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*A.L. Sokolskii, K.G. Kovalenko, V.I. Sivetskii, E.P. Kolosova***REALIZATION OF THE REVERSE PROBLEM OF GEOMETRICAL MODELING IN DESIGNING OF DIE HEADS FOR THE PRODUCTION OF POLYMER PRODUCTS****National Technical University of Ukraine «Igor Sikorsky Kyiv Polytechnic Institute», Kyiv**

In this paper, we present the procedure and results of refined design calculations of die (extrusion) heads intended for shaping profile products of polymeric materials. The effects associated with the change in shape and size of the profile after exiting the die head are taken into account in calculations. The polymer is considered as a viscoelastic fluid. The aim of the simulation is to determine the geometric shape of the head channel, which will result in a balancing of the outflow costs from the head and ensuring the condition for obtaining the given product profile. The modification of the channel shape by using the optimization algorithm allows calculating the geometry of the forming channel of the heads for the given sizes of the extruded articles. To solve the inverse extrusion problem, the Fletcher-Reeves algorithm is implemented, which is used in determining the geometry of the head forming channel to provide the desired shape of the extruded profile. To describe the dependence of the shear rate on the viscosity of the material being processed, the Berd-Carro model is used. The developed method allows solving the inverse problem of the process of extrusion molding of continuous products; that is to say, it makes it possible to design the necessary configuration of the die head if the properties of the thermoplastic material to be processed and the geometric parameters of the extruded product are known. The obtained results of the performed studies allow obtaining analytical dependencies and calculating the most expedient design parameters of the die heads, as well as choosing the optimal technological parameters of the process of products manufacture, including those with complex shapes originating from both existing and new polymer compositions.

Keywords: extrusion, die head, modeling, profile, thermoplastic, Barus effect.

Introduction

The calculations of equipment for the production of polymer products require consideration of many technological factors and complex geometric configurations. Therefore, they are carried out using computer numerical simulation methods [1–3]. The results of numerical simulation are used as a basis for the design and technological automated design of the technologies and equipment under investigation, in particular, for extrusion molding of polymer products.

One of the effective tools for geometric modeling of technology and equipment for the formation of polymeric products is the methodology of structural-parametric geometric modeling [4]. One example of the application of this promising modern methodology of computer-aided design is a determination of design and technological parameters of ultrasonic equipment. It is widely used as an

intensifying factor in the production of polymeric composite materials, both the thermosetting plastics and the thermoplastics [5].

In the case of forming extruded molded products, the main tool that defines the final shape of the product is a die (extrusion) head. The calculations of the die heads for forming profile products from polymeric materials also implies modern computational methods. They allow determining the distribution of pressure, velocity, temperature and polymer properties without performing costly experimental studies [6,7]. At the same time, in order to achieve a given geometric shape and profile dimensions, it is necessary to take into account the effects associated with changing the shape and size of the profile after exiting the extrusion die [8].

The task of numerical simulations is the refined design of the geometry of the forming channels of

die heads for the production of polymer profiles. In processes of the production of profile products, it is not enough to introduce changes in the specified technological parameters of the extrusion process, for example, the temperature regime or the screw rotation speed to compensate for imperfections in product dimensions.

The geometry of the extruded profiles largely depends on the phenomenon of swelling of the extrudate at the exit from the head. At the same time, polymer flow rates are rearranged in such a way that they are decreased in the direction of flow and increased in transverse directions (the so-called Barus effect). In the case of angular and other asymmetric profiles, the swelling phenomenon predetermines the need to perform shaping channels of a slightly different geometry. At the same time, the melt, leaving this necessary, but not orthogonal shape, will swell into the desired geometry of the product.

Procedure of numerical simulation

The aim of the numerical simulation is to determine the shape of the head channel, which will result in balancing the output costs from the head and ensuring the condition for obtaining the given product profile. The modification of the shape of the channel using the optimization algorithm makes it possible to calculate the geometry of the forming channel of the die heads for the given dimensions of the extruded articles [9].

The geometry of the forming channel of the die head is determined by solving the inverse problem of modeling, in which the target profile is defined as the shape of the extrudate in the direction of the flow. The task is to establish the required geometry of the die head forming channel at the output, which determines the equalization of the melt velocities in the free surface region and the given geometry of the section of the polymer profile [10].

To apply the algorithm, the initial bounded problem is transformed so that it can be solved as a series of unbounded problems.

The basic approach is to minimize the following function:

$$\Phi(\mathbf{X}) = F(\mathbf{X}) + f(\mathbf{X}),$$

where $\Phi(\mathbf{X})$ is the pseudo-target function of the geometry of the target profile; $F(\mathbf{X})$ is the geometric parameters that cannot be changed; $f(\mathbf{X})$ is the penalty function of deviating the geometry of the profile from the specified profile; \mathbf{X} is the set of geometric parameters of the forming channel ($\mathbf{X} = \{x^k\}$).

To solve the «inverse extrusion problem», a Fletcher-Reeves (FR) algorithm is implemented, which is used to determine the geometry of the head forming channel to provide the desired shape of the extruded profile.

The FR method implies the search for a string method to find the minimum function in a given search direction. The strategy of the FR method [11] consists in the construction of a sequence of points, $k=0, 1, 2, \dots$ such that $f(x^{k+1}) < f(x^k)$, $k=0, 1, 2, \dots$

The sequence points are calculated by the following rule:

$$x^{k+1} = x^k - t_k d_k, \quad k=0, 1, 2, \dots;$$

$$d_k = \nabla f(x^k) + b_{k-1} \nabla f(x^{k-1});$$

$$b_{k-1} = \frac{\|\nabla f(x^k)\|^2}{\|\nabla f(x^{k-1})\|^2}.$$

The step size is chosen from the condition of the minimum of the function $f(x^k)$ with respect to t in the direction of motion, that is, as a result of solving the one-dimensional minimization problem:

$$f(x^k - t_k d_k) \rightarrow \min (t_k > 0).$$

At the points of the sequence $\{x^k\}$, the gradients of the function $f(x)$ are mutually perpendicular. The construction of the sequence $\{x^k\}$ ends at the point for which

$$|\nabla f(x^k)| < \varepsilon,$$

where ε is the permissible deviation of the geometry.

The design process begins with specifying the shape of the product. The specified product is an L-shaped single-chamber hollow profile (Fig. 1,a) with external dimensions of 15×30 mm and with an internal rib thickness of 1.5 mm.

Only the shape of the forming channel is considered which is one of the most important elements in the extrusion process, because it must compensate the deformation of the extrudate after exiting the die head and ensure its predetermined geometry.

The shaping channel is divided into two sub-regions (as shown in Fig. 1,b) to enable the use of algorithms for reorganizing the grid in each sub-region when modeling their profiles. The first sub-

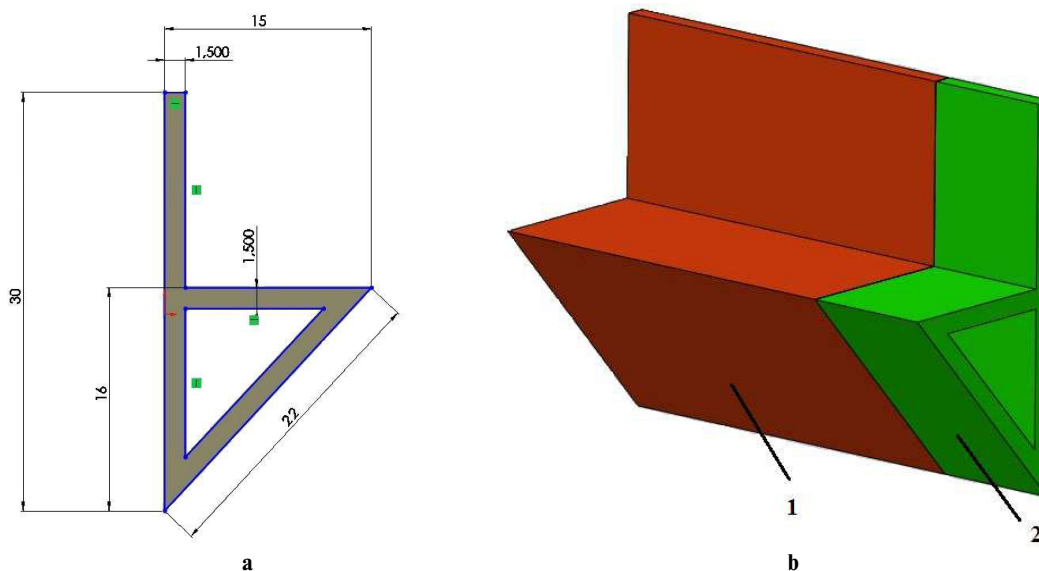


Fig. 1. Calculation model: a – the dimensions of the cross-section of the extruded profile; b – the scheme for splitting the die head and extrudate into sections of the forming channel of the die head and the extrudate that follows from it (1 – extruded profile, 2 – forming channel)

region is a channel of the die head where the melt flows. The second sub-region is an extruded profile that is in contact with air [10].

Polyvinyl chloride (PVC) is used as a recyclable material. To describe the dependence of the shear rate on the viscosity of the material being processed, the Berd-Carro model is used [1]. The polymer is considered as a viscoelastic fluid. In this study, it is assumed that the polymer temperature is constant and equal to 180°C. The flow of the polymer melt is considered incompressible. Gravitational and inertial forces are neglected.

The design area must have appropriate boundary conditions for displaying the actual conditions that are present in the melt that passes through the extruder head and leaves the free flow surface as follows:

- at the entrance to the forming channel, the melt flow rate is set;
- at the exit of the extrudate from the forming channel, the zero pressure gradient;
- on the free surface of the extrudate equilibrium conditions are set on the free surface and the zero value of the swelling speed;
- on the walls of the head, the boundary condition for the absence of slip is applied, which under the given conditions is sufficiently correct [12].

Only the last two extrusion channels for flow modeling have been developed and taken into account, since they have the greatest influence on the shape of the extruded profile [7].

The results of modeling and their analysis

At the first stage, a simulation was performed without taking into account the possibility of compensating swelling of the extrudate and other effects, as shown in Fig. 2,a. The incorrect shape of the final product is evidently due to the presence of local sections of unstable pressure and the flow velocity along the length of the section of the forming channel of the head. This causes the shaping in the process of extrusion of the profile of distorted shape and with different wall thicknesses. The difference in the local thickness is due to the heterogeneity of the polymer flow velocities along the section thickness (up to 20 mm/s), which is shown in Fig. 2,a.

Based on the results obtained in initial simulation, the next step was the implementation of an algorithm for solving the inverse problem of extrusion, which consists in determining the geometry of the shaping channel of the head to provide the desired shape of the extruded profile. In order to obtain the given final form of the extrudate by the FR method, the geometry of the forming channel over a length of 60 mm was changed. The results of this iterative simulation are shown in Fig. 2,a, b.

When considering each section of the channel, one can trace the features of the flow of the polymer and determine the regions with a slow motion of the polymer material. This can lead to distortion of the shape of the extruded product or to the local destruction of the polymer in it.

The deformation of the extrudate when the

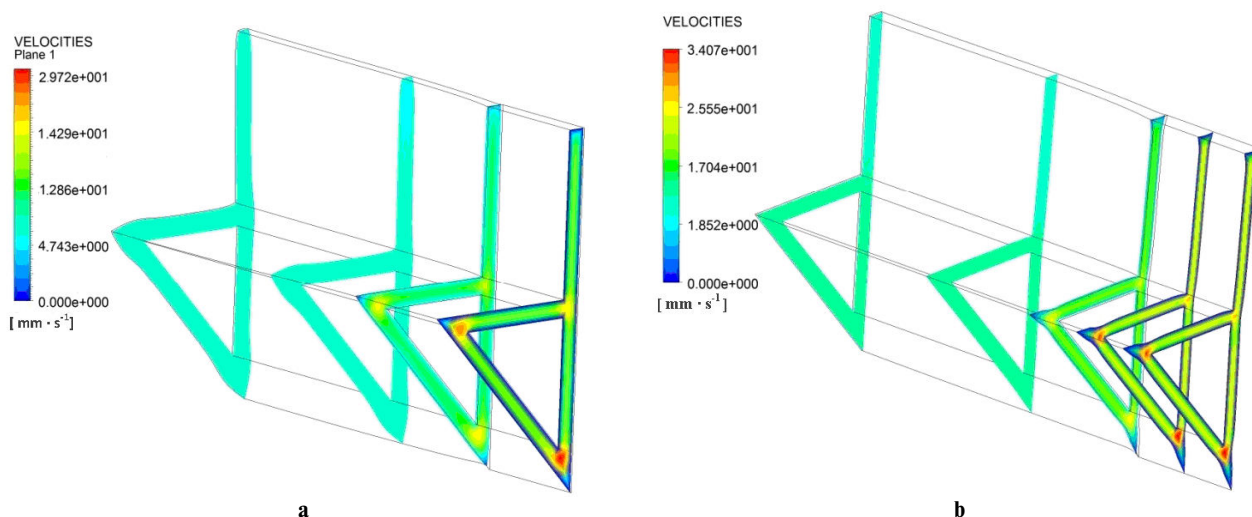


Fig. 2. Distribution of velocities in different sections of the head and extrudate: a – without an optimized forming channel; b – with an optimized channel shape

channel geometry is changed is the result of a rearrangement of the velocities occurring at the exit from the head. In areas where the flow of liquid has a high velocity, the cross section of the extrudate increases, and vice versa, the flow of liquid at a low speed reduces its cross-section. To avoid this, the considered modeling technique allows refining the geometry of the forming channel of the head and obtaining an extruded profile of a given shape.

Fig. 3 shows variants of the unoptimized and optimized geometry of the initial region of the head forming channel and the possibility of predicting the geometry of only the last section of the forming channel.

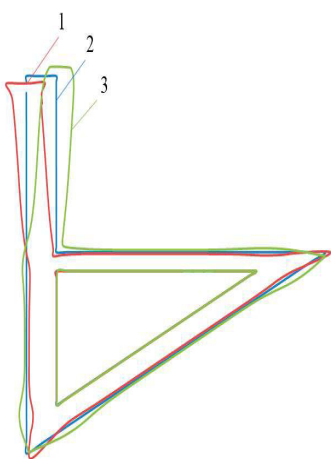


Fig. 3. Transverse output cross-sections of the region of the shaping channel of the head of an unoptimized and optimized

shape: 1 – the configuration of the cross section of the head matrix is necessary; 2 – the necessary profile configuration; 3 – irregular shape of the profile of the final product

The performed simulation implements the algorithm of the «inverse extrusion problem», which calculates the shape of the output section of the head necessary to achieve the dimensions of the target profile at the exit from the free surface. As a result, the shape of the head channel is calculated which will allow obtaining the shape of the specified target profile with compensation of the swelling effect of the extrudate.

The obtained results of the performed studies allow determining analytical dependencies and calculating the most expedient design parameters of die heads, as well as choosing the optimal technological parameters of the process of obtaining products, including those of complex shapes [13], from both existing and new polymer compositions. This makes it possible to achieve savings in structural materials in the manufacture of the die head [14] and improve the quality of polymer products [15] by increasing the accuracy and stability of their dimensions as well as reducing the amount of defective products.

Conclusions

The developed technique allows solving the inverse problem of the process of extrusion molding of continuous products. That means, it makes it possible to design the necessary configuration of the die head and, in particular, of its nozzle outlet if the properties of the thermoplastic material to be processed and the geometric parameters of the extruded article are known.

The procedure involves the use of multivariate calculations of the domain with the methods of grid reorganization, most suitable for 3D inverse problems of extrusion molding. This allows achieving maximum extrusion performance with high quality of the resulting products, including its dimensional accuracy and physical and mechanical characteristics.

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РЕАЛІЗАЦІЯ ОБЕРНЕНОЇ ЗАДАЧІ ГЕОМЕТРИЧНОГО МОДЕЛЮВАННЯ ДЛЯ ПРОЄКТУВАННЯ ЕКСТРУЗІЙНИХ ГОЛОВОК У ВИРОБНИЦТВІ ПОЛІМЕРНИХ МАТЕРІАЛІВ

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У даній роботі наведено методику та результати уточнених проектних розрахунків екструзійних головок, призначених для формування профільних виробів з полімерних матеріалів. У розрахунках враховувалися ефекти, пов'язані зі зміною форми і розмірів профілю після виходу з екструзійної головки. Полімер розглядався як в'язко-пружна рідина. Метою моделювання є визначення геометричної форми каналу головки, що приведе до збалансування витрат на виході з головки і до забезпечення умов одержання заданого профілю виробу. Зміна форми каналу з використанням алгоритму оптимізації дозволяє проводити розрахунок геометрії формуючих каналів головок за заданими розмірами екструдованих виробів. Для обчислення оберненої задачі екструзії реалізований алгоритм Флетчера-Рівса, який застосовується при визначенні геометрії формуючого каналу головки для забезпечення бажаної форми екструдованого профілю. Для опису залежності швидкості зсуву від в'язкості матеріалу, що переробляється, застосовується модель в'язкості Берд-Каро. Розроблена методика дозволяє вирішити зворотну задачу процесу екструзійного формування безперервних виробів, тобто при відомих властивостях перероблюваного термопластичного матеріалу і геометричних параметрах одержуваного екструзією виробу спроектувати необхідну конфігурацію екструзійної головки. Результати здійснених досліджень дозволяють отримувати аналітичні залежності і розраховувати найбільш доцільні конструктивні параметри екструзійних головок, а також вибирати оптимальні технологічні параметри процесу одержання виробів, у тому числі складної форми, з існуючих і нових полімерних композицій.

Ключові слова: екструзія, екструзійна головка, моделювання, профіль, термопласт, ефект Баруса.

REALIZATION OF THE REVERSE PROBLEM OF GEOMETRICAL MODELING IN DESIGNING OF DIE HEADS FOR THE PRODUCTION OF POLYMER PRODUCTS

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In this paper, we present the procedure and results of refined design calculations of die (extrusion) heads intended for shaping profile products of polymeric materials. The effects associated with the change in shape and size of the profile after exiting the die head are taken into account in calculations. The polymer is considered as a viscoelastic fluid. The aim of the simulation is to determine the geometric shape of the head channel, which will result in a balancing of the outflow costs from the head and ensuring the condition for obtaining the given product profile. The modification of the channel shape by using the optimization algorithm allows calculating the geometry of the forming channel of the heads for the given sizes of the extruded articles. To solve the inverse extrusion problem, the Fletcher-Reeves algorithm is implemented, which is used in determining the geometry of the head forming channel to provide the desired shape of the extruded profile. To describe the dependence of the shear rate on the viscosity of the material being processed, the Berd-Carro model is used. The developed method allows solving the inverse problem of the process of extrusion molding of continuous products; that is to say, it makes it possible to design the necessary configuration of the die head if the properties of the thermoplastic material to be processed and the geometric parameters of the extruded product are known. The obtained results of the performed studies allow obtaining analytical dependencies and calculating the most expedient design parameters of the die heads, as well as choosing the optimal technological parameters of the process of products manufacture, including those with complex shapes originating from both existing and new polymer compositions.

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