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D.E. Sidorov, E.P. Kolosova, A.E. Kolosov, I.A. Kazak

EVALUATION OF KINEMATIC PARAMETERS OF PROCESS OF GRAVITATIONAL STRETCH OF A BILLET FOR EXTRUSION-BLOW MOLDING OF POLYMER PRODUCT

National Technical University of Ukraine «Igor Sikorsky Kyiv Polytechnic Institute», Kyiv

Engineering methods for estimating the kinematic parameters and reduction of an extrusion billet in the process of blow molding under conditions of gravity stretching are developed in this work. The interrelation between the components of the speed of the billet motion in its various sections and the extension coefficient with the geometric and technological parameters of the gravitational elongation process is established. It is shown that the rate of gravity extension is not constant and can vary many times in different sections of the polymer billet. It is established that the instantaneous rate of gravity extraction in the zone of melt exit from the extrusion head (die) can be up to 18% of the linear extrusion rate. At the same time, an increase in the velocity of the cross sections due to the gravitational stretching is the more significant, the longer the length of the polymer billet is. It is stated that the dynamic viscosity of the melt as well as the extrusion temperature is not a decisive factor which might significantly affect the shape of the billet under conditions of normal technological regimes. It is shown that the coefficient of gravitational extension changes by 16–17% with the change of the length of a polymer billet in the process of its production. For the volumetric productivity of the extruder of 102 cm^3/s, the unevenness of the gravity extraction conditions of the extruded billet can be up to 14%. It is established that the unevenness of the conditions of the deformation of the extrusion billet increases with a decrease in the extruder's productivity, it can reach 33%.

Keywords: process, extrusion, gravitational stretch, blow molding, billet, melt, thermoplastic.

Introduction

The blow molding method is widely used for the production of inner hollow products from thermoplastic polymers [1]. For example, plastic canisters, bottles, three-dimensional toys with an internal cavity, plastic bellows and so on are obtained by this method.

The essence of the method of extrusion-blow molding consists in blowing a previously prepared polymer melt, which in the initial state has a form of a cylindrical bubble. The extruded polymer billet is blown up to the inner surface of the metal mold of the blow molding machine or semiautomatic machine and repeats the shape of its inner surface. After contacting with the cold metal of the press-form, the melt of the thermoplastic polymer cools, solidifies and forms a plastic product. Then, the molded article is unloaded and, if necessary, passes the finishing machining step including removal of the formed technological flash.

At the same time, the study of the kinematic parameters of the process of gravitational stretch of the billet for extrusion blow molding of a polymer product is of current importance in the context of influencing both the productivity of the forming equipment and the quality of the resulting product.

Analysis of literary data and definition of the problem

There are two-stage and one-stage methods of blow molding billet [1]. In the two-stage method of molding, the polymer billet is molded in the first stage, usually, by injection molding. In this case, it already represents the final commercial product, the preform. In the second stage, the preform obtained in the first stage is placed in an infrared heating furnace. It is heated there to reach a temperature above the glass transition temperature.

The features of this method have been investigated, for example, in study [2]. The preheated preform is transferred to the cavity of the press-form. In the press-form, it is inflated with subsequent cooling and molding of the final product, bottles.

The second stage can be technologically realized as a part of a line for bottling a product into a finished bottle. As can be seen from the foregoing, a thermoplastic polymer must undergo a double heat treatment in the two-stage molding method: firstly when the preform is prepared and secondly when the finished article is molded.

A one-stage blow molding method is devoid of this drawback, since this method does not include the stage of manufacturing the preform. The polymer melt emerges from the extrusion head, it is formed as a hollow cylinder and is directly an extrusion billet. A press-form is closed around it and the product is blow molded.

If the capacity of the worm extruder is not sufficient to prepare the desired amount of polymer melt, for example for the overall product, then the melt accumulators with a hydraulic ram are used to force it through the head. In some cases, the process of extrusion is replaced by the process of injection into a closed form [1]. Figure 1 illustrates the steps of a one-stage method for molding an extrusion blow molded article.

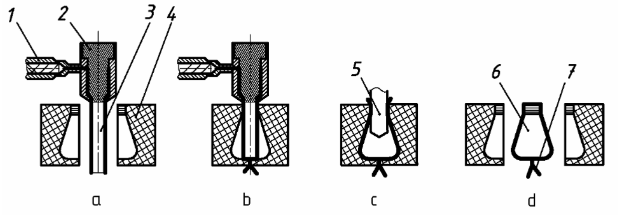

Fig. 1. Preparation of an extrusion blow-molded article by a single-stage blow molding method: a – extrusion of the billet; b – closing of the press-form; c – blowing of the polymer billet; d – unloading the finished product; 1 – extruder; 2 – molding die; 3 – polymer billet; 4 – the press-form; 5 – pneumatic blowing system of polymer billet; 6 – finished product; 7 – technological flash

The current level of scientific knowledge allows calculating almost all parameters of the technological processes occurring in extrusion equipment [3,4]. The modeling of the melt forming process of a polymer in extrusion heads has been carried out in work [5]. The process of surface formation during the production of corrugated polymer products has been considered in study [7]. The investigation [8] was devoted to the structural and parametric modeling of the operations of the process of molding polymeric composite materials by giving an example of reactoplastics which is also applicable to thermoplastics.

In study [9], the issues of calculations of extrusion blowing equipment for the analysis and optimization of the technological process in obtaining an equal-thickness product were investigated.

This problem was solved using the genetic algorithm, which significantly reduced the number of iterations to achieve the final result. The investigation of the influence of various factors of the blow molding process, including the geometry of a polymer billet, on the formation of polymer waste in the manufacture of the product was carried out in work [10].

The problem of optimizing the thickness of the billet for the blow molding of articles using the hybrid method of numerical calculations was presented in study [10]. The relationships between the parameters of the free extrusion process and the geometry of the extrusion tube billet in the processes of extrusion billet preparation and shaping of the surfaces of corrugated polymer pipes were revealed in studies [11–13].

The above studies were carried out numerically using significant computing resources and, in most cases, using commercial software. Such calculations can be performed by highly qualified engineers with special training. However, an operational express estimation of the parameters of gravity extension of a billet is often required for the process of extrusion blow molding of the product.

It should also be noted that the researchers paid a little attention to the kinematics of the motion of the extruded billet during its shaping in the process of gravitational stretch and the estimates of the stretch speed and the stretching coefficient. At the same time, the study of these issues is extremely important, because these parameters ultimately affect the productivity of technological equipment, the quality of the product and the amount of rejects [14].

The purpose of this work was to estimate the kinematic parameters and extrusion billet stretch ratio for blow molding under conditions of gravity stretch as well as to establish the relationship between the components of the billet movement speed and the extension ratio with the geometric and technological parameters of the gravity extension process. The research tasks also included obtaining and analyzing, based on mathematical modeling, the dependencies for the speed of gravity extension, the velocity of the cross sections, and the gravitational extension coefficient.

Results and discussion

A specific feature of the proposed approach to estimation of the kinematic parameters of the process of gravitational stretch of a billet for extrusion blow molding of a product is that it does not require special training of an engineer and significant computing resources.

The gravitational extension scheme of the polymer extrusion billet is shown in Fig. 2.

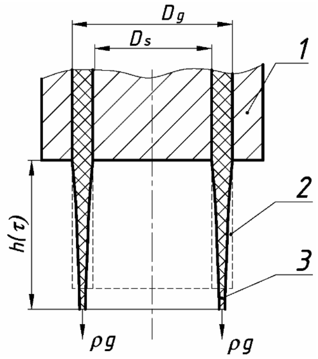

Fig. 2. Gravitational extraction of extrusion billet: 1 – head (die); 2 – polymer billet, provided there is no stretch; 3 – polymer billet after gravity stretch

The linear extrusion speed of the billet at the exit from the head, v_1, is determined by the productivity of the extruder:

$$v_1 = \frac{Q_v}{F_1}, \qquad (1)$$

where Q_v is the volumetric productivity of the extruder by the melt, (m^3/s); F_1 is the cross-sectional area of the head forming channel (m^2). The value of F_1 is given by the following equation:

$$F_1 = \frac{\pi}{4}\left(D_g^2 - D_s^2\right), \qquad (2)$$

where D_g and D_s are the outer and inner diameters of the head forming channel, respectively, (m).

The current value of the gravitational extension coefficient, k(z), in any section of the billet, provided that the volume flow of the polymer is maintained, is determined by the following ratio of the areas in these sections:

$$k(z) = \frac{F_1}{F(z)}, \qquad (3)$$

where F(z) is the cross-sectional area towards the current coordinate z.

It should be noted that the polymer billet has a shape of a sleeve and is a thin-walled shell of very small elasticity. In this case, the thin-walled condition will have the following form:

$$D_g > 8\delta_1, \qquad (4)$$

where δ_1 is the thickness of the billet wall at the exit from the die opening (m).

If the thin-walled condition (4) is satisfied, the process of gravitational stretch of the billet can be considered by the example of only half of its section in a system of Cartesian rectangular coordinates (Fig. 3).

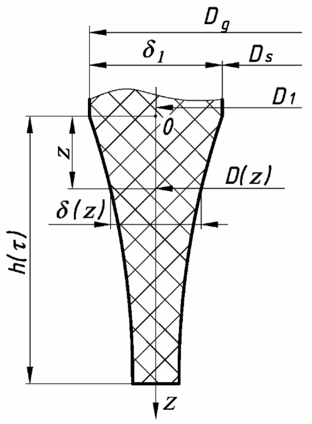

Fig. 3. Calculation scheme of gravity stretch of extrusion billet

Assuming that the shear rates for gravity stretch are insignificant, we can accept that the viscosity η of the polymer melt is constant.

The equation of motion for the polymer melt in the projection on the Oz axis will be as follows:

$$\rho \cdot g = -\eta \cdot \Delta v, \qquad (5)$$

where ρ is the density of the polymer billet (kg/m^3); g is the acceleration of gravity (m/s^2); η is the dynamic viscosity of the melt (Pa·s); v is the velocity vector of the extension.

We note that the symmetry conditions hold and the problem becomes flat.

Then equation (5) is simplified to the following form:

$$\rho g = -\eta \frac{\partial^2 v(z)}{\partial z^2}. \qquad (6)$$

The coordinate h of the free end of the billet is not fixed in space and varies with time τ.

Further, we take into account the boundary conditions for the extension speed at the free end of the billet at z=h(τ):

$$\frac{\partial v(z)}{\partial z}\Big|_{z=h} = 0; \quad v(h) = 0. \qquad (7)$$

Then the instantaneous stretch speed in the section with the coordinate z is determined by the following expression:

$$v(z) = \frac{\rho g}{2\eta}\left[h(\tau) - z\right]^2 . \quad (8)$$

Similarly, one can obtain an expression for the velocity of the displacement of the section v_d relative to the billet moving with the velocity v_l due to gravitational extension. In this case, the cross-sectional velocity at the exit from the forming gap $v_d(0)$ will correspond to the stretch speed v(0), and the condition $\frac{\partial v_d}{\partial z}\Big|_{z=h} = 0$ must be satisfied at the free end of the billet.

Then we have:

$$v_d(z) = \frac{\rho g}{2\eta}\left(h(\tau)^2 + 2h(\tau)z - z^2\right). \quad (9)$$

Here and further, the solution has a physical meaning when $0 \le z \le h(\tau)$.

If we take into account the presence of a linear extrusion rate, then the expression for the velocity of the section $v_z(z)$ will be as follows:

$$v_z(z) = v_l + \frac{\rho g}{2\eta}\left(h(\tau)^2 + 2h(\tau)z - z^2\right). \quad (10)$$

Figure 4 shows the results of the calculation of the velocity of gravity stretch v for different values of the billet dimension h.

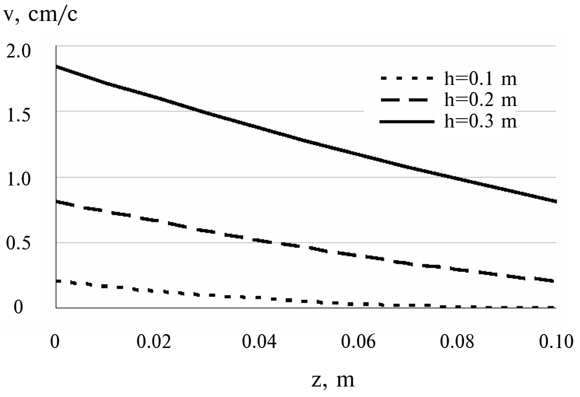

Fig. 4. Dependence of the velocity of gravitational extension v on the coordinate z for different values of the length of the billet z

The values of dynamic viscosity η=20050 Pa·s and density ρ=820 kg/m^3, which are accepted hereinafter for the calculation, correspond to the melt of polyethylene with a low density at extremely low (up to 1 s^{-1}) shear rates and temperature T=140^{0}C. As can be seen from Fig. 4, the velocity of gravity stretch v is not constant and may vary several times in different sections of the billet z.

In the framework of the solution of the plane problem (Fig. 3), expression (2) can be written in terms of the average diameter of the head forming channel:

$$F_l = \pi \cdot D_l \cdot \delta_l , \quad (11)$$

where $D_l = \frac{D_g + D_s}{2}$ is the average diameter of the head channel (m); δ_l is the size of the forming hole, which determines the initial thickness of the billet wall (m).

For further illustrations (unless specified separately), the extruder will be dimensioned in the size of WP90x30 for low density polyethylene of 300 kg/h, D_l=0.1 m and δ_l=0.003 m. Then the linear extrusion speed is v_l=10.3 cm/s. Comparing this value with the instantaneous velocity of gravitational extension v (Fig. 4), one can conclude that the instantaneous velocity of gravitational stretch, v, in the melt exit zone from the die can be about 18% of the linear extrusion rate. This indicates a very significant effect of gravity stretch on the process of shaping the extrusion billet.

We can write expression (10) with allowance for Eq. (1) as follows:

$$v_z(z) = \frac{Q_v}{\pi D_l \delta_l} + \frac{\rho g}{2\eta}\left(h(\tau)^2 + 2h(\tau)z - z^2\right). \quad (12)$$

The distribution of the velocities of the cross sections along the z coordinate is shown in Fig. 5.

As expected, the velocity v_z of the cross sections z of the polymer preform does not remain constant. The greater the length of the billet h, the larger is an increase in the velocity v_z of sections due to the gravitational extension. From equation (12) for z=h(τ), we can determine the velocity of the free end of the billet v_z(h):

$$v_z(h) = \frac{Q_v}{\pi D_l \delta_l} + \frac{\rho g}{\eta} h(\tau)^2 . \quad (13)$$

This dependence for different values of the volume capacity of the extruder is shown in Fig. 6.

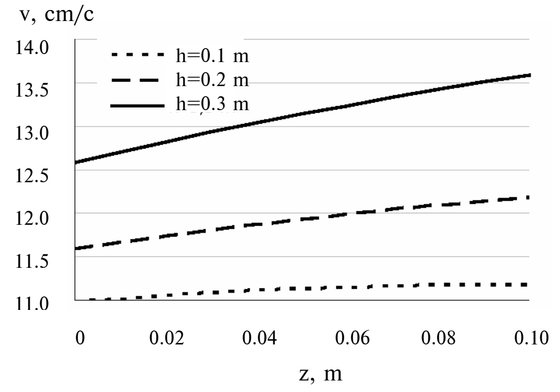

Fig. 5. The velocity of the cross-sections of the billet v_z as a function of the position coordinate z

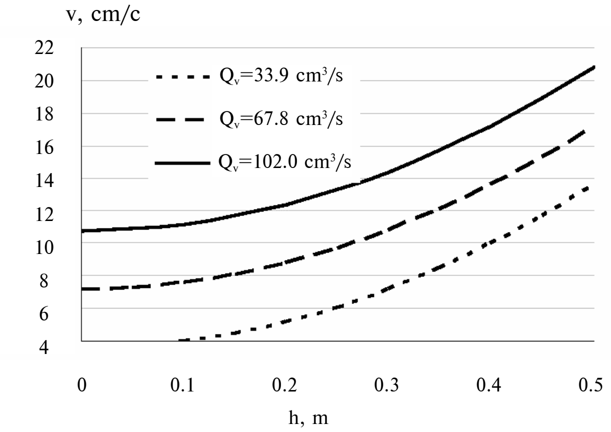

Fig. 6. The speed of the free end of the billet $v_z(h)$ as a function of its length h at different capacities of the extruder Q_v

The values of volumetric productivity (Q_v) hereinafter are taken equal to 33.9 cm^3/s, 67.8 cm^3/s, and 102 cm^3/s; they correspond to the mass productivity of the extruder of 100 kg/h, 200 kg/h, and 300 kg/h, respectively. It can be noted that, for example, when the maximum volume capacity of the extruder is Q_v=102 cm^3/s, the free end of the billet moves at the beginning of the extrusion process with a speed of v_z=10.7 cm/s. And at the length of the extruded billet of 0.3 m, the speed of the movement of the free end of the billet will increase by 26% and achieve 14.3 cm/s.

Fig. 7 shows the graphs of the velocity of the free end of the billet, $v_z(h)$, as a function of a change in the dynamic viscosity η of the melt in the range from 16050 Pa·s to 20050 Pa·s, which corresponds to a change in the melt temperature T from 190^{0}C to 140^{0}C.

Thus, all possible technological modes of extrusion billet molding are covered with excess. The observed relative changes in the speed of the movement of the free end of the billet with practically 20% change in the dynamic viscosity of the melt η do not exceed 6%. The dynamic viscosity of the melt η (and, correspondingly, the extrusion temperature T) will not be the decisive factor that would significantly influence the shape of the billet under normal process conditions. Probably, the same conclusion can be drawn with respect to the influence of the shear rate for gravitational extension.

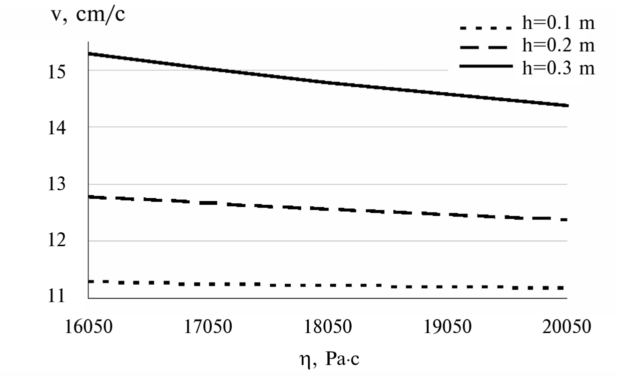

Fig. 7. The speed of the movement of the free end of the billet $v_z(h)$ as a function of a change in the dynamic viscosity of the melt η

The coefficient of gravitational extension of the billet k(z) (3) can also be determined through the ratio of the velocities of the cross sections as follows:

$$k(z)=\frac{v_z(z)}{v_1}. \qquad (14)$$

Then, taking into account the expression (12), we obtain:

$$k(z)=1+\frac{\pi}{2}\frac{\rho g}{\eta}\frac{D_1\delta_1}{Q_v}\left(h(\tau)^2+2h(\tau)z-z^2\right). \qquad (15)$$

The coefficient of gravitational extension of the billet k(z) determines the magnitude of the deformation effect of the gravitational stretch on the billet in its specific section.

Fig. 8 shows the dependence of the coefficient of gravitational extension of the billet, k(z), on the z coordinate. As before, the results are given for three cases: the length of the billet z takes the values of 0.1 m, 0.2 m, and 0.3 m.

It should be noted that the coefficient k(z) in the melt exit zone of the extrusion die will not be equal to 1. As can be seen from Fig. 4, the velocity of gravity extension in this zone does not equal to zero, moreover it has a maximum value. The values of the coefficient of gravitational extension k(z) at h=0.1 m vary in the indicated range of z from 1.02 to 1.04. However, at h=0.3, the values of the coefficient of gravitational extension k(z) vary from 1.17 to 1.26. Thus, the coefficient of gravity stretch k(z) has a pronounced dependence on the length of the billet h.

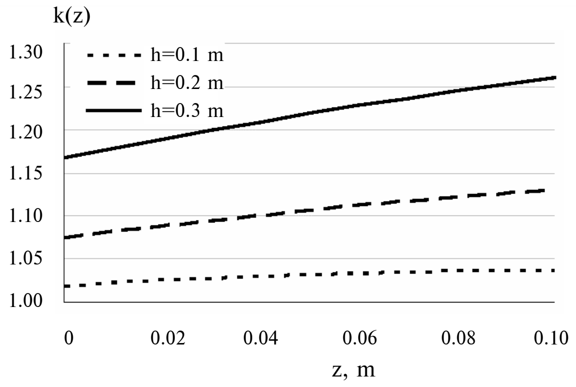

Fig. 8. Dependence of the coefficient of gravitational extension k(z) on the position coordinate z

Fig. 9 shows the dependence of the coefficient of gravitational extension, k(z), on the length of the billet, h, in sections of the billet located at a distance of 0.05 m and 0.1 m from the extrusion die. For the coordinate z=0.05 m, the coefficient of gravitational extension k(z) changes by 16% when the billet length varies from 0.1 m to 0.3 m (i.e. three times). And at z=0.1 m this change is about 17%. The obtained results indicate that the observed in Fig. 8 influence of the position of the coordinate of the section of the billet z on the qualitative and even quantitative behavior of the coefficient of gravitational extension k(z) cannot be regarded as significant.

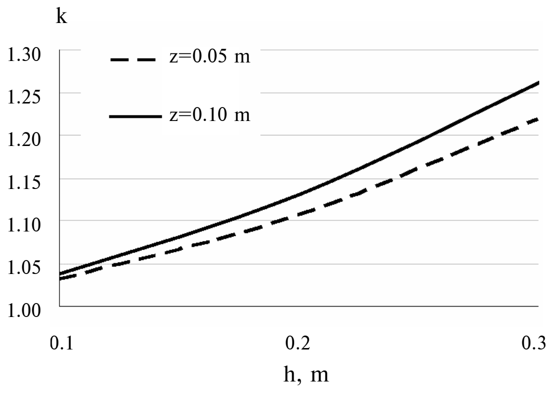

Fig. 9. Dependence of the coefficient of gravitational extension k(z) on the length of the billet h

The maximum degree of gravity extraction will be realized at the free end of the billet:

$$k(h)=1+\pi\cdot\frac{\rho g}{\eta}\cdot\frac{D_1\delta_1}{Q_v}\cdot h(\tau)^2. \qquad (16)$$

The relative change in the coefficient of gravitational extension of the billet k(z) can characterize the unevenness of the conditions for its shaping under gravity stretch:

$$S=\frac{|k(h)-k(0)|}{k(0)}\cdot 100\%$$

$$\text{or}\quad S=\frac{100\%}{1+\dfrac{2\eta Q_v}{\pi\rho g D_1\delta_1 h^2}}. \qquad (17)$$

Fig. 10 shows the dependence of the relative change in the coefficient of gravitational extension on the length of the extrusion billet, h, for various values of the extruder's volume capacity.

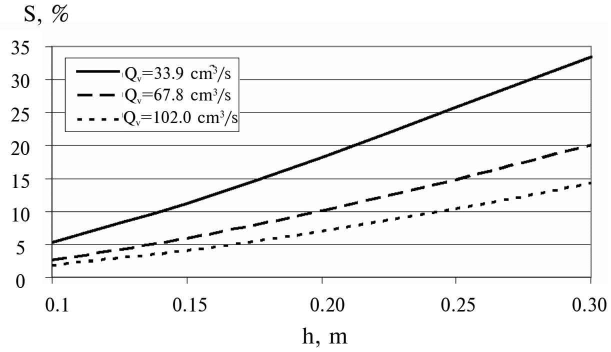

Fig. 10. Dependence of the relative change in the coefficient of gravity stretch on the length of the extrusion billet for different values of the extruder's volumetric capacity

From the analysis of the data presented in Fig. 10, it follows that the unevenness of the gravity extraction conditions of the extrusion billet can be up to 14% at the volumetric capacity of the extruder Q_v=102 cm^3/s. At the same time, as the productivity of the extruder (Q_v) decreases, the unevenness of the gravity stretch conditions grows, and, hence, the unevenness of the extrusion billet deformation conditions also increases, it can reach 33% at Q_v=33.9 cm^3/s. Thus, the reduction in the extrusion time, τ, due to the increase in the volume capacity of the extruder, Q_v, positively affects the uniformity of the conditions for shaping the extrusion billet.

It should also be noted that the proposed approach does not take into account the influence of the elastic properties of the polymer melt, as suggested, for example, in work [14]. The appearance of the elastic properties of the polymer melt can make a significant contribution to the results of the calculations in case of studying the gravitational extension of amorphous polymeric materials at a temperature close to the temperature of the highly elastic state of the polymer. This problem can be studied separately.

Conclusions

An engineering approach is proposed for estimating the kinematic characteristics of the gravitational stretch process during the extrusion of a polymer preform for the production of a hollow article by the blow molding method. Analytical dependencies are obtained to determine the instantaneous stretch speed, the speed of the cross sections of the extrusion billet, and the speed of the movement of the free end of the billet. The influence of technological factors (extruder productivity, dynamic melt viscosity and length of extrusion billet) and structural factors (the dimensions of the forming hole of the extrusion head) of the gravitational extraction process factors on the change in the extrusion billet draw ratio are revealed.

The influence of the extruder's volumetric efficiency on the coefficient of gravitational extension of the extruded billet and on the speed of the free end of the extrusion billet was investigated. Graphical illustrations and examples for the main technological cases of gravity extension of an extruded billet for producing a blown product are given. The appearance of the elastic properties of the polymer melt can make a significant contribution to the results of the calculations in case of the gravitational extension of amorphous polymeric materials at a temperature which is close to the that of the highly elastic state of the polymer.

The proposed approach opens the way for further studies on the effect of gravity stretch on the wall thickness of the resulting extruded billet and on the machine time of the extrusion blow molding process.

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ОЦІНЮВАННЯ КІНЕМАТИЧНИХ ПАРАМЕТРІВ ПРОЦЕСУ ГРАВІТАЦІЙНОГО ВИТЯГАННЯ ЗАГОТОВКИ ДЛЯ ЕКСТРУЗІЙНО-ВИДУВНОГО ФОРМУВАННЯ ПОЛІМЕРНОГО ВИРОБУ

Д.Е. Сідоров, О.П. Колосова, О.Є. Колосов, І.О. Казак

У даній роботі запропоновано інженерну методику оцінювання кінематичних параметрів і коефіцієнта витягання екструзійної заготовки для процесу видувного формування в умовах гравітаційного витягання. Встановлено взаємозв'язок складових швидкості руху заготовки в різних її перетинах і коефіцієнта витягання з геометричними і технологічними параметрами процесу гравітаційного витягання. Показано, що швидкість гравітаційного витягання не є постійною і в різних перетинах полімерної заготовки може змінюватися у кілька разів. Встановлено, що миттєва швидкість гравітаційного витягання в зоні виходу розплаву з екструзійної головки може становити до 18% від величини лінійної швидкості екструзії. При цьому зростання швидкості руху перетинів, що обумовлена гравітаційним витяганням, тим більша, чим більша довжина полімерної заготовки. Встановлено, що динамічна в'язкість розплаву (і температура екструзії) не є вирішальним фактором, який суттєво впливає на формоутворення заготовки в умовах нормальних технологічних режимів. Показано, що коефіцієнт гравітаційного витягання змінюється на 16–17% при зміні довжини полімерної заготовки в процесі її одержання. Для об'ємної продуктивності екструдера 102 см^3/с нерівномірність умов гравітаційного витягання екструзійної заготовки може становити до 14%. Встановлено, що зі зменшенням продуктивності екструдера нерівномірність умов деформування екструзійної заготовки збільшується і може досягти 33%.

Ключові слова: процес, екструзія, гравітаційне витягання, видувне формування, заготовка, розплав, термопласт.

EVALUATION OF KINEMATIC PARAMETERS OF PROCESS OF GRAVITATIONAL STRETCH OF A BILLET FOR EXTRUSION-BLOW MOLDING OF POLYMER PRODUCT

D.E. Sidorov, E.P. Kolosova, A.E. Kolosov, I.A. Kazak

National Technical University of Ukraine «Igor Sikorsky Kyiv Polytechnic Institute», Kyiv, Ukraine

Engineering methods for estimating the kinematic parameters and reduction of an extrusion billet in the process of blow molding under conditions of gravity stretching are developed in this work. The interrelation between the components of the speed of the billet motion in its various sections and the extension coefficient with the geometric and technological parameters of the gravitational elongation process is established. It is shown that the rate of gravity extension is not constant and can vary many times in different sections of the polymer billet. It is established that the instantaneous rate of gravity extraction in the zone of melt exit from the extrusion head (die) can be up to 18% of the linear extrusion rate. At the same time, an increase in the velocity of the cross sections due to the gravitational stretching is the more significant, the longer the length of the polymer billet is. It is stated that the dynamic viscosity of the melt as well as the extrusion temperature is not a decisive factor which might significantly affect the shape of the billet under conditions of normal technological regimes. It is shown that the coefficient of gravitational extension changes by 16–17% with the change of the length of a polymer billet in the process of its production. For the volumetric productivity of the extruder of 102 cm^3/s, the unevenness of the gravity extraction conditions of the extruded billet can be up to 14%. It is established that the unevenness of the conditions of the deformation of the extrusion billet increases with a decrease in the extruder's productivity, it can reach 33%.

Keywords: process; extrusion; gravitational stretch; blow molding; billet; melt; thermoplastic.

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