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Computer Modeling and Simulation of the Process of Information Microstructure Replication for Optical Data Storage

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Abstract: *Polymer injection moulding is very suitable for mass fabrication of high precision micro- and nanostructures. The optical disc information structures are both in the micro and nanometer range and being in the form of pits they are moulded into the disc through injection moulding. The key reason for the success of optical discs (CD) as storage media is the fact that injection molding makes possible the transfer of Gbytes of data points (surface pits) in a few seconds onto a cheap polymer carrier. The experience gained up to now in the field of injection moulding of optical disc substrates has shown that the mould and the sprue system design occupy a central place in the production process.*

A design concept and integrated 3D CAD models of the sprue system of an optical disc mould and the optical disc substrate are developed. The sprue system is known as a system, in which the central hole of the polymer substrate is formed by direct punching of the circle gate from the polymer substrate. In the process of the investigation a modified variant of the sprue system is developed, in which the melt distribution area with symmetrical shape is formed. The proposed models allow easy change of the geometric shape and dimensions of the sprue system and polymer substrate. The gate size, the polymer substrate thickness and the draft angle of the sprue are defined as variable parameters with three variants of the processing conditions in mould filling simulation. The results obtained show that small changes of the gate size and substrate thickness cause significant impact on the ability to fill the mould cavity. By means of iterative steps within the frame of the simulation program, a series of values of the polymer substrate thickness and the gate size are attained, in which easy mould cavity filling is obtained for all variants of processing conditions.

Keywords*: Optical disc, 3D CAD model, computer simulation, micro- and nanostructures.*

1. Introduction

1.1. Optical disc moulding

Polymer injection moulding is very suitable for the mass fabrication of high precision micro- and nanostructures. The optical disc information structures both in the micro and nanometer range and in the form of pits are moulded into the disc during the injection moulding. The key reason for the success of optical discs as storage media is the fact that injection molding makes possible the transfer of Gbytes of data points (surface pits) in a few seconds onto a cheap polymer carrier [1, 2, 3].

The production of polymer substrates for optical discs, which requires high dimension accuracy, exact copying of the information and low birefringence has introduced the notion high-precision moulding. The moulding of optical discs substrates on the basis of injection moulding or its modifications is regarded as the most precise moulding type at the present moment. The experience gained up to now in injection moulding of substrates for optical discs has shown that the mould and the gate design occupy a central place and are the most significant parts in the production process [4].

The obtaining of the geometrically simple substrate, being a circular washer with width of 1.20 mm, diameter of the central hole 15 mm and external diameter varying from 120 up to 300 mm, together with the necessity for precise copying of the information structure with the help of a stamper set in the mould, the accuracy of the geometric dimensions and the low level of birefringence, imply high requirements towards the mould, connected with precise construction and tolerances of the order of microns [5, 6, 7, 8].

1.2. Formulation of the technical problem in the optical disc moulding

In the process of injection moulding of optical disc substrates, a hot polymer melt is injected in the thin cooled mould cavity under high speed and pressure with the help of a circle gate located in the cavity centre. This practically means that substrate indicators such as birefringence, residual tensions and copying of the information structure are highly dependent on the behavior of the melt flow, filling the mould cavity. It becomes clear that great internal tensions are available in the final product as a result of improper location, form and dimensions of the circle gate, which result at the end in high level of the main indicator for substrate quality – the birefringence. Hence, the construction solution and the scheme of the circle gate location play a significant role in the quality of the final product [8, 9].

The problem for optical disc moulding starts with the fundamental difficulty of filling and packing a mould cavity of much greater length than depth, without incurring high levels of moulded-in stress and orientation. For instance, a 130 mm diameter erasable media disc has 54 times longer melt flow path than part thickness (or an aspect ratio of 54:1). Likewise, a CD-ROM disc has a 50:1 ratio and a 300 mm WORM disc – a 120:1 ratio [10, 11].

The approach applied up to now by the separate manufacturers in solving the problem of cavity filling and formation of the central hole substrate has not declined from the method used until now, i.e. filling through a thin film circle gate located at the place where the central hole is to be formed. This requires the use of a complex and precise cropping punch system, removing the circle gate, in order to form the central hole. On the other hand, the necessity to shape the central hole by punching, calls for minimal depth of the circle gate enabling its easy removal. This influence deteriorates the level of the product internal tensions and the orientation phenomena, accompanying the process of filling. A study of the mould cavity filling with melt shows that one of the conditions for low internal tensions in the final product is the application of a maximally wide circle gate, which contradicts to the possibilities of the mould constructions known recently [12, 13].

Computer simulation packages have shown success in predicting filling behavior in extremely complicated geometries. To improve the mould design and process control in injection moulding, increasing reliance has been placed on CAD/CAE/CAM. Mould-filling programs have proved successful in predicting filling behavior in extremely complicated geometries, assisting in gate placement, runner sizing, clamp-force requirements [14, 15, 16].

In optical disc technology the design is extensively supported by modeling and simulation. The optical disc product for data storages is complex and the production of a high-quality component requires optimum design coupled with exacting process control [17].

Computer simulation is playing a significant role in most of the the research activities, which consider the optical disc moulding, but they concern mainly the advantages of the program or creation of a viscoelastic models of the mould filling, without examining the influence of the concrete sprue system geometry on the mould filling process. Probably, the reason for this is that the sprue system is the key of successful optical disc moulding and its design represents a Know-How of the companies, working in this area.

The purpose of the paper is to develop a design concept and integrated 3D CAD models of the sprue system and the optical disc substrate and to provide a primary research to study the effect of the gate size, the polymer substrate thickness and the draft angle of the sprue on the process of mould cavity filling. This study aims to obtain a range of values of variable parameters in order to achieve easy mould cavity filling for all variants of the processing conditions, using the 3D CAD models developed and computer simulation code.

Another aim of the work is to serve as a basis for further studies, in which to achieve optimal values of the above parameters and to help the optical disc mould designers choose the correct dimensions of the sprue system and polymer substrate.

2. 3D CAD models of the polymer substrate and sprue system

The 3D modelling of an object is the first stage to be considered when computer simulation techniques are used [5, 16].

An author's flow chart diagram of the stages, necessary to study the effect of the gate size, polymer substrate thickness and the draft angle of the sprue on the process of mould cavity filling is developed (Fig. 1).

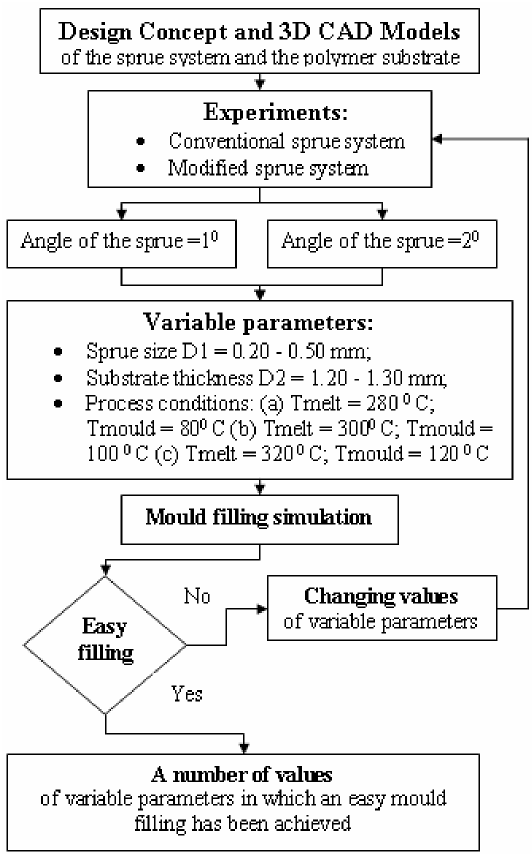

Fig. 1. Flow chart of the research scheme

The sprue system design concept is based on a well-known type of an optical disc mould with a sprue system, in which the central hole of the polymer substrate is formed by direct punching of the circle gate from the polymer substrate. For this purpose a punch bush is moved against the air supply bush, so that the circle gate is removed from the polymer substrate (Fig. 2).

The sprue system consists of a central sprue, melt distribution area with a conical shape and a circle gate (Figs. 3 and 4). The general disadvantage of this construction is the necessity to use a minimal size of the circle gate for its easier removal, which contradicts to the support of the optimal conditions of the process of mould cavity filling.

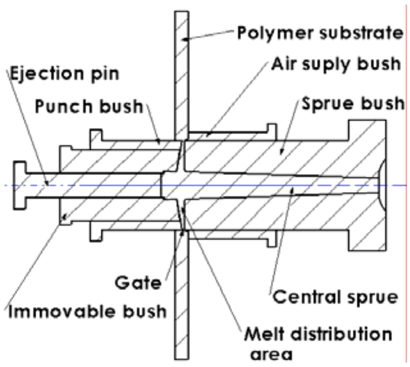

Fig. 2. Cross-section of the conventional sprue system design

In the process of the investigations, a modified design concept of the sprue system is realized. The modified sprue system has a symmetrical shape of melt distribution area (Fig. 5).

3D CAD models of the sprue systems above considered are built (Figs. 3-5). SolidWorks 2006 software is used for all the 3D CAD models. The 3D CAD models of the sprue systems and polymer substrate present an integrated 3D CAD model consisting of the sprue system and the polymer substrate, considered as one object.

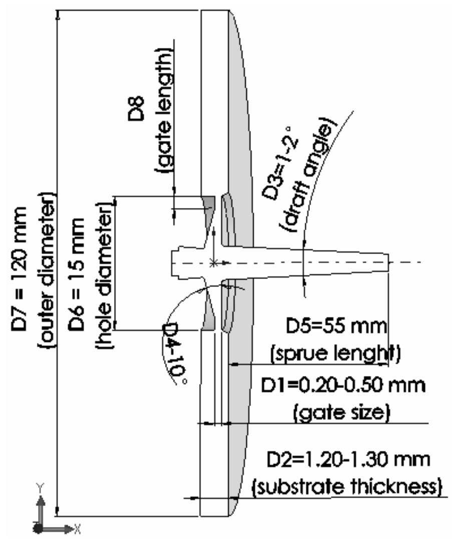

Fig. 3. Integrated 3D CAD model of the polymer substrate and a conventional sprue system

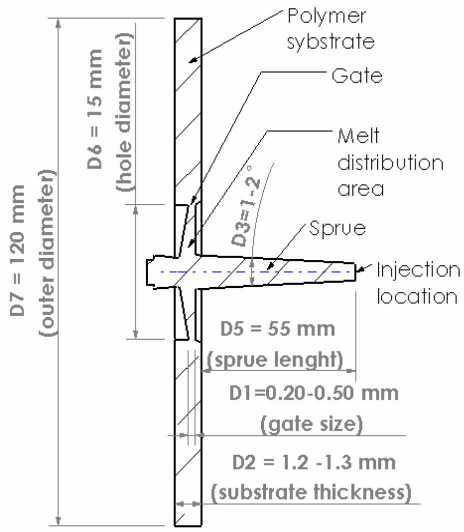

Fig. 4. Cross-section of the polymer substrate and a conventional sprue system with gate length D6 = 0.00 mm

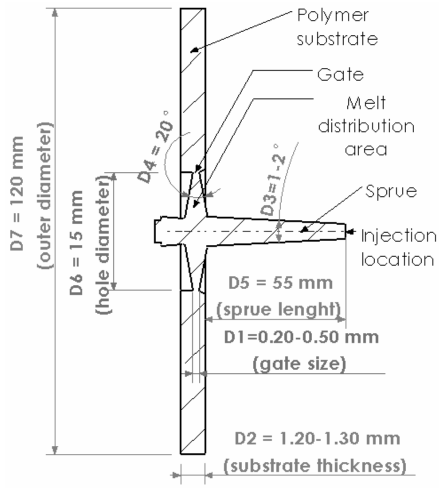

Fig. 5. Cross-section of the polymer substrate and a modified sprue system

3. Design of the experiment

For the purpose of investigations, the variable parameters are defined based on the previous author's investigations experience on the process of mould filling simulation [5, 16].

All the experiments are carried out in the case when the polymer substrate outer diameter is equal to 120 mm and the central hole diameter is equal to 15 mm.

Two types of the sprue system are considered: a conventional sprue system and its modified variant, in which the melt distribution area has a symmetrical shape. For every type of the sprue system, simulations with two different values of the draft angle of the sprue are carried out: when the draft angle D3 is equal to 1° and when it is equal to 2°.

The following parameters of the sprue systems and polymer substrate are defined as variables: the gate size D1 is equal to 0.20 up to 0.50 mm at intervals of 0.01 mm, the polymer substrate thickness D2 is equal to 1.20 up to 1.30 mm at intervals of 0.01 mm. The constant parameters are: the sprue length D5 is equal to 55 mm, the angle of the conical part of the melt distribution area D4 is equal to 10° (Fig. 3).

These variable parameters are combined with three variants of the processing conditions (melt and mould temperatures): (a) T_{melt} = 280 °C; T_{mould} = 80 °C (b) T_{melt} = 300 °C; T_{mould} = 100 °C and (c) T_{melt} = 320 °C; T_{mould} = 120 °C, where T_{melt} is the temperature of the polymer melt and T_{mould} is the temperature of the mould.

The main purpose of the investigations is to determine the values of the gate size and polymer substrate thickness, so that an easy mould cavity filling is achieved for all variants of the processing conditions.

4. Mould filling simulation and results

A mould filling simulation program MoldflowXpress (integrated with SolidWorks) is used in the primary investigation to study the effect of the gate size, polymer substrate thickness and draft angle of the sprue on the mould cavity filling process. The program can predict whether the injection moulding will be successful. The algorithm is based on the gate geometry, the plastic injection location, the type of plastic material and the processing conditions (melt and mould temperatures and injection time). A polycarbonate plastic material Makrolon (PC) of the BAYER AG supplier is used.

A number of simulations of the two types of the sprue system at values of the gate size equal of 0.20 up to 0.50 mm at intervals of 0.01 mm for every values of the polymer substrate thickness equal to 1.20 up to 1.30 mm at intervals of 0.01 mm are provided. The parameters selected in three variants of the processing conditions (melt and mould temperatures) are combined: (a) T_{melt} = 280 °C; T_{mould} = 80 °C (b) T_{melt} = 300 °C; T_{mould} = 100 °C (c) T_{melt} = 320 °C; T_{mould} = 120 °C.

Relatively good results for conventional sprue system are shown in Table 1.

Table 1. Mould filling simulation results

<table>
<tr><td colspan="6">Conventional sprue system:
Variant I and II: degree of the sprue draft angle D3 is equal to 1° to 2°</td></tr>
<tr><td rowspan="3">Gate size (D1), mm</td><td rowspan="3">Polymer substrate Thickness (D2), mm</td><td colspan="4">Mould filling status:
difficult filling – “no” or easy filling – “yes”</td></tr>
<tr><td colspan="4">Process conditions, °C</td></tr>
<tr><td>T_{melt}=280; T_{mould}=80</td><td>T_{melt}=300; T_{mould}=100</td><td>T_{melt}=320; T_{mould}=120</td><td>Fill time (t), s</td></tr>
<tr><td>0.21</td><td>1.25-1.30</td><td>no</td><td colspan="2">yes</td><td>0.60-0.70</td></tr>
<tr><td>0.22</td><td>1.20-1.30</td><td>no</td><td colspan="2">yes</td><td>0.60-0.70</td></tr>
<tr><td rowspan="2">0.23</td><td>1.25-1.26</td><td colspan="2">no</td><td rowspan="2">yes</td><td rowspan="2">0.60-0.70</td></tr>
<tr><td>1.27-1.30</td><td>no</td><td>yes</td></tr>
<tr><td>0.24-0.25</td><td>1.25-1.30</td><td>no</td><td colspan="2">yes</td><td>0.60-0.70</td></tr>
<tr><td>0.26</td><td>1.25-1.27</td><td colspan="2">no</td><td>yes</td><td>0.50-0.60</td></tr>
<tr><td>0.28</td><td>1.20-1.30</td><td>no</td><td colspan="2">yes</td><td>0.60</td></tr>
<tr><td>0.30</td><td>1.20-1.24</td><td>no</td><td colspan="2">yes</td><td>0.60-0.70</td></tr>
<tr><td rowspan="2">0.31</td><td>1.20</td><td colspan="2">no</td><td>yes</td><td rowspan="2">0.60-0.70</td></tr>
<tr><td>1.21-1.30</td><td>no</td><td colspan="2">yes</td></tr>
<tr><td>0.32; 0.34</td><td>1.20-1.21</td><td>no</td><td colspan="2">yes</td><td>0.50-0.60</td></tr>
<tr><td>0.33</td><td>1.20-1.30</td><td>no</td><td colspan="2">yes</td><td>0.60</td></tr>
<tr><td rowspan="2">0.35</td><td>1.22-1.23</td><td colspan="2">no</td><td>yes</td><td rowspan="2">0.50</td></tr>
<tr><td>1.24</td><td>no</td><td colspan="2">yes</td></tr>
<tr><td>0.36-0.37</td><td>1.20-1.22</td><td colspan="2">no</td><td>yes</td><td>0.50</td></tr>
<tr><td>0.38</td><td>1.21-1.23</td><td>no</td><td colspan="2">yes</td><td>0.50-0.60</td></tr>
<tr><td>0.39-0.40</td><td>1.20-1.28</td><td>no</td><td colspan="2">yes</td><td rowspan="2">0.60-0.70</td></tr>
<tr><td>0.41</td><td>1.20-1.30</td><td>no</td><td colspan="2">yes</td></tr>
<tr><td>0.42</td><td>1.20 - 25</td><td>no</td><td colspan="2">yes</td><td>0.60-0.70</td></tr>
<tr><td rowspan="2">0.43</td><td>1.20-1.22</td><td colspan="2">no</td><td>yes</td><td>0.60</td></tr>
<tr><td>1.23-1.29</td><td>no</td><td colspan="2">yes</td><td>0.60-0.70</td></tr>
<tr><td>0.44-0.50</td><td>1.20-1.21</td><td>no</td><td colspan="2">yes</td><td>0.60-0.70</td></tr>
</table>

Table 1 shows only the values of the gate size when a successful mould cavity filling is achieved.

The results of the experiment with the conventional type of the sprue system show that it is difficult to fill the mould cavity when the draft angle of the sprue is equal to 1°. Good results are obtained when the draft angle of the sprue is equal to 2°, but only in cases when the processing conditions are (b) T_{melt} = 300 °C; T_{mould} = 100 °C and (c) T_{melt} = 320 °C; T_{mould} = 120 °C. The results show that when the mould and melt temperatures increase, an easy mould cavity filling is achieved especially when the values of the gate size and the polymer substrate thickness have greater values.

The most significant results, in which a successful mould cavity filling is achieved for all of the process conditions are shown (Table 2).

The experiments with the modified sprue system show good results for all of the defined variable parameters and for all processing conditions. The best results are obtained with the modified sprue system when the draft angle of the sprue is equal to 2° and the values of the gate size and the polymer substrate thickness area are maximal.

For an example the plot view of the mould filing simulation is shown in Fig. 6 with shaded contours of the output data "fill time". In this figure, the positions of the melt front at different time moments are marked in the form of three-dimensional shaded plots. There is a possibility to show only the filled part of the cavity for each time moment.

Table 2. Mould filling simulation results

Conventional sprue system: Variant I: degree of the sprue draft angle D3 = 1°					
Gate size (D1), mm	Polymer substrate Thickness (D2), mm	Mould filling status: difficult filling – "no" or easy filling – "yes"			
		Process conditions, °C			
		T_{melt}=280; T_{mould}=80	T_{melt}=300; T_{mould}=100	T_{melt}=320; T_{mould}=120	Fill time (t), s
0.26	1.28-1.30	yes			0.70-0.90
0.27-0.38	1.24-1.30	yes			0.60
0.39-0.43	1.29-1.30	yes			0.70
0.44-0.49	1.22-1.30	yes			0.60
0.50	1.21-1.30	yes			0.50-0.60
Conventional sprue system: Variant II: degree of the sprue draft angle D3 = 2^0					
0.21-0.29	1.24-1.30	yes			0.60-0.70
0.30-0.50	1.20-1.30	yes			0.60
Modified sprue system: Variant I and II: degree of the sprue draft angle D3 is equal to 1° and 2°					
0.20-0.50	1.20-1.30	yes			0.60-0.70

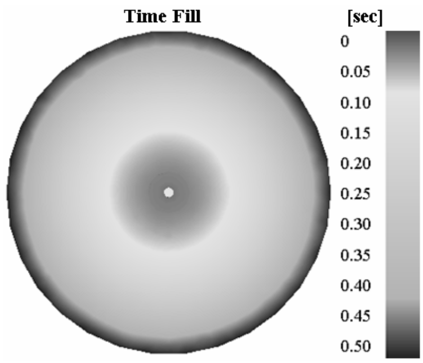

Fig. 6. Mould filling pattern (modified sprue system): $T_{melt} = 320$ °C; $T_{mould} = 120$ °C; fill time $t = 0.50$ s

5. Conclusions

A design concept of a sprue system of an optical disc moulding is presented in the paper. On this basis, integrated 3D CAD models of the sprue system and polymer substrate, considered as one object, are built. The sprue system is known as a system, in which the central hole of the polymer substrate is formed by direct punching of the gate from the polymer substrate and the melt distribution area of the sprue system has a conical shape.

The gate size, the draft angle of the sprue and the polymer substrate thickness are defined as variable parameters and are combined with three variants of the processing conditions in the process of mould filling simulation. By means of iterative steps within the frame of the simulation program MoldflowXpress (integrated with SolidWorks), a series of values of the variable parameters for all variants of the processing conditions are obtained, so that an easy mould cavity filling is achieved. The results show that small changes of the gate size, substrate thickness and draft angle of the sprue cause significant impact on the ability to fill the mould cavity. Hence, our main efforts are oriented to find the suitable combination of the gate size, polymer substrate thickness and draft angle of the sprue in order to assure easy mould cavity filling. The results show that the conventional sprue system design does not allow achieving of complete, uniform and easy filling of the mould cavity at low values of the melt and the mould temperatures. This restricts the possibility to propose optimal rules for the mould cavity filling. The good results with conventional sprue system are obtained when the melt and mould temperatures have the greatest values and when the gate size, polymer substrate thickness and draft angle of the sprue have maximal values. During the work process a modified sprue system is designed, in which the shape of the melt distribution area has a symmetrical form. The results of the experiments with the modified sprue system show that it is possible to fill the mould cavity for all variable parameters chosen, including also some cases, when the values of the gate size, the substrate thickness and the melt and mould temperatures are minimal.

The best results are obtained, using the modified sprue system, where easy mould cavity filling is achieved for all the processing conditions and for all values of the gate size, polymer substrate thickness and draft angle of the sprue.

The approach, presenting the 3D CAD models of the sprue system and polymer substrate and the values obtained of the variable parameters is a basis for further development of the mould filling simulation, oriented towards more precise determination of the resulting injection pressure, the residual stresses distribution and the temperature distribution. The results of the work are oriented to aid designers of optical disc moulds how to choose the correct dimensions of the sprue system and polymer substrate.

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