can significantly reduce production costs and allow for greater technical efficiency. Implementing DFD into a design specification allows the product and its components to be better suited for re-use or recycling, when it has reached its end of life, thus reducing the scale of resources required creating new products.

Automotive manufacturers in the world are now compelled with a sense of urgency to develop and practice the technologies for reducing the weight of a car body. This is because the car-body weight reduction is rated as the key solution to the following inconsistent issues (Fig.1) while the fuel-economy regulation to restrict carbon emissions for global environmental protection has become stricter internationally,

The most difficult for disassembly (dismantling) is the factors as corrosion dirty, permanent fastening, reduce

core damage, complexity, tight tolerances, sizes, equipment of special tooling, worn fasten heads [4]. The algorithm for reuse oriented dismantling is shown in the Fig. 2. [1,2,3,4].

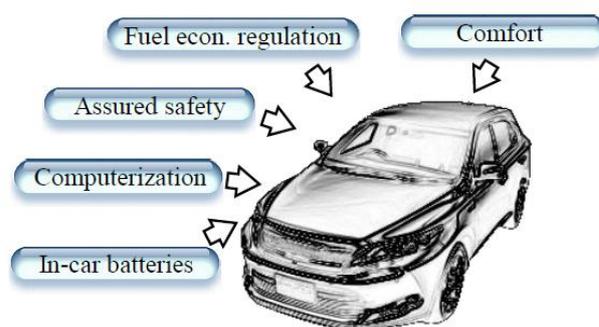


Figure 1. Latest requirements urge car-body weight reduction [3]

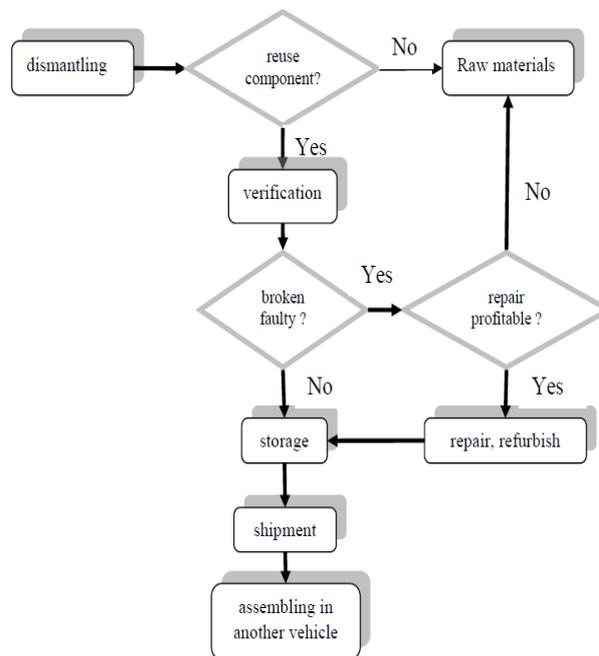


Figure 2. Algorithm for reuse oriented dismantling [4]

III. UTILIZATION OF FASTENERS

The fasteners play integral parts in the joining of components, subassemblies and disassembly. Designers should [4,5]:

- minimise the number of fasteners used within an assembly,
- minimise the types of fastener used within an assembly,
- standardise the used fasteners,
- not compromise the structural qualities of the assembly by using of too few or inadequate fasteners,
- use snap-fits where possible to eliminate the need for a fastener,
- consider work-hardening, fracture, fatigue failure and general wear when designing snap-fits,
- consider the use of destructive fasteners or those incorporating ADMS technology,
- if metallic fasteners are used, then ferrous types are preferable (for magnetic separation).
- access to the fasteners is also important. Holes, which are complete (i.e. follow through the entire section of the component) allow for the fastener (e.g. snap-fastener) to be tapped out as opposed to being pulled out.

IV. ADVANCED MATERIALS, MULTI-MATERIAL DESIGN AND ASSOCIATED PROBLEMS

The basic alternative strategies for reducing the weight of a car body are as follows (Fig. 3): (a) Use a higher strength material having the similar density of decrease the plate thickness needed; and (b) Use a lighter material with smaller density.

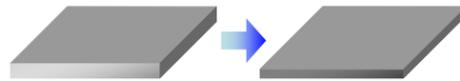
The typical case of (a) is the change to higher strength steel, e.g. from mild steel to high-strength steel (HSS) and further to advanced high-strength steel (AHSS) or ultra-high-strength steel (UHSS).

The main example of (b) is the shift of material to aluminium alloy or to carbon-fibre reinforced plastics (CFRP).

When manufacturing auto parts, the joining process for materials is indispensable in many cases, in which the joint can be assembled not only with similar type materials but also in some cases with dissimilar type materials such as a n HSS sheet to an aluminium alloy sheet.

However, such a new material that can contribute to the weight reduction is prone to have the problem of interior weldability. It has persistently been desired to develop such a joining method that feature higher strength, superior reliability, better productivity and lower costs, regardless of similar or dissimilar material joints. [3]

Reduced plate thick. with higher strength



Steel: General steel → HSS → AHSS/UHSS
 Aluminum: 5000 and 6000 types → 7000 type

Replacement with lighter material

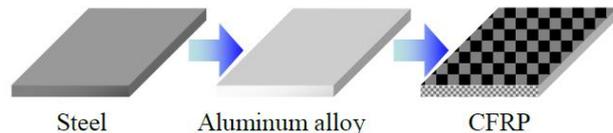


Figure 3. Car-body weight reduction by replacement of materials [3]

V. TRENDS AND JOINING TECHNIQUES FOR SHEETS IN AUTOMOTIVE

Mechanical fastening refers to use of a part or parts that physically limit some or all of the degrees of freedom of a part with respect to another. Below is a list of common fastening methods [4,5]:

- screws: joining pieces of wood in furniture; pens and mechanical pencils,
- nuts and bolts: Machine components, almost all mechanical products,
- rivets: structural beams in buildings, bridges; airplane bodies,
- staples: holding together sheets of metal, plastic,
- seams: sheet metal joints (e.g. trash cans),
- clips: spring clips, o-clips (commonly used in electrical motors to hold shaft in place with respect to housing),
- snap-fasteners: camera body, electronic toys, caps of containers, etc.

Steel is currently the main material used over whelming for car bodies because it features high strength and low price and excels in formability and joining capability.

However, these newly developed steel sheets are characterized generally by high carbon content and carbon equivalent (Ceq), thereby degrading the weldability.

It is reported that this degradation problem with the weldability in resistance spot welding (RSW) can be improved to a certain extent by the following electric current controls (Fig.4): (1) the tempering current. [3]

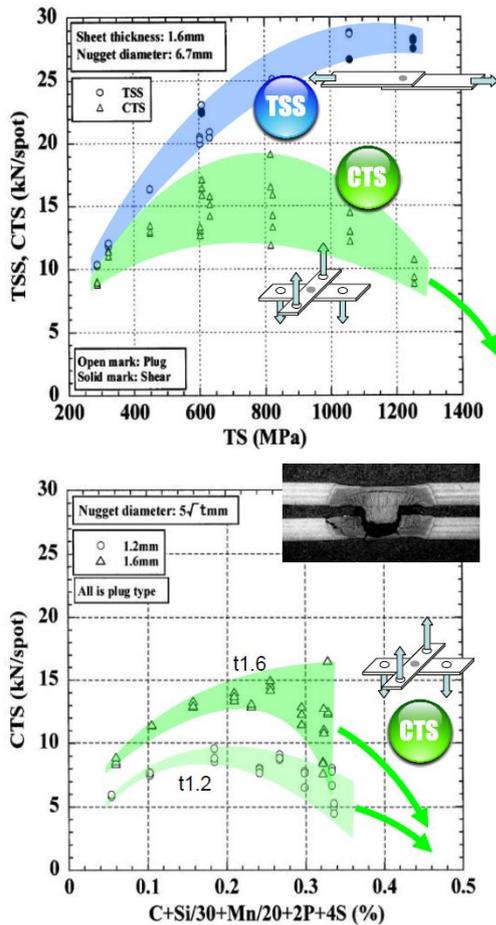


Figure 4. Resistance-spot-welded joint strengths vs. tensile strength/carbon equivalent of steel sheet [3]

VI. TREND OF DISSIMILAR-METAL JOINING TECHNOLOGIES ASSOCIATED WITH MULTI-MATERIAL DESIGNS

This is because the welded joint belongs to non-disassembled joining and it will easily be fractured due to the extremely brittle intermetallic compounds created by mixing the two dissimilar metals in the molten state.

Therefore, the industry and research organizations all over the world have been developing new dissimilar metal joining methods. A lot of such technologies that have already been put into practice in the automotive industry belong mainly to the category of mechanical joining method that creates the joint by using the clinching and engaging mechanisms, in which the dissimilar materials to be joined are controlled not to interfuse each other in a molten state. The typical joining process, as in this category, can be cited as follows: SPR (Self Piercing Rivet), Mechanical Clinch, FDS (Flow Drill Screw), ImpAcT, REW (Resistance Element Welding) Welding, and FEW (Friction Element Welding). These joinings help to easier disassembly of automotive pieces.

In many of the traditional mechanical joining methods, the steel materials to be joined are required to be plastically deformed or pierced; hence, the use of higher-

strength steel may occasionally make it difficult to apply such mechanical processes. Fig. 5 shows an arrangement of the existing dissimilar-metal joining methods by applicable strength of steel sheet. The SPR is the most famous and widely used dissimilar-metal joining method but is unfeasible for high-tensile steel. The FDS is used widely next to SPR and features one-side accessibility, and it is believed to be applicable up to 590~780 MPa-class steel sheets for through-thickness piercing.

To respond to this requirement, the following specific technologies have been developed for the mechanical joining methods to intend to exert higher performances: SSR (Special Semi-tubular Rivet) which was developed in order to make SPR applicable to a higher-strength steel sheet and ImpAcT, in which a nail-like element is driven in at a high speed.

On the other hand, taking into account the limitations of the mechanical joining, the hybrid joining process has been developed by combining a mechanical joining process and a welding mechanism, which requires no plastic deformation or piercing of a steel sheet.

The existing dissimilar - metal joining technologies are desired to be improved for some issues other than the difficulties mentioned above on the applicability to HSS sheets. These issues are summarized in Table 1.

TABLE I.
NEEDS FOR DISSIMILAR-METAL JOINING METHODS [3]

(1) Better applicability to high-strength steel sheets
(2) Consistency in high joint strength(Tensile shear strength, Peel strength)
(3) Lowering the costs(Equipment installation costs, Running costs)
(4) Higher applicability to part's shape variations(One-side access, Lower height of weld joint protrusion)

Many of the existing mechanical joining processes are equipped with a high-pressure generating mechanism, thus the joining tool becomes so heavy, and it must necessarily be supported at the forefront of a large-scale articulated robot.

As to the applicability to a variety of part shapes, many of the dissimilar - metal joining methods require the access from both - the face side and backside of the joining components for clamping in the same way as in the general RSW process. If the part shape does not allow the joining tool to access, the process cannot be applied.

The dissimilar metal joining method that allows the one side access is advantageous, because of the unlimited applicability, but the other side access is permitted by some joining methods, only such as FDS and ImpAcT.

On the other hand, the applicability of FDS to HSS sheets is low, and the ImpAcT is believed to have problems of the large noise in operation and of the high tendency to distortion in sheet metals. Moreover, it is another problem with both joining methods that they cause a sharp projection with a long and large size.

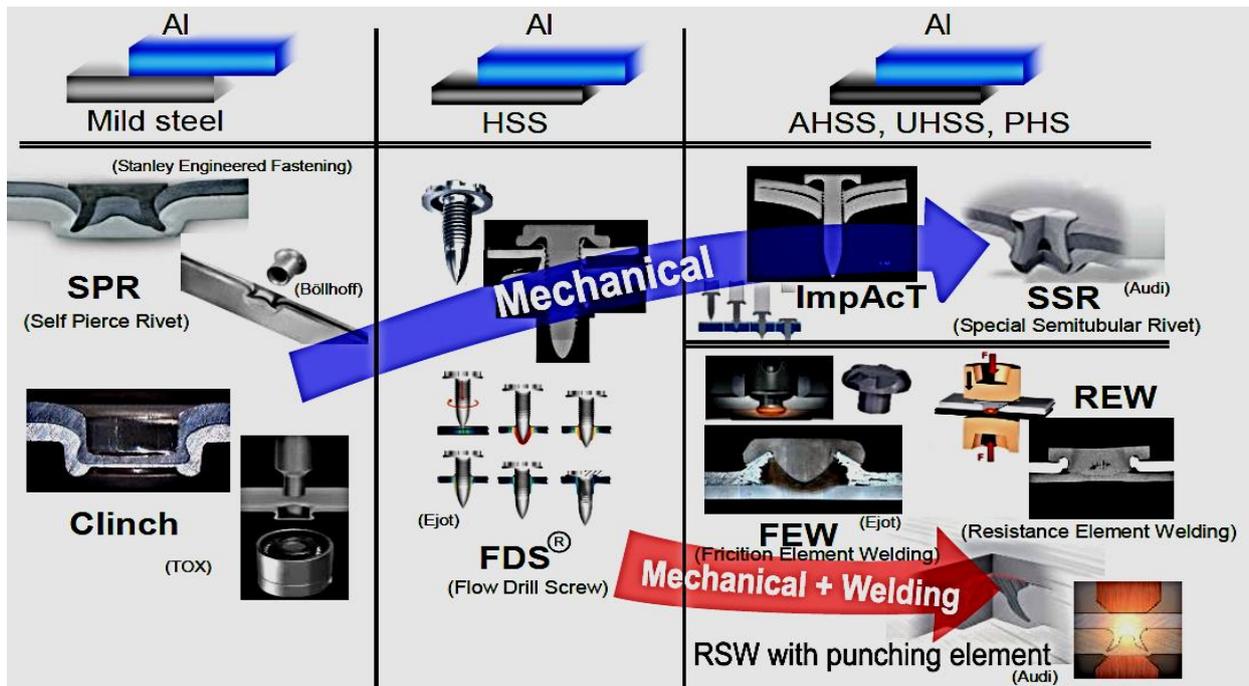


Figure 5. Steel sheet's tensile strength levels vs. suitable dissimilar-metal joining methods [3]

VII. NEW DISSIMILAR-METAL JOINING METHOD

In order to solve the above-discussed problems, the Element Arc-Spot-Welding (EASW) process was developed as a new dissimilar-metal joining method. The EASW process is the joining process developed for dissimilar metal joints by improving the ASW process for similar metal joints the features. Its joining mechanism and process are shown in Fig.6.

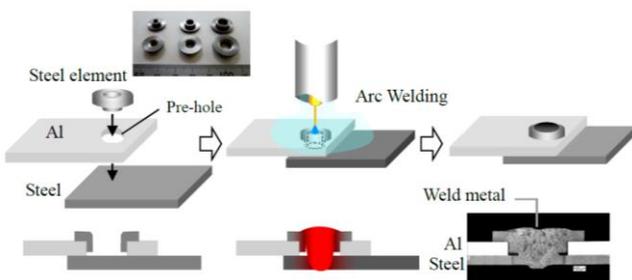


Figure 6. EASW process and mechanism [3]

The cross-sectional shapes of the joints made by the joining methods such as SPR, Tuk Rivet, Clinch, FEW, and REW are roughly flat, but such methods require to apply pressure on the joint from both face and back sides by using the C type tool.

In the joint design with combined dissimilar materials, a joint can contain not only two sheets but also three or more sheets. In the joint design with combined dissimilar materials, a joint can contain not only two sheets, but also three or more sheets. Fig. 7 demonstrates an example of the triple-sheet joint consisting of aluminum sheet and doubled steel sheets where EASW was applied.

For this triple-sheet joint, only the top sheet of aluminum alloy is required to be processed for the pre-hole, but the middle and bottom steel sheets need no such processing because the arc can melt through these steel sheets.

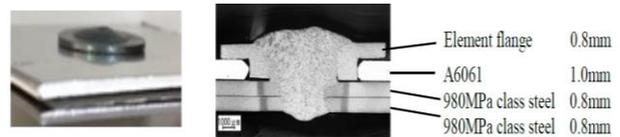


Figure 7. Example of triple-sheet dissimilar-metal joint by EASW

VIII. THERMAL DRILLING /FLOWDRILL METHOD AND EXPERIMENTS

The utilization of demount joint is the request and is usually used in the automotive practice. The thermal drilling- Flowdrill allows creating the mountable / assembly joints:

- joining without thread with bushing,
- joining with thread and bushing.

In the frame of experiments in the Department of Environmental Engineering, Faculty of Mechanical Engineering, TU in Košice, there were verified the suitability of thermal drilling technology, it means Flowdrill method for chosen materials for evaluation of quality of produced bushings, holes, threads at various conditions and for investigation of macro and micro structures of mentioned materials and creating joinings.

The experiments were made on box-column drilling machine of type Flott P 23, with hand operating. There were used the conical drill tools of type Flowdrill Short with diameter $\varnothing 7,9$ mm and drill Flowdrill Short Flat with diameter $\varnothing 7,9$ mm with cutter and tapping tool. At the same time there was compared the behaviour of

materials according to three spindle speeds: 1470 rpm, 2 490 rpm and 3 420 rpm.

The detail on working area is in the Fig.8, Fig. 9 and Fig.10, where we can see fastening of prism, semi-product into clamp and thermal drilling tool before drilling. During the thermal drilling material is flowing into two directions and is creating the collar and bushing.



Figure 8. The detail of the working area



Figure 9. Creating of threads after thermal drilling by tapping

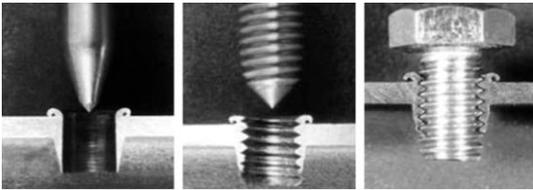


Figure 10. Detail of thermal drilling possibilities and demountable thread joint [9]

Material, which flow against drilling movement, created the collar. The collar can be removed by milling operation with special Flowdrill tool with cutting edge. In the Fig.11 is shown the collar in the testing of anti-corrosive material. After drilling operation we can create, the threads in the bushing by Flow tap method.

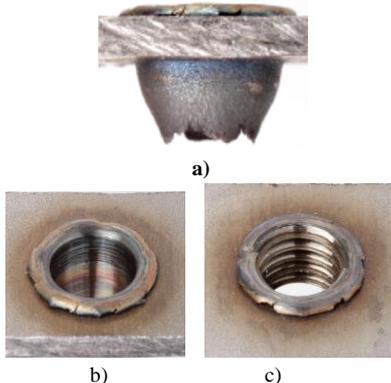


Figure 11. a) Bushing and width of original material b) Collar from anti-corrosive material, c) Anti-corrosive material with collar and threads

In the Fig. 12,A) is shown the cross section of bushing of anti – corrosive material with dimensions of collar and bushing in mm. The colour slips are occurred in the place with the biggest thermal friction.

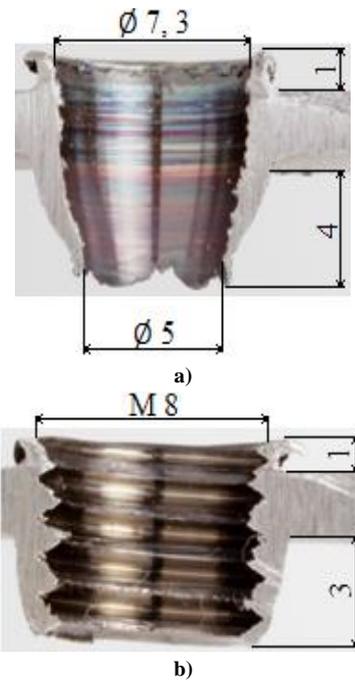


Figure 12. The cross section of testing sample without and with threads in bushing

The metallographic sample from the collar is shown in the Fig. 13, where we can see the roundness of collar and the grain deformation of material according to speed 2 490 rpm. [9]. In the Fig. 14 is shown the detail from the thread after tapping, there are no fractures and materials is compact. In the Fig. 15 is shown an inseparable connection of two materials - Steel 1, (vol. 100x, vol. 200x, vol. 500x), The examples 1 and 8 show details of the transition of the basic material to the collar, vol. 200x. The examples 2 and 9 show details of the joint of the upper and lower material, creating the bushing, vol. 200x. The examples details 3 and 10 show details of the bushing creep with visible creep, vol. 100x,. The examples 4 and 11 show details of creep with a visible crack, vol. 500x,. The examples 5 and 12 show details of the bushing connection, vol. 200x. The examples 6 and 13 show transition to the lower bushing, vol. 100x. The example 7 shows termination of the bushing, vol. 100x.



Figure 13. The sample of collar, ex.200x



Figure 14. The deformation of material fibres around threads, ex.200x

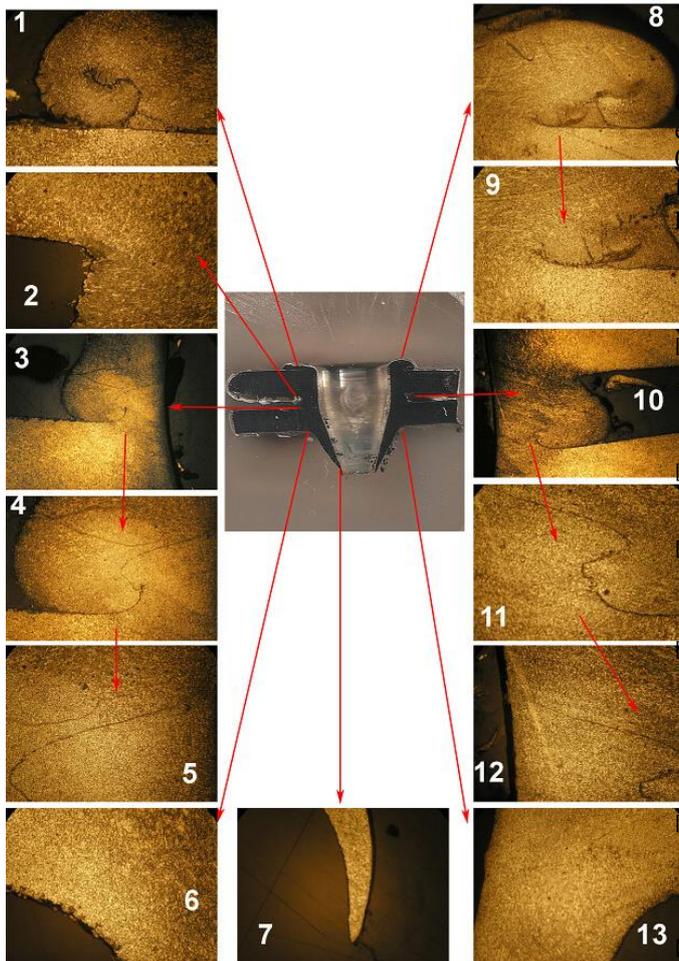


Figure 15. An inseparable connection of two materials - Steel 1, (vol. 100x, vol. 200x, vol. 500x), 1 and 8. Detail of the transition of the basic material to the collar, vol. 200x, 2 and 9- Detail of the joint of the upper and lower material, creating the case, vol. 200x, 3 and 10- Detail of the case creep with visible creep, vol. 100x, 4 and 11- Detail of creep with a visible crack, vol. 500x, 5 and 12- Detail of the case connection, vol. 200x, 6 and 13- Transition to the lower case, vol. 100x, 7- Termination of the case, vol. 100x.

IX. CONCLUSION

By development of new joining technologies, we can use them for joining of various types of materials. The automotive industry is utilized new materials, which need new possibilities of joining. Also in the end of life of automotive, they can help in disassembly and recycling operations.

The best utilization of thermal drilling operations is in joining of various types of materials, which not need melting and creating the bushing and collar enable for stronger joining. Also the quality of bushing depends on the strength quality of material. From copper and brass sheets, the bushings and collars were not so smooth; the bottoms is wrapped with comparison of steel ones, but are satisfied for mechanical screw of non-permanent joints. The worst material was aluminium from used materials, where the defined shapes of bushings were not sufficient quality and there were occurred more fractures on the bottom border of bushing. Created joining is partly demountable ones, which is convenient to recycling after end of life of parts or cars.

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Bicycle transport – an original solution for building cycle paths also on unused railway tracks

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Abstract — It is commendable that Slovakia is the world leader in the number of manufactured cars per capita. It is less commendable that the average age of cars in our country is more than 12 years and continues to increase. Processing of old vehicles leads to an increased quantity of waste materials that we cannot effectively recycle. Such waste includes, for example, plastic composite waste or rubber waste.

The issue of functional cycle paths is a long-term, pressing problem in Slovakia. Cycling combines many benefits that are related to a healthy lifestyle, an environmental approach to transport and, last but not least, to the development of the given region. The total length of railway tracks in Slovakia is 3,650 km, of which more than 100 kilometres have not been used for a long time. Construction of modular cycle paths on unused railway tracks is one of the possible and modern approaches. It includes a whole range of benefits, such as the meaningful use of unused tracks, the problem with legal aspects of land use, recycling of unusable waste, or the possibility of quick restoration of the original railroad track.

The aim of this article is to present an innovative view on building cycle paths on unused railway tracks with meaningful use of waste from the automotive industry.

I. INTRODUCTION

The issue of functional cycle paths is a long-term, pressing problem in Slovakia. Cycling combines many benefits that are related to a healthy lifestyle, an environmental approach to transport and, last but not least, to the development of the given region. The total length of railway tracks in Slovakia is 3,650 km, of which more than 100 kilometres have not been used for a long time. Construction of modular cycle paths on unused railway tracks is one of the possible and modern approaches. It includes a whole range of benefits, such as the possibility of recycling unusable plastic and rubber waste, simple and quick construction of a cycling path, no problem with legal aspects of land use, or the possibility of quick restoration of the original railway track.

Current statistical data of the Ministry of Transport and Construction of the Slovak Republic for the year 2020 indicate that the total length of railway tracks in Slovakia is approximately 3,650 km, of which more than 100 kilometres have not been used for a long time. The main reasons are the long-term lack of interest in the use of rail

transport by shippers, no declaration of a possible interest in resumption of rail transport in the future, a decrease in passenger numbers due to the loss of job opportunities in the region of interest, unsatisfactory technical condition of the track or the lack of strategic development near the tracks. The solution of the presented project is to enable the temporary or long-term use of non-operational railway tracks as routes for alternative modes of transport, such as cycle paths or pedestrian paths. Under Act no. 513/2009 on railways, as amended, the owner may lease or sell the unused railway tracks to a municipality, an association of municipalities or to a self-governing region to be used for transport purposes [1]. The use of the railway for the purpose of operating non-motorised rail transport, for temporary construction of local traffic paths – including a bicycle route or a footpath – is possible with the approval of the Ministry of Transport and Construction for the period of a minimum of 3 years, a maximum of 10 years with the possibility of extension for a maximum of another 10 years [2]. Giving unused railway tracks a new use also has undoubted economic benefits. Based on the available data of the Railways of the Slovak Republic, it is known that, for example, in 2017 they had to invest almost EUR 135,000.00 in maintenance of about 47 km of unused tracks.

Already in 2013, the Slovak government approved the draft of the National strategy for the development of bicycle transport and bicycle tourism in the Slovak Republic, [3]. One of its basic goals is to make bicycle transport equal to other types of transport, to improve the perception of cyclists in the transport space, to facilitate cycling tourism, to support tourism and improve mobility, and to improve the population's awareness of economic (increase in fuel prices and travel costs), ecological and health benefits of bicycle transport. The national strategy states that up to three fifths of bicycle lanes are separate lanes that serve only for cyclists (15%) or with mixed traffic for cyclists and pedestrians (22%) or separate traffic (23%). Two-fifths of bicycle lanes are located within the main or associated traffic corridors (separately (16%) or combined with pedestrians (18%). Only 6% of all bicycle lanes within the main traffic corridors are in the form of a separate cycling lane, strip or cycling corridor.

II. A PROGRESSIVE SOLUTION

The number of abandoned, non-functional and unprofitable railway tracks in Slovakia calls for their meaningful use.

The goal of the proposed solution is to cover such tracks with a modular prefabricated panel system [4]. The proposed modular system is based on two assembly elements – a prefabricated panel and a connector, Fig. 1.

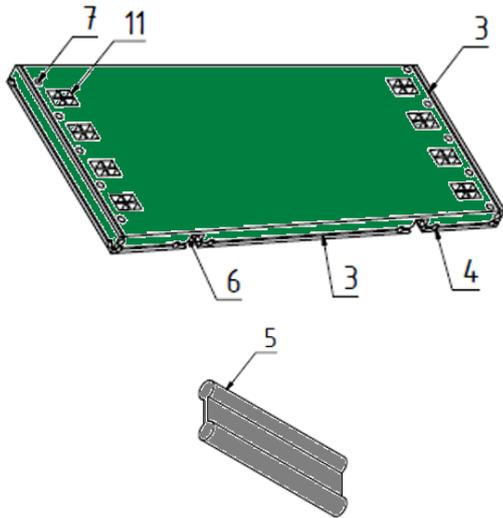


Figure 1. Prefabricated panel system and connector

The prefabricated panel is in the shape of a flat body with a square geometric shape made of a composite material based on recycled plastic, whereas the body has a continuous groove (3) on the circumference of the sides, Fig. 2. Each corner of the body has two mutually perpendicular holes (4) in the grooves (3) set off from the corner edge on the lateral sides to enable overlapping joints; the diameters of the holes (4) are larger than the width of the groove (3). The body has two continuous anchoring profile grooves (6) spaced from each other on the bottom side between the opposite sides of the body and two holes (4) in the groove (3) spaced on the sides of the profile groove (6) for creating a clamping connection between the body and external carrier, whilst the diameters of the holes (4) are larger than the width of the groove (3). The prefabricated panel system consists of a set of prefabricated panels (1) in at least a 2D arrangement, which are connected to each other by overlapping joints (2) between adjacent corners of the overlapped panels (1), where at the overlapping joint (2) fits into the hole (4) of one adjacent panel (1) and a complementary connecting member (5) fits into the hole (4) of the second adjacent panel (1), and into the adjacent grooves (3) of both adjacent panels (1). The prefabricated panels (1) have clamping joints (8) between the external carriers, where the external carriers fit into continuous anchoring profile grooves (6), whilst complementary connectors (5), whose free ends are in clamping contact with external carriers, are inserted into the holes (4) and grooves (3) at the clamping joint (8).

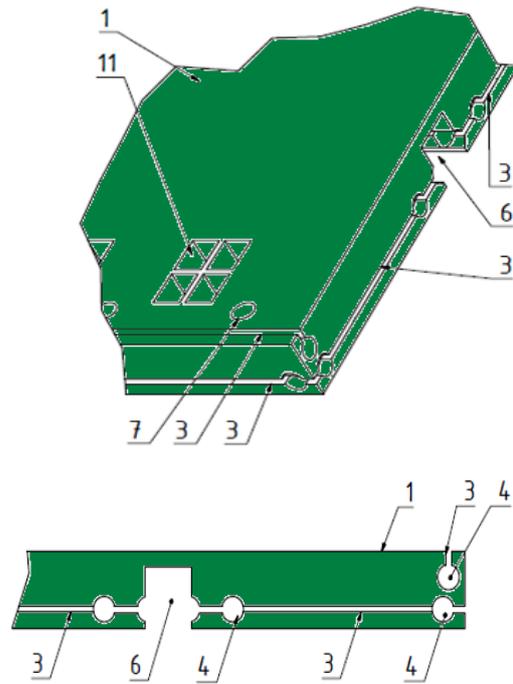


Figure 2. Design of the prefabricated panel

The design of the prefabricated panel system allows to connect panels in a plane behind each other (end to end) or next to each other (side to side) Fig. 3. This makes it possible to cover one track but also, for example, two tracks next to each other or even to cover entire platforms with several tracks. However, the design also allows creating a spatial arrangement of panels, Fig. 4.

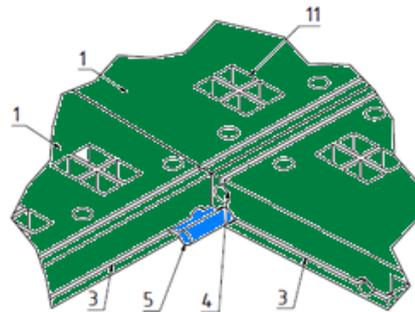


Figure 3. Panel layout options - connecting panels behind each other (end to end) and next to each other (side to side)

This system assumes panels of rectangular (3 x 1.0 m) or trapezoidal shape (3 x 1.3 x 1 m) and the assumed height of the panels is 0.2. The benefits of the prefabricated panel and the prefabricated panel system are the universality, the use of only two mounting elements, and a simple and clean design solution. The assembly is very simple and consists only of inserting the connectors into

the appropriate openings of the panels depending on the required joint. The original system of the construction ensures the use of connectors for fastening of the panels to the rails themselves and the simultaneous attachment of the panels to each other, Fig. 4.

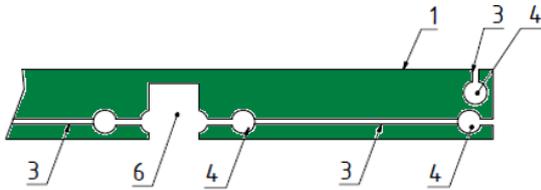


Figure 4. Panel layout options - spatial joining of panels

These connectors are not accessible from the outside. As a result, it is not possible to disassemble the panel system at any place without mechanical damage. The real possibilities of the prefabricated variable panel system are apparent from Fig. 5. By varying the arrangement of the trapezoidal panels, it is possible to cover straight or curved rails. The spatial arrangement of the panels also allows for the construction of small structures, such as shelters for cyclists, tunnels, or barriers against landslides on a slope. However, the panels do not have to be installed on railway tracks but can be used to cover any appropriately prepared surfaces, such as pavements, or various platforms or parking areas.

In the proposed solution for building cycle paths, we are also considering illumination. Red lights along the track are connected to photovoltaic cells installed on a black pole. Electronic contacts built into the panels serve to check the inviolability of the track and holes in the panels for drainage of rainwater and the possibility of easy installation of the railing over bridges and other elevated structures. Any utility networks can be installed in the available openings in the panels.



Figure 5 Mockup of the provided options of the variable prefabricated panel system Legend: 1 - covering of straight tracks, 2 - covering of curved tracks, 3 - covering of platforms, 4 - shelters, 5 - tunnels and underpasses, 6 - protection against landslides, 7 - easy bridging

When designing the structure of the panels, we also considered efficient and quick assembly or disassembly. The panels are equipped with holes for their attachment during transport and assembly itself. The resulting system assumes automated assembly of individual panels, and – in an alternative solution – also the transportation of panels directly by railway and the assembly of panels, e.g. by using a suitable crane system, Fig. 6.



Figure 6 Possible installation of panels

At present, we have produced the first demonstration models of panels at real scale, Fig. 7. We used wood for the demonstration panels due to the simplicity of the manufacturing. The picture shows the insertion of individual connectors.

When manufacturing the panels, we assume that up to 30% of the concrete filler would be made from rubber or plastic waste. The tables below show the total weight of one panel with the different ratios of the materials used.

TABLE I.
POSSIBLE PROPORTIONS OF THE COMPOSITE WITH THE RESULTING WEIGHT

Ratio (%)	100/0/0	90/5/5	80/10/10	70/15/15	60/20/20	50/25/25	40/30/30
Concrete	858	772,2	686,4	600,6	514,8	429,0	343,2
Plastic		29,0	57,9	87,0	115,8	144,8	173,8
Rubber		26,8	53,6	80,4	107,3	134,0	160,9
Total weight (kg)	858	827,0	797,9	767,0	737,9	707,8	677,9

The final proportions of added waste will depend on the continuous supply of a sufficient amount of waste, as well as on the results of strength analysis and experiments with real panels.

I. CONCLUSIONS

Slovakia has a total of more than 300 km of minimally used railway tracks. Of these, more than 100 kilometers have not been used for a long time. In general, it can be concluded that Slovak done by dismantling the tracks and then pouring a concrete-asphalt mixture, often also in nature.



Figure 7 Possible installation of panels

Railways has a problem of maintaining the currently operable tracks. Many foreign countries have turned abandoned railway tracks into Greenways – multifunctional paths, or for other tourist and commercial purposes. Usually, such repurposing was

The aim of the article is to present a new innovative technology for the use of abandoned railway tracks as a basis for building new cycle paths. The Trailpanel project proposes to transform abandoned railway tracks into cycle paths without removing the tracks, just by simply changing their purpose. The idea is based on the installation of prefabricated panels on existing tracks. The presented innovative project offers a comprehensive analysis of the possibility of transforming unused railway tracks into functional, modern cycle paths.

The objective of further research of the presented project is the proposal of a suitable composition of the composite material for the production of the panels, the design of the mould and the technological process of panel manufacturing, the manufacture of a prototype of the

panel, strength tests of the panel, and the design of the technological line for the mass production of the panels. In the production of composite concrete, we plan to use otherwise unusable waste, especially from plastic and rubber.

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Development and design of a line for the decomposition of waste laminated glass

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Abstract — We notice an increasing trend in the use of laminated glass in the construction industry, and this applies to the automotive industry. Laminated glass consists of two types of bendable flat glass with foil for increased glass safety. In the automotive industry, this applies mainly to front and rear windows, while in the construction industry, technical safety glass is used for railings and window panes. The film prevents shards of glass from entering the car and endangering the crew in the event of breakage in an accident. Likewise in the construction industry, such glass must provide sufficient resistance against mechanical influences and unpleasant weather effects. The foil is made of polyvinyl butyral, which is why we also call it PVB foil, heat-welded between two pieces of flexible flat glass. PVB foil is characterized by extreme hardness. Insufficient separation of the interlayer film leads to problematic and inefficient recycling of waste laminated glass in glass factories, while with effective separation of the film, it is possible to replace the glass seepage with the separated glass. The paper deals with the issue of laminated glass recycling, in particular the effective separation of glass (in the form of shards) from the polyvinyl butyral (PVB) interlayer film. Experimental research is focused on the mechanical separation of the glass from the interlayer film by vibrations and also on the chemical cleaning of the PVB film in order to enable the subsequent recycling of both materials. The results quantify the efficiency of the mechanical separation in the form of weight loss of the laminated glass sample and also define the particle size distribution of glass shards, which is an important parameter in the possibility of glass recycling. The result of the research is the design of a methodology for the separation of glass and PVB film and the design of a separation line for the decomposition of waste laminated glass.

I. INTRODUCTION

From an ecological, energy and technical point of view, glass recycling is a great benefit, waste glass is an important secondary raw material in production in glass factories. According to OICA data, global car production is approximately 90 million cars per year. Assuming that one vehicle windshield contains approx. 13 kg of glass and 1 kg of PVB film, the total amount of glass for the production of a windshield is approx. 1170 mil. kg and 90 mil. kg of PVB film per year. The total worldwide amount of PVB film produced for the automotive and construction industries is estimated at approximately 170 million. kg per year [1-4]. The production lines of world-famous manufacturers such as Solutia, DuPont, Sekisui and

Kuraray produce thousands of tons of PVB film for automotive and construction use every year, which is further pressed into laminated glass. Worldwide, 65% of all PVB films are used in automotive applications [1, 4]. By-products from processed PVB films (5%) and trimmed films (less than 10%) must also be included in the total quantities produced. This represents a total amount of 105 million kg of PVB film waste per year. According to the estimates of the Association of the Automotive Industry of the Slovak Republic [5], approximately 13,200 tons of flat waste from construction and automotive glass, around 3,600 tons, are available in Slovakia annually.

Researchers as well as recycling companies are increasingly focusing on the recycling and recovery of end-of-life vehicle (ELV) materials. This is due to various strict government directives and environmental regulations, such as the Resource Conservation and Recovery Act (RCRA) of the USA [6], K-REACH [7] and the EU directive on ELV [4]. European directive number 2000/53 / CE represents a challenge for the auto-motive industry, as it sets a recovery limit of 95% by weight of ELV, of which 85% by recycling. The automotive industry supports these efforts in all EU countries. However, material recycling has generally been oriented to materials such as steel and aluminum, and not on less attractive wastes such as glazing [8]. Clearly, it is necessary to significantly increase the efficient recycling of windshields as well. The removal of glazing is nonetheless given explicit mention in the minimum operations obligations when ELV comes to dismantling, [9].

The recovery priority should be the reuse of secondary raw material from waste glass as an input material for manufacturing new glass. When the secondary raw material fulfills the required technical parameters, the quality of the product is equal to a product manufactured from a primary material. By the recycling of glass waste, we save mainly primary material resources, energy and water and avoid the overloading of landfills. Energy demands on the production of container glass fluctuates around 4.5 - 5 GJ per ton of molten glass, [10]. If the proportion of shards in a batch increases by 10%, the energy intensity of the glass production will decrease by 2.5% (starting value is a 35% batch of shards). For container glass, the emission factor varies at present between 350 - 400 kg CO₂/t of molten glass. If the batch contains 35% of shards, the volume of CO₂ emissions is reduced by about 18,5%, and with a 60% share of shards,

the volume of CO₂ emissions is reduced by up to 32%, [10].

The technology for manufacturing laminated glass depends on the usage of a type of interlayer. In the process of technical layering an elastic material with good adhesiveness to glass is placed between the glass panes. The materials usually used include polyvinyl butyral (PVB), ethyl vinyl acetate (EVA), or the iconoclast SentryGlassPlus (SGP). PVB is the most frequently used material for the manufacture of the interlayer film in laminated glass. Laminated glass with film is usually produced under high pressure and temperature in an autoclave. Two glass are mostly joined by a film with a strong adhesive bond. However, this adhesion is an obstacle in the recycling process because the separation of the laminated film from the glass cullet causes the biggest problems. It is possible to obtain clean glass by separation, but the polymer is often contaminated with glass or other foreign substances to such an extent that it is unsuitable for further use or recycling, and ends up mostly in landfills. This is because the large glass content. Precludes burning it [2]. For perfect separation and achieving clean phases of the laminate, according to the literature [1, 4, 11-13, 42] a wet method of separating the layers of glass from the film seems to be the only usable one. This uses the reverse effect of the connecting technology – with a decreasing mixture of the film, its adhesion to glass increases. The basis of the decomposition technology is therefore the decrease of the PVB adhesiveness through an increasing content of water in the film. The problem with this method is the economic effectiveness of the entire technological process.

Based on scientific publications and research reports in this field [1, 4, 9, 13-18], the technology of combined separation must always be used for the effective separation of PVB film from glass. This includes mechanical treatment by breaking the glass or separating the glass (either with or without breaking the film), followed by chemical separation under thermal influence, and finally mechanical .e.g. hydrodynamic cleaning, washing and drying. All the mentioned technological influences affect the properties of the recycled PVB. Therefore, it is necessary to pay attention to research into changes in the PVB properties during processing and their impact on recycling.

II. PROPOSAL FOR THE EVALUATION OF WASTE LAMINATED GLASSES TECHNOLOGY

During mechanical separation, the windshield is crushed with the help of an input, receiving line, which is equipped with a crusher, capable of crushing auto glass from passenger cars and trucks, as well as from buses and trucks. Subsequently, the crushed glass is transported by means of conveyors to a station with separators that sort out metals and other impurities. Small parts of the glass are transported to a system of optical sensors, where dirt, parts of auto foil, sealing rubber, etc. are removed from the crumb.

This method of processing produces glass dust that can be contaminated with foreign substances and no longer represents a clean raw material for processing for the glass industry. The obtained PVB film also does not always

reach the required (100%) purity, therefore its further use is limited.

The dry method was developed by the company ZIPPE Industrieanlagen, [19] its principle is the mechanical wiping of glass in a dry way. The product of the process is only pure glass, the PVB obtained in this way contains a high amount (10-20%) of glass dust and other inhomogeneous particles (dust, paper or plastic). It is for this reason that such foil is deposited in landfills.

The essence of the proposed principle of highly effective decomposition of laminated waste glass, [20] is based on the fact that sheets of waste glued glass are not crushed into small pieces, the film is not torn, but remains in its original state as a whole, and individual fractions of broken glass are gradually separated from it glasses. The processed waste glasses are successively broken in the transverse and longitudinal direction between two pairs of breaking profile rollers, then the whole glasses broken in this way are abraded in the next module between a vibrating tool with needle-shaped spikes and a smooth roll off cylindrical tool, and finally they are finally clamped in the next module shards of glass to PVB foils wiped with wiper rollers.

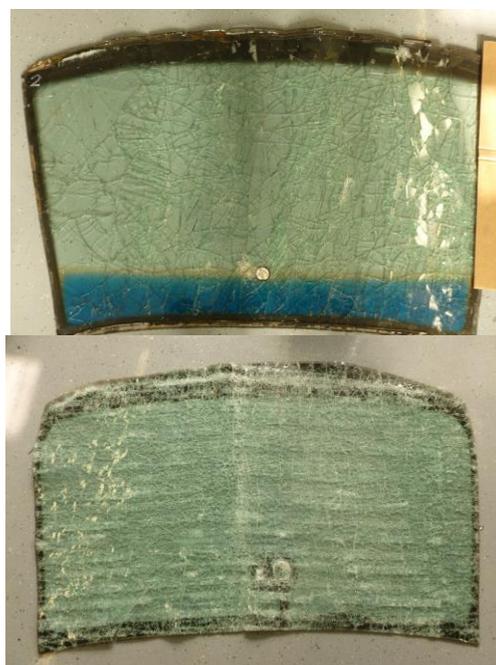


Figure 1. Car windshield after one and three stages of rolling

The goal of the designed vibration module is to ensure the greatest possible separation of the broken glass from the film itself. The principle of work in the vibration module consists in wrapping the glass between tools with conical tips and rolling smooth cylindrical tools, which ensure a smooth and even movement of the processed glass. The vibration module contains tools in two rows one above the other. The smooth rollers are driven by frequency-controlled drives. The actual process of wrapping the glass from the film is ensured by needle-shaped tools moving in a rectilinear reciprocating motion caused by an industrial vibrator.

III. DESIGN OF DIFFERENT VARIANTS OF THE SEPARATION LINE

The essence of the design of the designed technological device for processing waste laminated glass is that it consists of a multi-stage assembly of variable modules. Thanks to this fundamental feature, it is possible to process glued glasses of different thicknesses, dimensions, or even multiple layered glasses on one device. This creates new variable configurations for the specific requirements of individual customers. The described modules are able to work independently, as well as together with a smooth continuity of technology. Their mutual movements and cooperation can be linked thanks to the frequency-controlled drives of the individual cylinders as well as the frequency of the used industrial vibrator. On the one hand, individual customers get "tailor-made" machines, on the other hand, the "modular concept" enables the wide application of such machines in the processing of waste glued glass, especially in the construction and automotive industries, [21, 22].

The structural solution of the line is designed with a strong emphasis on modularity. Thanks to this fundamental feature, it is possible to process glued glasses of different thicknesses, dimensions, or even multiple layered glasses on one device. Individual modules can be arranged multiple times in a row. In the case of thick and multi-layered glasses, it is possible to use several breaking modules in a row in order to achieve uniform and dense horizontal cracking of the glasses, thereby significantly reducing the strength and adhesion forces between the glass and the foil. Similarly, depending on the type of glued glass, several vibration modules can be arranged in a row. In operation, the vibrating modules should be arranged mirror-like in pairs, in order to achieve a two-sided separation of the glass from the foil already during a single passage of the glass through the machine. For thicker glasses and glasses with a larger number of layers, it will be advantageous to include several pairs of vibration modules in order to increase the efficiency of glass separation and at the same time achieve a higher purity of the PVB film.

This modular waste laminated glass processing technology can be supplemented with other components as needed. This is, for example, the blowing of the last glass dust particles from the PVB foil with an air stream through a system of air nozzles located behind the wiper module.

A. Minimum configuration of the separation line

In the minimum configuration (fig. 2), the separation line consists of one breaking module (A), in which the glass is broken in both transverse and longitudinal directions between two pairs of breaking profile cylinders. The second module of the separation line is the vibration module (B). This is used to remove defragmented glass using vibrating tools with conical tips. The final module in the minimal assembly of the separation line is the wiper module (C). Based on the different rotation frequencies of the wiper rollers, the PVB foil is mechanically cleaned.

The advantage of the horizontal arrangement of the separation line is the simple possibility of changing or supplementing individual modules. Another advantage is the separate supporting structures of the individual modules and the simple modularity of the separation line. Higher requirements for spatial arrangement can be a certain disadvantage.

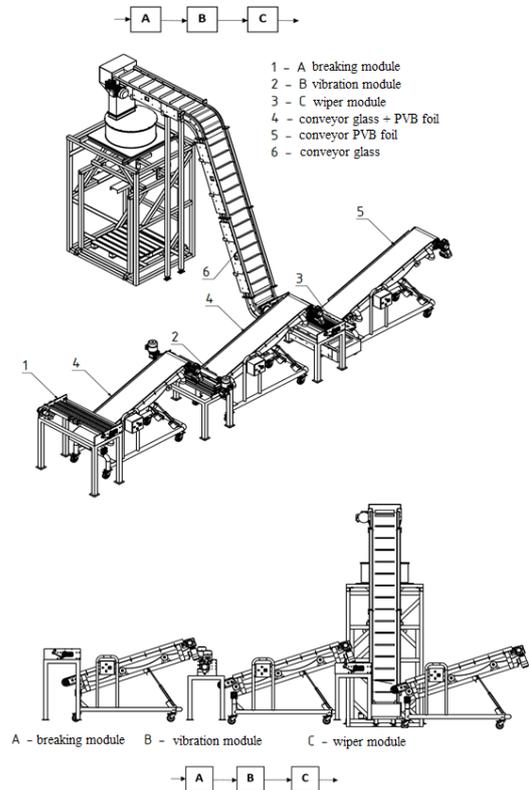


Figure 2. Minimum configuration of the separation line.

B. Vertical configuration of the separation line

The separation line can also be arranged in a vertical configuration. The advantage of vertical arrangement is:

- smaller requirements for space in the production hall, individual modules are arranged partially above each other,
- better removal of shards, after passing through the shards fall through the sieves into the reservoirs,
- lower energy consumption, the movement of waste glasses between modules is by gravity without the need for powered conveyors.

Disadvantages of this configuration include:

- the need for a higher height of the hall, the hall must have sufficient height due to the ordering of the modules,
- the necessity of manufacturing the support structure of the line is given by the requirement for the spatial arrangement of the modules themselves.

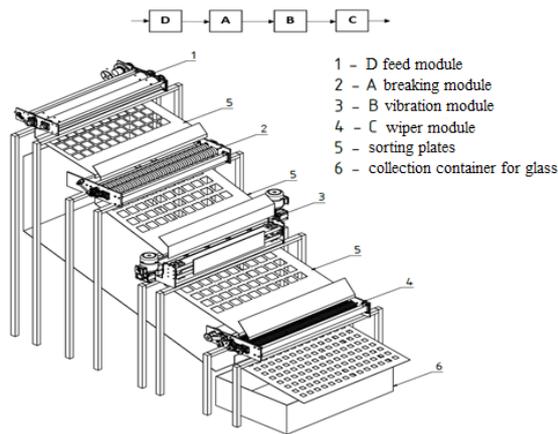


Figure 3. Vertical configuration of the separation line.

Figure 3 shows an example of the vertical layout of the line, and figure 4 shows an example of the vertical arrangement of the line with a service ramp.

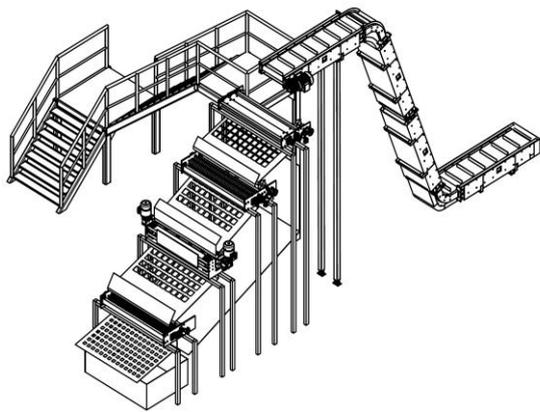


Figure 4. Vertical configuration of the separation line with a service ramp

C. Extended configuration of the separation line

The separation line provides a wide range of possible configurations adapted to specific customer requirements. This applies both from the point of view of the type of processed waste glass, the spatial arrangement of the line, and also from the point of view of the required performance of the line. In the case of thick and multi-layered glasses, some modules can be inserted repeatedly even several times in a row, fig. 19. In order to increase the performance of the processed waste laminated glass and the purity of the film obtained, the configuration of the line is supplemented with a washing module, where the PVB film is cleaned in a warm water solution.



Figure 5. Extended configuration of the separation line

IV. RESULTS AND DISCUSSION

In the experimental part, the research was focused on obtaining the results of the efficiency of the separation line. The experimental measurement was focused on the summary and evaluation of the results, while the authoritative data is the average weight loss of the samples with respect to the average original weight of waste laminated glass after each vibration cycle. The results of the experimental measurements are presented in Table 1.

Table 1 shows that the average original weight of the selected automotive glass sample of 1280 g was reduced by the mechanical separation method to a weight of 101 g, which represents a weight loss of 92.16% and an approximate - corresponding weight of the PVB film (Fig. 6). From the calculated average weight losses, it is clear that the biggest loss occurred after the first vibrations, when it was possible to observe the fall of larger glass shards from the PVB foil and the weight decreased by approx. 408 g, i.e. 31.68% of the original weight. On the other hand, the least was lost after the fourth vibration cycle, when the original weight dropped by an average of 98 grams.

TABLE I.
EVOLUTION OF WEIGHT LOSS OF ANALYZED SAMPLES OVER 6 VIBRATION CYCLES

sample weight (g)	original	after 1 st cycle	after 2 nd cycle	after 3 rd cycle	after 4 th cycle	after 5 th cycle	after 6 th cycle
sample 1	1273	866	558	390	309	192	98
sample 2	1282	844	594	473	355	213	100
sample 3	1288	930	540	436	342	225	103
sample 4	1289	914	572	413	315	198	98
sample 5	1272	886	580	456	347	217	105
sample 6	1276	842	540	430	342	215	102
average value	1280	880	564	433	335	210	101
average weight loss	-	408	326	131	98	125	109

On the basis of known data on the PVB interlayer, such as its density ρ , film thickness glued into the automobile glass h and the dimensions, it was possible to calculate the weight m of the original clean PVB interlayer:

$$F = \rho * h * (a * b) = 94,75g \quad (1)$$

where:

- ρ is the density of the PVB film, $\rho = 1.07 - 1.2 \text{ g.cm}^{-3}$, for the calculation this was the lowest mean value,
- h is the thickness of the interlayer film in the automobile glass, $h = 0.76 \text{ mm}$,
- a, b is the average dimension of the sample with PVB foil, $a = 395 \text{ mm}$, $b = 295 \text{ mm}$.

The difference between the calculated film weight and the cleaned film weight is 6.25 g.

TABLE II.
EVOLUTION OF WEIGHT LOSS OF ANALYZED SAMPLES OVER 6 VIBRATION CYCLES

Glass sample	Cullet sample I (above 4 mm)	Cullet sample II (2 - 4 mm)	Cullet sample III (1 - 2 mm)	Cullet sample IV (0.5 - 1 mm)	Cullet sample V (under 0.5 mm)
1 (g)	42	423	342	164	212
2 (g)	45,5	404	340	160	203
3 (g)	37	442	329	159	205
4 (g)	42	422	340	158	210
5 (g)	41,5	415	331	160	203
6 (g)	38	432	328	165	209
Average weight (g)	41	423	335	165	209
Average weight ratio (%)	3.5	36.2	28.8	13.8	17.7

The glass that was peeled off from the PVB film during the vibration cycles was captured in a collection vessel located below the vibration module of the separation line. The separated glass was subjected to granulometric analysis to determine the weight and proportion of glass in five size shard samples. A Retsch AS 200 sieving device was used to sort the glass particles. The results of the granulometric analysis are presented in Table 2. It is clear from the table that the highest mass ratio of II shards with particles of size 2-4 mm is 36% in all cases. Individual glass samples after sieve analysis and the final PVB interlayer film are shown in fig. 5.



Figure 4. Vertical configuration of the separation line with a service ramp

V. CONCLUSIONS

The overall concept of a modular and modular construction solution allows for variable changes in construction, control and regulation as well as coupling of the continuity of individual modules and their performance depending on the type and type of laminated glass being processed. The design enables optimization of performance and technology for processing different glass. It is precisely thanks to these adjustable properties that it enables very effective subsequent research in this area of recycling glass not only from old vehicles, but also from laminated glass from buildings or multilayer safety glass.

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APPLICATION OF PM MITIGATION MEASURES ON CONSTRUCTION SITES IN NOVI SAD DURING 2022

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Abstract— The beginning of the 21st century brought recognition of the importance and the effect that Particulate Matter (PM) has on the whole environment. PM has been marked as one of the key ambient air pollutants, due to its sorption ability. World Health Organization indicated that PM present in ambient air can have adverse, acute and hazard effect on human health and built environment. Rapidly expanding construction industry of the city of Novi Sad, Serbia is redefining urban matrix and has high effect on the environment. Construction sites are to be considered as unique spatial systems - pollution hot spots. High number of active building sites in Novi Sad increases the concentrations of PM in the ambient air. Goal of the research is to emphasize PM pollution problem on the construction sites in Novi Sad and to show the utilization of the selected mitigation measures. In the research 100 active building sites was monitored for application of PM mitigation measures.

I. INTRODUCTION

Globalization processes at the end of 20th and beginning of 21st century have stimulated augmented anthropogenic activities which are the most noticeable as urban transformations. Augmented anthropogenic activities and urban transformations change the environment and create pollution [1], [2]. Emitted polluting substances in the surrounding affect the build and living environment. Sensor development and society development has finally brought air pollution into the focus.

World Health Organization (WHO) and other health national organizations have marked suspended particles as one of the key polluting substances in ambient air [3]–[6]. Suspended particles are in literature recognized as Particulate Matter (PM). Particulate matter pollution as significant part of air pollution presents complex physicochemical problem. Excellent sorption abilities and large surface provides a great place for organic and inorganic pollutants to locate itself. PM smaller than 10 μm can easily be inhaled which allows polluting substances to get into human bodies. Small particles can also locate itself on the built environment and in long run damage it [7]–[9].

Numerous studies have confirmed adverse health effect of particulate matter on environment and human health [10]–[16]. Large study conducted consisted of 367.251 participants and it found that long term exposure to PM is associated with natural cause mortality [17]. Different studies have displayed correlations of respiratory health problems with Particulate Matter [14], [18]–[20]. Adverse

effect on natural environment can be traced to PM [12], [21]–[23]. Corrosion mechanisms and generally hazard effect on built environment also correlate to suspended particles exposure [15], [24]. In 2016 report World Health Organization pointed out that ambient air particulate matter pollutants directly and indirectly cause 4.2 million premature deaths in world [3]. PM10 particles are very dangerous due to prospect of easily entering respiratory system where they can cause difficulty breathing, asthma, chronic and acute respiratory diseases and cancer [8], [13]. PM2,5 have longer atmospheric life expectancy and due to its size have possibility to penetrate deeper than PM10 particles [16], [19], [25].

Construction sites are recognized as important source of suspended particles, but are not taken in consideration when city PM mitigation plans are made [25], [26]. This fact can be seen through the limited activity time of construction sites. Number of building sites can be considered as consequential indicator of city progress, expansion and development. All of the construction and demolition activities generate and emits PM in the environment [25]. Uncontrolled PM emission from building sites can cause damage to waterways and wetlands, upset aquatic ecological systems and wildlife communities, cause hazard effect on humane health and result in contamination of air, soil and groundwater [27]–[29]. The research by Canada's environmental agency indicated that more than 20% of total PM emission has construction origin [30].

The problem of PM emission from construction sites has been recognized by Developed countries. The problem of PM emission has been solved by creating legislative regulations and issuing numerous guidelines for mitigation and prevention of particulate pollution on construction sites [5], [31]–[34]. Countries in development such is Serbia typically don't have regulated legislative, monitoring and prevention systems which lead to uncontrolled and increased PM emission.

Being candidate for entry to European Union, the process of integration requires from Serbia to integrate strict environmental protection legislation. As ambient air pollution is becoming daily routine in Serbia this paper is part of the research with goal to emphasize the necessity of addressing this question. Understanding life cycle of PM includes source recognition, forming processes, particulate composition, dispersion and atmospheric fate, population exposure and health effects.

City of Novi Sad is regional center in rapid expansion. Markers of this expansion can be found in constant

development and urbanization processes. Indicators of increased urbanization processes are seen through large number of active construction sites. All the building processes generate and emits large amounts of polluting substances in surrounding environment.

II. EXPERIMENTAL

The study was implemented in the city of Novi Sad, Serbia, during period of eight months (01.02.-01.09.2022.). In this period research monitored 100 active construction sites. Active construction sites in 2022 are shown in the figure 1. marked blue. Selected PM mitigation measures were inspected in monitoring processes.

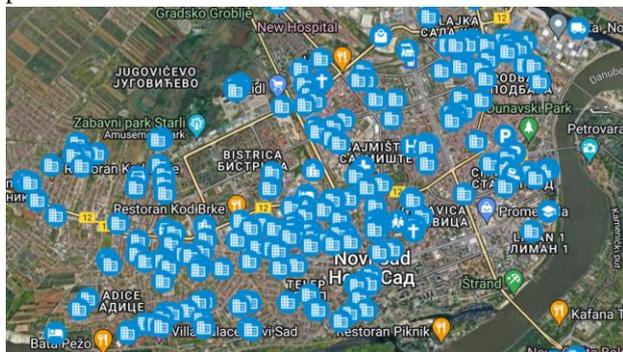


Figure 1. Blue markings indicate active construction sites in Novi Sad, Serbia in 2022.

The legislations and guidelines of the developed countries were analysed and observed. The measures were selected and tested to fit the application in Serbia's construction ecosystem. Testing and selection of the measures was performed during the authors PhD thesis research. Selected measures include: keeping the existing vegetation, stabilization covers and geotextile, vegetation covering, mulching, adequate material handling, stored material covering, material transport covering, machine installation of powder materials, protective curtains, wind fences, controlled entrance, washing machine tires before exit (manual or automatic), road paving, road definition and marking, speed limitation, transport road watering, maintenance, water spraying, and use of suppressants.

III. RESULTS AND DISCUSSION

The research results (table 1.) display low level of utilization for most of the selected PM prevention measures. The existing legislations was not designed for application of mitigation measures, but some of the demands are in compliment with environmental protection standards. It is best noticeable in the utilization of measures: setting up wind fences, controlled entrance, road definition and marking, and speed limitation. These measures are fully applied. Legislations prescribe that all building sites needs to have required to have defined and organized roads and entry point, maximum speed limit of 20 km/h, with closed fences installed around the site. High percentage of machine installation of powder materials can be seen in economical and practical reasons as it is more efficient, easier and cheaper measure. Road paving achieves high percentage for its practical reasons as it allows highly effective movement of machines and workers on the construction site.

Adequate material handling, covering of the stored material and material during transport, setting up the

protective curtains, road watering and water spraying results show medium to low usage. Lacking numbers of qualified workers together with increasing number of construction sites are the main reason in the quality of material handling, storing and transportation. Water spraying explanation can be found in the low experience of the leading engineers and water savings.

Keeping the existing vegetation, different area covering including mulching, maintenance, use of suppressants and washing of the tires monitoring indicated numbers that can be defined as statistical error. These results reasons are indicated through the lack of legislation and care for the environment, high prices and absence of education.

Table 1. Monitoring results of PM mitigation measures utilization for constructions sites in Novi Sad during 2022.

Monitored measures	Application %
Keeping the existing vegetation	4%
Stabilization covers and geotextile	0%
Vegetation covering	3%
Mulching	3%
Adequate material handling	25%
Stored material covering	35%
Material transport covering	38%
Machine installation of powder materials	93%
Protective curtains	47%
Wind fences	100%
Controlled entrance	100%
Washing machine tires before exit (manual or automatic)	3%
Road paving	81%
Road definition and marking	100%
Speed limitation	100%
Transport road watering	30%
Maintenance	11%
Water spraying	32%
Use of suppressants	0%

IV. CONCLUSION REMARKS

The results of PM mitigation measures indicate two economic/beneficial and legislations as leading factors in application of selected measures. Evidently results direct that legislations are the reason for fully applied measures. Measures not defined by law are mostly depends on the beneficial factor. Beneficial economic factor is one of the main strategic constituents in utilization of PM mitigation measures. Mechanization and material availability, efficiency, workers education and qualification level, time consumption and other are just some of the economic subfactors that effect total utilization processes. Application of the selected measures is to be considered as good practice of the contractor companies and leading engineers experience. The research and monitoring of construction sites in city of Novi Sad is the consecutive part of first ever research based on following the utilization of PM emission mitigation measures on

construction sites in Novi Sad. Goal of the research to investigate weak areas, addresses the need for legislation to be changed.

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AUTHOR INDEX

B

- J. Babics 52,103
M. Badida 8,13,62,93
M. Badidova 93
K. Belanova 88
J. Beniak 20,52

C

- I. Čabalová 38,58
V. Čačko 24,99,103
I. Čačková 24,99,103
A. Čaja 43
O. Chlebo 99

D

- T. Dzuro 8,13

G

- D. Gal 62
V. Gerasimov 62

H

- T. Havlik 31,47
M. Holubčík 43
H. Hybská 38

J

- J. Jandačka 43

K

- N. Č. Kantová 43
J. Klimko 31,47,68
J. Krilek 58,74
P. Križan 20,52

L

- P. Liptai 68
M. Lobotková 38

M

- V. Mancel 58
V. Marcinov 47,68
M. Matuš 20,52

- M. V. Miloradov 109
A. Molnar 62
M. Moravec 8,13

O

- B. Obrovski 109
D. Orac 47,68
M. Osvaldová 58,74

P

- M. Patsch 79
P. Pilát 79
M. Piňosová 8,13
J. Piroskova 47,68
M. Pokusová 84,103
M. Potkány 74

R

- V. Rajs 109
R. Réh 58

S

- D. Samešová 38
R. Šivák 88
L. Sobotova 8,13,93
L. Šooš 20,24,84,99,103
M. Šunjević 109
M. Šunjević 109
R. Szabo 99

T

- Z. Takáčová 47

V

- T. Vindt 68