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STUDIES OF DESIGN AND TECHNOLOGY INFLUENCE ON OPTICAL PROPERTIES OF INJECTION MOLDING PARTS BY SIMULATION

Yablochnikov E.I.[1], Pirogov A.V.[1], Vasilkov S.D.[1], Andreev Y.S.[1], Barvinsky I.A.[2]

[1]ITMO University, Kronverkskiy pr., 49, Saint Petersburg, 197101, Russia

[2]CSoft, Molodogvardeyskaya Str., 46, bld.2, Moscow, 121351, Russia

ABSTRACT

The methodology of obtaining a factors rating of the runner system design and technology process influencing on optical properties of the plano-concave lens of polycarbonate has been examined, using Taguchi method for injection molding simulation. The biggest influence on the refraction index (n) and the difference of the refraction index (Δn) among part areas characterizing its optical heterogeneity is made by the runner system design whilst the principal factor influenced on birefringence is melt temperature.

Different type of the refraction index and birefringence dependence from the packing pressure (in the last case is being observed a minimum value under the packing pressure 60 MPa) can be explained when considering the combinations of phenomena. These phenomena take place in a mold cavity in the process of melt filling, packing and shrinkage processes determining strain-stress state of molding in an injection mold and after ejecting from the mold.

Index Terms – Optical properties, simulation methodology, polycarbonate, injection molding, Taguchi method, volumetric shrinkage, shrinkage, warpage, residual stresses, packing pressure

1. INTRODUCTION

High requirements for the modern manufacturing of precision mechanical and equipment engineering including optical parts, considers the usage of robust design and technological solutions [1], providing required quality and improved reliability when changes process conditions caused by production factors, fluctuation of material properties and etc.

The use of simulation allows to significantly reduce (in comparison with experimental studies) financing expenses and time needful for studying influence of the part and injection mold design on molding processes distinctive features and obtaining information for decision making. Simulation gives the opportunity of integral study of parts manufacturing process on different stages of injection molding and it also allows estimating such phenomena as volumetric shrinkage. Experimentally it is very arduous or impossible to study it because of high irregularity in the density distribution in the part.

Although voluminous literature exists devoted to different aspects of injection molding simulation and practical use of software, nevertheless the design of science-based methodology of engineering analysis of this technological process goes with unsolved problems. In simulation it is preferably to reduce the time of performing calculations not to long preproduction time limit. The last condition has a great importance, first of all, for calculations using meshes with a large number of elements.

2. ESTIMATE OF FACTORS INFLUENCED ON OPTICAL PROPERTIES BY THE TAGUCHI METHOD

This is widely used Taguchi method in the experimental study of technological processes including thermoplastics injection molding and its simulation [2-3]. It allows with a rather small number of experiments estimating those factors that are given the biggest influence on characteristics of parts quality.

In this paper injection molding of plane-concave lens has been studied. Its diameter is 24 mm and thickness is in the range from 3 to 4.2 mm of polycarbonate Makrolon LQ3147 (Bayer). Also there are two cavities (Fig.1, a) and combined hot-cold runner system (hot channel was used for the part of sprue) [4]. The diameter of the cold sprue at the thinnest point (connection with the hot runner) is equal to 3 mm.

3D-simulation in Moldex3D R12 was made using the finite volumes method for combined BLM-mesh involving 14 layers of elements in direction of mold cavity thickness with hypothesis supposition about effective and homogeneous cooling of molding. Filling and packing in the mold cavity was simulated as a non-isothermal flow of a compressible melt at a constant flow rate and constant packing pressure. Characteristics of lens material used in the simulation were taken from the database Moldex3D R12.

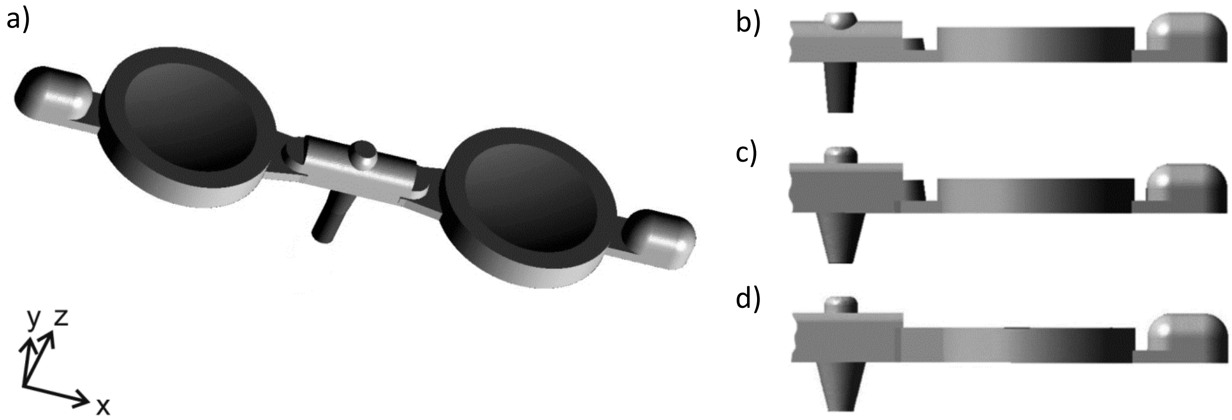


Fig.1. Lens model with overflow and runner for the level 1 (a); lens model with overflow and cold runner for the level 1 (b), 2 (c) and 3 (d)

Three-level orthogonal plan of the main effects L18 (3^6) is used in Taguchi method, represented in Table 1. Under the character of controllable factors the runner system design, the flow rate, melt temperature, mold temperature, packing pressure and cooling time (Table 2) were used. As the choice of levels has a high influence on the resulting factors rating in Taguchi method, this stage of the research is a very important for almost significant estimates.

Variants of runner system design for three-level plan were chosen so as to be able to estimate the influence of the thickness separately runners and gates which are known to exert a high influence on the polycarbonate injection molding. Selecting levels for runner system design the following considerations were taken into account.

Table 1. Orthogonal plan L18 (3^6) and results for maximal birefringence and the refractive index at the points 4 (n_4), 2 (n_2) and 5 (n_5); location of the points are shown in Fig.2

№ of experiment	Levels of controlled factors						Results			
	A	B	C	D	E	F	Birefringence (-) x10^{-3}	n_4	n_2	n_5
1	1	1	1	1	1	1	2.58	1.5622	1.5590	1.5629
2	1	2	2	2	2	2	2.03	1.5610	1.5595	1.5612
3	1	3	3	3	3	3	1.66	1.5610	1.5600	1.5611
4	2	1	1	2	2	3	3.34	1.5610	1.5595	1.5612
5	2	2	2	3	3	1	1.71	1.5608	1.5596	1.5610
6	2	3	3	1	1	2	1.69	1.5626	1.5591	1.5627
7	3	1	2	1	3	3	2.30	1.5544	1.5596	1.5616
8	3	2	3	2	1	1	1.32	1.5520	1.5595	1.5621
9	3	3	1	3	2	2	3.32	1.5568	1.5595	1.5612
10	1	1	3	3	2	1	1.63	1.5607	1.5598	1.5619
11	1	2	1	1	3	2	10.59	1.5616	1.5589	1.5627
12	1	3	2	2	1	3	3.60	1.5612	1.5591	1.5624
13	2	1	2	3	1	2	2.75	1.5603	1.5593	1.5612
14	2	2	3	1	2	3	1.84	1.5613	1.5591	1.5626
15	2	3	1	2	3	1	4.74	1.5612	1.5590	1.5621
16	3	1	3	2	3	2	1.30	1.5555	1.5599	1.5618
17	3	2	1	3	1	3	5.02	1.5566	1.5600	1.5617
18	3	3	2	1	2	1	2.26	1.5549	1.5599	1.5615

Table 2. Controlled factors and levels

Notation	Controlled factors	Levels		
		1	2	3
A	Runner system design	1	2	3
B	Flow rate (V), cc/s	35	40	45
C	Melt temperature (T_{melt}), °C	280	300	320
D	Mold temperature (T_{mold}), °C	80	87.5	95
E	Packing pressure (P_{pack}), MPa	30	55	80
F	Cooling time (t_{cool}), s	10	27.5	45

Increasing the gate thickness simplifies the flow rebuilding behind the melt front in the area of cavity entry facilitating to reduce risk of the jetting and flow lines appearance. Also this increase, in some range of thicknesses has a positive impact on the melt packing by increasing the time to shutdown the cavity from the heating cylinder. At the same time increasing of the gate thickness aggravates the runner system separation from the lens and may cause such a negative effect as melt backflow from the cavity into the runner system, for example, when freezing of the thin sprue occurs before the freezing of gate. Increasing the thickness of runners effects on reducing the pressure during filling and acts positively on the packing process. However it increases the weight of the runner, which increases the cost of the injection molding process. The following runners and gates are used in analyzed variants of the design: level 1 - 4.93 mm and 1.5 mm; level 2 - 6 mm and 1.5 mm; Level 3 - 6 mm and 4.2 mm, respectively (Fig.1).

The variation range of the technological parameters was established with allowance for material manufacturer recommendations based on preliminary examination of processing factors impact at the stage of filling, packing and cooling. At the same time the limitations of the available machine and equipment for mold cooling were taken into account. Other technological process parameters were chosen so that they would not affected on injection molding: the maximal pressure in the process of injection exceeded pressure loss significantly during the injection, and packing time corresponded to the time of the parts mass appears at a constant value.

Values of refractive index in points of the part 4, 2 and 5 (the location of points is shown in Fig.2) are used as output parameters that allowed to take impact of design features the parts (flow length and variations in thickness), the difference in the refractive index at points 5 and 4 ($\Delta n_{5,4}$) as well as at points 2 and 4 ($\Delta n_{2,4}$) (Fig.2) characterizing the optical lens heterogeneity and maximal birefringence (Table 1) into account. Birefringence was calculated according to the stress optical law: $\Delta n = C_B(\sigma_1 - \sigma_2)$, where σ_1 and σ_2 – the first and second principal stress determined taking into account the thermal and orientation residual stresses, C_B – the coefficient of the optical activity. Calculation of the refractive index was carried out taking into account the influence of density and anisotropy caused by the melt flow of polymeric material in the mold cavity by the method [5]. When calculating the optical parameters of the viscoelastic behavior was taken into account using the model of White-Metzner. Signal / noise ratio (S/N) for *n* was determined by the method "nominal-the-better", for *Δn* and maximal birefringence – by the method "smaller-the-better".

Results of S/N ratio calculations show that the main factor influencing on birefringence (Fig.3) is melt temperature, but the other factors influence is also significant too.

The main influence on refraction index (Fig.4) has runner system design, and for areas with higher thickness near the gate (point 4) and at the end of the cavity (point 5) the main influence on *n* has the gate thickness, and for low thickness areas (point 2) – the runner thickness. The most significant influence on the refraction indexes difference $\Delta n_{5,4}$ and $\Delta n_{2,4}$ (Fig.5) has the gate thickness.

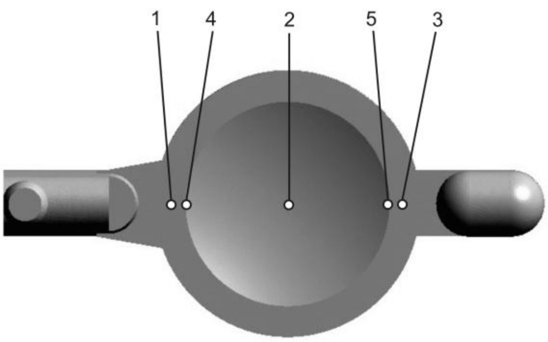


Fig.2. Measurement points of the refraction index (4, 2, 5) and volumetric shrinkage (1, 2, 3).

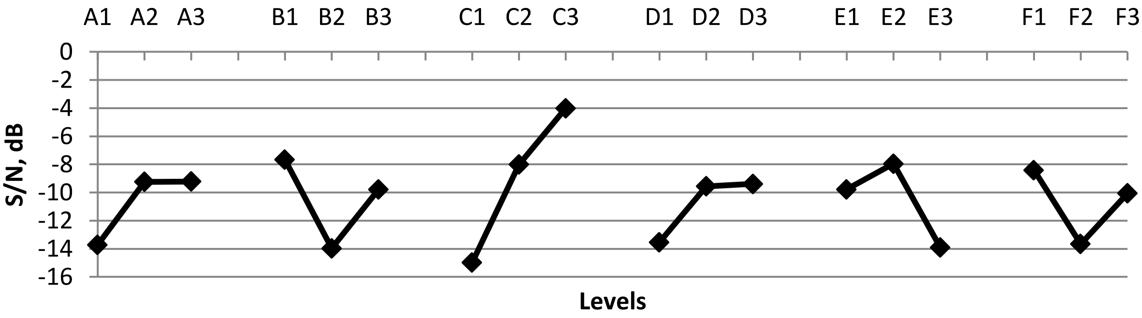
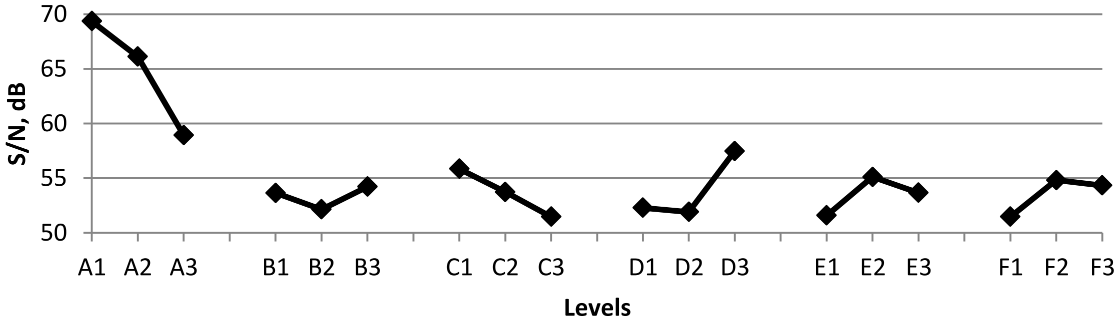
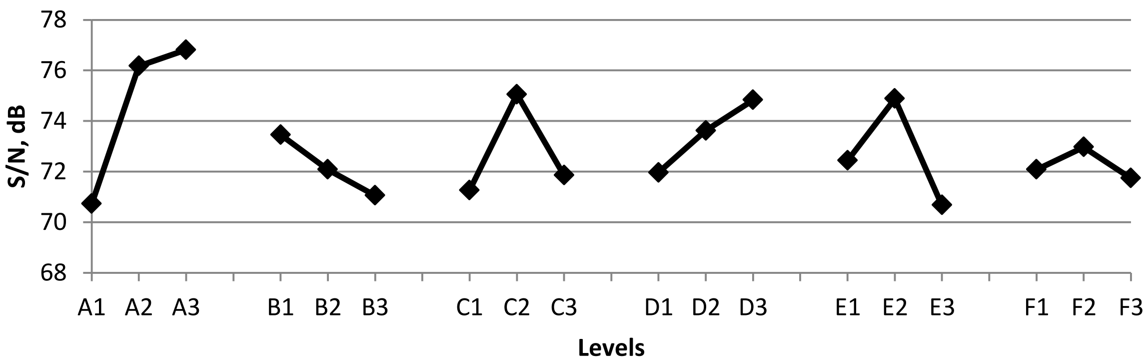


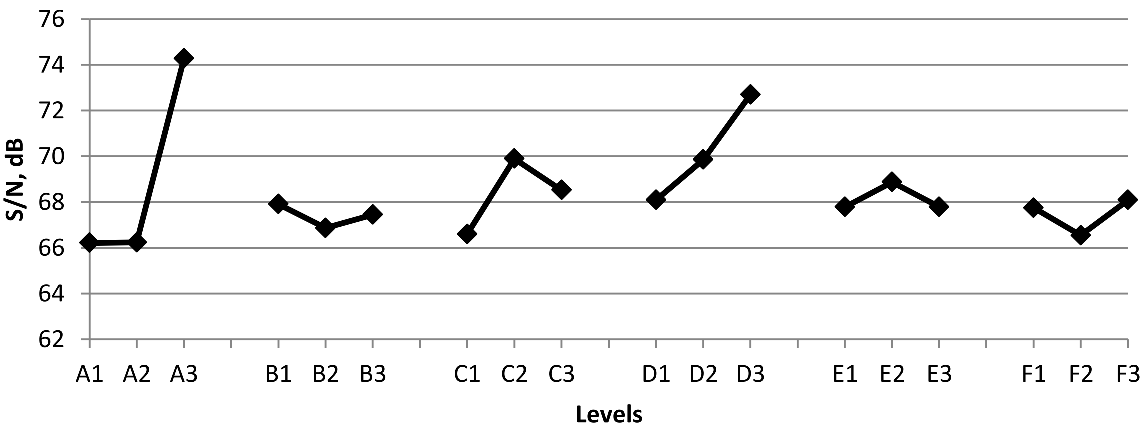
Fig.3. Signal / noise ratio (S/N) for maximal birefringence



a)

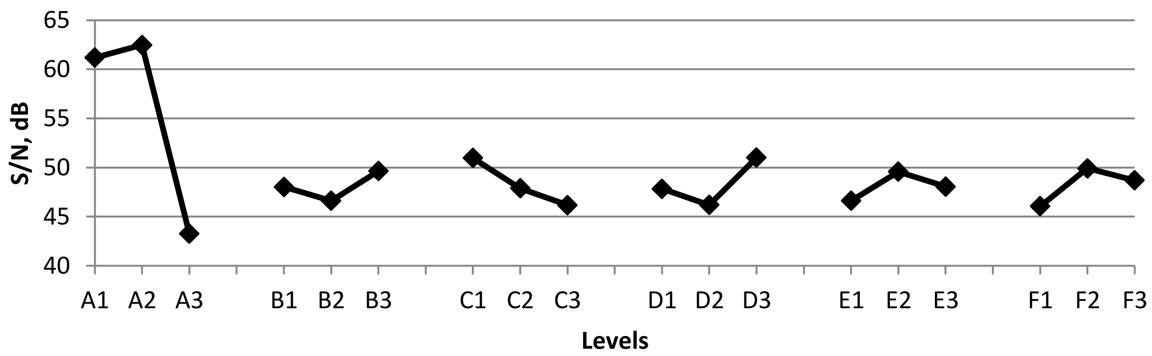


b)

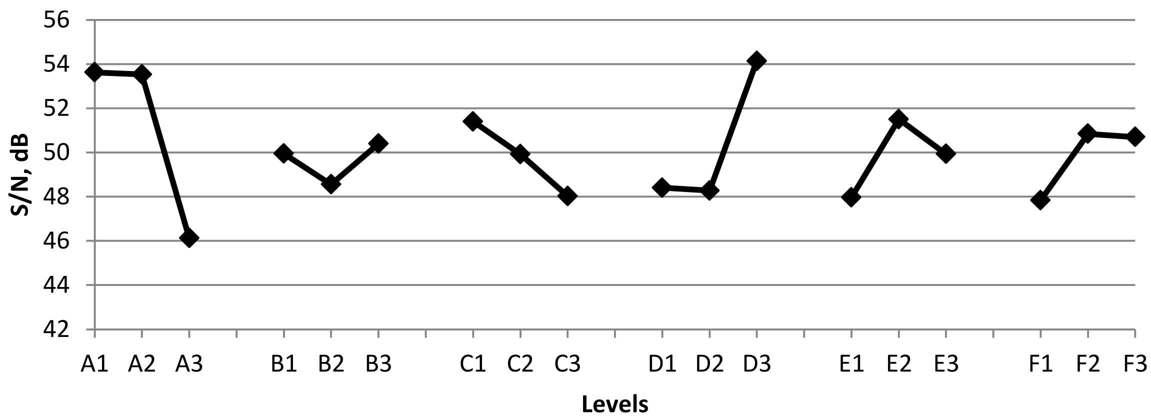


c)

Fig.4. Signal /noise ratio (S/N) for refraction index in points 4 (a), 2 (b) and 5 (c)



a)



b)

Fig.5. Signal / noise ratio (S/N) for refraction index difference in points 5 and 4 ($\Delta n_{5,4}$), and also in points 2 and 4 ($\Delta n_{2,4}$) (Fig.2)

3. THE INFLUENCE OF PACKING PRESSURE ON QUALITY CHARACTERISTICS

Packing pressure belongs to technological parameters, which can be easily set up in the real process so that they are relevant to conditions while simulation, in contrast, for instance, to melt temperature, which, in a real injection molding conditions is a complex function of other process parameters.

The relation of the lens quality characteristics to packing pressure is studied within the range from 30 to 80 MPa for the two types of runner system, corresponding to levels 1 and 3. The other technological parameters are: V = 40 cc/s; T_{melt} = 300 °C; T_{mold} = 95 °C; t_{cool} = 10 s for the runner system, corresponding to level 1, and t_{cool} = 45 s for the runner system, corresponding to level 3.

The influence of packing pressure on maximal birefringence (Fig.6) and refraction index (Fig.7) have different character that should be taken into account while choosing the optimal design and technological solution.

In relation of birefringence to packing pressure with two types of runner systems the minimum is observed under the pressure of 60 MPa (Fig.6). Moreover, the increase of gates thickness promotes lowering of maximal birefringence. However, for the runner system with the level 3, it is observed a large variation in the refractive index than with level 1. Moreover for the runner system with the level 3, the minimum values of the refractive index are observed near the gate, while for the runner system with the level 1 the minimum values of the refractive index observed in the thin central location of the lens. Obtained results can be explained while integral considering of phenomena, taking place in the mold cavity in the process of filling, packing and shrinkage.

With the flow rate of V = 40 cc/s variation in temperature of the melt front in the mold cavity does not exceed 1.8 ^{o}C, that is provided by the condition of approximate thermal balance between thermal losses through the mold walls and heat dissipation in melt. That's why the negative influence of melt front temperature on the optical properties on the lens is minimized in this case.

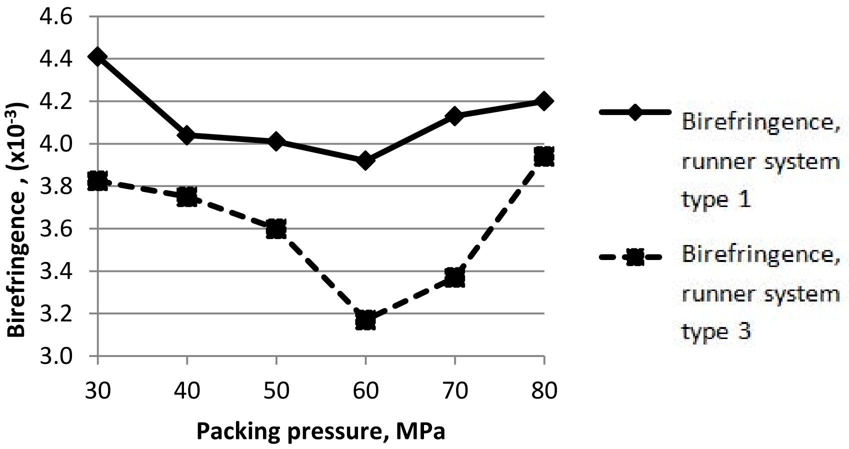


Fig.6. The relation of maximal birefringence to packing pressure, corresponding to levels 1 and 3

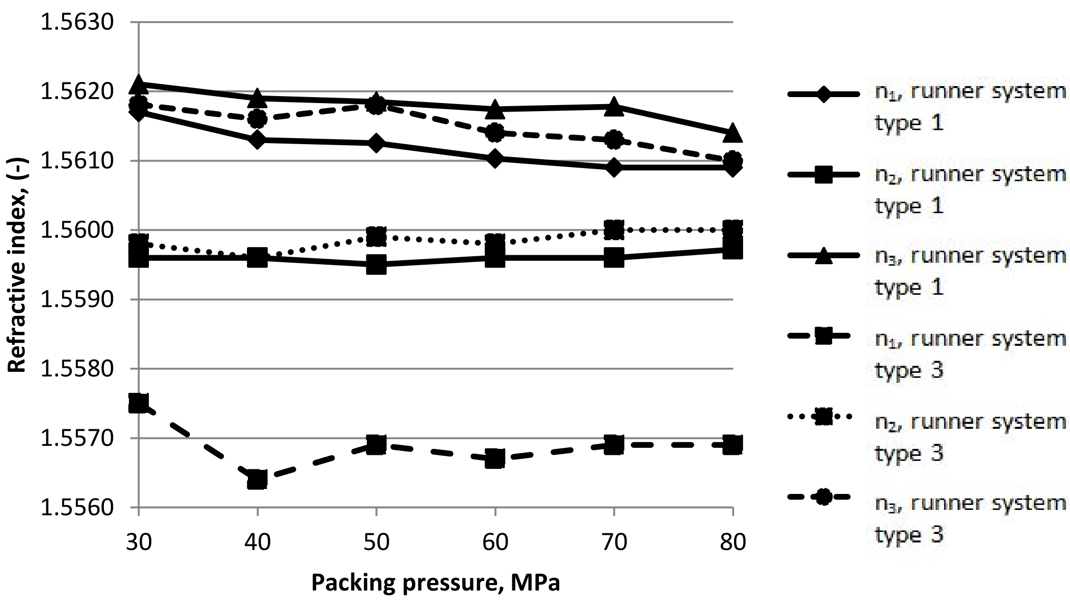


Fig.7. The relation of refraction index in points 4 (n_4), 2 (n_2) and 5 (n_5) for runner systems, corresponding to levels 1 and 3

Density distribution, influencing on refraction index allocation, is determined by the packing process, which can be characterized by the part volumetric shrinkage distribution. Volumetric shrinkage also influences on the level of the part in-mold thermal stresses.

Volumetric shrinkage was being calculated up to the moment of the mold opening while simulating of packing and cooling in the mold based on PVT-data according to the formula:

$$S_V = \frac{\bar{V}(T,P) - \bar{V}_f}{\bar{V}(T,P)} \times 100\%,$$

where $\overline{\mathrm{V}}(\mathrm{T},\mathrm{P})$ – specific volume with the polymeric material temperature and the pressure, $\overline{\mathrm{V}}_{\mathrm{f}}$ – polymeric material specific volume at room temperature and atmosphere pressure, determined for a mesh element.

Packing pressure rising leads to the lowering of volumetric shrinkage in all areas of the part (Fig.8). In the passing from the runner system, corresponding to the level 1, the runner system, corresponding to the level 3, there is improved packing, which appears with the lower values of volumetric shrinkage in the latter case. For the runner system, corresponding to level 3, there is an inappropriate area of negative volumetric shrinkage with packing pressure exceeding 70 MPa, because negative volumetric shrinkage leads to problems with part ejecting. However, the distribution of volumetric shrinkage in the mold cavity for two variants of the runner system design is different. In the case of the runner system, corresponding to the level 1, volumetric shrinkage at the end of the mold cavity exceed the volumetric shrinkage near the gate for areas with an equal thickness, which corresponds to the normal packing process. For the runner system, corresponding to the level 3, there is an opposite situation: volumetric shrinkage near the gate exceeds the volumetric shrinkage at the end of the mold cavity. Furthermore, for the runner system, corresponding to the level 3, there is more variation in volumetric shrinkage of the mold cavity, which is the cause of increasing of the optical lens heterogeneity.

These results can be explained by the phenomenon of the melt backflow from the mold cavity to the runner system at the end of the packing process for runner system according to level 3, since in this case, freezing of the gate, having a thickness of 4.2 mm, occurs after the freezing of the thin sprue with a diameter of 3 mm. Backflow arises of changes in the pressure gradient in the runner system and mold cavity after freezing of the sprue. Since the backflow primarily affects the area near the gate, it usually leads to an increase of volumetric shrinkage in this area.

The strain-stress part state after ejecting of the mold can be estimated only in integral consideration of shrinkages (changes in linear dimensions), warpage (form deviation), as well as residual stresses.

Shrinkage was estimated as an average value of the approximate diameter decrease for plane and concave sides of the lens in the longitudinal (along X-axis) and the transversal (along Y-axis) directions. In all the analyzed cases shrinkage decreases with the rising of packing pressure, the area of negative shrinkage values, as for volumetric shrinkage too, characterizes the problems of ejecting (Fig.9).

Warpage estimation was performed in two ways: in root-mean-square warpage and in maximal warpage for the plane lens side. Root-mean-square warpage W_σ was estimated by means of the formula:

$$W_\sigma = \sqrt{\frac{\sum_{i=1}^{n}(z_i - \bar{z})^2}{n}},$$

where z_i – deviation towards to Z-axis for the *i*-point, $\bar{z}$ – the average value of deviation, *n* – the number of points (11 points on the plane side were used).

Maximal warpage W_{max} was estimated as a sum of maximal deviation of points longitudinal and transversal profiles towards to +z direction and maximal deviation towards –z direction in modulus.

Warpage, as is known, is determined by irregularity of shrinkage processes, which, in its turn, depends on packing pressure. Relations of root-mean-square warpage and maximal warpage to packing pressure have the complicated character (Fig.10). If allocation changing of volumetric and, consequently, linear shrinkage with packing pressure rising leads to higher warpage about 60 MPa, it can result in lowering of residual stress close to that packing pressure value (it can be observed on curve relation of residual thermal stresses to packing pressure in the Fig.11). Flow-induced residual stresses (Fig.12), lowly depend on packing pressure that corresponds to visions of these stresses' forming mechanism at the filling stage, with the following relaxation at stages of packing and cooling. Studied combinations of phenomena reasonably explains the origin of birefringence minimum with the packing pressure of 60 MPa (Fig.6), as this phenomenon depends on the residual stressed condition of the molded part, determined by the sum of thermal residual stresses and flow-induced residual stresses.

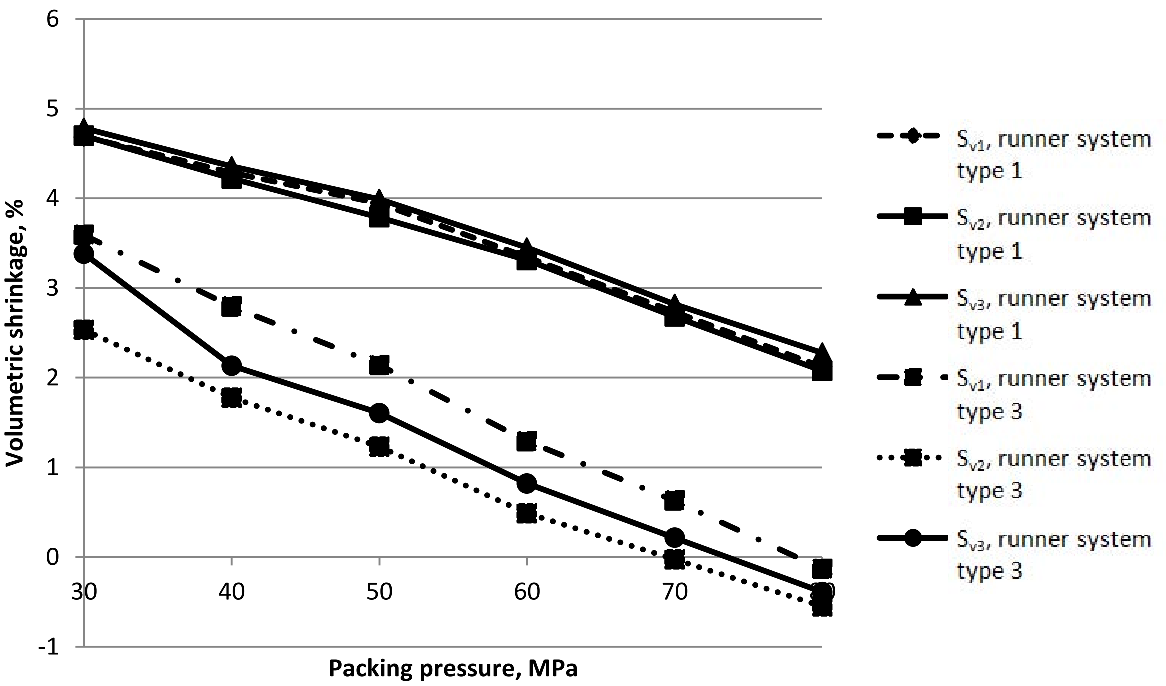


Fig.8. The relation of volumetric shrinkage in points 1 (S_{v1}), 2 (S_{v2}) и 3 (S_{v3}) to packing pressure for runner systems, corresponding to levels 1 and 3

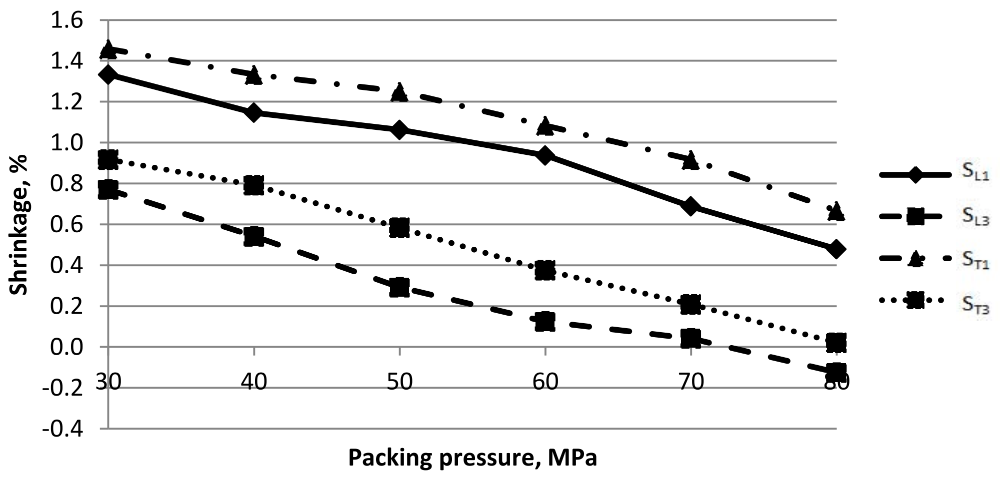


Fig.9. The relation of longitudinal (S_{L1}, S_{L3}) and transversal (S_{T1}, S_{T3}) shrinkage to packing pressure, corresponding to levels 1 (S_{L1}, S_{T1}) and 3 (S_{L3}, S_{T3})

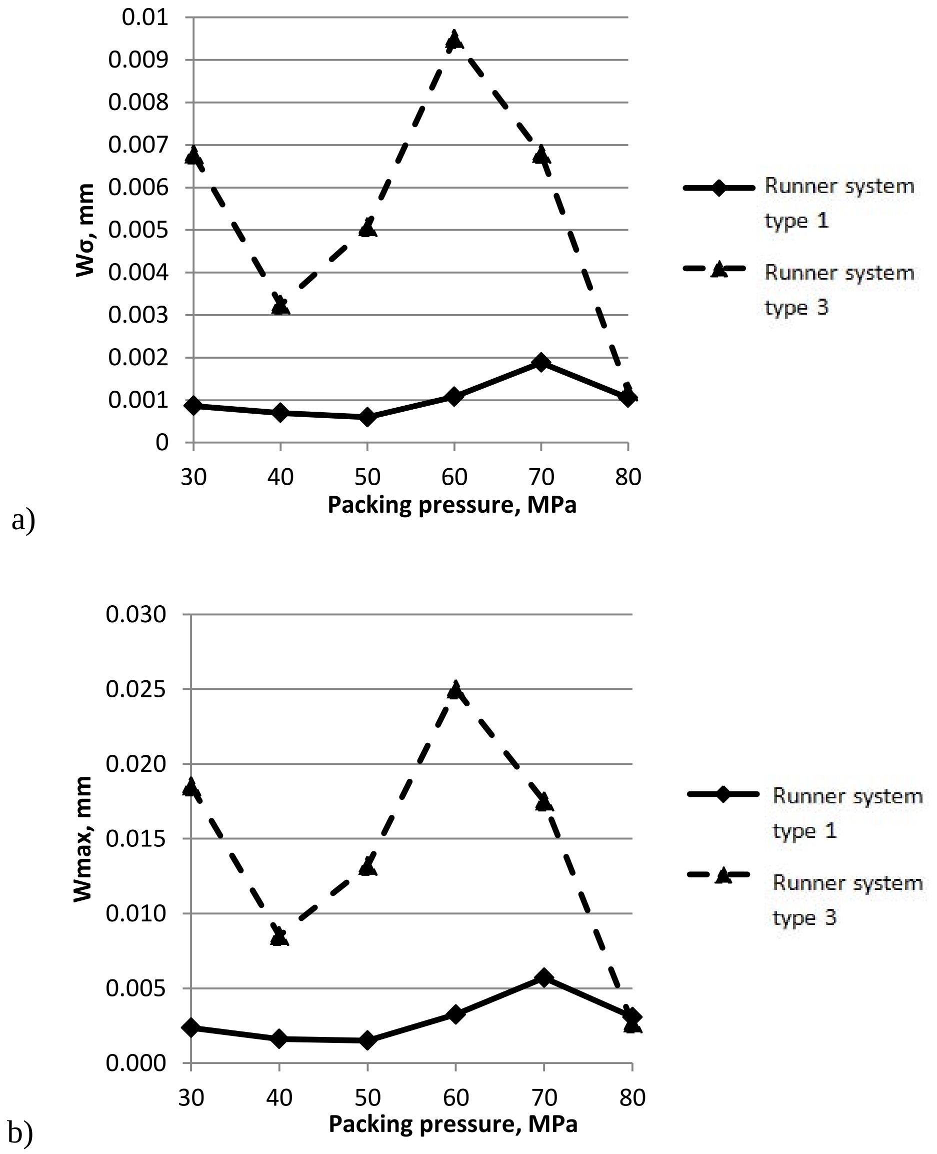


Fig.10. The relation of root-mean-square warpage (a) and maximal warpage (b) to packing pressure for runner systems, corresponding to levels 1 and 3, on plane side

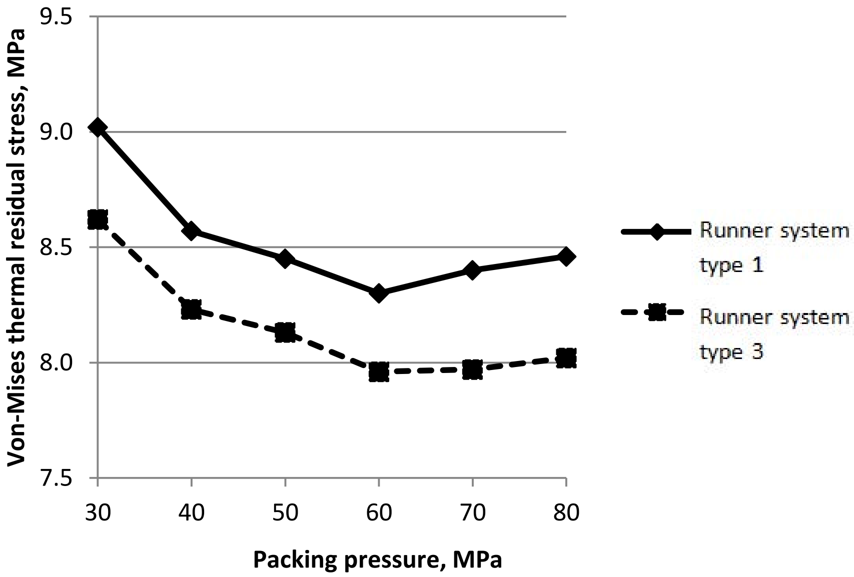


Fig.11. The relation of maximal Von-Mises thermal residual stresses to packing pressure

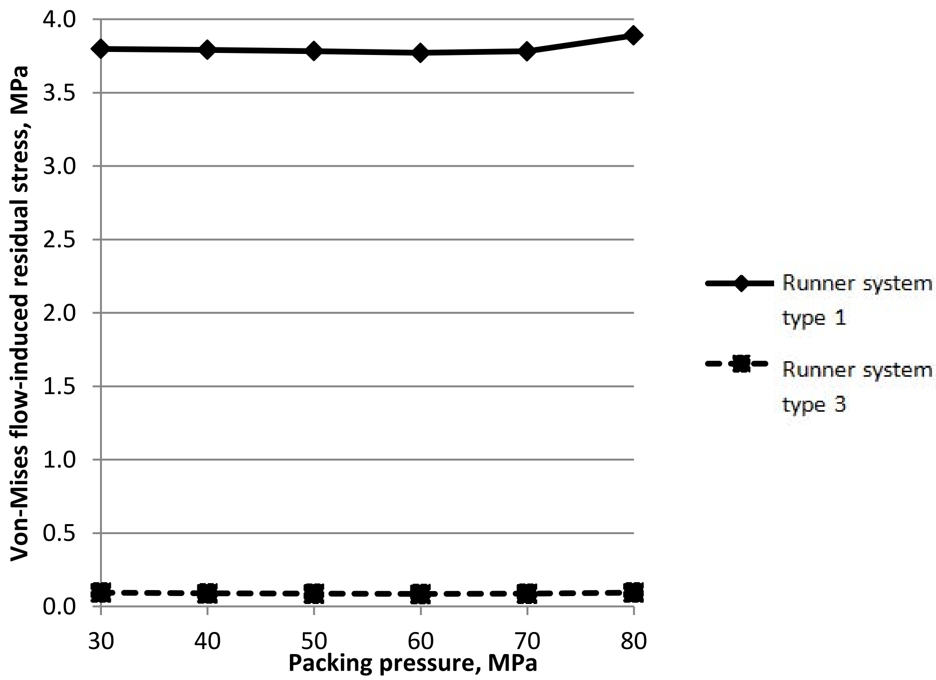


Fig.12. The relation of maximal Von-Mises flow-induced residual stresses to packing pressure

4. CONCLUSIONS

Taguchi method use in simulating the injection molding process allowed to obtain the rating factors associated with the design of the runner system and technological process. The main influence on the refractive index of the lens and its optical inhomogeneity (variation of the refractive index in the part), providing design of runner system. The main factor affecting the birefringence is the melt temperature. To obtain practically significant estimates using the Taguchi method of choice levels of controllable factors should be carried out taking into account the peculiarities of the process of injection molding a particular part, the capabilities of the injection and auxiliary equipment.

Study of the packing pressure dependence revealed the different nature of the influence of this parameter on the birefringence and refractive index. In the figure, depending on the birefringence to packing pressure occurs at a pressure of at least 60 MPa, exposure whose origin can be explained by considering the combinations of phenomena in the mold cavity at different stages of injection molding.

Increasing the packing pressure caused to lowering volumetric shrinkage in the molding cavity and, as a consequence, to a reduction of the longitudinal and transverse linear shrinkage. At the same time increase the maximal warpage of the lens at a pressure of 60 MPa (for runner system, corresponds to a level 1) or close to this area (for the runner system, corresponds to a level 3). Since the linear shrinkage (change in linear dimensions), warpage (deviation form) and the residual stresses are, in fact, the characteristics of a stress-strain state of the molding after ejecting, the local maximal warpage corresponds to a local minimum of thermal residual stresses, which determines the minimum birefringence in this case.

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CONTACTS

Dr.-Ing. habil.Yablochnikov E.I.	eugeny@beepitron.com
M. Sc. Pirogov A.V.	avpir@mail.ru
Dr.-Ing. Vasilkov S.D.	vasilkov@niuitmo.ru
Dr.-Ing. Andreev Y.S.	yandreev84@gmail.com
Dipl.-Chem. Barvinsky I.A.	ibarvinsky@yandex.ru