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AN INTEGRATED APPROACH TO DEVELOPMENT AND SIMULATION MANUFACTURING PROCESSES OF OPTICAL PRODUCTS

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Abstract
The engineering management process and automation method for making pilot set of optical polymer parts used in LED systems are considered. Optical system and lens geometry development are realized in Zemax. 3D model and molding tools with further generating of NC coded data are developed in Cimatron E. Pre simulation of injection molding process is realized in Moldex3D and thermo-mechanical analysis is provided by OOFELIE. 3D printer Objet is used for parts prototyping on different stages of the process. Data and process management are realized with a help of PDM system SmarTeam.

Keywords
optical products, polymer lens, simulation, CAD/CAM/CAE, technological process, injection molding, additive technologies, cyber-physical systems.

Introduction

Polymer-optical products find ever-widening applications, complementing the range of products made of inorganic glass and crystals. Studies of the production peculiarities for the specified class of products allows us to discover new opportunities for the development of instrumentation technologies in the field of "non-imaging" and "imaging" optics and to increase productivity, reduce costs and weight of products, as well as to combine the manufacturing processes for optical components and case parts [1].

The quality of polymer optical products depends largely on decisions made at the stages of design and technological manufacturing preparation (TMP). In spite of using computer-aided design, computer analysis and technological preparation systems at these stages, there are still current theoretical and practical tasks concerning problems of validation and development of models, methods and technologies ensuring quality, manufacturing accuracy and repeatability of products made of traditional and new polymer materials [2, 3].

Shortcomings of the existing models and methods of choosing the design solutions for a runner system, the behaviour of a polymer melt in a mold cavity, the arrangement of cooling system channels of a mold and techniques of choosing optimal injection molding modes determine the application of modern CAE systems of computer imitating simulation to analyze manufacturing process parameters [4]. For their effective use and in order to obtain reliable data, the tasks to investigate injection molding processes while designing optical products made of thermoplastic polymer materials, to define factors influencing product quality, and to determine the influence of design and technological factors on optical product characteristics have been set. The task to integrate all information obtained in TMP process within the unified information system has been also defined.

The process of studying and solving the tasks mentioned above allows to reduce significantly the design time and the time needed for optimization of a mold construction, to control all design data and to help the design engineers to make decisions in the process of designing new optical polymer products using the obtained data and knowledge. At the same time, optimization of technological parameters for injection molding by using computer simulation system and methods of designing the experiment allow to improve surface condition and to determine the dependencies, which will directly influence the accuracy of the manufactured products.

Determination of dependencies of optical parameters of a design and technological factors of injection molding process

To validate and to determine dependencies at design and TMP stages taking into account the application of CAD/CAM/CAE/PDM-systems, the investigation diagram, which is shown in Fig. 1, has been developed.

Application of computer-aided means for simulation of injection molding processes allows to reduce significantly the time needed for designing and testing a mold, as well as to determine in advance the possible defects of the products being designed and eliminate them at corresponding TMP stages.

The choice of design and technological solutions ensuring the quality of a molded product and the stability of its optical properties, requires to take into account the material properties, the features of a product design and a mold [3, 5]. One of the main factors influencing the calculation accuracy is the finite-element mesh (combined), built on the basis of a product's 3D-model for computer simulation. However, to make the computer simulation results close to the real ones, it is necessary to develop an adequate evaluation model which is to be based on a 3D-model of a product and should include 3D-model of a molded part with a runner system with a designed volumetric three-dimensional mesh.

The computer-aided analysis has been carried out in CAE system Moldex3D [6], which has an unique set of functions in its class, such as calculation of a refractive index and the possibility of 3D-analysis of injection molding processes. The optical product – a 24-mm-diameter plano-concave lens with thickness of 3.0–4.2 mm made of polycarbonate Bayer Makrolon LQ 3147 – has been chosen for simulation. The lens being under the study is a typical representative of the optical products, which are used in devices for various purposes. Figure 2 shows a 3D-model of a molded part and its sketch.

The quality of the product depends on a set of factors [7], the influencing extent of which can be estimated taking into account the dependencies, determined during the investigation process.

Using the DoE statistical methods in Moldex3D applying the Taguchi method [8, 9], the relationship between technological factors and the quality of the final product has been determined. On the basis of preliminary results of the engineering analysis the controlled factors have been determined to conduct the experiment using Taguchi method: the design of a runner system (A), the flow rate (B), the melt temperature (C), the mold temperature (D), the packing pressure (E) and the cooling time (F).

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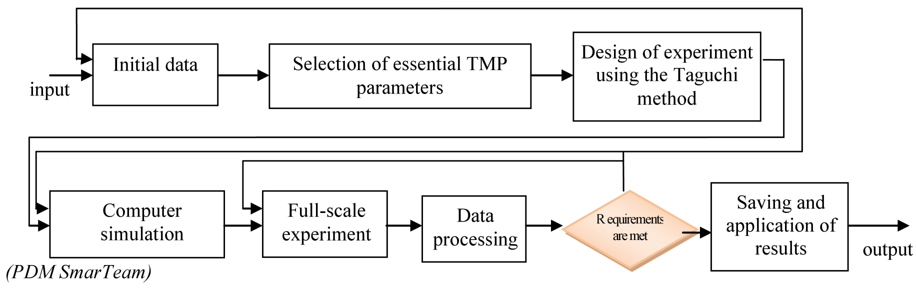

Fig. 1. Investigation stages.

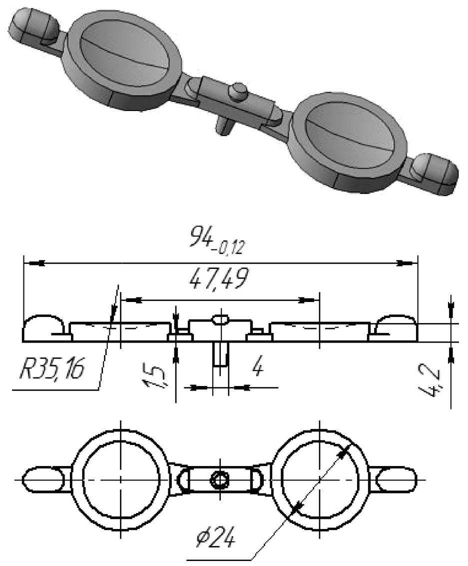

Fig. 2. A 3D-model (on the top) and a sketch (on the bottom) of a molded part for a double-cavity mold.

The design versions of a runner system for three levels of the experiment plan have been chosen in such a way as to make it possible to estimate separately the influence of the thickness of runners and gates, which are known to have a great influence on the polycarbonate injection molding process [10]. Increasing the thickness of a gate facilitates the reorientation of the melt flow behind the front in the area of the entrance to a mold cavity, helping to reduce the risk of the jetting and flow traces occurring. Also in the certain thickness range there is a positive influence on the process of melt packing by means of increasing the time to disconnection of a mold cavity from a material cylinder. At the same time, increasing the thickness of gates complicates the separation of a runner system from the product and may cause a negative effect such as the reverse melt flow from a mold cavity into a runner system. For example, such flow occurs when the freezing of the thin part of the sprue takes place earlier than the freezing of a gate. The increase in thickness of runners has positive influence on the pressure decrease while filling and on the packing process. However, it increases the runner system's weight thus increasing the cost of the injection molding process.

To carry out the experiment by Taguchi method L18 orthogonal array with 3 levels is applied [11], which allows to reduce the number of experimental samples required for optimization of technological parameters. Each parameter has been determined on the basis of the data obtained from Moldex3D at control points located on the surface and in the centre of the product, as shown in Fig. 3.

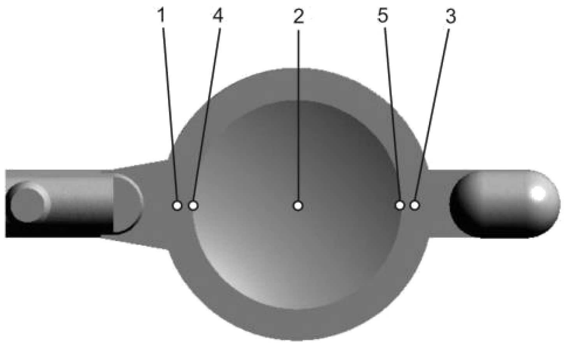

Fig. 3. Measuring points of refractive index (4, 2, 5), birefringence (4, 2, 5) and volume shrinkage, warping (1, 2, 3).

To determine the greatest impact of factors on the characteristics, the values of combined responses ("signal/noise" ratio) of output characteristics obtained in the process of computer simulation have been estimated [12]. The following parameters have been chosen for evaluation: volume shrinkage, linear shrinkage, warping, refractive index, birefringence.

Taking into account the data obtained on volume shrinkage (Sv), it is possible to explain the process of material compaction at the stage of pressure holding, which has the direct influence on optical characteristics of the final product. Due to the high non-uniform density obtained in the process of experimental injection molding, it's extremely difficult to calculate the volume shrinkage. The analysis of volume shrinkage values for a product showed that its value increases with the distance from a gate at the same thickness of the product, because at the entrance to a mold cavity the pressure is higher and the material is more compacted [13].

According to the results of the experiment, based on Taguchi method and realized using the computer simulation system Moldex3D, the major factors influencing the shrinkage value are the packing pressure, the selection of a runner, and especially the selection of a gate, which is shown on the response diagram of signal/noise values, presented in Fig. 4. This is the combination of these two factors that defines the value of volume shrinkage in the process of uniform cooling.

The analysis of the signal/noise responses for the refractive index (n), presented in Fig. 5, showed that the section of gates and runners, the packing pressure and the melt temperature have the main influence on the refractive index.

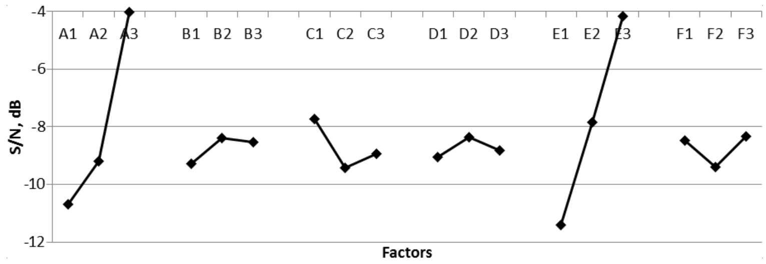

Fig. 4. Signal/noise ratio for the volume shrinkage in the center of a product.

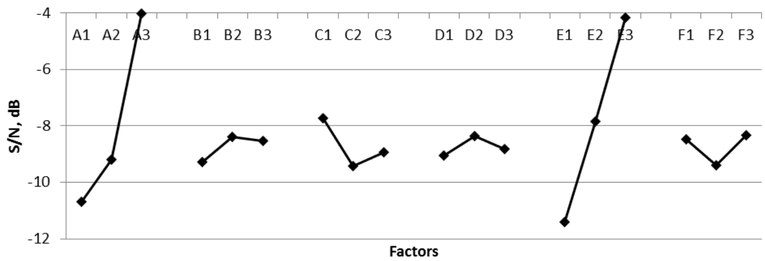

Fig. 5. Signal/noise ratio for refractive index values.

Table 1
Evaluation of the priority of design and technological factors having influence on the characteristics of the product.

Characteristics	Factors					
	Runner system type	Flow rate	Melt temperature	Mold temperature	Packing pressure	Cooling time
Volume shrinkage (Sv)	2	5	3	6	1	4
Longitudinal linear shrinkage (SL)	6	1	2–3	2–3	4	5
Transversal linear shrinkage (ST)	3	1	4	5–6	2	5–6
Warping (W)	2	5	3	4	1	6
Refractive index (n)	1	5	3	4	2	6
Birefringence	5	2	1	6	3	4

Such factors as the mold temperature and the cooling time have been found to have the least impact on the characteristics of optical products, presented in Table 1.

For each characteristic the factors having the maximum and minimum impact, which are marked respectively by numbers 1 and 6, have been determined. The quality of a final product is determined by the set of factors, and the neglect of insignificant factors in total can lead to the situation, when the product after the process doesn't meet the set of requirements. The variation of factors having the greatest impact reduces or completely eliminates the defects and allows to achieve the desired high quality of optical products.

The usage of computer simulation systems for injection molding processes, together with the methods of robust design, allowed to determine the relationship between the factors and the optical and geometric characteristics, which depend on the design of a runner system and a technological process. According to the experiments carried out using Moldex3D, the design of a runner system and the packing pressure have the greatest influence on the refractive index of the lens and its optical heterogeneity (variation of the refractive index in the product). The main factor influencing the birefringence was determined to be the melt temperature. To obtain estimates having practical significance using the methods of robust design, it is necessary to choose the levels of controllable factors taking into account the characteristics of a molding process for a particular product, as well as the capabilities of the existing molding and peripheral equipment.

Product design and full-scale experiments

Creating a new product is a complex process that requires the participation of a large number of specialists from different areas of knowledge. Successful realization of such projects depends on on-time information exchange between experts and the possibility of fast updating of obtained data. The process of designing the product, TMP and full-scale experiments within the frameworks of this investigation have been performed on the basis of various technological platforms. This required the creation of a unified information environment, realized on the basis of a PDM-system. Communication between the project participants was provided using the remote access to the multi-unit server, which allowed to make decisions very quickly and to make adjustments at all stages of investigation.

The initial stage of the project was to develop an optical system with a further computer simulation of thermo-mechanical loads, which was realized in systems Zemax [14] and OOFELIE [15]. Zemax allows to analyze and to perform the construction optimization of the product being designed. There is a possibility to optimize a large number of optical system parameters, such as radii, thicknesses, materials, distances, wave lengths, fields, and others. The products designed in Zemax can be easily transferred to CAD systems using *.stl, *.iges and *.step formats. Using OOFELIE the simulation and the analysis of the influence of thermo-mechanical loads on the form deviation of the lens have been performed. Thanks to the automatic exchange of information between OOFELIE and Zemax, as well as using the simulation results obtained in Moldex3D, the calculation accuracy of optical parameters (for example, the light wave front) increases. Using the integration of these applications, there is a possibility to perform the full preliminary analysis of influence of both technological factors, as well as various loads, on a specific product, and on the whole assembly. Figure 6 shows the simulation results obtained in OOFELIE.

The basic technology used to manufacture optical products with the required quality is the injection molding [16]. The main labor intensity and TMP terms when using this technology are accounted for mold design. When designing a mold it is necessary to know not only the information about the product, but also the peculiarities of using an injection molding machine, as well as construction and kinematics of the mold requirements. The usage of computer simulation systems at TMP stages significantly reduces the period of tooling development process and the number of full-scale experiments, and also allows for identifying potential defects that may occur during molding, such as incomplete filling, tightening, shrinkage, warping, occurrence of weld lines and air traps in the product.

The usage of computer simulation systems when processing basic solutions at the stage of designing a mold allowed for prediction and analysis of the melt flows which arise in the process of injection molding. As the output data the information on characteristics of the material at the stage of the molding process using an injection molding machine in diagrams, showing the distribution of temperatures, pressure and a melt flow, has been obtained. For example, Fig. 7 shows the results of the engineering analysis of a maximum volume shrinkage performed in Moldex3D. The simulation results allowed for making timely changes of a mold design, shape-molding parts (SMP) and the technological modes of the injecting molding.

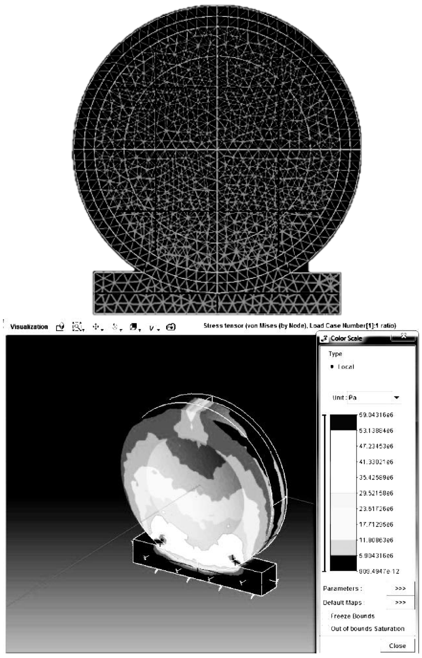

Fig. 6. Simulation results obtained in OOFELIE: finite-element mesh (on the top); calculation of thermo-mechanical loads (on the bottom).

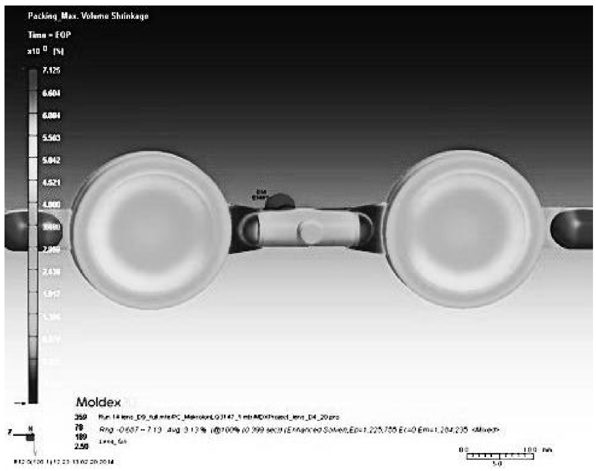

Fig. 7. Computer simulation results for a maximum volume shrinkage at packing.

In the integrated process of manufacturing optical products the method of group technology is used, which requires the classification of details and their combination in some groups representing the set of objects similar to each other according to geometrical form, dimensions, materials and manufacturing technological processes. When using group technology in the process of pressure molding, it is necessary to take into account the individual characteristics of a runner system and a mold cavity in the process of determining the group for the specific product. This approach allows for using unified reconfigurable molds [17].

On the basis of data obtained from the simulation of the molding processes, the specialized reconfigurable mold has been designed [18]. In world practice the standard assembly units and molding parts are commonly used, the 3D-models of which are included in the modern CAD/CAM-design systems, for example, in Cimatron E system [19]. The 3D-model of a mold built in Cimatron E is shown in Fig. 8. When using the designed mold at a later stage it is necessary to produce only sets of replaceable SMP for each new product, and the main tooling nodes remain the same.

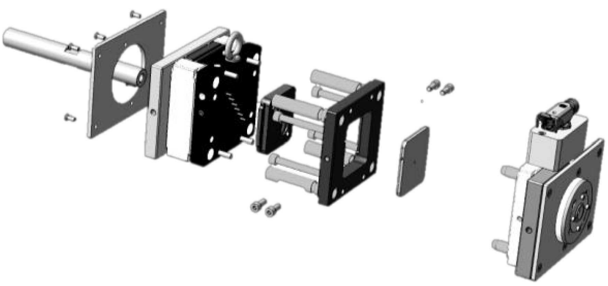

Fig. 8. Mold model in Cimatron E.

Application of additive technologies in the integrated process of polymer products manufacturing at the different stages of TMP allowed for reduction the time needed for designing the product and for reduction the process labour intensity. The key point of the technology is following: the products of a complicated geometrical form are designed according to a computer 3D-model using the systems of rapid prototyping. Such equipment allows for producing prototypes, products and tooling ready for their direct application and made of different materials (polymer materials, metal alloys, etc.) by their layer-by-layer growth [18].

The prototype of a product can be used as a conceptual model for visualization and analysis of a design for its technological effectiveness. The real physical model can be checked for easiness of assembly of its main nodes, and also can be put to some functional tests. The described capabilities allow the design engineers to perform timely the modification of a future product, thereby reducing expenses and terms of design manufacturing preparation. In our studies the photopolymer SMP set has been grown using the 3D-printer Objet Eden 350v to check the easiness of a mold assembly.

If there is a necessity to produce a small batch of parts made of the material with a low melting temperature, the ABS-like photopolymer composition can be used for SMP. The equipment for layer-by-layer polyamide powder (PA12) sintering, for example the EOSINT P unit, is also widely used. Application of a stereolithography technology and the new material Accura Bluestone Plastic [20] for SMP growth allows for receiving up to 200 molded parts using the injection-molding machine. This material, representing the epoxy resin filled with ceramics, withstands the temperature of heating up to 200°C, and an additional heat treatment increases the working temperature up to 280°C.

When using CNC machines the major task is to develop the control programs in CAD/CAM systems. When manufacturing the SMP set, the following equipment has been used: milling machine HAAS SuperMiniMill, turning machine HAAS SL-10T, 3/5D machining center with a vertical spindle Primacon PFM 24NGD. Cimatron E has been used for production process planning of machines mentioned above. For simulation and verification of the operating program for the machining center Primacon the VERICUT system has been used, which allowed to reveal the program errors and to perform its optimization before its application at the machine. The virtual model of a machine has been created for this purpose. The simulation process and the result of SMP production is presented in Fig. 9.

For carrying out studies the electric injection molding machine Ferromatik Milacron EE30-55 with the injection volume of 19 cm^3 and the locking pressure of 30 t has been used for polymer product manufacturing. This choice is based on the possibility to produce units in a small volume, because the main application area of lenses are devices, small optical systems, and the availability of an electrical drive allows to reach more accurate dosage of the injection volume for a polymer material, which is an important parameter in the process of manufacturing the optical products.

The quality control for the products made of polymer materials using the injection molding process has been carried out in two stages: firstly, SMPs at TMP stage and then the final products have been controlled. Next the parameters of the final products have been evaluated on their compliance

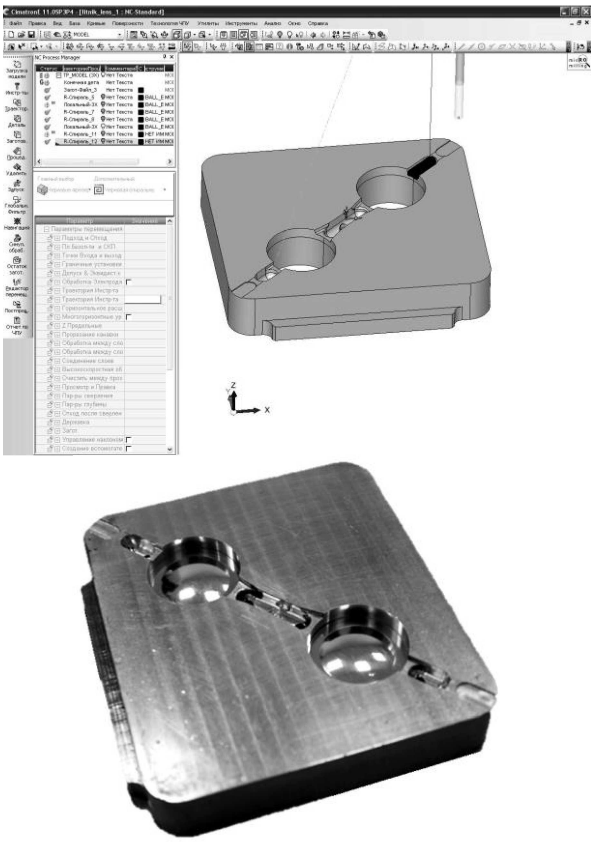

Fig. 9. Development of the operating program in Cimatron E (on the top), the result of SMP production (on the bottom).

with the source documentation, and on the basis of such assessments the conclusions about the suitability of the lens geometry have been made. Then some optical properties have been controlled. By means of CNC measuring machine Global Performance 05.07.05 the SMP geometry has been controlled. At the stage of SMP control the initial and real characteristics of the functional SMP surfaces have been compared at the measuring machine and roughness measuring station. The geometry control has been carried out not only for the purpose of determining the compliance with the set sizes, but also for the subsequent comparison with the final products for calculation of a shrinkage percent. In addition to the dimensions the key parameter is the roughness. The properties of a SMP molds surface have an essential impact on the quality of the final product. The assessment of the compliance with the SMP dimensions and roughness has been carried out using the stationary roughness measuring station Hommel Tester T8000. The measuring process using the measuring machine is shown in Fig. 10.

Based on the results of full-scale measurements the following values of the parameters have been obtained: the maximum values for a relative error of linear shrinkage – 5.3%, for a relative error of a warping in the direction of the melt flow – 5.5%, and across the direction of the melt flow – 4.9%. These values are comparable to the results of computer simulation. The obtained results show that the lens produced according to the developed method of TMP, using the CAE analysis, meets the set of requirements, and the proposed technique can be successfully used when developing new products.

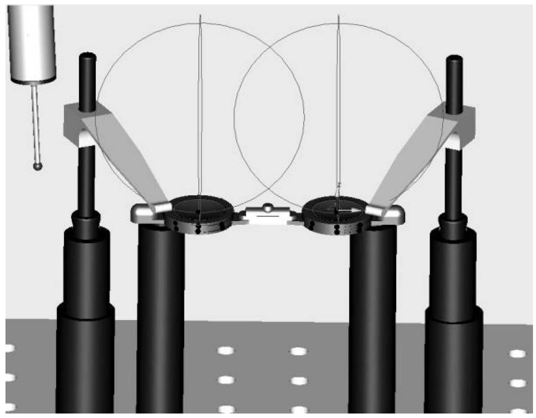

Fig. 10. Visualization of the geometry measuring process of molding using the measuring machine in the PC-DMIS system.

Support of business processes in the distributed integrated environment

An application of computer simulation systems for optical products, the automated design of production tooling and the distributed systems of decision-making support provides the effective organization of business processes for development of new optical products [21–23]. The application of scientifically-based techniques, processes and technologies of optical products manufacturing allows for using more effectively and properly the software and modern equipment for improving the quality of the products. Rational use of human resources, taking into account the lack of specialists, is possible due to the developed business processes implemented in management systems, which allows for increasing the competence of the project participants very quickly [24].

Design and technological production planning processes for optical products are of the iterative nature. Return to the previous stages allows for improving gradually the product design and technological solutions developed at the current stages. Actions planning at the subsequent stages, when performing the current one, allows for development of the pro-

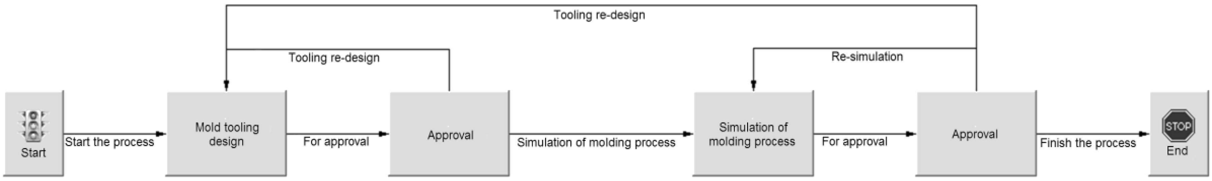

Fig. 11. WorkFlow diagram for the molding tooling design process.

cess as a uniform chain of serial operations. According to the principles of the rational production processes organization, the use of the available equipment, and also the reduction of the consumption of materials and energy, the integrated process of development and production of optical products made of polymer materials is described.

The developed algorithms and solutions are used as analogues when designing new products. Moreover, the well-run system of internal communications between different specialists and design stages allows not only to diagnose the arising problems (decrease of the product quality, detection of product defects, etc.), but also precisely defines what to change and at what stage.

The information integration is achieved using the means of the PDM-system SmarTeam [25], and the project management can be automated using the WorkFlow diagrams. For example, the process of designing of a mold for an injection molding machine introduced in the PDM system is shown in Fig. 11.

According to the current stage SmarTeam sends the notice to a certain specialist (to the design engineer, the production engineer, the engineer, etc.) or the group of specialists (using the SmartBox mechanism) about the necessity to complete the certain stage and solve some relevant tasks. Each task implies the addition of one or several products in the system using the passports describing each product with a set of special attributes. Attributes can be responsible both for the general connections of the products, and for their connection with other products or with the file storage SmarTeam. For various products the passports of different types having their own set of attributes (for example, "projects", "documents" and "technological techniques") are used.

According to the WorkFlow process the main process is the specification analysis. The information required to start the process is presented in the form of 3D-models, drawings, schematic diagrams, sketches, etc. The system functionality allows for studying the information, which is stored in a file memory, if the connection between the file and the product is established. The design process is based on the creation of a 3D-model of the product, if it was not included in the specification. Examination of 3D-models is carried out in the similar way using appropriate CAD systems (Fig. 12), including the use of the annotated models. The products or product prototypes are also described in the form of information objects in the system. For example, the prototype of a mold can be described in the form of the document with an attached photo.

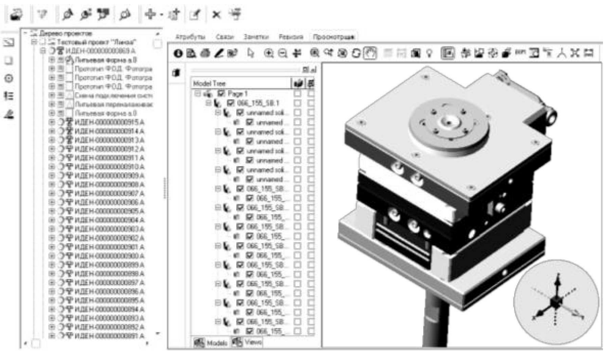

Fig. 12. Visualization of a 3D-model of a mold in the PDM system.

In addition to the general documents of various types special documentation is also used. For example, when designing the product and tooling it is necessary to simulate the process of molding under the pressure using CAE system Moldex3D. Calculations of different types of loads of a product, for example in OOFELIE in the case of an integration with Zemax, are also performed. In SmarTeam the corresponding results are presented as the "Engineering evaluation" object with the corresponding project file from the calculation system being attached to it.

Since the engineering evaluation is considered to be a special tool which is used quite frequently at every stage of the product life cycle, it is impossible to provide the built-in means of visualization in SmarTeam. For studying such data the integration with appropriate means is used. For example, to perform the engineering evaluation it is possible to call the visualization mean directly from the system, which will automatically load the data connected with the product.

The description of the product development and production project would be incomplete without the description of the equipment, which is used in this process. For the process described above the user can search for the equipment using data base and choose the one which is to the maximum extent in accordance with parameters, and establish its connection with a product using the passport of the equipment from the SmarTeam.

Conclusions

Project management in the information system starting from the product development and finishing with its production provides the support for decision-making on the basis of the complex analysis of the design data obtained at various design and TMP stages.

According to the results of the complex investigation of the production process for the optical products made of polymer materials the new approach to TMP performance has been developed. The main principle of the method consists in the complex application of imitating simulation and consideration of the iterative nature of the integrated design and manufacturing process for new products.

When carrying out TMP the possibilities of using additive technologies at various stages have been considered. Their introduction allows for elimination the most expensive TMP stages connected with mechanical treatment.

In the course of manufacturing the products using the molding technology under the pressure the robust approach has been used, which allowed to choose optimum technological parameters. The virtual experiments, which have been carried out using CAE systems, allowed to determine the necessary range of the molding modes and the plan of full-scale experiments at the TMP stage, and also to modify the geometry of a runner system before carrying out full-scale experiments, being the most significant.

Carried out investigations and obtained results allowed to develop and introduce business processes for production of pilot batches of polymer lenses. The advanced computer technologies and the sophisticated equipment, integrated by developed business processes, allowed to create the distributed, research base for the development of the production technologies for polymer products. The processes are realized within the network of distributed laboratories with manufacturing and control equipment, where the product development and simulation of the production processes are carried out. The improvement of the integrated distributed environment is carried out on the basis of the concept of cyber-physical systems, providing the better information integration of systems and equipment and ensuring the quick access for specialists of various disciplines to the results obtained at the various stages of the product life cycle.

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