Extrusion of Polymers during Ultrasonic Action

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The highly elastic restoration of melts extruded through forming tools is well known in the processing of plastics. A number of works,[1–4] in which models of various degrees of complexity used to estimate this phenomenon quantitatively are discussed, are devoted to the description of this phenomenon. However, the use of simplified models gives an approximate estimate that does not correspond to experimental data well enough. More complex models big enough for practical applications are, as a rule, not effective enough.[3] Moreover, no model considers one of the most important operational and technological characteristics: the swelling of polymeric products of complex profiles under the influence of ultrasonic fluctuations. Usually, a description of swelling is limited to extruders shaped like twigs with round cross section or flat sheets.[4]

In this respect, a mathematical dependence allowing us to quantitatively define the effect of swelling on polymer melts in channels of complex sections during the use of intensive ultrasonic vibrations is of practical interest.

The size of extrudate swelling is influenced by the molecular characteristics and physical properties of a material, the technological conditions of processing (temperature, speed, and shift pressure), and the geometrical shapes of the channels.

Modeling the effects of extrudate swelling, we shall consider that when a polymer runs through a channel, its particles, undergoing shift deformation, become longer and, after departing from the channel because of the relaxation, are reduced; in addition, the stretching and reduction of particles are elastic in character.

Thus, in an equation mathematically describing the coefficient of swelling (K), it is necessary to consider the length of the channel (L) and its area (S). Besides these values, it is necessary to consider the pressure (P) at the extrusion of the polymeric composition, the effective viscosity (η_{eff}), the gradient of the shift speed ($\bar{\gamma}$), and a parameter (Θ) describing the highly elastic properties of the environment:

$$K = A\bar{\gamma}^{n_1}\Theta^{n_2}P^{n_3}\eta_{\text{eff}}^{n_4}L^{n_5}S^{n_6} \qquad (1)$$

where A is a dimensionless coefficient describing the nature of the material and n_1 to n_6 are degree parameters.

Using the p theorem and the theory of groups,[3] we can determine the dependence for K of a polymeric material in a cylindrical channel:

$$K = A(\bar{\gamma}\Theta)^{n_1}\left(\frac{\eta_{\text{eff}}}{P\Theta}\right)^{n_2}\left(\frac{L}{S_K}\right)^{n_3} \qquad (2)$$

The constant A and n_1 to n_6 are defined experimentally (Table I).

To determine the necessary model for the calculation of factor K for channels of complex forms, we must introduce the form coefficients of the channels (a and b), which are also determined experimentally according to a membrane analogy method,[3] into the following equation:

$$K = Aa^{m_1}b^{m_2}(\bar{\gamma}\Theta)^{n_1}\left(\frac{\eta_{\text{eff}}}{\text{P}\Theta}\right)^{n_2}\left(\frac{L}{\sqrt{S_K}}\right)^{n_3} \qquad (3)$$

where m_1 and m_2 are degree parameters (Table I).

When ultrasonic fluctuations are imposed on the melt stream, a significant decrease in K is observed because of the decrease in the effective viscosity of melting up to some value j/wt determined from the following equation:[5]

$$\eta_{\omega} = \frac{\eta_{\text{eff}}}{1 + \omega^2 r^2} \qquad (4)$$

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TABLE I
Values of the Physical Quantities and Constant Coefficients

Material	Temperature (K)	$\bar{\gamma}(1/s)$	Θ(s)	η_ω(Paas)	n_1	n_2	n_3	A	m_1	m_2
Polythene	338	3.546	0.1	4550	0.077	−0.015	−0.118	2.625	−0.021	−0.017
	403	3.548	0.1	3020	0.077	−0.015	−0.118	2.625	−0.021	−0.017
	418	3.548	0.1	1897	0.077	−0.015	−0.118	2.625	−0.021	−0.017
	433	3.548	0.1	1479	0.077	−0.015	−0.118	2.625	−0.021	−0.017
	488	3.548	0.1	1324	0.077	−0.015	−0.118	2.625	−0.021	−0.017
Polystyrene	438	3.548	0.1	4514	0.089	−0.088	−0.127	6.150	−0.016	−0.014
	448	3.548	0.1	3388	0.089	−0.088	−0.127	6.150	−0.016	−0.014
	458	3.548	0.1	2729	0.089	−0.088	−0.127	6.150	−0.016	−0.014
	468	3.548	0.1	2483	0.089	−0.088	−0.127	6.150	−0.016	−0.014
	478	3.548	0.1	2300	0.089	−0.088	−0.127	6.150	−0.016	−0.014
Poly(vinyl chloride)	403	3.548	0.1	5889	0.065	−0.020	−0.107	2.147	−0.005	−0.004
	413	3.548	0.1	3981	0.065	−0.020	−0.107	2.147	−0.005	−0.004
	423	3.548	0.1	3715	0.065	−0.020	−0.107	2.147	−0.005	−0.004
	433	3.548	0.1	3506	0.065	−0.020	−0.107	2.147	−0.005	−0.004
	443	3.548	0.1	1514	0.065	−0.020	−0.107	2.147	−0.005	−0.004

where η_ω is the viscosity of the polymer influenced by ultrasound, ω is the angular frequency of ultrasonic fluctuations, and r is the time of relaxation describing the speed of decreasing pressure:

$$r = \frac{\eta_{\text{eff}}}{E} \tag{5}$$

where E is the modulus of elasticity of the environment (Pa).

Therefore, it is expedient to introduce the parameter r, characterizing the influence of ultrasound on the degree of swelling of the extrudate of the polymeric material, instead of r_{eff}, into eq. (3):

$$K = Aa^{m_1}b^{m_2}(\bar{\gamma}\Theta)^{n_1}\left(\frac{\eta_\omega}{P\Theta}\right)^{n_2}\left(\frac{L}{\sqrt{S_K}}\right)^{n_3} \tag{6}$$

Equation (6) represents a mathematical model describing the influence of ultrasonic fluctuations on the swelling of an extrudate during the extrusion of a polymeric material under ultrasonic influence.

To confirm the adequacy of eq. (6) for describing this phenomenon, we have experimentally estimated K according to the geometry of the channel, the parameters of the extrusion process, physical and other properties of the polymer, and the frequency of the ultrasonic fluctuations.

For the experiments, an industrial extruder (ATL-45) has been used with the following characteristics: worm length = 0.8 m and diameter = 4×10^{-2} m. The extrusive installation includes a forming knot, which consists of connecting and forming heads; the latter has a square section of 0.045 m × 0.045 m and is able to fasten the forming channel. For the creation of ultrasonic fluctuations on the forming head, two magnetostrictive converters (e.g., PMS-6-22), connected to a generator of ultrasonic fluctuations (UZG1-4), have been mounted. Experimental extrudate data have been obtained for 12 channels and three kinds of polymers [polythene, polystyrene and poly(vinyl chloride)] within a temperature interval of 403–453 K, at extrusion pressures of up to 6 MPa, and at various ultrasound frequencies (18.5, 20.5, 21.6, 22.1, and 23.5 kHz).

Ultrasound has a positive influence on the decrease in K. Extrudates with triangular channels have the largest K values without ultrasound; (Fig. 1) the II, Γ, and III with the appropriate Roman letters. forms have the lowest values. Moreover, the

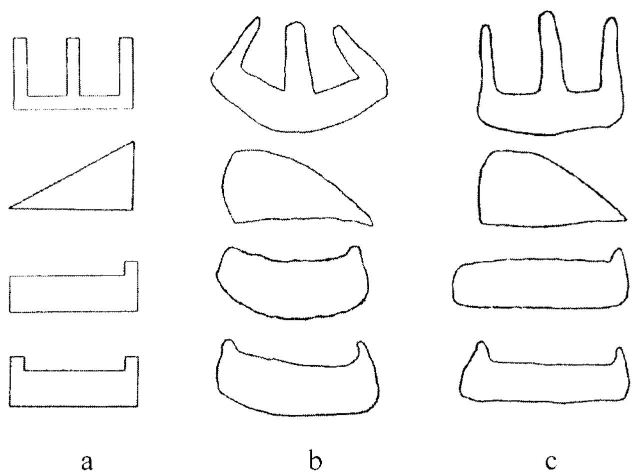

Figure 1 Characteristic contours of extruded poly(vinyl chloride), polystyrene, and polythene: (a) a section of a sample, (b) a section of an extruded sample not treated with ultrasound, and (c) a section of a sample treated with ultrasound.

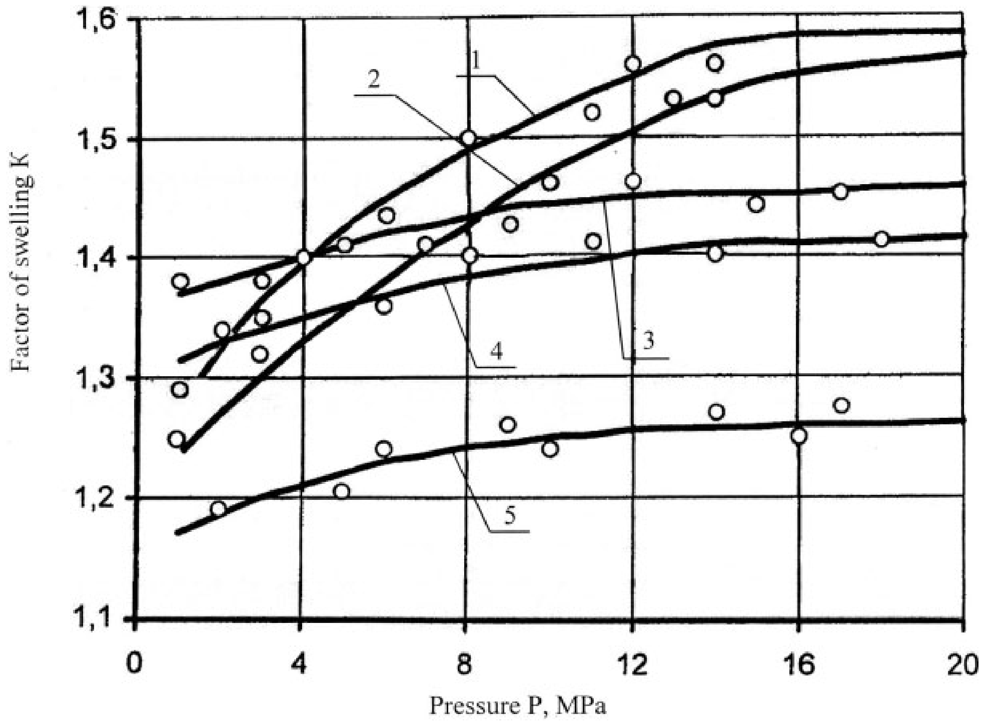

Figure 2 Dependence of K on P when a triangular channel is formed: (1) polystyrene, $L = 70$ mm at 453 K; (2) polystyrene, $L = 70$ mm at 438 K; (3) polythene, $L = 110$ mm at 430 K; (4) polythene, $L = 110$ mm at 418 K; and (5) poly(vinyl chloride), $L = 90$ mm at 413 K. The ultrasound frequency was 21.6 kHz.

greatest swelling of the extrudates is observed on the long sides of samples and near the sharp corners of triangular sections.

When ultrasound is used, the picture noticeably changes. The distortion of samples is considerably less. A decrease in K of 10–12% takes place on average; the greatest decrease in K is observed for the III channel form, and the least is found for the triangular form. The numerical value of K is also influenced by the chemical nature of the polymeric material.

The greatest extrudate swelling is for polystyrene, and the least is for poly(vinyl chloride).

A decrease in K is also observed when L increases in the extruder. This is true for all the channel forms and for all the investigated polymers. The lower the formation temperature is, the lower K is. Besides, the best results are received when the ultrasound frequency is 21.6 kHz.

A comparison of the experimental results and the calculated values of K (Fig. 2) reveals the following peculiarities:

1. A decrease in K of polymeric materials under the influence of ultrasound is observed for all forms of the investigated channels in an extruder. The divergence between the calculated and experimental data is about 15%.
2. The frequency of ultrasonic fluctuations also influences the productivity of the extruder, that is, the mass expenditure of the polymeric products. The best results are received when the ultrasound frequency is 21.6 kHz.
3. When comparing the influence of the shape of the channel section in an extruder, we find the greatest positive influence of ultrasound for channels of triangular and III figurative forms. This is obviously due to the fact that there are stagnant zones and sharp corners in these channels because of ultrasound.
4. When the pressure increases during polymer extrusion, the rate of growth of K is reduced, and when the pressure is greater than 5.0 MPa, its value is practically unchanged. The sharp increase in K when the pressure is not great is a characteristic feature of the investigated polymers. It has also been confirmed in other works.[3,4]
5. The reduction of K is typical of the polymers investigated in this work [polythene, polypropylene, and poly(vinyl chloride)] when the length of the channel increases. Besides, there is a critical value of $L = 110$ mm above which the swelling remains practically unchanged. It is the essential factor used in designing forming channels.

6. When the extrusion temperature increases, *K* also increases. The increase in *K* is more noticeable for polystyrene than for the other investigated polymers.

Thus, the results for estimating *K* can be used to calculate the forming tool both with and without ultrasonic influences. Moreover, the given results can be used in free extrusion when the product, which has left the forming head, does not adjoin the calibrated tool and does not undergo an extraction and mechanical process.

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