Doi: https://doi.org/10.63333/eem.v1n26 Vol. 1 No. 2 (2025)

Experimental Study of the Process of Obtaining Filament for 3D Printing from Plastic Waste

Hrechanyi Oleksii*, Khudiakov Rostyslav, Dernovyi Oleksandr, Vernydub Mykhailo, Mylenkyi Bohdan

Department of Metallurgical Equipment, Zaporizhzhia National University, Zaporizhzhia, Ukraine
* Correspondence: hrechanyi@znu.edu.ua

Abstract: In the modern world, the problem of plastic waste disposal is becoming increasingly urgent. The growth of production and consumption of plastic products creates a serious environmental burden on the environment. Plastic waste makes up a significant part of solid household waste, and its decomposition can take hundreds of years. This not only pollutes the environment, but also poses a threat to human and animal health. An effective solution to this problem is possible through the introduction of new methods of plastic recycling - the process of processing it for reuse. Recycling allows not only to reduce the amount of waste, but also to reduce the need for the production of new polymers, which contributes to the reduction of consumption of natural resources and energy. Plastic is a fairly good structural material that is successfully used in metallurgical equipment components as sealing elements, as well as in the creation of various types of composite materials used in friction components, such as universal spindle liners. The rapid development of 3D printing allows you to quickly and efficiently perform various types of plastic parts of various configurations. Therefore, a natural question arises of considering the possibility of processing various types of plastic waste into consumables for 3D printing, with the possibility of its further use for the manufacture of metallurgical equipment parts. It has been determined that the effective processing of plastic waste depends on the selection of optimal process parameters and technological equipment. Familiarization with the technology and equipment for recycling showed that the selection of raw materials and the determination of optimal speed-temperature characteristics of the process have a significant impact on the efficiency of the process. It has been established that the optimal temperature regime for recycling plastic bottles from PET plastic by the drawing method for forming filament for 3D printing is 160-200°C. At these temperatures, the material retains high mechanical properties, is evenly formed, is not subject to thermal destruction, and allows obtaining an equiaxed, maximally filled filament structure of a circular cross-section.

Keywords: Plastic; Recycling; 3D Printing; Nozzle; Filament

1. Introduction

According to numerous studies, humanity consumes almost 60 million plastic bottles daily [1].

Recycling of plastic waste is a necessary condition for preserving the environment and rational use of natural resources. Plastic materials are widely used in industry, but due to their low biodegradability, they pose a serious environmental threat. One of the effective ways to dispose of them is recycling, which includes mechanical and chemical processing methods [2]. Mechanical recycling involves the

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use of physical processes to recover plastics, while chemical recycling uses chemical reactions to return materials to their original state or to create new polymers [3-5].

Chemical recycling involves transforming plastic waste at the molecular level. Chemical recycling allows plastics to be restored to their original properties, opening up opportunities for reuse in more responsible or high-quality products. However, this process is more energy-intensive and expensive compared to mechanical recycling [6].

Mechanical recycling is the most common method of processing plastic waste. This process involves several steps:

– collection and sorting – first, plastic waste is collected and sorted by type of plastic;
– crushing – plastic materials are crushed into small particles or granules;
– melting and forming – after grinding, the particles are melted and formed into new products or pellets for further use.

Mechanical recycling has several advantages: it is energy efficient, cheap, and often gives materials that can to use for manufacturing less demanding of quality products [7].

One of the most promising areas of plastic waste processing is the creation of standard equipment for their recycling into the main consumable element in 3D printing - filament. [8].

Given the economic and technological advantages of mechanical recycling methods, the task was set to consider the possibility of recycling plastic bottles in laboratory conditions with its subsequent use in the details of production equipment.

Analysis of recent research and publications. Plastic is a fairly good structural material, which is successfully used in the units of production equipment of all industries, including metallurgical. It is used as consumables as sealing elements, as well as in the creation of various types of composite materials, for use in fairly responsible structures, such as various types of housings, bushings, couplings [9-13].

Significant progress in 3D printing technologies allows you to quickly and efficiently produce various types of plastic parts of various configurations.

There are several main types of 3D printers, each of which has its own design features that determine the printing technology and application in different industries. FDM printers are economical and easy to use, but have limitations in the complexity of parts and surface quality. SLA printers provide high detail, but require additional hardening of materials and have a high cost of photopolymers. Printing with metal powders using DMLS technology is optimal for complex industrial products, but is expensive and requires environmental control [14-19].

Thus, FDM printing, which uses plastic in its technological process, is best suited for testing the mechanical recycling method in laboratory conditions.

An important factor in conducting the experimental part, in addition to the choice of the type of equipment, is the correct choice of the material on which the first tests will be carried out. There are more than 100 types of plastics in the world, to which many different components are added to give them special technological properties. The types of plastics and their codes were defined by the "Society of the Plastics Industry" (SPI), and this marking system is widely used to designate packaging materials. In many countries, such marking is mandatory and is shown in Figure 1 [20].

The laboratory of the Department of Metallurgical Equipment has installed a fairly easy-to-maintain and undemanding 3-D printer model of the GRABER i3 type, which is best suited for conducting experimental research on the possibility of recycling plastic waste in laboratory conditions. Of the seven types of plastic listed, PET plastic is best suited for testing the mechanical recycling process in laboratory conditions, as it is one of the most common thermoplastic polymers used for the production of packaging, especially beverage bottles.

PET type plastic known for its transparency, strength and lightness, as well as good barrier properties against gases and moisture.

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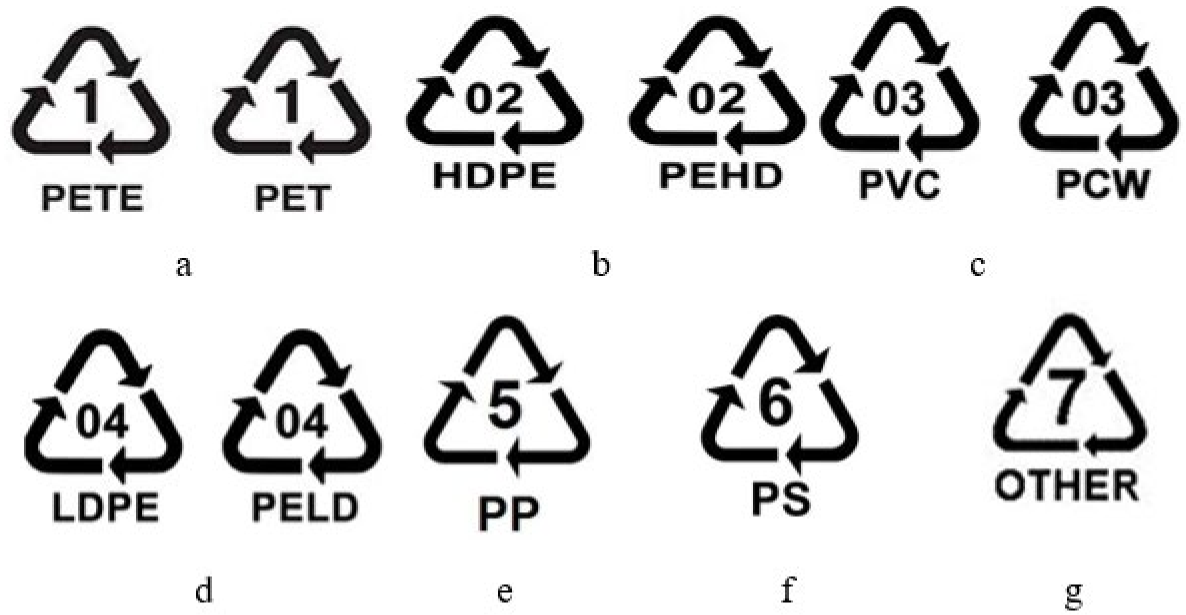

Figure 1. Graphic marking of different types of plastic: a – polyethylene terephthalate (PET, PETE); b – high-density polyethylene (PEHD, HDPE); c – polyvinyl chloride (PVC, PCW); d – low-density polyethylene (PELD, LDPE); e – polypropylene (PP, PP); f – polystyrene (PS); g – plastic type (Other) [20].

2. Materials and Methods

Considering the prospects of obtaining filament for 3D printers by thermomechanical recycling methods, the question arises of developing a set of unified equipment and researching the technological process of processing. This approach correlates well with the main concept of sustainable development and energy-saving production, because 3D printing is currently the most economical way to manufacture parts, which is close to waste-free.

3. Results and Discussion

The most common technological process of final processing of materials is pressure processing. Given the widespread use of drawing and rolling processes, a decision was made to develop equipment for recycling plastic, which uses the basic technological principles of these processes. In this case, the processes will be combined, and the process of heat treatment of the material with its simultaneous drawing will be used in part. The main idea of the device (Figure 2) is to use a heating element that will maintain a certain constant temperature of the plastic strip during the main process - drawing, in order to improve the plasticity of the material and achieve the specified characteristics of the final product.

The combined process of drawing plastic through a heating element has several key advantages, namely increasing the accuracy of strip thickness control, improving the mechanical properties of the material due to optimal temperature distribution, and minimizing defects in the production process. Heating the plastic before passing it through a system that is as close as possible to the drawing tool in terms of its functional purpose (Figure 2), allows you to reduce the resistance to deformation, which contributes to obtaining a more uniform and high-quality product.

A chipboard cut to size 15×35 cm is used as the basis of the structure. The base serves as a platform on which all the working elements of the installation are fixed, ensuring their stability and ease of operation (Figure 3).

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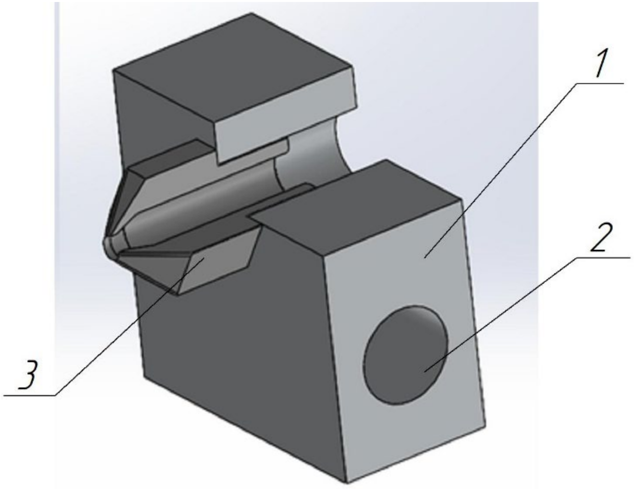

Figure 2. 3D model of the proposed device for recycling plastic waste: 1 – housing, 2 – heating element, 3 – nozzle (drawing tool).

The installation is designed for processing prepared PET plastic by thermal deformation. It consists of several interconnected components that ensure efficient processing of plastic in the form of filament or tubular material.

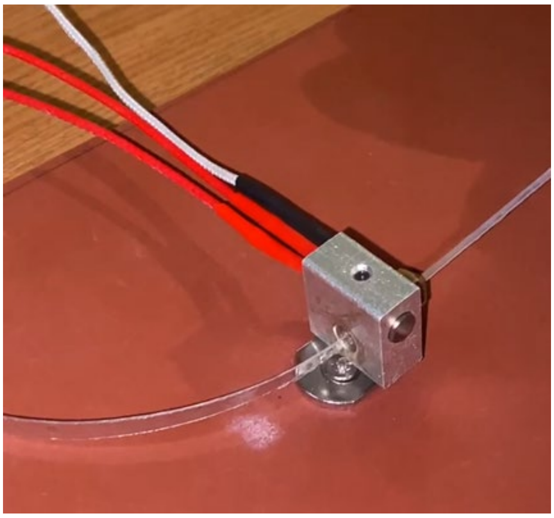

Figure 3. Securing the experimental setup to the base.

At the first stage of experimental research, the following technological scheme of the filament manufacturing process was developed: sorting plastic bottles → cleaning from contamination and labels → removing stiffening ribs from the bottle surface by heat treatment under high pressure → cutting the bottle into a plastic strip → direct processing of the strip into filament on a developed installation.

During the experiment, plastic bottles from different manufacturers, with different shapes, sizes and shades of color, were used for recycling. According to the labeling, in all cases the main material of the bottles was polyethylene terephthalate (PET 1). The color of the bottles is an important factor in recycling, as colored and transparent versions can react differently to heating and molding. In particular, transparent PET often contains fewer impurities than colored ones, which can improve the quality of the recycled material. Additional additives in colored PET plastic – stabilizers and modifiers that affect the process deformation and formation.

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It has been experimentally confirmed that clear PET heats more evenly and is easier to heat treat. Colored PET can heat unevenly, which makes thermoforming difficult and requires more precise temperature control.

During the recycling process, it was discovered that mixing PET bottles of different colors results in a heterogeneous material.

Analysis of available analogues of the proposed solution from open sources indicates an empirical approach to the processing of bottles into filament. Therefore, a scientific approach has been proposed, namely, to use the theory of similarity of planes, i.e. the cross-sectional area of the plastic strip entering the nozzle of the installation should be equal to the cross-sectional area of the exit nozzle (Figure 4).

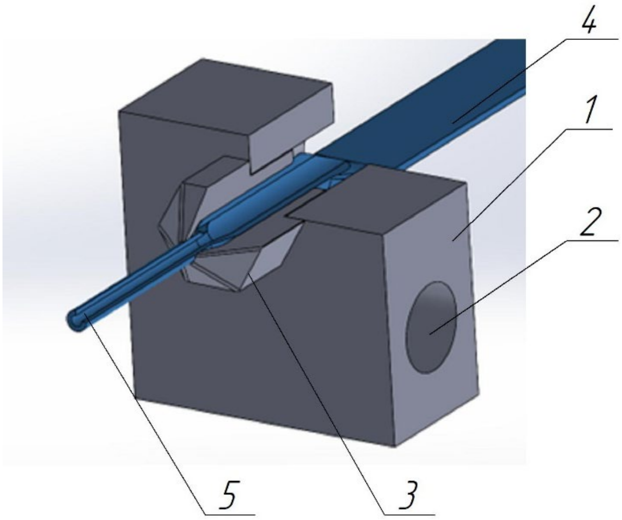

Figure 4. 3D model of the proposed device for recycling plastic strip: 1 – housing, 2 – heating element, 3 – nozzle (drawing tool), 4 – rectangular plastic strip at the inlet to the nozzle, 5 – filament of circular cross-section at the outlet from the nozzle

Thus, if a strip of rectangular cross-section enters the nozzle, it has an area that is calculated by the formula:

$$S_{ш}=a\cdot t,\ mm^2 \quad (1)$$

where a – is the width of the strip, mm; t – is the thickness of the strip, mm

and the area of the filament is calculated as:

$$S_{ф}=\frac{\pi\cdot d^2}{4},\ mm^2 \quad (2)$$

where d – is the diameter filament, mm. We take it equal to the initial nozzle diameter.

By solving (1) and (2) together, we can determine the width of the plastic strip, assuming that the filament profile is 100% filled:

$$a=\frac{\pi d}{4t},\ mm \quad (3)$$

It has been experimentally established that to obtain a dense, pore-free filament, the width of the plastic strip should be 10-15% larger than the calculated one.

The temperature and speed characteristics of the technological process are of great importance for obtaining high-quality filament during the recycling of plastic bottles .

During the experiment, the effect of temperature on the process of drawing PET plastic in the range of 120-260 °C was studied. The analysis showed that temperature significantly affects the fluidity of the material, its mechanical properties and uniformity of molding. Due to the lack of equipment at the department that is capable of performing macro photography with the required level of detail, all the

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results of the experimental part to establish the optimal temperature regime are presented in the format of 3D modeling.

When heated to 120-160 °C, the plastic softened, but did not reach the state necessary for uniform filament formation by the single-drawing process. This led to the appearance of internal stresses, tears and surface defects. The formation of the thread in this range occurred unevenly. The resulting filament was mechanically unstable (Figure 5a).

Figure 5. Definition experimentally determining the optimal temperature regime for recycling plastic headquarters: a – t=120…160°C; b – t=160…200°C; c – t=200…230°C; d – t=230…260°C

When testing the technological process in the temperature range of 160-200 °C, optimal material behavior was observed. PET plastic acquired sufficient plasticity, ensuring uniform molding without significant internal stresses. The finished workpiece had a satisfactory surface for implementation in the subsequent 3D printing process and retained an equiaxed structure (Figure 5b).

At temperatures above 200°C the material became excessively fluid, which led to the formation of micropores and changes in mechanical properties. In some cases, signs of overheating were observed, which were expressed in the appearance of bubbles and increased brittleness (Figure 5c).

Upon reaching 230-260 °C, the decomposition of PET plastic occurred with the release of gaseous compounds (Figure 5d). This led to a change in color, deterioration of mechanical properties and the appearance of porosity in the structure. Visually, it was possible to observe the blackening of the material, which indicates its partial oxidation.

Thus, it can be concluded that the optimal temperature range for recycling plastic bottles from PET plastic is the combined casting-drawing method when forming filament for 3D printing temperature is 160-200 °C.

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4. Conclusion

During the research, it was found that the minimum complex for processing plastic bottles into filament should include:

- equipment for preparing bottles for recycling;
- equipment for cutting bottles from headquarters;
- heating device;
- winding and drawing device.

When selecting the width of the plastic strip for drawing-casting, it is worth being guided by the evenness of the area, namely, the cross-sectional area of the plastic strip should be equal to the cross-sectional area of the output nozzle.

The optimal temperature regime for recycling plastic bottles from PET plastic for forming filament for 3D printing is 160-200°C. At these temperatures, the material retains high mechanical properties, is evenly formed and is not subject to thermal destruction.

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