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**LIGHT INDUSTRY
POLYMERIC WASTE RECYCLING
IN THE CONDITIONS OF
URBANISTIC ENVIRONMENT
DEVELOPMENT**



Wydawnictwa Uczelniane
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w Bydgoszczy

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INTRODUCTION

Today waste recycling of polymer materials is an important issue not only in terms of the natural environment protection, but also due to the fact that, in the absence of polymer materials, plastic waste becomes a powerful material and energy resource [1].

Moreover, solving environment-related issues requires significant investments. The cost of processing and destroying plastic waste is approximately 8 times higher than the cost of processing most industrial waste and almost 3 times that of household waste treatment. This is due to specific features of plastics, which complicate the methods of solid waste destruction and make them unsustainable. The use of waste from polymers can significantly save primary raw materials (primarily oil) and energy [2].

There are a lot of problems connected with utilization of polymer waste. Polymers have their own specific characteristics, but they cannot be considered as insoluble [3].

Effective utilization is impossible without organization of collection, sorting and initial processing of used materials and products, without developing a system of prices for secondary materials to encourage enterprises to undertake their processing, without creating effective methods for processing of secondary polymeric materials and methods for its modification aimed at improving the quality of raw materials, without creating special processing equipment or without developing a range of products to be manufactured from secondary polymer materials [4].

Today, polymer waste can be recycled or reused to manufacture new products [5].

Financial and operating costs involved in polymer waste recycling do not exceed their destruction costs and in some cases are even lower [6].

The positive consequence of recycling is also that it provides useful products for various industrial sectors and is environmentally friendly [7].

For these reasons, utilization is not only an economically justified but also environmentally friendly solution to the problem of the polymer waste management.

Modern technologies for recycling of light industry polymeric waste include chemical recycling or mechanical grinding of polymers [8]. Solutions to many problems of chemical processing of polymer waste are presented in a number of scientific works [9].

The methods for obtaining high-calorific fuel, semi-finished products to be used in various technological processes, as well as monomers for the synthesis of new polymers, lubricants, emulsions and other materials obtained through the polymer waste pyrolysis, have already been studied by many researchers [10].

Modern technologies for polymeric waste recycling are proposed in the works of different authors [11, 12]. The main advantage of polymer waste chemical recycling is that it is very easy to sort, in fact, sometimes contamination degree of untreated polymer waste rules out the possibility of mechanical processing, whereas, in recovery of monomers they can be cleaned from various impurities [13]. However, apart from the advantages, chemical recycling has also drawbacks [14]. Chemical processing of polymer waste makes the macromolecular structure of polymers collapse [15].

Complexity of operations and reagents required to recover a monomer suitable for re-polymerization requires significant financial investments; monomers and useful oligomers can be obtained only from a limited set of polymers [16]. Thus, a progressive way of polymer waste recycling is mechanical processing, which is simpler, cheaper and more productive than other processing methods [17].

Mechanical recycling of polymer waste does not require expensive and sophisticated equipment and can be implemented at any place of waste accumulation [18].

The main advantage of mechanical recycling is that it does not significantly affect the polymer structure.

There are not many works devoted to mechanical processing of polymer waste. Thus, some papers [19–21] present an analysis of plastic waste mechanical processing with various additives: modifiers, stabilizers, pigments and dyes. Such processing involves additional expenses.

Technological processes of polymer waste recycling which use mechanical stresses seem to have a big potential [22]. Extruded grinding of polymeric materials, based on the polymer complex-stress state was investigated in the research whose results are presented in a scientific work which describes the process of rubber waste milling in an extruder and a rotary crusher, and presents the parameters for which the minimum energy costs are provided [23].

There are studies which include analyses of the equipment and processes involved in recycling of thermoplastic materials using secondary raw materials [24, 25]. These works have provided scientific basis for the development of efficient processes and equipment for treatment of thermoplastic materials with the use of secondary raw materials, which provides energy and material resources savings and reduces pollution of the environment [26].

An analysis of recent scientific research results in the field of polymer waste mechanical processing has shown that today there is almost no equipment for mechanical processing of polymer waste to provide the recycled waste with oriented structure, which would make them usable as reinforcing elements in the manufacture of light industry products without additional treatment [27].

This implies a necessity to develop a method for designing equipment for polymer waste processing that will ensure destruction of the polymer materials along their structural formation boundaries, thus maintaining the physical and mechanical characteristics of the primary polymer, providing them with anisotropy and reducing the energy consumption [28].

1

GENERATION OF LIGHT INDUSTRY POLYMER WASTE

1.1. Classification of light industry waste

So far polymer materials have been widely used in all industries, including light industry. This is due to a number of factors – the possibility of obtaining unlimited volumes of polymers, lower costs as compared to traditional materials, technological advancement and physical and mechanical characteristics which allow to provide products with predefined properties [29]. Various polymeric materials are characterized by a wide range of properties such as strength, rigidity, hardness, ductility, thermal stability, heat and electrical conductivity, color and transparency, and so on. Thanks to this, polymers can act as substitutes for a variety of materials – from natural fibers to metals.

Light industry, apart from the problems involved in equipment modification to obtain competitive products, has to deal with utilization of waste [30].

Light industry waste accounts for a fairly large share of all solid waste. The share of textiles in solid household wastes is 4.6–5.4%. A further share is made up of waste from the textile industry itself and other industries. It reaches 25% of all recycled waste in the world. These are huge reserves that can be used to produce various products.

Nowadays there is a wide assortment of polymeric materials for manufacturing of light industry products. The purpose of the product determines the polymer material to be used.

In industrial production of textile products (fabrics, knitwear, carpets, nonwoven cloths, threads, ropes, ropes, etc.) wastes occur in the form of scraps, shreds, fibers, ends of yarn, etc. In other industries, textile wastes are produced as a result of the use of ready-made textile materials (overalls, filtering, wiping and packing fabrics, etc.). In addition, there are textile wastes from household consumption, that is, worn out and invalidated articles of personal use (clothing, footwear) and household goods (carpets, draperies). Today, the textile industry is largely based on synthetic materials. Technologies for recycling of these materials are described below.

Another group of textile industry waste including leather and fur processing – is waste waters, which appear in processing of wool containing wool grease, wool remnants and mechanical impurities of vegetable, waste of organic and mineral origin, soluble organic and inorganic compounds. Most of the impurities include the strongest oxidizers, stimulants that damage and destroy cul-

tivated plants. In the process of preparation and processing of leather and fur, there are waste materials that are included in the following groups [31–35]: waste of tanning (marginal areas of skins); waste after tanning (chips, cuts, pieces of skins); powdered leather waste; waste from treatment facilities after tanning (tannin solutions of vegetable, waste of organic and mineral origin).

All light industry enterprises use equipment that includes rubber products which should be disposed of at the end of their service time. Most rubber products are used in technological equipment and in automobile transport of light industry enterprises and other industries. The most important types of rubber products are automobile tires, conveyor belts, drive belts, various friction parts, floor and roof coverings, rubberized fabrics, lining and waterproof materials.

Depending on the amount of sulfur injected during vulcanization, rubber can be divided into soft (2–8% S), semi-soft (8–12%), semi-solid (12–20%) and solid (25–30%). Waste rubber products, as well as plastics occur in four main areas: the primary production of polymers; production of rubber products; industrial consumption; household use.

Rubber product wastes are divided into non-vulcanized and vulcanized. The former can be returned to the primary production, the latter are subjected to mechanical or chemical processing. Secondary mechanical processing allows to obtain a number of valuable products and materials: slabs, slate, anti-vibration, hydro and electrical insulating pads, blocks for dam edges, quays, breakwaters, anti-slip fences. In addition, fillers for new polymeric light industry products, for example for soles, can be obtained from vulcanized rubber waste.

The production of plastic in the world doubles every 5 years, while the period of other materials doubling is 10, 15 and even 20 years. Hence, well developed countries report a catastrophic growth of solid waste which, despite all efforts, does not fall below 1% of production and is: in the US – 6 million tons, in Japan – 4 million tons, in Germany – 1.5 million tons, in England – 1 million tons, and in other countries – 0.5 million tons in a year.

In general, waste plastics are clearly divided into four types: waste of production, waste of recycling, industrial consumption waste, household consumption waste. The share of each type increases from year to year. The main problem is that the increasing the recycling degree, the utilization processes become more complex. At this point it would be right to analyze the quality of waste in terms of utilization possibilities; and it needs to be noted that plastic waste is the most difficult to utilize.

Therefore, two technological approaches are being developed. They are supposed to solve the problem of polymer waste by improving the production technology and processing of plastics to minimize waste; as well as improving the technology of polymer waste recycling [36].

Before being processed the polymer materials need to be grinded which is a complex operation. Polymeric materials are found to be viscous, viscos-elastic and plastic, soft, foam-shaped, fibrous or film materials which makes them difficult to grind [37].

According to the processing possibility, polymer materials are arranged in the following series: polystyrene (PS); polyethylene (PE); polyethylene terephthalate (PETF); polypropylene (PP); polyamide (PA); polyvinyl chloride (PVC); polyurethane (PU) [30].

In some cases, processing can be excluded; for example, individual (homogeneous) wastes of thermoplastic polymers are processed on a typical equipment to provide products of less responsible purpose. Collective waste is subjected to hydro-extrusion (extrusion through narrow openings), in which certain types of polymers are observed to self-regulate the viscosity characteristics.

Two-channel hydro-extrusion is also used, where wastes make up the polymer internal layers, and the thin outer layer is formed by the primary high-quality polymeric material. Much of the waste of polymeric plastics is recycled to provide polypropylene, using a mixture of carbonates with citric acid for foaming.

In general, it must be remembered that the mechanical characteristics of secondary products are generally worse than those of the primary ones, yet the economic effect of recycling is rather good due to its better environmental performance, cheapness of raw materials, simplicity of technology and energy savings. In addition, due to low price of secondary materials, they can be used for making building materials, sealed containers and containers for disposal of poisonous substances.

This monograph presents the investigation results of recycling process of polymer waste produced during manufacturing of light industry goods such as new footwear, textiles and clothes. Let us consider the major polymer materials used in light industry.

In shoe production, polymers are used for manufacturing of soles, heels, heelpieces, napkins and backs, aggregate knots, full-shaped shoes, shoe lasts and other products and accessories.

Recently open shoes, boots which can be of monolith or composed character, have become popular. Polymeric footwear is a volumetric product with a surface of complex geometric shape and a significant drop in thickness in the structural element connection points.

As previous studies have shown, the use of complex parts involves the need to provide products with increased performance characteristics, but these parts become the cause of shoe failures due to structural or technological errors committed at the production stage.

Shoe production is a well-developed branch of industry in Ukraine. Domestic enterprises offer practically all kinds of shoes of different purposes, different price categories, made from a wide range of materials. However, as in other light industry sectors, there are numerous problems that shoe manufacturing companies have to face. First of all, this is the need to import raw materials which involves considerable expenses.

1.2. Production volumes of consumer goods made from polymeric materials

The general trend in footwear manufacture in Ukraine over the past 10 years can be seen in Fig. 1.1 [38, 39].

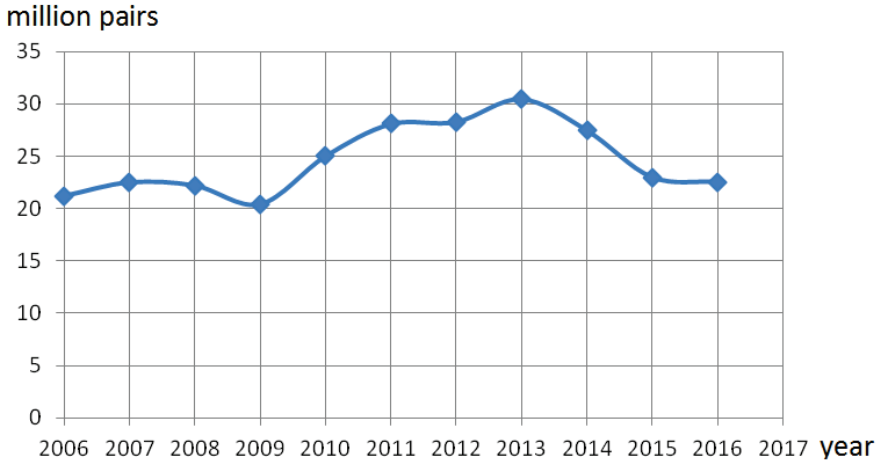


Fig. 1.1. Shoe manufacturing in Ukraine in 2006–2016 [38]

The shoe industry enterprises need to develop a new approach to the production and sale of their own products for successful competition with the footwear imported from abroad. In general, about 60–70 million pairs of shoes are sold annually in Ukraine [40].

Taking into account that the maximum annual amount of footwear manufactured in Ukraine during the last 20 years was about 30 million pairs, Ukrainian enterprises are likely to increase production capacity at least twice only to meet the needs of the domestic market.

Exporting shoes abroad offers even more opportunities. To do this, you have to offer a product that will meet the consumer needs in terms of quality, assortment and price.

The Fig. 1.2 gives information on production volumes of leather, textile and polymer footwear in Ukraine in 2011–2016 [41].

As can be seen in the diagram, this is the production of textile top footwear that has been prevailing in Ukraine so far. The production of leather footwear has decreased by half during the last 5 years. This was caused by a lack of raw materials, the manufacturing process complexity, large amount of production waste and, subsequently, the final product high price. However, production of polymeric footwear remains at approximately constant levels 5–6 million pairs per year.

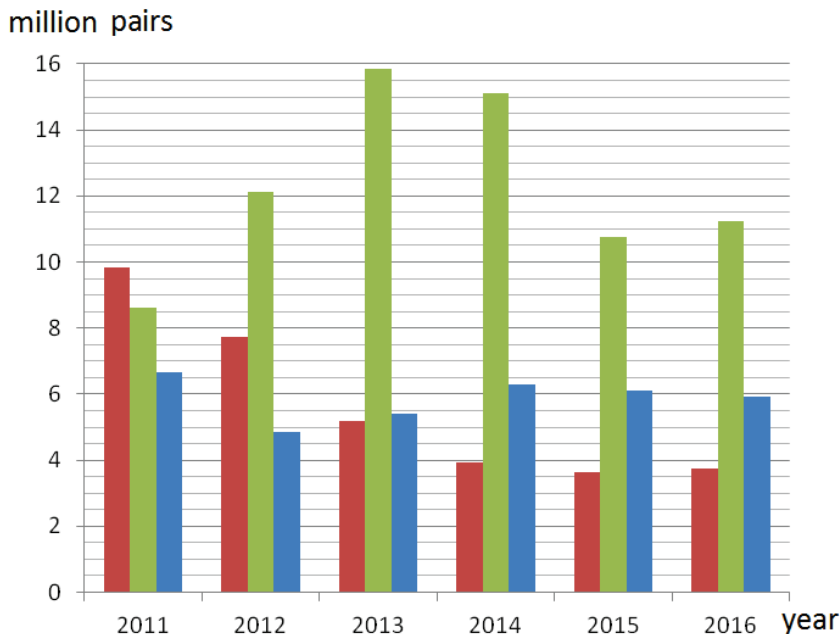


Fig. 1.2. Manufacture of footwear from different types of materials in Ukraine during 2011–2016: ■ shoes with a top of leather of natural; ■ footwear with a top of textile materials; ■ polymer footwear [41]

Although the raw material for polymeric footwear manufacturing is mostly imported, its cost is significantly lower than that of natural leather, which is practically not produced in Ukraine. In addition, polymeric materials have several advantages over leather: high technological and productive performance; homogeneity of properties; high performance characteristics, the possibility to be provided with specific, predefined properties, moisture resistance and resistance to aggressive environments, etc.

Thus, today, exact application of polymeric materials is a promising direction for extending the footwear production range in Ukraine. Depending on the material composition, footwear can be divided into three groups:

- **combined shoes** (Fig. 1.3), which include parts (mainly top) from various types of materials (textile, leather or artificial leather, etc.). At the same time, common sewing techniques are used for sewing the tops, and the bottoms are made by the technology of polymer processing;
- **polymer-textile shoes** (Fig. 1.4) containing a textile frame (substrate), in-soles, backs and other parts. The technology of producing such shoes is often original, characteristic not only of shoe production, but also processes commonly used in the elastomer and plastics processing industry;

- **polymer shoes** (Fig. 1.5), which excludes the use of any textile or other types of materials. In this case, different polymer materials or different colors of the same material can be combined in one product;
- **other footwear**, which may include parts from different types of materials, but differs by the presence of complex configuration polymer parts or contain inserts made of metal or non-metallic materials.



Fig. 1.3. Combined footwear with leather or textile top and polymer soles: a – men's; b – children's; c – women's; d – special (army bridges) [own study]



Fig. 1.4. Polymer and textile footwear: a – children's; b – women's; c – men's [own study]

The production of shoes of the first group is well-established in Ukraine. Such shoes are the main range of shoes produced in Ukraine, a large number of scientific studies is devoted to improving their quality.

Footwear of the second and third groups – polymer-textiles and solid polymer – has also been manufactured in Ukraine for decades, but its assortment needs to be extended, it is necessary to increase the operational and aesthetic indices of such shoes.



Fig. 1.5. Polymer shoes [own study]

The production of multi-layer polymeric shoe products or polymer parts with inserts is insufficiently studied today and requires detailed study in order to develop optimal structures of the equipment and to establish optimal technological parameters of the molding process. This will allow to predict the quality of production and reduce the costs of the product manufacturing and repair.

The assortment of polymeric footwear of domestic manufacturers is represented by footwear for protection of feet from moisture, sports and special footwear. Traditionally, these are boots, galoshes, as well as outdoor shoes for the pool, beach, etc.

In recent years, the range of fully-polymer shoes has considerably increased. Today, foreign manufacturers offer a wide selection of bright children's and junior, comfortable household and even exquisite shoes made entirely of polymeric materials [40].

A distinctive feature of modern polymeric shoes is a variety of styles, shapes and types. Modern models often combine elements of household, sports, and sometimes working shoes. Characteristic features are: brightness of the color, the volume of structural elements, asymmetry of the location of parts, finishes and fasteners. Sports and special-purpose polymer shoes are nowadays often used as casual, thanks to the convenience of design, flexibility, elasticity, high reliability and other benefits.

Working shoes include polymeric and protective shoes, for example, for doctors, builders, electricians, workers in the chemical and oil refining industry, athletes, pool and diving shoes deserve special attention.

Such shoes combine a number of properties that meet the requirements for special footwear: protection from moisture, industrial pollution, chemicals and

biological factors, protection against electric current and antistatic properties, easy cleaning.

Such shoes are comfortable to use – soft, elastic, do not rub legs, do not slip, easy to care and durable. Full-polymer shoes successfully combine hygienic, operational and aesthetic properties. They are lightweight, waterproof, durable and, if necessary, can reliably protect the holder from various adverse environmental conditions. It is possible to easily remove contamination from such shoes and even disinfect them, which is hardly possible with textile and leather footwear.

Crocs (USA) [42] is one of the leaders in the production of polymeric footwear on the world market. The company has developed and patented Croslite™ material, which provides the manufactured footwear with unique properties. The material composition is kept secret. Crocs shoes are comfortable, soft and elastic, the foot does not sweat and does not slip.

The company products are quite expensive, but the demand for them is increasing each year, the markets are expanding – since the company was founded in 2002, the brand has spread to 125 countries. Also, the assortment of products is growing – if the first products were of a rather rough look, today the company can offer not less comfortable but bright and stylish shoes of different collections, numbering more than 300 models to meet different demands (Fig. 1.6).



Fig. 1.6. Full-polymeric shoes Crocs: a – men's; b – women's; c – children's [42]

Another well-known company producing fully-polymeric shoes is the Brazilian firm Melissa [43]. The company produces exquisite model shoes completely made of polymeric material, the range of which is striking – sandals, shoes, ballet shoes, boots, etc. (Fig. 1.7).

Mel flex material, developed and patented by the company, is a particularly mild plastic, similar to rubber, but more ductile and sophisticated. It is based on all of Melissa's shoes, from shoes to boots. The products of Melissa have a characteristic feature – the shoes have a candy flavor.



Fig. 1.7. Polymeric shoes Melissa [43]

The Melissa shoes are an example of advanced technology – created from a unique soft plastic; for a long time they maintain high quality including appearance and durability.

Prominent representatives of the fashion industry cooperate with the brand. A German fashion designer, Carl Lagerfeld created several shoe collections for the company (models of one of them are shown in Fig. 1.8).



Fig. 1.8. Polymeric shoes Melissa, Carl Lagerfeld collections [43]

Crocs and Melissa's footwear is so popular that these names began to be treated as one regardless of the manufacturer. Thus, all polymeric shoes of a characteristic shape with a wide rounded toe and round apertures in its upper part today are commonly referred to as crocs, and elegant rubber women's and girls' slippers are called Melissa.

Among the new products that have recently appeared in the production of polymer-based shoes and footwear products, one can distinguish original designer galoshes (Fig. 1.9), which are not similar to the domestic industry products.



Fig. 1.9. Modern men's and women's galoshes [44, 47]

Such products are offered, for example, by Swims (Norway) [44], John Lobb (United Kingdom) [45], Tingley (USA) [46], Mir Galosh (Russian Federation) [47].

A wide range of various polymeric shoes is offered by Chinese manufacturers. Such shoes are mainly intended for rainy weather and beach activities (Fig 1.10).



Fig. 1.10. Polymeric shoes of Chinese manufacturers [own study]

Today's designers offer even more original models, for example, transparent shoes on extreme high heels, barefoot aquariums or shoes the sole of which consists of a sock and heel and does not contain the middle part (Fig. 1.11).



Fig. 1.11. Original designer shoes made of polymeric materials [48]

The invention of 3D printing technology enabled implementation of the most incredible ideas and the creation of unique shoes, which until recently were impossible to make (Fig. 1.12).



Fig. 1.12. Polymeric footwear created using 3D printing technology [48]

In Ukraine, all-purpose footwear is manufactured by a number of companies (RIF-1 in Kyiv, Vitaliya in the town of Vyshneve, Kyiv region, Rosem and ELPO enterprises in Chernivtsi, Litma in Khmelnytsky etc.), but they mainly specialize in the production of rubber boots, galoshes and flip-flops and do not have a large assortment of models.

Introduction of advanced technologies for production of full-polymeric footwear will help expand its range and increase competitiveness of the manufactured products.

Polymeric shoe soles which contain different types of inserts – polymer or metal take an important place on the shoe market. Such shoes can be either completely polymeric or combined, but their manufacture technology is complicated due to the presence of additional elements or the design complexity. This group includes sports shoes, for example, for playing football, for running, as well as studded shoes, designed for use on slippery surfaces (Fig. 1.13).

Single-layer molding is used to manufacture soles and polymeric shoes, relatively simple in design: low shoes, sandals, children's shoes.

In this case, the production unit includes a single molding machine where the polymeric material is fed to the mold through one channel.



Fig. 1.13. Shoes with soles with inserts: a – football boots with spikes; b – runners for running; c – shoes for use on slippery ground [own study]

Multilayer casting allows to provide more sophisticated products, for example, soles that contain colored elements, or parts that combine materials with different properties. In this case, two variants may arise – when the boundary of the product division of parts runs along its width (Fig. 1.14a) or its height (Fig. 1.14b).



Fig. 1.14. Connection of layers of material in combined footwear products: a – horizontally; b – vertically [own study]

In recent years, advanced manufacturing companies started to produce shoes, primarily sportswear, with soles of complex geometric shapes – in the form of tubes, rods, springs, etc. Details of the complex form can be decorative in nature, but more often such a sole is intended to absorb shocks and optimally distribute loads that occur during the footwear operation.

There is also a demand for sports shoes on the so-called airbag, that is, footwear that uses air to mitigate the impact during running. Such a system was developed by Nike in 1979 and was named Nike-Air; the inside of the sole is insulated and made up of elastic urethane chambers, filled with compressed air to absorb the energy of external impacts during running and jumping. Since then, the company has developed a series of models and configurations of Air Max airbags offering shoes with different degrees of shock absorption for each sport.

Today, almost all famous sports shoes manufacturers, such as Adidas, Reebok, Skechers, Diadora and others, produce airbags.

In Fig. 1.15 shoes with polymeric details of complex geometric shape are presented. The problems that designers and technologists need to address when producing these types of footwear were analyzed.



Fig. 1.15. Footwear with polymeric details of complex geometric shape: a – sneakers with soles of complex shape; b – sneakers on an air cushion; c – gloves for feet for parkour [own study]

In the manufacture of the studied shoes, it is necessary to provide a reliable connection of metal or plastic pins with the material of the sole. It is necessary to secure the pins from falling out or pushing against the foot.

The elements of soles that have complex shapes such as teeth, tubes, springs, etc., as well as their joints with each other and with the main sole need to be provided with adequate strength. Air cushion soles in turn need to be provided with air tightness and reliable connections of all elements.

A shoe whose soles are attached not only to the upper part, but also partially overlaps it, must be provided with reliable connection of the polymer with the product textile (or leather) part.

When manufacturing a multilayer sole it is important to ensure a reliable connection of its layers with each other, as well as in all other types of shoes, high strength of the sole attachment to the top of the work piece.

The main problems involved in the operation of shoes with polymeric soles of any configuration are their wear zones, which are subjected to the most intense loads due to the foot anatomy and the nature of the man's movements, constant compression-stretching as a result of the foot bending during running.

Fully shaped shoes are prone to destruction in thin places and in places with the highest stress concentration which usually is the point of connection of the shoe bottom with the top.

1.3. Defects of light industry polymeric parts

In order to meet the demand for shoes it is not necessary to increase the production volume but rather to improve the quality of shoes and extend its range to meet various consumer demands.

According to researches [49], the most important consumer preferences are reliability (for 93.5% of surveyed consumers) and convenience (for 94.5% of respondents). The consumers pay much attention to the footwear design (74.2%). The cost of footwear is important for 79.4% of respondents, while the brand is important for only 25.6% of consumers.

Thus, it can be concluded that providing footwear products with the characteristics indicated by the consumers in combination with affordable prices will allow Ukrainian enterprises to successfully compete with foreign producers. For this purpose, it is necessary to use the latest technologies, equipment, and to develop the most rational methods of footwear design.

The properties of shoes involve complex and contradictory requirements. Shoes should protect the foot from moisture, from the effects of high and low temperatures, but at the same time, they should not complicate removal of excess moisture and heat, produced by the foot. The materials to be used should, on the one hand, provide comfortable conditions for the foot, be soft and elastic, but, on the other hand, should have high indicators of strength and wear resistance. In this case, the shoes must satisfy the aesthetic requirements of the user.

To date, a number of normative documents have been developed in Ukraine that regulate the requirements for the footwear quality. First of all,

these are standards that determine the quality of shoes, test methods, modes and parameters of technological processes and equipment, marking, packaging, transport and storage of shoes, conditions for the shoe core in the process of its operation.

It is known that during the operation different parts of the shoes are exposed to different loads. Even the same part can take different loads depending on the anatomy of the foot and features of the walk.

To design high-quality shoes with high performance, it is necessary to determine what work each piece performs and what kind of load it is subjected to. This will allow to determine rational geometric parameters that will provide the required strength and stiffness during the shoe operation.

During operation the shoe bottom is usually exposed to higher loads than the top elements. In addition to the loads caused by the human foot exert significant pressure on the shoe sole increasing its contact with soil, atmospheric and other conditions.

The sole of the shoe during the operation constantly bends and is subjected to intense wear. Depending on the material, thickness of the part and the step phase, a sole bends with the radius of curvature 4–8 cm, extending to 16–25%.

In the case of stresses exceeding the material boundary strength, the part is destroyed (Fig. 1.16).



Fig. 1.16. The destruction of the cantilevered shoe parts at their bend [own study]

In the case of a faulty design or poor quality material the sole may crack in result of such bending leading to its complete fracture or gradual material loss (Fig. 1.17).



Fig. 1.17. Destruction of double-shoe polymer parts of shoes when bending [own study]

2

POLYMERIC MATERIALS IN WASTE OF LIGHT INDUSTRY

2.1. Basic polymeric materials used in the production of light industry goods

Light industry products are consumer goods. Depending on the purpose of the products they have to meet different requirements. As regards woman's bags the main requirements to be met is the aesthetic factor, appearance, and social status of the customer. Business bags need to have a simple form, reliable of fastening of handles, smooth material, etc. Sports bags must, in the first place, comply with the requirements of ergonomics, be easy to use and the design must be consistent with the sports style [50].

The product properties reveal in the process of its consumption and affect the consumer choice. For example, consumer properties of a suitcase are determined by the design and materials (properties and technology of their processing). The consumer properties of all light industry products include such properties as ergonomics, aesthetics and endurance.

Most of the light industry products contain polymer materials in the product and its accessories, sewing threads and various finishing elements.

Polymeric material, most widely used to manufacture various types of light industry products (clothing, footwear, bags, suitcase, gloves, etc.) is artificial leather of various colors and surface texture, as well as synthetic materials. Artificial leather has certain advantages over the natural one: it can provide the product with lower mass; cheapen the production process; diversify the product appearance and provide enhanced functional characteristics.

Physical and mechanical properties of artificial leather such as durability and flexibility are largely dependent on the base material. The fibrous basis for artificial leather is fabrics, knitwear, paper, as well as various non-woven materials that are used depending on the product purpose. Textile materials which provide the basis of artificial leather include: polyamide, polyesters, glass and others.

The coating of artificial leather is formed by impregnating the fibrous base (through coating) or by applying a polymer to the surface of the substrate (surface coating). A combination of these methods can also be used. The main component of artificial leather is a film-forming polymer composition. Synthetic macromolecular compounds are used in modern production as film-forming

agents: polyvinyl chloride, polyurethanes, synthetic latexes, rubber mixtures based on various rubbers, etc. [51] are used.

Artificial leather with a porous polyvinylchloride (PVC) coating made of a knitted, woven or non-woven base with a 0.5–0.7 mm thick layer of porous polyvinyl chloride deposited on it or non-porous 0.10–0.15 mm. thick layer. The non-porous polyvinyl chloride coating has increased sticky and unpleasant shine, which is associated with the appearance of a thin layer of plasticizer on the surface of the film. To eliminate this disadvantage, artificial leather is covered with a thin layer of finishing lacquer based mixtures of polyvinyl chloride and acrylic resins dissolved in organic solvents, which makes the polymeric coating non-stick, and the texture is similar to natural leather. Today, polyurethane is used to make the film in the production of artificial leather.

In the production processes of soft suitcases on wheels, usually the main material is polyester or nylon. Also, polyurethane foam (reliable and elastic material) is used in the manufacture of suitcases in thermoforms for the purpose of obtaining fully formed rear and side walls.

In the production of rigid suitcases, a wide range of other polymeric materials are available to provide protection against deformation. Rigid plastic suitcases are made of polycarbonate, polypropylene and ABS plastic.

The functionality of light industry products and their suitability are largely determined by the quality of the fittings used. Polyurethane, polyethylene, polyamides, polyester, polystyrene, polypropylene and other plastics are used to manufacture of fittings.

Today, the materials used for shoe production are natural leather and polymer materials: natural, artificial and synthetic leather – for details of the shoe top; rubber, polyurethanes (PU), polyvinyl chloride (PVC), thermo elastic plastics (TEP), ethylene vinyl acetate (EVA) – for molded details of footwear; cardboard, thermoplastic materials – for frame parts [52].

Although the polymers are inferior to natural materials in terms of hydro capacity, moisture content and some other properties, they also have a number of significant advantages: low cost, high technology, isotropy of properties, resistance to abrasion and moisture, microorganisms and aggressive media.

The use of polymeric materials in production of footwear allows to develop new, more advanced methods of manufacturing by replacing traditional mechanical methods with cheaper chemical ones.

Thus, the use of synthetic polymeric materials allows not only to increase the efficiency of production, but also significantly improve the quality of shoes with specific desirable properties.

Polymer materials used in shoe manufacturing can be classified into the following main groups:

- rubber of various compositions,
- compositions based on plasticized polyvinyl chloride (PVC),
- thermoelastic plastic compositions (TEP),
- polyurethane (PU) liquid forming compositions,

- thermoplastic polyurethane (TPU) compositions,
- compositions based on polymers of ethylene and vinyl acetate (EVA).

Table 2.1 provides information on the use of polymeric materials in the manufacture of various types of shoes in accordance with the domestic standards and European norms.

Table 2.1. The use of polymeric materials in the manufacture of various types of shoes

Type of shoes	Material of the sole						
	Leather	Rubber	PU	TPU	PVC	TEP	EVA
Everyday	+	+	+	+	+	+	+
Model	+	+	+			+	
Athletic		+	+		+		+
Tourist		+	+	+	+		+
Protective		+	+	+	not allowed		

Polymers of each group have their own specific properties, which vary considerably from material to material. In addition, within each group there are materials of different structure and with different physical and mechanical characteristics.

Advanced companies of the footwear industry are constantly developing new materials with unique characteristics to be used in their products. The recipe for such materials is often a commercial secret of the company and is not disclosed.

However, the basis of these polymer compositions is provided by the listed materials. The main properties and scope of application of polymeric materials in shoe production were considered.

2.2. Rubber mixtures

Shoe rubber is a complex combination of polymeric base (rubber, mainly synthetic: butadiene styrene SCS-10, SKS-30, SKS-50, SCS-85, butadiene SKB and isoprene SKI-3) and various additives.

Shoe rubber – elastic material, formed as a result of vulcanization of rubber. There are porous and non-porous rubbers. The lightweight, durable and waterproof material can be painted in any color. Today about 30% of shoes have rubber soles. Also heels and heelpieces are made of rubber.

Rubber mixtures are obtained from rubber with addition of other ingredients (fillers, vulcanizes, dyes, etc.). Formulation of rubber mixtures depends on the production method and the requirements for the shoe details.

Rubbers are macromolecular compounds whose molecules consist of the same or different monomer units connected to one another in a polymer chain. By origin, rubbers are divided into natural and synthetic rubbers.

Natural rubber is obtained from milk juice (latex) of cucumber trees. Synthetic rubbers are obtained from low molecular weight organic compounds (monomers) by polymerization (main method) or poly condensation.

According to the structure, shoe rubbers are: porous, monolithic and skin-like. For the manufacture of sole rubber, various types of butadiene-styrene or butadiene-methyl styrene rubbers (SCS-30, SCMS-30, SKMS-30RP, etc.) are used. In the manufacture of hard rubber, high-tensile rubbers (BS-45AKM) are used, as well as high-tensile resins, polystyrene, polyethylene.

The rubber details of the footwear bottom are cut from vulcanized plates to be later machined or formed with simultaneous vulcanization in molds. Molding of rubber mixtures under pressure can be carried out for individual parts, and direct molding for the footwear top.

Rubber, especially porous, has a high slip resistance for both dry soil and ice. The slip stability increases when the sole running surface is provided with deep corrugations with sharpened outer edges and protrusions. Resistance to slipping of skin-like rubber is unsatisfactory, and it is possible to provide these materials with deep corrugations because of their small thickness.

Mechanical properties and abrasion resistance of rubber are at a satisfactory level. There are also brands of wear-resistant rubber, whose durability is significantly higher.

The disadvantages of rubber include multicomponent composition of rubber mixtures, energy consumption involved in their processing due to high viscosity and the need for vulcanization while the product formation. Accordingly, rubber is most commonly used in special types of shoes, which are operated under high or low temperatures and under the influence of various aggressive environments. Rubber is also used for production of soles for some types of sports, tourist and casual shoes.

2.3. Materials based on polyvinyl chloride

PVC-plastic is a composition of polyvinyl chloride resin PVC C-63-M, PVC C-64-M, PVC C-65, PVC C-70-M with plasticizers, stabilizers and pigments. Soles made of PVC are made by injection molding. According to the structure of the material, they can be monolithic and porous-monolithic (micro porous) and are used mainly for walking shoes and sports-style shoes.

Polyvinyl chloride is obtained by polymerization of vinyl chloride in temperatures from 20 to 100°C with peroxide initiators. Plasticizers are added to the polymer to improve elastic plastic properties, stabilizers to increase resistance to external influences, converters, dyes and other ingredients that change the properties of the polymer.

The introduction of plasticizers in PVC allows to radically change its properties. This increases the material softness and flexibility.

PVC has a number of shortcomings – low thermal stability and light resistance, insufficient frost and friction properties, poor mechanical characteristics as compared to other materials. Monolithic PVC products are of great importance.

However, this material is one of the cheapest for the production of footwear, its melt is highly liquid and easily processed. Therefore, plastic PVC is widely used in the manufacture of children's, summer and home shoes, that is, when there are no special requirements for strength, wear resistance or reliability.

Some types of PVC-plastics can have a satisfactory resistance to the effect of aggressive substances, so they can be used in the manufacture of special footwear, but such shoes should not be used in low temperatures and on frozen soil.

In order to modify the properties of plastics, they are provided with various polymeric fillers including polymers that are not compatible with PVC. The heterogeneous systems obtained at the same time have better mechanical properties, which exceed the values of corresponding indices of the mixture individual components. Neoprene, butyl rubber, EVA, ABS plastics, thermoplastic polyurethane and other polymers can be used as such fillers. In recent years PVC-based compositions have been developed to be modified with butadiene-nitrile rubber and EVA copolymers.

Modified plastic materials are characterized by increased indexes of frost resistance, elasticity, increased resistance to erosion and slip. However, such materials are still inferior to the characteristics of other shoe materials. PVC can be used both for the manufacture of individual products, as well as for direct molding of the sole and for preparation of the shoe tops.

2.4. Thermo elastic plastic materials

A special place among footwear materials is occupied by thermo elastic plastics (TEP), which combine the elastic properties of rubber and the plastic properties of thermoplastics and are widely used in the footwear industry.

Thermo elastic plastics – are modern polymeric materials, which have high operational properties and high technological capacity. TEPs are gradually replacing rubber in many types of casual shoes, due to the number of their unique properties – a combination of elasticity, wear resistance and frost resistance. In addition, these materials are suitable for recycling, which significantly reduces the amount of waste, as well as the negative impact on the environment by using worn bottom footwear as a secondary raw material.

Such a combination of properties is determined by the structure of polymers. TEPs are block copolymers of A-B-A or A-B-C-B-A structure, where A is a rigid thermoplastic block (often polystyrene, also polypropylene, poly methyl methacrylate, polyvinyl chloride, etc.), B – flexible elastic block (poly isoprene, poly butadiene, poly isobutylene, etc.), C is a polymerization agent.

According to this scheme, the specific structure of TEP is formed due to location of polystyrene blocks on the ends of the macromolecules of the block copolymer. When forming such a structure, polystyrene blocks, due to their chemical affinity, aggregate in macromolecular formations (domains), which play the role of nodes of a three-dimensional structure (Fig. 2.1).

In normal temperatures, the TEP strength is provided by physical (van der Waals) bonds of thermoplastic blocks in the domains, and elasticity is provided by flexibility of the elastic blocks. Therefore, these polymeric materials are capable of significant reverse deformations.



Fig. 2.1. Schematic structure of butadiene styrene thermo elastic plastic: 1 – polystyrene blocks; 2 – butadiene blocks; 3 – polystyrene domains [own study]

In high temperatures, the physical bonds of thermoplastic blocks in domains are reversibly destroyed, releasing macromolecules of the block copolymer, which acquires the ability to flow. In this case, the chemical bond between the thermoplastic and elastic blocks is preserved. The turnaround of the destruction of domains means that they can be restored in lower temperatures, which results in the material retaining its original properties.

Di vinyl styrene thermo elastic plastics DST-30, DST-50 and DST-75 are most widely used in shoe manufacturing. They are used for the production of porous molded soles.

When marking the type of TEP which characterizes homo polymers of its blocks, the content of bound thermoplastics is usually indicated (for example DST-30 – di vinyl styrene TEP with the content of bound styrene 30%). Optimal properties provided by 1 three block polymers with styrene content of 20–30%.

In order to improve the properties and increase the productivity, as well as to reduce the cost, softeners, fillers, powder formers, stabilizers, dyes, etc. are introduced into the TEP.

The TEPs are characterized by high frost resistance, their modulus of elasticity does not change over a wide range of temperatures, the strength and resistance to erosion is much higher than that of other thermoplastics and some

rubber. The TPP soles have a high coefficient of friction on the asphalt and on slippery ground, it is possible to perform deep corrugations on the running surface of the sole. TEP can be painted in any color, have a different surface texture.

A significant drawback of the TEP is a relatively low heat resistance. In temperature of 50–70°C, due to the material fluidity, the strength of products with the TEP can be reduced, if the load is applied. Another disadvantage of TEP is its unsatisfactory oil and gasoline resistance and acid-resistant stability, lack of oxygen and ozone resistance, especially for thermo mechanical loads. TEP melts, especially of high molecular weight, has a high viscosity, which makes it difficult to process them.

Due to its characteristics, TEP is widely used in the manufacture of the bottom of everyday winter shoes. Considering simplicity of the TEP product formation and numerous possibilities of decorative design of the bottom details, these materials are successfully used in the production of spring-autumn and summer shoes. Soles of TEP can also be used in some types of sports shoes and active recreation shoes.

2.5. Polyurethanes

In shoe manufacturing, the most promising material is polyurethane, providing soles with high performance of its physical and mechanical properties, in compliance with both the operational and technological requirements for light industry products. Although the TEP is widely used on the domestic market its performance characteristics are slightly inferior to PU. Polyurethanes are used to obtain wear-resistant soles, whereas, synthetic leather for the footwear top and shoes.

Polyurethanes are a wide class of polymers containing the urethane group -NHCOO-. The main source products for polyurethane are poly- and di isocyanines and high-molecular substances with hydroxyl and ether groups. When PU is obtained, the hydroxyl-containing components react with isocyanines.

Compositions based on complex polyesters are processed at a temperature of 40–60°C, on simple polyesters – at a temperature of 20–22°C.

Soles from PU are produced by two methods: liquid forming and injection molding. A more common method is the liquid forming. The soles obtained by this method have a microstructure that provides ease, excellent heat-shielding properties and material savings.

The ability of PU liquid composition to be evenly distributed over the area with slight strain forces allows to use molds and their closing devices of simple design. Due to this, the manufacture of molds is cheaper and takes less time, which is important in view of the assortment dynamic variability. Energy consumption during heating of molds while shoe bottom liquid forming with PU is much lower than when hot vulcanization of rubber is performed.

Physics – mechanical and chemical properties of PU are determined by the type of components, their content ratio in the composition, as well as the type of functional modifiers used. The mechanical properties of polyurethane systems based on complex olio esters, especially wear resistance, are significantly higher than those based on simple olio esters. However, the latter have a higher frost resistance and are more resistant to the action of hydrolyzing agents.

Physical and mechanical properties and frost resistance of polyurethane systems and their chemical stability can be increased by introducing various functional additives. In this way materials with different properties are obtained depending the product application.

For production of the footwear bottom details, the following polyurethane systems are used:

- standard,
- increased elasticity,
- high wear resistance,
- high frost resistance,
- for molding the inner layer of two-layer soles,
- for forming the external (running) layer of soles.

A significant advantage of PU products is the material low density with sufficiently high mechanical properties, which makes it possible to provide massive soles with high thickness. Accordingly, the products with such a micro porous structure have high shock absorption, thermal insulation and heat-shielding properties. PU are characterized by high resistance to petroleum products, oils, fats, alkalis, many types of solvents, surpassing even special types of rubber.

Due to its high adhesion properties, PU is the most effective material for direct molding of the bottom on the footwear top, and can also be used for the manufacture of multilayer products.

The disadvantages of PU products include possibly unsatisfactory slip resistance on ice and cold soils, insufficient acid resistance and the need for strict measures to be taken when transporting and storing the source components of polyurethane systems that are toxic substances.

With the use of PU shoes for walking, many kinds of casual shoes of sports type are made. PU is widely used in the manufacture of special types of shoes, since these materials, in addition to high wear resistance and shock absorbing properties, are resistant to the effects of harmful environments. However, special types of footwear with molded polyurethane bottoms are not intended for use under acidic conditions or low temperatures.

Thermoplastic polyurethane and foamed thermoplastic polyurethane are relatively new materials. Thermoplastic polyurethanes or urethane thermoplastics are block type polymers (A-B). Blocks A are formed by molecules of simple or complex olio esters and characterized by weak intermolecular interaction and high elasticity. Urethane blocks B, on the contrary, have strong intermolec-

ular interaction and stiffness. Rigid blocks are aggregated into domains, which are distributed in the matrix of elastic blocks. Adjustment of the ratio of hard and elastic blocks allows to obtain TPU with different hardness and elasticity.

Compositions of TPU are characterized by the best mechanical properties and wear resistance among modern footwear materials. They can be used in temperatures from $-40 \dots -45^{\circ}\text{C}$ to $+70 \dots +110^{\circ}\text{C}$, they are highly resistant to aggressive environments and have a high coefficient of friction with soil. However, the popularity of these materials is restrained by their high cost (2–3 times more expensive than PVC plastics and compositions based on TEP) and more complex processing than thermoplastic materials.

Materials based on TPU are used for the production of ski boots and soles for special and casual shoes. The most advisable is to use these materials for formation of running layers for combined soles. Rigid materials based on TPUs are the best material for heelpieces, especially for heels with a small supporting surface.

2.6. Materials based on ethylene vinyl acetate

The polymeric material of ethylene vinyl acetate (EVA), a copolymer of ethylene and vinyl acetate, found a fairly wide application in the manufacture of soles for home, beach and sports shoes.

Ethylene vinyl acetate refers to polyolefin and is a copolymer of ethylene and vinyl acetate monomer. Acetate oxy groups are arbitrarily distributed in the ethylene group. The mass fraction of vinyl acetate determines the mechanical properties of the material, as well as its type – thermoplastic or elastomer:

- low vinyl acetate content (up to 4%) – polyethylene modified with vinyl acetate – thermoplastic material, recycled as ordinary low density polyethylene, different from polyethylene with increased luster, softness and flexibility,
- average content of vinyl acetate (4–40%) – copolymer of ethylene and vinyl acetate, not vulcanized, but has some properties of rubber,
- high content of vinyl acetate (more than 40%) – ethylene vinyl acetate rubber, processed as a thermoset.

In polymeric compositions for the production of footwear and its parts, it is optimal to use EVA with vinyl acetate content of 20–30%.

EVA – ultra-light, very elastic material has high flexibility, elasticity and excellent shock-absorbing properties. Thanks to the foam-shaped composition, the shoes on the EVA-sole elastic, easily restores its shape during deformation, retains heat, but with time such a sole loses damping characteristics.

EVA provides the soles with oil-resistant properties, but does not have a high friction coefficient on a slippery surface, frost resistance or protection against punctures and cuts.

This material is widely used for the production of fully polymeric shoes (beach shoes, shoes for agricultural works and boots). EVA does not cause allergies, which allows it to be used in all types of orthopedics. Often used as material for intermediate soles – its properties allow you to achieve the required ease, softness and elasticity of the sole, and securely fasten it to the top of the footwear.

The materials described above are traditional in shoe manufacturing. Some of them have been used for decades, others, such as TEP and EVA, have appeared relatively recently. The formulas of polymeric compositions to be made on their basis are constantly being improved, as well as the technology of their processing, however, each of these materials is important for the shoe production and has its own field of application.

There are also polymeric materials that are used in much smaller amounts in the manufacture of footwear and its parts, but they are also important for the footwear industry. Such materials include, for example, acrylonitrile butadiene styrene (ABS), polyethylene, polypropylene, polystyrene, polyamide, from which heels, shoe pads, as well as details of light industry – fittings, pens, cases, covers etc. are made.

With the advent of 3D printing technology, the range of shoe materials has expanded. Materials such as ABC plastics, nylon, polyethylene, poly lactates, and others are used to manufacture footwear in this way.

It is worth noting that thermoplastic polymeric materials have advantages over thermosetting not only due to more convenient processing and energy saving, but also due to greater environmental friendliness. Waste from production and post-use products can be reused after appropriate treatment. This is very important for the environment, since the polymer waste is less prone to self-degradation, and therefore considered most environmentally hazardous.

3

TECHNOLOGIES AND EQUIPMENT FOR RECEIVING POLYMERIC RECYCLATE

As a result of the analysis of the factors that affect the quality of light industry products obtained from recycled polymer waste, it has been established that the physical characteristics of these products are significantly impacted by the physical and mechanical properties of the recycled polymer waste and they largely depend on the processing equipment design parameters and its operation modes.

The basic methods of leather and polymer processing are significantly different, as the polymer and leather reaction to the mechanical and thermal field created by the processing equipment is quite different. However, some approaches to equipment design are similar and can be used to develop scientific bases for designing equipment for the polymer waste processing.

Therefore, the main goals of the study are as follows:

1. Development of a method for processing equipment design to provide the polymer waste with oriented structures so that it can be used in reinforcing elements for light industry production of details of footwear, suitcases, various accessories and others.
2. Determination of rational structural parameters of the equipment and efficient technological characteristics of the polymer waste destruction process to provide particles with oriented structure at minimum energy consumption.
3. Development of a design of a mold and a supply device for the recycled waste particles to obtain their mixture with the polymer melt and to be applied in production of shoe bottoms.

In order to achieve the study goals, an analysis of the structure of devices used for waste processing in light industry enterprises and other industries has been carried out.

Today, there is not much special equipment for polymer waste processing, and the available equipment does not always meet modern requirements. In fact, such equipment is not produced in series, but is experimental, created in the design departments of large footwear, textile and clothing enterprises and in research institutes. The equipment used for mechanical processing of polymeric materials is often borrowed from other industries.

Technological equipment that can be used for waste processing produced in light industry enterprises is divided according to the type of destructive working element, that is, loose and fixed fracture bodies. This is due to the fact that it is the working element that is the main element of the processing device structure,

which depends on the type of material, energy efficiency, processing efficiency and the final result – the shape, size and physical and mechanical properties of the recycled material.

The equipment with fixed working elements is the most effective for polymer waste processing. This is due to the fact that the energy goes directly to the working element which during rotation, destroys the material by interacting with it. The efficiency of such equipment is characterized by the drive power, the shape and the size of working elements. Thus, when designing equipment with fixed working elements, physical and mechanical properties of the polymer material, geometry of the working elements and dynamics of their interaction with the material should be taken into account. Such equipment can include: crushers, rollers, conical and disk mills, screw and roller devices.

3.1. Technologies and equipment for shredding polymer waste

Benefits of cutting have extended the scope of cutting devices. Depending on the loading conditions, cutting with a counter-knife (centered) and without a counter-knife (unbounded) is used.

Unbreakable cutting is used for disintegration of large-sized materials. The device can be made in the form of a rotating multi-blade knife or a fixed one with the material rotating.

Concentrated cutting is used in rotary knife cutters (Fig. 3.1), in which the knives are located both in the rotor, and in the stator.

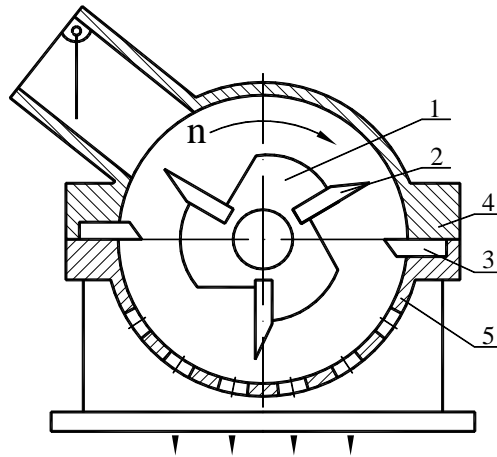


Fig. 3.1. Rotary knife shredder: 1 – rotor; 2 – rotor knives; 3 – case; 4 – grid; 5 – stator knives [own study]

Such a device consists of rotor 1, a knife of rotor – 2, case – 3, grid – 4, stator knife – 5. The process of the material grinding begins with its being loaded

into a hopper, from which it falls on rotor 1 and on its knives. 2. The material is grinded upon contact with the knives of rotor 2 and fixed knives 5. After this, the material is shifted through grid 4 and gets into the bin for the finished product (not shown).

The knife of a rotary grinder is used for grinding elastic materials, plastic-viscous materials, polyvinylchloride materials, fibrous materials, frozen materials.

This type of grinder can find application in the chemical industry, pulp and paper, food, building and light industry.

After processing of fibrous materials, the waste can be used to create new types of short-term and single use, various hydro, sound and heat-insulating materials, geotextile materials for residential and road construction, gaskets, industrial wool, etc.

As mentioned above, cutting is one of the most common methods of grinding. In mechanical shredding of waste most of the energy is dissipated on elastic deformation. Thus, from the point of view of energy saving, grinding should be carried out under conditions that will minimize the material deformation. So while the destruction of light industry waste, the material cutting part is near the cutting edge of the knife.

This reduces fracture during cutting.

The process of shredding in shredders of this type is in most cases quite simple. This is due to the fact that during operation the equipment does not require any additional adjustment or regulation. Adjustment is needed only if changing the type of the crushed material. In some shredders there are rolls for pre-compressing the material to improve the quality of grinding. The grid that is installed at the bottom of the chamber controls passage of the particles of given dispersion. Uncrushed particles are recaptured with knives and shredded again. There is no need to divide various materials into groups. The dispersity that can be achieved with this shredding method is from 0.5 mm to 10 mm.

The equipment is quite easy to maintain. When the equipment is in operation, the wear of knives occurs; their replacement is not a problem. It is advisable to set knives at an angle to the shredder rotational axis to improve the cutting process (kinematic angle). The angle of the knives leads to appearance of a kinematic cutting angle, which in turn reduces the cutting power.

The process of grinding in such devices involves destruction of a concentrated material. With such crushing, the energy costs are minimal, since the deformation zone is minimal and, accordingly, there is no energy loss for deformation of useless layers.

Such choppers have simple and reliable designs. They are also easy to maintain, which is a very significant factor to be taken into consideration while purchasing equipment. It is possible to control the crushed material dispersion by application screening grid with holes of different diameters and increase the speed of the rotor rotation.

However, this type of equipment has also a disadvantage: during operation the working bodies get worn under the influence of friction and impact. Each knife is equipped with one cutting edge and requires an separate installation which has a negative effect on their durability. Another disadvantage is that the design of this type of shredder does not allow to actively influence the degree of the material shredding; when crushing a plastic-viscous material it sticks to the working bodies in result of elevated temperatures so due to its laceration the grinding process efficiency is significantly reduced. The rotary knife cutter (rotary crusher) does not allow to process polymeric waste into oriented structure particles, therefore they cannot be used as fillers in the production of light industry polymers.

This type of equipment is quite widespread. Thanks to small energy costs associated with the grinding process itself, the equipment is viable. Such equipment is already used in the above-mentioned industries. The test results are quite good. Shredders of this type have proven to be useful in the processing of light industry waste.

Roller machines equipped with a set of discs with cutting edges of various configurations are widely used for pre-shredding (Fig. 3.2).

Additionally, cutting elements can be installed on the disc surface which allow to improve the material shredding efficiency due to additionally placed cutting elements, which allow to obtain even dispersion of the material, excluding the process of re-grinding.

Since the depth of the disk knife infeed is equal to half its total height, pieces of material are of the same size.

The design of the disk chopper includes racks 1, disks – 2, a cover with a hopper for loading – 3, gear transmission – 4 and bed – 5. The disks are mounted on the shafts, which, in turn, are fixed in the bearing supports. The sharpening angle of one disk cutting edges is the opposite of the sharpening angle of the other disk cutting edges.

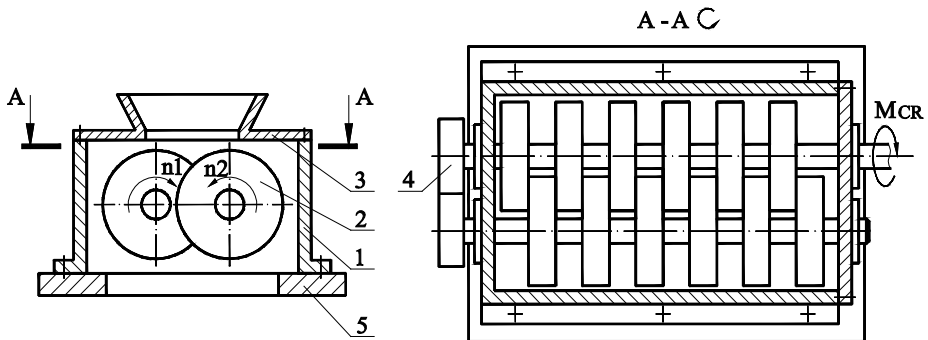


Fig. 3.2. Disk chopper: 1 – racks; 2 – discs; 3 – cover with hopper for loading; 4 – gear transmission; 5 – a bed [23]

Grinding of material is carried out by cutting elements that capture the material and destroy it by counter movements. The material enters the grinding zone through a loading hopper after turning on the device, that is, when the rolls start rotating.

The knife disk chopper is used to disintegrate polymers, wood, etc. The fineness degree that can be achieved with this kind of grinding is from 2 mm to 30 mm. It depends on the size and configuration of the cutting elements.

Disk knife grinders, as well as most of this type of equipment, are quite easy to maintain. The only difficulty is that before activation it is necessary to install the cutting elements on the discs in such a way that forming cutting elements correspond to the crushed material. This is done in order to provide better grinding quality and increase productivity.

The advantages of this group of shredders are as follows: the equipment is easy to use and maintain; use of the equipment enables processing of a wide range of industrial waste. This kind of equipment performs concentrated cutting, which is the most economical in terms of energy consumption; use of additional disks placed on the surface of the cutting elements allows to obtain the sour material of uniform fineness degree.

Apart from the advantages, disk choppers have the following drawbacks: while being used the equipment elements undergo significant wear, which results impairs the product quality, the process productivity and increases energy costs; When processing plastic-viscous materials by using high temperature, the polymer begins to flow and stick to the working element which significantly reduces the process efficiency. Devices of this group do not allow to provide the recycled material with oriented structure.

Rollers with a set of discs with differently designed cutting edges are widely used. They are used for grinding polymeric materials, rubber-woven waste, polyethylene films and textile waste. They have found application in chemical, rubber, tire and in the textile industry.

Shredded waste is used as a filler in various polymer compositions, for the production of rubber items, in the manufacture of thermoplastics. Waste textile industry is used to create new types of products, such as technical wool, various linings.

Disk rollers for waste recycling by its processing can be divided into two groups: disk cutting and disk tearing devices. It should be noted that the latter devices, due to the polymer structure, are unsuitable for the polymer waste processing, since the crushed pieces would vary in size and form, which is not acceptable, and energy costs will be significant.

Recycling devices with cutting discs have been used in the chemical and rubber industry. Shredded waste is used as an additive to mixtures in production of rubber items, as fillers in various polymer compositions. The design of this device is shown in Fig. 3.3. During operation, the discs cut off small pieces, gradually grinding all the material (for example, a car tire).

In devices with a set of different cutting discs it is necessary to pre-separate the various materials into groups (for example, to separate the rubber from the metal) before milling.

Disc cutting devices for waste processing can be used for grinding of polymeric materials, rubber wastes, polyethylene films, paper and household waste.

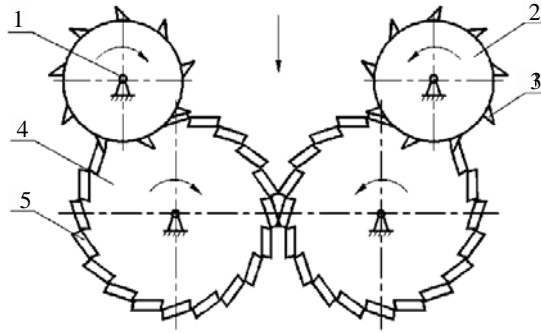


Fig. 3.3. Disc cutting blades: 1 – shafts; 2 – disk knives; 3 – cutting elements; 4 – toothed discs; 5 – teeth [23]

The machine for shredding large amounts of rubber waste and cutting of tire waste, includes a device with a multi-linking roller for cutting, made by three driven knife rollers installed in the case, so that rollers 1 and 2 cut the material onto strips, and rollers 2 and 3 – cut into pieces (Fig. 3.4).

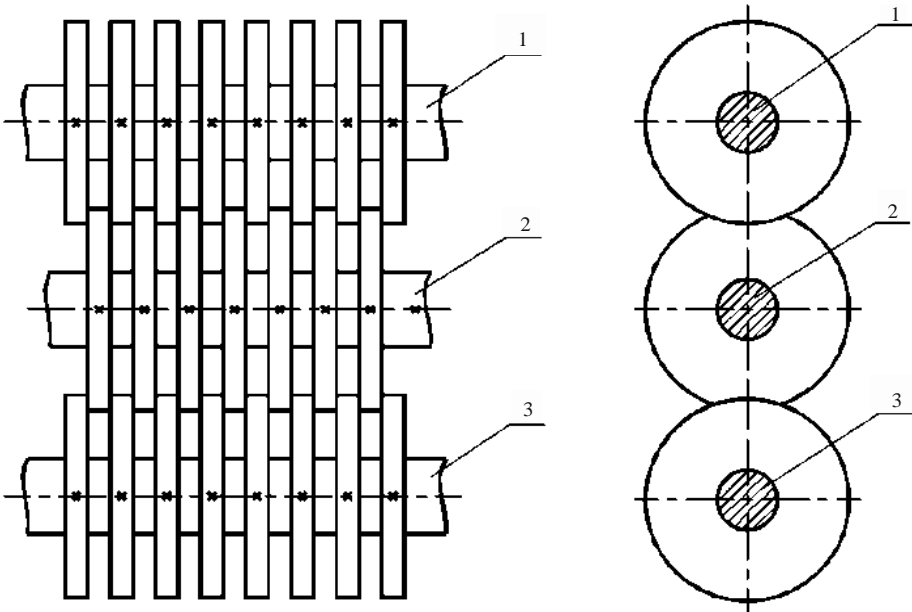


Fig. 3.4. Discs: 1, 2, 3 – driven knife rollers [own study]

The dispersity that is achieved with this method of grinding depends on the size of the discs and the distance between them.

Disc cutting devices are complicated in design and provide poor quality grinding. Another disadvantage of this type of equipment is that it yields large fractions of the material. Therefore, this type of processing equipment can be used for pre-shredding of waste.

In the process of polymer milling, the disc rollers for waste processing cut small pieces of material, thus destroying the polymer crystalline zones, which requires significant energy consumption making use of these devices ineffective for polymer waste recycling.

Extruder shredders have recently been widely used in waste recycling. These devices are used mainly for grinding polymer materials and in particular for grinding rubber of high-plastic state. They can also be used for grinding textile waste. According to the plant design and the type of the material to be crushed, extruder devices can be divided into the following groups: extruder grinding shredders, screws with teeth, screws with cutting elements.

The dispersity achieved by the extruder is about 2 to 10 mm.

This type of processing has not been sufficiently explored yet. Although experimental calculations for models of similar processing equipment are available, the technological process of waste processing in extruders is noteworthy. Before recycling waste in these devices, it is necessary to separate different materials from each other, that is, polymers from textiles, rubber from metal. Secondly, the waste must be pre-grounded. In comparison with roller shredders, extruder devices are much more complicated both in terms of structure and maintenance. The main drawbacks of extruder devices are: the material intensive sticking to the device working elements, which greatly complicates the process of further operation; impossibility of processing of solid polymers; significant energy costs.

Extruder grinding devices are used for processing and separation by size of low hardness materials, for example, rubber for production of regenerates. Such devices have been used in the automotive and regeneration industry. The crushed material is used as a filler in various composites for the manufacture of rubber products.

The extruder shredder consists of housing 1, which contains screw 2 with screw head 3 (Fig. 3.5). The shredded materials are fed through hopper 4 to the device. Screw 2 serves for transportation of the crushed material, more precisely – for moving waste along casing. Rubbing and fracture of the material particles occurs between casing 1 and screw head 3, due to compression forces.

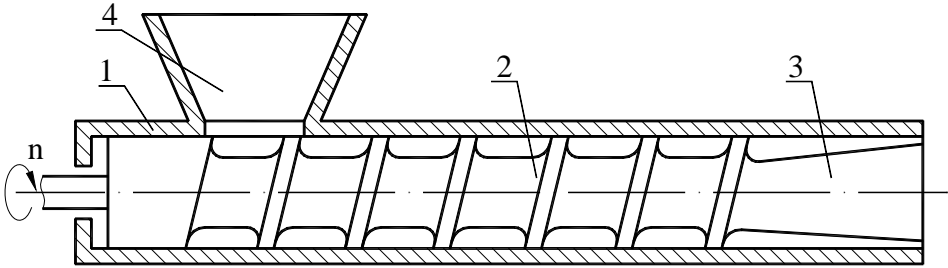


Fig. 3.5. Extruder for waste processing: 1 – casing; 2 – screw; 3 – screw head; 4 – hopper [23]

These devices are used mainly for grinding of rubber in a high plastic state which can be characterized as elastic-deformable. The idea of this waste processing method is to use the field of mechanical forces, in which the material is subjected to compression with shear.

The advantage of extruder grinding is that the device is used only for grinding of rubber waste in its high-plastic state, although on the other hand it can be considered as a drawback. Other disadvantages include energy intensity, uncertain temperature, the material heating and sticking to the working elements that slow down the process.

Another group of extruder devices are those whose working elements are screws with teeth. These devices are used for oily and elastic materials, for example, for rubber.

Extruder devices, in which the screw contains teeth, have been used in oil-fat, winemaking, canning branches of the food industry, in the chemical, construction as well as in agriculture.

Shredded waste is used as a filler in polymeric compositions, for the production of rubber items, films, as well as for the production of oils, juices and other foodstuffs.

Extruder devices with a toothed screw consist of casing 1, in which screw 2 is mounted with teeth 3 of different shapes and sizes (Fig. 3.6). The shredding material is fed into the hopper and crushed by the friction and compression forces that arise between the casing 1 and screw 2.

In devices of this type, the crushed mass adheres to the surface of the screw between the teeth depressions and then slowly rotates together with the screw, which reduces the quality of the crushed material and the process efficiency and increases energy intensity of the device.

Devices in which the operating element is a screw with cutting elements, are used for processing of both hard and textile materials.

Screw extruder devices with cutting elements are used in the construction, textile and mining industries.

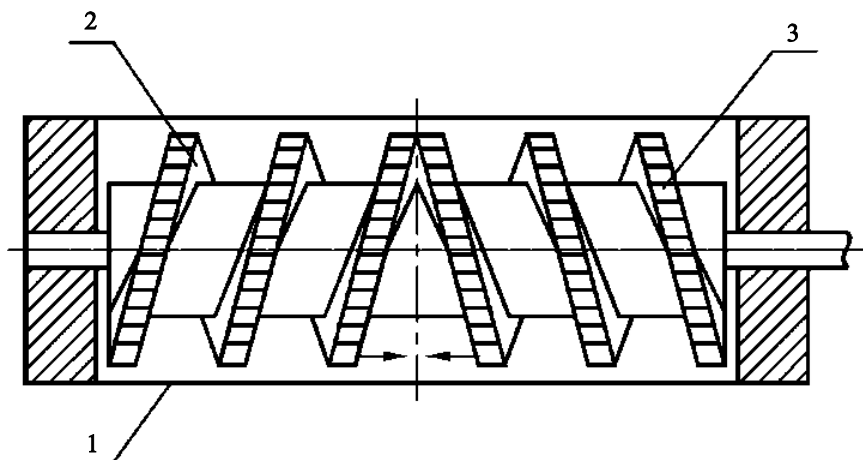


Fig. 3.6. Extruder device with screw, on which the teeth are cut [23]

The crushed materials are used in various polymer compositions as additives to manufacture of polymer products. The crushed textile waste is used in production of technical cotton, various gaskets and other products of one-time and short-term use.

The device consists of a casing 1, screws, which revolve in relation to each other. Teeth shaped screw elements are fixed in the screws (Fig. 3.7).

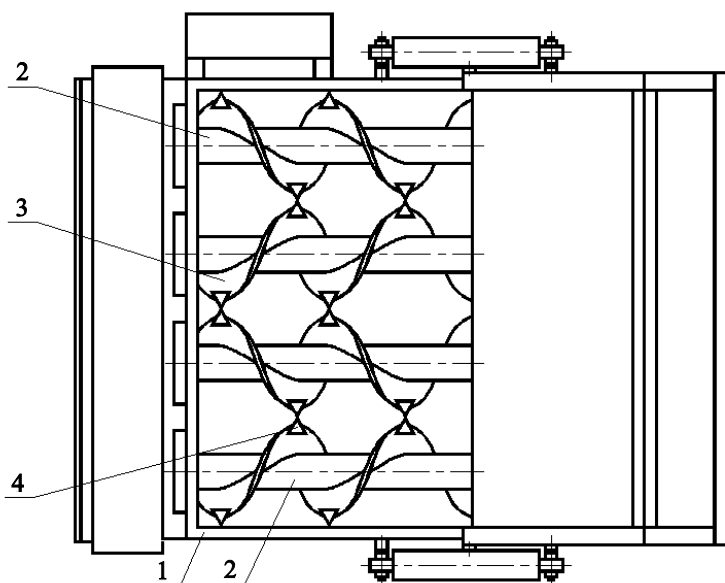


Fig. 3.7. Recycling auger with cutting elements: 1 – casing; 2 – screw; 3 – screw winding; 4 – teeth [23]

Screw processing devices of this type are used for grinding trash of textile waste, provided that teeth are located not only on the screw, but also on the processing zone surface.

Such a device can be used for preliminary grinding of polymeric waste or other large size items.

The processing of light industry waste in grinders is carried out at the expense of impact. Equipment of this type can include a device that has a rotor and a stator (Fig. 3.8). The stator is made in the form of a case with counter-knives and loading and unloading holes. In turn, the rotor has the form of a cylindrical metal brush – a needle-cutter or the form of a set of plates parallel to the axis, which has different heights (Fig 3.8).

Such processing devices can be used for grinding worn car tires, elastic materials, including briquettes of synthetic rubber, artificial and natural leather.

This type of shredder can be used in the chemical and paper industry for production of powders in the manufacture of plastics, for example, polystyrene, where the degree of shredding of rubber depends on the time of its dissolution in styrene; in the manufacture of polymeric building materials, where creation of compositions requires crushing rubber.

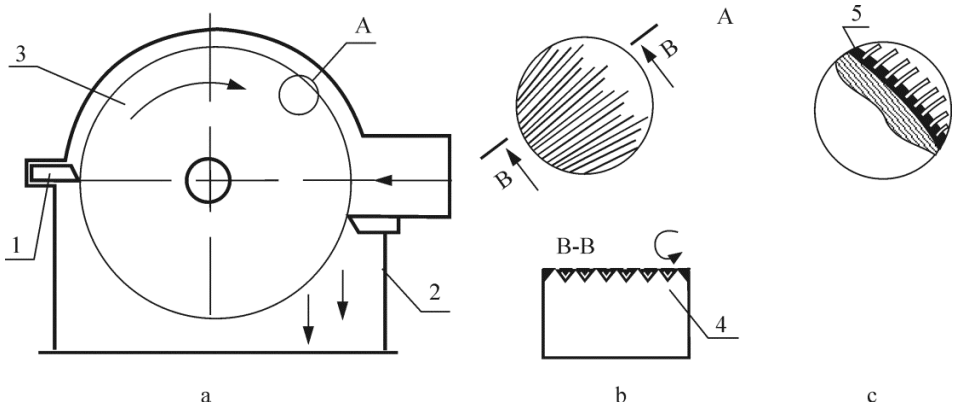


Fig. 3.8. Device for polymer waste treatment: a – disintegrator; b – plate rotor; c – needle rotor; 1 – stator knives; 2 – body; 3 – rotor; 4 – plate; 5 – needles [own study]

When composite materials are chopped with a needle rotor it is possible to separate a variety of materials, for instance monolithic materials from fibrous ones. At the same time, the monolithic material is crushed into a powder, and fibers are obtained from the fibrous material, maintaining the material main properties which is a rather a significant advantage.

The material obtained in effect of processing can be used as rubber mixture fillers and in the manufacture of light industry polymer products. Using this filler

will reduce abrasion of products without decreasing their elasticity. So recycled material can also be used as filler for processing of phenol-formaldehyde resins.

In a mixture with latex or PVC, the crushed material can be pressed into thin films, which can be stamped with a pattern.

When fibrous materials are processed, they are then used for the manufacture of tracks, laces, and as fillers for building products.

Waste processing can be carried out in a needle-rotor machine in different modes. By changing the speed of rotation and the amount of material feed, it is possible to adjust the dispersion of the product, within a fairly wide range.

Also, in order to reduce the energy consumption before shredding, the material elastically pre-deformed to provide it with significant internal stresses that can increase the fracture efficiency due to the fact that pre-stressed bodies require much less energy to be destroyed.

The processes of scrubbing and scratching, which are used for pre-processing fibrous mass in the light industry are most similar to processing in disintegrators.

The fineness degree that can be achieved by recycling waste in such equipment is 0.1–2 mm for monolithic materials, from 1 to 45 mm for fibrous materials.

Despite the lack of knowledge and rare use of the above equipment, it has its advantages: the possibility of processing in different modes, as well as the ability to regulate the fineness degree of the original product by changing the number of revolutions and the value of the product; the main properties of materials are preserved; after crushing the monolith we get powder, after shredding fibrous materials – fibers.

However, there are also disadvantages including: the work of such shredders is designed for milling of only small fractions; productivity of the grinding process is low.

The analysis shows that the processing of light industry waste in a needle-milling machines is very effective in terms of the milling product quality. Such equipment makes it possible to process a wide range of materials with different properties and structures, while preserving their basic properties.

Rolling devices are intended for mixing, crushing, plasticization in the processing of polymers and their compositions.

The material in the form of granules, powdered or fibrous masses or separate pieces is fed to the rollers. When rotating the rollers in opposite directions and due to friction, the material is forced into the gap between them and processed. First, the material is exposed to compression forces, resulting in its plastic deformation or destruction.

According to the design there may be from one to several rollers, which rotate both in one direction and in opposite directions. Depending on the material strength and the degree of its shredding, the surface of the rollers can be smooth, grooved, toothed, disk, conical, and other. Also, in order to improve the recycling process, rollers can have different shapes. They can be found in the form of truncated cones, and also in the form of parts of the thoraxes.

Rolling processing devices are offered in two versions: with a constant (Fig. 3.9 a) and alternating (Fig. 3.9 b) gap between the rollers. It is possible to change the gap between the rollers by providing one roller of the spring-loaded type.

By technical features, rollers for processing of polymer waste can be divided into blenders, plasticizers and shredders.

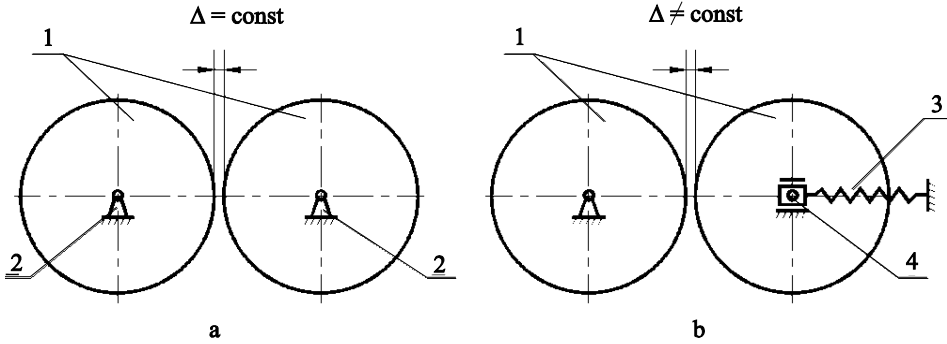


Fig. 3.9. Rollers for waste treatment with constant (a) and alternating (b) gap: 1 – rolls; 2 – fixed support; 3 – elastic element; 4 – slider [own study]

The batch material for this type of processing is mainly powder, and in the case of monolithic polymeric materials – small pieces.

Operation of the roller-type devices is quite simple. They also have their advantages and disadvantages. The advantages of this group of crushers include simplicity and reliability of the design, the ability to adjust the gap between the rollers, which allows to adjust the magnitude of the fineness degree of the crushed material.

The disadvantage of roller shredders is relatively rapid wear of the working element surfaces, high energy consumption per the crushed material unit volume.

Productivity of roller shredders ranges from 10 to 400 m³/h, depending on the roller design, the crushed material and the equipment.

Slabs with smooth rollers are used for processing of loose, brittle, solid and abrasive materials (grains, coal, polymer materials, various ore and non-metallic materials, paints, putty), that is, these shredders are used for virtually all kinds of waste, except for textile.

Such equipment is used in fodder mixing, brewing, construction, mining, chemical, and light and food industries.

Shredded waste is used as a filler in polymeric compositions, as a filler for the manufacture of special types of glue, as a filler in the manufacture of linoleum, as a filler for rubber mixtures.

Rolling devices with smooth surface rollers consist of: casing 1, in which there are smooth rollers 2, loading hopper 3 and discharging hopper 4 (Fig. 3.10).

Waste is guided through a loading chamber to be seized by the rollers, rotating relative to each other. Due to compressive deformations, the material is

crushed. And only in the case when the roller rotational speed is different, sliding deformations are added to compressive deformations. The value of the compressive loads depends on the inter-roller gap and on the shear deformation.

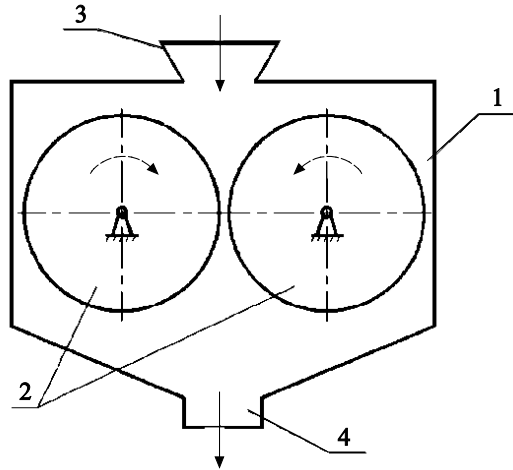


Fig. 3.10. Rolling processing unit with smooth roller surfaces [23]

The process of waste grinding in devices with smooth rollers is fairly common and well-studied. It is quite simple to design and maintain. The dispersity achieved by this method is from 0.2 mm to 2 mm. The fineness degree value can be obtained by adjusting the inter-roller gap. The ability to adjust the dispersity allows to recycle almost all types of pre-shredded waste, the simplicity of the device design and ease of maintenance – all this leads to widespread use of devices with smooth rollers.

As for the disadvantages of the above discussed devices, one of them is the impossibility of high-quality grinding of fibrous materials.

Shafts with toothed rollers are intended for crushing minerals, various building materials, loose materials (grain), polymeric materials, film and foam materials, rubber, wood, ceramic masses.

These processing devices are used in mining, construction, woodworking, pulp and paper, food and other industries. Shredded waste can be used as fillers in polymeric compositions, for manufacturing of rubber products, various food additives.

Roller shafts have the same structural design as a shredder with smooth rollers (Fig. 3.11). The only difference is that the surface of the rollers can be made with teeth of different configurations. The toothed rollers can be divided into two main groups according to the position of teeth on the roller: rollers whose teeth are perpendicular to the axis of rotation (used for shredding sheet material, for example, film and foam materials, paper, sheet polymers); rollers whose teeth are parallel to the axis (used for grinding granular materials, for example, grain, rubber).

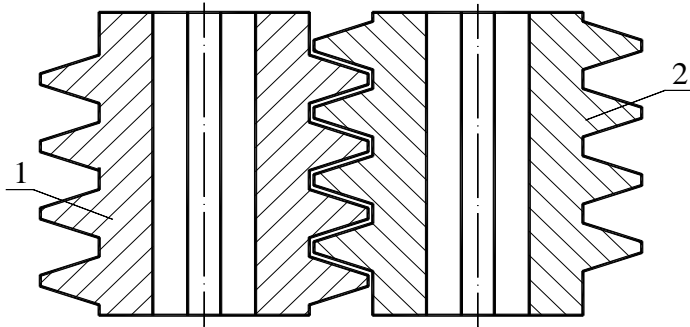


Fig. 3.11. Rolling processing unit with toothed rollers: 1, 2 – toothed rolls [23]

The main types of toothed roller devices can include devices with rollers with a zigzag profile. In the waste recycling device inside the casing there are drive rollers 1 and 2 with the surface longitudinal zigzag profile. In order to increase the shredding degree of the material various solid particles and the reliability of the device operation, the roller surface it is provided with additional corrugation in the form of transverse grooves (Fig. 3.12).

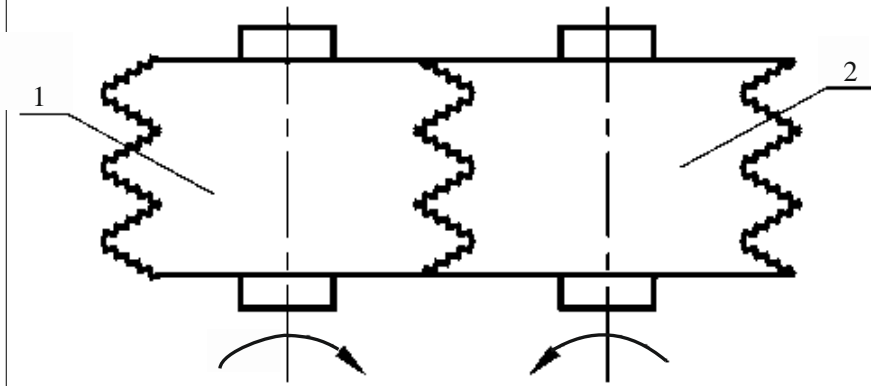


Fig. 3.12. Zigzag profile rollers: 1,2 – rolls [23]

There is a similar device for grinding a polymer film. The only difference is that in order to improve grinding quality, the cutting elements of drum 1 are made in the form of circular knives, each with cross section triangular profile and the cutting elements of drum 2 are made in the form of teeth with a beveled cutting edge, with the teeth edges of the two connected rows are directed into the opposite sides (Fig. 3.13).

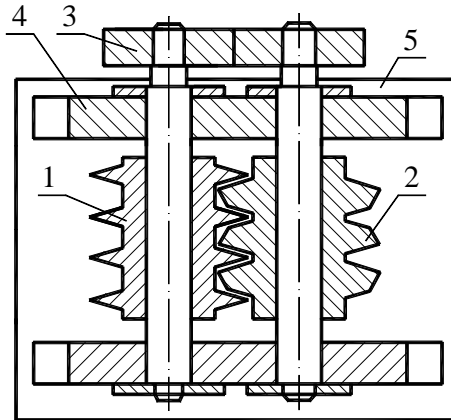


Fig. 3.13. Roller device for grinding polymer film: 1 – drum with cutting teeth; 2 – toothed drum with a beveled cutting edge; 3 – gear transmission; 4 – racks; 5 – casing [23]

Devices with toothed rollers allow to recycle waste, focusing on the type shredded material, which means that to grind bulk materials more efficiently one can use rollers with longitudinal teeth. For shredding of sheet materials it is advisable to use rollers with transverse teeth. This enables to obtain a higher degree of the material dispersion. However, at the same time it accelerates the wear of the surfaces of both of the rollers and the casing. Moreover, it reduces the efficiency of the chopper, which are essential disadvantages of such a device.

Slabs with curvilinear surface are used for grinding loose, polymeric, plastic materials (for example, rubber), ore and non-metallic minerals, grains. These devices are used in chemical, food, mining, construction, agriculture and other industries. Shredded waste is used as fillers for the manufacture of concrete, rubber products, flour, as fillers in polymeric compositions.

The unit for crushing of inert materials in the manufacture of building concrete, as well as for grinding of coal in boilers, consists of a housing with two curvilinear surface rollers with square edges installed on the horizontal shafts.

Rollers 1 are connected by a gear and can rotate in opposite directions. They are placed with a displacement of 45° on the sides of the square ends, which lie in one plane, with the lateral faces triangular shape (Fig. 3.14).

The process of grinding is carried out at the expense of similar processes, inherent in smooth rollers. In this case, improvement of the grinding process is achieved by shape the rollers.

The dispersity that can be achieved with this shredding method is from 0.1 mm to 4 mm.

Curvilinear surfaces of the rollers allow to extend the range of recycled materials and, subsequently increase the scope of such equipment.

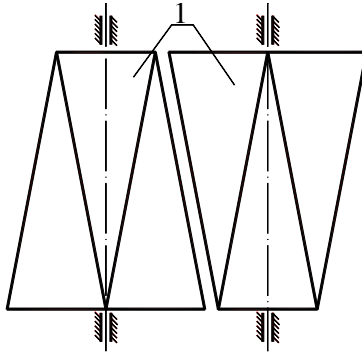


Fig. 3.14. Rolling processing unit with conical surface of rolls: 1 – cone shaped rolls [23]

With regard to the disadvantages of the curvilinear roller surface structures with curved surface of rolls, it should be noted that the main of them is the unevenness of the dispersion of the source material.

Curvilinear rollers surface of a wide variety of shapes makes possible to obtain fine particles of polymeric elastic materials (rubber). The device consists of roll 1 with a horizontal axis of rotation and a curvilinear working surface and roll 2 with a vertical axis of rotation in the form of a cut cone is used (Fig. 3.15).

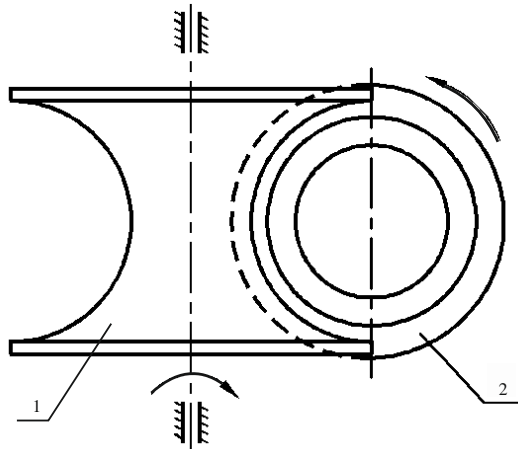


Fig. 3.15. Roller device for waste treatment: 1 – roller with vertical axis of rotation; 2 – roller with horizontal axis of rotation [23]

The destruction of material occurs directly between rolls 1 and 2, which are the working elements of this processing unit. The process of destruction is due to the compression and displacement of layers of the processed material, between the surfaces of rolls in different planes. The dispersity in this method of waste processing is from 0.1 to 4 mm. The roller device of this design provides an improvement of the product quality due to the possibility of achieving a uniform of the inter-roller gap curvilinear surfaces time contact with a wide range of its value change.

All characteristics of the roller shredder can also be found in the design of the processing unit. The difference between them is that in order to increase the grinding process efficiency, rollers of this design are located one above the other. The working surface of upper roller 1 is of spherical shape, and the working surface of lower roller 2 is respectively concave, with semicircular shape of the roller contact line (Fig. 3.16).

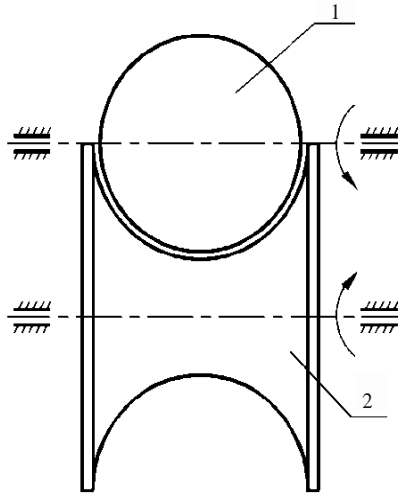


Fig. 3.16. Rolling device for waste process: 1 – roller is made in the form of a layer; 2 – a roller with a concave surface [23]

Such a structure enables improving the processing efficiency. But the design of the device is difficult to manufacture. This also applies to the design of the previous shredder (Fig. 3.17).

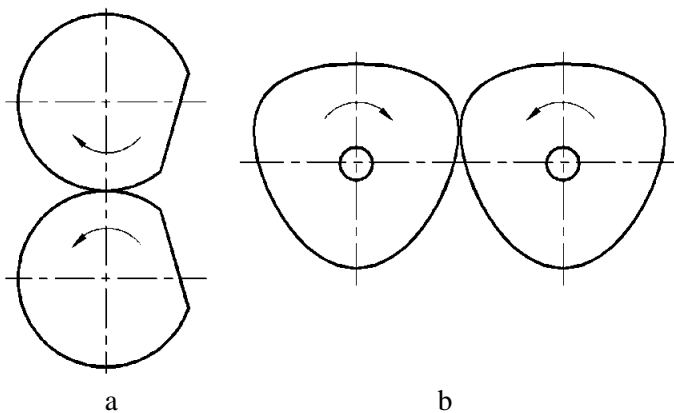


Fig. 3.17. Roller device for waste treatment: a – rolls are located vertically and executed with a cut on the entire surface; b – the rolls have the form of an equilateral triangle with convex sides [23]

For separation of defective cartridges of a polyethylene tube and a metal base, a device with two vertically arranged rollers, which have a cut across the cylindrical surface (Fig. 1.17a) are used. The main advantage of this device is that such a profile takes into account the shape of the shredded waste. However, this argument can also be viewed as an disadvantage of the described design because the devices with profile rolls make it possible to process only a certain type of waste that is consistent with the profile. The device is easy to maintain, as well as simple in design.

Rollers (Fig. 1.17b), with equilateral triangle cross sections, convex sides and rounded vertices, are used in the crushers of the mining, chemical and food industries. The grinding of material is caused by compressive deformations.

The value of compressive loads depends on the inter-roller gap. As for the size of the crushed material, it is very difficult to adjust the gap, which is the main disadvantage of this design.

The main advantage of such devices is an increased waste capturing angle. There is no methodology to calculate the parameters of equipment of this type; although there are methods for calculating the parameters of mixing devices, but they are imperfect.

3.2. Development of equipment for polymer waste processing

According to the above presented concept of polymer waste processing equipment which takes into account the polymer material super molecular structure change and anisotropy of its properties when creating a complex stress-strain state, a scheme for polymer waste processing was developed (Fig. 3.18).

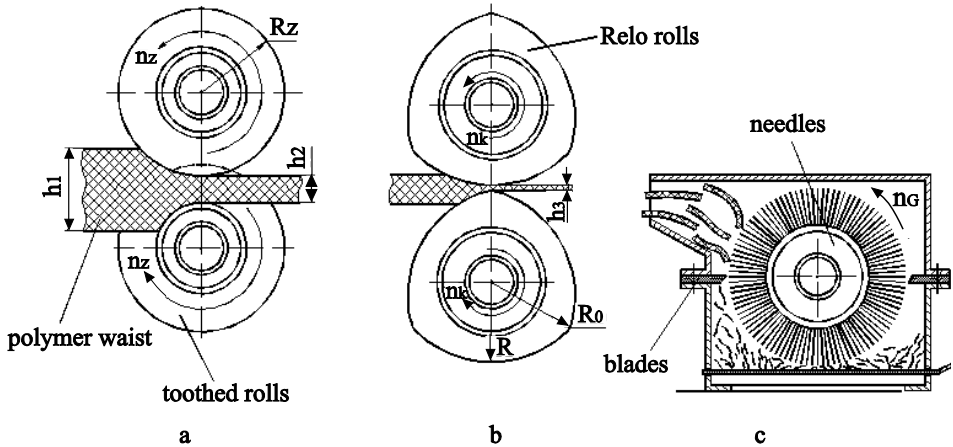


Fig. 3.18. Scheme of transformation of polymer waste into particles: a – toothed rolls unit; b – rolls with a curvilinear surface unit; c – needle cutter unit [own study]

As can be seen in Fig. 3.18, in the first stage, the polymer waste is processed on the toothed rollers where it undergoes stretching and compression, and as a result – an oriented structure with transverse tears formed at the tops of the teeth is provided; in the second stage, the oriented polymeric waste is processed on a device with rollers of the Relo profile, where they undergo compression and shear deformations; consequently, major strains occur in the amorphous region between the oriented conglomerates of the polymer crystallites; in the third stage, the polymer waste is exposed to the needle-cutter, where, under the impact of the needles, it is comminuted into particles with anisotropic structure.

To determine rational performance parameters of the processing devices and the technological operation modes, the deformation processes of the polymer material need to be considered (Fig. 3.19). In a device with toothed rollers the material is first elongated, and then compressed which provides the material with an oriented super molecular structure. After that, the oriented polymeric material enters the device with Relo rolls, where it is exposed to deformation by compression and shear

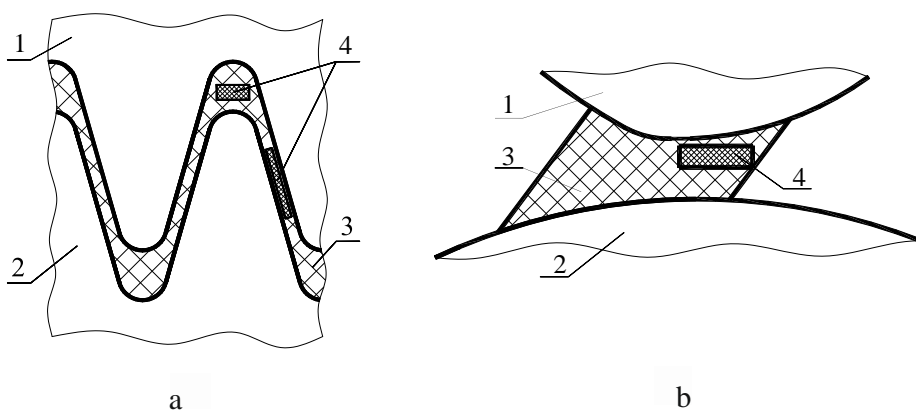


Fig. 3.19. Scheme of deformation of the polymer between the toothed rollers (a) and Relo-profile rollers (b): 1, 2 – the upper and lower rolls; 3 – polymer waste; 4 – infinitely small volume of polymer [own study]

Polymers are elastic-viscous-plastic materials, characterized by structural instability in time and dependence on temperature change. Their strength and deformation change over time with constantly acting, gradual and variable loads. Under the influence of the load, instant elastic deformations, deformations that develop in time (viscoelastic) and plastic deformations occur in the polymer material. Two types of deformations, which are caused in the polymeric material by the processing equipment were discussed in this work: viscoelastic and plastic. According to the external result they are identical – in both cases there is a shift of super molecular structures, macromolecules or their chains, but essentially these deformations are different. In the process of viscoelastic deformation,

the displacement is determined by thermal fluctuations and is carried out gradually, as space is available. Therefore, viscoelastic deformation is not related to disruption of the material integrity and the polymer initial structure as only time is necessary for its development. The viscoelastic deformations are irreversible as plastic ones, but they do not destroy the structure of the polymer, therefore, the viscoelastic properties of the polymer do not change in effect of viscous deformation.

Plastic deformations do not disappear after complete unloading for an indefinitely long period of time. The magnitude and velocity of plastic strain development in time depend on the load value and time. The growth of these deformations is explained by progressive development and occurrence of local destruction. Numerical simulation shows the distribution of tangential stresses on the polymer sample plane (Fig. 3.20), which occur in result of its deformation between the rollers of the Relo profile.

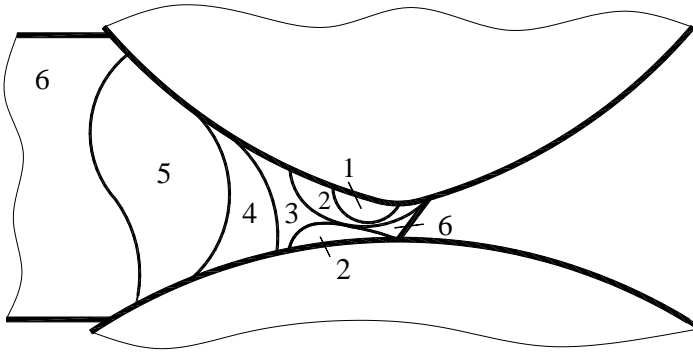


Fig. 3.20. Distribution of tangential stresses on the plane of a polypropylene sample due to its deformation between Relo profile rolls: 1 – shear stress $\tau = 1.25$ MPa; 2 – $\tau = 1.10$ MPa; 3 – $\tau = 0.86$ MPa; 4 – $\tau = 0.62$ MPa; 5 – $\tau = 0.50$ MPa; 6 – $\tau = 0.35$ MPa [own study]

Fig. 3.20 shows that the maximum shear stresses occur in region 1, which borders with the upper roller. This is due to the fact that in the specified area, the maximum deformation rates are created. Consequently, by changing the structural parameters of the rollers and the processing equipment technological parameters, it is possible to determine a rational design of the equipment working elements and effective modes of their interaction with the polymer waste.

According to the results of a numerical simulation, that relate the velocity of shear strains created by the equipment working elements with tangent stresses occurring in the polymeric material graphs have been created (Figs 3.21, 3.22).

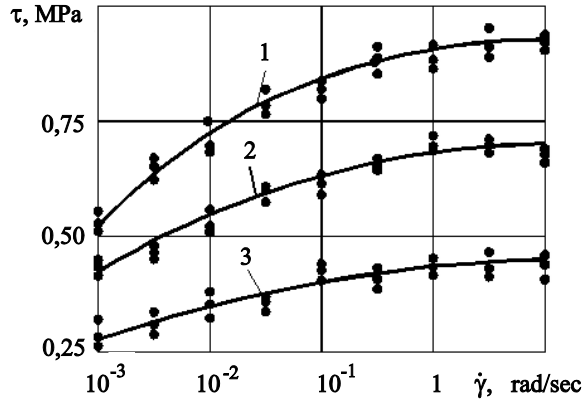


Fig. 3.21. Dependence of shear stress on the rate of deformation of polyethylene at a temperature: 1 – $T = 20^{\circ}\text{C}$; 2 – $T = 50^{\circ}\text{C}$; 3 – $T = 80^{\circ}\text{C}$ [own study]

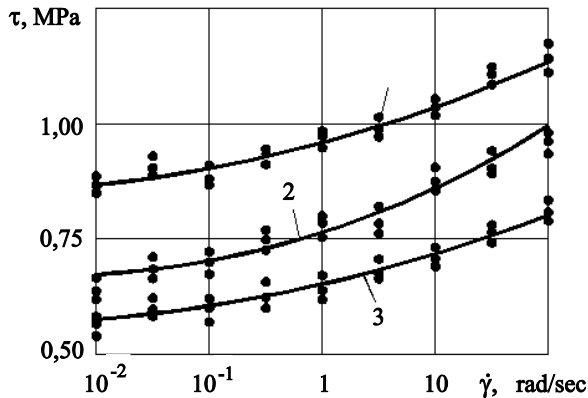


Fig. 3.22. Dependence of shear stress on the rate of deformation of polypropylene at a pressure generated by rolls: 1 – $\sigma = 5 \text{ MPa}$; 2 – $\sigma = 3.5 \text{ MPa}$; 3 – $\sigma = 2 \text{ MPa}$ [own study]

Fig. 3.21, 3.22 shows that in result of the strain velocity increase, which is determined by the circular velocities and the roller rotations, the value of the material maximum tangent stresses goes up. At the same time, there is a significant influence of the temperature and the pressure generated by the rollers on the value of these stresses in the material.

The test was carried out on a device designed to test materials for tension in a wide temperature range from -20 to 200°C . This experimental device has undergone the required metrological certification.

The main purpose of these experiments was to test the results obtained on the basis of mathematical models of polymeric material destruction in the oriented conglomerates of elongated shape. Therefore, the loads, which lead to the destruction of polymer samples in the direction transverse to the previous stretch are of great importance.

At the first stage of the experiment with the use of the above-mentioned measuring device, a polymer sample is stretched before being heated up to a certain temperature. At the second stage of the test, we remove the stretched polymer sample, turn it clockwise and fix it again in the grip. After fixing the sample, it is stretched at a certain temperature until it is destroyed. At the time of destruction, the value of the load and deformation is recorded. Determining the area of the sample cross-section and knowing value of the load that led to the sample rupture, one can determine the stresses which causes breakage of the bonds between the elongated conglomerates of the oriented structure.

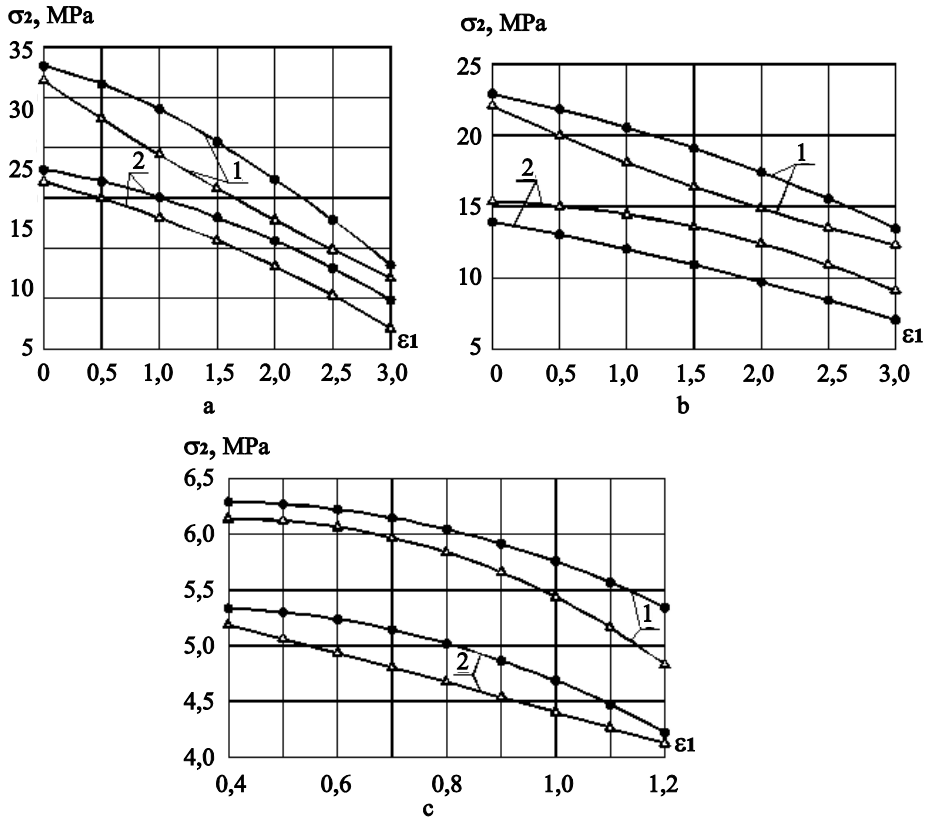
The load acting on the polymer specimen during its deformation is measured by a dynamometer. The deformation of the polymer sample, which occurs under the action of a certain load and at a certain temperature, is measured by means of an optical-mechanical device.

Accuracy of the measurement and registration of the load-deformation curve was: for loading – 1% of the maximum load value, and for deformation – 0.5% of the maximum deformation value for a given scale of the curve registration system. To study the influence of the polymer material temperature on its strength, a thermal chamber was used.

The above-mentioned measuring device provides the polymer specimen with a wide range of tensile load and temperature adjustment possibilities, which makes it possible to investigate the impact of the polymeric material preliminary stretching degree and its temperature on its physical-mechanical properties in the direction transverse to the previous direction of stretching.

The choice of fracture toughness as the analyzed parameter is due to the fact that the stresses that destroy the polymer materials applied across the pre-oriented material structure are significantly lower than the load applied to the conventional polymer. Determination of the previous stretch limiting deformations and destructive stresses in the direction transverse to the previous strain will allow to design energy-efficient devices for the polymer waste processing.

In Fig. 3.23 graphs of the strength dependences of polypropylene, polyethylene and polyvinyl chloride on the previous transverse direction deformation are shown. Functional dependences shown in the figures represent the results of analytical and experimental studies of the polymer breaking strength.



● – approximation of experimental data; ▲ – analytical dependencies [own study]

Fig. 3.23. The dependencies of strength of polypropylene (a), polyethylene (b) and a sample of polyvinylchloride (c) across the direction of deformation of the previous tension on this deformation: 1 – the heating temperature $T = 50^\circ\text{C}$; 2 – heating temperature $T = 100^\circ\text{C}$

In order to establish a correlation between the working element design parameters and the technological rules of polymer waste processing, experimental tests of the polymer specimen stretching strain rate impact of the destructive stress on the value were conducted. Determination of the maximum velocities of tensile strains and their corresponding destructive stresses will enable calculation of a rational design and effective technological parameters of the equipment for polymer waste processing into particles providing them with anisotropy of physical and mechanical properties. This will enable the design of energy-efficient equipment for polymer waste recycling and its subsequent use as raw materials for the production of light industry goods.

The tests were carried out on a device, which is designed to determine the strength of materials for stretching in a wide temperature range.

The test unit for testing tensile strength on the basis of RM-30 machine consists of a tension mechanism with a specified constant speed, a monitoring and support systems for a given temperature of the chamber with the polymer material and a system for automatic measurement data recording (load and deformation) on a computer.

The polyvinyl chloride strength dependence on the velocity of tensile strain v and temperature T is presented in Fig. 3.24.

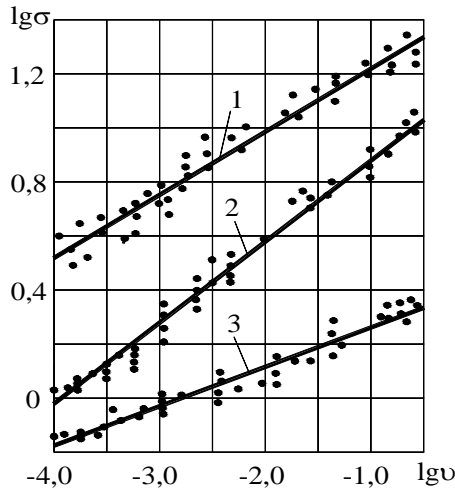


Fig. 3.24. Dependence of destructive stress on the tensile rate of polyvinyl chloride: 1 – $T = 20^{\circ}\text{C}$; 2 – $T = 50^{\circ}\text{C}$; 3 – $T = 80^{\circ}\text{C}$ [own study]

Fig. 3.24 shows that the destructive stress value increases in result of an increase in the polyvinyl chloride sample strain rate. This is due to the fact that in such a short period of time equilibrium strain cannot increase, because the macromolecules chains do not have time to pass through the potential minimums, and subsequently the viscoelastic module far exceeds the equilibrium module, which results in destruction at higher stresses.

The boundary strain of the polymeric material previous structure orientation is important for designing the processing equipment. In order to establish a relation between the destructive deformation in the direction transverse to the polymer orientation and the deformation of the polymeric material, tensile experimental research was carried out on 2167 R-50 device for testing plastics. Polymer samples were made of polyethylene and polypropylene.

During the experiment, the polymer specimen was first stretched in x direction. After recording the deformation and stress values, the stretched polymer

sample was removed, rotated clockwise and re-fastened in the grip of the experimental setup in a perpendicular direction. After this, the polymer sample stretched out until it was destroyed. At the time of the sample destruction the values of destructive strain and stress were recorded using a computer. Destructive deformation of the displacement of a pre-stretched polymer sample strain was experimentally determined.

Experimental studies of the influence of the initial tension on the extreme tensile deformation and shear strain in the transverse direction have shown that an increase in the previous tension deformation of the polymer material leads to an increase in the values of destructive deformations in the transverse direction (Figs 3.25, 3.26).

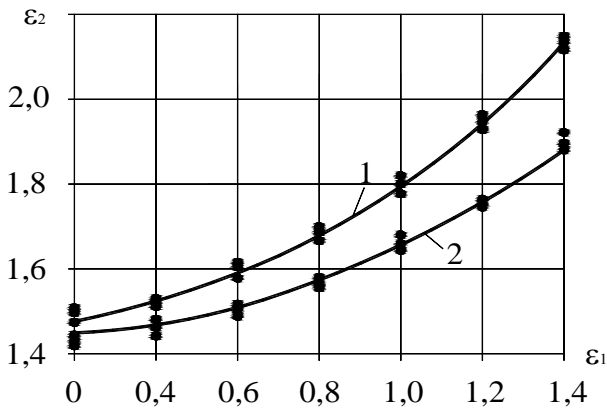


Fig. 3.25. Dependence of the destructive strain deformation of polyethylene on previous tension at tensile rate: 1 – $v_1 = 1.5 \cdot 10^{-3}$ m/s; 2 – $v_1 = 3.0 \cdot 10^{-3}$ m/s [own study]

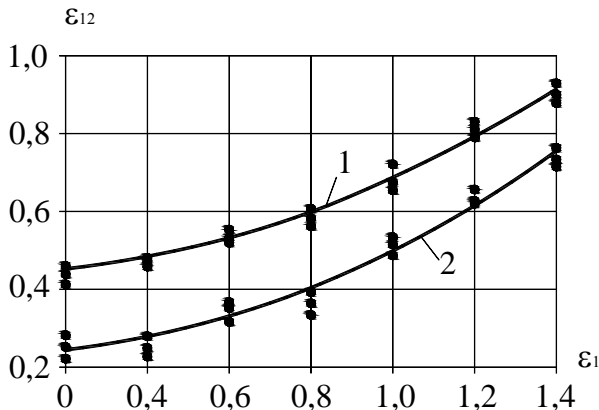


Fig. 3.26. Dependence of the destructive shear deformation of polyethylene on previous tension at shear rate: 1 – $v_1 = 1.5 \cdot 10^{-3}$ m/s, $v_2 = 1.5 \cdot 10^{-3}$ m/s; 2 – $v_1 = 1.5 \cdot 10^{-3}$ m/s, $v_2 = 3.0 \cdot 10^{-3}$ m/s [own study]

As a result of experimental studies, effective values of the previous tension deformation were determined: for polyethylene $\epsilon_1 = 1,3$; for polypropylene $\epsilon_1 = 1,2$; for polyvinyl chloride $\epsilon_1 = 0,32$. With such values of the previous stretching deformation for polyethylene, the transverse direction deformation increases by 18%, and the value of the destructive stress decreases by 10%.

In Fig. 3.27 microphotographs of ruptures in the deformation of polymers appearing in the amorphous region between the crystallites are depicted.

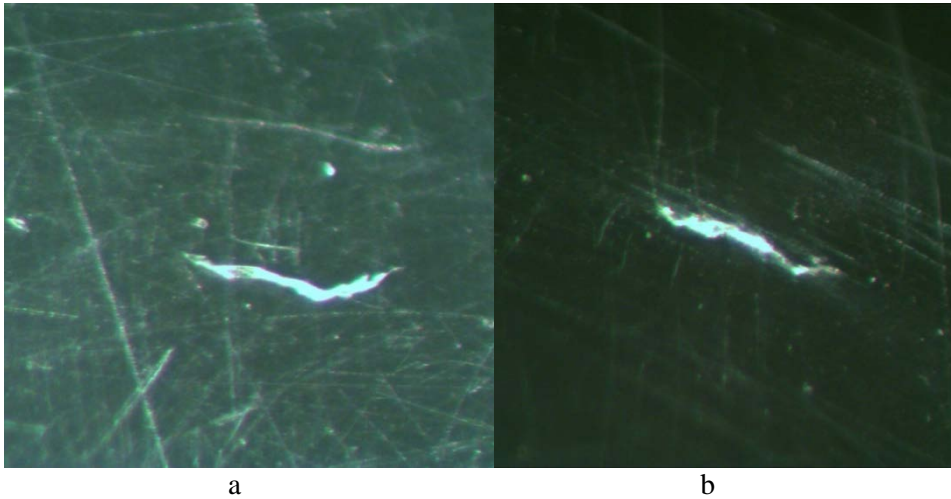


Fig. 3.27. Formation of gaps in polyethylene: a – non-oriented structure; b – oriented structure [own study]

Fig. 3.27 shows that during transverse deformation of the pre-stretched polymer structure in the amorphous zone between oriented crystallites there are ruptures in the form of a straight line (Fig. 3.27a), which increases along with the polymer structure orientation. If the structure is not oriented (Fig. 3.27b), the ruptures look like a wavy line, as a result of this destruction, the polymer is unmanaged, which requires much more effort than during the transverse destruction of the pre-stretched polymer, which in turn leads to larger energy consumption by recycling equipment.

Consequently, the experimental studies have shown that an increase in the deformation caused by the previous tension leads to an increase in destructive deformations and reduction in destructive stresses in the transverse direction. This allows to disregard the polymer waste structure orientation before the processing. The orientation or reorientation of the structure is carried with toothed rolls, after which waste with the same oriented structure is destroyed on the device with profile Relo rollers.

3.3. Determination of valid parameters for the polymer waste processing equipment

To design equipment for this process, mathematical models that allow to trace changes in the physical and mechanical characteristics of a polymeric material in different types of stress-strain state that are generated by the equipment during the polymer waste processing were developed. This makes it possible to provide the necessary loads in a certain sequence, which will allow processing of waste polymer materials into particles with oriented structures with minimum energy resource.

If the polymer material is affected by a certain load, then it is possible to achieve changes in its structure, thus ensuring anisotropy of its physical and mechanical properties. As a result, this polymeric material will have maximum strength in one direction and minimum – in another. By applying a load in the direction of the polymer minimum strength, it is possible to reduce the device energy consumption.

An analysis of existing devices for polymer waste grinding has shown that in order to provide a polymeric material with a complex stress-strain state in which the material is comminuted into particles with oriented structure, it is necessary to consistently expose it to stretching with compression and shear strains, which changes its structure to provide it with the desired physical and mechanical properties. For this purpose, the processing equipment should include devices which in a certain arrangement provide the above mentioned strains, that is, initially create boundary tension and compression strains for the polymer structure, and then – destructive deformations of the displacement, in which the polymer material destruction occurs in amorphous areas between the oriented conglomerate crystalline areas.

The authors suggested a design of equipment for processing of polymer waste, which is made up of three main units: a toothed roller; a roller device with a curvilinear surface; a needle-cutter device.

A simulation of the polymeric material destruction allows to obtain initial data (boundary strains, in which the orientation of the polymer structure is ensured, destructive deformations at which its destruction is ensured, and corresponding stresses) to be use for the design of the above devices. This enables, development of energy-efficient processing equipment and processing of polymer waste into particles of a given shape and size, for example, to obtain elongated particles with a conventional structure, and hence to ensure anisotropy of physical and mechanical properties.

The particles of polymeric material with oriented structure can, like polymeric fibers, be used as reinforcing elements for manufacturing of polymeric products of light industry, such as a shoe bottom parts, suitcase sidewalls, various fittings and other products.

It is known that polymeric materials have a wide range of properties. In the usual state, the polymer has an isotropic structure of the super molecular formations contained in the amorphous matrix.

When the polymeric material passes between the toothed rolls its structure becomes changed. As a result of the influence of tensile loads, the super molecular formations are stretched and moved, causing orientation of polymer material structure. Compressive loads cause transverse tension of the polymer, as a result of which micro cracks are formed along the polymer oriented structure between the elongated conglomerates of its crystalline zones.

Taking into account that the stresses necessary for destruction of crystalline elements are twice higher than the stresses required for destruction of the amorphous zone, we can speak of significant energy savings in the destruction of polymers in designed and presented can be made.

After machining on a device with toothed rollers, the polymeric waste with a weakened structure must be passed between curvilinear surface rollers. For convenience of calculations and control of the roller basic parameters, and also for simplification of their manufacturing, using Relo rollers is suggested. After processing the polymer sample between the Relo profile rollers, the shear stresses in the amorphous zone, there occur considerably large gaps between the oriented conglomerate of the elongated crystallites, the so-called main gaps caused by shear stresses. The growth rate of the gaps rapidly increases along with a slight increase of the load.

For complete destruction and separation of the polymer waste fragments, which are processed between rollers of the Relo profile, they need to pass through a needle-cutter device, which, with the help of needles, at the needle-cutter rotational speed from 500 min^{-1} to 800 min^{-1} will create tensile stress of value significantly higher than the mean values which causes formation of gaps on the entire sample destroying them to particles with anisotropic structure. Energy consumption will be minimal.

Fig. 3.28 shows the dependence of the power that must be created to destroy the material structure by the rotating toothed rollers, on the polymer material deformation.

The graph shows that in order to ensure deformation of the polymeric material $\varepsilon_p = 3.0$, at which its structure turns into a structure of oriented elongated conglomerate of crystalline zones with transverse bonds partially destroyed between conglomerates, it is necessary to spend: for a polyamide film – 0.75 kW; for polyethylene film – 0.25 kW and for polyethylene terephthalate – 1.25 kW.

In order to reduce energy consumption, it is necessary to determine effective parameters of the roller device. To do this, it is necessary to analyze the influence of technological (speed of rotation of rolls) and structural (roll diameter, profile angle and step of the teeth) parameters of the processing equipment on the power consumed to create a given deformation of the polymer material under the impact of the toothed rollers.

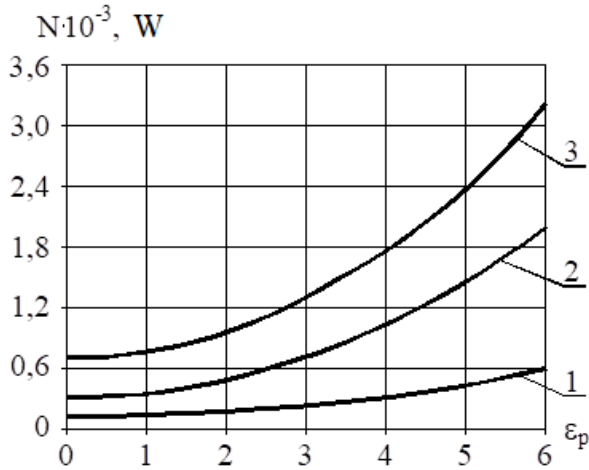


Fig. 3.28. Dependence of power consumed on the deformation of polymeric materials: 1 – polyethylene; 2 – polyamide; 3 – polyethylene terephthalate [own study]

Fig. 3.29–3.30 shows power dependencies on rotational speed and the roller diameter, the profile angle and the step of the teeth. By changing the design parameters such as the profile angle and the step of the teeth, minimization energy consumption without affecting the device performance can be done.

As can be seen in Fig. 3.29, the larger the value of the teeth profile angle, the less power the device consumes. However, the profile angle may increase to 78° . A further increase in the angle may result in the device being unable to provide the desired deformation, that is, when the polymer material structure is oriented as much as possible.

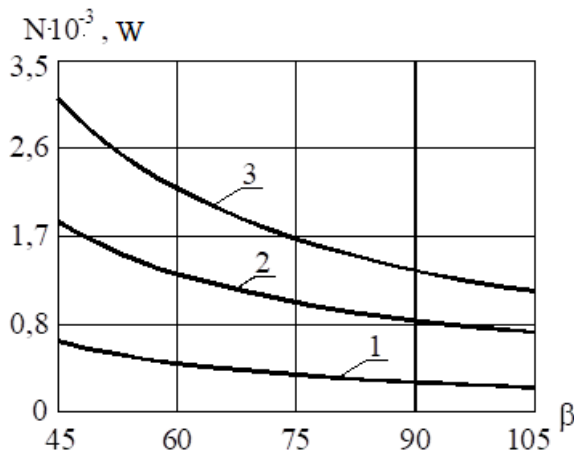


Fig. 3.29. Dependence of power on the profile angle of the teeth for: 1 – polyethylene; 2 – polyamide; 3 – polyethylene terephthalate [own study]

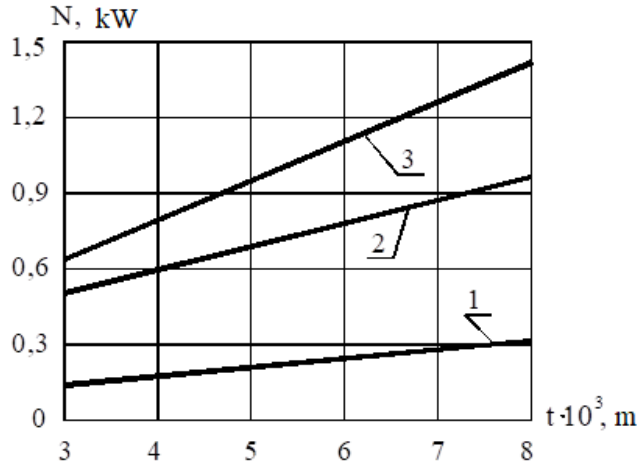


Fig. 3.30. Dependence power on the step of the teeth: 1 – polyethylene; 2 – polyamide; 3 – polyethylene terephthalate [own study]

Fig. 3.29 shows that an increase in the step between the teeth will lead to an increase in power consumption. According to the known angle of the tooth profile which provides the required deformation and consumes a minimum of power, the step between the teeth can be determined.

In Fig. 3.31 and 3.32 the dependencies of the power consumed by the roller device, on the diameter of the toothed rolls and on the speed of their rotation are shown.

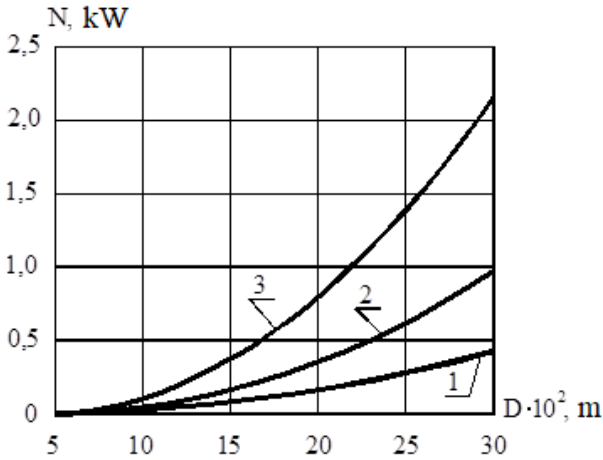


Fig. 3.31. Dependence of the toothed rollers diameter on the power consumption for: 1 – polyethylene; 2 – polyamide; 3 – polyethylene terephthalate [own study]

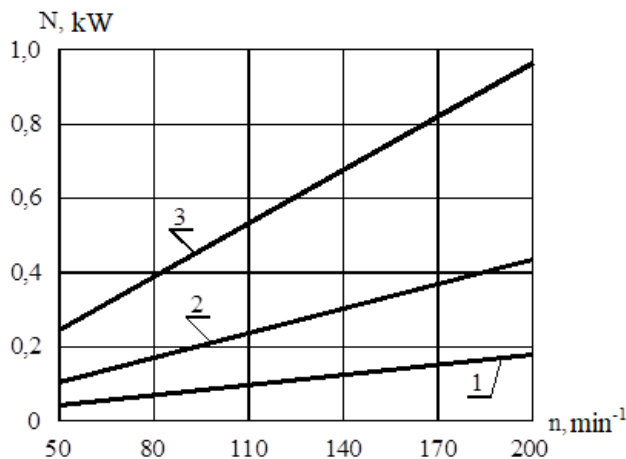


Fig. 3.32. Dependence of the toothed rollers rotational speed on the power consumption for: 1 – polyethylene; 2 – polyamide; 3 – polyethylene terephthalate [own study]

As dependences in Fig. 3.30 and 3.21 show, an increase in the diameter of rollers and their rotational speed leads to an increase in electric power consumption. This is due to an increase in the inertial forces that rise during the rotation of the rollers, and their interaction with the polymeric material.

Reducing the diameter and rotational speed of the toothed rollers will reduce the power consumption, but it will reduce the device performance. Therefore, it is worth for further investigating which of these two parameters has the greatest impact on power consumption.

A similar analysis was performed for polyethylene film and polyethylene terephthalate.

As a result of the analysis, the material loading scheme was determined and analytical dependencies were obtained that related the main structural and technological parameters of the device to a stress-strain state created in the polymer waste.

The obtained analytical dependences for determining the power consumption by the processing equipment can be used to calculate the rational structural and technological parameters of the roller device (the radius of the rolls, the profile angle and the step of the teeth, the rotational speed of the rolls), in which the power consumption is minimal. On this basis, a method for determination of technological (speed of rolls) and design (diameter of rolls, angle of profile and step of the teeth) parameters, which provide the minimum power consumption for certain polymer materials processing, has been proposed.

Using the proposed method, analytical studies of the influence of design and technological parameters of modern roller devices on the power exerted on the maximum orientation of the polymeric material structure and a partial destruction

of the oriented structure in the transverse direction (at the vertices of the teeth) were carried out. It was found that in the processing of polymer waste, the least power consumption will be at the following ratios of the device parameters: step and height of teeth, respectively, 5.2–6.3% and 6.0–7.2% of the diameter of the rolls; the angle of the profile of the teeth from 65° to 72° ; the speed of rollers from 110 min^{-1} to 128 min^{-1} .

The power consumed by the roller device depends on the torque generated on the rollers by the drive. Due to a large number of factors affecting the torque and, subsequently, the power, today there is no complete and reliable method of calculating the energy consumption. However, there are various methods of calculating torque (power) based on the theory of plastic or viscoelastic deformation.

The power consumed by the rollers depends on such factors as: the properties and temperature of the processed polymer material; roller speed; the size of the gap between the rolls; geometric shape and size of the rolls.

The velocity growth leads to an increase in the volume of the polymeric material that is deformed between the rollers made with the Relo profile and, accordingly, increases the deformation. In addition, the roller velocity change also affects the rate of deformation. Elastic deformation does not depend on time and does not play a significant role. Viscous elastic and, especially plastic deformation, evolve with a time increase which leads to an increase in the roller load and power consumption. The volume of deformable polymer material and the rate of deformation increases along with the friction increase and, accordingly, power consumption and productivity also increase.

This is due to the fact that gap increase leads to an increase in the volume of polymer material passing through the gap, which in turn increases the deformation. On the other hand, as the gap increases, the value of linear compression decreases, which reduces deformation.

With periodic action of rollers, energy consumption by rollers can change dramatically over time. For example, in the first period, the load on the lower roller can be 2–3 times higher than the load on the upper roll.

When processing the polymer material in this roller device, the power is used to overcome the friction forces, compression deformation, and tension in the material (the upper and lower layers of the material will stretch differently).

The power consumption of the device with the rollers of the Relo profile with its design and technological parameters is shown in Fig. 3.33.

As can be seen in Fig. 3.33, the dependence of on the power consumed by the roller dependence of the gap between Relo rolls on the power consumed device is close to a linear one. So, a gap increase by 10 mm to 40 mm in the processing of polyamide, polyethylene and polyethylene terephthalate will reduce energy consumption by 15%. Therefore, when designing a processing unit with rolls of the Relo profile, it is necessary to take into account energy costs and optimize the design and technological parameters of the device, taking into account the quality and energy efficiency of the process.

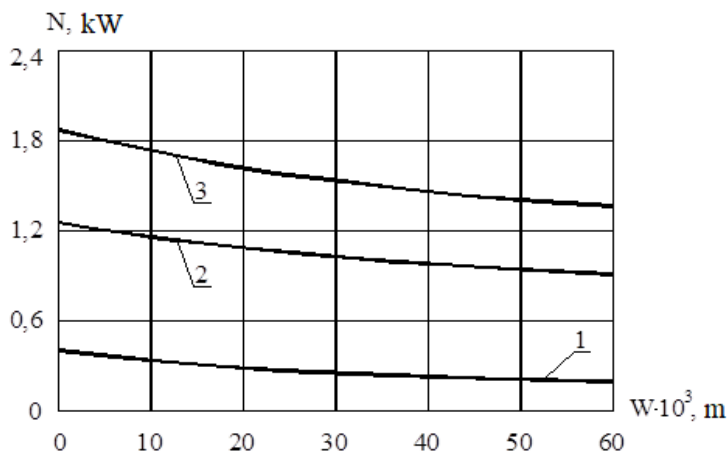


Fig. 3.33. Dependence of gap between Relo rollers on power consumption: 1 – polyethylene; 2 – polyamide; 3 – polyethylene terephthalate [own study]

Consequently, the equipment designed for processing of polymeric waste in the light industry does not require expensive, special devices and can be used in any place of polymer waste accumulation. In addition, mechanical processing of polymeric materials enables formation of an anisotropic structure in the recovered material which is similar to the oriented polymer, that is, fragments of the destroyed polymeric material will have increased physical and mechanical properties along their length. Thus, they can be used as fillers in the manufacture of new polymeric light industry products for improving the performance of the product zones that are subjected to significant loads during their daily use.

A design of equipment for polymer waste processing has been proposed. It consists of a device with toothed rollers, in which the polymer is subjected to strain and compression stresses, a device with Relo profile rollers, in which the polymer undergoes compression and shear stress and a needle-cutter where complete disintegration of the polymeric material into oriented structure particles occurs (Figs 3.34, 3.35).

To provide marginal deformation by initial tension on the toothed rollers when processing 1 to 4 mm thick polymer waste, the following parameters were determined: the teeth step and height, respectively, 3–6% and 4–7% of the roller diameter, the angle of the teeth profile from 60° to 80°. To ensure destructive deformation for 0.8 mm to 1.5 mm thick waste, the gap between the Relo rollers should be 12–28% of the base diameter.

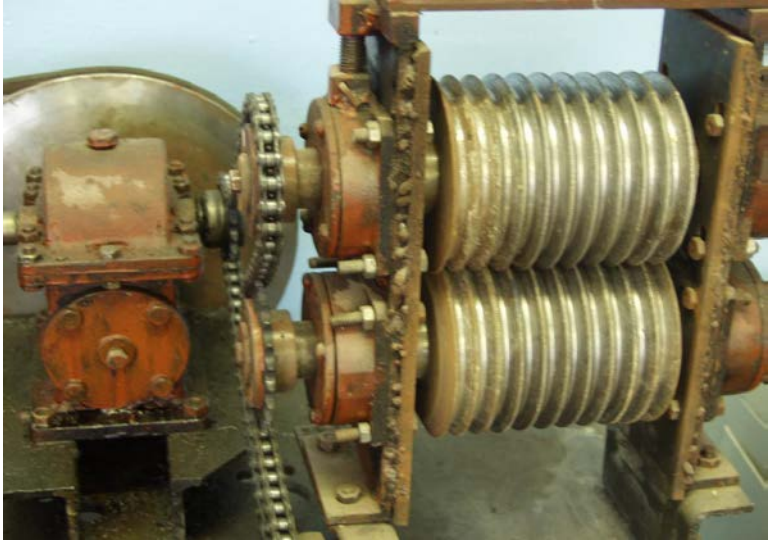


Fig. 3.34. The device with toothed rolls [own study]



Fig. 3.35. Measuring device set up [own study]

Fig. 3.36–3.37 shows graphs of the dependence of the design and technological parameters of the toothed roller device, in which the polymer material is plastically relaxed with its non-oriented structure being transformed into a structure of elongated conglomerates on specific power consumption.

When polyethylene and polypropylene samples pass between the toothed rollers they are exposed to pulling. In addition, destruction of the polymer amorphous zone occurs along the direction of its movement. This is due to the fact that while the polymer material is processed between the toothed rollers by means of compressive and tensile loads, a stress-strain state is created, in which the structure of the polymer material is initially influenced by tensile stresses caused by rotation of the rollers.

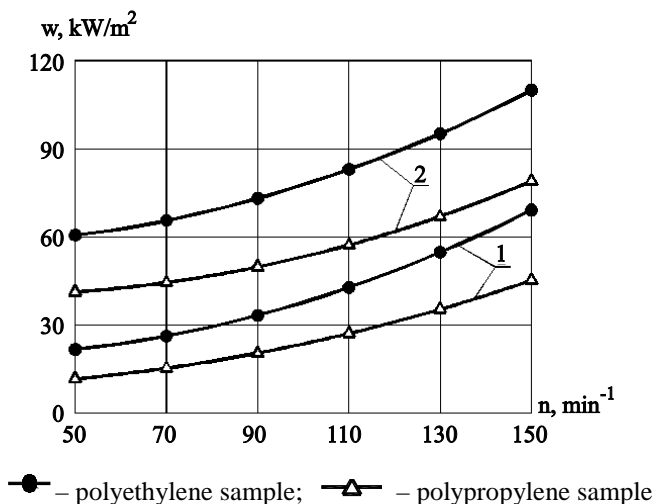


Fig. 3.36. Dependence of the a unit formation of free surface on the rotational speed of the rolls teeth on specific power consumption: 1 – the step of the teeth is 0.004 m; 2 – step of teeth 0.01 m [own study]

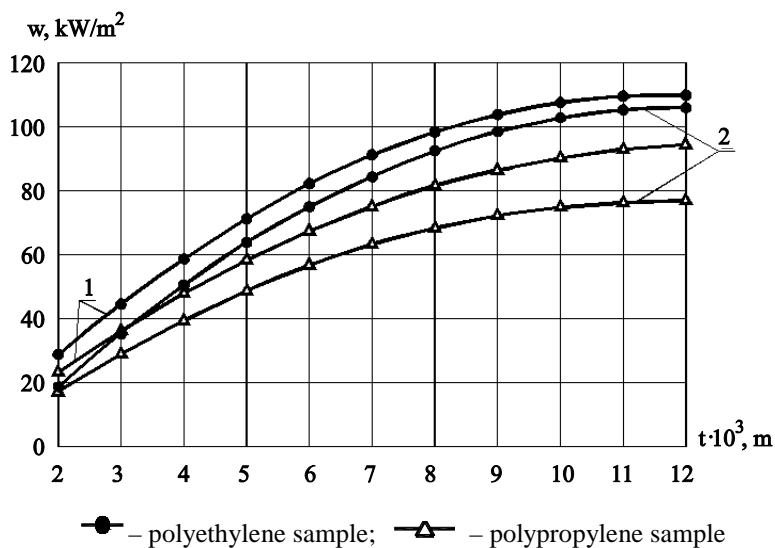


Fig. 3.37. Dependence of the a unit formation of free surface of a polymer sample on the step of the roller teeth on specific power consumption: 1 – rotational speed 150 min^{-1} ; 2 – the frequency of rotation is 50 min^{-1} [own study]

As a result of frictional forces between the polymer and the rollers, the material is pulled along the roller axis, and then, as a result of compressive stresses occurring at the teeth tops it collapses across the pulling direction.

Fig. 3.36 shows an increase in the rotational speed of the toothed rollers results in an increase in power consumption per a free surface (specific power consumption) unit. Increasing the roller speed causes an increase in the rate of the polymeric sample deformation which enhances the destructive tension. This is due to the fact that deformation equilibrium cannot develop in such a short period of time because the macromolecules have no time to pass through potential minimums; as a result, the viscoelastic module far exceeds the equilibrium module, which results in destruction at higher extreme stresses.

Fig. 3.37 shows that with an increase in the roller teeth step the power consumption increases to form a unit of a free surface. This can be explained by the fact that when the tooth step increases, more effort is needed to provide the material structure with maximum orientation. This in turn, requires an increase in the clamping load to prevent the material from being slipped.

In addition, an increase in the teeth step leads to a decrease in the polymeric material deformation across its structure orientation, resulting in a smaller amount of discontinuities and, hence, the polymer free surface area decreases.

When determining rational structural parameters of the disintegration device based on the use of Relo rollers experimental equipment was developed, which is presented in Fig. 3.38–3.40.



Fig. 3.38. Device with Relo profile rolls [own study]

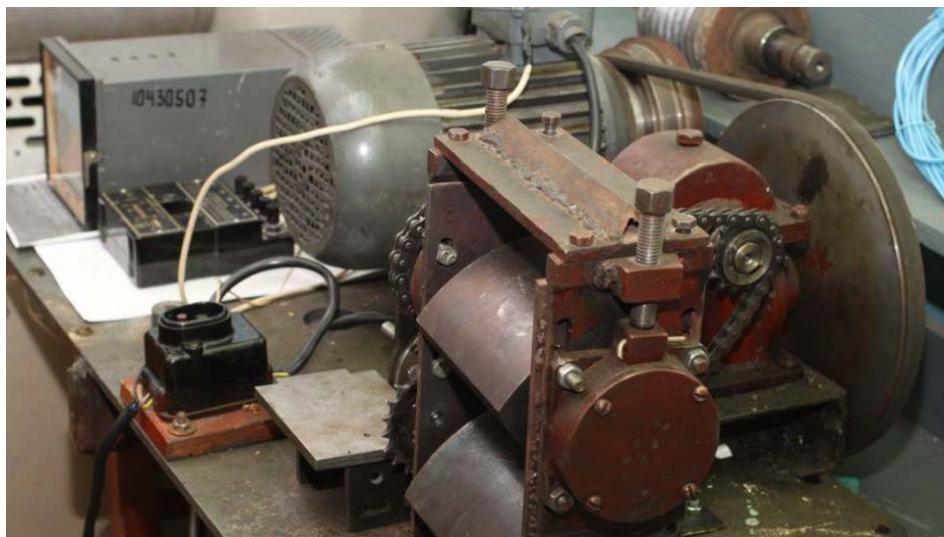


Fig. 3.39. The measuring device set up [own study]



Fig. 3.40. Formation of the free surface of the polymeric specimen: a – polypropylene artificial leather; b – PVC sole [own study]

Fig. 3.41–3.42 depicts graphs of the dependence of power consumed for formation of a free surface unit on the parameters of the Relo roller device and on the roller relative position which is determined by the angle between the rotation of the toothed rollers and Relo rollers.

Fig. 3.42 shows that while using the rollers of Relo profile, like with the use of toothed rolls, the power consumed to form the material free surface unit increases along with an increase in the roller rotational speed.

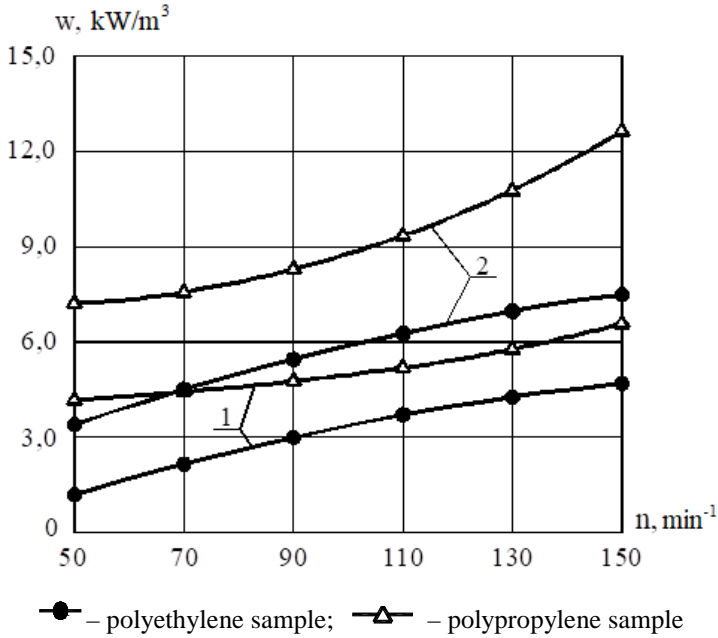


Fig. 3.41. Dependence of the formation of a unit of free surface of a polymer sample on the rotational speed of rolls with the angle between the axes of rotation of rolls on power consumption: 1 – 20°; 2 – 60° [own study]

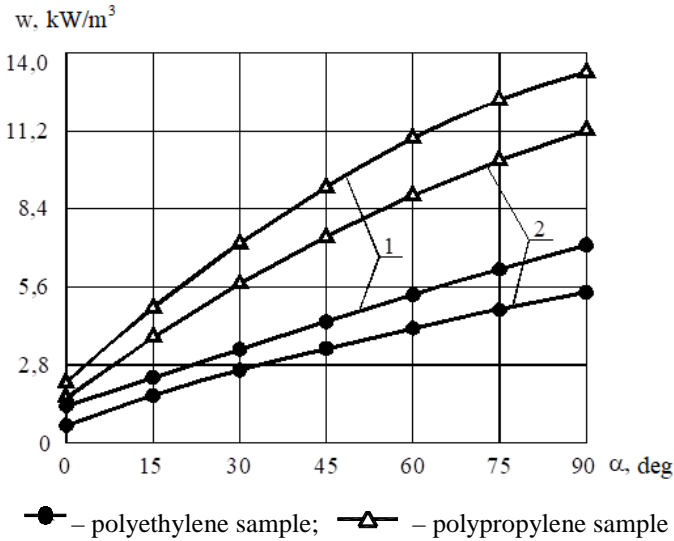


Fig. 3.42. Dependence of the formation of a unit of free surface of a polymer sample on the feed angle at the speed of rotation on power consumption: 1 – 150 min^{-1} ; 2 – 50 min^{-1} [own study]

It has been established that the specific power used for formation of the polymer waste free surface unit in result of increasing the speed of rollers, (from 60 min^{-1} to 120 min^{-1}) increases by 40% for processing of polypropylene and 25% for processing of polyethylene waste. Such a difference in the specific power can be explained by the fact that polyethylene is characterized by a greater fraction of plastic deformation than polypropylene. In this regard, at identical deformation rates, corresponding, for example, to the roller rotational speed of 120 min^{-1} , the structure of polyethylene is more deformable than the structure of polypropylene. Hence, the marginal load for the destruction of polyethylene waste is not so much dependent on the rate of deformation.

As can be seen in Fig. 3.40, the angle between the axes of rotation of the toothed rollers and Relo rollers has a significant effect on the amount of power used for formation of the polymeric material free surface unit. This is due to the fact that the relative position of the rollers depends on the angle of impact of the shear deformations relative to the direction of the polymer structure previous orientation. In this regard, the physical-mechanical characteristics of the polymer are the lowest for the perpendicular direction to its structure orientation, hence, the destructive shear loads in the direction perpendicular to the polymer structure orientation are minimal.

As noted earlier, each separate unit of the experimental equipment has a certain effect on the polymer waste. Accordingly, at each stage of the experimental studies, various power values were obtained per unit of the recycled polymer free surface area.

Thus, at the first stage of processing, when the polymer samples were passed between the toothed rolls, the power used per unit of the sample free surface area was the greatest. Slightly less power was consumed per unit of the polymeric sample free surface at the second stage of processing, when the samples were passed between the Relo profile rolls. The lowest power consumption in formation of the free surface of the recycled polymer samples was found for the third stage of processing, when the samples were treated with a needle-cutter, which resulted in their complete disintegration into oriented particles.

For the first two polymer processing stages, experimental studies were carried out which provided functional dependences of the power used for formation of the polymer sample free surface on the design and technological parameters of the considered equipment.

Minimization of power consumption in formation of a unit free surface area in polymer samples at each processing stage made it possible to provide a rational design and technological parameters of individual devices used in the experiment. However, the investigated devices do not allow to obtain the desired final result, that is, the defined above parameters allow to minimize power consumption for the maximum orientation of the polymer structure and its partial fracture in the transverse direction to the polymer structure orientation.

Experimental studies of a complete cycle of polymer waste recycling were carried out to determine rational design parameters of all equipment devices and

effective technological modes of their operation to provide the minimum energy consumption for formation of the polymeric material unit free surface.

Of course, unlike the previous two models, this model will be less accurate and will describe only general tendencies, but it is quite enough to perform pre-design calculations.

Investigation of the final destruction of polymer specimens using a needle-cutter was carried out on a device whose scheme is shown in Fig. 3.43.

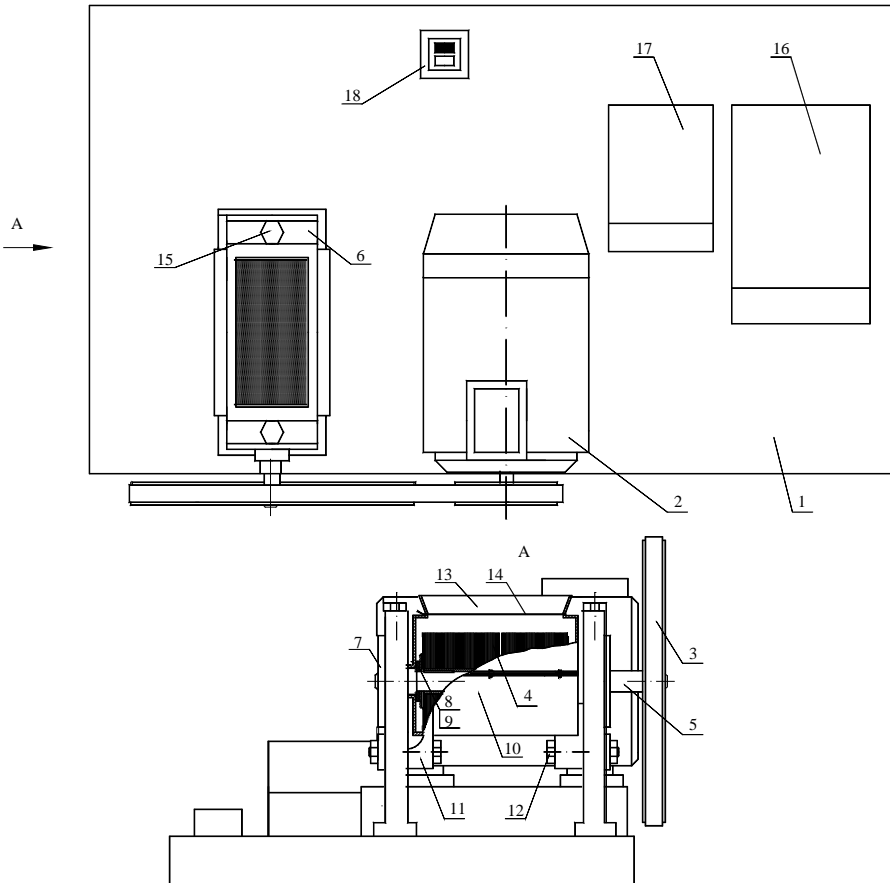


Fig. 3.43. Experimental needle-cutter device: 1 – plate; 2 – electric motor; 3 – belt drive; 4 – needle-cutter; 5 – shaft; 6 – racks; 7 – bearing units; 8 – washers; 9 – nuts; 10 – loading camera; 11 – special lockers; 12 – bolts; 13 – loading camera hatch; 14 – shutter; 15 – adjusting bolts; 16 – device for measuring power; 17 – transformer; 18 – switch [own study]

Polymer samples, which were plastically weakened on the previous two devices, were processed in this device where they were cut into particles of different sizes and shapes using a needle-cutter (Fig. 3.44, 3.45, 3.46).



Fig. 3.44. Needle-cutter [own study]

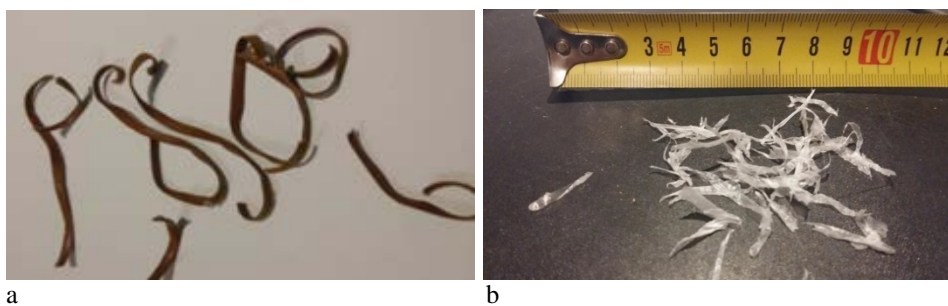


Fig. 3.45. Formation of the free surface of the polymeric specimen: a – polypropylene artificial leather; b – polyethylene film [own study]

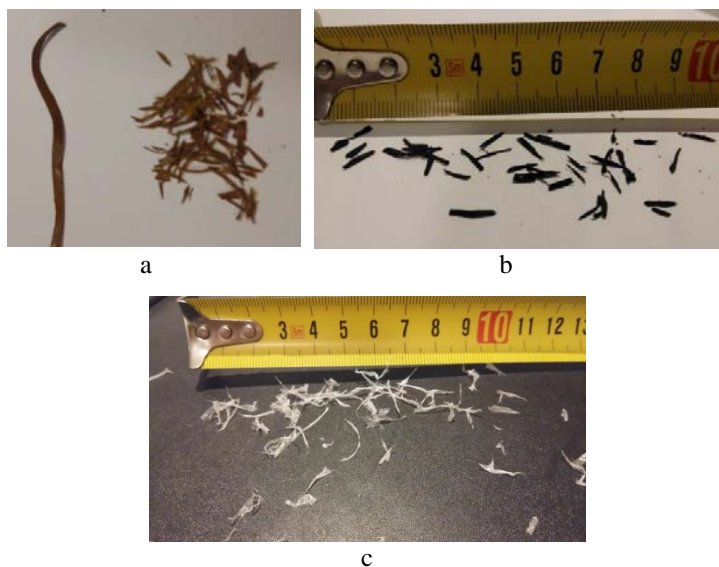


Fig. 3.46. Formation of the free surface of the polymeric specimen: a – polypropylene artificial leather; b – polyvinylchloride for soles; c – polyethylene film [own study]

If the polymer specimens have not been sufficiently weakened on the two previous devices, the particles of the waste recycled by needle-cutter may be too small or too large.

In result of optimization of the processing equipment structural and technological parameters, the following parameter values for the rollers and the needle cutter: the speed of the toothed rolls 148 min^{-1} , the speed of Relo rolls 85 min^{-1} , the speed of the needle cutter 600 min^{-1} , step of the teeth 4.8 mm, the distance between the needle cutter and the stator blades 0.8 mm were obtained. The processing device designed according to the optimization results enables to obtain the minimum value of power consumed to form a free surface unit during the processing of polyvinyl chloride used for molding shoe bottoms which is 2.62 kW/m^2 .

Thus, the research has provided the basis for development of an experimental device for determining the amount of power used for the structure orientation and destruction of the polymeric material. This equipment was used for studies of the influence of the design parameters of the processing equipment and technological characteristics on the power needed to form the recycled polymer free surface unit.

It has been established that during processing of the polymeric material between the toothed rolls, by means of tensile and compressive loads, a stress-strain state is created in which the structure of the polymeric material is initially stretched in the direction transverse to the filament, and then, under the influence of compressive stress generated by Relo rolls, gaps occur across the material orientation structure. This fact suggests a dependence of the waste particle length on the step of the roller device teeth.

During processing of the polymeric material using Relo rolls, strained-deformed states are created by means of compressive and shear loads, causing gaps in the polymeric material oriented structure along its orientation, whose rate of growth rapidly increases with a slight increase in the load.

In result of experimental studies, it was found that an increase in rotational speed of the toothed rollers and reduction of the teeth step lead to a decrease in the power consumption in formation of the free surface unit.

It has also been found that with the use of Relo rolls, like with the use of toothed rolls, the power consumed to form a unit of free surface increases with the roller rotational speed increase. Thus, in effect of a double speed increase (from 60 min^{-1} to 120 min^{-1}) the specific power consumed in the processing of polypropylene waste increases by 40%, and in the processing of polyethylene waste – by 25%. This suggests that the marginal load for the destruction of polyethylene waste does not significantly depend on the deformation rate, contrary to the marginal load for the destruction of polypropylene waste.

The angle between the toothed roller axes of rotation and the rollers of the Relo profile has a significant effect on the amount of power consumed to form a unit of free surface of the recycled polymer material. This is explained by the fact that the relative position of the rollers affects the angle of shear strain relative

to the direction of the polymer structure previous orientation and, as established in the previous chapters, the physical-mechanical characteristics of the polymer in the direction perpendicular to its structure orientation are the lowest, so for parallel rotation of rolls, destruction occurs at minimum loads.

The equipment rational design parameters (the step of the teeth, the angle between the roller rotation axes, the distance between the stator blades and the needle cutter) were determined for the processing of the polymer waste and the effective technological characteristics of its operation (the speed of rotation of the toothed rolls, of the Relo profile rolls and of the needle cutter) are established, which contributes to minimum power consumption.

4

THE USE OF POLYMERIC RECYCLATE IN LIGHT INDUSTRY

4.1. Application of recycled polymer waste

Recycled polymeric materials are used in the production of many products in various spheres of industrial production of goods. The development of production on the basis of recycled plastics has significantly accelerated, driven by the need to reduce costs, supply the market and meet the requirements of more stringent legislation.

Only in the USA more than 1400 kinds of products are manufactured from recovered plastics. Catalogs of products are presented to help managers and consumers find products from recycled materials and check their compliance with legal requirements.

Despite its current growth, the production of light industry goods from secondary polymer materials has to face a number of problems. These include the development and implementation of necessary technologies and equipment for the processing of light industrial waste, significant costs and poor market awareness.

Recycled polymeric materials can be used in most manufacturing processes of light industry products, such as: injection molding, compression pressing, extrusion, thermoforming and rotational molding. However, in order to obtain the specified properties of new polymeric products, these processes require a number of changes. Recovered materials may differ in their properties from original polymer materials due to destruction during their prolonged use, during re-processing, and also due to the presence of impurities of other polymers, contaminants and paper. The determining factor is the source of recovered material, for example, it may be industrial or domestic waste.

It is important to formulate the technical requirements and performance criteria for the polymer to be used in light industry products and to establish their quality limits. It is necessary to minimize the number of defects in the above discussed material by: developing new technological processes and equipment for the polymer waste processing into raw materials, without worsening the mechanical properties of polymers; developing a molding tool that will allow to use the recycled polymers as fillers or connecting elements for the manufacture of new light industry polymeric products to increase their performance properties; de-

signing products that eliminate the material defects (for example, it may be thickening or strengthening the wall; or, in the case of double-layer molding, the use of primary material in critical places, and recycled in other parts).

Recycled materials are more suitable for manufacturing of products for which the color is not critical. Plastics from household waste usually have different colors and secondary polymer is dark green or black. Dyes can be added to hide the original color (for example, when processing milk bottles).

The most suitable technological processes and equipment for production of light industry polymers with the use of recycled waste are those with a wide range of technological parameters. In this regard, the following processes can be applied in which recycled polymer waste can be used: pressure molding, compression molding and extrusion. Other forms of molding can only be used in cases where the secondary polymer has properties similar to those of the original material.

To ensure the possibility of introducing a larger fraction of recycled polymer material into a product, special technological methods should be applied including:

- co extrusion – the process of obtaining a multi-layer product with an intermediate layer of recovered material forming a "sandwich" with side layers of the original polymer (Fig. 4.1);

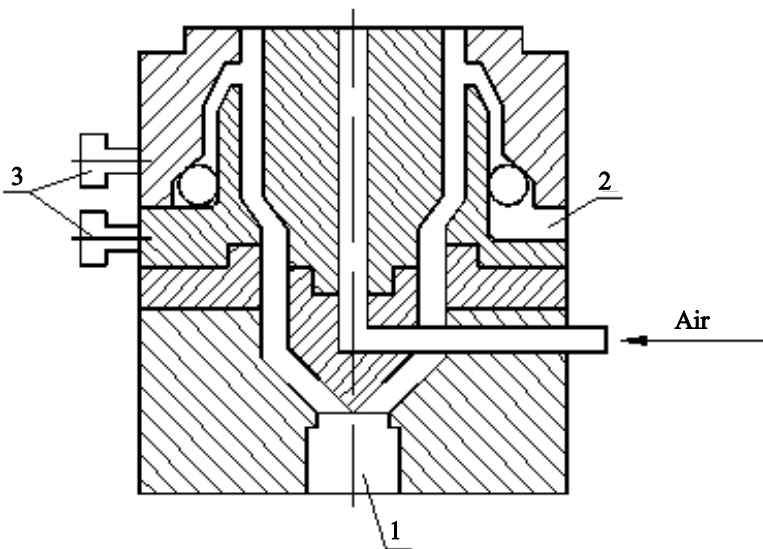


Fig. 4.1. Co extrusion head for dual layer films: 1 – entrance for the melt forming the inner layer; 2 – entrance for the melt forming the outer layer; 3 – adjusting bolts [own study]

- multicomponent injection molding ("sandwich-molding") (Fig. 4.2), when recovered polymers form a core of a thick-walled product in which the walls are made of the original material. When choosing the location of mold channels,

it should be remembered that a certain amount of surface material is injected first, and then the surface and the core materials are injected simultaneously. In principle, most types of mold channels can be used, but changing their geometric parameters is often necessary. Allowable variants are circular, slot, point and tunnel channels, but the use for multi-component molding under the pressure with a conventional hot-channel system is impossible, since in this case, the surface and the core materials would be mixed in the heated channel.

- injection molding of "mixed" polymeric materials – technologies that are successfully applied when introducing a significant proportion of recycled polymer waste as a connecting material.

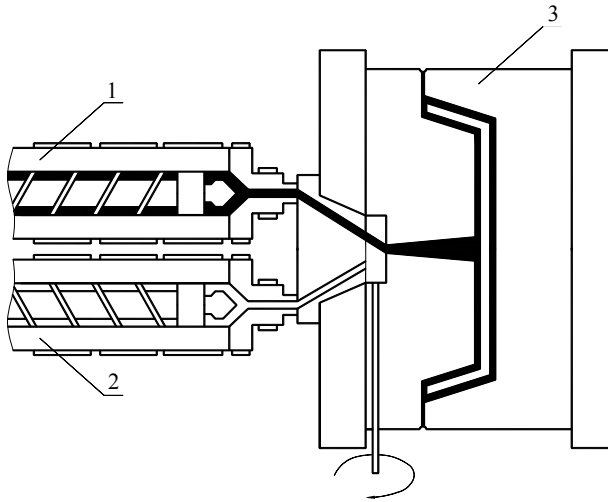


Fig. 4.2. Equipment for multicompartment injection molding: 1 – extruder for formation of a surface layer; 2 – extruder for forming the core of the product; 3 – mold [own study]

The advantage of these technologies is that they often do not require washing of materials before processing, but the drawback – low strength and high creep. The solution to this problem is a scientific and practical interest in the manufacture of pressure injection molding of light industry polymeric products, reinforced with recycled waste.

4.2. Ways of reinforcing plastic products of light industry

Most modern polymer products are made from the compositions of two polymers, which provides the products with combined properties. The joint work of heterogeneous materials gives an effect of a new material that combines the properties of the source materials.

In most cases, the components of the composition are different (one continuous – matrix, another intermittent – reinforcement). Depending on the type of reinforcement, the composite materials are dispersed-strengthened and fibrous.

Disperse-strengthened polymer products have the matrix of one polymer with evenly distributed crushed fractions of another polymer, which can withstand certain loads under the influence of mechanical or thermal fields.

In fiber-reinforced polymeric products, fibers are evenly distributed in the matrix, which bears the main stresses under the influence of external loads, and provide stiffness and strength in the direction of the fibers. The same material as the matrix or other polymeric materials with improved performance can be used as the fibers.

Practical applications are found in methods used for manufacturing of goods made of reinforced plastics: contact forming with stacking resin impregnated with fibrous cloth on the form; spraying a fibrous-polymeric composition onto the surface of the mold; different ways of forming in a closed form; winding of impregnated fiber resin on the form; forming of profiled products by pulling the fiber through a bath with a polymer.

Depending on the forming technology, the properties of the polymer composites can vary significantly. The choice of technology depends on the product design, the conditions of its operation, the volume of production and available production resources.

For the manufacture of small series of large-sized products with complex geometric form, laying of laminate layers is performed, using a cold hardening resin (epoxy, polyester, etc.) as a connecting material. This technology is called a contact formation (Fig. 4.3).

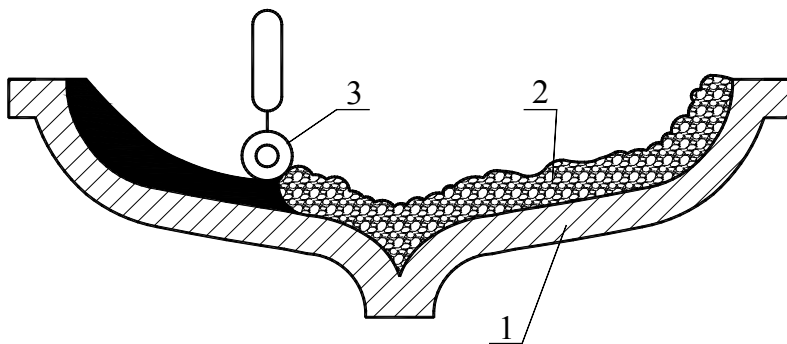


Fig. 4.3. Contact formation: 1 – form; 2 – laminate; 3 – roller [own study]

In this method, laminate 2, which is a reinforcing material impregnated with a polymeric composition, is placed on a special negative form 1 (matrix), then carefully sculpted with roller 3 to seal and remove air bubbles, after which

the polymeric composition solidifies. The surface of the finished product is a mirror image of the surface of the form and completely reproduces its texture.

Upon obtaining high thickness a fiberglass product undergoes lamination which is carried out in several stages to allow each layer to solidify and cool. This is due to the fact that resin solidification accompanied with a significant amount of heat (Fig. 4.3). Thus, the composition becomes overheated; there are significant internal stresses, which lead to deformation, distortion and cracking of finished products.

In recent years, the method of manufacturing large-sized fiberglass products has been developed by spraying into a mold a composition containing a connecting material (polyester resin and hardening catalyst) and chopped fiberglass (Fig. 4.4).

An important feature of the latest generation of spray equipment is that the resin mixing and the catalyst curing take place outside the spray gun, that is, in the air that transports and mixes all the three components (resin, catalysts and cured glass fiber). Such a design of the spray equipment prevents solidification of the polymer composition inside the mixer chamber. The airflow performs two functions: mixes the components and transports the mixture to the matrix.

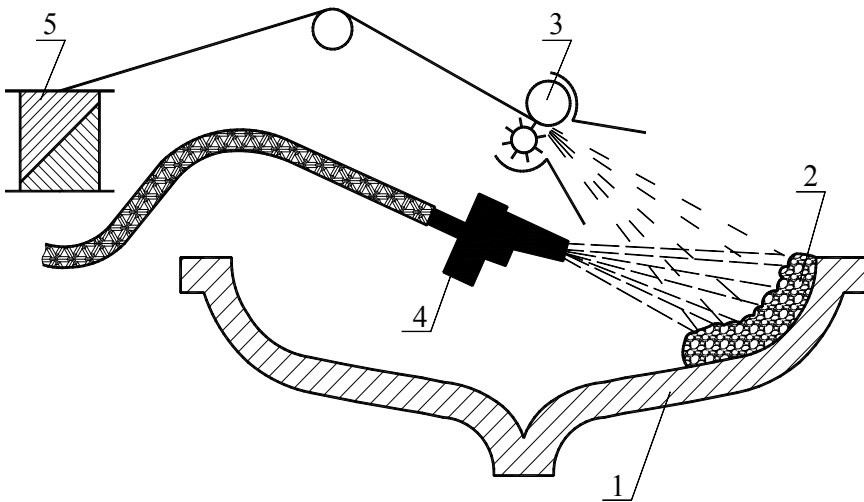


Fig. 4.4. Production from fiberglass by spray technology: 1 – form; 2 – laminate; 3 – cutting unit; 4 – spray gun; 5 – bobbin [own study]

An increase in the composition fiber content leads to an increase in its strength properties. However, for a good impregnation of the fiber with a binder material, its content using such a technology should not exceed 33–35% of weight.

With the use of the spray technology, preliminary cutting of glass materials, polymer impregnation with a reinforcing filler is unnecessary. It allows to reduce production areas, increasing productivity and reducing the production costs.

The technology of making products by spraying is best applicable in the manufacture of large-sized products, because the amount of waste generated is dependent the product size and decreases along with its increase. So, with a product size larger than 1 m², the amount of waste should not exceed 2%.

Fiberglass finds application in many industries, especially in the manufacture of architectural and construction products, products of cultural and household purposes, water slides and attractions and therefore, the product color and design are of great importance. The fiberglass product need to be provided with different colors with simultaneous increase in UV resistance, resistance to various aggressive media, abrasion and other loads. The colors are applied by using special polymeric compositions (gel covers) are painted as an external layer. To manufacture them polyester resins with better physical-mechanical and physical-chemical properties than those used for the manufacture of fiberglass are used.

Organic and inorganic pigments are used to provide gel coatings with the required colors. Modern industry supplies consumers with hundreds of gel coatings of various color shades. The thickness of the coating is 0.4–0.6 mm. For high values of coating thicknesses the reinforcing filler penetrates it, the durability of the coating is reduced, and in case of high thickness, the gel coating is prone to cracking and other defects. Uneven thickness of the gel coating layer also leads to impairment of its properties, so the spray application on the matrix must be carefully monitored.

Pressing fiberglass in closed volumes is a well-known process. It is used for the production of molded products of a given surface and exact dimensions. Formation is carried out under pressure at ambient or elevated temperature. Closed space corresponding to the product geometry can be created by a split-shaped mold (Fig. 4.5) or by means of an elastic diaphragm (Fig. 4.6).

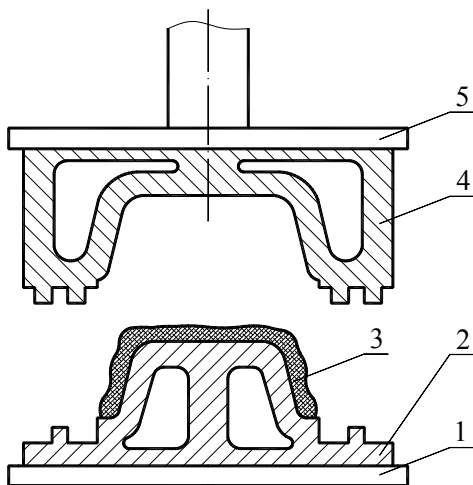


Fig. 4.5. Pressing product in a closed mold: 1 – a fixed plate of press; 2 – punch; 3 – work piece; 4 – matrix; 5 – moving plate of the press [own study]

The role of an elastic diaphragm is often performed by a rubber bag that can bend the work piece due to the supplied air pressure, or by creating a vacuum between the bag and the workpiece.

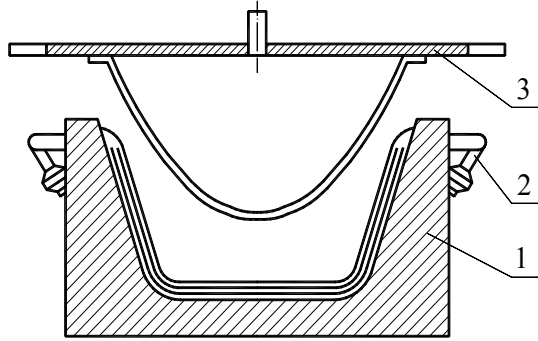


Fig. 4.6. Pressing product using elastic diaphragm: 1 – form; 2 – stop bolts; 3 – upper plate; 4 – elastic diaphragm [own study]

Necessity heat the mold with the work piece is determined by the connecting material properties. Thus, using phenol formaldehyde resins as a connection material requires it to be heated for 15–20 min at a temperature of 190–200°C. Application of polyester and epoxy resins allows to cure the product in ambient temperature.

In recent years, formation of reinforced plastics by the RTM-process (resin transfer molding) has been widely used. In this technology, closed molds are also used, consisting of two parts (Fig. 4.7).

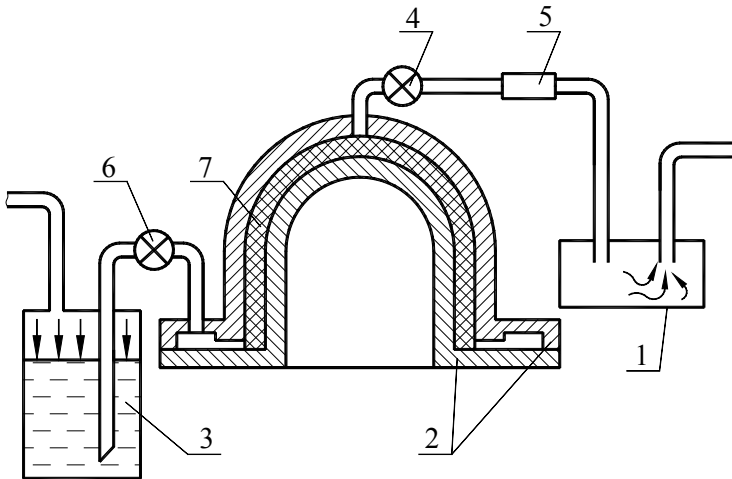


Fig. 4.7. Formation of products by RTM-process: 1 – water filter; 2 – mold; 3 – vessel with connecting material; 4 – faucet of the vacuum line; 5 – vacuum pump; 6 – connecting material feed line faucet; 7 – reinforcement filler [own study]

Solidification of the connecting material occurs in room temperature. The formation process is as follows. In form 2, reinforcing fibrous filler 7 is laid in the form of a cloth or other fibrous material. The mold is sealed hermetically, and vacuum is created with vacuum pump 5. After that, a polymer composition is fed to the mold of the tank 3 under low pressure. At the same time, the connecting material spills over the entire volume of the form and impregnates the reinforcing filler.

The form should be stiff enough so that its interior space does not change either under the action of vacuum or when the resin is applied under pressure. Changing the mold geometry leads to distortions in the product. Stability of the internal space of the mold during the product formation is achieved by creation of rigidity ribs on its outer surface. However, since the formation occurs at low pressure, the shape can be made of fiberglass, concrete and other inexpensive materials.

Hot pressing and RTM-process allow to receive products from reinforced polymer composites with high quality of the whole surface. Since in both cases the formation is carried out in a closed mold under pressure, the obtained product reproduces the mold surface having a given form, geometry and texture.

The application of these technologies has important advantages. It accelerates the process of resin hardening, increases productivity, reduces production space, reduces the complexity, increases the product size accuracy and stability, reduces the amount of waste generation, increases the mechanical properties of products and improves the sanitary and hygienic conditions of production.

It should be noted, however, that the cost of press equipment is quite high and therefore, all the listed benefits of pressing are provided only in mass production of the same type of products.

Proper selection of disconnecting materials that cover internal surfaces of semi-molds is of great importance for compressing products in closed molds. Such a selection facilitates opening of semi-molds and the removal of molded products, as well as extends the equipment life.

Winding technology is used in the manufacture of cylindrical devices made of reinforced polymers. In this technology, the fiber, impregnated with the connecting material, is wound on a rotating mandrel. Impregnation is carried out in a bath using a connecting material through which a continuous fiber passes.

Winding is carried out for a mandrel set at an angle to the longitudinal axis to increase the finished product strength in the axial direction. Laying of a reinforcing filler is carried out according to different schemes, depending on the working conditions of the finished product. The industry uses the following winding schemes: ring, orbital, longitudinal, transverse and spiral.

In this way large diameter pipes are produced (up to 5 m) for transportation of chemical products and other goods. The formation of cylindrical shaped closed bodies is carried out in the form of cocoons by means of orbital winding with individual strengthening of the most loaded body parts. The winding process is carried out automatically and computer assisted.

The most common way of manufacturing parts from polymeric materials is injection molding. Today, nearly one third of thermoplastics are processed in this way. Due to its productivity and machinability, injection molding is very effective for large production volumes. Shoe soles, heels and other polymer parts of shoes are manufactured with the use of this method.

Molded products have high accuracy and clean surface, good appearance; have a low cost in mass production. The molded parts do not require additional finishing treatment, which significantly reduces material costs and manufacturing time. In addition, the injection molding method allows to obtain products of various configurations and complexity that cannot be provided by mechanical processing of materials.

The layout of the casting process is shown in Fig. 4.8. The process of manufacturing shoe products by the injection molding method is as follows: rubber compound or thermoplastic material in the form of granules is fed through loading hopper 1 to cylinder 2, in which screw 3 rotates.

The polymer material is warmed up in a cylinder and transferred to the viscous-state; the screw melts the mixture and puts it into the injection chamber (at the front of the material cylinder).

As the material is accumulated, the screw is pushed to the extreme rear position by increasing the pressure. The reverse of the melt is blocked by piston return valve 5.

After filling the form, the screw performs the function of the plunger, moves forward and creates necessary pressure to fill the mold with the product.

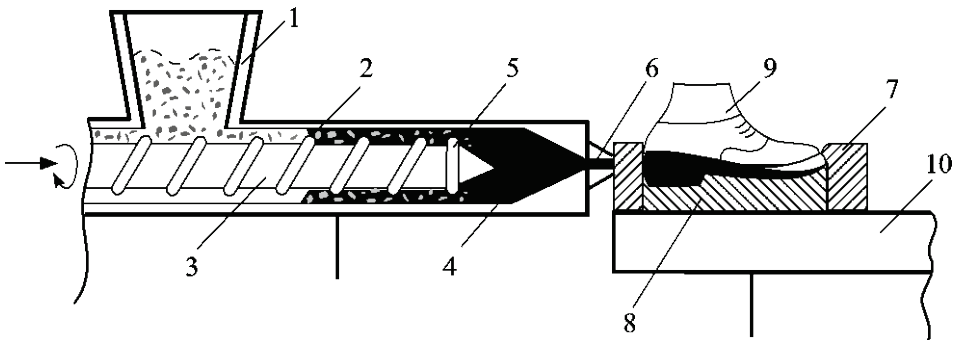


Fig. 4.8. Scheme of injection molding of shoe products: 1 – hopper; 2 – material cylinder; 3 – screw; 4 – polymer; 5 – check valve; 6 – channel; 7 – matrix; 8 – punch; 9 – shoe; 10 – roundabout table [53]

When using rubber mixtures (elastomers), the product in the mold is further vulcanized in a temperature of 180–200°C for several minutes. In the case of using thermoplastic materials, the mold is cooled intensively to eliminate the product excessive plasticity.

The production of footwear and its elements by the injection molding method has significant advantages over other existing methods: increase of labor productivity by reducing the time of vulcanization; the possibility of complete mechanization and automation of the production process; improving the quality of shoes; reduction of material waste due to the lack of cutting operations.

Injection molding equipment is produced by a number of foreign companies: Stübbe and Desma (Germany), Main Group and Otogalli (Italy), Sefom (France), Engel (Austria) and others.

Nowadays there are many designs of injection molding machines, but all of them have the following components and mechanisms: injection head, dosing device, mold, heating and cooling system, injection molding drive and automatic control system with control panel.

The injection method of fastening the sole to the shoe top is the most widespread operation in footwear mass production due to its high productivity, durability and tightness of the connection and attractive appearance. The technological process of injection soles from thermoplastics to the top of the shoes consists of the following operations:

- 1) preparation of the workpiece (the shoe top),
- 2) forming of the workpiece,
- 3) preparation of the workpiece footprint for the sole casting,
- 4) putting the workpiece on the shoe last,
- 5) locking the mold,
- 6) injection of the polymer mixture and forming the sole on the top of the work piece,
- 7) unlocking the mold,
- 8) quality control of shoes.

For injection molding of a single-layer soles made of polyvinylchloride (PVC) or thermo elastic plastic (TEP), there are injection molding machines of the 701, 702, 704, 721, 752, 781 firms Desma (Germany), machines 100470 / P, 100484 / P (Czech Republic) and others.

The technological process of manufacturing a PVC boot with a textile substrate by the injection molding method can be described by the following scheme:

- 1) putting the lining-stockings on the core of the mold.
- 2) lifting the substrate on the pin,
- 3) locking the mold,
- 4) injection of PVC composition for the shoe top,
- 5) moving the punch shield to the injection position,
- 6) injection of the PVC composition into? the sole,
- 7) unlocking the mold and removing the boot from the core.

Lining stocking sewn from a knitted fabric are used. The sewn lining is fed to a casting machine, for example, "Desma 609/10".

For the manufacture of studded soles, rubber or thermoplastic material and metal or plastic pins are used. After cooling (or vulcanization, in the case of rubber use), the studded sole is removed from the mold.

For molding of two-colored bottom of PVC and TEP injection, the following molding machines are used: 077 / 2P; 145 series of the company "Union" (Italy); 723, 783, 784, 785 series of the Desma company (Germany); Y28 / 14 series of the Main Group (Italy) and others.

Most of the combined shoe products are made by injection of two or more molten polymers from different casting devices into one mold.

The sequence of technological operations in the injection molding of polymer products are clearly stated and have undergone virtually no change since the beginning of polymer manufacturing methods.

Therefore, the quality of the finished product is determined not by the injection molding technology, but rather by a correct design of the equipment, proper selection of materials and technological processing parameters. The main technological parameters of the polymer injection molding process are the melt temperature, the mold temperature, the mold filling and the product cooling time.

Application of high pressure during injection molding is necessary not so much to force the material into the mold, but mainly to compensate its shrinkage after cooling.

The higher the molding pressure, causes smaller workpiece shrinkage as due the polymer melt susceptibility to compression at high pressure, the volume reduction during intense cooling is partially or fully compensated.

If this compensation is only partial, then additional injection of the polymer into the mold is applied – additional feeding at the initial stage of cooling. Apart from the polymer melt pressure, the most important technological parameter is the material temperature which varies considerably at different stages of the process, starting with preheating of the material cold granules prior to entering it into the mold cavity.

Another important parameter of the process is duration of the molding cycle – the main factor that determines not only the technological mode of molding, but also the equipment performance. Time reserves for increasing productivity are enclosed in the technological part of the cycle, which is mainly determined by the time of injection and cooling.

Molding polyurethanes with formation of polymer material in a mold is called liquid forming. This method can be used to make soles, heels, tight-fitting for shoes, elastic pads in shoes, profiled insole (for sports and other kinds of shoes), and also fasten the shoe bottom to the shoe top.

The initial components are pre-mixed with special equipment, poured into molds, where a polymeric material – polyurethane is obtained in result of chemical reactions, which is formed by its internal volume under the influence of pressure produced in the mold.

The equipment for liquid forming of polyurethane products is produced by the companies "Desma" (Germany) – machines D581S, D562S, D507S; "Mine

Group" (Italy) – MODEM, VILOR machines; Otogalli (Italy) – machines SSI 200T, JPS, JPB, EPS1 – EPS2; Elastogran (Germany), World (Czech Republic), Tiraspol (Moldovia), etc.

A number of machines are intended for molding exclusively polyurethanes, but also there is equipment, which apart from polyurethanes can process thermoplastic materials and rubber.

There are also machines for direct molding of polyurethane soles on the shoe top and for production of two-layer soles made of materials of different colors or with different properties.

There are a large number of types of polyurethanes with a wide range of physical and mechanical properties – rigid dense to soft porous elastomers and foam materials of low density. This is achieved by appropriate selection of the initial components involved in the polymerization reactions and the reaction conditions.

The basic scheme of the liquid forming process is shown in Fig. 4.9.

Components A and B are pre-poured into tanks 4 and 5 with a controlled temperature. To ensure homogeneity, reagents in tanks are mixed with stirrers. From the reservoirs, components are fed to the mixing device through dosing pumps 8 and 9 on flexible hoses a and b. To maintain the required temperature and viscosity of the mixer components, they circulate through distributors 10 and 11 and the hoses and back to the reservoirs.

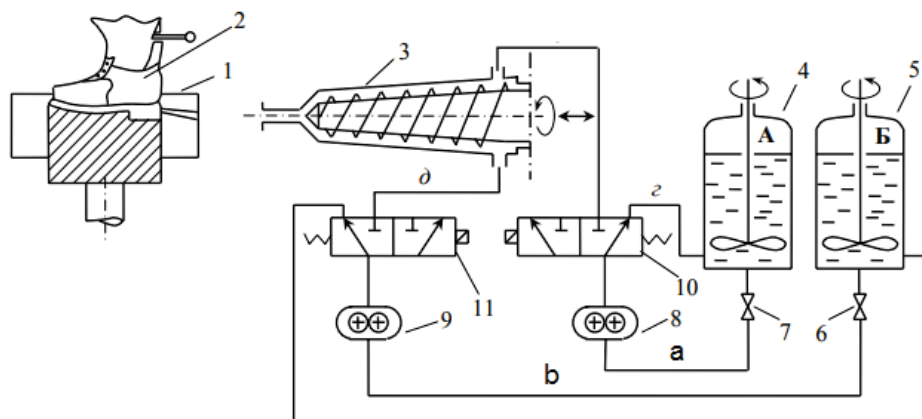


Fig. 4.9. Scheme of liquid forming process of the polyurethane bottom on the workpiece of the top of the shoes: 1 – block of molding form; 2 – work piece of shoe top; 3 – mixer; 4, 5 – tanks; 6, 7 – valves; 8, 9 – dosing pumps; 10, 11 – distributors [54]

To mix the components, the distributors are switched, and the reagents are directed along the ducts to mixer 3. The mixer is a high speed conical screw rotating at a speed of 250–350 rev/sec which carefully mixes the components and feeds the mixture to mold 1.

Due to high speed of the screw, the mixing of A and B components lasts for a fraction of a second, and filling the injection mold cavity is filled with a mixture

of reagents within 5-10 seconds. The composition is characterized by low viscosity, therefore, the injection pressure to fill the mold does not exceed 0.5 MPa.

During mixing of A and B components and injection of reagents to the mold, the mixture temperature rises up to 100–200°C due to its intense mixing and occurrence of chemical reactions. Therefore, the faucet housing is cooled to 50–60°C, and the temperature of the molds is maintained within 40–55°C.

After injection of the mixture chemical reactions, accompanying polyurethane formation and growth of the material caused by foaming, occur. This forming stage lasts 2–6 minutes (depending on the thickness of the products), after which the product temperature is reduced to 60–80°C, and the material turns into a solid state and becomes form-resistant.

Thus, technological possibilities of production from reinforced composite materials are diverse; the choice of production technology is a very important stage in the design of products, which affects not only the properties of finished products, but also their costs.

When choosing a production method, it is necessary to take into account: the product design, the conditions of its operation, the properties of raw materials, the conditions of solidification of the connecting material, the technology of preparation of reinforcing materials, the cost of technological equipment and the volume of production of goods made of composite reinforced plastics.

The above review of the methods for reinforcing polymer products in the process of their manufacturing shows that the existing technology uses the primary unprocessed polymer as a reinforcing material.

The study presents methods for use of recycled polymer as part of a multi-layer product, deposited in hard-to-recycle area of this product.

It is also proposed to use recycled polymer waste as a matrix of reinforced polymer products.

It has been established that there is not enough equipment for mechanical processing of polymeric waste or it is not efficient enough. The equipment offered on the market is usually designed for processing of polyethylene or polyethylene terephthalate, but in most cases this equipment adapted from other branches of industry.

The development of modern processing equipment is carried out without taking into account changes in the polymer physical and mechanical properties during the production process.

Thus, the main drawbacks of the polymer waste processing by the available equipment are: significant energy consumption due to the destruction of crystallites; low productivity, due to rapid wear of working elements under the influence of friction and impact forces; significant reduction of the polymer operational properties; impossibility of shredding polymeric waste into oriented structure particles, and consequently, their subsequent use as fillers in the manufacture of light industry polymer products.

4.3. Designing equipment for footwear molding from a mixture of polymer and particles of recycled waste

Fig. 4.10 shows photographs of an experimental mold for investigating the effect of the presence of recycled waste in a polymeric material on the physical and mechanical properties of the soles.

The parameters of rational design of a device for transporting polymer particles and efficient modes of their delivery to the mold inlet channel are also determined, which provides a required distribution of particles in the sole volume. At the same time, it is possible to change the volumetric flow rate of the polymer particles into the mold inlet, changing: roughness of the screw surfaces and inner walls of the material cylinder; friction area (add certain elements or cut grooves); the material cylinder temperature.



Fig. 4.10. Mold for soles with particles of recycled waste addition: a – semi-closed state; b – closed state [own study]

If the screw slope angle is close to 90° , then the steady process of transporting the recycled waste particles into the molding inlet can be provided only with such a screw that the coefficient of friction between its surface and the polymer material is close to zero. It is clear that such conditions are not real. On the other hand, as the slope of the screw channel decreases, larger values of the friction coefficients ratio become acceptable (Fig. 4.11, 4.12).

The analysis has shown that at small screw slope angle values better conditions are created for transport of the polymeric material particles, and this angle should lie in the range between 19° (0.33 rad) and 24° (0.42 rad).

To ensure 10% concentration of recycled waste particles in the sole of male shoes and their even distribution in the soles, the performance of the mold filling with polymer melt of $250 \text{ cm}^3/\text{s}$ is needed, it is necessary to feed the particles into the mold inlet channel at a performance of about $25 \text{ cm}^3/\text{s}$, which is provided by the following parameters of the screw device: screw diameter $D = 0.05 \text{ m}$; revolutions $n = 80 \text{ min}^{-1}$; depth of screw channel 0.006 m ; angle of the screw channel 45° ; the friction coefficient ratio between the polymer particles and of the screw channel walls and the coefficient of friction between the polymer particles and the internal wall of the material cylinder 0.6.

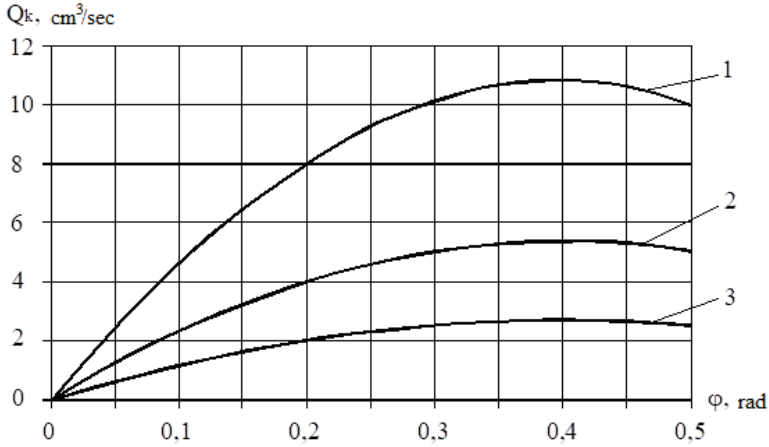


Fig. 4.11. Dependence of particles on screw slope angle on volumetric velocity: 1 – $n = 100 \text{ min}^{-1}$; 2 – $n = 50 \text{ min}^{-1}$; 3 – $n = 25 \text{ min}^{-1}$ [own study]

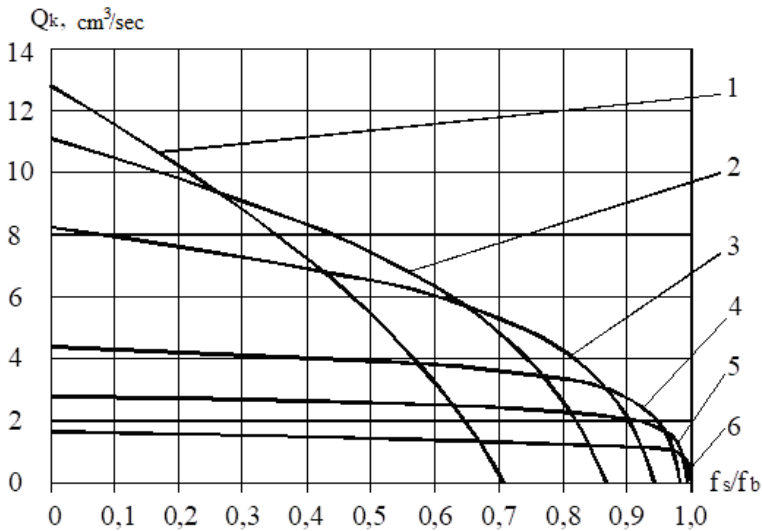


Fig. 4.12. Dependence of friction coefficients ratio at screw slope angle on volumetric velocity particles: 1 – $\phi = 45^\circ$; 2 – $\phi = 30^\circ$; 3 – $\phi = 20^\circ$; 4 – $\phi = 10^\circ$; 5 – $\phi = 6^\circ$; 6 – $\phi = 3^\circ$ [own study]

The feature of polymer products made with addition of particles of recycled polymer waste is a significant anisotropy of their mechanical properties, which is determined by the particle orientation in the matrix in one or more directions. The choice of orientation, concentration and size of these particles is determined by the distribution of stresses in the process of exploitation of light industry plastics.

This makes it possible to optimize the structure of the material according to the weight characteristics, which allows receiving polymer products with a minimized material capacity.

General and important characteristic of almost all types of filled polymer products is the length of the particles of recycled polymer waste, which is due to the structural and technological parameters of the processing equipment.

The main correct method for evaluating the physical and mechanical properties of filled polymers can be defined as the analysis of their tensile strength. Under tension of the filled polymeric products, the particles are submitted to tensile load, and the main polymer (matrix) – to shear load. Consequently, the polymer surrounding the particles must withstand the amount of shear load equal to the tensile load of the particle. The polymer strength is much lower than the strength of a particle with oriented structure. To ensure high strength of the filled polymeric products the particle length ratio to its transverse dimension, should not be less than 10.

In order to determine the influence of the size of the waste particle recycled from polyvinyl chloride on the physical and mechanical properties of soles for shoes made of polyvinyl chloride, experimental studies were carried out on the relationship between tensile stresses and deformations of the shoe soles for the particle size different values. Studies were conducted for polyvinylchloride soles with the inclusion of short ($l/d = 4..6$) and long ($l/d = 8..10$) particles of recycled polyvinyl chloride. The transverse particle size was about 1 mm.

Fig. 4.13 shows a graph of the stress tension dependence on the deformation of polymer samples cut from a filled sole along and across the particle orientation, from a long fraction of polyvinyl chloride.

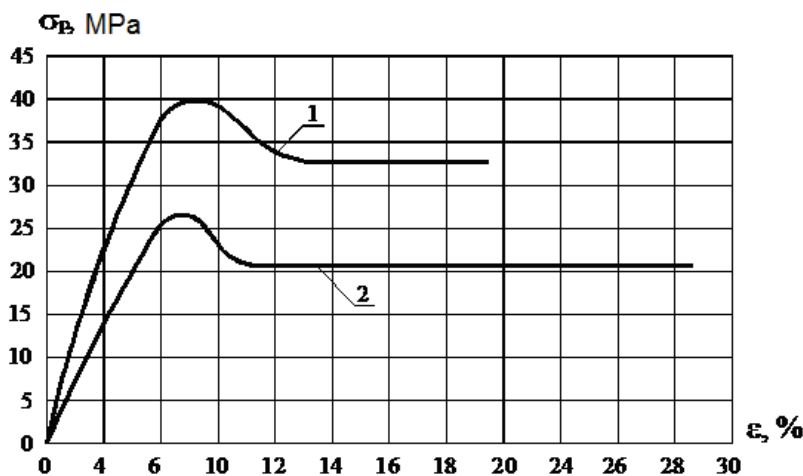


Fig. 4.13. Diagram of breaking of polymer specimens, filled with long polyvinyl chloride particles: 1 – along the orientation of particles; 2 – across the orientation of particles [own study]

As can be seen in Fig. 4.13 the impact of the particle length on the properties of the soles is significant. Thus, the improvement in performance characteristics of polymeric light industry products can be achieved by filling them with long particles that need to be oriented along the direction of the load during the operation. To ensure greater flexibility of a polymeric product without its rupture, long particles should be oriented across.

The shorter the filler particles, the less efficient it is. In the case of short particles, the matrix cannot provide the particles with tensile stress sufficient to destroy them. Thus, the reinforcing ability of short particles (increasing the operational properties of a polymeric product) is rather low, especially taking into account the particle orientation which is not ideal for molding or extruding polymer products. The structure of polymer products being filled with particles of a short fraction is chaotic. The advantage of fillers with particles of a short fraction is the possibility of the polymer faster processing into products.

On the basis of the obtained results, a mold for experimental studies of the influence of its design parameters and technological characteristics of injection molding on formation of the shoe sole structure with particles of polymer waste was designed and manufactured. The process of the mold filling and the shoe sole structure forming from a mixture of polyvinyl chloride and particles of recycled waste from polyvinyl chloride was conducted.

Analytical dependencies that connect the parameters of the device for transporting recycled polymer waste particles to the molding inlet channel with the particle bulk feed rate have been developed to determine rational structural parameters of the device and efficient transport modes for which necessary concentration and distribution of particles in the sole volume is achieved.

The experimental tests of breaking strength and fatigue life the soles made by injection molding from a mixture of PVC and particles of recycled polyvinyl chloride have shown that the concentration and orientation of the recycled polymer waste particles in the finished product substantially affects its performance.

It has been established that for 10% concentration of the recycled polyvinylchloride waste particles in the process of injection molding, their durability and endurance along the particle orientation increased by 28% and 14%, respectively, and across the orientation by 9% and 12%. With an increase in the recycled waste concentration by more than 15%, the strength and endurance of the sole is reduced.

Improvement in the performance characteristics of shoe soles made by injection molding of a mixture of polyvinyl chloride with particles of recycled polypropylene was confirmed by experimental tests of breaking strength and fatigue life. The results of these tests can be used in the design of processing equipment to obtain particles of the required shape and size and in the design of molds to provide the required concentration and orientation of particles in light industry polymeric products.

SUMMARY

The goal of the monograph was to provide solution to the scientific and technical problems involved in designing resource-saving technologies and equipment for environmentally friendly recycling of polymer waste.

Today, polymer waste of light industry and other industries is processed by chemical recycling and mechanical grinding. Chemical processing of polymeric materials has significant drawbacks including high cost of the process and a significant reduction of the physical and mechanical characteristics of the recycled material. Mechanical recycling of polymer waste is simpler, cheaper and more productive than chemical, but there are not many devices for mechanical processing of light industry polymer waste. The equipment available on the market is used for processing of polyethylene terephthalate (PET), however, in most cases it is adapted from other industries. Modern methods of designing equipment for the polymer waste processing do not take into account changes in the structure of the polymer that appear during processing that cause the following drawbacks: significant energy consumption and reduced performance properties of the recycled polymer due to destruction of super molecular formations of the polymeric material.

New technological processes and equipment for polymer waste recycling have been developed for the manufacture of light industry polymeric products with increased performance characteristics. Manufacturing of such products was possible by the development of a mathematical model for movement of the mixture of polymer material with particles of recycled polymer waste in the process of filling the mold cavity which, unlike the existing models, allows to observe formation of the polymer product structure with the content of recycled waste particles.

Key words: light industry equipment, polymer waste, design, toothed rolls, Relo profile rolls, polymer structure, deformation, loading, fracture, molding soles, reinforced soles.

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