UDK 678.027.74
Original scientific article/Izvirni znanstveni članek

ISSN 1580-2949
MTAEC9, 57(3)299(2023)

INJECTION MOLDING OF POLYCARBONATE THICK-WALLED PARTS USING A TOOL WITH VARIOUSLY DESIGNED GATE INSERTS

UPORABA ORODJA Z RAZLIČNO OBLIKOVANIMI VLOŽKI ZA INJEKCIJSKO BRIZGANJE POLIKARBONATNIH DEBELOSTENSKIH IZDELKOV

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Prejem rokopisa – received: 2022-11-22; sprejem za objavo – accepted for publication: 2023-04-25

doi:10.17222/mit.2022.692

Injection molding is an advantageous technology for the mass production of plastic parts without the necessity for additional procedures. The applicability of this method is still partially limited by the required properties of the manufactured parts. Especially in the field of optics, there is a need to produce thick-walled parts while maintaining their transparency. This paper reports on how various shapes of gating systems affected the process parameters and cavity filling during the injection molding of polycarbonate thick-walled specimens. These outcomes demonstrated that film gates and their alternatives are more suitable for the standard injection molding of thick-walled optical products than the triple-edge gating systems. Favorable results were observed particularly in the uniformity of cavity filling, size of shrinkage, and in the occurrence of defects such as voids or sink marks.

Keywords: injection molding, cavity filling, thick-walled part, gating system

Postopek oblikovanja izdelkov z injekcijskim brizganjem je napredna tehnologija za masovno proizvodnjo plastičnih izdelkov kompliciranih oblik brez potrebe po nadaljnjih postopkih obdelave. Uporabnost tega postopka je še vedno delno omejena z zahtevanimi lastnostmi izdelkov, še posebej na področju optike, kjer je potrebno izdelovati debelostenske izdelke in pri tem ohraniti njihovo prozornost. V članku opisujejo, kako na različne oblike sistemov zapiranja orodja vplivajo procesni parametri in polnjenje votline orodja med injekcijskim brizganjem polikarbonatnih debelostenskih preizkusnih vzorcev. Rezultati izvedenih preizkusov so pokazali, da so filmska vrata in njene alternative bolj primerne za standardno injekcijsko brizganje debelostenskih optičnih izdelkov kot pa trirobi sistemi zapiranja. Ugotovili so, da je prišlo do bolj enovitega polnjenja votline orodja z materialom in posledično se je pojavljalo manj napak na izdelkih, kot so na primer pore, luknjice, vdolbine, nalitja in ostale površinske napake.

Ključne besede: injekcijsko brizganje, polnjenje votline orodja, debelostenski izdelki, sistem zapiranja orodja

1 INTRODUCTION

Injection molding is a method of processing plastics that is still expanding. Currently, it is used for the manufacturing of most plastic products for a wide range of industries. Injection-molded parts are generally designed as thin-walled shells, but with increasing demand, there is a need in some areas to produce components with greater thickness. For this purpose, the commonly known injection-molding technology with foaming is often used. Nevertheless, this process does not achieve the required transparency of optical parts as well as water- or gas-assisted injection-molding technologies. Because this area has been little studied so far, many unanswered questions are arising in industrial practice towards the fabrication of such parts. Therefore, the examination of the cavity-filling process using differently shaped gates presents essential knowledge leading to the production of quality, thick-walled optical parts.

Several researchers have already studied possible solutions for the injection molding of thick-walled components. The options for producing thick lenses using the method of sequentially injected layers were presented by Maier.[1] Furthermore, an application of similar multilayer injection-molding technology for optics was discussed by Hopmann[2] and Nian.[3] A similar issue was further studied by Liu.[4] Since these studies dealt with special injection-molding methods, which may not be suitable for more complex parts, their conclusions should not be universally applicable.

On the other hand, the numerical and experimental single-component injection molding alternative of manufacturing thick products was examined by Han.[5] An analogous process focused on restraining voids generated inside a thick test sample was carried out by Motegi.[6] Within both of these studies, the injection-compression molding method was applied to produce the samples. This procedure requires a specially designed injection mold and places high demands on the injection-molding

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machine, which makes it not directly applicable to a conventional injection-molding process.

Further research studying the production possibilities of a thick-walled part using a standard injection-molding technology was conducted by Gotlih.[7] The objective of this work was to examine the influence of selected process conditions on the resulting part quality. Parameters such as deflection rate, volumetric shrinkage, and depth of sink marks were determined as quality indicators. Simulations of the injection-molding process for technical parts with large wall thickness with respect to process parameters have been performed, evaluated and discussed in articles published by Fu[8], Solanki[9] and Dogossy.[10] The outputs of these studies could lead to the improvement of some quality parameters of similarly designed products, or to shortening the cycle time of their production.

The study including an issue of designing a conformal cooling system of an injection mold for the optical part with a considerable wall thickness, was performed by Hopmann.[11] This research was conducted to reduce the deformations and internal stresses in the molded part by controlling the temperature of the core and the cavity mold inserts. The results can be applied during the design of conformal cooling channels to produce thicker parts with fewer defects. An article covering a similar topic of conformal cooling channels design was published by Park.[12] and Torres-Alba.[13] In these studies, conformal cooling channels were designed and simulated to homogenize the temperature distribution of the molded part during the injection-molding process. The results of these works could provide basic general knowledge about the complexity of conformal cooling channels design, which may be applicable for the production of thick-walled parts.

Another study carried out by Sykutera[14] aimed to determine the effect of nitrogen pressure on the rheological properties and structure of thick-walled parts produced by microcellular injection-molding technology. Use of this method affected the apparent viscosity value, which led to the reduction of the pressure in the mold compared to the standard technology. Subsequently, this could improve the course of processes in the mold, thus increasing the production efficiency.

The effect of process parameters and component thickness on the shrinkage of an injection molded component was analyzed using the appropriate tools by Yang[15] and Studer[16] The results showed that increasing melt temperature caused the effect of shrinkage to be more significant. In addition, changing other process parameters, such as mold temperature, injection pressure, holding time, and cooling time affected the shrinkage behavior to only a limited extent. This knowledge can contribute to the efficient setting of process parameters while manufacturing components with greater wall thickness. Besides, according to the results presented by Ch'ng,[17] Nasir[18] and Roslan,[19] the method of response surface methodology could be beneficial while optimizing the settings of process conditions, therefore reducing the deformation of injection-molded parts.

The approach of manufacturing plastic parts supported by simulation and subsequent experimental injection molding to reduce the time of development and the production of large aspherical plastic lenses was performed by Shieh.[20] The presented research consisted of using a real amount of shrinkage after the initial injection molding of an aspherical plastic lens as a reference for shaping a core insert. This approach can outline the solution of shaping the cavity and core inserts to prevent part deformations. Besides, the production of precise plastic lenses concerning mold surface parameters, together with process conditions and their influence on optical properties, was described by Lai,[21] Dick[22] and Speck.[23]

Injection compression molding with regards to process conditions and their influence on the resulting quality of plastic lenses was studied by Young.[24] Furthermore, the studies where the standard injection molding of relatively thick parts has been examined were realized by Michaeli,[25] Höll,[26] Huang[27] and Chung.[28] However, the conventional injection-molding method was discussed only marginally, contrary to the injection-compression molding technique. These studies were focused on the examination of the optical properties rather than on the process itself.

Thus, this research deals with the conventional injection molding of thick-walled optical parts made of polycarbonate (PC) using variously shaped gating systems. Acquired knowledge about the cavity-filling process of such a component can significantly contribute to the clarification of the questions arising from their manufacturing.

2 EXPERIMENTAL PART

The experiment was conducted to examine how various shapes of gating systems affect the cavity filling during the injection-molding process. Two variants of thick-walled test specimens made of polycarbonate were produced using a special injection mold with replaceable gating inserts. This approach was preceded by the validation of the filling phase through the flow-analysis software. As the uniform process parameters were defined, it was possible to evaluate how different geometries of the gating influences the individual aspects of cavity filling, thus determining the overall quality of the specimens.

The test specimens were made of polycarbonate with the trade name Makrolon LED 2245. This material is widely used for the optics because of its versatility, excellent light transmittance, shape stability, and temperature resistance. In addition, another advantage of this polymer is the light conductivity over a wide range of radiation.

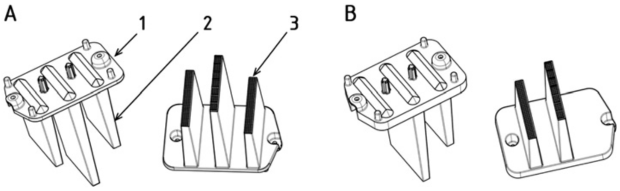


Figure 1: Test specimens (1 – mounting base, 2 – optical rib, 3 – optical pattern)

The melt temperature was set to 325 °C during both the simulations and the injection itself. Since the PC absorbs water, it was necessary to dry the raw material before processing for 3 h at 120 °C, which was done with a Arburg Thermolift 100-2 dryer.

Within the experiment, a functional thick-walled optical specimen was designed in two variants using the same material. As can be seen in **Figure 1**, the difference between variant A and variant B is the number of optical ribs and the thickness of the mounting base, which was 3 mm for the first variant and 8 mm for the other. Since the intended function of the sample is to distribute the light beam consistently, there is an optical pattern on the underside of the ribs. The largest dimensions of the sample were (80 × 50 × 75) mm, whereas the maximum thickness of the rib reached 10 mm.

All test specimens were prepared by injection-molding technology. As shown in **Figure 2**, a special injection mold for testing differently shaped gates was used. Accordingly, the design of the mold allowed the simple attachment of individual gating inserts. Moreover, to prepare both specimen variants, the mold was provided with replaceable cavity-defining parts. Other mold components were standardized parts or conventionally designed plates.

For the test sample in both variants, an injection-molding process was performed using three different gating inserts to determine the most suitable filling method. **Figure 3** shows the visualization of individual gating systems related to the injected part. In the first case, a 1-mm-thick triple-edge gate was used. The second variant was similar, but with the gate thickness increased to 1.5 mm. Another option was the use of a

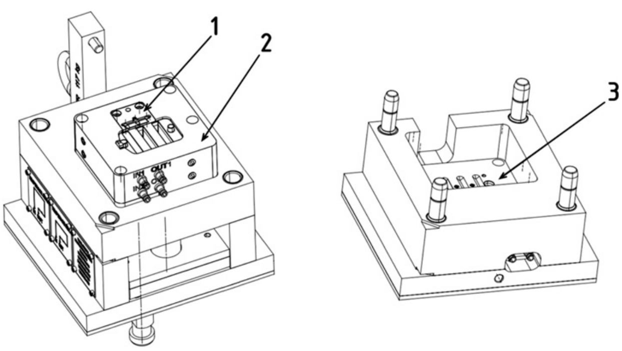


Figure 2: Testing injection mold (1 – gating insert, 2 – core insert, 3 – cavity insert)

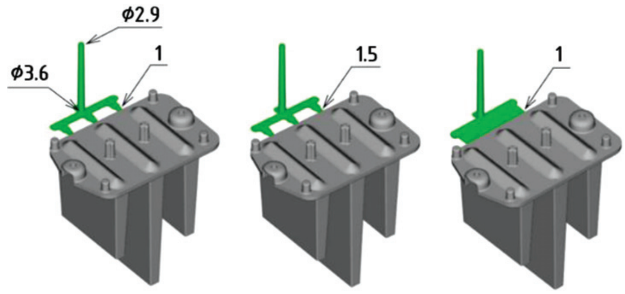


Figure 3: Different shapes of gating systems

1-mm-thick film gate. The size and shape of the sprue bushing was the same in all cases.

To determine the influence of different gating systems on the filling and packing phase, it was necessary to prepare all the testing specimens under uniform process conditions. Recommended values received from the material sheet were considered as well as the parameters suggested by the Moldflow software.

Table 1 shows that due to the thick-walled character of the specimens, the conditions of the holding phase were set manually. Because a thicker wall takes a longer time to cool down, the holding time was set to 10 s. The moment of switching from injection to the holding phase was defined at a 99 %-filled cavity. The amount of holding pressure was determined as 80 % of the maximum injection pressure. The values of these parameters were derived from the results of a preliminary flow analysis.

Table 1: Selected process parameters

Fill time	4.7 s
Melt temperature	270 °C
Mold temperature	100 °C
Injection pressure	37–47 MPa
Holding pressure	80 % of max. injection pressure
Holding time	10 s
Switching point to holding	at 99 %-filled cavity

The sample preparation itself was preceded by the process validation through flow analysis, which was performed by the Autodesk Moldflow Synergy 2016 software. This enabled the simulation of filling, holding and cooling phases of the process. Thus, it was possible to detect and reduce the occurrence of defects and to identify those process parameters that could be optimized. Moldflow includes an extensive database of polymeric materials and injection molding machines, so the simulation conditions were as close to reality as possible.

All test samples were produced using an electric injection molding machine Allrounder 470 E 1000–290 Golden Electric with a maximum clamping force of 1000 kN.

3 RESULTS

All test samples were used to analyze how the individual type of gating system affects the cavity-filling process. In particular, it was essential to examine the increase in the melt temperature due to high shear stress that occurs when it flows through the gating system. This phenomenon could cause overheating of the material and its subsequent degradation. Additionally, the moment when the gate solidifies was identified because only to this point is the holding phase effective.

The results of how each type of the gate affected specific values of the actual injection-molding conditions are shown in the following tables. These are accompanied by figures displaying the result of a simulation performed by the Moldflow software. Its output is a graphical evaluation of the time required to fill the mold cavity, with the blue areas being filled first and the red ones last. It is assumed that the uniformity of filling illustrated by the analysis corresponds sufficiently to the injection molding.

As can be seen in **Table 2**, an uneven filling of the mold cavity occurs since the center rib is filled first, while the side ribs are almost unfilled. Due to the minimum flow rate of the melt through the side gates, they are already frozen in the cycle time of 3 s. This caused the holding phase to be effectively performed for only 5 s. Besides, due to the high flow rate of the polymer melt through the central gate, enormous shear stress occurred, resulting in excessive heating of the melt.

According to **Table 3**, it is apparent that the filling of the cavity by the film gate is more uniform than the previous gate type. However, the melt has reached the rest of the cavity only after the center was filled, similar to the previous case. At the cycle time of 9.9 s, the gate was already completely solidified, thus the holding phase lasted only for 4.5 s.

Table 4 shows that using a 1.5-mm-thick side gate led to a significantly lower melt temperature, mainly due to the enlarged size of the gate. Nonetheless, it exceeded the absolute maximum recommended by the Moldflow database.

As presented in **Table 5**, due to the lack of one optical rib and the greater thickness of the mounting base, the mold cavity is filled nearly evenly, although still mostly through the central gate. For this reason, the side gates were almost solidified during filling at a time of 5.4 s. In addition, the polymer melt was shear stressed,

Table 2: Results for sample A with a 1-mm tripple-edge gate

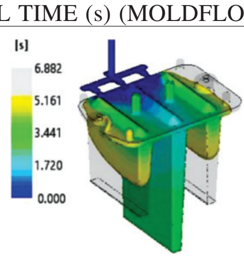
PARAMETER	VALUE	UNIT	FILL TIME (s) (MOLDFLOW)
Fill time	6.9	s	
Max. injection pressure	47	MPa	
Max. melt temperature	430	°C	
Side-gate solidification time	3	s	
Central-gate solidification time	11.7	s	
Defined/Effective holding time	10/5	s	
Cooling time	48.7	s	
Total cycle time	65.6	s	

Table 3: Results for sample A with a 1.5-mm triple-edge gate

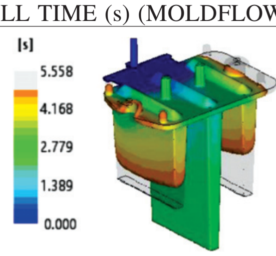
PARAMETER	VALUE	UNIT	FILL TIME (s) (MOLDFLOW)
Fill time	6.7	s	
Max. injection pressure	37.7	MPa	
Max. melt temperature	341.5	°C	
Time of gate solidification	4	s	
Defined/Effective holding time	10/5.5	s	
Cooling time	166	s	
Total cycle time	182.7	s	

Table 4: Results for sample A with a 1-mm film gate

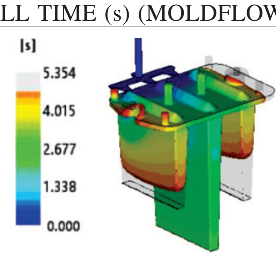
PARAMETER	VALUE	UNIT	FILL TIME (s) (MOLDFLOW)
Fill time	5.4	s	
Max. injection pressure	37.2	MPa	
Max. melt temperature	325.9	°C	
Time of gate solidification	9.9	s	
Defined/Effective holding time	10/4.5	s	
Cooling time	182.3	s	
Total cycle time	197.7	s	

Table 5: Results for sample B with a 1-mm triple-edge gate

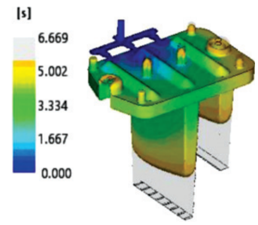
PARAMETER	VALUE	UNIT	FILL TIME (s) (MOLDFLOW)
Fill time	6.7	s	
Max. injection pressure	37.4	MPa	
Max. melt temperature	343	°C	
Side-gate solidification	5.4	s	
Central-gate solidification	11.4	s	
Defined/Effective holding time	10/5.3	s	
Cooling time	44.8	s	
Total cycle time	61.5	s	

Table 6: Results for sample B with a 1-mm film gate

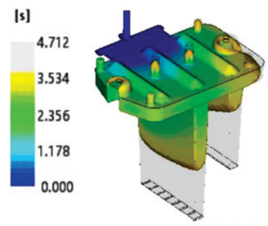
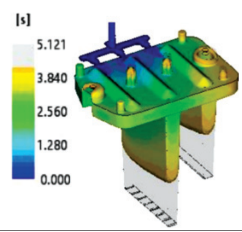
PARAMETER	VALUE	UNIT	FILL TIME (s) (MOLDFLOW)
Fill time	4.7	s	
Max. injection pressure	37.3	MPa	
Max. melt temperature	323	°C	
Time of gate solidification	10.3	s	
Defined/Effective holding time	10/5.6	s	
Cooling time	206.7	s	
Total cycle time	221.4	s	

Table 7: Results for sample B with a 1.5-mm triple-edge gate

PARAMETER	VALUE	UNIT	FILL TIME (s) (MOLDFLOW)
Fill time	5.1	s	
Max. injection pressure	38.2	MPa	
Max. melt temperature	336	°C	
Side-gate solidification	4.2	s	
Central-gate solidification	9.5	s	
Defined/Effective holding time	10/4.8	s	
Cooling time	206.2	s	
Total cycle time	221.3	s	

thus reached high temperatures causing the degradation of the material.

Table 6 shows that considering the design of the part, the central optical rib is filled first, followed by the filling of the mounting base, resulting in a more intensive melt flow into the right optical rib. Since the gate solidifies already in 10.3 s, the effective time of the holding phase is only 5.6 s. Despite that, this gating system is the only one that meets the absolute maximum melt temperature for the defined process conditions.

As shown in **Table 7**, compared to the alternative with a 1-mm triple side gate, the filling time decreased from 6.7 to 5.1 s, moreover, the melt temperature dropped significantly. Due to both the increased gate size and the reduced filling time, the melt was notably less shear stressed.

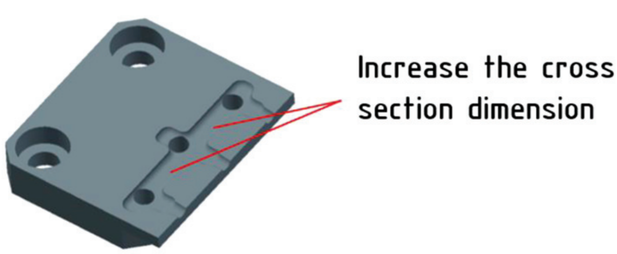


Figure 4: Possible modification of the gating insert

It is generally known that the melt passing through the gate is heated by shear stress. When using a triple side gate, the cavity filling took a relatively long time, thus the melt was considerably shear stressed, which resulted in its degradation. An increase of the gate size to above 1.5 mm would reduce the shear stress, therefore, the melt may not overheat. Further, the more prolonged holding phase would be achieved. As shown in Figure 4, an improvement of the cavity- filling uniformity could be achieved by increasing the cross-sectional dimension of the side distribution channels. However, this modified version of the gating insert was not tested in this study.

4 DISCUSSION

In our research, more satisfactory results in both sample variants were obtained when using a film gate. Since its cross-section is larger than was in the previous case, the melt was not heated so intensively, which allowed the production of functional samples shown in **Figure 5**. Also, the influence of the holding phase was more appar-

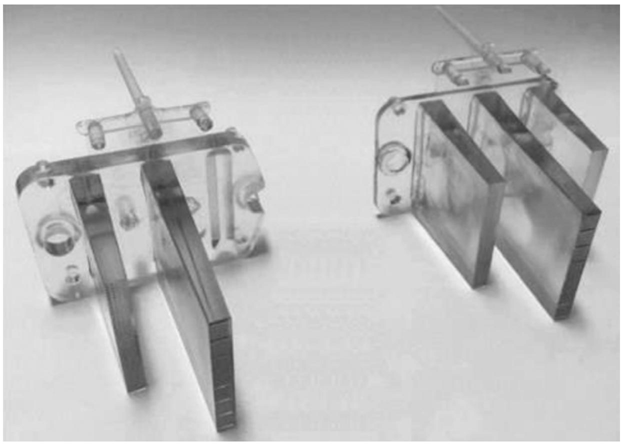


Figure 5: Both variants of injection-molded samples

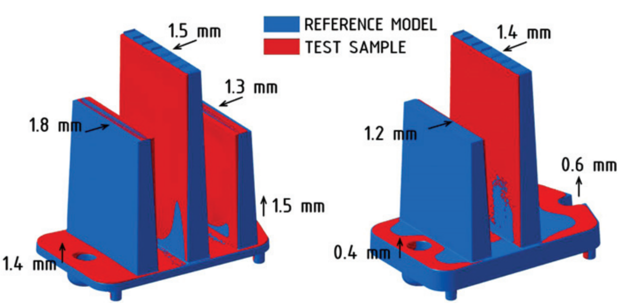


Figure 6: Comparison of the test sample with the reference model

ent, as it lasted longer. This improvement reduced the shrinkage and occurrence of defects such as voids or sink marks. Additionally, the use of a film gate appears to be efficient due to a more uniform cavity filling. Based on this knowledge and the results in **Tables 3** and **6**, it is possible to assume that contrary to the edge gating systems, film gates and their alternatives are more suitable for the injection molding of thick-walled optical products.

One of the possible procedures for the specific evaluation of deformations and defects is scanning the surface of the manufactured sample with a 3D scanner and subsequent comparison of the obtained data with the geometry of the reference model. In this way, dimensional and shape deviations can be graphically displayed, their extent evaluated, and determined whether the obtained values lie within the tolerance range. Based on the results obtained, the influence of the individual process parameters on the occurrence and size of deformations can be investigated, or the design of the mold can be adjusted and thus come as close as possible to all the defined requirements.

Figure 5 compares the scanned areas of the injected sample with the reference model. The surface of the injected sample was scanned with a 3D scanner to obtain a cloud of points, which was then converted to a mesh. The surfaces generated in this way were interlaced with the surface of the reference model, and then the individual geometries were compared and the degree of deformation was evaluated. In this case, however, these are only indicative results used to verify the applicability of the chosen method. The quality of the results is closely related to the accuracy of the scanning and the subsequent processing of the obtained data, so to receive relevant results, it is necessary to pay more attention to this issue.

5 CONCLUSIONS

The study examined the influence of various shapes of gating systems on cavity filling during the injection molding of PC thick-walled specimens in two variants. The results provide information about specific values of process parameters affected by differently shaped edge and film gating systems. Accordingly, the application of the film gate seems more appropriate than the triple-edge gate since the cavity filling is more uniform, and the occurrence of defects is noticeably lower.

In conclusion, the overall quality of standard injection-molded PC thick-walled specimens is more favorable when using the film gate. The main reason is the lower shear stress of the polymer melt, which minimizes its overheating. Furthermore, the duration of the holding phase is more effective since the film gate solidifies later than with the triple-edge gate. These findings may be valuable for the design of the optical parts themselves and the injection molds for their production. The knowledge about the cavity filling through differently shaped gating systems could save time and resources during the development of injection molds for producing transparent thick-walled parts. Nevertheless, the influence of the other applicable gating systems on the cavity-filling process of such parts has not been considered in this study and requires additional examination.

Acknowledgment

This work was supported by the Internal Grant Agency of TBU in Zlin: no. IGA/FT/2023/005 and project "Plastics, metals and technology (PLAKOTECH)", CZ.01.1.02/0.0/0.0/15_007/0003397..

6 REFERENCES

[1] Ch. Maier, Thick-Walled Lenses: Efficient Production of Thick-Walled Parts, https://en.kunststoffe.de/a/specialistarticle/thick-walled-lenses-efficient-production-263942

[2] C. Hopmann, M. Röbig, Application of a multilayer injection molding process for thick-walled optical components, J. Polym. Eng., 36 (**2016**) 6, 557–562, doi:10.1515/polyeng-2014-0259

[3] S. C. Nian, P. W. Chen, M. S. Huang, Multilayer injection molding of high-profile convex lens, J. Appl. Polym. Sci., 137 (**2020**) 17, 48600, doi:10.1002/app.48600

[4] Y. Liu, L. Cao, W. K. Chi, L. Y. Zhang, W. M. Yang, P.C. Xie, Multi-layer counter-pressure injection molding for thick-walled optical lens, Int. Polym. Process., 36 (**2021**) 2, 131–136, doi:10.1515/ipp-2020-3994

[5] S. R. Han, J. R. Cho, S. K. Beak, J. A. Hong, Y.v S. Lee, Numerical and experimental studies of injection compression molding process for thick plastic gas valve stem, Int. J. Adv. Manuf. Technol., 80 (**2017**) 1–4, 651–660, doi:10.1007/s00170-016-9139-6

[6] A. Motegi, T. Hishida, Y. Murata, Restraint of voids generated inside injection molded products by in-mold pressing method, Int. J. Autom. Technol., 12 (**2018**) 6, 930–939. doi:10.20965/ijat.2018.p0930

[7] J. Gotlih, M. Brezočnik, I. Drstvenšek, T. Karner, K. Gotlih, Influence of injection molding process parameters on part quality, Proc. Of the Inter. Conf. on New Technologies, Development and Application, Sarajevo 2018, 33–40

[8] J. Fu, J. Liu, L. Quan, Y. Ma, Partial solidification ejection criteria for injection molding production to reduce cycle time, Robot. Comput. Integr. Manuf., 74 (**2022**), 102263, doi:10.1016/j.rcim.2021.102263

[9] B. S. Solanki, H. Singh, T. Sheorey, Modeling and analysis of cavity modification effect on quality of injection molded polymer gear, Int. J. Interact. Des. Manuf., 16 (**2022**) 4, 1615–1632, doi:10.1007/s12008-022-00887-0

[10] G. Dogossy, T. Morauszki, F. Ronkay, Experimental investigation and applicability of multi-stage simulations in the case of a thick-walled injection-moulded composite, Appl. Sci., 12 (**2022**) 17, 8415, doi:10.3390/app12178415

[11] C. Hopmann, J. Gerads, T. Hohlweck, Investigation of an inverse thermal injection mould design methodology in dependence of the part geometry, Int. J. Mater. Form., 14 (**2021**) 2, 309–321, doi:10.1007/s12289-020-01604-6

[12] H. S. Park, X. P. Dang, Development of a smart plastic injection mold with conformal cooling channels, Proc. of the 45th SME North American Manufacturing Research Conf., Los Angeles 2017, 58-59

[13] A. Torres-Alba, J. M. Mercado-Colmenero, J. de D. Caballero-Garcia, C. Martin-Doñate. Application of new triple hook-shaped conformal cooling channels for cores and sliders in injection molding to reduce residual stress and warping in complex plastic optical parts, Polymers, 13 (**2021**) 17, 2944, doi:10.3390/polym13172944

[14] D. Sykutera, P. Czyżewski, P. Szewczykowski, High-performance of a thick-walled polyamide composite produced by microcellular injection molding, Materials, 14 (**2021**) 15, 4199, doi:10.3390/ma14154199

[15] B. Yang, W. Guo, G. Cheng, L. Su, R. Xia, J. Qian, 3D simulation of shrinkage behaviour of injection-molded poly(lactic acid) : Effect of Processing Parameters and Part Thickness. Asian J. Chem., 26 (**2014**) 5, 1337–1340, doi:10.14233/ajchem.2014.17224

[16] M. Studer, F. Ehrig, Minimizing part warpage in injection molding by optimizing wall thickness distribution, Adv. Polym. Technol., 33 (**2014**) 1, 21454, doi:10.1002/adv.21454

[17] S. Q. Ch'ng, S. M. Nasir, M. Fathullah, N. Z. Noriman, M. H. M. Hazwan, Warpage Analysis on Thick Shell Part Using Response Surface Methodology (RSM) to Optimize Parameter Setting in Injection Molding Process, Proc. of the 4th Inter. Conf. on Green Design and Manufacture, Ho Chi Minh City 2018, 020167

[18] S. M. Nasir, Z. Shayfull, S. Sharif, A. E. H. Abdellah, M. Fathullah, N. Z. Noriman, Evaluation of shrinkage and weld line strength of thick flat part in injection moulding process, J. Braz. Soc. Mech. Sci. Eng., 43 (**2021**) 10, 452, doi:10.1007/s40430-021-03060-y

[19] N. Roslan, S. Z. Abd Rahim, A. E. H. Abdellah, Optimisation of shrinkage and strength on thick plate part using recycled LDPE materials, Materials 14 (**2021**) 7, 1795, doi:10.3390/ma14071795

[20] J. Y. Shieh, L. K. Wang, S. Y. Ke, A feasible injection molding technique for the manufacturing of large diameter aspheric plastic lenses, Opt. Rev., 17 (**2010**) 4, 399–403, doi:10.1007/s10043-010-0074-8

[21] H. E. Lai, P. J. Wang, Study of process parameters on optical qualities for injection-molded plastic lenses, Appl. Opt., 47 (**2008**) 12, 2017–2027, doi:10.1364/ao.47.002017

[22] L. Dick, S. Risse, Tünnermann A. Injection molded high precision freeform optics for high volume applications, Adv. Opt. Technol., 1 (**2012**) 1–2, 39-50, doi:10.1515/aot-2011-0009

[23] A. Speck, B. Zelzer, M. Speich, R. Börret, A. Langenbucher, T. Eppig, Deflectometric analysis of high volume injection molds for production of occupational eye wear, Z. Med. Phys., 23 (**2013**) 4, 314–323, doi:10.1016/j.zemedi.2013.08.003

[24] W. B. Young, Effect of process parameters on injection compression molding of pickup lens, Appl. Math. Model., 29 (**2005**) 10, 955–971. doi:10.1016/j.apm.2005.02.004

[25] W. Michaeli, S. Heßner, F. Klaiber, J. Forster, Geometrical accuracy and optical performance of injection moulded and injection-compression moulded plastic parts, CIRP Ann. Manuf. Technol., 56 (**2007**) 1, 545–548, doi:10.1016/j.cirp.2007.05.130

[26] S. Holl, M. Haupt, U. H. P. Fischer, Injection molding of a WDM system for POF communication, Proc. of the IEEE 63rd Electronic Components and Technology Conference, Las Vegas 2013, 2292–2297

[27] M. S. Huang, J. Y. Chen, Y. Q. Xiao, Quality monitoring of micro-shrinkage defects in thick-walled injection molded components, Measurement, 201 (**2022**) 111733, doi:10.1016/j.measurement.2022.111733

[28] C. Y. Chung, Integrated optimum layout of conformal cooling channels and optimal injection molding process parameters for optical lenses, Appl. Sci., 20 (**2019**) 9, 4341, doi:10.3390/app9204341