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Integrated Optimum Layout of Conformal Cooling Channels and Optimal Injection Molding Process Parameters for Optical Lenses

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Abstract: Plastic lenses are light and can be mass-produced. Large-diameter aspheric plastic lenses play a substantial role in the optical industry. Injection molding is a popular technology for plastic optical manufacturing because it can achieve a high production rate. Highly efficient cooling channels are required for obtaining a uniform temperature distribution in mold cavities. With the recent advent of laser additive manufacturing, highly efficient three-dimensional spiral channels can be realized for conformal cooling technique. However, the design of conformal cooling channels is very complex and requires optimization analyses. In this study, finite element analysis is combined with a gradient-based algorithm and robust genetic algorithm to determine the optimum layout of cooling channels. According to the simulation results, the use of conformal cooling channels can reduce the surface temperature difference of the melt, ejection time, and warpage. Moreover, the optimal process parameters (such as melt temperature, mold temperature, filling time, and packing time) obtained from the design of experiments improved the fringe pattern and eliminated the local variation of birefringence. Thus, this study indicates how the optical properties of plastic lenses can be improved. The major contribution of present proposed methods can be applied to a mold core containing the conformal cooling channels by metal additive manufacturing.

Keywords: gradient-based algorithm; robust genetic algorithm; warpage; design of experiments; fringe pattern; birefringence

1. Introduction

The demand for plastic optical lenses has been increasing in the industry. The precision requirements for high-tech optical products have become stringent, which has led to the growth of global markets for high-precision optical articles [1,2]. Although the optical properties of glass, such as the refractive index and dispersion, are quite stable, the glass fabrication process is very complicated and difficult. Moreover, plastic products are lightweight, colorable, robust, and low cost. They can be manufactured using a one-step process regardless of their geometric complexity. Thus, plastic products have become crucial in contemporary industrial development.

Despite the aforementioned advantages, plastic optical lenses may encounter volumetric shrinkage, which leads to the formation of thermally induced residual stress during the cooling process of injection molding. This residual stress slightly results in local variations in the birefringence, which affects the image quality [3]. Achieving a uniform temperature distribution for removing the residual stress is difficult in conventional cooling channels. Uneven shrinkage occurs if conventional cooling channels are used during the cooling process [4]. For designing conformal cooling channels, the geometric shape of conventional cooling channels can be appropriately adjusted through injection molding simulation. This helps to improve the defects caused by conventional cooling channels. The use of conformal cooling channels facilitates an even distribution of the surface temperature of the mold cavities, thereby reducing the thermally induced residual stress formed during the cooling process [5], effectively shortening the cooling time, and improving the cooling efficiency [6].

Researchers have devoted considerable attention to hybrid manufacturing processes, which combine metallic powder-based laser additive processes and subtractive machining processes. These hybrid manufacturing processes are considered the most promising technology for fabricating conformal cooling channels [7]. With metal additive manufacturing technology, complex conformal cooling channels can be fabricated to closely fit the shape of the mold cavity and core. Thus, uniform cooling can be achieved for products even in narrow regions or areas that may easily accumulate heat. Consequently, the quality of the products improves, and the cycle time decreases. This technology can be applied to products that vary in thickness. It allows the products to achieve uniform heat dissipation with a high cooling efficiency [8].

In recent years, optimization algorithms have been used to design cooling channels for plastic injection molds. Qiao [9] combined the advantages of the Davidon–Fletcher–Powell (DFP) method and the simulated annealing (SA) algorithm to optimize a cooling system layout. First, the DFP method was used to find the local optimum layout of the cooling channel. Then, the SA algorithm was adopted to determine the global optimum layout of the cooling channel, which allowed the surfaces of the mold cavities to possess a uniform temperature distribution. Park and Dang [10] used design of experiments (DOE) and response surface methodology for designing an array of baffles in cooling channels. They established a mathematical model for obtaining the optimal configuration of cooling channels with an array of baffles. This technique can effectively improve the heat removal performance and is applicable to large-sized molds and molds with complex cavity shapes. Dang and Park [11] also proposed an optimization method for the design of U-shaped milled groove cooling channels. This method aimed to achieve temperature uniformity for the mold and utilized computer-aided engineering (CAE) for design modification. The mold of a car fender was selected to analyze its cooling channel design and verify the theoretical calculation. The quality levels of the products were compared before and after the optimization. After the optimization of the cooling channels, the warpage decreased, and the temperature uniformity increased.

Optimization strategies involving the use of various algorithms for designing the shape and layout of cooling channels have been frequently discussed in the literature [12–14]. Moreover, many studies have used DOE to set optimal process parameters for injection molding [15,16]. However, these two issues have rarely been integrated in the literature. This study combined finite element analysis with optimization algorithms to analyze the temperature field during the cooling stage. Subsequently, the entire injection molding process was conducted using DOE to obtain the best process parameters. The aim of this study was to uniformly cool melt within a cavity. An optimization was conducted to design conformal cooling channels, which alleviated the thermally induced residual stress formed during the manufacturing of optical lenses and solved the uneven shrinkage problem. Such optimization can also effectively shorten the cooling time and enhance the cooling efficiency during the manufacturing process, which can improve the image quality of plastic optical lenses.

2. Methods

2.1. Materials

The lens employed in this study was a plastic optical lens commonly used in projectors. This projector lens was a large-diameter aspheric lens [17] with a diameter of 46 mm (Figure 1). The lens was composed of cyclo-olefin polymer (COP; Zeonex 480R) from the Zeon Corporation (Tokyo, Japan). This material had low water absorption, high optical transmittance, and low birefringence [18].

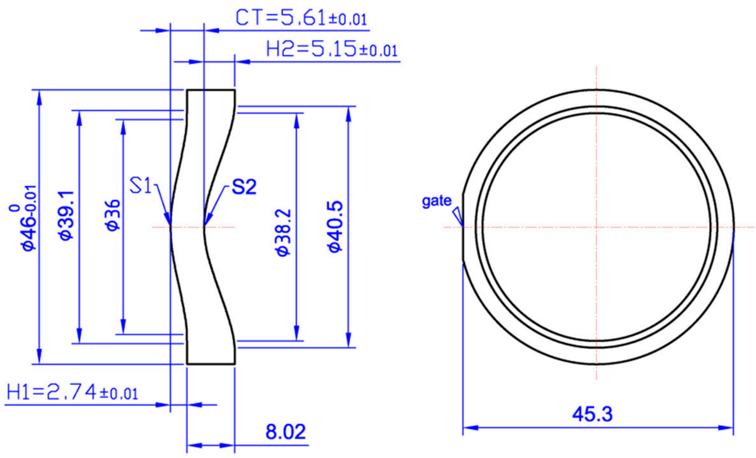


Figure 1. Specifications of the large-diameter aspheric plastic lens provided by Glory Science Company Limited.

2.2. Design of the Runner and Gate System

Figure 2 displays the shape and dimensions of the cold runner and gate system. The volume of the runner and gate system was 8.984 cm^3. A uniform melt flow front was injected into the mold cavity by using the wide cross-sectional inlet of the fan gate. This enabled a molded product with large width to be filled quickly. The warpage and size stability of wide molded products are major concerns [4]. Although the fan gate necessitated manual trimming, it reduced the formation of flow-induced residual stress when the melt polymer passed through the gate into the mold cavity. Therefore, the fan gate was adopted in this study. Residual stress may lead to poor optical properties, such as uneven distribution of the fringe pattern and local variation in the birefringence.

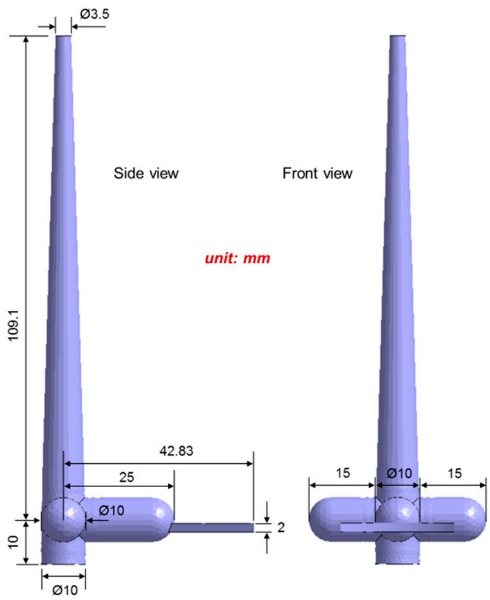


Figure 2. Shape and dimensions of the runner–gate system.

2.3. Mold Design for Conventional and Planar Conformal Cooling Channels

The core and cavity plates used in this study were made of NAK80, which is prehardened steel. The dimensions of the mold were 150 mm (L) × 150 mm (W) × 205 mm (H). A single-cavity mold containing both conventional cooling channels and planar conformal cooling channels was adopted (Figure 3) because the lens was large. The total number of elements in the cavity was 222,720. The conventional cooling channel diameter was suggested in the design [4] to be 10 mm. The layout of the planar conformal cooling channel adhered to the channel design guidelines proposed in the literature [19] for laser additive manufacturing of metals. These rules were used to determine the appropriate distance between channels or between the channel and mold cavity surface according to the cooling channel diameter (Figure 4). Following these rules was the way to ensure that the mold cavity and core have enough mechanical strength. To alleviate the thermally induced warpage [20], the parameters of the planar conformal cooling channel were set as follows: b = 4 mm, a = 8 mm, and c = 8 mm, as displayed in Figure 5.

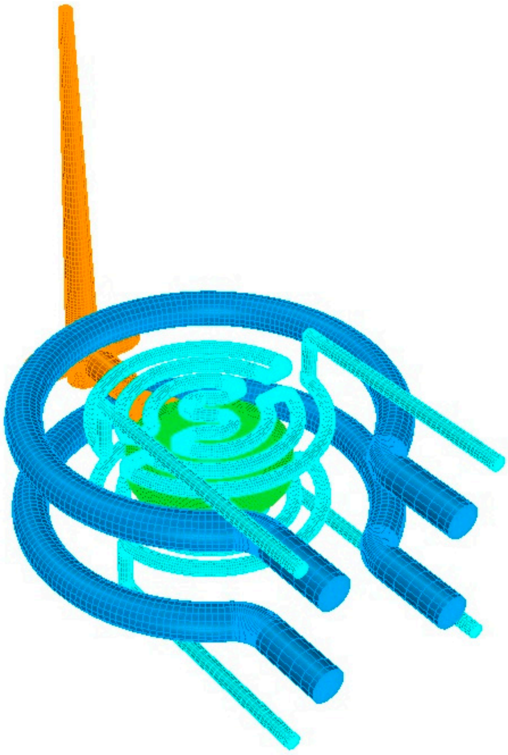
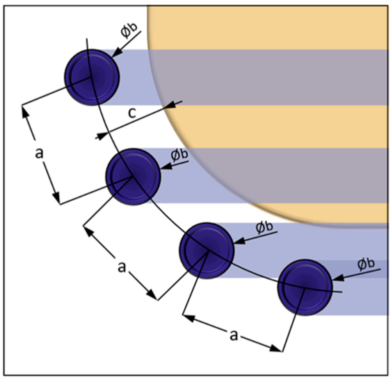


Figure 3. Internal arrangement of the mold used in this study. Deep blue, bright blue, green, and orange components represent the conventional cooling channels, planar conformal cooling channels, lens, and runner–gate, respectively.



Wall thickness of molded product (mm)	Hole diameter (mm) **b**	Centerline distance between holes **a**	Distance between center of holes and cavity **c**
0 ~ 2	4 ~ 8	**2b** ~ **3b**	1.5**b** ~ **2b**
2 ~ 4	8 ~ 12	**2b** ~ **3b**	1.5**b** ~ **2b**
4 ~ 6	12 ~ 14	**2b** ~ **3b**	1.5**b** ~ **2b**

Figure 4. Design rules for the three-dimensional conformal cooling channel [19].

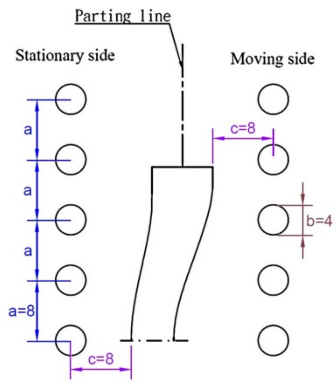


Figure 5. Schematic of the planar conformal cooling channel.

2.4. Simulation of the Filling and Packing Stages

In this study, the CAE mode of Moldex3D was used to simulate injection molding because no empirical data were available for the machine settings. The maximum injection pressure and maximum packing pressure were set as 250 MPa. The initial melt temperature was set as 270 °C, and the initial mold temperature was set as 100 °C according to the process parameters [21,22] from the Moldex3D (CoreTech System Corporation, Taiwan) databank. The filling time was set as 0.79 s, and the packing time was set as 7 s. The filling flow rate was set in six steps (Figure 6a). The first step involved the process of filling the runner. The subsequent five steps varied according to the variations in the cross-sectional area of the plastic lens. The packing pressure was set in three steps (Figure 6b). The packing pressure of the first step was set as 85% of the filling pressure at the end of filling. In the following two steps, the packing pressure was decreased to release stress.

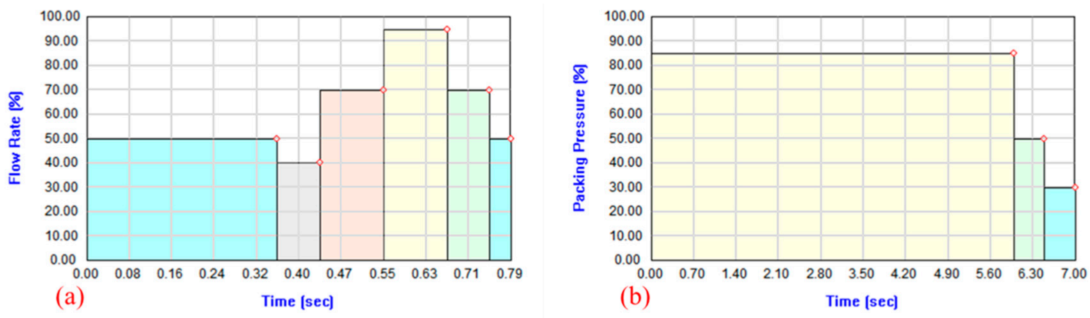


Figure 6. (**a**) Multistep setting of the filling flow rate profile and (**b**) multistep setting of the packing pressure profile.

2.5. Geometric Optimization of the Conformal Cooling Channels

The average mold temperature was 89.5 °C and the average melt temperature was 215.6 °C at the completion of the Moldex3D simulation of the filling and packing stages. These temperatures were input into COMSOL Multiphysics (Version 5.2, COMSOL Inc., Burlington, MA, USA) and served as the initial conditions of the cooling stage. According to the default settings in Moldex3D, the suggested channel temperature was 100 °C, and the suggested cooling time was 18.6 s. However, the cooling time in the COMSOL software was set as 20 s, and neither the runner nor the mold base was included in the simulation. The simulation only focused on the heat transfer between the cooling channel and lens. The cooling channel was assumed to have a turbulent flow. By using the Reynolds number formula, the volumetric flow rate of the conventional cooling channel with a diameter of 10 mm was derived as 28.81 cm^3/sec and that of the planar conformal cooling channel with a diameter of 4 mm was derived as 11.53 cm^3/sec. Moreover, COMSOL was adopted to couple the non-isothermal pipe flow interface with the heat transfer in solids interface [23] for simulating the temperature distribution of the melt in the mold cavity during the cooling process. The solidification of the polymer melt flow near the cold cavity wall was not considered. Furthermore, two approaches in SmartDO (FEA-Opt Technology Inc., Miaoli County; Taiwan), namely the gradient-based algorithm (GBA) [24] and robust genetic algorithm (RGA) [25,26], were separately integrated with COMSOL to optimally design the layout of the conformal cooling channels. The conventional cooling channels were not involved in optimization. The integration framework is displayed in Figure 7. The script loop is available in the online supplementary data. The pros and cons of the two optimization algorithms were compared according to the temperature distributions on the lens surfaces.

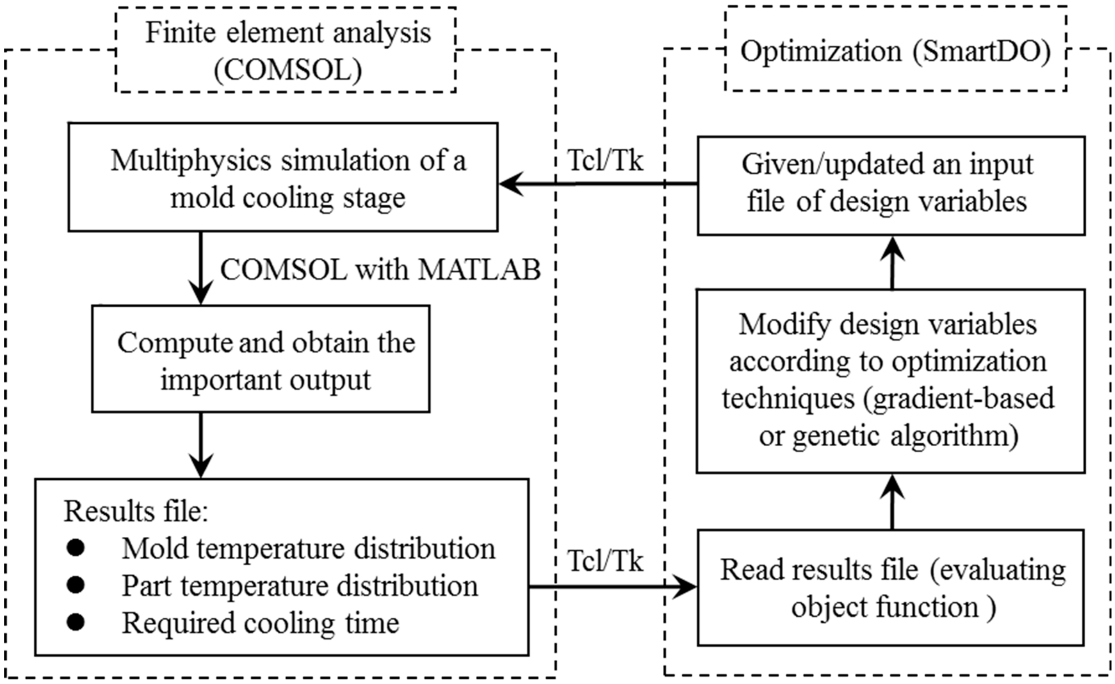


Figure 7. Flow chart of finite element analysis integrated with the optimization algorithms, gradient-based algorithm (GBA) and robust genetic algorithm (RGA), for the design of conformal cooling channels.

The value of the distance between the conformal cooling channel and mold cavity surface must satisfy the rules suggested in Figure 4 so that the design variables (DVs) have a reasonable range, as displayed in Figure 8. Moreover, at the suggested cooling time of 18.6 s, COMSOL indicated that the maximal and minimal surface temperatures of the mold cavity for the planar conformal cooling channels were $T^0_{sur,\max}$ and $T^0_{sur,\min}$, respectively. After each iteration of the optimization, the maximal and minimal surface temperatures of the mold cavity for the modified conformal cooling channels were $T_{sur,\max}$ and $T_{sur,\min}$, respectively. To ensure that the temperature of mold cavity surface was evenly distributed (i.e., the value of $T_{sur,\max} - T_{sur,\min}$ was small), the objective function was set as following Equation (1):

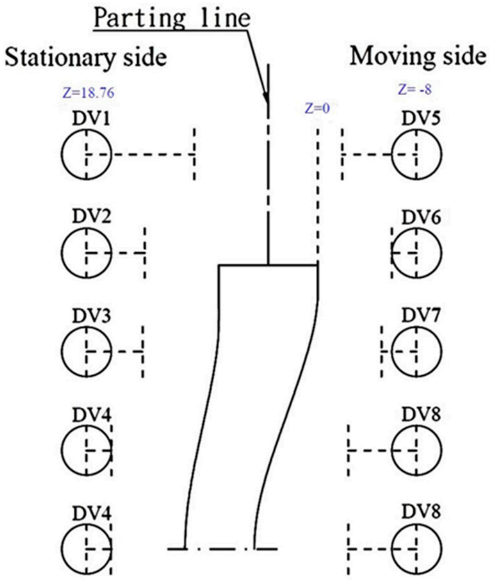
$$[1 - (T_{sur,\min}/T_{sur,\max})] \times 10,000 \tag{1}$$

The scaling factor of 10,000 in Equation (1) increases the accuracy of the calculation. To ensure that the overall temperature of the mold cavity surface after optimization was lower than that of the initial state, the following constraints were set:

$$T_{sur,\max} - T^0_{sur,\max} < 0 \tag{2}$$

$$T_{sur,\min} - T^0_{sur,\min} < 0 \tag{3}$$

After setting the DVs, objective function, and constraints, the planar conformal cooling channels could be designed and modified as three-dimensional channels by using the optimization algorithm. This modification improved the cooling efficiency and allowed the temperature of the melt in the mold cavity to be evenly distributed.



Design Variable	Initial Value	Upper Bound	Lower Bound
DV1	18.76	18.76	10.01
DV2	18.76	18.76	14.02
DV3	18.76	18.76	14.192
DV4	18.76	18.76	16.76
DV5	-8	-1.99	-8
DV6	-8	-6	-8
DV7	-8	-5.176	-8
DV8	-8	-2.467	-8

Figure 8. Lower and upper bounds on the design variables (DVs) according to the distances suggested in Figure 4 between the cooling channel and mold cavity surface, where the initial value represents the geometric layout of the planar conformal cooling channels.

2.6. Molding Process Optimization for the Optimized Conformal Cooling Channels

After obtaining the optimized DVs for the conformal cooling channels by using the GBA and RGA algorithms, the geometric layouts of these two types of cooling channels were converted into solid mesh models by using the Rhinoceros 3D software and were then imported into Moldex3D. The process conditions for the filling and packing stages were the same as those mentioned in Section 2.4. The cooling time, ejection temperature, and mold-open time were set as 18.6 s, 139 °C, and 5 s, respectively. After the entire injection molding process had been simulated, the three types of conformal cooling channels (the planar, GBA- and RGA-optimized channels) were compared with regards to warpage and temperature distribution.

Finally, the geometric layout with the highest cooling efficiency was selected for DOE to determine the optimal combination of process parameters and key parameters impacting the manufacturing process. Studies [21,22] have indicated that lenses made of Zeonex 480R material have high flow-induced birefringence and low thermally induced birefringence. This study focused on the shear stress related to flow and the flow-induced residual stress. Residual stress leads to defective optical properties [16]. Therefore, shear stresses at the end of the filling stage, shear stresses at the end of the packing stage, and the total warpage were set as the quality factors, and each quality characteristic was based on the smaller-the-better approach. The traditional trial and error method for predicting and controlling injection molding conditions is inefficient and costly because of the complexity of interactions between multiple manufacturing process parameters. Therefore, the DOE module provided by Moldex3D is more suitable than the trial and error method for evaluating the ideal molding conditions [15]. Moreover, the melt temperature, mold temperature, filling time, and packing time were selected as the control factors in the DOE. It was assumed that each control factor contained five levels of variation (Table 1). A Taguchi's orthogonal array $L_{25}(5^4)$ [27] was adopted for the DOE. Subsequently, statistical analysis was used to determine the optimum combination of levels for the control factors.

Table 1. Four control factors and five levels used for the design of experiments (DOE) in Moldex3D.

	Control factors	Level 1	Level 2	Level 3	Level 4	Level 5
A	Melt temperature (°C)	240	255	270	285	300
B	Mold temperature (°C)	80.00	89.75	99.50	109.25	119.00
C	Filling time (sec)	0.69	0.79	0.89	0.99	1.09
D	Packing time (sec)	6	7	8	9	10

3. Results and Discussion

In this research, COMSOL software simulated the cooling process of injection molding. Moreover, SmartDO optimization software was used to design the conformal cooling channels for improving the temperature distribution of the melt and the cooling efficiency. Furthermore, Moldex3D software was used to simulate a complete injection molding cycle at the same manufacturing conditions. The temperature difference between the inlet and outlet, average surface temperature of the lens, and warpage deformation of the lens were investigated for the three types of conformal cooling channels (the planar, GBA- and RGA-optimized channels). Finally, the optimum layout with the highest cooling efficiency was selected to optimize the molding conditions by using a DOE module. This optimization improved the birefringence and the fringe pattern of the lens.

3.1. Optimum Layout of Conformal Cooling Channels for the Cooling Stage

According to the Moldex3D simulation, the average mold temperature was 89.5 °C and the average melt temperature was 215.6 °C at the end of the packing stage. These temperatures were input into COMSOL and served as the initial conditions of the cooling stage. By simulating the cooling process for the planar conformal cooling channels, the variations in the maximum and minimum surface temperature of the melt in the mold cavity were determined (Figure 9a). According to the cooling time suggested by Moldex3D, the lens was ejected at 18.6 s. Figure 9b displays the surface temperature distribution for the lens, with a maximum temperature of 359.713 K, a minimum temperature of 358.601 K, and a temperature difference of 1.112 K.

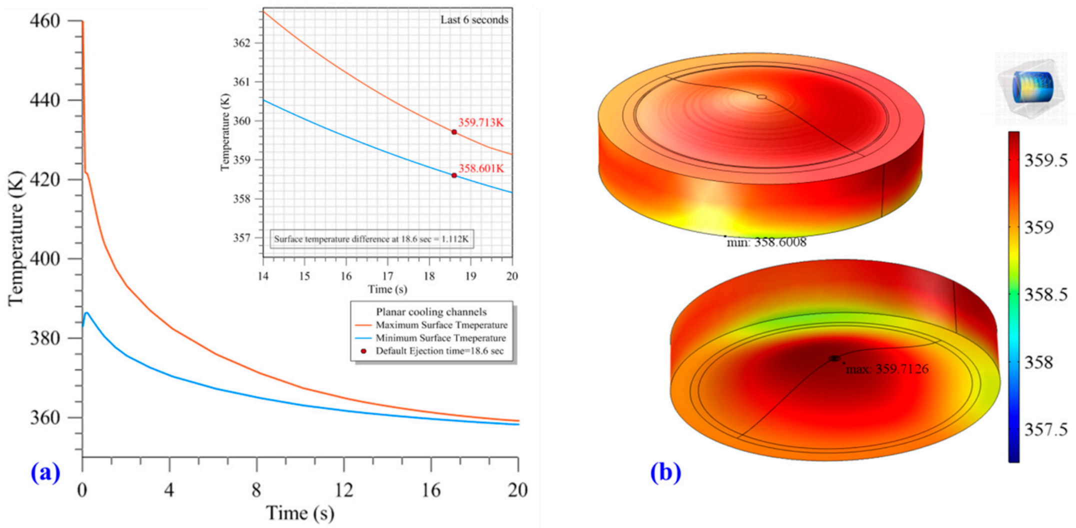


Figure 9. (**a**) Surface temperature of the melt during the cooling stage and (**b**) surface temperature of the melt at the default ejection time of 18.6 s when using the planar conformal cooling channels.

The GBA and RGA algorithms of the SmartDO software were employed for evenly reducing the surface temperature of the melt in the mold cavity. The objective function of the two algorithms converged to a minimum value in the optimization procedure (Figure 10). The objective function value of the GBA was 19.78, whereas that of the RGA was 16.54. The optimized design parameters obtained using these two algorithms are displayed in Figure 11. By using these design parameters (Table 2), two conformal cooling channels with different geometric layouts could be created and imported into COMSOL to simulate the cooling process. The cooling efficiency and improvement in the lens temperature distribution were compared between the GBA- and RGA-optimized channels.

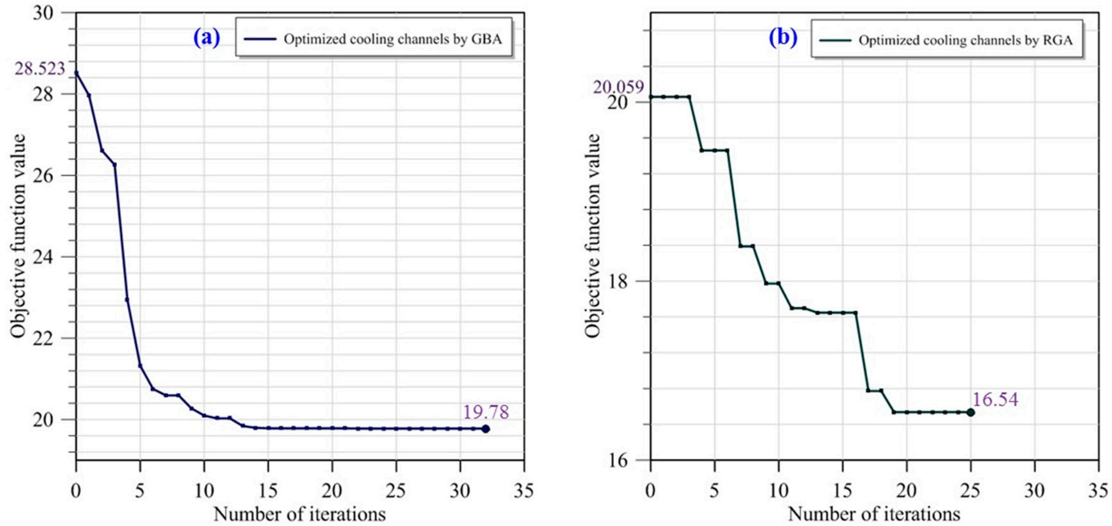


Figure 10. History of the objective function evolved from: (**a**) the GBA and (**b**) RGA during optimization.

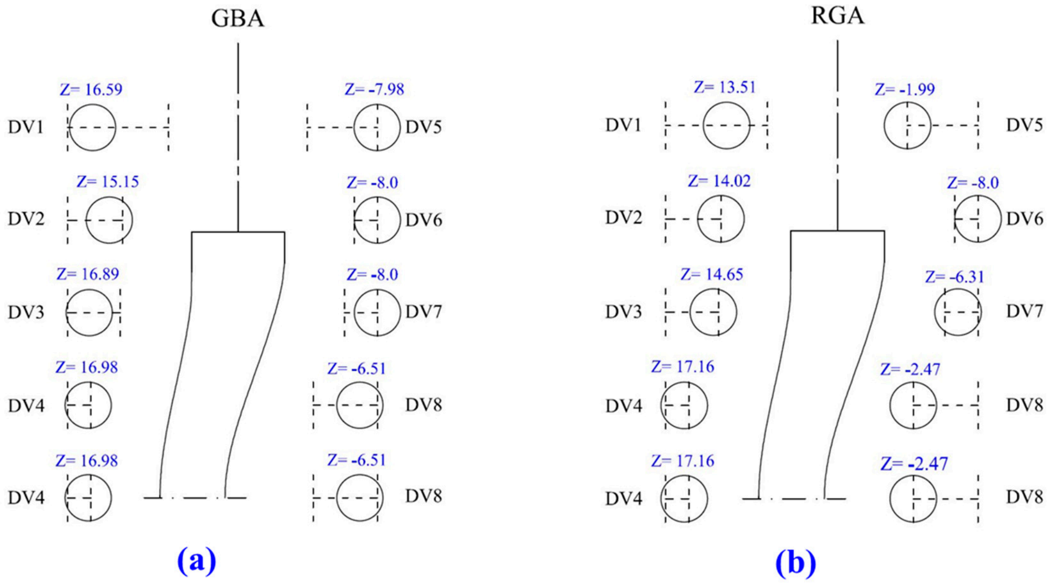


Figure 11. Optimized DVs obtained from: (**a**) the GBA and (**b**) RGA.

Table 2. The optimized DVs in Figure 11 were obtained from the GBA and RGA.

Optimized Parameters	DV1	DV2	DV3	DV4	DV5	DV6	DV7	DV8
Results of GBA	16.59	15.15	16.89	16.98	−7.98	−8.00	−8.00	−6.51
Results of RGA	13.51	14.02	14.65	17.16	−1.99	−8.00	−6.31	−2.47

The conformal cooling channels designed using the GBA were used to simulate the cooling process. The results indicated the variations in the maximum and minimum surface temperature of the melt in the mold cavity, as displayed in Figure 12a. For the planar conformal cooling channel, the default maximum surface temperature for the ejected lens was set as 359.713 K. For a temperature of 359.713 K, the ejection time for the GBA-optimized conformal cooling channels was 16.9 s. However, according to the cooling time suggested by Moldex3D, the lens was ejected at 18.6 s. The temperature distribution for the surface of the lens at 18.6 s is displayed in Figure 12b, with a maximum temperature of 358.906 K, a minimum temperature of 358.173 K, and a temperature difference of 0.733 K. Moreover, the ejection time for the RGA-optimized conformal cooling channels was 14.55 s (Figure 13a). The temperature distribution on the lens surface at 18.6 s for the RGA-optimized channels is displayed in Figure 13b, with a maximum temperature of 357.861 K, a minimum temperature of 357.255 K, and a temperature difference of 0.606 K. Thus, after the planar conformal cooling channels were modified, the GBA- and RGA-optimized three-dimensional conformal cooling channels enhanced the cooling efficiency and improved the temperature distribution of the melt in the mold cavity.

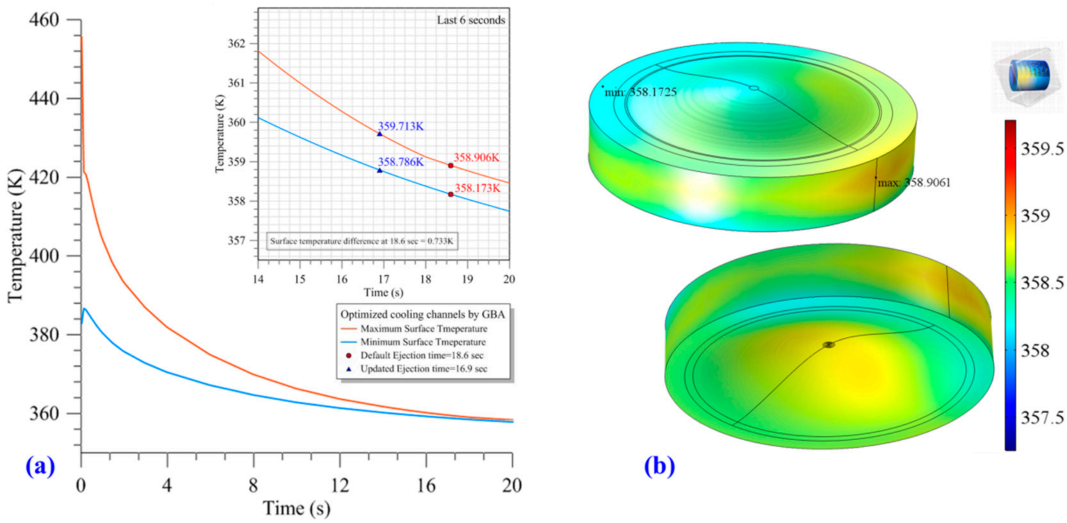


Figure 12. (**a**) Surface temperature of the melt during the cooling stage and (**b**) surface temperature of the melt at the default ejection time of 18.6 s when using the GBA-optimized cooling channels.

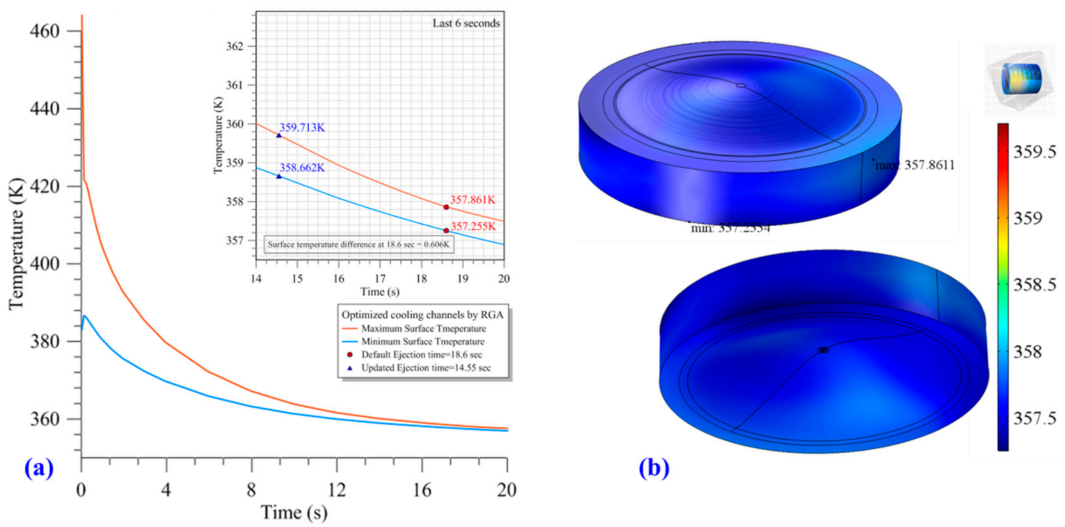


Figure 13. (**a**) Surface temperature of the melt during the cooling stage and (**b**) surface temperature of the melt at the default ejection time of 18.6 s when using the RGA-optimized cooling channels.

3.2. Comparison of the Conformal Cooling Channels Designed by Using Different Algorithms for the Entire Injection Molding Process

The conformal cooling channels designed using the GBA and RGA optimization algorithms were imported into Rhinoceros 3D software, which was used to construct the solid mesh models. The models were then used to execute the entire injection molding simulation with the Moldex3D software. The computation time was approximately 45 min when using two 2.4-GHz Intel Xeon E5-2620 CPUs with 64 GB of RAM. The results indicated that the optimized conformal cooling channels exhibited a lower average surface temperature for the melt compared with that exhibited by the planar conformal cooling channels (Figure 14). At the end of cooling, the surface temperatures simulated using Moldex3D were consistent with those simulated using COMSOL (Figure 9b, Figure 12b, and Figure 13b). If the temperature on the lens surface could be evenly distributed, the thermal-displacement-induced warpage could be improved. Therefore, to evaluate the thermally induced warpage, 18 measured nodes were selected on the lens surface. The locations and numbering of these measured nodes are displayed in Figure 15a. Measured nodes 1–16 were located on the top and bottom edges of the lens and used to calculate the total thermal warpage. The results were used to evaluate the variation in the circularity (roundness) due to the warpage. The average thermal warpage values for the planar conformal cooling channels, GBA-optimized conformal cooling channels, and RGA-optimized conformal cooling channels were 98.296, 98.214, and 98.121 µm, respectively (Figure 15b,c). Thus, the optimized conformal cooling channels exhibited a lower thermal warpage than the planar conformal cooling channels. Moreover, measured nodes 17 and 18 were located at the centers of the top and bottom surfaces of the lens, respectively. These two measured nodes were used to observe the relative thermal warpage in the vertical direction (z-direction). The vertical thermal warpage values for the GBA- and RGA-optimized conformal cooling channels were 21.617 and 21.565 µm, respectively. Both these values were lower than the vertical thermal warpage of the planar conformal cooling channels (21.638 µm).

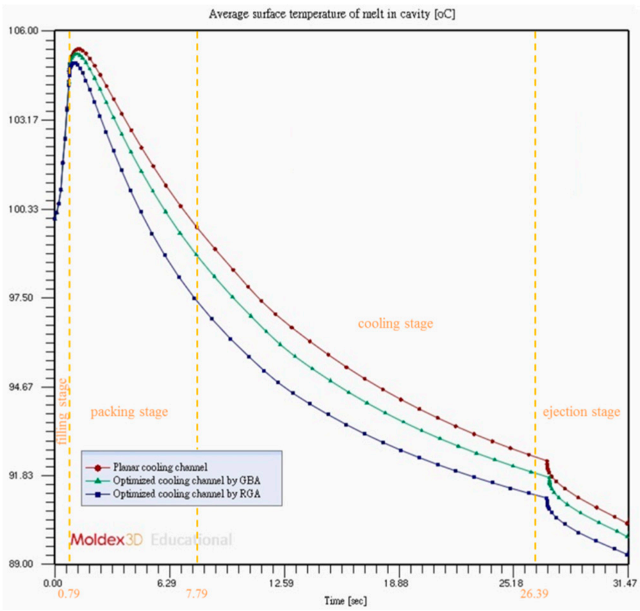


Figure 14. Average surface temperature of the melt in cavity during the complete injection molding cycle with different conformal cooling channels.

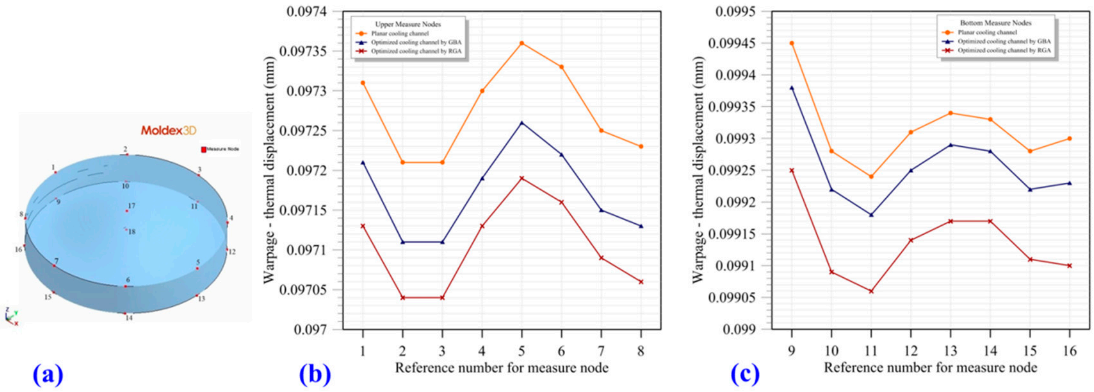


Figure 15. (**a**) Reference numbers and locations of the 18 measured nodes on the lens; (**b**) total thermal warpage values measured using the upper nodes (1–8); and (**c**) total thermal warpage values measured using the bottom nodes (9–16).

When designing cooling channels, the rules for their geometric layout should be considered and the temperature difference between the inlet and outlet should be minimized to prevent the warpage of the lens due to uneven temperature distribution in the mold. Generally, if the product requires high accuracy, the temperature difference between the inlet and outlet should be lower than 2.5 °C [28]. The simulation results of the GBA- and RGA-optimized cooling channels indicated that the temperature difference between the inlet and outlet of the optimized cooling channels was lower than that of the planar conformal cooling channels regardless of the upper and bottom channels (Figure 16). The GBA- and RGA-optimized conformal cooling channels improved the temperature uniformity of the mold.

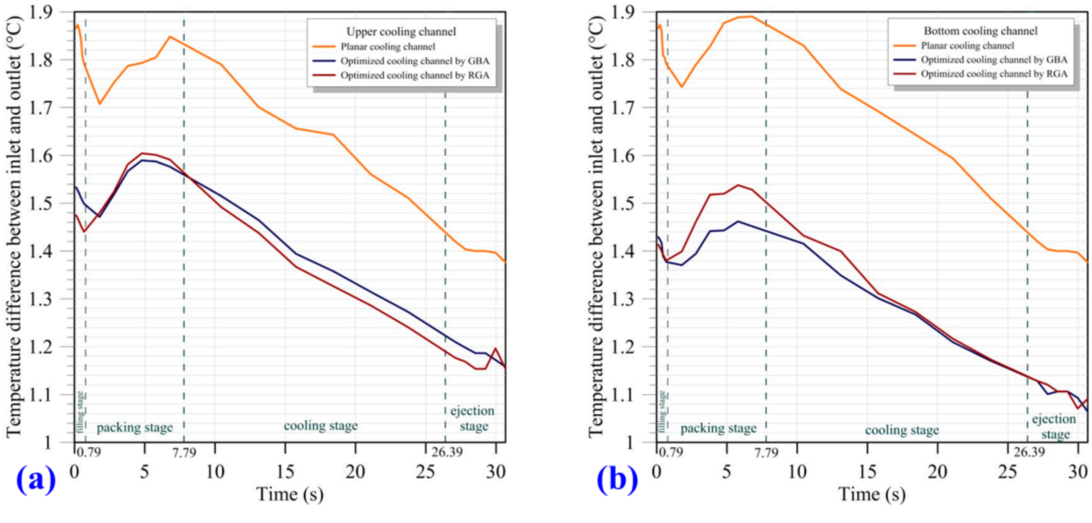


Figure 16. Temperature difference between the inlet and outlet for: (**a**) the upper cooling channel and (**b**) bottom cooling channel.

3.3. Optimal Process Parameters for Injection Molding

After the geometric optimization, the cooling channel with the highest cooling efficiency for the mold and the most even temperature distribution for the lens surface was adopted. Thus, the RGA-optimized cooling channel layout was selected for the DOE to determine the most suitable molding conditions. The optimal process parameters were selected on the basis of the signal/noise (S/N) ratio response. The optical properties of the lenses were compared before and after performing the DOE. Figure 17 illustrates the calculation results of the S/N ratio response from the DOE module of Moldex3D. The total S/N ratio response was obtained by adding the S/N ratio responses from three quality factors under four control factors and five levels (Figure 17d). A high S/N ratio indicates low noise (external influence). According to the Taguchi method, the level with the maximum S/N ratio was selected as the optimal condition [16,29]. Therefore, the optimal combination of control factors, reported in Table 1, and their corresponding levels was A4B2C4D1. The optimal control factor level settings were A4 (melt temperature: 285 °C), B2 (mold temperature: 89.75 °C), C4 (filling time: 0.99 s), and D1 (packing time: 6 s). This combination of process parameters (A4B2C4D1) was used in the injection molding simulation. The optics module of Moldex3D was adopted to predict the birefringence and fringe pattern of the lens. After the DOE analysis, the birefringence of the lens considerably decreased (Figure 18a), which indicated that the residual stress within the material also diminished [16]. Moreover, after the processing optimization, the fringe pattern on the lens resembled concentric circles (Figure 18b). The distributions of the fringe pattern on the optimized molded lens were rarefied near the gate, which implied that the optical properties of the lens had been improved.

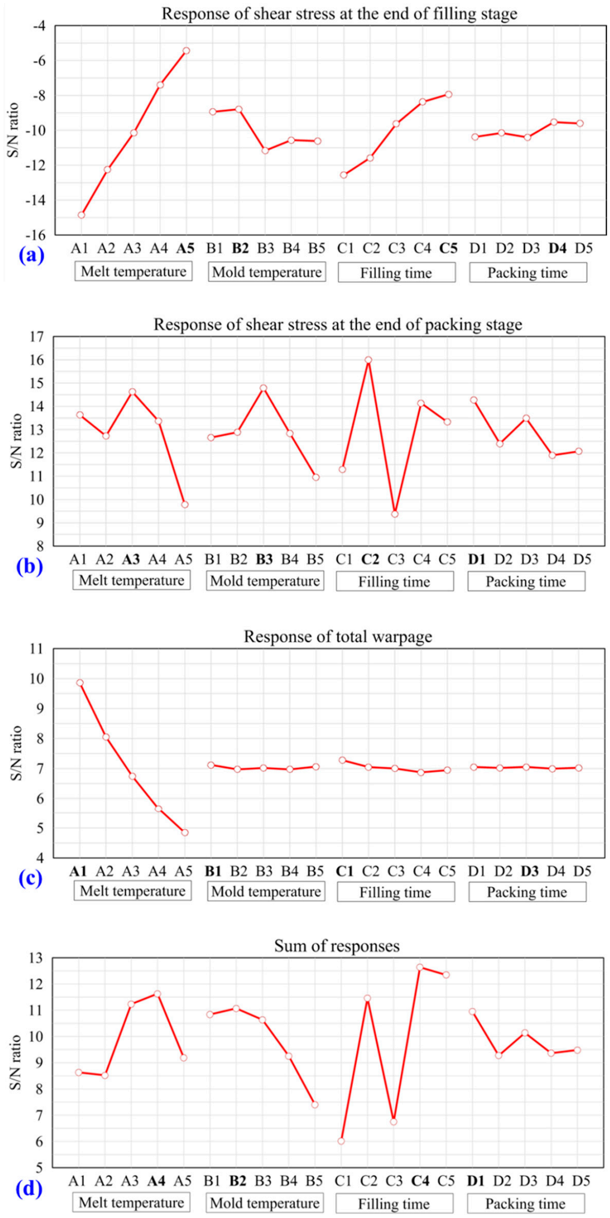


Figure 17. S/N ratios for: (**a**) shear stress at the end of the filling stage; (**b**) shear stress at the end of the packing stage; (**c**) total warpage; and (**d**) sum of responses from (**a**) to (**c**).

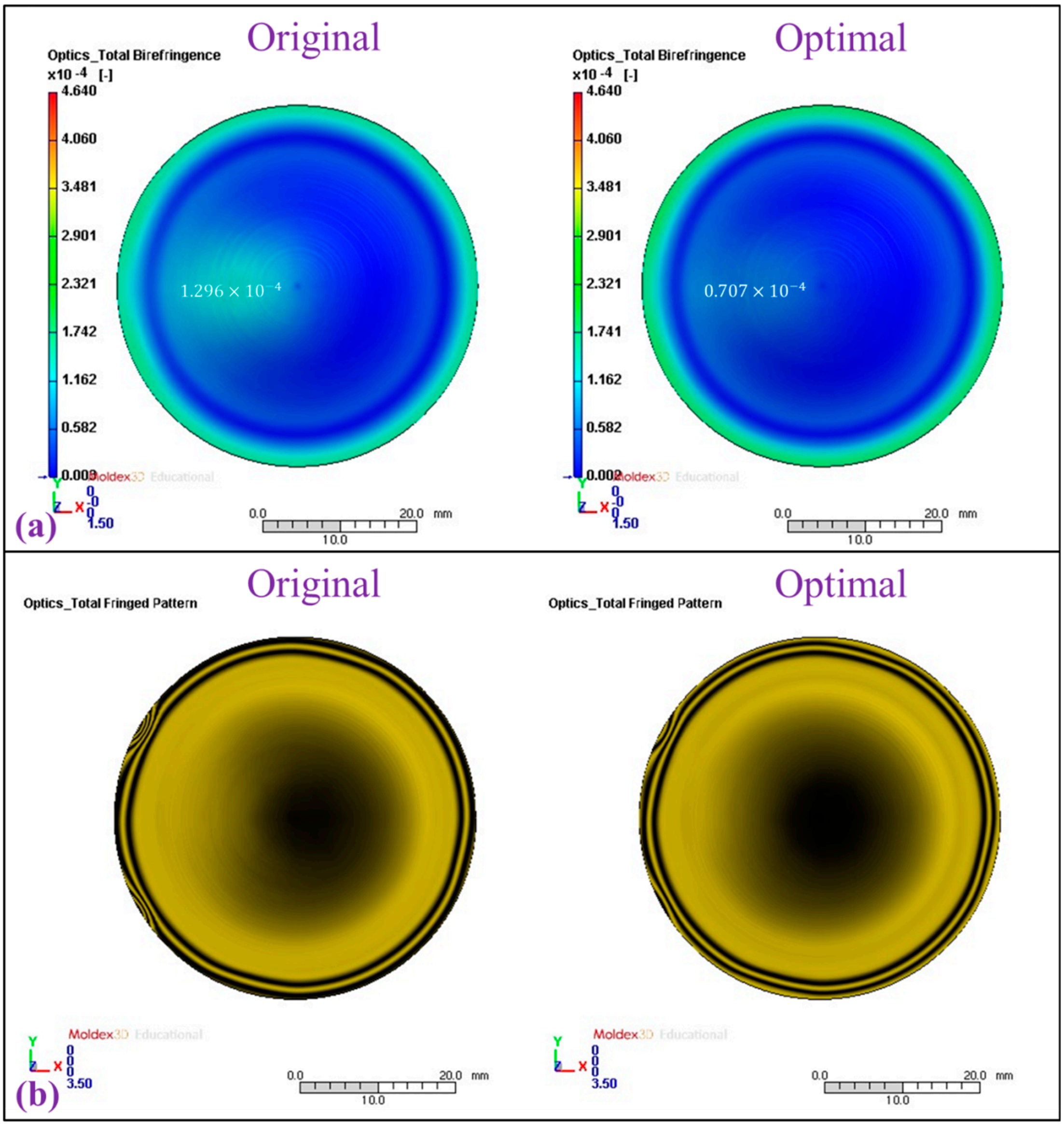


Figure 18. Comparison of the (**a**) birefringence properties and (**b**) fringe patterns before and after the optimization of process parameters.

4. Conclusions

In this study, the GBA and RGA optimization algorithms were used to design the geometric layout of conformal cooling channels. The planar conformal cooling channels had a lens surface temperature difference of 1.112 K with an ejection time of 18.6 s. The GBA-optimized conformal cooling channels reduced the ejection time to 16.9 s and improved the cooling efficiency by approximately 9.14%. The RGA-optimized conformal cooling channels had an ejection time of 14.55 s and improved the cooling efficiency by approximately 21.77%. The GBA-optimized conformal cooling channels exhibited a decrease in the temperature difference on the lens surface from 1.112 to 0.733 K, which was an improvement of 34.08%. Furthermore, the RGA-optimized conformal cooling channel exhibited a decrease in the temperature difference on lens surface from 1.112 to 0.606 K, which was an improvement of 45.5%.

During the entire injection molding cycle, the planar conformal cooling channels exhibited the highest average surface temperature of the melt, followed by the GBA-optimized conformal cooling channels. The RGA-optimized conformal cooling channels exhibited the lowest average surface temperature of the melt. Furthermore, the distribution of the thermal-displacement-induced warpage of the lens could be used as an index to evaluate whether the cooling channel system was suitably designed. The GBA- and RGA-optimized conformal cooling channels exhibited improvements of 0.18% and 0.52%, respectively, in average thermal warpage of measured nodes as compared with the planar conformal cooling channels. However, thermally induced warpage still could not be compared with experimental results because of insufficiently available experimental data.

In summary, the RGA-optimized conformal cooling channels had the highest cooling efficiency for the mold and a superior temperature distribution for the melt in the mold cavity, which reduced thermally induced warpage. Therefore, using RGA-optimized conformal cooling channels shortened the development time and considerably improved the quality of the plastic lens. DOE was used to evaluate the effect of manufacturing process parameters on the optical properties. The optimal process parameters reduced the birefringence and improved the shape of the fringe pattern.

Recently, three-dimensional printing and additive manufacturing have attracted tremendous attention worldwide. Among these technologies, the additive manufacturing of metal powder has quickly developed into a feasible technique for fabricating metal parts. Additive manufacturing typically uses a high-energy electron beam or laser beam to sinter or melt the metal powder to form the solid parts [30,31]. This method can be used to fabricate mold cores for plastic product manufacturing and construct three-dimensional conformal cooling channels [32,33]. The methods presented in this study can serve as useful references to obtain optimized cooling channel layouts and injection molding conditions for the initial stages of mold development. Mold tooling with conformal cooling channels can be used to improve the cooling efficiency and temperature distribution of the melt, which solves warpage issues. Optimal injection molding conditions can improve product quality. By controlling key molding conditions, the product yield rate can be enhanced, and the product cost can be decreased.

Supplementary Materials: The following are available online at http://www.mdpi.com/2076-3417/9/20/4341/s1. The integration of the COMSOL finite element model and SmartDO genetic optimization algorithm is available in the online version.

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