

Original Research

Study on the Sorting Process on the Basis of the Effect of Shrinkage and Melting of Plastics and Its Impact on Further Processing of the Materials

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Abstract

In the era of high generation of waste, it is necessary to improve the sorting processes in order to obtain clean, homogeneous secondary raw materials suitable for recycling. The article presents the results of experimental studies aimed at finding the optimal separation method for two-component waste, in which one of them is plastic, and the previously known methods are ineffective or are not economically justified. Two methods have been proposed based on the use of two specific properties of plastics: precisely defined melting point and temperature shrinkage. As a result, the two technologies of separation were developed. Both involve heating the waste until the expected changes in the waste material are achieved. Determined experimentally the optimal melting point parameters for the tested polystyrene and polypropylene waste were 150°C and 180°C, respectively, with a 7-second contact time with a metal surface. The optimal shrinkage for PS occurred at 160°C with a 2-minute heating time, and for the tested PP, the optimal shrinkage temperature was 170°C, applied for 4 minutes. Both proposals were tested in laboratory and technical conditions, giving satisfactory results, and then successfully used in the industry. In order to extend the research, it is planned to expand the range of plastics and their mixtures with other wastes, as well as to develop a comparative test of the adhesion strength of melted plastics to various surfaces. At the suggested temperatures of thermal sorting, there is no depolymerization of materials. Thus, the proposed method of shrinkage and melting in the sorting process can serve as a step of separating the PP or PS material from the waste mixture without its negative impact on further processing processes in thermal, chemical or mechanical recycling.

Keywords: recycling, waste separation, plastics sorting, multi-component waste

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Introduction

Plastic, as a material consisting of synthetic polymers or modified natural polymers with various additives, is a very widespread material in the industry, but not only. This wide use of plastics results from its numerous properties, which include: low production cost, lightness and at the same time durability, corrosion resistance, hydrophobicity, etc. [1]. Plastic packaging and containers, especially for food, are an important branch of the plastics industry. It is indicated that the share of these products in relation to all plastic materials produced in the world is 36% [2]. The types of plastics most commonly used in packaging products include: high and low density polyethylene (HDPE and LDPE), polyethylene terephthalate (PET), polypropylene (PP), polystyrene (PS) and polyvinyl chloride (PVC) [2, 3]. The most commonly used polyethylene, both HD and LD, in Europe accounted for almost 30% of all plastics produced in 2018 [4].

The ubiquitous presence of plastic products, the increase of which is estimated from 300 to 1800 million tonnes per year in the years 2015-2050, causes and will continue to cause a heavy burden on the natural environment [5]. One of the problems caused by the presence of plastics in the environment is the pollution of seas, oceans and soils [4,6]. The activities of many international organizations indicate the need to recycle and reuse plastic raw materials. The leaders here are the European Union and its bodies such as the European Commission or the European Parliament, which have jointly agreed for the states of the Community, inter alia, the rate of recycling of packaging waste, including plastic waste, at 50% in 2025 and 55% in 2030. It is part of the strategy of the EU for plastics in the circular economy, which includes a whole package of actions to increase recycling rates and implementation phases [7]. Data from previous years indicate that in the EU the rate of packaging waste recycling for 2016 is on average 42% [8, 9]. In the global perspective, according to the work [2], it is estimated that the level of plastic recycling is only 9%. Important in this context is also the implementation of the EU principle: Extended Producer Responsibility (EPR). According to its rules, producers will be responsible for covering the costs of selective collection, transport and treatment of waste [10]. Taking into account the direction of economic and legal changes, research aimed at increasing the efficiency of recycling seems to be of key importance, both from the point of view of environmental protection and the finances of enterprises and states.

Two-component waste containing plastic is most often beverage, yoghurt and other food packaging with a short expiry date, in which other types of materials, especially paper, are attached to the surface of the plastic packaging, most often a cup. This type of combination of two different materials causes problems in the segregation and recycling of waste, which makes these processes characterized by low efficiency. The currently

used methods of separating these wastes are based on the differences in physical and chemical properties of the various components of the waste. In most separation methods, the waste is shredded in advance. One can mention here separation based on the difference: in density, in interaction with water (hydrophilic and hydrophobic properties), in electrostatic interaction, in interaction with a specific solvent, in melting point [11-14]. It should be also mentioned specific separation devices, such as a Zig-Zag separator, in which the light fraction is carried away by the air stream and the heavy fraction falls to the bottom of the separator, a ballistic panel separator in which the mixture is divided into fractions: 2D – flat fraction (e.g. foil) and 3D – spatial fraction, as well as automatic sorters equipped with appropriate sensors to identify the type of material and/or its color [14-17]. The most frequently used method is comminution followed by separation in a liquid medium, using differences in density [18, 19]. It is worth mentioning the environmental impact of this method through the consumption of water and the generated sewage, the unsuitability of very wet paper waste and the possibility of fragmented plastic fibers entering the water [19]. The use of automatic sorters for separation is more effective, but due to costs it is not profitable [19, 20]. In addition to the above methods, the scientific literature also includes research on separation methods using biological and thermal processes.

Authors of the study [19] propose a method of separating paper from plastics, here: PE, with the use of enzymes produced by specific fungi (*Dichomitus squalens*). The work is focused on the issue of paper waste covered with a layer of plastic, including magazine covers and food packaging. Most of these wastes are subject to thermal treatment or landfilling, mainly due to the difficulty and cost-effectiveness of recycling. Researchers [19] have developed a method of separating two raw materials using fungi producing enzymes that decompose, among others lignin, as well as various types of impurities added to the paper during the formation of the above-mentioned product. The fungal enzymes, by decomposing these substances, partially degrade the paper, thanks to which it is possible to release the plastic coating. A different approach was used by the authors of the research [21], who subjected a mixture of paper and plastics to a two-stage pyrolysis process at temperatures of 350°C and 500°C. In the case of these studies, however, no secondary raw materials were recovered: paper, polystyrene, polyethylene, but only the products of their transformations as a result of raised temperature.

This article presents two methods of separating two-component packaging based on: shrinkage and melting of plastics. The technological solutions proposed in the paper are novelty, both in terms of literature review and market reports. Therefore they have been submitted for a patent. It should be emphasized that new sorting technologies and the optimization of these processes are currently a priority in the European Union, and

the objectives pursued under the article perfectly fit into its policy, constituting a step towards achieving higher rates of recycling of municipal waste, especially packaging waste.

The research carried out by the authors of the study is a response to the demand identified by representatives of the plastics recycling industry. As a result of the review of the separation technologies, a significant lack of effective methods of separation of two-component waste was identified. The aim of the study was to establish actions enabling the efficient separation of individual fractions from packaging waste, here: plastics (polipropylene and polystyrene) and paper. In particular, these are: development of technology allowing for large-scale application in waste management and determination of optimal process parameters enabling effective separation of packaging waste components.

Materials and Methods

Basic Characteristic of the Tested Waste

The subject of the research were unused containers for beverages and yoghurts from the return of a shipment batch of unused containers due to non-sterile conditions of delivery, transport or storage. The tested waste with their basic characteristic are presented in Table 1.

The waste in question was shredded in a knife mill equipped with 10 mm sieves limiting the size of the shredded fraction, the view of which is shown in Fig. 1.

Table 2 shows the granulometric analysis of the shredded waste and the bulk density according to [22] for the PP/paper and PS/paper fractions. A 4 dm³ beaker was used in the test, with fourfold measurement to determine the bulk density in each sample.

Introduction to the Research

Searching for the optimal method of separation, a number of experiments were carried out, which turned out to be ineffective for the separation of the tested waste mixture, or are unacceptable due to market conditions (e.g. no sales for wet paper or too high separation costs).

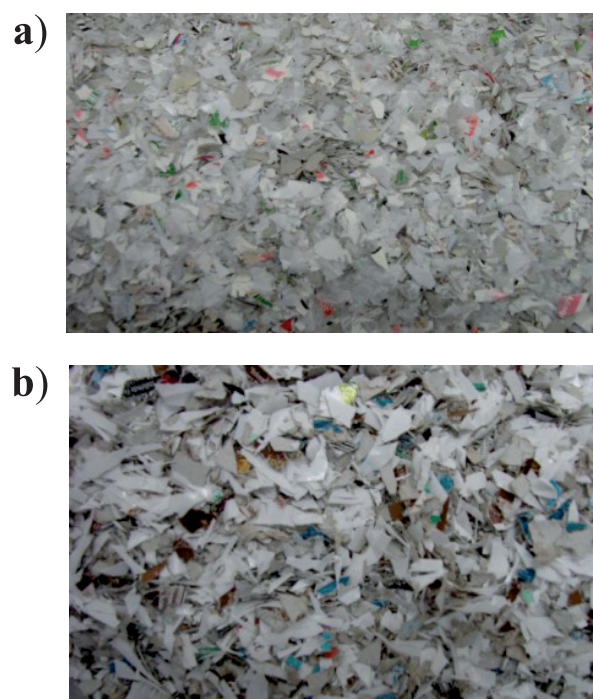


Fig. 1. View of the shredded fractions: a) PS/paper; b) PP/paper, granulation below 10 mm.

The conducted ineffective tests of material separation include, among others, tests: on screens and vibrating feeders, on a Zig-Zag air separator, on a demonstration stand for the fluidization process, gravity separation in water. Tests were also commissioned to Hamos in Germany, but the results of the electrostatic separation test proved unsatisfactory for each fraction.

It is possible separation with the use of opto-pneumatic separators, and in the case of the separation of the PP/paper or PS/paper fraction with a grain size of less than 10 mm, the so-called flake sorters. These separators identify the type of material based on NIR (near infrared) sensors. However, due to the high costs of this type of installation and not too large a waste stream to be separated, this possibility was not analyzed.

Only tests on the separation of two-component waste containing plastic, carried out with the use of

Table 1. Basic characteristic of the tested waste.

Code of the packaging (mass/volume of the product)	Materials	Mass of package [g]	Mass of plastic [g]	Mass of paper [g]
TLJ (400 g)	PS/paper	13.25	7.4	5.85
LPS (150 g)	PS/paper	8.2	4.3	3.9
HM (100 g)	PP/paper	7.5	5.5	2.0
K–RV (180 g)	PP/paper	8.5	4.6	3.9
LE (250 ml, 262 g)	PP/paper	10	5.2	4.8
C/TIOZIO (250 ml, 263 g)	PP/paper	10.16	5.2	4.9

Table 2. Properties of the analyzed waste.

Granulometric analysis of the fraction PP/paper			Granulometric analysis of the fraction PS/paper		
Granulation [mm]	Mass share [%]	Bulk density [kg/m ³]	Granulation [mm]	Mass share [%]	Bulk density [kg/m ³]
0-5	31	175	0-5	35	196.5
5-10	69		5-10	65	

two phenomena changing their properties, brought the expected results. These analyzed phenomena are melting and material shrinkage. The research methodology and the results of the experiments are presented in the further part of the work.

Method with Melting of Plastics

The first method of the separation process was based on the use of the melting phenomenon occurring due to the increased temperature, which is related to the increase in the viscosity of the material to the transporting surface. The test consisted in placing a metal cuvette with shredded pieces of PS and PP (pieces 1.5x1.5 cm in size) in the dryer in the specified time in order to determine the optimal temperature at which the material would start to melt and adherence to the metal surface in the shortest possible time. The important issue was to capture the beginning of the melting, not the complete melting of the material. The condition was also to lay the mixture of materials on the cuvette (surface) in one layer at distances that prevent contact of particles with each other. This is to protect against possible sticking of the mixture components.

The tests were carried out using the following devices:

- BINDER dryer type FD 240 with temperature regulation in the range from 1°C to 300°C, adjustable by 1°C,
- metal laboratory cuvette,
- electronic stopwatch.

The authors of this study analyzed the possibility of using standard methods in the quantitative and qualitative description of the research on shrinkage and melting of plastics. The mass and volumetric melt flow rates [23-25], known in the polymer technology, are important indicators, but in the processability of plastics (e.g. by injection method), and therefore important when choosing the appropriate type of granulate from which we want to produce a filament. However, when applied to sorting techniques, these indices will not provide practical information on thermal parameters of shrinkage and melt as useful in sorting processes.

In the literature there are available the melting points of individual types of plastics [26], however, each plastic producer uses different modifiers added in different proportions depending on its intended use. The use of various components: coloring and

improving the physico-chemical properties of plastics, as well as the dimensions of the particles (e.g. the thickness of the particle wall determines the rate of its heating), make it necessary to determine the operating parameters (melting and shrinkage temperature) for the sorting process each time. Significant differences in the properties (density, melting point, shrinkage temperature) of pure plastics (PP and PS) and the materials used in the study were noticed. Therefore, it was necessary to conduct individual tests to find the temperature for the tested plastics, which would allow for effective separation of two-component waste.

Considering the above and the lack of unambiguous indication in the literature [27] of the appropriate criterion for measuring the quality of the adherence (the adhesive strength, the quality of the adhesive connection, the value of friction force between two surfaces, etc.), it was established that the indicator of the adherence strength will be the range of the surface inclination. This interval will be included between the steps: adherence of the molten plastic particles - pouring all of the molten plastic material from the surface.

Method with Shrinkage of Plastics

The second method of the separation process was based on the use of the shrinkage phenomenon occurring due to the increased temperature, preceding the material melting. The principle of the experiment was not to increase the viscosity and the adhesion of the material to the other surface. The waste in question was tested, but they were not subjected to the shredding process.

The tests were carried out using the following devices:

- BINDER dryer type FD 240 with temperature control in the range from 1°C to 300°C, adjustable by 1°C,
- electronic stopwatch.

The tests were carried out in the dryer within the specified temperature range and time of its occurrence. The aim of these tests was to find for PS and PP the optimal temperature and residence time in the dryer, for which there will be an appropriate shrinkage of the plastic and separating of the paper label (for larger PS/paper cups). The vertical position of the cups on the cuvette in the dryer was used, using the profile of the vessel tapering downwards.



Fig. 2. Polystyrene adhering to the metal surface of the cuvette.

Results and Discussion

Melting of Plastics

Fig. 2 presents the cuvette, which was positioned vertically after being removed from the dryer. One can notice the shrinkage of the plastics and their adherence to the metal (stainless steel) surface. After a while, when the cuvette cooled down to the determined temperature, the plastics began to fall off its surface. If the cuvette with adhering plastic particles is rotated at 180°, 100% of the particles do not detach from the surface of the

metal cuvette during all three tests. This was the basis for the proposed technological concept in the solution of cooling the sorting roller with compressed air nozzles until the particles detach from the surface.

The experimentally determined optimal process parameters for PS and PP are presented in Table 3. The parameters measured included: optimal temperature of the metal surface, ensuring melting of the plastic and its adhesion to the metal surface (T_i), optimal contact time (τ) of the plastic with the metal surface at a specific temperature T_i , ensuring the adhesion of the material, optimal temperature of the metal surface ensuring the detachment of the plastic (T_o) and efficiency (η) defined as the ratio of the amount of particles detached to the amount of particles in a metal cuvette at temperature T_o . Data in the table are average values of three repetitions of measurements.

Shrinkage of Plastics

The experimental results for the PS/paper cups are shown in Table 4. The shrinkage test was repeated for PP/paper cups. The results of the experiment are presented in Table 5.

In Fig. 3a) large PS/paper cups are shown after being removed out of the dryer after two minutes at a temperature of 160°C (visible large shrinkage of the material and a disconnected paper label). After shrinkage and cooling in some cups the plastic was

Table 3. Optimal parameters of melting process.

Type of plastic	Optimal temperature T_i [°C]	Optimal contact time τ [s]	Optimal temperature T_o [°C]	Efficiency η [-]
PS	150°C	7	138°C	1
PP	180°C	7	167°C	1

Table 4. Results of thermal shrinkage of the PS/paper cups.

Tests for PS/paper cups			
Temperature	Residence time in dryer	Effect	Comments
105°C	7 minutes	Appropriate shrinkage and separation of paper label	PS/paper larger cups TLJ
105°C	10 minutes	Appropriate shrinkage (plastic has separated from paper)	PS/paper cups LPS
120°C	3 minutes	Appropriate shrinkage (plastic has separated from paper)	PS/paper larger cups
130°C	2 minutes	Appropriate shrinkage (plastic has separated from paper)	PS/paper larger cups
140°C	2 minutes	Appropriate shrinkage and separation of paper label	PS/paper larger cups
150°C	1 minutes	Not all paper labels have separated, shrinkage was not uniform in all cups and were not satisfactory	8 cups were placed simultaneously (PS/paper larger cups)
160°C	1 minutes	Not all paper labels have separated	8 cups were placed simultaneously
160°C	2 minutes	Optimal shrinkage and separation of all paper labels	8 cups were placed simultaneously. The test was also repeated for small PS cups, the required repeatability was achieved.

Table 5. Results of thermal shrinkage of the PP/paper cups.

Tests for PP/paper cups			
Temperature	Residence time in dryer	Effect	Comments
<170	Independently	Lack of shrinkage	-
170°C	4 minutes	There is shrinkage, but smaller than in case of PS	
180°C	4 minutes	PP started to „flow” and after cooling it bonds with paper	

connected with the paper, as shown in Fig. 3b). It is not a strong connection, the materials can be separated mechanically, for example by intense shocks.

As a result of the research, it turned out that the paper part joined with the plastic part after thermal shrinkage and cooling. It has been shown that the proportion of these cups depends on their size. In the case of larger cups (PS/paper; code TLJ) it was 10% of all cups, while in the case of smaller (PS/paper; code LPS) this share was 18%.

The next stage of the tests was to select the optimal mesh diameter of the sieves to separate the mechanical

plastic (PS cups) from the paper, as shown in Fig. 4. The mass loss of the PS cup at the selected temperature and residence time in the dryer was also tested, as shown in Table 6.

The influence of the residence time in the dryer of the PS cup at a specific temperature (140°C) on the change of the cup volume was also investigated. It turned out that the volume of the cup after being removed from the dryer decreased by the same value regardless of the residence time in the dryer (here: 1-5 min).

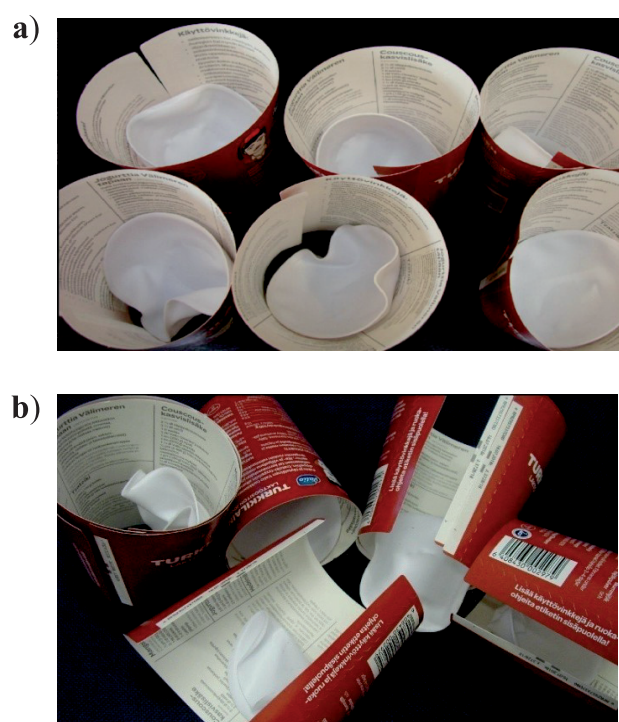


Fig. 3. PS cups after removal from the dryer a), connection of the plastics and paper after cooling b).

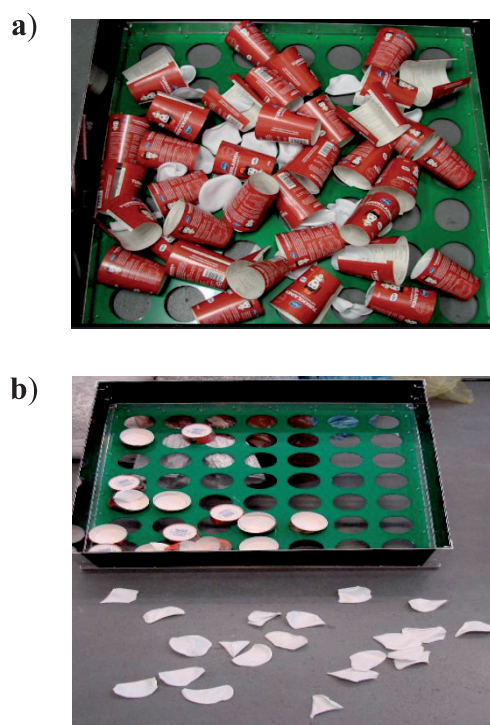


Fig. 4. Separation of fractions: a) paper and b) plastic of PS cups on a sieve with mesh diameter – 80 mm.

Table 6. Share of cups with plastics-paper connection.

Type of cup	Share of cups with plastic-paper connection [%]
PS/paper cups (larger - TLJ)	~ 10
PS/paper cups (smaller - LPS)	~ 18

Melting of Plastics

As established in the presented studies, the optimal melting point parameters for the polystyrene and polypropylene waste in question were 150°C and 180°C, respectively, with a 7-second contact time with the metal surface. The optimal shrinkage for PS occurred at 160°C with a 2-minute heating time, and for the tested PP, the optimal shrinkage temperature was 170°C, applied for 4 minutes. The authors of the study [28] conducted a thermogravimetric analysis of the pyrolysis of some plastics, which results are shown in Fig. 5 and Table 7.

As clearly shown in Fig. 5 and Table 7 the TG characteristic temperatures (T_{onset} , T_{peak} , T_{endset}) of the pyrolysis of the tested polymer samples were in the following order: PS<P<LDPE<HDPE. Polypropylene pyrolysis temperatures are expected to be lower than

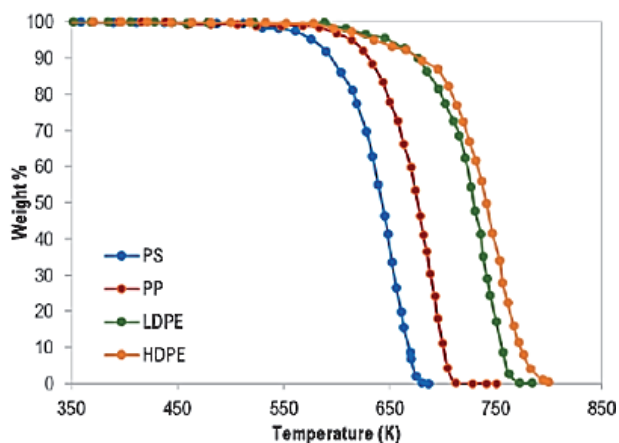


Fig. 5. Thermogravimetric analysis of plastics in pyrolytic decomposition in inert atmosphere with heating velocity 60 K/min.

that of HDPE and LDPE due to the third carbon atom that decreases the polymer stability. Reported that substituted and branched polymers like PS and PP decompose at lower temperatures when compared with linear polymers (LDPE and HDPE). Furthermore, LDPE has a higher degree of branching and thus lower density and thermal decomposition temperatures than HDPE.

The temperature range of the pyrolysis processes was as follows: 389-687 K (PS), 459-728 K (PP), 445-785 K (LDPE), and 444-800 K (HDPE). The maximum decomposition rate was between 670-757 K.

In other work [29] the authors also studied the thermal decomposition of several plastics, including PS and PE. Thermogravimetric analysis was carried out for each type of plastic waste on an individual basis to determine the optimum temperature for thermal degradation. All types of plastic waste show similar degradation behavior with the rapid loss of weight of hydrocarbons within the range of temperature (250-500°C) (Fig. 6). The maximum degradation for each type of plastic waste was achieved within 420-490°C. PS and PP showed single step decomposition. PP degradation started at a very low temperature (240°C) compared to other feedstocks. Half of the carbon present in the chain of PP consists of tertiary carbon, which promotes the formation of carbocation during its thermal degradation process. This is probably the reason for achieving maximum PP degradation at a lower temperature. The PS initial

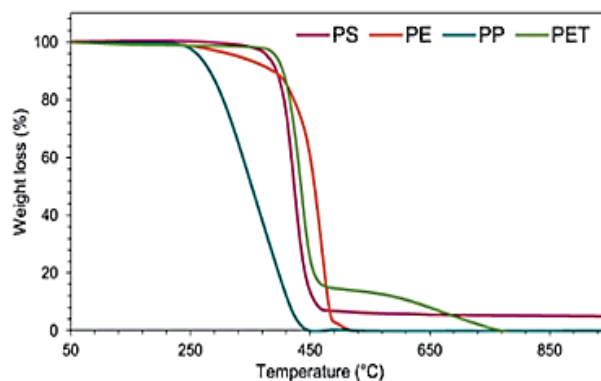


Fig. 6. Thermogravimetric analysis of the pyrolysis process of selected plastics.

Table 7. Characteristics temperatures of the pyrolysis of the tested plastics.

Polymer	T_{onset} [K]	T_{peak} [K]	T_{endset} [K]	ΔT [K]
PS	545	652	680	135
PP	583	696	710	127
LDPE	608	738	770	162
HDPE	614	737	790	176

degradation started at 330°C and maximum degradation was achieved at 470°C. PS has a cyclic structure, and its degradation under the thermal condition involves both random chain and end-chain scission, which enhances its degradation process.

As can be seen, thermal conditions of segregation using shrinkage and melting do not pose a risk of earlier depolymerization of PP and PS materials, and do not have a negative impact on the processes of their further thermal processing. At the suggested temperatures of thermal sorting, there is no depolymerization of materials as it happens in the case of full processing of thermoplastics, for example in the process of injecting the material into molds. Thus, the proposed method of shrinkage and melting in the sorting process can serve as a step of separating the PP or PS material from the waste mixture without its negative impact on further processing processes in thermal, chemical or mechanical recycling.

The Concept of Technological Separation of the Shredded Fraction of the PS/paper or PP/paper Mixture Based on the Melting Point

Technological concepts of the technical use of the phenomenon of melting and shrinkage of plastics in the separation of two-component waste containing plastic have been submitted to the Patent Office of the Republic of Poland [30, 31]. It should be noted that one of these concepts (using the phenomenon of shrinkage of plastic) was implemented on a technical scale. Below, both studied phenomena in the developed technological sorting processes are presented.

In Fig. 7 a proposal for a technological concept for the separation of the fragmented fraction of the PS/paper or PP/paper mixture based on the melting point was presented.

The method and installation are used to separate shredded two-component waste: paper/cardboard-plastic or glass-plastic or metal-plastic or mineral fraction-plastic or textiles-plastic or wood-plastic, using the melting phenomenon of plastic. When thermoplastics are heated, there is a change from a solid state to a plastic state and then a liquid state. The process takes advantage of the moment when the thermoplastic becomes more viscous, which occurs mainly in the melting phase.

The method of separating the shredded two-component waste is based on the fact that the shredded waste, preferably with a grain size of less than 20 mm, is fed by means of a vibrating feeder that provides a loose, unfolded single layer to a heated metal or ceramic cylinder (preferably steel) with a surface temperature in the range of 100-190°C, the roller diameter in the range from 0.3 to 3 m, the width depending on the size of the fragmentation of the waste and the roller speed in the range of 0.5-15 rpm. Then the shredded pieces of plastic melt and adhere to the roller until it hits the element (here: a scraper with a compressed air nozzle) which separates the plastic attached to the roller. The non-plastic waste falls off the roller. The advantage of the solution according to the invention is a cheap and effective method of separating plastic from paper/cardboard, wood, glass, textiles or mineral fraction [30].

The effectiveness of the separation process with the use of plastic melting will depend on the effectiveness of adhesion individual pieces of plastic to the heated roller. The effectiveness of adhesion of a given type of plastic to the roller heated to the optimal temperature will reach 100% due to the fact that the shredded waste will be fed to the roller in the form of a single layer, thus there will be no situation that there will be a piece of paper between the roller and the plastic, which would reduce the efficiency of the process.

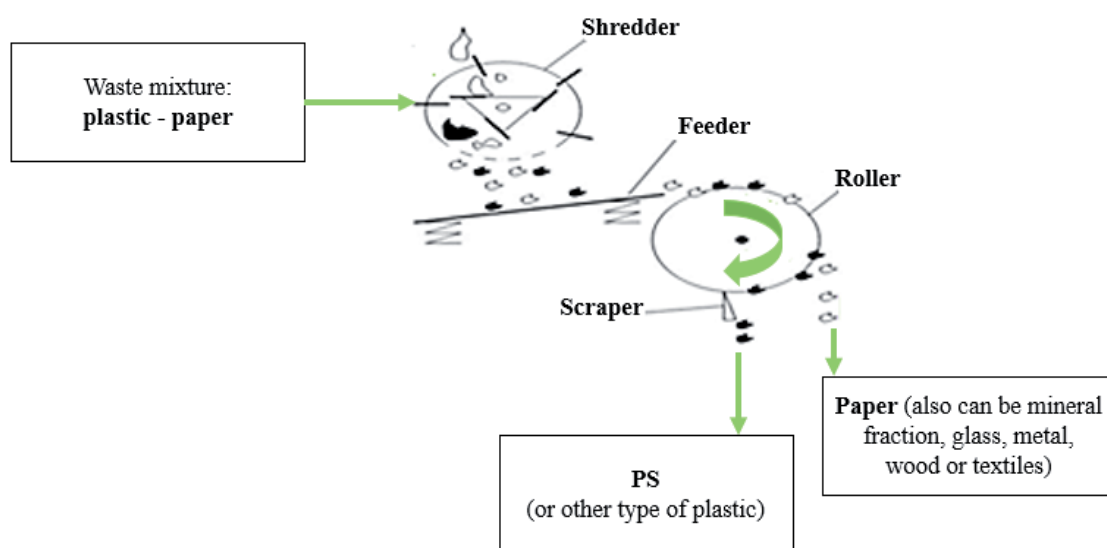


Fig. 7. Technological concept of separation based on the melting point (Jaworski and Hryb 2020).

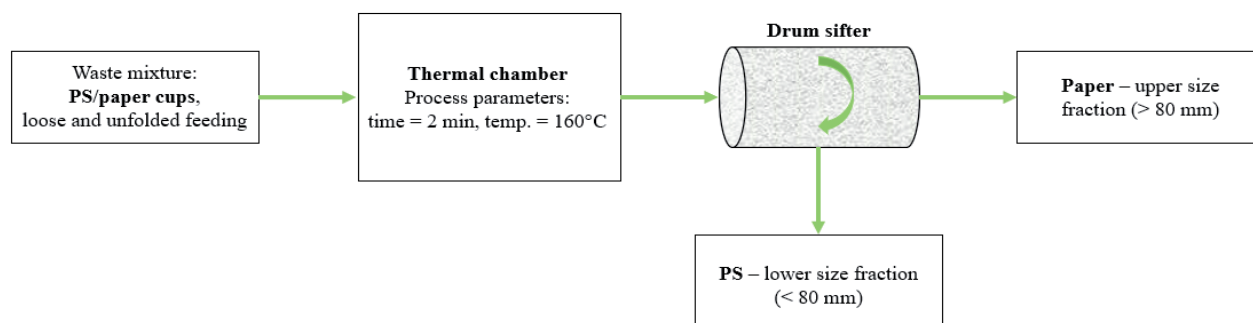


Fig. 8. Technological concept of separation with the use of thermal shrinkage of plastic (Jaworski and Hryb 2020).

The Concept of Technological Separation of the Shredded Fraction of the PS/paper or PP/paper Mixture Based on the Shrinkage of Plastics

Separation of two-component packaging waste (paper-plastic) was achieved through the use of thermal shrinkage of plastic, which causes separation of paper from plastic, unsticking of the paper label and changing the physical properties of the plastic. The volume of the plastic part of the cups is reduced whereby it is effectively separated from the unchanged paper part by means of a drum sifter. Plastic is here the lower size fraction, and paper – the upper size. Fig. 8 presents the developed technological concept of separation with the use of the phenomenon - thermal shrinkage of plastic.

The effectiveness of the separation process with the use of plastic shrinkage will be limited by the bonding of plastic to paper, which was observed for some of the packaging after thermal shrinkage and cooling. The tests carried out have shown that this may concern 10 to 18% of polystyrene packaging. It is not a strong connection, it is possible to mechanically, e.g. by intense shocks, disconnect most of these bonded materials, thus increasing the efficiency of the process.

On an industrial scale, the developed concept of separation using plastic shrinkage is used by Multi-Plast in the following work variant: shredding two-component waste plastic/paper, feeding the shredded fraction into a thermal chamber, separating. After the thermal shrinkage of plastic, the mixture is effectively separated using an air separator type Zig-Zag reaching the throughput of 100 kg/h. The advantage of the solution according to the invention [31] is a cheap and effective method of separating paper from plastic in two-component packaging waste.

Conclusions

Use of Melting Phenomenon in the Separation of Plastics

The defined indicators of the temperature level and the residence time in the heating device will always

require an individual approach depending on the type of plastic. However, for the PP and PS materials in question, the actual parameters of the melting process were determined, ensuring a sufficient strength of adhesion to the surface, they are:

- temperature ensuring melting of the plastic and adherence to the metal surface,
- heating time,
- temperature of decay of the strength of adhesion to the metal surface.

The first two parameters are decisive in order to obtain a satisfactory adhesion of plastic to the metal surface until separation from the surface of the second component, e.g. paper. In order to finally detach the adhering plastic material from the metal surface in the final phase of the sorting process, the surface should be cooled to a lower temperature (temperature T_o , Table 3). The above satisfactory results of the experiment were used in the development of the technological concept presented in Fig. 7. It should also be emphasized that the type of heating surface to which plastic adheres was selected. A metal surface was used in the tests, further tests are planned in the concept of a test variant with surfaces made of other materials with varying degrees of roughness.

Use of Shrinkage Phenomenon in the Separation of Plastics

The study of the shrinkage phenomenon was performed for the unchanged shape of waste two-components cups (plastic-paper/cardboard) after beverages. The possibility of the influence of thermal shrinkage of the plastic was investigated for two purposes:

- unsticking a cardboard sticker from a plastic part of the cup,
- separating detached sticker by shrinkage of the plastic container.

In these studies, the optimal temperature and time were searched, which caused plastic shrinkage with the maximum effect of purity of the separated components. Table 4 shows the optimal temperature and time for PS/paper cups. For this test, the separation effects were very satisfactory in the temperature range from 105°C

to 160°C depending on the size of the cup and the residence time in the heating device. The volume of the containers decreased by about 1/3 during shrinkage, this was sufficient for the separation of both components. For PP/paper cups, the shrinkage method to separate the components seems inappropriate.

Defined indicators of the temperature level and the residence time in the heating device will always require an individual approach depending on the type of plastic, although in fact the list of the most common plastics in packaging is about ten. The described tests can be extended, and this is the intention of the authors, to include other types of plastics and mixtures with other wastes, as well as to develop a comparative test of the adhesion strength of melted plastics to various surfaces.

General Summary

In conclusion, the intended aims were achieved through: development of two innovative technologies for sorting two-component waste and experimental determination of optimal process parameters for the tested two-component waste, in which plastics were polystyrene and polypropylene. On an industrial scale, one of the developed separation concepts - with the use of shrinkage - was implemented by Multi-Plast, which confirms that the solution has great implementation potential and that there is a need for this type of solution in the plastics industry.

The importance and topicality of the issue undertaken by the authors is in line with the priority actions of the EU under the European plastics strategy in the circular economy. One aspect of the strategy is to modernize the plastics recycling sector by implementing effective solutions. On the other hand, the economic aspect is important. In the face of introducing changes in states of the Community, failure to adapt to the aims of the strategy will result in financial consequences. This applies both to individual member states and, taking into account the implementation of the EPR, also to enterprises. Thus, it is predicted that up to a certain cost limit, the implementation of new technologies will be profitable in the long-time perspective. One of the separation technology developed by the authors, currently used in industry, contributes to a more effective sorting of two-component waste. Furthermore, it is characterized by low implementation costs and greater processing capacity compared to other competing solutions like automatic sorters.

Authors of the study are aware of the limited scope of the materials tested, therefore they envisage the continuation of the research on the separation of two-component waste with the use of other types of plastics and their adhesion surfaces. In addition, it is important to develop a universal tool that determines the process parameters for various waste materials or, in the case of difficulties associated with it, a simplified procedure for examining the properties of materials, here: plastics, to select the appropriate parameters of the

separation process. Nevertheless, the positive result of the research with the use of selected types of plastics is an introduction to a wider analysis, which may result in the development of a technology for the separation of multi-component waste containing plastic, allowing for the recycling of individual components.

At the suggested temperatures of thermal sorting, there is no depolymerization of materials, as it happens in the case of full processing of thermoplastics, like in the process of injecting the material into molds. Thus, the proposed method of shrinkage and melting in the sorting process can serve as a step of separating the PP or PS material from the waste mixture without its negative impact on further processing processes in thermal, chemical or mechanical recycling.

Patents

Two patent applications have been developed as a result of the study reported in this manuscript. Applications titles are: "Method of separation of two-component packaging waste" and "Method and installation for separation of shredded two-component waste". Patent applications have been submitted to the Patent Office of the Republic of Poland in 2020.

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Conflict of Interest

The authors declare no conflict of interest.

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