Improvement of extrusion equipment and technologies for processing secondary combined polymer materials and mixtures

V V Dyadichev1, A V Kolesnikov2, S G Menyuk1 and A V Dyadichev1

1V.I. Vernadsky Crimean Federal University, Academy of Construction and Architecture, Engineering Center “Bio-positive Construction and Resource-Saving”, 3 Pavlenko Str., Simferopol, Crimea, 295000, Russia
2Lugansk National University named after Vladimir Dal, Department of Automation and Computer-Integrated Technologies, 20-A Molodezhnyi Sq., Lugansk, 91034, Ukraine

Abstract. The article is devoted to the solution of scientific and technical problem of perfecting the extrusion equipment and technology for processing secondary combined polymeric materials and polymeric mixtures including wastes, by the method of extrusion with use of multi-section screw that allows to manufacture new high-quality products and reduce the environment pollution. A new screw design is proposed consisting of several functional sections. A mathematical model for operation of the extruder with the multi-section screw has been developed to analyse the operation parameters and produce new designs of the extruder screw. Based on the studies of the functional purpose of the extruder zones and features of processing the polymeric mixtures with secondary raw materials, a functional diagram of the screw is proposed. The thickness values of the strips of the polymer mixture components at the outlet of the extruder sections for analysing the mixing capacities have been obtained. It has been established that the extruder with the multi-section screw can be used with effective combination of two stages: mixing and basic processing. With the help of mathematical modelling the diagrams of linear velocities and shear rates for each extruder section have been obtained.

1. Introduction

In view of the ever-increasing waste streams and shrinking of natural resources, it is environmentally reasonable to produce and use recycled materials. A significant proportion of secondary raw materials is made of polymeric materials [1].

One of the major refining technology processes is extrusion of polymeric materials [2]. It varies by the types of manufactured products: films [3], sheets [4], pipes [5], a variety of moulded plastic profiles, etc.

2. Formulation of the problem

The extruder is a technological equipment that implements the extrusion process [6]; the extruder main part is the screw. The screw takes unplasticized material from the hopper, uniformly mixes it and applies it evenly as a homogeneous melt to the head [7].

While moving up the extruder channel, the material is heated and melted by the heat generated due to viscous friction and the heat supplied from the heaters located on the housing [8].
The main technological parameters of the extrusion machine are: the speed of the extruder screw rotation [9], the temperature of the heaters, and the pressure developed by the extruder [10].

In the process of recycling plastic polymers and mixtures, the quality of products produced from the polymer wastes is highly influenced by the polymer melt indices at the extruder outlet [11].

The polymer melt indices imply the melt structural homogeneity and absence of unmolten and degraded inclusions, uniform temperature field [12], and absence of pressure fluctuations [13]. It is possible to achieve the rational melt parameters by improving the extruder screw design directly for the waste processing of a certain classification group and successive determination of the necessary ranges of the technological parameters for the recycling process [14].

The scientific literature and articles about practical results of tests point out that among the existing kinds of second polymeric raw materials the most complex and least studied ones are secondary composite materials [15].

Thus, the development of specialized designs of screw assemblies for the extrusion process is an actual scientific and practical task.

3. Theory
The single-section screws, when used in procession of secondary combined polymer raw materials, have a poor performance quality [16]. The products obtained with use of these screws have a heterogeneous structure [17]; the melt being moulded contains unmelted inclusions [18]; the strength values are low [19]. This is due to certain properties of combined secondary raw materials [20], which require the material to undergo several successive modification stages in the extrusion unit [21].

It is possible to ensure such processing by designing a screw with several functional sections [22], in other words, by developing a special multi-section screw [23] meant for processing combined secondary polymer raw materials.

However, the operation of the extruder screw with multiple units has not been studied sufficiently, besides, the rational design parameters of the sections for different groups of recyclable materials have not been defined [24].

The multi-section screw has been developed for processing the polymeric mixtures containing second combined raw materials by the method of the extrusion shaping. The screw provides uniform melting of mixture components, homogeneous mixing, removal of volatile mixtures, and creation of a molten polymeric stream at the output with stabilized pressure and productivity.

Based on the results of studies of the functional purposes of the extruder zones and features of processing the polymeric mixtures with secondary raw materials, the functional diagram of the screw is proposed (Figure 1).

The proposed extruder for processing thermoplastics comprises: the body (1), the gripping device (2), the screw (3), the supply zone (4), the compression zone (5) composed of the barrier section (6) and the decompression section (7), the dosing zone (8) consisting of the conical section (9) and the cylindrical section (10). This extruder provides uniform melting of the mixture components, homogeneous mixing, removal of volatiles from the melt and creation of a molten polymer flow at the outlet with stabilized pressure and performance.

![Figure 1. Functional diagram of the screw for procession of second polymeric raw materials.](image-url)
To determine the rational parameters of the extruder screw design with multiple units it is necessary to create a mathematical model [25]. The model is a consistent and parameter-integrated mathematical representation of the extruder operation in processing plastics, with calculation of the specific consumption of the polymer melt being extruded at the extruder outlet, the pressure developed at the outlet, the average thicknesses of the strips of the processed polymer mixture components at the outlet.

The mathematical model is a cycle at the independent coordinate \( l \), the exit from which occurs in case of a coincidence of the current coordinate position of the length and the screw length.

At the end of each cycle step \( i \) the modelling parameters \( i (1), Li[i] (2) \) and the dependent geometrical dimensions of the sections (mainly the \( h_i \) channel depth) are building up from the screw length coordinate, according to the following equations (1) and (2):

\[
i = i + 1
\]

\[
Li[i] = Li[i-1] + dl
\]

where

\( Li[i-1] \) is the screw length at the current step of the cycle, mm;
\( Li[i] \) is the screw length at the next step of cycle, mm.

4. Experimental results

With the help of mathematical modelling diagrams the linear velocities and shear rates for sections of the extruder were obtained. Figures 2 and 3 show the diagram of the linear velocity and shear gap in the barrier where the melt is subjected to the greatest shear deformation, and, consequently, to the mixing effects.

Based on the analysis of the relative contributions of the sections to the mixing process, it is established that the best mixing is achieved in the barrier section, and the extruder with the multi-section screw can be used with an effective combination of the two stages: mixing and primary processing.

![Figure 2. Diagram of linear velocities in the barrier gap.](image-url)
Figure 3. Diagram of shear rates in the barrier gap.

With the help of mathematical modelling the influence dependencies of the design parameters: the width of the barrier turn along the screw axis (\( e_b \)), the gap between the surface of the barrier turn and the extruder barrel (\( z_b \)) were determined (Figure 4.).

Figure 4. The plots of the effect of the geometrical dimensions of the barrier turn on the quality of the mixture components in the barrier section.

5. Discussion of the results

The plots in Figure 4 show that the mixing quality improves inversely proportionally to the increasing width of the barrier turn and improves directly proportionally to the decreasing gap between the surface of the barrier turn and the extruder cylinder.

A similar evaluation of the existing designs of single-section screws was carried out to compare the parameters of the developed multi-section design by the method of modelling [26, 27].

For this purpose, the program of the mathematical model was adjusted considering the type of the section that represents the appropriate type of the screw.
The two most commonly used prototypes were selected for comparing:

– the cylindrical screw with the constant channel depth \( h = 4 \text{ mm} \);
– the taper screw with the channel depth decreasing linearly along the screw length from the hopper size \( h_1 = 4 \text{ mm} \) up to the size at the end of the dosing zone \( h_2 = 1 \text{ mm} \).

The first prototype in the analysis of the mixing screw abilities is represented as two mixing sections: the feed section and the cylindrical section of the dosing zone.

The second prototype in the analysis of the mixing screw abilities is represented as two mixing sections: the feed section and the taper section of the dosing zone.

The thickness of the strips for the single-section prototypes under consideration is much larger than for the multi-section screw. Thus, such single-section designs can be used only as a tool for melting the polymer mass uniformly. If the polymer mass is a multi-component mixture, before using the standard single-section extruder it is necessary to mix the components using additional mixing machines. This incurs an additional stage in the processing technology and extra expenses of using such mixing equipment.

And if the extruder with the developed multi-section screw is used, the two processing stages are technologically combined: the preparation stage (mixing) and the main stage (processing to produce a new product).

Let us make a comparative estimation of the developed design and the multi-section screw that is used for processing of plastic waste by coextrusion [28, 29]. A significant fault of this prototype is a narrow range of rational operative frequencies: 0.24-0.42 s\(^{-1}\). Figure 5 shows the comparative dependencies of the component strip thicknesses at the operative frequency bands. The operative frequency range of processing secondary polymeric raw materials for the designed extrusion screw is 1.13-1.92 s\(^{-1}\), the range width is 4.4 times larger than the value of the prototype.

Thus, the developed multi-section screw is more appropriate for extrusion processing of second polymeric raw materials due to the wider range of effective operative frequencies. Using the frequency values with maximum quality of the mixing performance will increase the mixing productivity by a factor of 4.71, which is necessary for the extrusion process. Furthermore, the use of the channels with different roughness in the barrier section and rational design parameters gives a mixing quality increase by a factor of 4.3 compared to the prototype value.

6. Conclusions
1. Based on the results of the mathematical modelling, the thickness values of the strips of the polymer mixture components at the outlet of the extruder sections has been obtained to analyse mixing capabilities.
2. By the method of sequential modelling of certain parameters values, an assessment of the influence of the barrier turn design parameters on the strip thicknesses has been made to rationalize the barrier section structure. The rational range of the barrier turn width \((e_b)\) is 4-6 mm, with the strip thicknesses of the components \(r = 0.00173-0.00112\) mm. A further increase in size has a minor effect but reduces the overall width of the barrier section channel.

3. By mathematical modelling the range of rational values of the extruder screw speed has been established, which is 1.13-1.92 s\(^{-1}\) and provides the component strip thickness \(r = 0.00007-0.00004\) mm.

4. On the basis of mathematical modelling and comparative assessment of the proposed multi-section design of the screw versus the existing prototypes it has been established that unlike the single-section design, the multiple-section screw can combine both mixing and processing features in order to improve the processing of multicomponent polymeric structures.

5. Based on a comparative analysis of the operative frequency ranges for the considered prototype and the multi-section design it has been established that the width of the operating frequency range of the developed screw is by a factor of 4.4 larger and the minimum thickness of the strips is in by a factor of 4.3 smaller than these of the prototype under consideration. Therefore, the developed multi-section design allows to achieve an increase of productivity of processing combined secondary polymeric materials by the extrusion method by a factor of 4.8 and enhance the flexibility of the equipment adjustment for other secondary products.

7. References

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